The influence of gas expulsion on the survival rate of young star clusters

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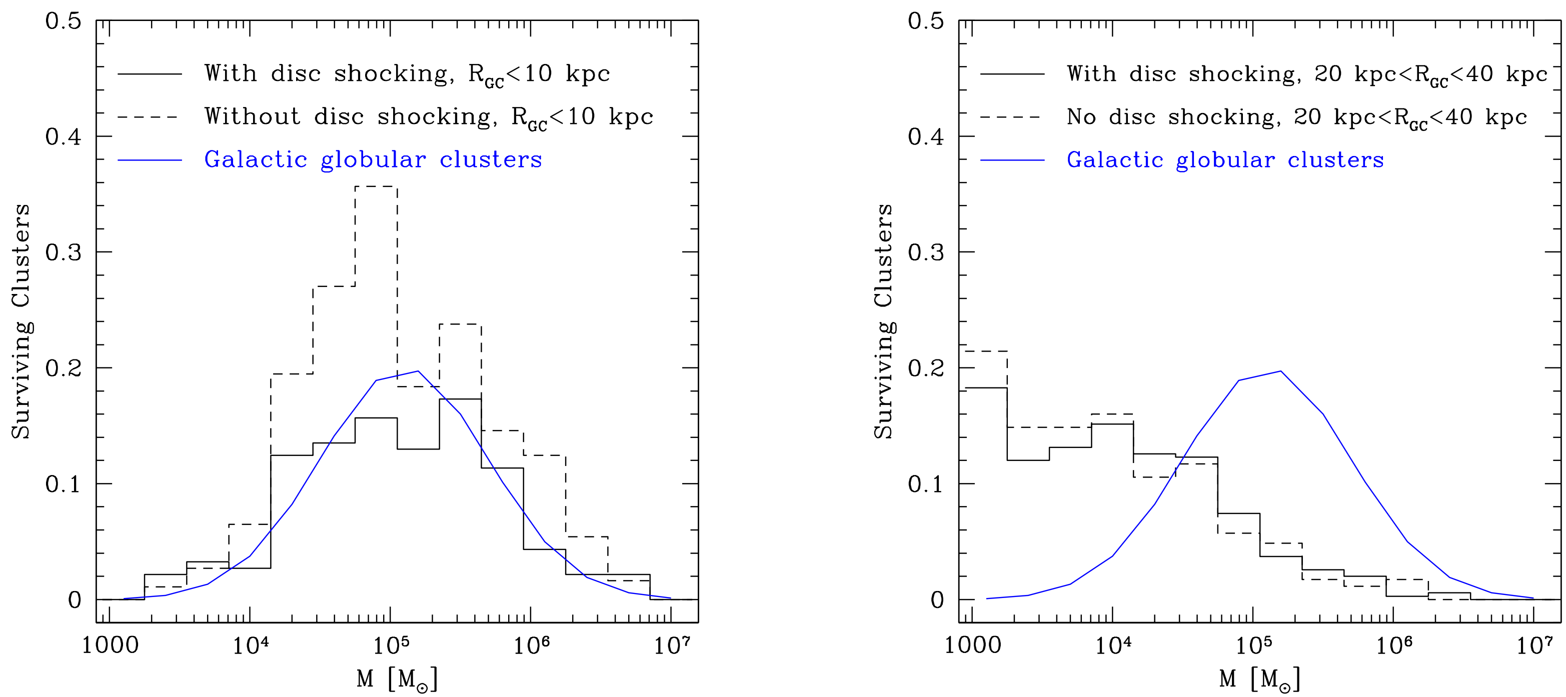
Dissolution of Globular Clusters

- Of all the processes acting on star clusters (gas loss, stellar evolution, relaxation, external tidal fields), gas loss is most likely the most important one, since:
  - In the Antennae galaxies, Fall et al. (2006) found that the number of clusters drops exponentially with age and that the median age of clusters is only 10^7 yrs.
  - In the Milky Way, Lada & Lada (2002) found that only a small fraction of embedded clusters ($\sim 10\%$) can become open clusters.

$\Rightarrow$ Nevertheless, gas expulsion has been largely neglected in most star cluster simulations.

Dissolution of Globular Clusters

- There is also a problem between the initial mass distribution of star clusters (a power-law), and the observed one for globular clusters (a log-normal). Dynamical evolution is not strong enough to turn a power-law into a log-normal with $log < M_C > \approx 10^5 M_\odot$.



