Effective timescales *of* embedded clusters

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Outline

- Embedded clusters

  Infant mortality & cluster destruction

- Clusters in a molecular cloud

  Model & simulatiom

- Cloud dispersion

  General case

  Indicator of cluster destruction

- Effective timescales
- Summary

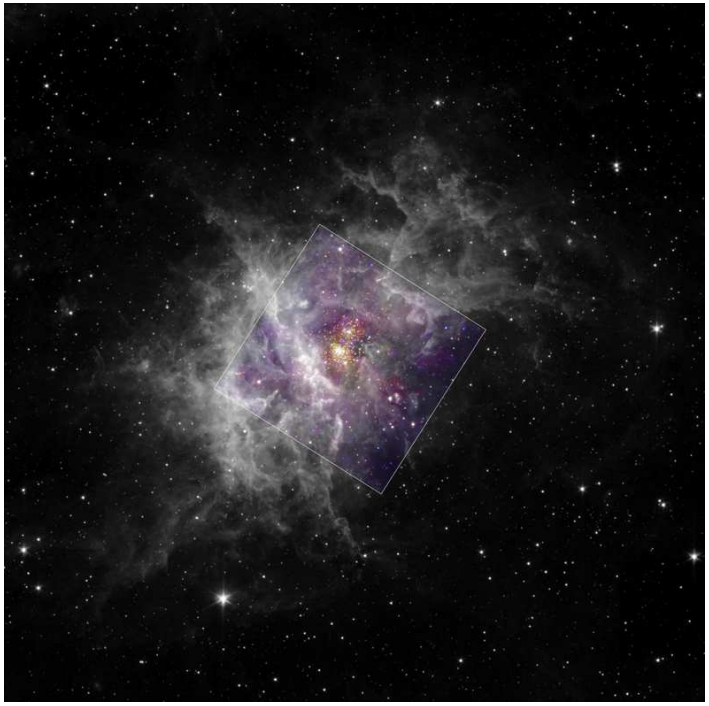
Embedded clusters

- Most stars are formed in groups inside molecular clouds
- While with their natal molecular clouds, they are not visible.
  $\Longrightarrow$ Embedded clusters
- The lifetime of molecular clouds is about a few to a few tens of Myr (Blitz & Shu, 1980; Elmegreen, 2000; Hartmann et al., 2001; Bonnell et al., 2006)
  $\Longrightarrow$ The embedded clusters live short, too.
- There are many of them, but only 4 to 7 % survive (Lada & Lada (2003)).
  $\Longrightarrow$ Infant mortality of stellar clusters in the Milky Way
- Infant mortality found in other galaxies:
  Antennae galaxies (Fall et al. (2005)), SMC (Chandar et al. (2006))

Star forming region

30 Doradus

(Spitzer, ESO)

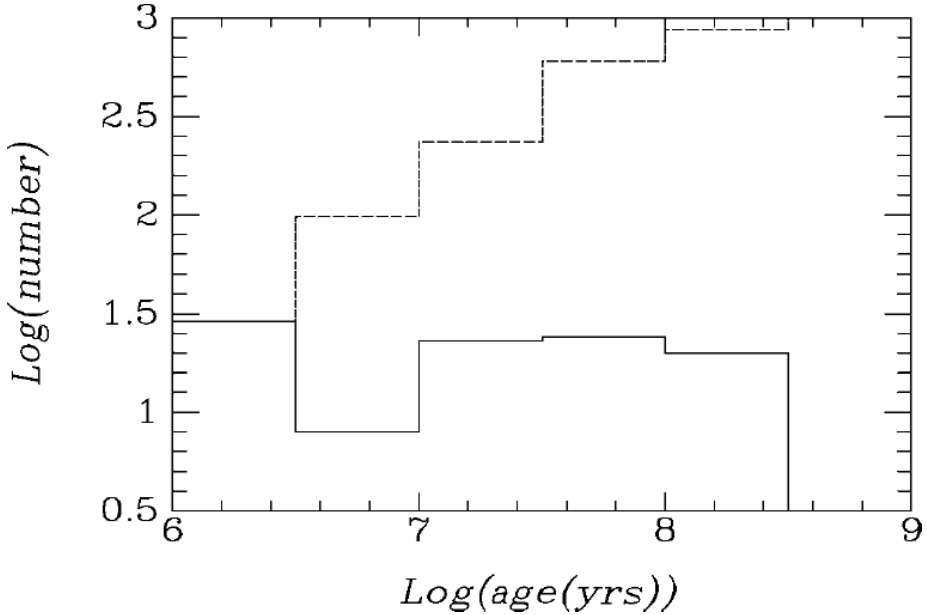


Westerlund 2

(HST, NASA)

Infant mortality

- $\sim$ 70-90% of stars in the Milky Way are formed in stellar clusters and only 4-7% of embedded cluster could survive after natal cloud dissipating (Lada & Lada 2003)



