Dynamics in the Galactic halo

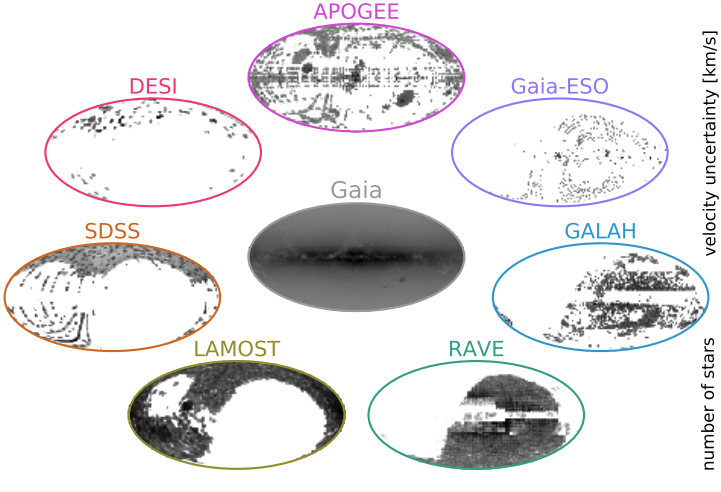
Eugene Vasiliev

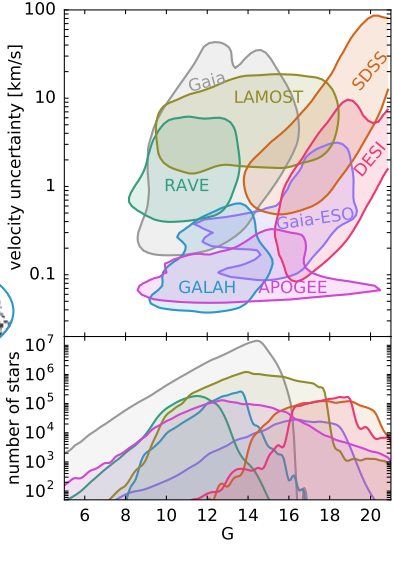
University of Surrey

Sexten, 29 January 2024

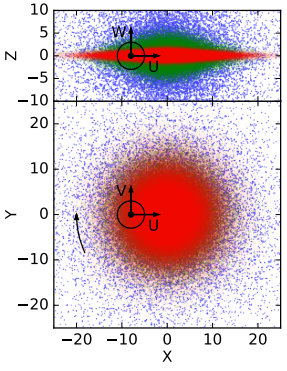
[Giovanni Segantini]

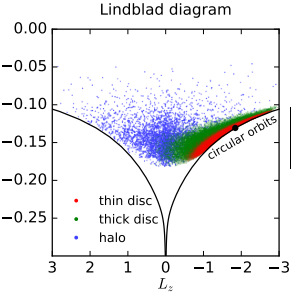
Observational data: spectroscopic surveys

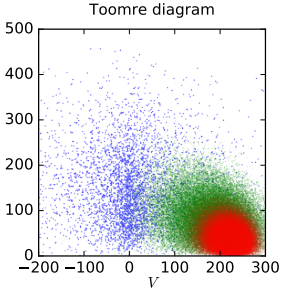


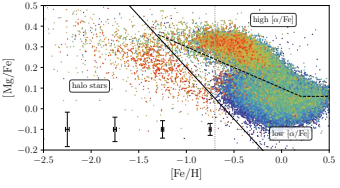


Observational data: local halo – kinematic and chemical selection

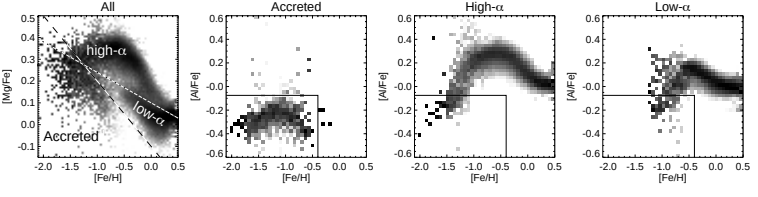






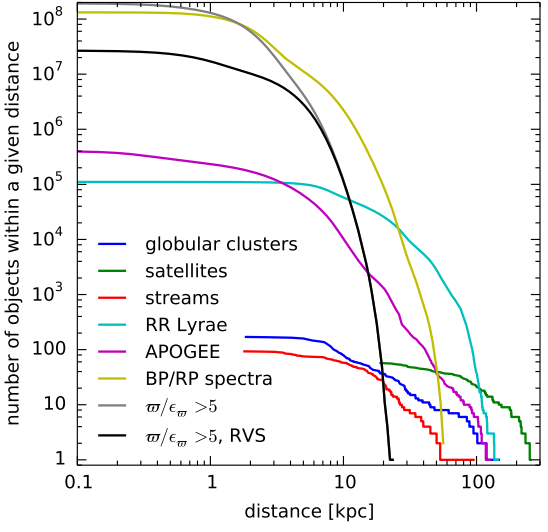


[Mackereth+ 2019]



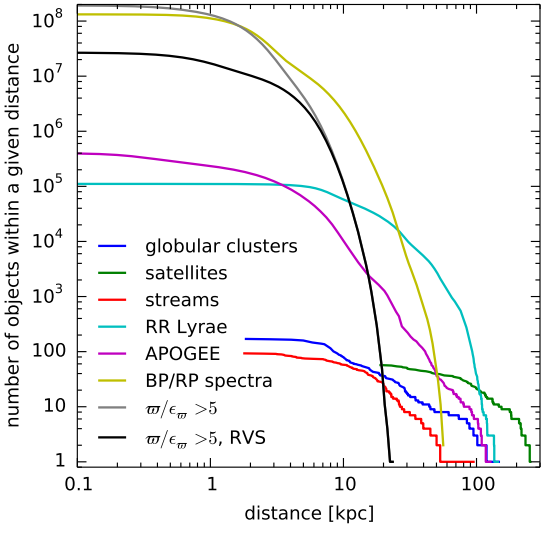
[Belokurov & Kravtsov 2022]

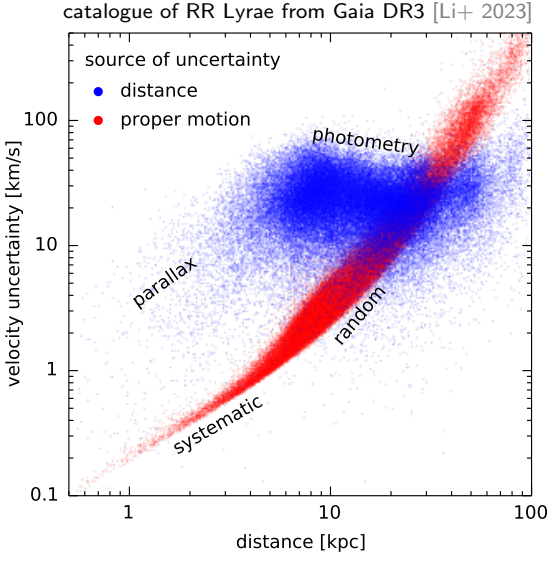
Observational data: distant halo



[Baumgardt & Vasiliev 2021]
[Battaglia+ 2022]
[Mateu 2023]
[Clementini+ 2023; Li+ 2023]
[Abdurro'uf+ 2022; Queiroz+ 2023]
[Zhang+ 2023]