$\Rightarrow$ Could the key to this problem lie in the gas expulsion phase ?

A simple model for Gas Expulsion

- Doing a full scale simulation of gas expulsion is impossible since it would have to treat star formation and radiation feedback, magnetic fields etc.
- What I have done is to assume that the gas can be treated as an external potential that is slowly lost from the cluster.
- More specifically, I assume that the fraction of gas present at any time $t > t_s$ in the cluser is given by:

$$\rho(t) = \rho_0 \; exp(-(t - t_s)/\tau_G)$$

- Initially, gas and stars follow the same distribution.

A simple model for Gas Expulsion

Within the framework of this model, the impact of gas expulsion on the evolution of a star cluster only depends on three quantities:

- The star formation efficiency SFE:

  low SFE: Clusters are destroyed or lose a large mass fraction
  high SFE: Most clusters will survive

- Ratio of the gas expulsion timescale to the crossing time τ_G/T_{Cross}:

  small τ_G/T_{Cross}: "Instantenous gas loss", leading to large mass loss
  high τ_G/T_{Cross}: Clusters expand adiabatically

- The ratio of the half-mass radius to the tidal radius r_h/r_t:

  high r_h/r_t: Expanding clusters are easily destroyed
  small r_h/r_t: Clusters are nearly isolated and more likely to survive

