Evolution of Star Clusters in Galactic Tidal Field

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Why Star Clusters

- **Building blocks of galaxies** — understand their formation and evolution will bring valuable insight into the early history of galaxies.
- **Astrophysical laboratory** (e.g. stellar evolution, cosmic distance indicator)
- **Natural N-body dynamical systems**

M4/NGC6121 (ESO)

Dissolution of Star Clusters

- **Star clusters are doomed to dissolve.**
- **Internal Effects**
  - Two-body relaxation → expansion and evaporation *(Spitzer & Chevalier 1973, Antonov 1962, Lynden-Bell & Wood 1968)*
  - Stellar evolution of individual stars → mass loss → weakens the binding of the cluster *(Applegate 1986)*
- **External Effects**
  - Tidal effect → lowers the limiting energy for bound stars *(Spitzer 1987)*
  - Dynamical friction → Orbit decay *(Chandrasekhar 1942)*

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ISIMA Project

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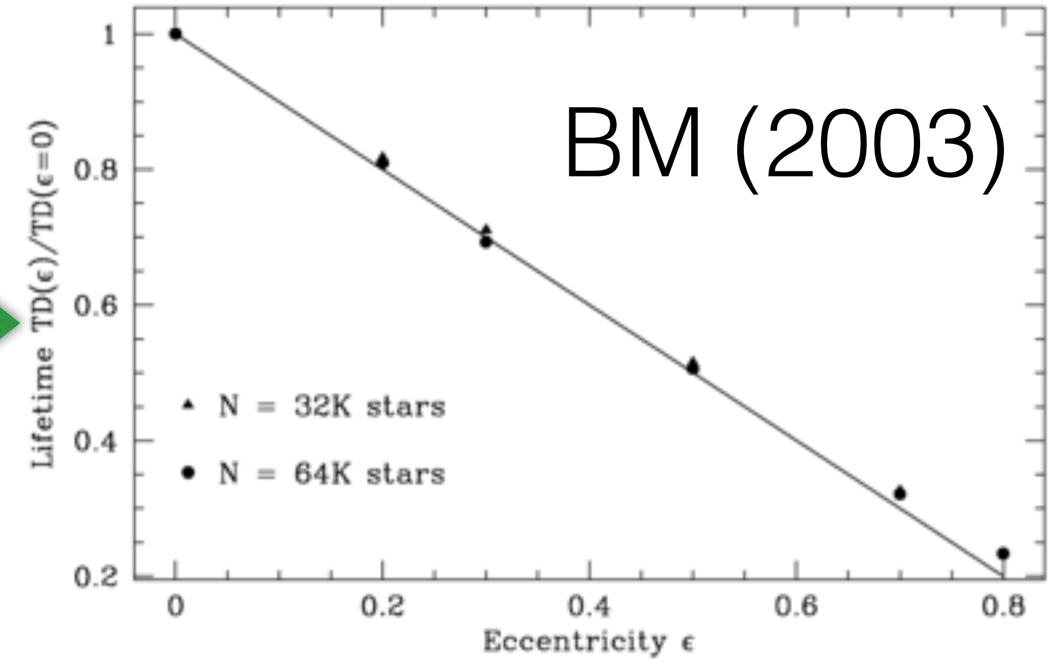
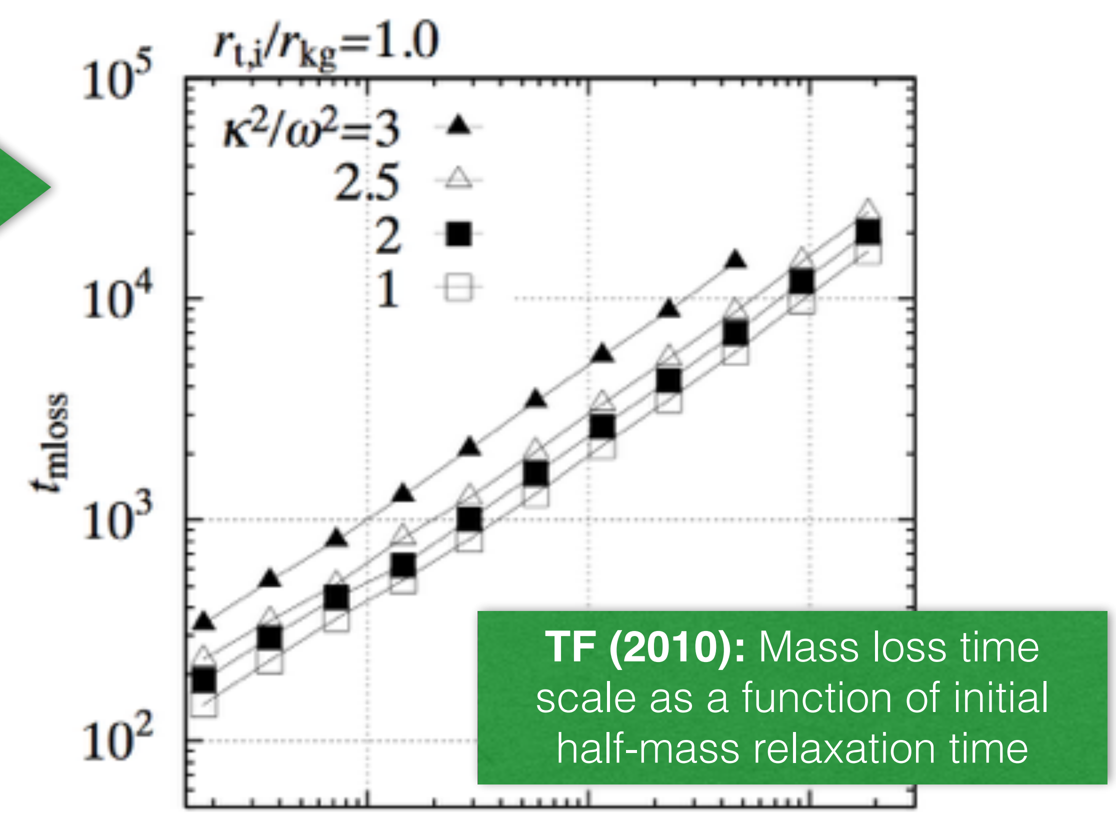
Related Work

- **Baumgardt & Makino (2003):** dependency of lifetime on eccentricity, half-mass relaxation time, mass of the individual star.