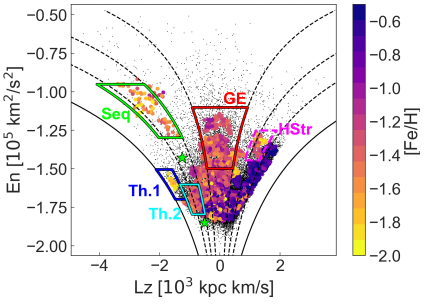
Observational data: distant halo



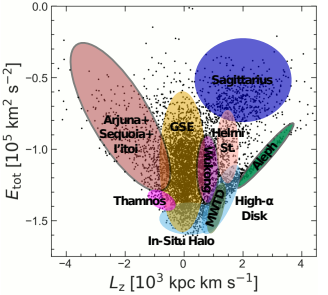


sky-plane velocity uncertainty: $\epsilon_v = \frac{\epsilon_D}{D} v + \epsilon_\mu D$

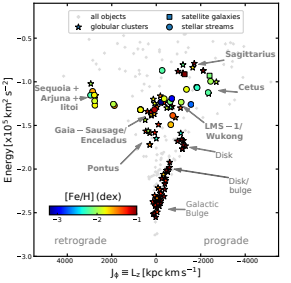
Substructures in the halo



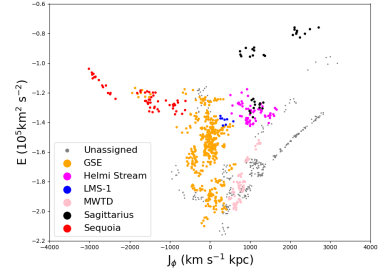
[Koppelman+ 2019]



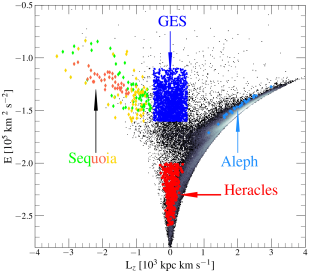
[Naidu+ 2020]

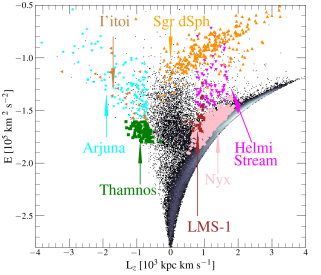


[Malhan+ 2022]



[Cabrera-Garcia+ 2023]





[Horta+ 2023]

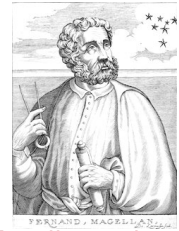
. . . and many others

The Milky Way assembly history

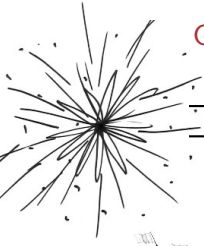
Gaia–Enceladus / Sausage

[Helmi+ 2018, Belokurov+ 2018]

Sagittarius



Magellanic clouds



10 Gyr

3 Gyr

0.5 Gyr

Kraken

[Kruijssen+ 2019]

Herakles

[Horta+ 2020]

Koala

[Forbes 2020]

Sequoia

[Myeong+ 2019]

Pontus

[Malhan+ 2022]

Arjuna

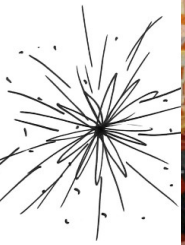
[Naidu+ 2020]

Thamnos

[Koppelman+ 2019]

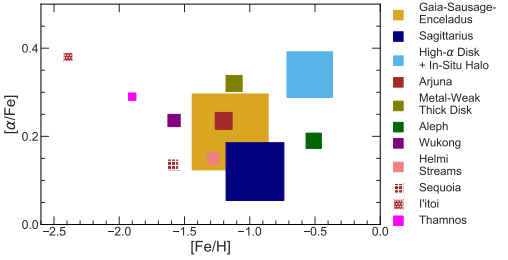
The Milky Way assembly history

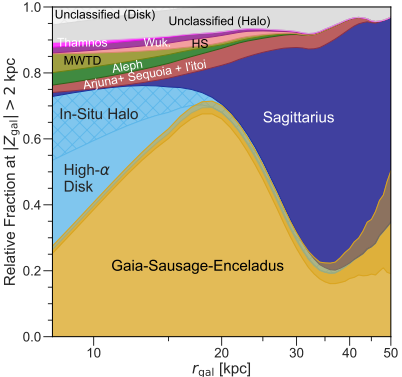
"a delightful anarchy has ensued" [Grillmair & Carlin 2016]



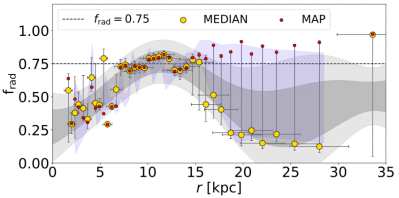
[Gino Severini]

Stellar halo: composition

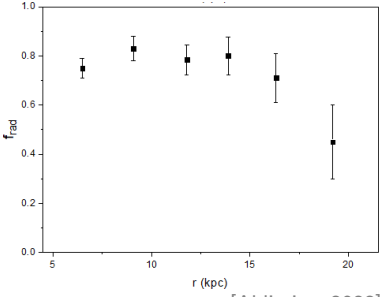




[Naidu+ 2020]



[Iorio+ 2021; Lancaster+ 2019]



[Ablimit+ 2022]

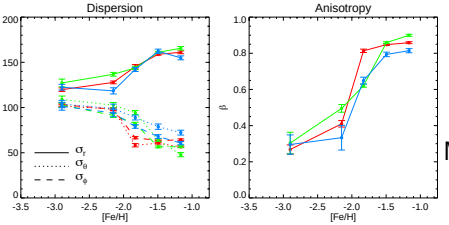
Total mass of the stellar halo: $(1\text{–}1.5)\times10^9\,M_\odot$

[Deason+ 2019; Mackereth&Bovy 2020]

GSE fraction: 30–60% [Iorio+ 2019; Han+ 2022; Lane+ 2023]

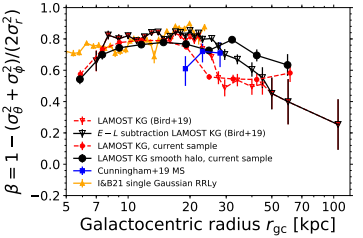
Stellar halo: kinematics

[Belokurov+ 2018]