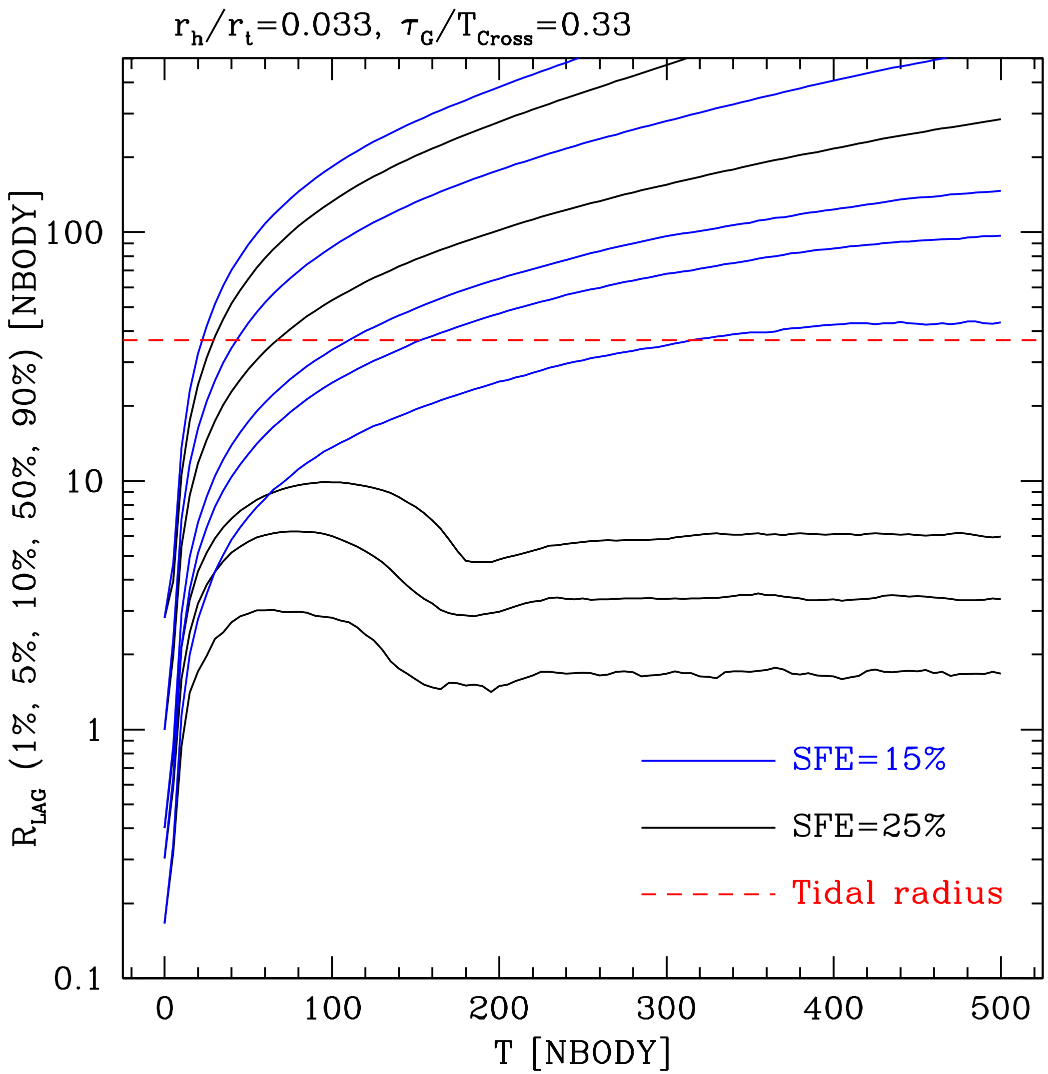
N-body simulations of gas expulsion

- A grid of N-body simulations was created, starting with different values for SFE, τ_G/T_{Cross} and r_h/r_t:

SFE:	5%, 10%, 15%, 20%, 25%, 33%, 40%, 50%
τ_G/T_{Cross}:	0.00, 0.05, 0.10, 0.33, 1.00, 3.00
r_h/r_t:	0.01, 0.033, 0.06, 0.1, 0.15, 0.2

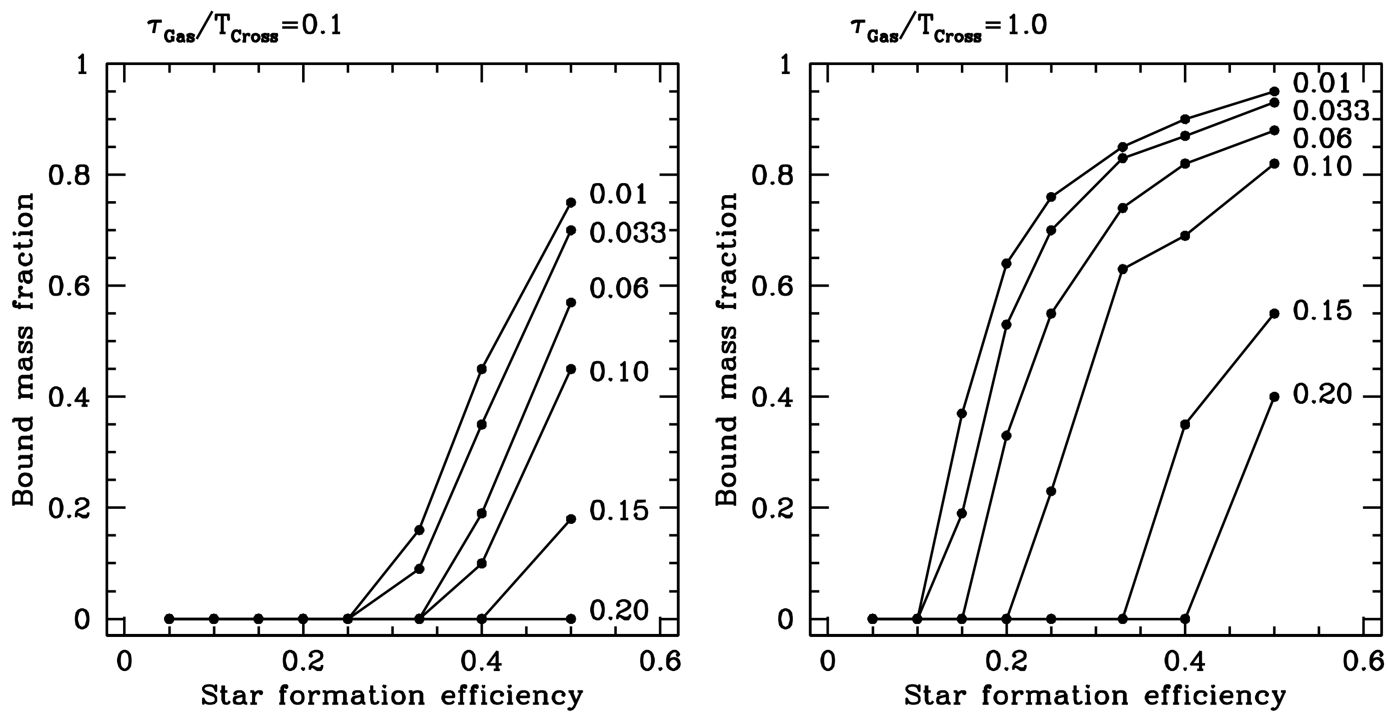
- Overall, these are 288 combinations. However, by carfully chosing the order of the runs, less than 100 runs have to be actually done.
- Each simulation started with 20.000 stars and was done for 1000 N-body times at which time the fraction of remaining stars and the final radius were determined.

