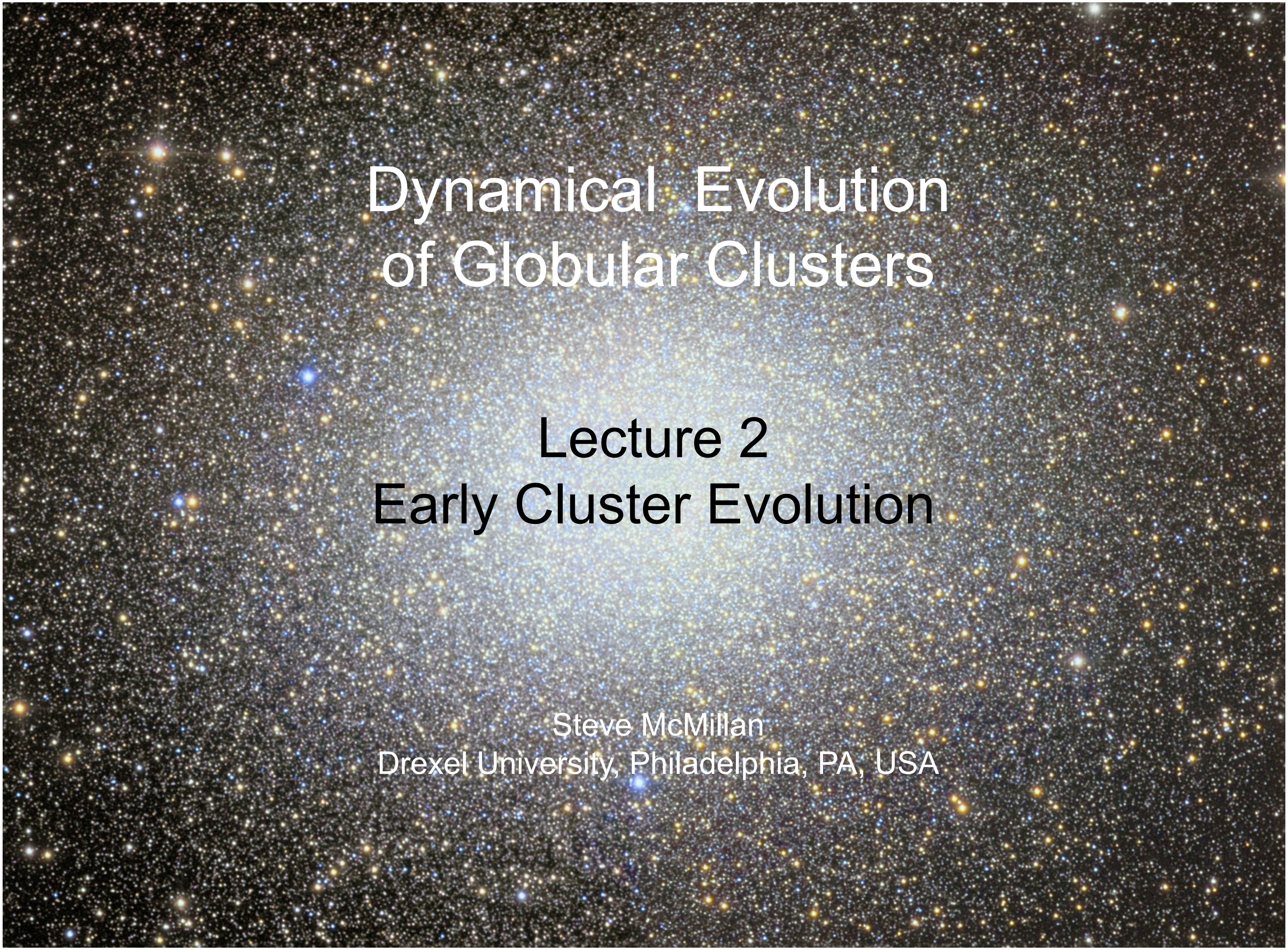


Dynamical Evolution of Globular Clusters

Lecture 2
Early Cluster Evolution

Steve McMillan
Drexel University, Philadelphia, PA, USA

Outline

- virialization
- stellar masses
- mass segregation
- early mass loss
  - gas
  - stars
- multiple stellar populations

Virialization

- example
  - initially cold system

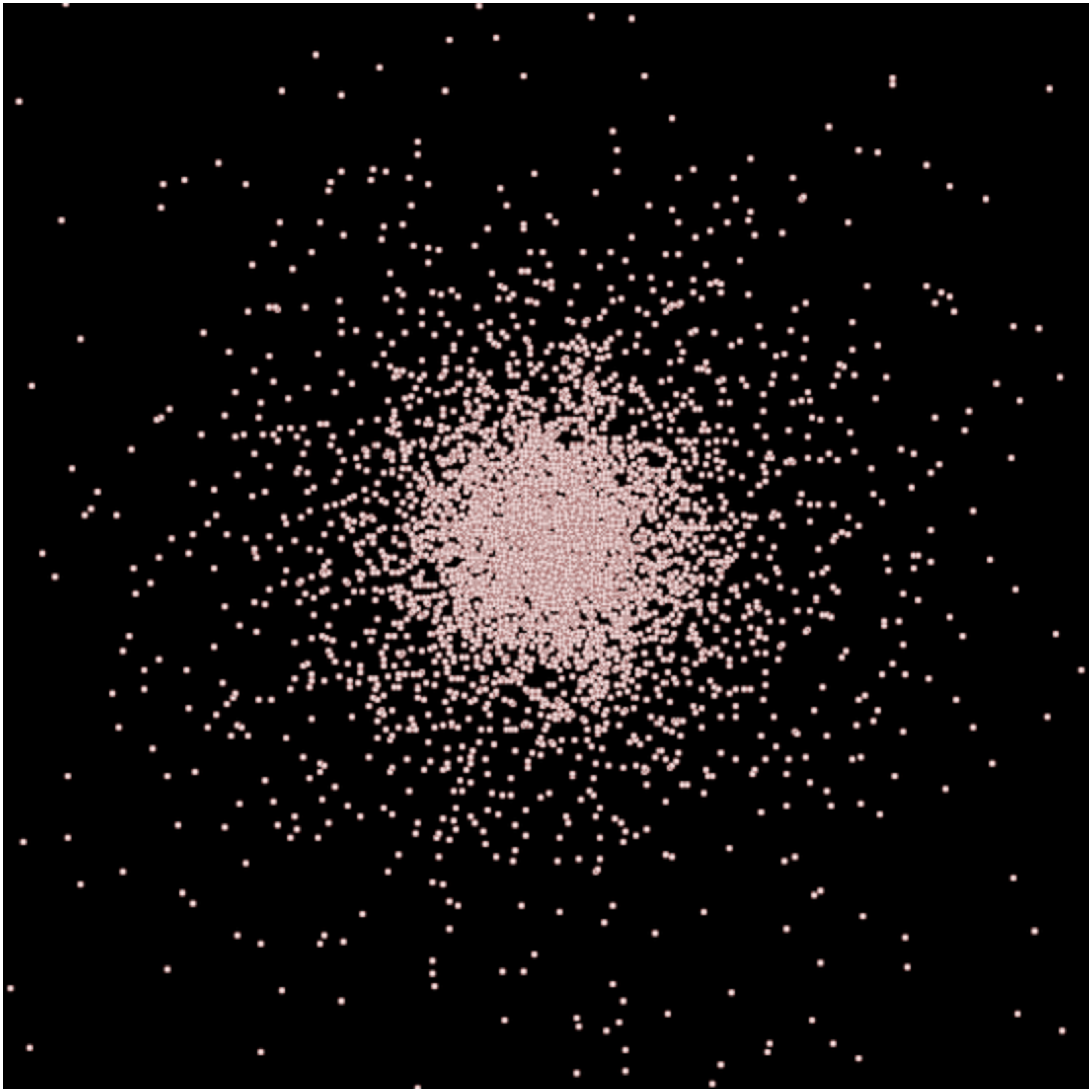
$$\mathcal{T} = 0,\ \mathcal{U} = -GM/2R_0,\ \ E = -GM/2R_0$$

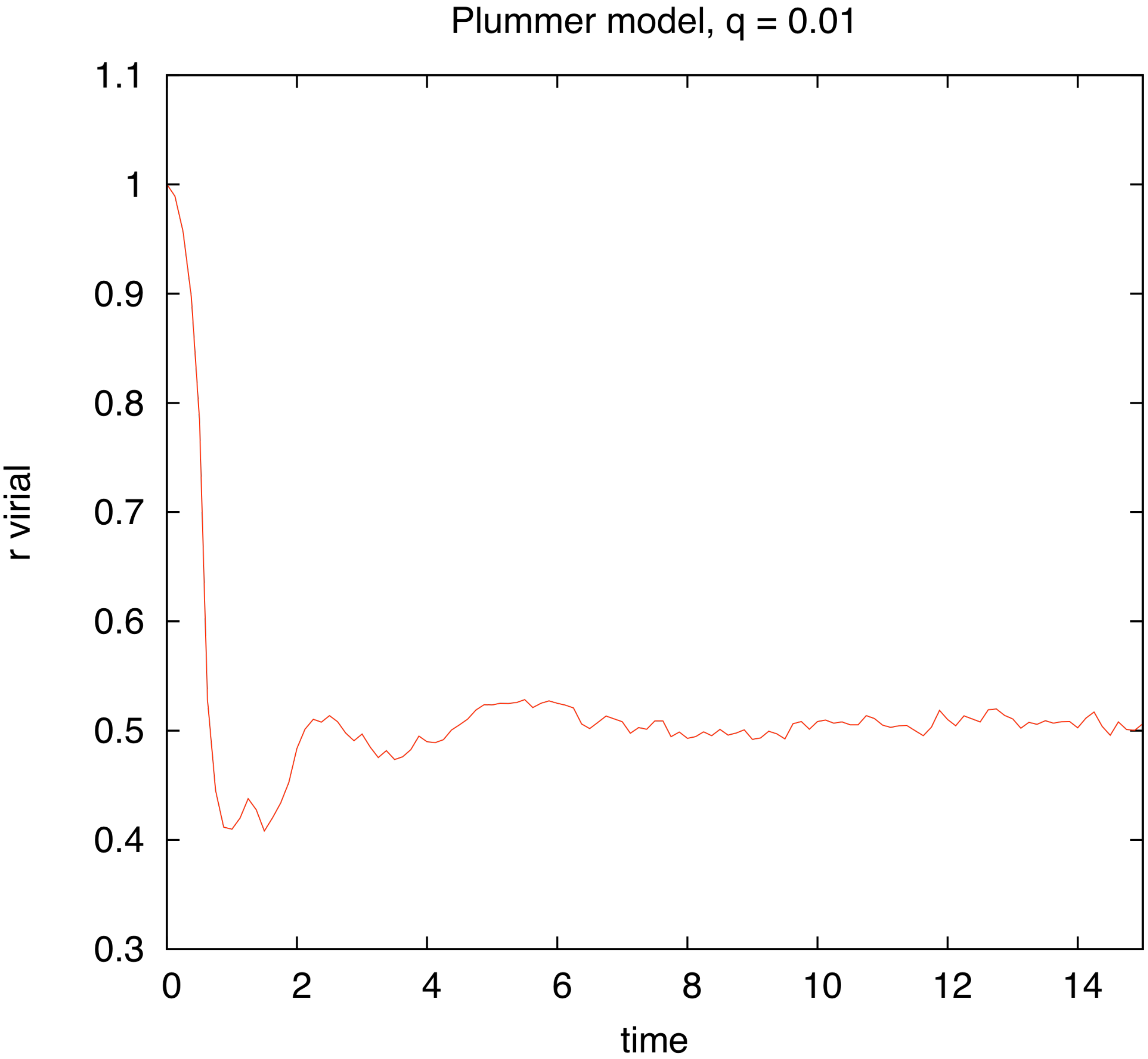
  - in virial equilibrium

$$\mathcal{T} = -\tfrac{1}{2}\mathcal{U} = GM/4R_1 = -E = GM/2R_0$$

so

$$R_1 = \tfrac{1}{2}R_0$$




Plummer model, q = 0.01
r virial
time
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
2
4
6
8
10
12
14

Virialization

- violent relaxation

$$E = \tfrac{1}{2}v^2 + \Phi(\mathbf{x})$$

$$\frac{dE}{dt} = \frac{1}{2}\frac{dv^2}{dt} + \frac{d\phi}{dt} = \mathbf{v}\cdot\frac{d\mathbf{v}}{dt} + \frac{\partial\Phi}{\partial t} + \mathbf{v}\cdot\nabla\Phi = \frac{\partial\Phi}{dt}$$

- time scale to establish virial equilibrium ~ 5–10 t_{dyn}
- should be <u>independent</u> of mass
- resulting distribution function?