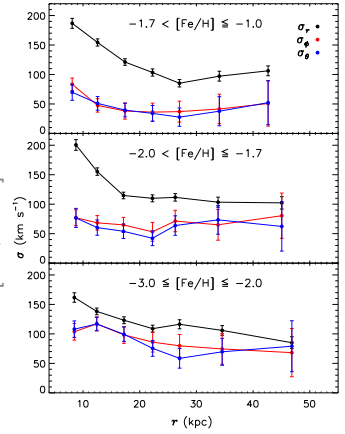
MS

K giants



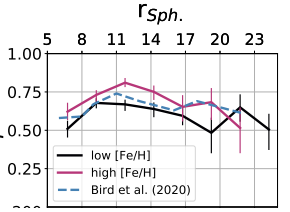
[Bird+ 2021]

[Liu+ 2022]

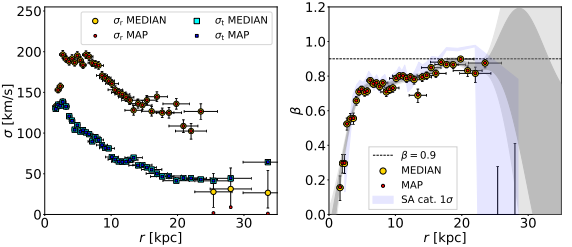


RR Lyrae

BHB

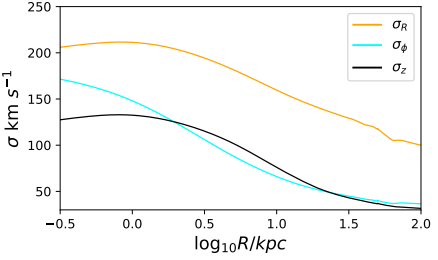


[Vickers+ 2021]

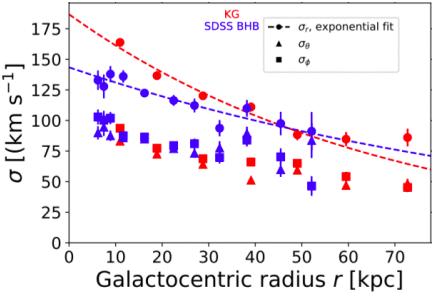


[Iorio & Belokurov 2021]

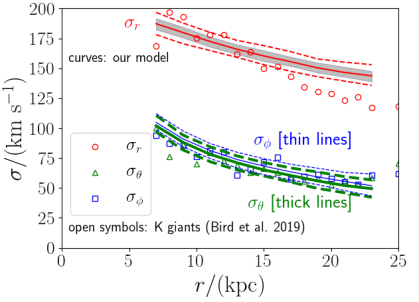
Stellar halo: dynamical models

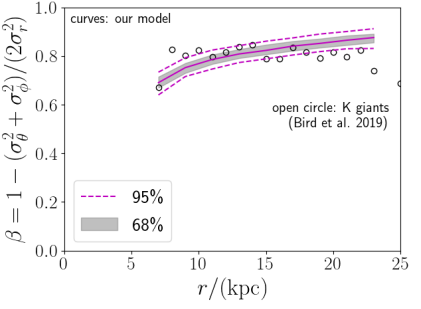


[Li & Binney 2022] – RR Lyrae, fixed Φ



[Bird+ 2022] – K giants & BHB



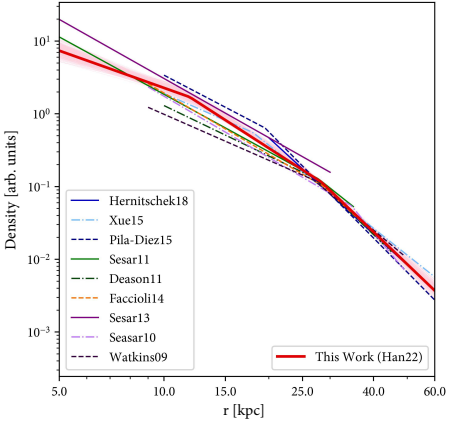


[Hattori+ 2021] – RR Lyrae

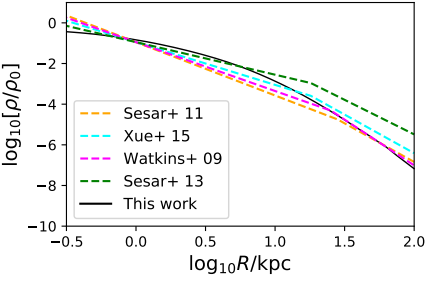
see also: Wegg+ 2019 – RR Lyrae, Deason+ 2021, Shen+ 2022 – giants; all single-component models!

Stellar halo: density profile

density profile $\rho \propto r^{-\gamma}$ with $\gamma \simeq 2.5$–3 in the Solar neighbourhood; further in/out the slope must be shallower/steeper, i.e., have a break likely associated with apocentre(s) of GSE debris [Deason+ 2018]

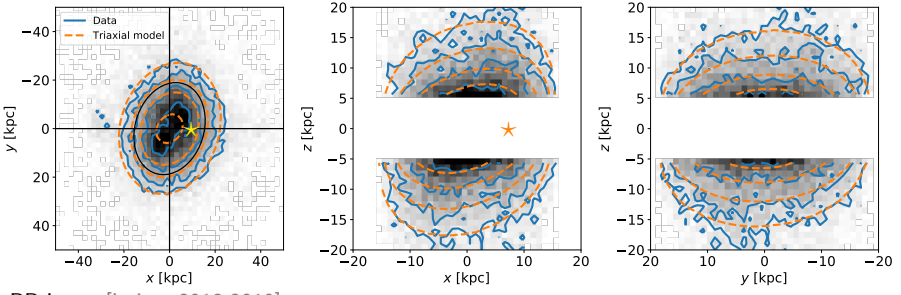


[Han+ 2022]

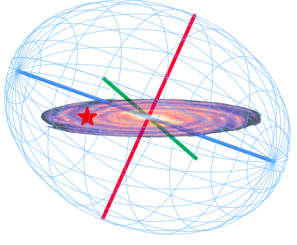


[Li & Binney 2022]

Stellar halo: shape and orientation

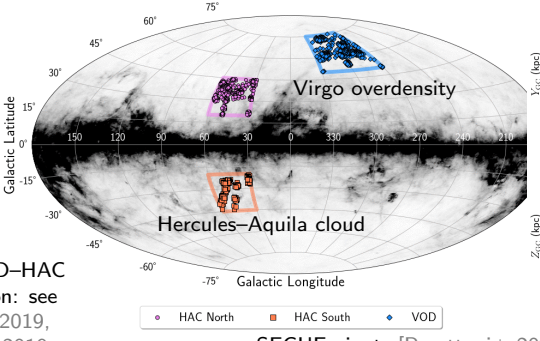


RR Lyrae [Iorio+ 2018,2019]

