The OC stream's evolution in the dark matter haloes of the Milky Way and LMC

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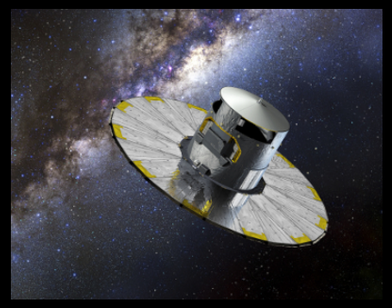
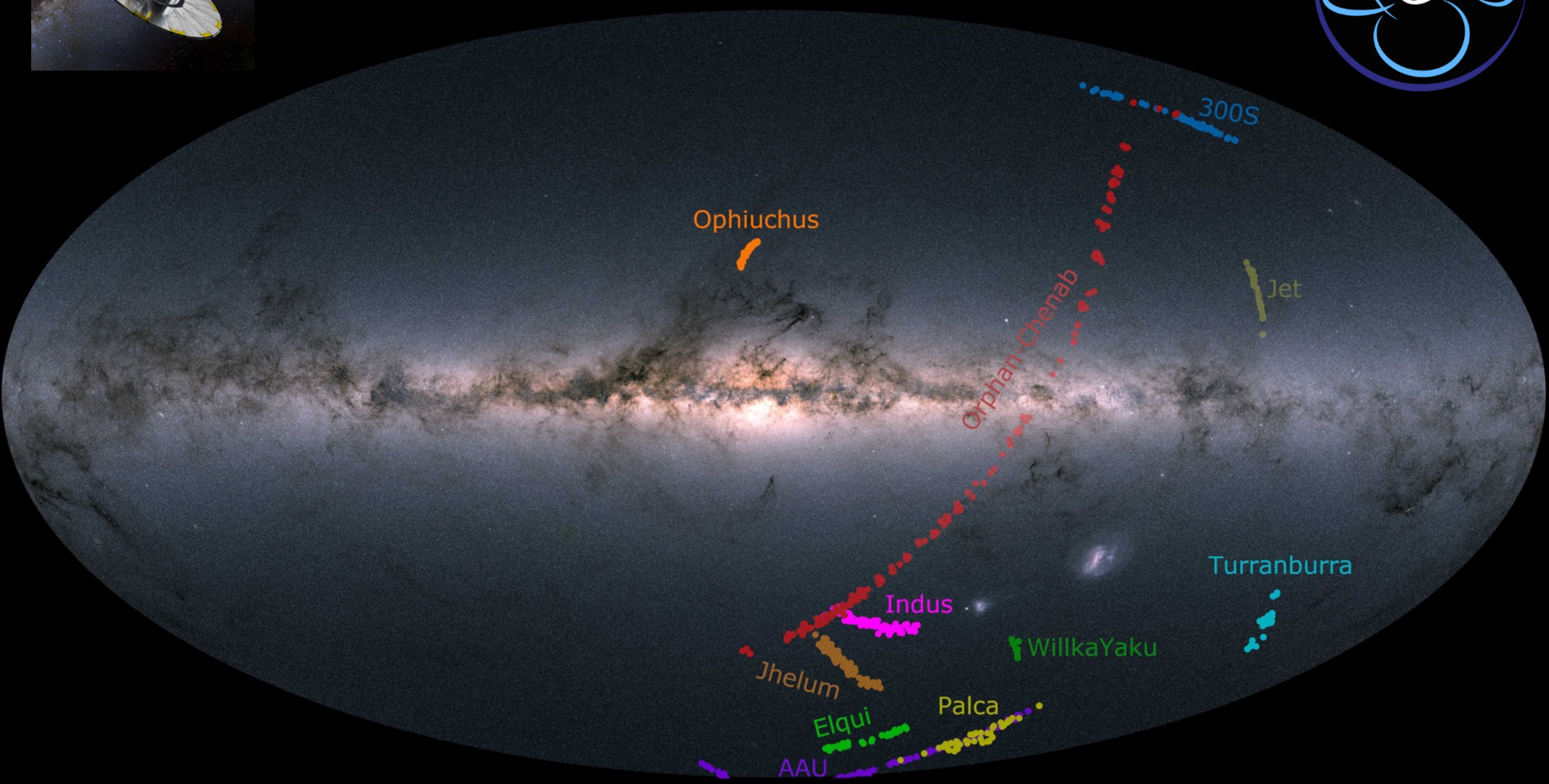
Based on Koposov, Erkal, Li + S^5 2023

IAUS379 - Dynamical Masses of Local Group Galaxies, March 23rd, 2023





Gaia for PMs
S⁵ for rvs (101 nights on AAT)
BHB+RRL for distances

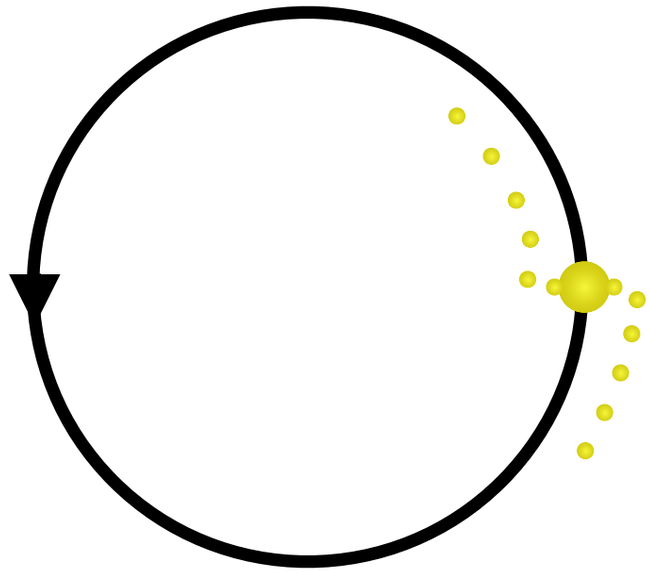
6D data for these streams!

