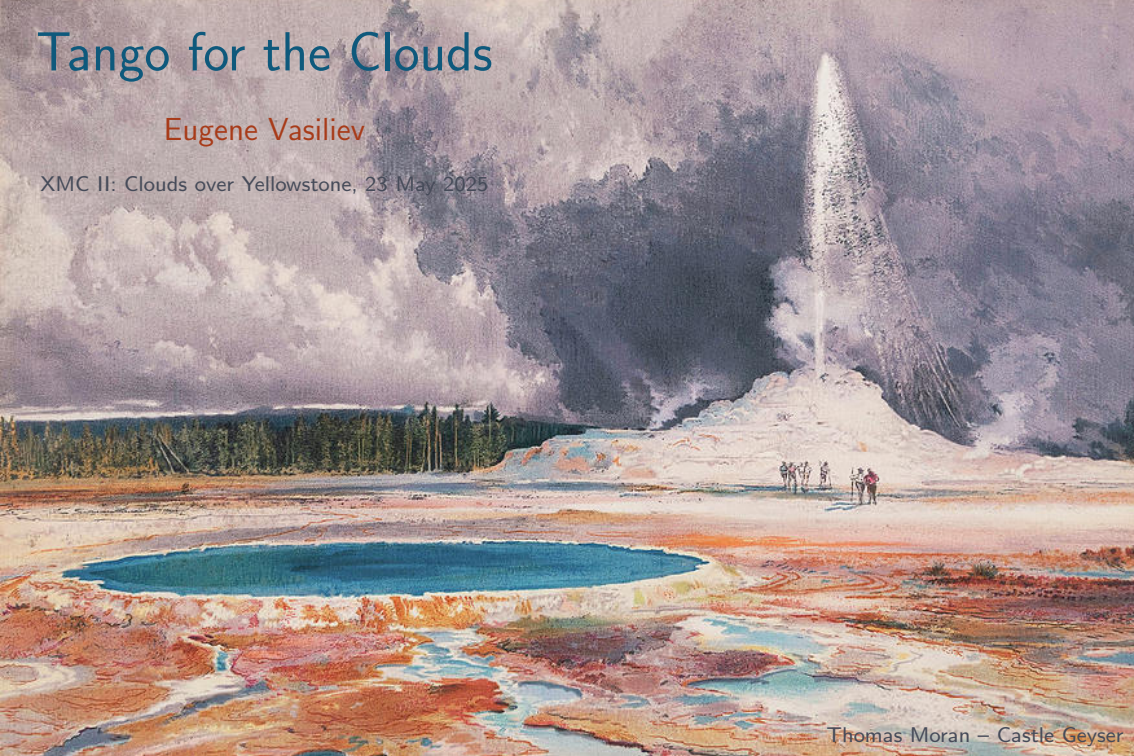
Tango for the Clouds

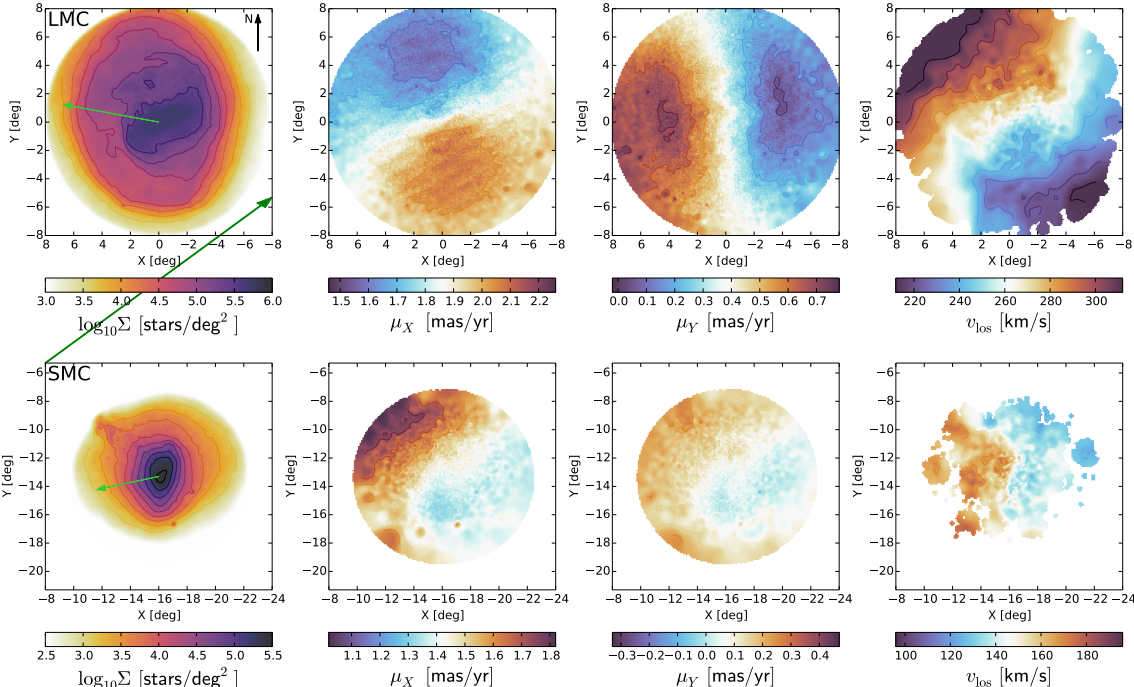
Eugene Vasiliev

XMC II: Clouds over Yellowstone, 23 May 2025

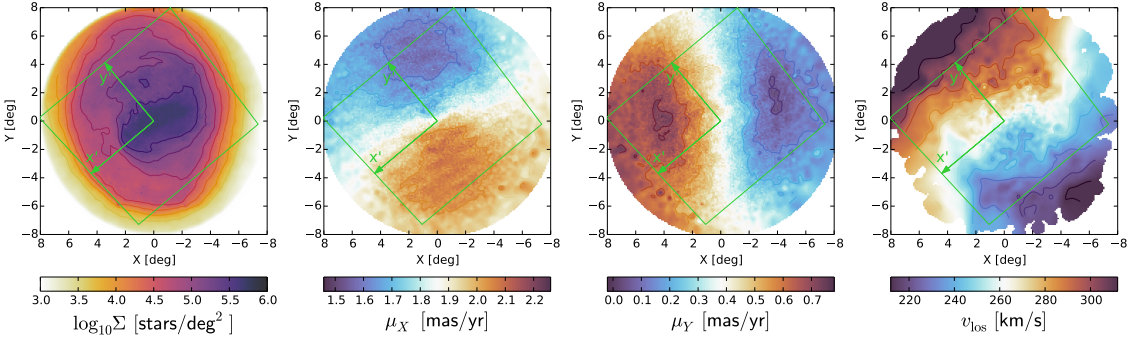


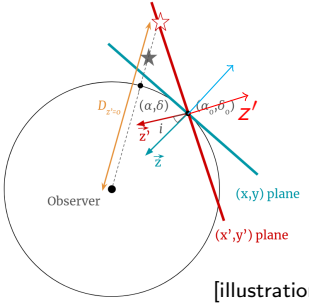
Thomas Moran – Castle Geyser

Observed kinematic maps (from *Gaia* DR3)



Kinematic deprojection of the LMC



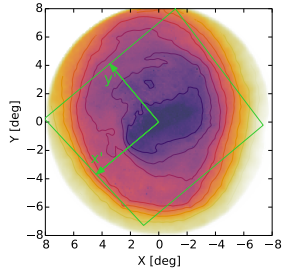


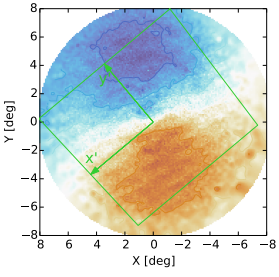
thin-disc approximation:
assume that all stars are located in one plane ($z' = 0$);
determine its orientation (inclination i, line-of-nodes Ω)
by minimising the vertical velocity $\overline{v_{z'}}$.

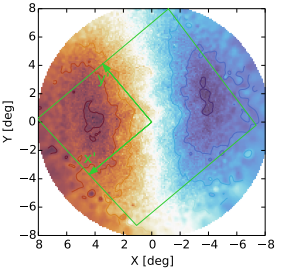
[illustration from Jiménez-Arranz+ 2023]