Stellar Mass Function

- mass function $\phi(m) \equiv dN/dm$
- Salpeter (1955)

$$\phi(m) \;=\; A\,m^{-2.35}, \quad m > m_{min}$$

- Kroupa (2001)

$$\phi(m) \;=\; \begin{cases} C\,m^{-0.3} & (m < 0.1 M_\odot) \\ B\,m^{-1.3} & (0.1 M_\odot < m < 0.5 M_\odot) \\ A\,m^{-2.35} & (m > 0.5 M_\odot) \end{cases}$$

- same total number, mass, luminosity for

$$m_{min} \;\sim\; 0.1,\; 0.2,\; 0.3\,M_\odot$$

Mass Segregation

- equipartition

$$m\langle v^2\rangle \;\sim\; \mathrm{constant}$$

- massive stars move more slowly, sink to the center
- time scale

$$t_{seg} \;\sim\; \frac{\langle m\rangle}{m}\, t_{rh}$$

- for Kroupa mass function, time for formation of a massive core is

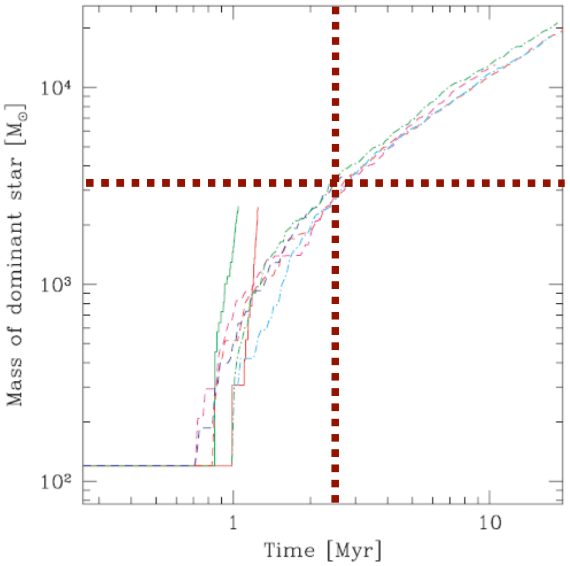
$$t_c \;\sim\; 0.2\, t_{rh}$$

(Portegies Zwart et al. 2002, Gurkan et al. 2004)

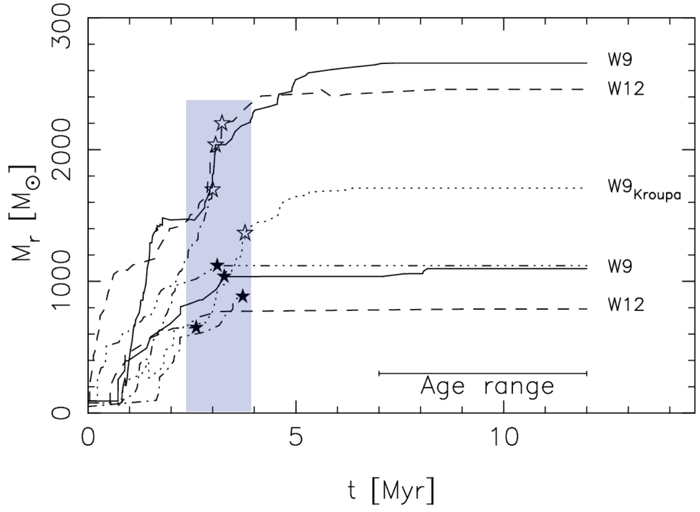
Runaway Stellar Mergers

- runaway mergers in clusters
  - dynamics → high densities
  - collisions → mergers
  - no mass loss
    → supermassive star?
  - evolution
    → IMBH??

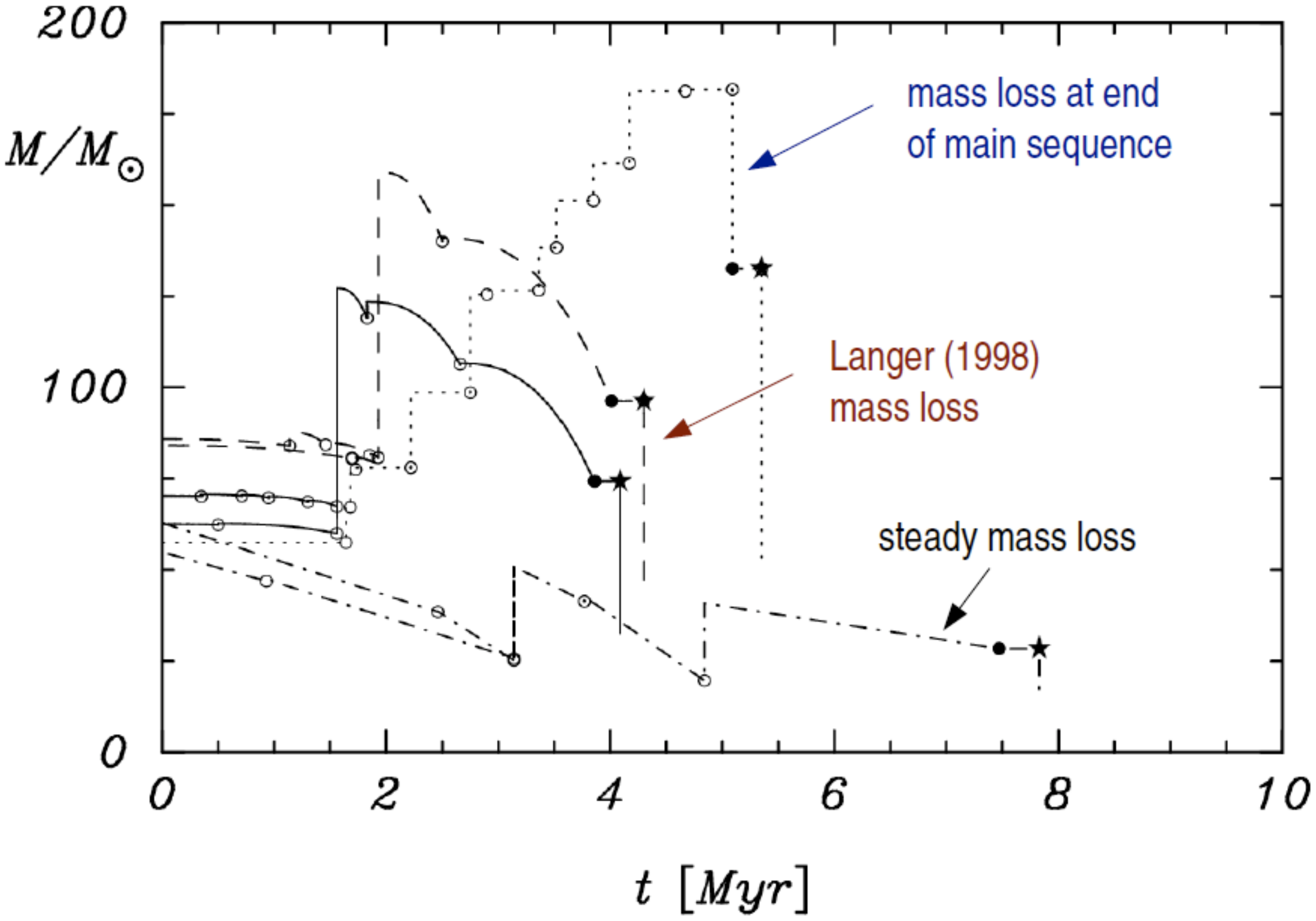
Freitag, Gürkan, & Rasio (2006)



Portegies Zwart et al. (2004)



Portegies Zwart et al (1999)



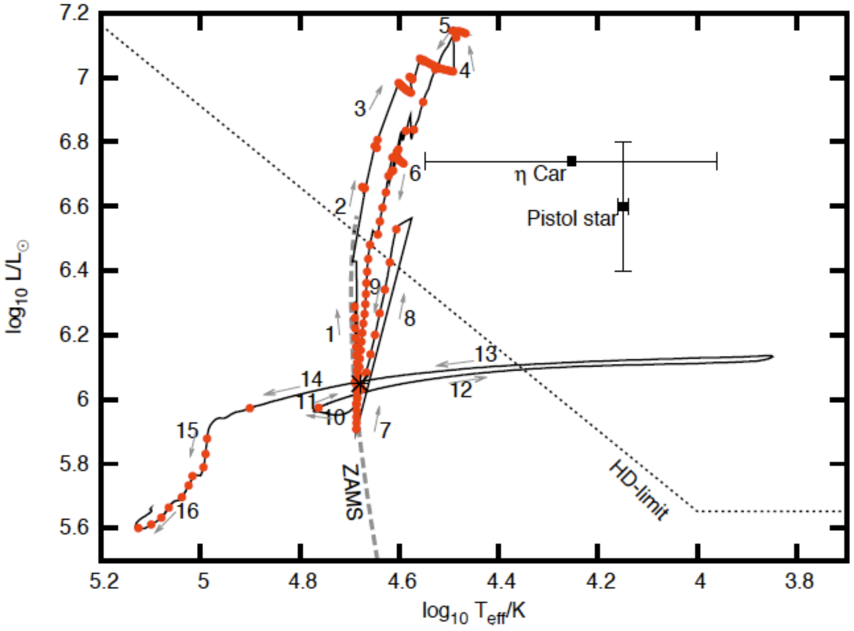
mass loss at end of main sequence

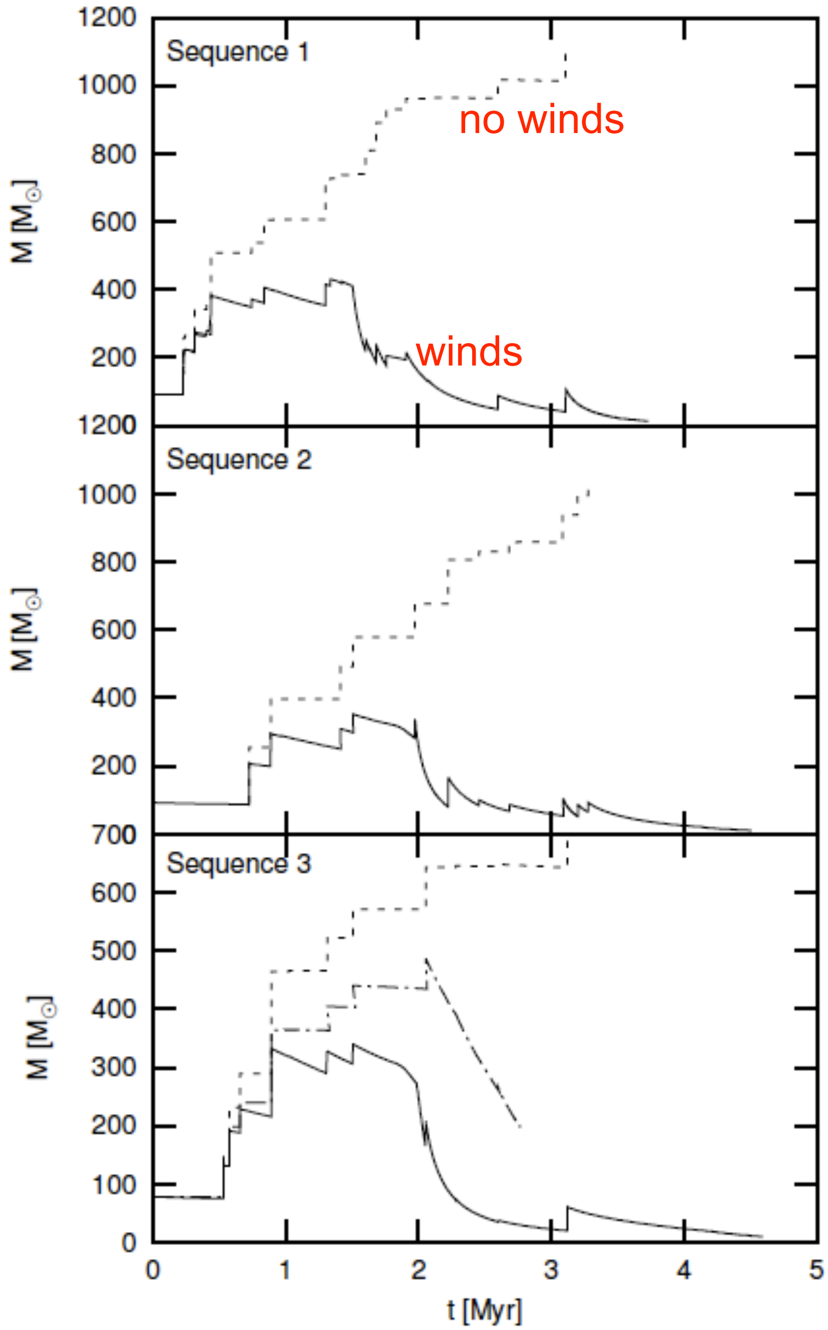
Langer (1998) mass loss

steady mass loss

Glebbeek et al. (2009)

Z = 0.001



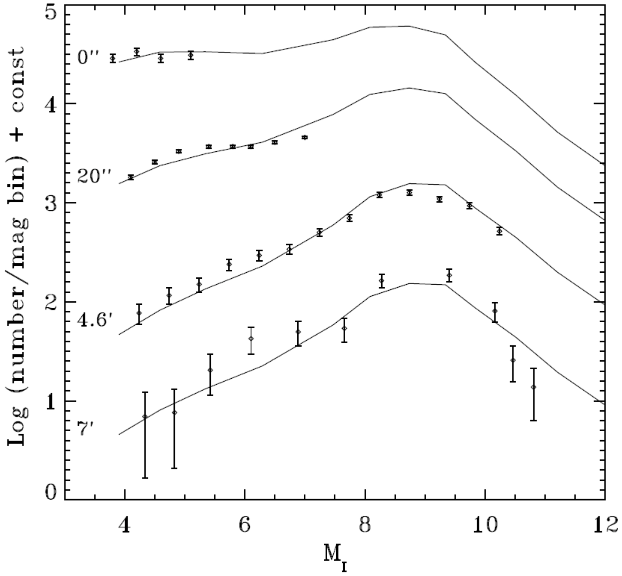


Mass Segregation

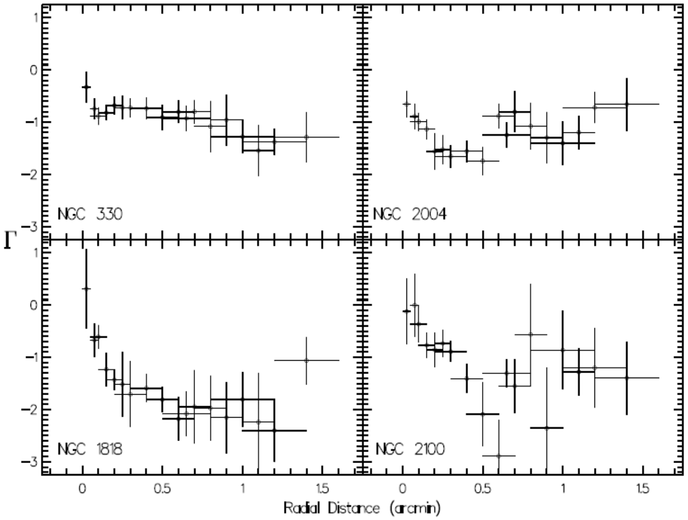
well known in old clusters (e.g. M15)…

…and in young ones

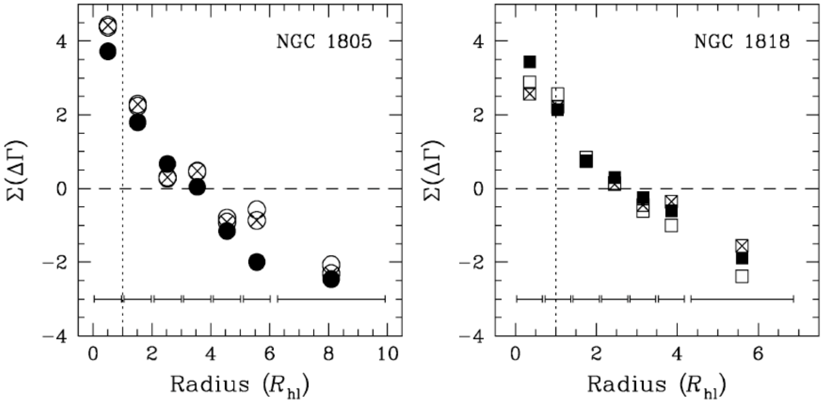
Pasquali et al. (2004)