S⁵ survey
https://s5collab.github.io/

Image credit: Ting Li + ESA

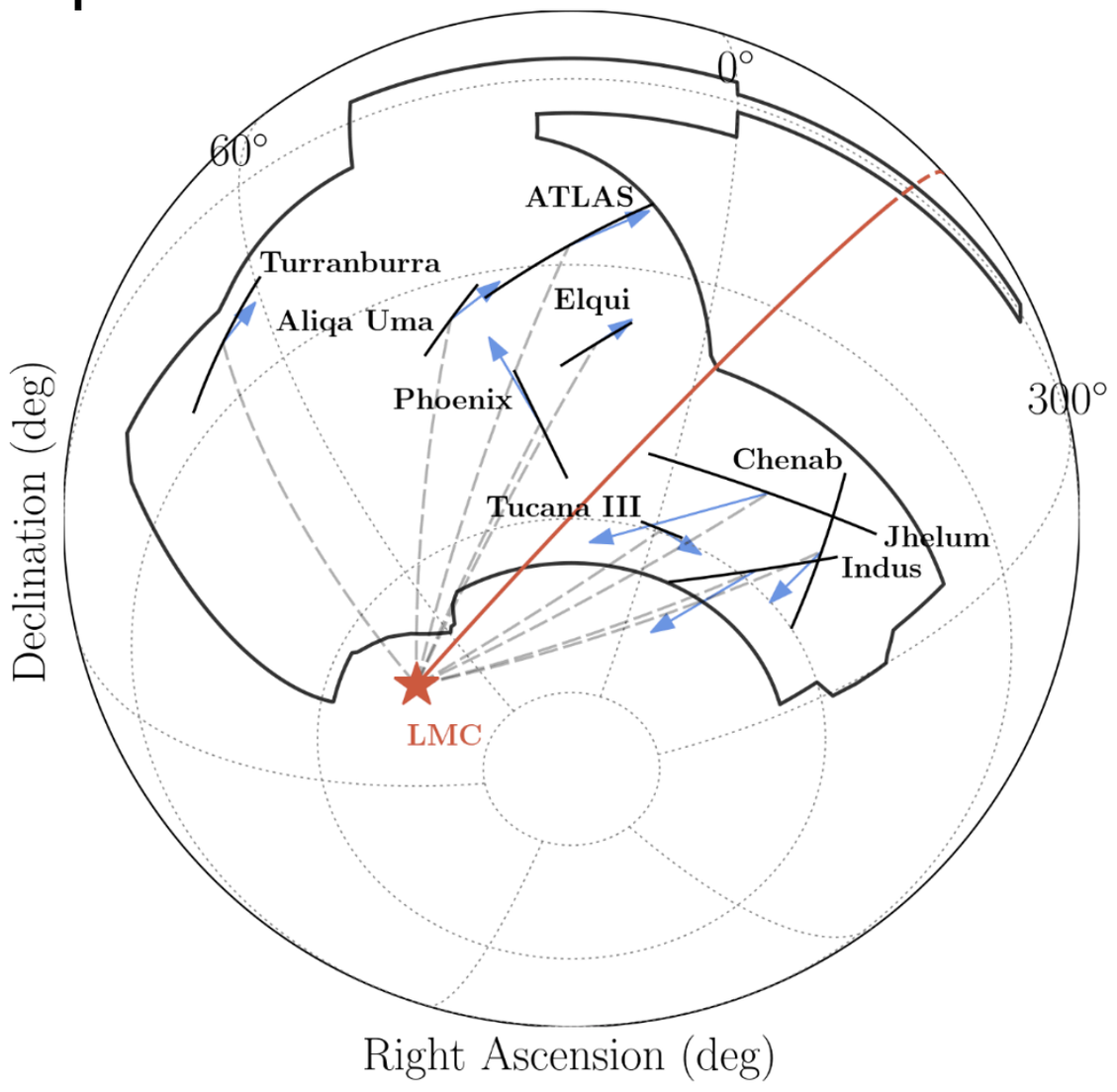
Tidal stream primer

- Stars stripped at tidal radius
- Once in the stream, each star follows an orbit
- Velocities point along the stream



How do real streams look?

- Nearly all distant streams in the Southern Hemisphere have misaligned proper motions



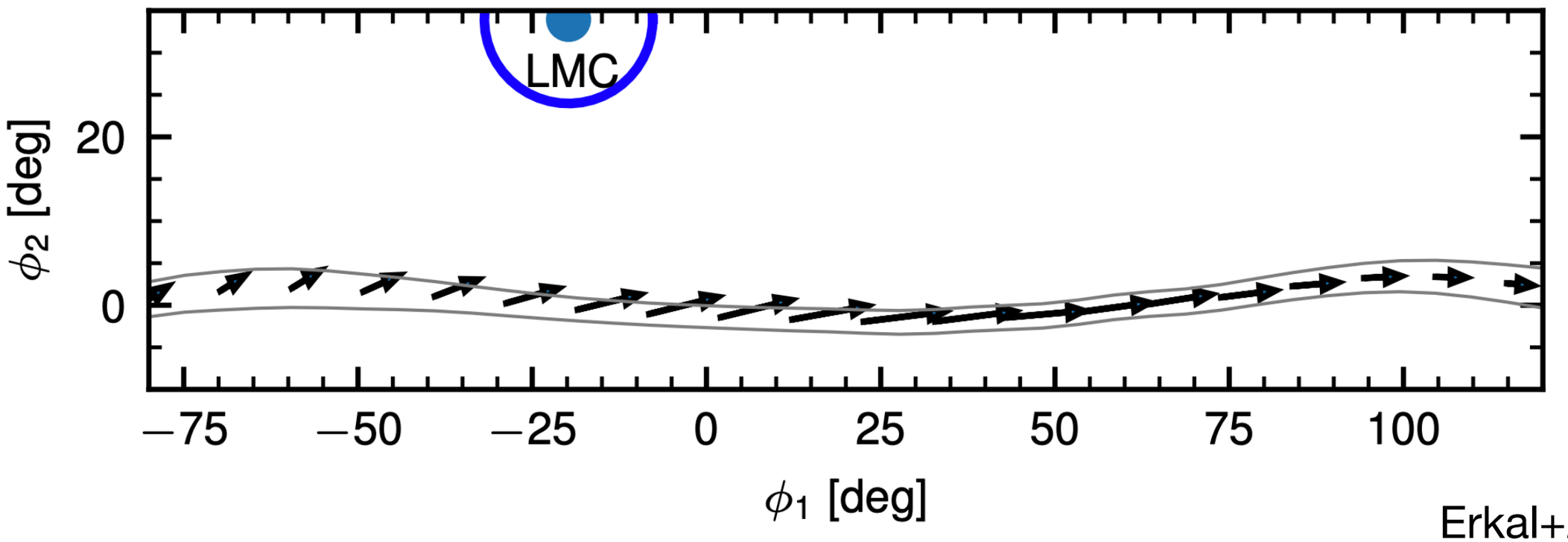
Proper motion 1.0 mas/yr

Track

Shipp+(w/DE) 2019

How do real streams look?

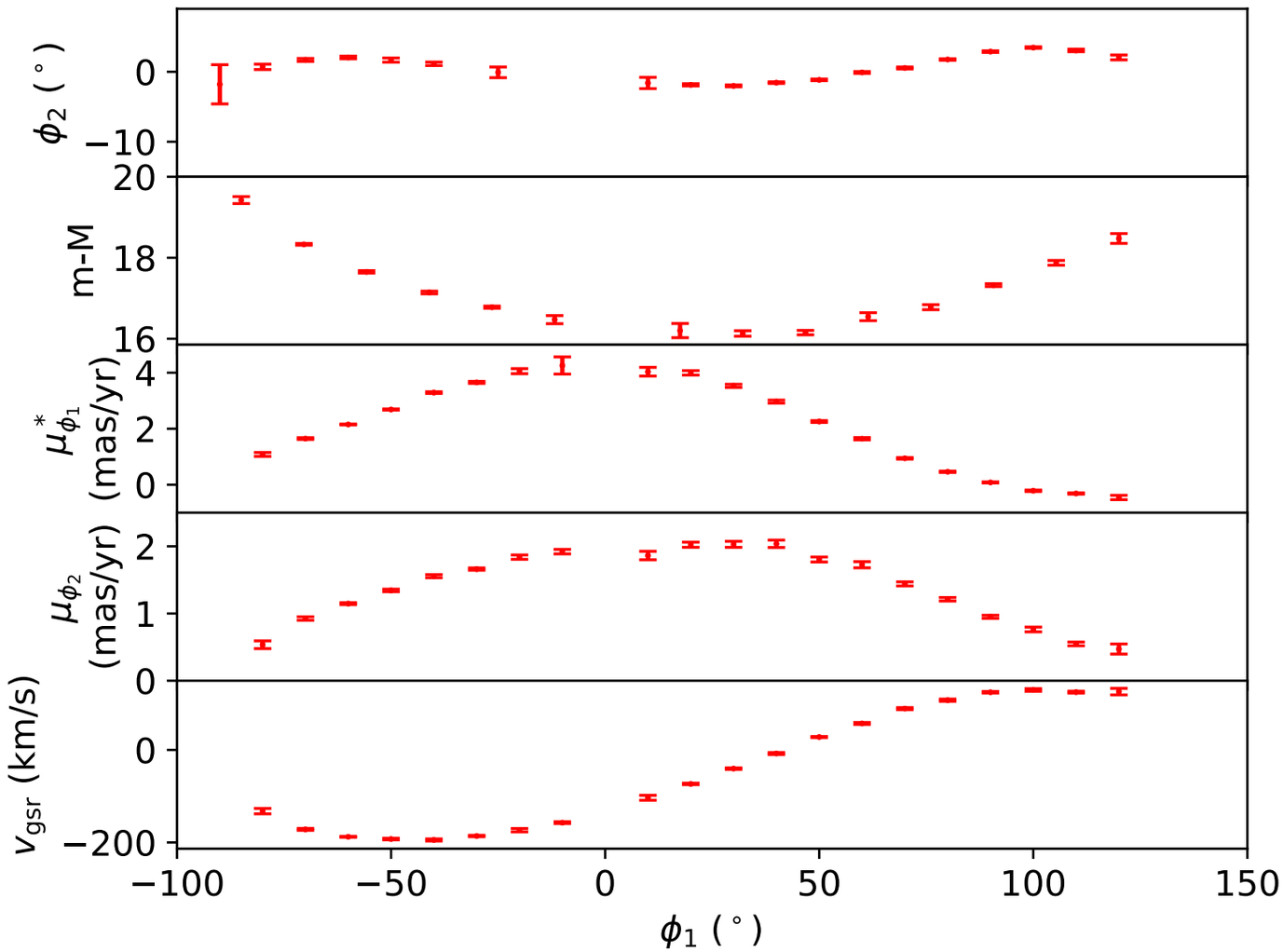
- Orphan-Chenab stream has the largest misalignment
- Proper motions across the stream are ~100 km/s
- Need an external perturber to explain this… LMC!