solid line: number of embedded clusters and open clusters from 2 kpc to the Sun

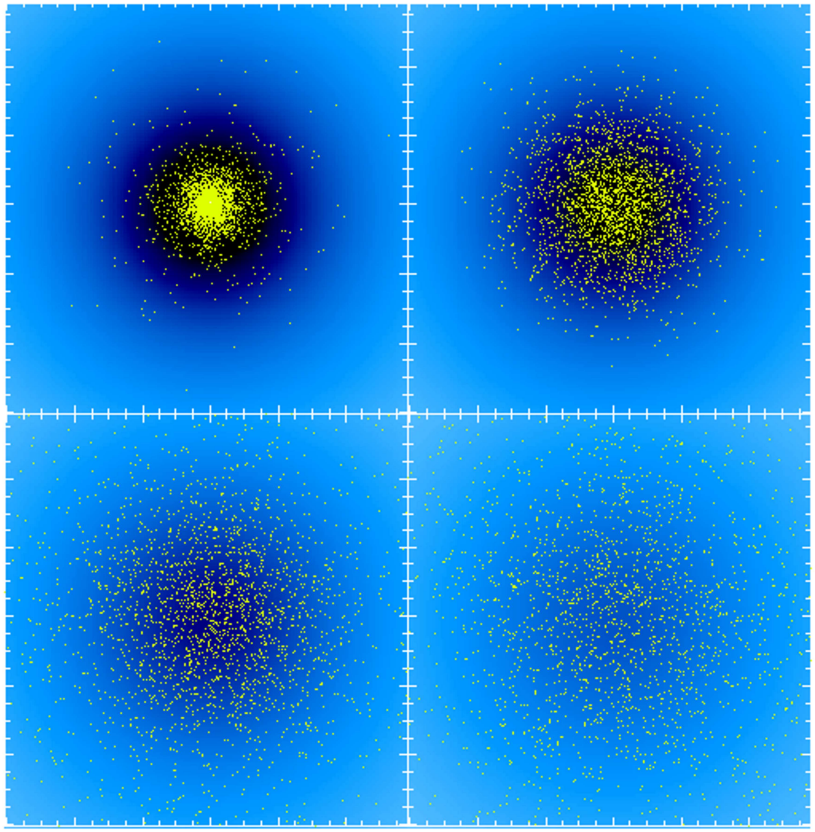
dash line: predicted number for a constant cluster formation rate 2-4 /Myr

Cluster destruction mechanism

- Gas removal: $\sim 10^6 - 10^7$ yrs (Adams 2000)
- Close encounter with GMCs: $\sim 10^8 - 10^9$ yrs (Gieles et al. 2006)
- Shock heating: $\sim 10^9 - 10^{10}$ yrs (Binney & Tremaine 1987, Ashman & Zepf 1998, Elson 1999)
- Evaporation: $\sim 10^{10}$ yrs (Binney & Tremaine 1987)
- The lifetime of molecular clouds is between a few to a few tens of Myrs (Blitz & Shu (1980), Elmegreen (2000), Hartmann et al. (2001), Bonnell et al. (2006)). Clusters older than 5 Myr are rare associated with molecular gas (Leisawitz et al. (1989))

Simulation of Clusters

- open clusters in a dispersing molecular cloud (Chen & Ko 2009)



- N-body simulation
- clusters with parent molecular clouds
- cloud dispersing
- clusters get loosed, destroyed, or remain intact

Clusters in a Molecular cloud

Cluster

- 2500 stars (2500 $M_\odot$)
- Plummer distribution
- initial half-mass radius = 0.8 pc
- Salpeter mass function
- no primordial mass segregation

Cloud

- cloud mass: 0.5 - 10 cluster mass
- cloud size: 0.125 to 2.5 pc
- Plummer distribution

- Plummer model

$$\phi_p = \frac{-GM_b}{\sqrt{r^2+a^2}}$$

- Star formation efficiency

$$\eta = \frac{M_c}{M_c+M_b}$$

- Cloud dispersion

$$a = a_0 e^{t/t_e}$$

G: gravitational constant

M_c: cluster mass, 2500 [$M_\odot$]

M_b: cloud mass [M_c]

r: radius [pc]

a: length scale of the cloud [pc]

a_0: initial length scale of the cloud [pc]

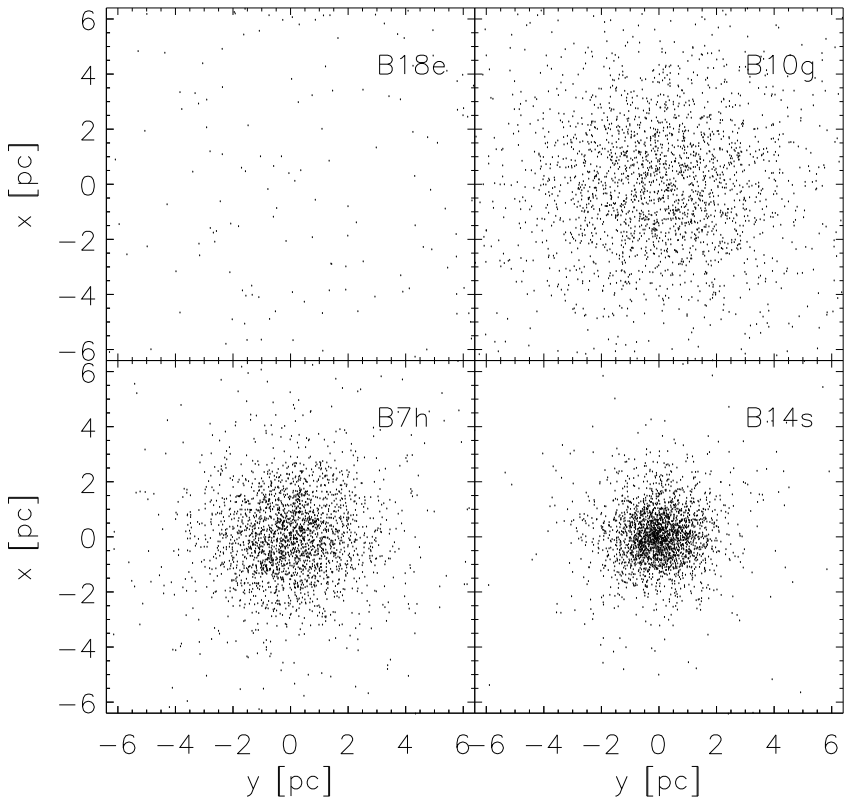
t_e: dispersion timescale [Myr]

t: time [Myr]

Parameters

- Particle numbers : 2500
- Cluster mass (M_c) : 2500 $M_\odot$
- Cluster size (a_c) : 0.6 pc (length scale)
- Cloud mass (M_b) : 0.5 to 10/19 M_c
- Cloud size (a_0) : 0.125 to 2.5/10 pc (length scale)
- Dispersion rate (t_e) : 0.33 to 3.3 Myr
- Mass function :
  1. single mass
  2. Salpeter mass function
- Spatial distribution of clusters: Plummer/uniform

General cases



xy-plane projection of stars at 30 Myr after dispersing.

