The Kinematics of Multiple Stellar Populations in 25 Milky Way Globular Clusters

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Context

The formation physics of globular clusters (GCs) is currently unknown.

Most Galactic globular clusters contain multiple stellar populations (MPs), which may provide insight into the formation conditions - for clusters that still display their initial kinematic signatures.

Typically, the multiple stellar populations include:

P1 stars –> with light element abundance patterns similar to the surrounding field stars

P2 stars –> enriched in N & Na, but depleted in C & O, in comparison to the P1 stars

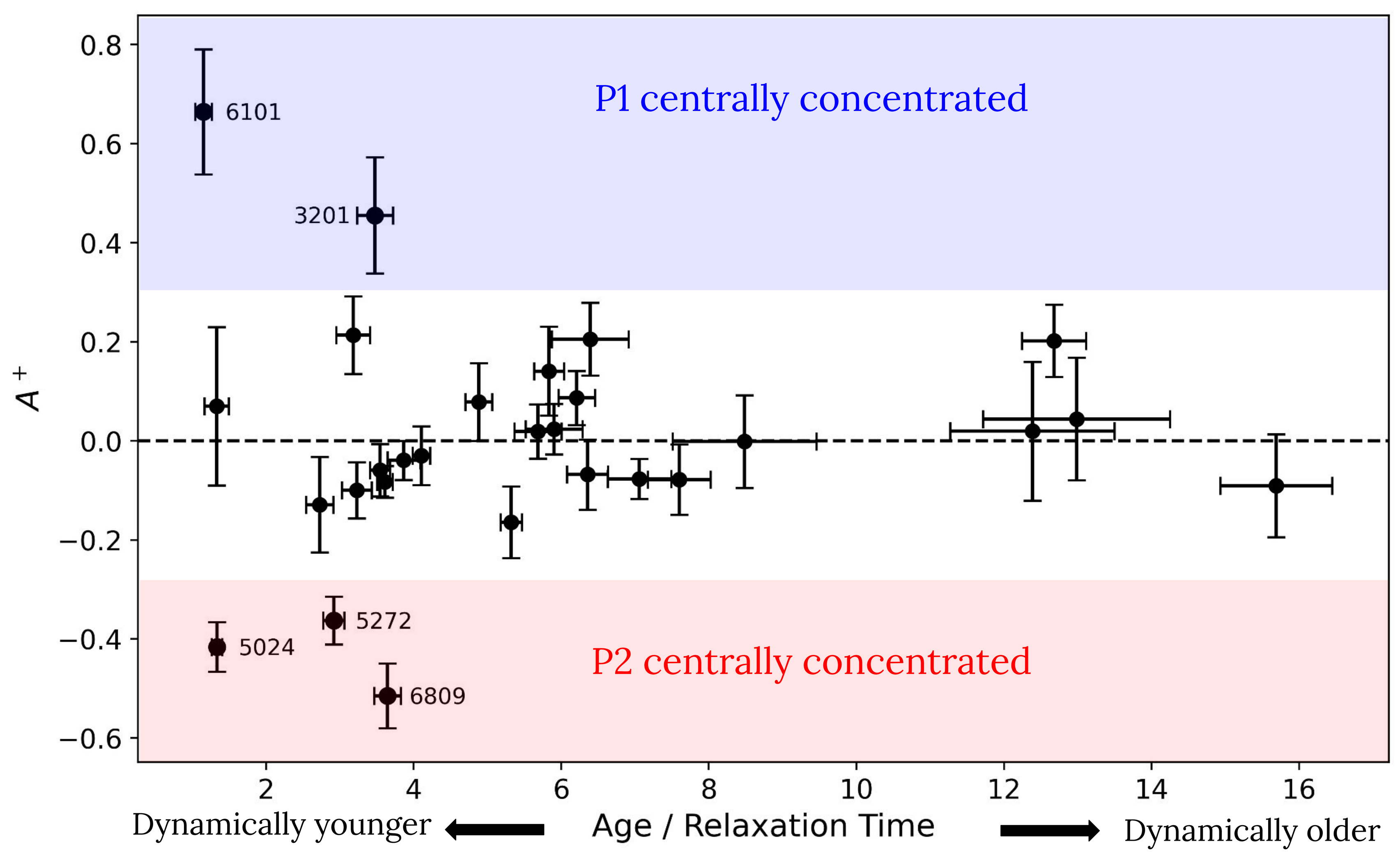
Predictions

★ Formation theories:

Many formation scenarios suggests a generation gap between the MPs: P1 stars exist first and P2 stars are born from their ejected enriched material mixed with primordial gas. Therefore, the P2 stars should be centrally concentrated within the clusters [1][2].