N-body simulations of gas expulsion



N-body simulations of gas expulsion

- Results of surviving mass fraction as a function of r_h/r_t and SFE:



- These results can now be used to calculate the impact of the initial gas expulsion on the evolution of star cluster systems.

Evolution of Star Cluster Systems

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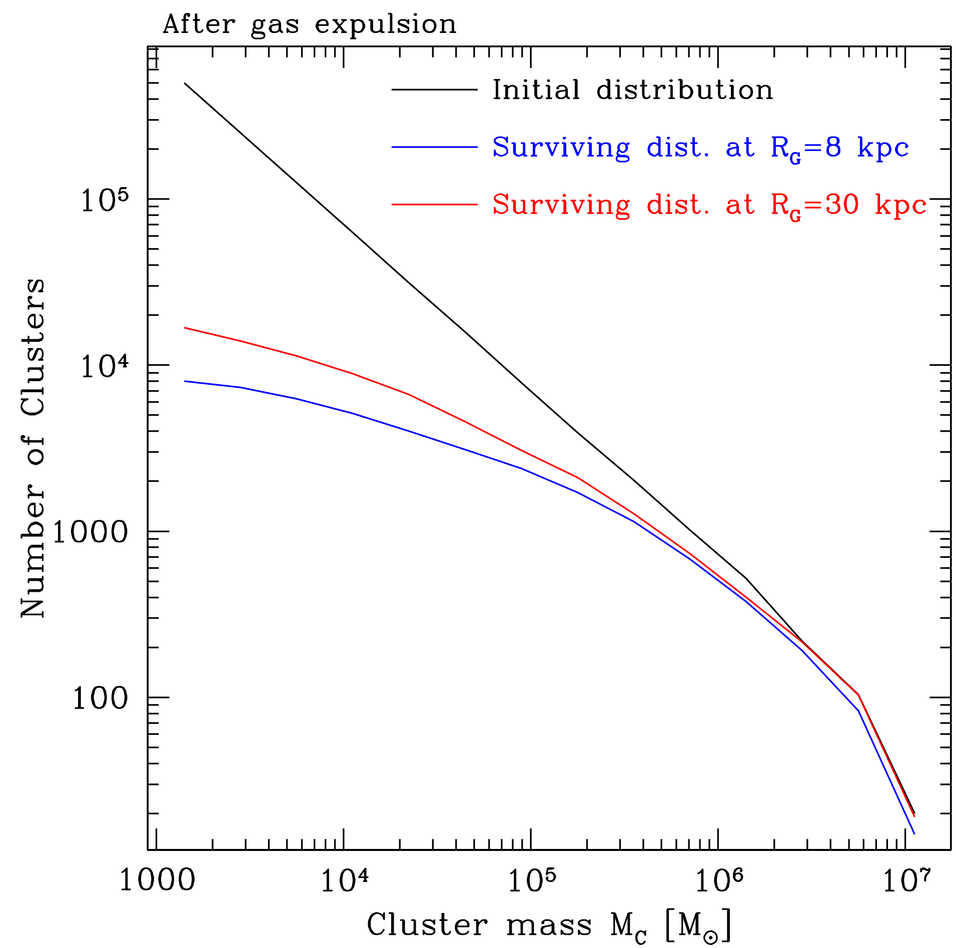
- Gas expulsion timescale $\tau_G = 0.3$ Myrs

