Effects of dynamical evolution on the internal kinematical properties of star clusters

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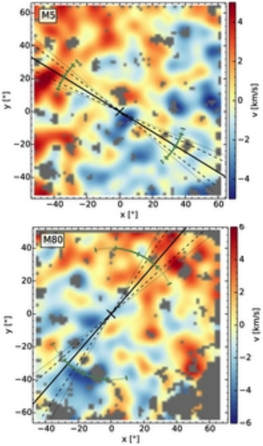
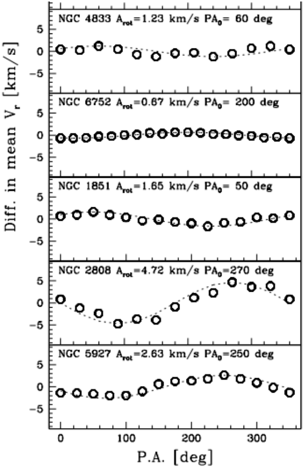
Globular Clusters

M15 (ESA/Hubble)

Observations of Internal Kinematics of GCs



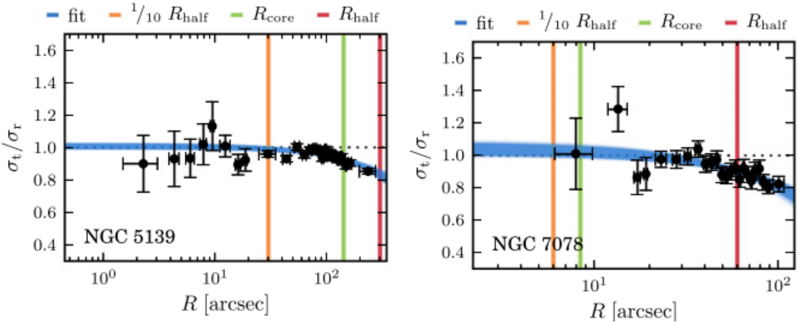
Fabricius et al. 2014, McDonald Observatory



Lardo et al. 2015, ESO/VLT

Measurements of Internal Rotation in GCs

Observations of Internal Kinematics of GCs

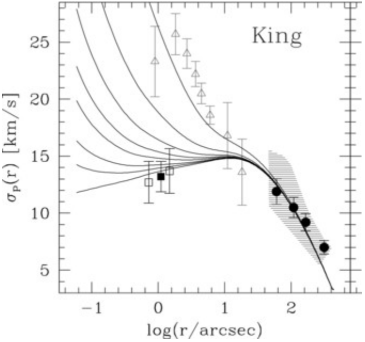


Bellini et al. 2014, Watkins et al. 2015, HSTPROMO

Measurements of Velocity Anisotropy - GCs generally have mildly radially anisotropic velocity distributions near the half-mass radius

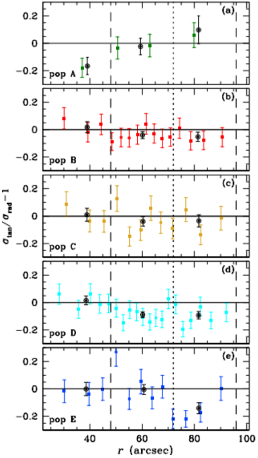
Observations of Internal Kinematics of GCs

Velocity Dispersion as a potential signature for IMBHs



Lanzoni et al. 2013, ESO/VLT

Kinematical Differences between Multiple Stellar Populations



Bellini et al. 2015, HST (see also Richer et al. 2013)

Dynamical Evolution of Kinematical Properties

Survey of N-body simulations studying the long-term evolution of the internal kinematics of star clusters

- Velocity anisotropy (Tiongco et al. 2016)
- The role of prograde/retrograde stellar orbits on rotation curve (Tiongco et al., submitted)
- Evolution of rotating clusters in an external tidal field (Tiongco et al., in prep.)
- Evolution of rotation in multiple population clusters (Tiongco et al., in prep.)