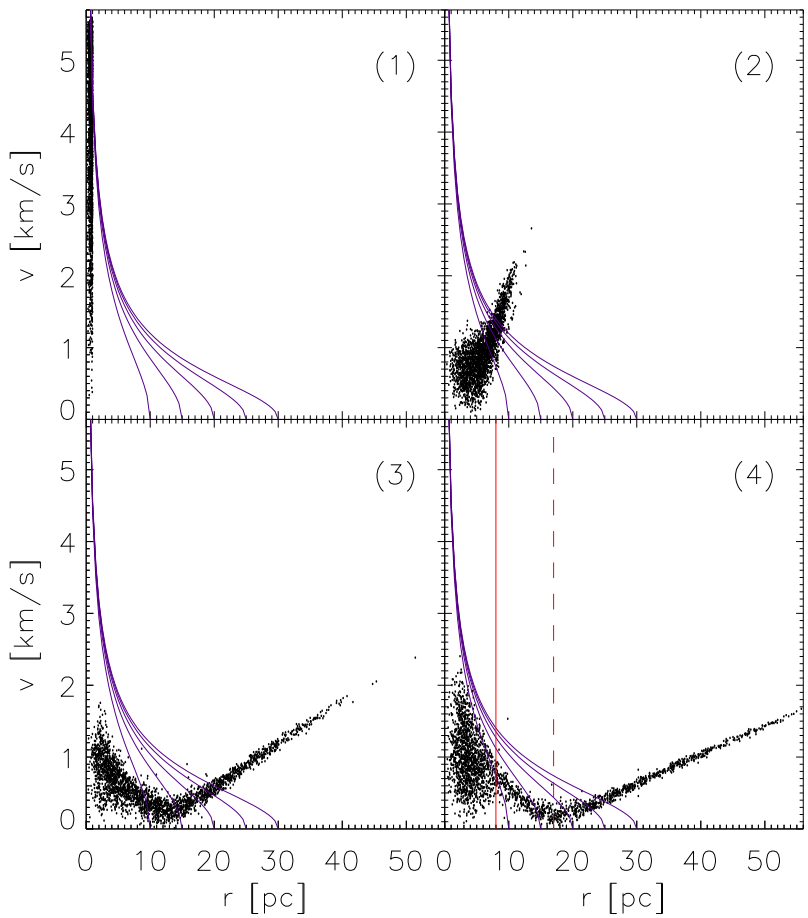
Case B18e destroyed

Case B07h loosed

Case B10g loosed

Case B14s remains intact

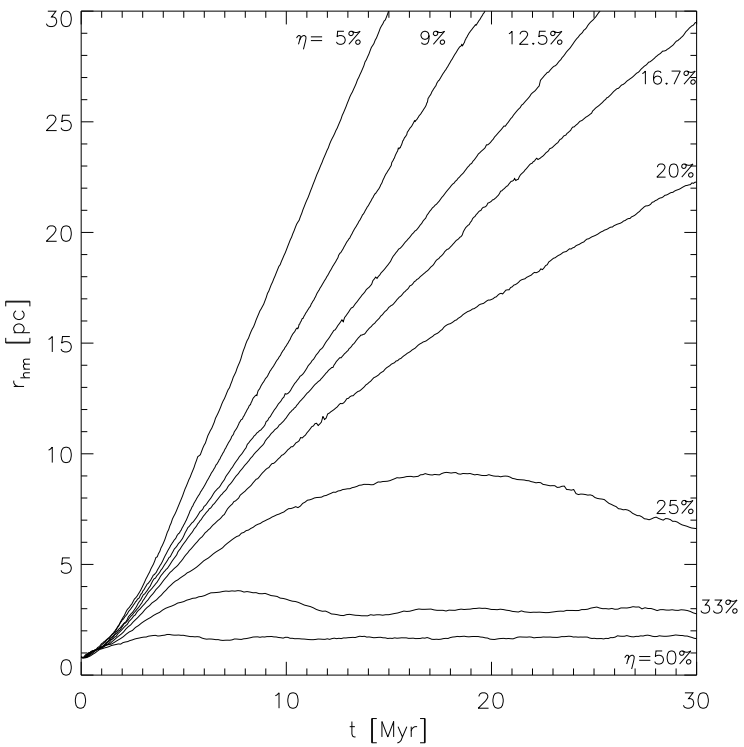
Dynamical evolution



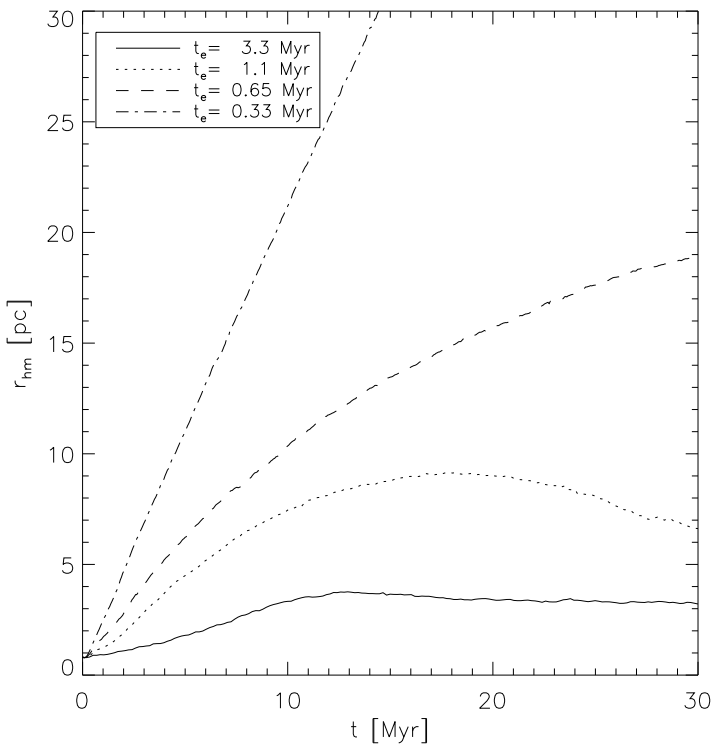
- t_e=0.625 Myr.
  with Salpeter mass function
  M_b = 5 M_c
  a_0 = 1.125 pc
- Solid lines : tracks of elliptical orbit which semimajor axes are 10, 15, 20, 25 and 30 pc.
- There are four stages:
  1. initial state,
  2. expansion,
  3. inner part formation,
  4. final structure at 30 Myr.
- Red solid and dash lines in (4) separate inner part, return stars and stars do not reach their aphelion.

Evolution of r_{hm}

Same dispersion time (1.1 Myr)

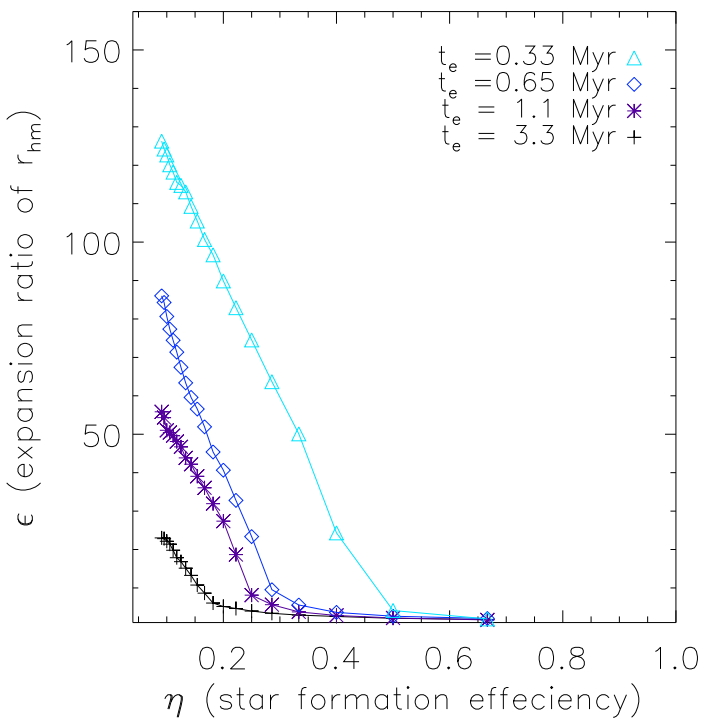


Same SFE (25%)



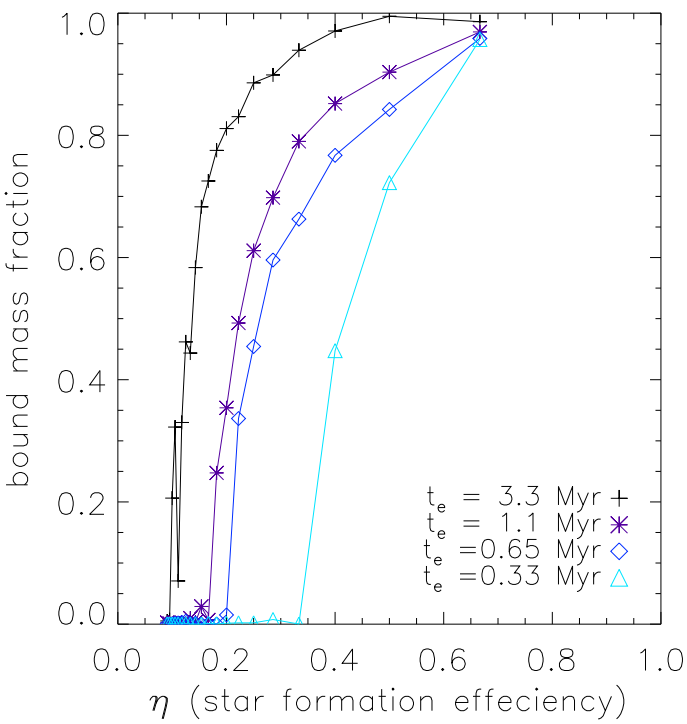
expansion ratio: $\epsilon_{r_{hm}} = \frac{r_{hm,f}}{r_{hm,i}}$

