DYNAMICAL EVOLUTION OF STELLAR SYSTEMS

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OVERVIEW

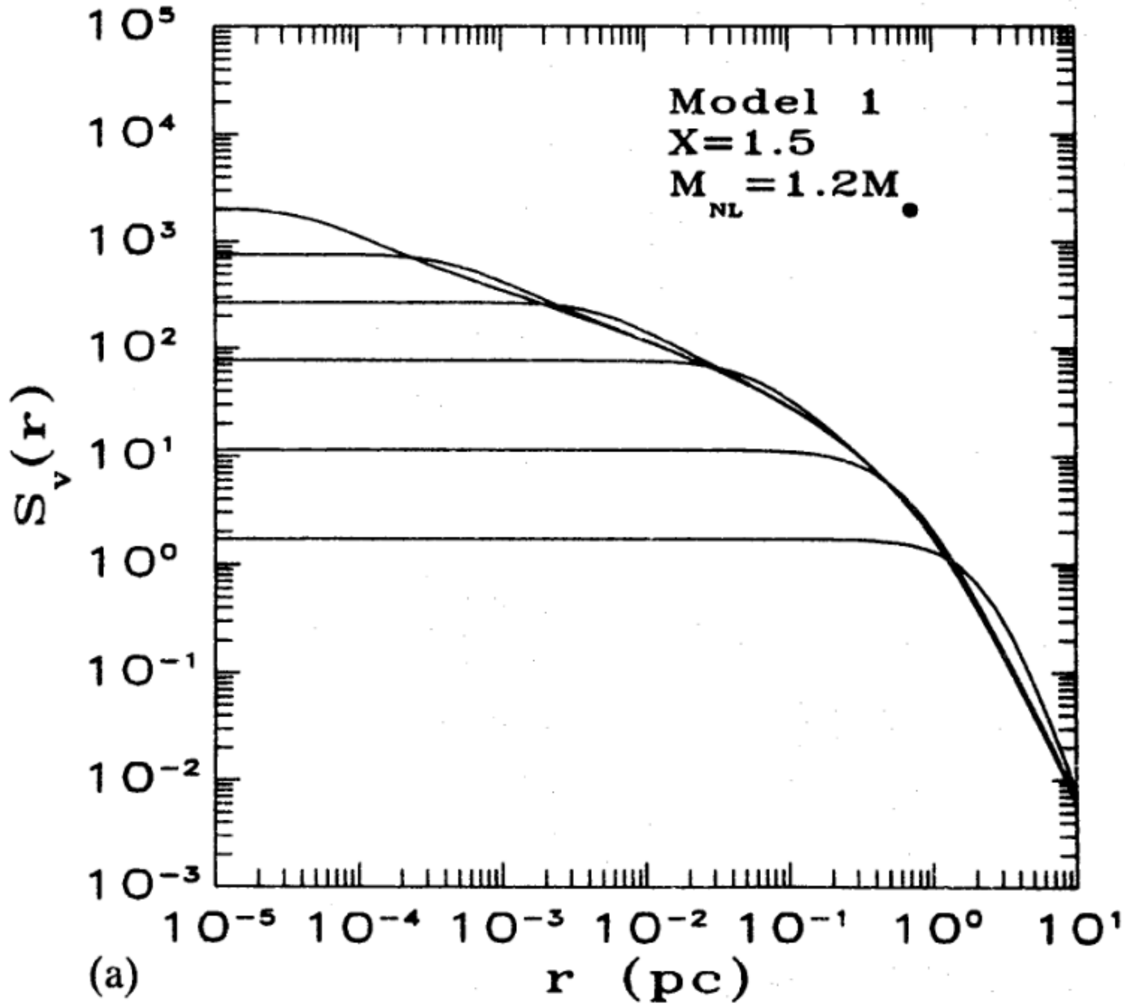
- **Lecture 1:**
  - Dynamical Processes in Star Clusters.
  - Core Collapse and two-body Relaxation
- **Lecture 2:**
  - Dissolution of Star Clusters
  - Ultra-Compact Dwarf Galaxies
- **Lecture 3:**
  - Nuclear Clusters and Massive Black Holes

DYNAMICAL PROCESSES

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

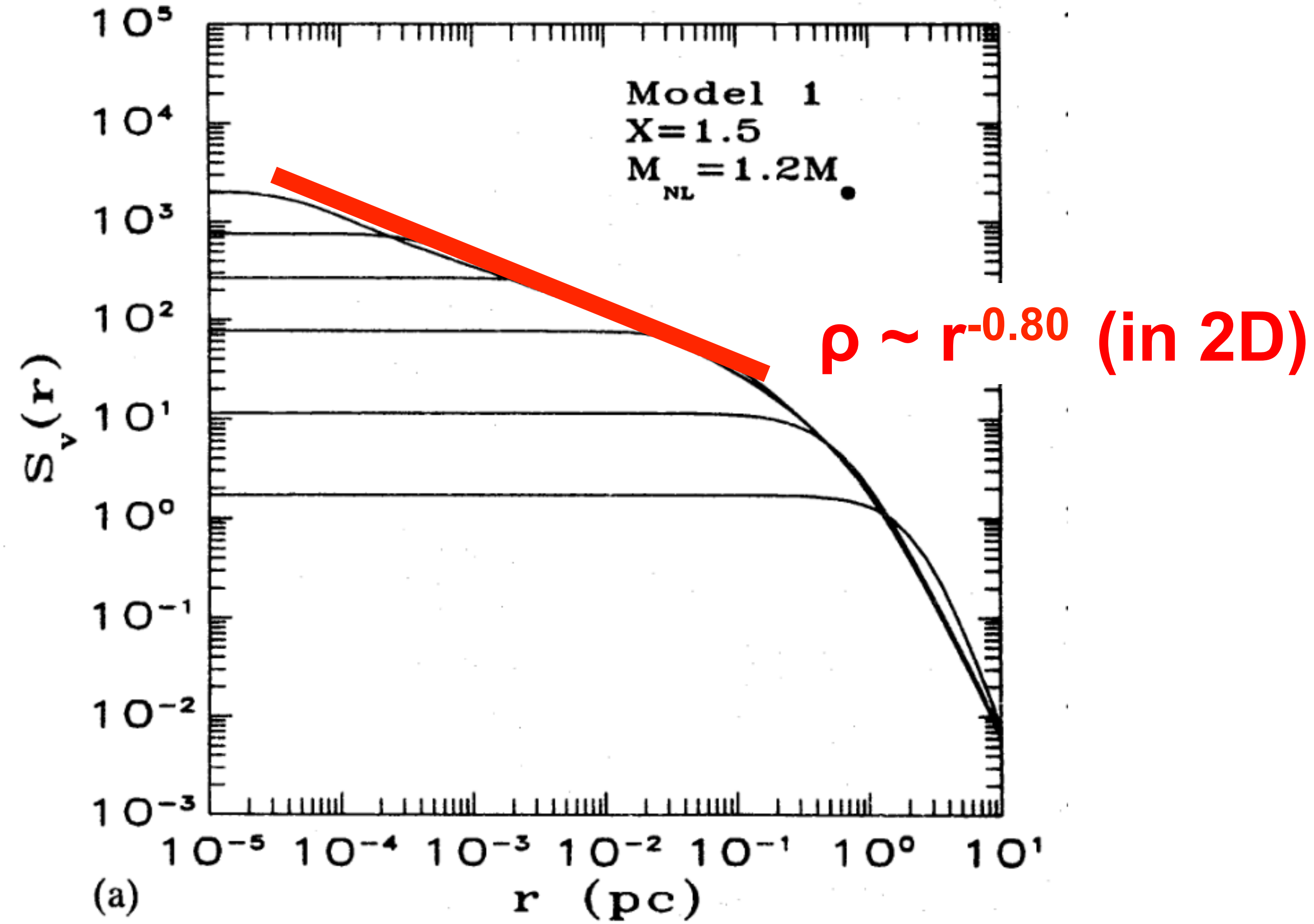
Time

CORE-COLLAPSE EVOLUTION



from Murphy&Cohn (1988)

CORE-COLLAPSE EVOLUTION



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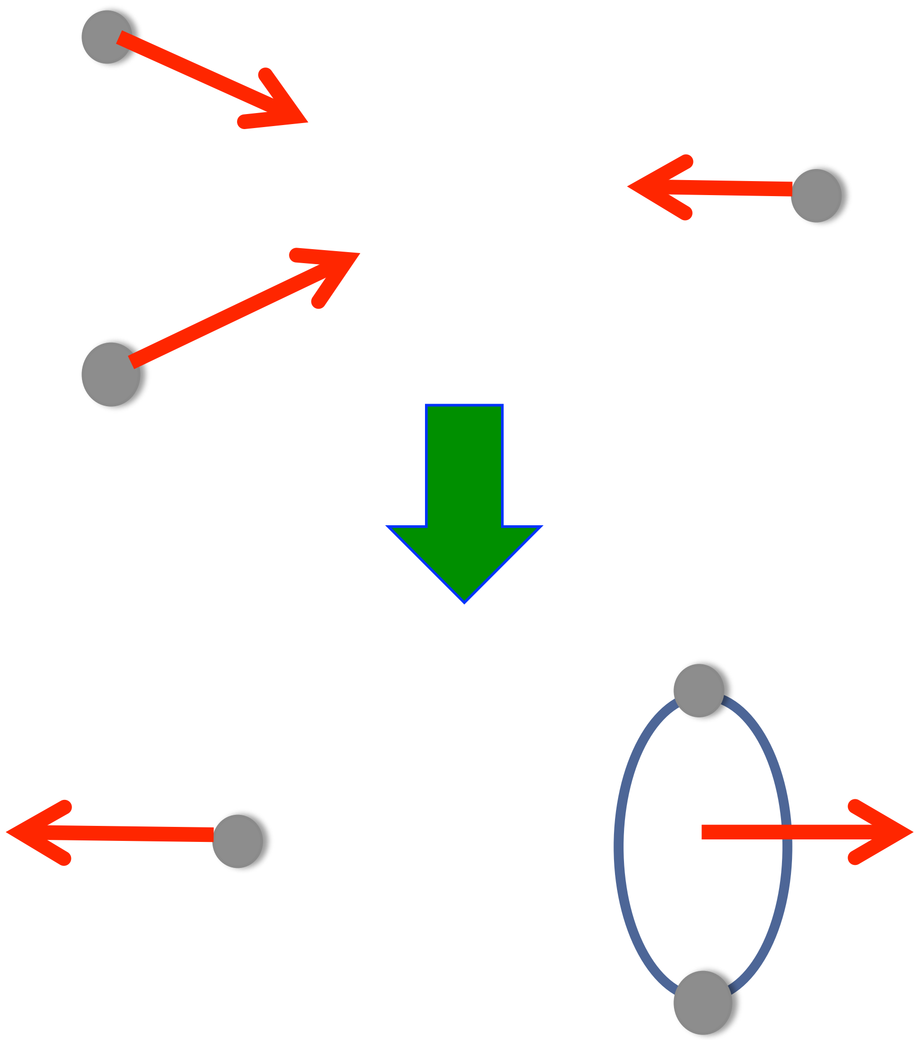
I) BINARY FORMATION THROUGH THREE-BODY INTERACTIONS



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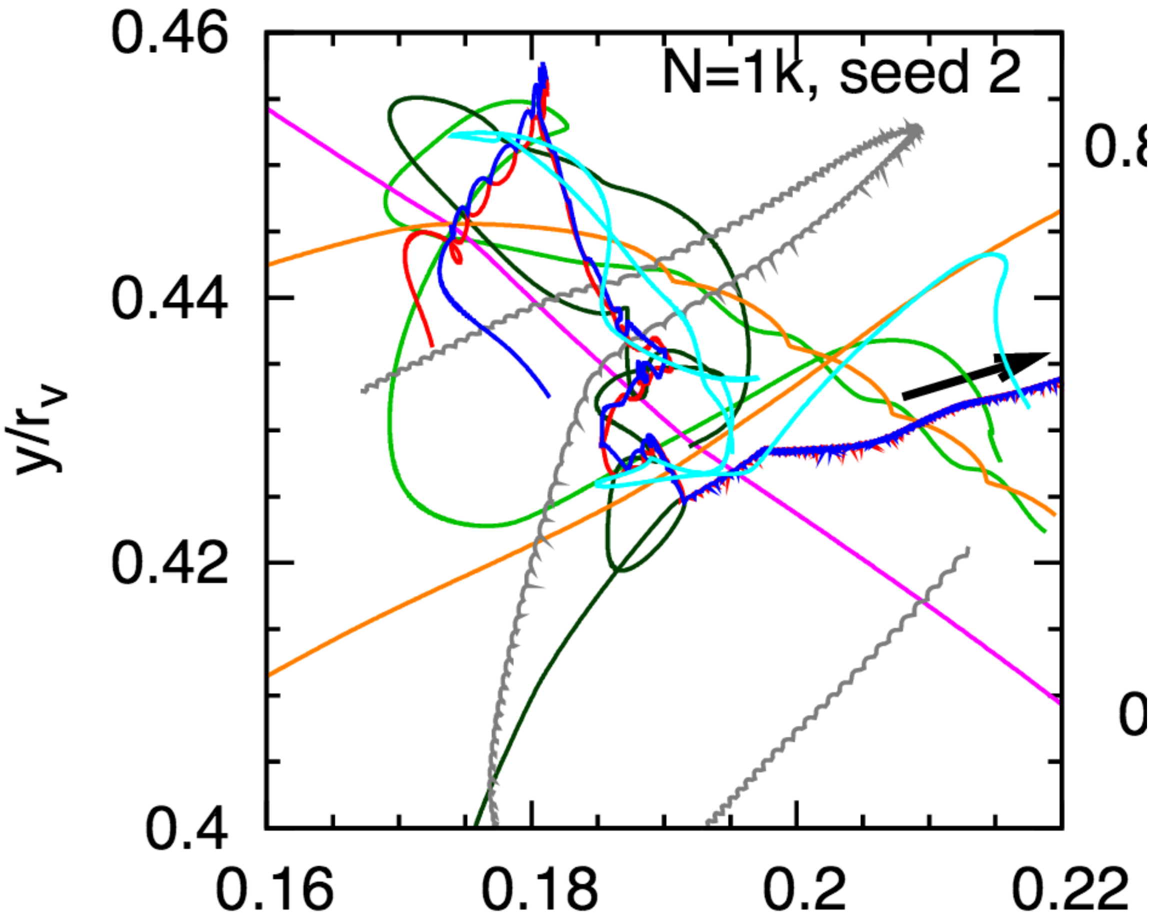
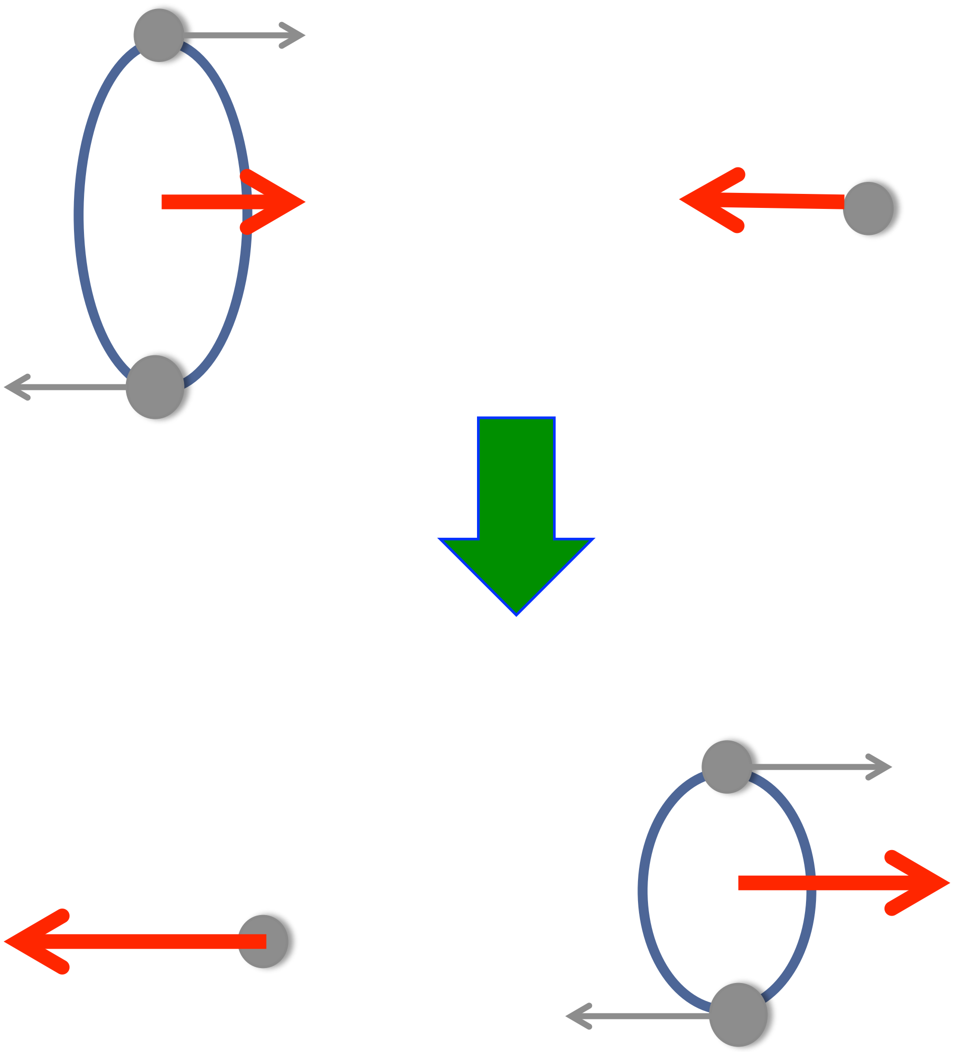