- **Tanikawa & Fukushige (2010):** dependency on galactic mass profile (bottom figure)

- **Gieles, Heggie & Zhao (2011):** a simple model of the life cycle of a star cluster in a tidal field.



TF (2010): Mass loss time scale as a function of initial half-mass relaxation time

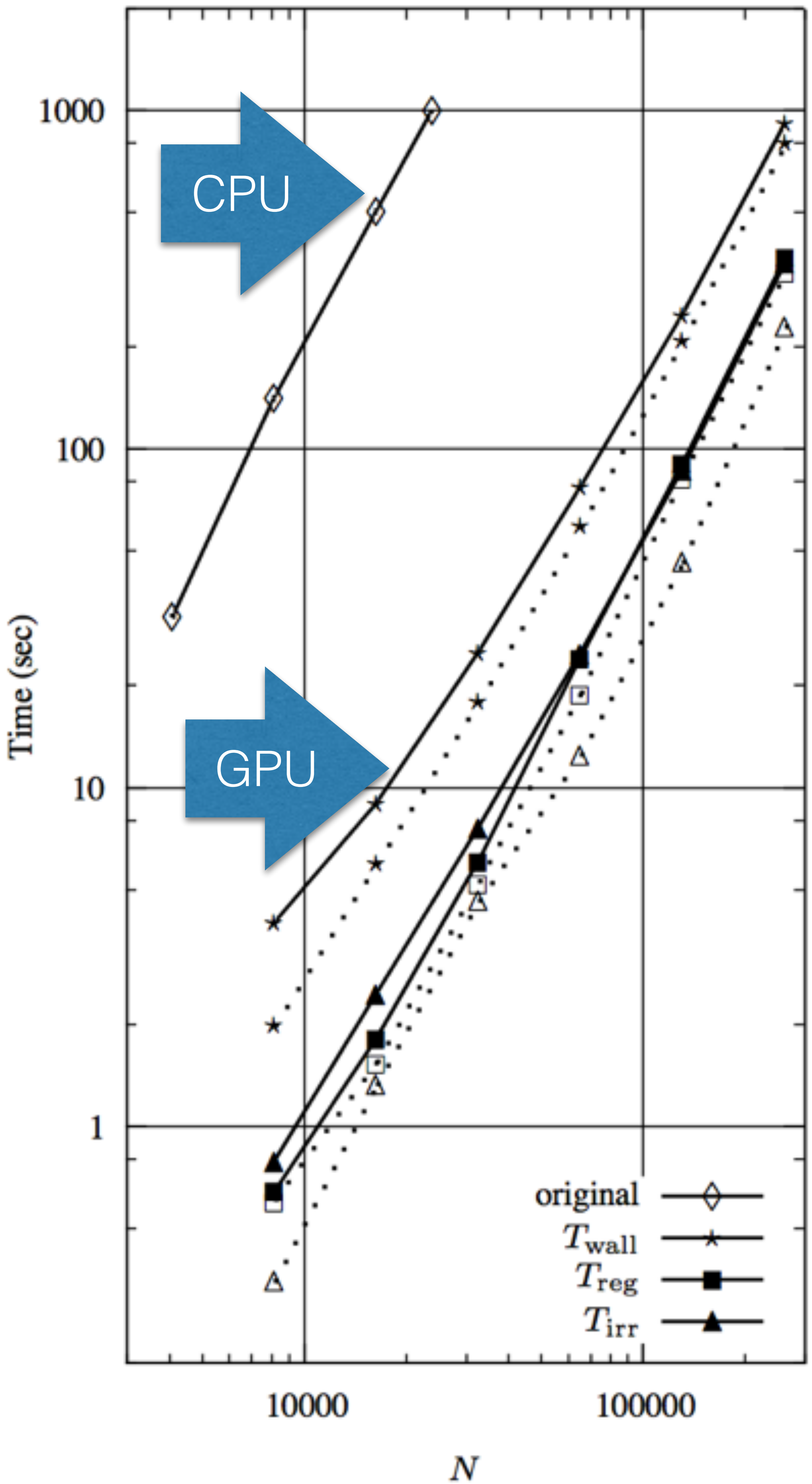
Methodology: Direct *N*-body Simulations

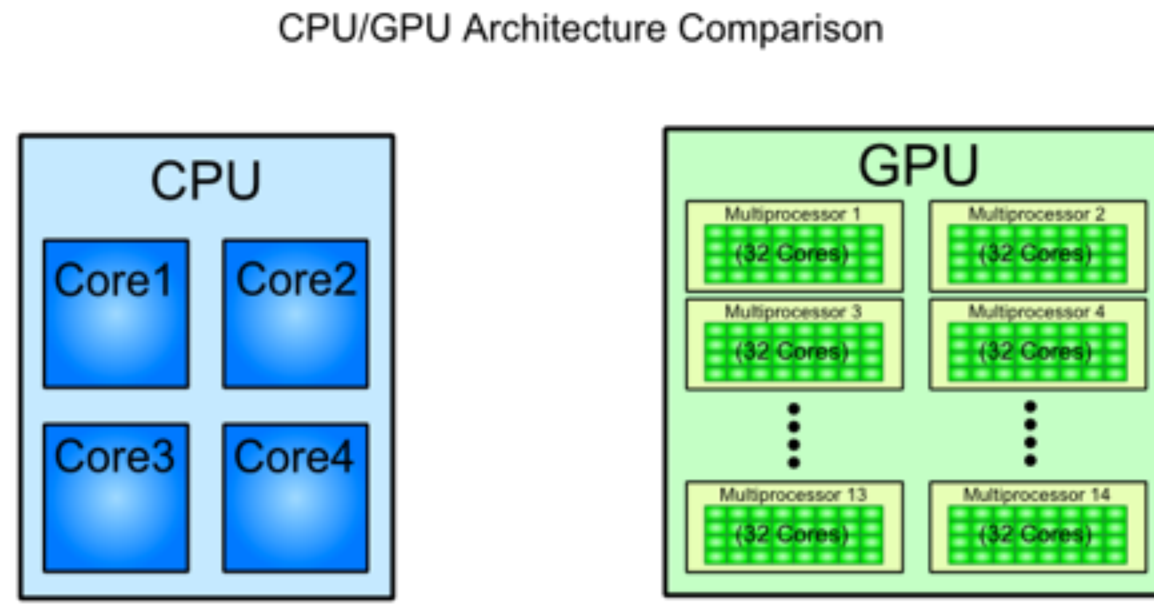
- Potential escapers → It is desirable for the orbits of stars to be modeled with the minimum of simplifying assumptions, and N-body simulation is more appropriate than orbit-averaged methods, such as Fokker-Planck method. *(Tanikawa & Fukushige 2010)*

