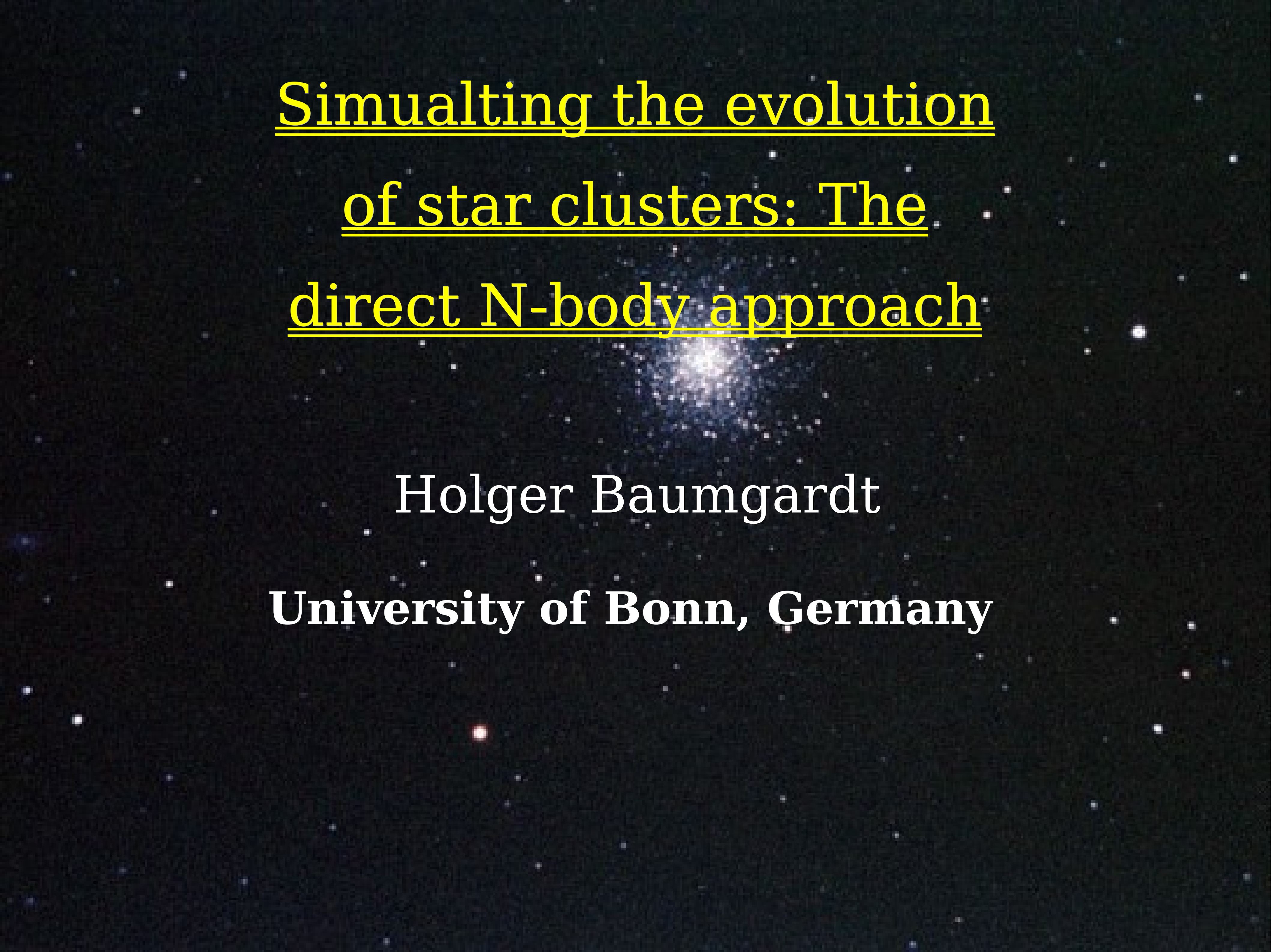

# Simualting the evolution of star clusters: The direct N-body approach

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## N-body simulations:

Follow the motions of stars directly as they move through the cluster. Individual particle data is not correct, but statistical average should be.

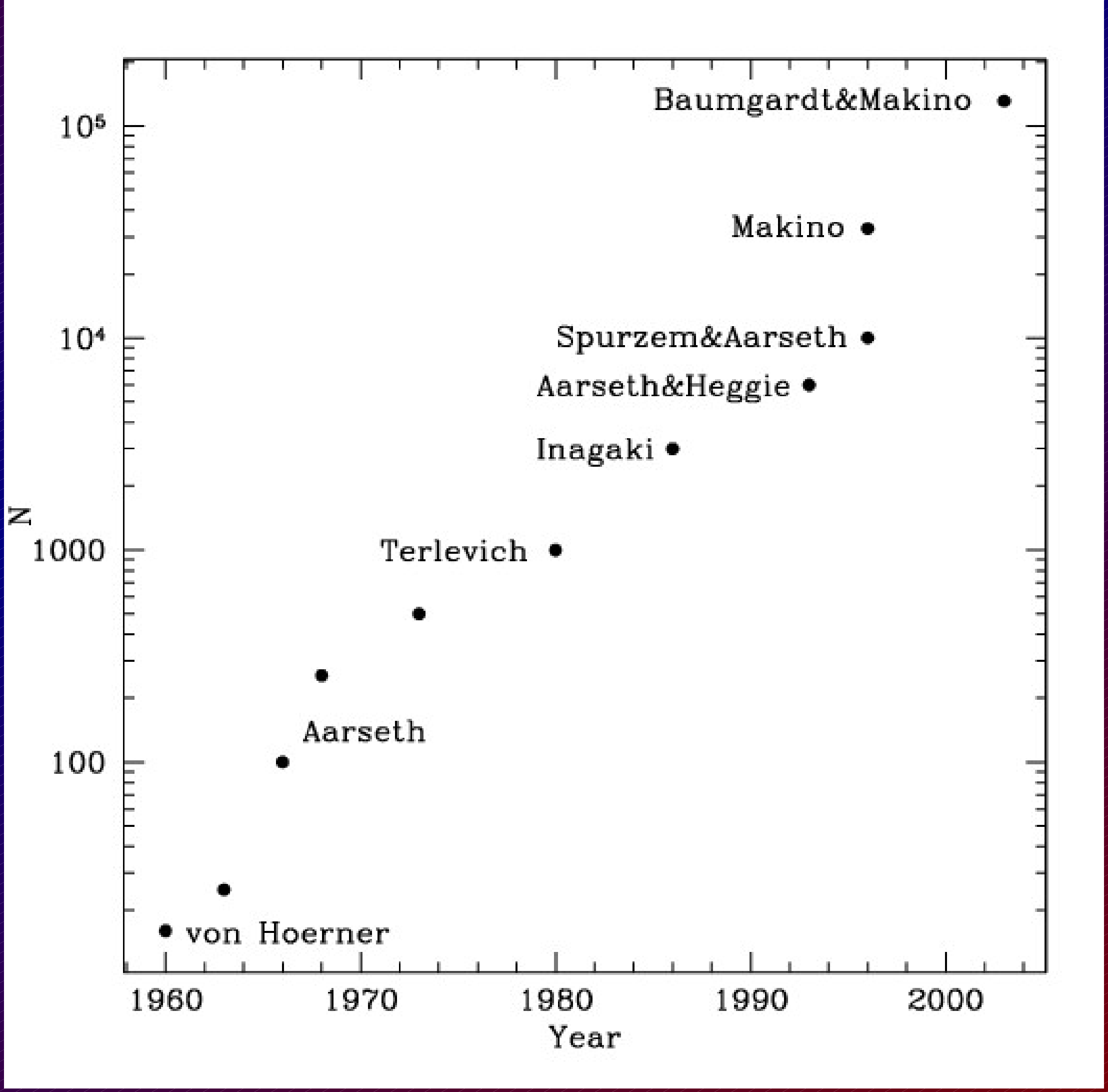
### Advantage:

- To a large degree free of assumptions about the underlying physics. Easy to implement additional physical processes.

