Dynamical Evolutionary Effects on Star Cluster Kinematics

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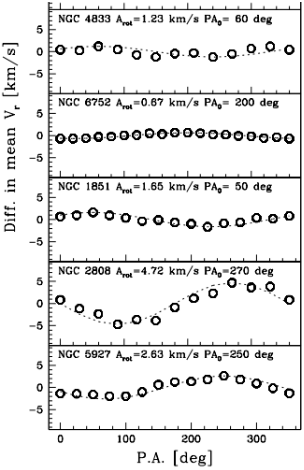
21 April 2016

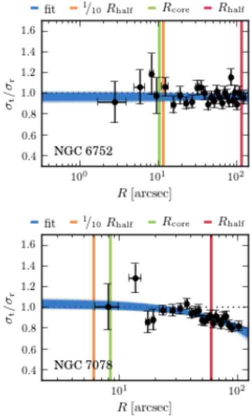
Observations of Internal Kinematics of GCs

Internal Rotation



Lardo et al. 2015, ESO/VLT

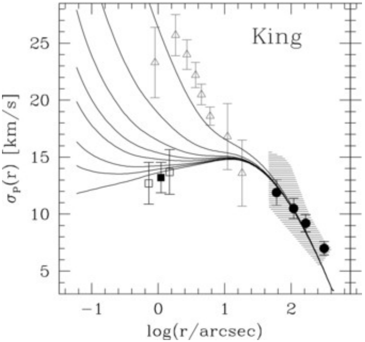
Velocity Anisotropy



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

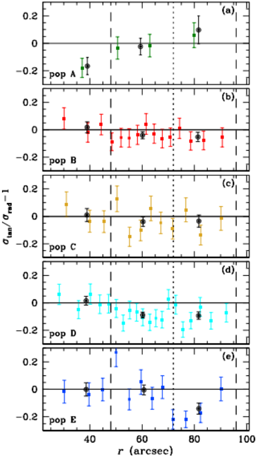
Observations of Internal Kinematics of GCs

Velocity Dispersion



Lanzoni et al. 2013, ESO/VLT

Multiple 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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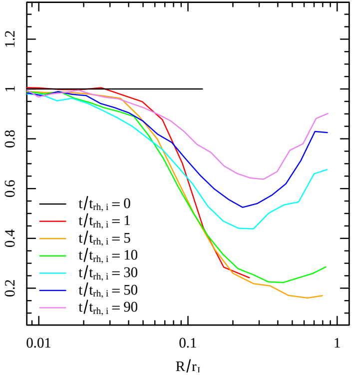
Method and Initial Conditions

- 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

σ_T/σ_R



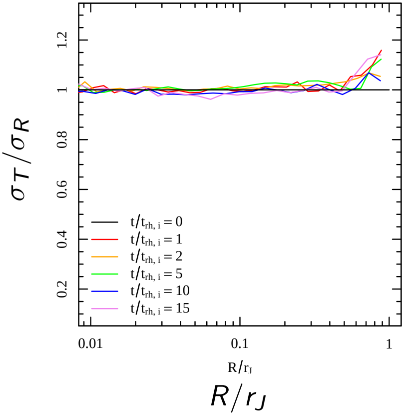
R/r_J

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

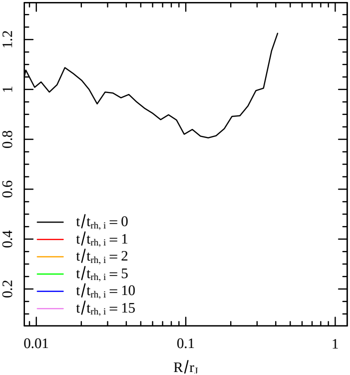


King model (r_h/r_J=0.116)