Cluster and cloud have the same initial density profile

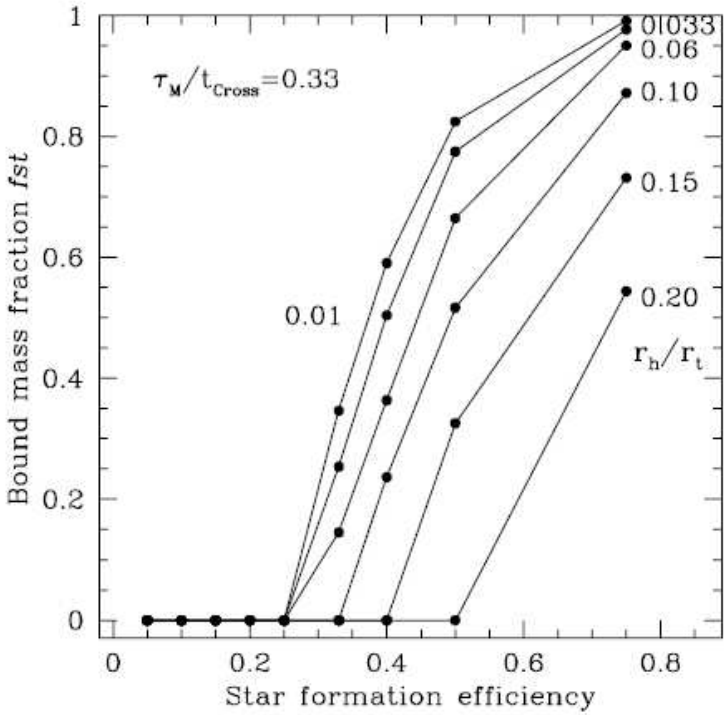


- not every cluster survives
- final structures: (i) is destroyed, (ii) has a loose structure, and (iii) has a compact core
- the expansion ratio of half mass radius $\epsilon_{r_{hm}} = \frac{r_{hm,f}}{r_{hm,i}}$ has a relation with η (star formation efficiency) in different dispersing timescales