Gouliermis et al. (2004)



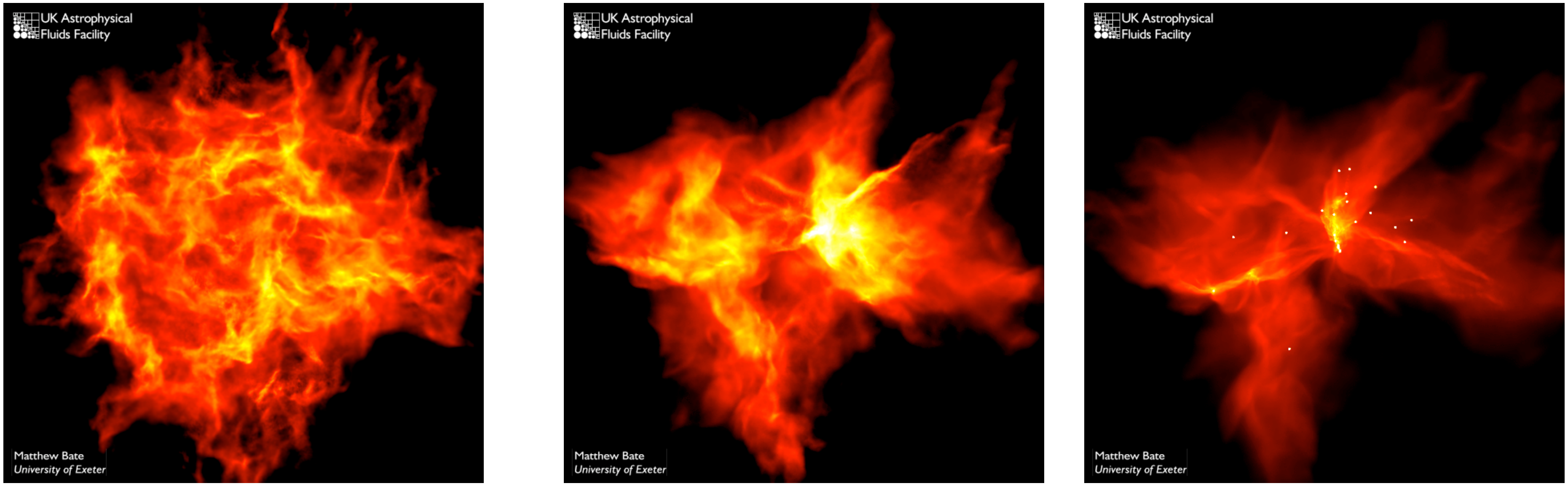
de Grijs et al. (2002)



…too young?

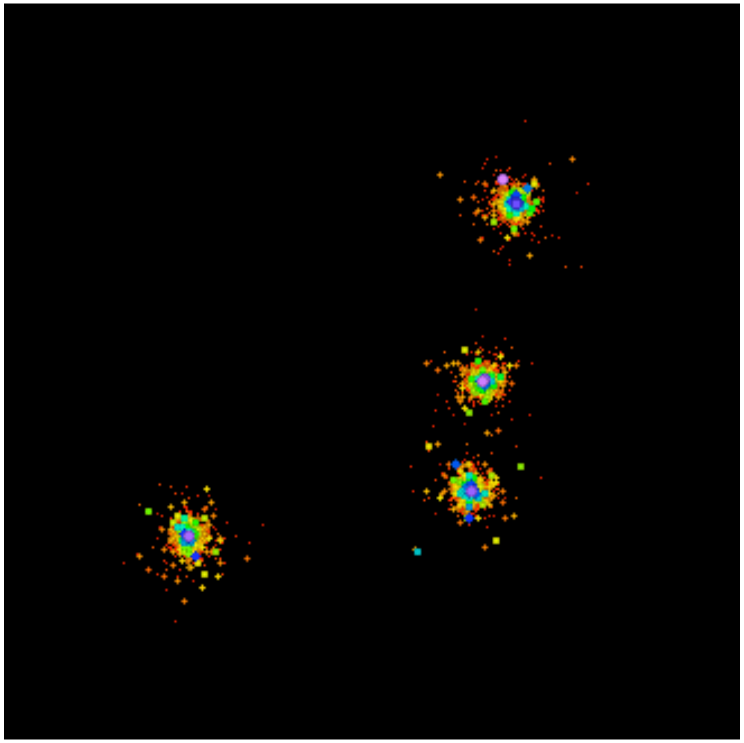
Star Formation

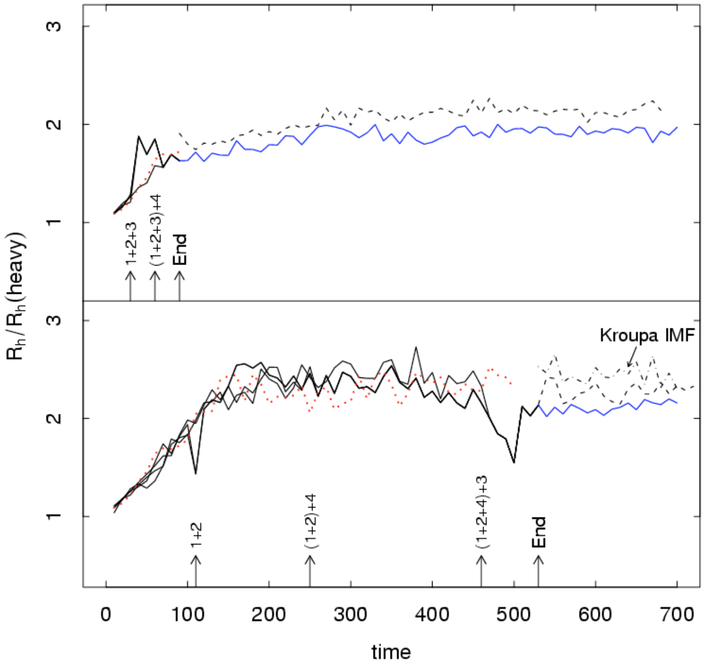
- stars form in clumpy environments
- massive stars form preferentially at the centers of the clumps



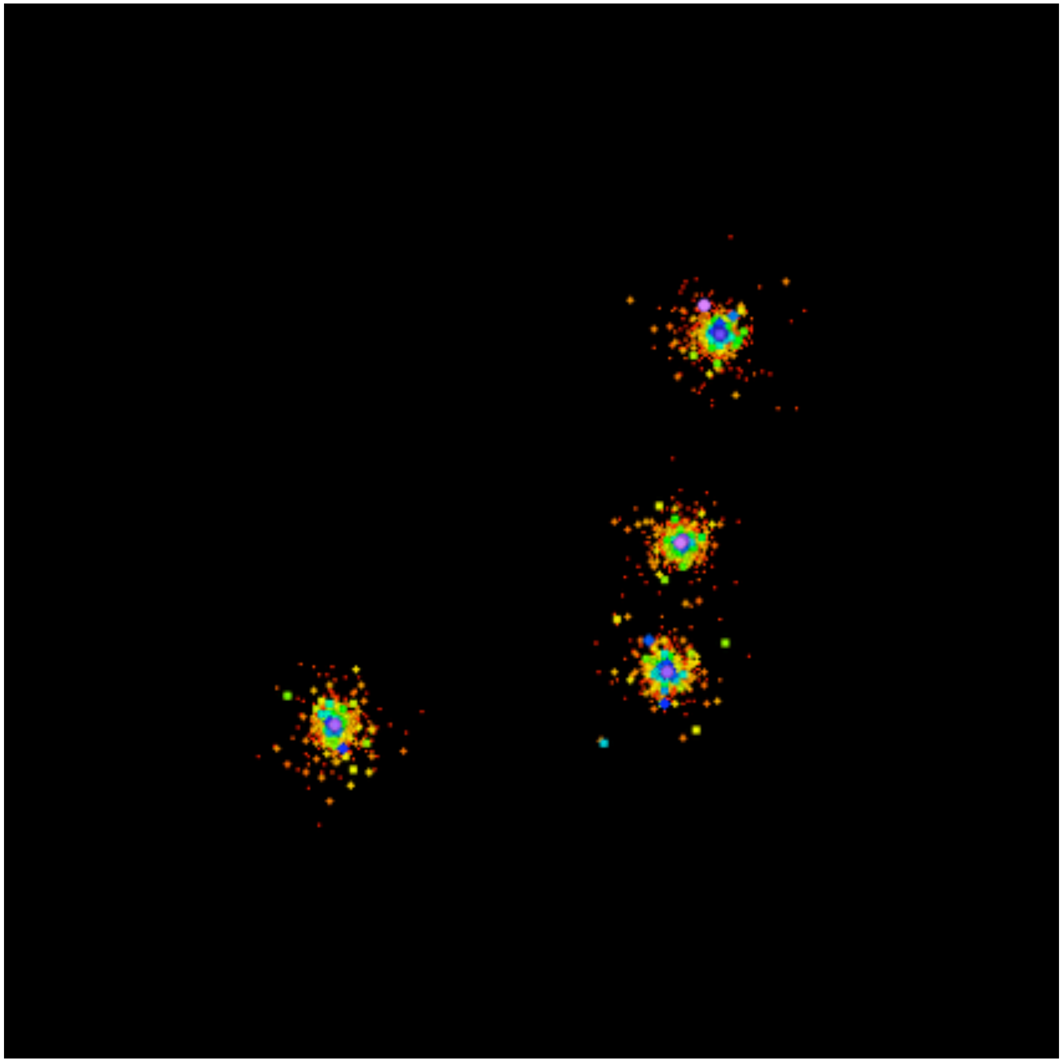
(Bonnell & Bate 2006)

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



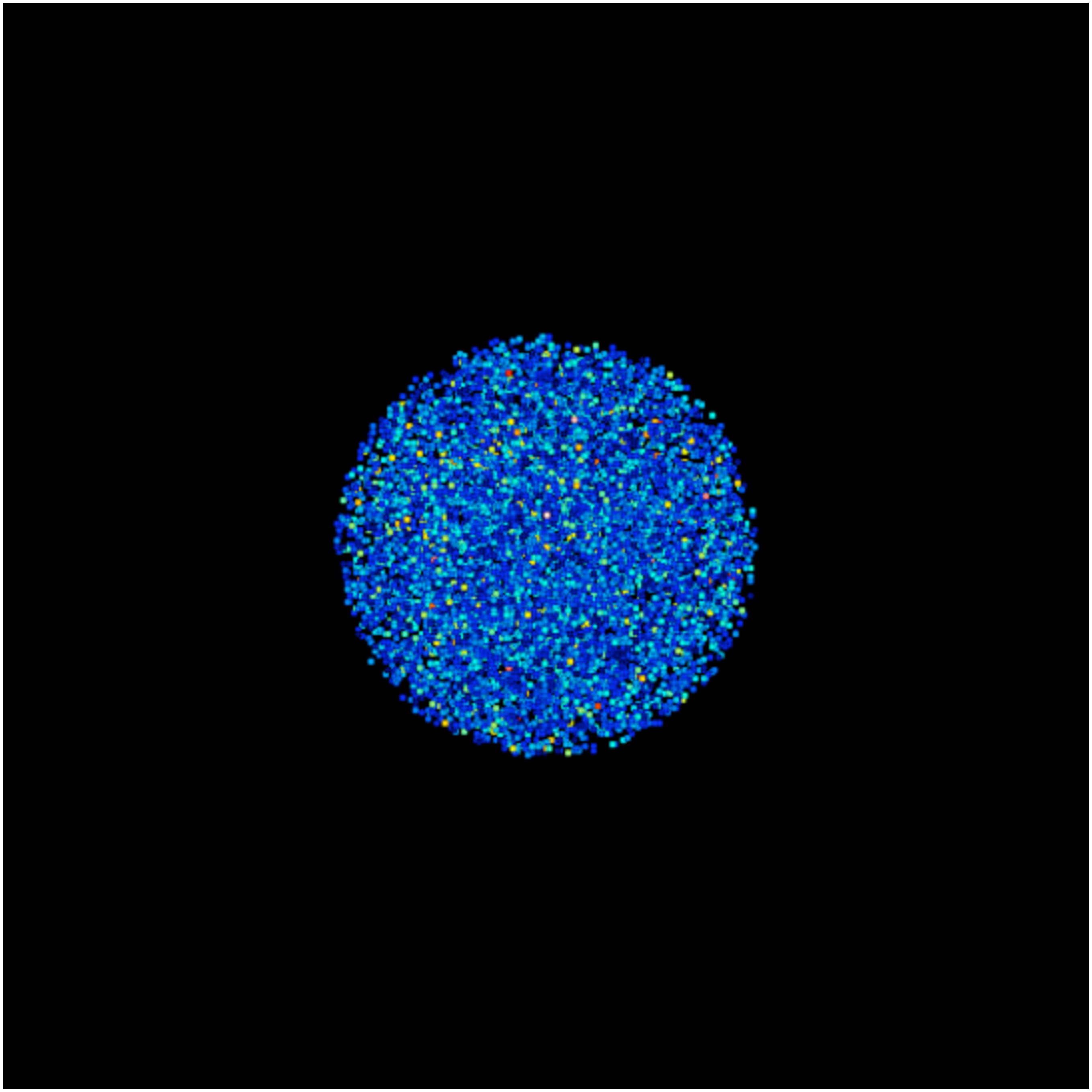


- did this continue to globular cluster scales?



