Modern stellar dynamics, lecture 12:

perturbations, disequilibrium and other challenges

Eugene Vasiliev

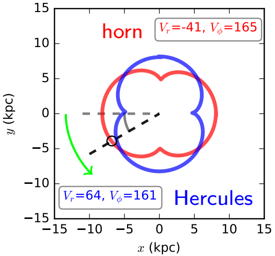
Institute of Astronomy, Cambridge

Part III / MAst course, Winter 2022

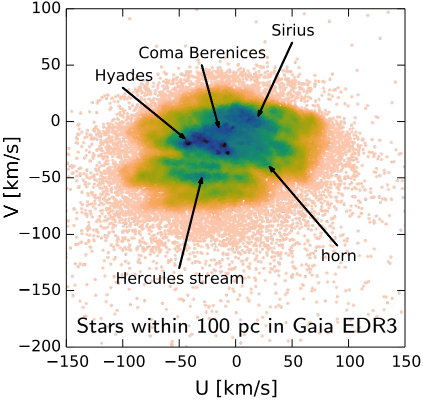
Velocity distribution of stars in the Solar neighbourhood

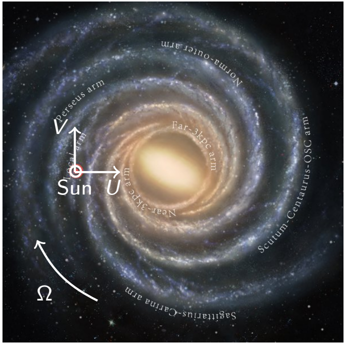
The velocity distribution in the equatorial plane (U, V) is rather complicated: in addition to several "moving groups" associated with coherent streams or clusters, it also contains features (Hercules stream, "horn") likely created by orbits resonantly trapped by the bar or the spiral arms [Dehnen 2000; Quillen & Minchev 2005]. Explaining these features places constraints on the pattern speed Ω of these structures, and is an active area of research.

orbits in the corotating frame

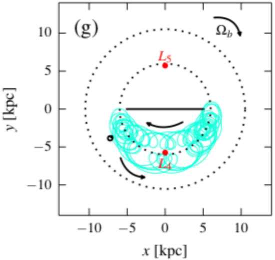


[Fragkoudi+ 2019]



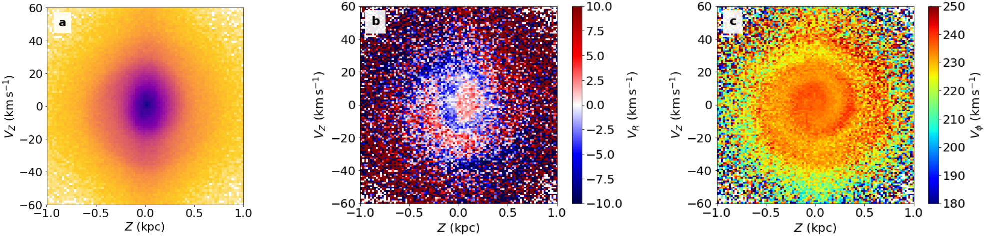


[credit: X.-W.Zheng, M.Reid]



[Pérez-Villegas+ 2017]

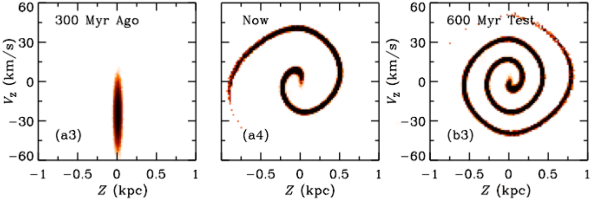
Vertical perturbations in the Galactic disc



Phase-space spiral in Gaia DR2 [Antoja+2018]

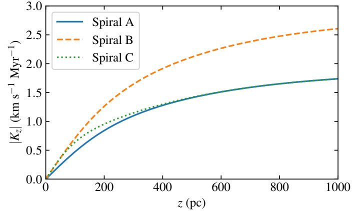
Leading theory: phase mixing after an impulsive perturbation from a $(2-10)\times10^{10}\,M_\odot$ satellite crossing the disk 200 – 400 Myr ago (Sgr dSph?)

