Dynamical Evolution of Clusters with Primordial Mass Segregation

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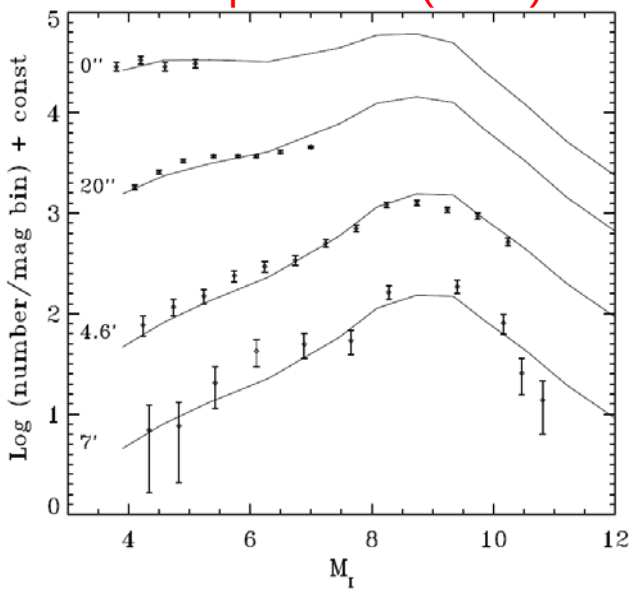
Overview

- mass segregation in clusters
- simple analytical considerations
- N-body simulations
- cluster lifetimes and structural evolution
- cluster mass function

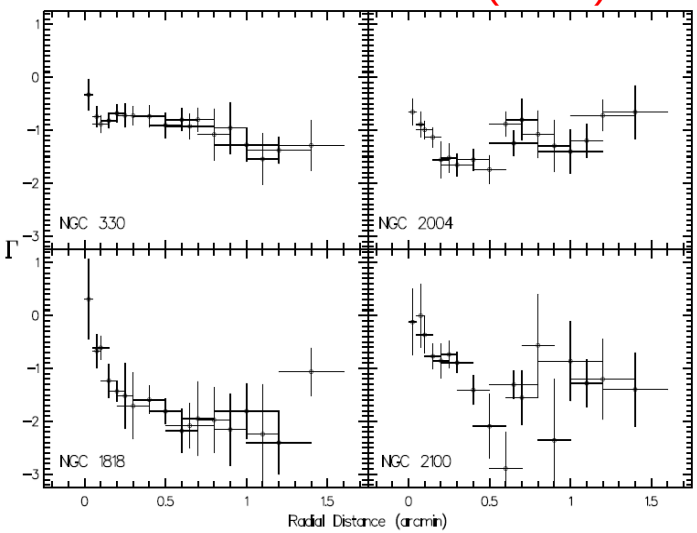
- mass segregation well known in old clusters (e.g. M15)…

…and in young ones

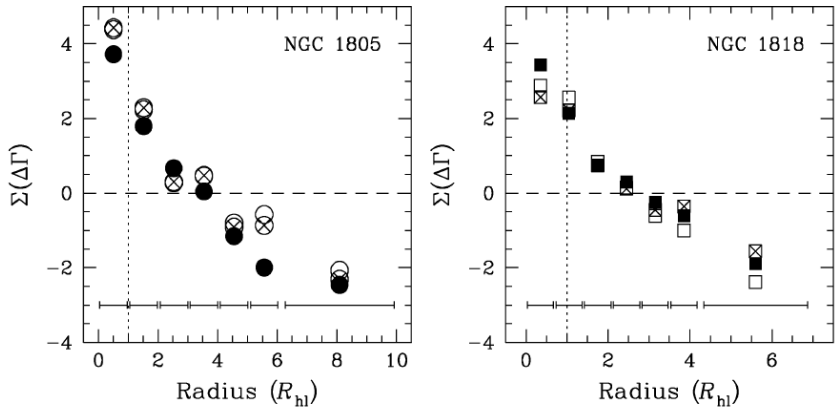
Pasquali et al. (2004)



Gouliermis et al. (2004)

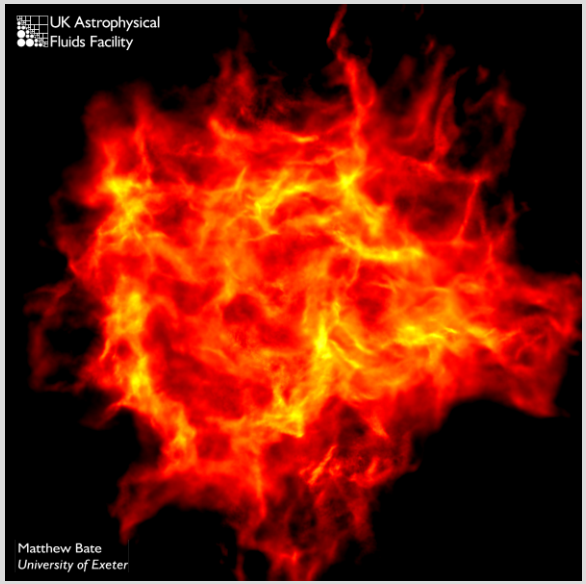


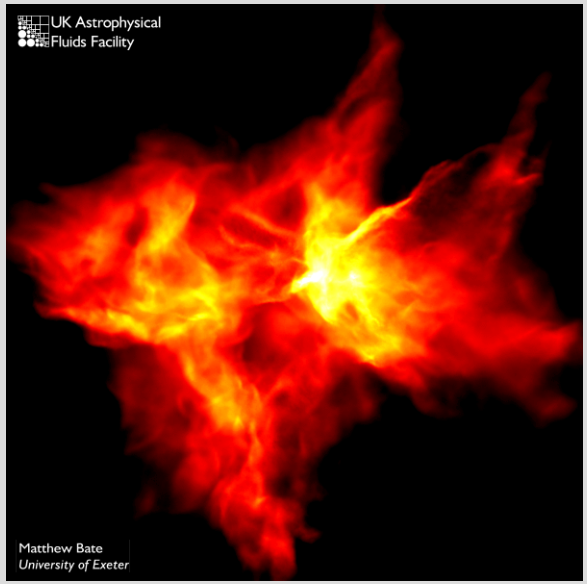
de Grijs et al. (2002)

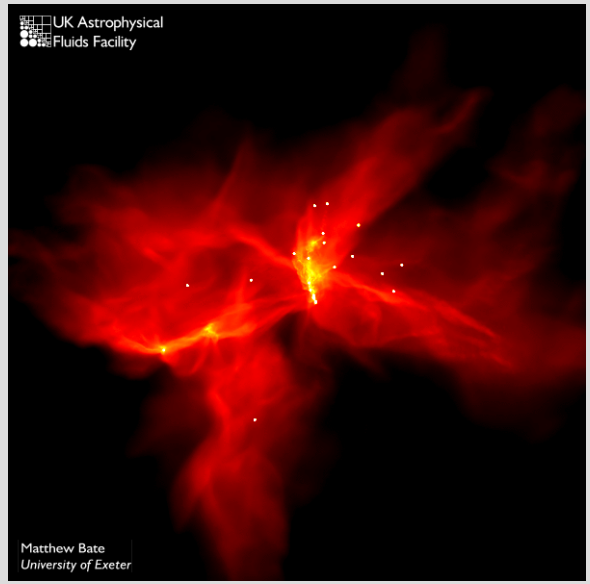


…too young?

- stars form in clumpy environments
- massive stars form preferentially at the centers of the clumps