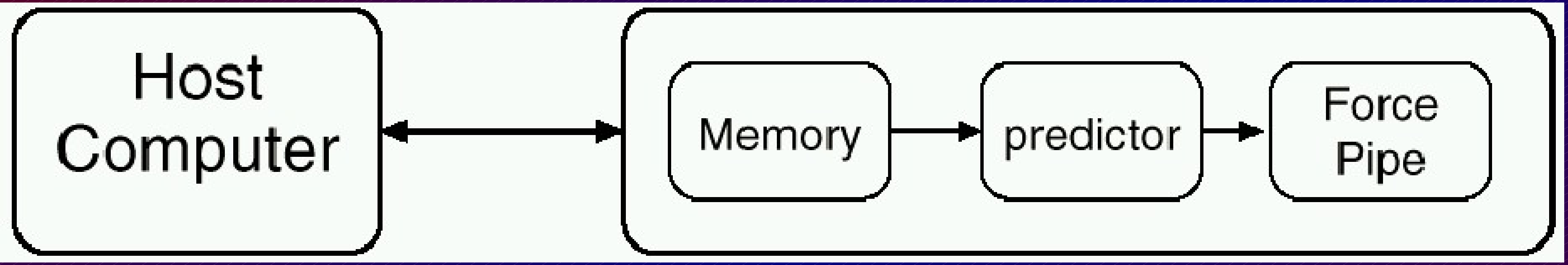
### Disadvantage:

- Slow since force computation scales as $N^2$

The progress of N-body simulations has therefore been very slow:



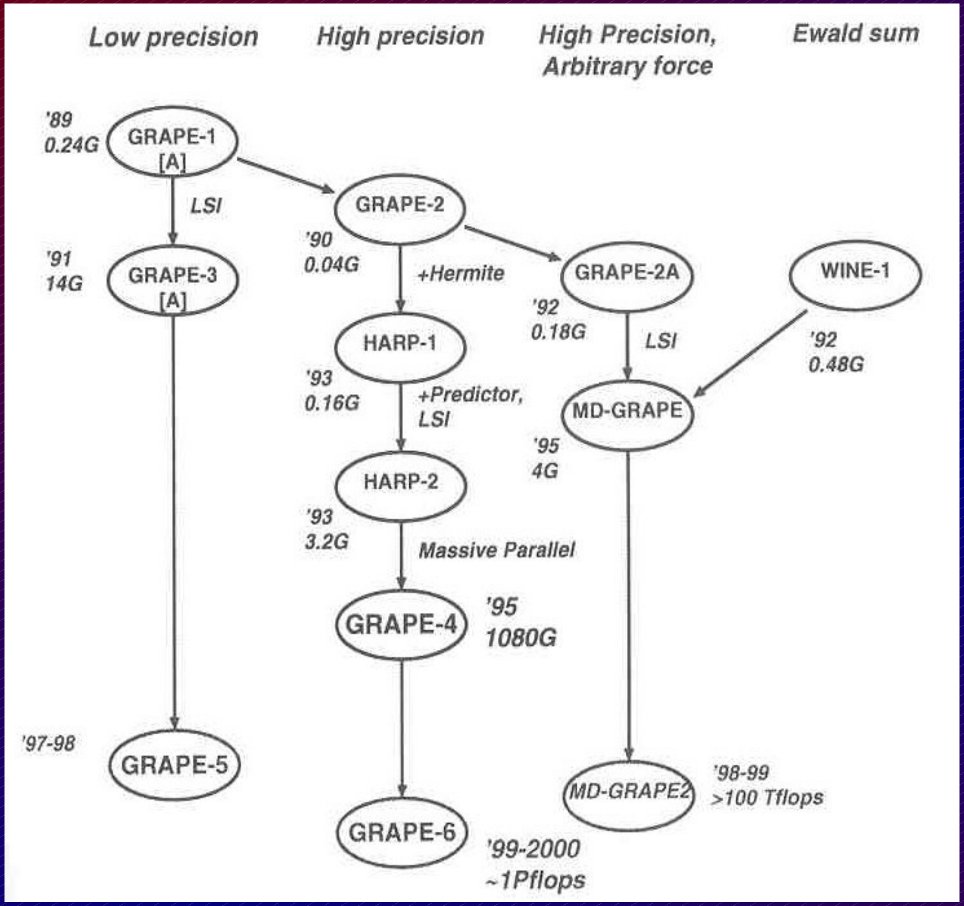
# Principle design of GRAPE computers.

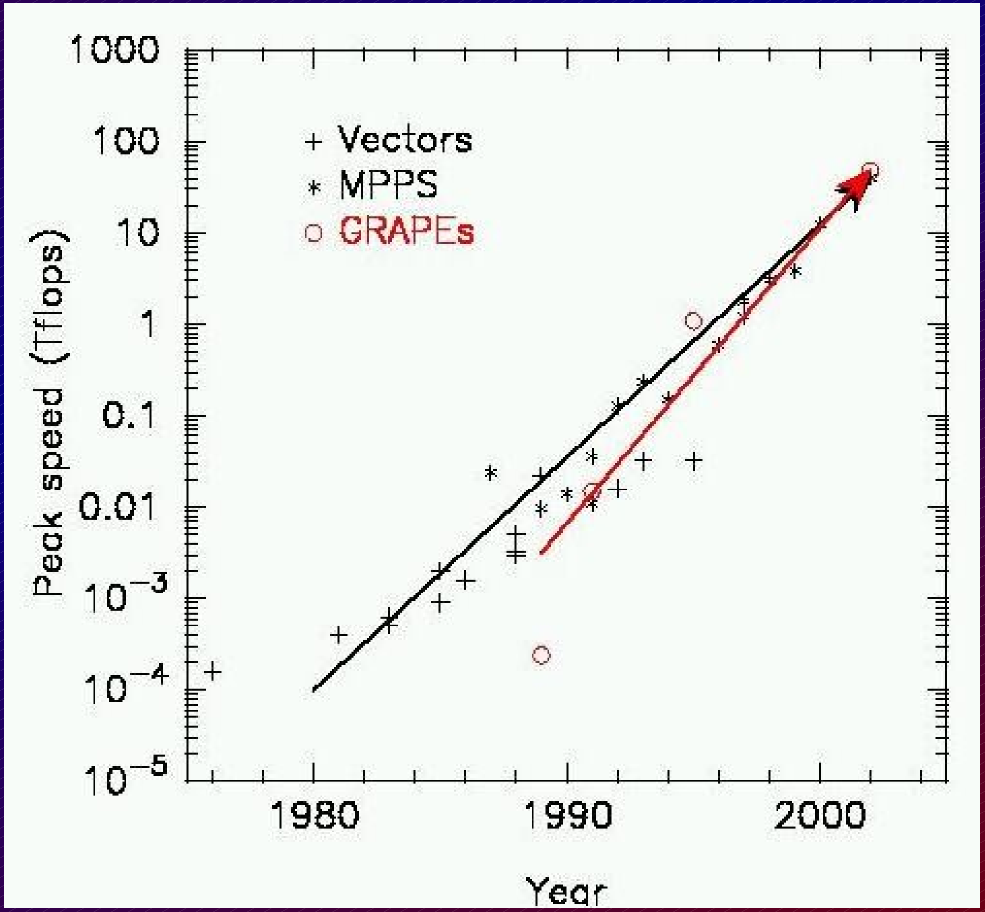



(1) Host computer (PC) sends $m, \vec{x} + \vec{v}$ of all particles to GRAPE board.

(2) GRAPE hardware calculates $\vec{F} + \dot{\vec{F}}$ and sends them back to host.

