Long-Term Dynamical Evolution of Rotating Multiple-Population Globular Clusters

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Introduction

Globular clusters host multiple stellar populations differing in the chemical abundances of a number of light elements (such as Na, O, Al, Mg, C, N, He); in many Galactic clusters multiple stellar populations have also been found to have different dynamical properties (see e.g. Milone & Marino 2022 for a recent review). In this project, we investigate the long-term dynamical evolution of multiple stellar populations in rotating globular clusters using N-body simulations. Following the results of a number of theoretical studies modeling the formation of multiple stellar populations (see e.g. Bekki 2010, 2011, Lacchin et al. 2022; see also e.g. Mastrobuono-Battisti & Perets 2013, Henault-Brunet et al. 2015, Tiongco et al. 2019 for some studies of the dynamics of rotating multiple-population clusters), our simulations starts with initial conditions including a rapidly rotating, flattened second generations (SG) subsystem centrally concentrated in the inner regions of a slow rotating, spherical first generation (FG) system. The cluster internal angular momentum is parallel to the orbital angular momentum. Our models include a spectrum of masses between 0.1 and 1 $M_\odot$ distributed with a Kroupa IMF.

We explore the spatial and kinematic mixing of the stellar generations in our simulations, as well as the dependence of those properties on stellar mass.

In order to explore the interplay between the effects of the host galaxy tidal field and the internal rotation of globular clusters we have also carried out a suite of N-body simulations following the evolution of systems starting with different orientations of the internal stellar rotation with respect to the orbital angular momentum.

A complete description of the result of this study will be presented in White et al., in preparation.

Methods & Initial Conditions

- Suite of N-body simulations run with NBODY6++GPU (Wang et al. 2015).
- 100,000 stars split evenly between First Generation (FG) and Second Generation (SG).
- FG is a slowly rotating, spherical system.
- SG is a rapidly rotating, flattened system, centrally concentrated within the FG system ($r_{h1}/r_{h2} \sim 6$).
- Cluster moves on a circular orbit around the Galactic center.
- Mass spectrum between 0.1 and 1 $M_\odot$ with a Kroupa IMF.