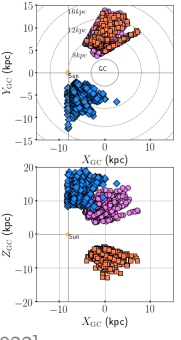


Axis Ratios
10 : 8 : 7

H3 giants [Han+ 2022]



GSE–VOD–HAC association: see Simion+ 2019, Donlon+ 2019



SEGUE giants [Perottoni+ 2022]

GSE merger: dynamics

GSE–proto-MW mass ratio estimates:

1:2.5 [Naidu+ 2021],

1:5–1:10 [Helmi+ 2018; Fattahi+ 2019; Koppelman & Helmi 2020; Renaud+ 2021]

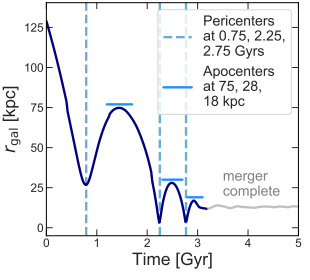
$\lesssim$1:20 [Fragkoudi+ 2020; Grand+ 2020; Mackereth & Bovy 2020].

Accretion time: $\sim$ 8–10 Gyr ago

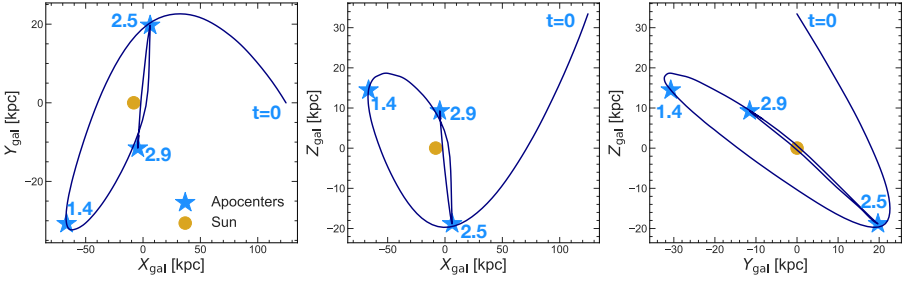
(but see Donlon+ 2020,2023 for a minority view)

Orbit of a massive satellite rapidly radializes

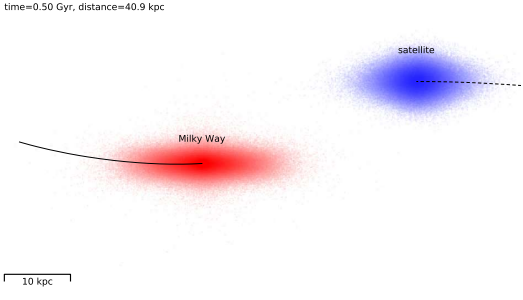
[Amorisco 2017; Vasiliev+ 2022]

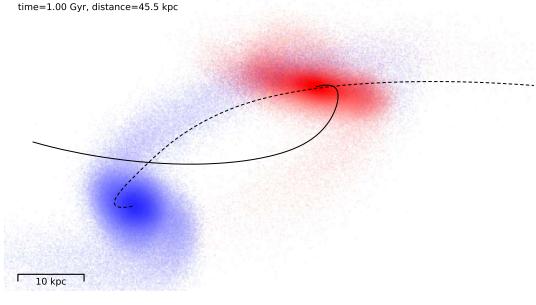


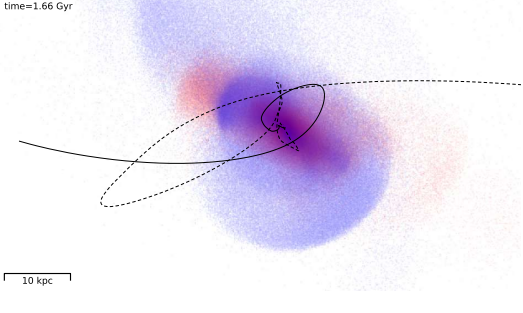
[Naidu+ 2021]

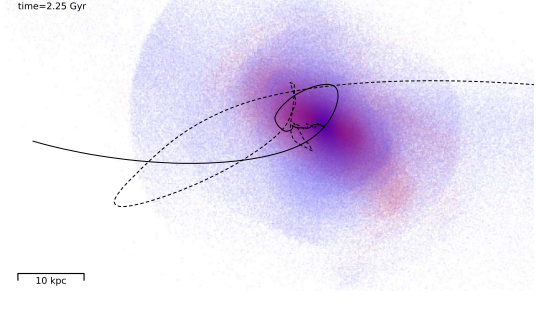


GSE merger: formation of shells



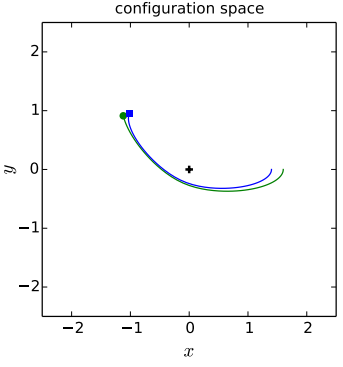


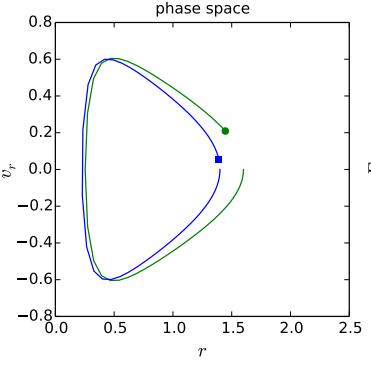


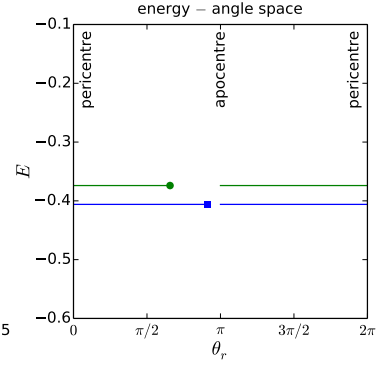


Evolution of tidal debris

- stars from the disrupted satellite span a range of energies in the host potential
- each star travels on a closed loop in the $r - v_r$ phase space, or on a straight horizontal stripe in the $E - \theta_r$ space
- orbital period is shorter for more tightly bound stars, so they travel faster through these spaces