Anomalous Relaxation

- cold collapse of a homogeneous multi-mass (Kroupa) system
- violent relaxation shouldn't distinguish among masses, but…



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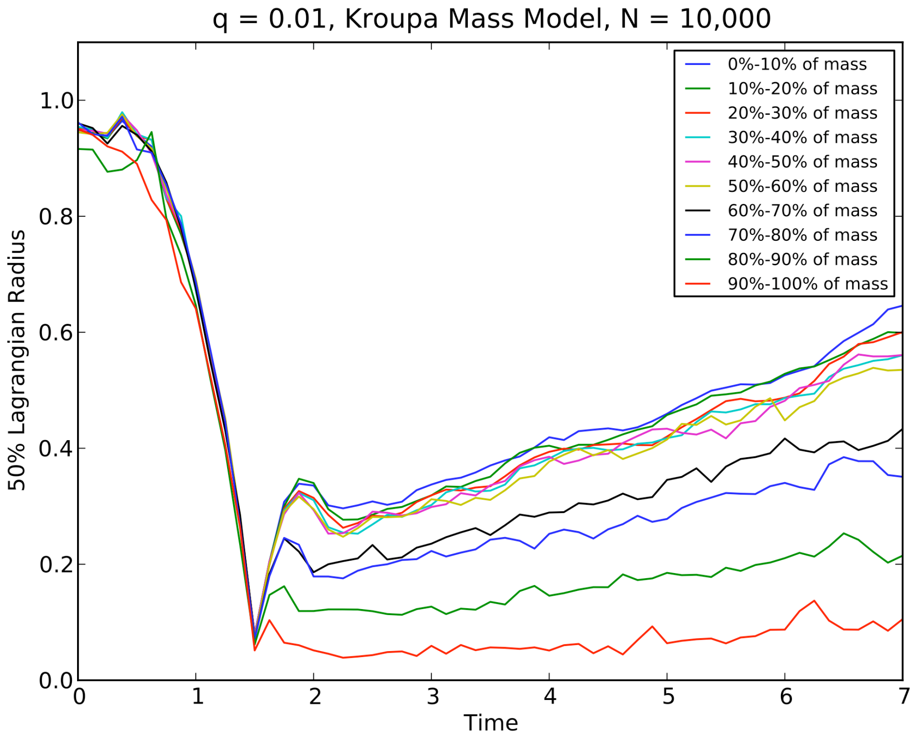


Removal of Intracluster Gas

Removal of Intracluster Gas

- star formation efficiency

$$\epsilon \;=\; \frac{M}{M + M_{gas}}$$

- instantaneous removal of cluster gas results in expansion by a factor

$$f \;=\; \frac{\epsilon}{2\epsilon - 1}$$

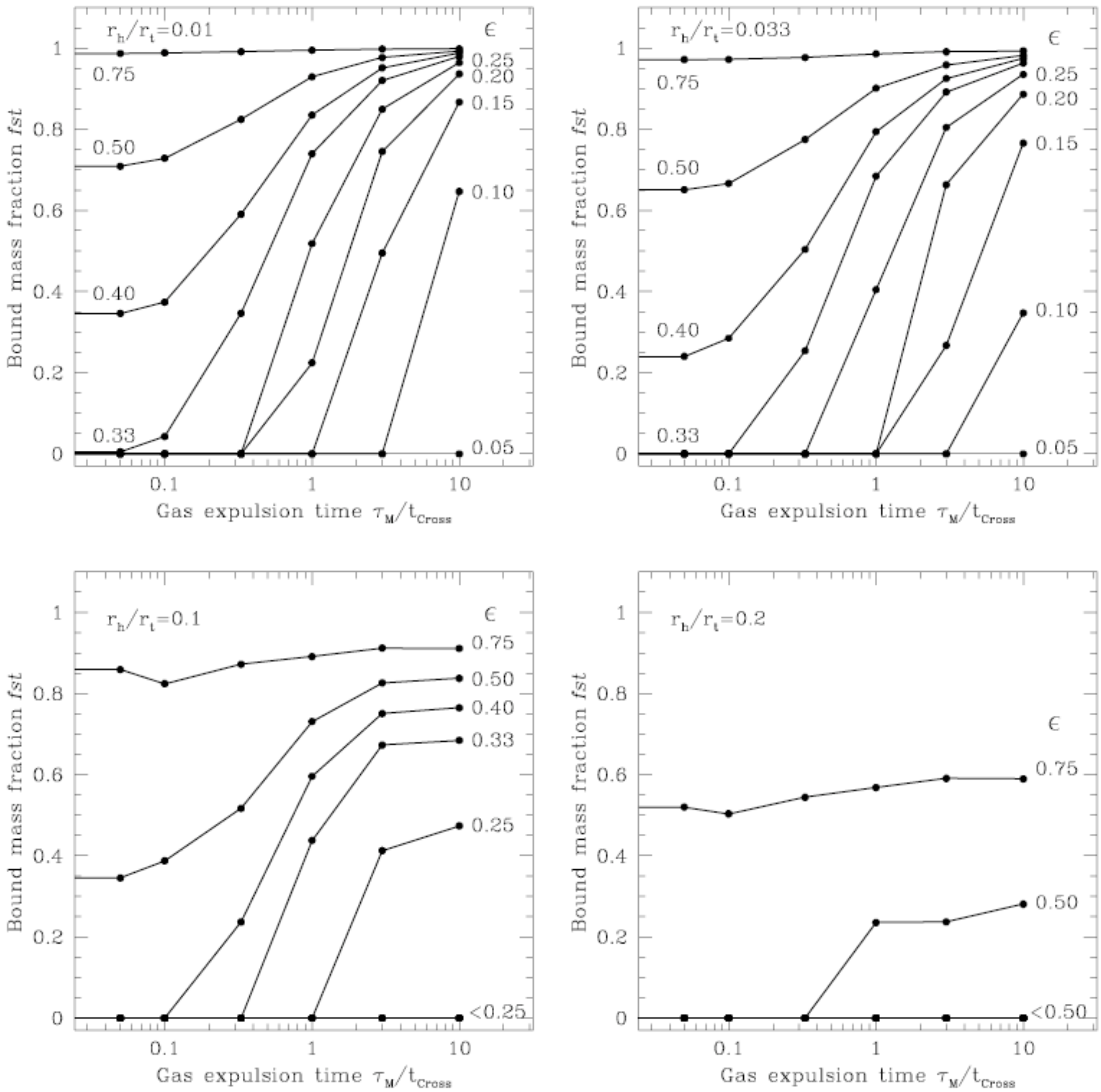
$\Rightarrow$ cluster dissolution for $f <$ 50%

- significant decline in numbers of clusters at age 3 Myr

Removal of Intracluster Gas

- gas ejection not instantaneous, depends on local dynamical time scale
- ϵ as low as 10–20% may be sustainable
- clumpiness and inhomogeneous energy production may both be important
- modeling gas removal
  - Baumgardt & Kroupa (2007): simple prescription
  - more detailed simulations in progress

Baumgardt & Kroupa 2007

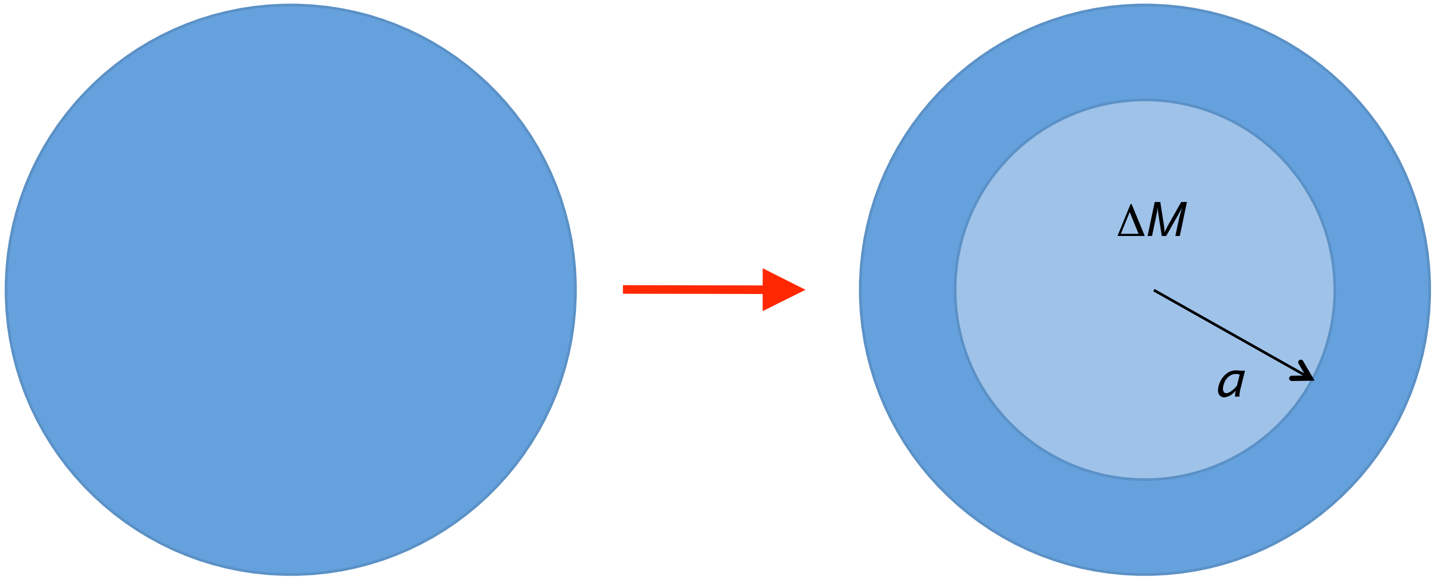


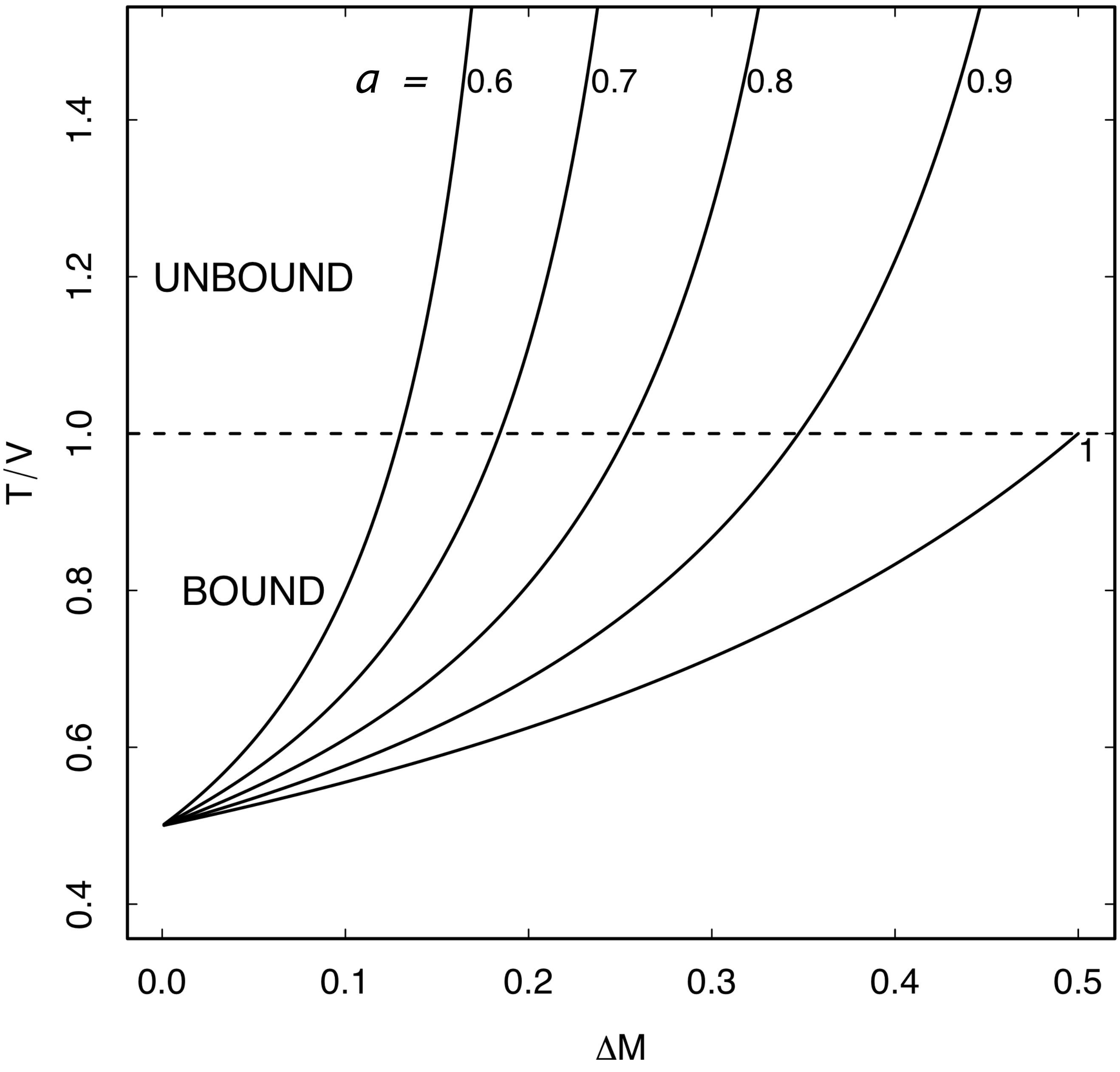
Stellar Mass Loss

- for a Kroupa mass function, cluster mass loss is
    - 10% after 10 Myr
    - 20% after 100 Myr
    - 30% after 500 Myr
- rapid mass loss from supernovae
- slow mass loss from stellar winds
- mass segregation <u>important</u>