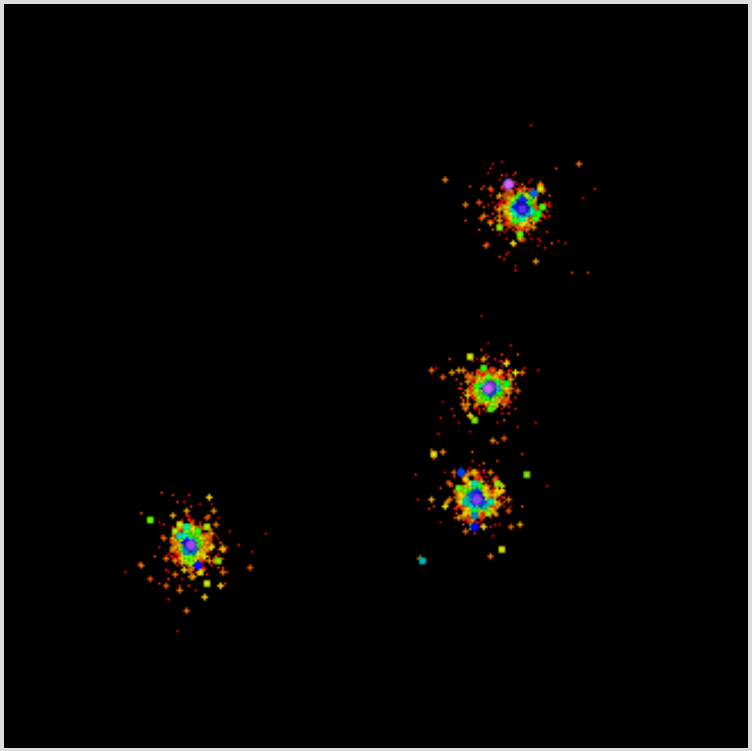


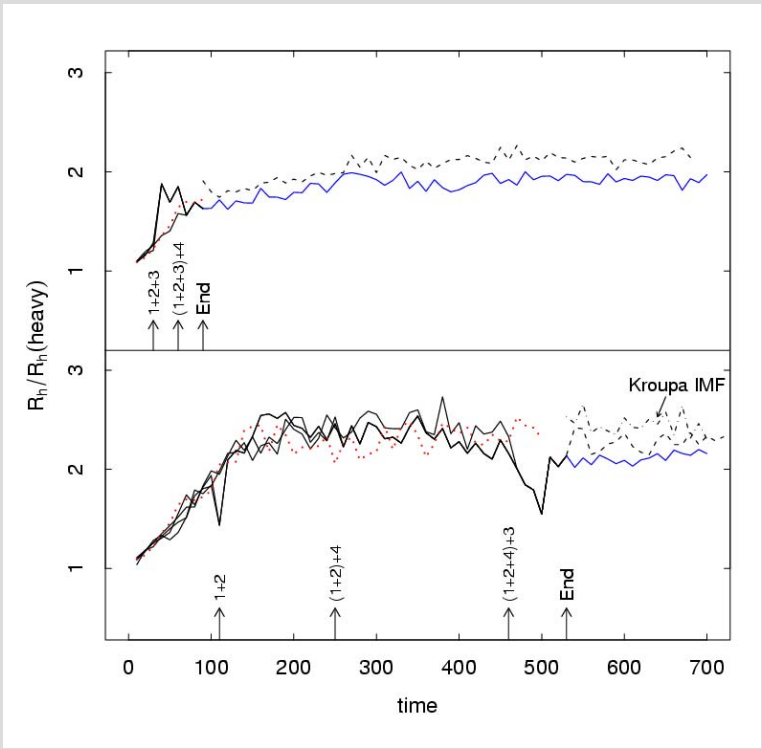




(e.g. Elmegreen & Krakowki 2001, Klessen 2001, Stanke et al. 2006, Bonnell & Bate 2006, Elmegreen 2006)

- segregation persists as small clumps merge to form larger ones (McMillan, Vesperini, & Portegies Zwart 2007)

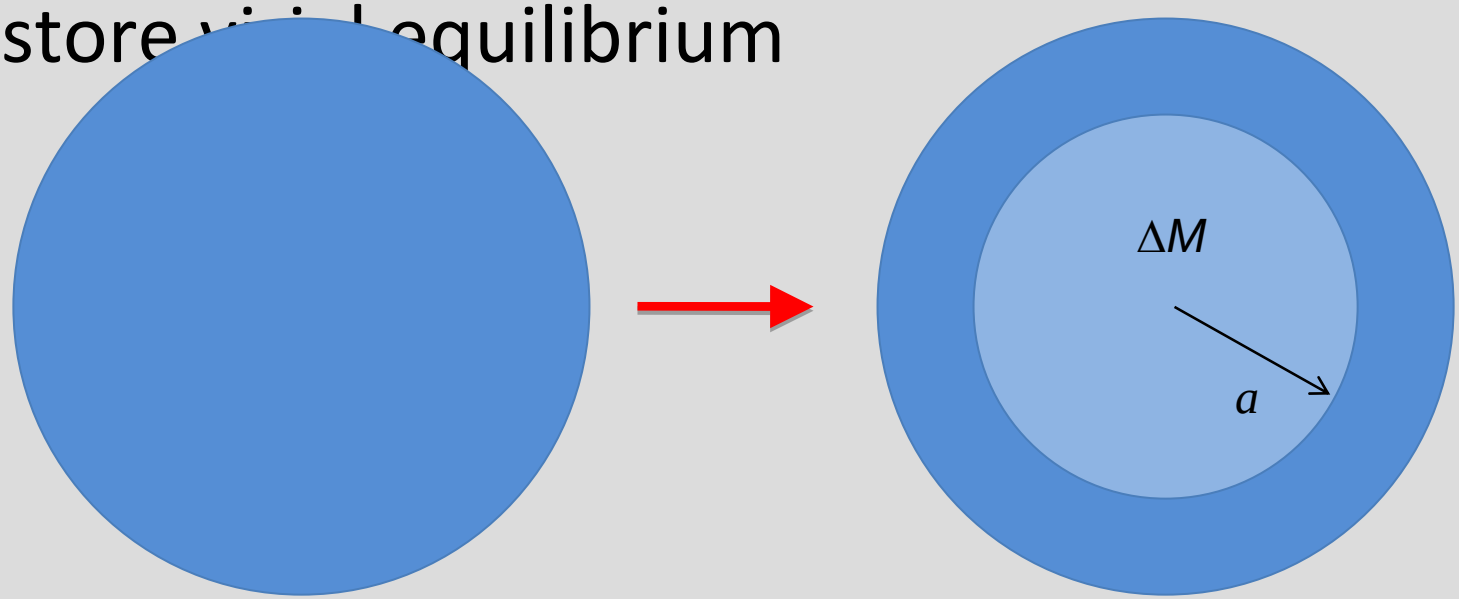


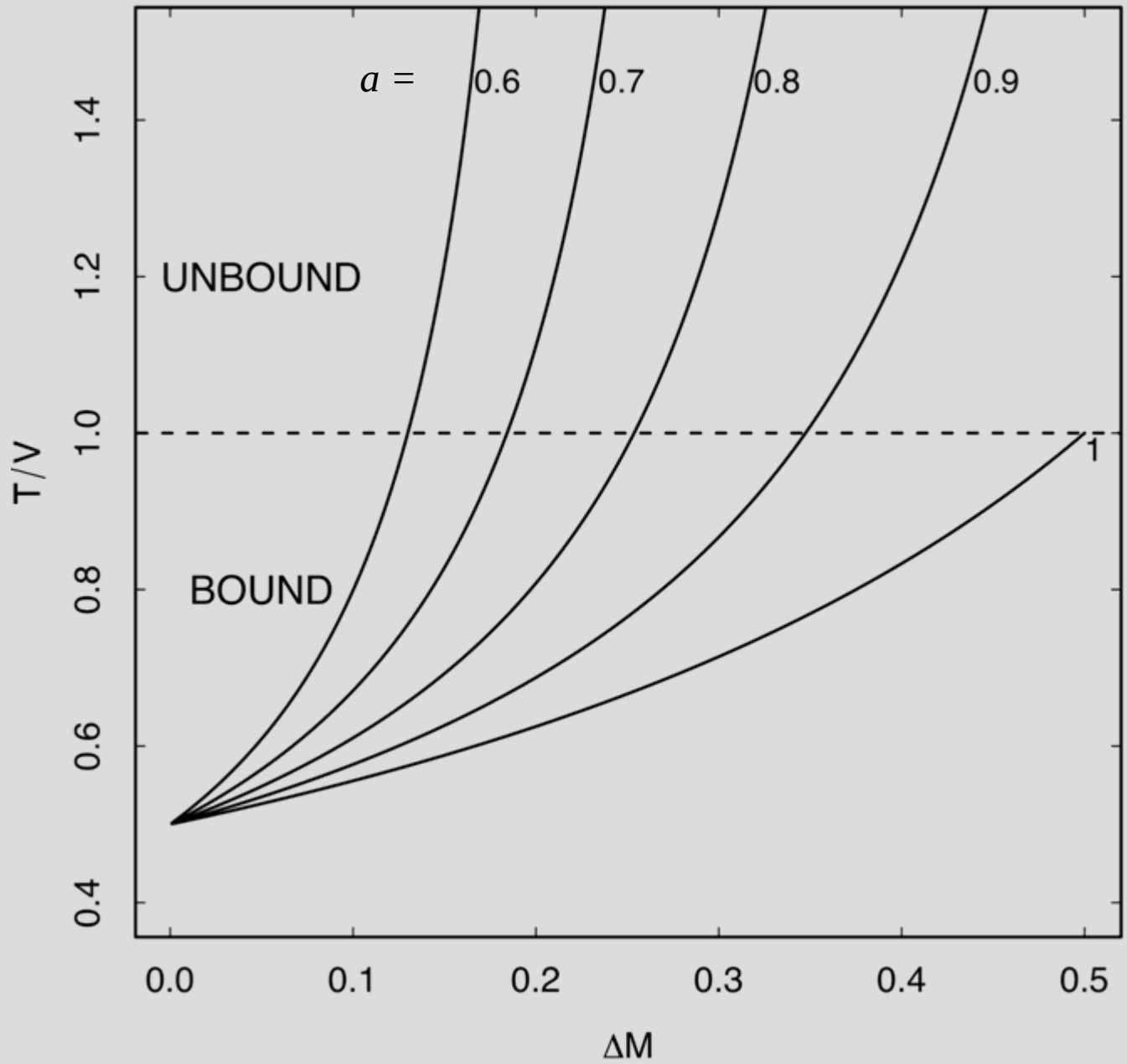


- did this continue to globular cluster scales?
- how could we tell?

