# EARLY DYNAMICAL EVOLUTION OF ROTATING STAR CLUSTERS

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## Introduction

In part due to the Gaia Revolution, we have made major progress towards a complete phase space portrait of star clusters, and revealed that bulk rotation of the cluster is an integral part of its dynamical history and evolution. The dynamical origin of rotation and why in some observed clusters (e.g., recently, [4]) there is a radial variation of the direction of the rotation axis are still a matter of investigation. This poster presents some of the results of *N*-body simulations investigating how the early internal rotational properties of star clusters are affected by the external potential of their host galaxies. We also show a possible kinematic signature of dynamically young star clusters.

## Initial Conditions and Simulations

The initial conditions (ICs) of our star clusters are those of homogeneous density spheres of stars (all stars have equal mass) with a rotation curve following a solid-body profile. The varying parameters of the ICs are the amount of kinetic energy (KE) in rotational motion and random motion (Cold: less random KE, Slow: less rotational KE, and Even: equal amounts of random and rotational KE), and also the initial angle (45, 90, and 135°) between the rotation axis and the orbital angular momentum vector of the cluster. The small initial virial ratios of the clusters indicate that the cluster will collapse and undergo a process called violent relaxation [1] to reach a quasi-equilibrium state.

The star clusters are then evolved under the effects of their own self-gravity with the collisional *N*-body code `NBODY6` with GPU acceleration [2], and also under the influence of the tidal forces of a point-mass host galaxy. Most of the clusters are evolved for 18 free-fall times ($t_{ff}$), where a free-fall time is the amount of time it takes for the cluster to collapse and reach its highest central density. This is enough time for the violent relaxation process to finish and long before two-body relaxation can begin to erase some of the structural and kinematic signatures.

## Images and Animations

Fig. 1 demonstrates the varying position of the rotation axis as we go farther from the center of the cluster. Shown is the line-of-sight velocity field when looking at the cluster along the *z*-axis (left image) and *y*-axis (right image). The variation in the position of the rotation axis is demonstrated by the difference in the position of the axis of symmetry in the velocity field between the inner and outer regions of the cluster.

Depending on the initial viral ratios of cluster, a variety of cluster shapes emerge; with the 'Cold' series being the most flattened because it had the deepest collapse and consequently the fastest rotation (via conservation of angular momentum) and the 'Slow' series having the roundest shape.

Animations of how the surface density and line-of-sight velocity fields of each simulation evolve can be viewed at https://mtiongco.github.io/vrrot-anims/. There is also a table that shows more complete information about the ICs.