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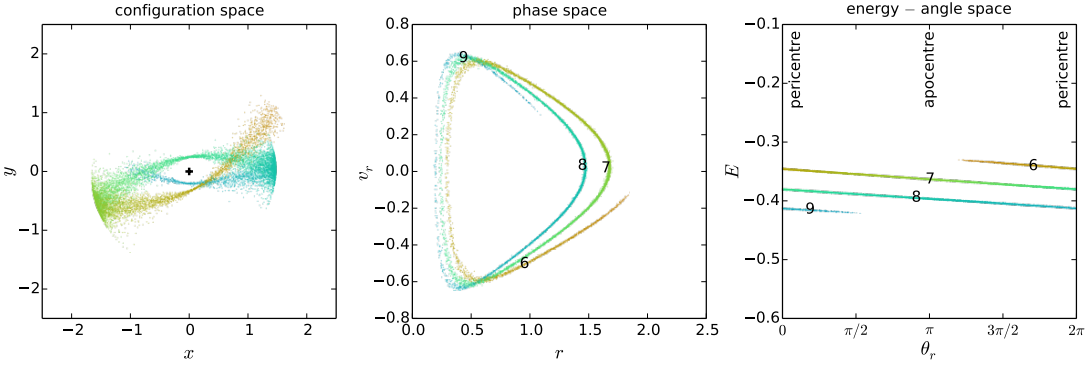
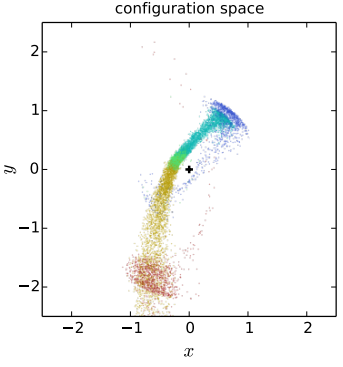
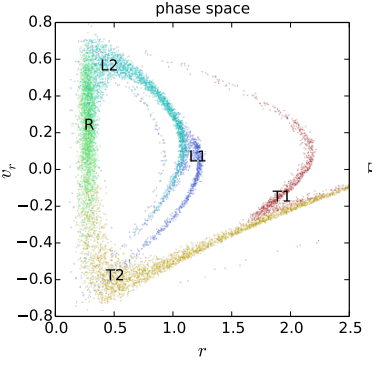
- each star travels on a closed loop in the $r - v_r$ phase space, or on a straight horizontal stripe in the $E - \theta_r$ space
- orbital period is shorter for more tightly bound stars, so they travel faster through these spaces
- the number of folds in the $r - v_r$ space or stripes in the $E - \theta_r$ space increases with time

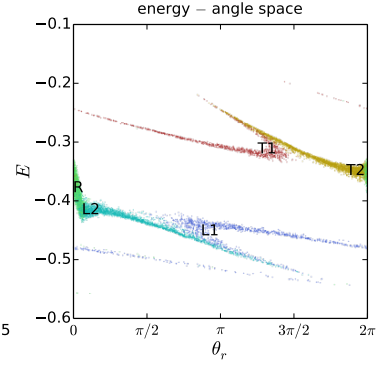


Gradual tidal stripping of a massive satellite

- usually a satellite is not abruptly disrupted but gradually stripped
- stars in the leading arm have lower energies than in the trailing arm
- each stripping episode thus produces two series of folds / shells / stripes
- these shells eventually overlap in all spaces!







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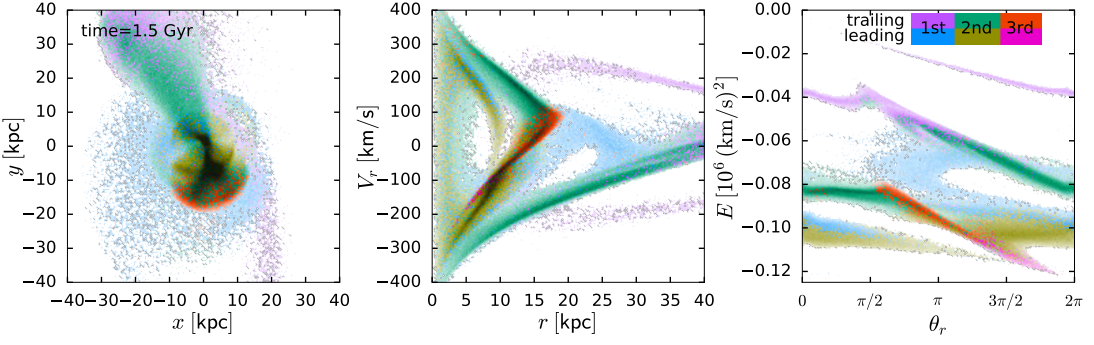
- a sufficiently massive satellite experiences dynamical friction,
  thus each subsequent stripping episode occurs at a lower energy



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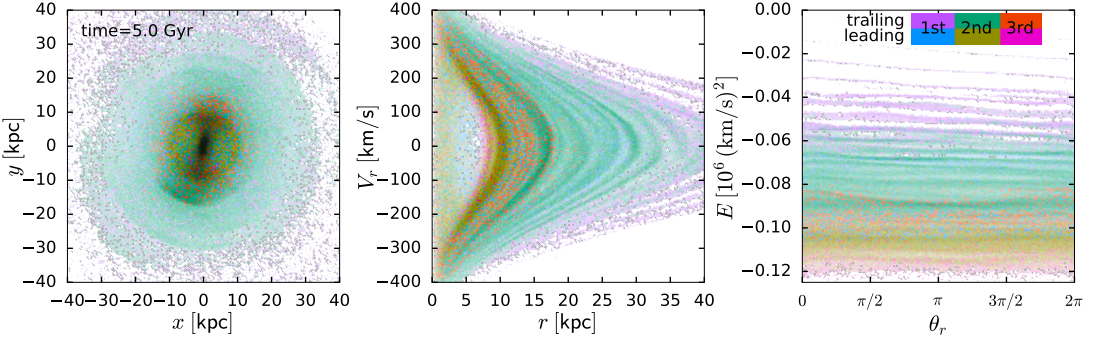
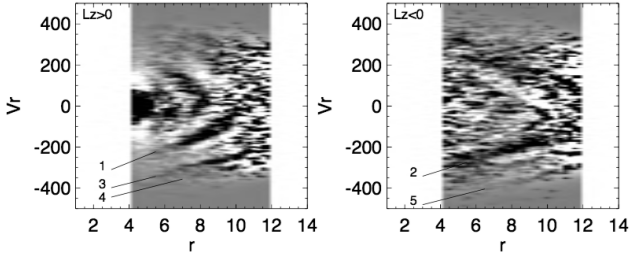
- these shells eventually overlap in all spaces!
- a sufficiently massive satellite experiences dynamical friction,
  thus each subsequent stripping episode occurs at a lower energy
- eventually all folds / stripes from each arm of each stripping episode merge