- More fair comparison with previous results *(e.g. Baumgardt & Makino 2003).*

- Parameter space: N, e, potential, IMF, cluster model… → Numerical efforts → Special hardware (GPU)

- Analytical model: Ben Bar-Or’s talk





← Nitadori & Aarseth (2012):
computing time as a function of N

NBODY6 and its Variants

- **Direct *N*-body code with ~50 years of history** *(Aarseth 1963, Aarseth 2003)*
- **Advanced treatments**
    - 4th order Hermite scheme *(Aarseth 1985, Makino 1991, Aaresth & Makino 1992)*
    - Individual time-step *(McMillan 1988, Makino 1991)*
    - Ahmad-Cohen neighbor scheme *(Ahmad & Cohen 1973, Makino & Aarseth 1992)*
    - KS regularization *(Kustaanheimo & Stiefel 1965, Mikkola & Aarseth 1998)*
    - Chain regularization *(Mikkola & Aarseth 1990,1993,1996)*
    - Stability criterion for hard-triples and high-order systems *(Mardling & Aarseth 1999, Mardling 2008)*
- **Variants: NBODY6GPU (Nitadori & Aarseth 2012), NBODY6++ (Spurzem et al 1999), NBODY6tt (Renaud, Gieles & Boily 2011), NBODY6tid, …**

Models & Initial Conditions

1D Galactic Potentials

	Point Mass Galaxy	Isothermal Galaxy	Power-law Galaxy
Density Profile	$\sim R^{-\infty}$	$\sim R^{-2}$	$\sim R^{-1}$
Enclosed Mass	const	$\sim R$	$\sim R^2$
Potential	$-GM/R$	$v_c^2 \ln(R)$	GM_0R/a^2
Tidal Radius	$\sim R$	$\sim R^{2/3}$	$\sim R^{1/3}$
Angular Frequency	$\sim R^{-3/2}$	$\sim R^{-1}$	$\sim R^{-1/2}$

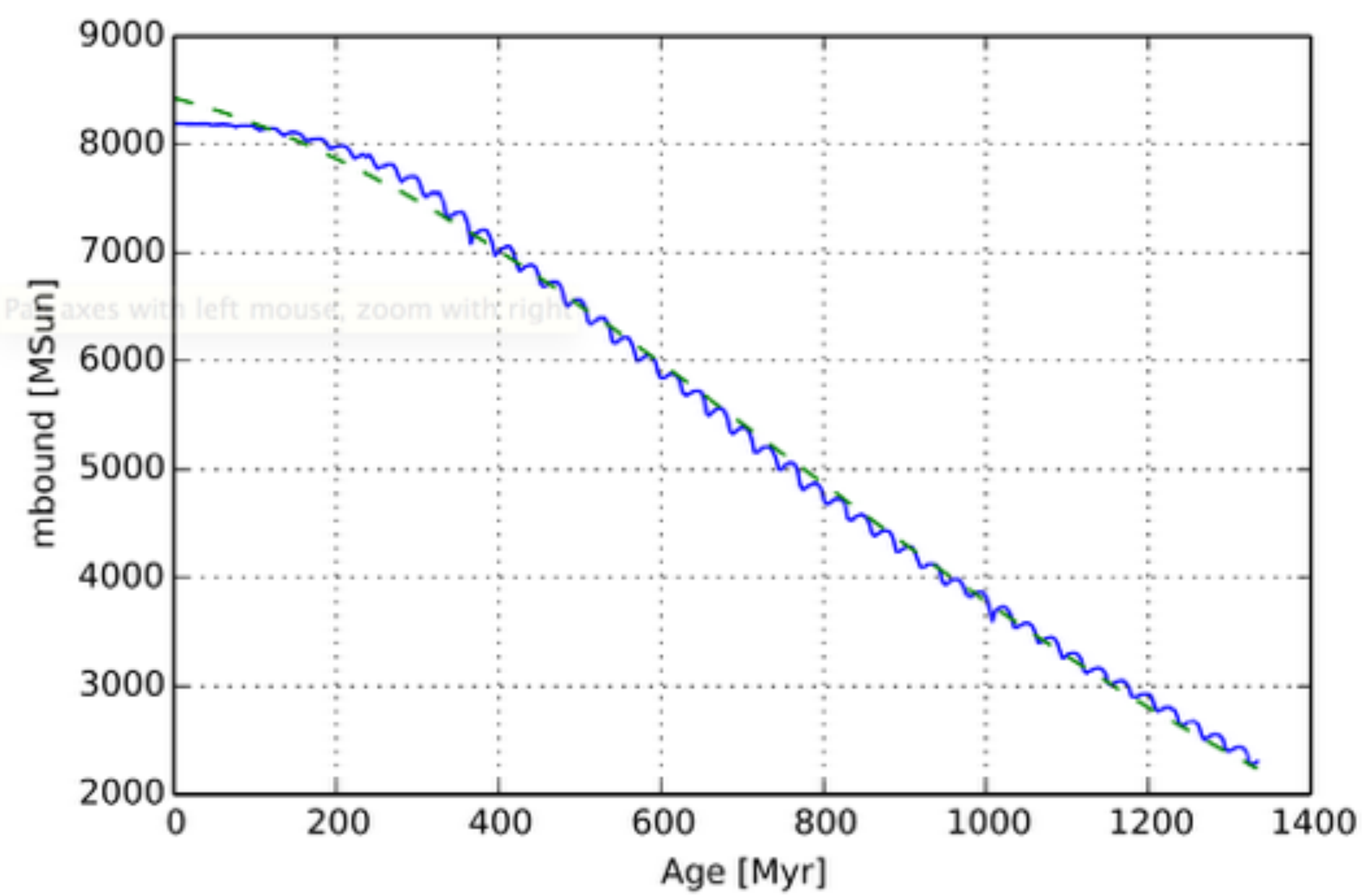
Define three types of galaxy as: $M(R) \sim R^{\lambda}$

