Perturbations and disequilibrium

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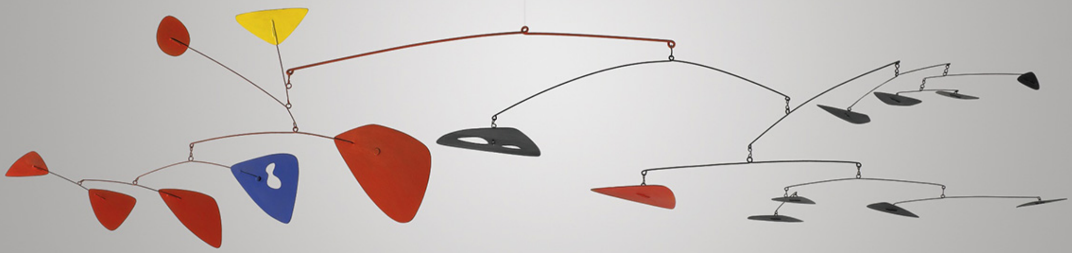
Perturbation theory



A. Calder

Perturbation theory in action space

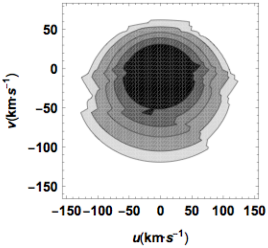
$$
\begin{aligned}
f(\mathbf{J},\boldsymbol{\theta},t) &= f_0(\mathbf{J}) + \epsilon f_1(\mathbf{J},\boldsymbol{\theta},t),\\
H(\mathbf{J},\boldsymbol{\theta},t) &= H_0(\mathbf{J}) + \epsilon H_1(\mathbf{J},\boldsymbol{\theta},t) = H(\mathbf{x},\mathbf{v},t) \equiv \Phi_0(\mathbf{x}) + \epsilon\Phi_1(\mathbf{x},t) + \tfrac{1}{2}v^2.
\end{aligned}
$$

Linearized Vlasov / collisionless Boltzmann equation:

$$
0 = \frac{\partial f}{\partial t} + [H, f] \approx \frac{\partial f_1}{\partial t} + \frac{\partial f_1}{\partial \boldsymbol{\theta}}\frac{\partial H_0}{\partial \mathbf{J}} - \frac{\partial f_0}{\partial \mathbf{J}}\frac{\partial \Phi_1}{\partial \boldsymbol{\theta}}.
$$

$\Phi_1(\mathbf{x},t)$ is the external perturbation augmented with internal self-gravity (diverges at resonances!).

For the given f_0 and Φ_1, one may compute the perturbed DF $f_1(\mathbf{J},\boldsymbol{\theta},t)$ [e.g., Monari+ 2016, 2017, 2018] –
so far has only been done under epicyclic approximation, but a Stäckel generalization is possible.