Simple Analytic Model

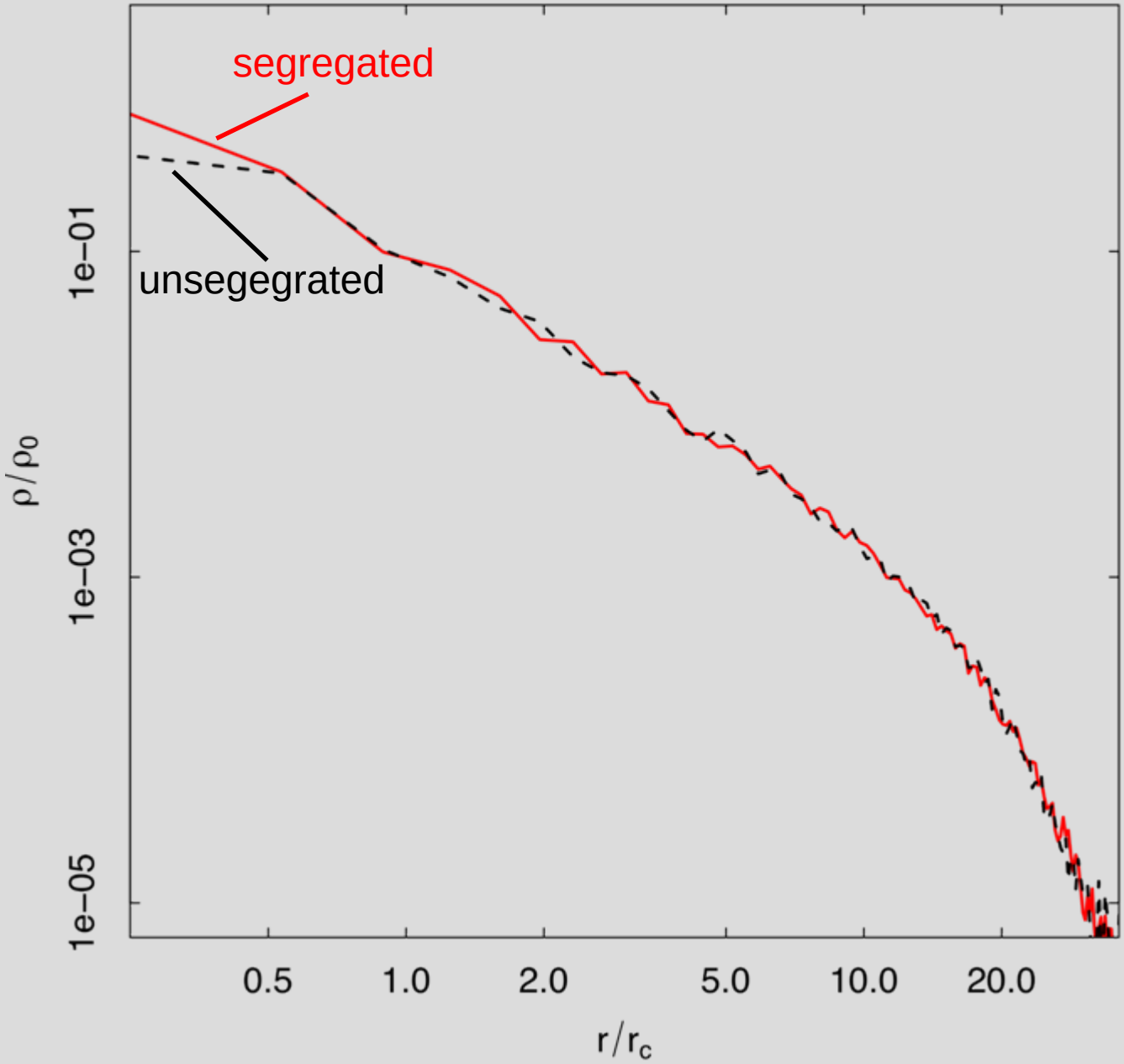
- start in virial equilibrium
- remove a fraction ΔM of the total cluster mass from within a fraction a of the cluster radius
- restore virial equilibrium

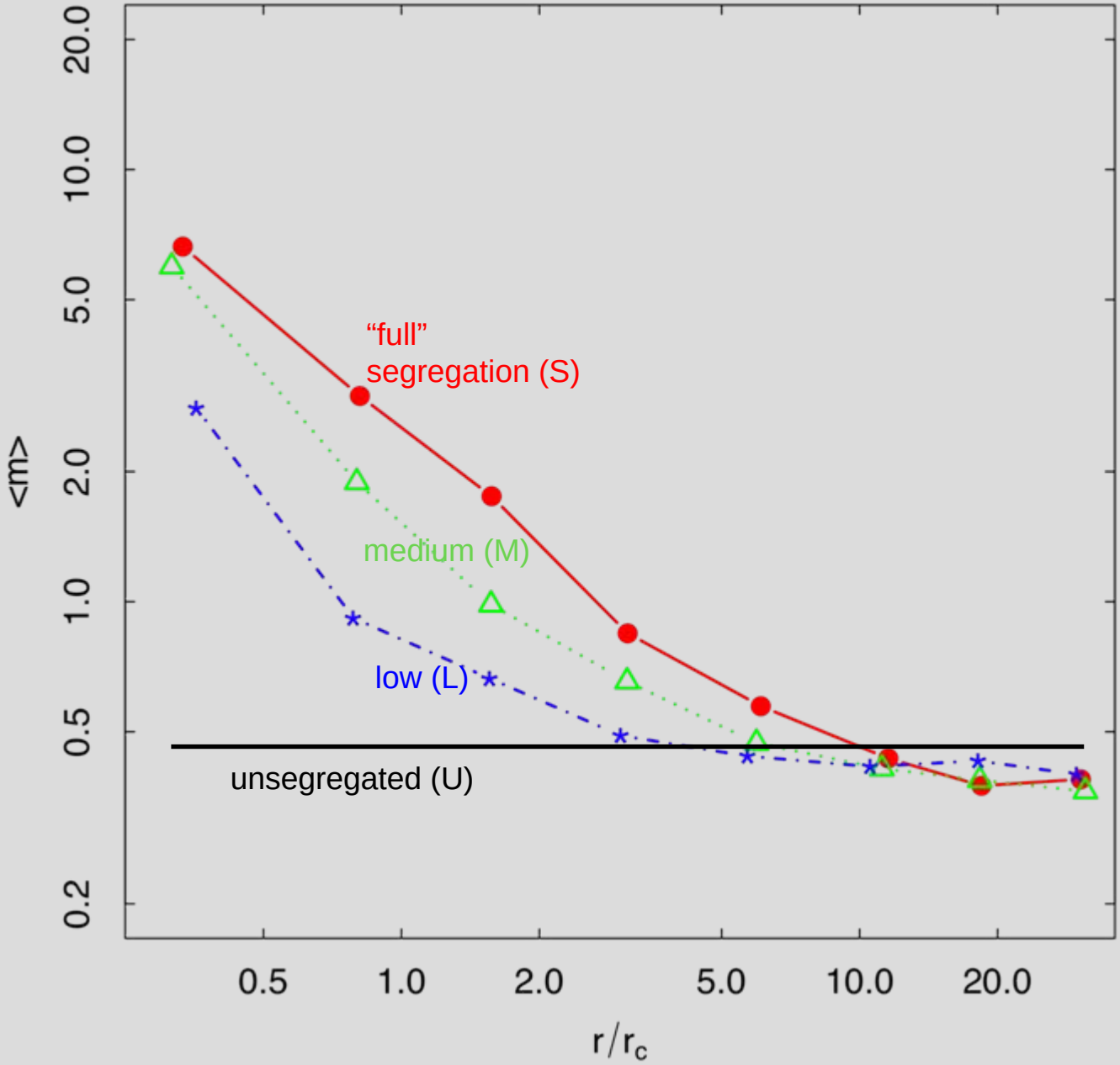



a =
0.6
0.7
0.8
0.9
1
UNBOUND
BOUND
T/V
0.4
0.6
0.8
1.0
1.2
1.4
0.0
0.1
0.2
0.3
0.4
0.5
ΔM

Initial Conditions

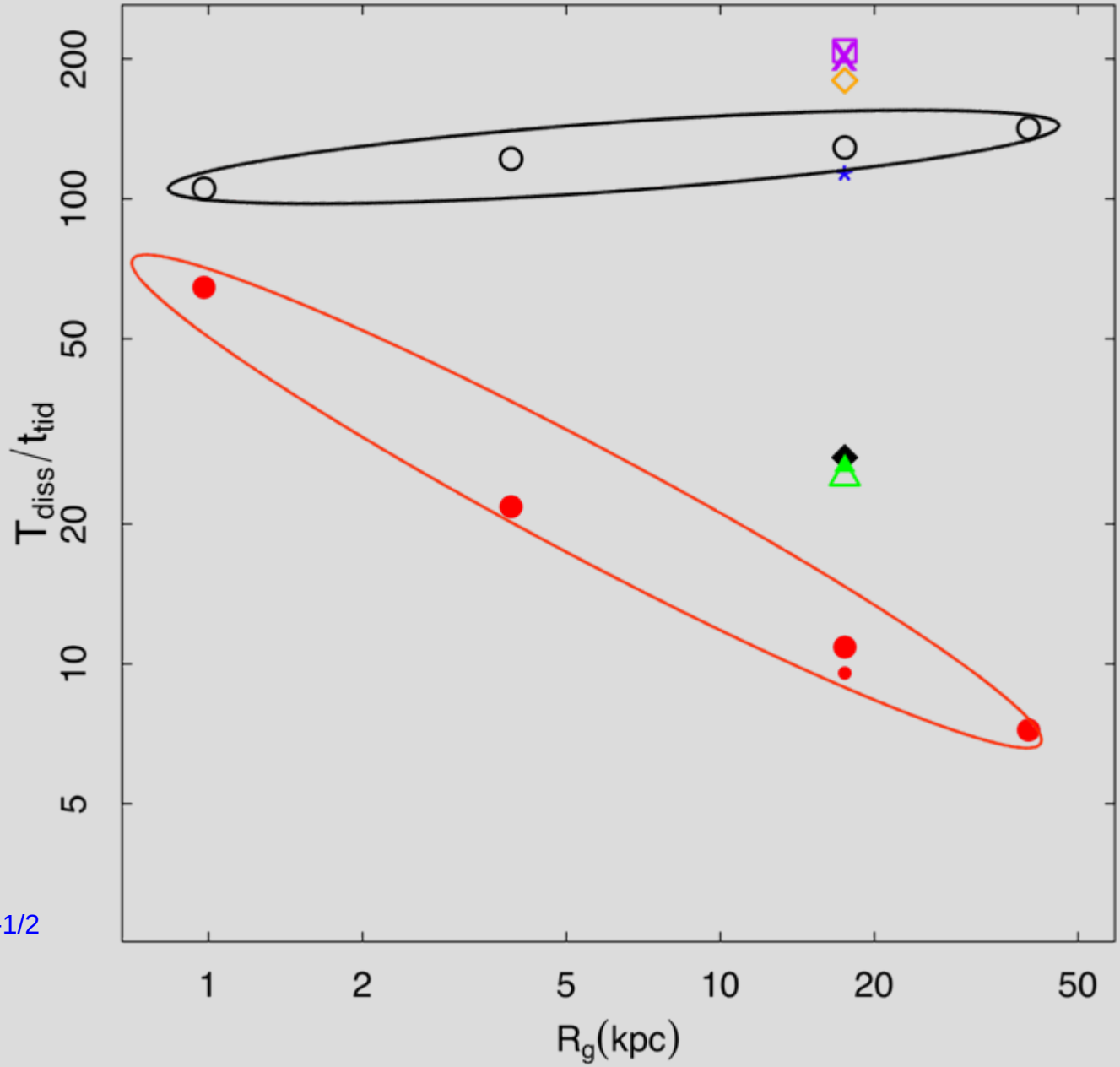
- $N \approx$ 30k, 70k, 100k particles
  - software: starlab, MUSE (see MODEST-9)
- galactocentric radii R_g = 1, 4, 18, 40 kpc
- clusters initially unsegregated or segregated
  - also “medium” and “low” initial segregation
- clusters may fill or underfill their Jacobi radii
  - “filling factor” $f = r_t/r_J$
- (“normal” IMF, no gas expulsion)