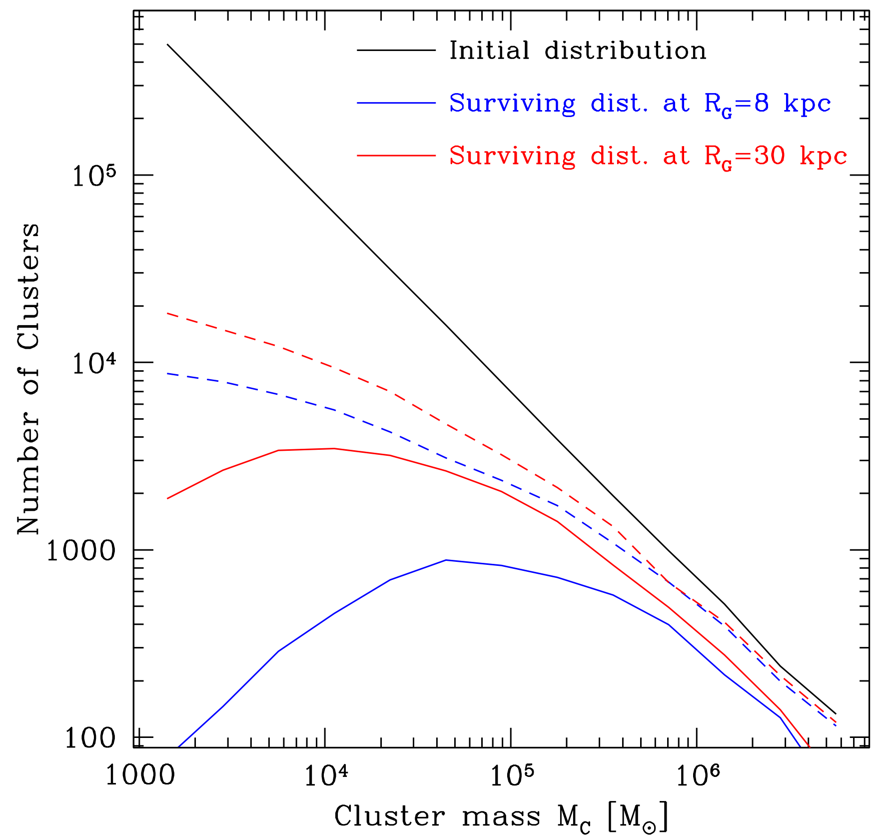
Evolution of Star Cluster Systems

- Mass distribution of surviving clusters after gas expulsion:
  - About 96% (93%) of all clusters are destroyed at $R = 8$ kpc (30 kpc).
  - The initial power-law slope of $\alpha = 2.0$ is flattened into a slope $\alpha = 0.5$.



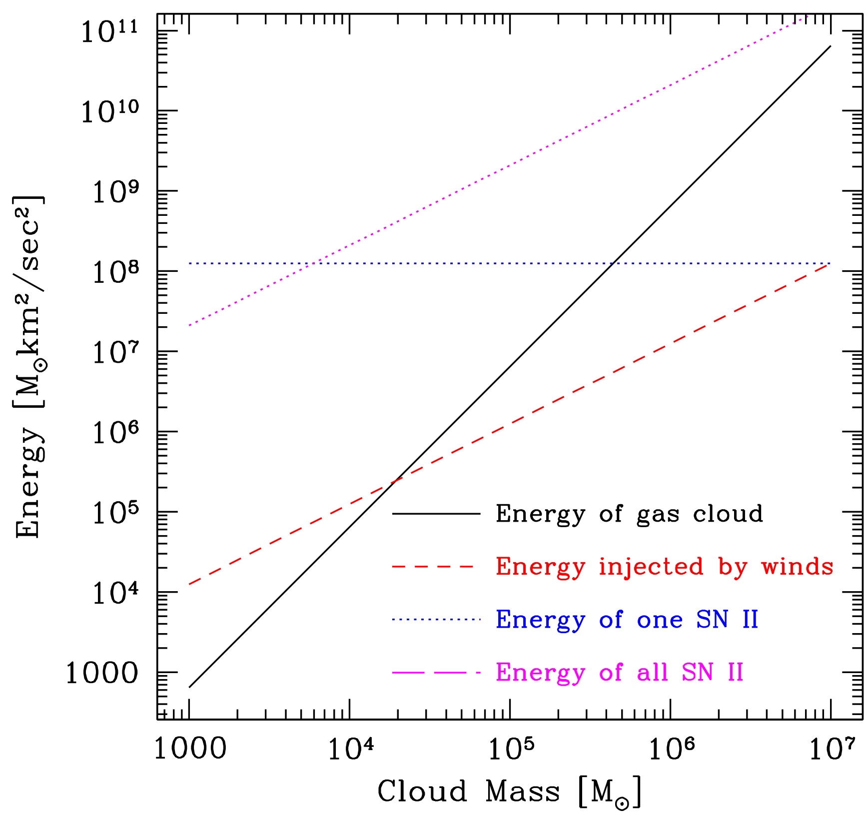
Evolution of Star Cluster Systems

- Mass distribution of clusters after 13 Gyrs:
  - At small galactocentric distances, the final distribution is consistent with observations.
  - But the mismatch at large distances is still not removed.