from Tanikawa et al. (2011)

II) BINARY HARDENING

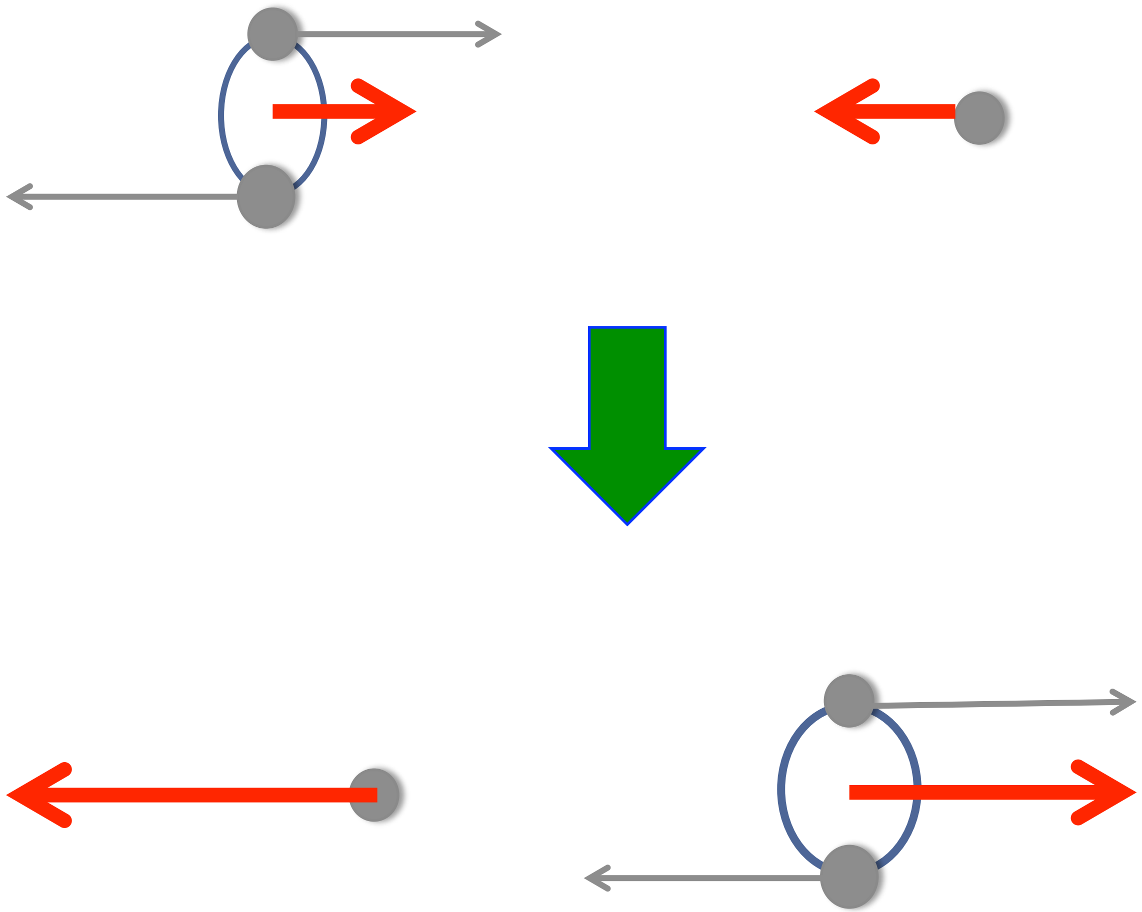


II) BINARY HARDENING AS HEAT SOURCE FOR THE STAR CLUSTER

	Star	Star cluster
Energy generation	Nuclear reactions in the core	Binary interactions in the core
Energy transport	Convection and radiation	Orbital motion and two-body interactions
Energy loss	Radiation from surface	Escapers

Radius

III) BINARY EJECTIONS

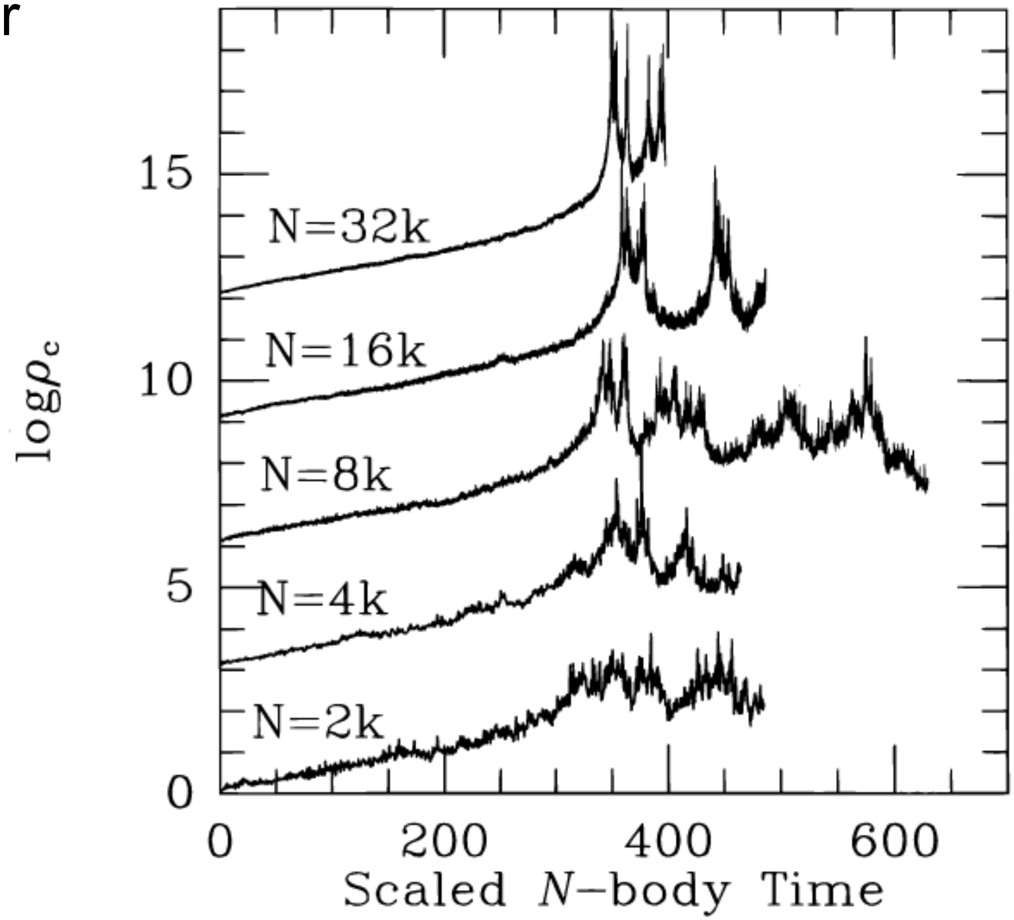


POST-COLLAPSE EVOLUTION

- Core collapse is halted when the core becomes so small that it contains only a few dozen stars.
- At this point binaries form through three body interactions.
- These binaries harden by further encounters and provide an energy source for the core.
- If a binary is ejected, the core can re-collapse until a new binary is formed. This process is known as gravothermal oscillations (Bettwieser & Sugimoto 1986).

POST-COLLAPSE EVOLUTION

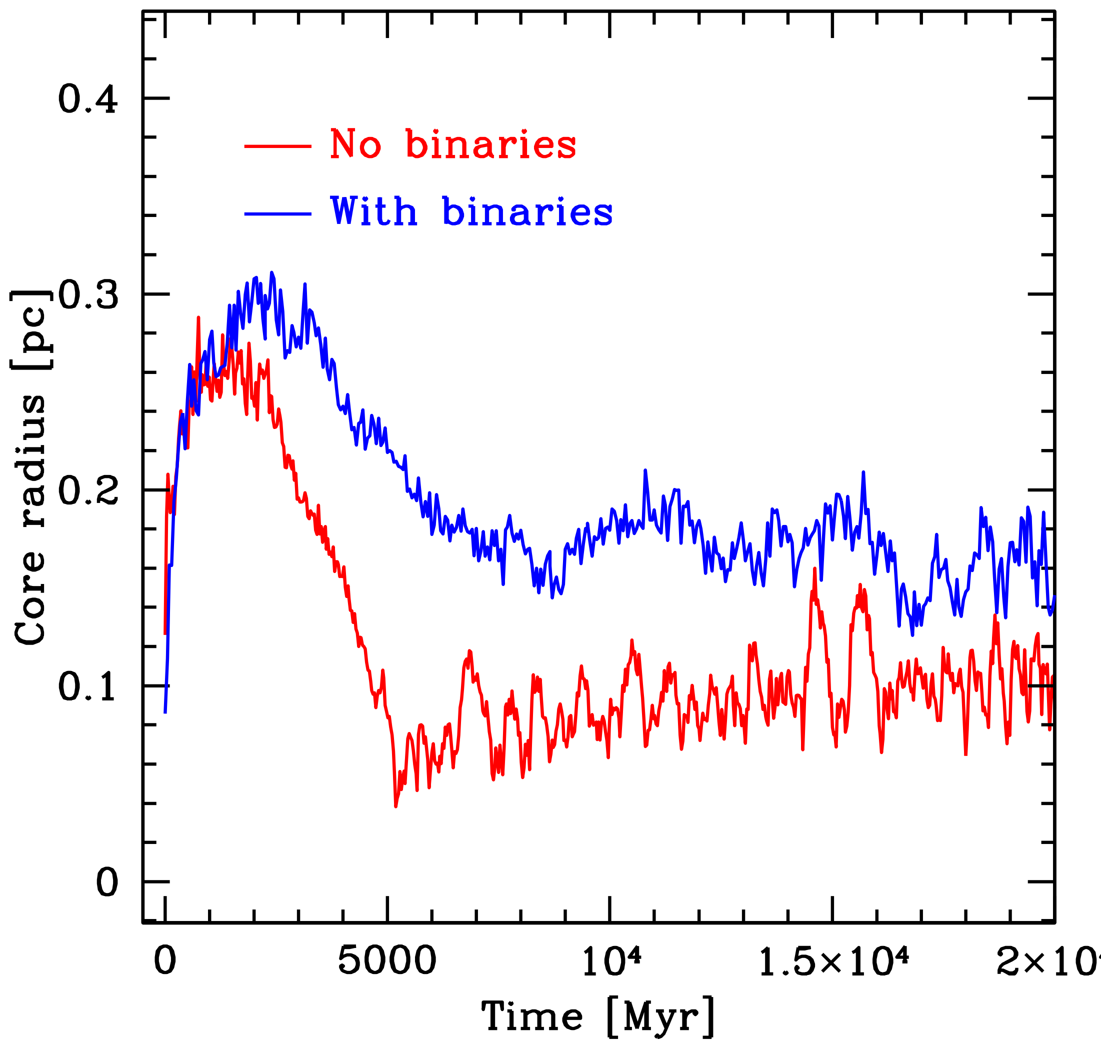
Evolution of central density for star clusters with different particle numbers showing core-collapse and post-collapse oscillations.



from Makino (1996)

POST-COLLAPSE EVOLUTION

Primordial binaries soften post-collapse oscillations and lead to clusters with larger core sizes (Hurley 2008).



POST-COLLAPSE EVOLUTION

After core collapse, cluster starts expanding due to binary heating.