segregated
unsegegrated
1e−01
1e−03
1e−05
ρ/ρ0
0.5
1.0
2.0
5.0
10.0
20.0
r/rc


20.0
10.0
5.0
2.0
1.0
0.5
0.2
<m>
"full"
segregation (S)
medium (M)
low (L)
unsegregated (U)
0.5
1.0
2.0
5.0
10.0
20.0
r/r_c

Cluster Lifetimes and Evolution

- effect of full and partial segregation
- effect of Roche lobe underfilling
- scaling with N
- internal structural evolution



unsegregated

T_{diss}/t_{tid} ~ constant

~ $(N/\log N)^{0.8}$

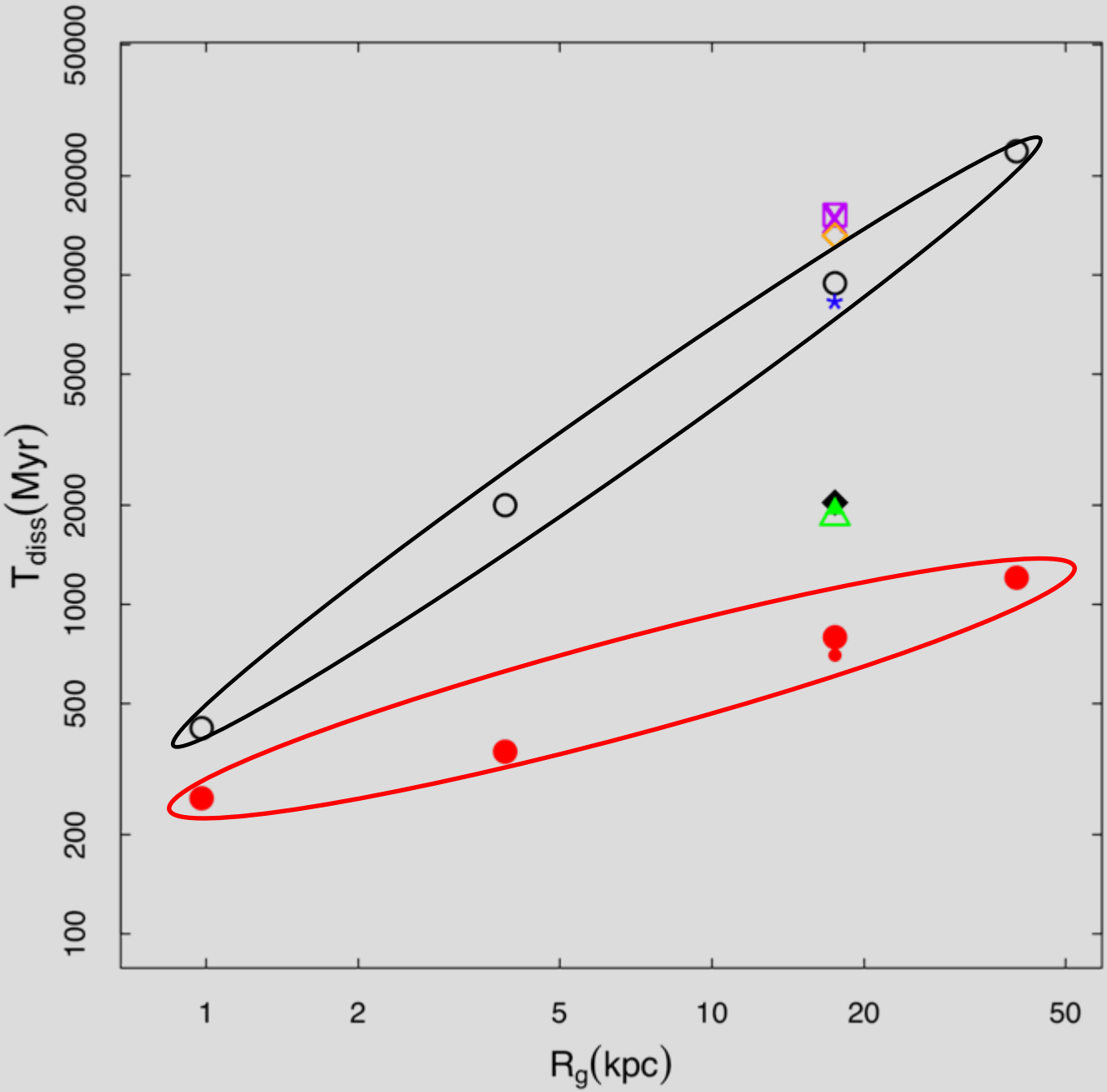
segregated

T_{diss}/t_{tid} ~ $R_g^{-0.48}$

independent of N

t_{tid} ~ $\rho_{tid}^{-1/2}$

~ R_g



unsegregated

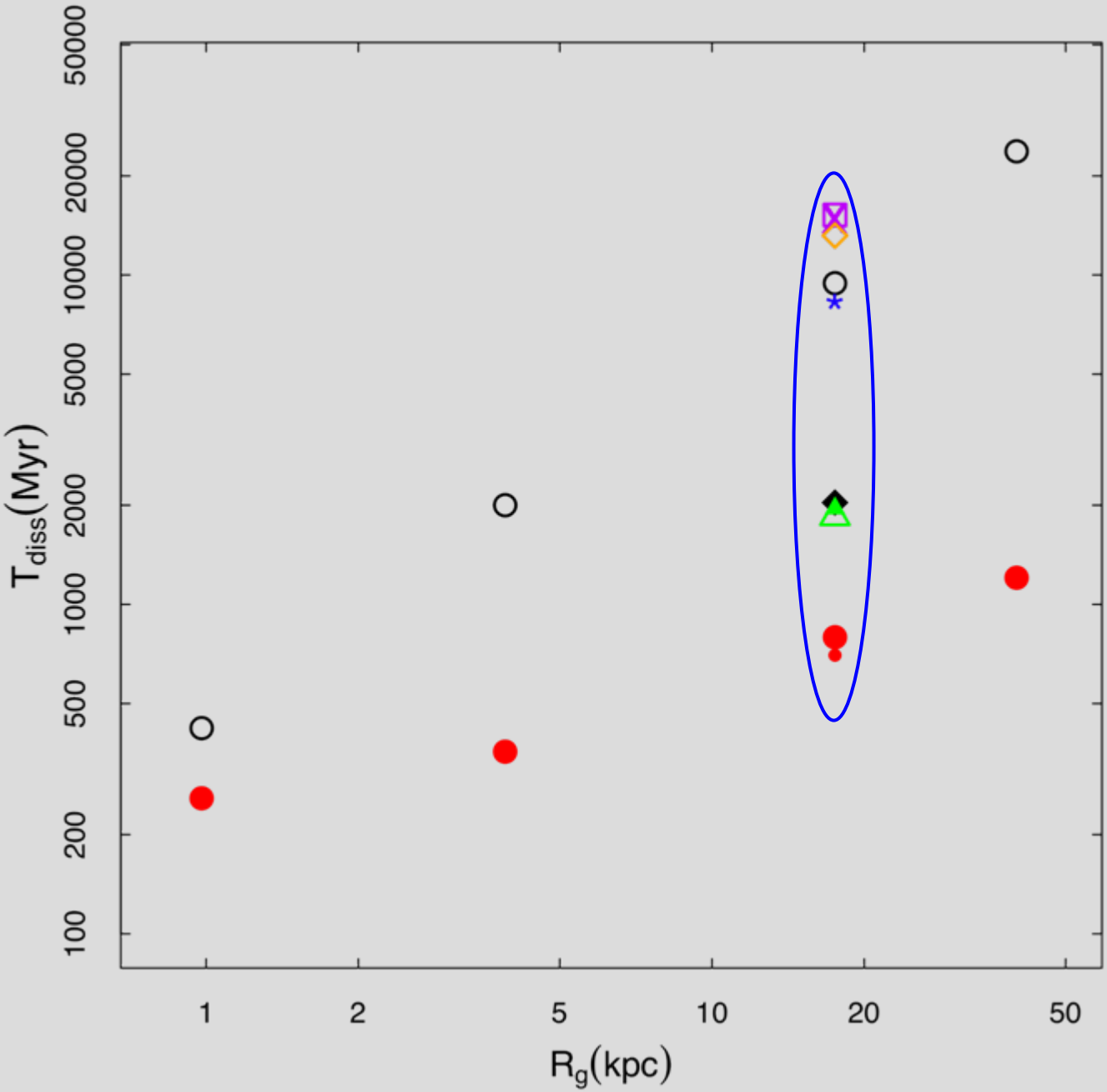
T_{diss} ~ R_g

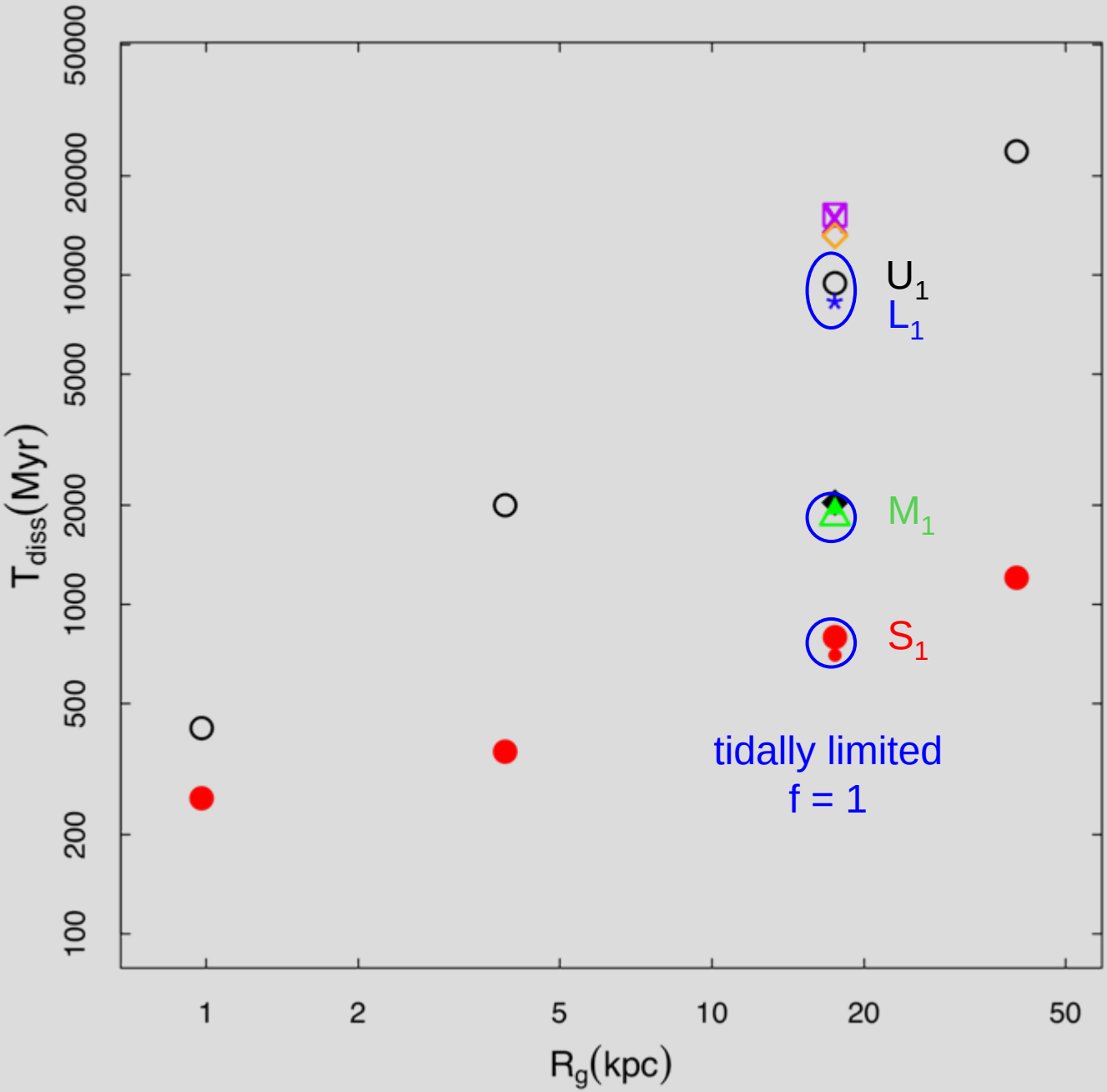