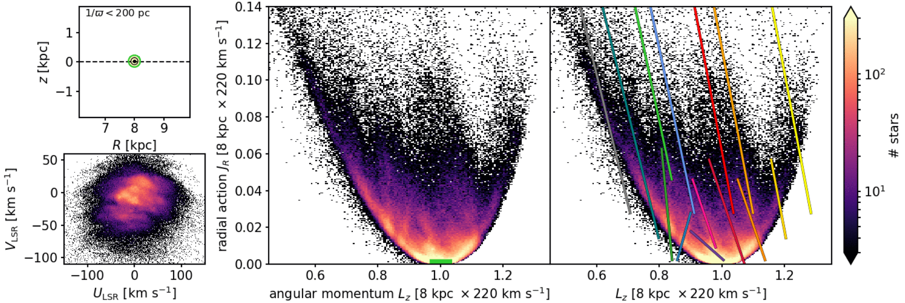


Non-axisymmetries and resonances in the galactic disc

Motion in the rotating frame specified by the bar pattern speed Ω_b

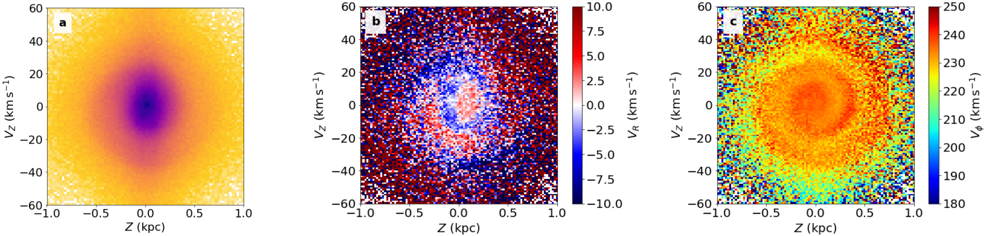
resonance condition: $m\,(\Omega_\phi - \Omega_b) = k$, for some integer k, m

$k = 0$: corotation resonance; $k = \pm 1$: inner/outer Lindblad resonance



[Trick+ 2018]

Vertical perturbations and the disc seismology

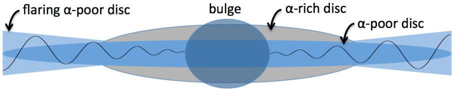


Phase-space spiral [Antoja+2018]

perturbation from a $(2-10)\times 10^{10}\,M_\odot$ satellite crossing the disk $200-400$ Myr ago (Sgr dSph?)

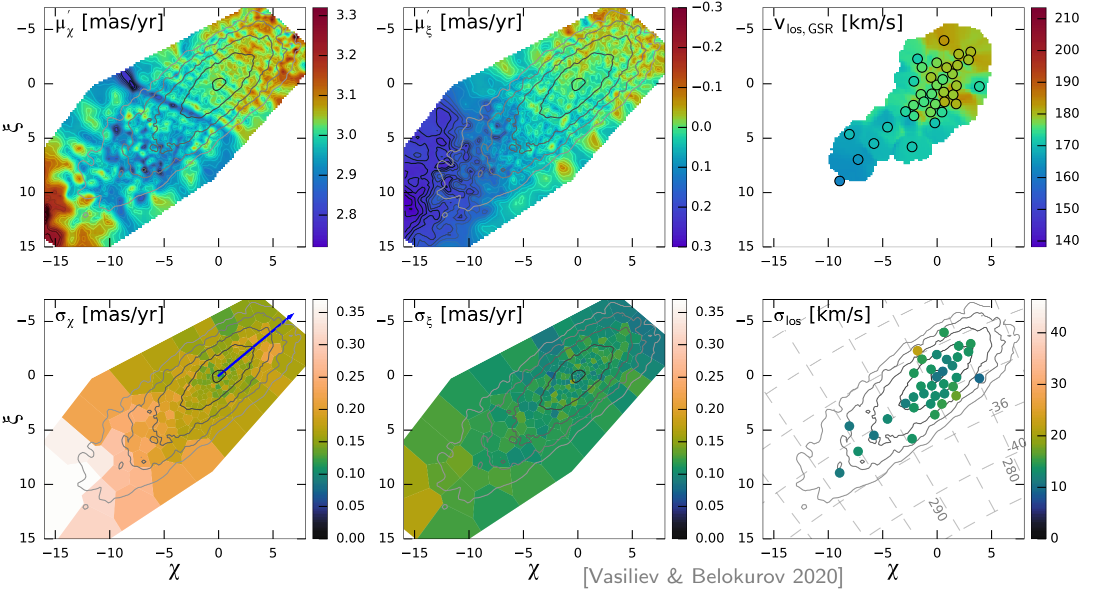
[Laporte+ 2018, 2019; Darling & Widrow 2018; Binney & Schönrich 2018; Bland-Hawthorn+ 2018; Li & Shen 2019]

Alternative scenario: bar buckling [Khoperskov+ 2019]