Gas expulsion from star clusters

- Gas expulsion is driven by mainly two processes: Stellar wind mass loss and Supernova explosions
- The importence of these processes depends on the initial mass of the gas cloud:



A new model for τ_{Gas}:

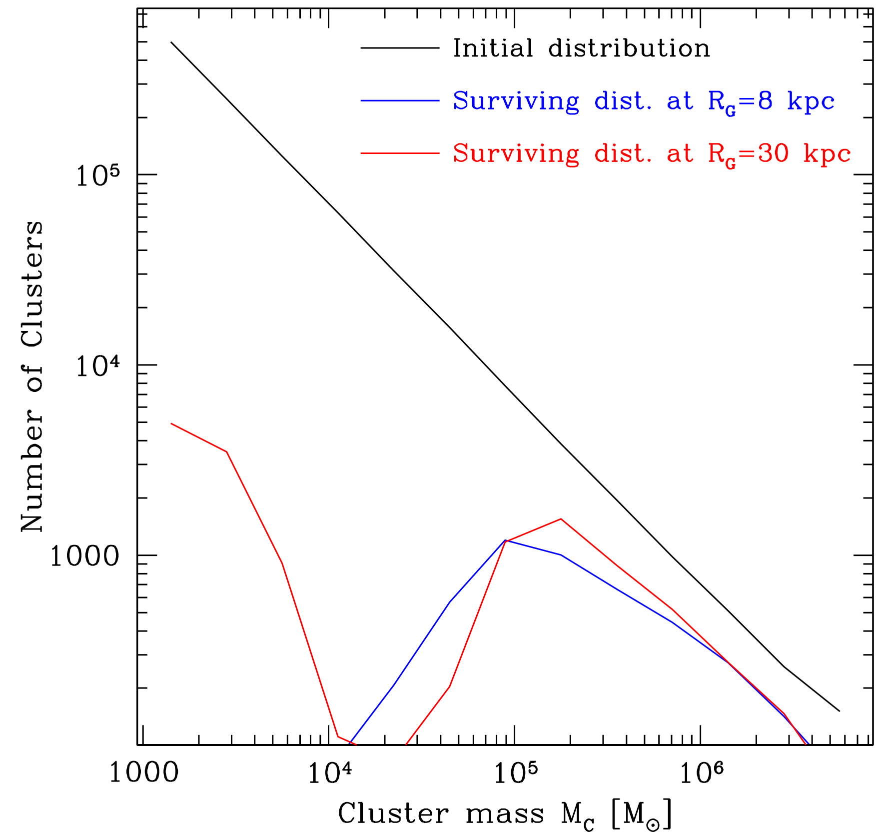
Based on these considerations, a new model for gas expulsion was created:

- $M_{Cloud} < 2 \cdot 10^4 M_\odot$: Gas expulsion by stellar winds, $\tau_{Gas} = 0.5$ Myrs.
- $2 \cdot 10^4 M_\odot < M_{Cloud} < 2 \cdot 10^5 M_\odot$: Gas expulsion by a single supernova, $\tau_{Gas} = 0$ Myrs.
- $M_{Cloud} > 2 \cdot 10^5 M_\odot$: Gas expulsion by multiple supernovas: $\tau_{Gas} = 0.3$ Myrs.