# Evolution of GRAPE computers:



**MicroGRAPE**

Peak speed: 123 Gflops
Maximum N: 131.072
Price 4.000 Euro

**GRAPE6-Pro**

Peak speed: 1.0 Tflops
Maximum N: 1.000.000
Price 40.000 Euro

# The GRAPE world:

## Japan:

- Tokyo University (16 Grape6, 16(?) MicroGrape)
- National Observatory, Mitaka (10 Grape6, 10 MircoGrape)
- Tsukuba University (8 Grape6, 256 MicroGrape planned)
- Smaller installations at TIT, Gunma, NIFS

## Europe:

- Amsterdam (4 Grape6)
- Heidelberg ARI (32 MicroGrape)
- Bonn (1 Grape6, 2 MicroGrape)
- Munich, Cambridge, Edinburgh...

## USA:

- Rochester (32 MicroGrape)
- AMNH, New York (5 Grape6)
- Drexel, Michigan....

Successor GRAPE-DR will be available by 2008. Peak spead will be about 30x larger than that of GRAPE6.

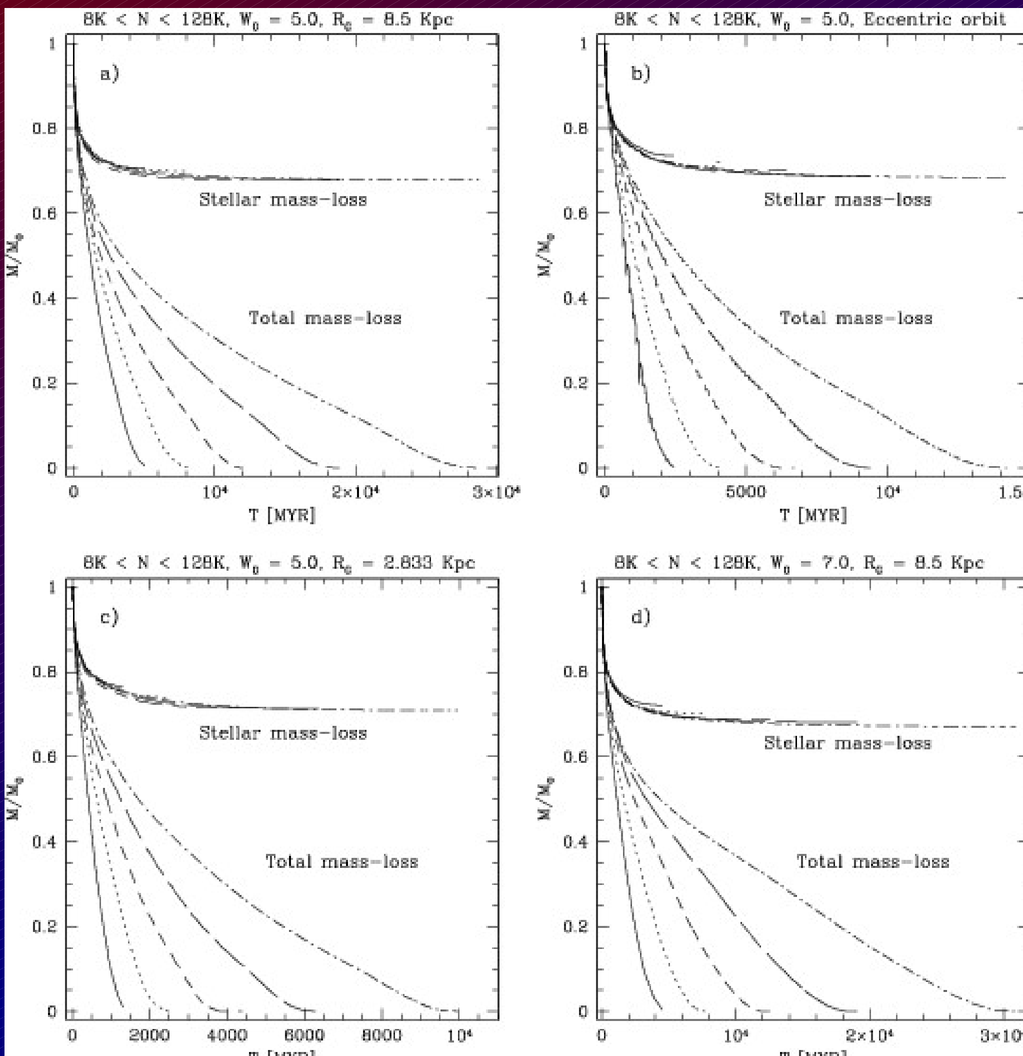
# Ingredients of N-body simulations:

- External (tidal) fields (Cut-offs, Spherical, Discs, Full 3D, Time-variable)
- Stellar evolution (in form of look-up tables, e.g. Hurley et al. 2000), so far no combination of an SEV code with an N-body code.
- Binary-stellar evolution (tidal circularisation, Roche-lobe overflow, gravitational waves...)
- Stellar collisions

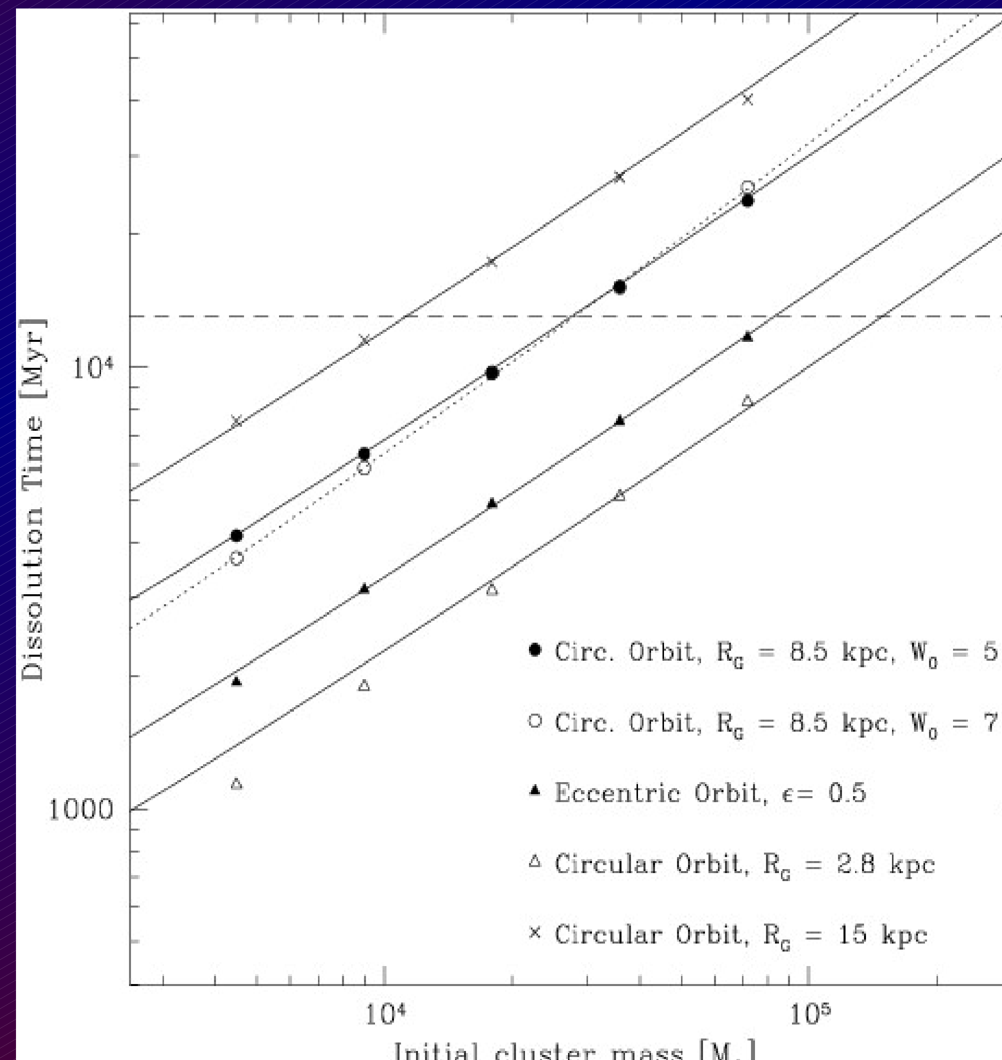
Examples of such codes are: NBODYx (Sverre Aarseth), KIRA (Simon Portegies Zwart, Steve McMillan). New codes are also being developed (e.g. Bonn)...