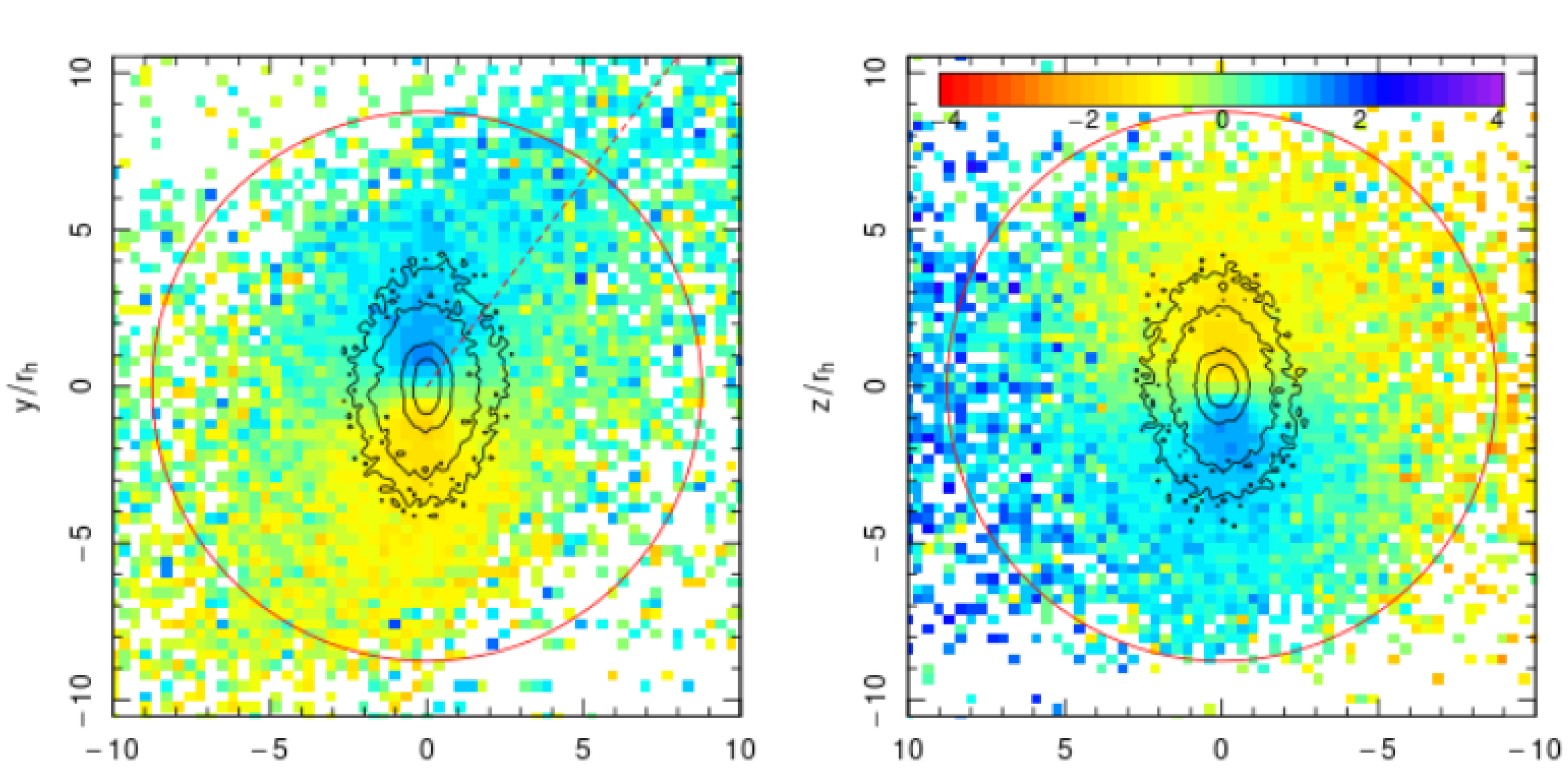


**Figure 1:** Line-of-sight velocities map for model 'Cold th90' at the end of the simulation (at 18 $t_{ff}$). The black solid lines are some of the surface density contours of the cluster, and the red circle shows the Jacobi radius/Hill sphere. The change in rotation axis position angle as we move away from the center of the cluster is demonstrated by the change in the axis of symmetry in the velocity field.

## Radial variation of the rotation axis direction

Fig. 2 shows for one model the evolution (from 0-18 $t_{ff}$) of the radial profiles of the azimuthal ($\phi$) and polar ($\theta$) components of the net angular velocity vector ($\omega$) measured in concentric spherical shells dividing the cluster. The major result here is that **the radial variation in angular velocity vector direction occurs along both the polar and azimuthal directions**, unlike previous studies where it was only found along the polar direction [3].