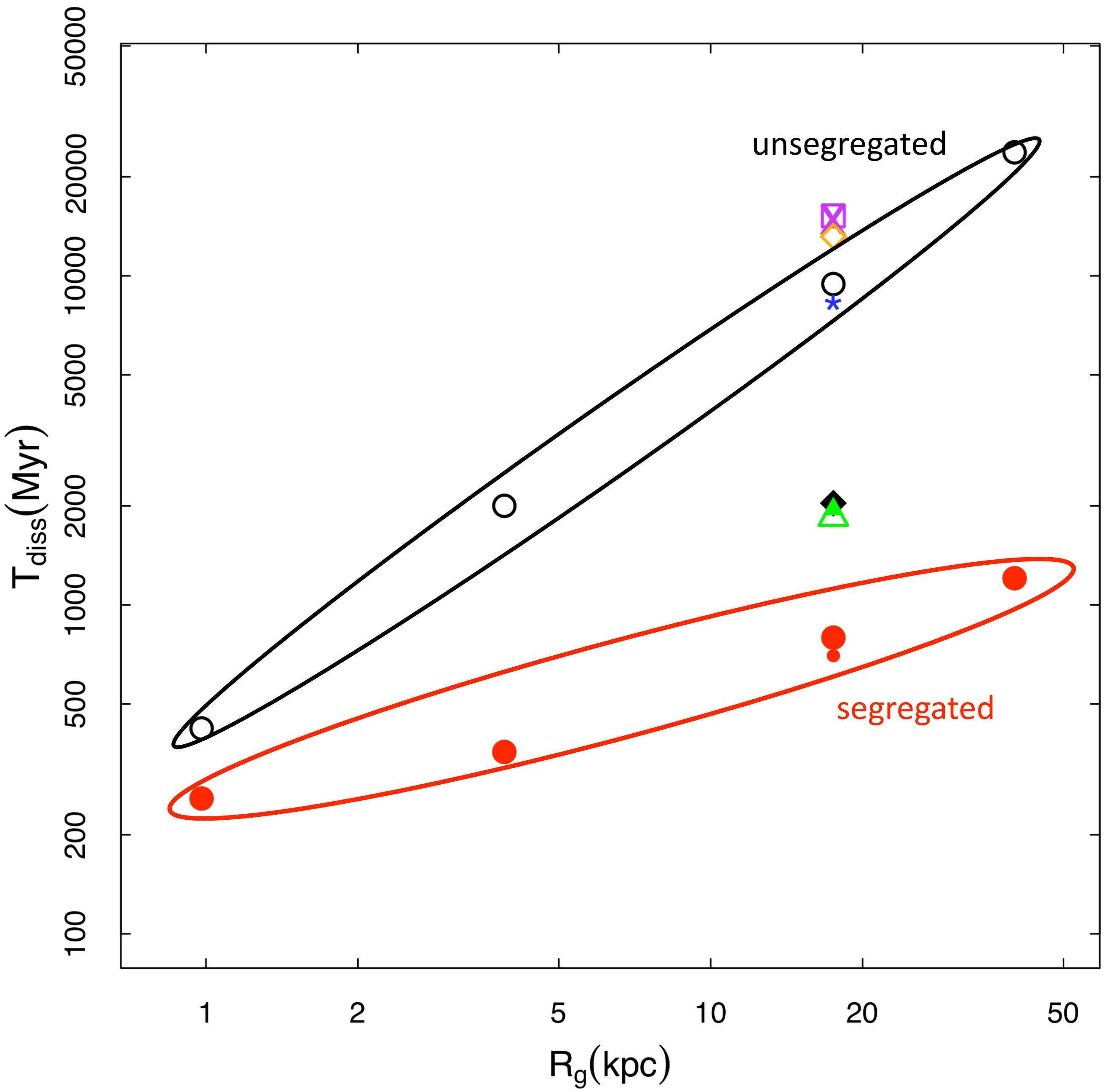
Simple Mass Loss Model

- 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





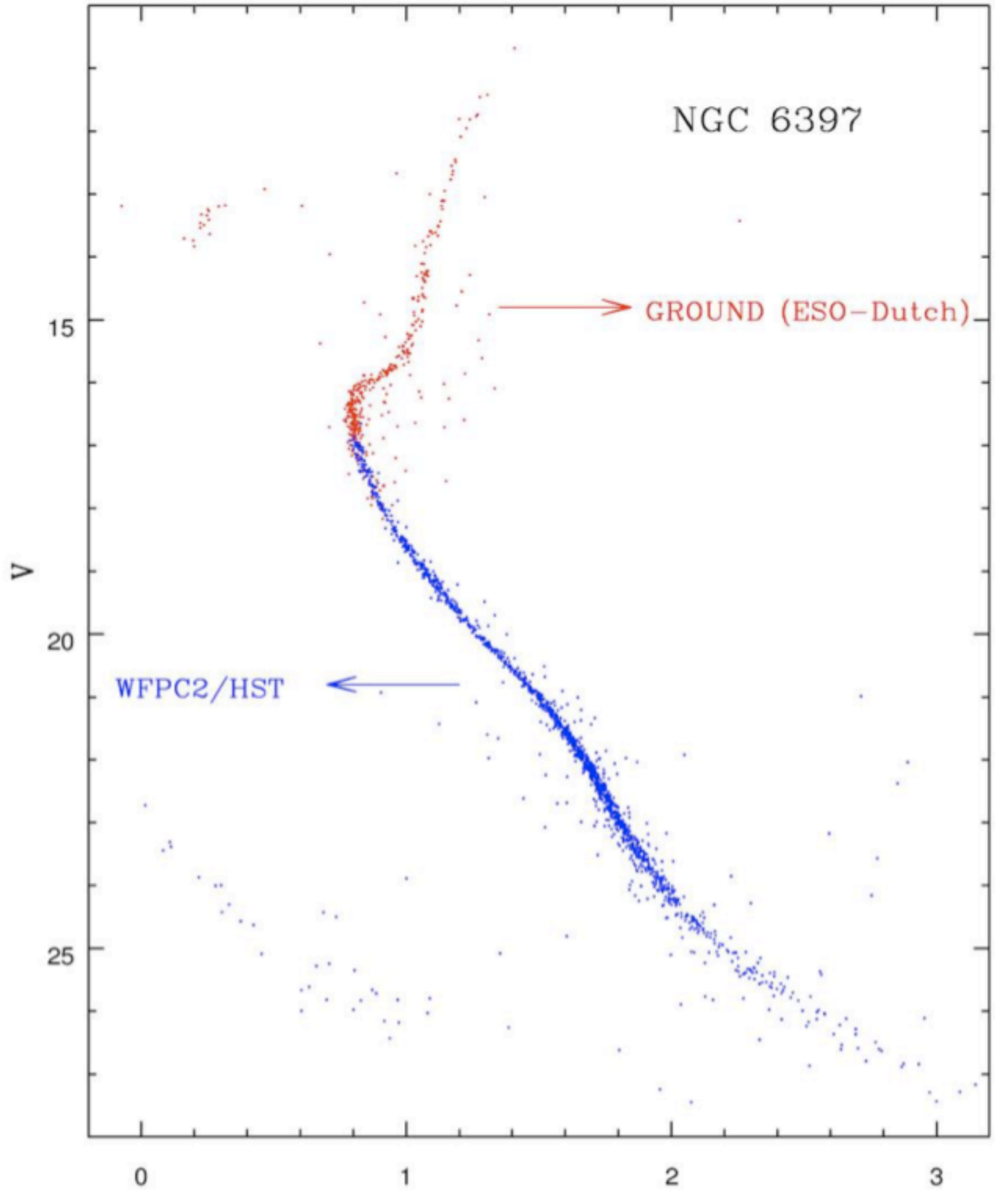
a = 0.6
0.7
0.8
0.9
1
UNBOUND
BOUND
T/V
ΔM
0.4
0.6
0.8
1.0
1.2
1.4
0.0
0.1
0.2
0.3
0.4
0.5


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

Simple Stellar Populations?

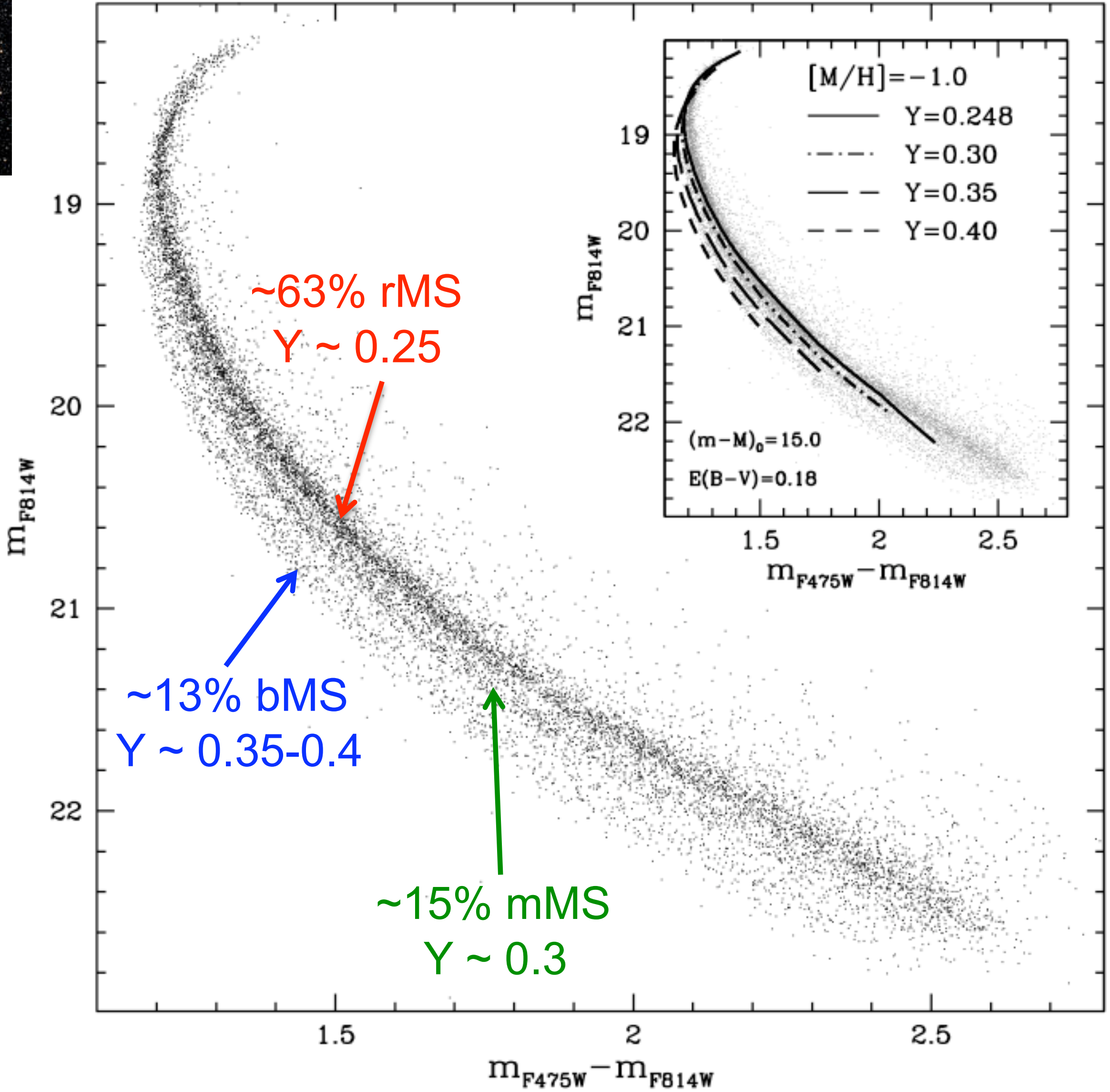
"Globular clusters are excellent examples of simple stellar populations and thus natural laboratories to study stellar evolution"

a single component cluster?



from Piotto
(2008)

NGC 2808, Piotto et al. (2007)

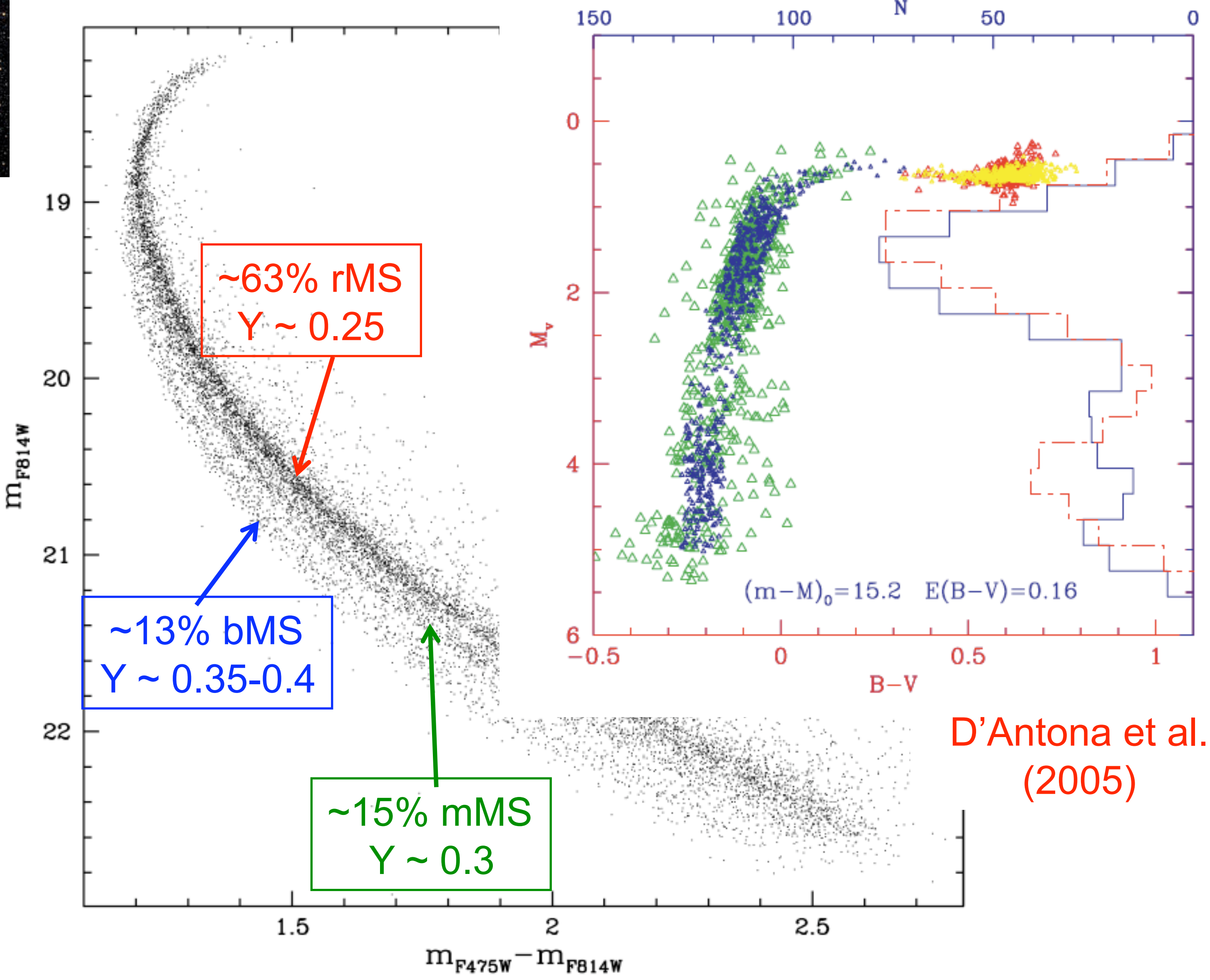


~63% rMS
Y ~ 0.25

~13% bMS
Y ~ 0.35-0.4

~15% mMS
Y ~ 0.3

NGC 2808, Piotto et al. (2007)