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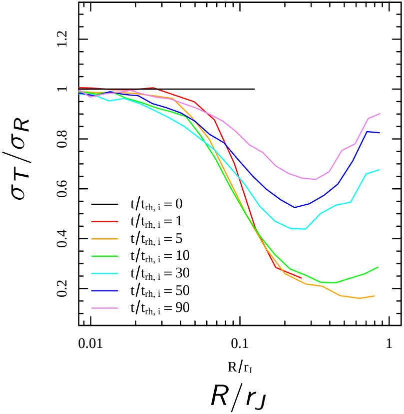
Method and Initial Conditions

- NBODY6+GPU (Nitadori & Aarseth 2012)
- Tidally limited
- King $W_0 = 7$
- Rotating cluster models by Varri & Bertin 2012
- Models evolved through violent relaxation in tidal field
- Explore evolution for different initial filling factors r_h/r_J and different virial ratios

Evolution of Velocity Anisotropy

See also pioneering works by Giersz & Heggie 1994,1997,2011, Spurzem & Aarseth 1996, Takahashi et al. 1997, Takahashi & Lee 2000, Baumgardt & Makino 2003

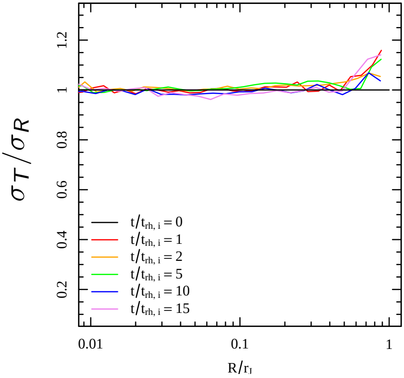


King model (r_h/r_J=0.015)

Tiongco et al. 2016

- Initially isotropic, underfilling clusters develop strong radial anisotropy
- Profile developed: isotropic core, radially anisotropic intermediate region that peaks at 0.2-0.4r_J, outer regions decreasing radial anisotropy
- System evolves toward an isotropic velocity distribution as mass is lost

Evolution of Velocity Anisotropy



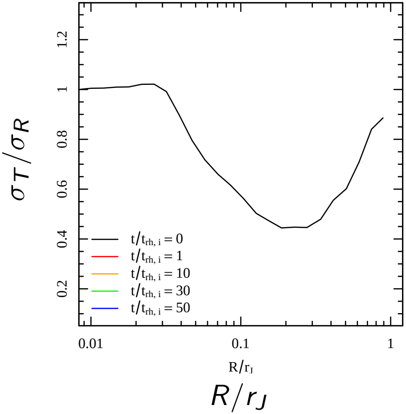
R/r_J

King model (r_h/r_J=0.116)

Tiongco et al. 2016

- Degree of radial anisotropy developed decreases as models become more filling
- Isotropic, tidally filling clusters do not develop significant radial anisotropy

Evolution of Velocity Anisotropy

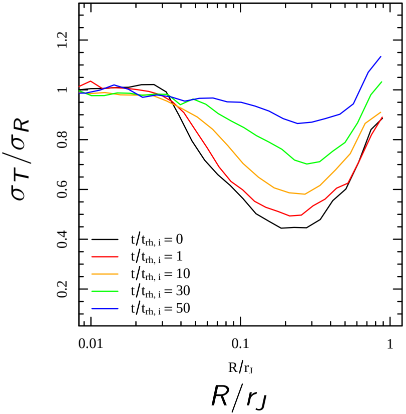


Violent relaxation model (r_h/r_J=0.036)

- Models that first undergo violent relaxation begin their long-term evolution with a profile that has an isotropic core, radially anisotropic intermediate region that peaks at 0.2-0.4r_J, outer regions decreasing radial anisotropy

Tiongco et al. 2016, see also Vesperini et al. 2014

Evolution of Velocity Anisotropy



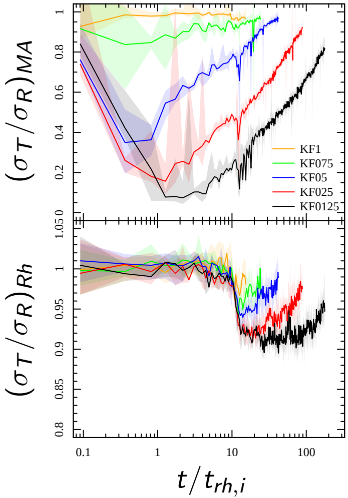
Violent relaxation model (r_h/r_J=0.036)