Star Cluster Initial Conditions

- Plummer model, equal mass
- N: 4k and 8k
- Cluster radius: r_v = 1pc (r_v: virial radius)
- Filling factor: r_h/r_t = 1/20 (**r_h**: half-mass radius; **r_t**: tidal radius)
  Different filling factors: Filippo Contenta's talk
- Galaxy model: λ = 0, 1, 2
- Orbital eccentricity: 0.0, 0.2, 0.4, 0.6, 0.8

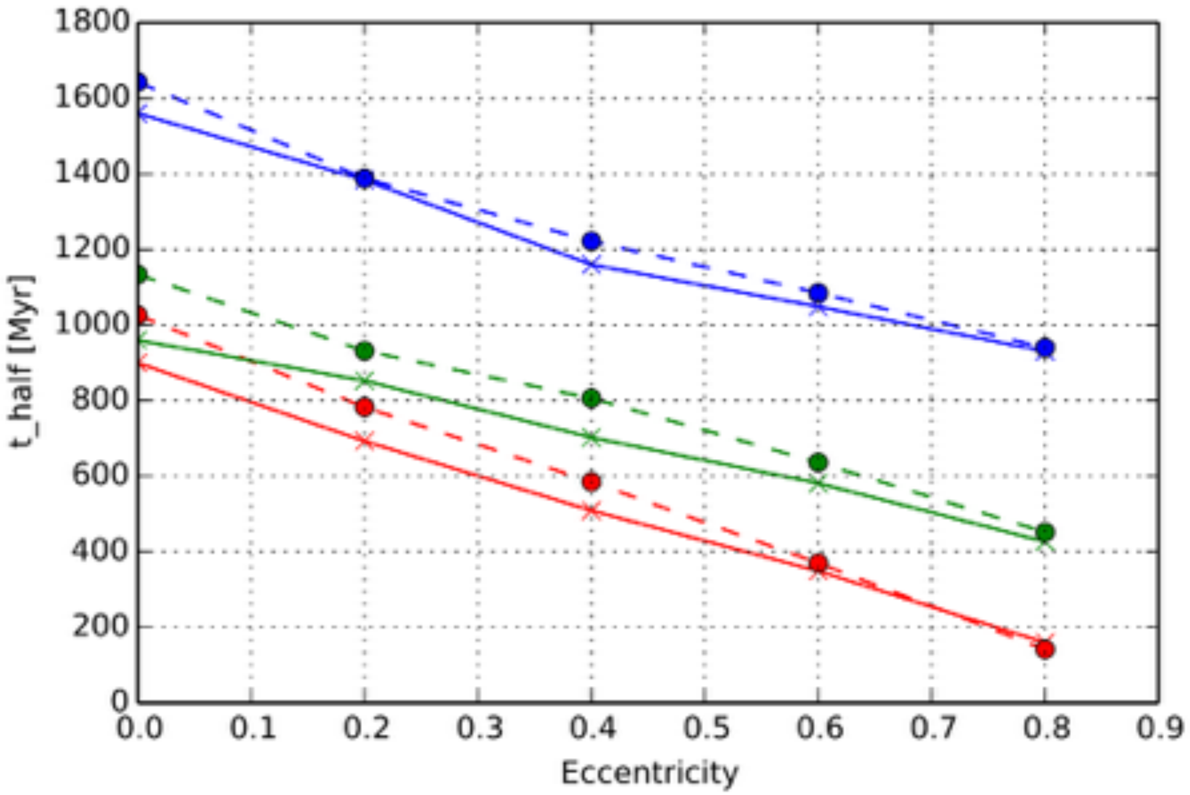
Life-time determination

- Half-life time: the time it takes for the cluster to lose 50% of its initial mass.
- Life time (dissolution time): the time it takes for the cluster to to lose 90% of its initial mass.
- Bound mass criteria:
  $E_{tot}<0$ (excluding ghost particles and binaries)
- Kinetic energy of cluster stars is defined with respect to the centre of mass velocity; potential energy defined with respect to the cluster geometric centre.
- Fluctuation of bound mass → Gaussian fitting