~63% rMS
Y ~ 0.25

~13% bMS
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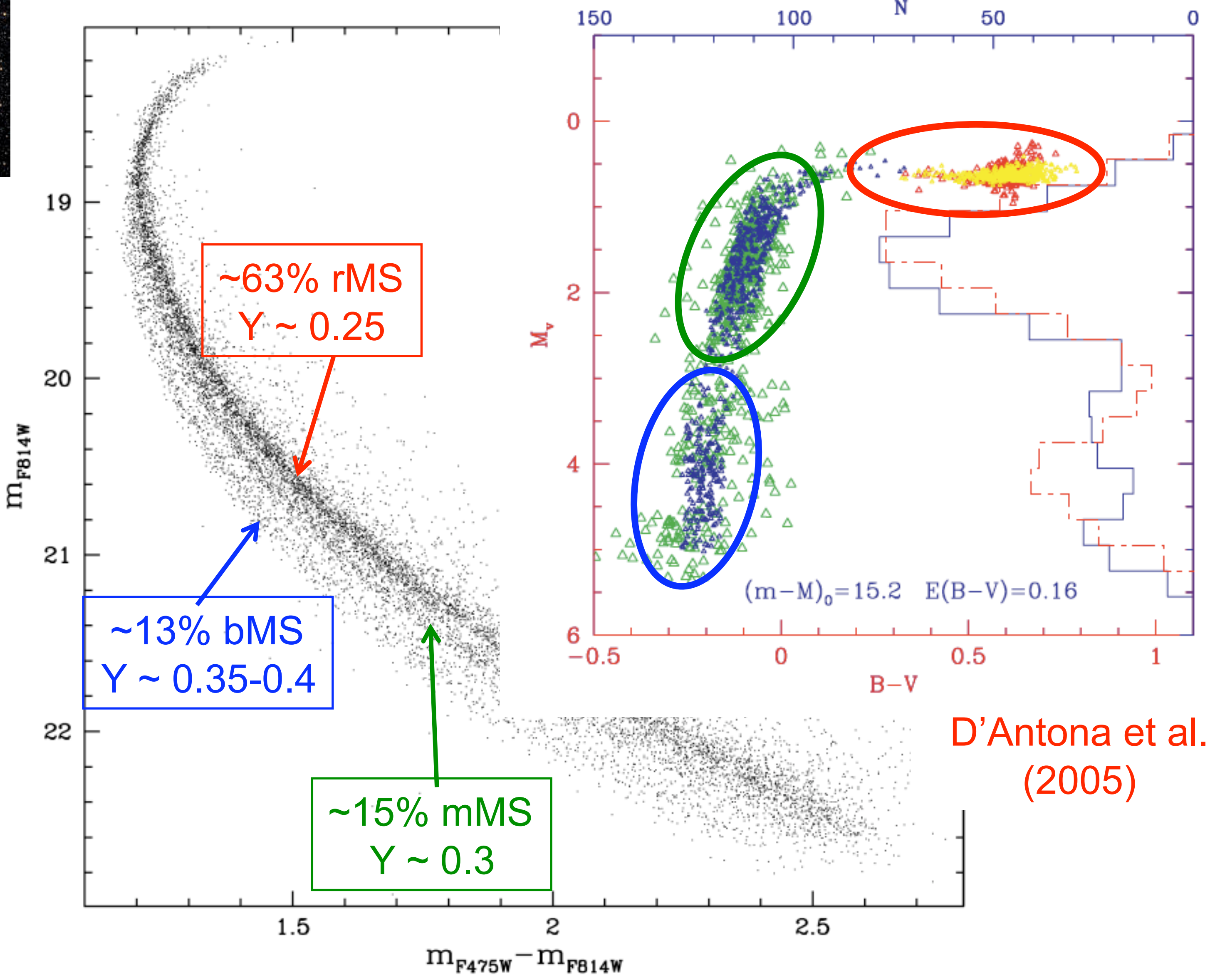
~15% mMS
Y ~ 0.3

D'Antona et al.
(2005)

NGC 2808, Piotto et al. (2007)



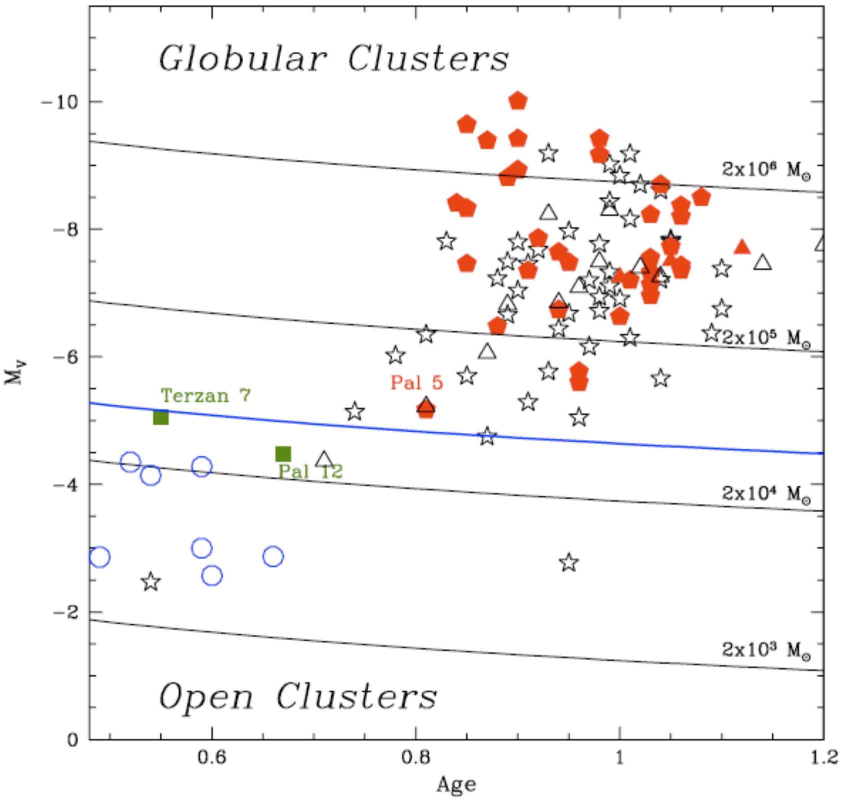
~63% rMS
Y ~ 0.25

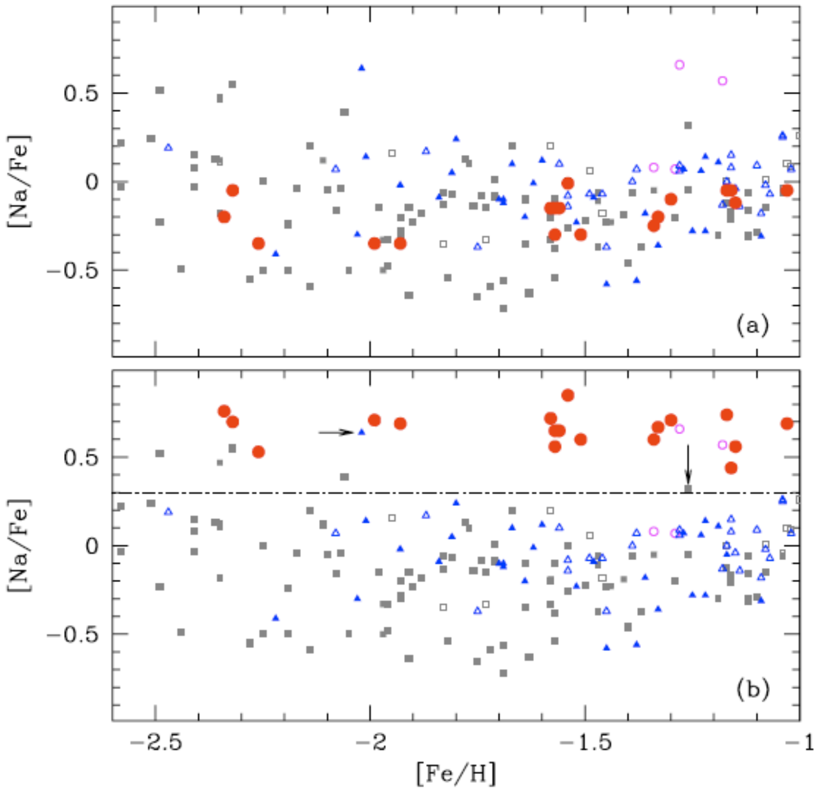
~13% bMS
Y ~ 0.35-0.4

~15% mMS
Y ~ 0.3

D’Antona et al. (2005)

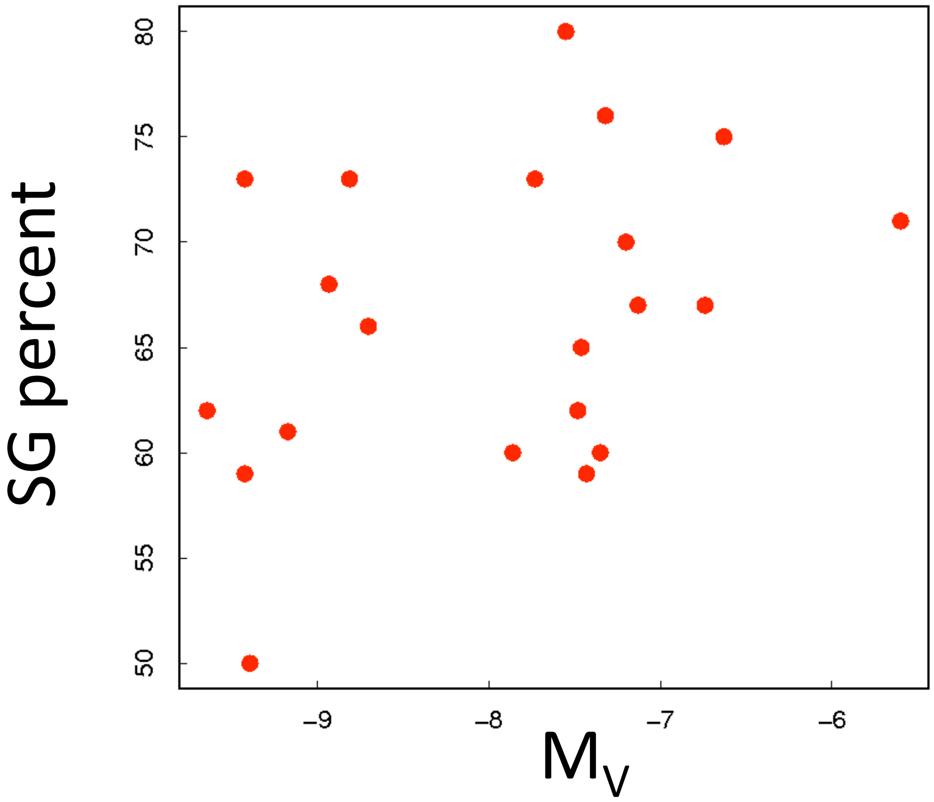
Multiple stellar populations are widespread in globular clusters





Carretta et al. 2010

Second-generation stars represent a significant fraction of the total

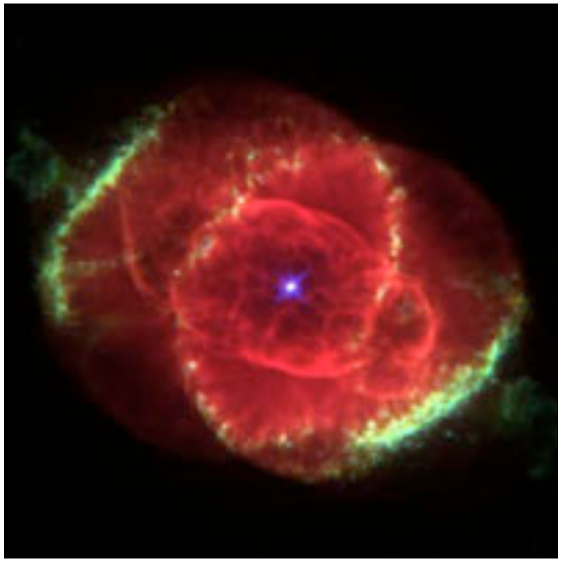


data from
Carretta et al.
2009, 2010

Source of the SG gas

- Progenitors of SG stars
  - AGB stars

    (Cottrell & Da Costa 1981; D'Antona, Ventura et al. 2001….)



