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THE STATE UNIVERSITY
OF NEW JERSEY

# Testing the Robustness of Via Machinae Stellar Stream Candidates

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# What are Stellar Streams?

- Groups of stars with a common orbit around a galaxy
- Formed by tidal forces that stretch out orbiting globular clusters or dwarf galaxies
- Around 100 known streams in the Milky Way

# What can Stellar Streams Teach Us?

- Learn the history of mergers that formed the Milky Way
- Measure the Galactic potential
- **Gaps in streams linked to dark matter substructure**
  - Sensitive to dark matter subhalos down to $10^6$ $M_\odot$
  - Subhalo mass function puts constraints on dark matter models

# Searching for Streams in *Gaia* Data Release 2

- *Gaia* DR2 contains kinematic data for roughly 1.5 billion Milky Way stars
- Traditional (non-neural net) algorithm example:
  - *Streamfinder* looks for 6D position+velocity “hypertubes” with high occupation
- Neural networks provide a more model-agnostic alternative

# Anomaly Detection with ANODE

Define a signal region (SR) encompassing the signal

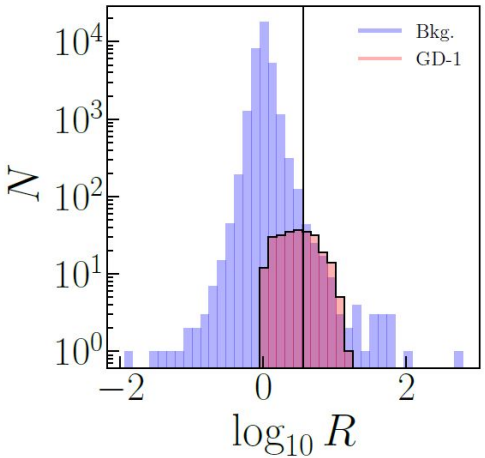
Sidebands (SB) complement the SR

Learn density in both regions (normalizing flow)

Interpolate from SB into SR

Calculate test statistic R for each $x$ in SR

$$R = \frac{p_{data}(x|x_i)}{p_{background}(x|x_i)}$$




Known stream stars have higher *R* than background stars

*Shih, Buckley, Necib, Tamanas 2021*

# An Overview of *Via Machinae*

Tile the sky into 15° circular patches

Bin each patch into SRs in proper motion

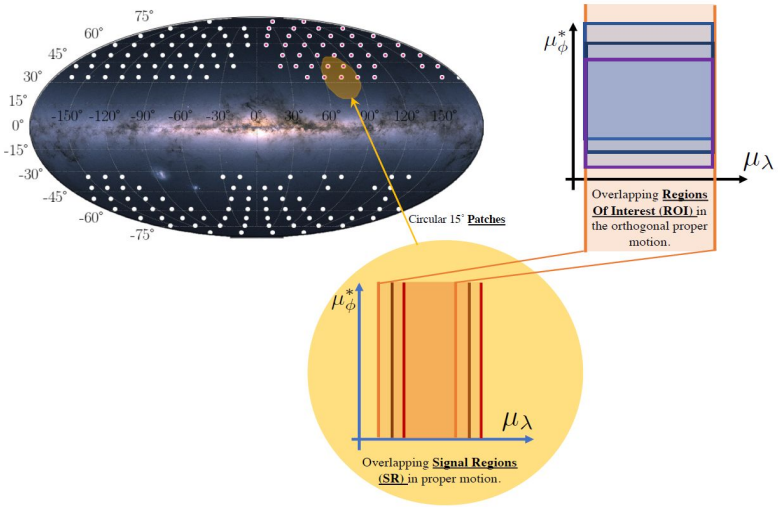
Run ANODE on each SR

Discard SRs containing other anomalies (globular clusters)

Bin SRs into ROIs

Run line-finding on high-*R*-stars

Cluster ROIs into protoclusters, protostreams (1 per 15° patch), and then streams