★ Simulations:

Kinematic differences are predicted between the populations, with some simulations predicting the P2 stars rotate faster than P1 stars [3][4]. However, these simulations assume P2 stars are created *after* P1 stars, leading to more centrally concentrated P2 stars.



Spatial Distributions

1. The multiple populations of stars were separated using HST and ground-based photometry.
2. The cumulative radial distributions of each population were calculated, along with the A^+ parameter, defined as the area between the P1 and P2 cumulative radial distributions.
3. We found that *dynamically younger* globular clusters (i.e. with lower age/relaxation time) display a range of A^+ values, with either P1 or P2 stars more centrally concentrated, or a homogeneous mix of the populations.

The multiple stellar populations of GCs can be spatially distributed in many different ways, but dynamically evolve to become mixed after multiple relaxation times

Leitinger et al. (2023)

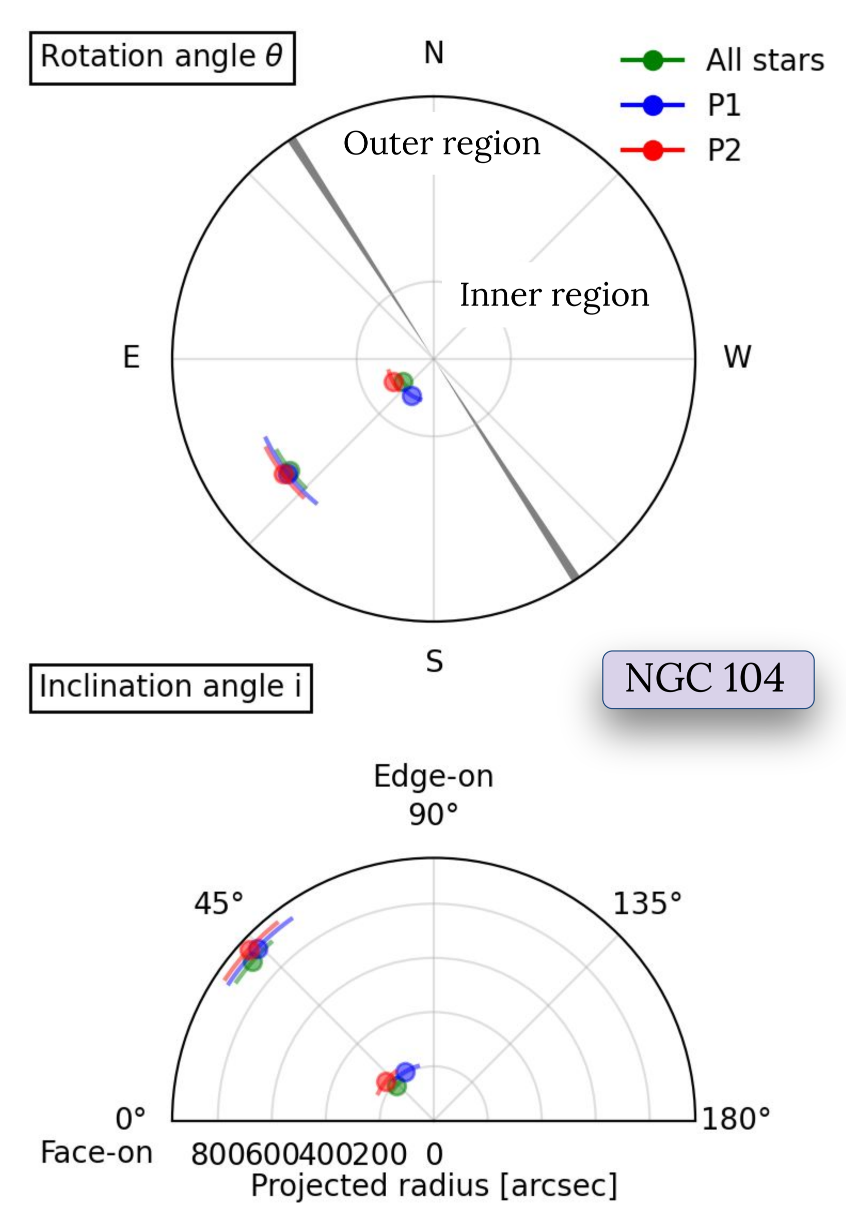
Rotation axes

The rotation axis of the stars in a GC can be described in spherical geometry using two angles:

★ Rotation angle **θ** in the plane of the sky, using proper motions from Gaia DR3 [5]

★ Inclination angle **i**, using line-of-sight velocities from the Galactic Globular Cluster Database [6], in which obvious binaries are removed

We computed the rotation axes of each GC using: all stars, only P1 stars, or only P2 stars. For clusters with a large sample of stars, we performed this analysis for different radial bins.