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



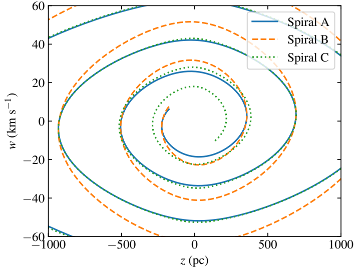
Constraining the Galactic potential by vertical perturbations

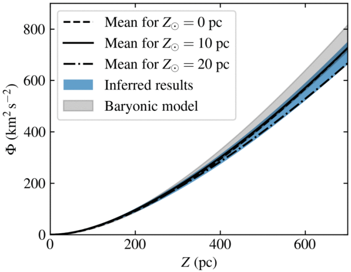
Obviously, these perturbations pose an obstacle for standard methods for measuring the potential (e.g., Jeans equations or DF fitting), but they can be used in a different way.

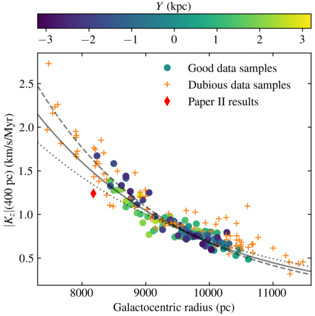


Assuming that the phase spiral is caused by an impulsive perturbation, its shape results from phase mixing in a non-harmonic potential (stars with low energy have higher frequency and are winding up faster). Thus the vertical potential ($\Leftrightarrow$ 1d mass distribution in the Galactic disc) can be inferred by fitting the shape of the spiral overdensity.

[Widmark+ 2019-2022]







Time-dependent potential and DF

Distribution function of stars $f(\mathbf{x}, \mathbf{v}, t)$
satisfies [sometimes] the collisionless Boltzmann equation:

$$\frac{\partial f(\mathbf{x}, \mathbf{v}, t)}{\partial t} + \mathbf{v}\,\frac{\partial f(\mathbf{x}, \mathbf{v}, t)}{\partial \mathbf{x}} - \frac{\partial \Phi(\mathbf{x}, t)}{\partial \mathbf{x}}\,\frac{\partial f(\mathbf{x}, \mathbf{v}, t)}{\partial \mathbf{v}} = 0.$$

Potential $\Leftrightarrow$ mass distribution

not measured directly on human timescales

In order to infer anything about the potential from a time-dependent DF, need to make further assumptions, e.g., that the stars belong to a single stream, etc.

Time-dependent potential and DF

Distribution function of stars $f(\mathbf{x}, \mathbf{v}, t)$
satisfies [sometimes] the collisionless Boltzmann equation:

$$\mathbf{v}\,\frac{\partial f(\mathbf{x}, \mathbf{v}\quad)}{\partial \mathbf{x}} - \frac{\partial \Phi(\mathbf{x}\quad)}{\partial \mathbf{x}}\,\frac{\partial f(\mathbf{x}, \mathbf{v}\quad)}{\partial \mathbf{v}} = 0.$$

3D
(want to infer)

Steady-state assumption $\Longrightarrow$ Jeans theorem:

$$f(\mathbf{x}, \mathbf{v}) = f\left(\mathcal{I}(\mathbf{x}, \mathbf{v};\ \Phi)\right)$$

3D – 6D
(observed)

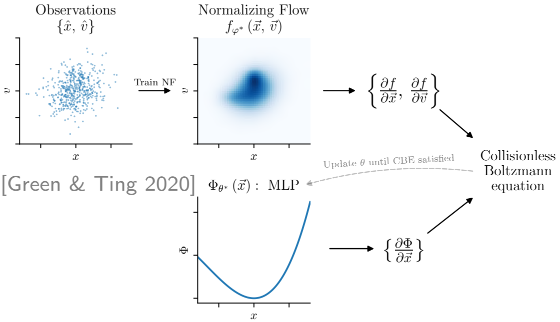
integrals of motion ($\leq$ 3D?), e.g., $\mathcal{I} = \{E, L, \ldots\}$

With fully 6d phase-space measurements, the potential is overconstrained!

