Orlin Koop with H.C. Woudenberg, E. Balbinot, A. Helmi
Contact: koop@astro.rug.nl
See also https://arxiv.org/abs/2202.02132

Milky Way Modelling with Stellar Streams

university of groningen
faculty of science and engineering
kapteyn astronomical institute

Jhelum

(1.1) Introduction: stream substructure and Jhelum

Stellar Streams form when stars are stripped from a Milky Way satellite during its orbit. They are good **probes** of the underlying gravitational **potential**, and can be used to study the Milky Way's **dark matter subhalo** population. These subhalos will leave gaps or other **substructure** in a stream after an encounter. However, other possible causes for substructure are possible. We will study the peculiar structure in the Jhelum stream using N-body simulations.

(1.2) Data

The stream **Jhelum** was first discovered in DES data [1] and consists of a **narrow** and a **broad** component [2]. Gaia eDR3 data shows a possible **tertiary** component *(Fig. 1)*.

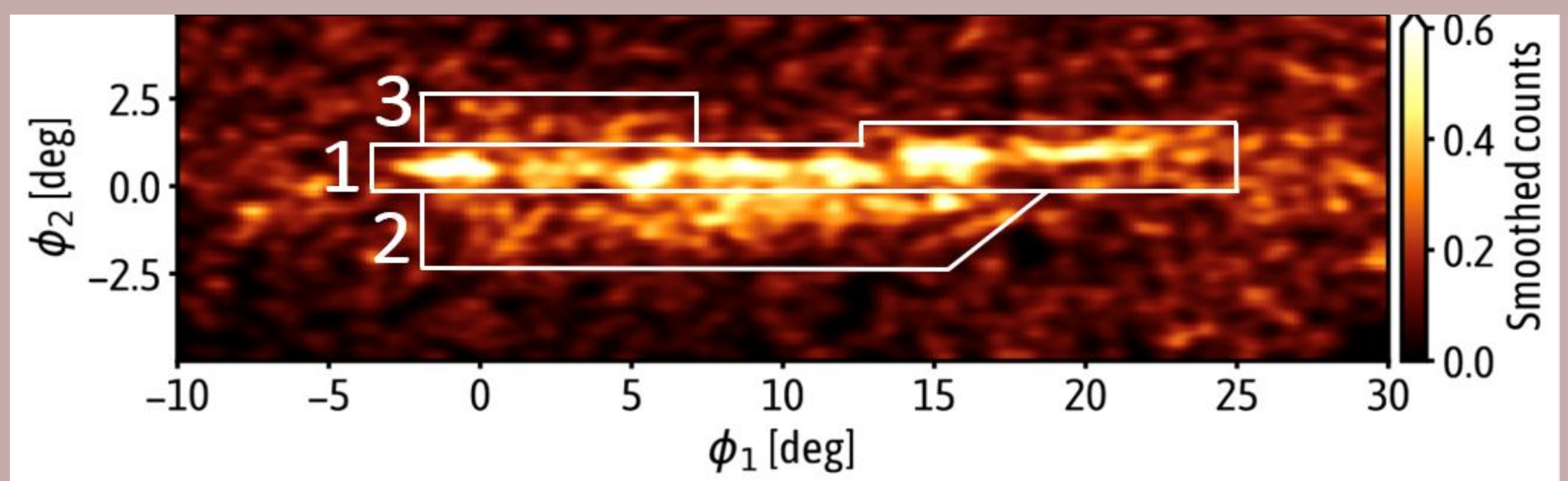

Fig 1: Smoothed density map of the positions in (φ1, φ2) of likely Jhelum stream members. The boxes show the **Narrow** (1), **Broad** (2) and **Tertiary** Component (3).

(1.3) Jhelum's peculiar kinematics

We were unable to fit one orbit to Jhelum in realistic galactic potentials [3], pointing to the peculiar kinematics of the stream. Jhelum **shares an orbital plane** with the **Sagittarius** Dwarf Spheroidal Galaxy (Sgr), which causes **close interactions** between the two systems.

(2) Results: multiple stream morphologies are possible

Figure 2 shows the position and radial velocity of a simulated stream from one N-body simulation with a globular cluster and a dwarf galaxy undergoing mass loss. (φ1, φ2) are the Jhelum stream aligned coordinates [2]. **Multiple different morphologies are possible.** See the link from the QR code for more results.