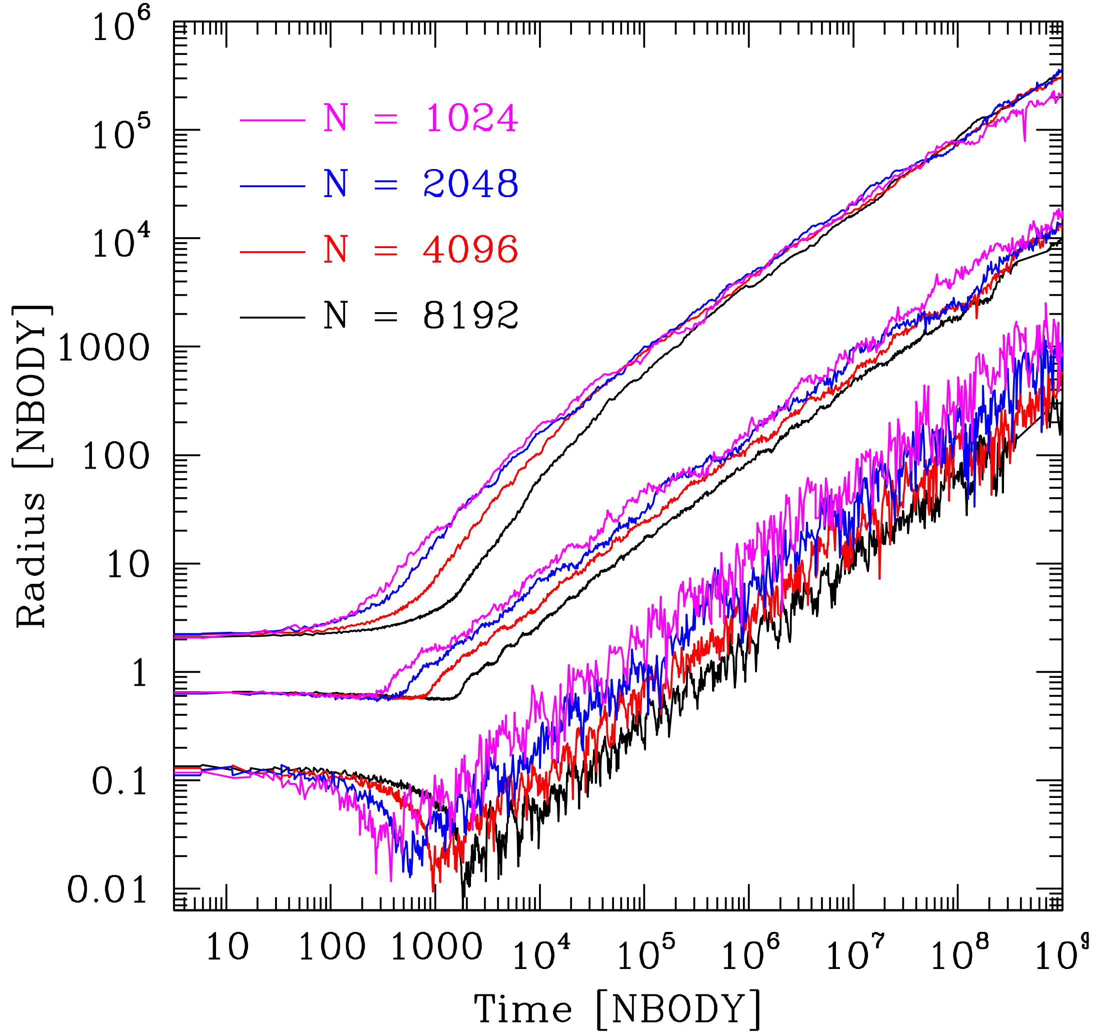
Expansion is described by the following equation:

$$\frac{dr_h}{dt} \sim \frac{r_h}{T_{RH}} = \frac{1}{\sqrt{r_h}}$$

which leads to a scaling

$$r_h \sim t^{2/3}$$

for **isolated** star clusters.



from Baumgardt et al. (2002)

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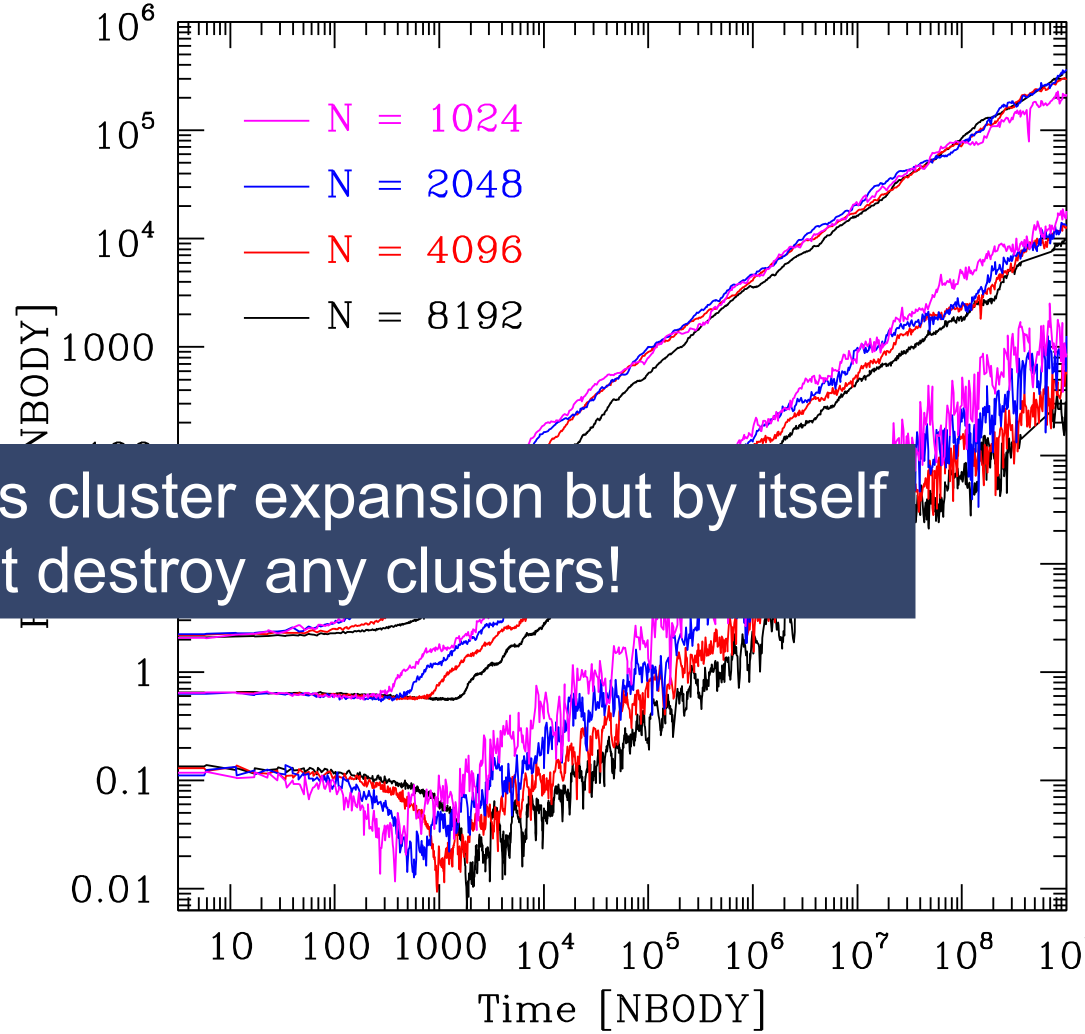

from Baumgardt et al. (2002)

Relaxation causes cluster expansion but by itself does not destroy any clusters!

DYNAMICAL PROCESSES

IV) EXTERNAL TIDAL EFFECTS

Two different types of tides:

Steady tidal field:

External galaxy puts a tidal force on all stars in the cluster. Strength of tidal force increases with distance from the centre of the cluster while grav. force from other stars decreases. There has to be a radius where the galactic tidal force is stronger and stars are pulled away from the cluster.

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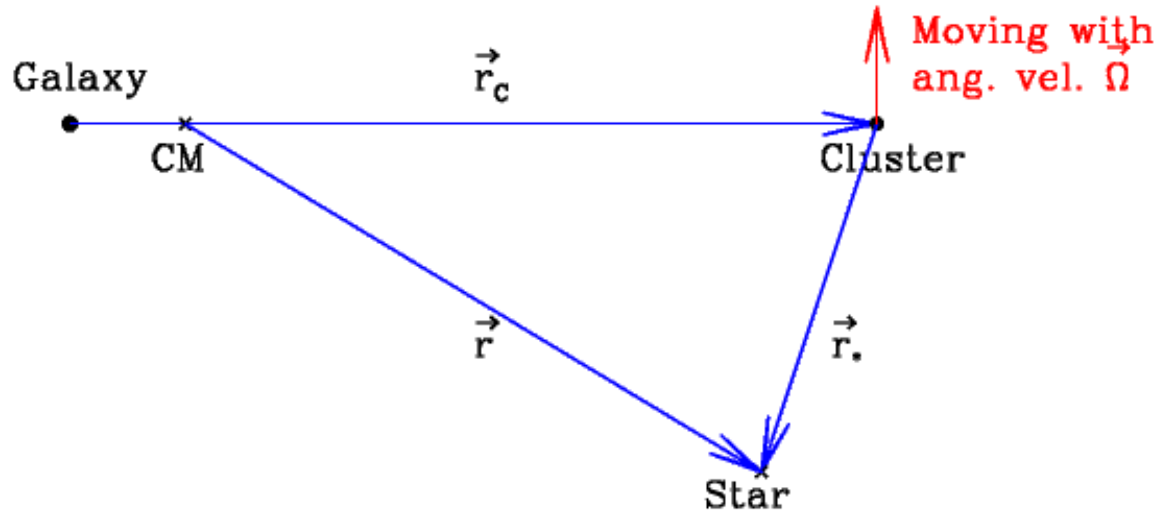
Tidal shocks:

Tidal shocks occur when star clusters pass near a molecular cloud, move through the disc of a spiral galaxy or are move on eccentric orbits.

In order to understand effect of a constant tidal field, go into rotating coordinate system:



Equation of motion:

$$\frac{d^2\vec{r}_R}{dt^2} = \frac{d^2\vec{r}_I}{dt^2} - 2\vec{\Omega} x \vec{v} - \vec{\Omega} x \left(\vec{\Omega} x \vec{r}\right) - \frac{d\vec{\Omega}}{dt} x \vec{r}$$

3 additional terms: Coriolis, centrifugal and Euler-force

For a star in a cluster which moves in a circular orbit around an external galaxy, the so-called Jacoby energy is a conserved quantity:

$$\begin{aligned} E_J &= \frac{1}{2}\dot{\vec{r}}^2 + \phi(r) - \frac{1}{2}\left|\vec{\Omega}\times\vec{r}\right|^2 \\ &= \frac{1}{2}\dot{\vec{r}}^2 + \phi_{eff}(r) \end{aligned}$$

with $$\phi_{eff}(r) = -\frac{GM_G}{\left|\vec{r}-\vec{r}_G\right|} - \frac{GM_C}{\left|\vec{r}-\vec{r}_C\right|} - \frac{1}{2}\left|\vec{\Omega}\times\vec{r}\right|^2$$

being the so-called effective potential.

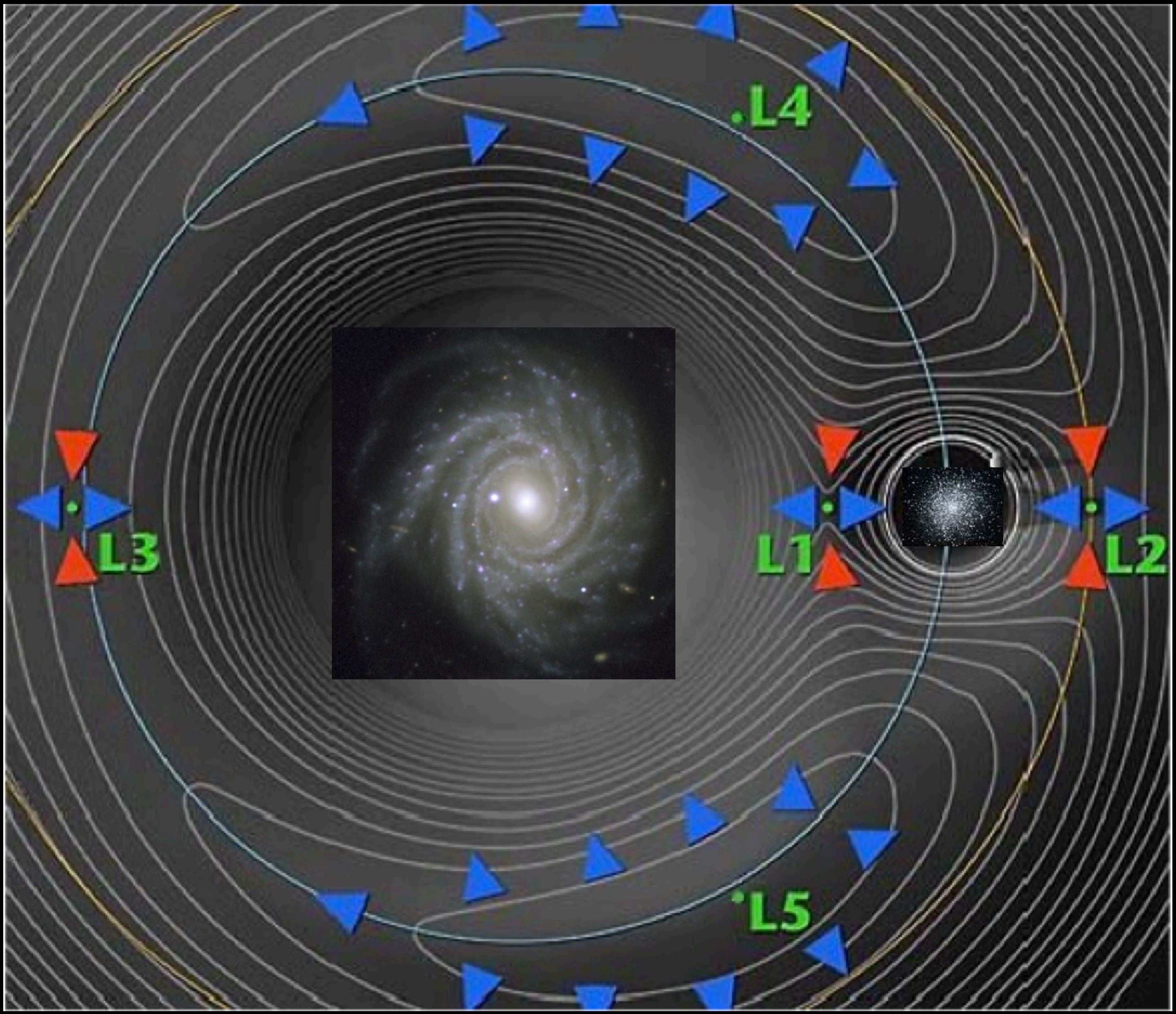
Contour-lines of constant effective potential ϕ_{eff} for two orbiting point-masses:

L1-L3:

Saddle points

L4 and L5:

Maxima



For a point-mass galaxy, the tidal radius (i.e. the distance of the Lagrange points L1and L2 form the centre of the cluster is given by:

$$r_t = \left(\frac{M_C}{3M_{Gal}}\right)^{1/3} R$$

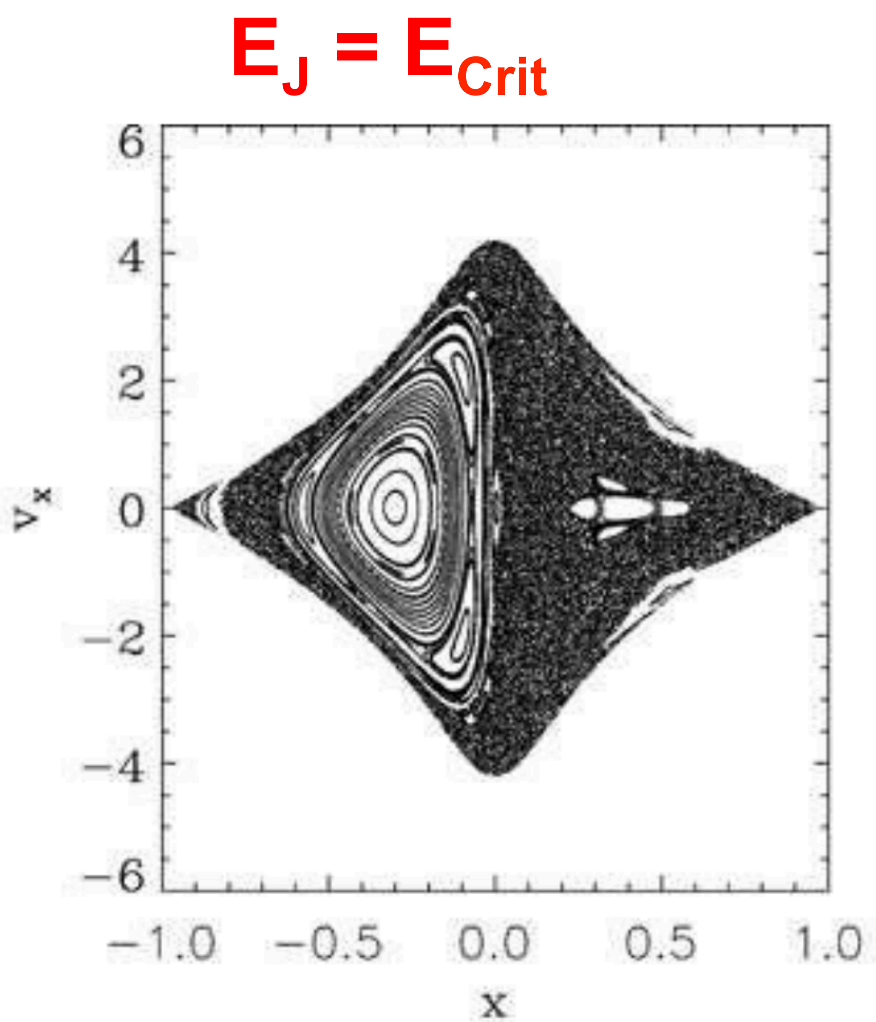
And the critical Jacoby energy needed for escape is given by:

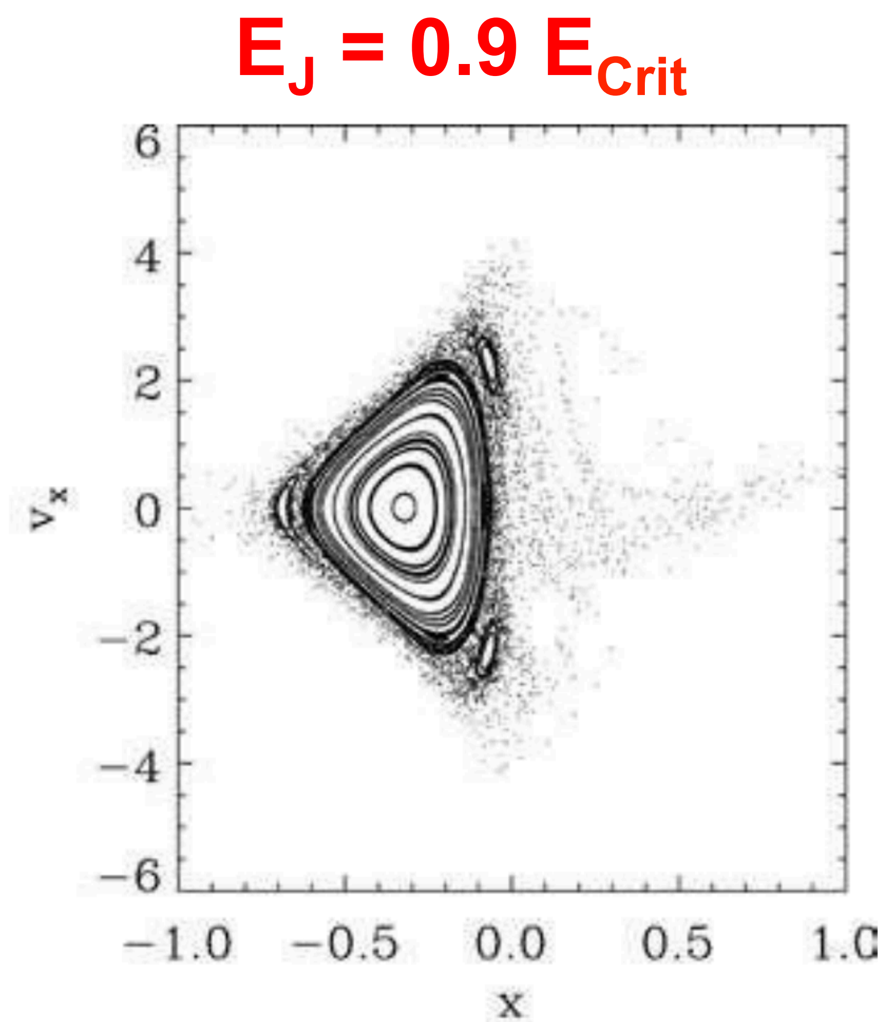
$$E_{Crit} = -\frac{3}{2}\frac{GM_C}{r_t}$$

If a star has an energy $E<E_{crit}$ it can't escape. If it has a Jacoby energy only slightly larger than E_{Crit} , it has to make many crossings of the cluster before it finds a hole near one of the Lagrange points L1 or L2.

Retrograde stars can be trapped even if $E>E_{crit}$.

POINCARÉ SURFACE OF SECTION PLOT FOR STARS AT TWO DIFFERENT JACOBY ENERGIES





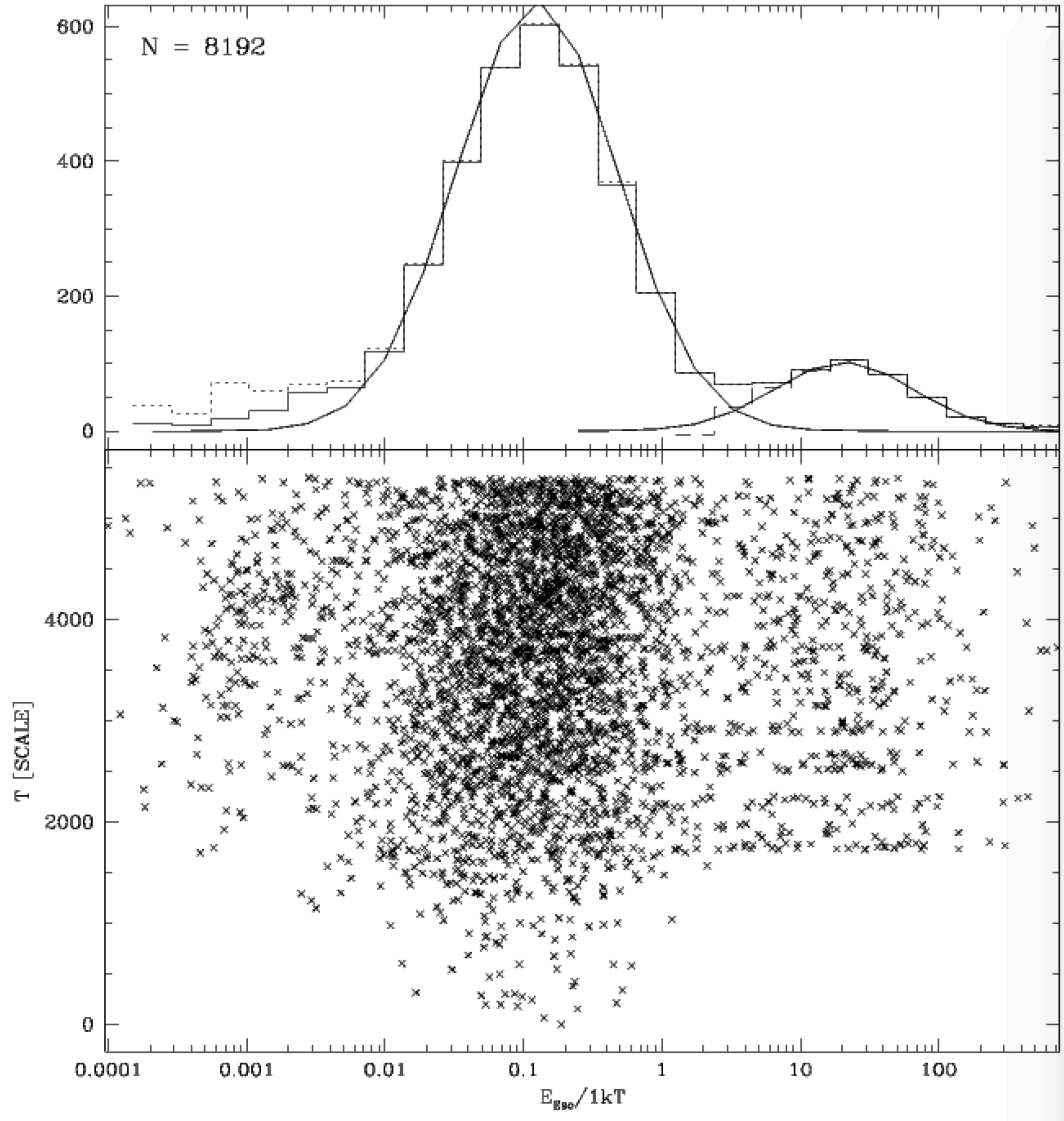
from Ernst et al. (2008)

Energy distribution of stars escaping from a star cluster:

Bi-modal distribution:

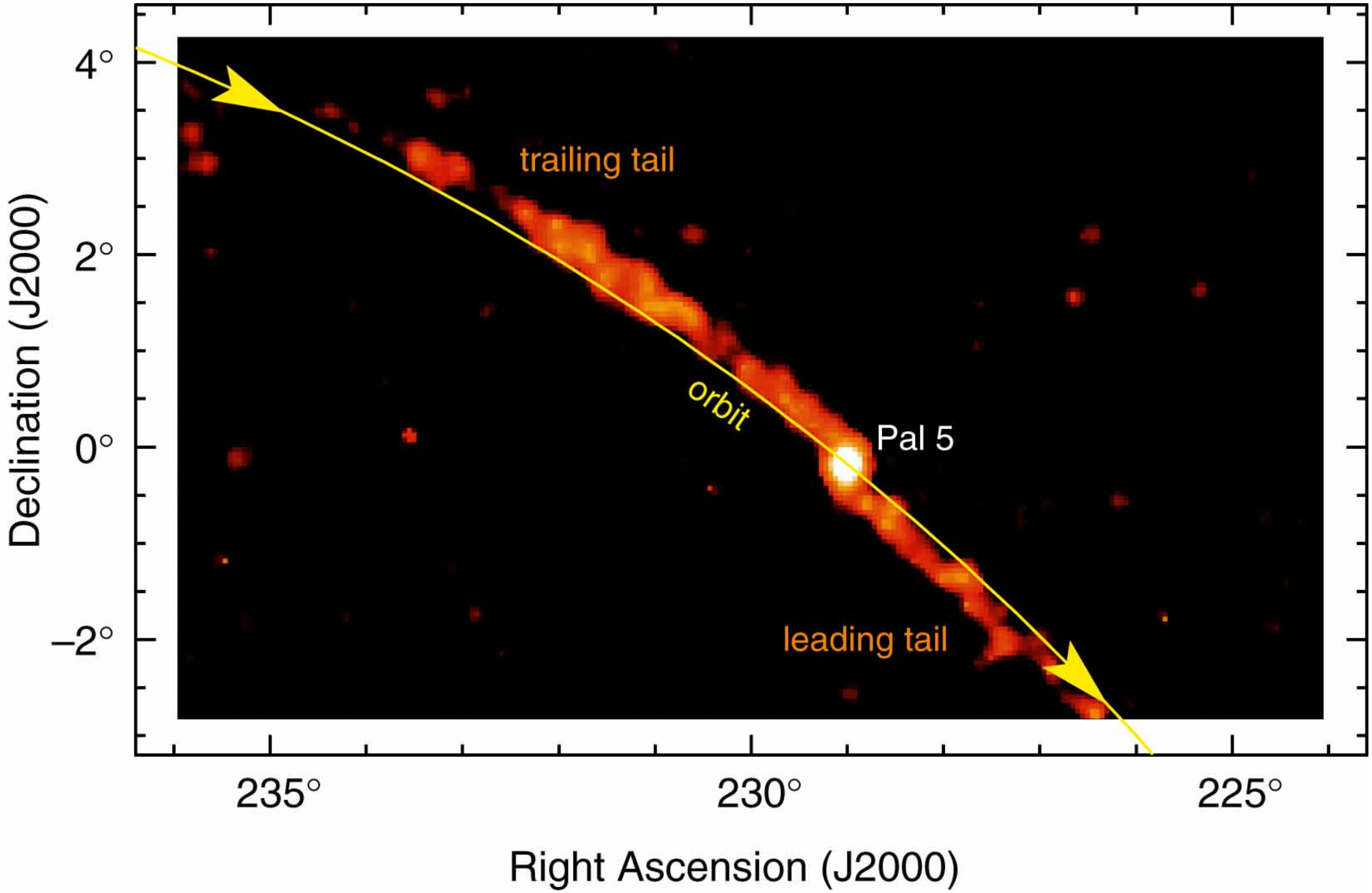
a) Slow escapers due to relaxation

b) Fast escapers due to binary scatterings in the cluster core



from Baumgardt et al. (2002)

Escaping stars can leave the cluster only through the Lagrange points L1 and L2. Once they have left the cluster, the Coriolis force deflects them and the stars follow the orbit of the cluster, leading to the formation of tidal tails:



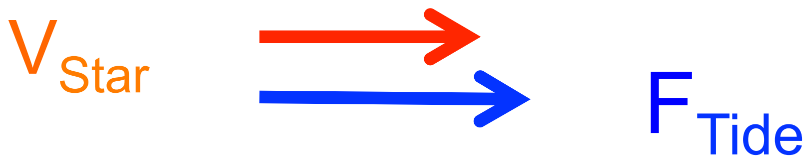
ECCENTRIC ORBITS

For clusters on eccentric orbits, the strength of the external tidal field varies along the orbit. The changing tidal field changes the orbital energy of the stars.