Erkal+2019
Koposov+2019
Koposov,DE+2023

OC stream data

- We now have 6d data for the stream across ~200 degrees
- Data comes from Gaia, S^5, APOGEE DR17, LAMOST DR7, and SDSS DR14



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Modelling ingredients

- We generate streams by stripping particles from the progenitor's Lagrange points
- Progenitor is rewound in the presence of MW+LMC and then disrupted
- Include dynamical friction on LMC from MW based on N-body sims
- Include reflex motion of the Milky Way

Modelling ingredients

- 25 parameters in our model

Parameter
OC progenitor
$\mu^*_{\alpha,\,\mathrm{prog}}$
$\mu_{\delta,\,\mathrm{prog}}$
$v_{r,\,\mathrm{prog}}$
d_{prog}
$\phi_{2,\,\mathrm{prog}}$
Milky Way
M_{NFW}
r_s
q_{NFW}
x_{NFW}
y_{NFW}
z_{NFW}
γ
β
LMC
M_{LMC}
$r_{s,\,\mathrm{L}}$
$r_{\mathrm{max,\,L}}$
$\mu^*_{\alpha,\,\mathrm{LMC}}$
$\mu_{\delta,\,\mathrm{LMC}}$
$v_{r,\,\mathrm{LMC}}$
d_{LMC}
Noise nuisance parameters
σ_{ϕ_2}
σ_{DM}
$\sigma_{\mu^*_{\phi,1}}$
$\sigma_{\mu_{\phi,2}}$
σ_{v_r}

Present-day OC progenitor phase space coordinates

Milky Way modelled as generalised NFW with axisymmetric flattening

LMC modelled as truncated NFW

Nuisance parameters to inflate observational uncertainties if needed

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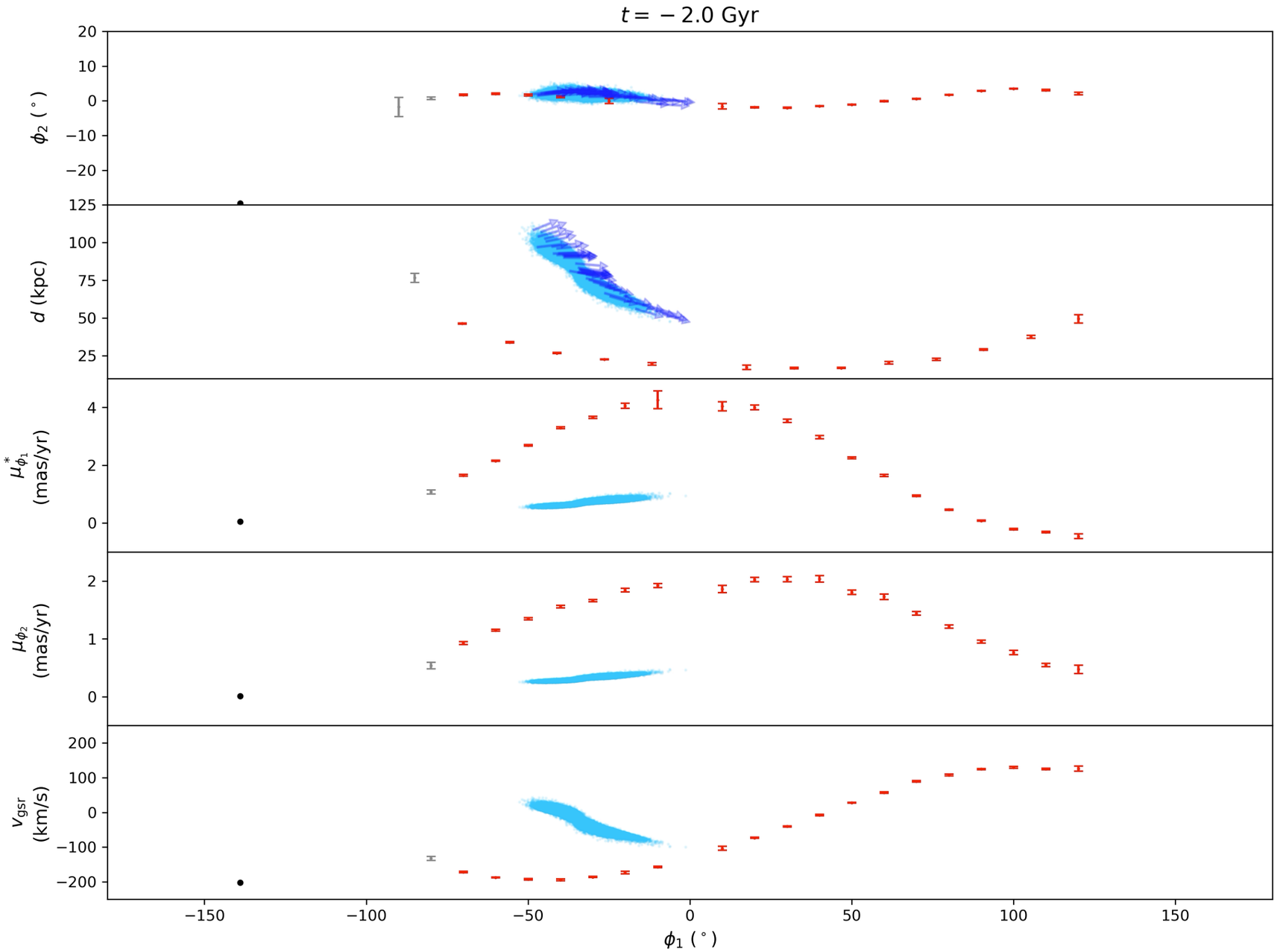
Best fit to OC stream

- OC over the past 2 Gyr



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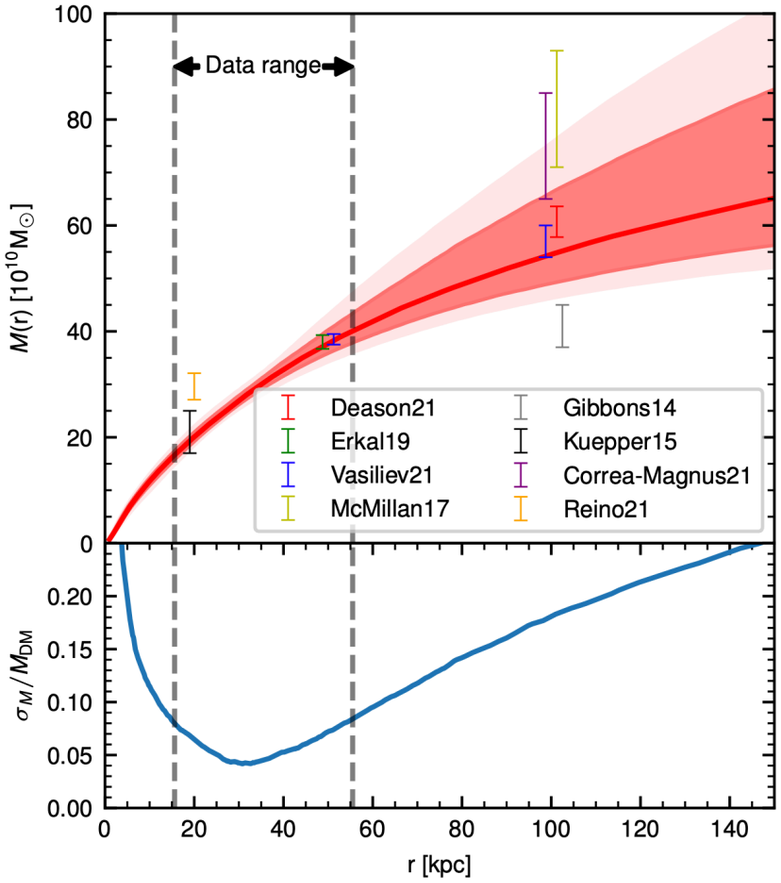
Milky Way mass profile