Boundmass fraction

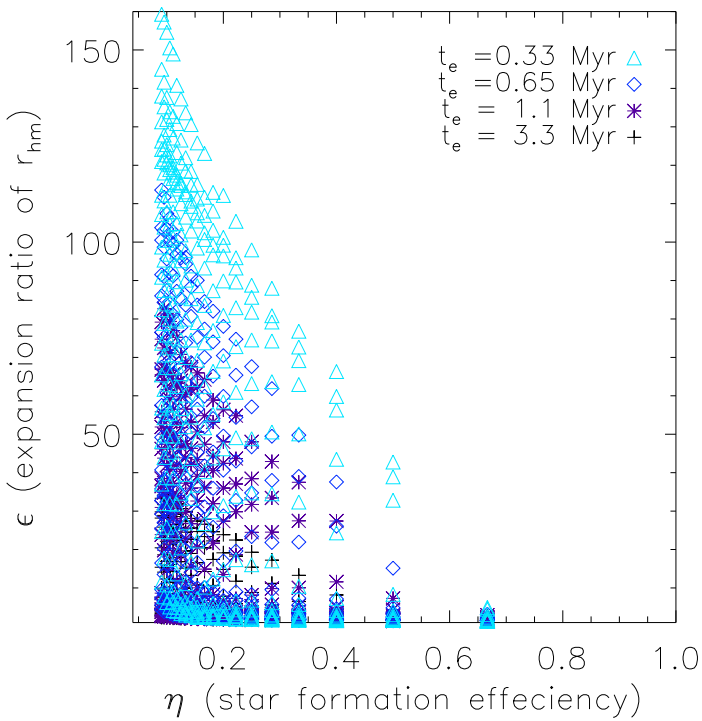


Chen & Ko, 2009



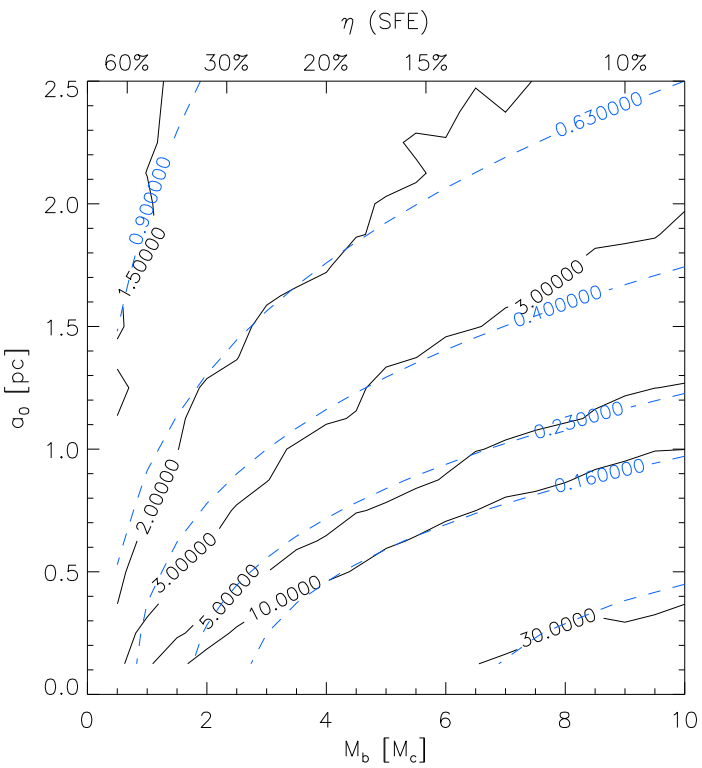
Baumgardt & Kroupa, 2007

Cluster and cloud have different density profile



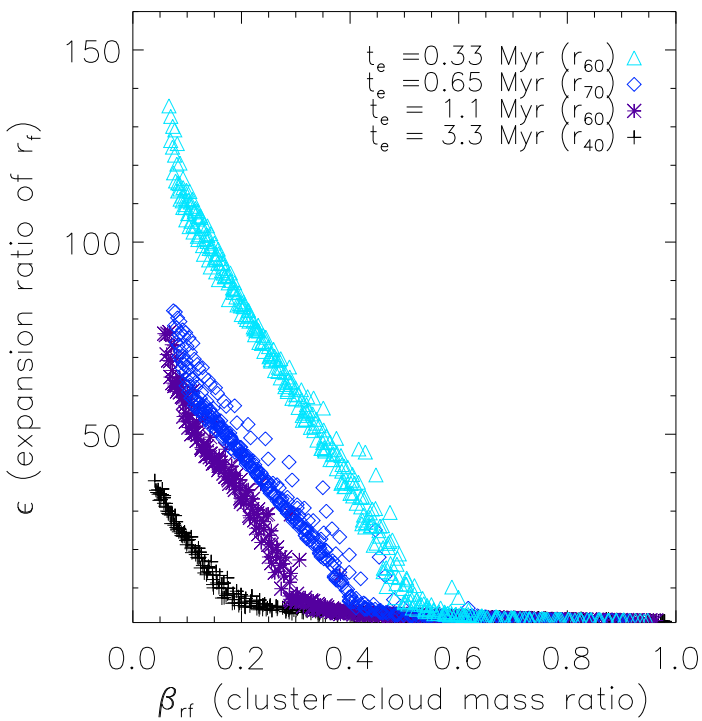
- cluster and cloud may have different initial density profiles
- difficult to find the relation between η and $\epsilon_{r_{hm}}$
- however, $\epsilon_{r_{hm}}$ does show a "simple relation" with $\{M_b, a_0\}$

$\{M_b, a_0\}$



- t_e = 3.3 Myr.
- black solid line: $\epsilon_{r_{hm}}$
- blue dashed line: cluster-cloud mass ratio at certain Lagrangian radius (50% in this case)
- $\epsilon_{r_{hm}}$ is larger/smaller (cluster is destroyed/remains intact) when a_0 is smaller/larger and M_b is large/small (or η is smaller/larger).

Cluster-cloud Mass Ratio



- cluster-cloud mass ratio $\beta_{r_f} = \frac{M_{c,r_f}}{M_{c,r_f}+M_{b,r_f}}$
- r_f: Lagrangian radius with cluster mass fraction f
- M_{c,r_f}: fM_c, cluster mass within r_f initially
- M_{b,r_f}: cloud mass within r_f initially
- for each dispersing timescale t_e, f can be tuned such that data from the 2-D parameter space $\{M_b, a_0\}$ collapse to a relation in $\beta_{r_f} - \epsilon_{r_f}$ plane

Cluster-cloud Mass Ratio

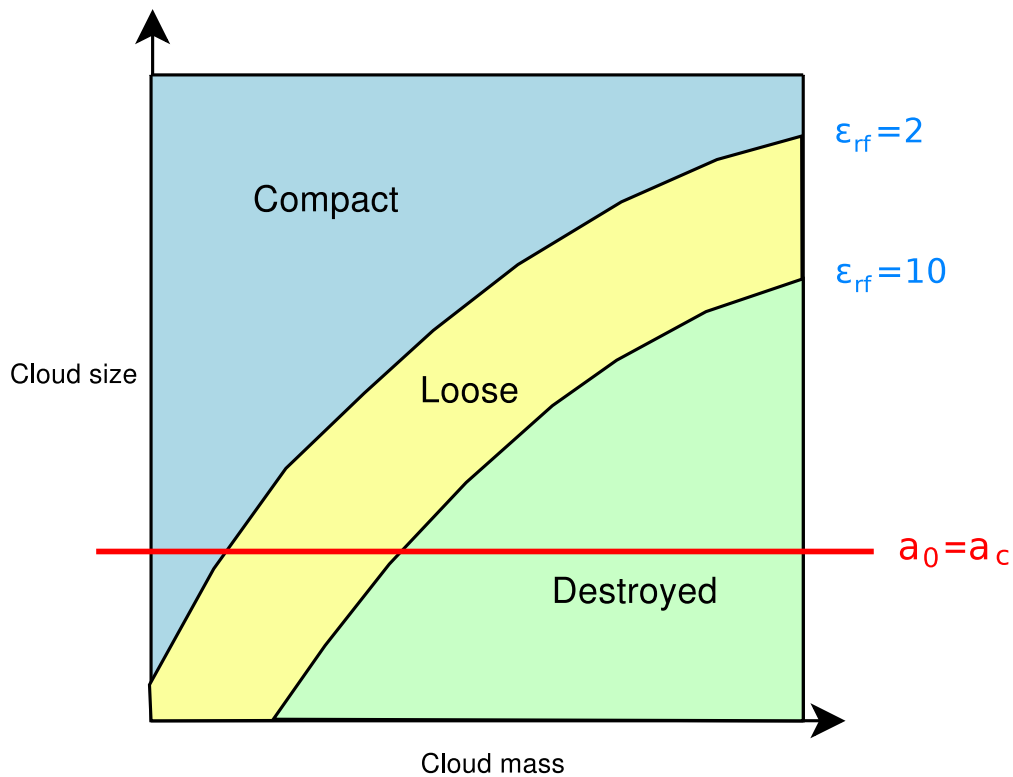
SFE CCMR

$$\eta = \frac{M_c}{M_c + M_b} \qquad \beta_{r_f} = \frac{M_{c,r_f}}{M_{c,r_f} + M_{b,r_f}}$$

$$\epsilon_{hm} = \frac{r_{hm,f}}{r_{hm,i}} \qquad \epsilon_{r,f} = \frac{r_{f,f}}{r_{f,i}}$$