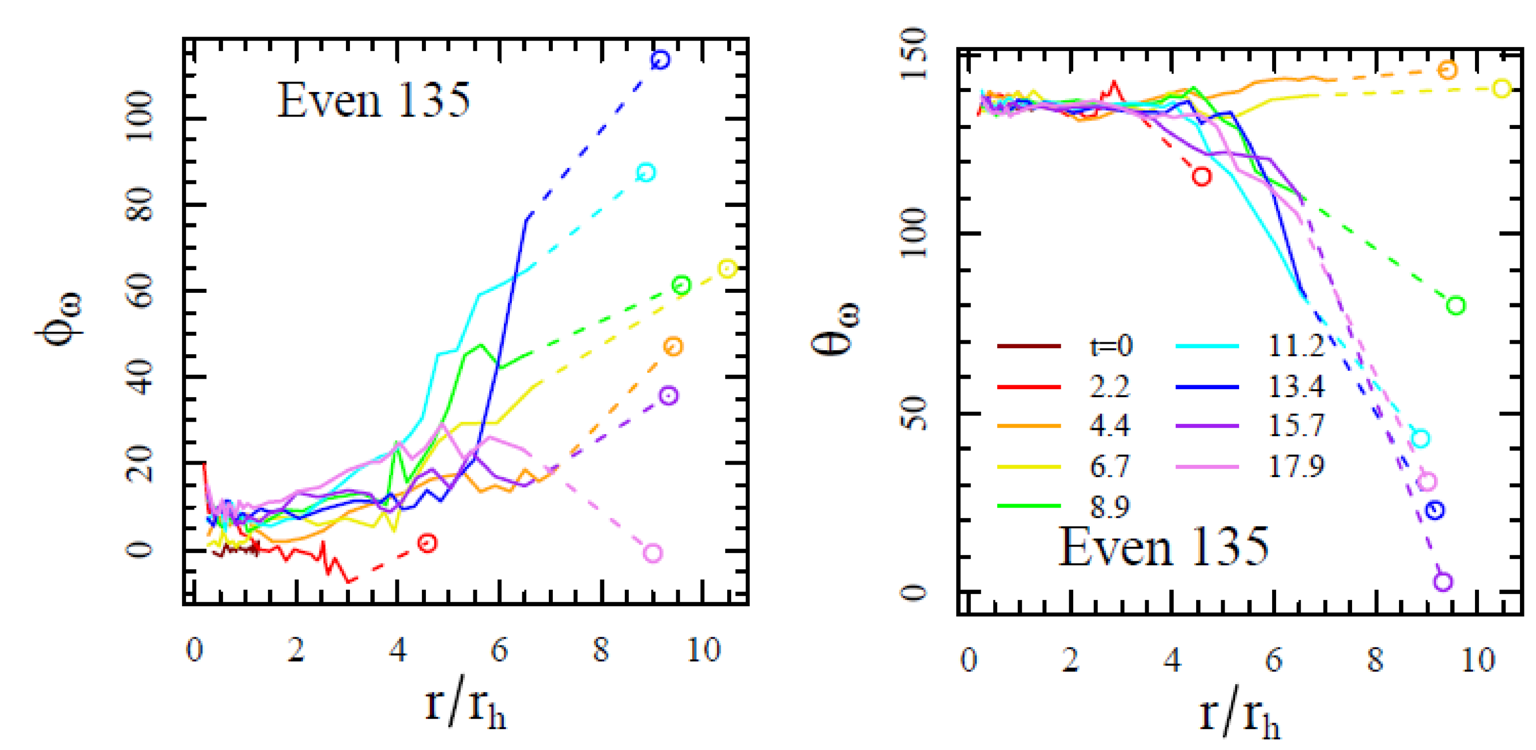


**Figure 2:** Evolution of the radial profiles of the azimuthal ($\phi$) and polar ($\theta$) components of the angular velocity vector $\omega$ measured in concentric spherical shells. Each line represents a different time in the simulation (the legend shows the time in $t_{ff}$). The open points connected to the profile by dashed lines show the quantity measured outside the Jacobi radius/Hill sphere.

## Long-term evolution and kinematic signatures

We evolved one of the simulations, 'Cold th45,' further up to core collapse of the cluster at about 9 initial half-mass relaxation times. Shown in Fig. 3 is the long-term evolution of the radial profiles of azimuthal and polar components of the angular velocity vector. We find that the radial variation in the azimuthal ($\phi$) component gets erased over one half-mass relaxation time, suggesting that **a radial variation of the rotation axis direction along the azimuthal direction may be a kinematical signature of a dynamically young cluster**. The radial variation in the polar component does not go away even after several relaxation times.