- Agrees with previous measurements
- Best measured at stream's location (~4%), in agreement with Bonaca & Hogg 2018
- Inner and outer halo profile consistent with NFW
- Can extrapolate out to virial mass



Inner NFW slope $\gamma = 1.27^{+0.31}_{-0.39}$

Outer NFW slope $\beta = 2.97^{+0.32}_{-0.41}$

$$M_{\rm vir} = 7.7^{+4.1}_{-1.5} \times 10^{11} M_\odot$$

$$r_{\rm vir} = 242^{+37}_{-17}\ {\rm kpc}$$

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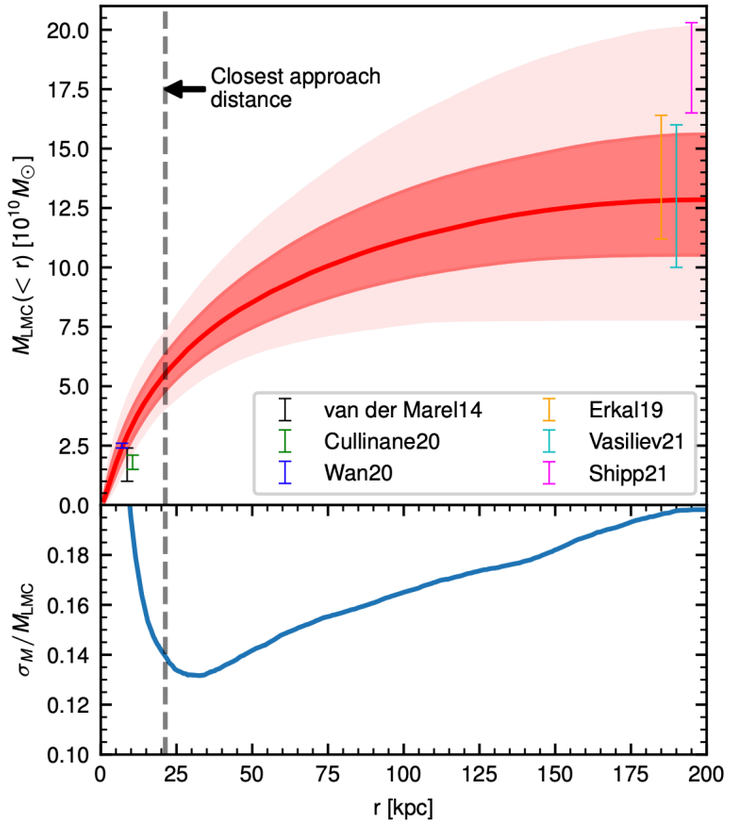
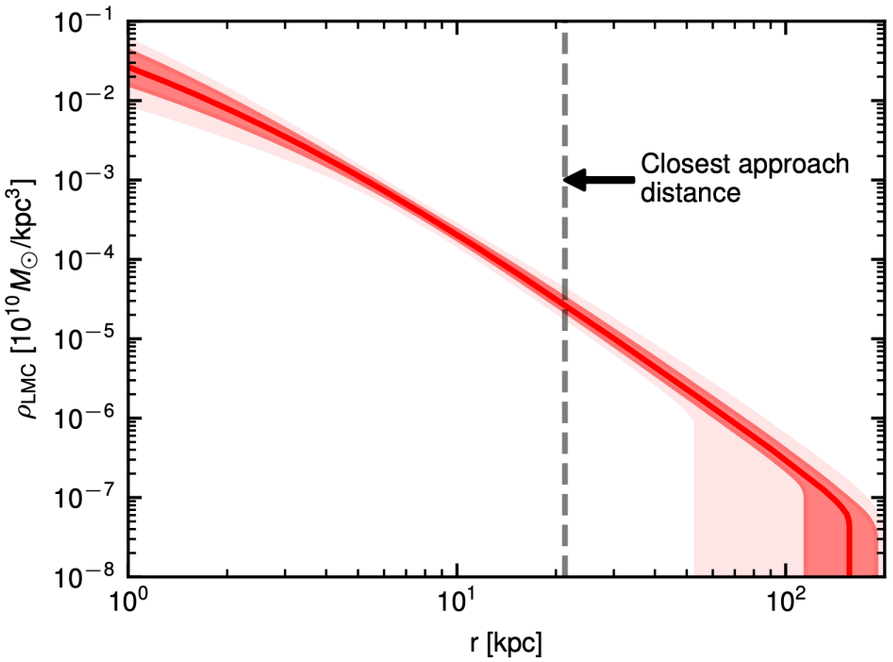
LMC mass profile

- Agrees with previous measurements (1:6 mass ratio with MW)
- Best measured close to the closest approach distance of the OC stream
- Models need LMC to be extended beyond ~53 kpc

$$M_{\rm LMC} = 1.29^{+0.28}_{-0.23} \times 10^{11} M_\odot$$





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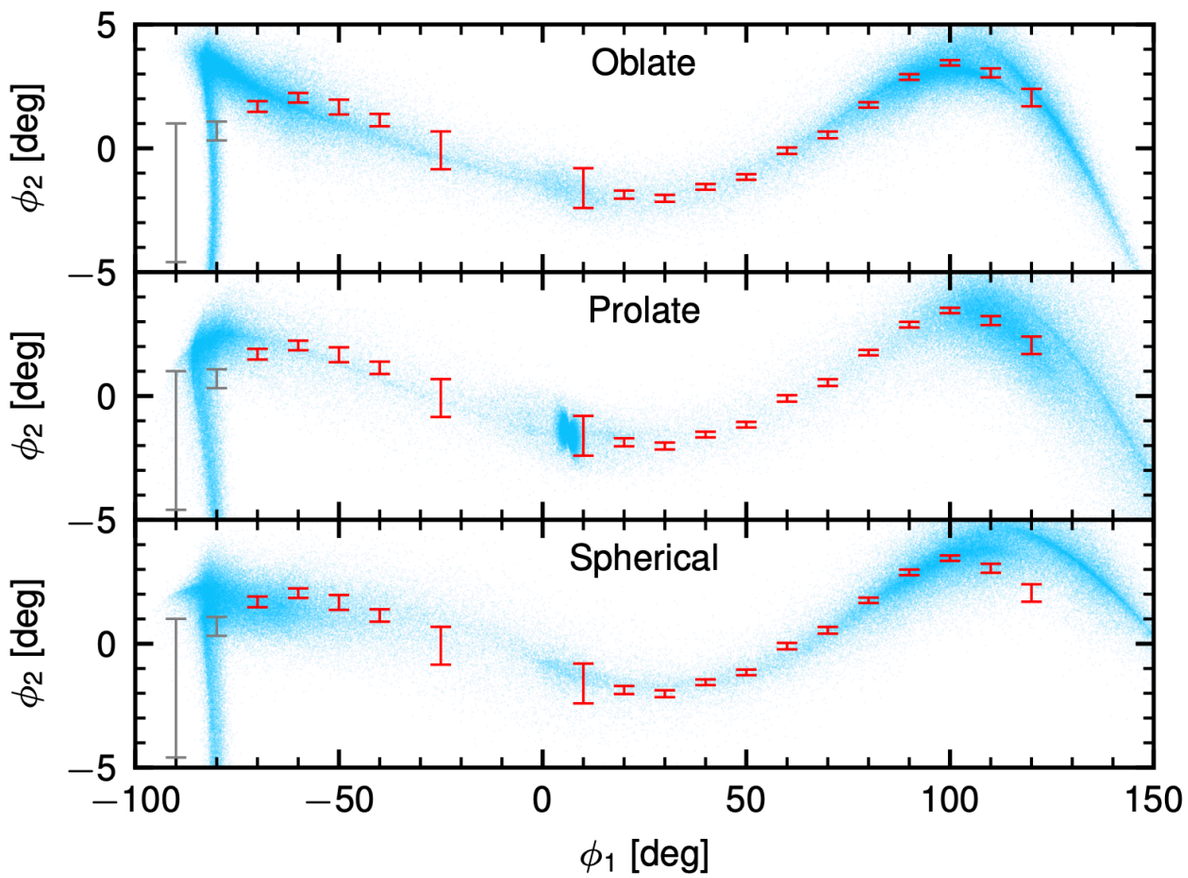
Milky Way halo shape