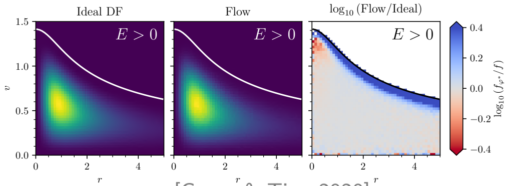
Constraining the Galactic potential directly from the CBE

1. Infer a smooth $f(\mathbf{x}, \mathbf{v})$ from the observed discrete samples (with uncertainties in $\mathbf{x}, \mathbf{v}$).
2. Measure the acceleration $\partial\Phi/\partial\mathbf{x}$ at different spatial locations $\mathbf{x}$ by fitting a linear least-squares regression to the DF derivatives (different values of $\mathbf{v}$ at a fixed $\mathbf{x}$ should give a consistent estimate of accelerations).

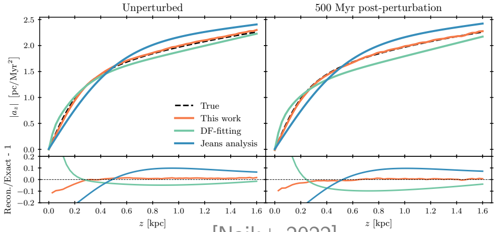
Ignore the Jeans theorem, sidestep the computation of integrals of motion.



[Green & Ting 2020]



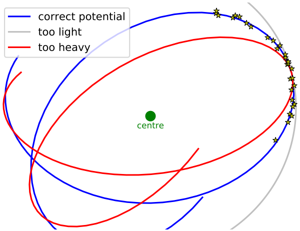
[Green & Ting 2020]



[Naik+ 2022]

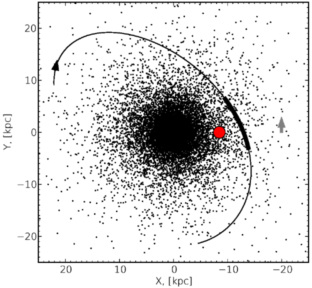
$$\mathbf{v}\,\frac{\partial f(\mathbf{x},\mathbf{v})}{\partial \mathbf{x}} - \frac{\partial \Phi(\mathbf{x})}{\partial \mathbf{x}}\,\frac{\partial f(\mathbf{x},\mathbf{v})}{\partial \mathbf{v}} = 0$$

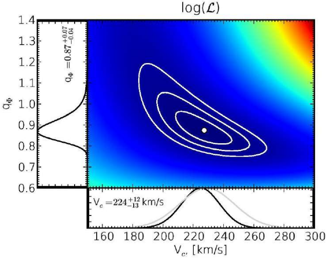
Constraining the Galactic potential with streams

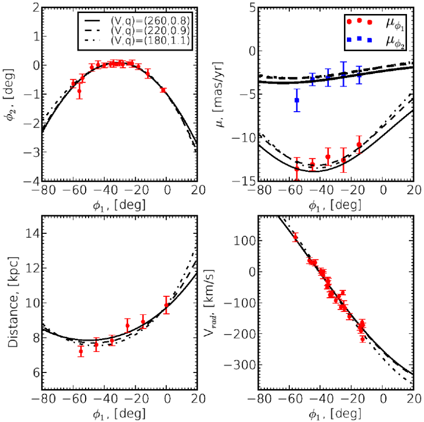


stars in the stream travel along [roughly] the same orbit, which depends on the Galactic potential.

Example: GD-1 stream – old, thin, no remnant; fit the orbit track, proper motions and velocities of stream stars.

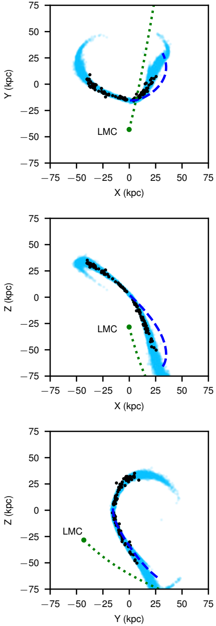




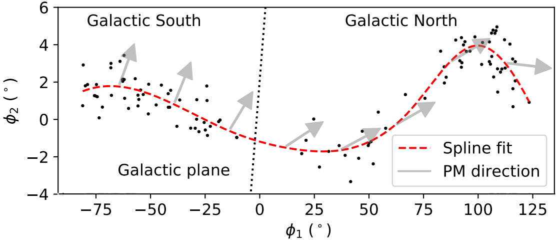


[Koposov+ 2010]

