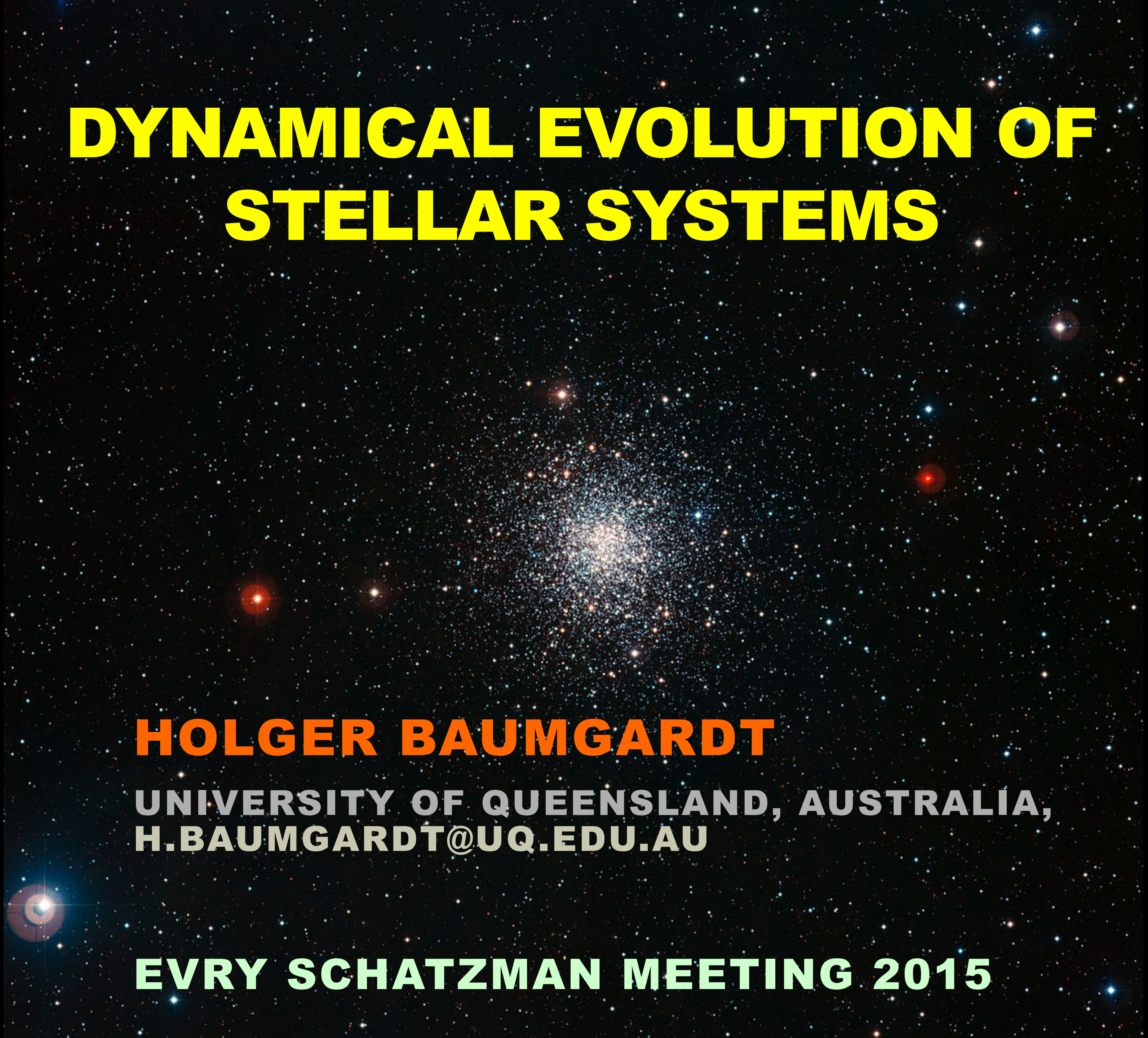
DYNAMICAL EVOLUTION OF STELLAR SYSTEMS



HOLGER BAUMGARDT

UNIVERSITY OF QUEENSLAND, AUSTRALIA,
H.BAUMGARDT@UQ.EDU.AU

EVRY SCHATZMAN MEETING 2015

OVERVIEW

- **Lecture 1:**
  - Dynamical Processes in Star Clusters.
  - Core Collapse and two-body Relaxation
- **Lecture 2:**
  - Dissolution of Star Clusters
  - Ultra-Compact Dwarf Galaxies
- **Lecture 3:**
  - Nuclear Clusters and Massive Black Holes

WHY WORRY ABOUT THE DYNAMICAL EVOLUTION?

WHY WORRY ABOUT THE DYNAMICAL EVOLUTION?

T=12 Gyr

WHY WORRY ABOUT THE DYNAMICAL EVOLUTION?

T=0 Gyr

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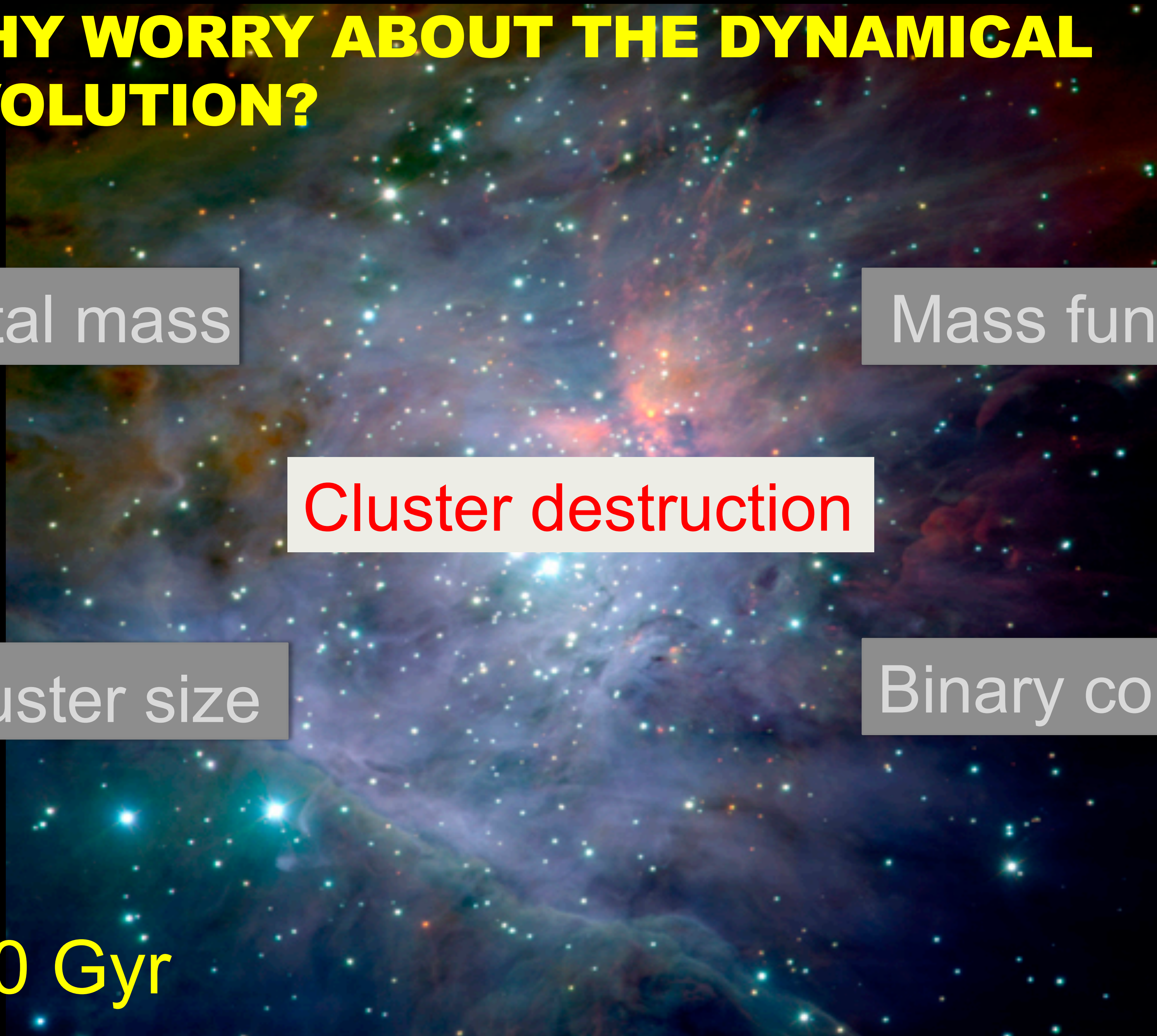


Total mass

Mass function

Cluster destruction

Cluster size

Binary content

T=0 Gyr

DYNAMICAL PROCESSES

- Gas expulsion
- Stellar evolution
- Two-body relaxation
- External tidal fields and tidal shocks

Time

Dynamical processes

I) GAS EXPULSION

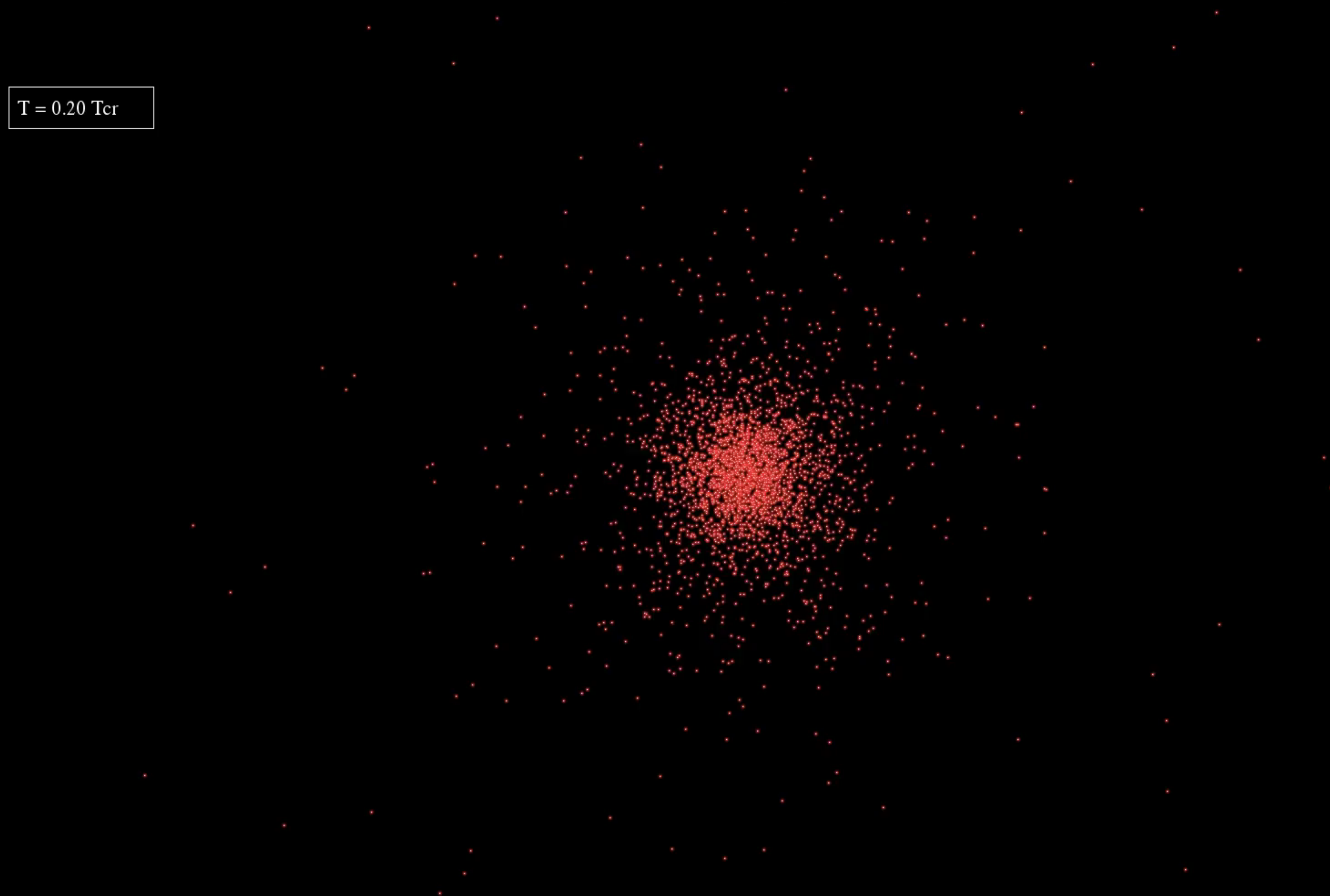
Gas expulsion is the loss of the gas out of which a star cluster has formed and which is not converted into stars during the star formation process.