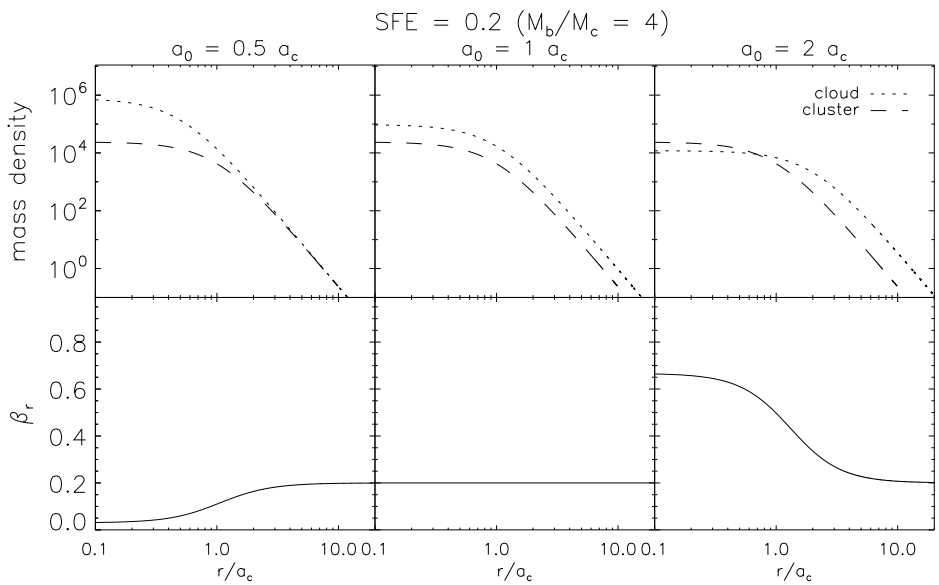
$$\left(\frac{1}{\eta} - 1\right) = \frac{f}{F}\left(\frac{1}{\beta_{rf}} - 1\right)$$

where $f = \frac{M_{c,f}}{M_c} = \left(\frac{f_f^2}{r_f^2 + a_c^2}\right)^{\frac{3}{2}}$ and $F = \frac{M_{b,f}}{M_b} = \left(\frac{f_f^2}{r_f^2 + a_0^2}\right)^{\frac{3}{2}}$



- relation between η and β_{r_f}:
  $\left(\frac{1}{\eta} - 1\right) = \frac{f}{F}\left(\frac{1}{\beta_{r_f}} - 1\right)$
  (while using Plummer model for both cluster and cloud)
- $F = M_{b,r_f}/M_b = r_f^3/(r_f^2 + {a_0}^2)^{3/2}$
- expansion ratio of radius r_f:
  $\epsilon_{r_f} = \frac{r_f(\text{final})}{r_f(\text{initial})}$
- $\eta = \beta_{r_f}$ while $a_0 = a_c$

eSFE (effective SFE)



$a_0 < a_c$ $a_0 = a_c$ $a_0 > a_c$

- mass density profiles with $M_b/M_c = 4$ and $\eta = 0.2$
- $\beta_r \to \eta$ as $r \to \infty$
- while $a_0 = a_c$, β_r is always 0.2
- while $a_0 < a_c$, β_r increases with r (from $\beta_r < \eta$ towards η)
- while $a_0 > a_c$, β_r decreases with r (from $\beta_r > \eta$ towards η)

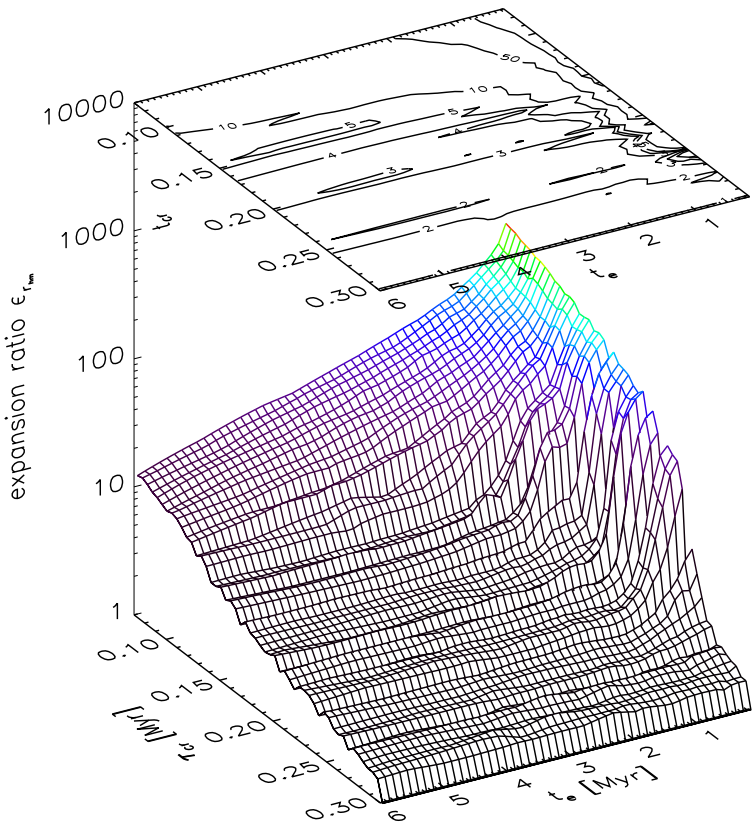
- similar idea was introduced as eSFE (Goodwin 2008)
- clusters have better/worse opportunities to survive when the eSFE is larger/smaller