- Milky Way can be either prolate or oblate (same as Erkal et al. 2019)
- Flattening is needed to match the stream's downturn



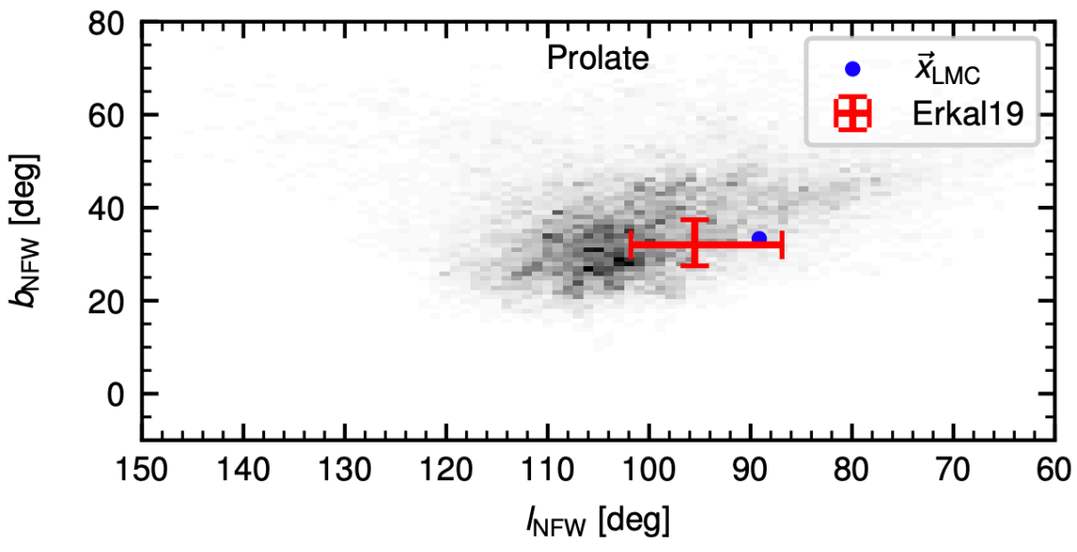
$q = 0.6 \pm 0.1$

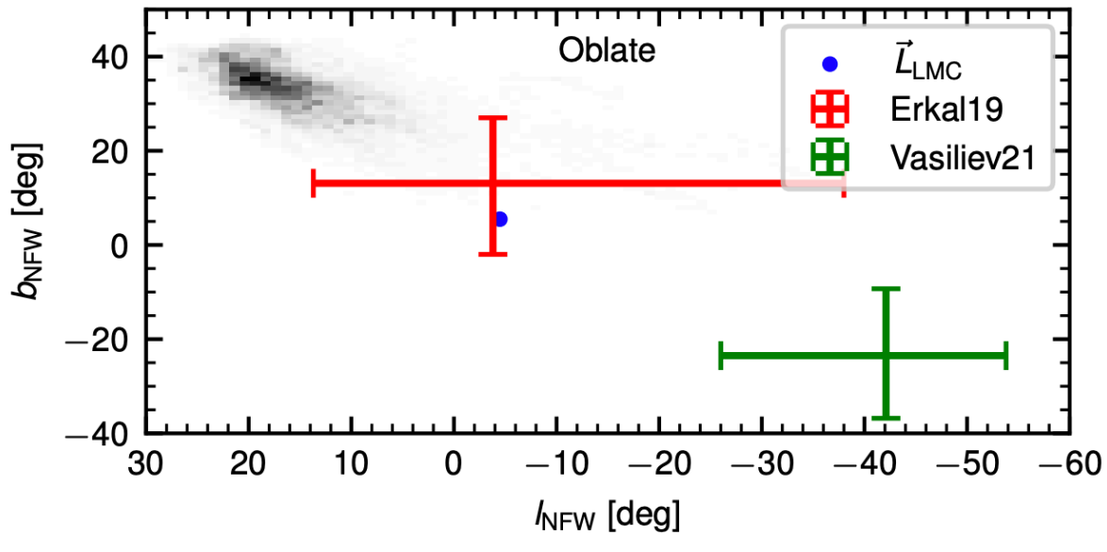
$q = 1.4 \pm 0.1$

Koposov,DE+2023

Milky Way halo shape

- Prolate halo is pointed at LMC's present-day location
- Oblate halo is somewhat aligned with the LMC's angular momentum
- Oblate halo has similar flattening but different orientation from inference with Sagittarius stream (Law & Majewski 2010, Vasiliev, Belokurov, Erkal 2021)





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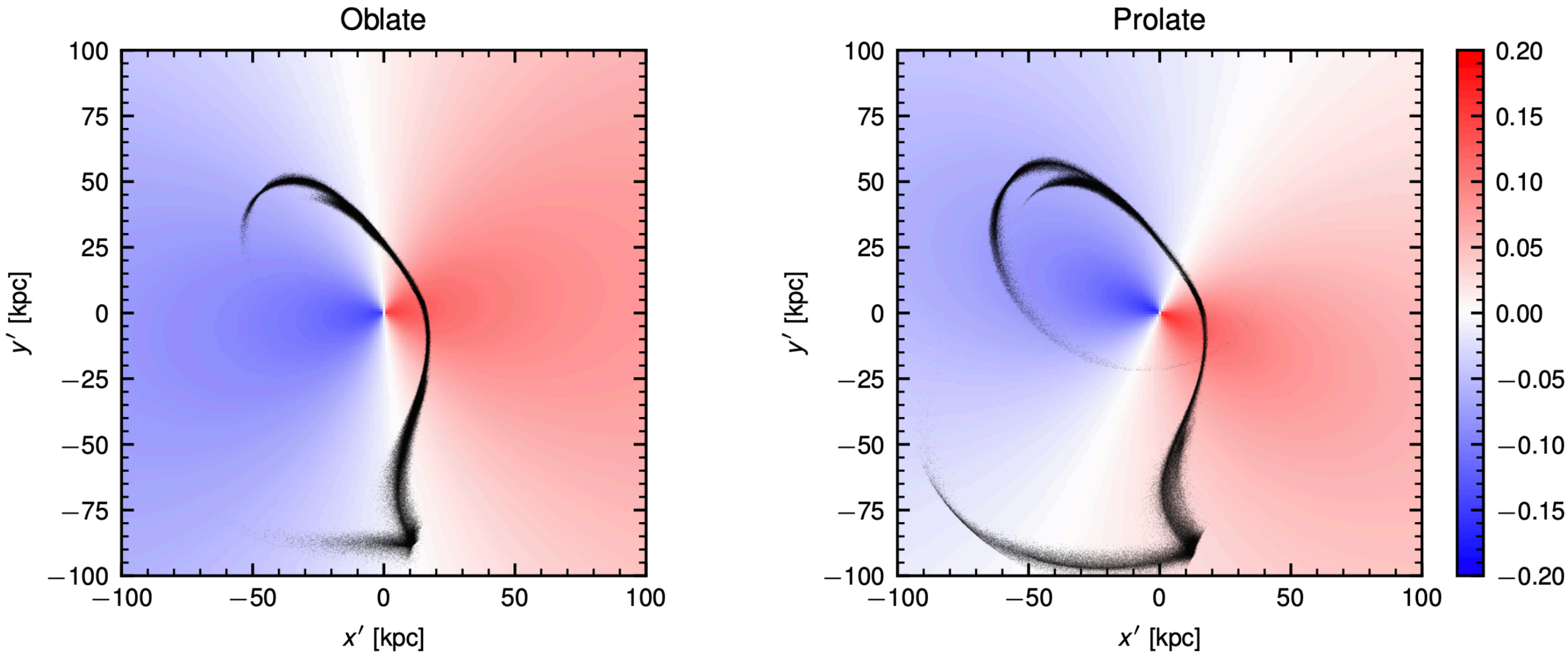
Milky Way halo shape

- The acceleration field from the prolate and oblate halo is qualitatively similar

- Both act to bend the right part of the stream downwards



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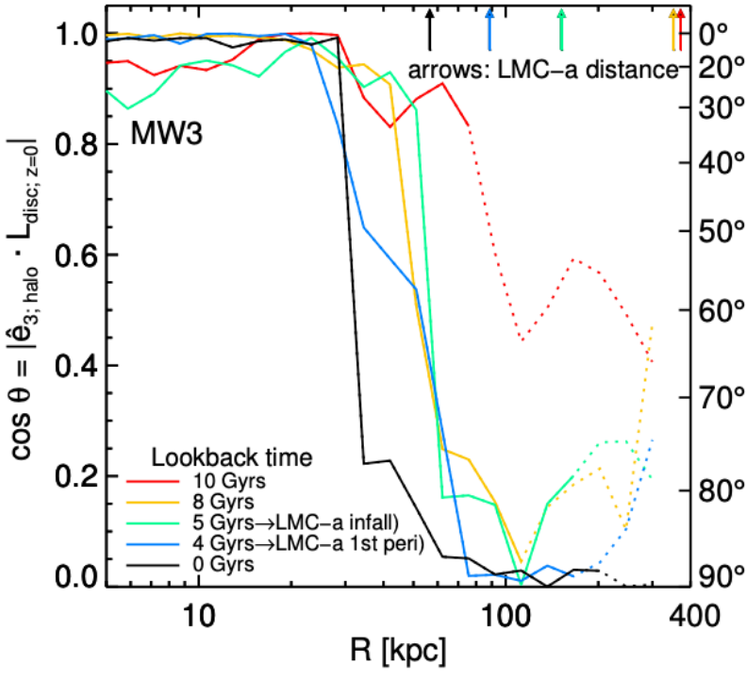
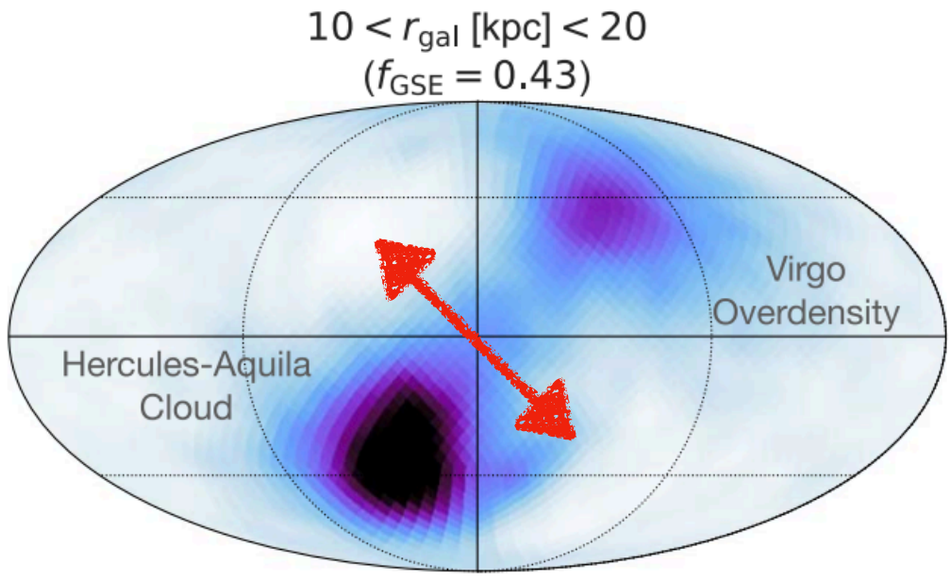
Milky Way halo shape

- Possible explanations:
    - Shao+2020 see an alignment of the outer Milky Way and LMC's orbital plane in cosmological simulations
    - Prolate halo misaligned with expected GSE debris
    - Not due to classical satellites (including SMC)
    - Incorrect modelling of MW+LMC?