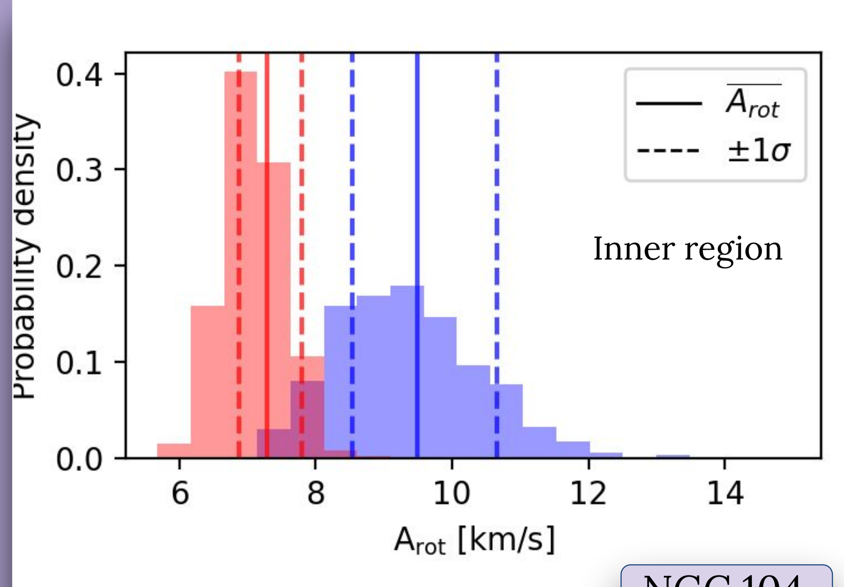
Rotational Amplitude

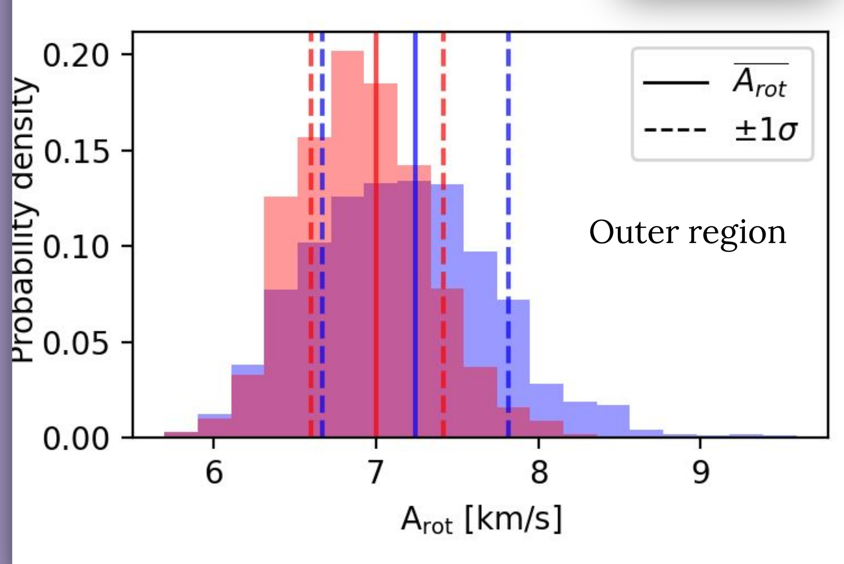
The total rotational amplitude for each population was calculated using the line-of-sight velocity and tangential component of the proper motion.