~ $(N/\log N)^{0.8}$

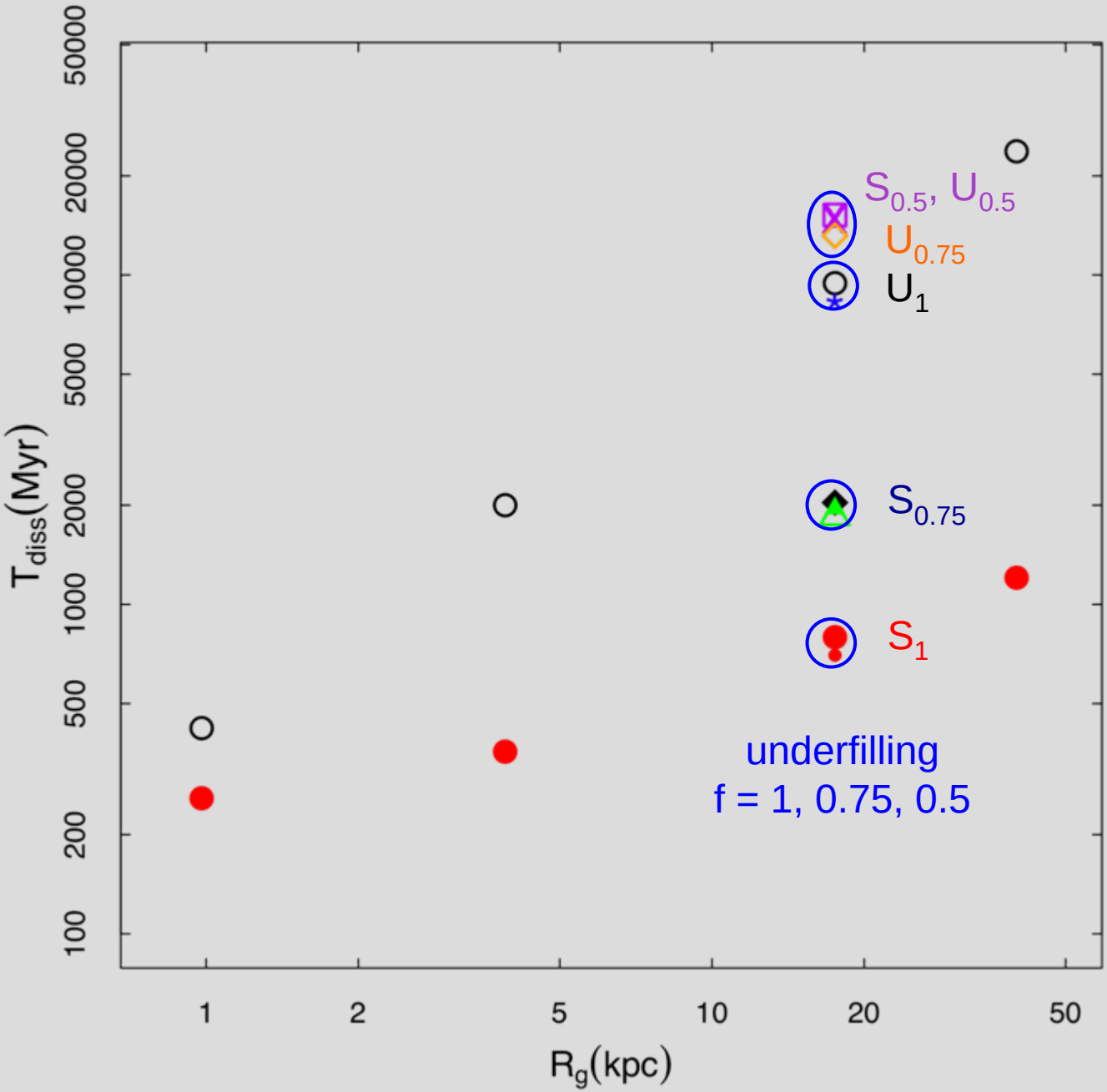
segregated

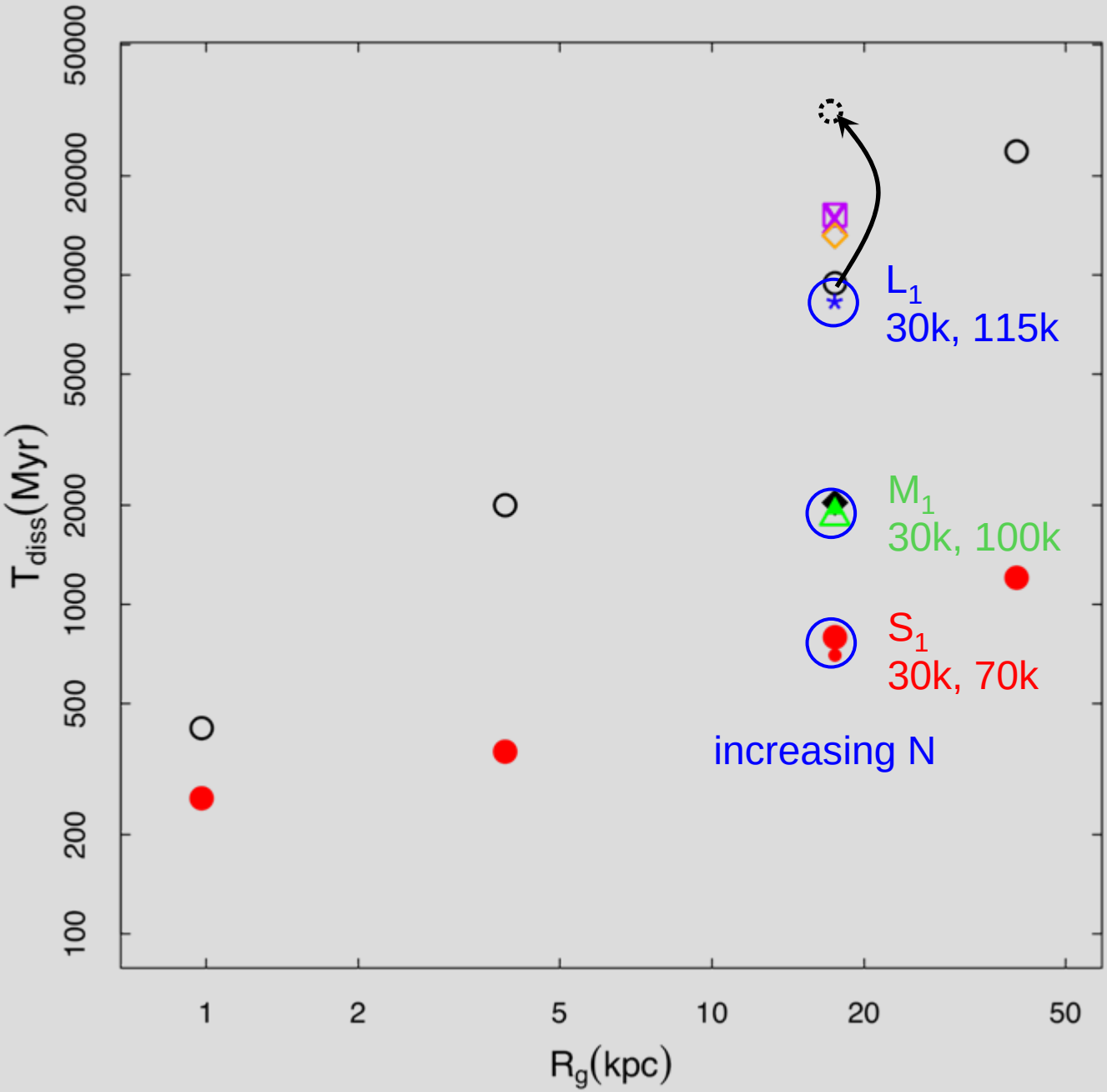
T_{diss} ~ $R_g^{0.52}$

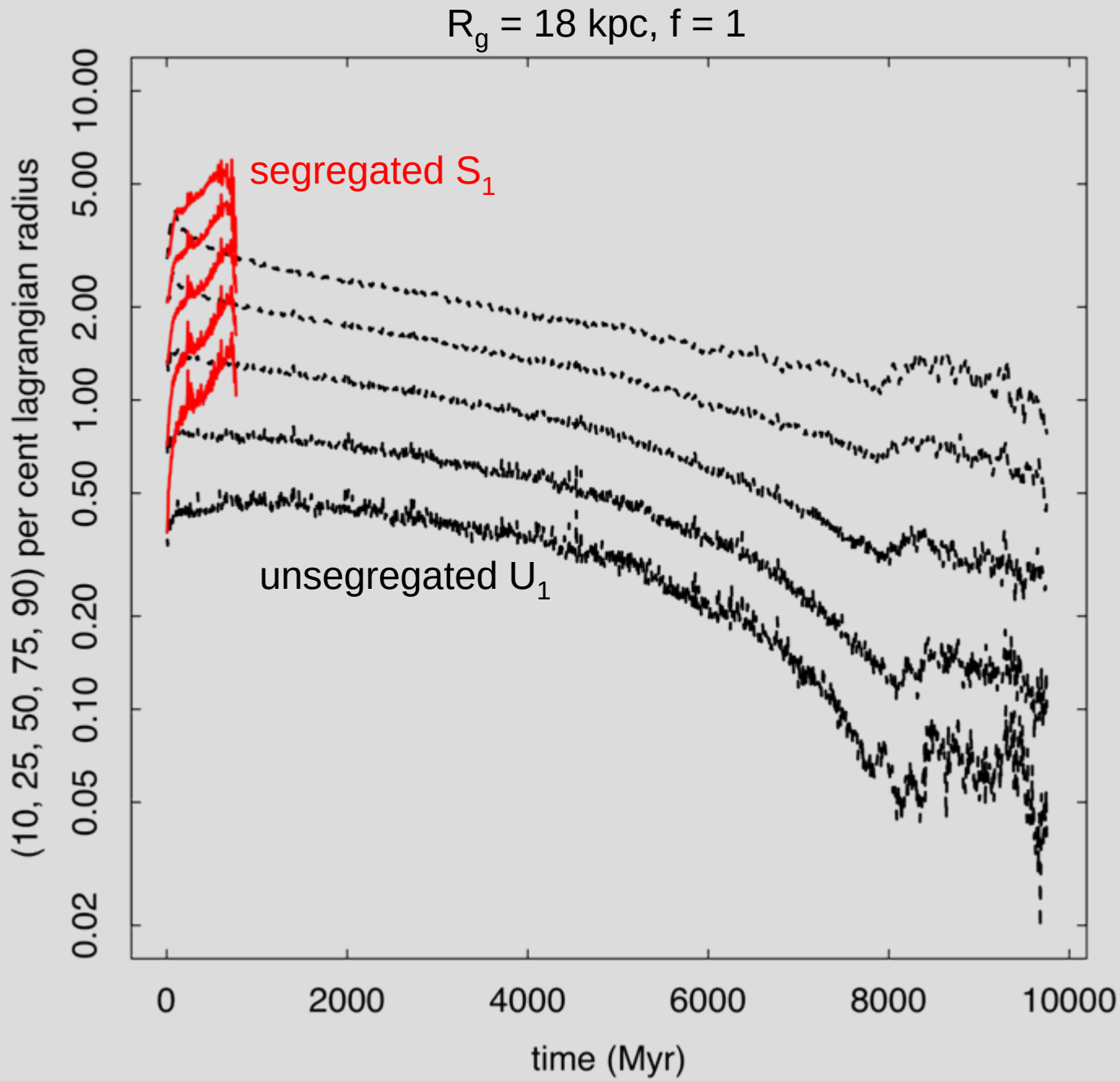
independent of N

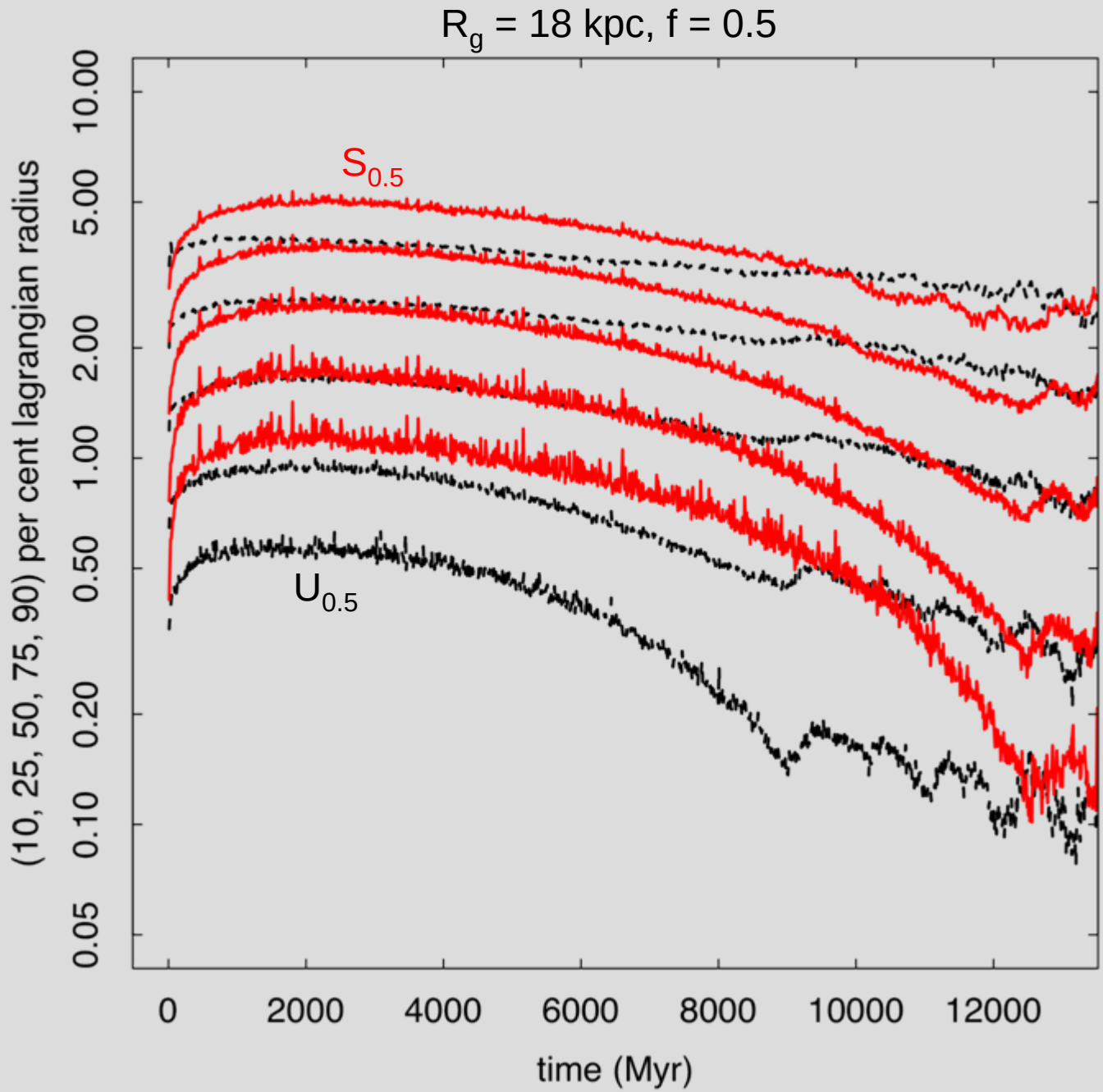

T_{diss}(Myr)
50000
20000
10000
5000
2000
1000
500
200
100
1
2
5
10
20
50
R_g(kpc)