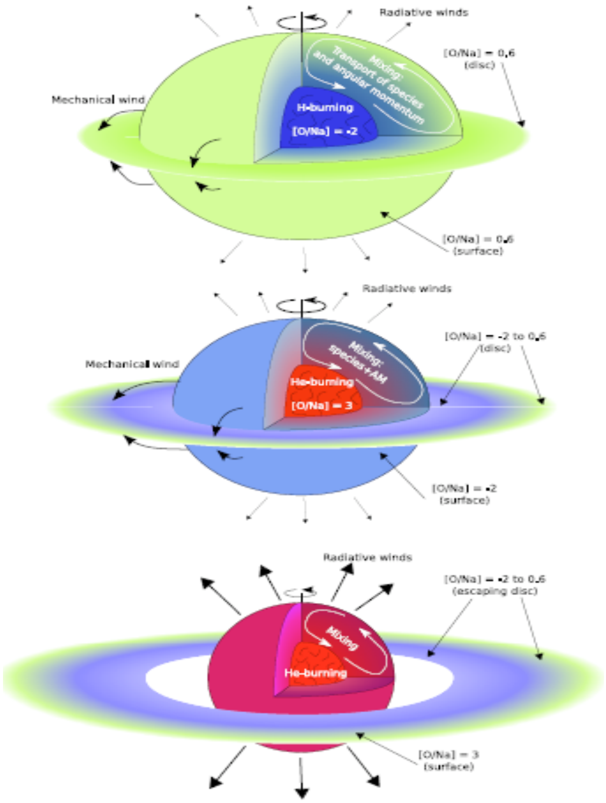
Low-velocity winds (10-20 km/s) retained in clusters. Hot Bottom Burning products pollute the gas

Source of the SG gas

- Progenitors of SG stars
  - AGB stars

    (Cottrell & Da Costa 1981; D'Antona, Ventura et al. 2001….)
  - "Fast-Rotating" Massive Stars

    (Prantzos & Charbonnel 2006; Decressin et al. 2007)



CNO-processed matter transported by rotational mixing and an outflowing equatorial disk

Source of the SG gas

- Progenitors of SG stars
  - AGB stars

    (Cottrell & Da Costa 1981; D'Antona, Ventura et al. 2001)
  - "Fast-Rotating" Massive Stars

    (Prantzos & Charbonnel 2006; Decressin et al. 2007)
  - Massive Binaries

    (De Mink et al. 2009)

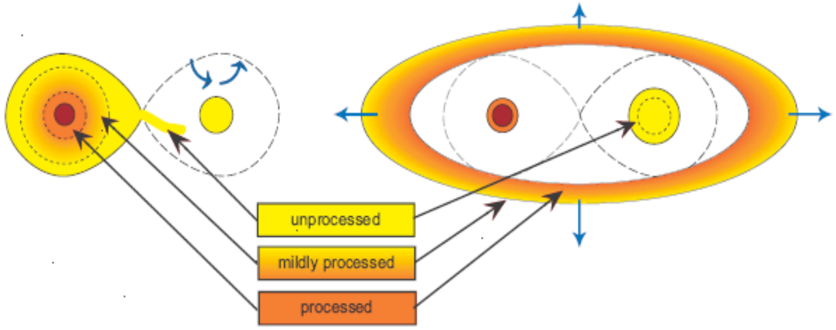


Figure 1. Cartoon representation of the proposed scenario. **Left**: A binary system at the onset of mass transfer. The deepest layers in the donor star have been processed by proton capture reactions. The accreting star spins up as it accretes mass and angular momentum until it approaches the break-up limit. **Right**: The same system after the donor star has been stripped from its envelope. The companion star acrreted just a fraction of the transferred mass, mainly unprocessed material originating from the outermost layers of the donor star. Material orginating from deeper layers in the donor star are shedded into a circumbinary disk.

CNO-processed matter transported by mass transfer and a circumbinary disk

Second Generation Stars

- AGB ejecta retained, cool and sink to the cluster center, form SG stars, total mass = $5 \times 10^5\ M_\odot$
  (D'Ercole, Vesperini, D'Antona, McMillan, Recchi, 2008, MNRAS, 391, 825)

- for "standard" IMF (e.g. Kroupa et al. 1993 or Kroupa 2001), large initial FG mass needed

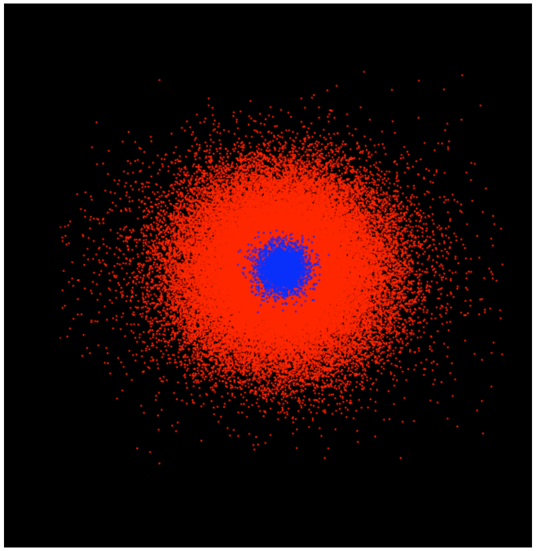
  $M_{FG} \sim 5\text{–}10 \times$ current cluster mass

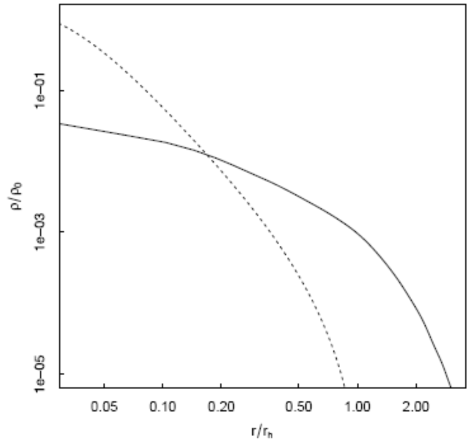
- gas collects in the cluster core, so SG strongly concentrated in the cluster core

- infall of pristine gas is required to explain chemistry

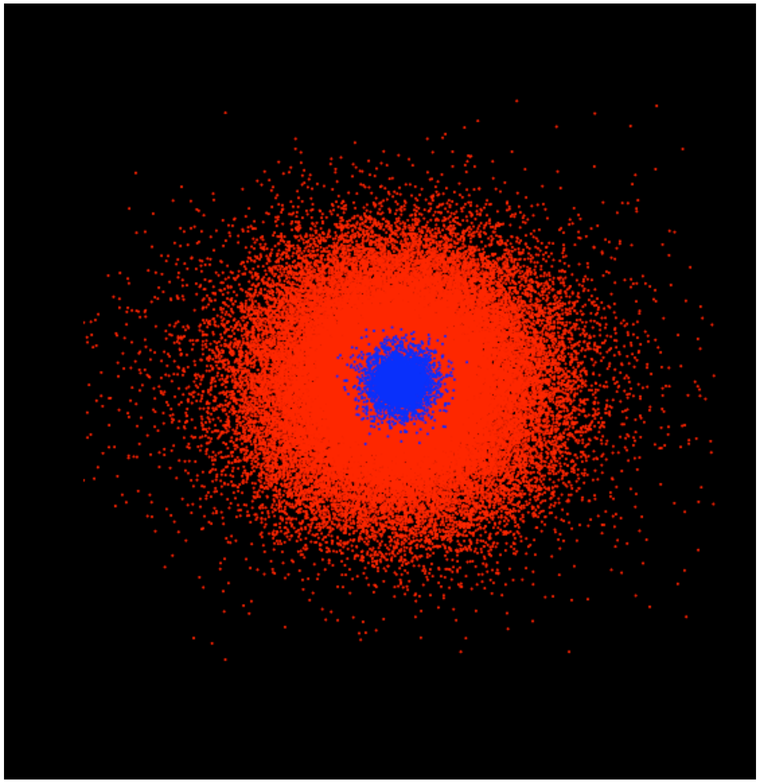
Stellar Dynamics

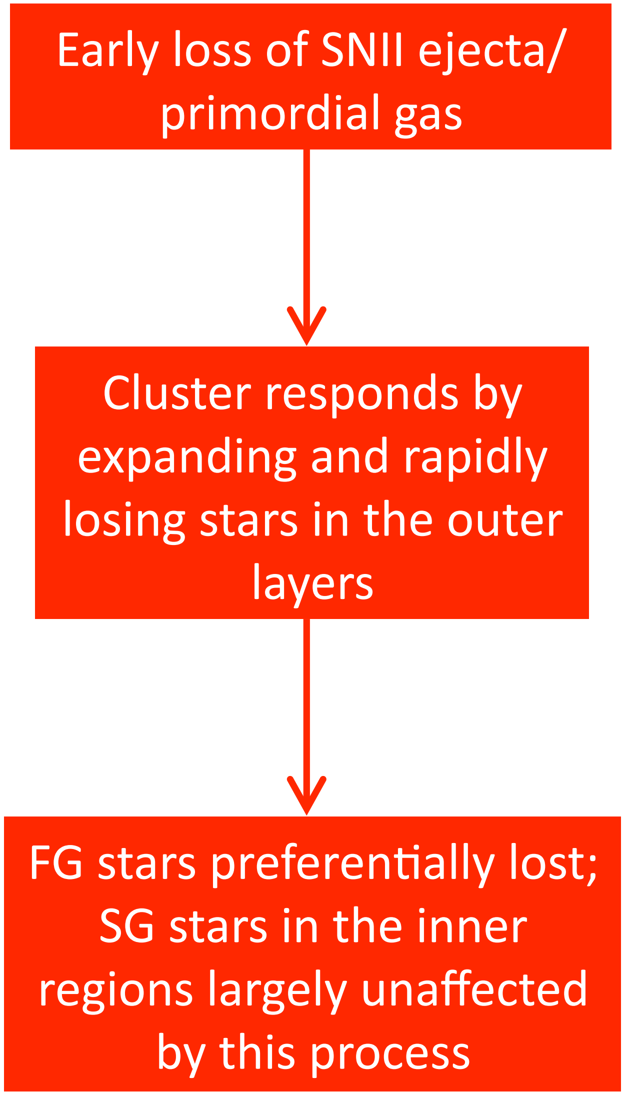
- how to lose ~80–90% of the FG stars?
- two-body relaxation?
  - $10^7 M_\odot$, $R_g = 4$ kpc, T_{diss} ~ 500 Gyr
  - $10^6 M_\odot$, T_{diss} ~ 100 Gyr
  - too slow
- need a mechanism that preferentially removes stars from the cluster *outer layers* and *also* acts *rapidly* in massive clusters





Losing the FG stars

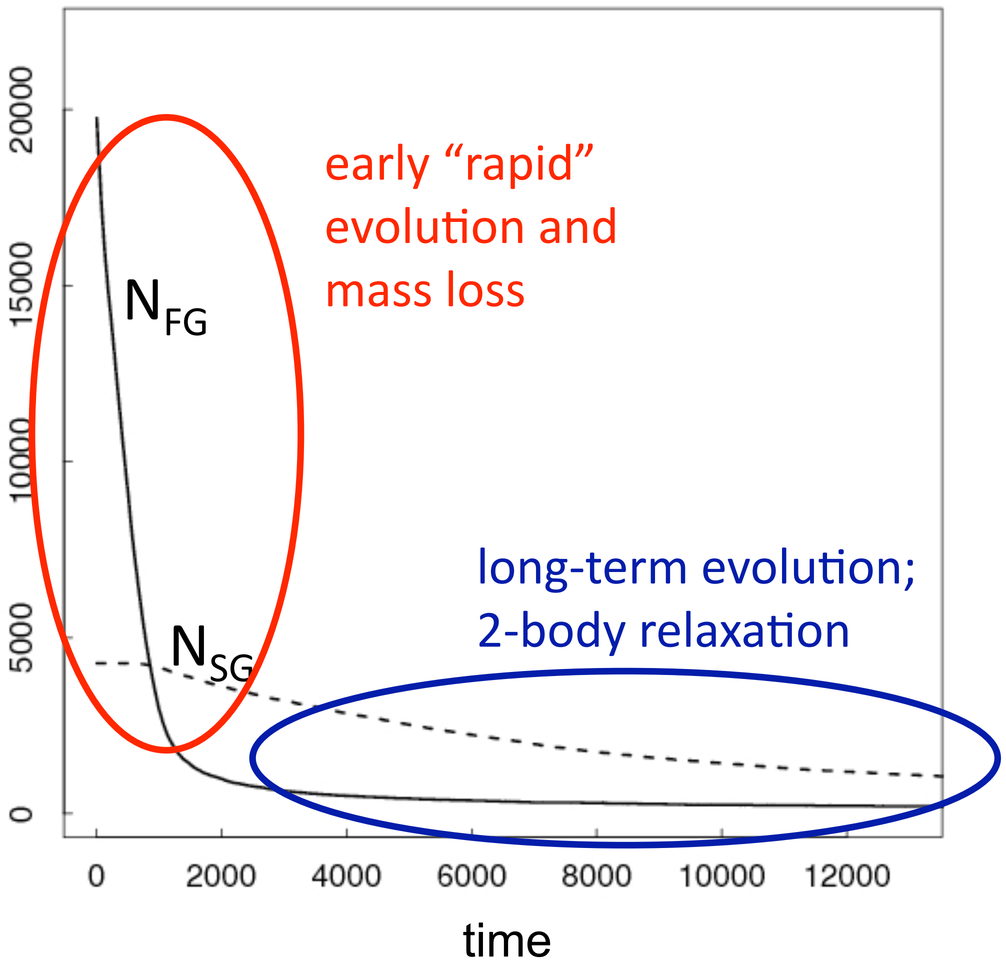




Early loss of SNII ejecta/ primordial gas

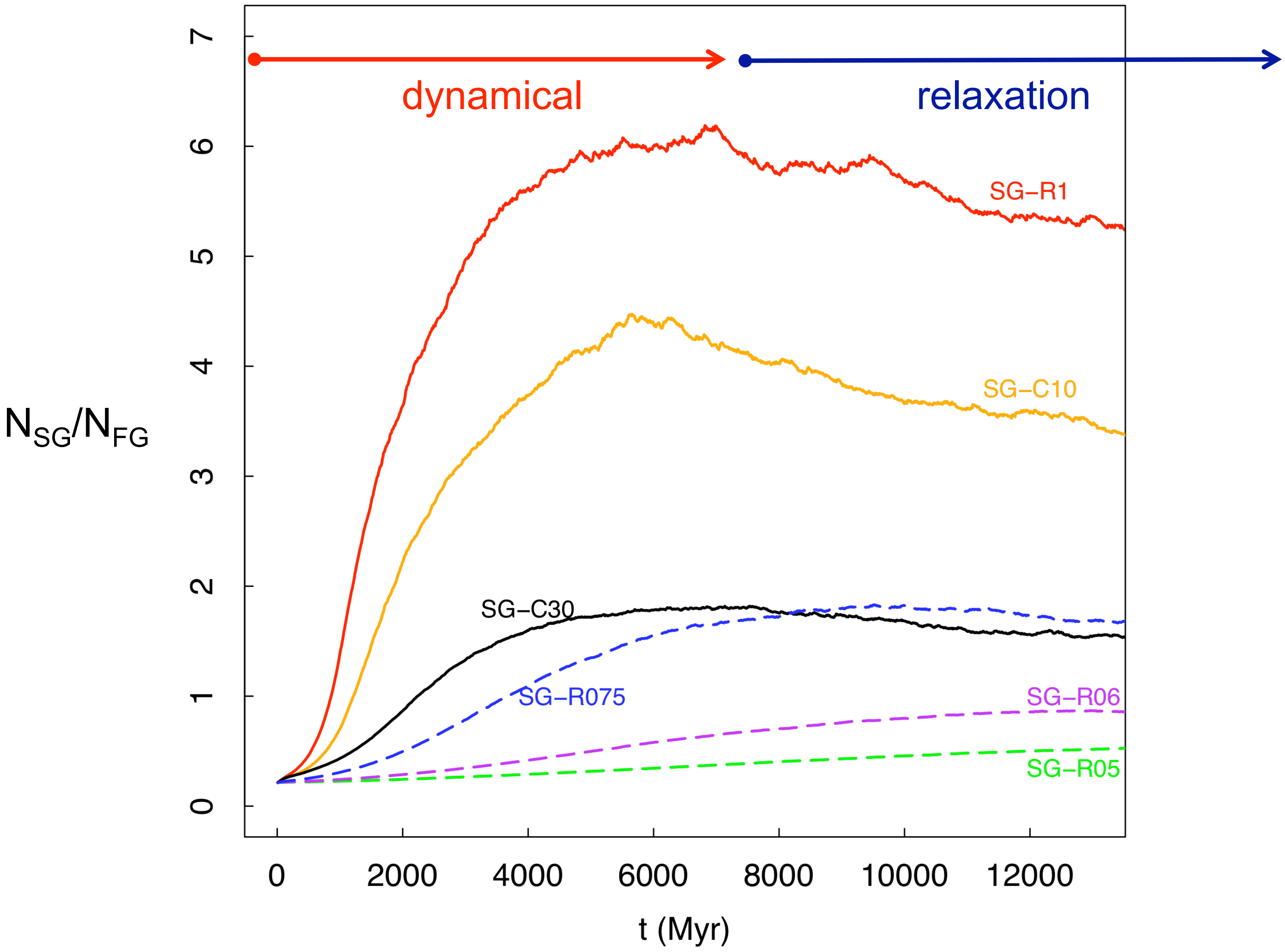
Cluster responds by expanding and rapidly losing stars in the outer layers