Modelling of a strongly tidally perturbed galaxy: Sgr dSph

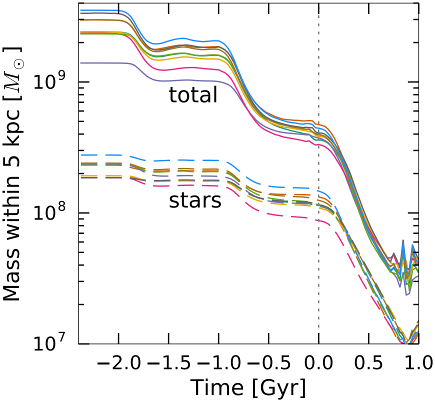
3d kinematics maps from $\sim 250\,000$ Gaia stars and ~ 3300 stars with spectroscopy

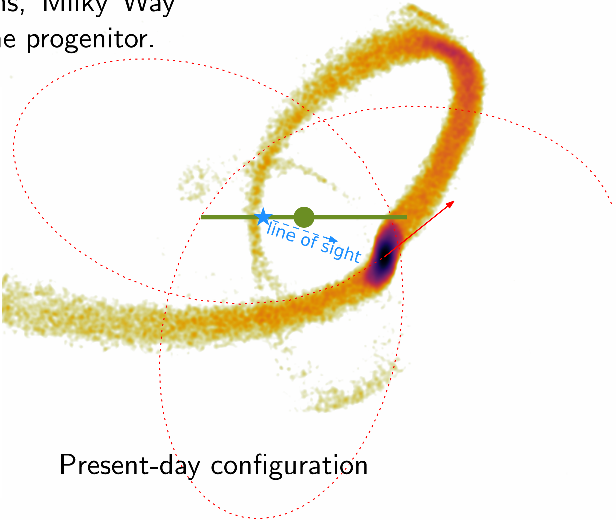


[Vasiliev & Belokurov 2020]

Modelling of a strongly tidally perturbed galaxy: Sgr dSph

Run a large suite of N-body simulations of a disrupting satellite, fitting the present-day morphology, kinematics, and properties of the tidal stream, varying the orbital initial conditions, Milky Way potential, and initial structure of the progenitor.





Present-day configuration

Modelling of a strongly tidally perturbed galaxy: Sgr dSph

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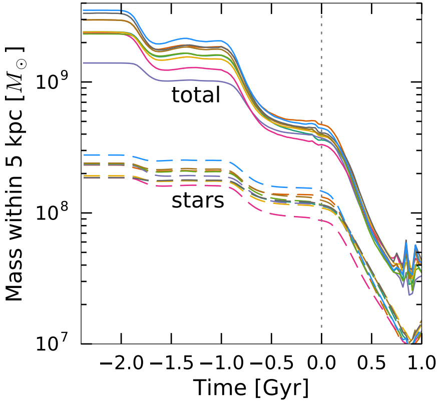
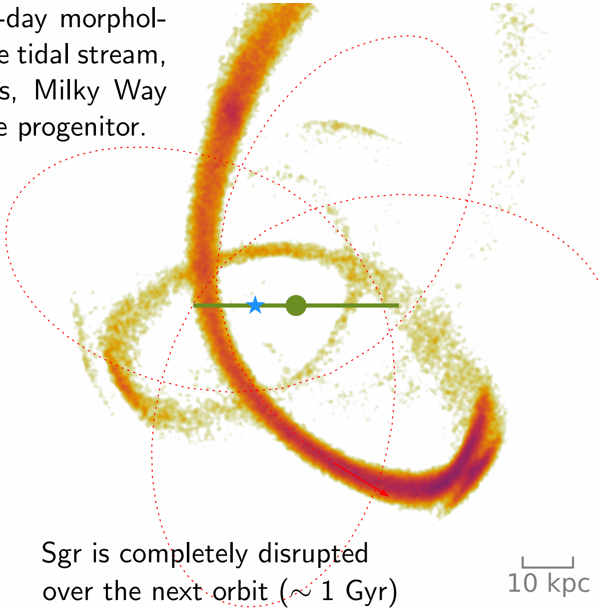
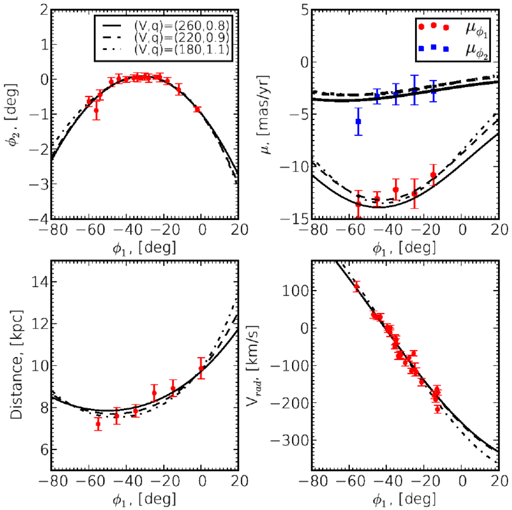