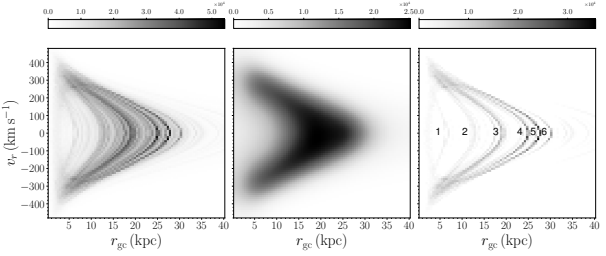


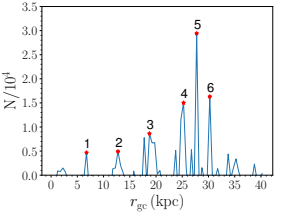
Phase-space folds in the Milky Way

halo stars with $|L_z| < 850\,\mathrm{kpc\,km/s}$, unsharp-masked



[Belokurov+ 2022]

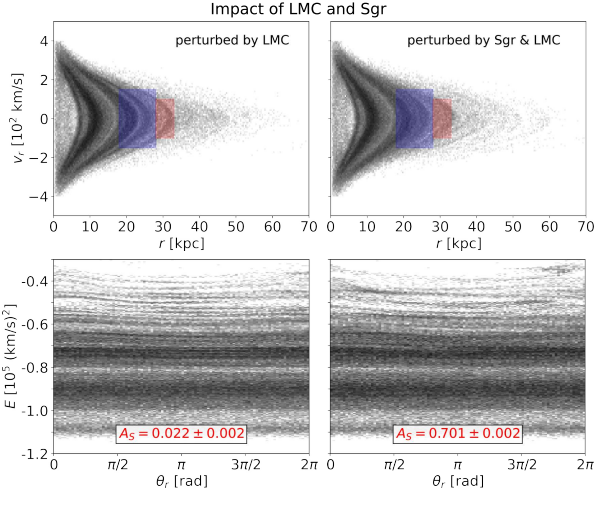




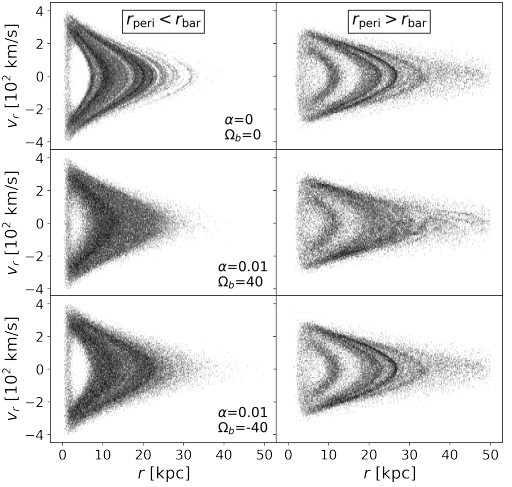
[Wu+ 2023]

Should we expect the phase-space folds to survive?

they could be blurred by flying-by massive satellites or the Galactic bar



[Davies+ 2023a]

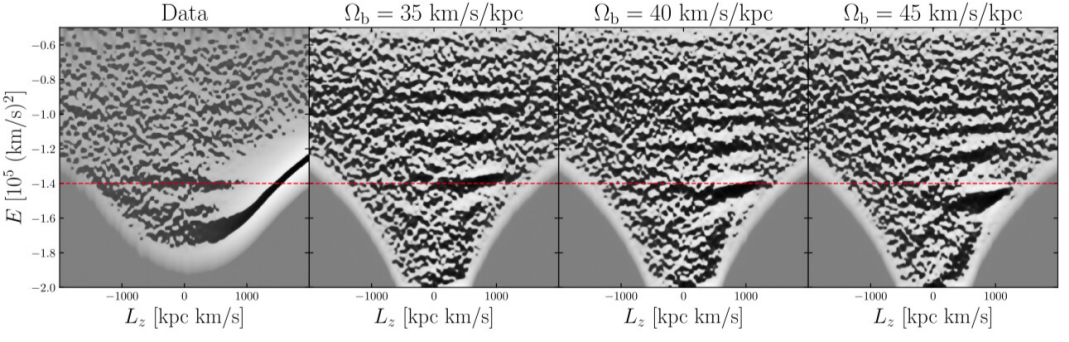


[Davies+ 2023b]

Should we expect the phase-space folds to survive?

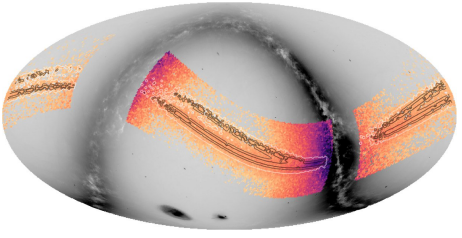
they could be blurred by flying-by massive satellites or the Galactic bar

or even produced by the bar?

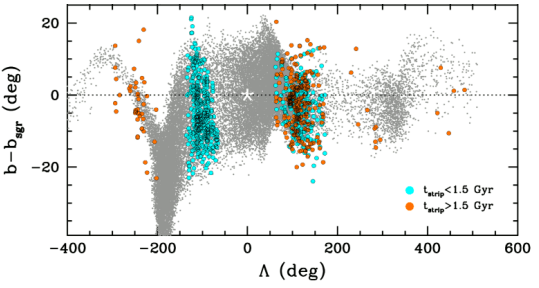


[Dillamore+ 2023]

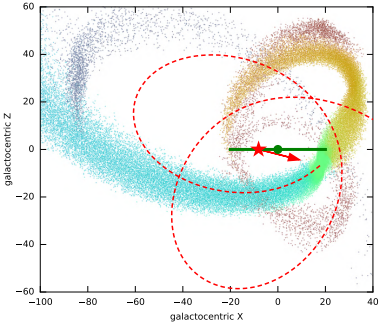
Sagittarius stream



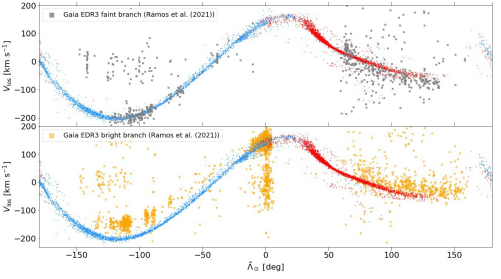
Sgr stream in Gaia EDR3 [Ramos+ 2022]



older wraps of the stream [Peñarrubia+ 2021]



stream model [Vasiliev+ 2021]



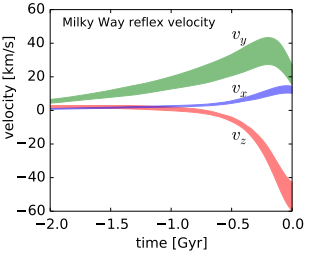
bifurcation from a disky progenitor [Oria+ 2022]

