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MOdelling DEnse STellar systems

A personal survey

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Outline

0. Introduction

1. Tools of the trade

2. Tidal effects

3. Dynamics of binaries

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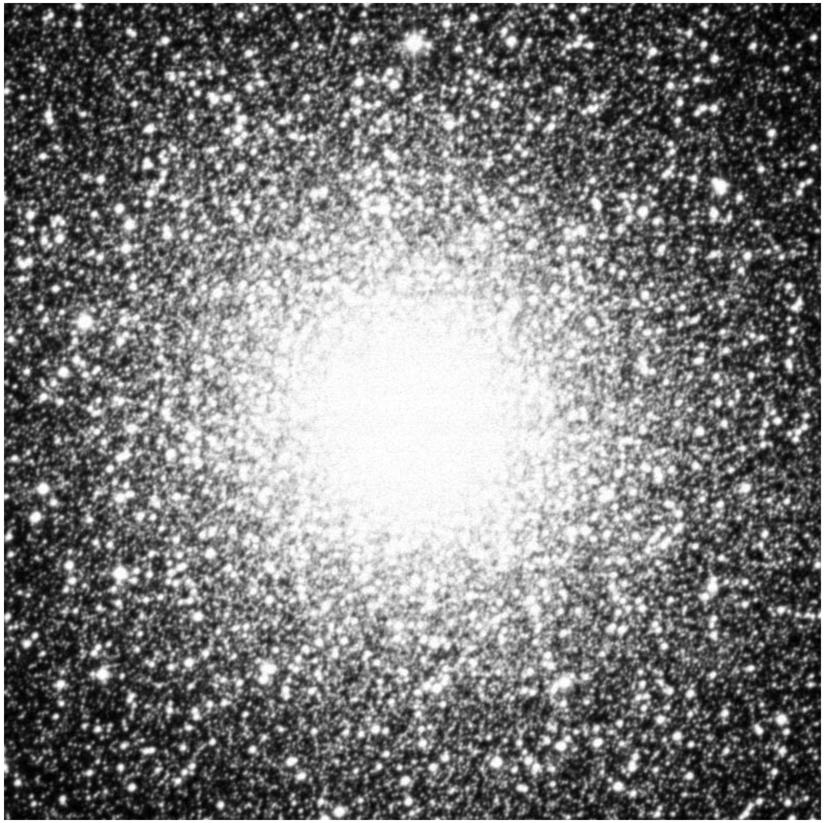
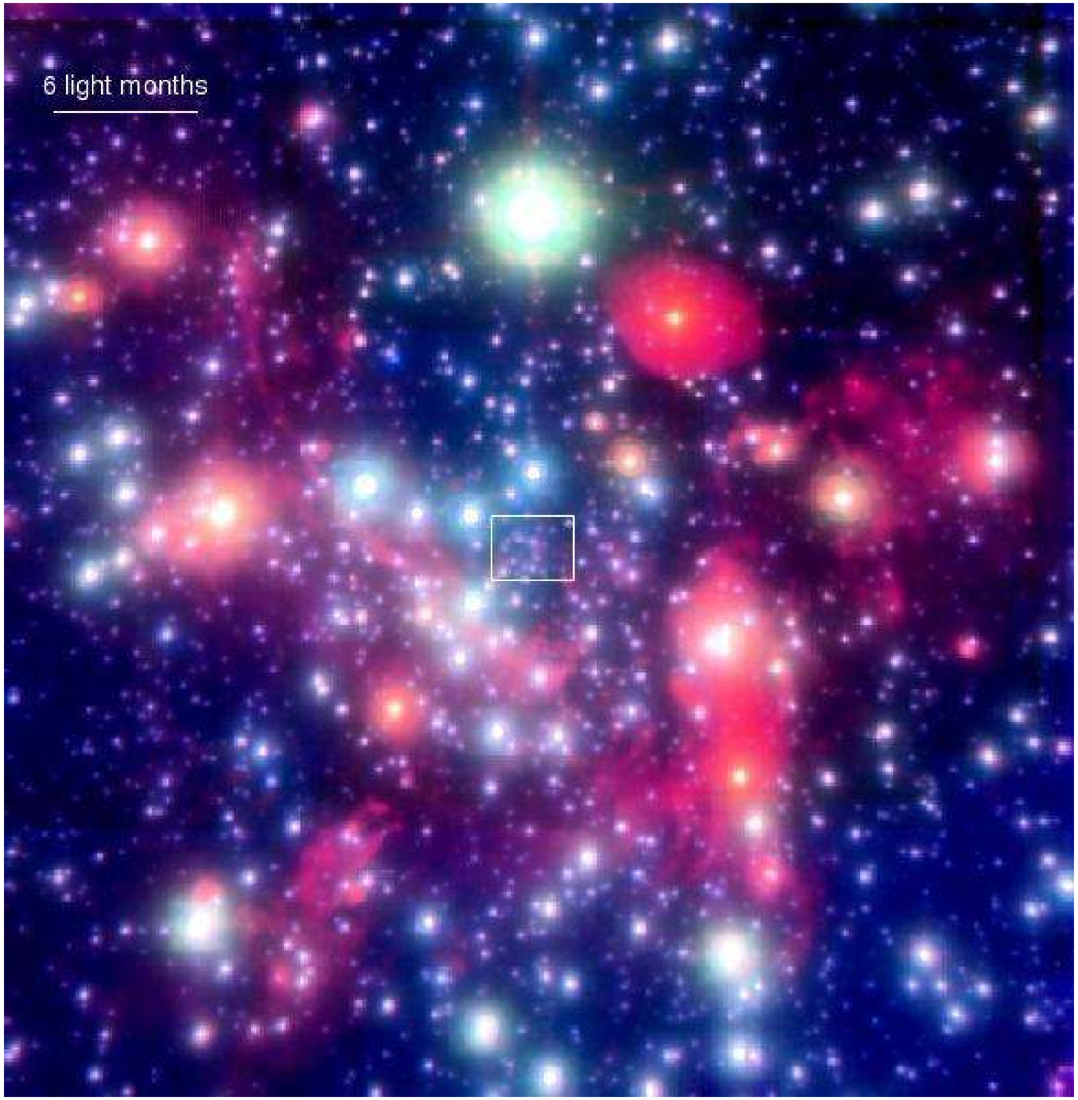
0. Introduction to Dense Stellar Systems



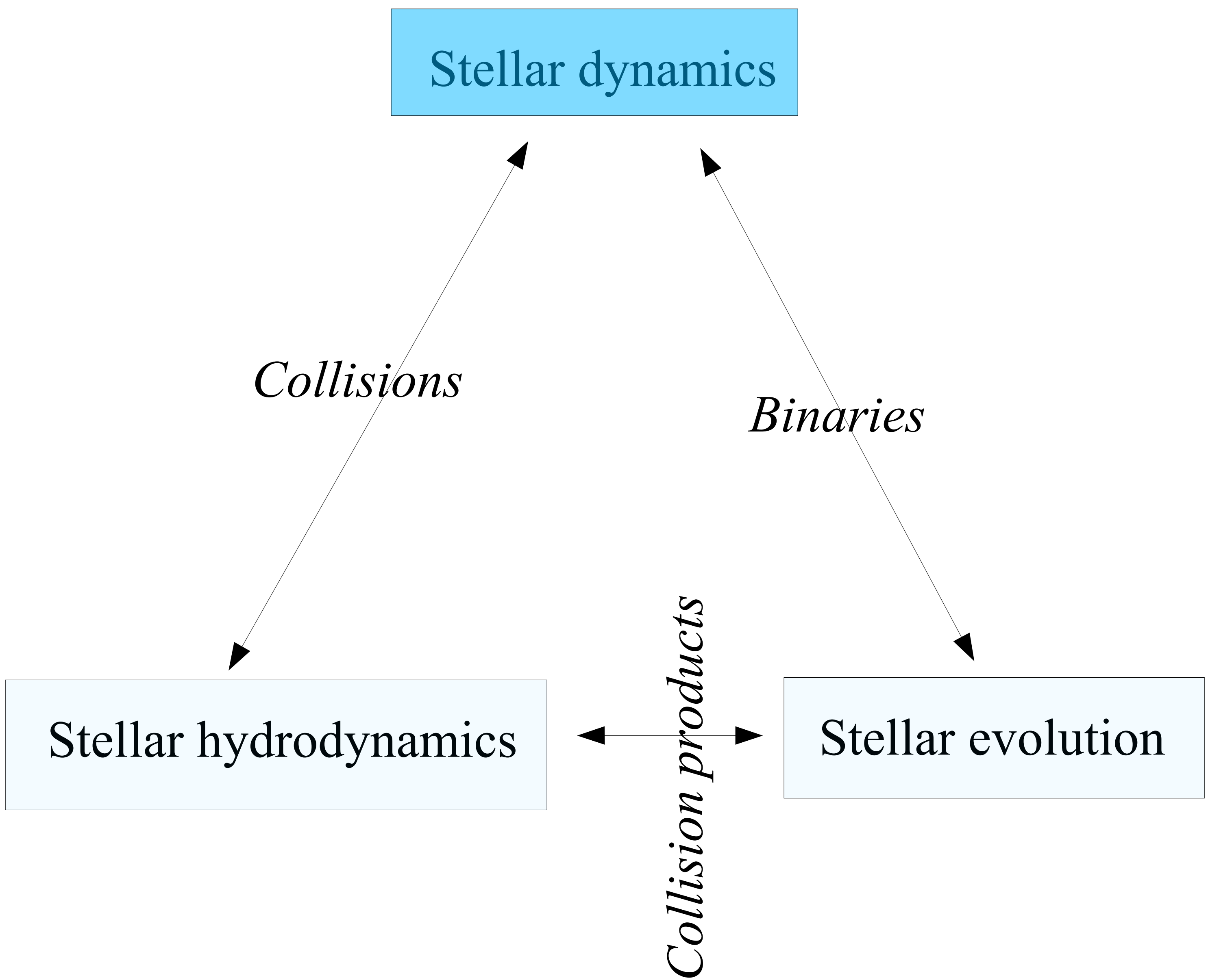
47 Tuc

M67

The Galactic centre



The MODEST Arena
(in theory)



Dynamical ingredients (focusing on star clusters)

Stars

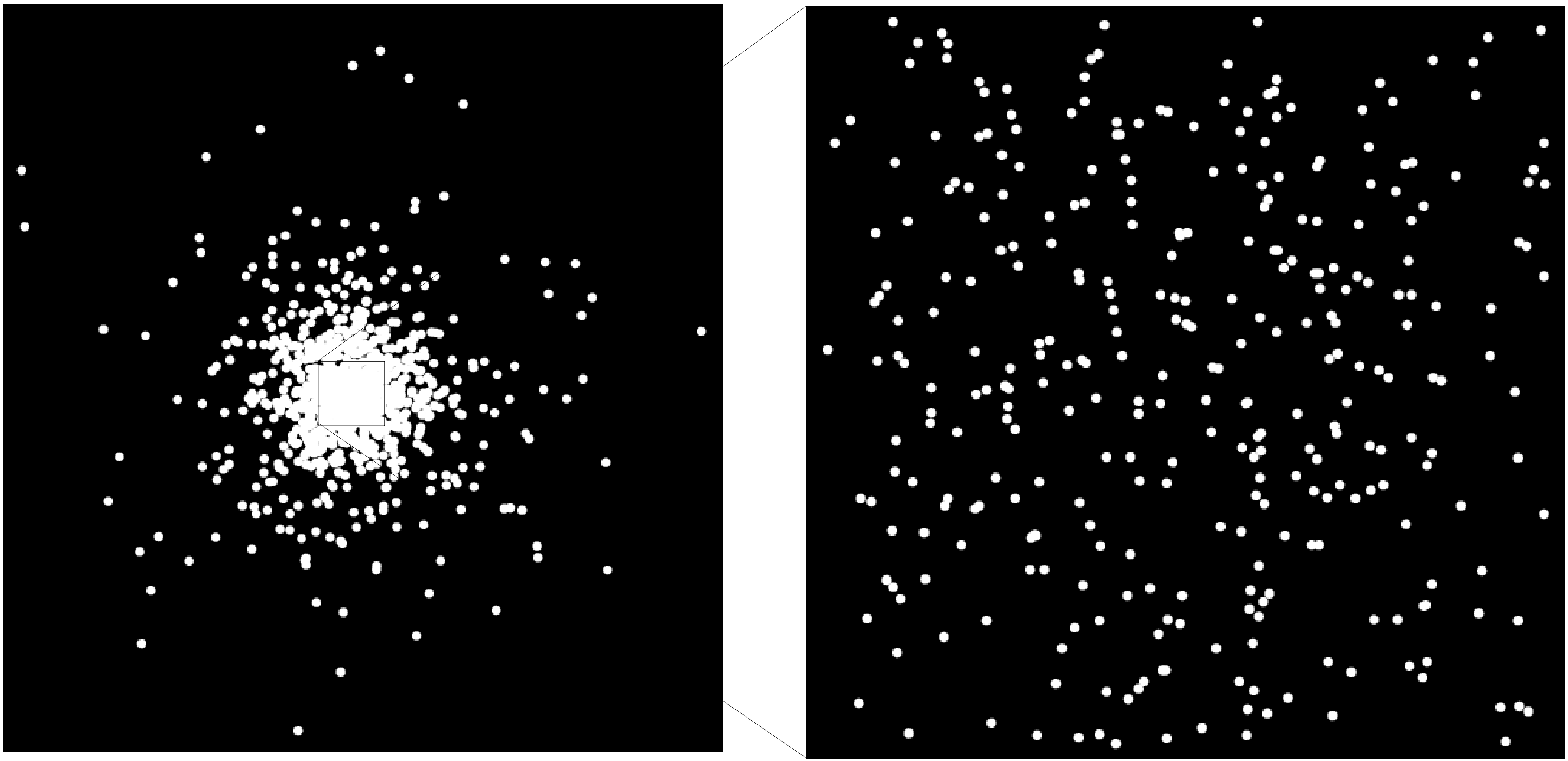
Binary stars

External effects (the galactic tide)

Two time scales:

1. The crossing (orbital) time
2. The relaxation time (for effects of gravitational encounters to become significant)

Two simulations



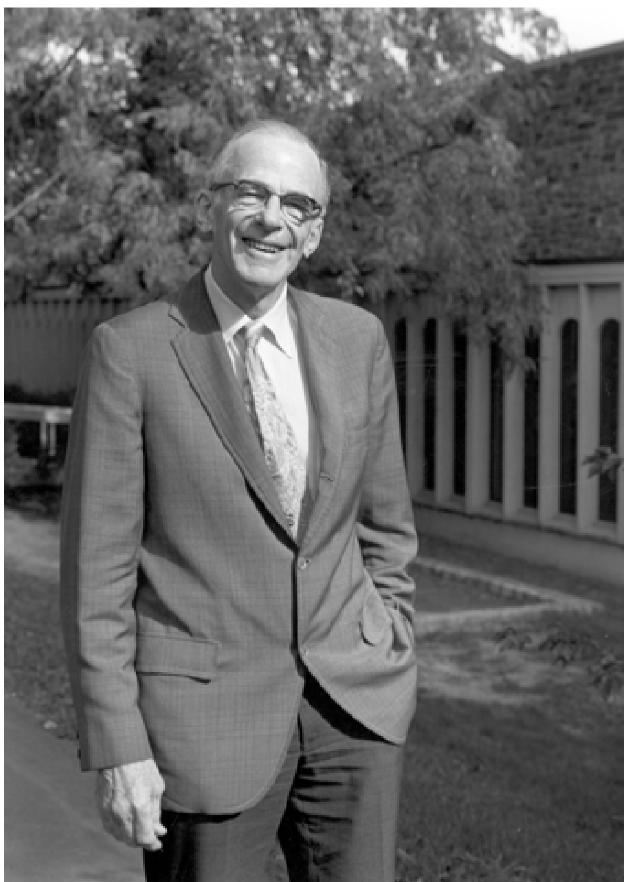
Entire system
13 seconds to t = 3.3

Central area
13 seconds to t = 330

The initial conditions

1. The theory of star cluster dynamics

Direct N-body simulations



$$\ddot{\boldsymbol{r}}_i = -\sum_{j=1,\, j\neq i}^{N} G m_j \frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{\left|\boldsymbol{r}_i - \boldsymbol{r}_j\right|^3}$$

"These equations have an appealing - if deceptive – simplicity"