# Modeling the evolution of star clusters in an external galactic field:

## Evolution of bound mass



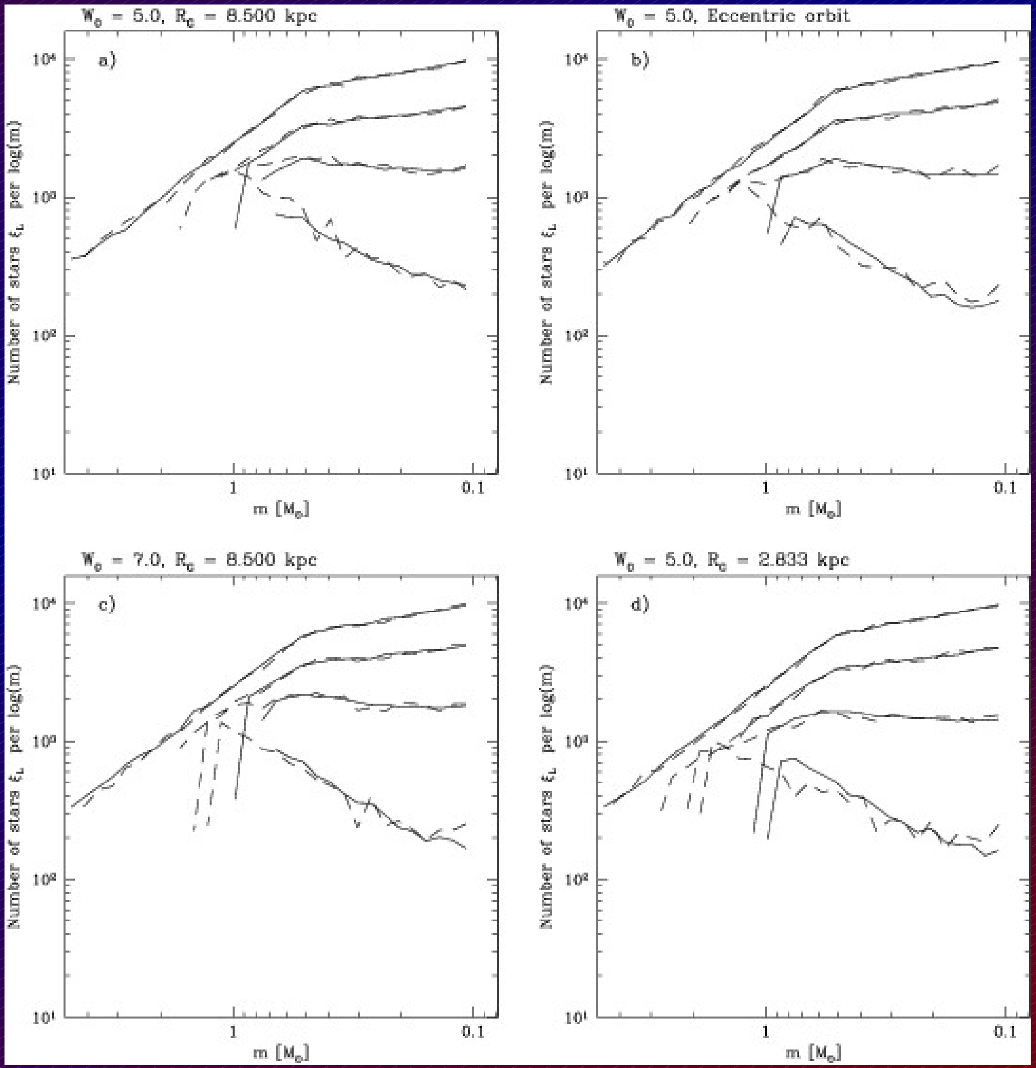

## Cluster lifetimes




from Baumgardt & Makino (2003)

Cluster evolution shows increasing depletion of low-mass stars and mass segregation.

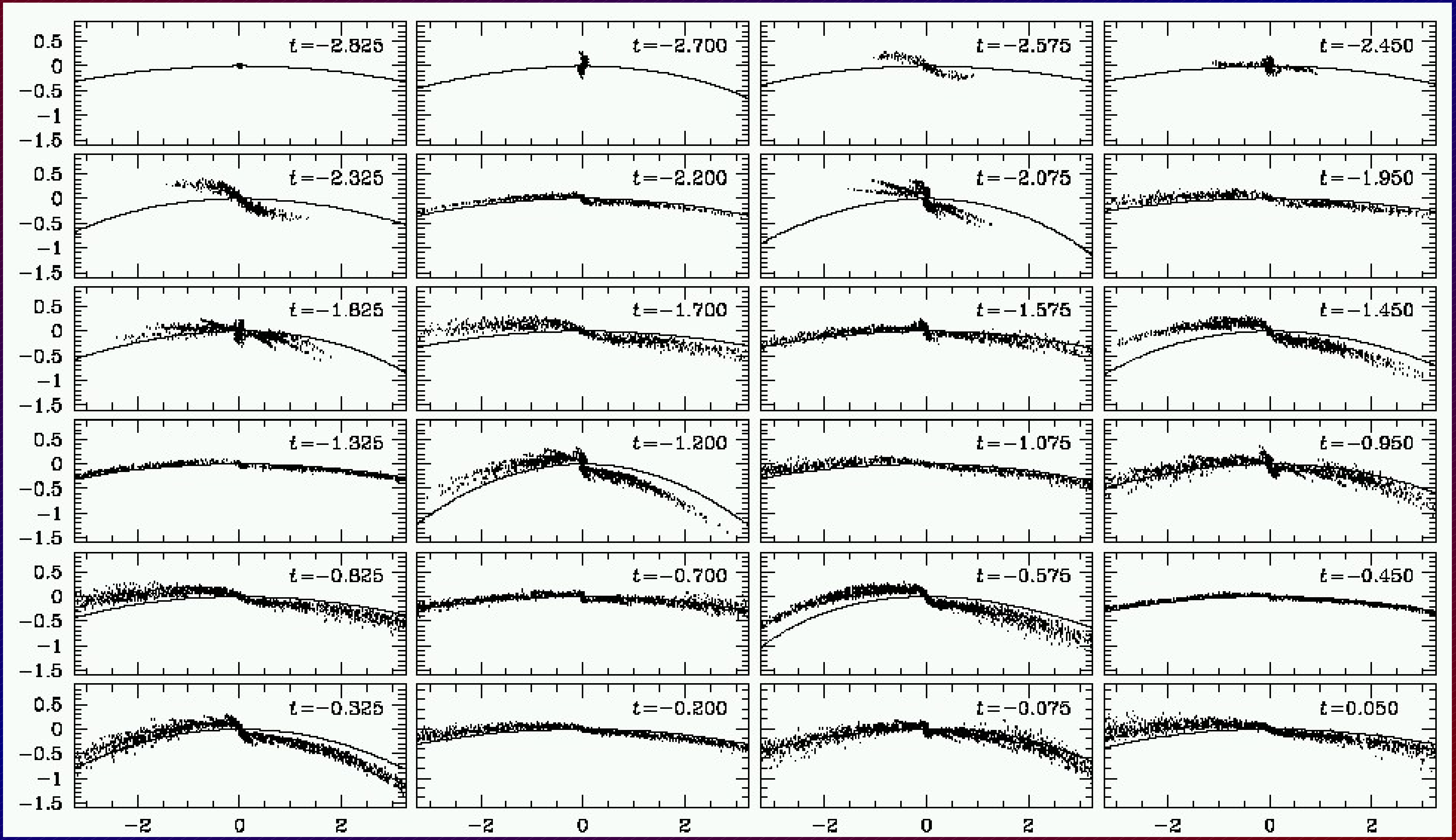
However overall M/L ratio is not affected until close to final dissolution.