*Shih, Buckley, Necib 2023*

# Estimating the False Positive Rate

Many candidates correspond to known objects

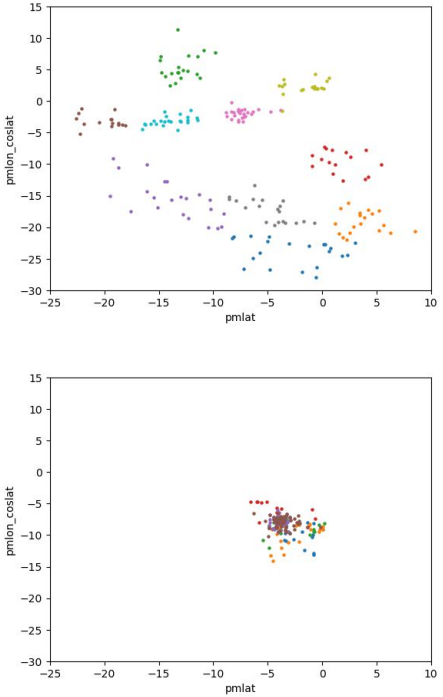
False positives: background mismodelling, random alignment

Ran VM on a mock dataset containing no stream-like structures (made using *Galaxia* code)

- Stream significance is used to classify mock vs *Gaia* DR2 candidates

“Control protoclusters” were generated from *Gaia* DR2

- Made using ROIs that are separated in proper motion but have aligning best-fit lines




ROIs in a control PC (top) vs in a regular PC (bottom)

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# Robustness of *Via Machinae* Candidates

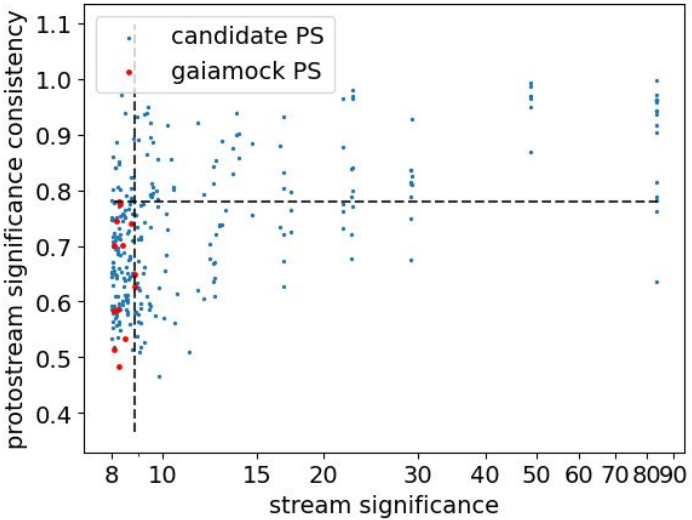
Retraining the density estimators should reproduce real streams more often than false positives

Reran ANODE 9 additional times

- Only used search regions that were part of an original candidate

Define significance consistency as

$$\frac{\text{mean rerun significance}}{\text{original significance}}$$

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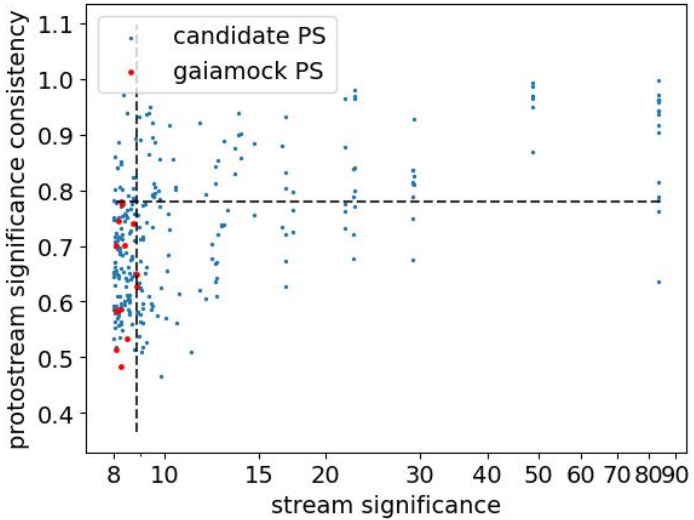
# Robustness of *Via Machinae* Candidates