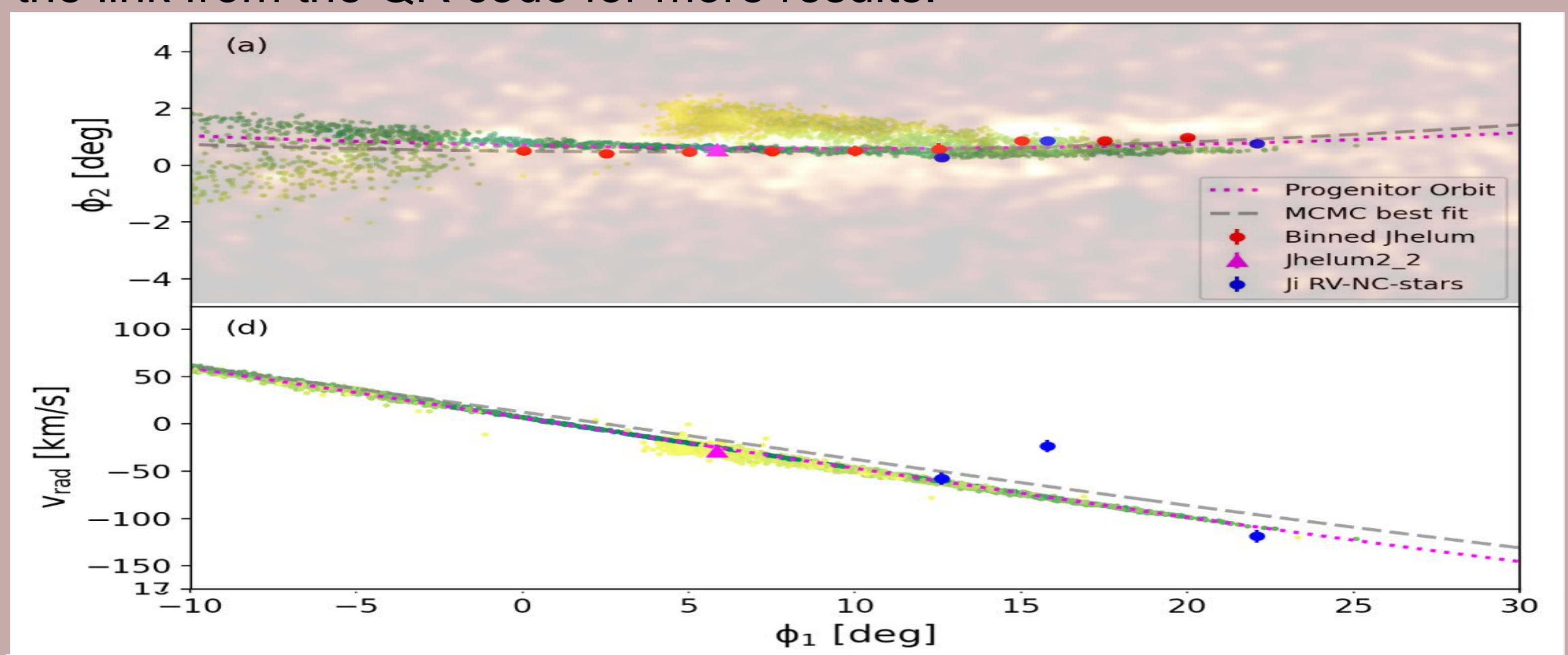

Figure 2: Simulation results. Particle colours show **time of release** from the progenitor. Lighter colours mean an earlier release. The **backdrop** is Fig 1. Larger dots and lines are (binned) datapoints and orbit models respectively.

Abstract

We studied the complex **stellar stream Jhelum**. It **shares an orbital plane** with Sagittarius, leading to close **encounters** between the two. Using N-body simulations, we show that these encounters can explain Jhelum's peculiar morphology and kinematics. Therefore, interactions with objects like Sgr should be added to the list of **possible causes** for **stream substructure**.