from Baumgardt & Makino (2003)

# Modeling the disruption of star clusters in an external galactic field:

## Dissolution of Pal 5




from Dehnen et al (2004)

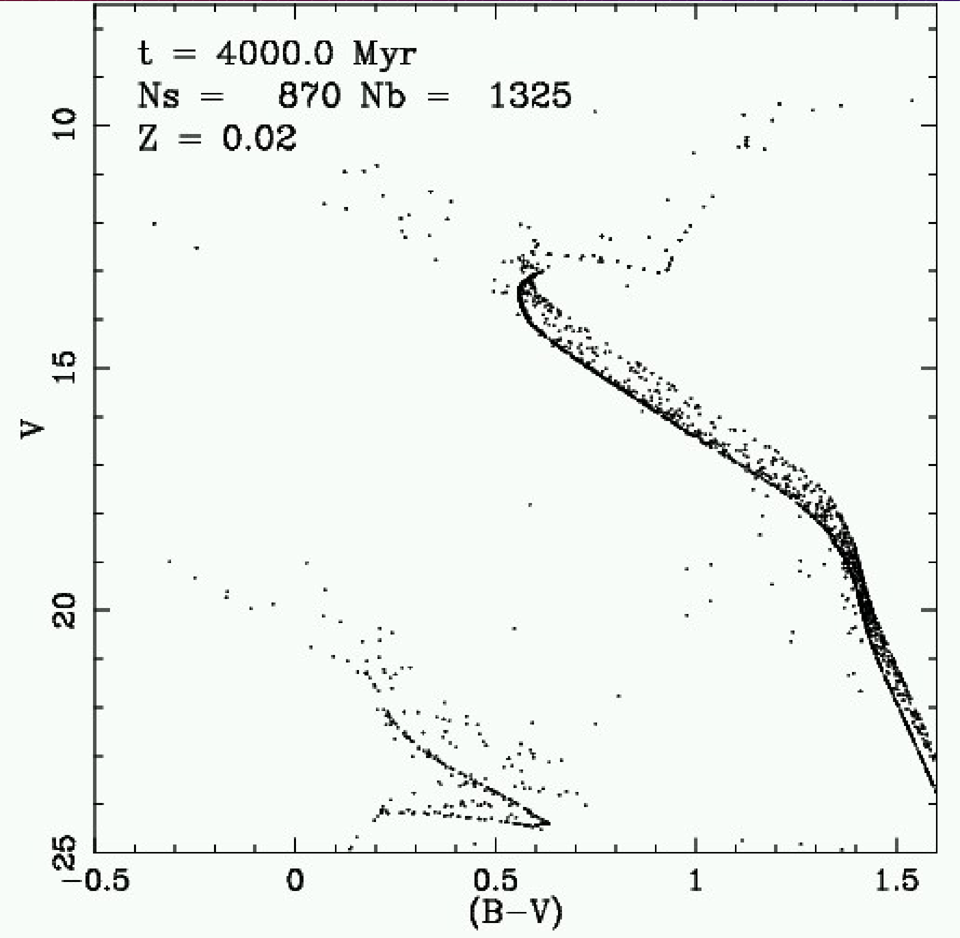
Dehnen et al. (2004) followed the evolution of an individual star cluster (althoguh through softened N-body simulation) in order to constrain cluster orbit and further evolution.

They found that the remaining lifetime of Pal 5 is only of order 100 Myrs.

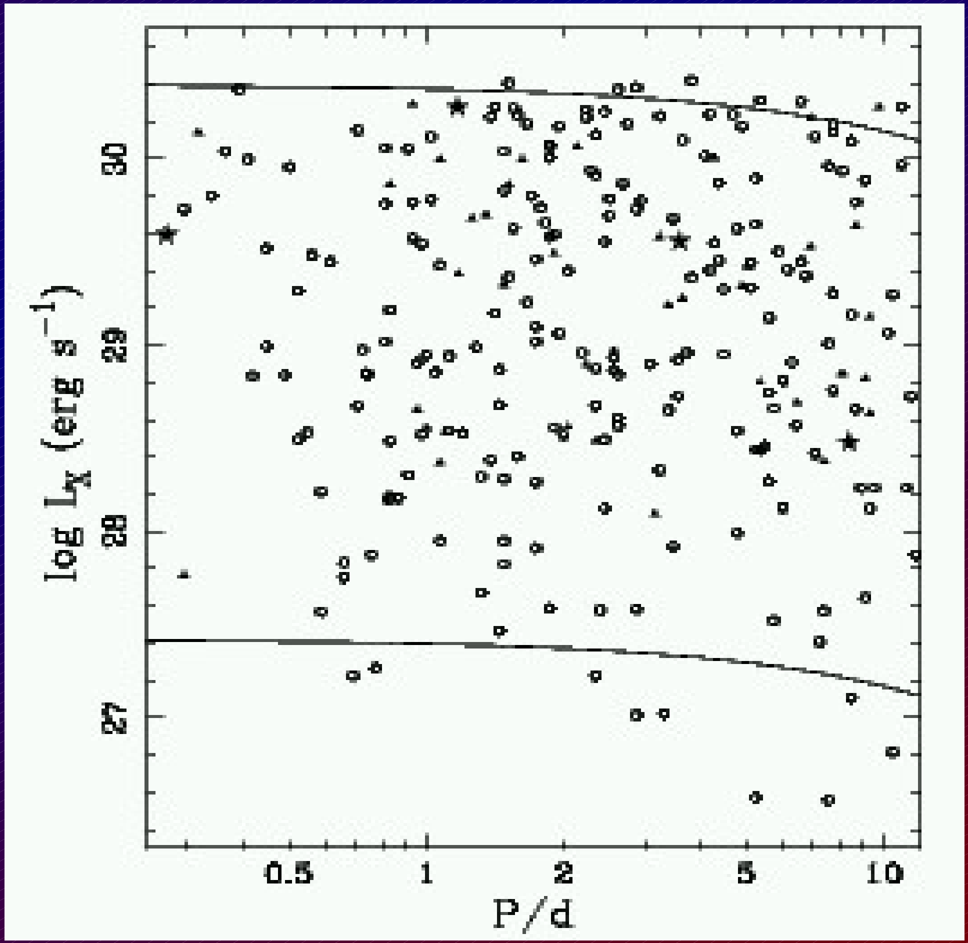
With increasing computer power and better data on cluster orbits, expect more such simulations in the future !