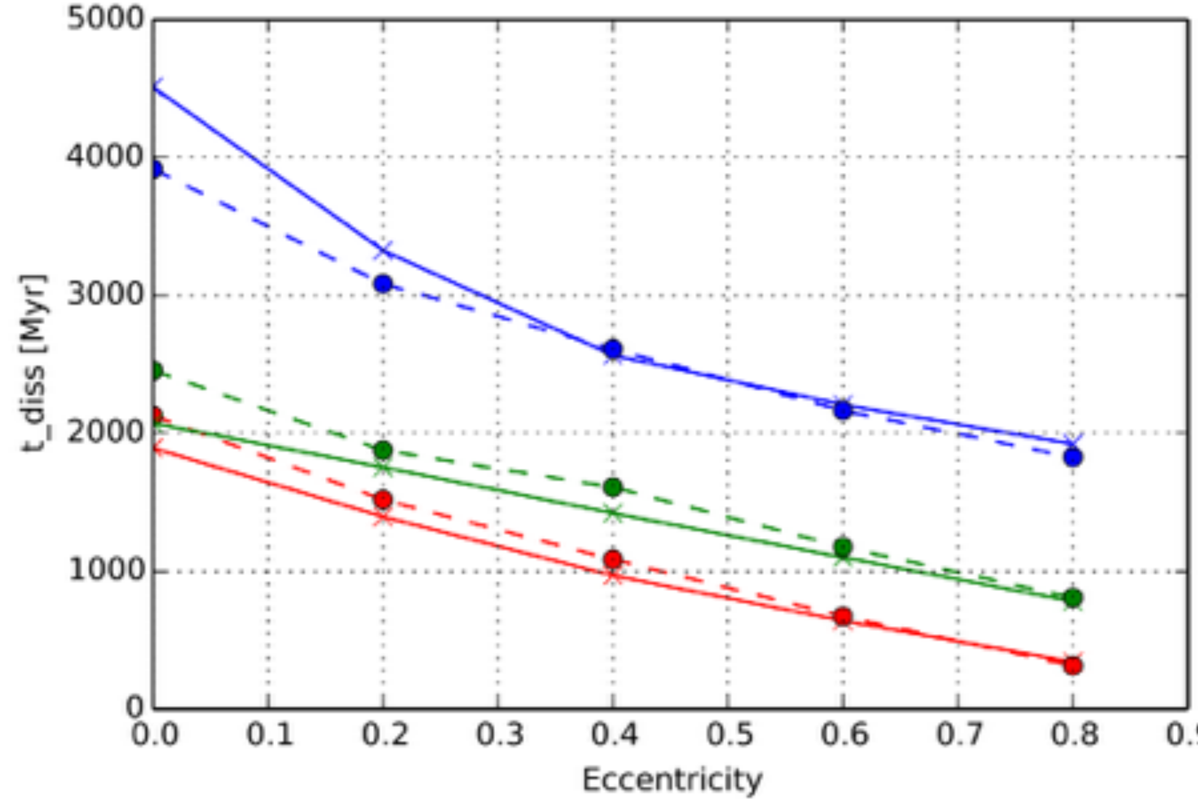


Example of bound mass fitting with a Gaussian function.
N=4096, e=0.8, λ=2, rh/rt = 0.05