References and Acknowledgements

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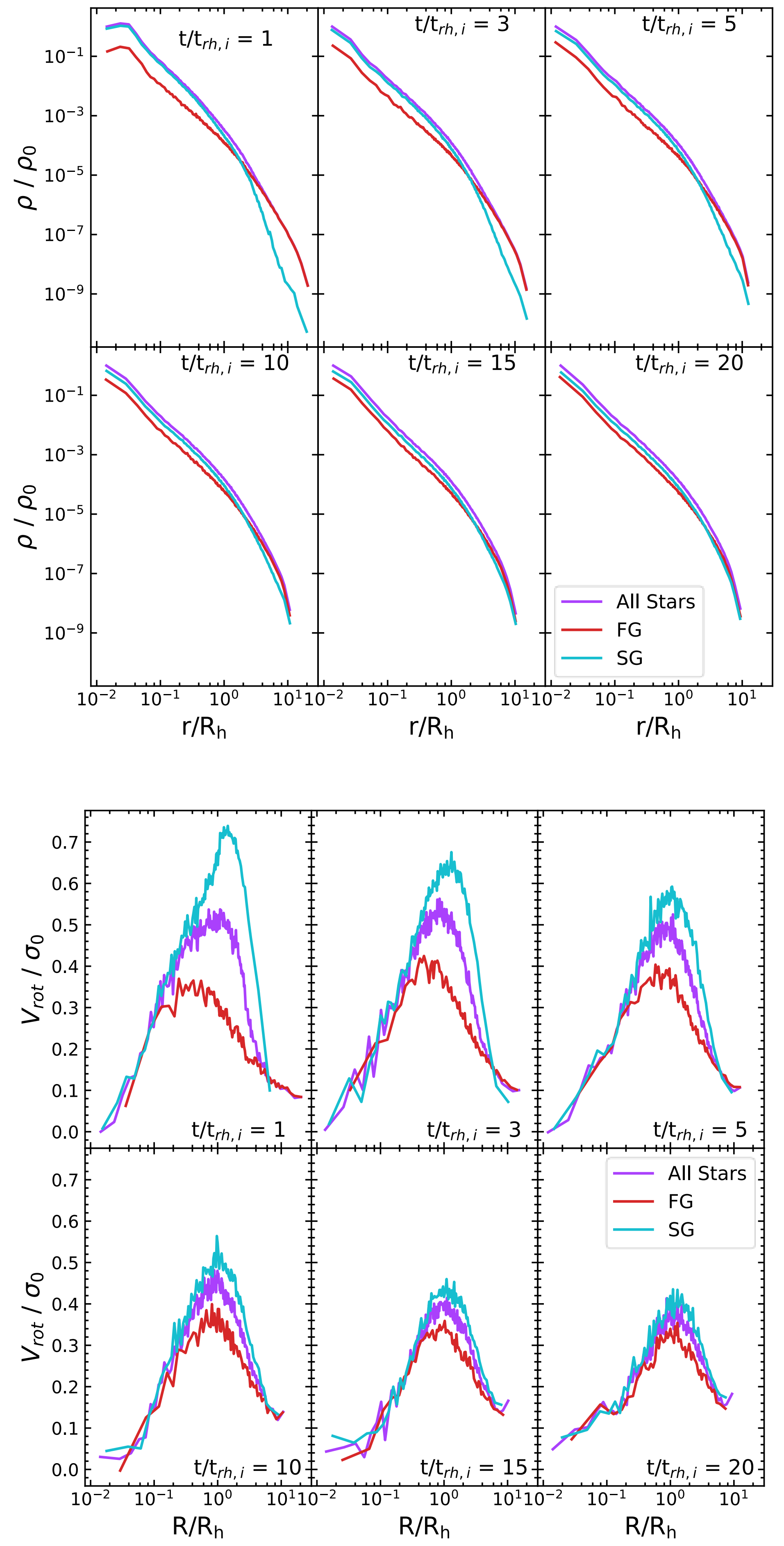
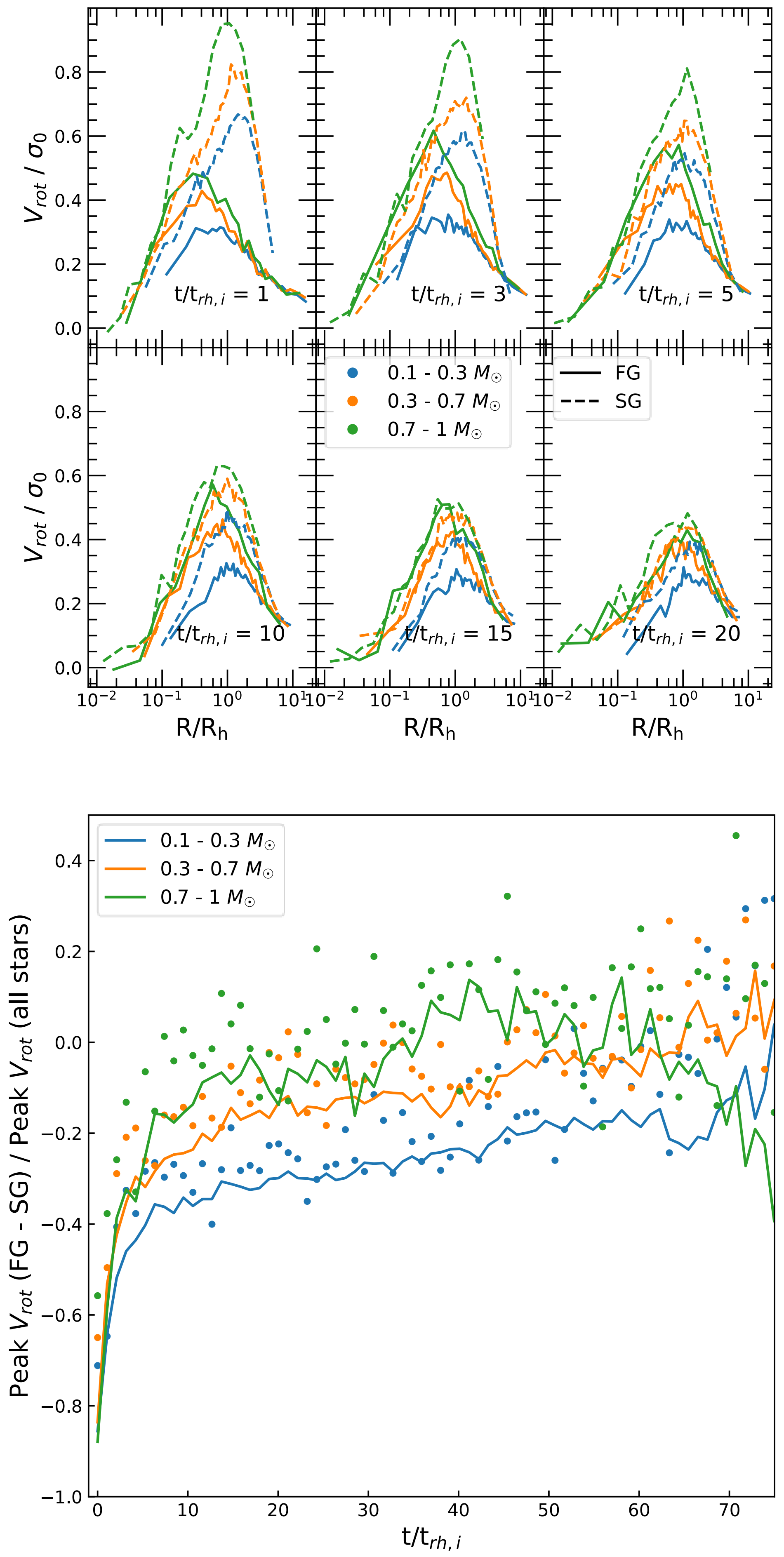
Spatial and Kinematic Properties