# Evolution of the binary content and formation of X-ray binaries in rich open clusters, e.g. M67 (Hurley et al. 2005):

Color-magnitude evolution



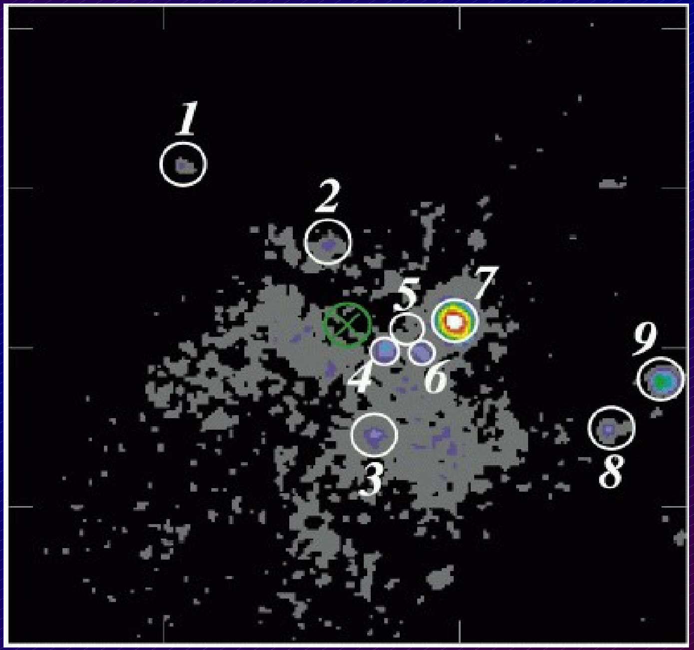

X-ray binaries

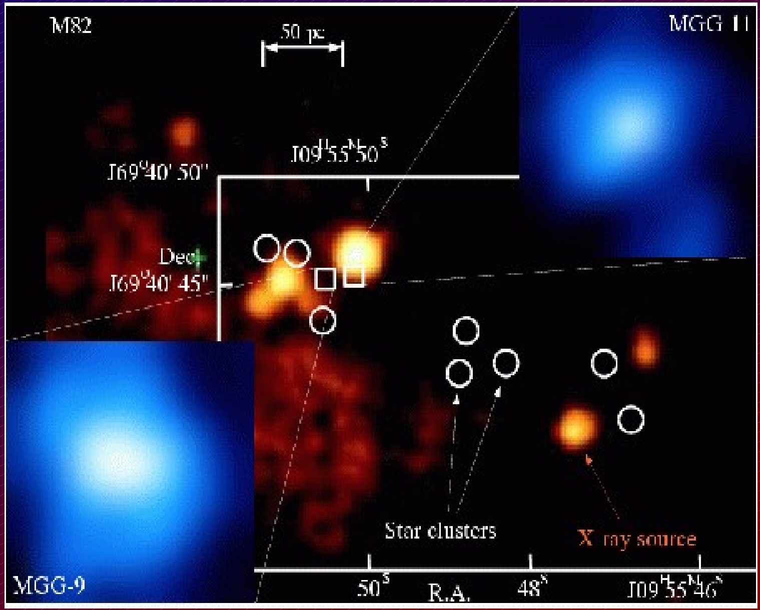



See also Portegies Zwart et al (2004) for similar runs on other clusters.

# Formation of IMBH's in star clusters

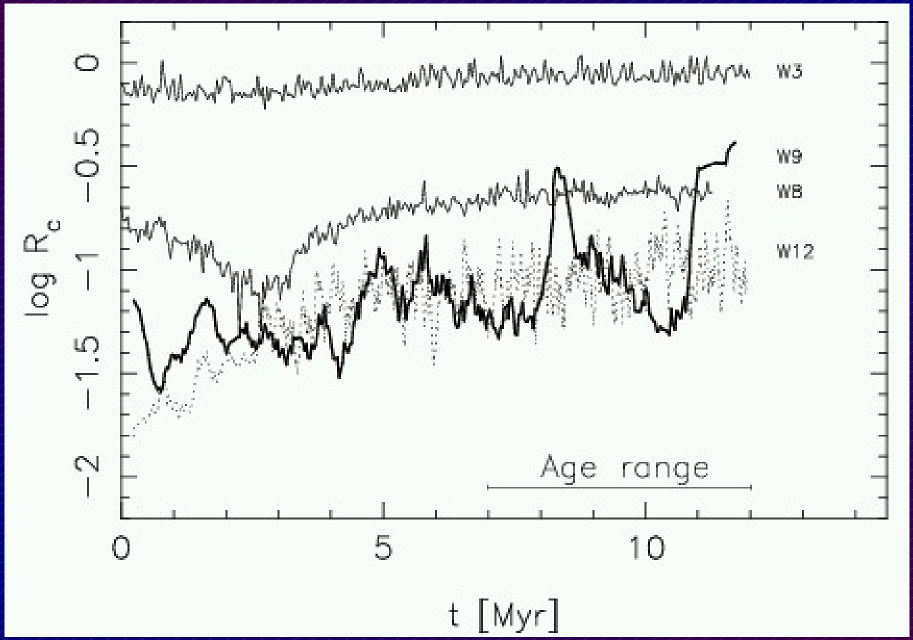
- Observations indicate that there might be a connection between ULX (ultra-luminous X-ray sources) and star clusters.
- Matsumoto et al. (2001) for example found a bright X-ray source at the center of the starburst galaxy M82 with an Eddington luminosity corresponding to a black hole of several hundred solar masses.
- Optical follow-up observations showed that the position of this source coincides with that of a young luminous star cluster.

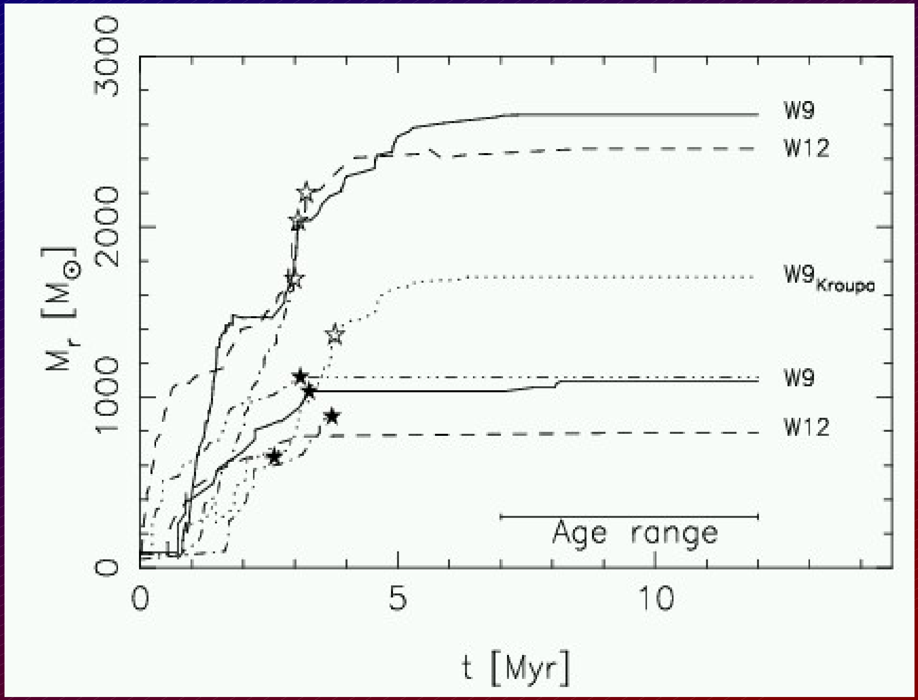


# Formation of IMBH's in star clusters

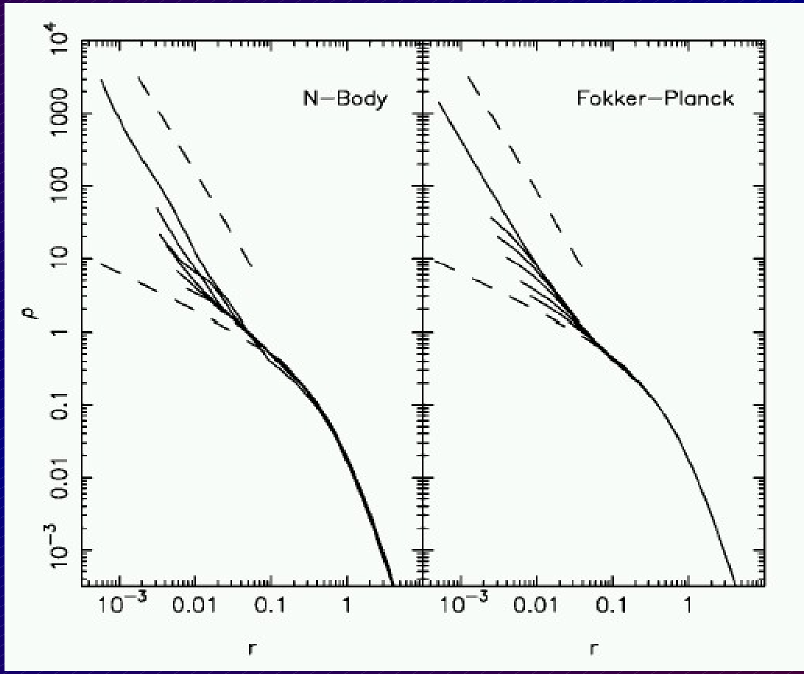
- Portegies Zwart et al (2004) followed the evolution of MGG-11 by N-body simulations, starting from King models with initial concentrations in the range 3.0 < Wo < 12.0.
- They found that heavy mass stars sink into the cluster center as a result of dynamical friction.
- For central concentrations Wo>9.0, this happened fast enough that runaway merging of stars occurs in the center.