Tiongco et al. 2016

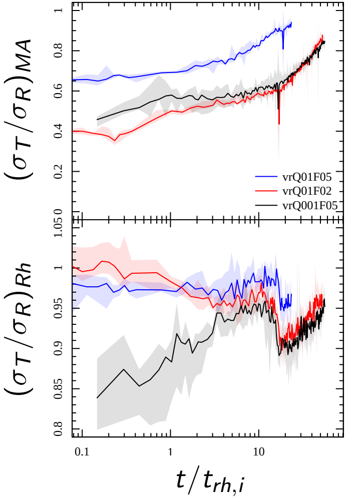
- Models that first undergo violent relaxation begin their long-term evolution with a profile that has an isotropic core, radially anisotropic intermediate region that peaks at 0.2-0.4r_J, outer regions decreasing radial anisotropy
- Subsequent evolution is toward an isotropic velocity distribution

Evolution of Velocity Anisotropy

King Models



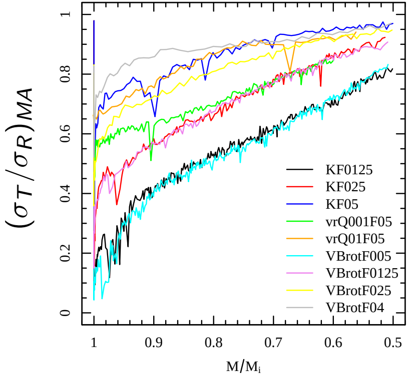
Violent Relaxation



Value of maximum radial anisotropy and its location over time

Tiongco et al., 2016

Evolution of Velocity Anisotropy



M/M_i

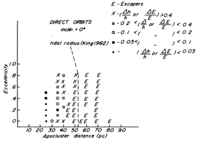
Underfilling models

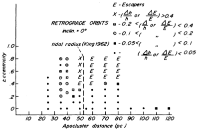
Tiongco et al. 2016

- Underfilling models need to lose significant mass in order to erase the strong anisotropy developed
- Relation between amount of mass lost, strength (or lack of) of radial anisotropy, and dynamical history/initial cluster properties

Role of Prograde and Retrograde Stellar Orbits

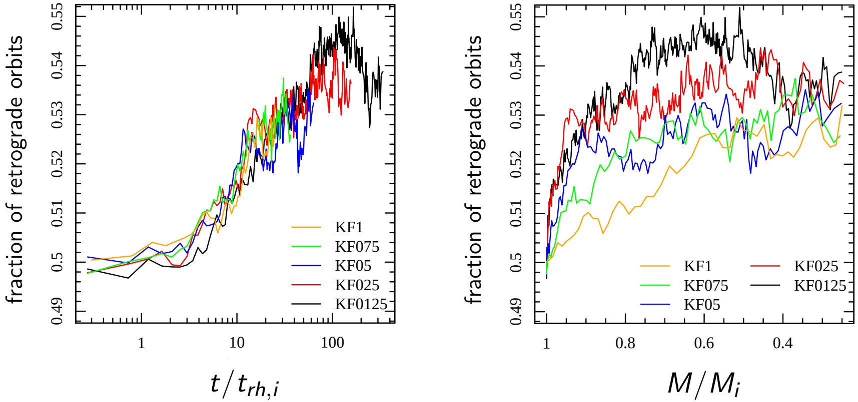
- Prograde orbits are less stable and preferentially lost compared to retrograde orbits (see e.g. Hunter 1967, Hénon 1969,1970, Keenan & Innanen 1975, Fukushige & Heggie 2000, Domingos et al. 2006, Ernst et al. 2007, Zotos 2015)
- Net effect should be a retrograde rotating cluster