(3) Cause: velocity kick gradients

In most cases, **one significant interaction** with Sgr causes a **large velocity kick** to the progenitor, **combined** with a large **gradient in Δv** along the stream *(Fig. 3)*. This causes the two tails to start precessing around the new orbit of the progenitor. To see this effect in full, check out the videos the QR code links to.

The Δv are calculated using the **impulse approximation** [5] and depend on the relative velocity, distance and geometry of Jhelum and Sgr, the mass of Sgr and the orbital phase of Jhelum.

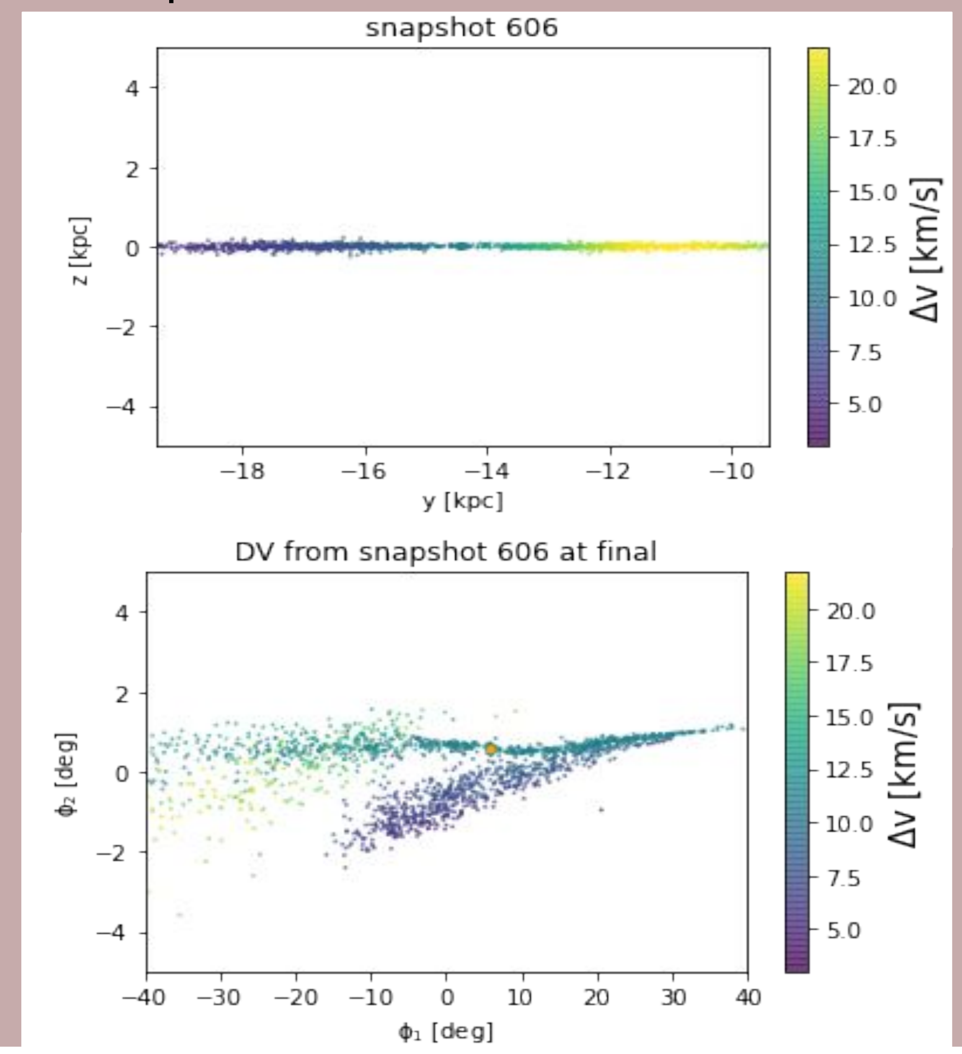

Figure 3. One simulation at the time of the **most significant interaction** (top) and in the **final snapshot** (bottom) with colours according to the Δv experienced by each particle at time of the interaction. (y,z) correspond to (ŷ,ẑ) in *the videos.*

Helmi Streams

Abstract:

The Helmi streams show **dynamical substructure in angular momentum** space [6]. This structure can be explained by the location of resonances in **prolate galactic dark matter halo** potentials. In **MOND** (Modified Newtonian Dynamics), the potential is determined by baryons only. We show that **MOND needs to be expanded to explain the observed substructure.**

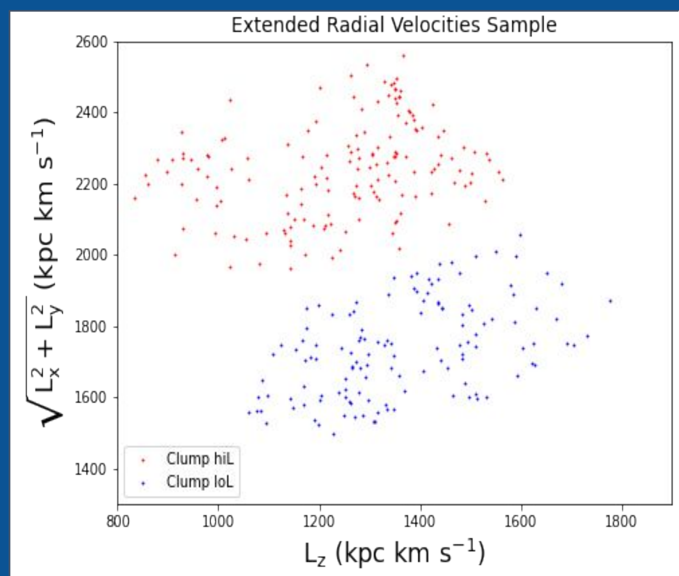

Figure 4. Helmi streams stars in L_z-$L_\perp$ space. The stream separates into two clumps.