Top: Density profiles for FG, SG, and all stars (FG + SG) are shown at representative times. The density is normalized by the central density of all stars. The radius is normalized by the 3D half-mass radius. Time is normalized by the initial half-mass relaxation time ($t_{rh,i}$). **Bottom:** Rotation velocity profiles are shown at the same representative times. The rotation velocity is calculated in cylindrical bins and is determined from the tangential velocity on a plane perpendicular to the rotation axis. The rotational velocity is normalized by the central velocity dispersion. The radius is normalized by the 2D half-mass radius.

- The spatial differences between the generations are gradually erased, as displayed in the **top** figure. The density profiles are nearly identical after about 10 $t_{rh,i}$.
- The differences between the rotational kinematics of FG and SG (**bottom**) are erased more gradually and persist beyond 10 $t_{rh,i}$.
- Some memory of the initial kinematical differences may be found in clusters after initial spatial differences have been erased. In some cases, differences may be small and difficult to detect depending on the orientation between the rotation axis and the line of sight (see also Tiongco et al. 2019).

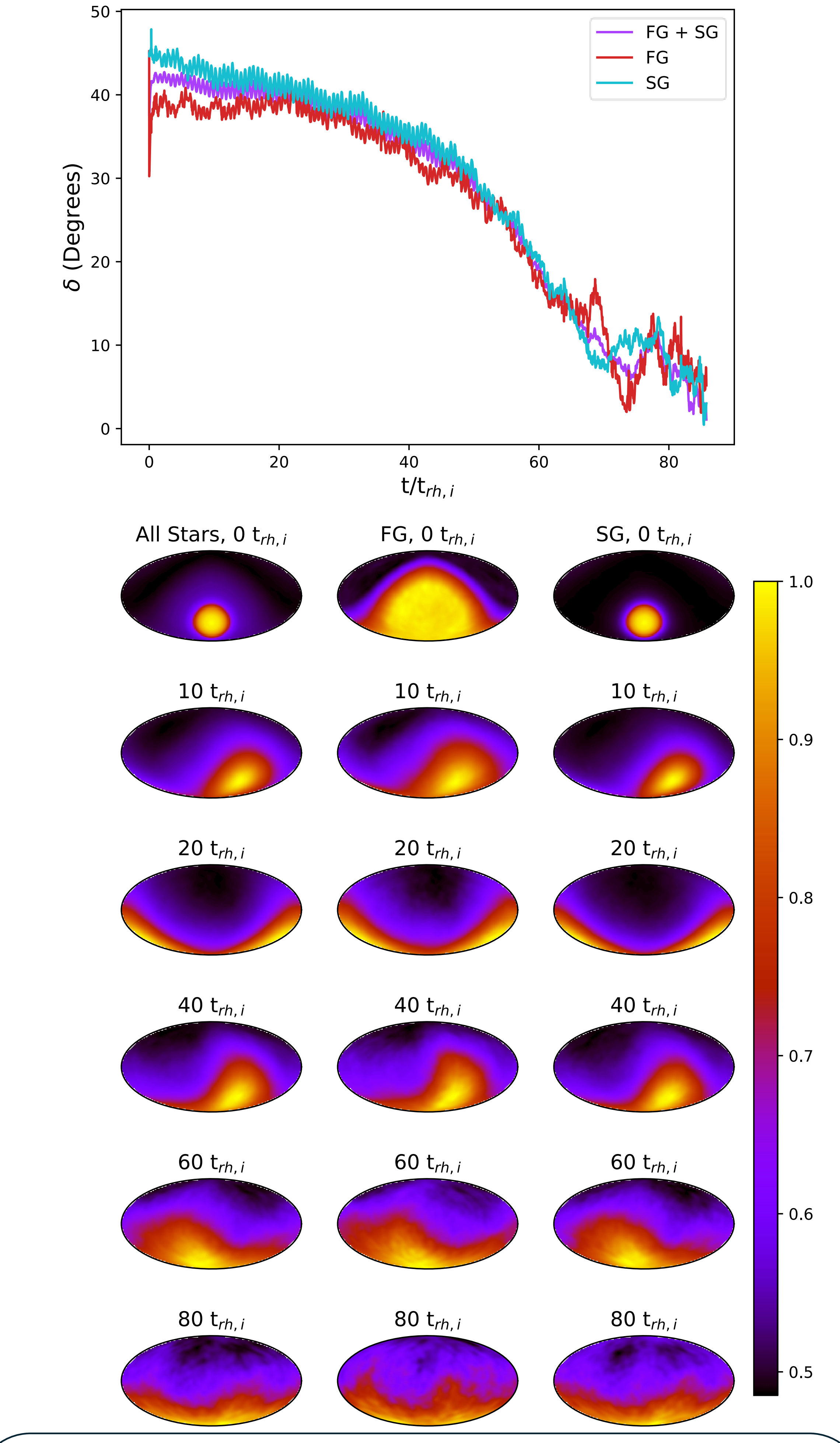
Dependence on the Stellar Mass



Top: Rotation velocity profiles are shown for the different mass bins in the FG and SG. The velocity is normalized by the central velocity dispersion of all stars. The radius is normalized by the 2D half-mass radius of all stars. Time is normalized by the initial half-mass relaxation time ($t_{rh,i}$). **Bottom:** Time evolution of the difference between the FG and SG peak rotation velocity for different mass bins. The peak velocity difference is normalized by the peak rotation velocity of all stars. Dots represent the difference in the peak rotation velocity obtained from the rotation profiles. Lines represent the difference in the peak rotation velocity obtained from fits to the rotation profiles.

- For both FG and SG, the strength of rotation depends on stellar mass.
- More massive stars rotate more rapidly around the cluster's center than low-mass stars.
- Differences between the rotational velocity of FG and SG stars are erased more rapidly for more massive stars.

Evolution of the Orientation of the Angular Momentum



Top: Time evolution of the direction of net angular momentum for our model with initial internal rotation axis inclined by 45 degrees with respect to its orbital angular momentum. **Bottom:** Density maps showing the distribution of the direction of angular momentum of all stars (FG + SG), FG, and SG on a Mollweide map projection for the same model at a few representative times. The direction of the orbital angular momentum is located at the bottom of the map. The color is normalized by the maximum density in each map.

- The tidal field of the host galaxy torques the internal rotation of the cluster causing it to gradually align with the orbital angular momentum (bottom of the map) by the end of the simulation.
- Similar results are found for models starting with different inclinations between the internal and orbital angular momentum.
- The tidal field torque affects both FG and SG similarly; we find only small differences between the inclination of the rotation axis of the FG and SG populations.
- The outward migration of low-mass stars leads to the more rapid alignment between their internal angular momentum and the cluster angular momentum compared to high-mass stars (further details on this result presented in White et al. in prep.).