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



σ_T/σ_R

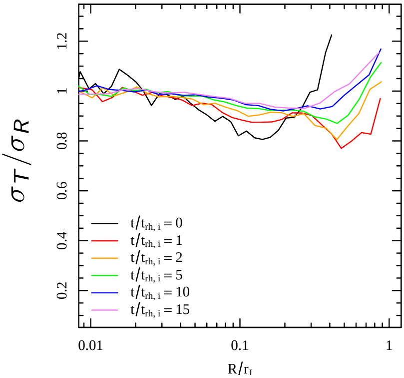
R/r_J

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

Evolution of Velocity Anisotropy



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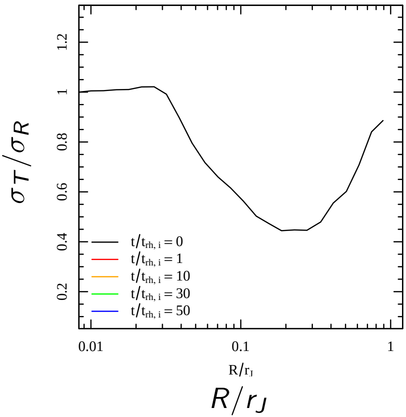
Evolution of Velocity Anisotropy

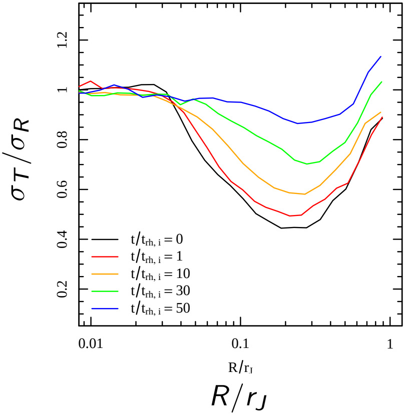


Violent relaxation model (r_h/r_J=0.036)

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

- 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

Evolution of Velocity Anisotropy



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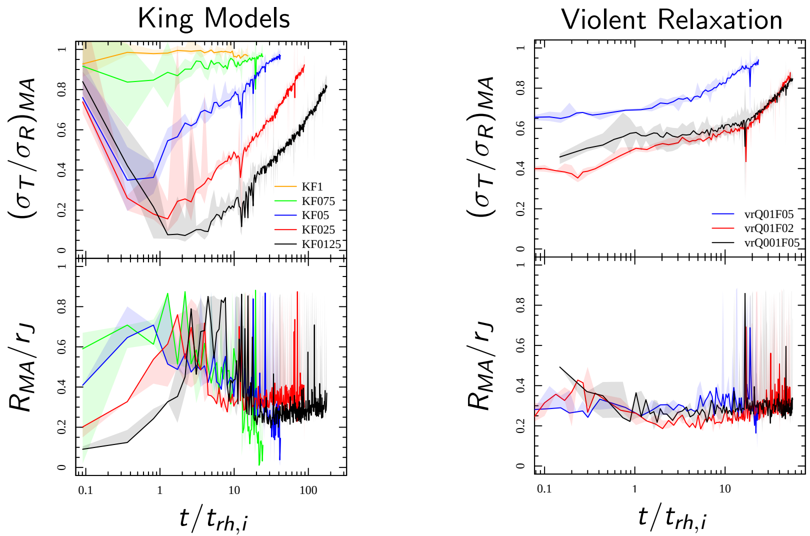
Tiongco et al. 2016

- 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

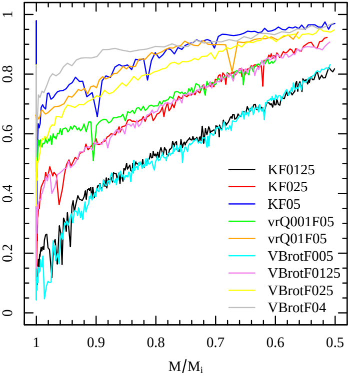
Evolution of Velocity Anisotropy



Value of maximum radial anisotropy and its location over time

Tiongco et al., 2016

Evolution of Velocity Anisotropy



$(\sigma_T/\sigma_R)_{MA}$

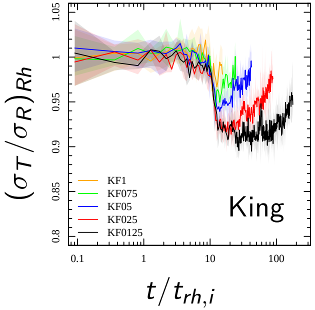
M/M_i

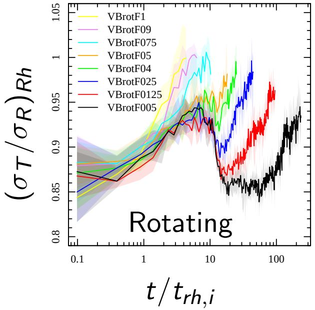
Underfilling models

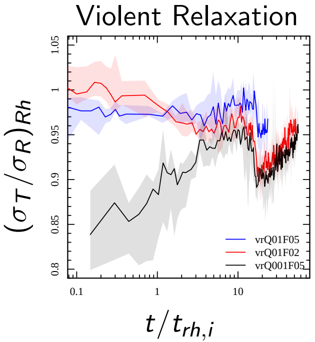
Tiongco et al. 2016

- 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

Evolution of Velocity Anisotropy





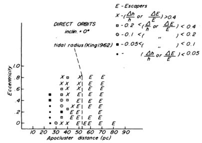


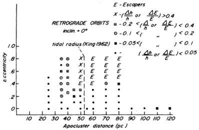
Anisotropy observed at R_h

Tiongco et al. 2016

Role of Prograde and Retrograde Stellar Orbits

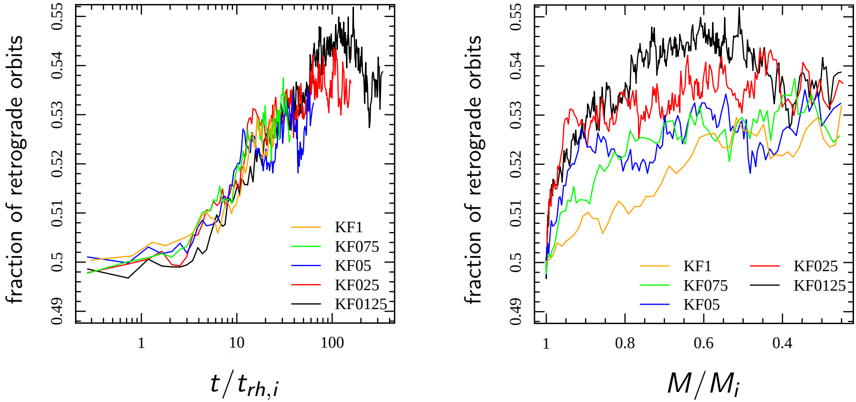
- Prograde orbits are less stable and preferentially lost compared to retrograde orbits (see e.g. Hénon 1969,1970, Keenan & Innanen 1975, Fukushige & Heggie 2000, Ernst et al. 2007, Zotos 2015)
- Net effect should be a retrograde rotating cluster





Keenan & Innanen 1975

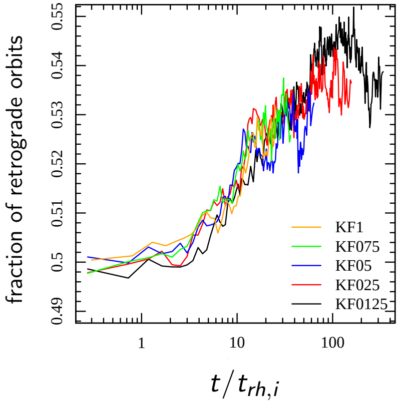
Role of Prograde and Retrograde Stellar Orbits

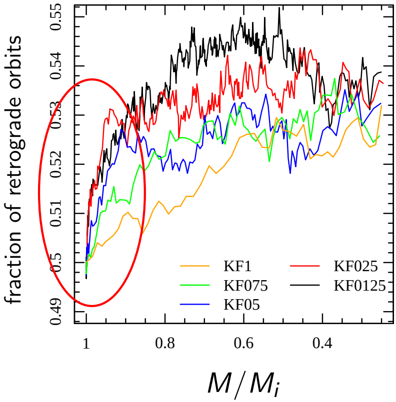


Tiongco et al., submitted

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

Role of Prograde and Retrograde Stellar Orbits





Tiongco et al., submitted

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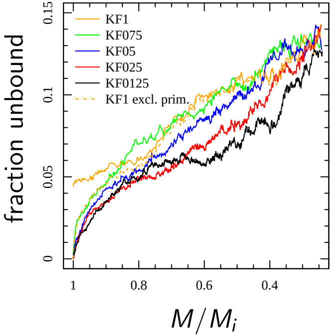
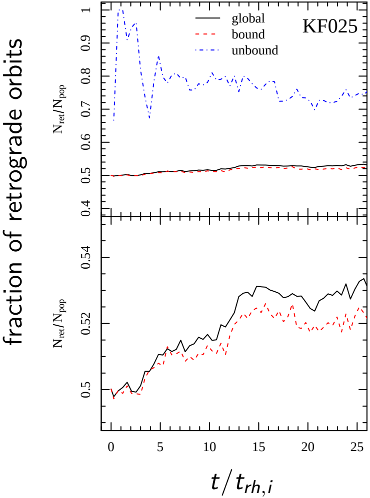
Orbital Properties of Potential Escapers

Tiongco et al., submitted





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

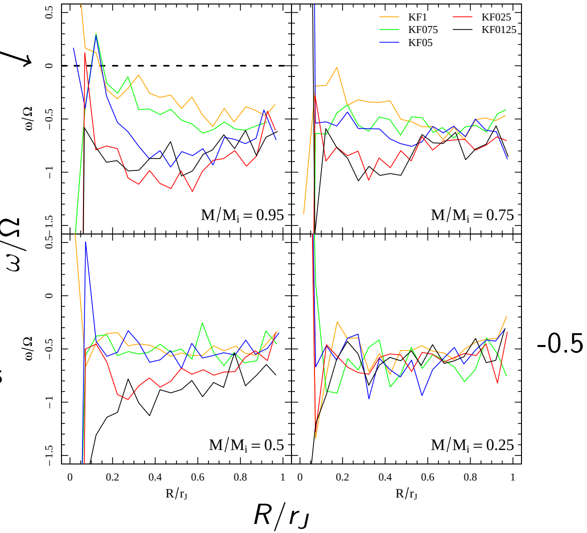
see also Baumgardt 2001, Küpper et al. 2010

Development of Internal Rotation

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

$\Omega =$
angular velocity
of cluster orbit

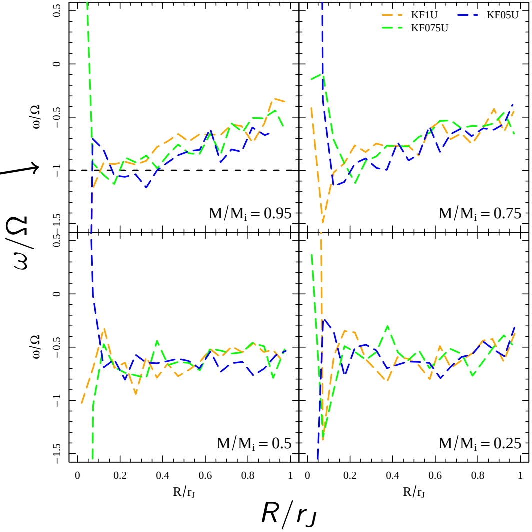
Filling vs.
Underfilling differences



Tiongco et al., submitted

Development of Internal Rotation

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

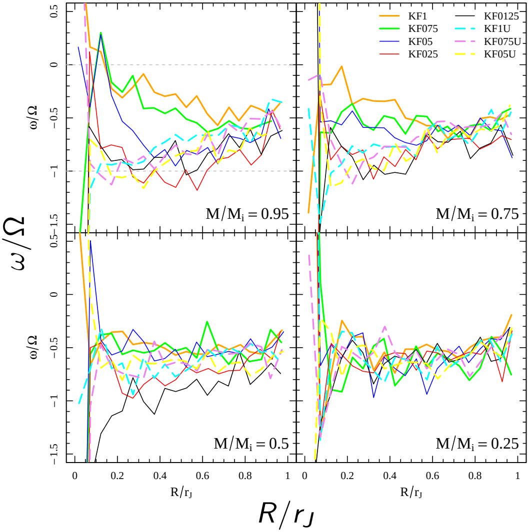


-0.5

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 $R > 0.1 r_J$



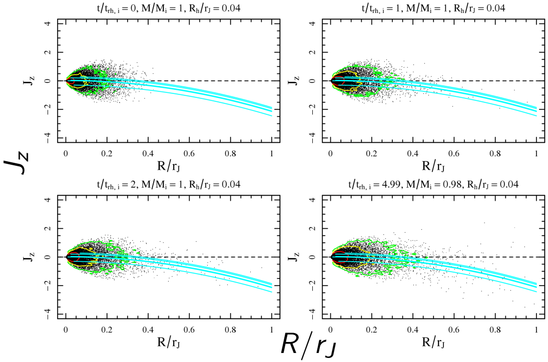
-0.5

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

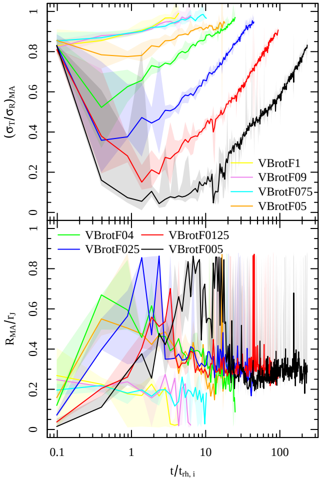
Backup Slides

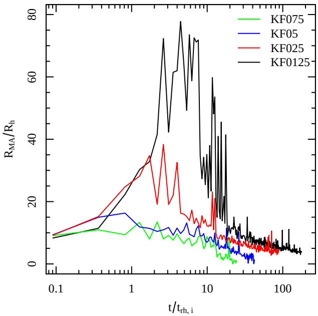


Tiongco et al., submitted

- 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

Backup Slides





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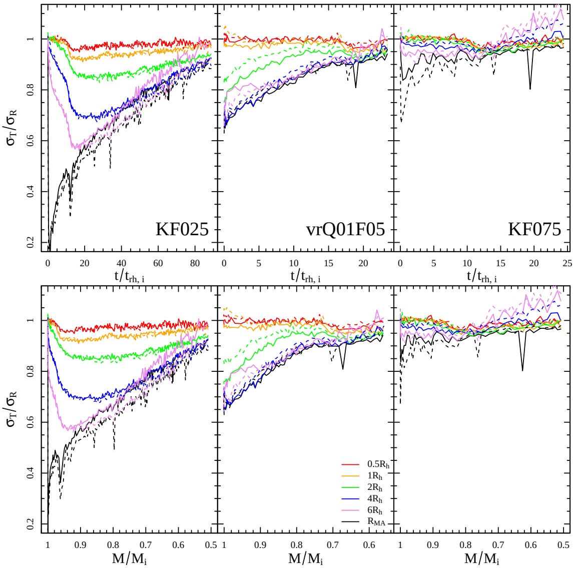

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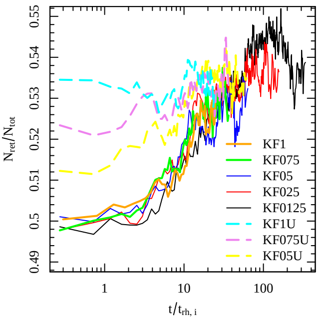

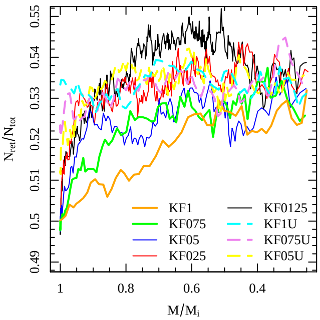

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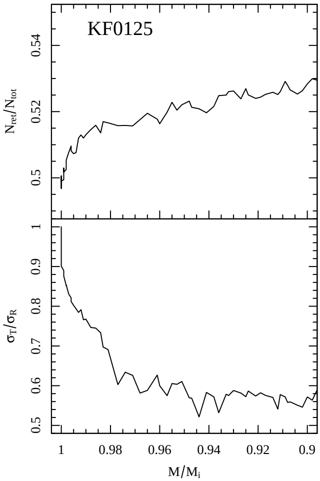

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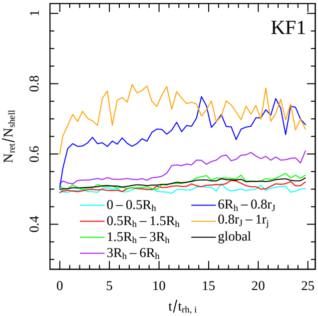

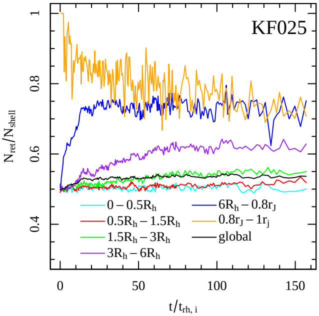

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