Evolution of Star Cluster Systems

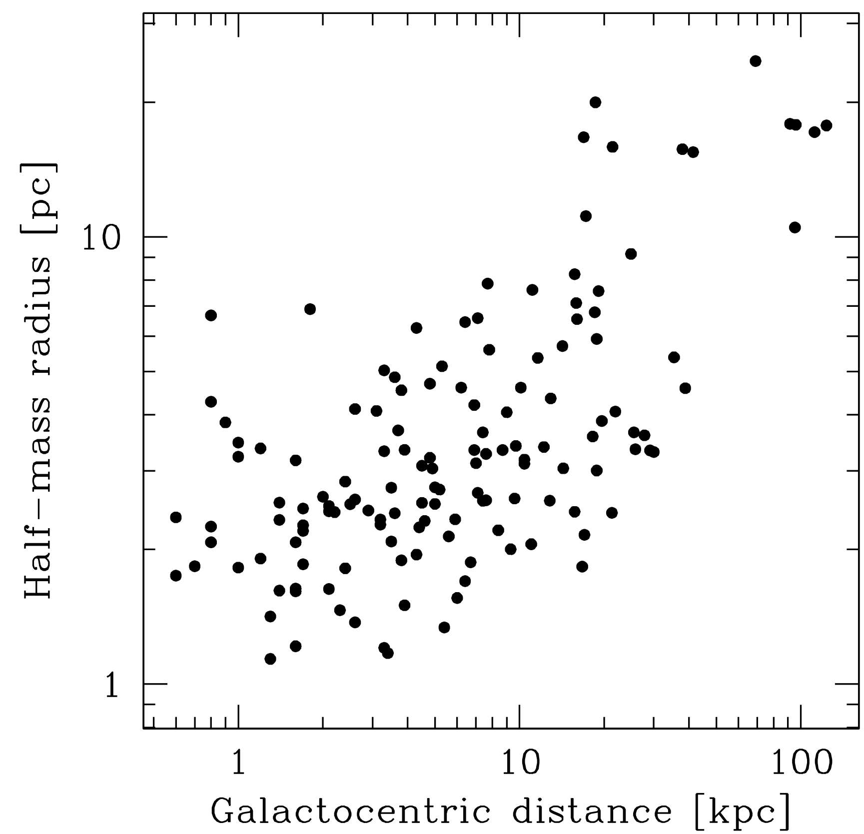
- Good fit of the peak of the globular cluster luminosity function at all radii.

- A low-mass tail of globular clusters with masses $M < 10^4 M_\odot$ is also present. This shows that a further refinement of the model is necessary (or that observers should look for these clusters).



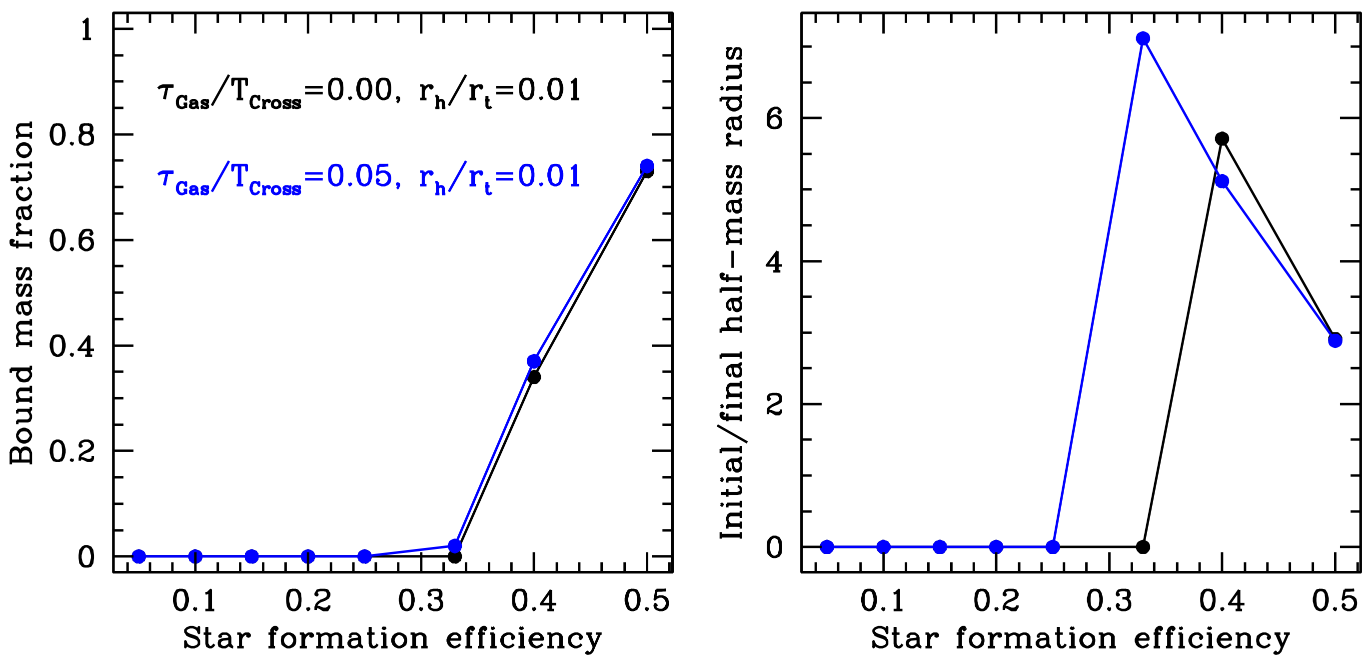
Half-mass radii of halo globular clusters

- Globular clusters in the Milky Way halo have sizes significantly larger than inner globular clusters.
- This might be due to differences in their formation or the later dynamical evolution. Evolution would be the simpler explanation. But relaxation cannot have created such clusters ($T_{Rel} > T_{Hubble}$).