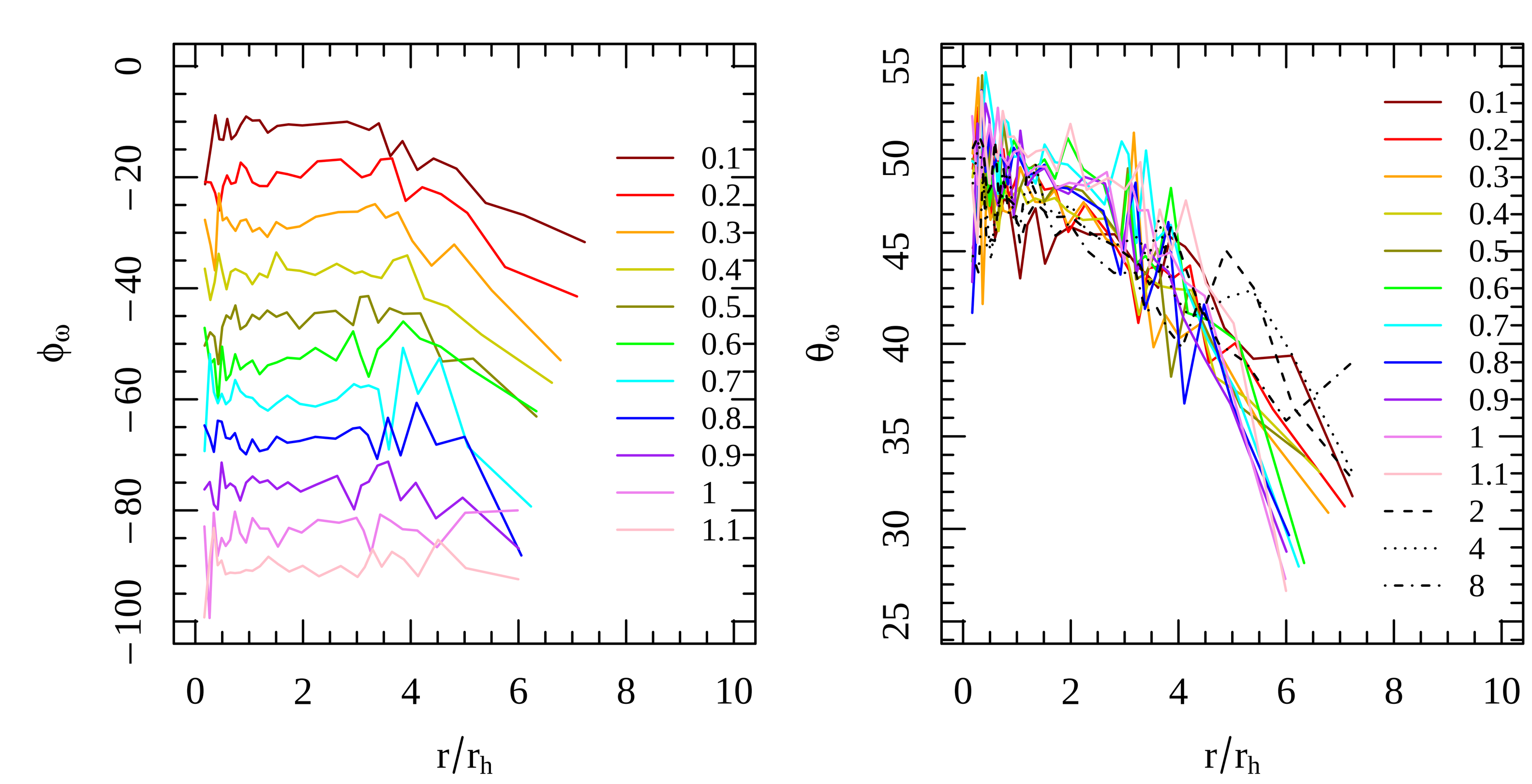


**Figure 3:** Long-term evolution of the radial profiles of the azimuthal and polar components of the angular velocity vector. Each line represents a different time in the simulation (the legend shows the time in initial half-mass relaxation times). The shifting profile in the left panel is due to the general precession of the rotation axis the cluster undergoes in its long-term evolution.

## References

[1] D. Lynden-Bell. *MNRAS*, 136:101, 1967.
[2] K. Nitadori and S. J. Aarseth. *MNRAS*, 424:545, 2012.
[3] M. A. Tiongco, E. Vesperini, and A. L. Varri. *MNRAS*, 475:L86, 2018.
[4] C. Usher, S. Kamann, M. Gieles, et al. *MNRAS*, 503:1680, 2021.