Stream deflection by the Large Magellanic Cloud

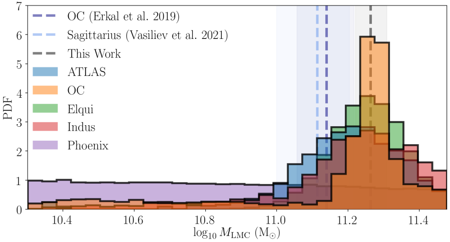


Orphan–Chenab stream: no remnant, spans $> 200^\circ$ on the sky. Proper motion is misaligned with the stream track in the southern part of the stream due to a close encounter with the LMC.



[Erkal+ 2019]

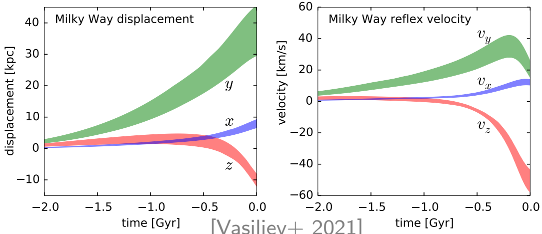
Many streams in the Southern hemisphere show signatures of deflection by the LMC, which can be used to measure the LMC mass – it turns out to be $(1{-}2)\times10^{11}\ M_\odot$, compared to $\sim 10^{12}\ M_\odot$ for the Milky Way itself!



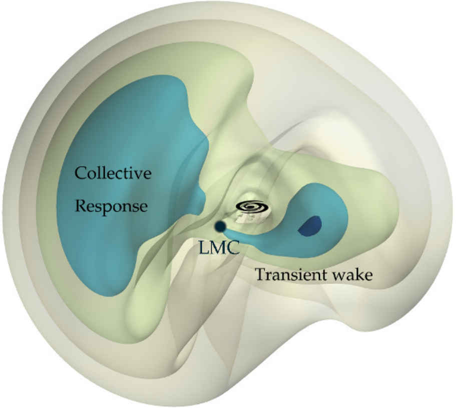
[Shipp+ 2021]

Milky Way—LMC encounter

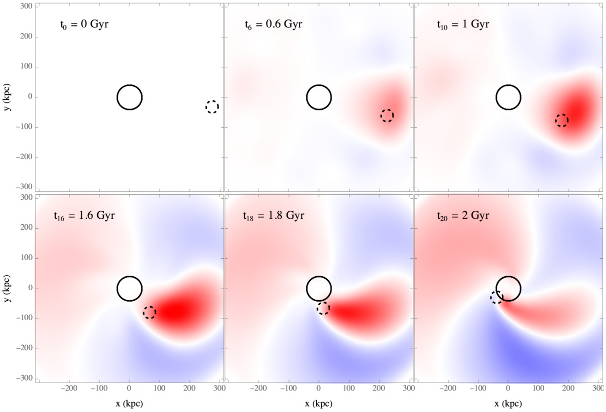
- central part of the Milky Way is pulled towards the LMC;
- outer halo is too slow to catch up;
- this creates a dipole "polarization cloud" (collective response) in addition to the "local wake" from dynamical friction.



[Vasiliev+ 2021]



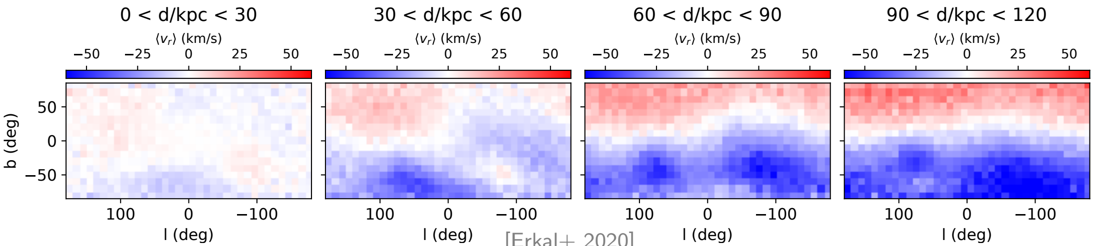
N-body sims [Garavito-Camargo+ 2020]



perturbation theory [Rozier+ 2022]

Milky Way—LMC encounter: kinematic signature

Since the MW is pulled "down" (in z) recently, most of the kinematic signal is in the north–south asymmetry of line-of-sight velocities in the outer halo ($\gtrsim 50$ kpc).