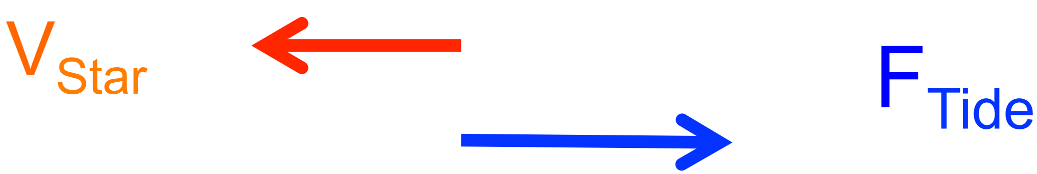
As a result, no analogue to the Jacoby energy exists in this case.

ECCENTRIC ORBITS

Some stars will move in the direction of the tidal force near pericentre:



Since V_{Star} and F_{Tid} go in the same direction, these stars will become faster by an amount δv. However there will be an equal number of stars that will have velocities in the other direction:



and which will slow down by δv.

ECCENTRIC ORBITS

The total energy change is given by:

$$\begin{aligned}
\Delta E &= \frac{1}{2}m\left(v+\delta v\right)^2+\frac{1}{2}m\left(-v+\delta v\right)^2-2\frac{1}{2}mv^2 \\
&= \frac{1}{2}mv^2+mv\delta v+\frac{1}{2}m\delta v^2+\frac{1}{2}mv^2-mv\delta v+\frac{1}{2}m\delta v^2-mv^2 \\
&= m\delta v^2 \\
&> 0
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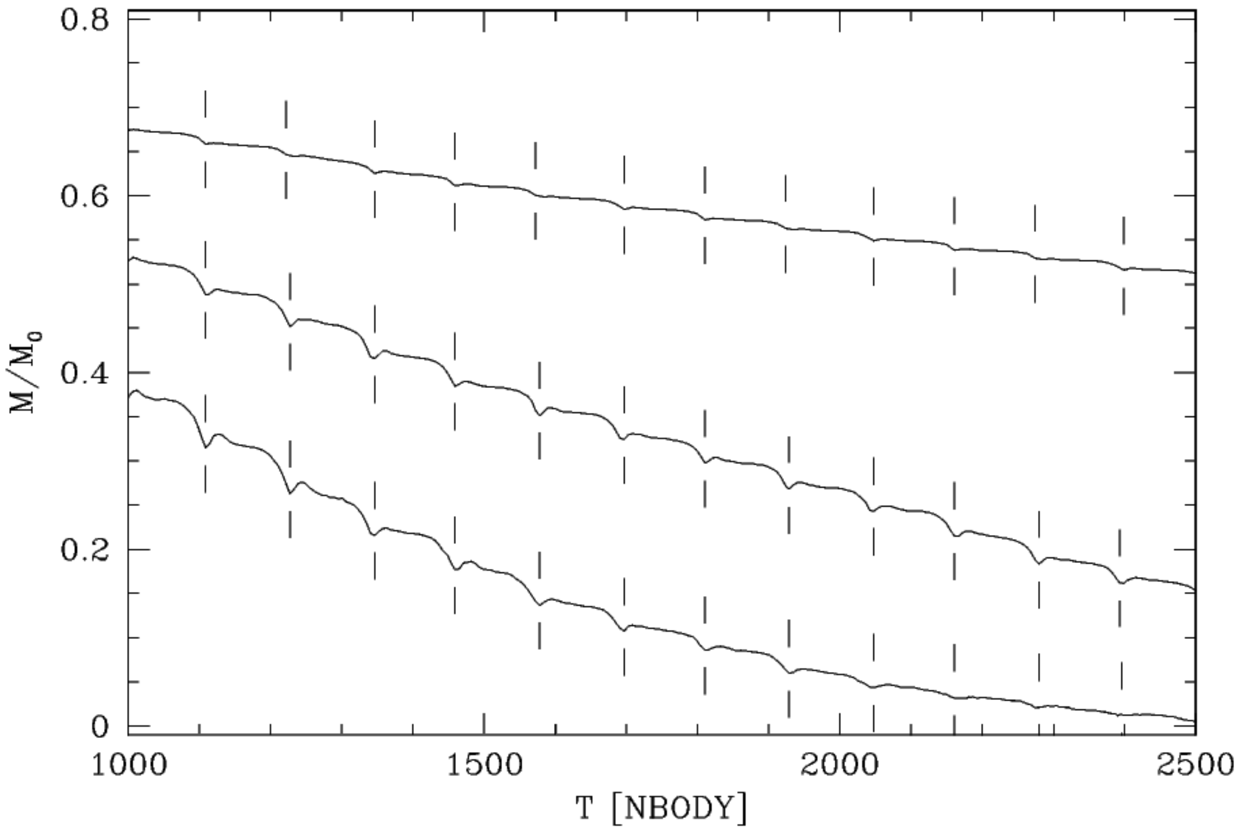
&= m\delta v^2 \\
&> 0
\end{aligned}$$

Varying tidal field inserts energy into the cluster. In addition, *$\Delta E^2>0$*, so tidal shocks also enhance relaxation!

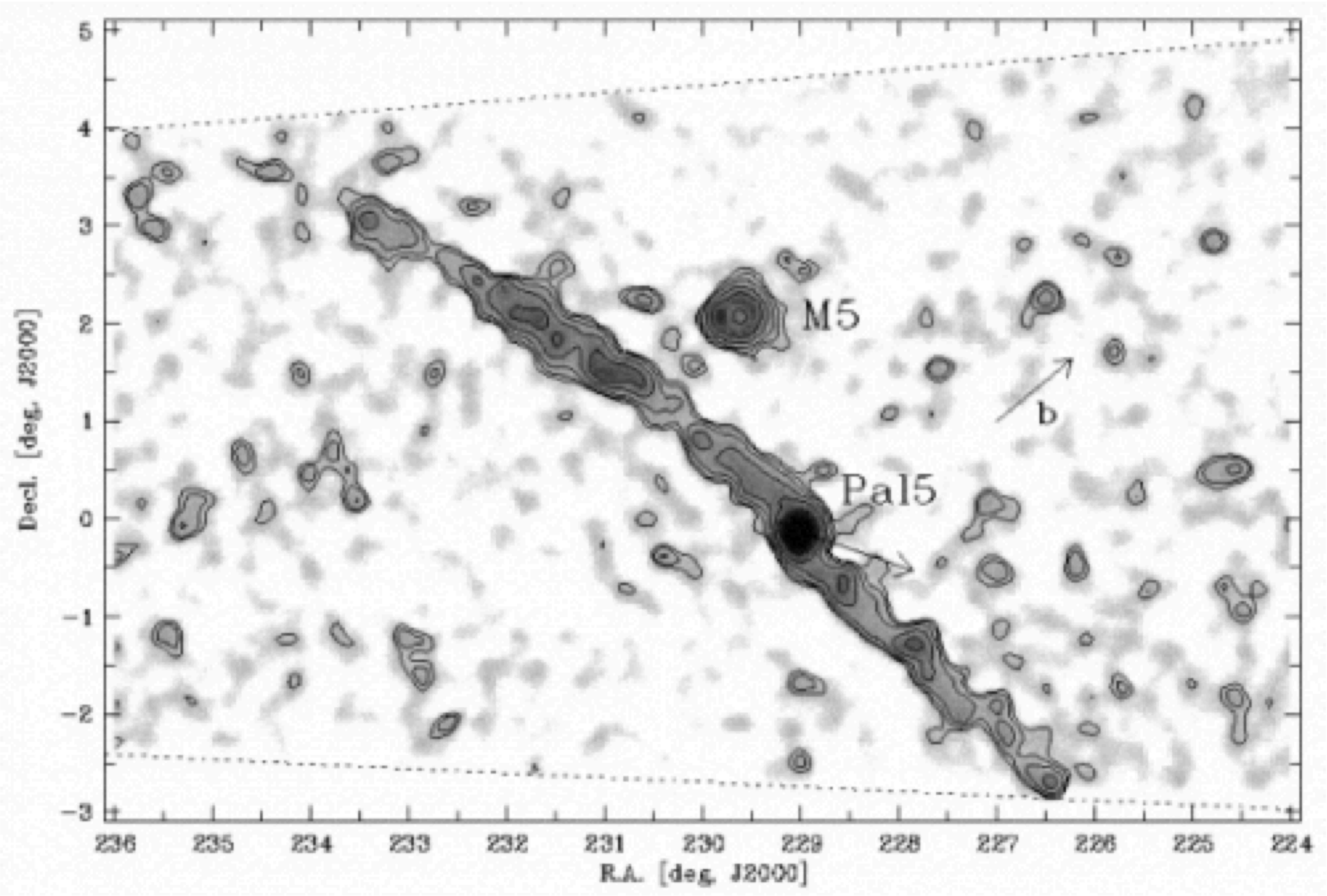
ECCENTRIC ORBITS

The number of bound stars decreases with each pericenter passage:

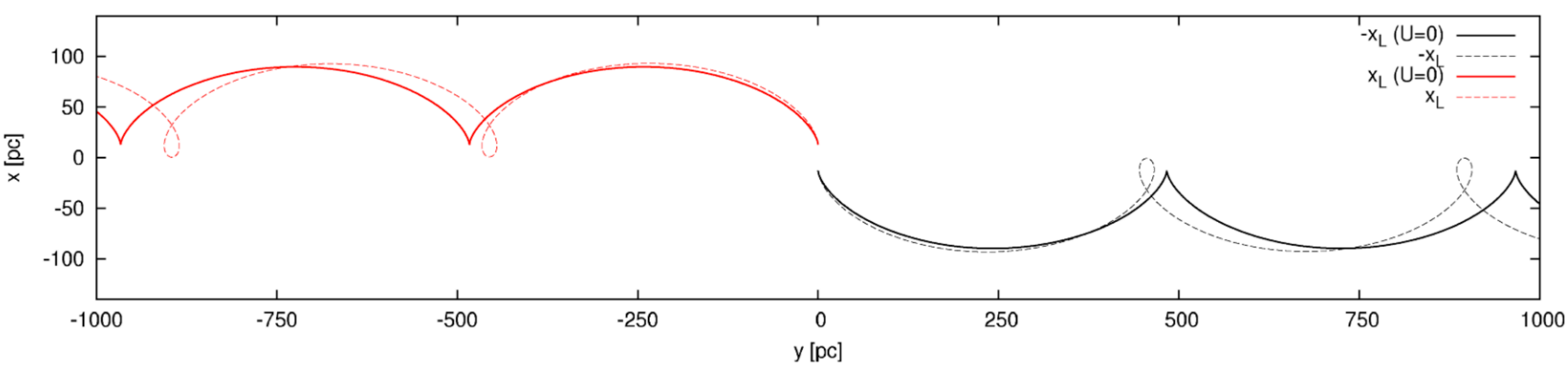


In the above simulation escapers were counted as all stars being beyond the **current** tidal radius.

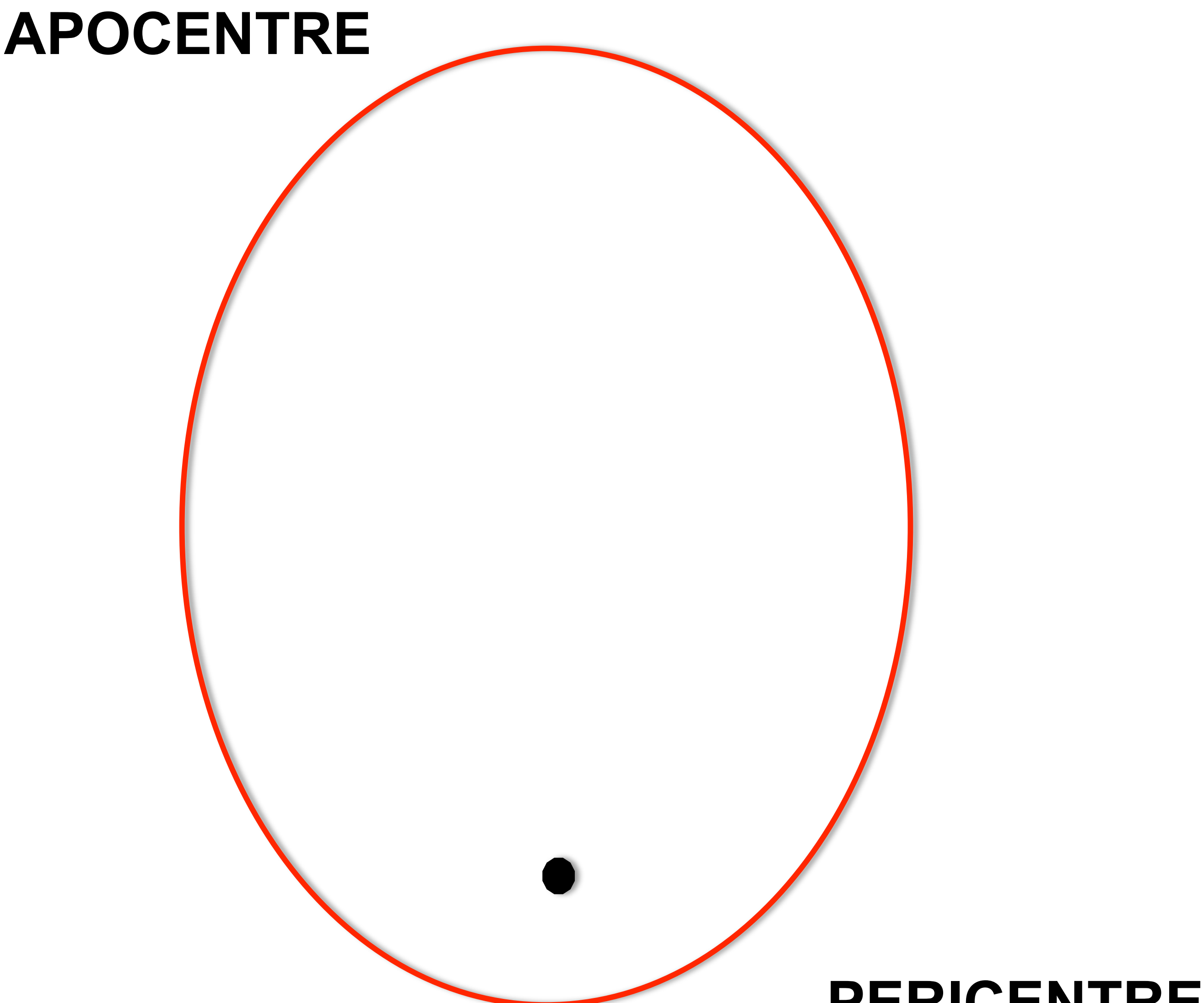
In the tidal tails of some clusters one can see overdensities of stars. These were thought to be due to the higher escape of stars near the pericentre or possible even clumps of dark matter scattering the stars in the tails:



However Küpper et al. (2008, 2010) have shown that these over-densities are more likely due to the epicyclic motion of stars in the tidal tails:

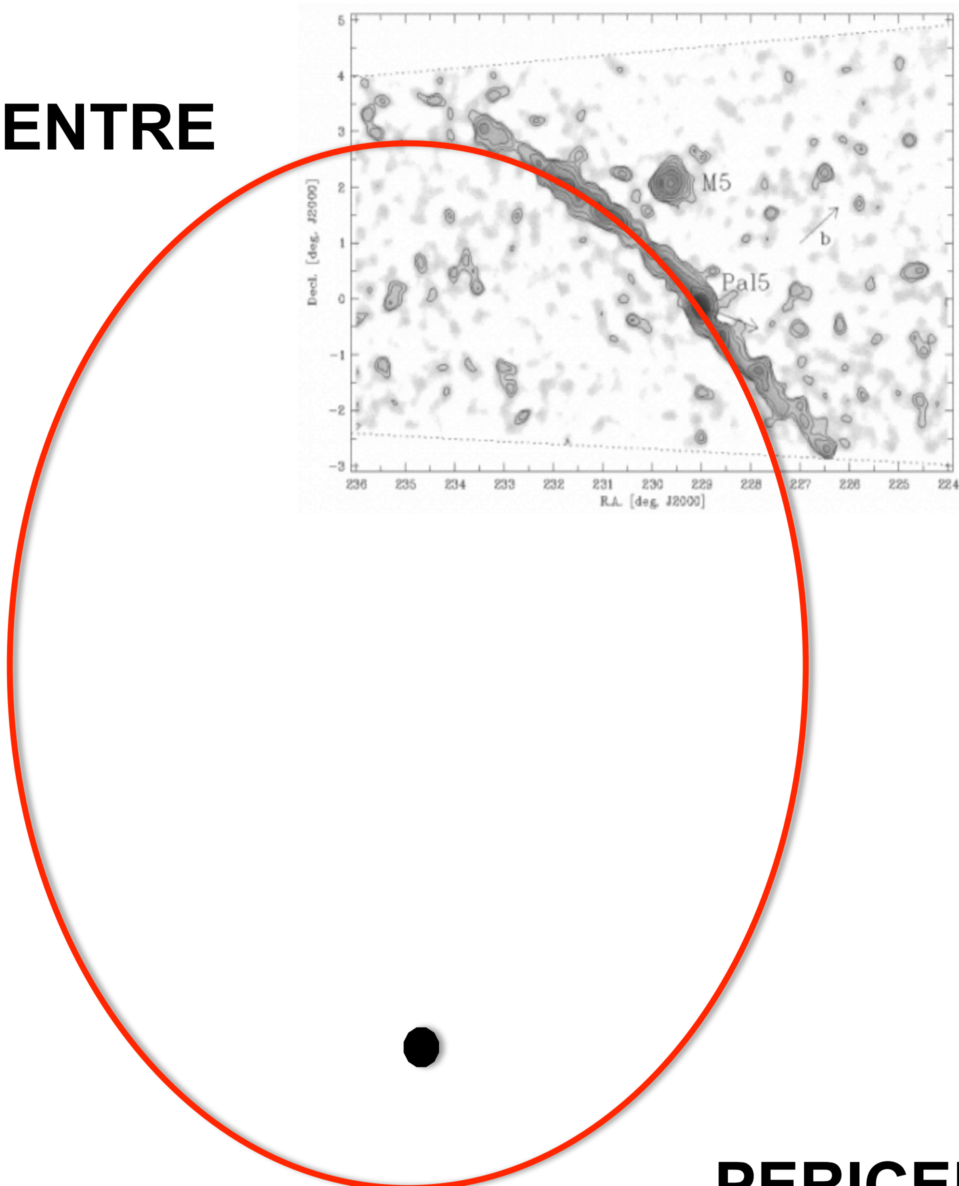


ECCENTRIC ORBITS



ECCENTRIC ORBITS

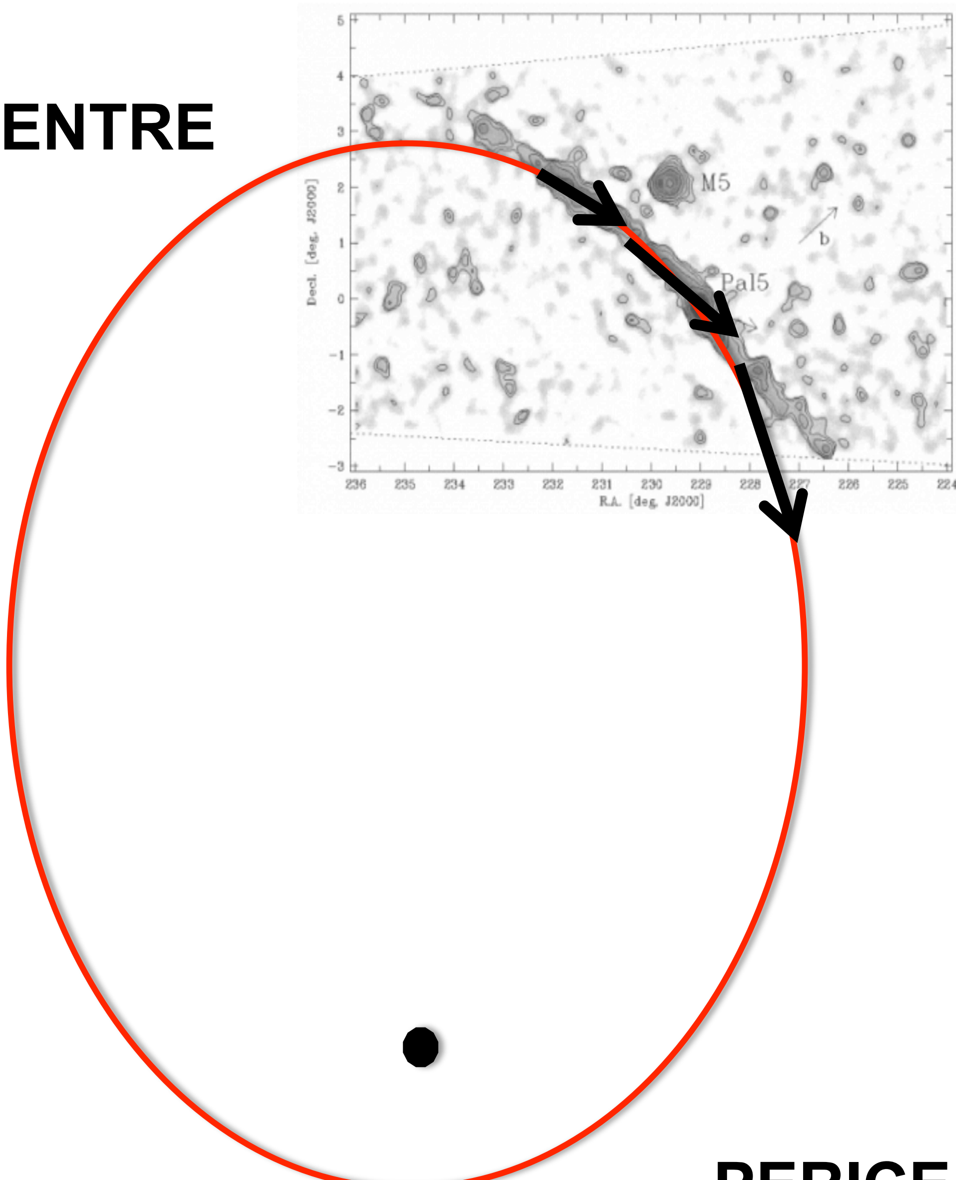
APOCENTRE



PERICENTRE

ECCENTRIC ORBITS

APOCENTRE

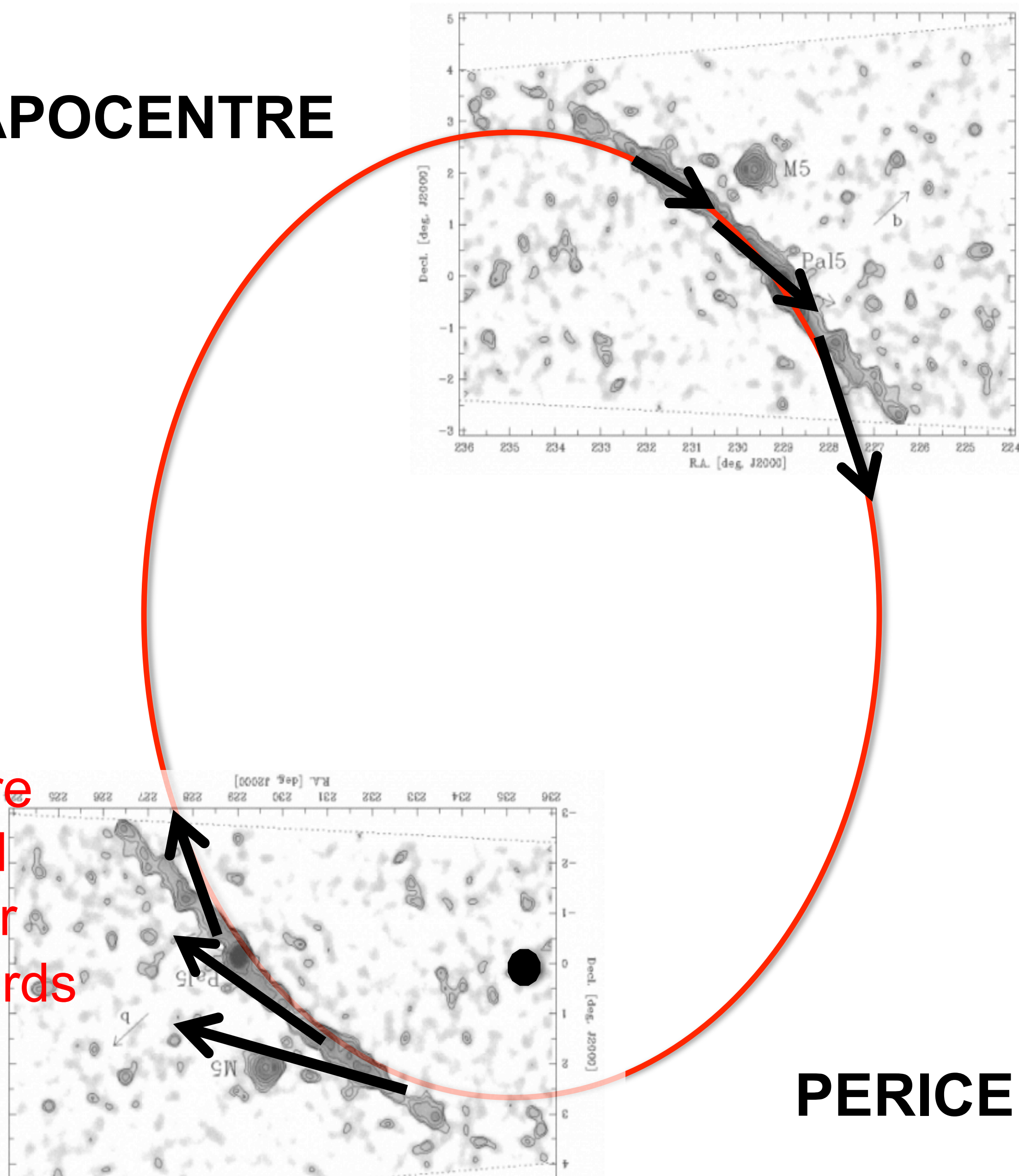


Tidal tails
are stretched
when cluster
moves towards
pericentre.

PERICENTRE

ECCENTRIC ORBITS

APOCENTRE



Tidal tails are stretched when cluster moves towards pericentre.

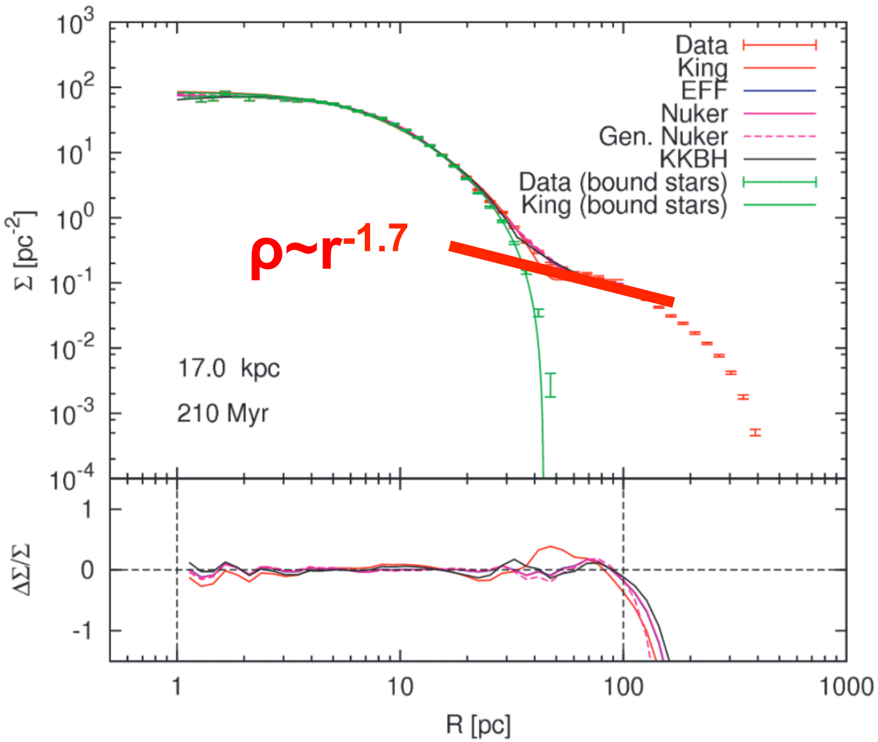
Tidal tails are compressed when cluster moves towards apocentre!