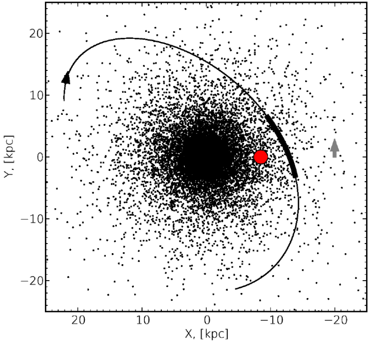


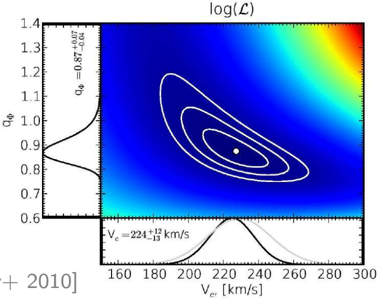
Sgr is completely disrupted over the next orbit ($\sim$ 1 Gyr)

Constraining the Galactic potential with stream orbits

GD-1 stream: old, thin, no remnant







[Koposov+ 2010]

Constraining the Galactic potential with stream orbits

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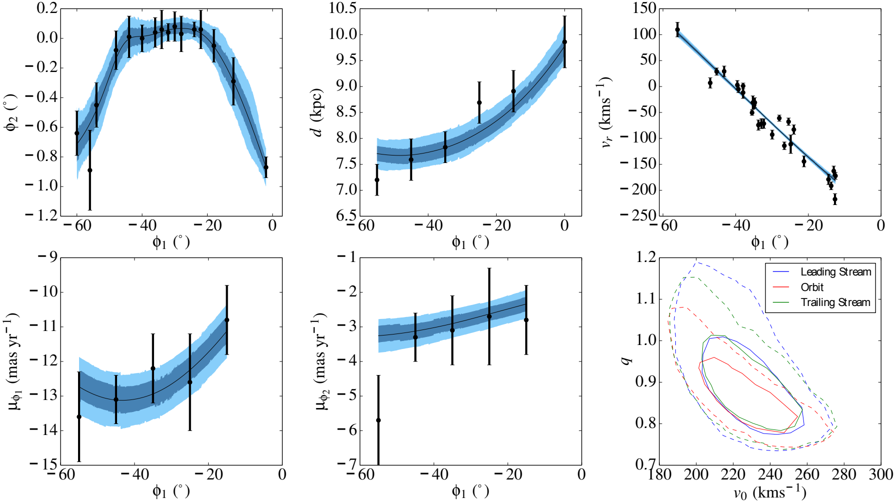

[Bowden+ 2015]