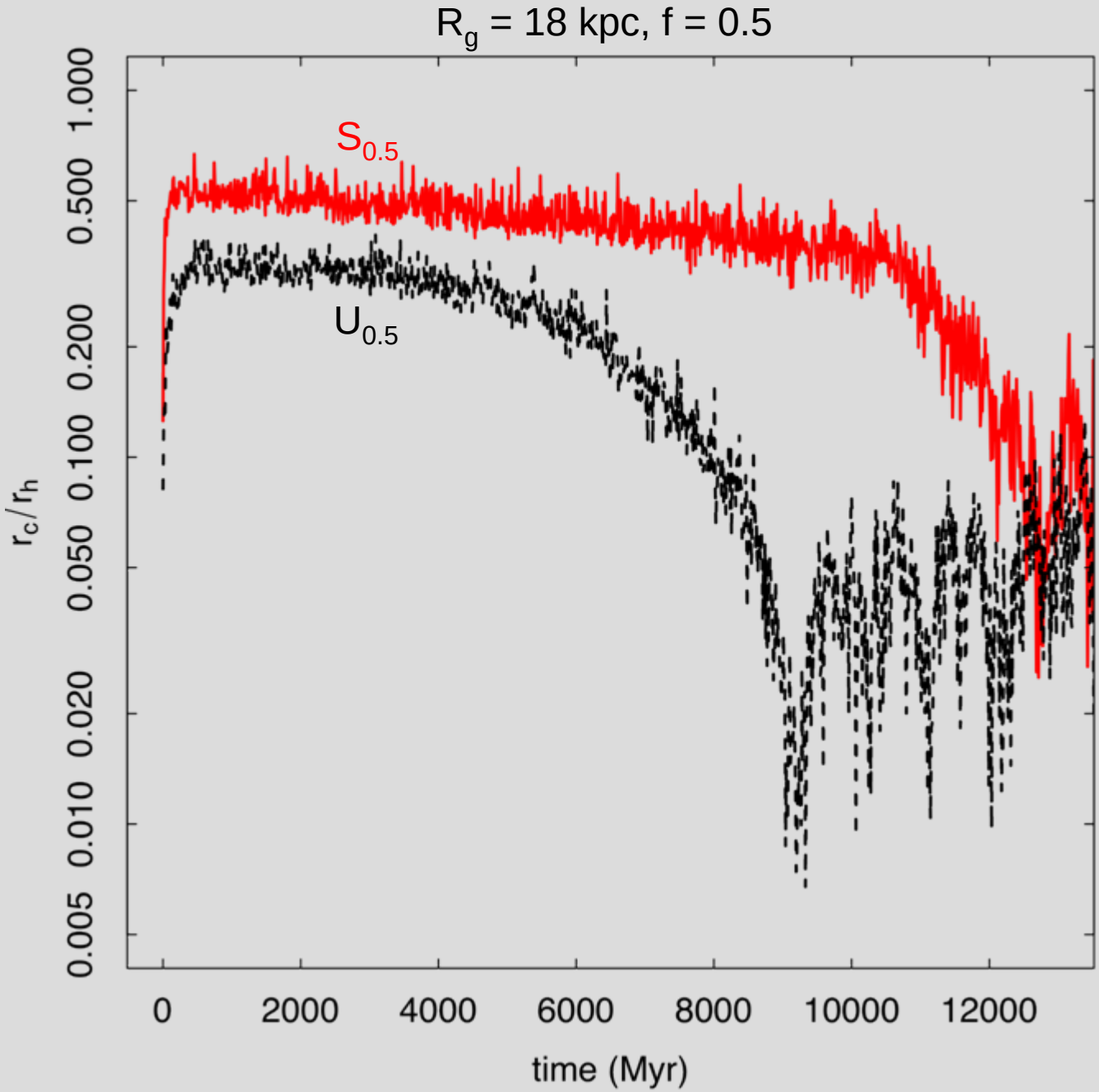

T_{diss}(Myr)
50000
20000
10000
5000
2000
1000
500
200
100
1
2
5
10
20
50
R_g(kpc)
U_1
L_1
M_1
S_1
tidally limited
f = 1


T_{diss}(Myr)
50000
20000
10000
5000
2000
1000
500
200
100
1
2
5
10
20
50
R_g(kpc)
$S_{0.5}$, $U_{0.5}$
$U_{0.75}$
U_1
$S_{0.75}$
S_1
underfilling
f = 1, 0.75, 0.5


T_{diss}(Myr)
100
200
500
1000
2000
5000
10000
20000
50000
1
2
5
10
20
50
R_g(kpc)
L_1
30k, 115k
M_1
30k, 100k
S_1
30k, 70k
increasing N

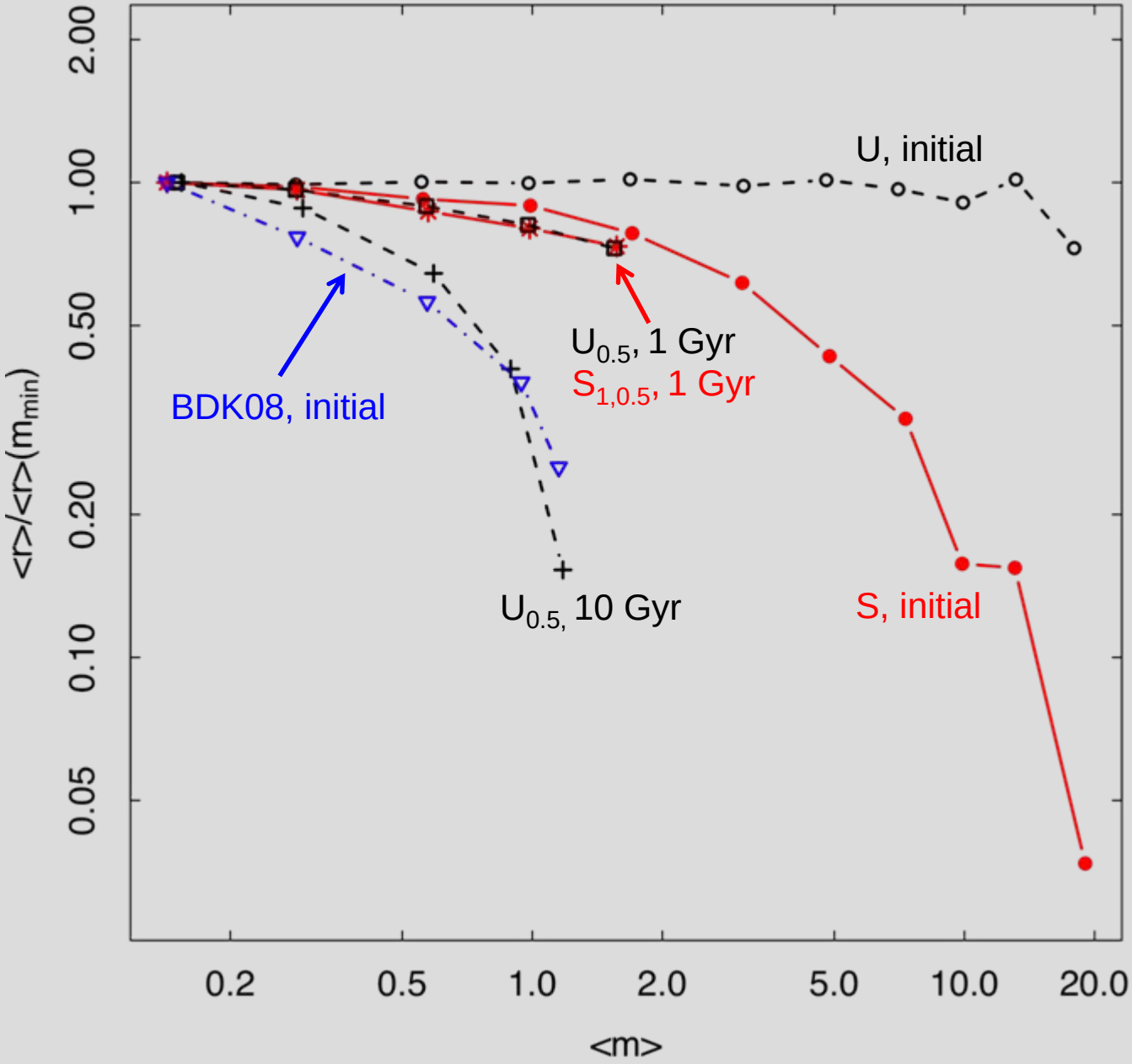

R_g = 18 kpc, f = 1
segregated S_1
unsegregated U_1
(10, 25, 50, 75, 90) per cent lagrangian radius
0.02
0.05
0.10
0.20
0.50
1.00
2.00
5.00
10.00
0
2000
4000
6000
8000
10000
time (Myr)