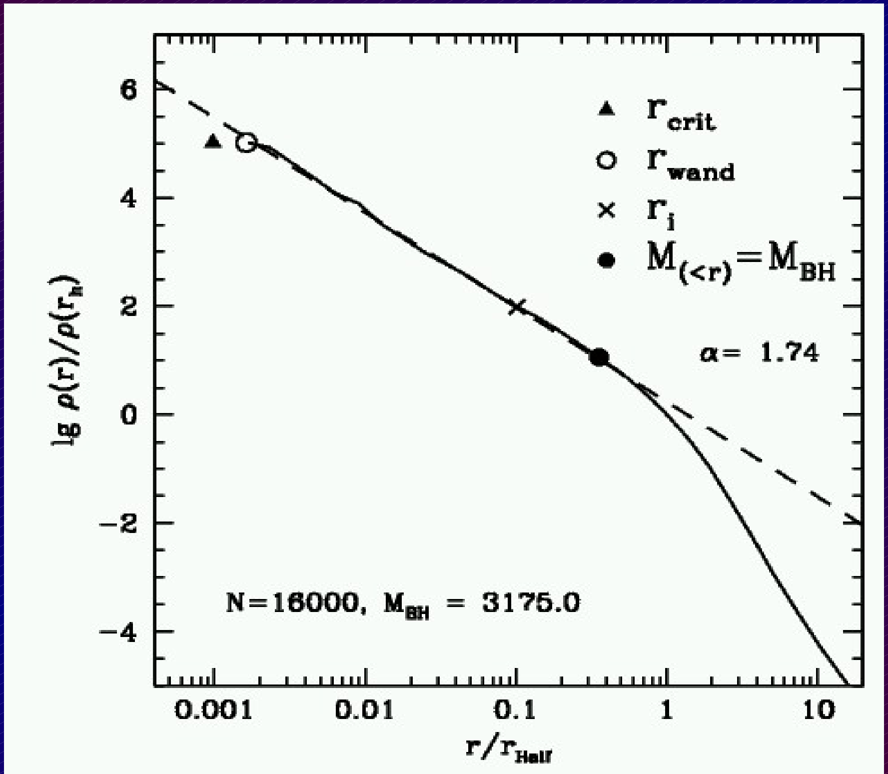



# Evolution of clusters with an IMBH

Recent N-body results have confirmed that $r^{-1.75}$ power-law cusps form around IMBHs.



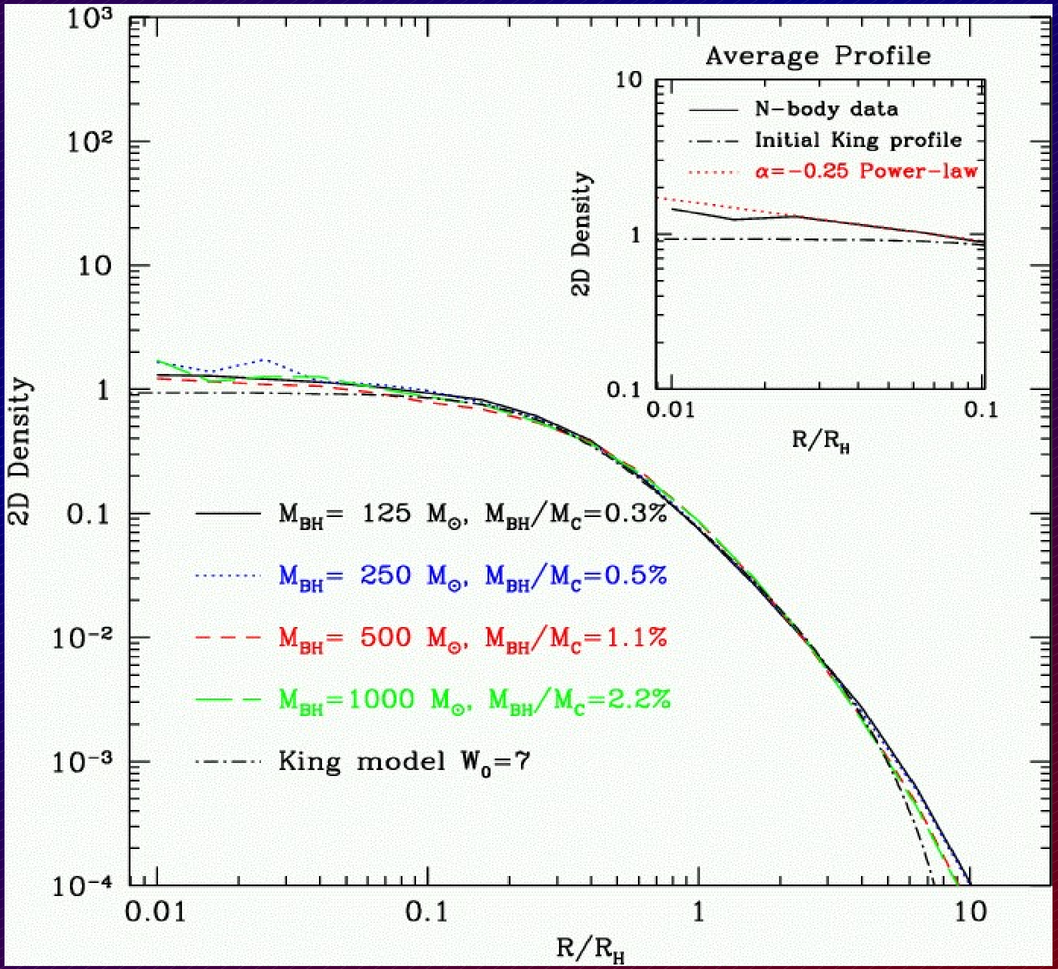

Preto, Merritt & Spurzem (2004)




Baumgardt, Makino & Ebisuzaki (2004ab)