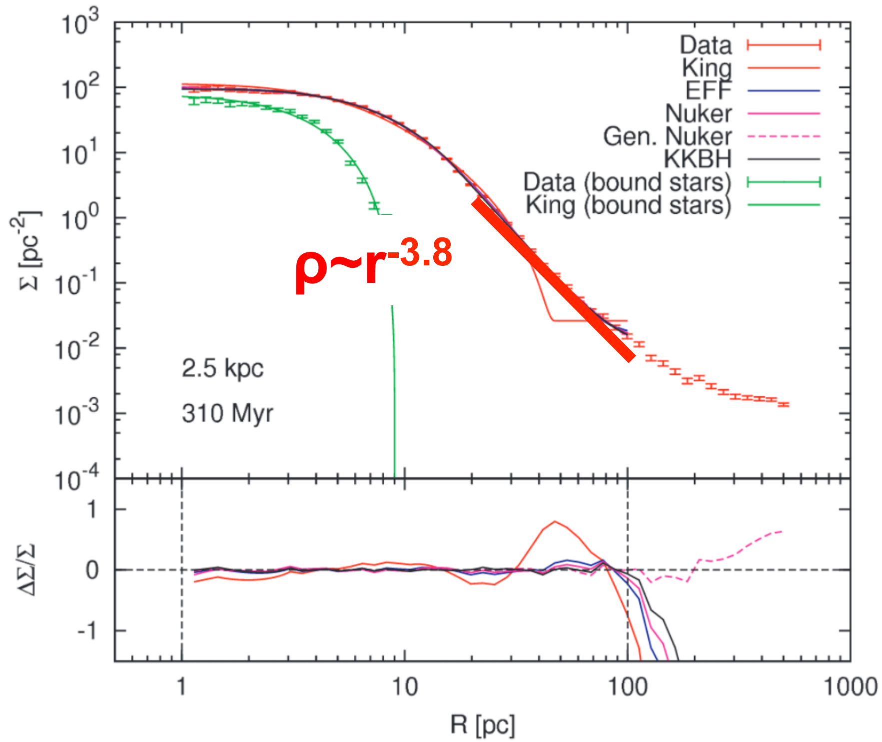
PERICENTRE

Density profile of extra-tidal stars is changing with the orbital phase. Steep drop at pericentre but flat density profile near apocentre. Also number of extra-tidal stars depends on orbital phase.

Just before apocentre

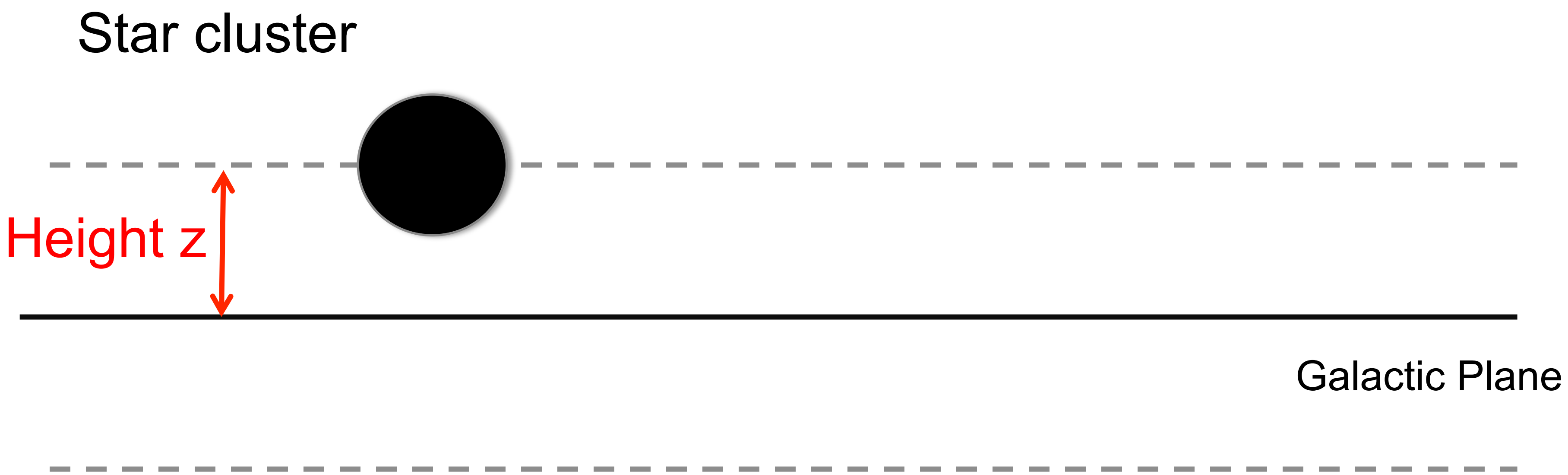
At pericentre





from Küpper et al. (2010)

DISC SHOCKS



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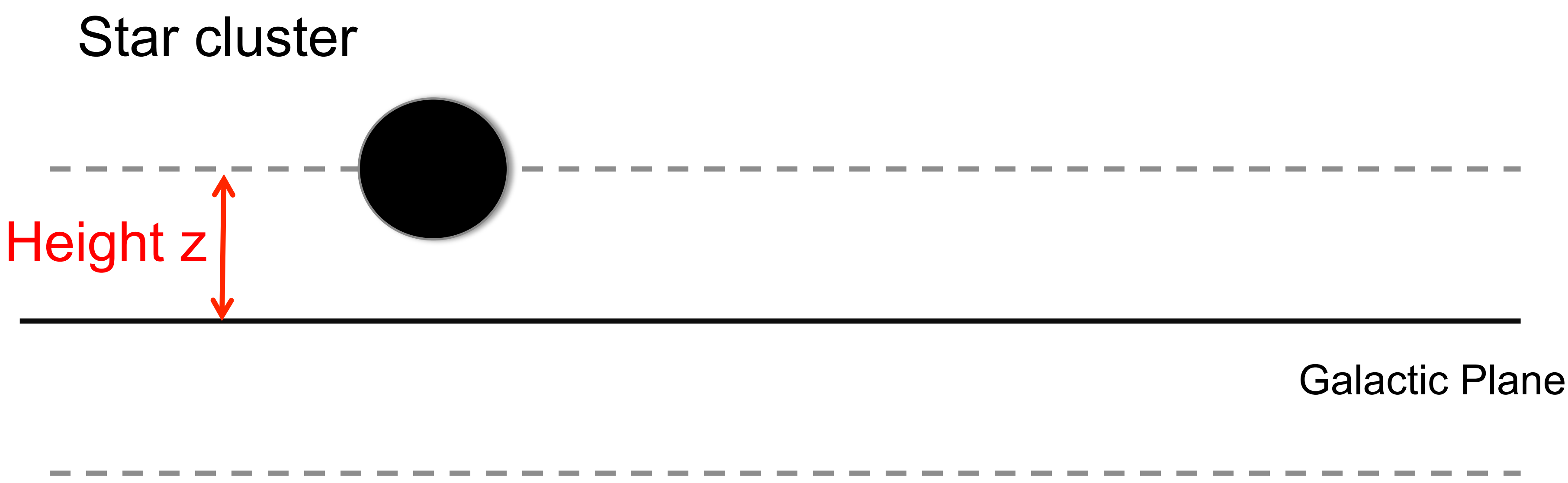
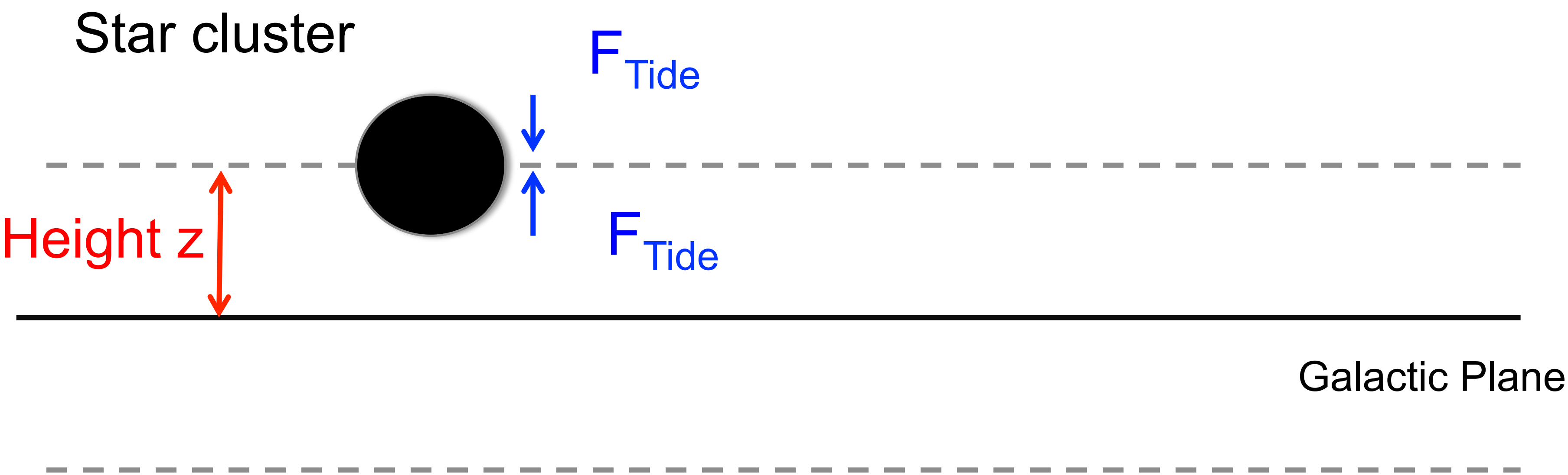


$$F_{Disc} = -2\pi G \Sigma \frac{z}{z_d}$$

DISC SHOCKS



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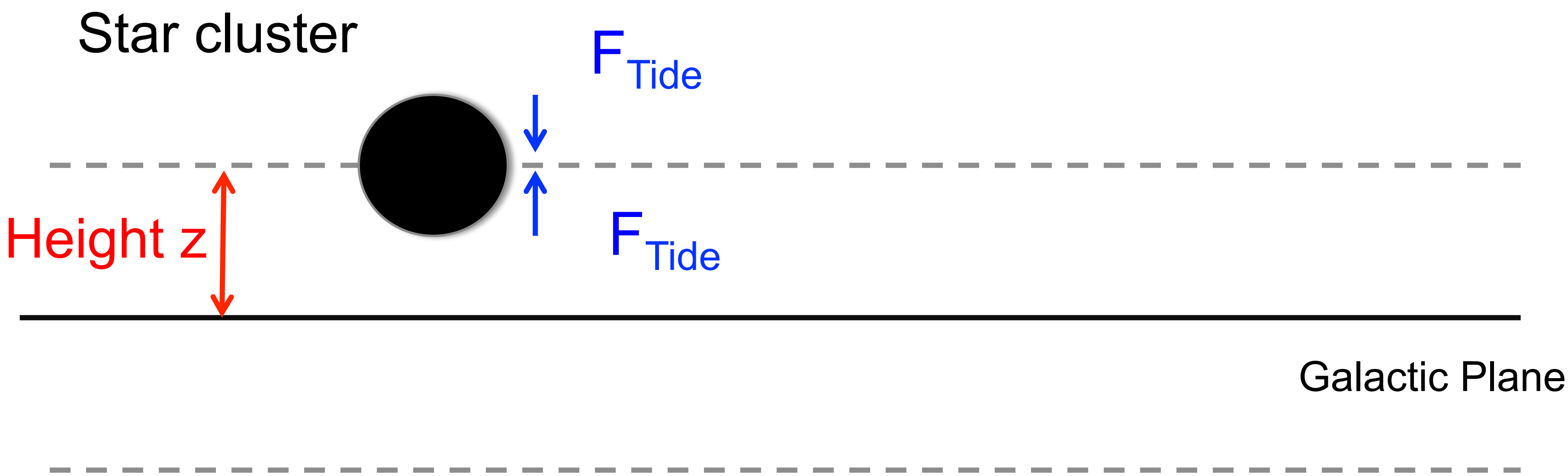
Disc passages subject star clusters to compressive tidal shocks.

DISC SHOCKS



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Disc passages subject star clusters to compressive tidal shocks.

Disc shocks are important for globular clusters orbiting the Milky Way between 2 to 5 kpc (Vesperini & Heggie 1997).

MOLECULAR CLOUD SHOCKS

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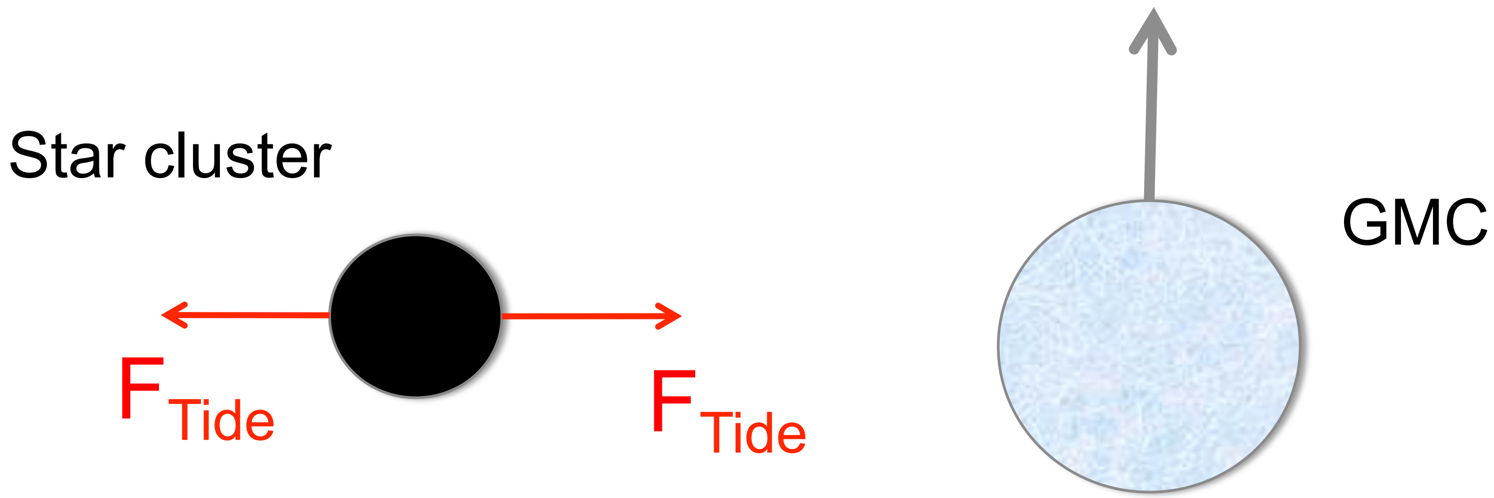


Passing molecular cloud creates a tidal force which causes stars to leave the star cluster.