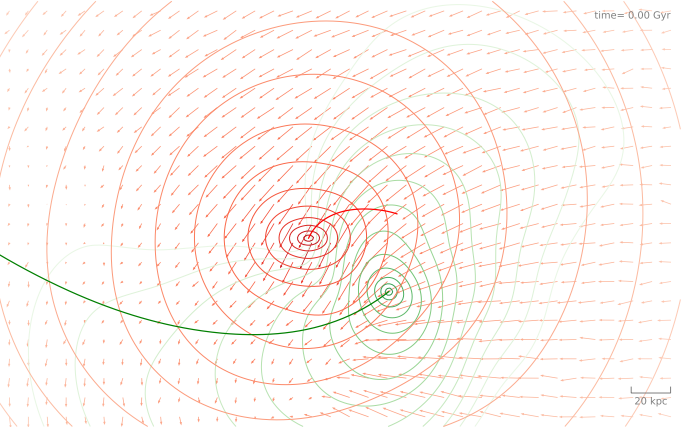
see also Davies+ 2023c,d for a merger scenario for bifurcations

Milky Way–LMC encounter

The LMC is only $\sim 5 - 10\times$ smaller than our Galaxy, and is currently just past its pericentre at ~ 50 kpc.

The Milky Way is pulled towards the LMC, but the displacement is not uniform in space.



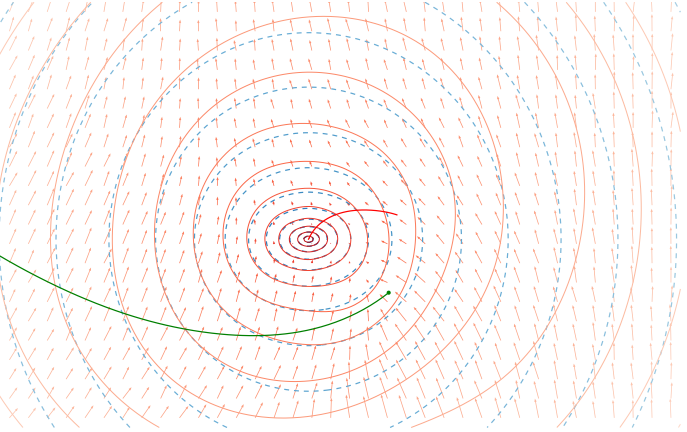


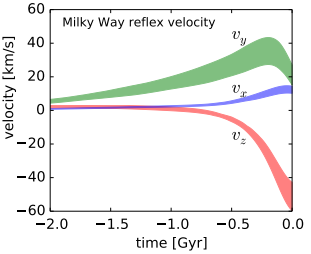
Milky Way–LMC encounter

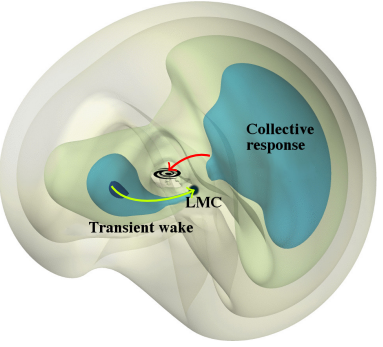
The LMC is only $\sim 5-10\times$ smaller than our Galaxy, and is currently just past its pericentre at ~ 50 kpc.

The Milky Way is pulled towards the LMC, but the displacement is not uniform in space.

In the MW-centred reference frame, outer halo appears to move up and acquires a dipole "polarization pattern".





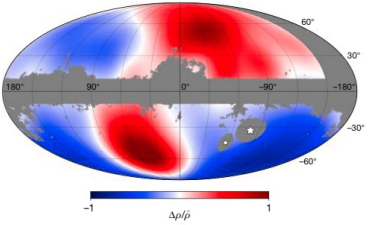


N-body sims [Garavito-Camargo+ 2021, see also Petersen & Peñarrubia 2020], perturbation theory [Rozier+ 2022]

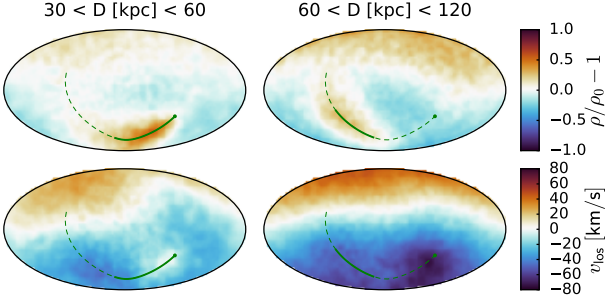
LMC-induced halo perturbation

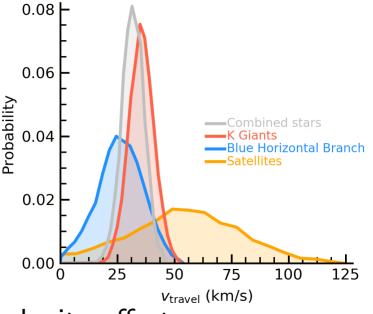
Since the MW is pulled "down" (in z) recently, perturbation is most visible in the north–south asymmetry of density and line-of-sight velocities at distances $\gtrsim 30$ kpc

[Erkal+ 2020; Cunningham+ 2020; Petersen & Peñarrubia 2020].



density polarization [Conroy+ 2021]

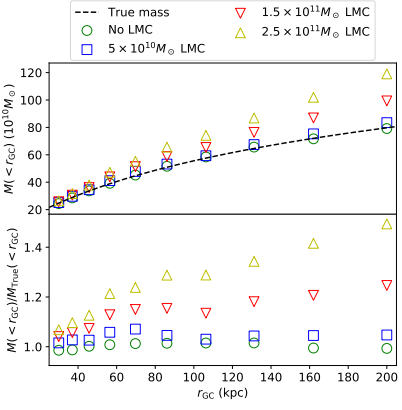




velocity offset [Petersen & Peñarrubia 2021, see also Erkal+ 2021]

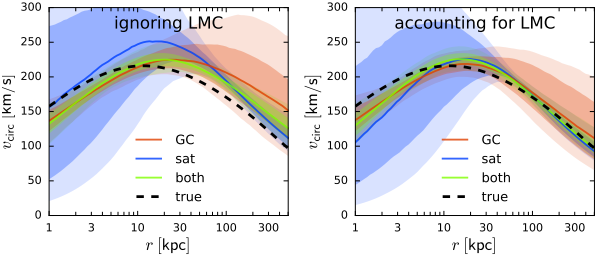
Perturbations and dynamical modelling

It is necessary to account for the LMC-induced perturbations when modelling stellar streams: Orphan–Chenab [Erkal+ 2019; Koposov+ 2023], Sagittarius [Vasiliev+ 2021] and a few others [Shipp+ 2021]