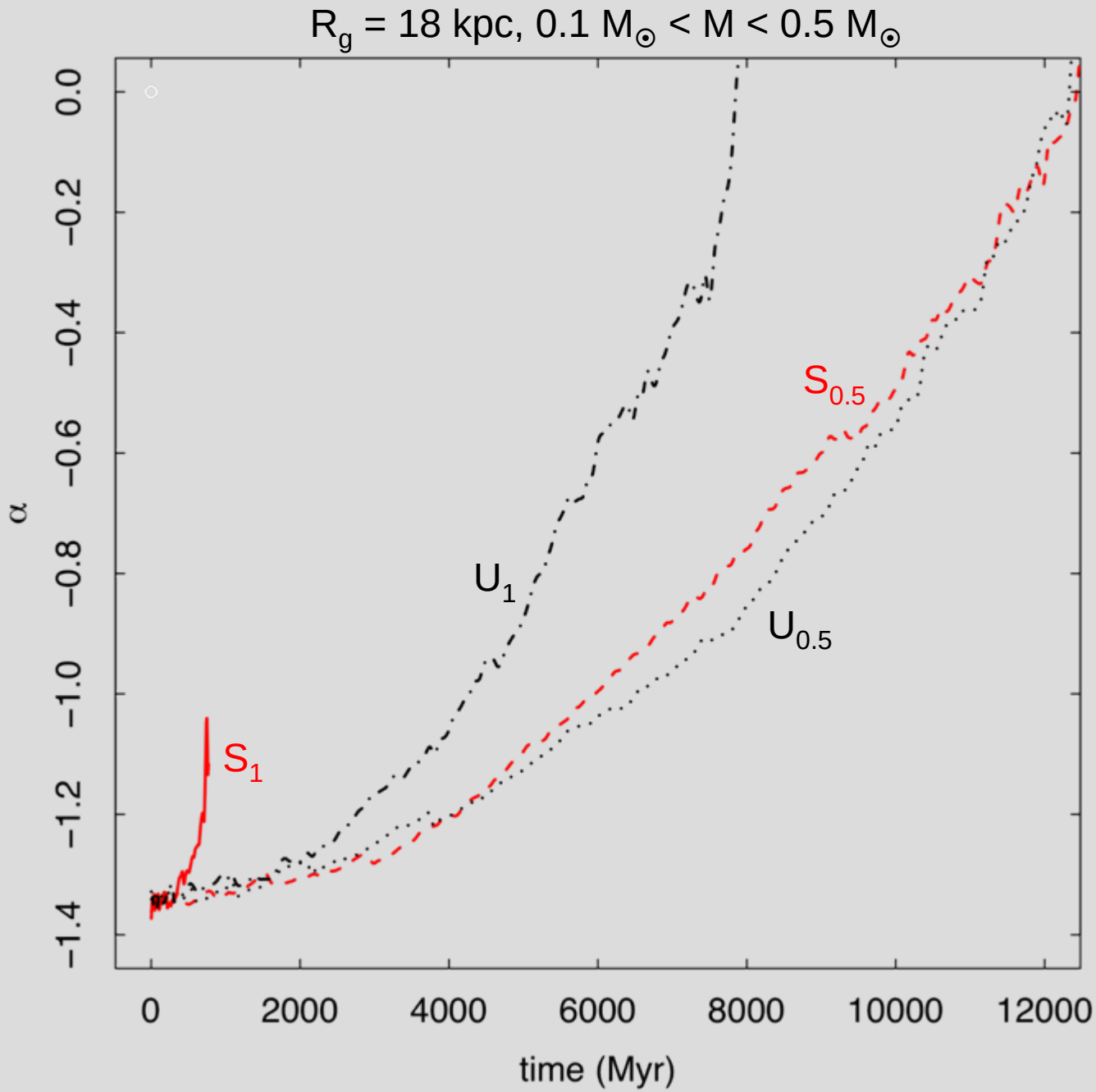

R_g = 18 kpc, f = 0.5
$S_{0.5}$
$U_{0.5}$
(10, 25, 50, 75, 90) per cent lagrangian radius
0.05
0.10
0.20
0.50
1.00
2.00
5.00
10.00
0
2000
4000
6000
8000
10000
12000
time (Myr)

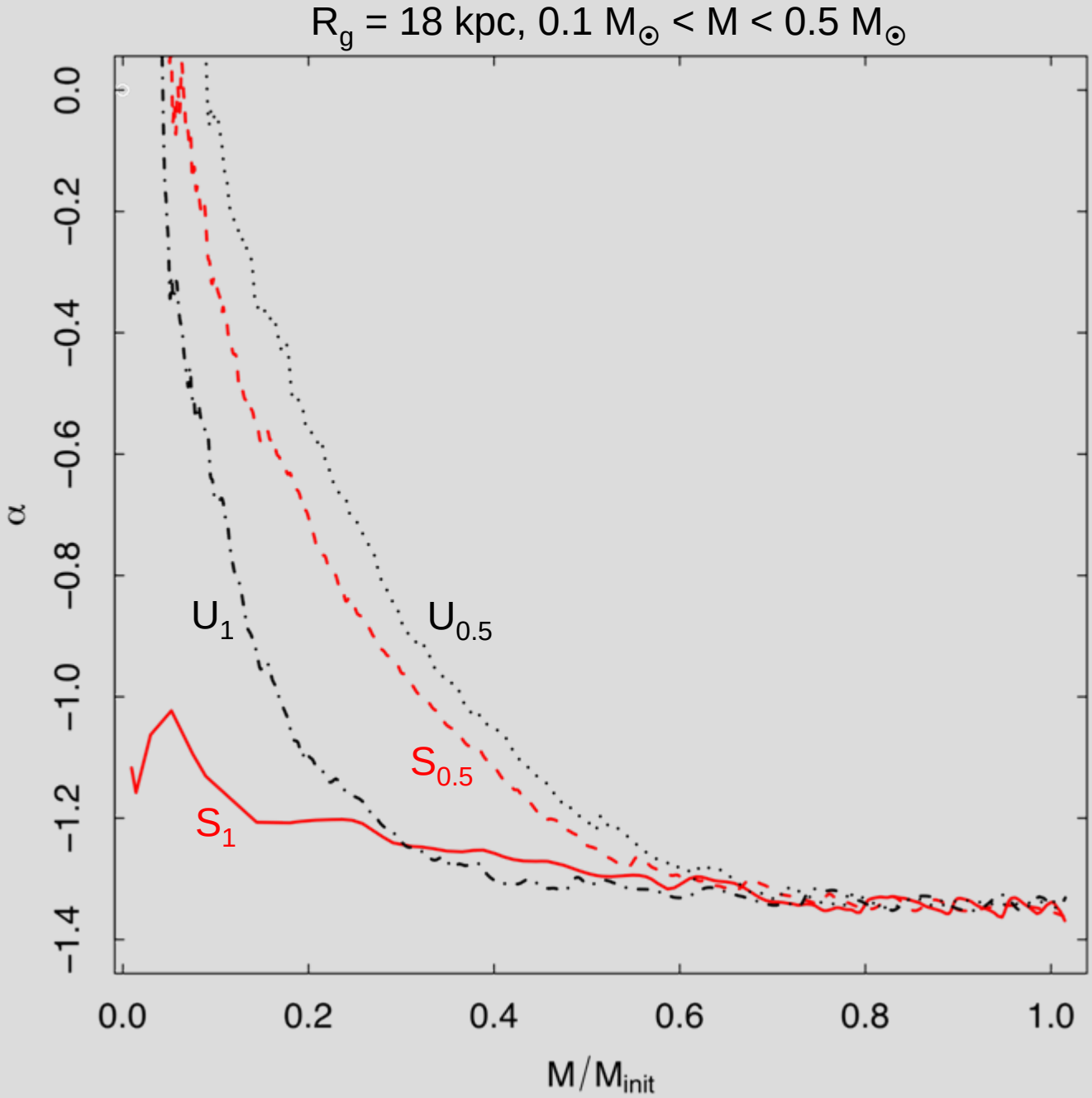

R_g = 18 kpc, f = 0.5
$S_{0.5}$
$U_{0.5}$
r_c/r_h
0.005
0.010
0.020
0.050
0.100
0.200
0.500
1.000
0
2000
4000
6000
8000
10000
12000
time (Myr)

Cluster Mass Function

- mass loss versus mass segregation
  - flattening of the mass function
- evolution of the mass function slope


2.00
1.00
0.50
0.20
0.10
0.05
<r>/<r>(m_min)
0.2
0.5
1.0
2.0
5.0
10.0
20.0
<m>
U, initial
BDK08, initial
U0.5, 1 Gyr
S1,0.5, 1 Gyr
U0.5, 10 Gyr
S, initial


R_g = 18 kpc, 0.1 $M_\odot$ < M < 0.5 $M_\odot$
α
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
0
2000
4000
6000
8000
10000
12000
time (Myr)
U_1
$U_{0.5}$
S_1
$S_{0.5}$


R_g = 18 kpc, 0.1 $M_\odot$ < M < 0.5 $M_\odot$
α
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
0.0
0.2
0.4
0.6
0.8
1.0
M/M$_{init}$
U_1
$U_{0.5}$
$S_{0.5}$
S_1

Conclusions

- initial mass segregation can significantly affect the dynamical evolution of a cluster
  - early expansion triggered by impulsive mass loss
  - underfilling competes with segregation to preserve the cluster
  - delayed dynamical evolution in the survivors
- less mass function flattening for given mass loss in segregated clusters
- no unambiguous indicator of initial segregation (yet)