Constraining the Galactic potential with stream orbits

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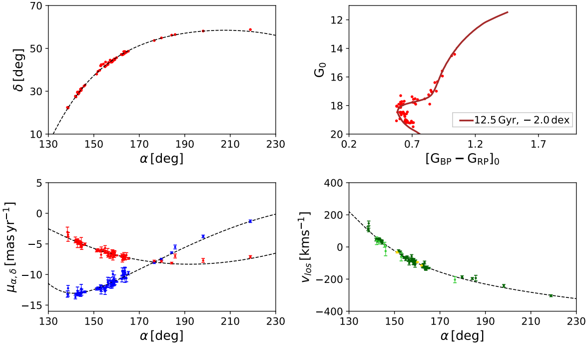
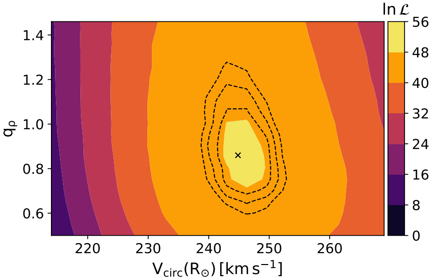
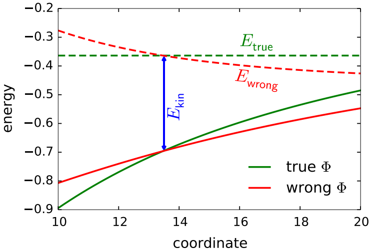


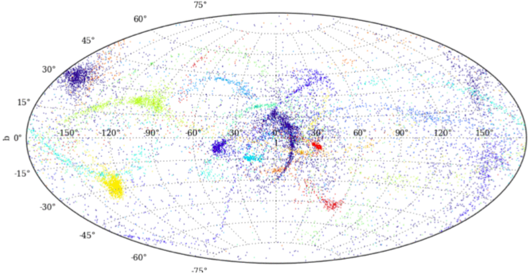


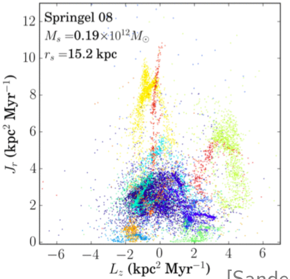
[Malhan&Ibata 2018]

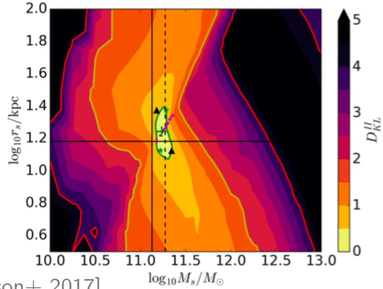
Constraining the Galactic potential by action-space clustering

Another approach is to minimize the spread of stream members (or entropy) in the space of integrals of motion (e.g. $E - L$ or actions).





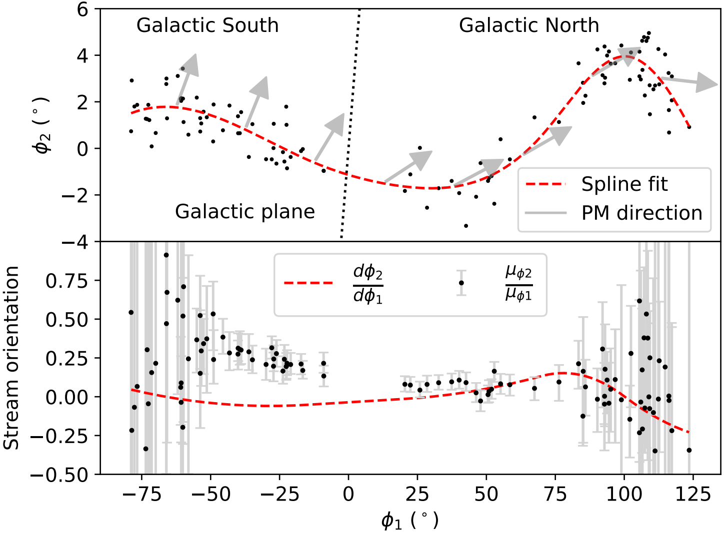




[Sanderson+ 2017]

Stream deflection by the Large Magellanic Cloud

The Orphan stream: no remnant, spans $> 200^\circ$ on the sky



Sky-plane velocity is misaligned with the stream track

[Erkal+ 2019]