Cut only on significance: 87 candidates, FPR = 12.8%

Cut on both consistency and significance: 106 candidates, FPR = 10.5%

Streams that pass *both* significance and consistency cuts are our top candidates

- 42 candidates have at least one PS in top right of plot

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# Orbit Fitting

Stream candidates that track an orbit around the Galactic center are more likely to be real

Independent test since VM does not take orbits into consideration

*Gaia* DR2 provides 4D data

Choose a seed star, optimize 2 missing coordinates such that integrated orbit minimizes chi2 distance to other stars

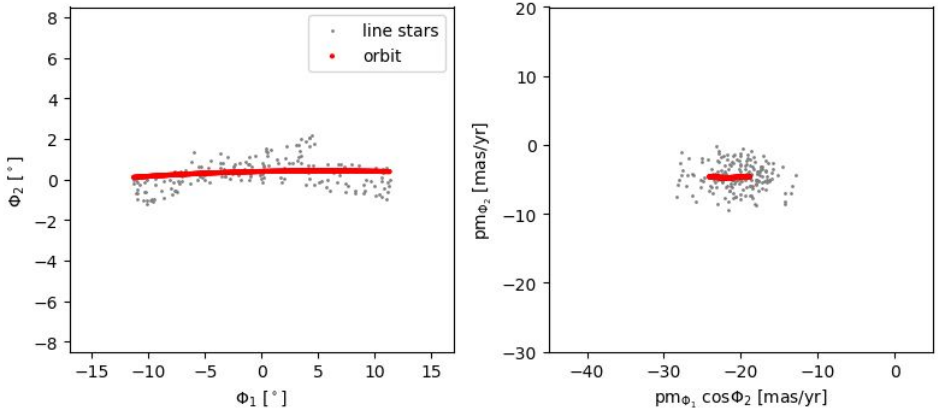
# Orbit Fitting

Some but not all candidates produce good fits

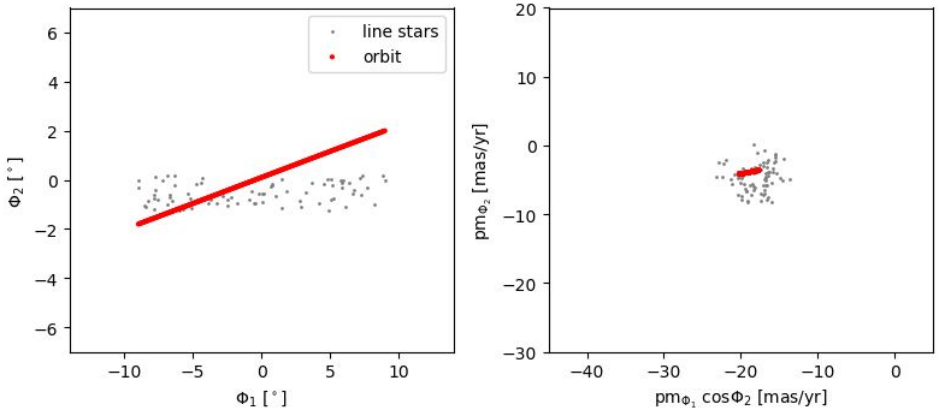
Orbits are evaluated by eye (in position and proper motion), and values of free parameters must be reasonable