[Erkal+ 2020]

$\Uparrow$

prediction

$\Leftarrow$ observations $\Rightarrow$

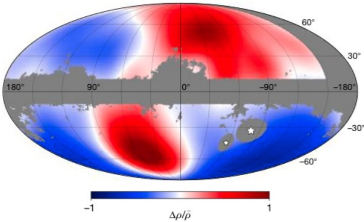
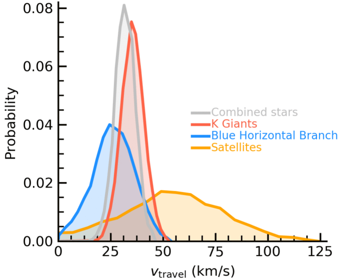


Fig. 1 | Distribution of stars in the Galactic halo. All-sky Mollweide projection maps of the density of stars at 60 kpc < R_{gal} < 100 kpc, smoothed by a Gaussian kernel with FWHM = 30°. **a**, Data based on K giant stars.

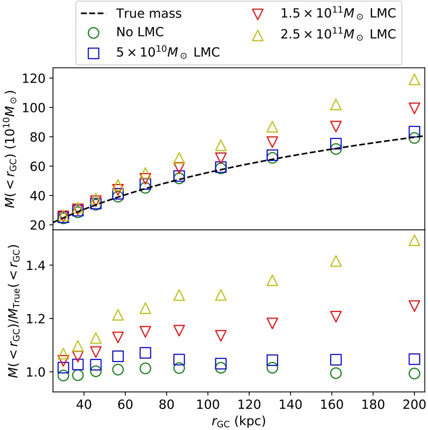
density polarization [Conroy+ 2021]



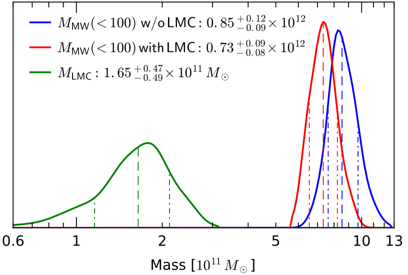
velocity offset [Petersen & Peñarrubia 2021]

Milky Way—LMC encounter: biases and their mitigation

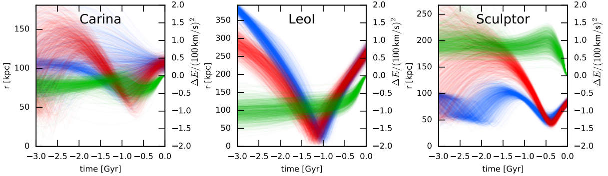
Estimates of Milky Way mass based on equilibrium models are biased high by the LMC perturbation, but we may "undo" it by integrating back the orbits of tracers (stars, satellites, etc.) in a time-dependent MW+LMC potential until the LMC is far enough not to cause trouble, and then use standard equilibrium modelling techniques to measure the MW mass profile.



[Erkal+ 2020]



blue: orbit w/o LMC;
red: orbit with LMC;
green: energy evolution



[Correa Magnus & Vasiliev 2022]

Summary

We have reviewed various tools for analysing the current structure and dynamics of stellar systems: density and potential profiles, orbits and integrals of motion, distribution functions, etc.

Some of these are conceptually straightforward, even if technically challenging (e.g., solving the Poisson equation or computing actions); others are intrinsically ill-defined or degenerate (e.g., deprojection of surface brightness profiles or inference on the mass distribution from projected kinematics).

The observational data grow enormously both in quantity and in quality, necessitating more sophisticated analysis techniques and modelling efforts.

Summary

In the end, what matters are the science questions that we wish to answer with these and other tools at hand, for instance:

- The interplay between dynamics and chemical properties of stars.
- The inference about the history from the present-day state.
- The Milky Way system can now be studied in exquisite detail, but how much does it help in understanding the galaxy evolution in general?