Star formation efficiency:

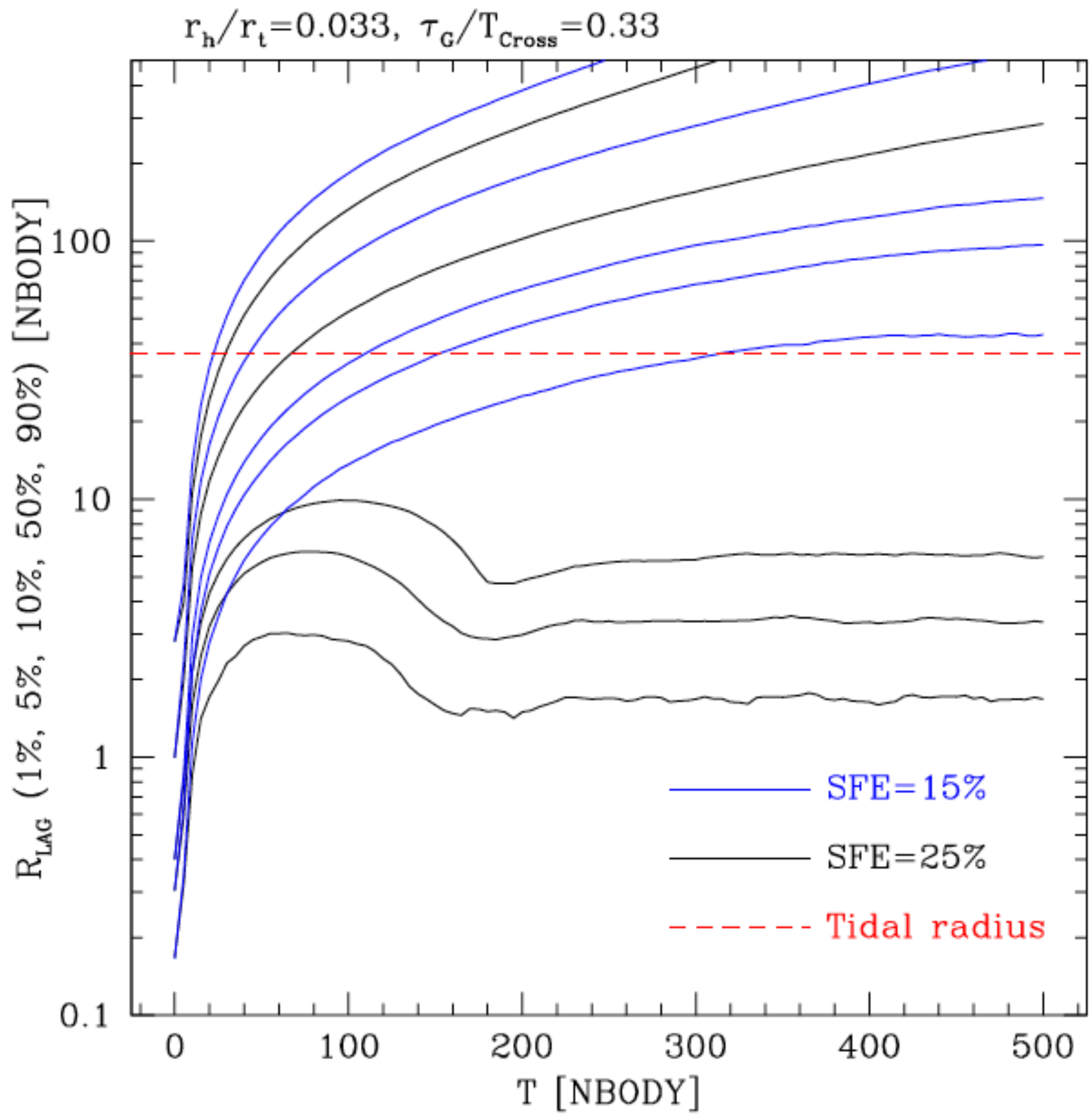
$$\eta = \frac{M_{Star}}{M_{Star} + M_{Gas}}$$

Observations of young open clusters in the Milky Way show that only about 3% of the gas of a molecular cloud is converted into stars (Lada & Lada 2003).

Higher SFE values are usually found in the center of GMCs (e.g. 10% in the center of Serpens, Olmi & Testi 2002).

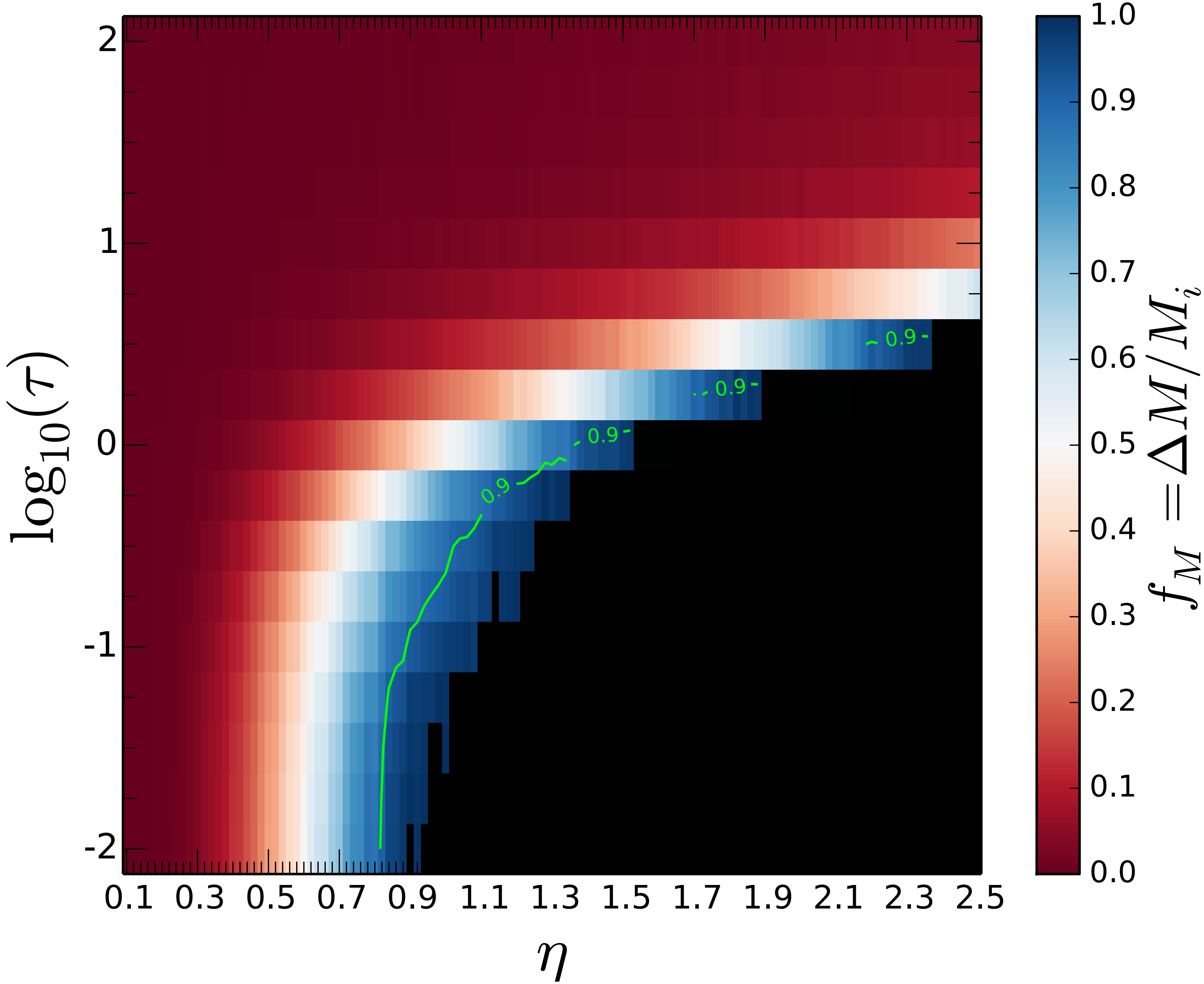

T = 0.20 Tcr

Evolution of Lagrange radii in two gas expulsion simulations (Baumgardt & Kroupa 2008):



Impact of gas expulsion will depend on a number of parameters:

- **Star formation efficiency**
  - Low SFE: Clusters are easily destroyed or lose a large mass fraction
  - High SFE: Clusters will survive
- **Ratio of gas expulsion timescale over crossing time of cluster**
  - Small τ/T_{Cross}: Instantaneous gas expulsion, large mass loss
  - High τ/T_{Cross}: Slow gas expulsion, clusters expand adiabatically
- **Ratio of clusters half-mass radius r_h to its tidal radius r_t**
  - High r_h/r_t: Expanding clusters are easily destroyed
  - Small r_h/r_t: Clusters are nearly isolated and have room to expand



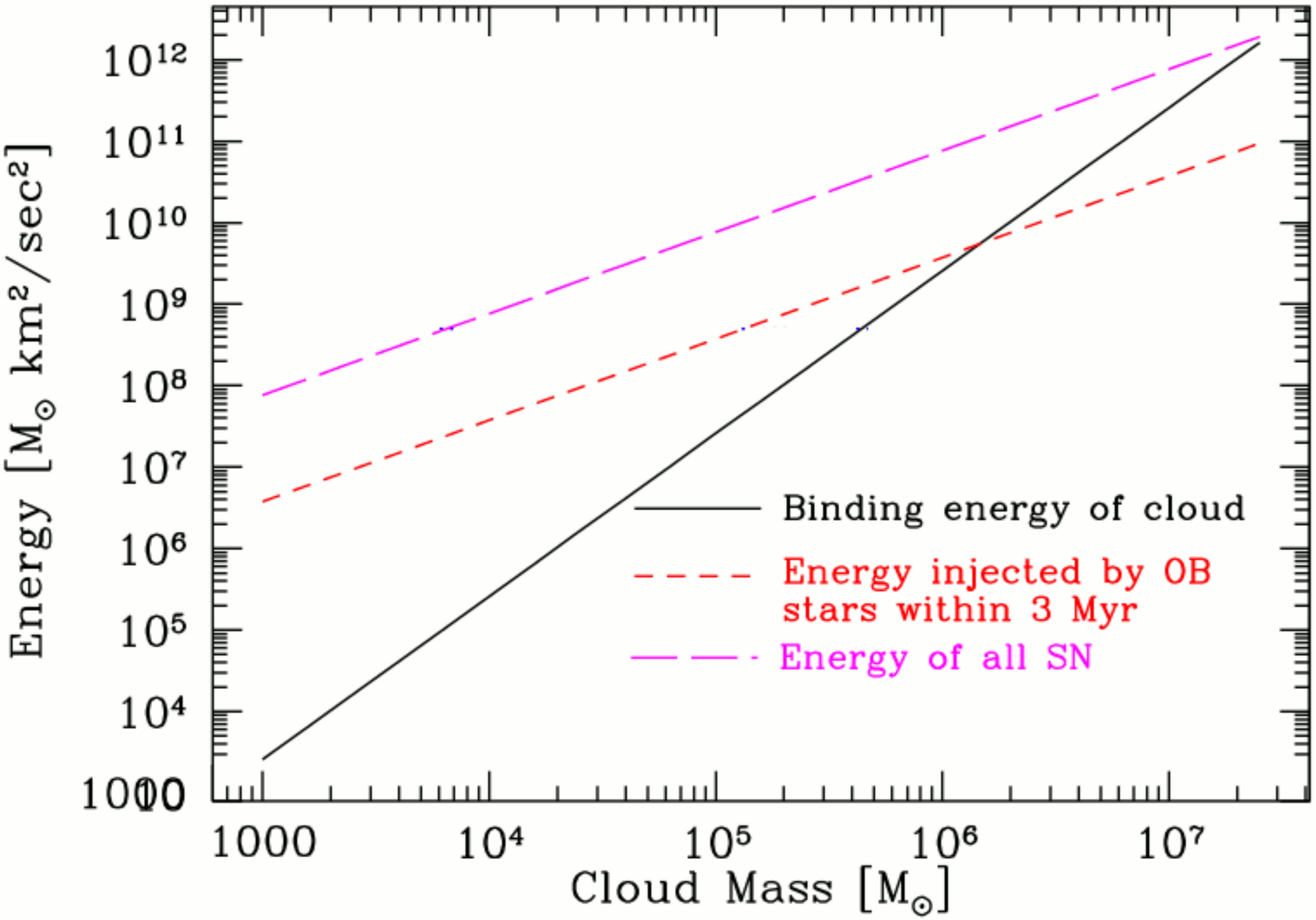
from Khalaj & Baumgardt (2015)

Gas not converted into stars can be expelled by three mechanisms:

- ❑ **Winds and radiation from massive stars**
- ❑ **Supernova feedback (e.g. Brown et al. 1995)**
- ❑ **Accreting compact remnants (Krause et al. 2012)**

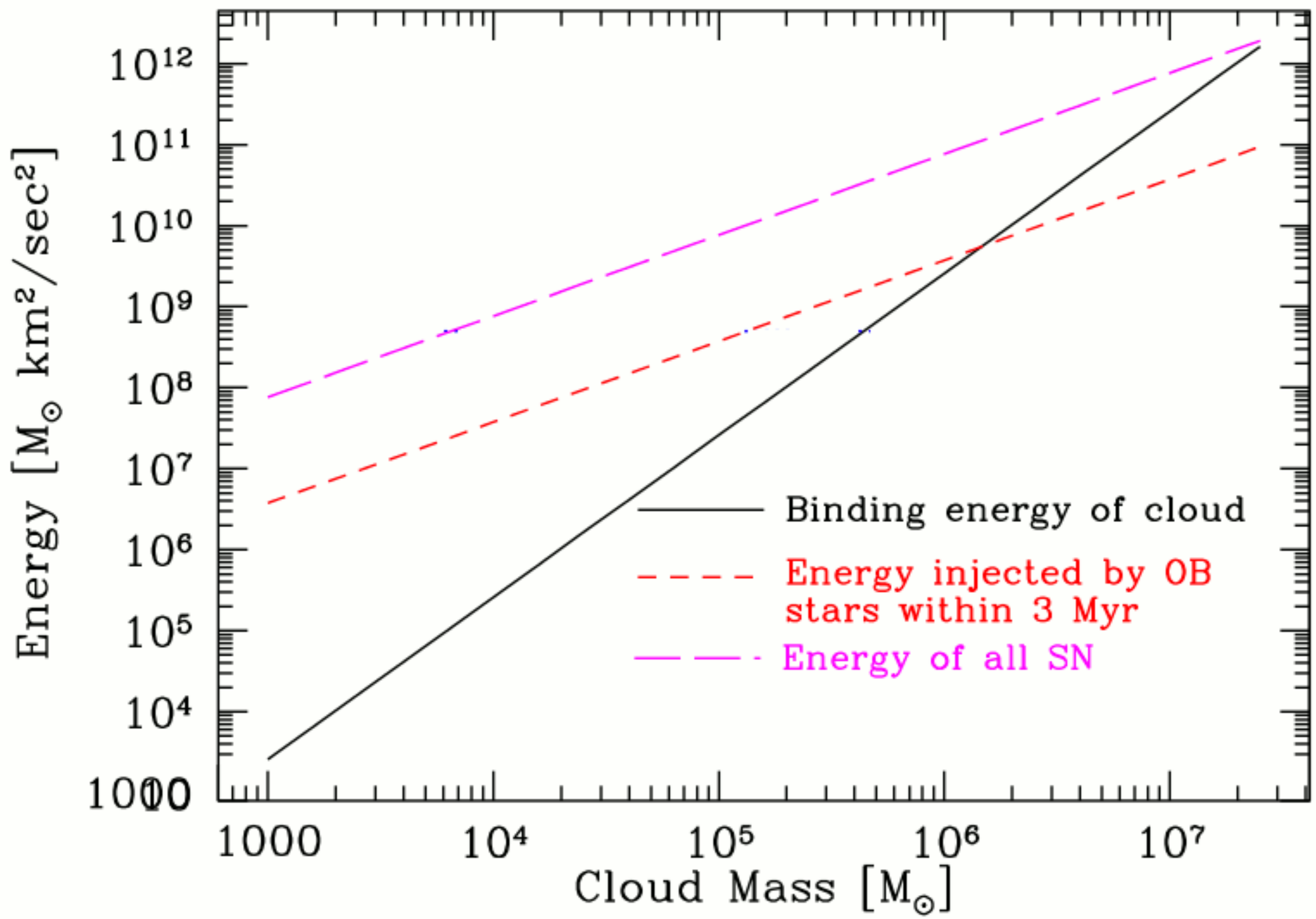
Since cluster energy scales with cluster mass as M^2, the energy provided the above processes only scales only linearly with M, it gets increasingly harder to expel the gas.