Gaiamock candidates do not produce good fits

Optimal initial conditions: d = 5.36 kpc, rvel = 26.99 km/s




Optimal initial conditions: d = 34.17 kpc, rvel = 1000 km/s

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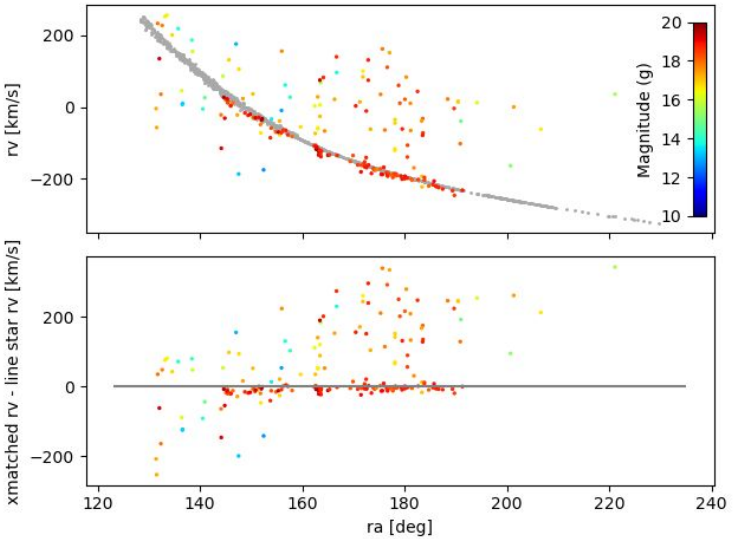
# Orbit Fitting

We can predict the distances and radial velocities of candidate stars by matching them to the closest point on the best-fit orbit

GD-1 radial velocity predictions largely agree with measurements from other surveys




Crossmatching GD-1 stars to other surveys allows us to compare our radial velocity predictions to real measurements. (mostly from DESI edr)

# Results and Future Work

Of 42 candidates with high significance *and* consistency, 26 have reasonable best-fit orbits

11/26 appear to match previously known streams (in galstreams database)

This leaves us with 15 top candidates to investigate in further detail

# Results and Future Work

List of candidates that have high significance, high consistency, **and** have decent looking best-fit orbit

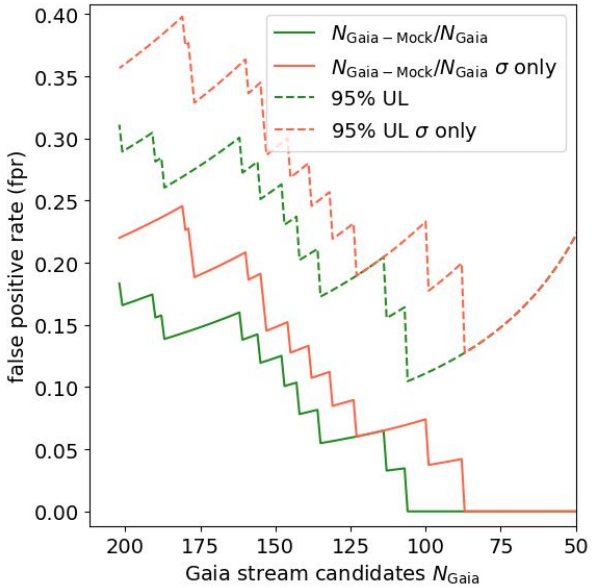
For each candidate, list stars in order of how many times they appeared in the 9+1 VM runs

Obtain spectra (metallicity, radial velocity, distance) for stars in top candidates

- Stream stars should have similar metallicities (same progenitor)

# Summary

- Via Machinae produced 202 stream candidates, of which we've selected the most promising
  - High significance
  - High consistency across retrainings
  - Good best-fit orbit
- We cannot discard the other candidates based on these tests (some correspond to known streams!)
- Observations of these candidates would confirm or reject their discoveries


0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
false positive rate (fpr)
200
175
150
125
100
75
50
Gaia stream candidates $N_{Gaia}$
$N_{Gaia-Mock}/N_{Gaia}$
$N_{Gaia-Mock}/N_{Gaia}$ $\sigma$ only
95% UL
95% UL $\sigma$ only