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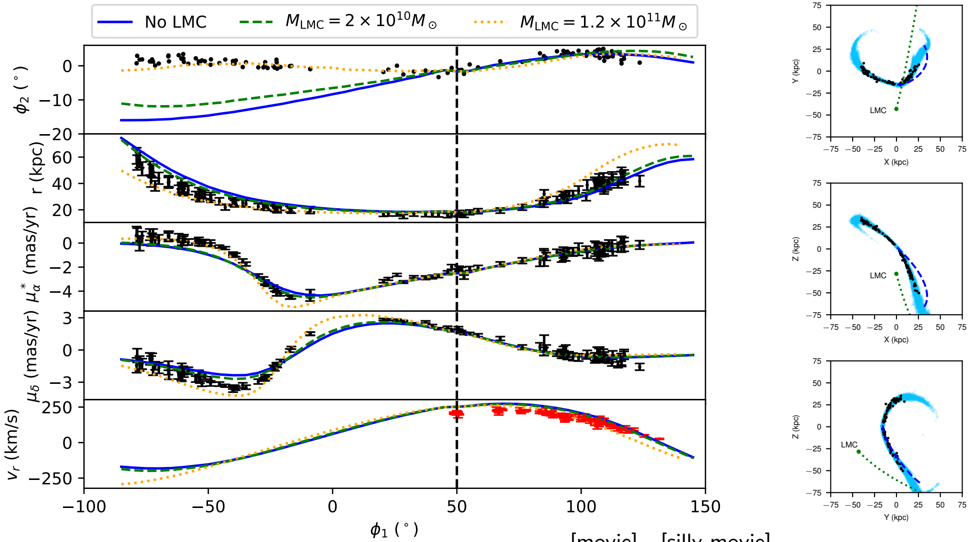


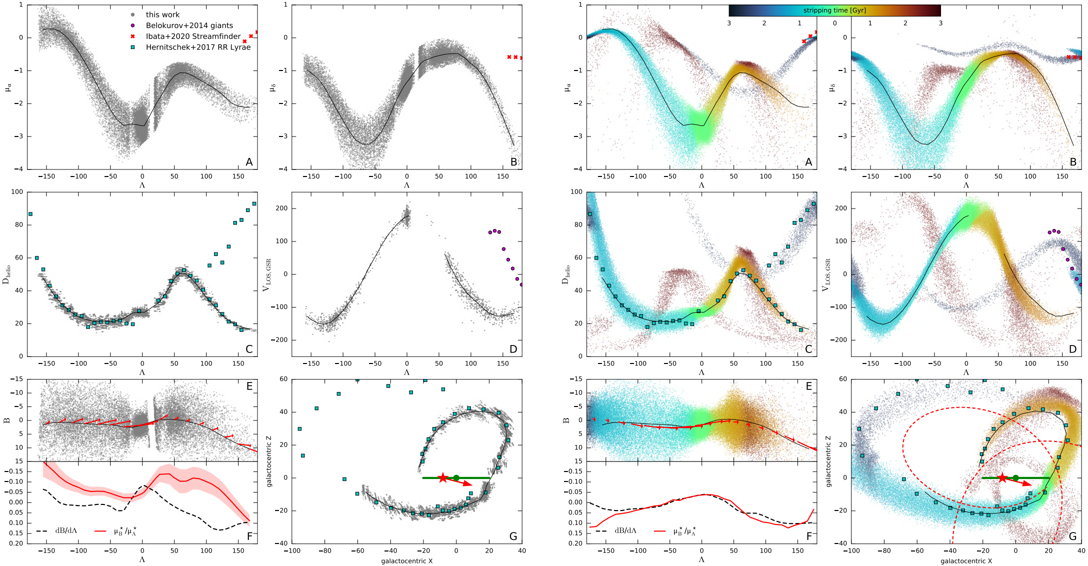
[movie] [silly movie]

Stream can be fitted only when taking LMC into account

[Erkal+ 2019]

Stream deflection by the Large Magellanic Cloud

The Sagittarius stream: thick, complex, spans $> 360^\circ$ on the sky



observations model without LMC [Vasiliev+ 2020]