# Evolution of clusters with an IMBH

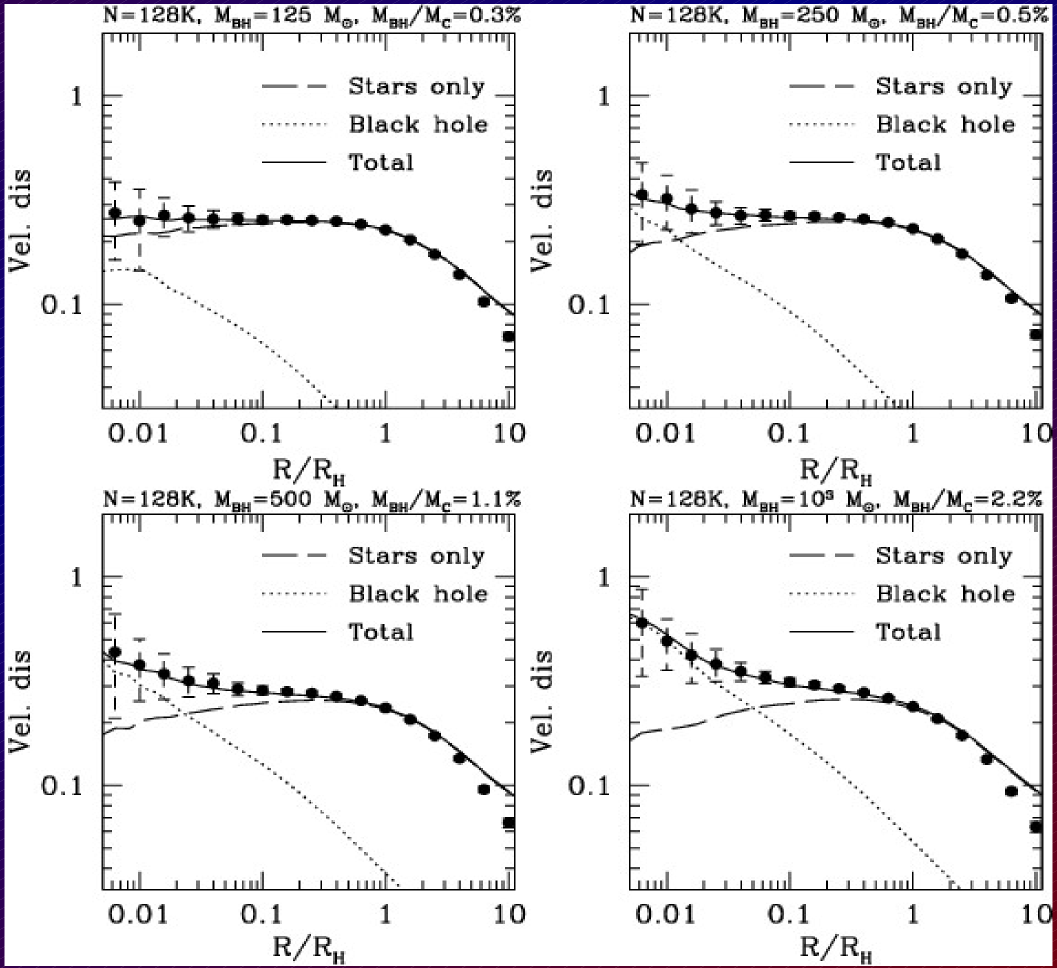
The projected light profile follows a $r^{-0.25}$ cusp, much flatter than in core-collpse clusters.




from Baumgardt, Makino & Hut (2005)

# Evolution of clusters with an IMBH

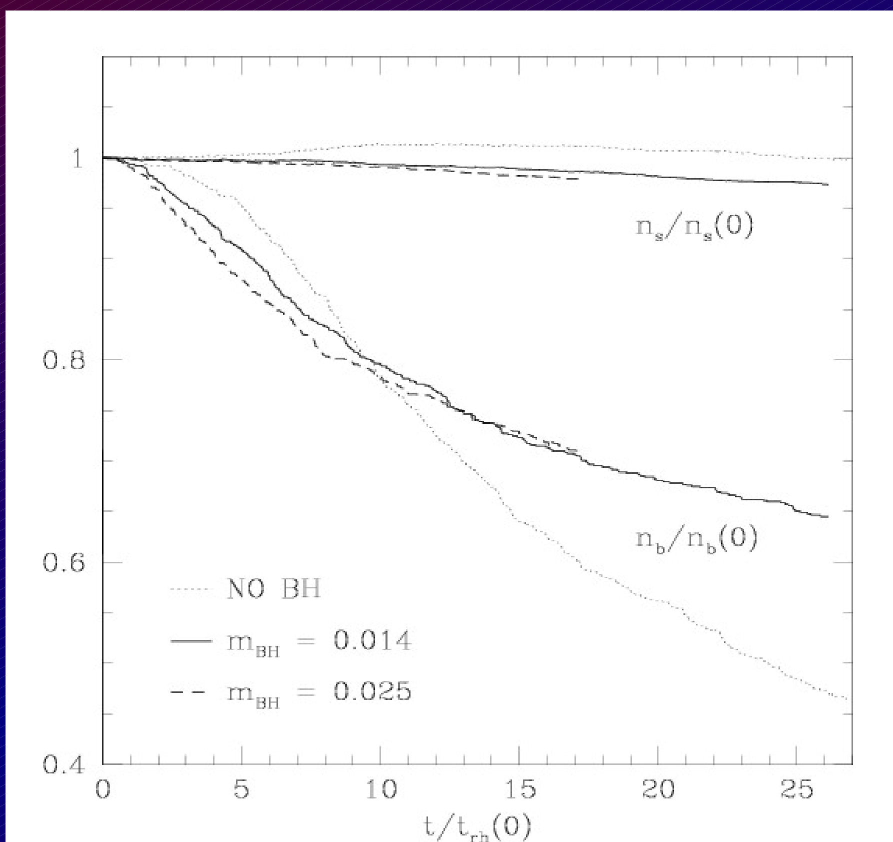
Finding the central rise in the velocity dispersion will nevertheless be challenging unless the IMBH is of relatively high mass.

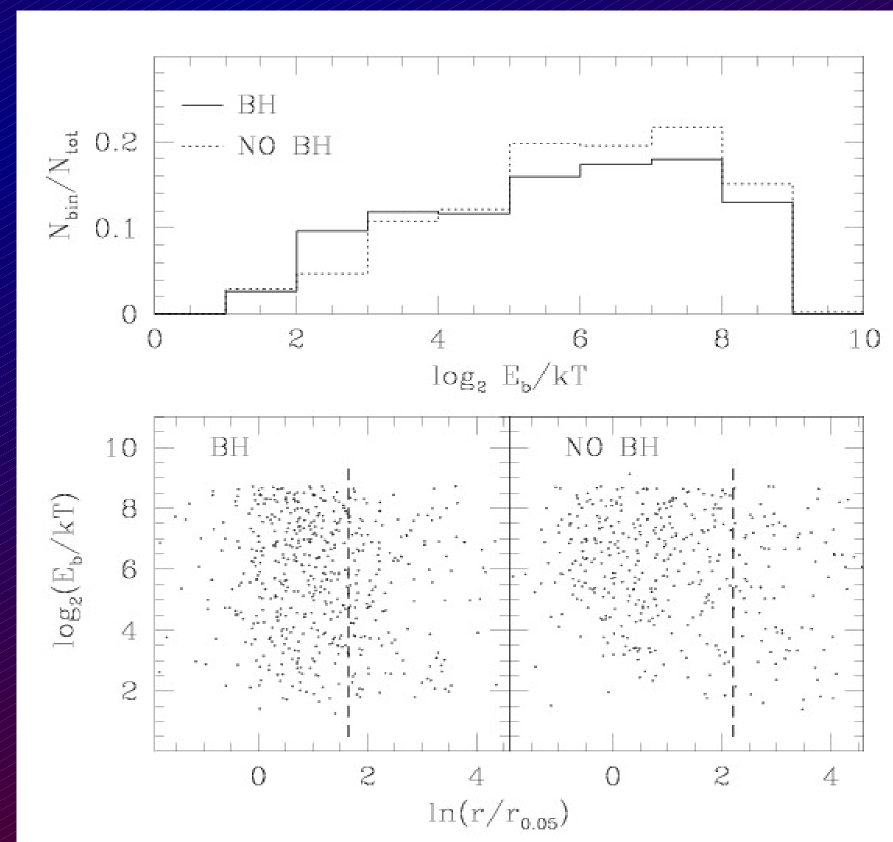



from Baumgardt, Makino & Hut (2005)

# Evolution of clusters with an IMBH

Another way of IMBH detection might be through GW emission. GW emission could be increased if primordial binaries are present (Pfahls 2005). First runs with primordial binaries show a depletion of the binary population, similar to clusters without IMBHs:




from Trenti et al. (2005)