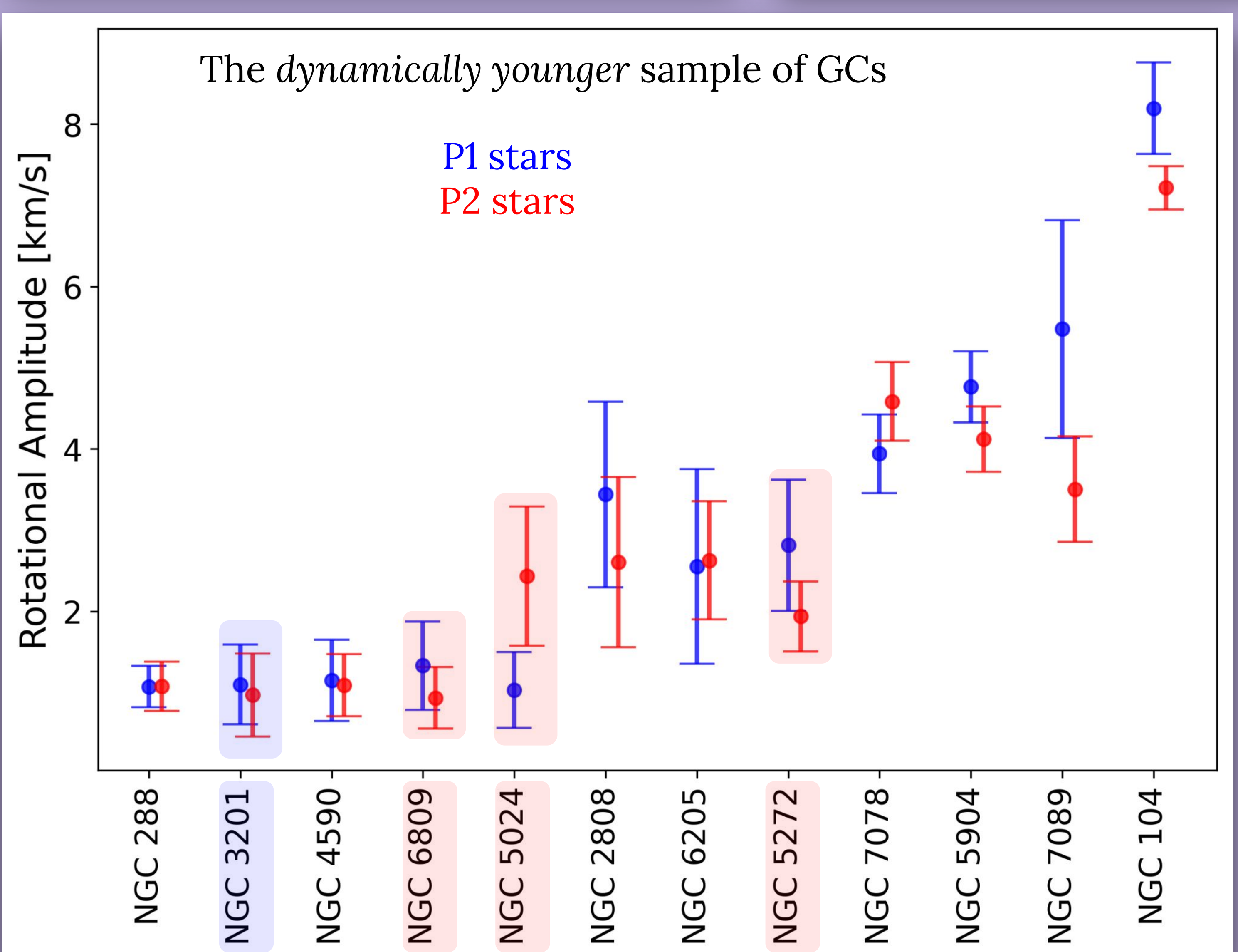
To determine the significance of the differences between the total rotational amplitudes of P1 and P2 stars, we performed bootstrapping by sampling the distribution of stars 1000 times.

The probability density histograms show that there is no *significant* difference between the rotational amplitude of P1 and P2 stars.

We find no significant differences between the *rotational axes* or *rotational amplitudes* of P1 and P2 stars







Implications on formation

For the *dynamically youngest* GCs in our sample, we find differences in their spatial distributions, i.e. P1 or P2 centrally concentrated, or both populations mixed. However, despite these differences in spatial distributions, we found no differences between the total rotational amplitudes of each population, nor in their rotational axes.

This result contradicts the predictions made by simulations, most notably due to the assumption that P2 stars form more centrally concentrated - and after P1 stars - therefore resulting in rotational differences between the populations during their formation process.

By pursuing alternative theories on the formation of multiple stellar populations, such as including binary populations and their interactions and also hierarchical merging, we may begin to find agreement between theory and observations.

References:
[1]D'Ercole et al. (2008), [2]Charbonnel & Schaerer (2013), [3]Lacchin et al. (2022), [4]McKenzie & Bekki (2021), [5]Gaia Collaboration et al. (2016a,b), [6]https://people.smp.uq.edu.au/HolgerBaumgardt/globular/