Shao+2020



Naidu+2021

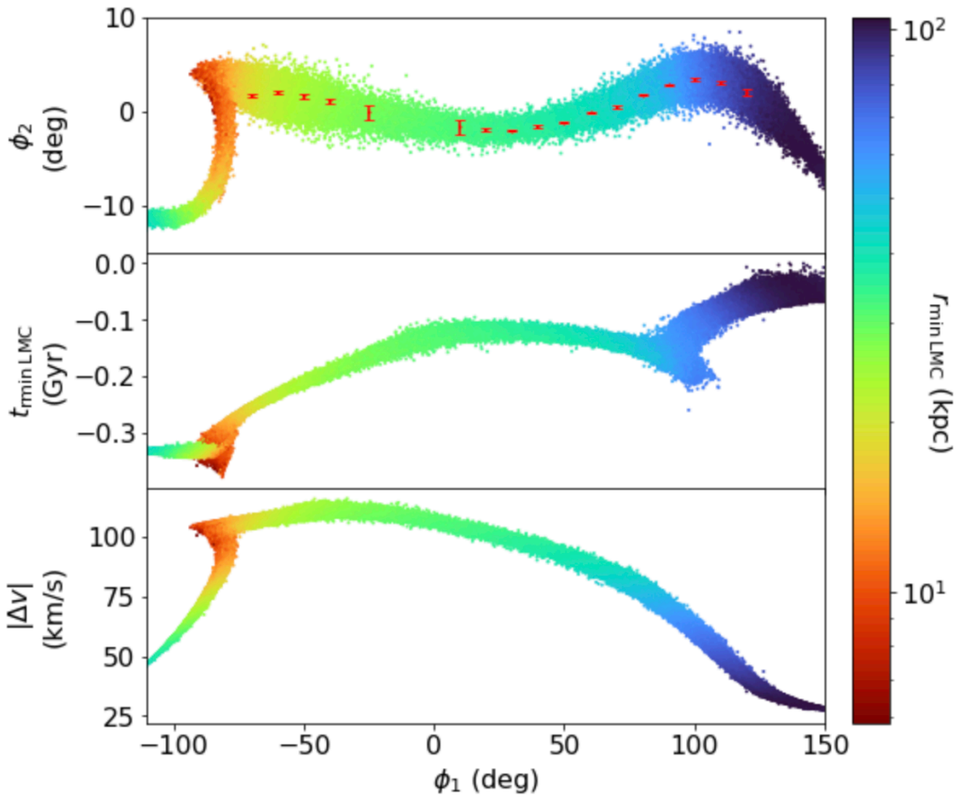
Deforming MW+LMC system

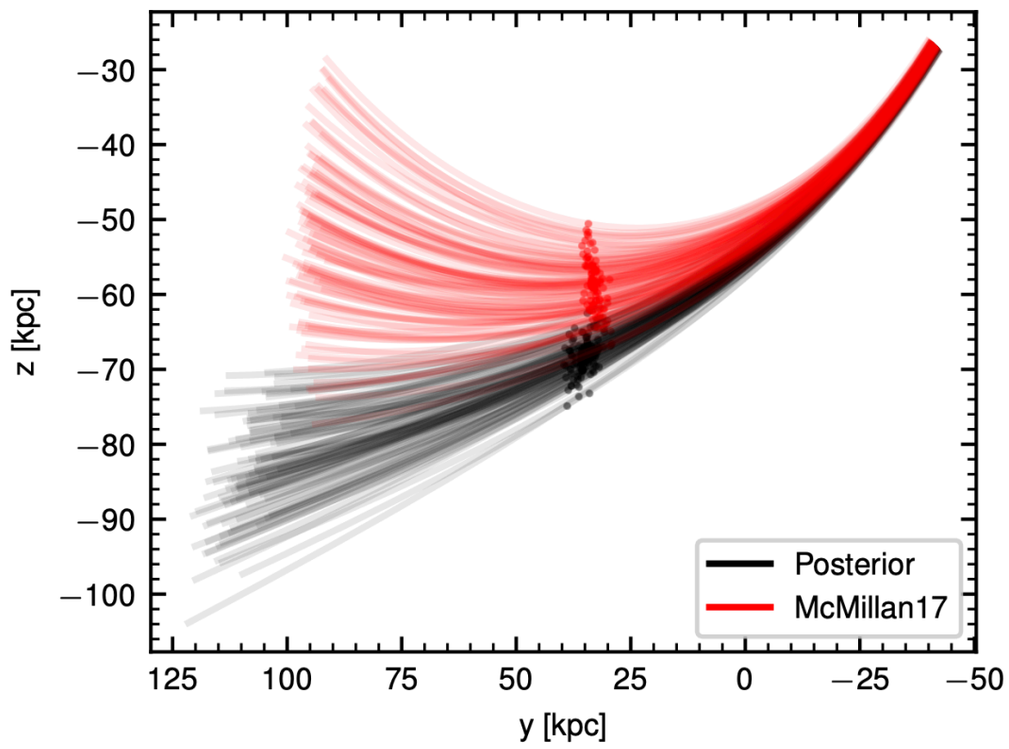
- Sophia has shown the deforming MW+LMC system should affect the OC stream

- Our Milky Way may be effectively describing this

The LMC’s past orbit

- The LMC passed within ~19.1 kpc of the observed portion of the OC stream ~254 Myr ago
- LMC has a closest approach within ~6 kpc of the OC stream ~366 Myr ago
- Fits to the OC stream let us constrain the LMC’s past trajectory





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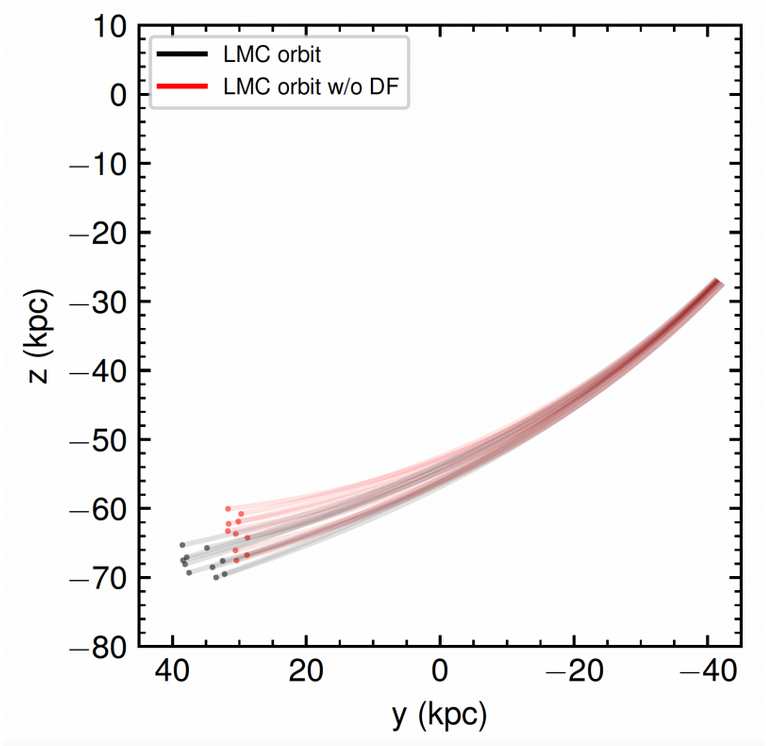
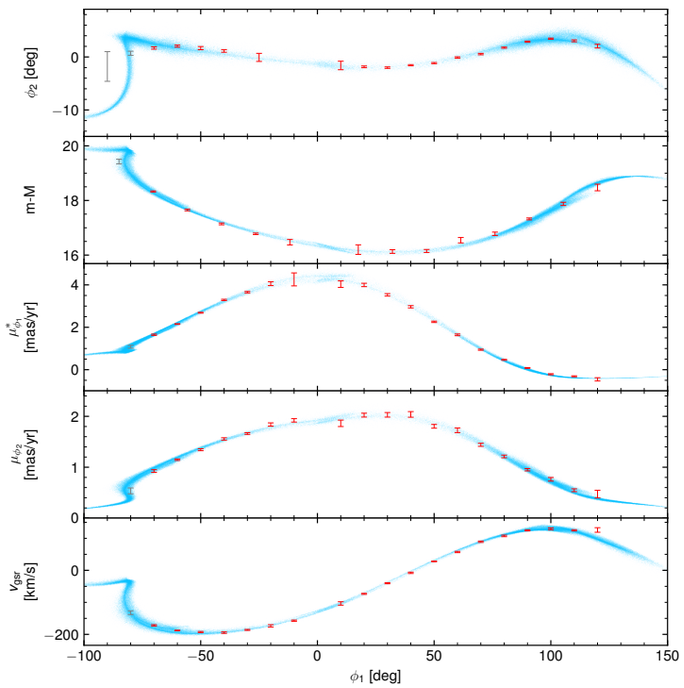
Dynamical friction on LMC

- The LMC passed within ~19.1 kpc of the observed portion of the OC stream ~254 Myr ago
- Dynamical friction moves the LMC by ~5.7 kpc over 254 Myr
- This slight change has a huge effect on the OC stream
- Refit with a free parameter to scale the dynamical friction, $f_{\rm DF}$