Results — Raw Data



Half life time

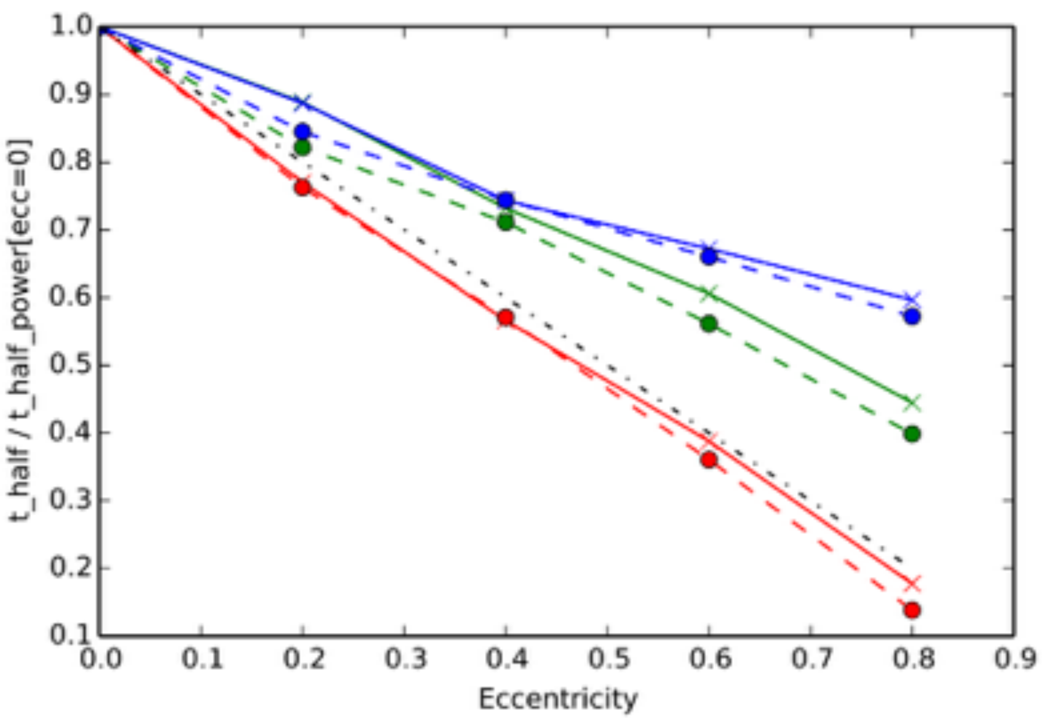


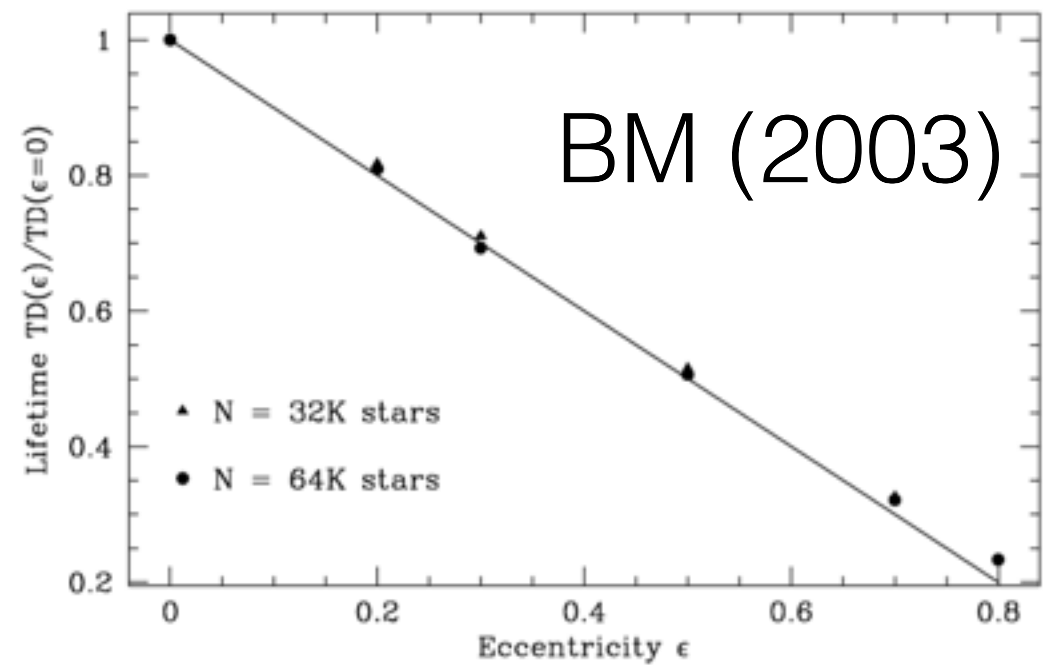
Dissolution time

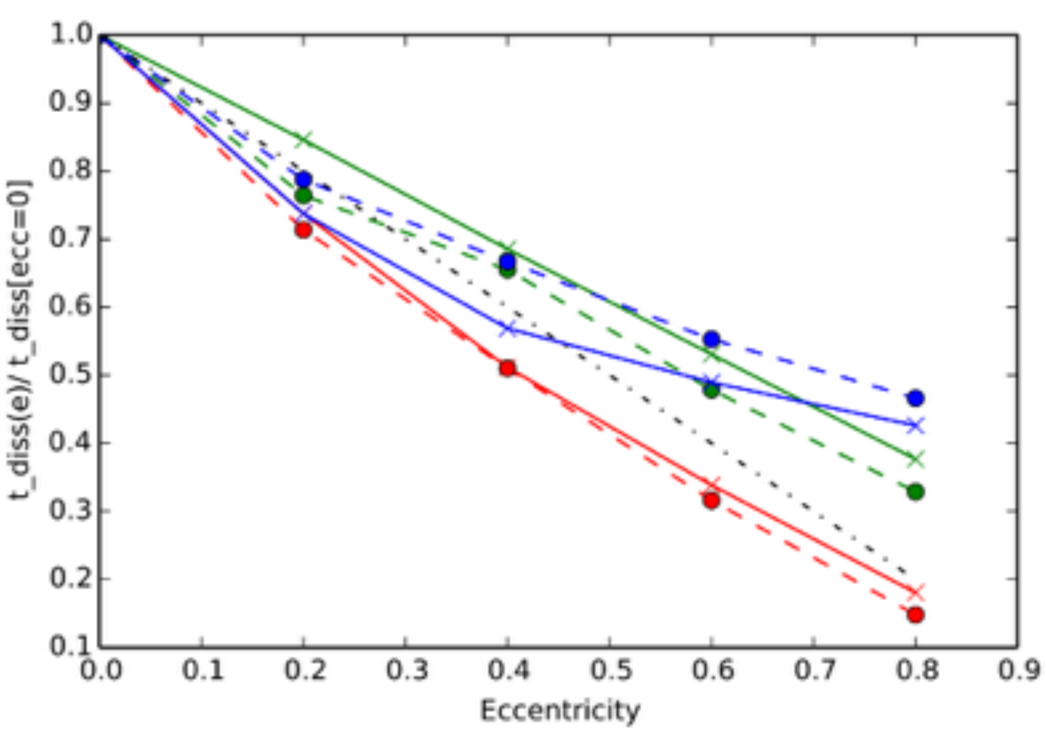
Color: RED (λ=0), GREEN (λ=1), BLUE (λ=2)

Filling factor: rh/rt = 1/20, solid line: 4k; dashed line: 8k

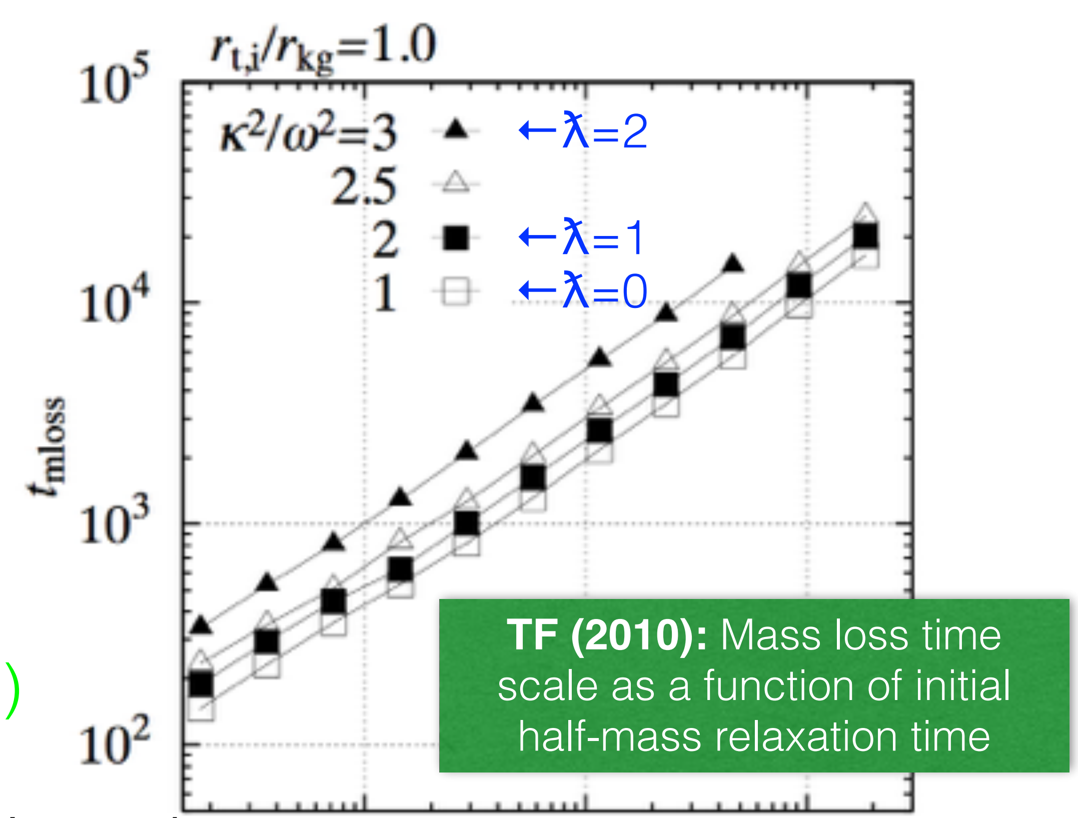
Comparison







RED (ƛ=0)
GREEN (ƛ=1)
BLUE (ƛ=2)