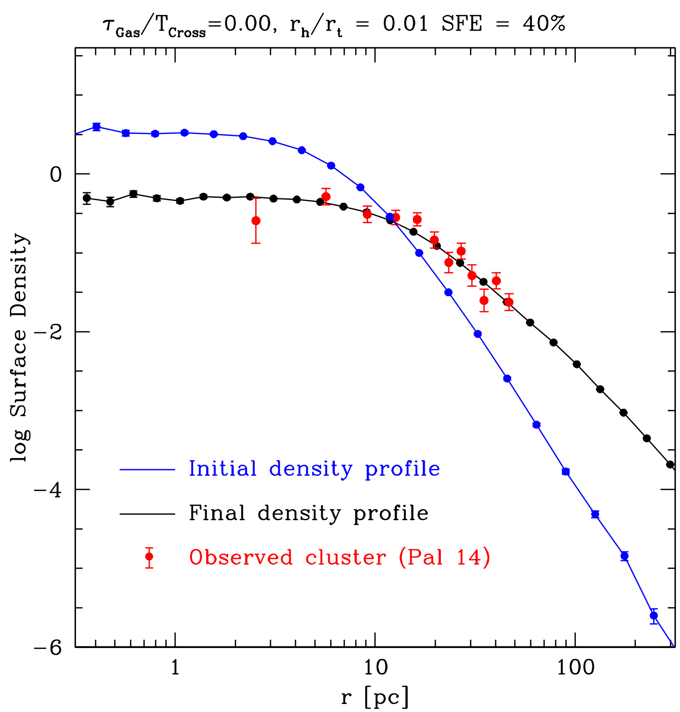
Gas expulsion in halo globular clusters

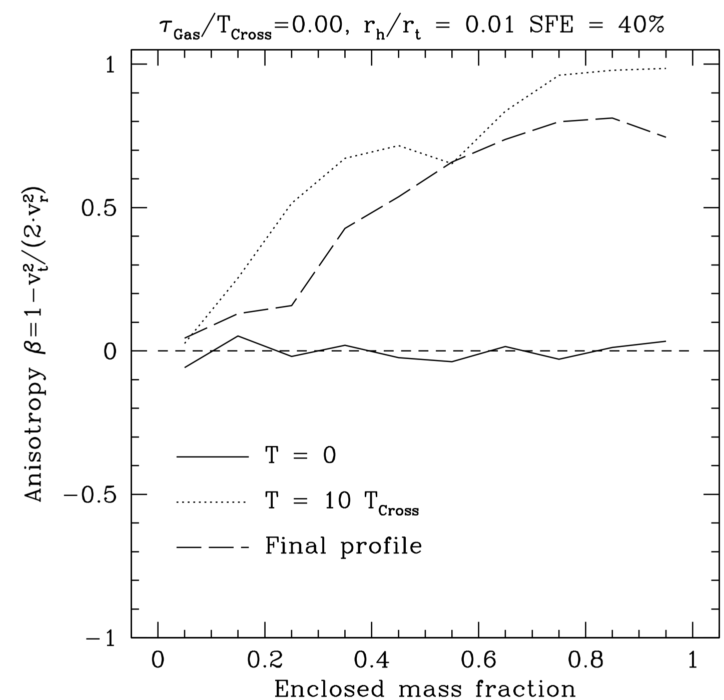
- If gas expulsion is fast in halo globulars, only those with SFEs>33% will survive. Most surviving clusters should have expanded strongly !



Gas expulsion in halo globular clusters

- The density profile of a cluster which expanded strongly is in excellent agreement with the observed profile of halo clusters (left).





- The scenario also predicts that halo globular clusters should have strongly radial velocity anisotropies in their outer parts (right).

Summary

The results can be summarised as follows:

- We have created a grid of models of clusters with different SFEs, gas expulsion timescales and strengths of the external tidal field.
- The simulations confirm that gas expulsion is important for the dynamical evolution of star clusters and destroys most of them within 10 to 30 Myrs.
- Gas expulsion might be responsible for the log-normal mass function of globular cluster systems.
- It could also be responsible for the large sizes of halo globular clusters.