MOLECULAR CLOUD SHOCKS

The energy impact of an encounter with a molecular cloud is given by (Spitzer 1958):

$$\Delta E = \frac{4\alpha^2}{3}\left(\frac{GM_{Cloud}}{p^2 V}\right)^2 M_C r_h^2$$

GMC encounters are the dominant destruction mechanism of open clusters in the Galactic disc (Wielen 1985, Gieles et al. 2006).

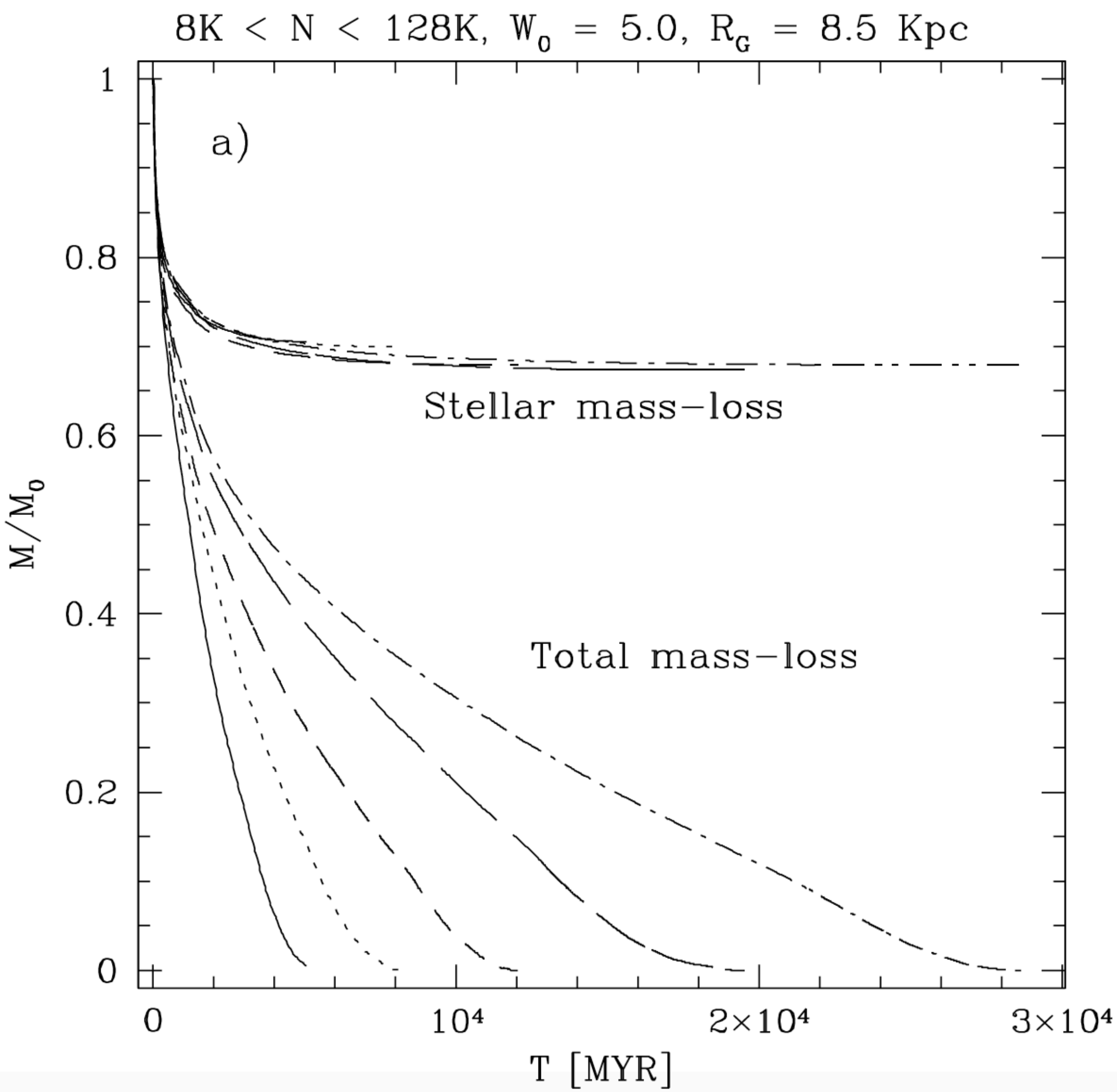
They are not important for present-day GCs, but could have been important in the past if GCs spent a significant time in discs of highly gaseous dwarf galaxies (Kruijssen 2011).

SUMMING ALL UP.....

PUTTING IT ALL TOGETHER…

Evolution of bound mass of star clusters with different mass:

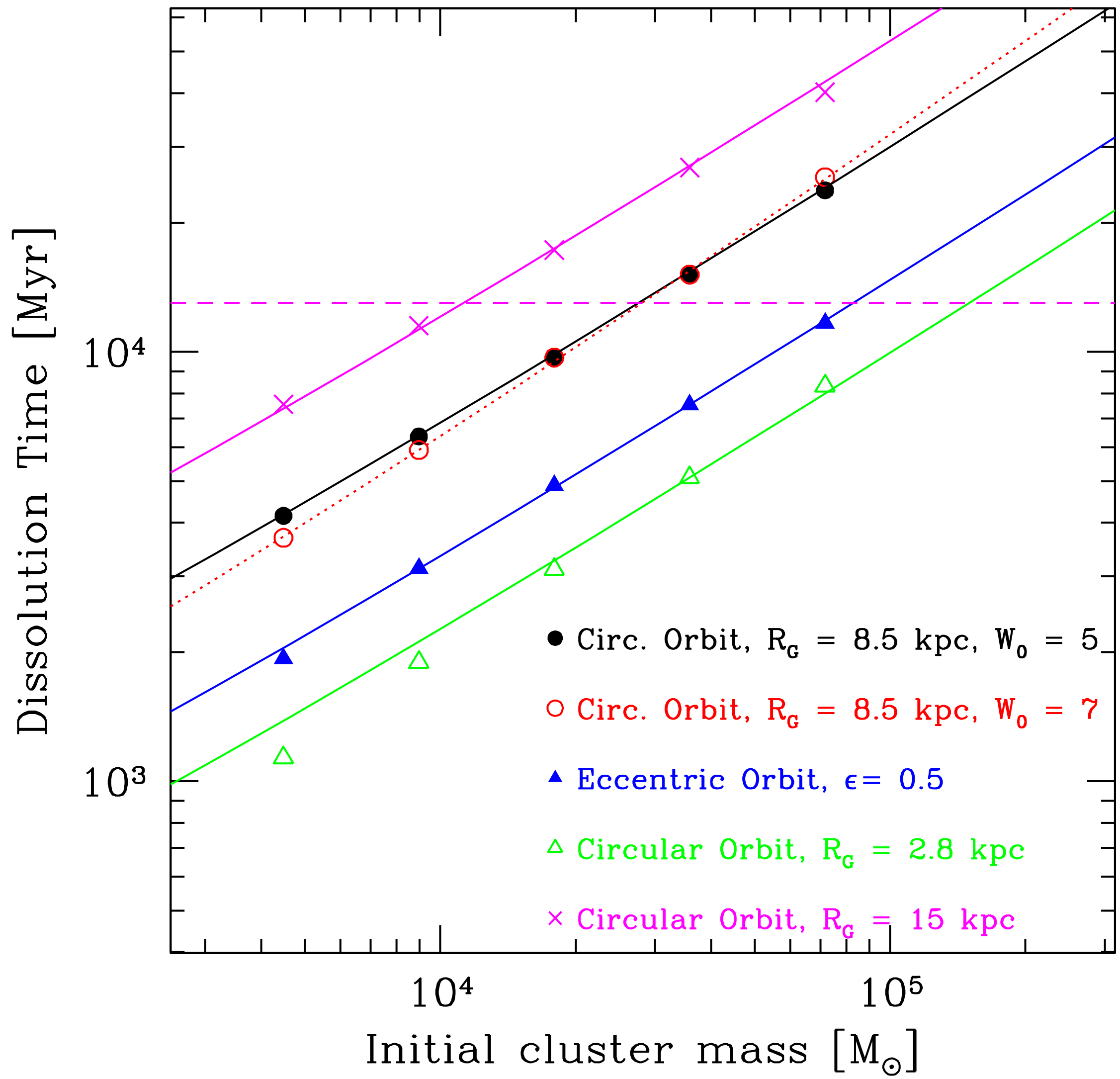
High-mass clusters live longer.



PUTTING IT ALL TOGETHER…

Lifetimes of star clusters with different mass and in different orbits:

Star clusters live longer in weaker tidal fields.



PUTTING IT ALL TOGETHER...

Dissolution time of star clusters in a spherical isothermal galaxy is given by (Baumgardt & Makino 2003):

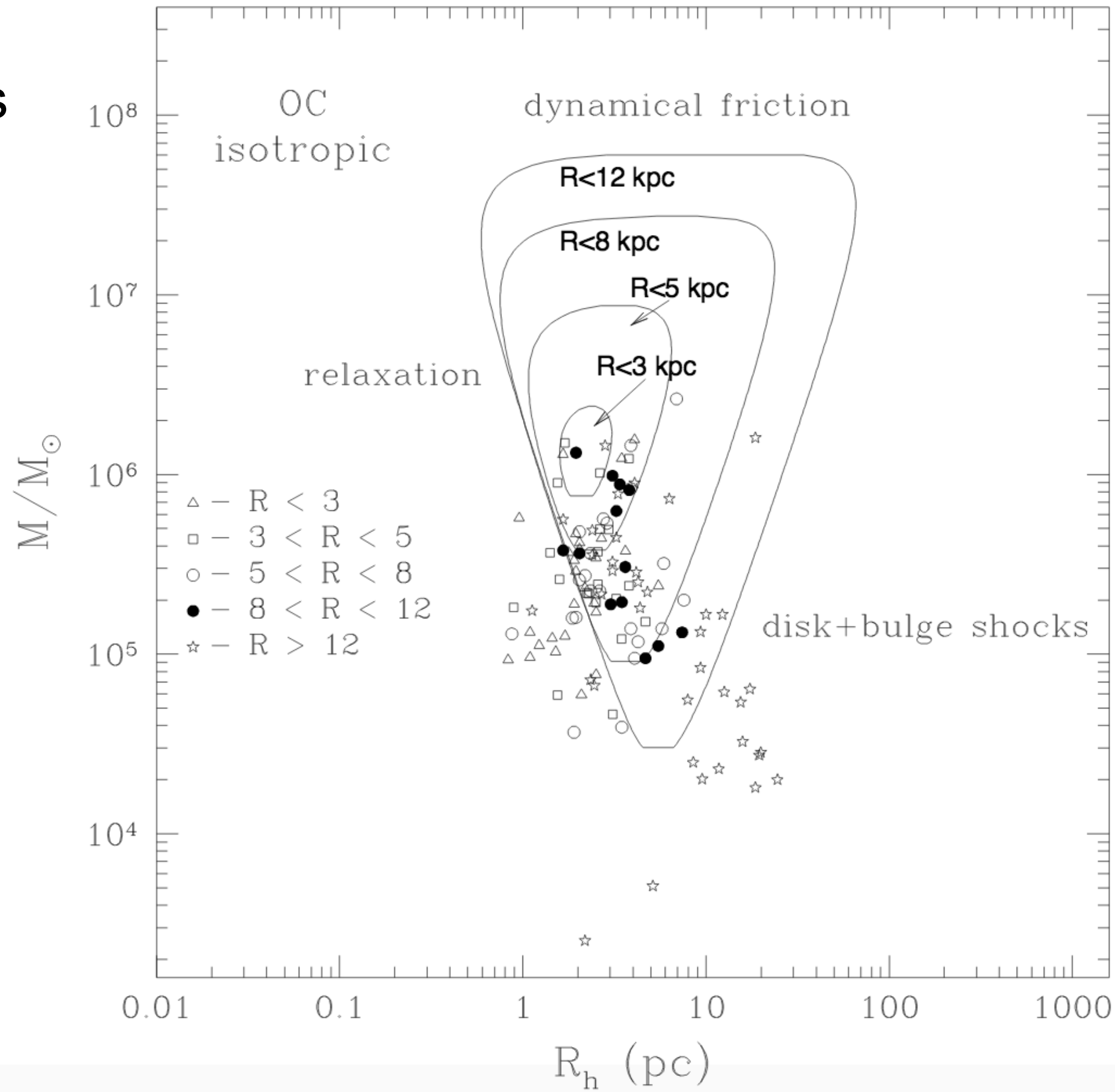
$$\frac{T_{Diss}}{Myr} = 1.9\left(\frac{M}{\ln\left(0.02N\right)}\right)^{0.75}\frac{R_G}{kpc}\left(\frac{V_C}{220km/\sec}\right)^{-1}\left(1-\varepsilon\right)$$

At the solar radius in the Milky Way, all globular clusters with initial masses less than 30.000 $M_\odot$ have completely dissolved. Typical, 10^5 $M_\odot$ globular cluster has lost about 30% of its mass due to dissolution.

Cluster lifetimes are not strongly influenced by initial cluster radius (Gieles et al. 2009), initial binary fraction or initial black hole retention fraction (Lützgendorf et al. 2013).

PUTTING IT ALL TOGETHER...

Survival triangle of galactic globular clusters according to Gnedin & Ostriker (1997):



PUTTING IT ALL TOGETHER...

Relaxation alone cannot destroy a cluster, so the previous diagram should look more like this: