The effect of primordial mass segregation on the size scale of the star clusters

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Outline

- The physics of **dense** stellar systems
  - Globular clusters
  - 2-body relaxation
  - Numerical methods: Test simulation

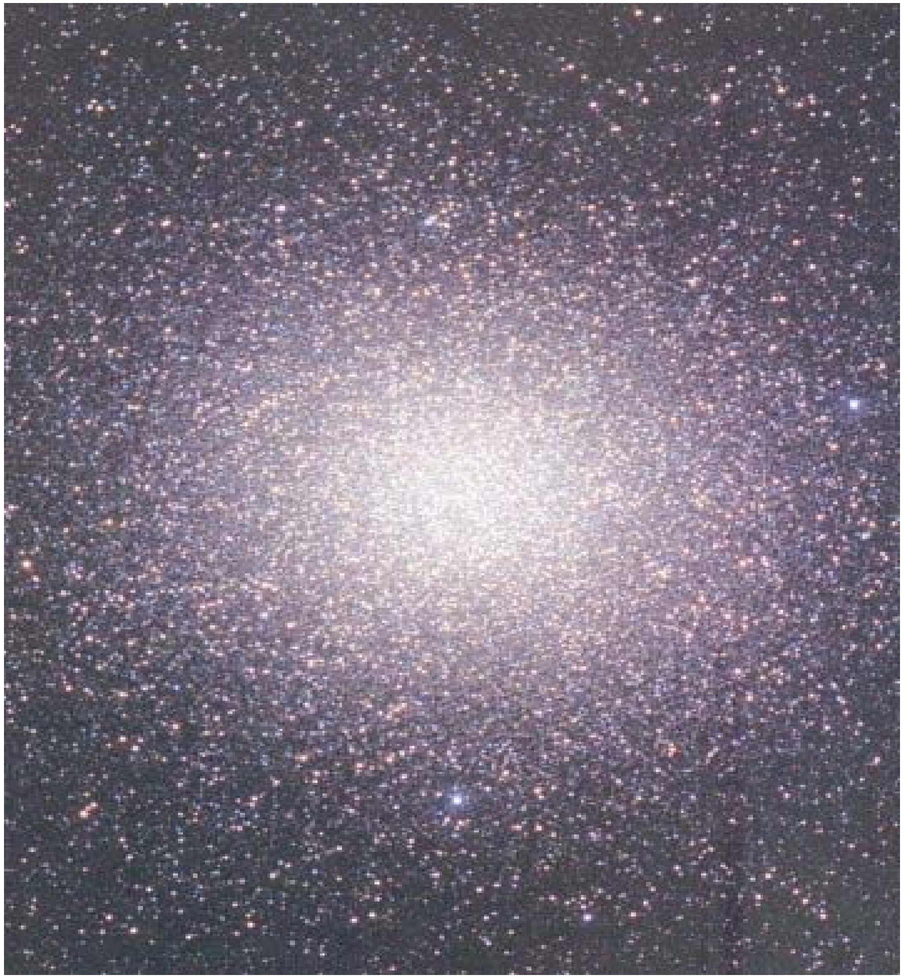
- The **size scale** and erosion of Galactic GCs
  - Tow phases of mass-loss
  - R_h – R_{gc} relation
  - T_{diss} -- R_{gc} relation
  - The impact of PMS on the size scale and dissolution of GCs

Part I

The physics of dense stellar systems

Introduction: Globular clusters (GCs)

- ~160 Milky Way GCs
- Distributed out to 100Kpc.
- Contain coeval stars ~ 12Gyr
- Gas/dust-free systems



Why GCs are important? Stellar evolution, Galaxy formation and evolution

Dynamic Evolutionary modeling of GCs

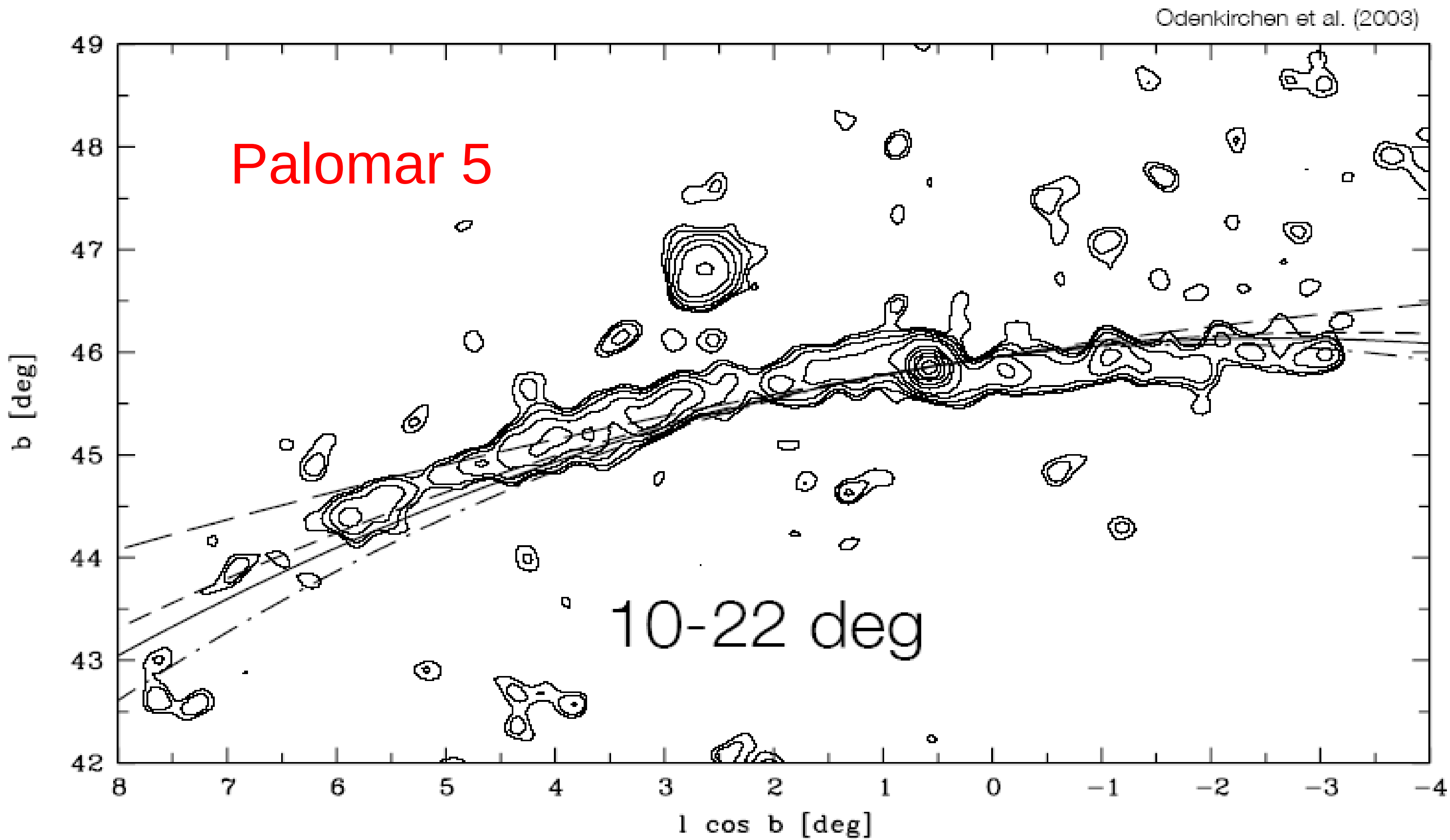
- Until the late 1970s, GCs were thought of to be relatively static stellar systems: fitted with equilibrium models like King (1966) profiles. This view has changed significantly over the last thirty years:

On the observational side:

Strong indications for the ongoing dynamical evolution:

1- The discovery of **extratidal stars** surrounding globular clusters (Grillmair et al. 1995, Odenkirchen et al. 2003)

Dynamic Evolutionary modelling of GCs



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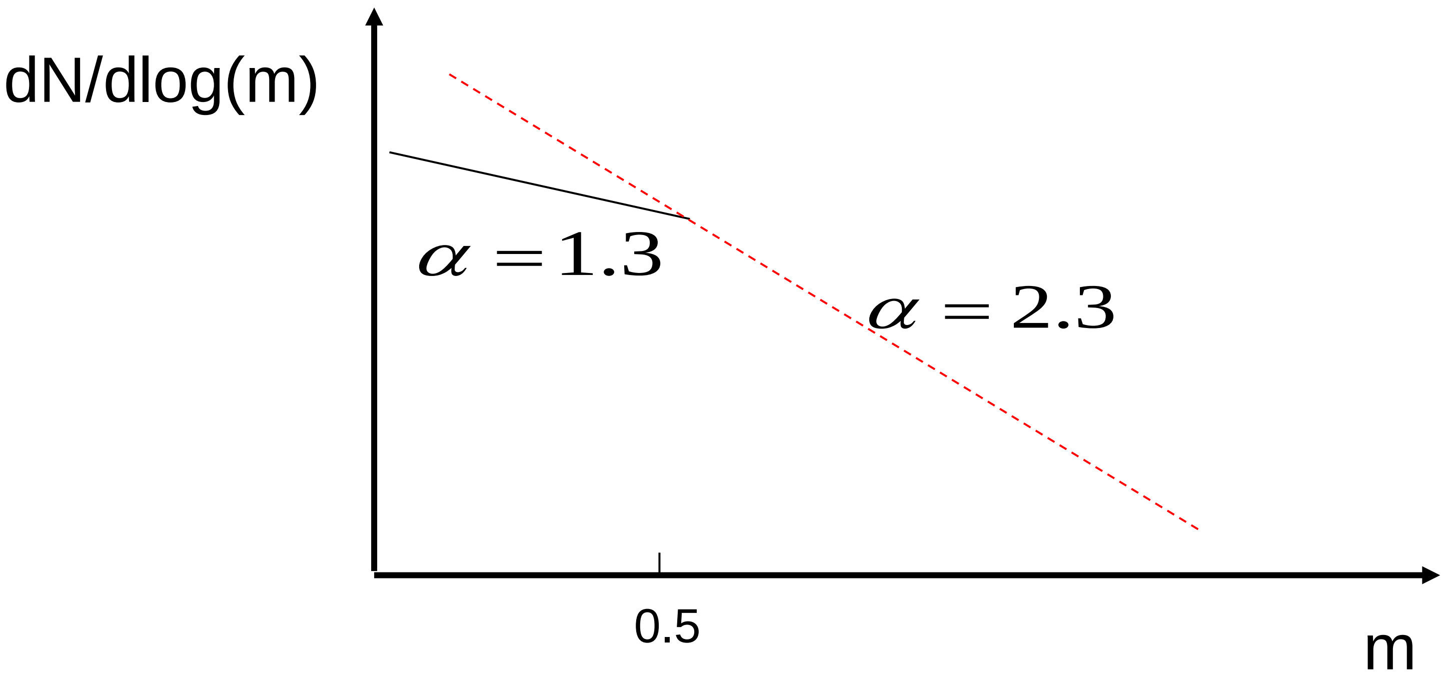
2- The differences in the stellar **mass-functions** of globular clusters (Piotto, Cool & King 1997, de Marchi et al. 1999).

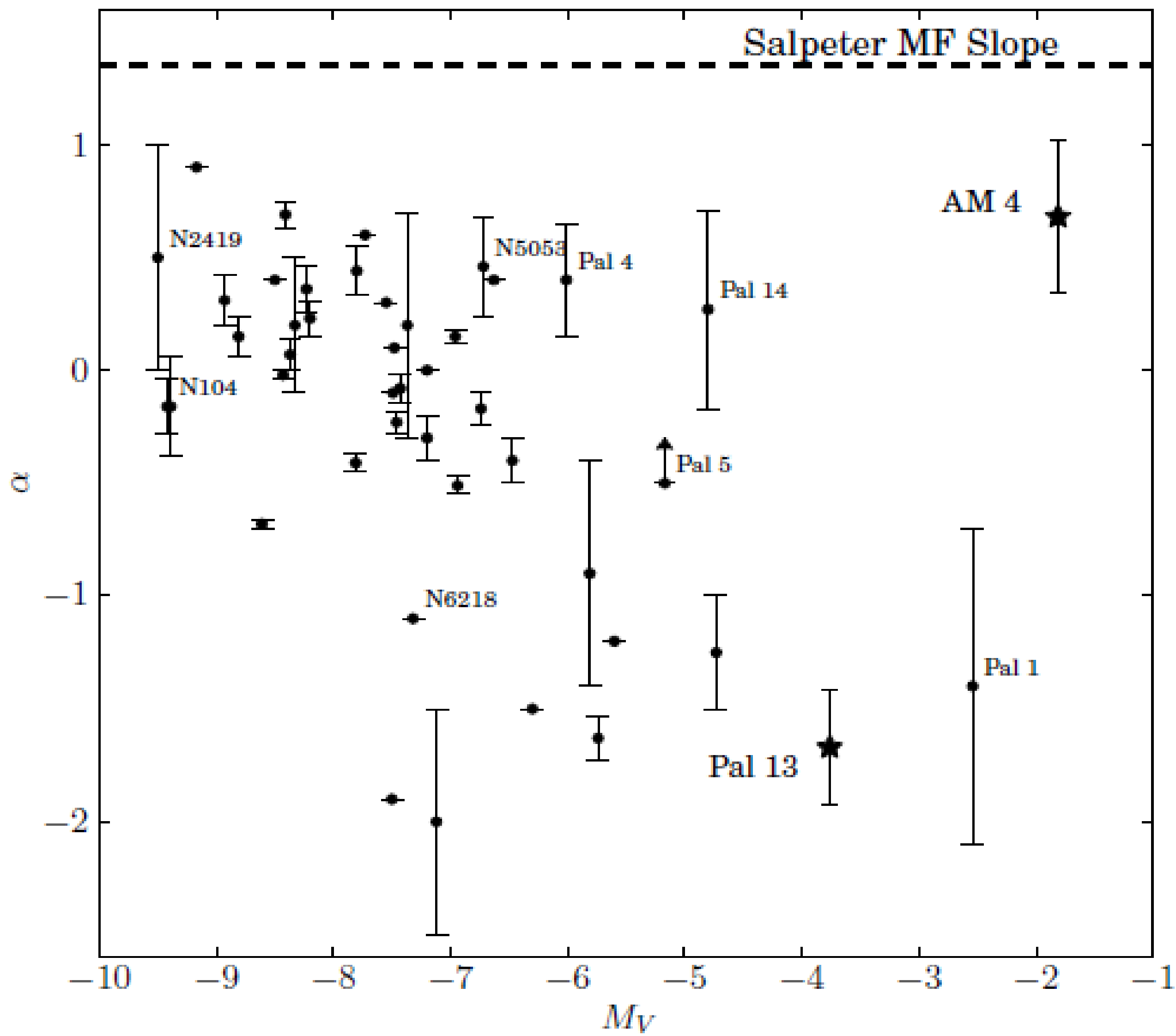
Initial mass function (IMF)

IMF: The initial mass distribution of stars

(Salpeter 1955, Kroupa 2001, 2012)



Mass-function slope is a tracer of mass loss



Hamren et al., 2013, ApJ

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On the theoretical side:

N-body simulations of star cluster evolution :

1- Progresses in simulation **techniques** (e.g. Mikkola & Aarseth 1993, Aarseth 1999) .

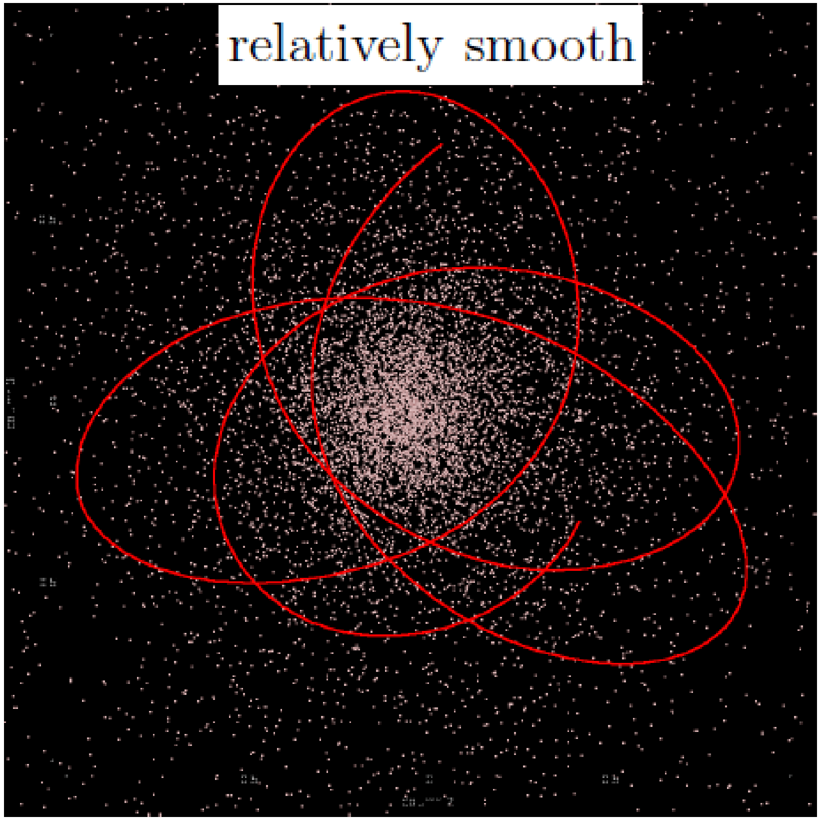
2- Development of the **hardware** (GRAPE: Makino et al. 2003, GPUs) which allows to simulate the evolution of star clusters with increasingly larger particle numbers.

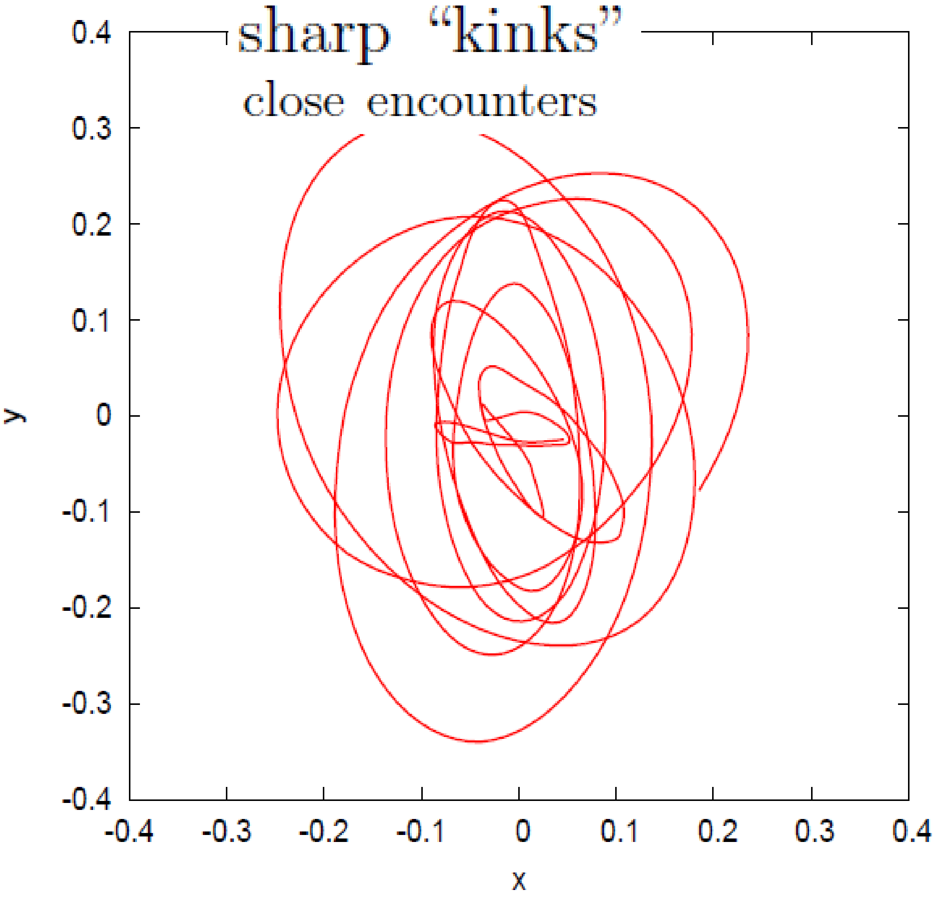
Relaxation of Stellar Systems : Weak encounters

The two time scales of star cluster dynamics

1. The crossing time t_{cr}
   - $\sim$ 1Myr for the globular star clusters of the Milky Way
   - $\sim$ “period” of orbital motions of stars
   - $\sim$ time scale of virialisation
2. The relaxation time t_{rh}
   - $\sim \dfrac{N}{\log N} t_{cr}$
   - $\gg t_{cr}$
   - A fraction of the age of the universe for the globular clusters
   - The time scale of evolution of a virialised cluster
   - Escape rate is $\sim 100 t_{rh}$[1]

2-body Relaxation





GCs are collisional systems

2-body interactions of stars are important in driving the dynamical evolution

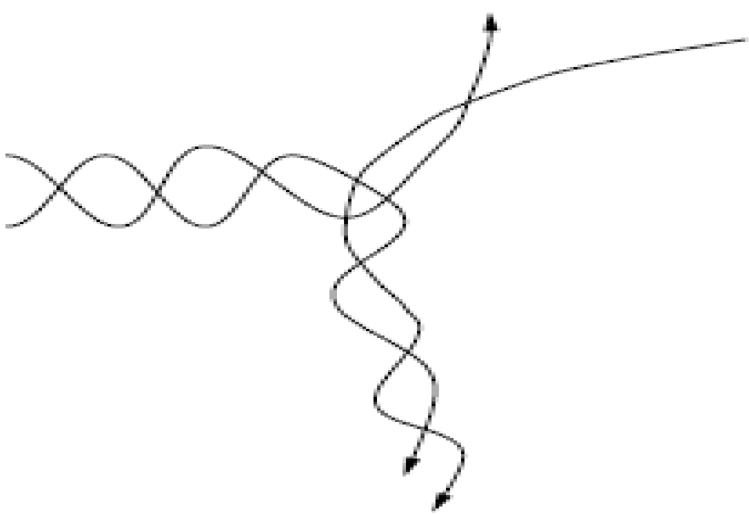
Galaxies that are collisionless

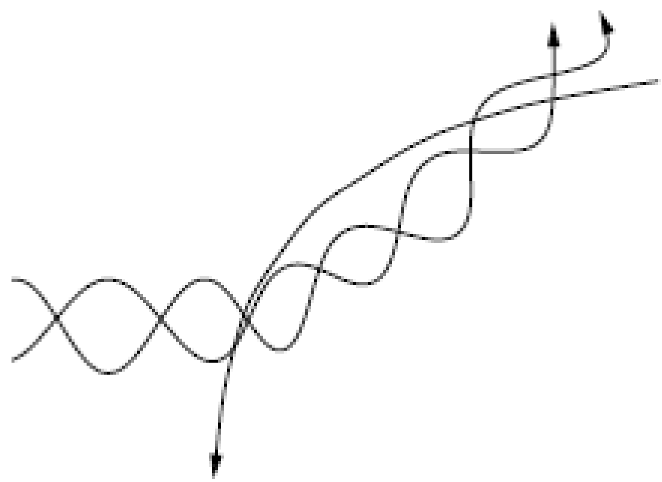
stars are mainly moving in the collective gravitational field

Possible outcomes of encounters between a binary and a single star

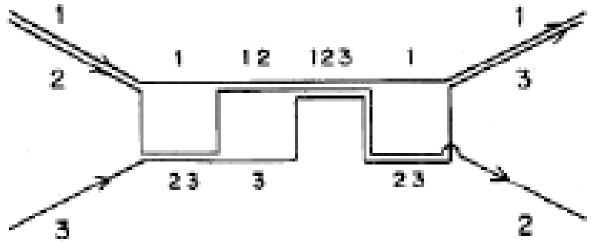
- Soft binaries get broken up
- Hard binaries get harder
- Clean exchanges: lowest-mass star ejected

E_{bin}/kT_c

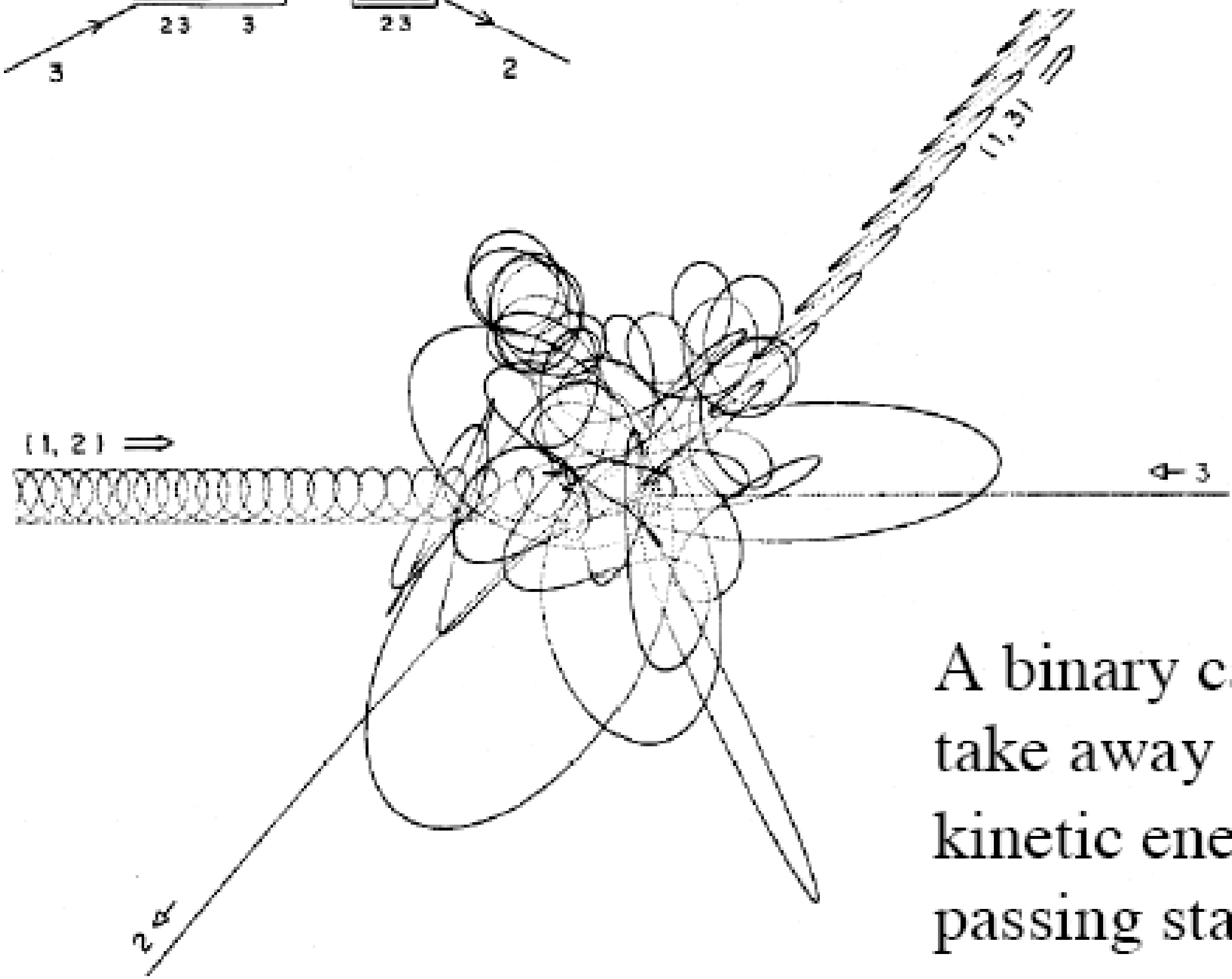




Examples of 3-Body Interactions



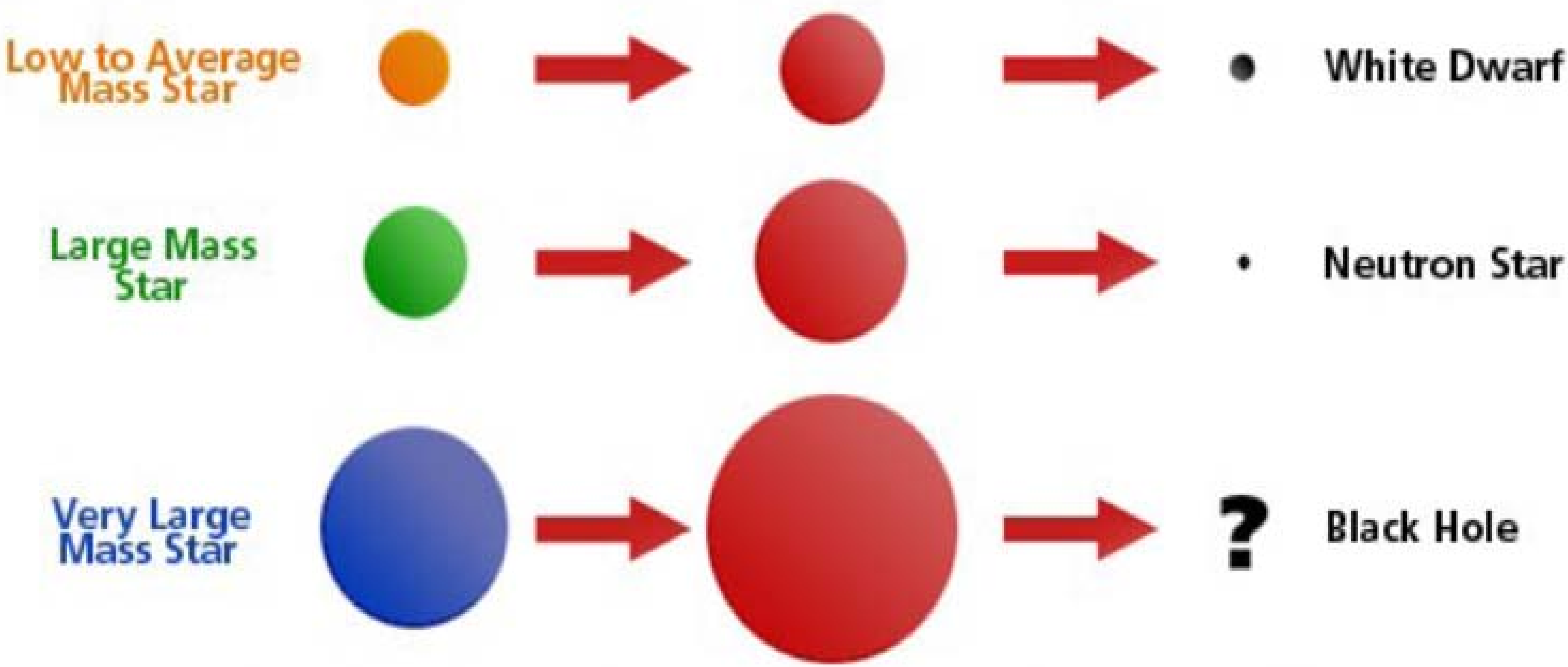
(Numerical simulation by P. Hut and J. Bahcall)



A binary can either take away or give kinetic energy to a passing star

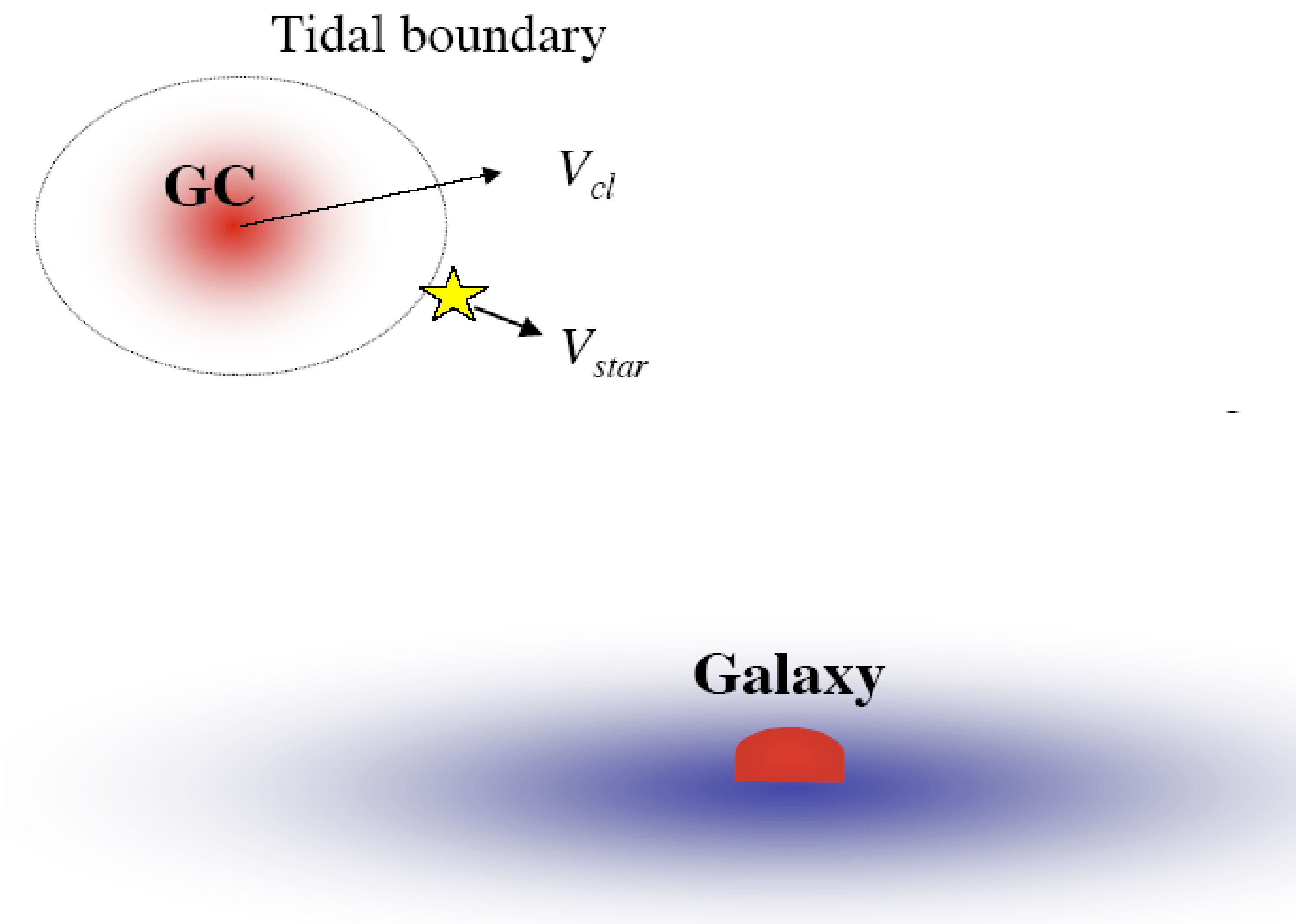
Particles evolve due to Stellar Evolution

The lives (and deaths) of stars

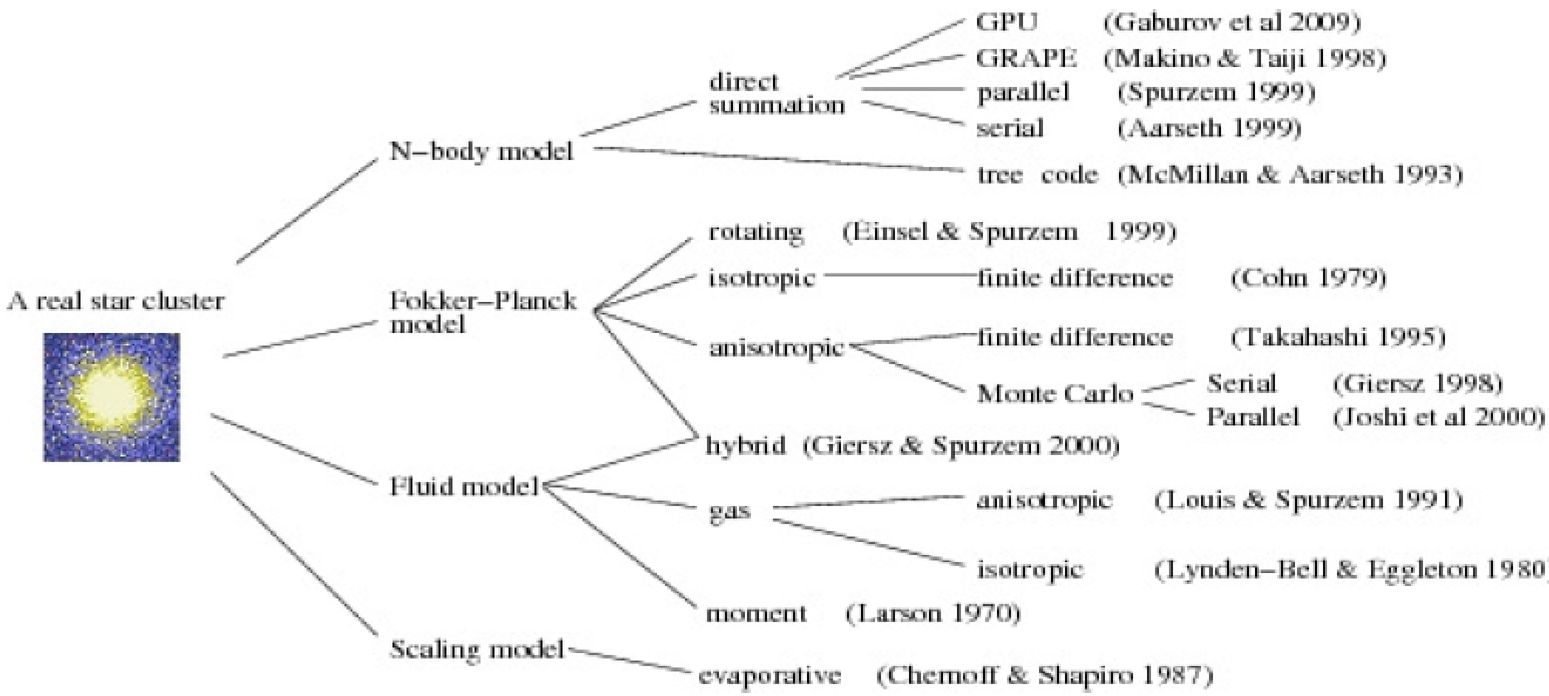


The fate of a star depends on its mass (size not to scale)

External tidal perturbations



Numerical methods



Model	Number of papers since 2010
Fluid/Moment	1
Gas	2
Fokker-Planck	6
Monte Carlo	12
N-body	$\simeq$37

Approach: C

Dir

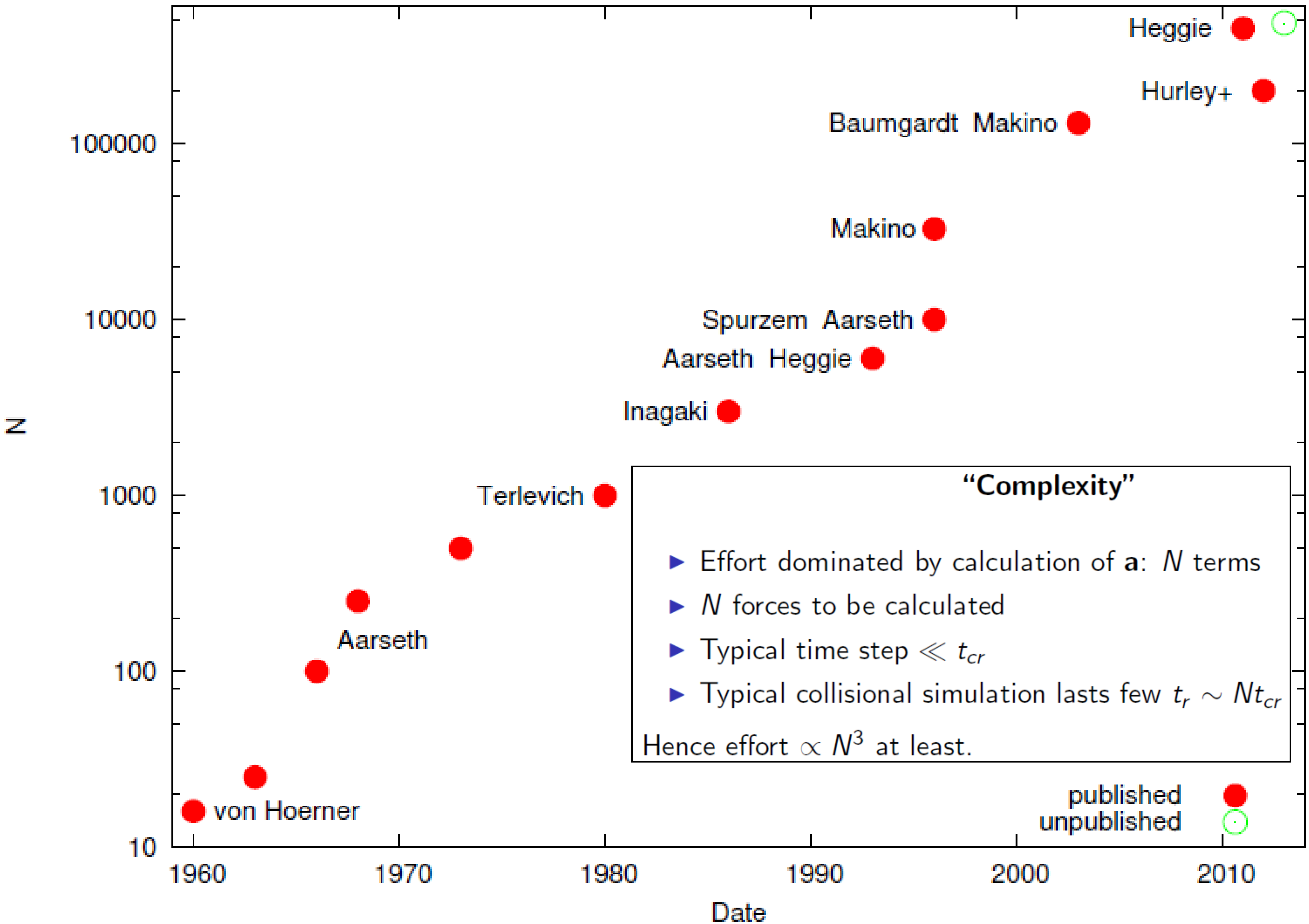
1 INTRODUCTION

The problem of the dynamical evolution of a globular cluster can be stated very simply. The only important force is the mutual attraction between the stars of the cluster; the other forces (like radiative pressure, electromagnetic forces, relativistic effects, etc.) are negligible. Therefore, the topic is the classical n-body problem: finding the motion of n points of given masses, mutually attracting themselves as the inverse square of their distance.

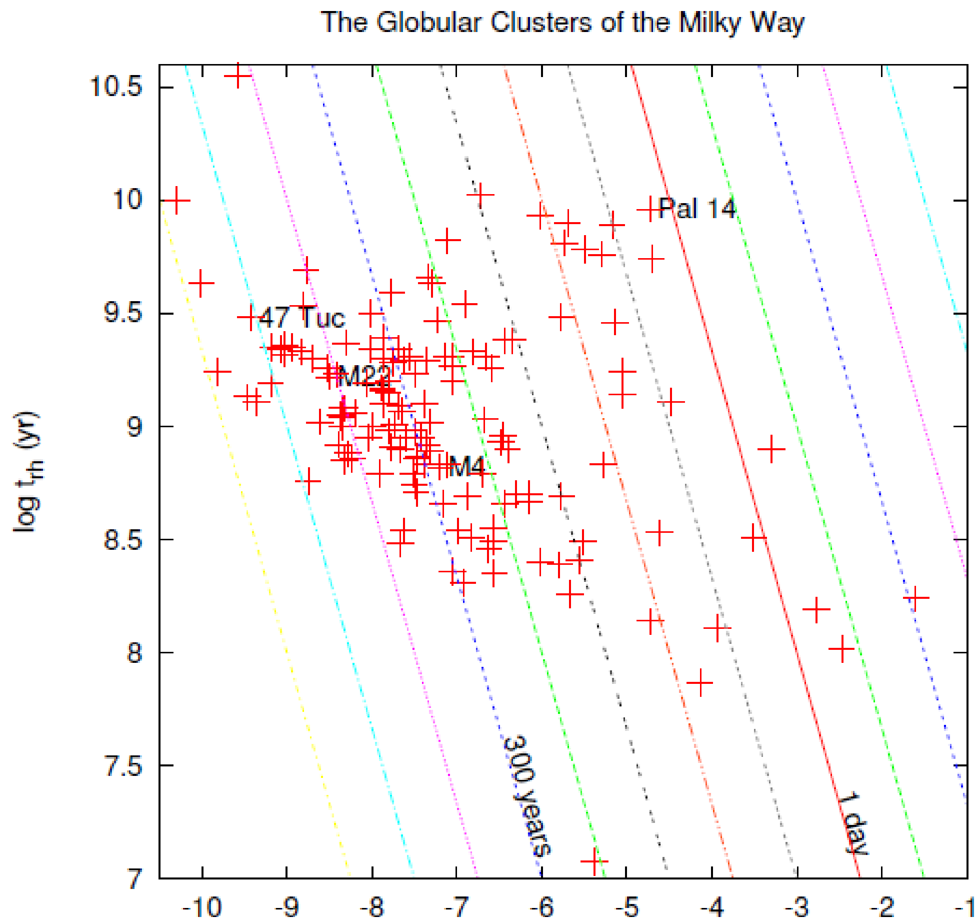
This exposition, whereas simple, relates to an extremely arduous mathematical problem. Despite a large number of studies, it has not been possible to find an explicit solution, which very likely does not exist. Hence, one can think of the numerical integration. This way, von Hoerner (1960) computed the evolution of artificial clusters comprising up to 16 stars, thanks to an electronic device. But high values of n are out of reach with such a method, as the computational time becomes rapidly extreme, even for a machine; the case of $n = 16$ already corresponds to a system of 96 simultaneous differential equations.

In the globular clusters, n is of the order of magnitude of 10^{5-6}. Such a high value naturally suggests to give up following the individual motions, and to use a statistical

The slow progress of N-body simulations



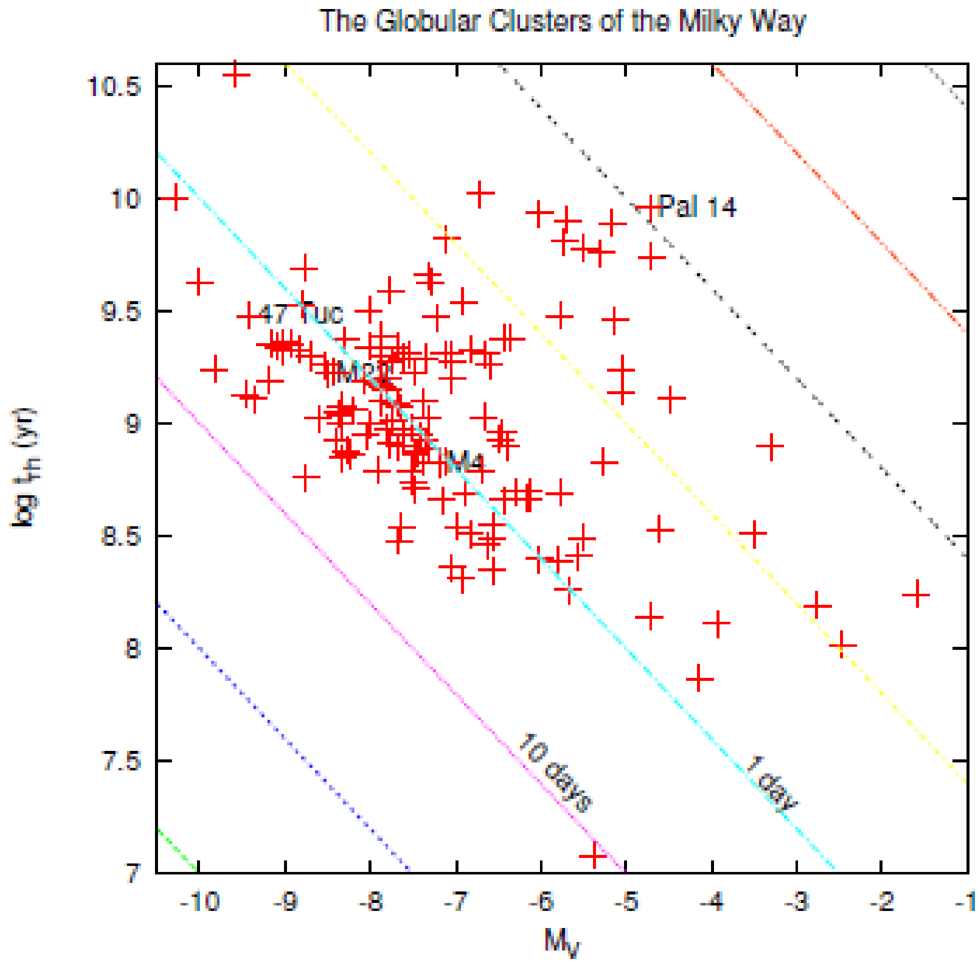
The Challenge of Milky Way Globular Clusters for N-body



- Direct N-body modelling a serious computational challenge
- Monte Carlo modelling the most realistic practical alternative at present

The efficiency of the MC code

The time step dt is of order the relaxation time. Each step takes of order $N \ln N$ operations. Computational effort of order $N \ln N$ per relaxation time. (Cf. direct N-body, which is of order $\dfrac{N^{10/3}}{\ln \gamma N}$ per relaxation time.)

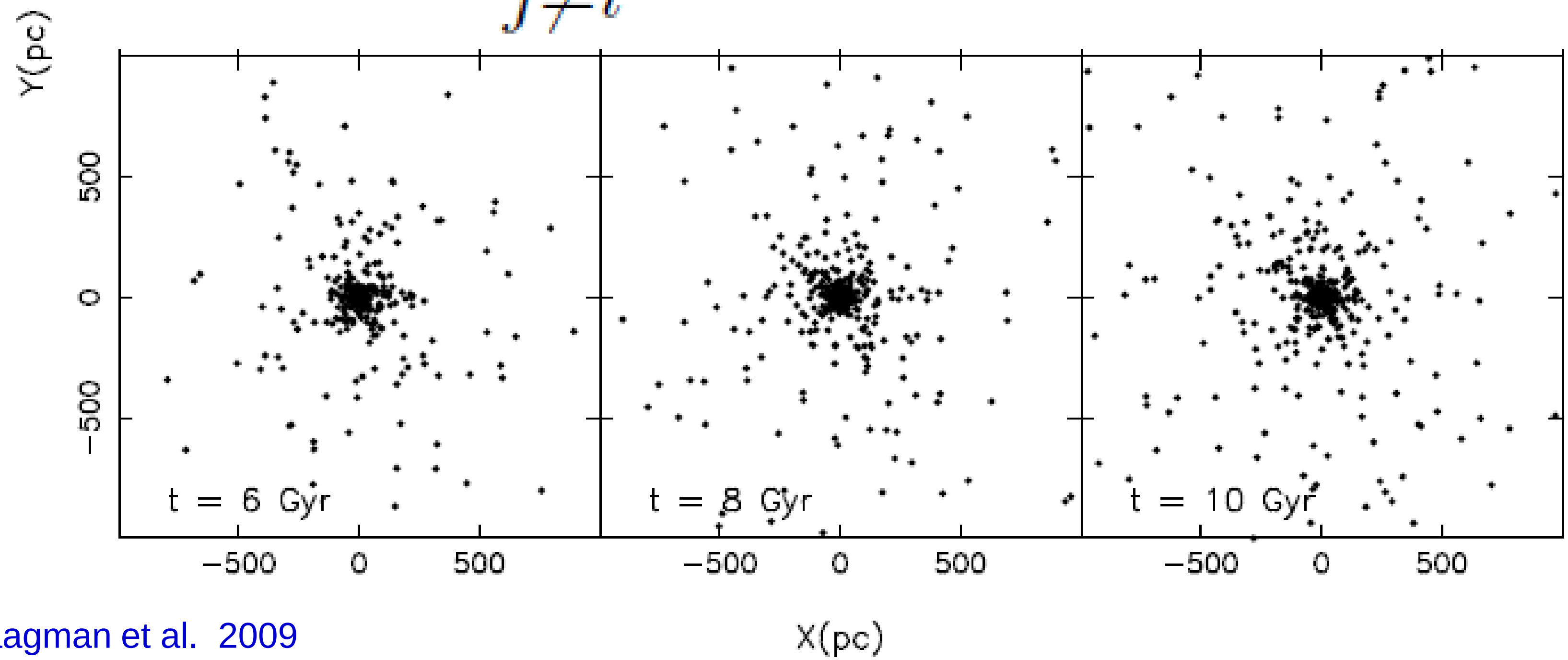


Test simulation

Spatial distribution

Test run: N=1000 equal mass, No SE, softening parameter

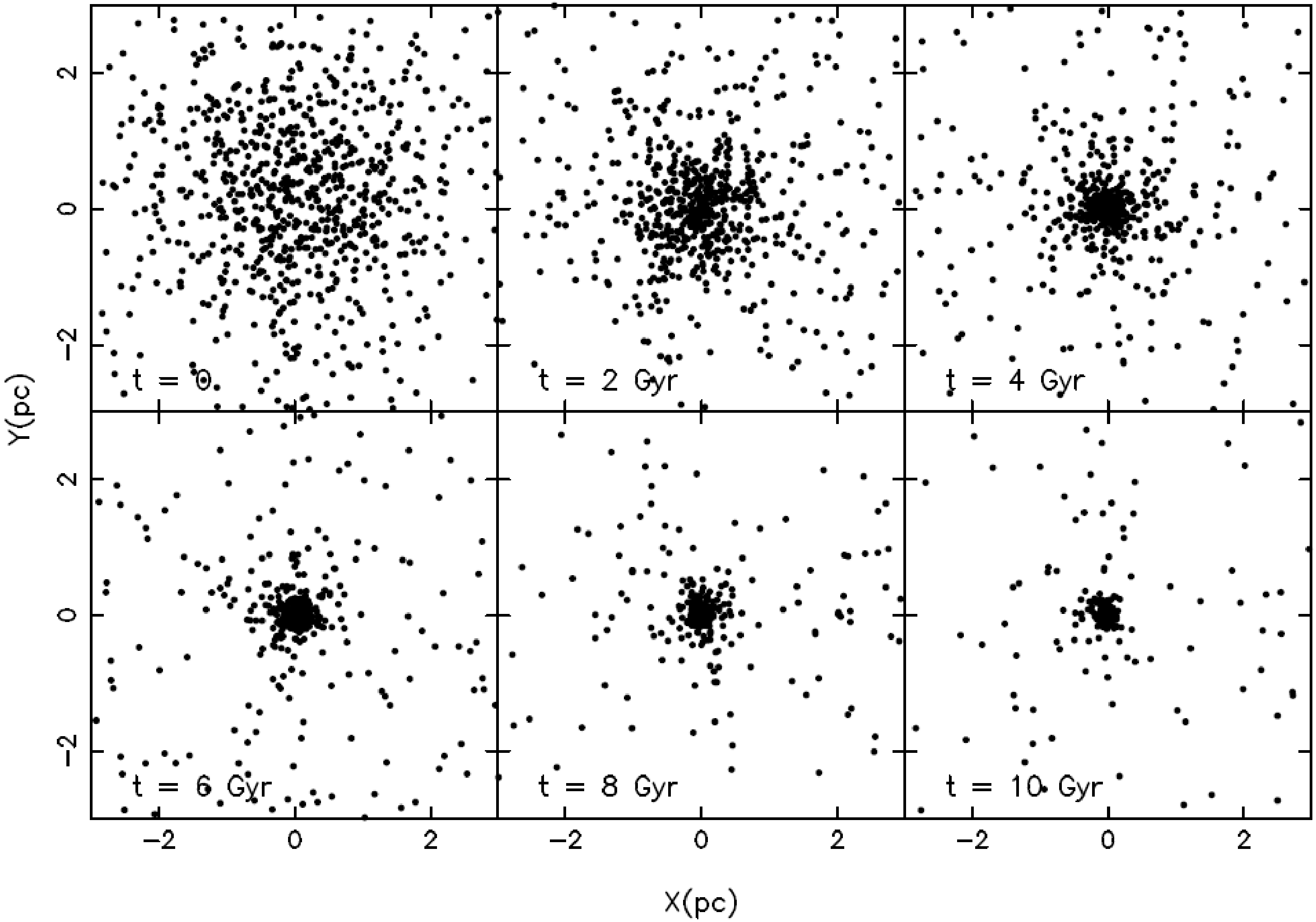
$$\ddot{\mathbf{r}}_i = -G \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{m_j(\mathbf{r}_i - \mathbf{r}_j)}{((|\mathbf{r}_i - \mathbf{r}_j|)^2 + \epsilon^2)^{3/2}}$$



Praagman et al. 2009

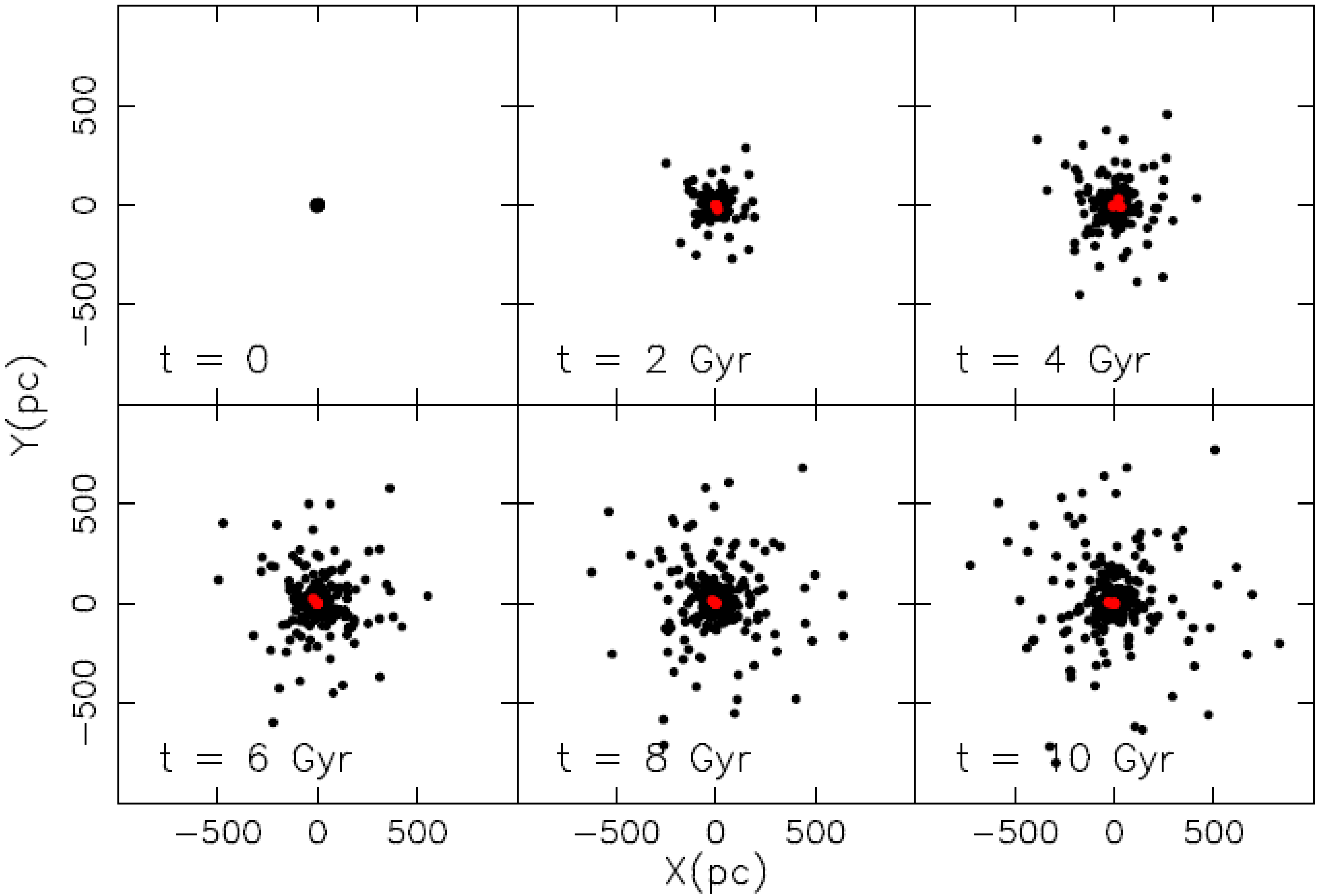
Density distribution

Zooming in shows that the core collapses inwards.

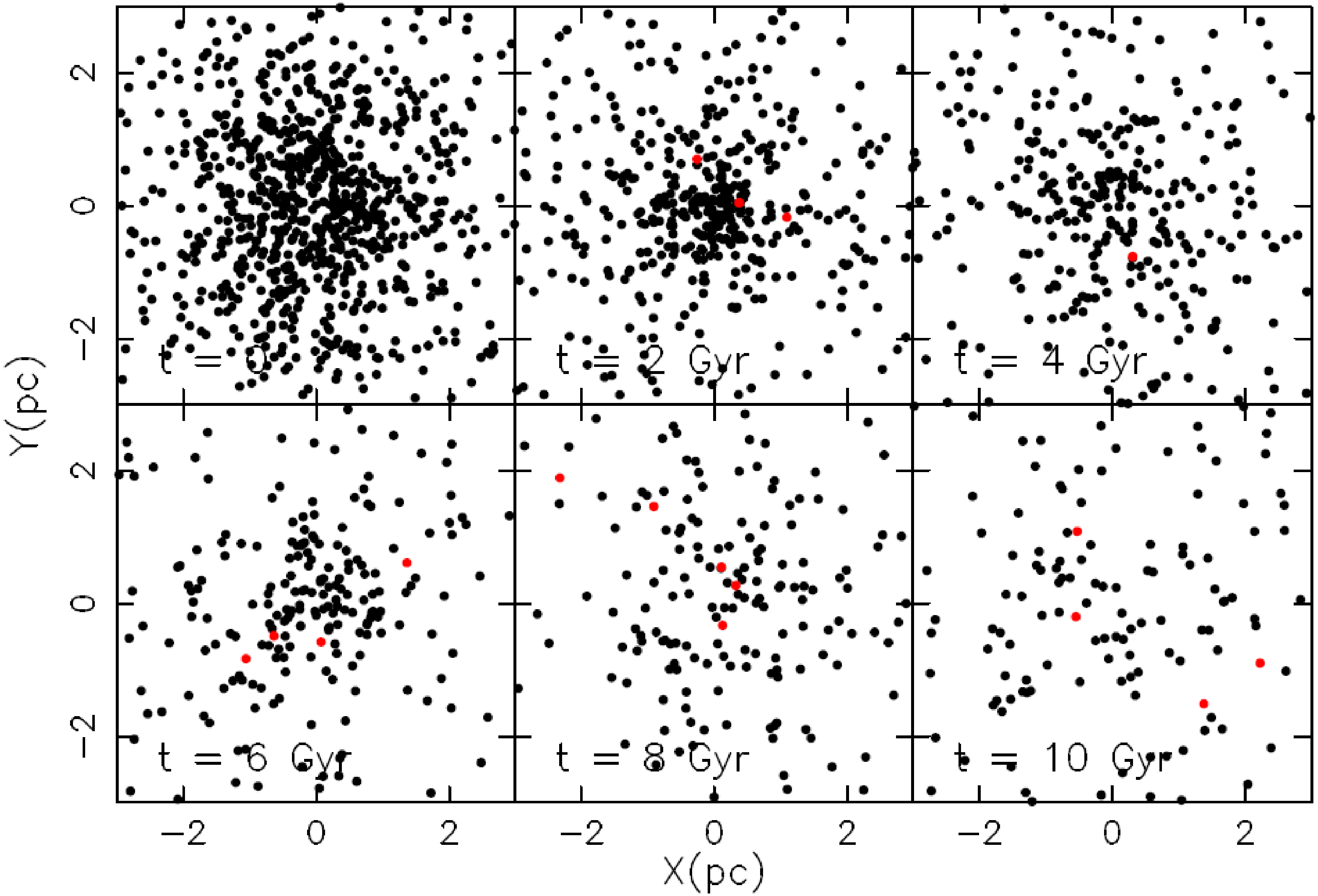


Thus a distinct core-halo structure is established where a diffuse halo surrounds a high-density core.

Spatial distribution: Red dots are binaries



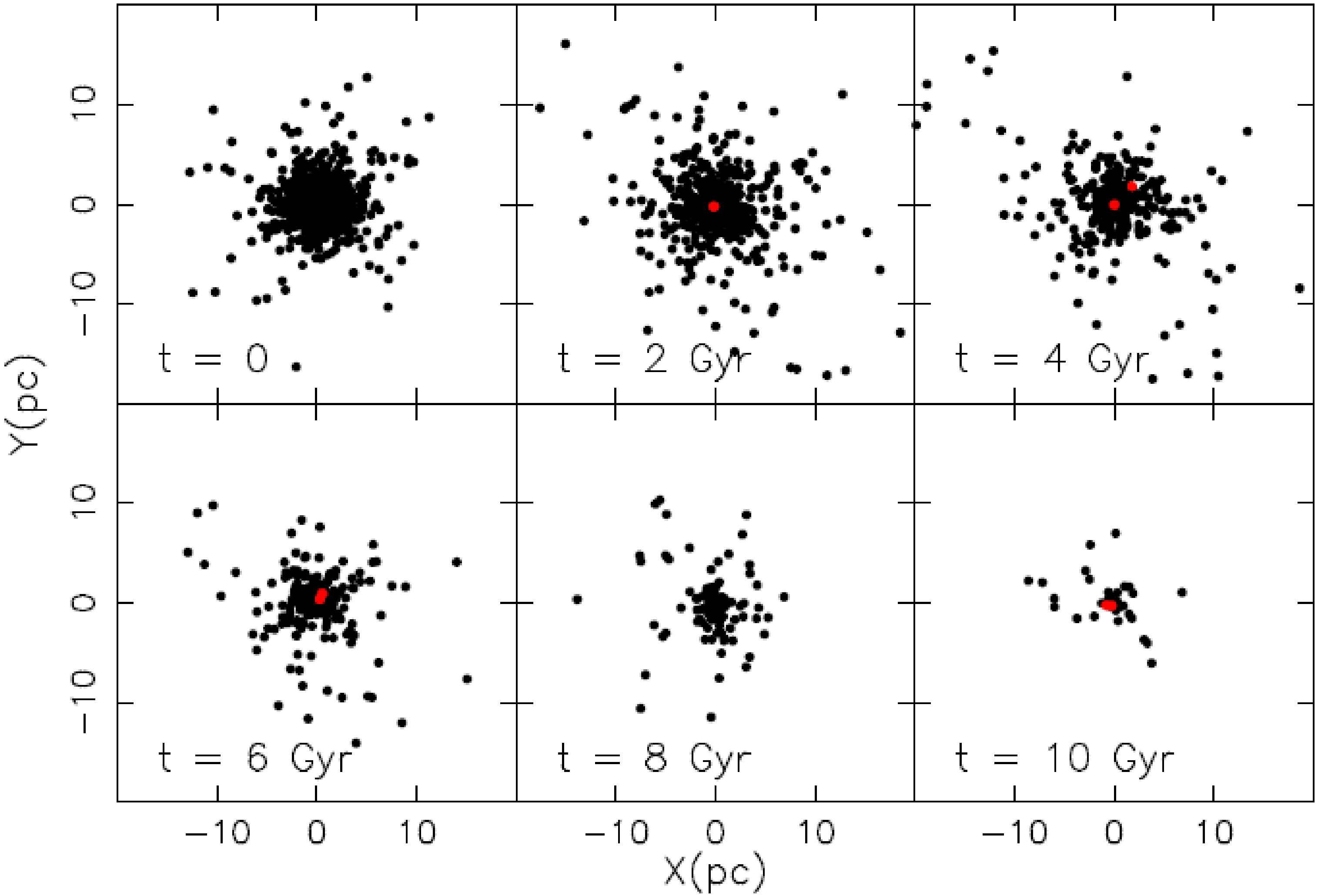
Zooming in (model 1) : No core collapse



The collapsing core that was evident in the sample simulation is not so obvious in this model. One of the main differences between the sample code and nbody6 is the ability to deal with close encounters.

Model 4

Model nr.	IMF	Stellar evolution	Tidal field
1	·	·	·
2	+	·	·
3	+	+	·
4	·	·	+

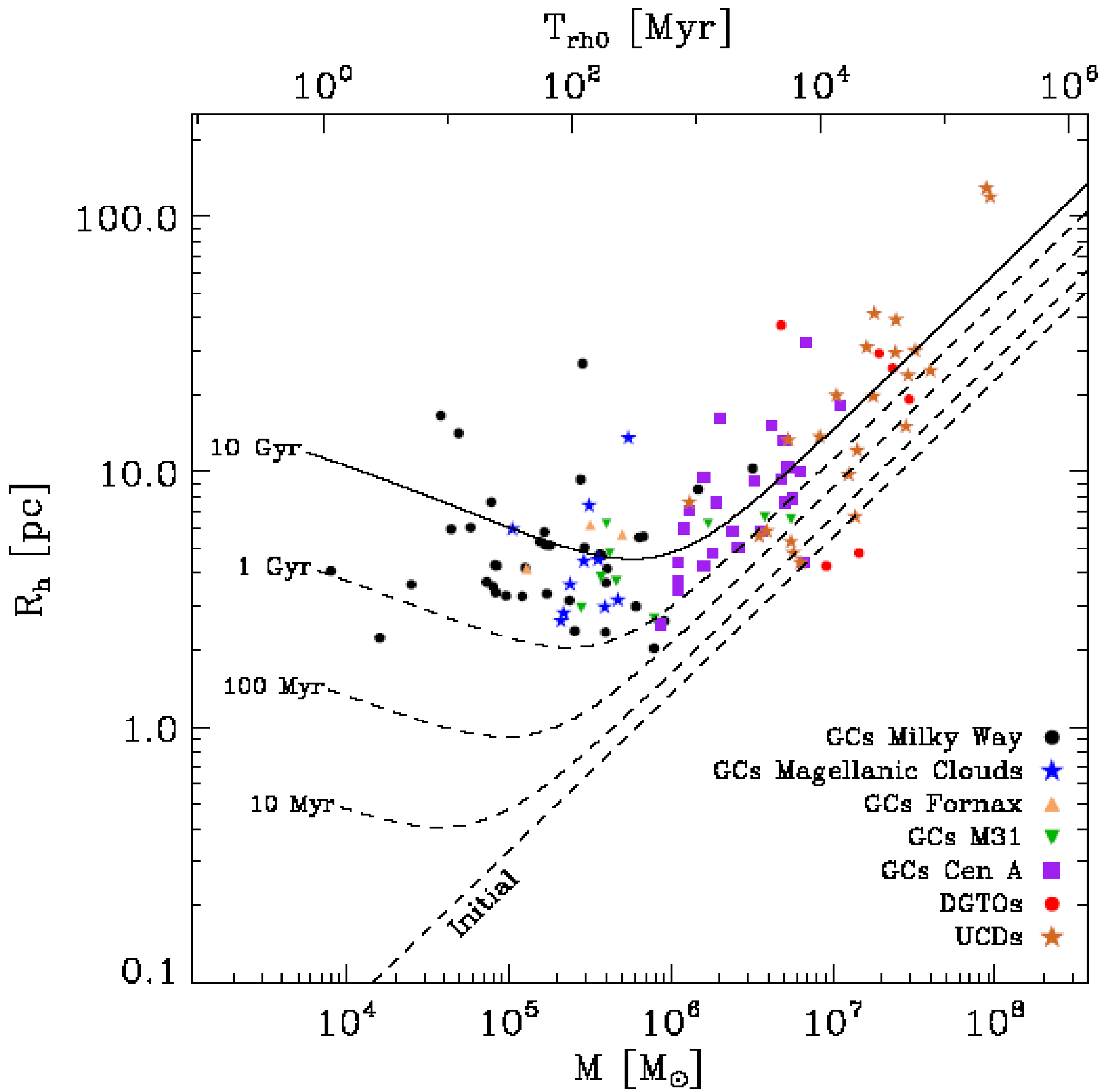


Part II

Size scale of GCs

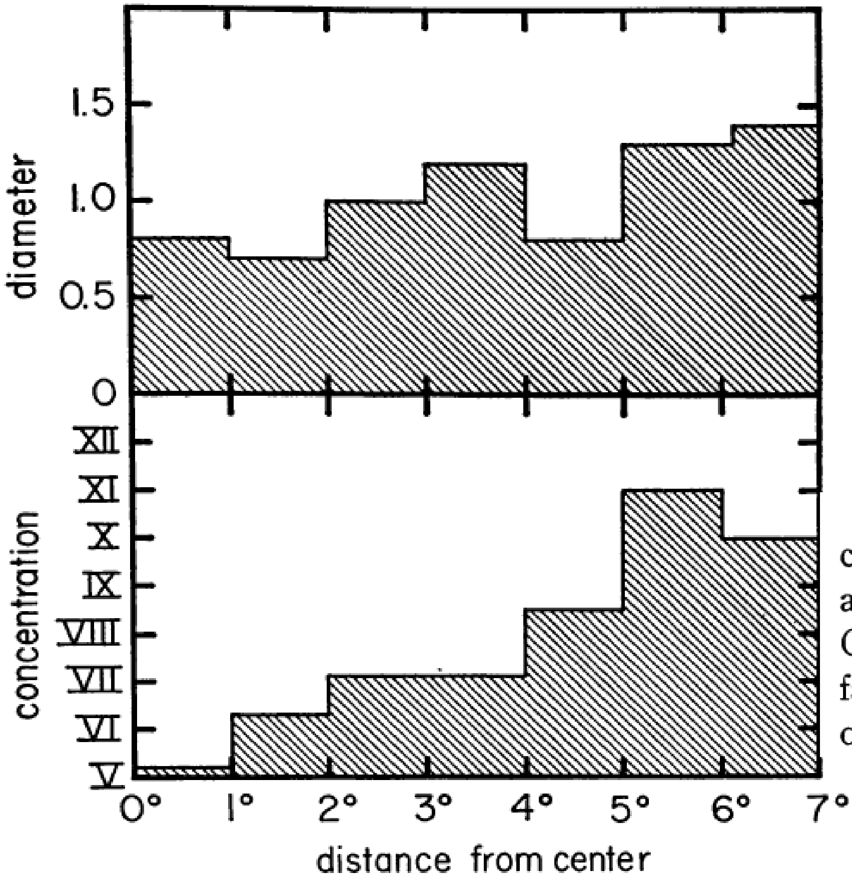
Why study the size scale of star clusters

- Gap in t
- Ultra-cc …)7).
- A well-k … ıe Galaxy mass m
- Why is … ɜred around Rh=3 pa
- Why do … ɣe radii of ten pars … 2012,MNRAS)
- There is … n
- No appa … osity, metalici … ns the orbital s



Rh-Rgc Relation

- Historically there are empirical relation between the cluster size and RG (Hodge 1960-62)



NOTES FROM OBSERVATORIES

: Radius of isolated star cluster remains constant

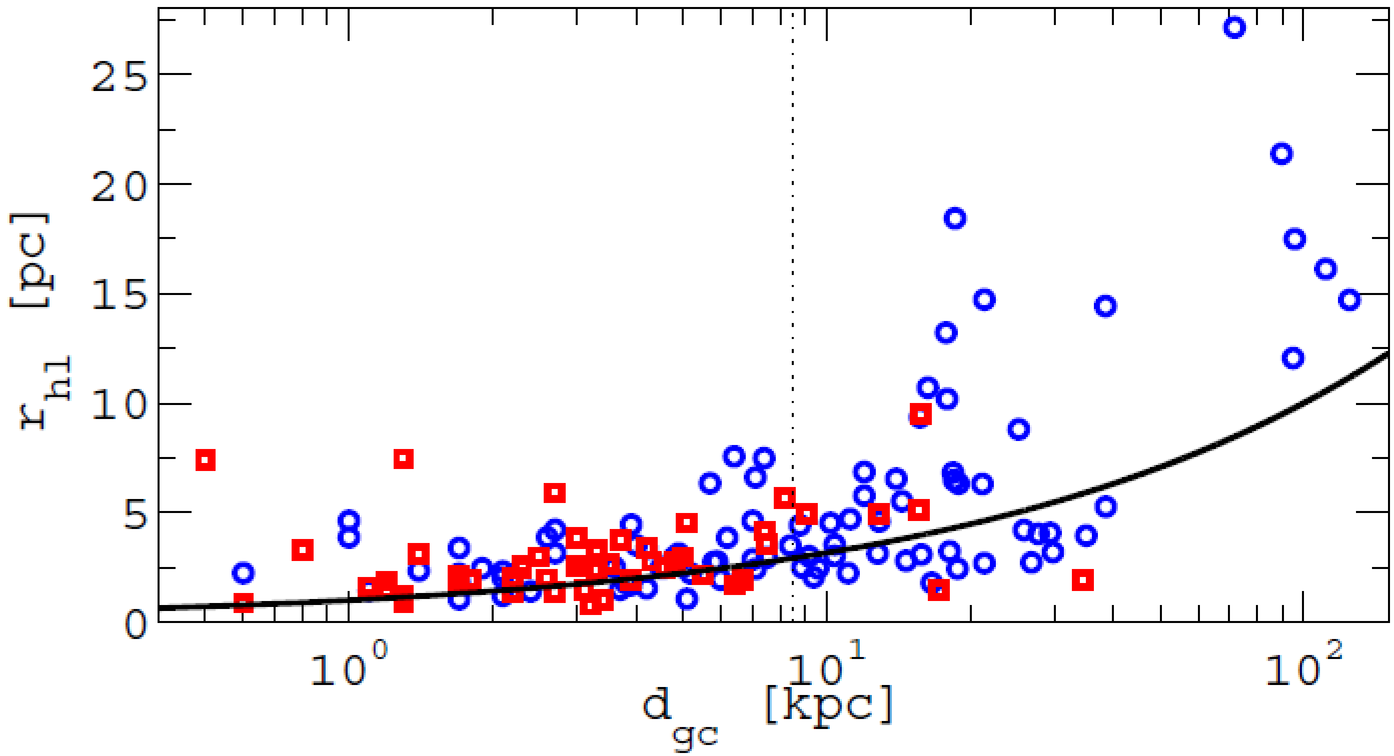
TIDAL EFFECTS ON CLUSTERS OF THE LARGE MAGELLANIC CLOUD

PAUL W. HODGE

Berkeley Astronomical Department
University of California

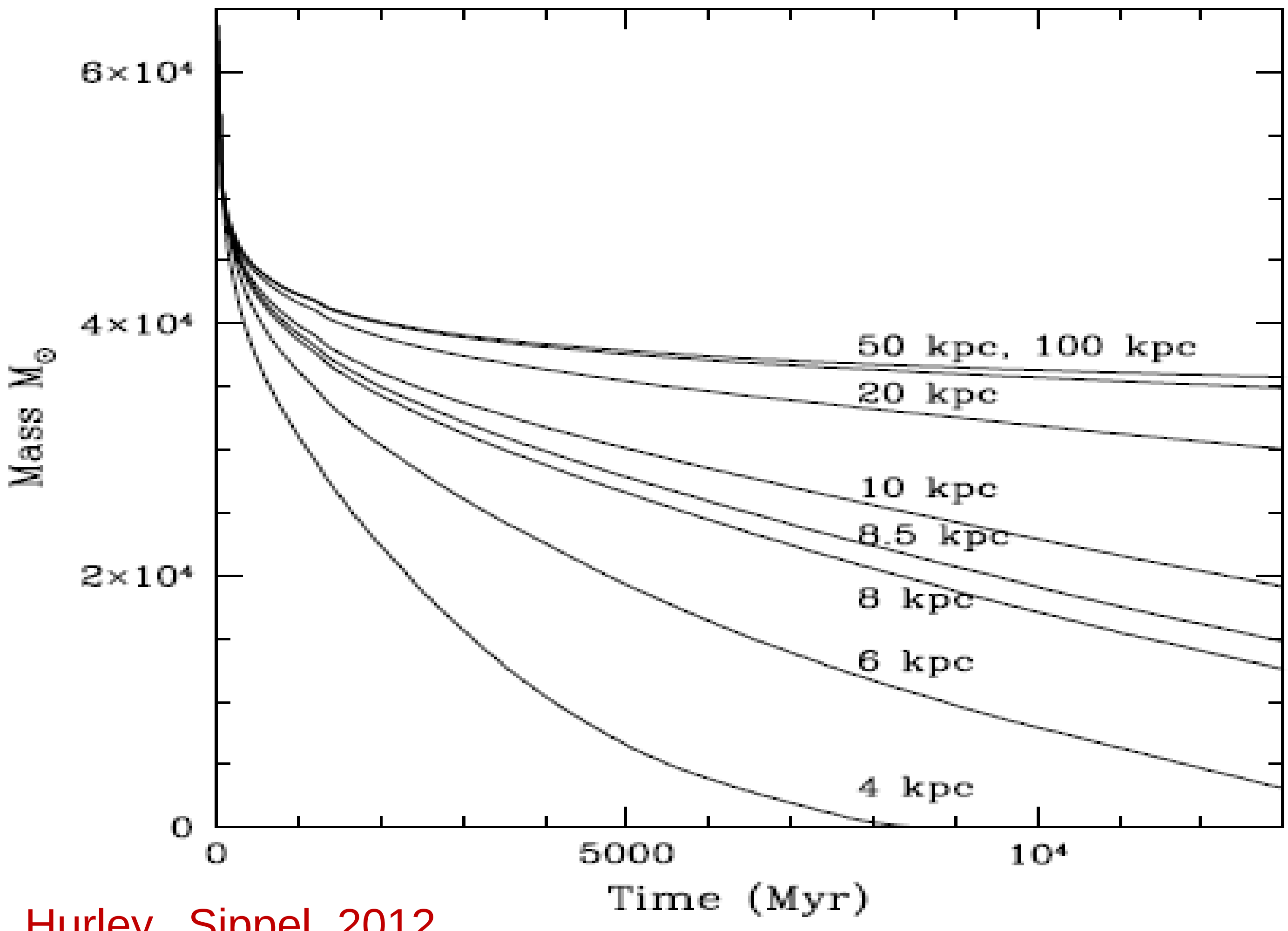
Sizes. Figure 1 shows the way in which the mean sizes of the clusters, as estimated on plates of limiting magnitude $V = 18.5$, are related to their projected distances from the center of the Cloud. There is a tendency for the clusters to be larger the farther out they are. This tendency is expected on the grounds of the tidal effect on the cluster by the galaxy. In the idealized

Rh-Rgc relation (van den Bergh 1991)



- Size and galactocentric distance of the MW GC population. Blue circles are used for **metal-poor** and red squares for **metal-rich** clusters. The solid **black** line denotes the size-distance relation

Mass lose of simulated clusters at different galactocentric distances



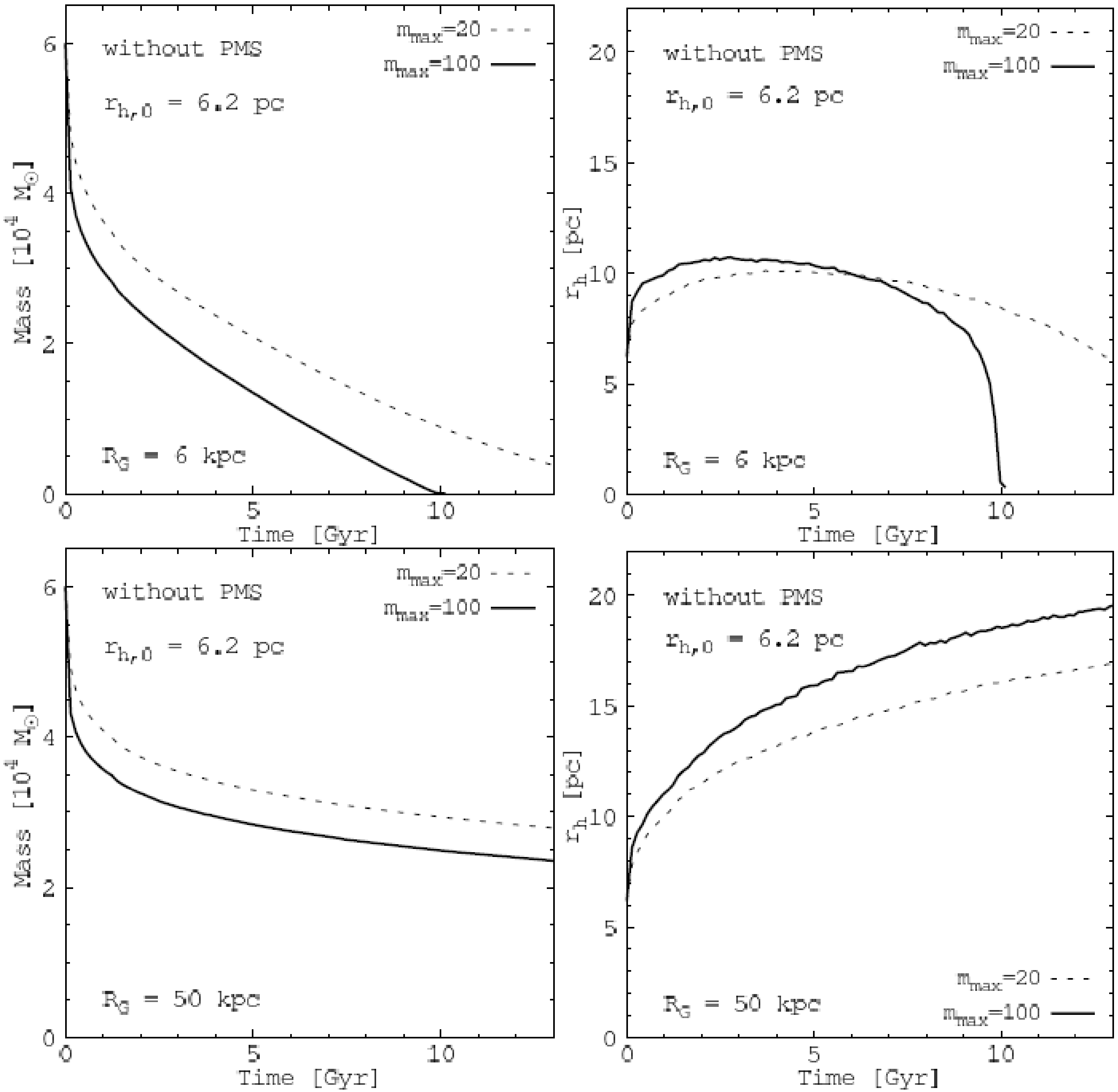
Madrid, Hurley, Sippel, 2012

Phases of mass-loss

- Mass loss from Stellar Evolution + 2-body relaxation
    - Initially increases the cluster size in short time-scale

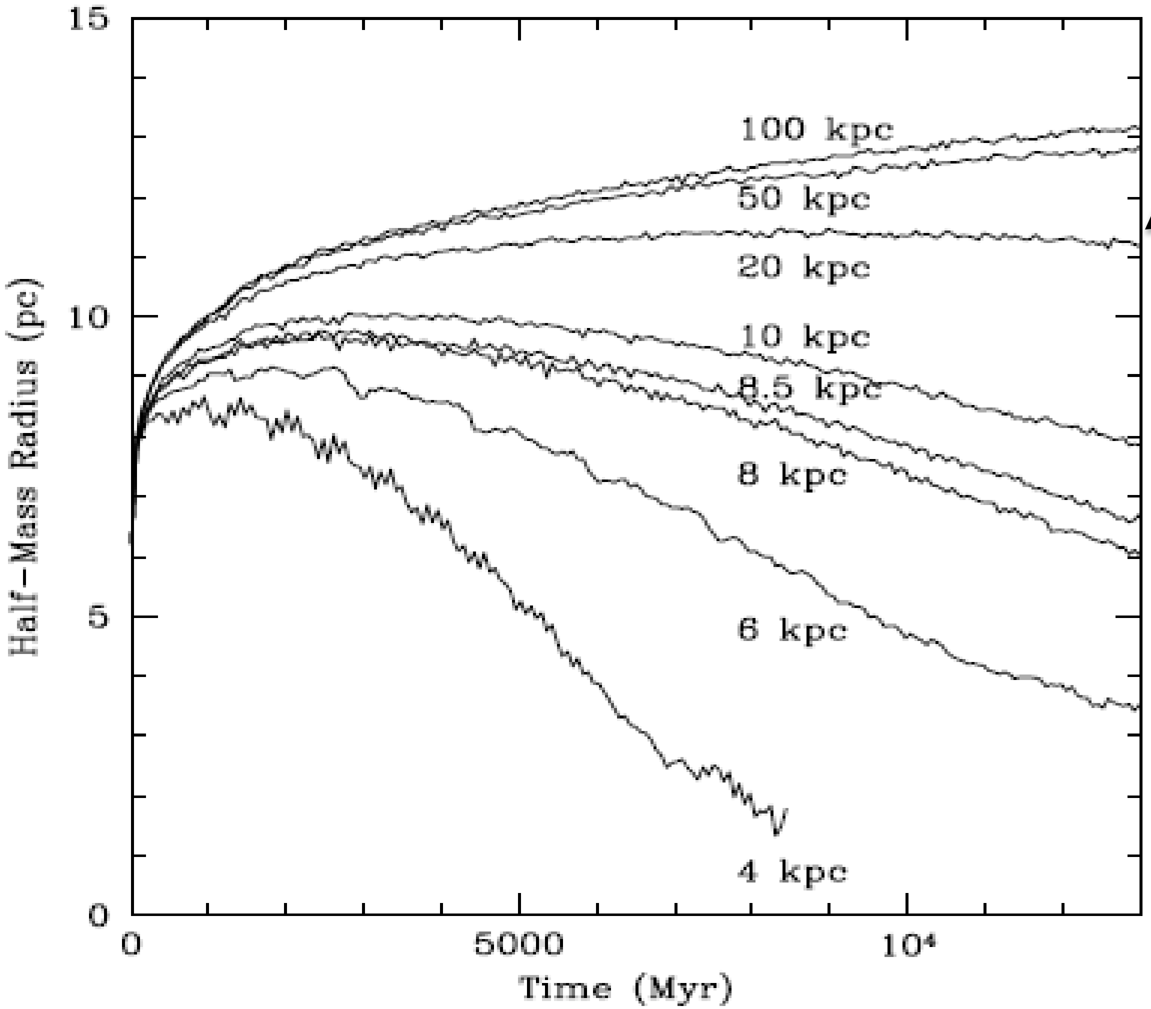
- Mass loss due to tidal stripping
    - Decreases the size scale scale.

Whether or not either of the two mechanisms dominates will determine the size of the star cluster (Gieles et al. 2011).



Haghi et al 2014, MNRAS

The evolution of half-mass radius of simulated clusters at different galactocentric distances

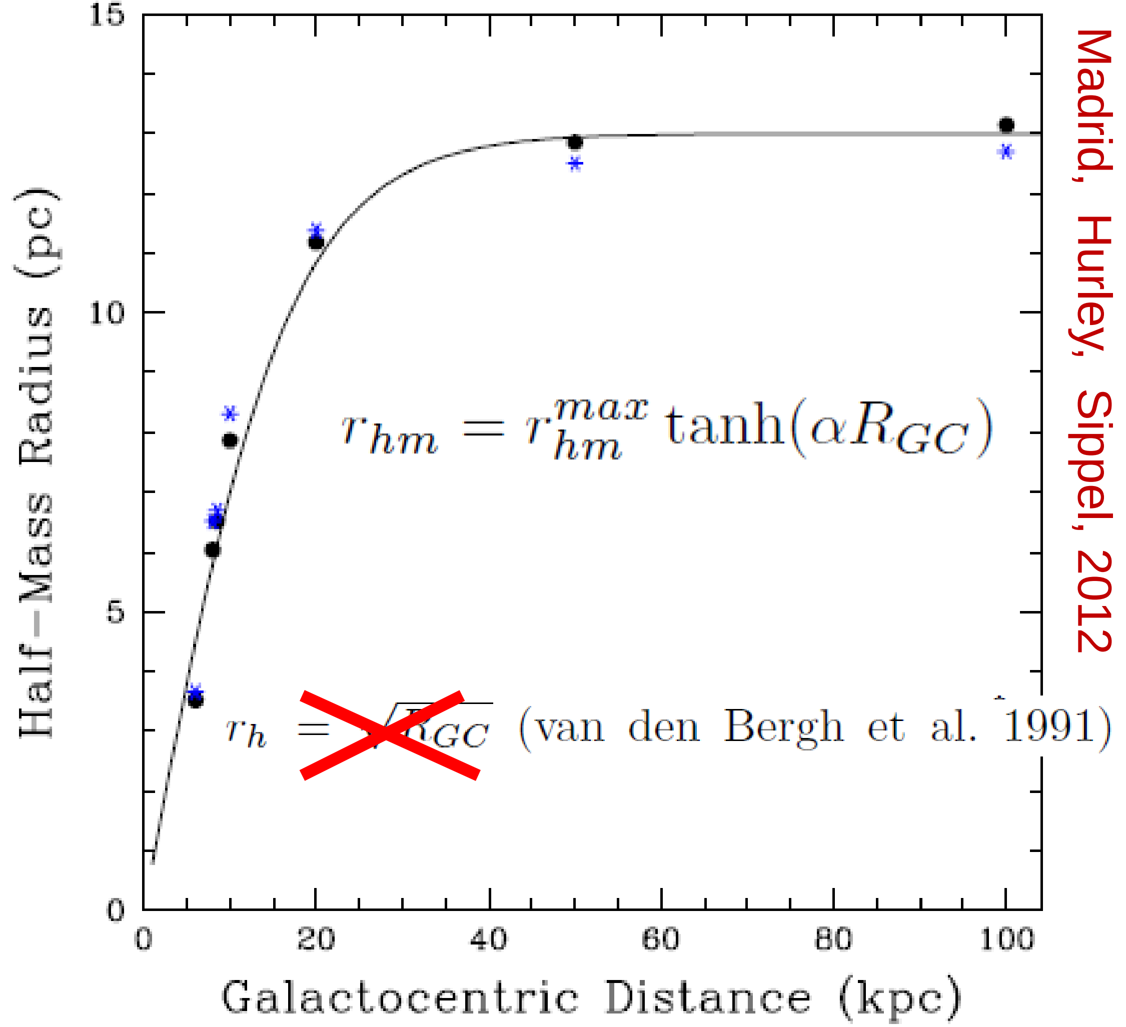


expansion driven by the internal dynamics is balanced by the presence of the tidal field

an initial radius of 6 pc

Madrid, Hurley, Sippel, 2012

New Rh-Rgc relation



Direct N-body simulation

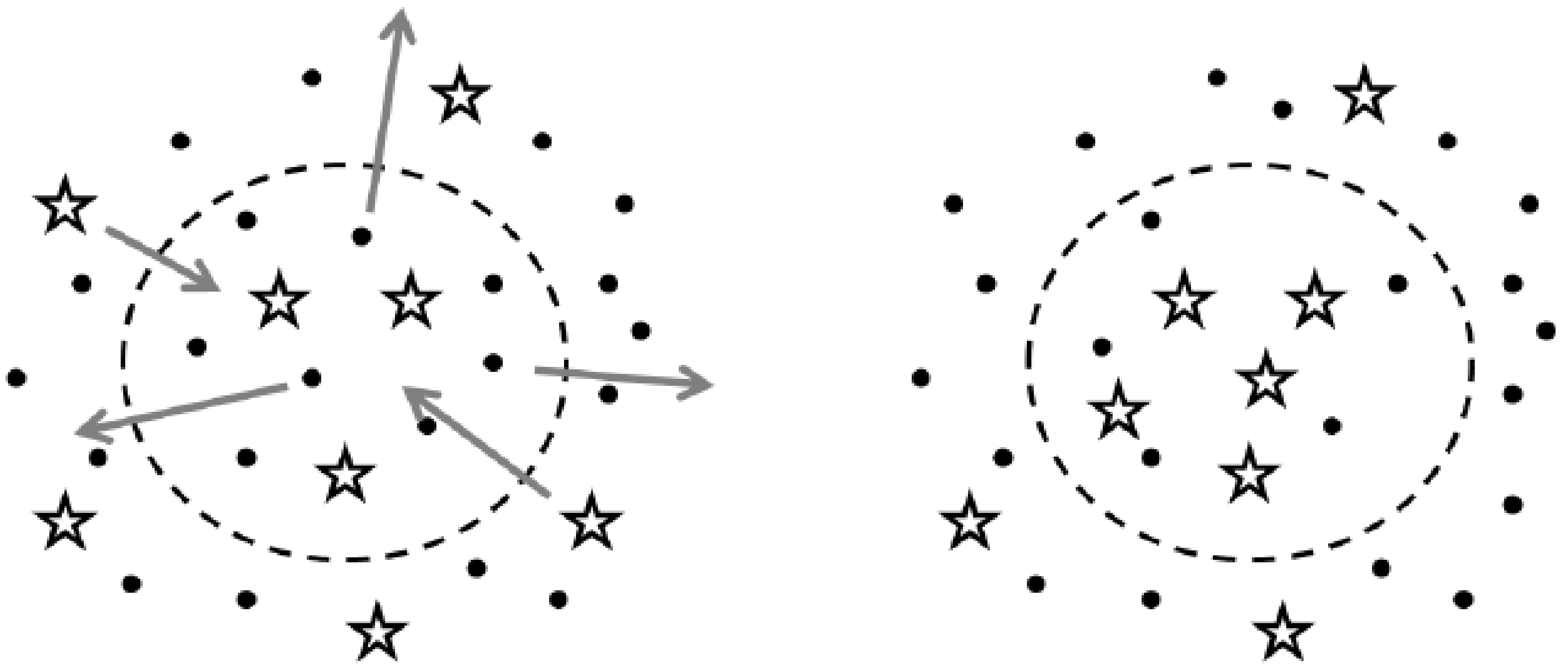
DESCRIPTION OF THE MODELS

- Direct N-body modeling on the GPU computers of the IASBS.
- Number of stars N ~ 100,000 with Plummer (1911) distribution
- Evolution time: 13 Gyr
- Stellar Evolution: SSE/BSE routines developed by Hurley et al. 2001
- Tidal effect: galactic potential (3-component) (Allen & Santillan 1991).
- We used **MCLUSTER** (Keupper et al 2010) using the routine described in Baumgardt, De Marchi & Kroupa (2008) to set up initially segregated clusters.

How Primordial Mass Segregation can affect on the size scale of GCs?

Setting up
INITIALLY MASS SEGREGATED equilibrium star cluster

Mass Segregation



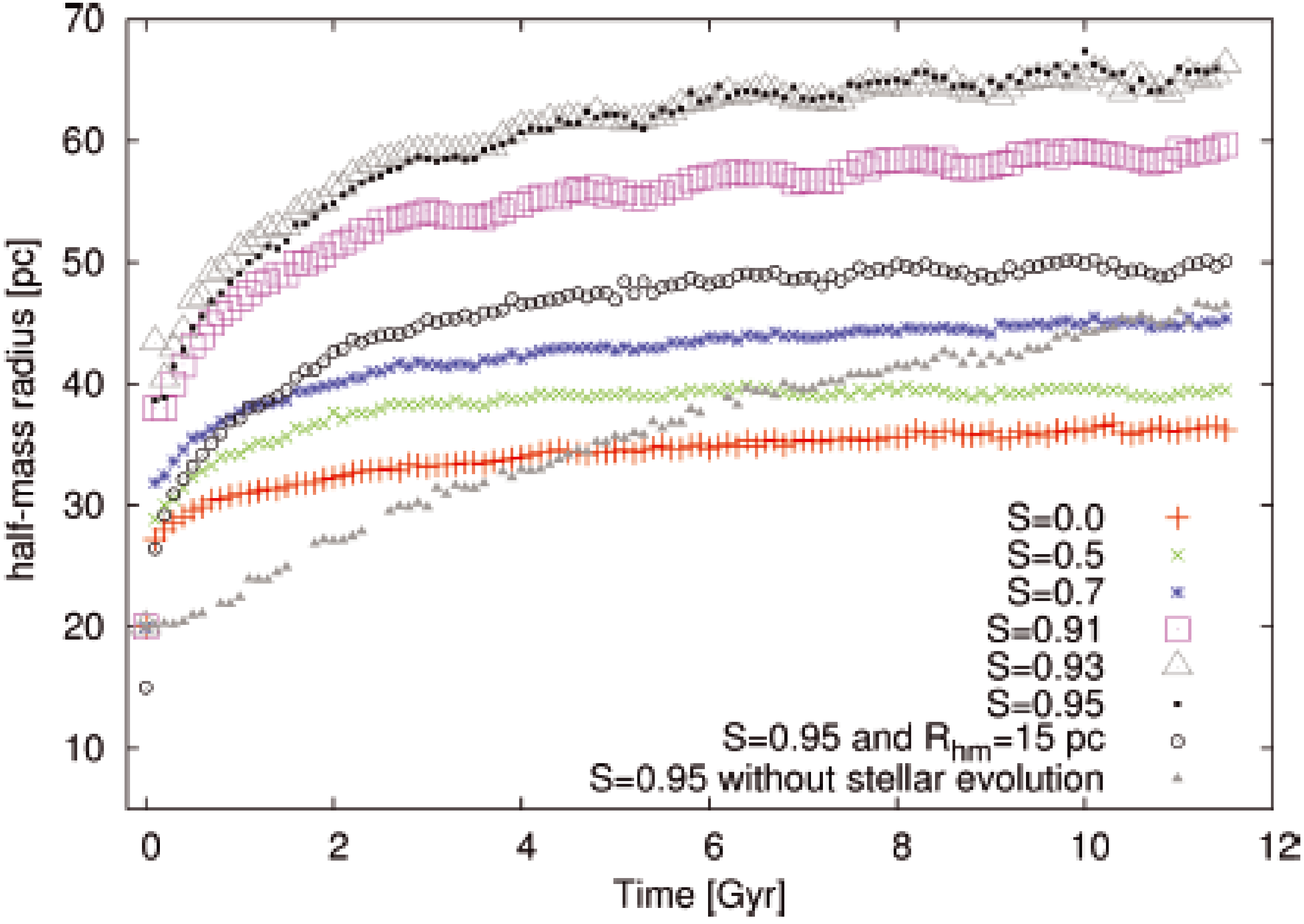
t = 0

The prediction of energy equipartition is confirmed in **globular cluster 47 Tucanae**: The average squared speed of Blue stars was 72 (km/s)^2, which is half the value found for the red stars, 144 (km/s)^2. (Meylan 2007)

Primordial Mass Segregation

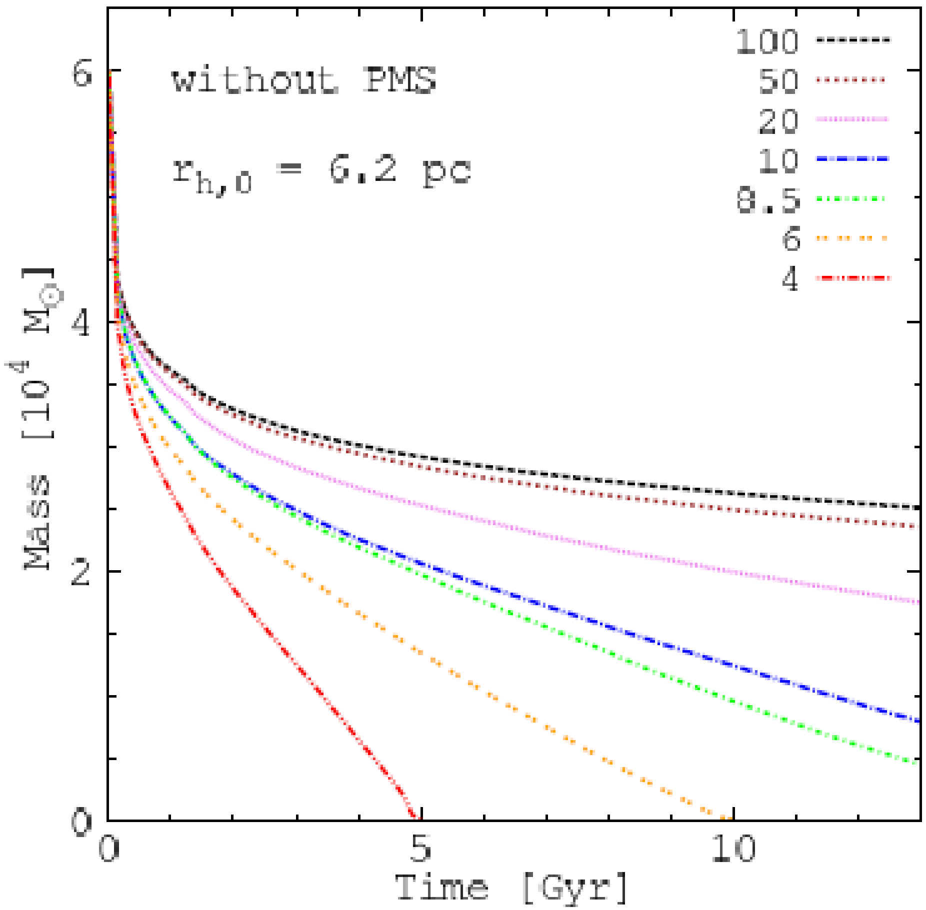
- A number of observational studies have found evidence of mass segregation in clusters with ages shorter than the time needed to produce the observed segregation by two-body relaxation (de Grijs 2010)
- Observed segregation in young clusters would be primordial and imprinted by the star-formation process.
- Direct N-body modeling: we found that only models with a flattened IMF and primordial segregation are able to fit the observed slope of the mass function of diffused distant GCs, e.g., Pal 4 and Pal 14 (Zonoozi et al 2011, 2014,MNRAS).

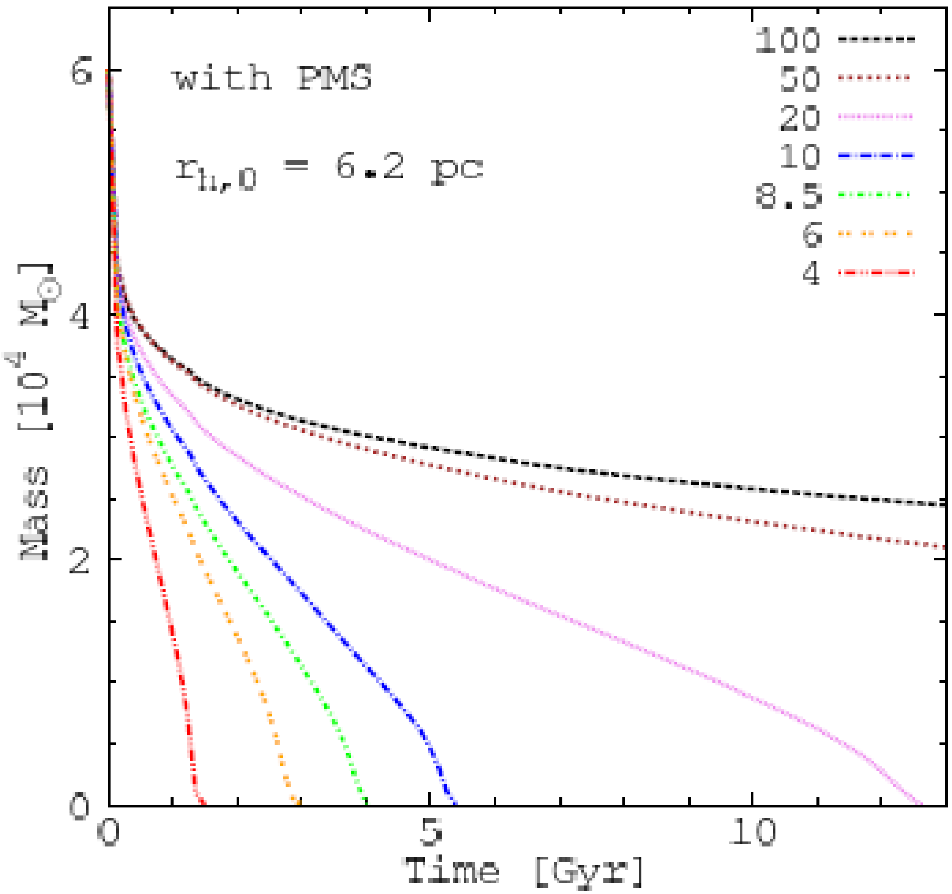
Size evolution of a diffused halo cluster: with and without PMS



Zonoozi, Haghi et al. 2011, MNRAS

Non-segregated vs. Segregated models





Haghi et al. , 2014, submitted MNRAS

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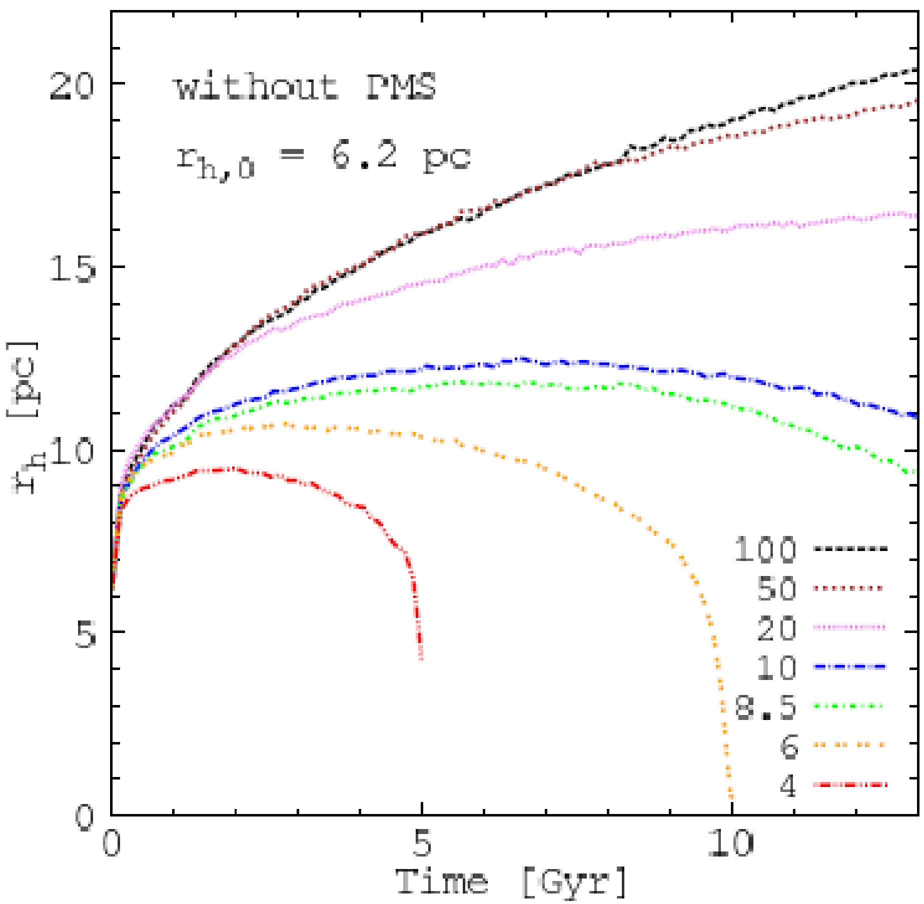

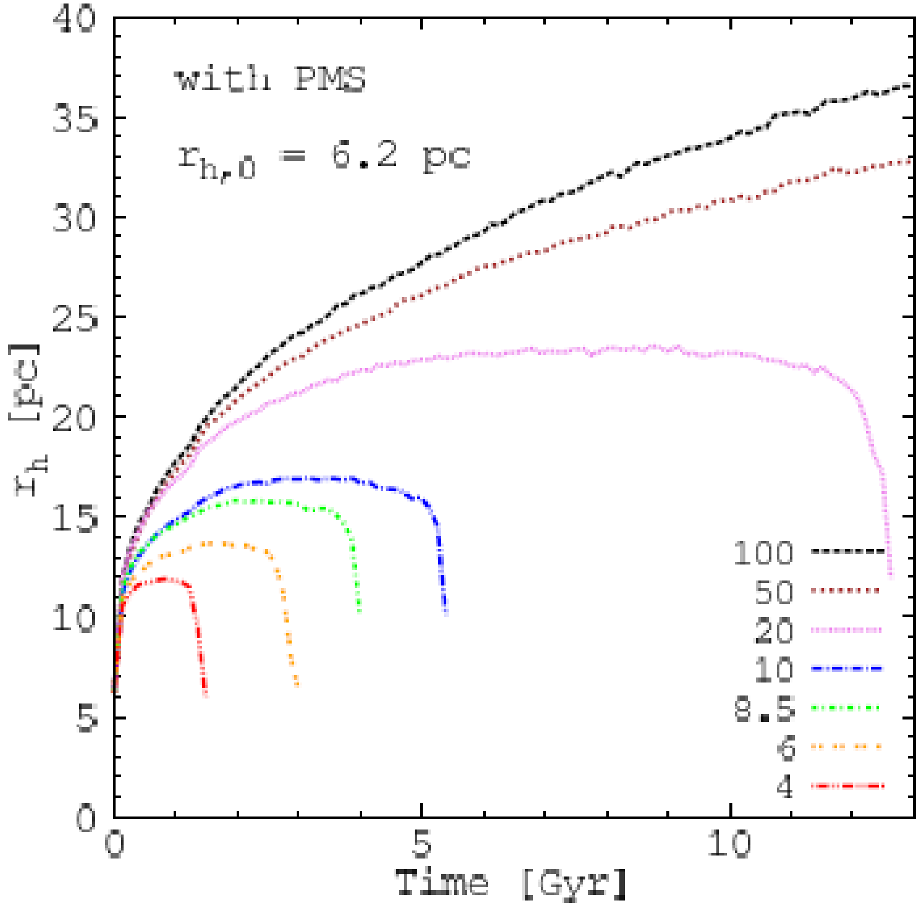

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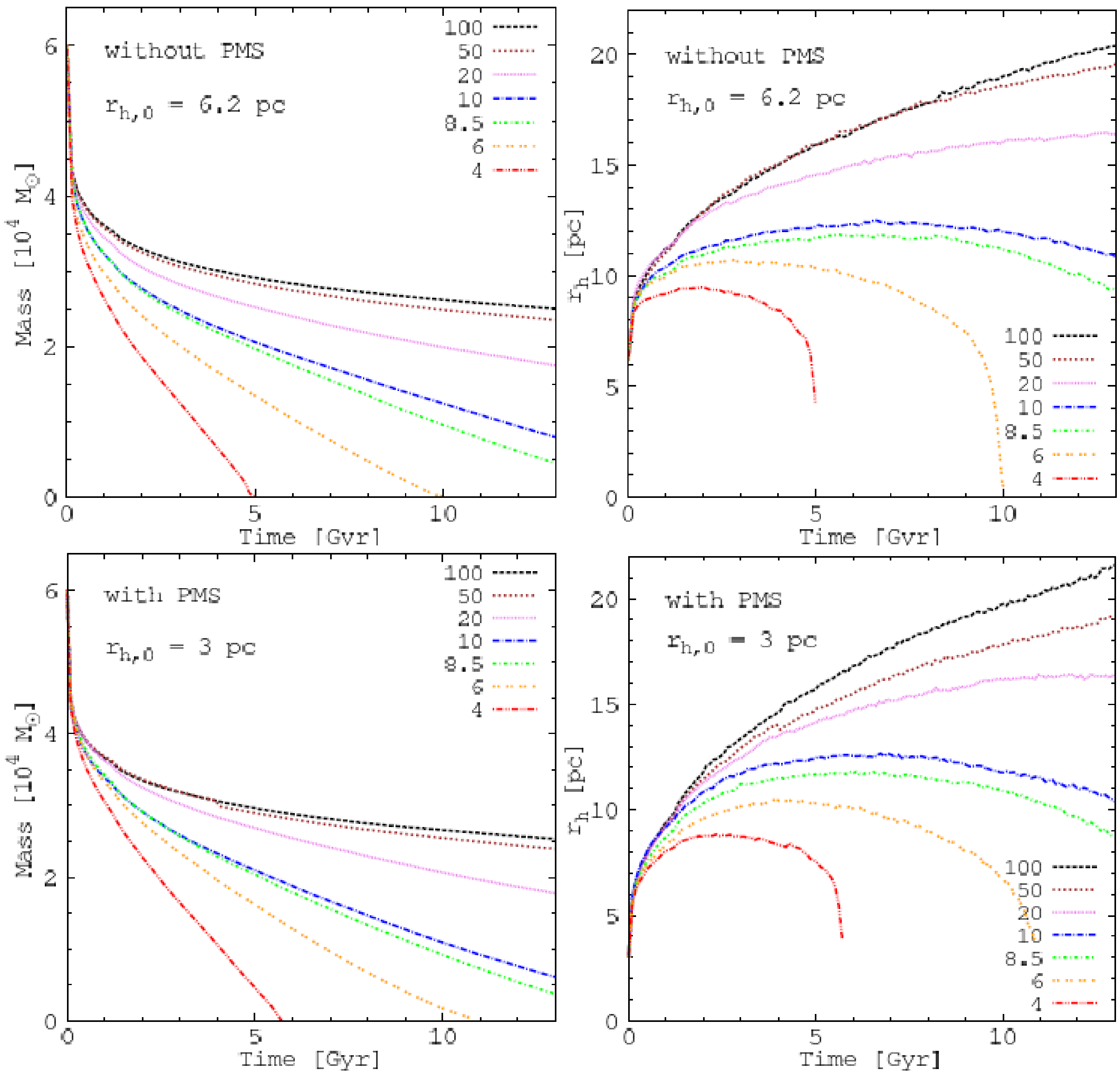
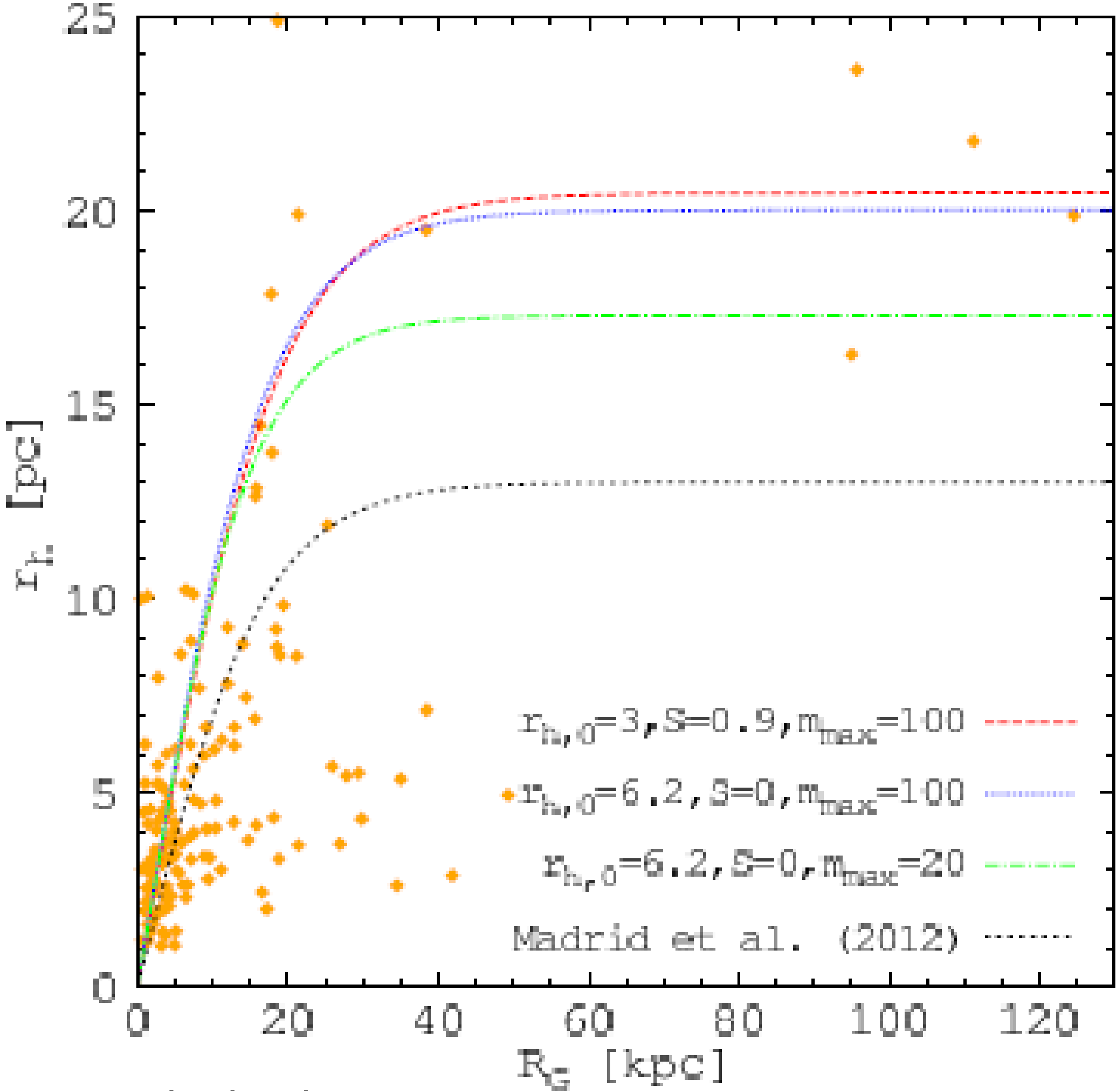


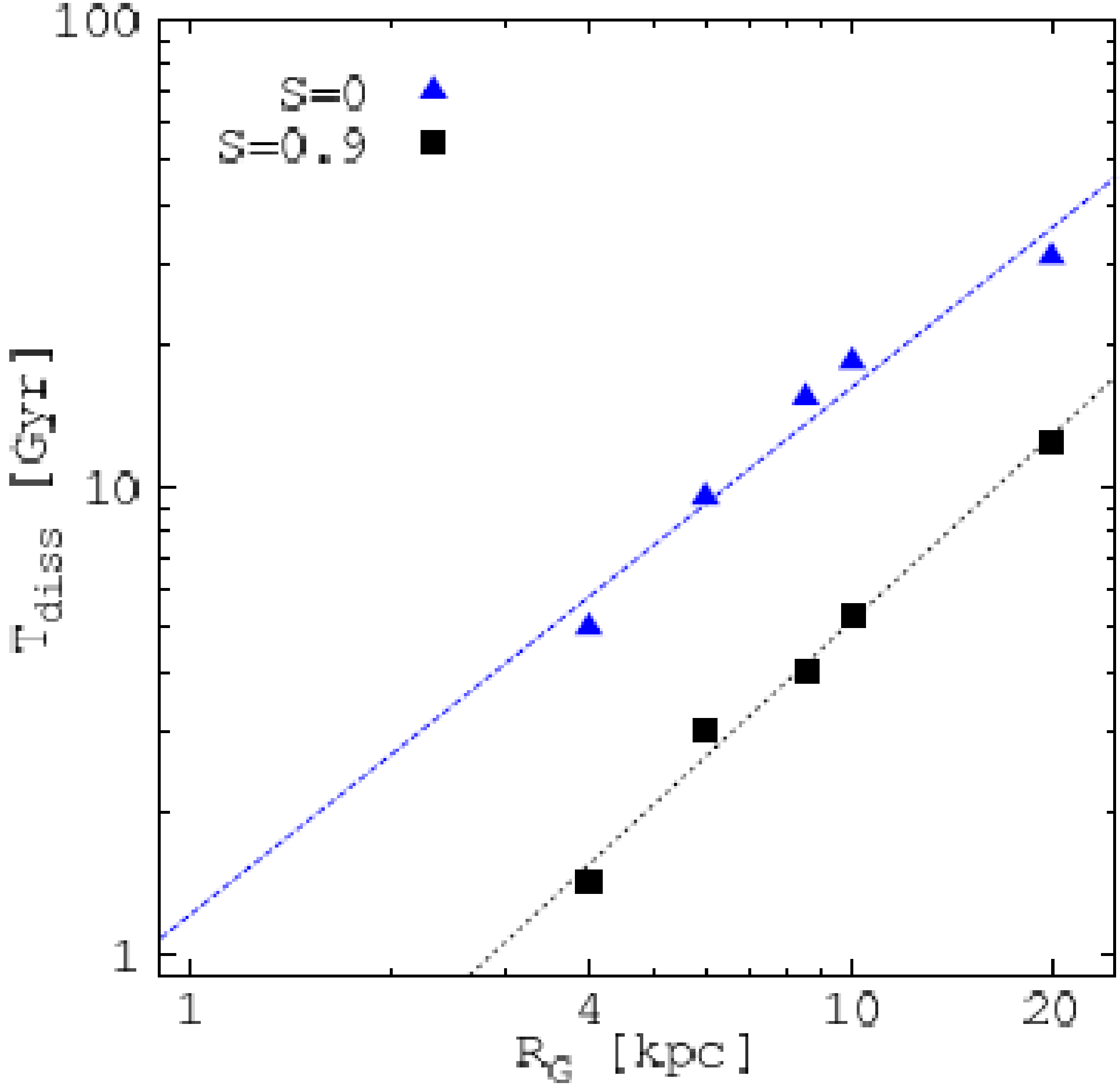
Rh-Rgc relation for PMS clusters



Haghi et al. , 2014, submitted MNRAS

Dissolution of GCs

The $T_{diss} - R_G$ relation



$$T_{diss} \propto R_G^{\alpha(S)}$$

$$S = 0.9$$

$$\alpha = 1.31 \pm 0.08$$

S=0

$$\alpha = 1.12 \pm 0.13$$

Baumgardt 2003

$$T_{diss} \propto R_G$$

Vesperini 2009 $T_{diss} \propto R_G^{0.43}$

Conclusion

- Primordial mass - segregation are able to fit the observed slope of the mass function of diffused distant GCs, e.g., Pal 4 and Pal 14 (Zonoozi et al 2011, 2014, MNRAS).
- Further exploring the initial values used for the set-up of the simulations is needed. Especially assuming the PMS.

  (Haghi , Hosieni Rad, Zonoozi, Kuepper, 2014, Submitted to MNRAS)
- We proposed a new explanation for very diffused halo GCs without invoking a "merger events with dwarf galaxies to grow extended star clusters in the Milky Way at large galactocentric distances".
- Highly eccentric orbit approach

  (Kuepper, Zonoozi, Haghi ,et al, 2014, Submitted to MNRAS)
- Dissolution rate of GCs is faster for PMS clusters