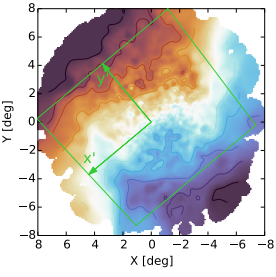
Kinematic deprojection of the LMC

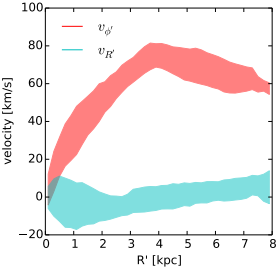
$i = 27°, \Omega = 310°$

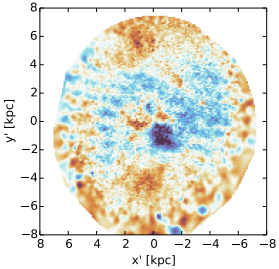


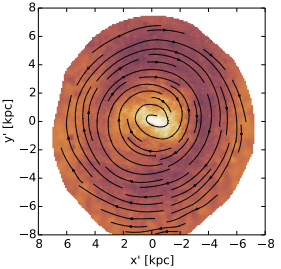


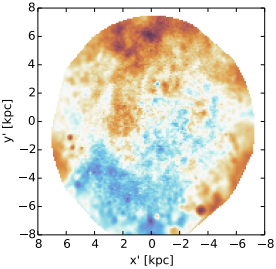