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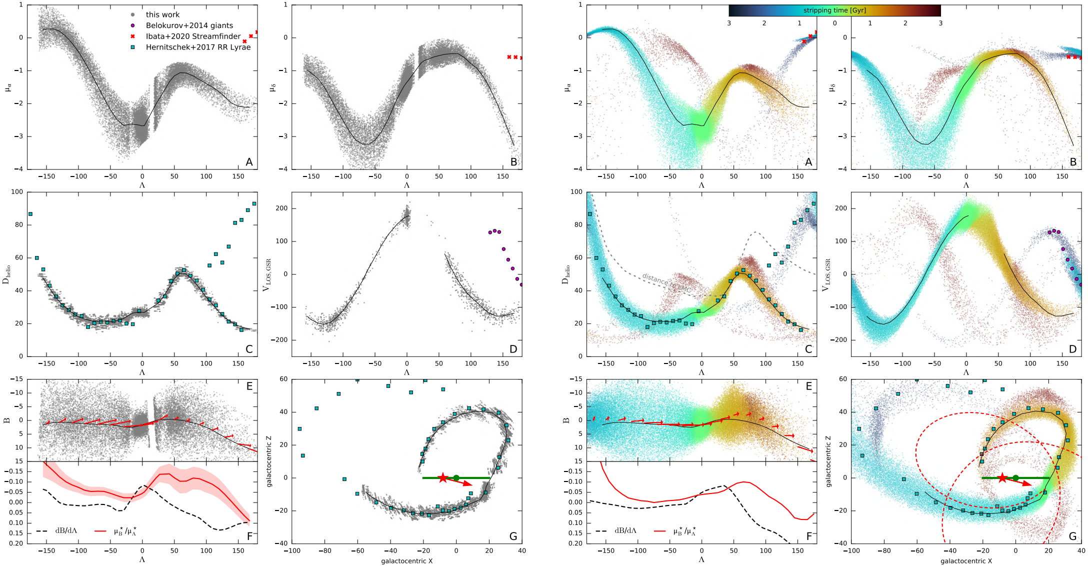
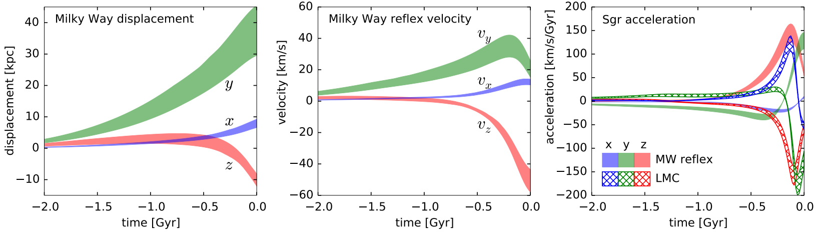


observations

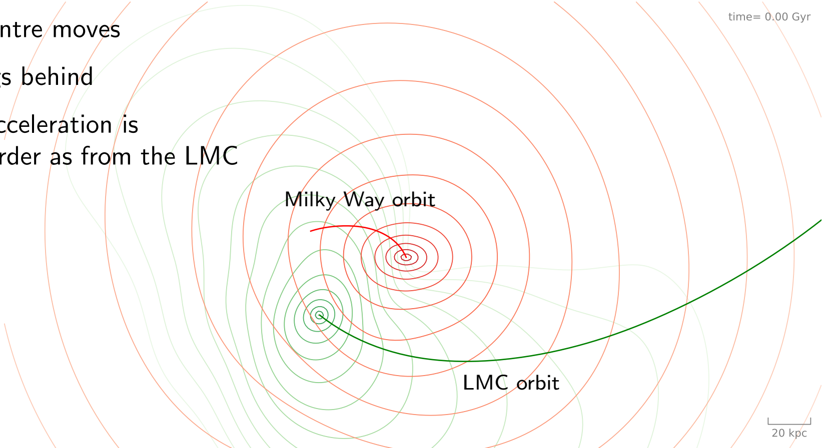
model with LMC

[Vasiliev+ 2020]

Milky Way + LMC encounter



1. Milky Way centre moves
2. outer halo lags behind
3. non-inertial acceleration is
   of the same order as from the LMC



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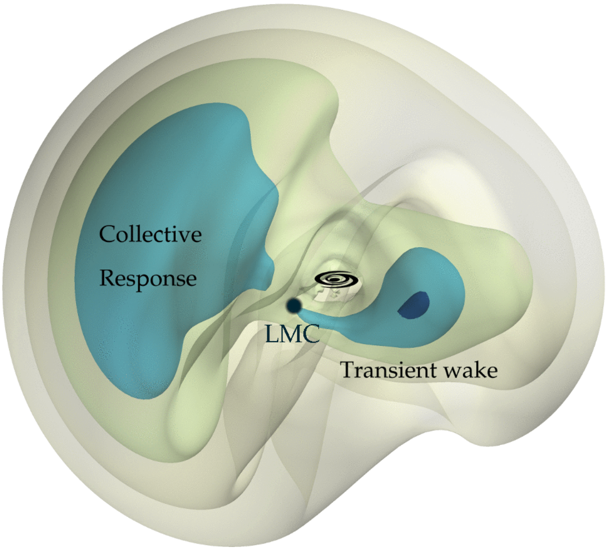
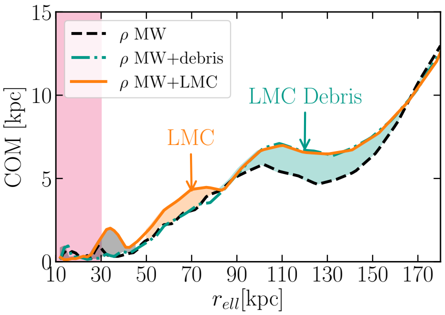
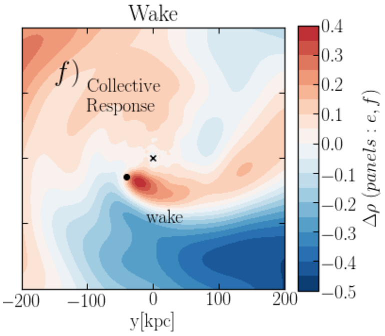


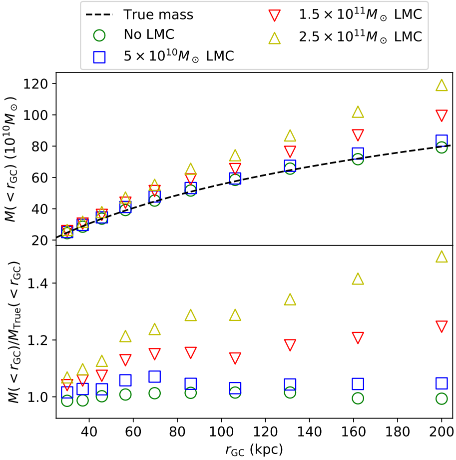


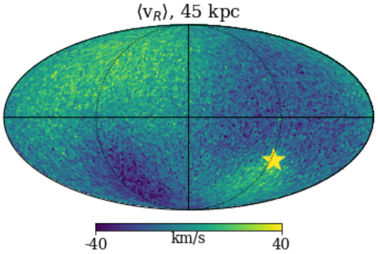


[Garavito-Camargo+ 2020]

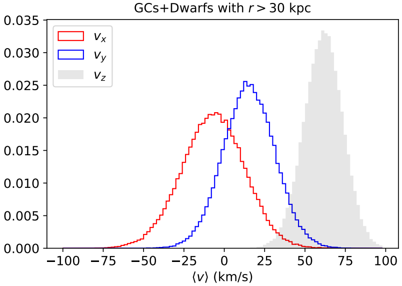
Milky Way + LMC encounter: kinematic signature

Estimates of Milky Way mass based on equilibrium models are biased high by the LMC perturbation





predicted map [Cunningham+ 2020]



[Erkal+ 2020]

Summary

Although the Milky Way history has been relatively quiescent over the last 10 Gyr, we now have sufficiently precise observational data to study in detail the recent perturbations caused by the central bar and nearby satellites, and discern the traces of its assembly history well into the past.

Are we facing a paradigm shift for the Galactic studies?

Would this be the next major thing for extragalactic astronomy?