Keenan & Innanen 1975

Role of Prograde and Retrograde Stellar Orbits



Tiongco et al., submitted

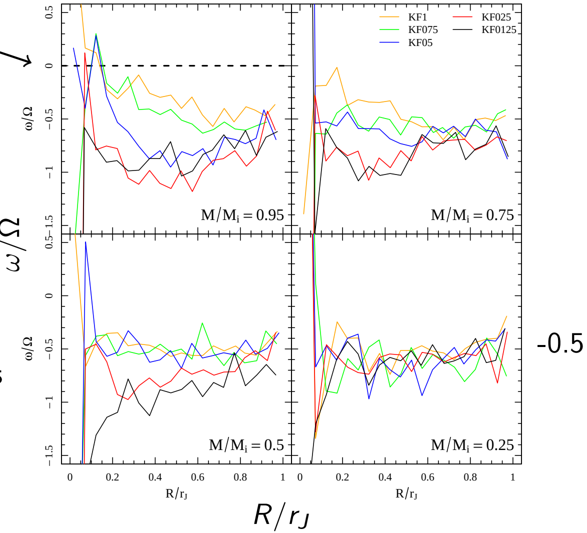
King models: Fraction of retrograde orbits increases until it reaches a plateau

Development of Internal Rotation

$t = 0$
$\omega = 0$
(zero rotation in co-rotating r.f.)

$\Omega =$ angular velocity of cluster orbit

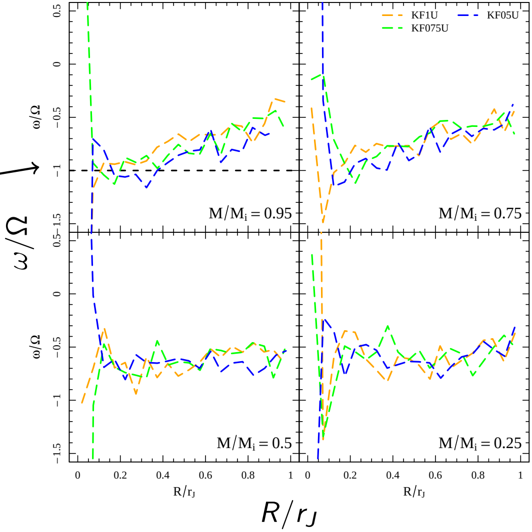
Filling vs. Underfilling differences



Tiongco et al., submitted

Development of Internal Rotation

$t = 0$
$\omega = -\Omega$
(zero rotation in inertial r.f.)

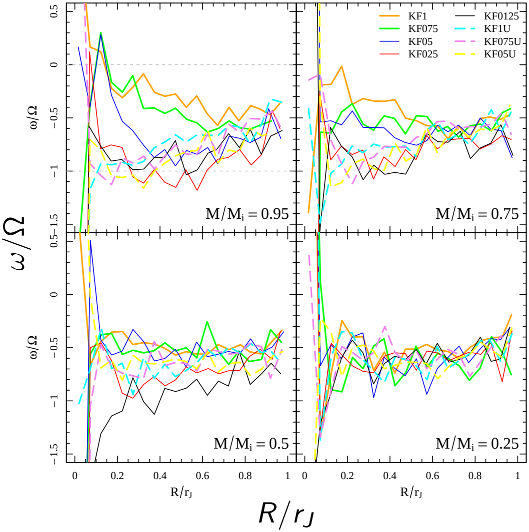


-0.5

Tiongco et al., submitted

Development of Internal Rotation

All profiles eventually reach an approximately solid body rotation of $\omega/\Omega \approx -0.5$ in the outer regions $R > 0.1 r_J$



-0.5

Tiongco et al., submitted

Conclusions

- Current cluster kinematical properties contain imprints of cluster initial properties and dynamical history
- Presence of radial velocity anisotropy increasing with radius may indicate initial compactness, though significant mass loss will erase this signature
- Non-rotating clusters become retrograde rotating in their outer regions due primarily to the preferential loss of prograde orbiting stars

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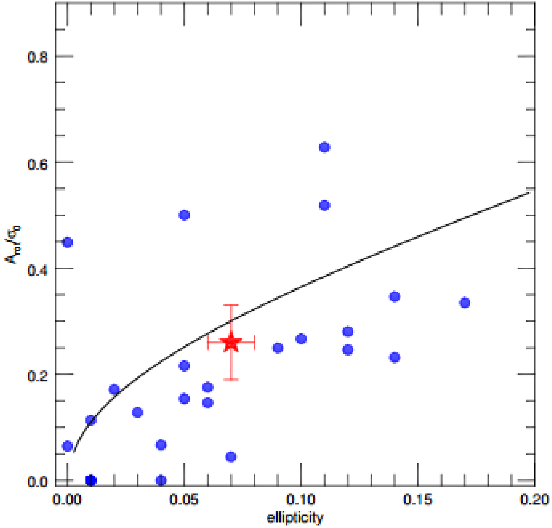
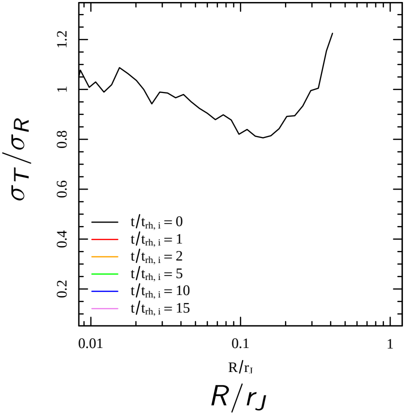


Kacharov et al. 2014, Bellazzini et al. 2014 ESO/VLT



Rotating model (r_h/r_J=0.116)

Tiongco et al. 2016

- Rotating models by Varri & Bertin 2012
- Initial anisotropy profile: isotropic core, radially anisotropic near r_h, then becomes tangentially anisotropic outwards

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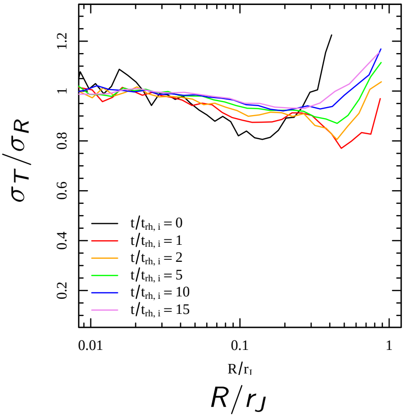

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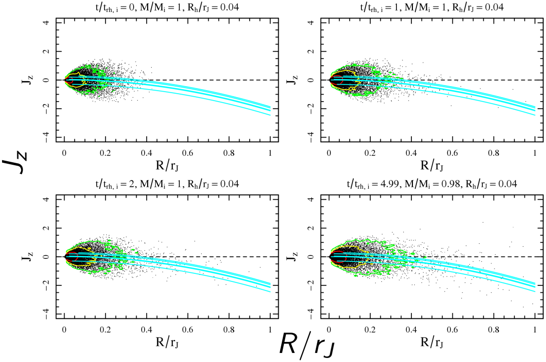

Tiongco et al., submitted

- Expansion of underfilling clusters causes orbits of stars in outermost regions to slow down w.r.t. to the reference frame, thus more likely to be retrograde

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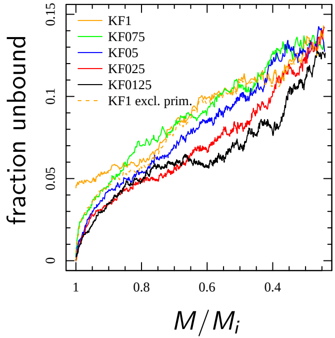
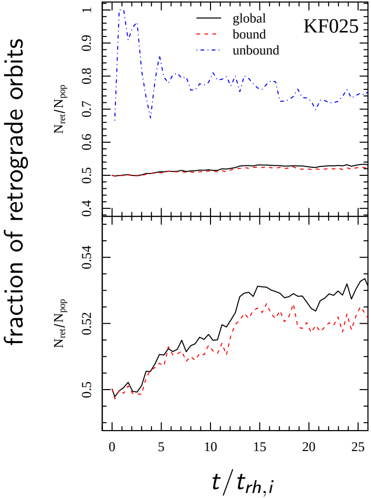
Tiongco et al., submitted



Fraction of potential escapers ($E > E_{crit}$ within r_J) increases until almost 15%

see also Baumgardt 2001, Küpper et al. 2010



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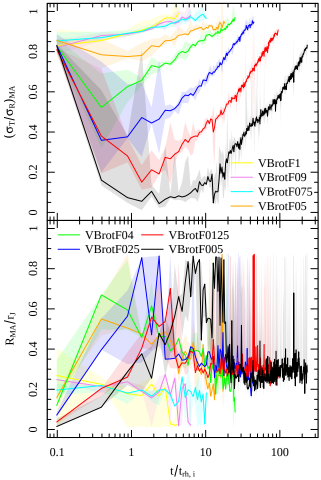

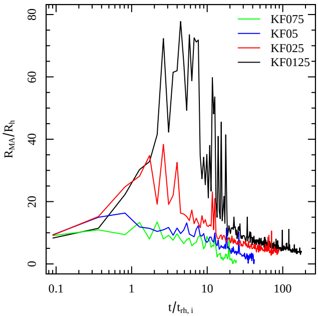

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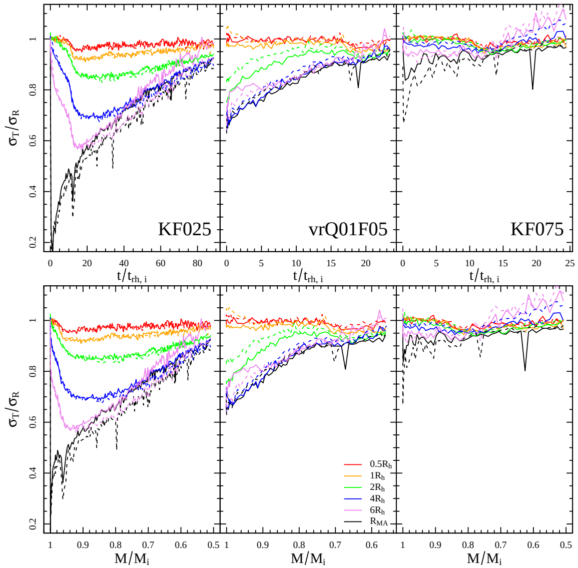

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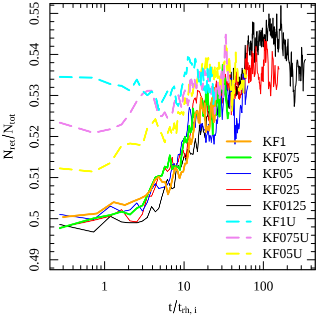

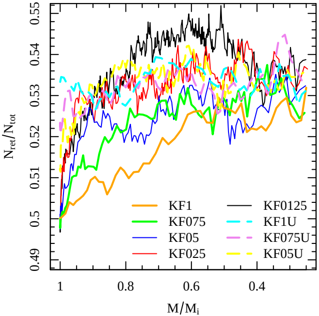

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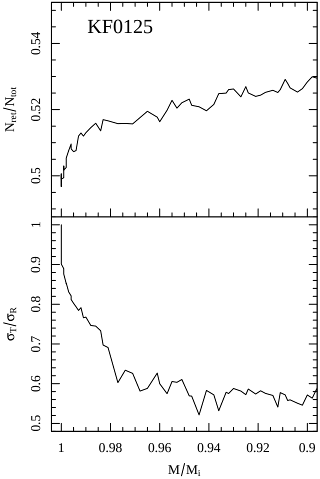

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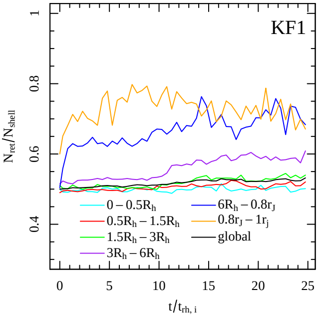

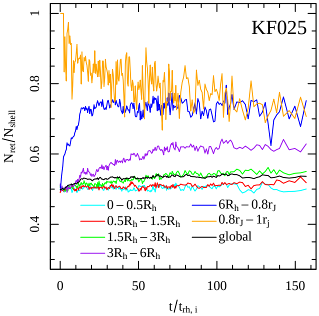

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