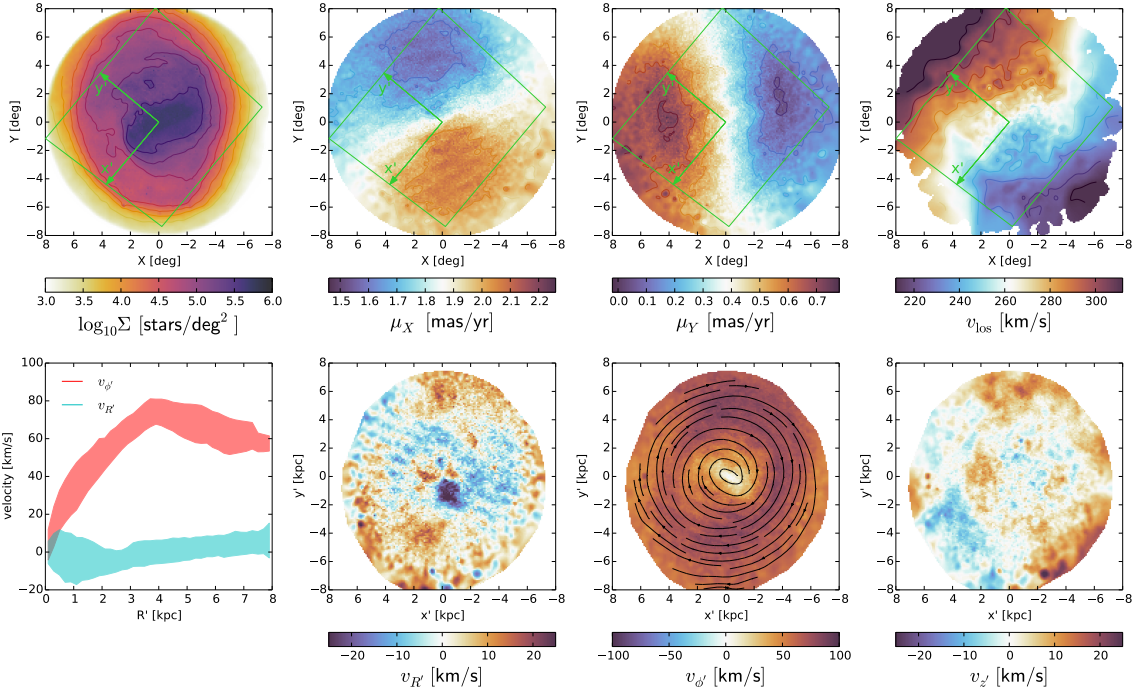






Kinematic deprojection of the LMC

$i = 27°, \Omega = 320°$



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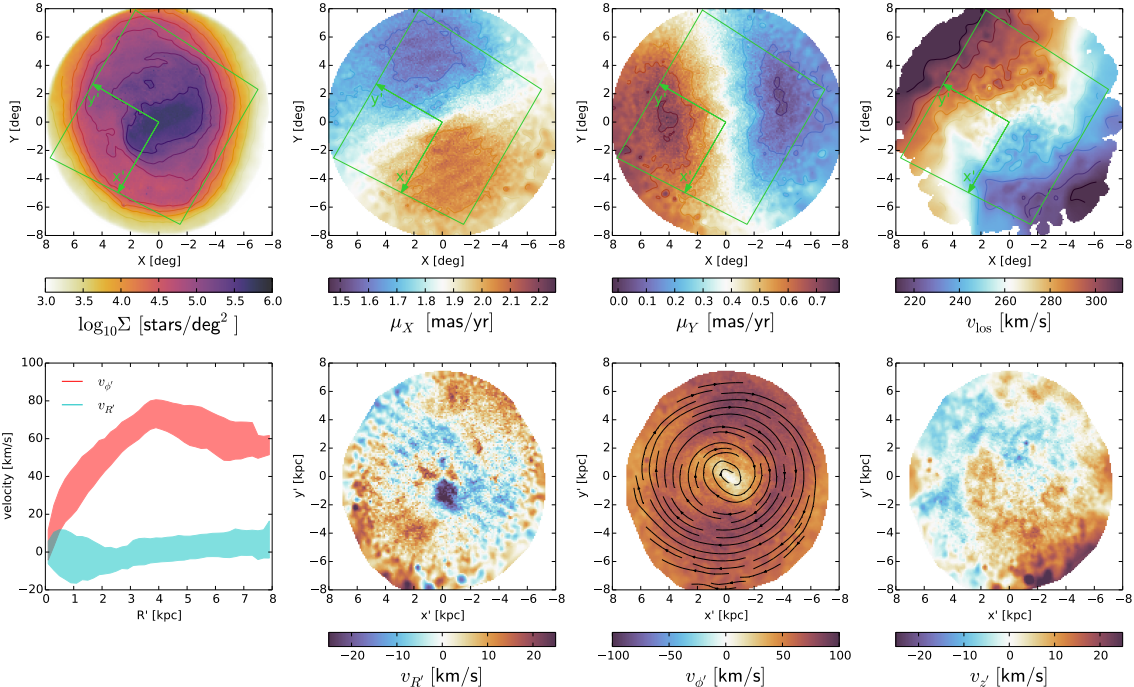
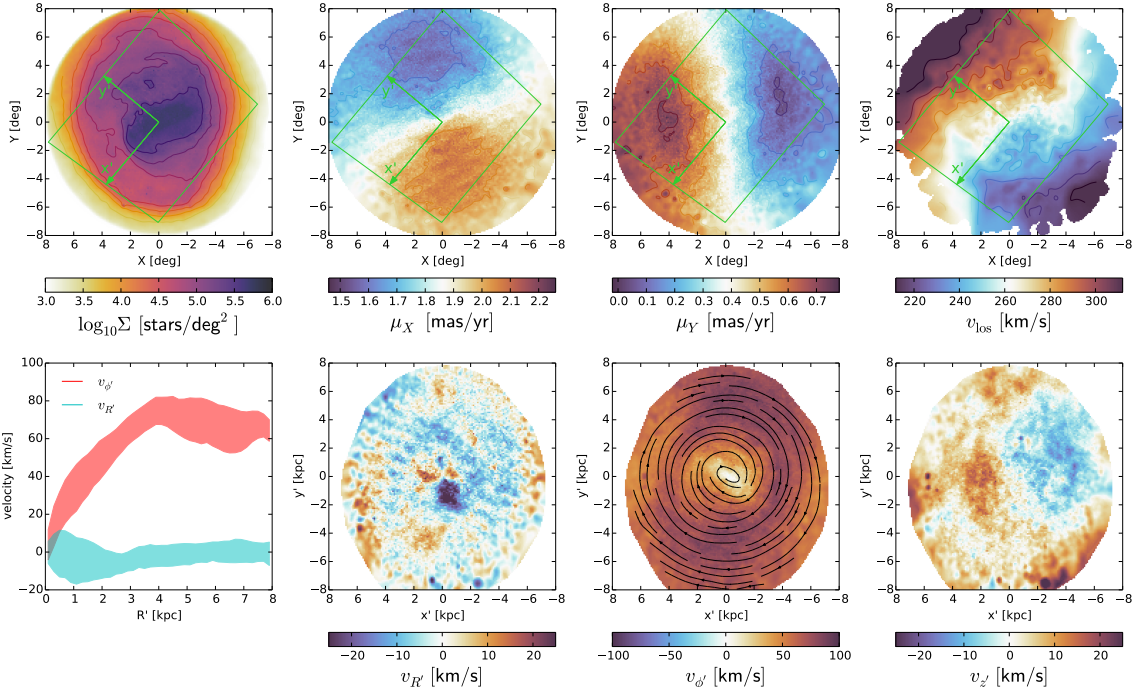