FG stars preferentially lost; SG stars in the inner regions largely unaffected by this process

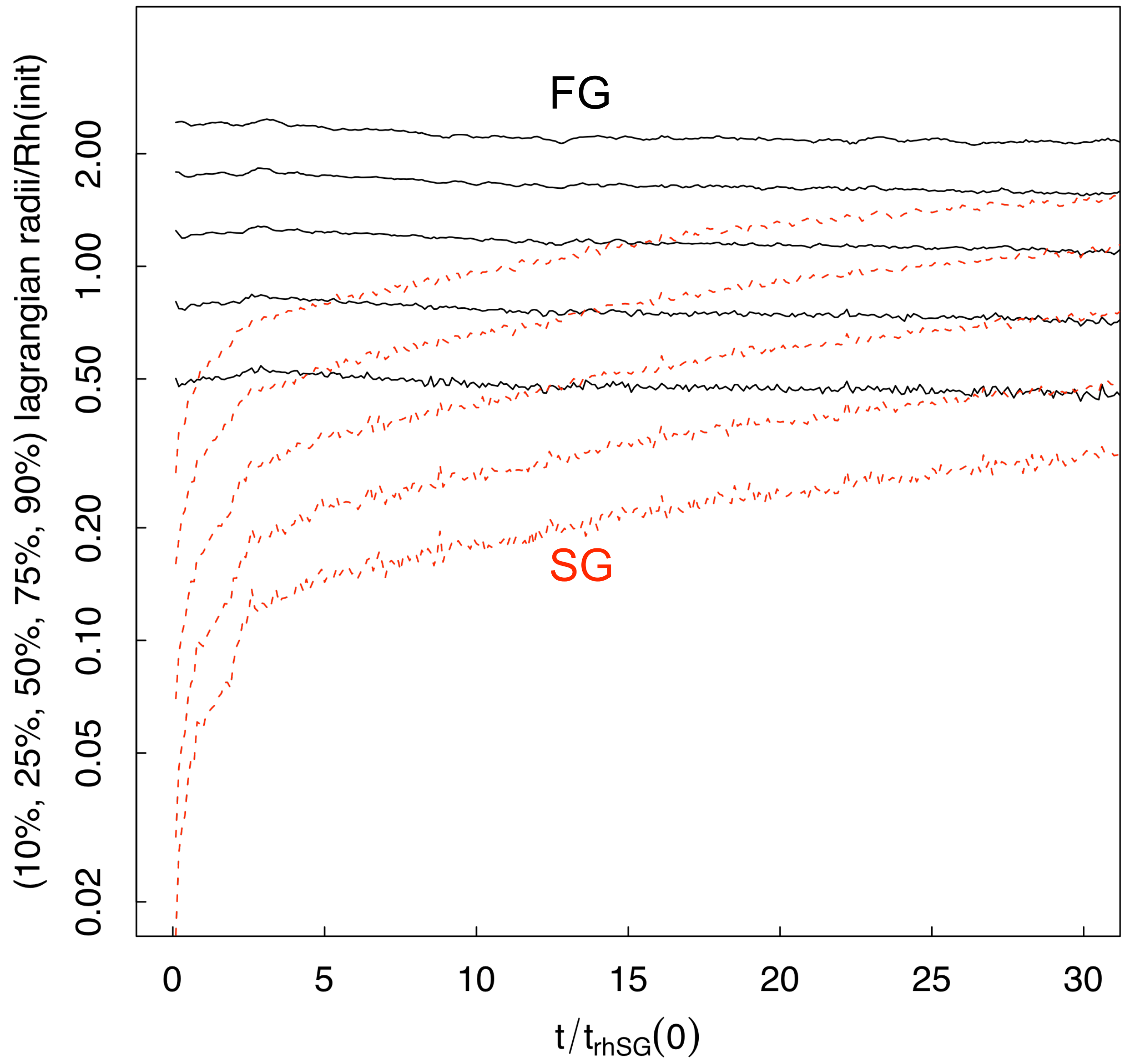


early "rapid" evolution and mass loss

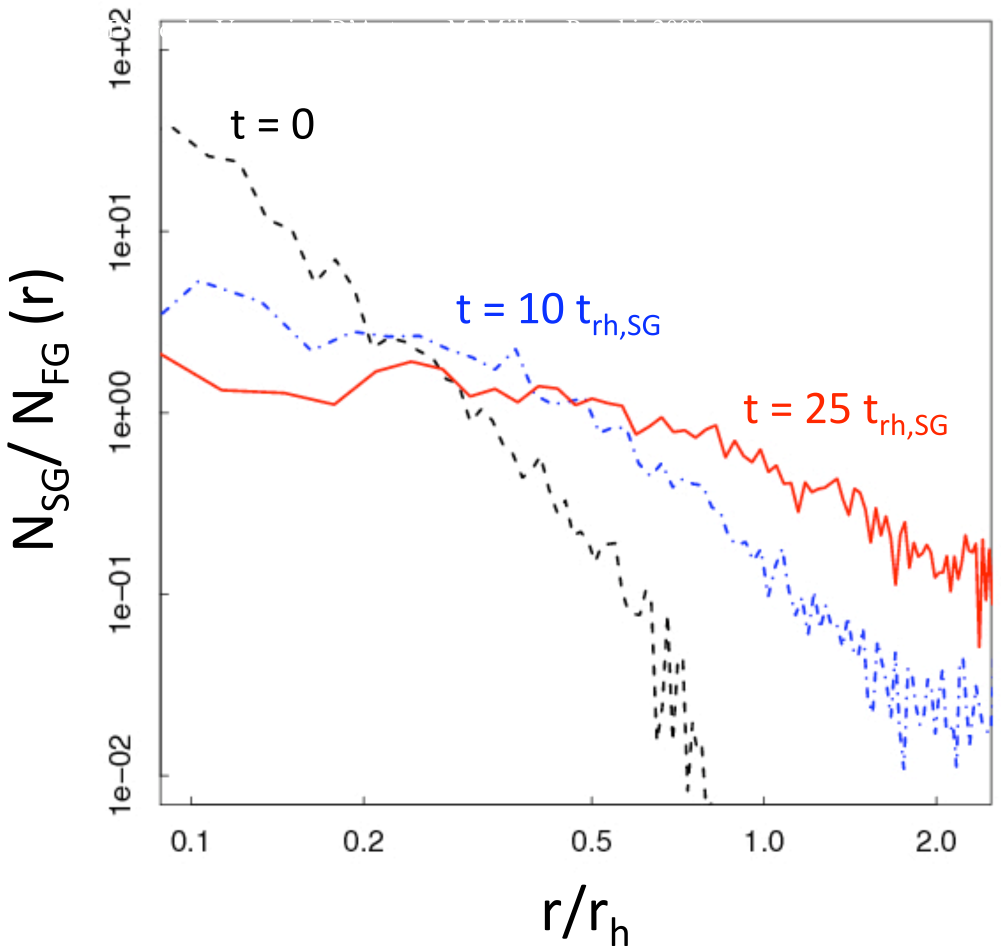
long-term evolution; 2-body relaxation


dynamical
relaxation
SG−R1
SG−C10
SG−C30
SG−R075
SG−R06
SG−R05
N_SG/N_FG
t (Myr)
0
1
2
3
4
5
6
7
0
2000
4000
6000
8000
10000
12000

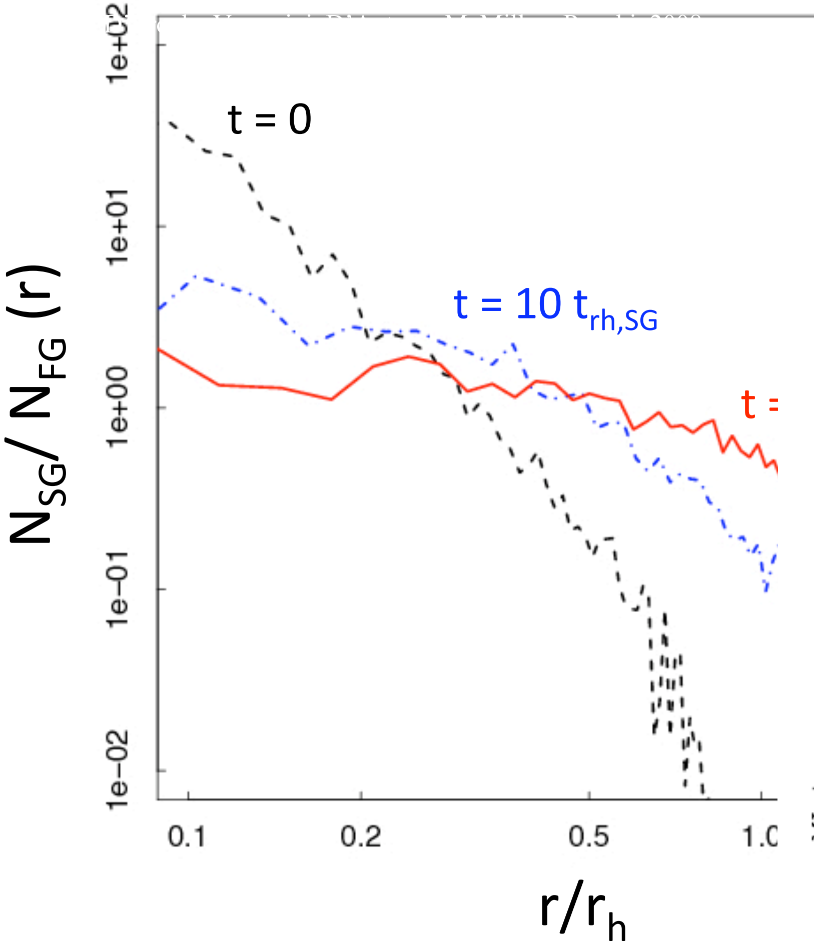
Mixing by 2-body Relaxation



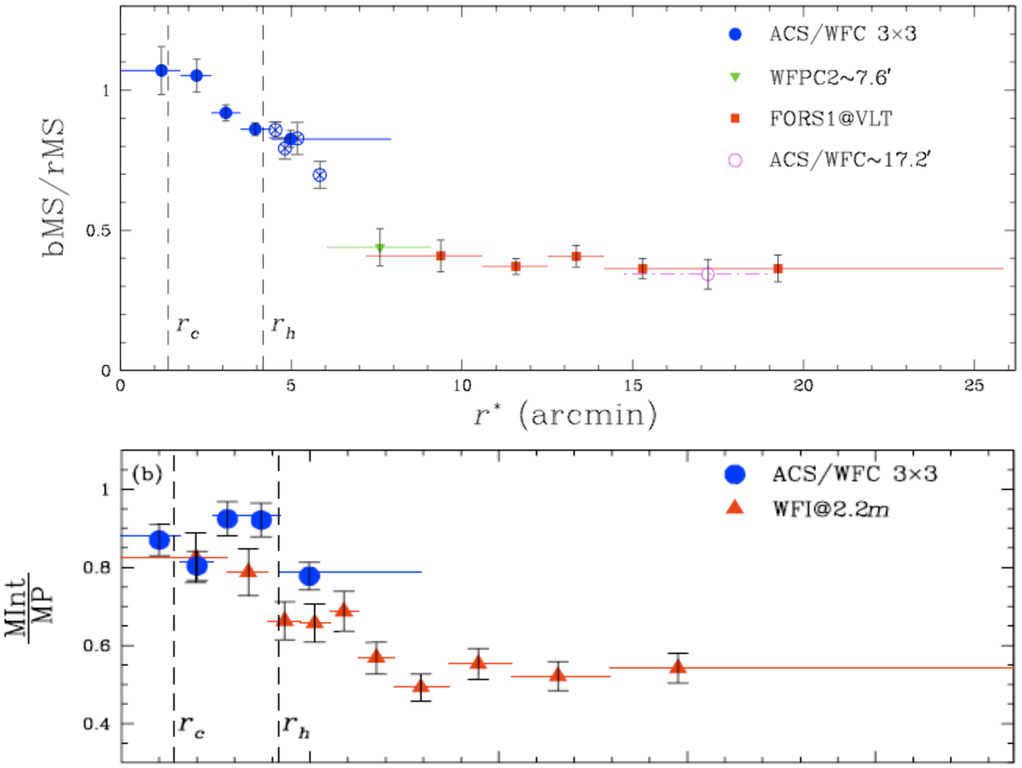
Long-Term Evolution



Long-Term Evolution



Omega Cen: Bellini et al 2009



Up Next (Lecture 3)

- numerical techniques—N-body integration
- force evaluation
- integration schemes
- high-performance computing
- kitchen-sink codes
- the AMUSE project