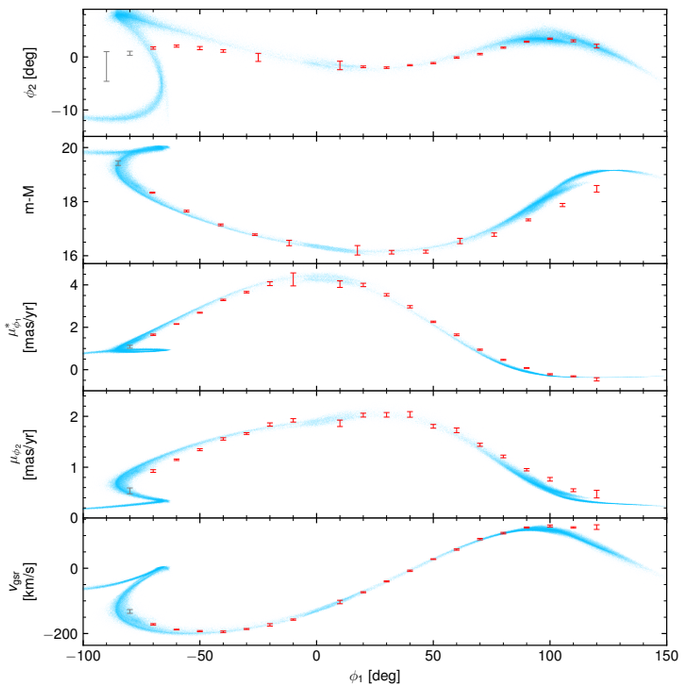
LMC orbit over 254 Myr



Best-fit OC model



Best-fit with no DF on LMC

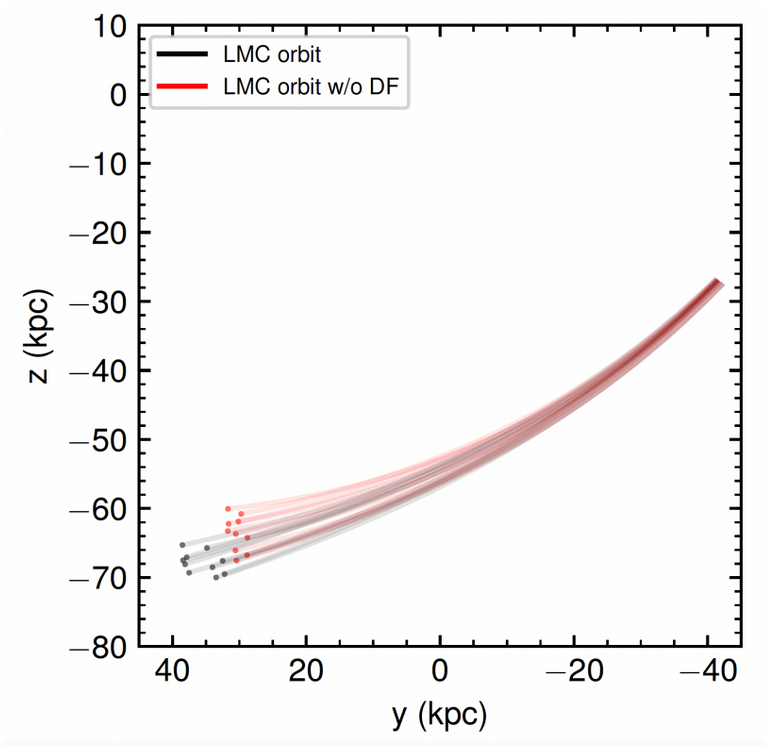


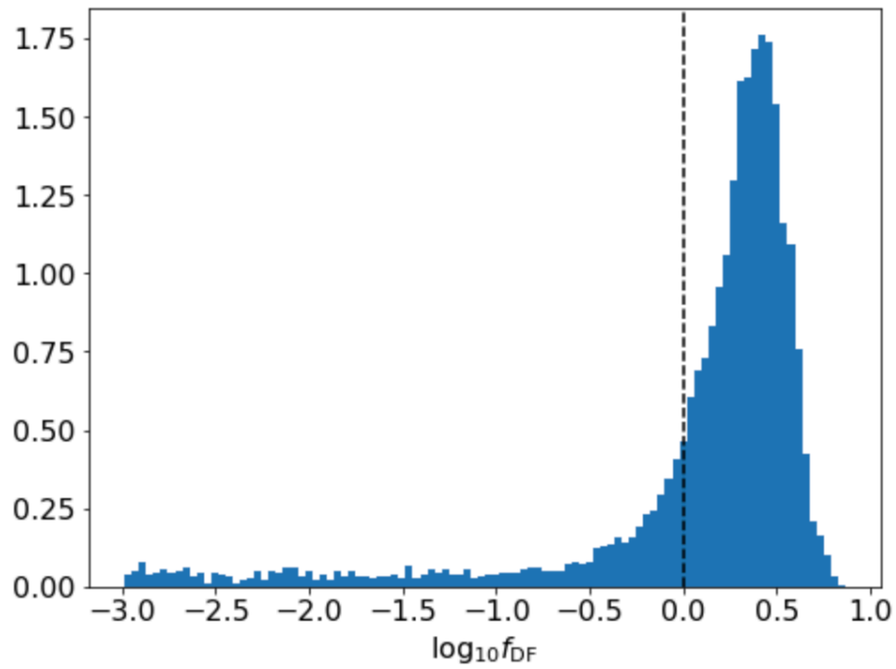
Koposov,DE+2023

Dynamical friction on LMC

- The LMC passed within ~19.1 kpc of the observed portion of the OC stream ~254 Myr ago
- Dynamical friction moves the LMC by ~5.7 kpc over 254 Myr
- This slight change has a huge effect on the OC stream
- We measure $\log_{10} f_{\rm DF} = 0.3^{+0.2}_{-0.5}$ where $\log_{10} f_{\rm DF} = 0$ is Chandrasekhar DF

LMC orbit over 254 Myr





Koposov,DE+2023

Next steps

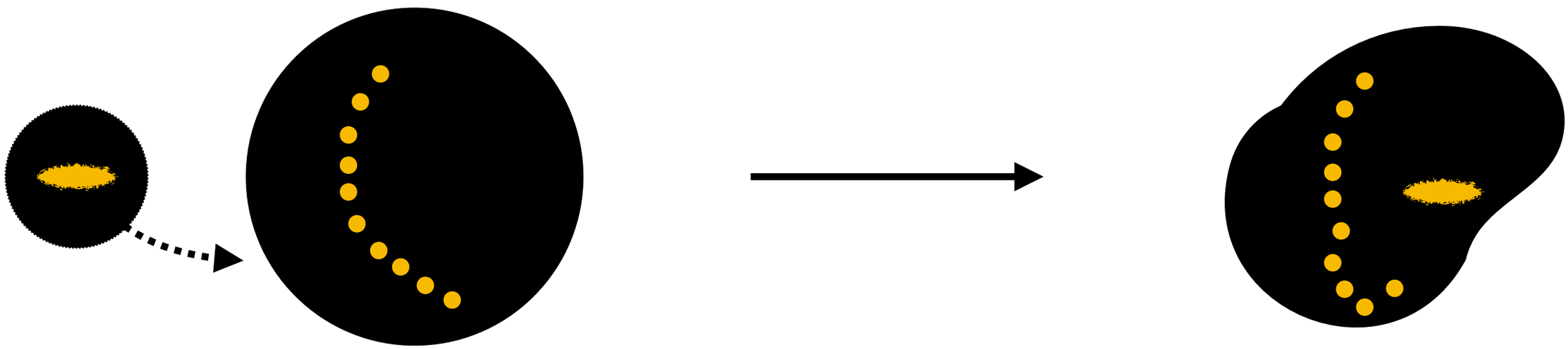
- Find the kink!
- Develop models which include deformations (Sophia's talk)
- Fit these to the OC stream and other Milky Way streams to measure deformations to test fluid nature of dark matter
- Test with alternative dark matter and gravity models

Stream	$M_{\rm LMC}$ (10^{10} $M_\odot$)	$r_{\rm approach}$ (kpc)	$v_{\rm approach}$ (km s^{-1})	$t_{\rm approach}$ (Myr)
ATLAS	$14.3^{+6.7}_{-3.5}$	23.9	467.1	80.0
OC	$18.8^{+3.5}_{-4.0}$	25.4	371.2	310.0
Elqui	$16.8^{+5.2}_{-3.0}$	11.2	419.6	99.0
Indus	$15.6^{+8.6}_{-3.6}$	38.0	268.5	10.5
Phoenix	$2.7^{+8.5}_{-0.7}$	30.7	433.9	49.2
Tucana III	···	4.2	382.4	98.8
Jhelum	···	40.6	367.2	2.8

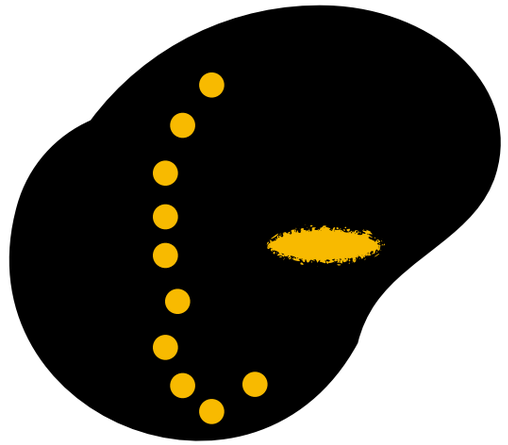
Shipp,DE+2021

Milky Way + LMC as a local dark matter collider

- We know the LMC's present-day location
- Streams can tell us where it came from
- Streams (+ other tracers) act as time-dependent detectors
- (Somewhat) controlled dark matter collider!



Conclusions



- Gaia+S^5 provides phenomenal stream data
- Need sophisticated models including LMC to fit this data
- Milky Way is consistent with an NFW profile
- LMC is massive (1:6 with Milky Way) and needs to be quite extended
- Milky Way flattening may be telling us about deformations
- OC stream is sensitive to past trajectory of LMC
- We can measure how much dynamical friction LMC experienced, $\log_{10} f_{\rm DF} = 0.3^{+0.2}_{-0.5}$
- These measurements should be even tighter with the OC stream kink!