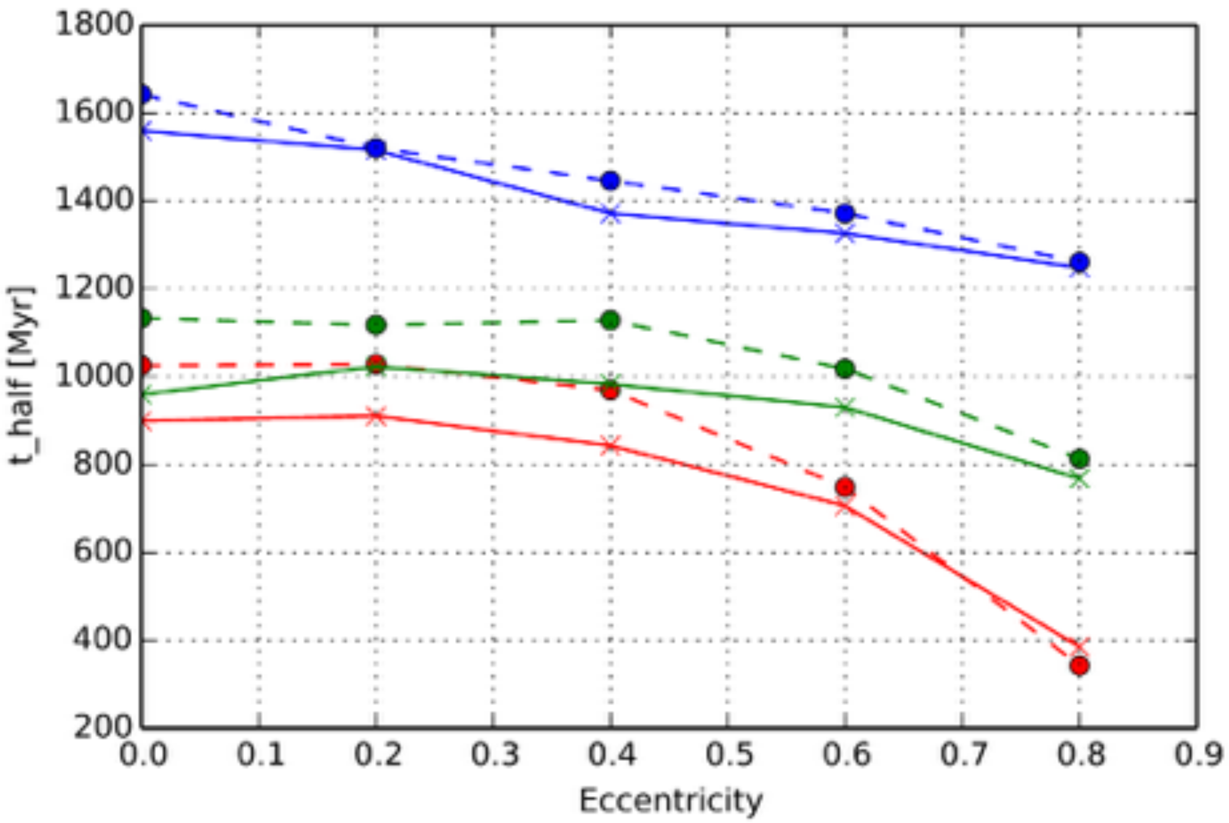
Filling factor: rh/rt = 1/20, solid line: 4k; dashed line: 8k

Scaling to the Same Semi-Major Axis

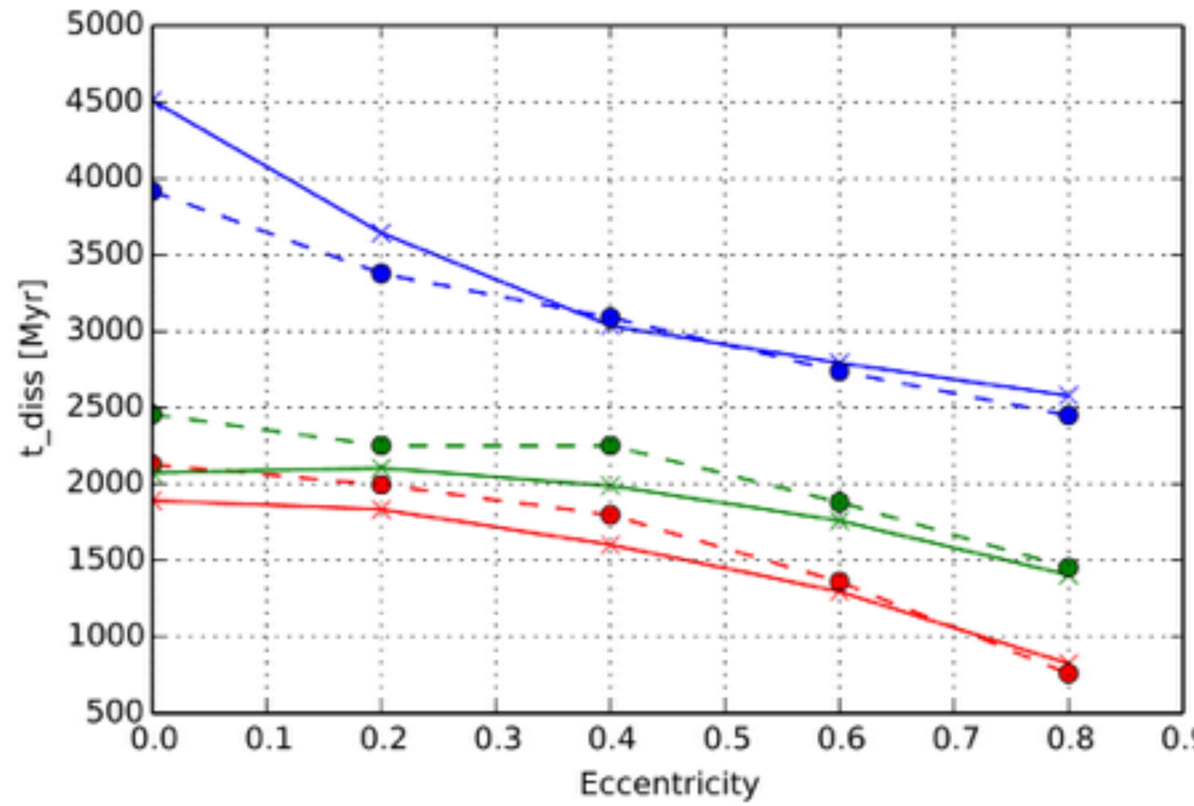
- All the simulations are done by placing the cluster at the same apocenter
- It is possible to scale the orbit to the same semi-major axis
- Orbital period scales in the same way as the crossing time of cluster → Filling factor preserved

	length scaling	time scaling
λ=0	$R' = \alpha R$	$T' = \alpha^{3/2} T$
λ=1	$R' = \alpha R$	$T' = \alpha T$
λ=2	$R' = \alpha R$	$T' = \alpha^{1/2} T$

Results — Scaled



Half life time



Dissolution time

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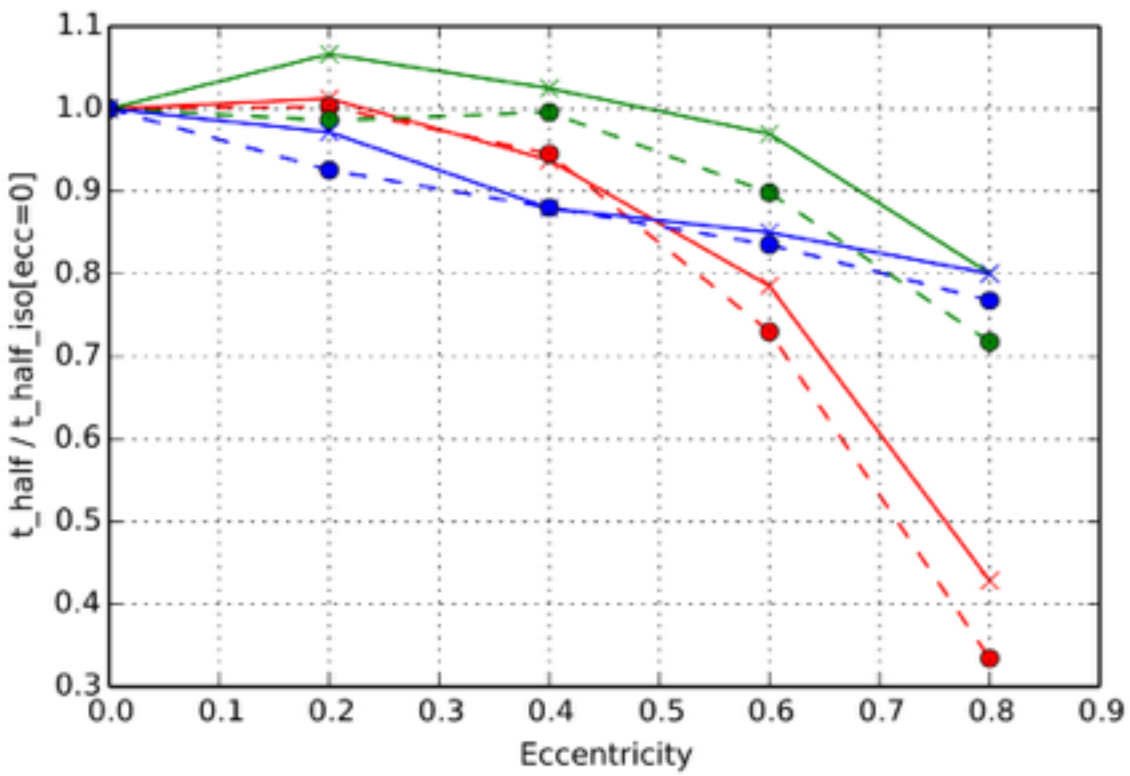
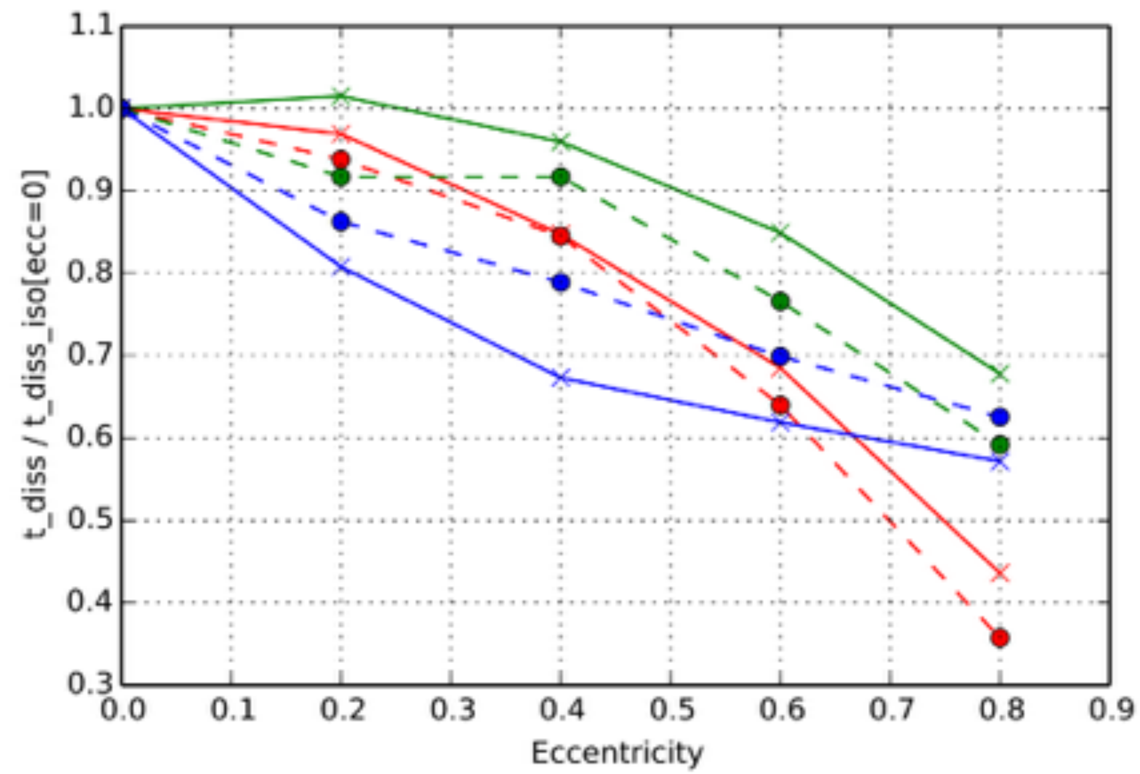
Results — Scaled & Normalized

difficult to compare
among different ƛ models



Half life time



Dissolution time

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Filling factor: rh/rt = 1/20, solid line: 4k; dashed line: 8k

Conclusions

- **Simulations shows life-time dependencies on:**
  - Galactic potential model (characterized by λ, the power index of enclosed mass within radius R.
  - Total number of stars in the cluster
  - Eccentricity of the orbit
- **Result deviation from previous work probably due to:**
  - Initial mass function
  - Stellar evolution
  - Filling factor

Future Agenda

- Explore the dependency of N (16k, 32k, …)
- Further investigation of the deviation from the scaling illustrated by Baumgardt & Makino (2003)
- Quantitively compare with Tanikawa & Fukushige (2010)
- Investigate the effects of filling factor and stellar evolution
- Compare with Ben Bar-Or's analytical studies

Visualization & Acknowledgment

$\mathcal{END} — \mathcal{FIN}$