Injected energy as a function of the cloud mass



from Baumgardt et al. (2008)

Injected energy as a function of the cloud mass



Single stellar populations

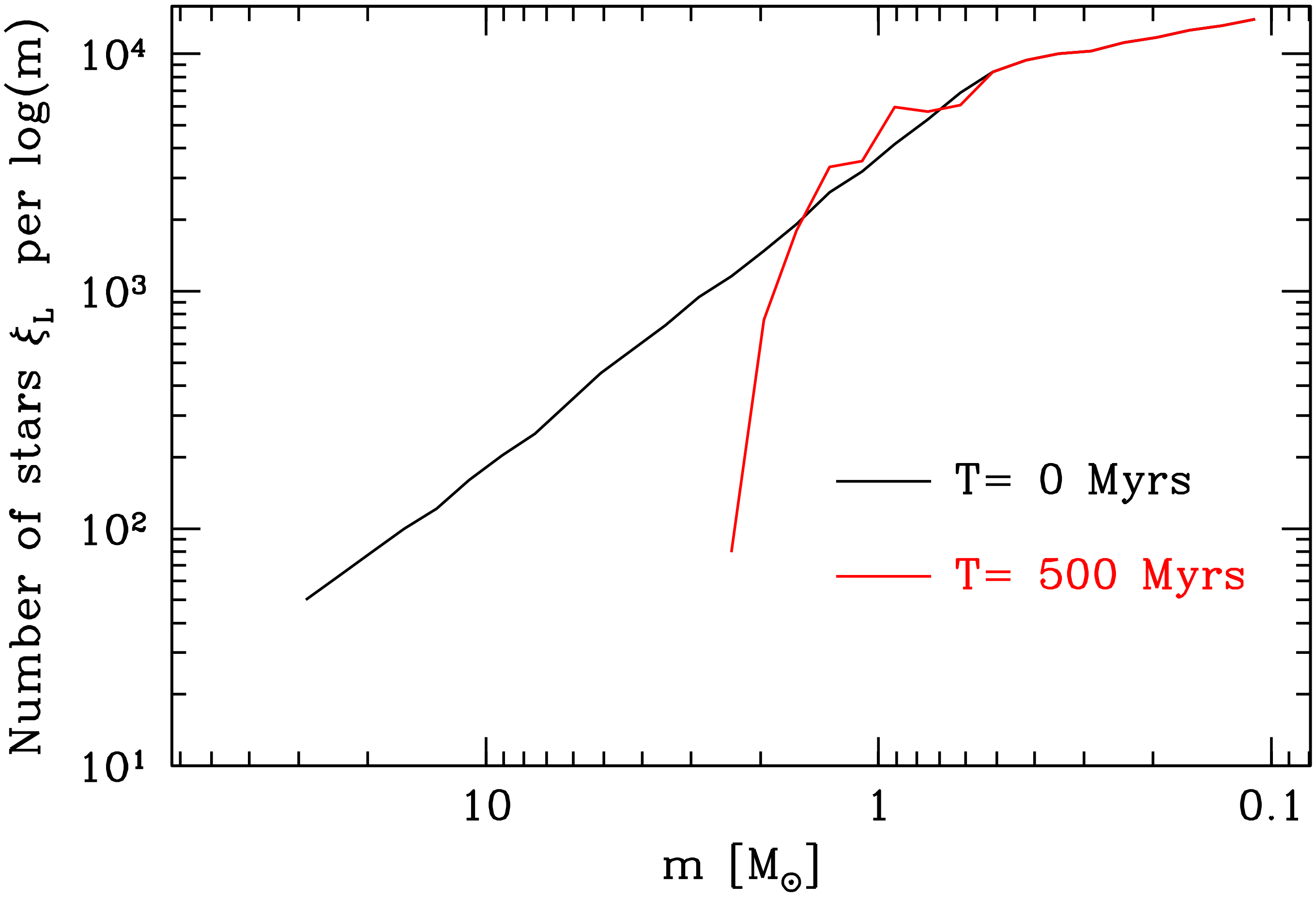
Light element variations

Iron spread

Dynamical processes

II) STELLAR EVOLUTION

STELLAR EVOLUTION



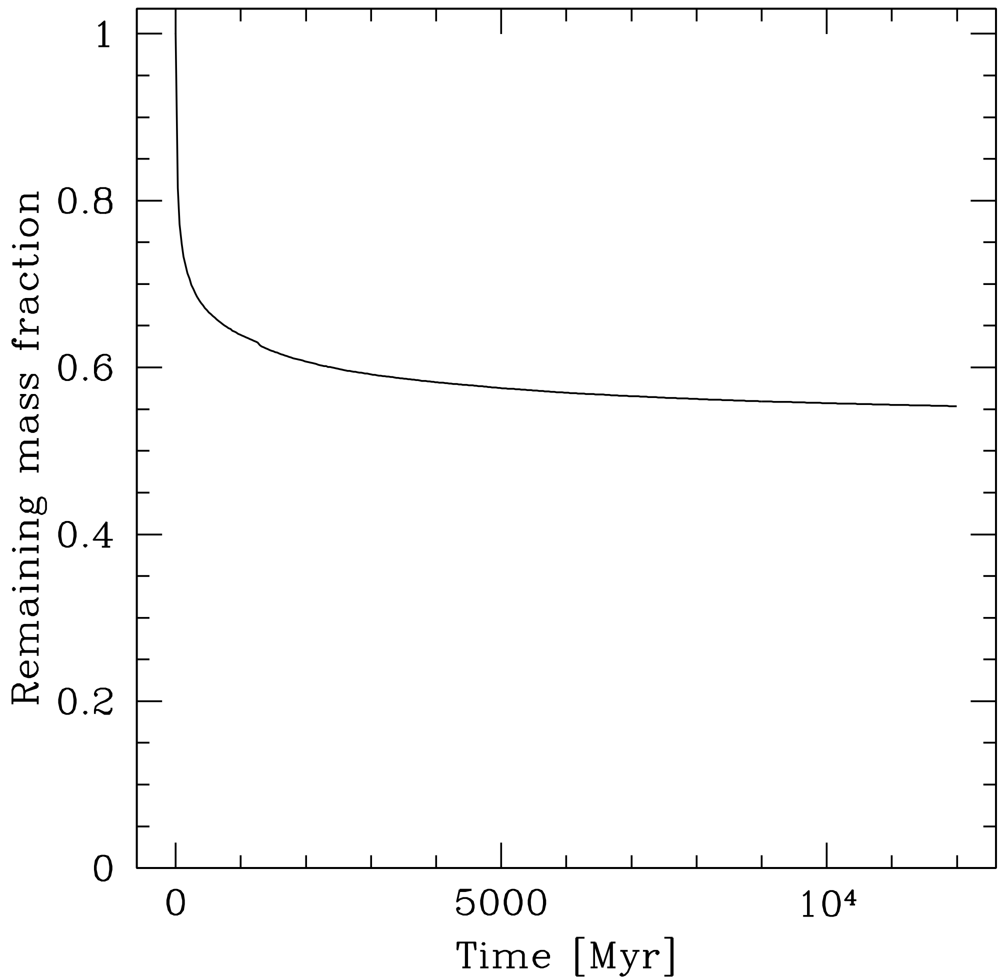
Heavy-mass stars transform into compact remnants, so cluster mass is decreasing over time…

STELLAR EVOLUTION

35% of initial cluster mass lost after 100 Myr, 45% after 10 Gyr.

SEV mass loss is adiabatic, so if cluster is unsegregated cluster radii expand as:

$$\frac{r_f}{r_i} = \frac{M_i}{M_f}$$



Influence of SEV mass loss is more dramatic if clusters are mass segregated (Vesperini et al. 2009).

BINARY EVOLUTION

Large fraction of stars (somewhere between 50-100%) are in binaries.

Average number of companions to OB stars is about 1.9 (Moe & Di Stefano 2013) !

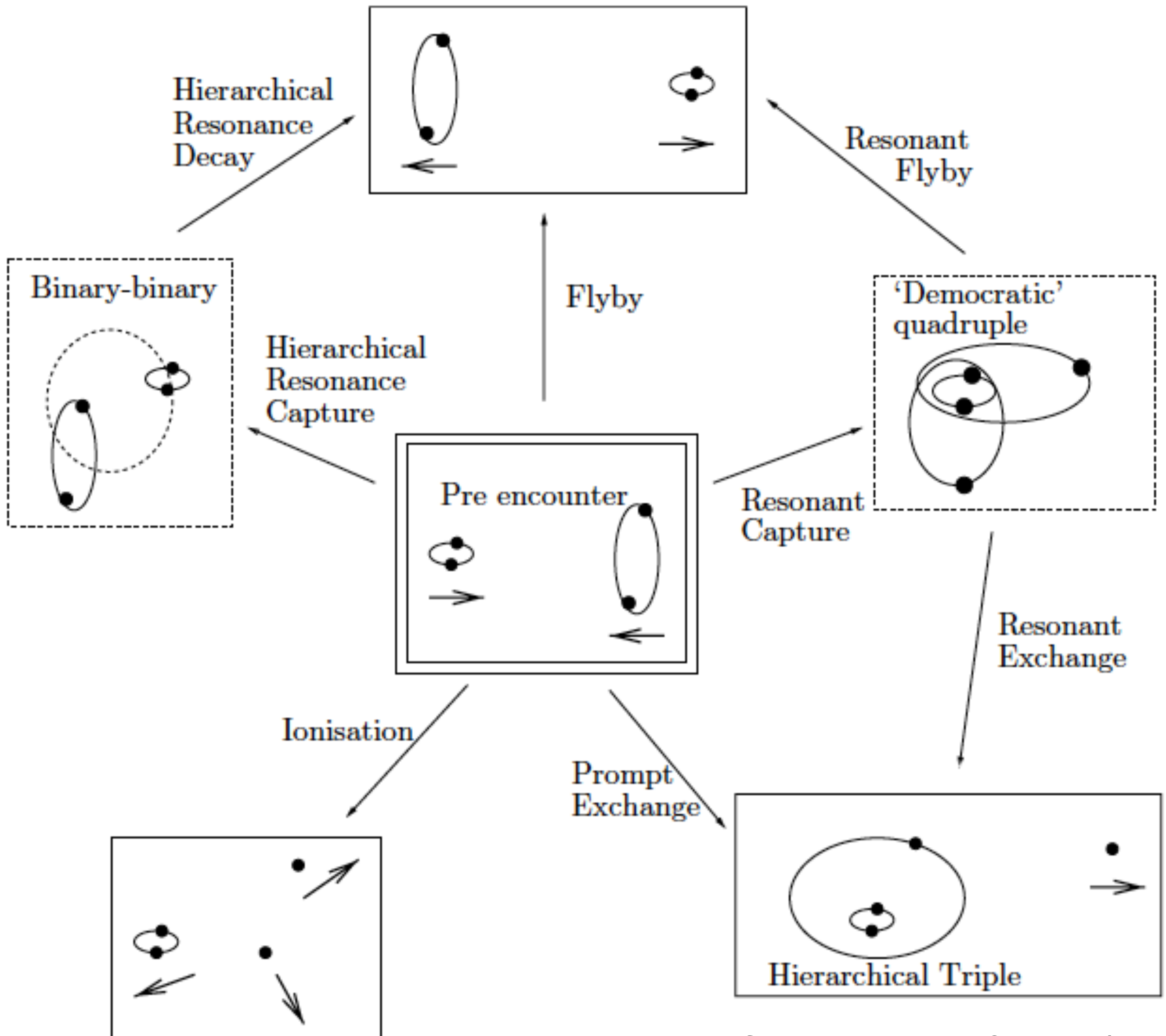
Hard binaries:

Orbital velocity larger than velocity dispersion of cluster

Soft binaries:

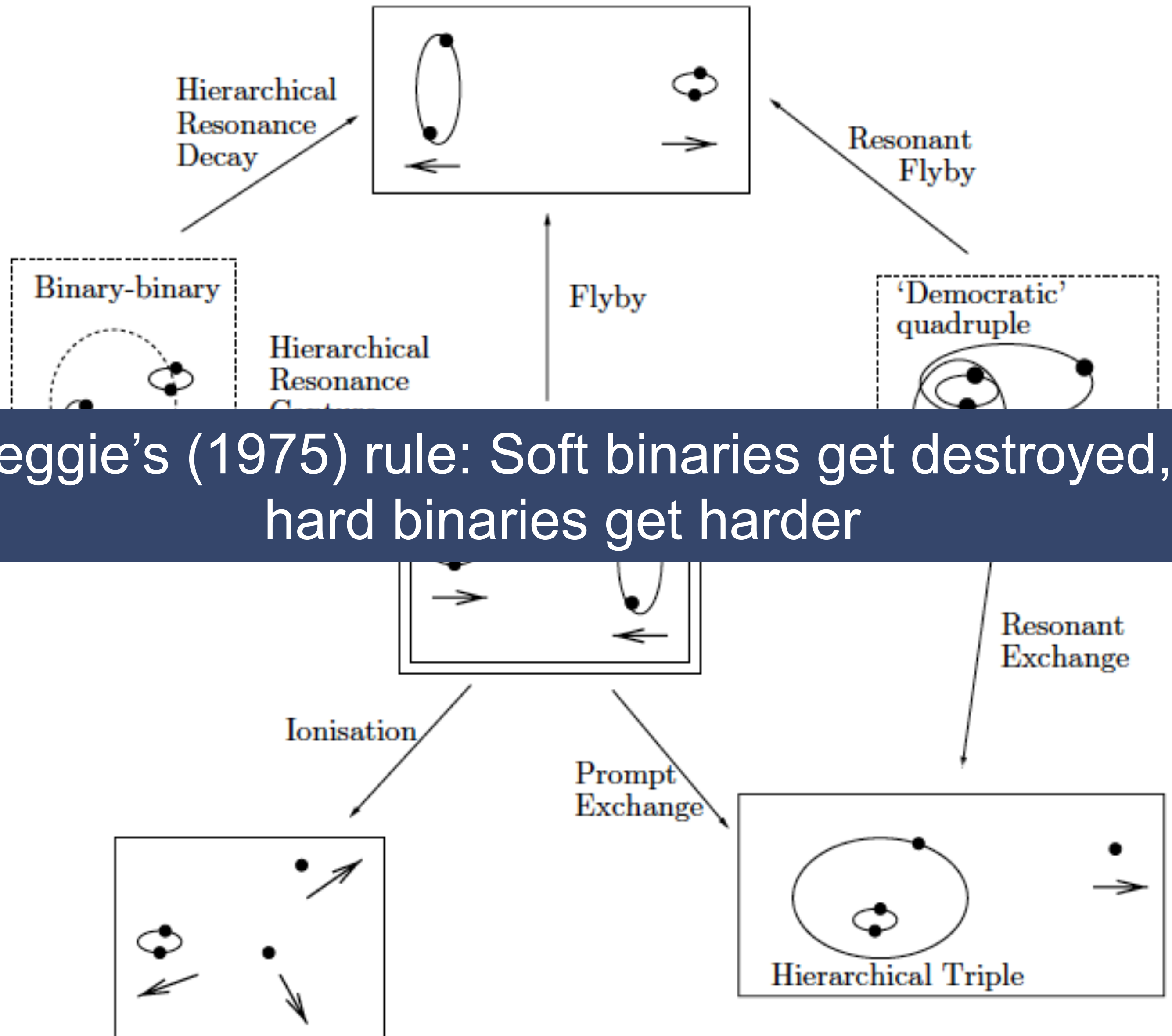
Orbital velocity larger than velocity dispersion of cluster

BINARY EVOLUTION



from Heggie & Hut (2003)

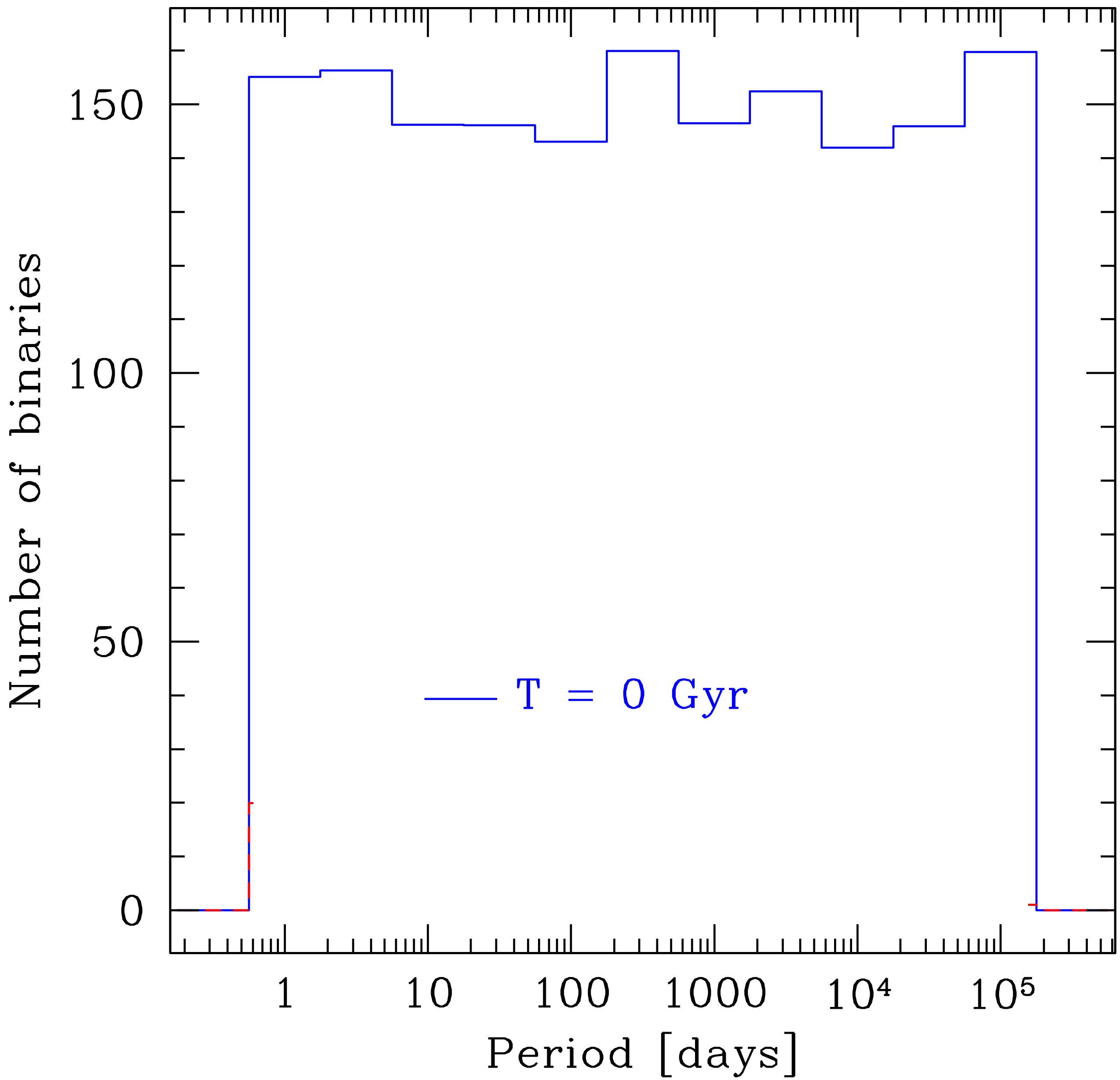
BINARY EVOLUTION



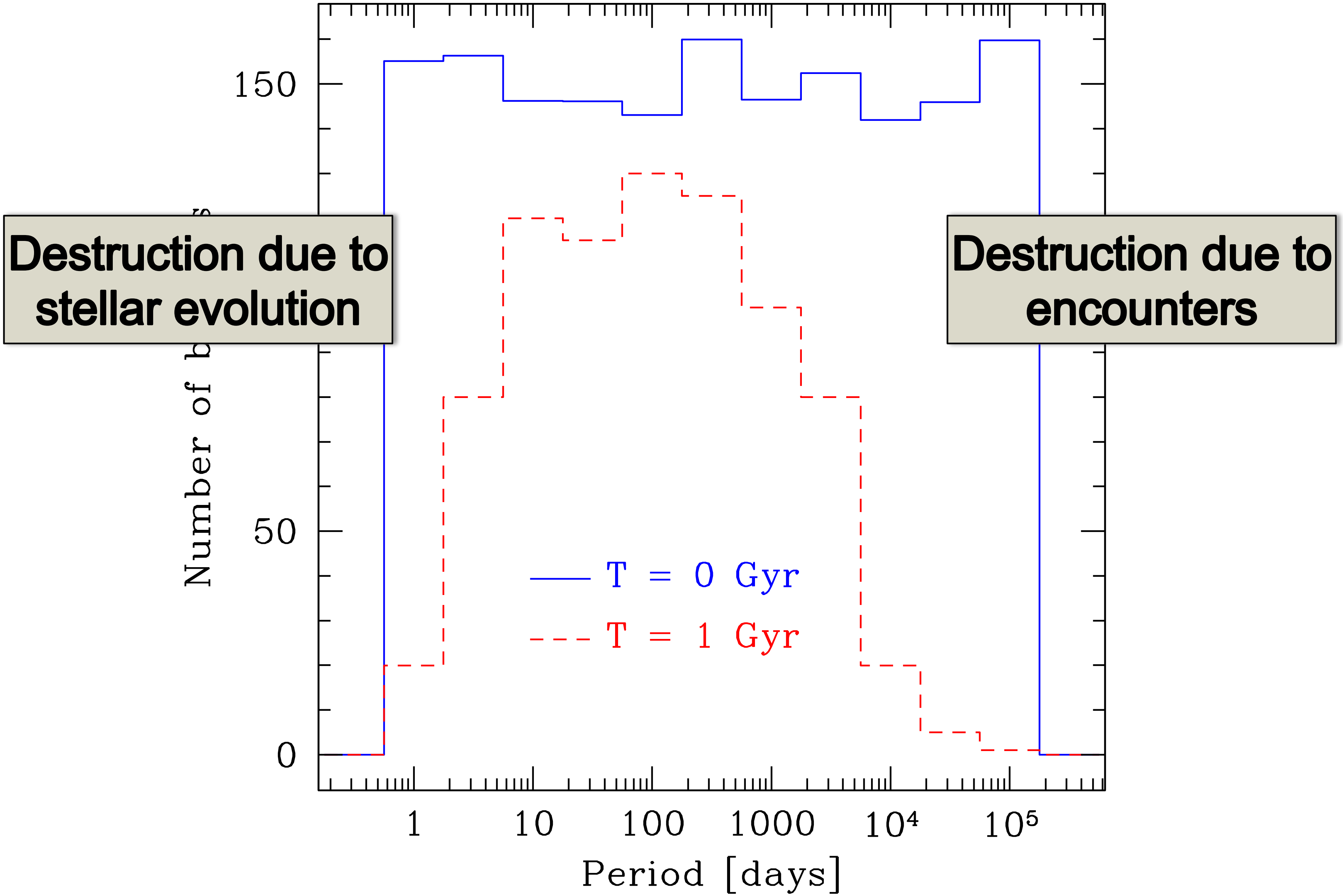
Heggie's (1975) rule: Soft binaries get destroyed, hard binaries get harder

from Heggie & Hut (2003)

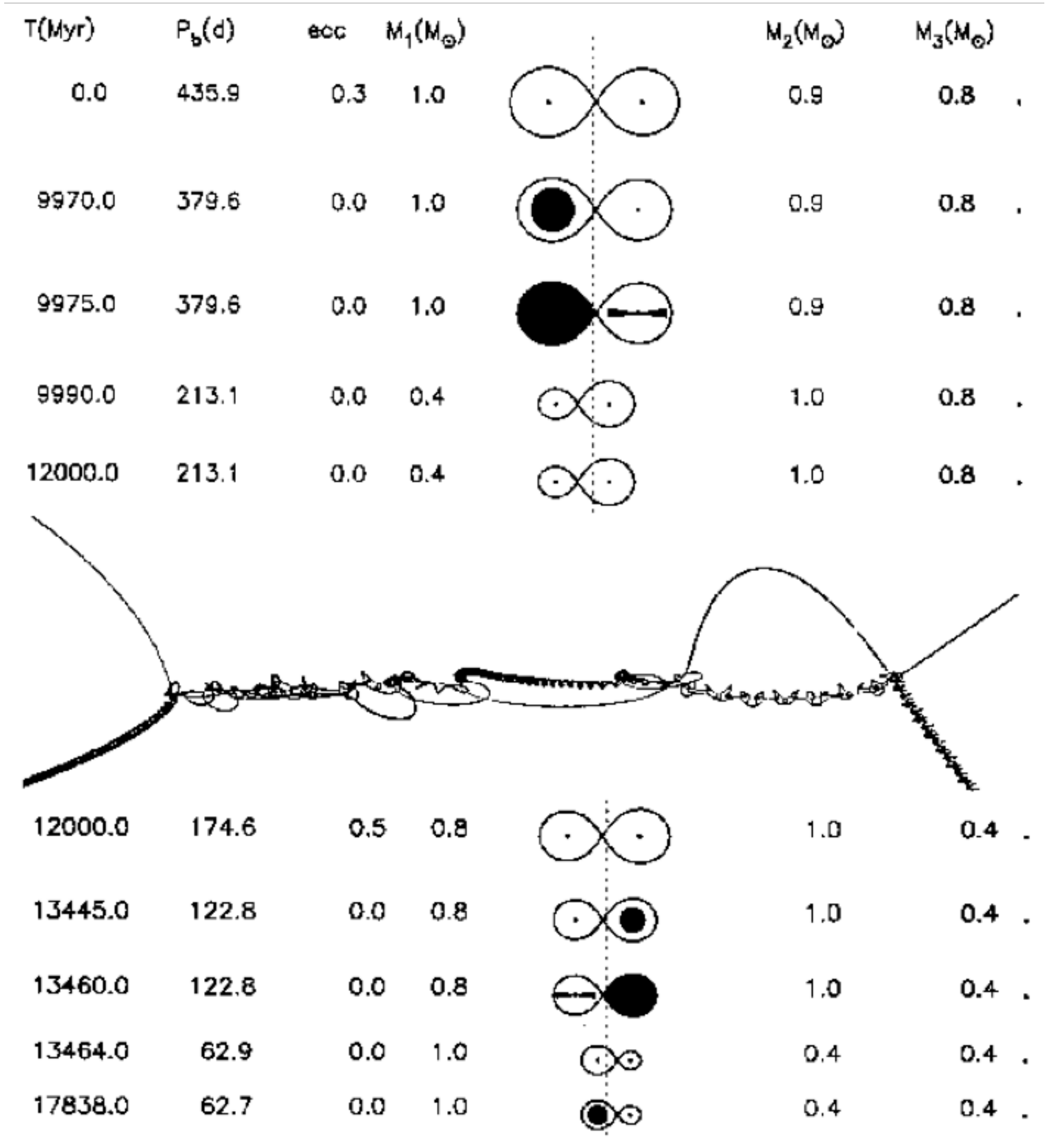
EVOLUTION OF THE BINARY POPULATION



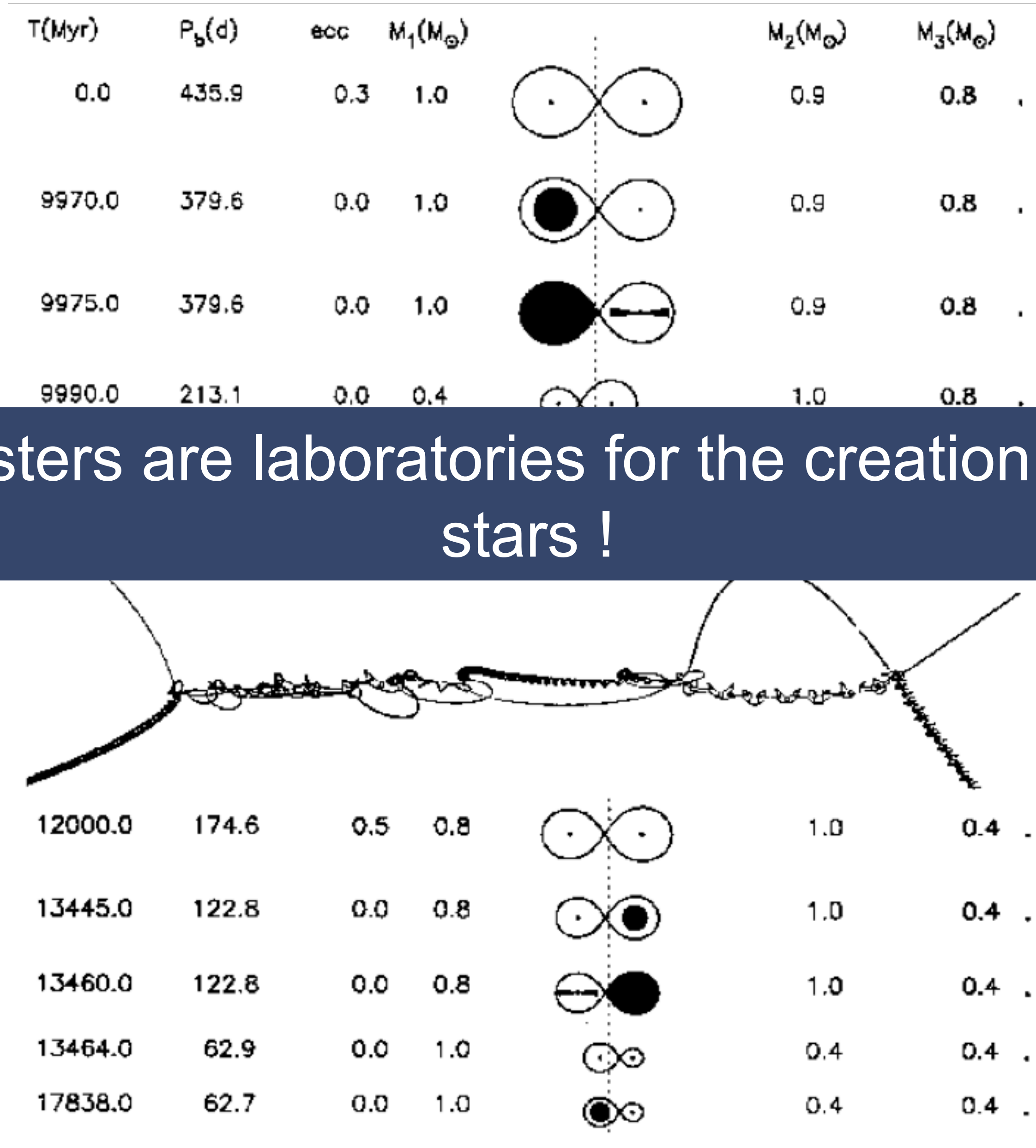
EVOLUTION OF THE BINARY POPULATION



BINARY-STELLAR EVOLUTION

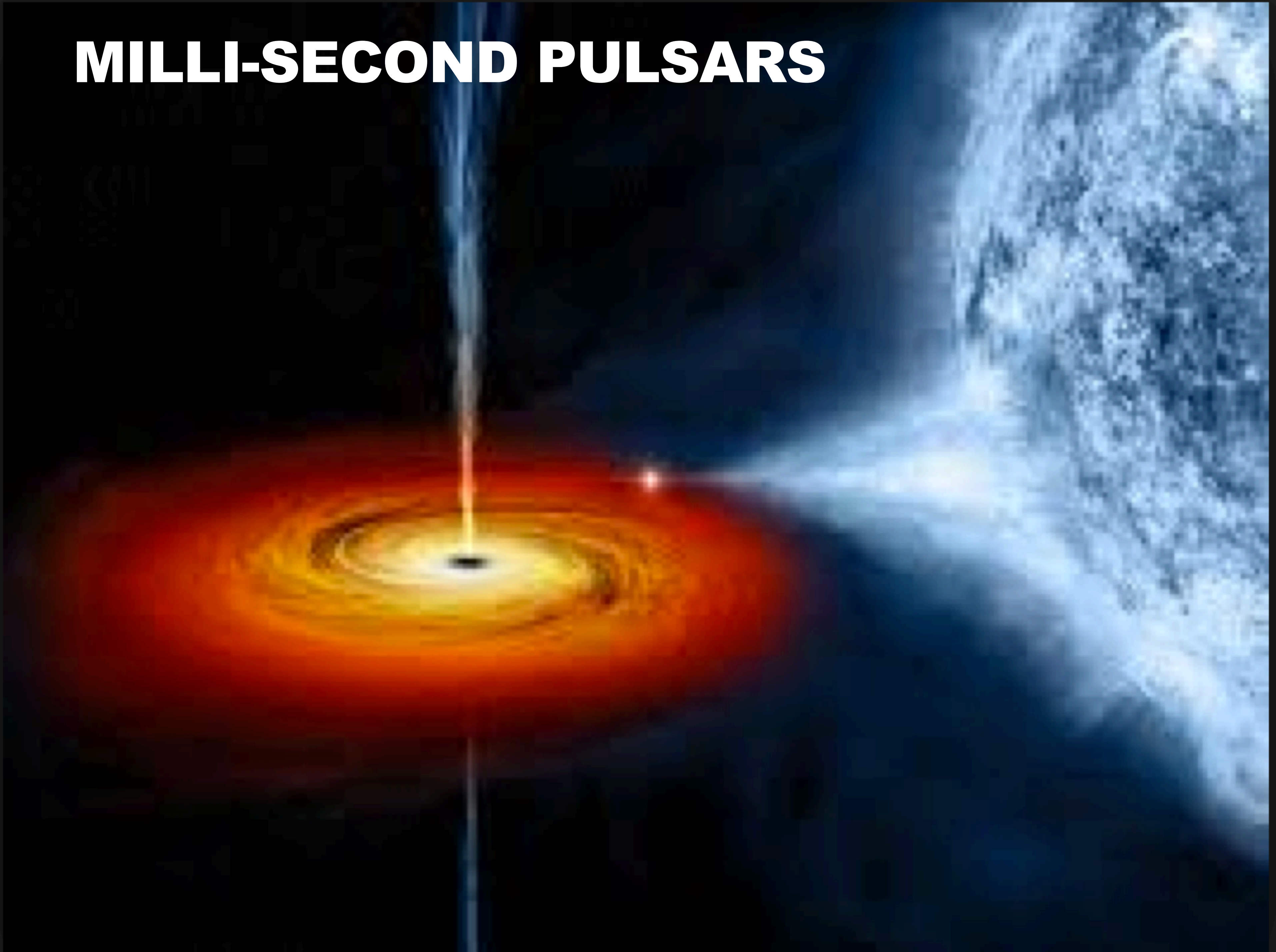


BINARY-STELLAR EVOLUTION



T(Myr)	P_b(d)	ecc	$M_1(M_\odot)$	$M_2(M_\odot)$	$M_3(M_\odot)$
0.0	435.9	0.3	1.0	0.9	0.8
9970.0	379.6	0.0	1.0	0.9	0.8
9975.0	379.6	0.0	1.0	0.9	0.8
9990.0	213.1	0.0	0.4	1.0	0.8
12000.0	174.6	0.5	0.8	1.0	0.4
13445.0	122.8	0.0	0.8	1.0	0.4
13460.0	122.8	0.0	0.8	1.0	0.4
13464.0	62.9	0.0	1.0	0.4	0.4
17838.0	62.7	0.0	1.0	0.4	0.4

Star clusters are laboratories for the creation of exotic stars !


MILLI-SECOND PULSARS

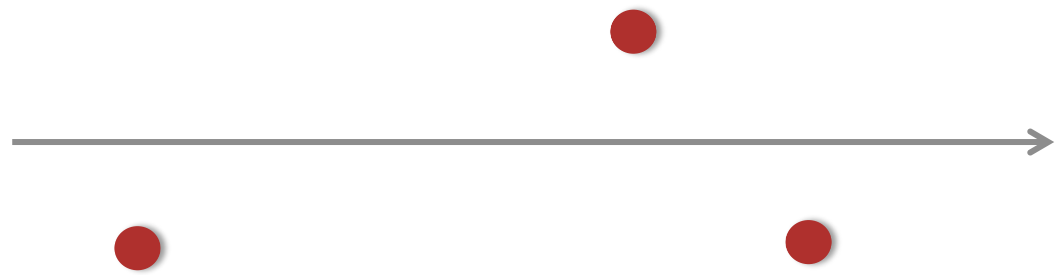
MILLI-SECOND PULSARS

- Pulsars spinning with periods between 1 to 10 milliseconds.
- Of the 200 discovered up to 2010, 130 were in globular clusters.

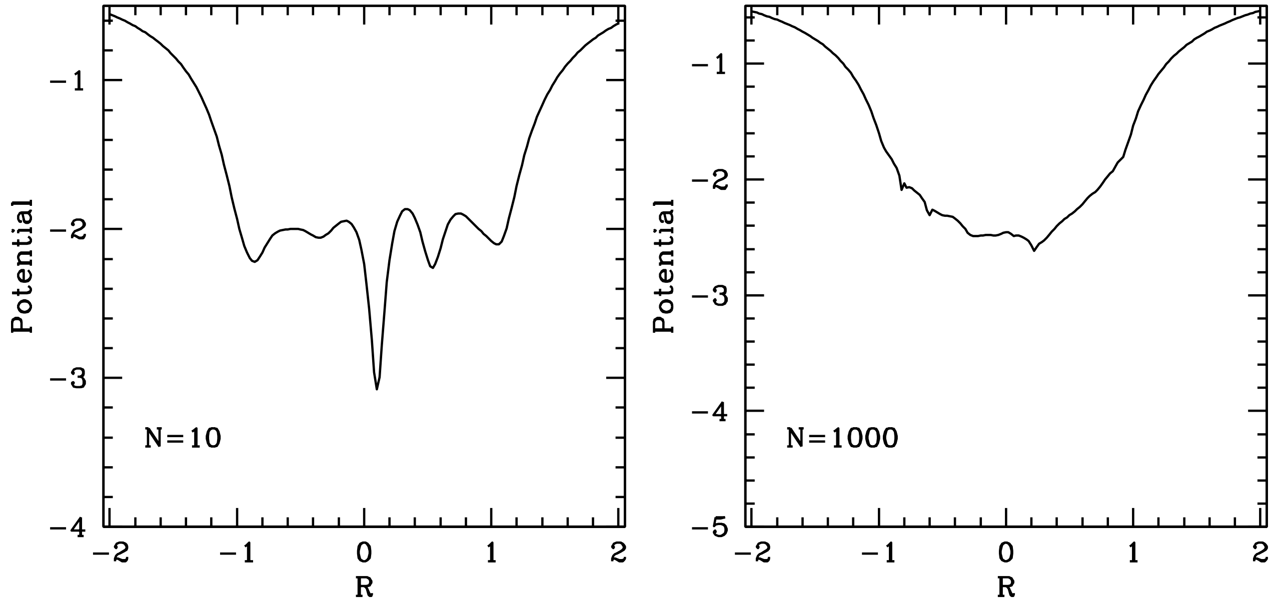
DYNAMICAL PROCESSES:

III) TWO-BODY RELAXATION

Imagine star moving through a cluster made up of other stars:



The potential experienced by the moving star will look like this:



The relaxation time is defined as the time it takes for a star to change its orbital energy due to encounters by an amount equal to its initial energy:

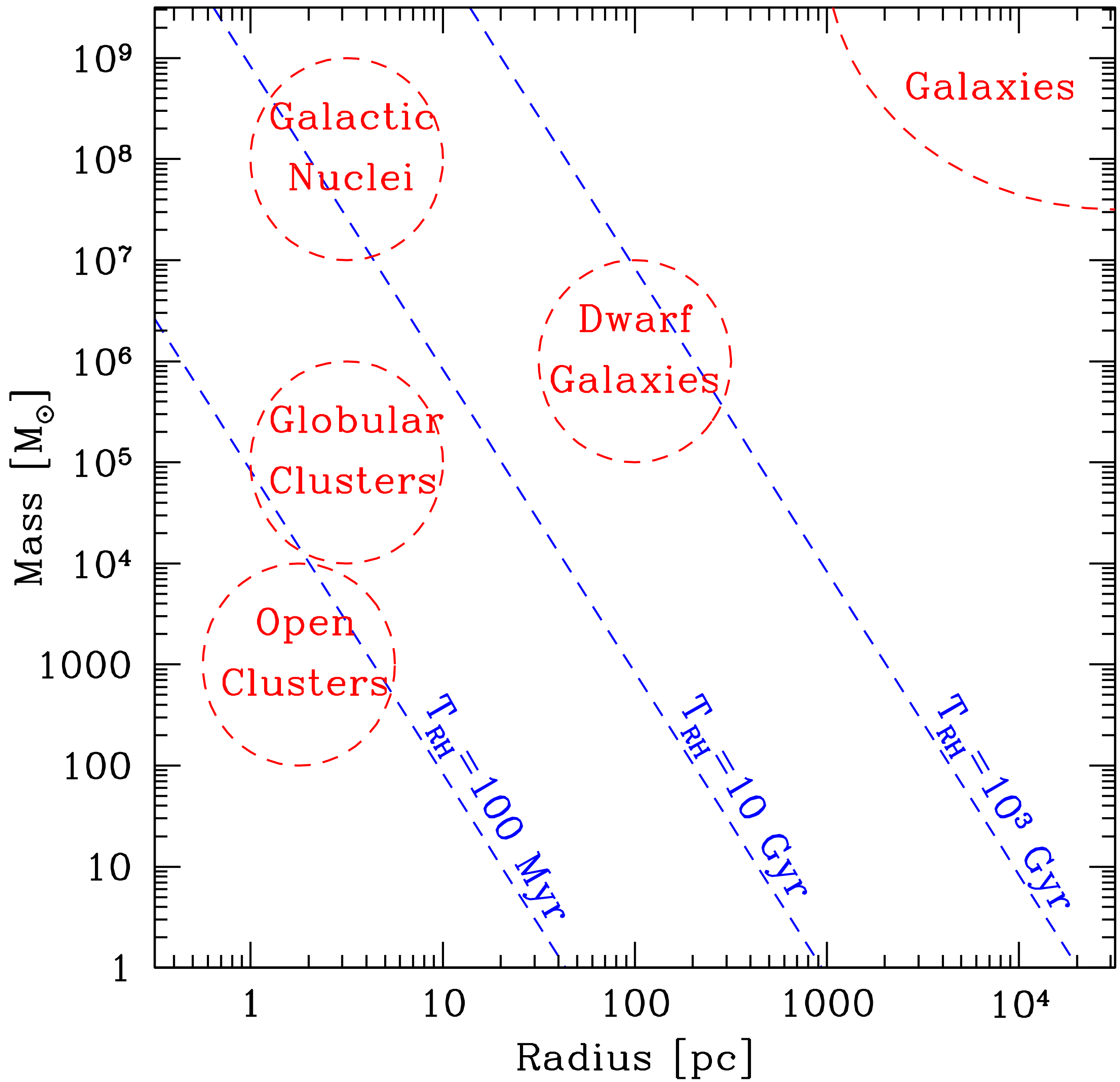
$$T_{\mathrm{Rel}} = \frac{E_{Orb}}{\frac{dE_{Orb}}{dt}}$$

The half-mass relaxation time of a star cluster is given by (Chandrasekhar 1942, Spitzer 1987):

$$T_{RH} = 0.138 \frac{\sqrt{M}\, R_H^{3/2}}{<m> \sqrt{G} \ln \gamma N}$$

M = Cluster mass, R_H = half-mass radius, <m> = mean stellar mass, N = number of cluster stars, γ = constant in Coulomb logarithm = 0.11 (Giersz & Heggie 1995)

RELAXATION TIME OF STELLAR SYSTEMS



EFFECTS OF RELAXATION

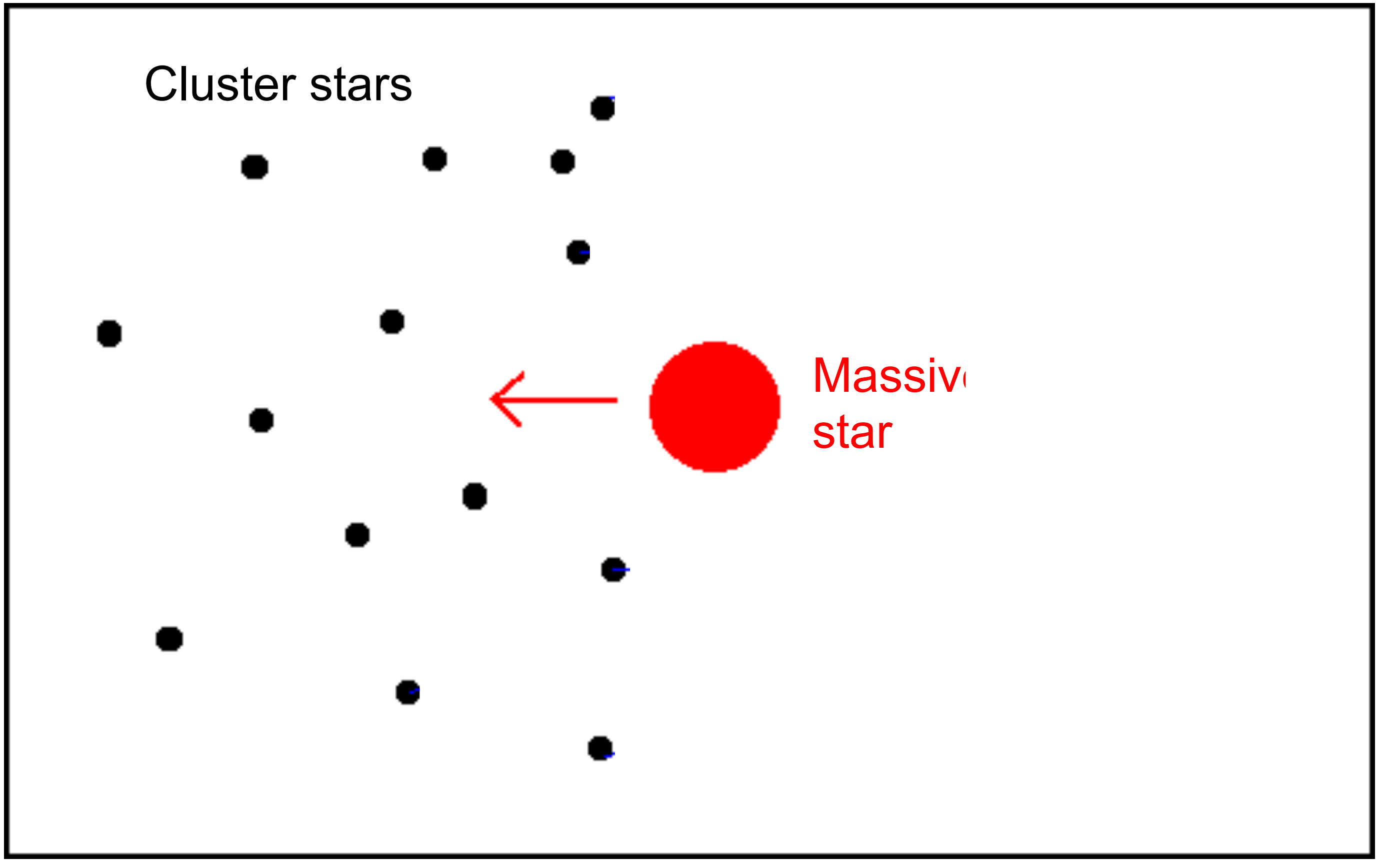
- Dynamical friction and mass segregation

  More massive stars lose energy and sink into the centre of the cluster, less massive stars gain energy and are pushed outwards

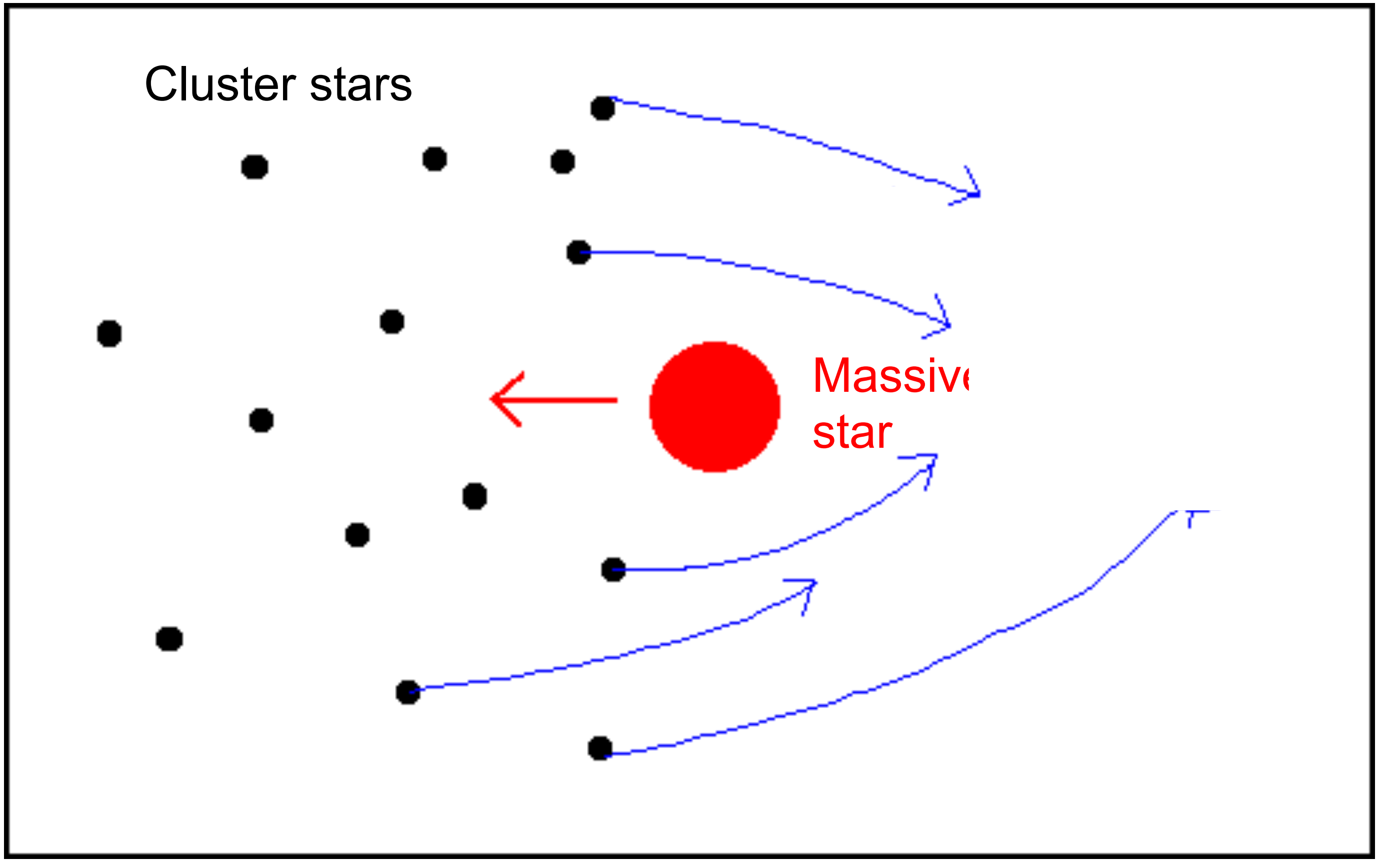
- Star cluster dissolution

  Stars that gain enough energy are pushed beyond the tidal radius and are removed from the cluster

DYNAMICAL FRICTION



DYNAMICAL FRICTION



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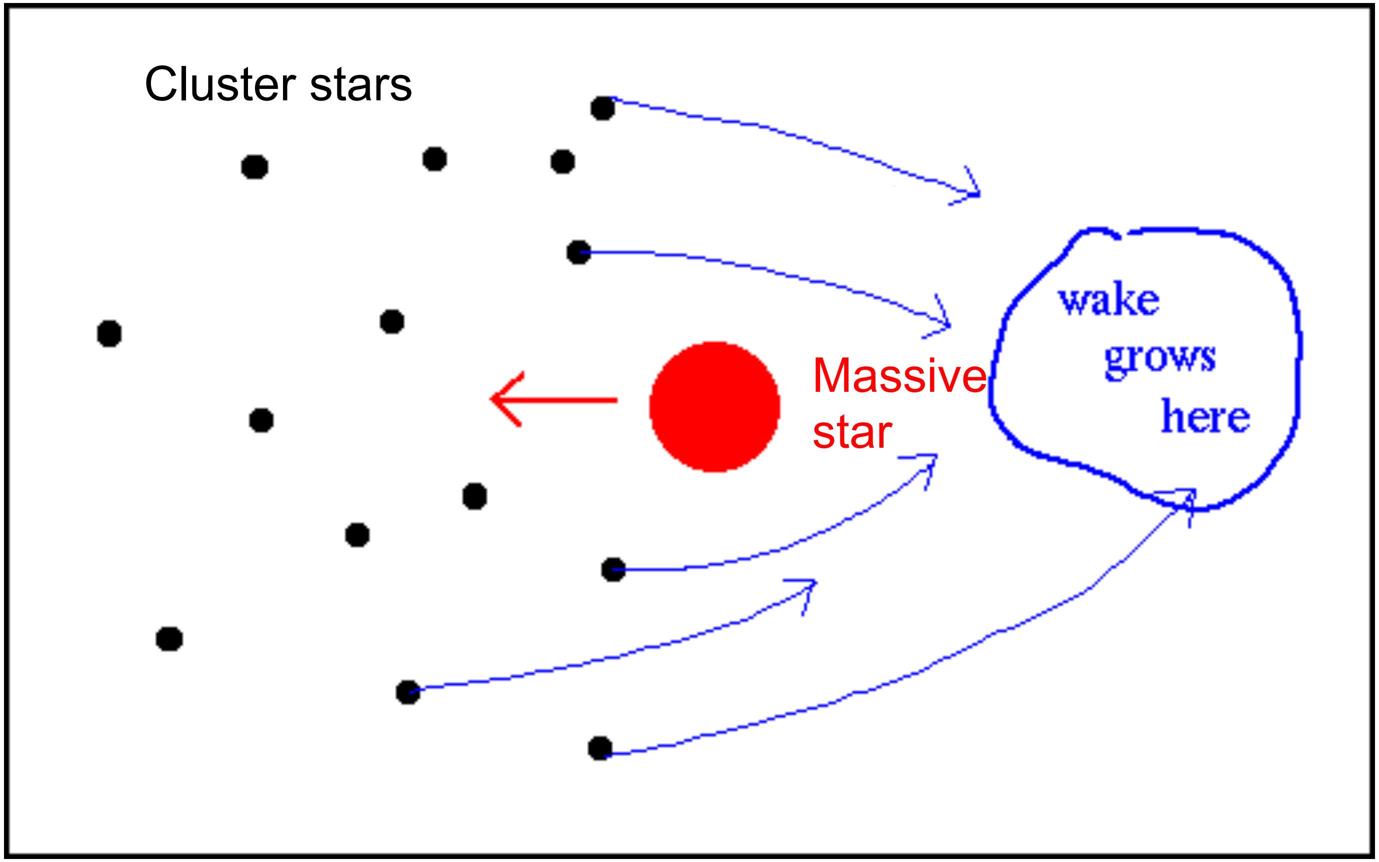
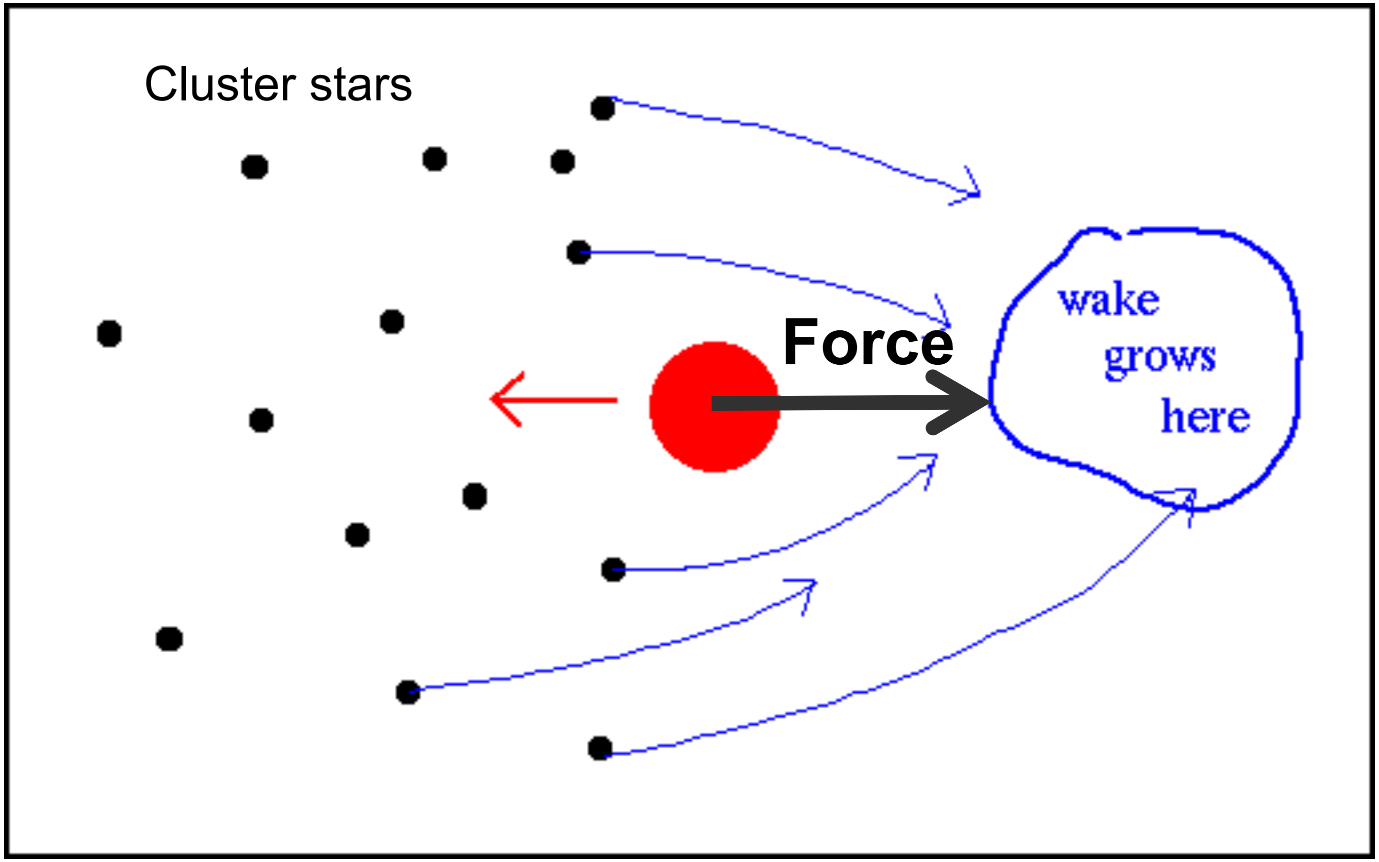


DYNAMICAL FRICTION



DYNAMICAL FRICTION

The result of dynamical friction is that a cluster evolves towards **energy equipartition**, so that **at each radius** the kinetic energy of stars of different masses are the same:

$$m_1 v_1^2 = m_2 v_2^2$$

DYNAMICAL FRICTION

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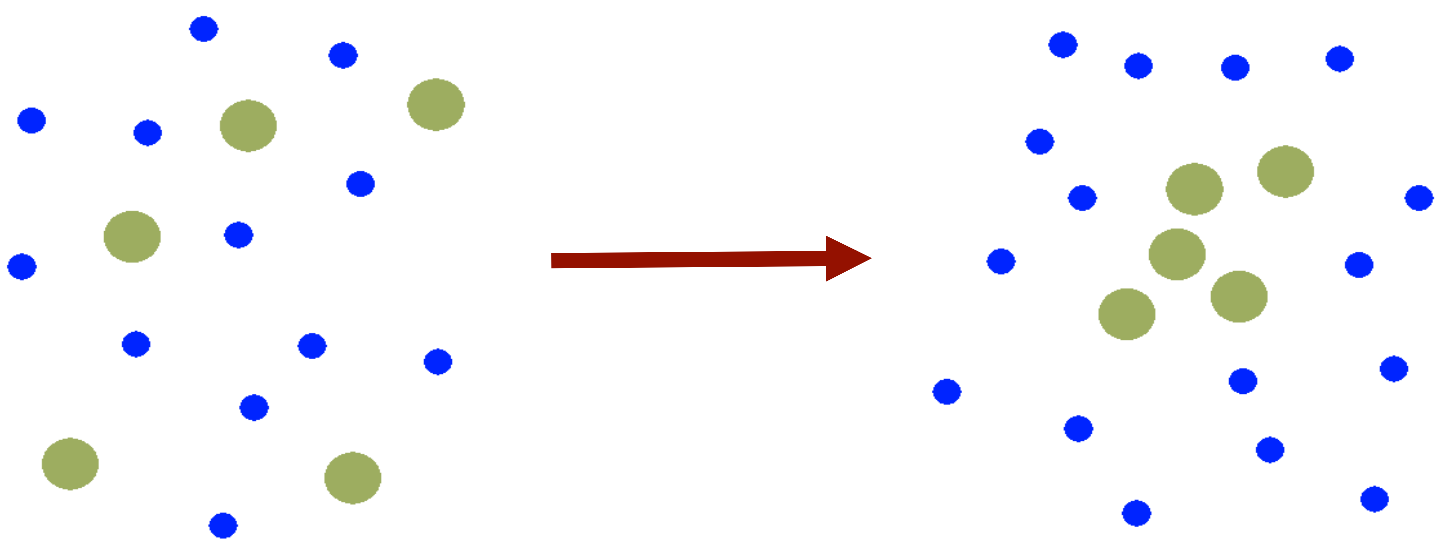
This implies that massive stars will sink towards the center of the cluster:

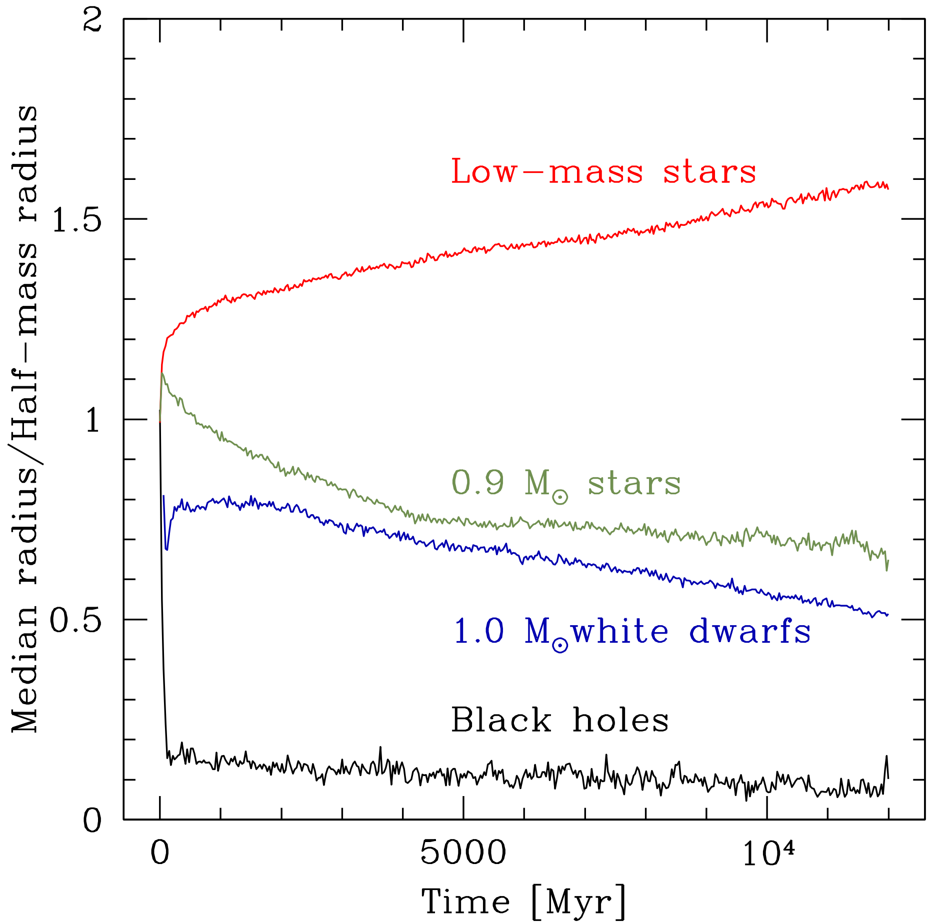


MASS SEGREGATION

Massive O, B type stars and black holes can reach the cluster centre within a few Myr.

The inspiral of all other stars takes many Gyr. In a typical globular cluster the giant stars are more concentrated than the average cluster star.

➔**M/L ratio is not going to be constant over the cluster.**



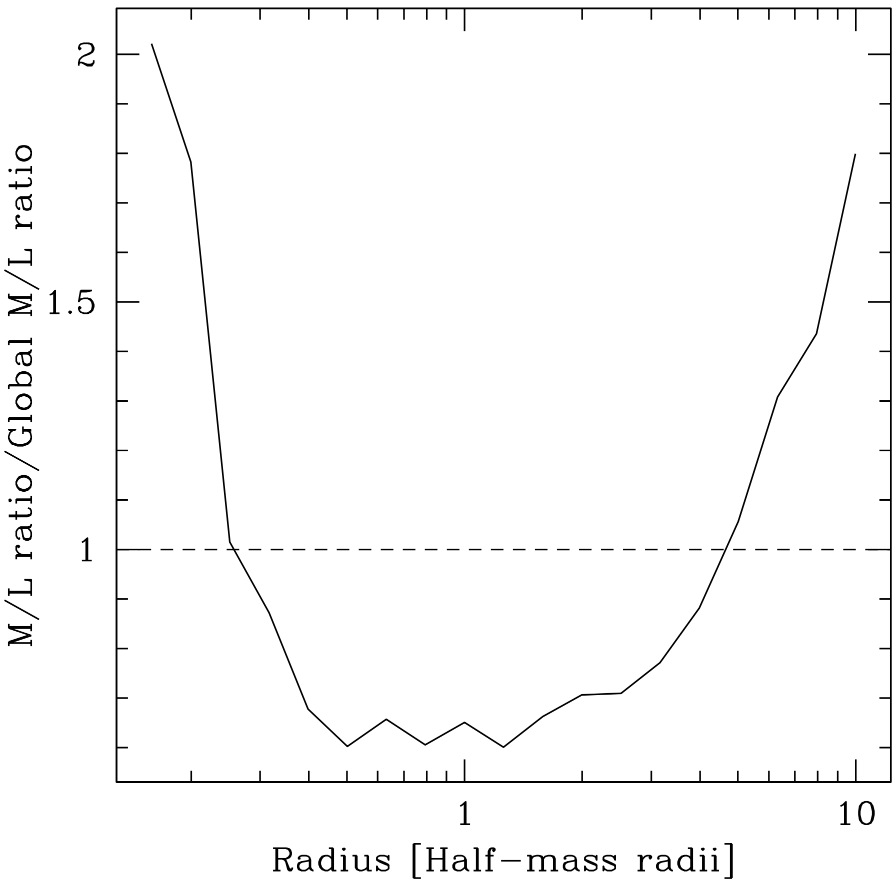
Complete energy equipartition is not achieved over the lifetime of star clusters (Giersz & Heggie 1997, Baumgardt & Makino 2003, Trenti & van der Marel 2013).

MASS SEGREGATION

The M/L ratio of a globular cluster is typically lowest around the half-mass radius.

It is higher in the cluster outskirts due to the large number of low-mass stars that have been pushed there due to two-body relaxation.

It is also high at small radii due to the white dwarfs which have segregated into the centre.



CORE-COLLAPSE

Image a single-mass cluster where one can group the cluster stars into two categories:

Core stars which sit in the inner parts and move fast.

Halo stars which sit in the outer parts and move only slowly.

If a core star encounters a halo star they will exchange orbital energy. As a result, the core star will slow down and the halo star will speed up.

CORE-COLLAPSE

However self-gravitating systems are systems with negative heat capacity!

Speed up and you will move out of the potential well and become slower.

Slow down and you will sink into the potential well and become faster.

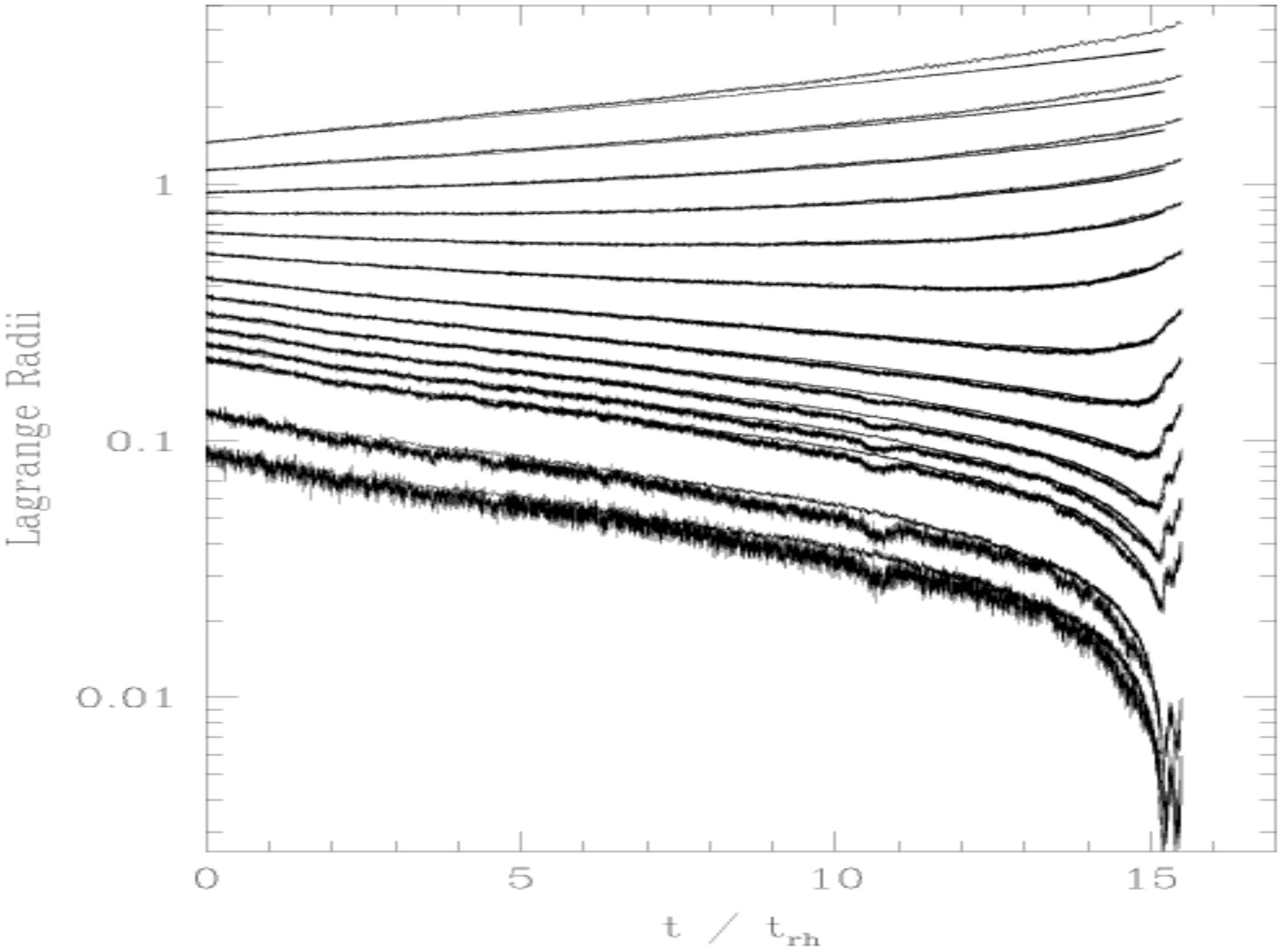
CORE-COLLAPSE

The net result of the interactions is therefore that the core contracts and the core stars get on average faster, while the halo expands and the halo stars get slower.

As a result the velocity difference between core and halo becomes even more pronounced and a runaway process sets in.

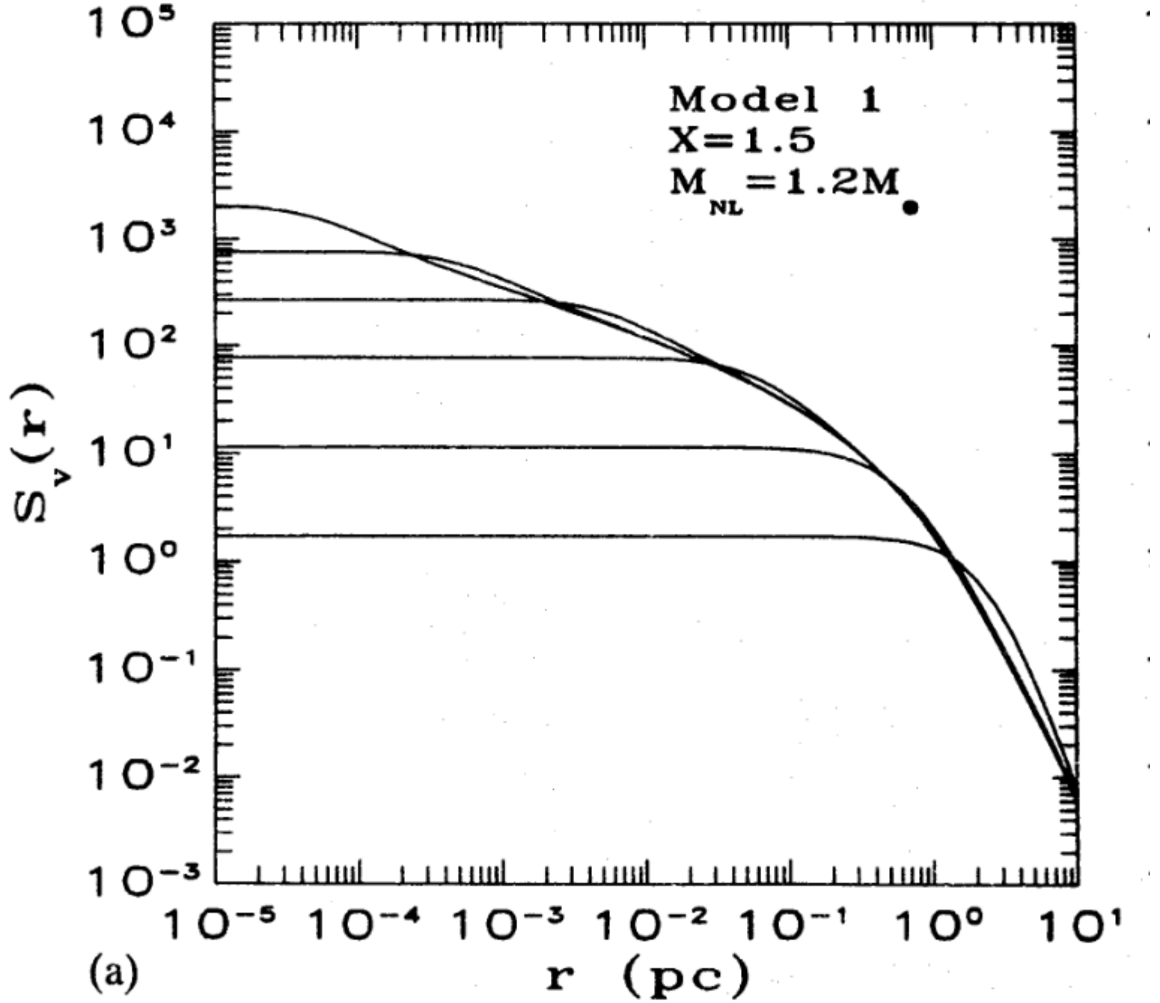
This process is known as core-collapse (Antonov 1962, Lynden-Bell & Wood 1968).

CORE-COLLAPSE EVOLUTION



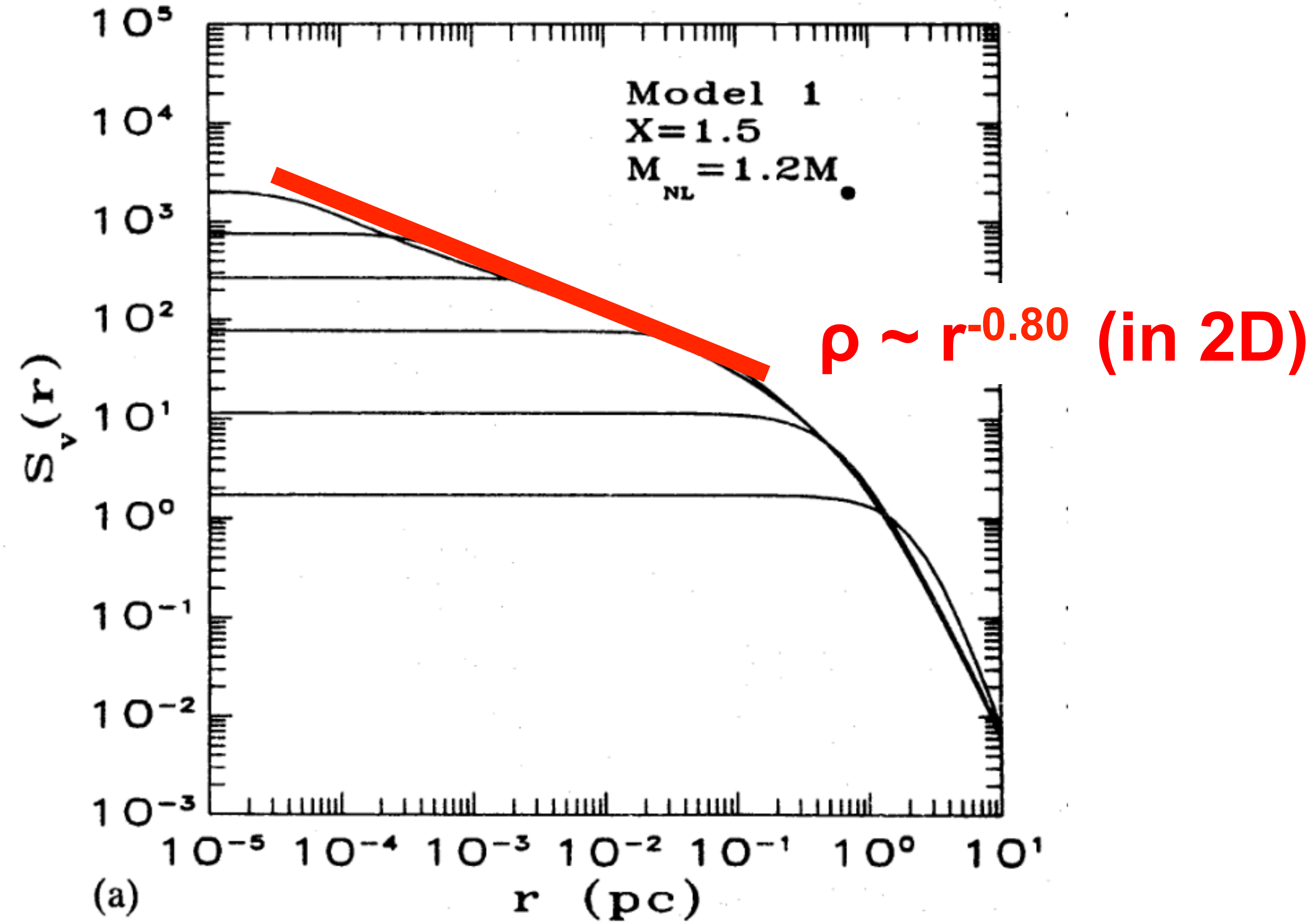
from Joshi et al. (2000)

CORE-COLLAPSE EVOLUTION



from Murphy&Cohn (1988)

CORE-COLLAPSE EVOLUTION



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