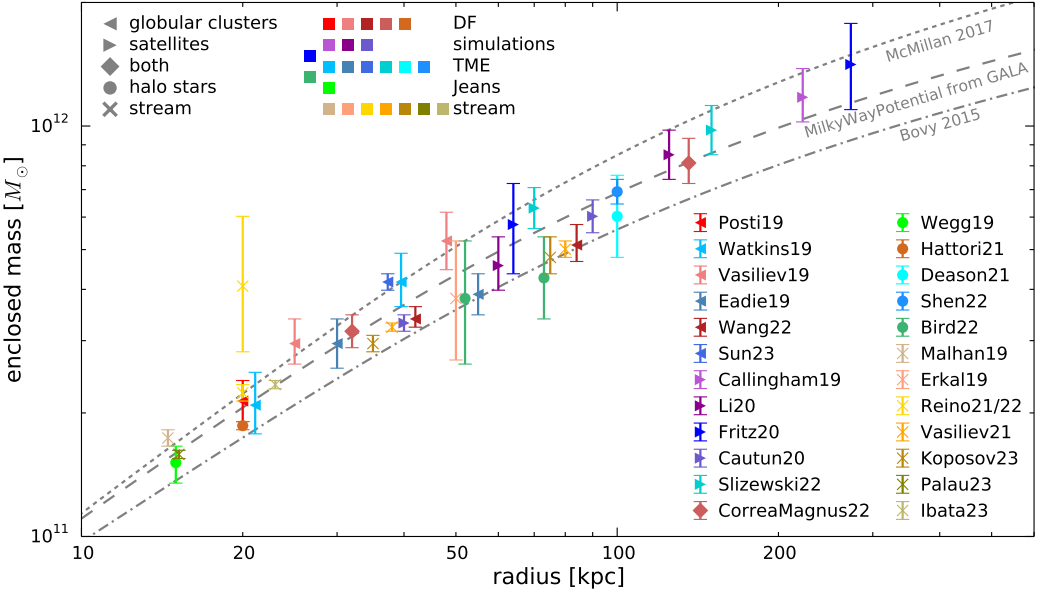
[Erkal+ 2020]

LMC perturbations also bias up the MW mass modelling

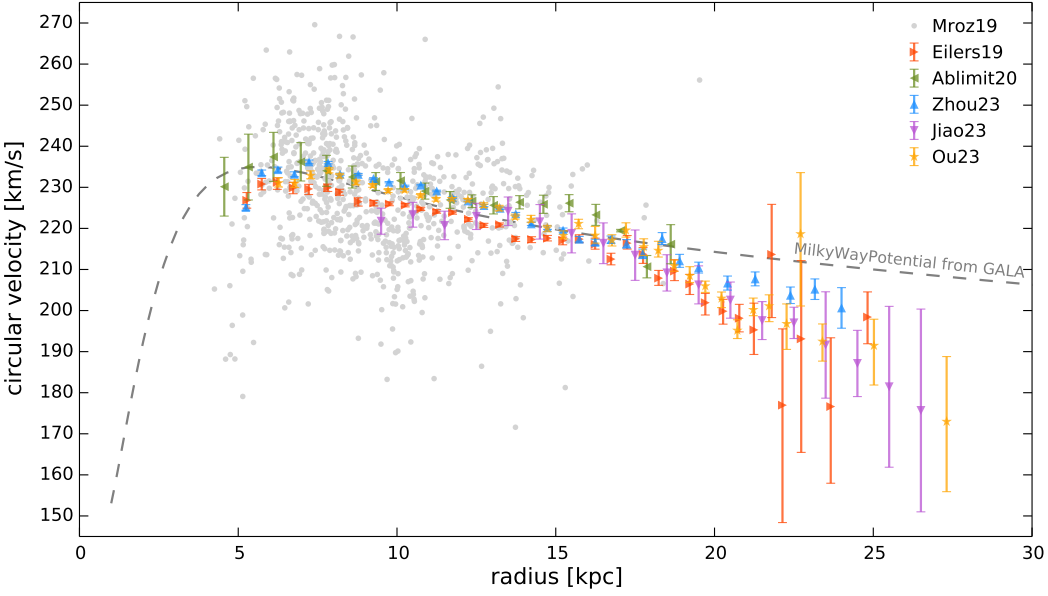


[Correa Magnus & Vasiliev 2022]

Constraints on the Galactic mass distribution

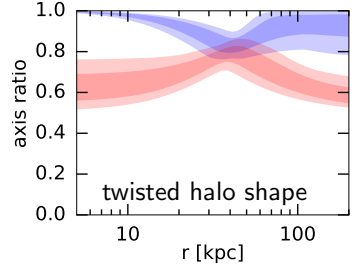


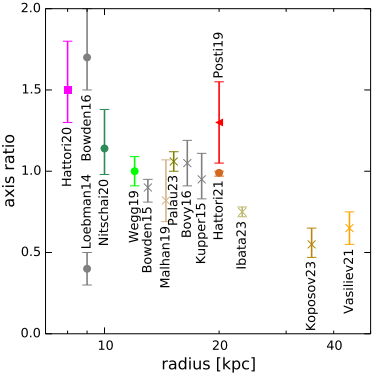
Constraints on the Galactic mass distribution

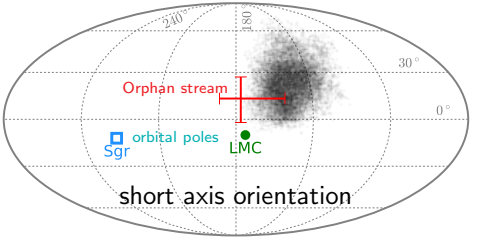


Constraints on the Milky Way halo shape

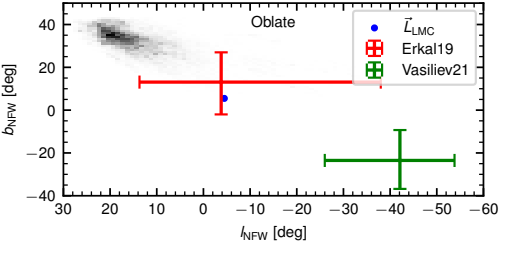
Inner halo – close to spherical,
outer halo – likely twisted and/or tilted
(see also Shao+ 2021, Han+ 2022, 2023)







Sgr stream [Vasiliev+ 2021]



Orphan–Chenab stream [Koposov+ 2023]

Summary

- Stellar halo is a mess!
  - GSE debris contribute $\sim {}^{1}/_{2}$ of the halo mass;
  - various other identified substructures might be [partial] duplicates;
  - dynamical models should consider [at least] two halo populations.
- dynamical signatures of the GSE merger:
  - triaxial, tilted stellar halo with a break radius $\sim$ 25–30 kpc;
  - shells in the r–v_r phase space (?).
- ongoing encounter with the LMC:
  - creates a dipole perturbation in the outer halo;
  - destroys the dynamical coherence of previously accreted populations;
  - needs to be accounted for in dynamical models.


[Giacomo Balla]