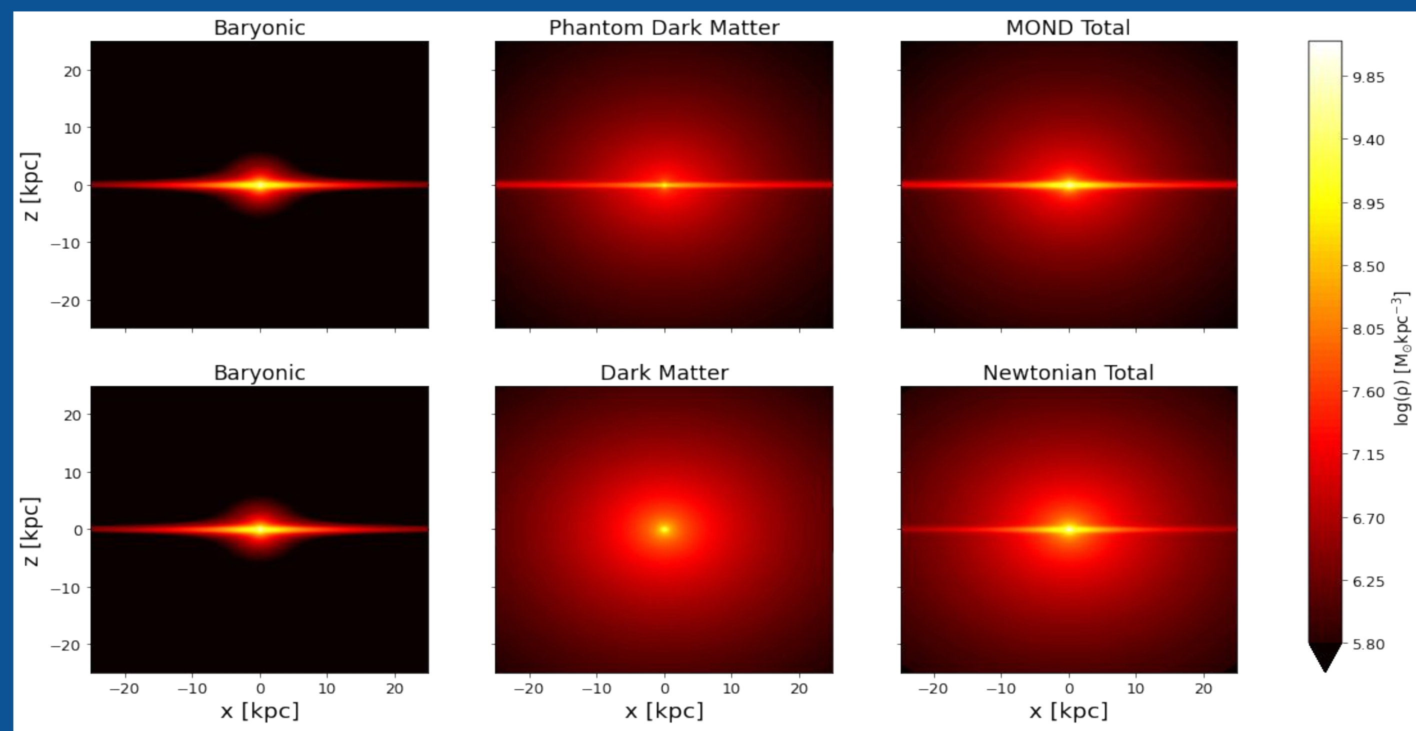

Figure 5. Density profiles of the **baryonic** (left column), **(phantom) dark matter** (middle column) and **total density** (right column) for the Price-Whelan model, showing how the phantom dark matter is constrained to follow the shape of the disk baryonic distribution.

Movies of the simulations

Scan the QR code for more figures and videos of the simulations in this poster:

(1.1) Introduction: Helmi streams substructure

The **Helmi streams** are thought to be the debris of a massive dwarf galaxy with a stellar mass of ~ 10^8 M_{sun} that was accreted ~5-8 Gyr ago. Its stars have **phase-mixed** implying that they do not define spatially tight structures. [6] have shown that the Helmi streams in fact define **two distinct clumps in angular-momentum space** (L_z-$L_\perp$) *(Fig. 4)*. The stellar populations of these two clumps are **similar**, and the clumps are able to **survive in time** if the Galactic dark matter **halo** has a **prolate shape** due to orbital resonance.

We study if MOND can also explain the behaviour of the two clumps in L_z-$L_\perp$ space.

(1.2) MOND (Modified Newtonian Dynamics)

MOND states that gravity behaves differently in the **low acceleration regime**. The gravitational acceleration in MOND ***g*** is given by [7]:

$$\mu(a/a_0)\mathbf{g} = \mathbf{g}_N,$$

where $\mathbf{g}_N$ is the Newtonian acceleration, μ is the **'interpolation function'** between MOND and Newtonian gravity and $a_0 \approx 10^{-10}$ **m s^{-1}** is the constant defining the regime of low acceleration.

(2) Method: Orbit integrations in MOND models

We study **two Milky Way models**. One from [8], the Price-Whelan model, and one from [9], the McMillan model. We use **only** their **baryonic** components in the MOND framework. We did need to **increase the mass of the disk** component to fit the circular velocity at the solar radius. *Figure 5* shows the shape of the Milky Way potential in MOND and Newtonian gravity.

(3) Results: substructure is not retained in MOND

In the videos found through the QR code, we show how the substructure in the Helmi streams dissolves within ~0.2 Myr in a MOND framework, meaning that MOND needs to be expanded to explain the Helmi streams substructure.

References: [1] Shipp, N., et al., 2018, ApJ, 862, 114 [2] Bonaca, A., et al., 2019, ApJL, 881, 2 [3] Woudenberg, H. C., Koop, O. et al, 2022, A&A 669, A102 [4] Ji, A., et al., 2020, AJ, 160, 181 [5] Erkal, D. & Belokurov, V., 2015, MNRAS, 450, 1136 [6] Dodd, E., et al., 2022, A&A, 659,A61 [7] Milgrom, M., 1983, ApJ, 270, 365 [8] Price-Whelan, A., 2017 JOSS, 2(18), 388 [9] McMillan, P., 2017, MNRAS, 465, 76.

Conclusions

- **Interactions with Sgr** can explain the **unusual morphology** of **Jhelum** discovered in Gaia DR2 and eDR3.
- The cause of the substructure is always one interaction with a **large velocity kick** in combination with a **velocity kick gradient** along the stream.
- This mechanism is **robust** against our simplifications and requires **no finetuning**.
- We should include interactions with heavy MW satellites to the list of **possible causes** of stellar stream **substructure**.
- **MOND** needs to be expanded to explain the substructure in the Helmi Streams