Timescales

The evolution of the embedded clusters correlated with the β_{r_f} tightly, thus we propose the relevant (initial) effective timescales, like the corssing time, should be defined in terms of β_{r_f} (or roughly of $\beta_{r_{hm}}$)

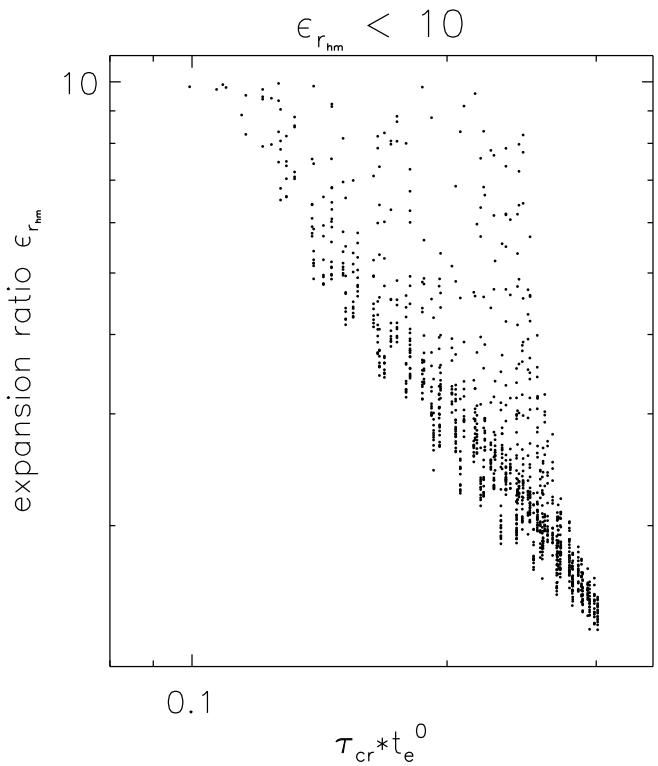
	general definition	here
crossing time	$t_{cr} \approx \frac{{r_{hm}}^3}{M_c}$	$\tau_{\mathrm{cr,r_f}} \approx \sqrt{\frac{\beta_{r_f} r_f^3}{fGM_c}}$
relaxation time	$t_{rlx} \approx \frac{N}{8 \ln N} t_{cr}$	$\tau_{\mathrm{rlx,r_f}} \approx \frac{fN}{8\beta_{r_f}^2 \log(fN/\beta_{r_f})} \tau_{\mathrm{cr,r_f}}$

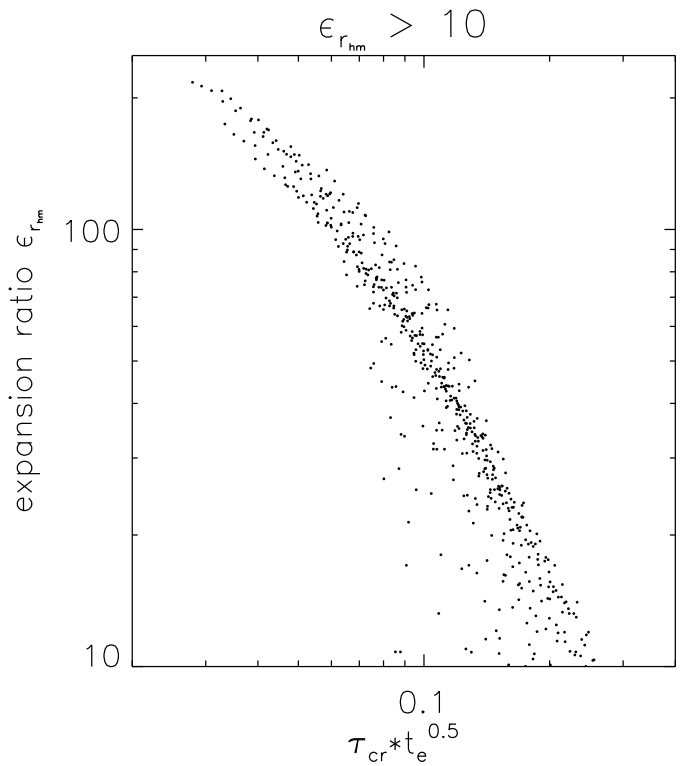
Expansion ratio and timescales



- the $\epsilon_{r_{hm}}$ is also related with $\{\tau_{\mathrm{cr,r_{hm}}}, t_e\}$ (figure in the left)
- when less/more cloud dominant (larger/smaller $\tau_{\mathrm{cr,r_{hm}}}$), $\epsilon_{r_{hm}}$ is less related to the t_e when t_e is larger/smaller
- the relation between $\epsilon_{r_{hm}}$ and $\{\tau_{\mathrm{cr,r_{hm}}}, t_e\}$ could be separated by $\epsilon_{r_{hm}} = 10$ (boundary of suvival and destroyed cases)

timescale figure





$\epsilon_{r_{hm}}$ is related with $\tau_{\mathrm{cr,r_{hm}}} * t_e{}^{0}$

$\epsilon_{r_{hm}}$ is related with $\tau_{\mathrm{cr,r_{hm}}} * t_e{}^{0.5}$

Summary

- we study the survivability of clusters in dispersing clouds by means of N-body simulations
- clusters will be destroyed, loosed, or remain intact after cloud dispersing
- the expansion and bound mass of clusters are related to the SFE only when clusters and clouds have the same density profile initially
- for clusters and clouds with different initial density profile, cluster-cloud mass ratio, β, (based on M_b,a_0) is a better indicator for cluster survivability
- we propose the initial τ_{cr} and initial τ_{rlx} defined in terms of β
- β also has a relation with the mass segregation
- clusters with different IMF have no significant difference in result