Kinematic deprojection of the LMC

$i = 34°, \Omega = 320°$



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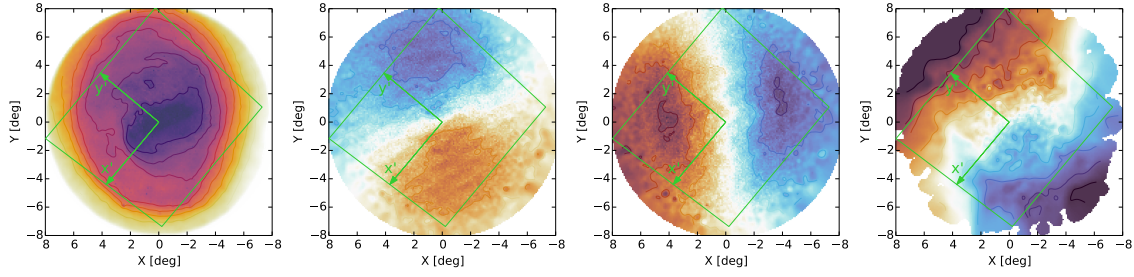

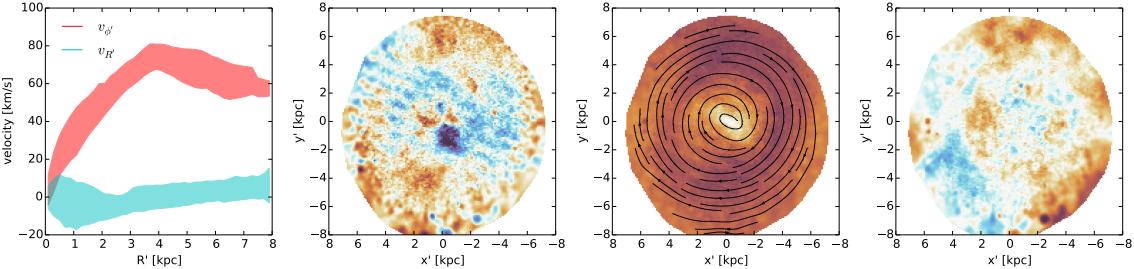

cf. $i = 24°, \Omega = 327°$

[Jiménez-Arranz+ 2025]

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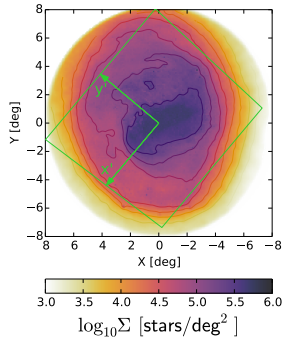
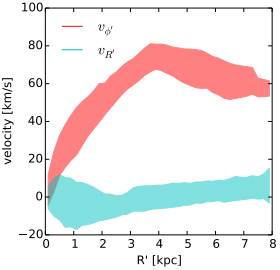
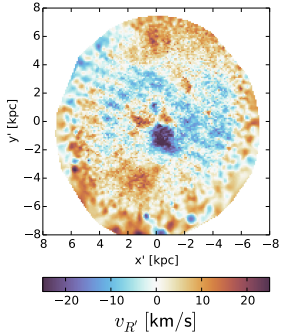
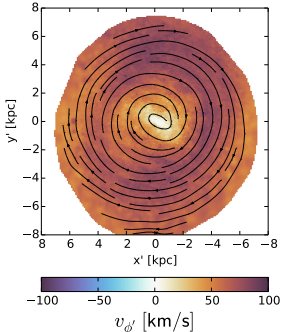
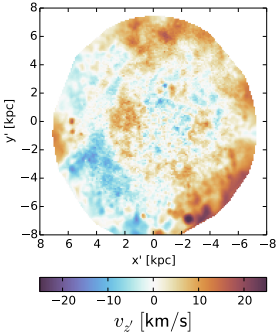


- apparent disc major axis misaligned with the line of nodes
- residual $\overline{v_{z'}} \sim$ a few km/s even in the best orientation
- clear (and asymmetric) quadrupole in $\overline{v_{R'}}$ in the bar region
- $\overline{v_{R'}} > 0$ in the outer parts of the disc (for $i = 27°$)









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

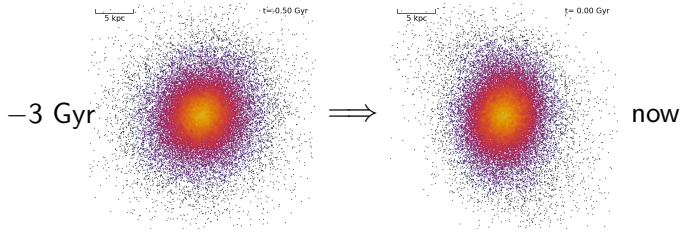
- current location and velocity of both Clouds
- orientaion of the LMC disc and the bar
- kinematic features of the LMC disc: $\overline{v}_\phi(R')$, bar-induced quadrupole in $\overline{v}_{R'}$, velocity dispersions in all three components...
- geometry of the SMC (extended depth along the line of 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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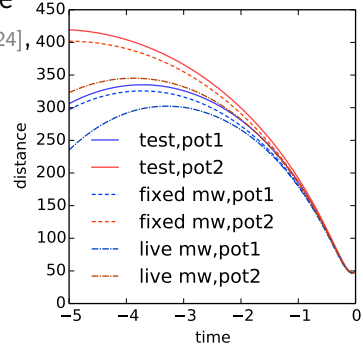
\+ a workable iterative approach for fitting the orbit of one or two galaxies has been developed [Vasiliev+ 2021, 2023, 2024], but it needs to be generalised to fit all three..

illustration of fitting the orbit of the LMC around the MW in two potentials (lighter/heavier MW) and three cases:
test-particle LMC;
live LMC but fixed MW potential,
and both galaxies moving/deforming



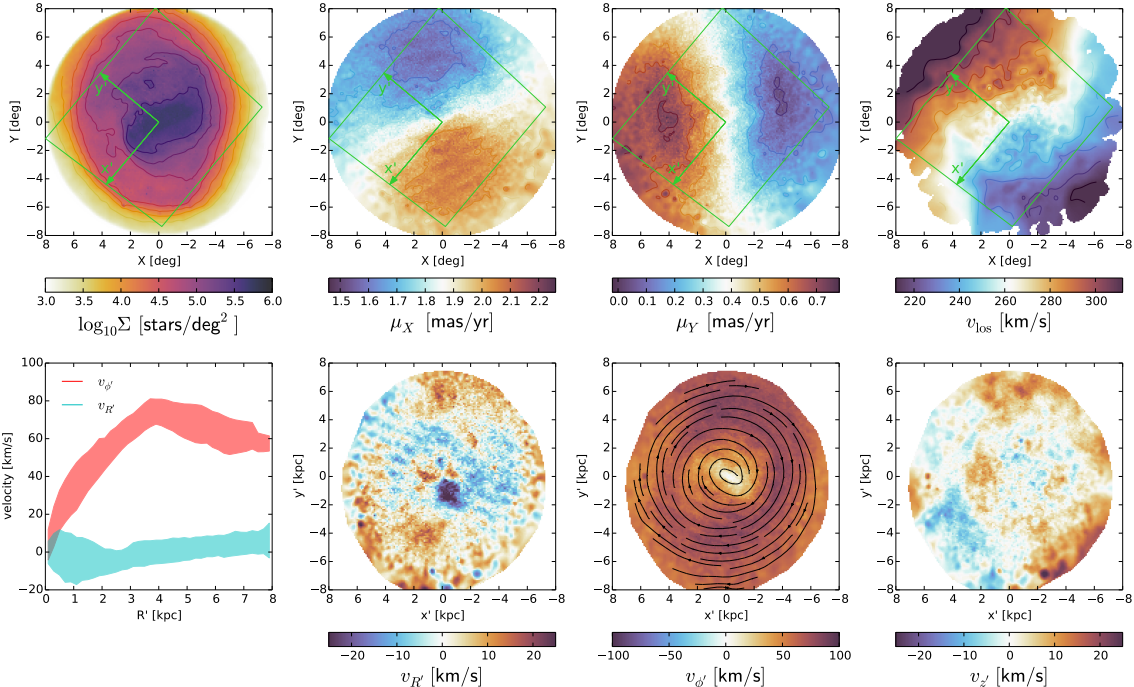
Modelling approaches (2)

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

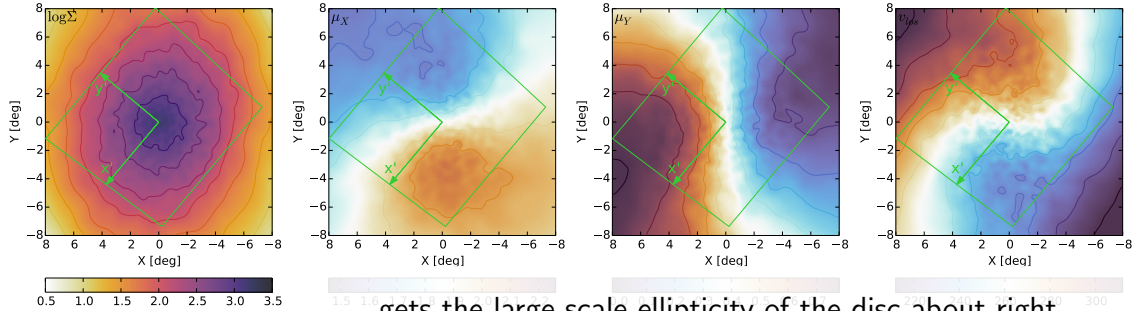
sit between test-particle sims and SCF (self-consistent field) method;
integrate particle trajectories and update the potential once in a while,
using a low-order multipole expansion.

+ 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

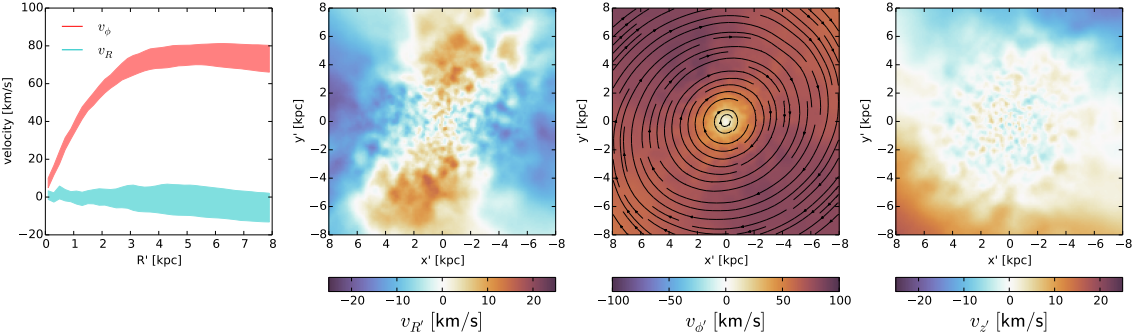
Observational kinematic maps of the LMC



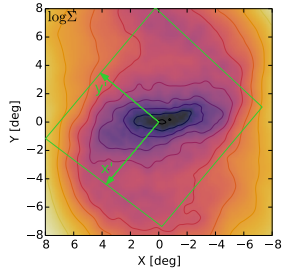
Simulation of LMC passing around MW (no SMC, TP)

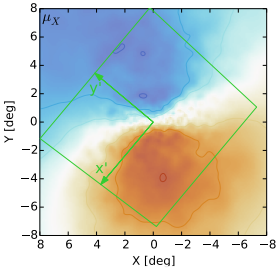


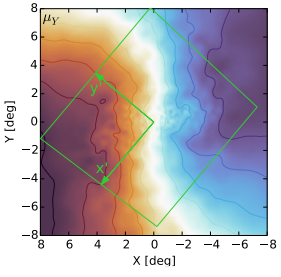
gets the large-scale ellipticity of the disc about right

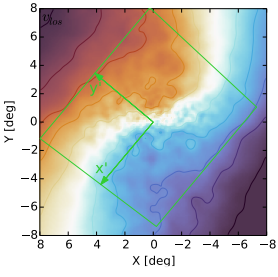


Simulation of LMC passing around MW (no SMC, RNB)

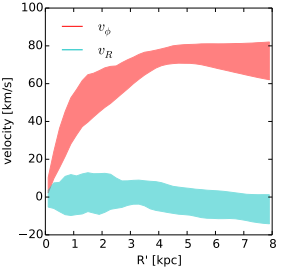


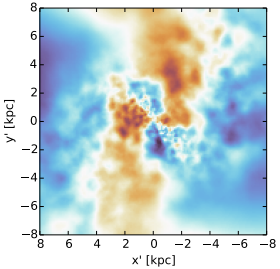


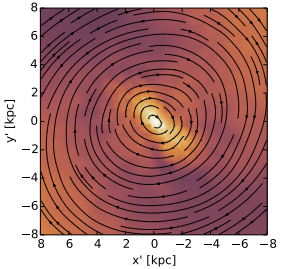


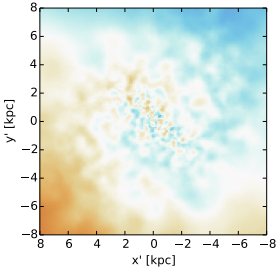


forms a bar (independently of the MW tidal perturbation!); qualitatively matches the quadrupole pattern in $\overline{v}_{R'}$

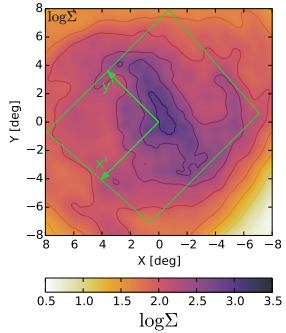


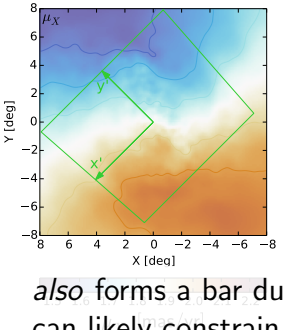


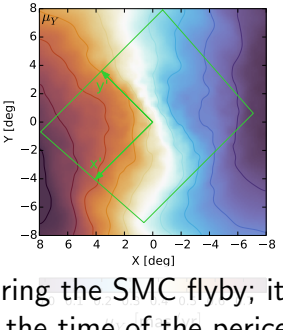


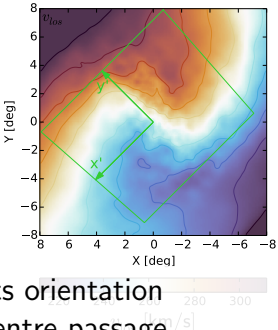


Simulation of LMC perturbed by SMC flyby (no MW, NB)

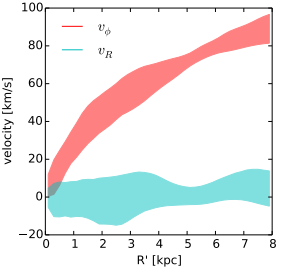


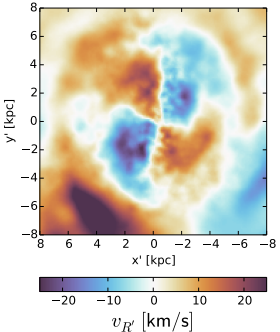


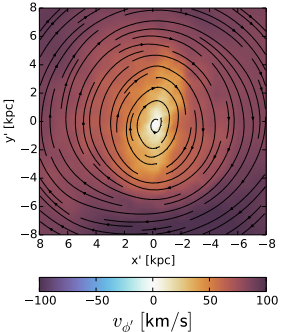


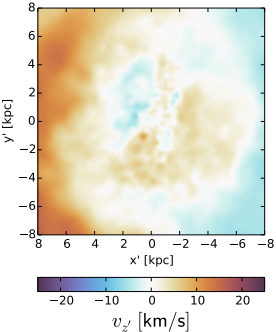


also forms a bar during the SMC flyby; its orientation can likely constrain the time of the pericentre passage



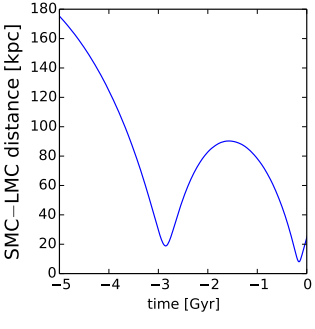






Past orbit and constraints on the masses of all three galaxies

Is SMC even bound to LMC at early times?
or how many pericentre passages around the LMC it has completed?



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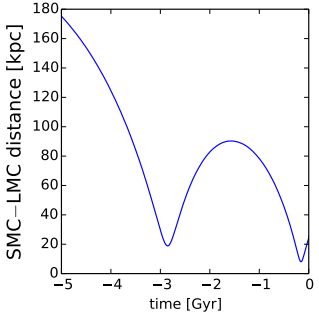
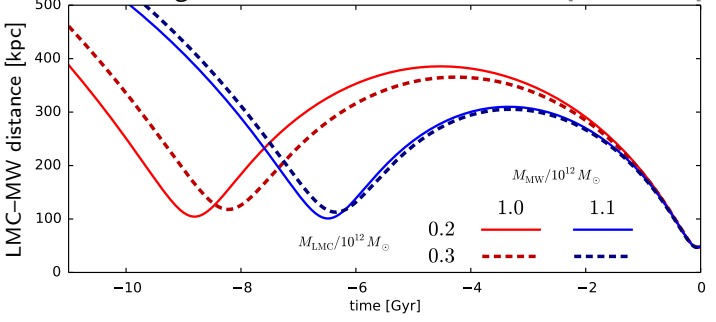
Could it remain bound to the LMC in the second-passage scenario, in which the LMC had another encounter with the MW at a distance ~ 100 kpc?

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



Dear Magellanic Clouds, welcome back! [Vasiliev 2024]



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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