Lyman Spitzer Jr

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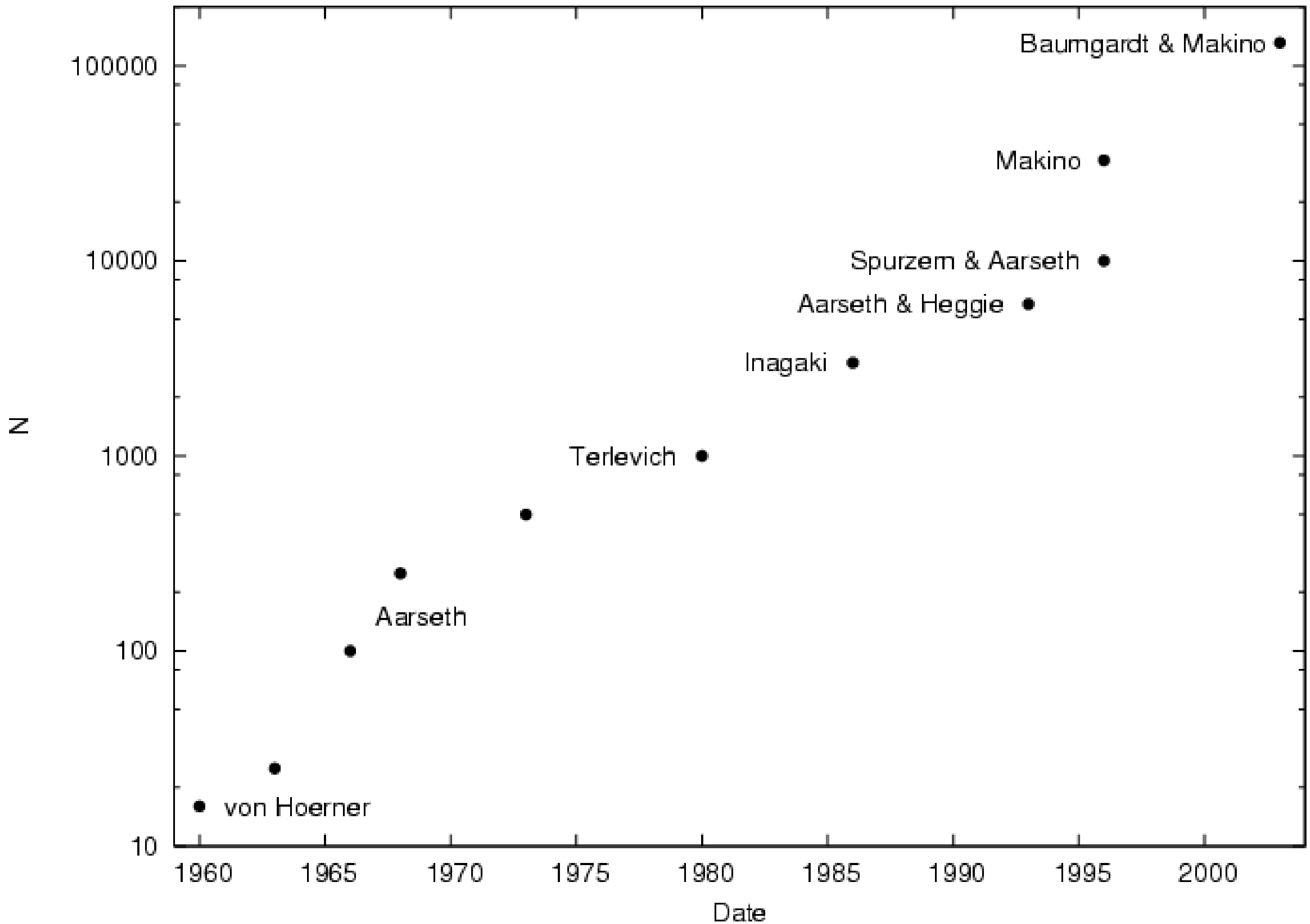
$$\ddot{\boldsymbol{r}}_i = -\sum_{j=1,\, j\neq i}^{N} G m_j \frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{\left|\boldsymbol{r}_i - \boldsymbol{r}_j\right|^3}$$

Effort scales as N^3:

- force on each particle has N contributions
- there are N particles with forces to compute
- evolution scales as N (relaxation time/crossing time)

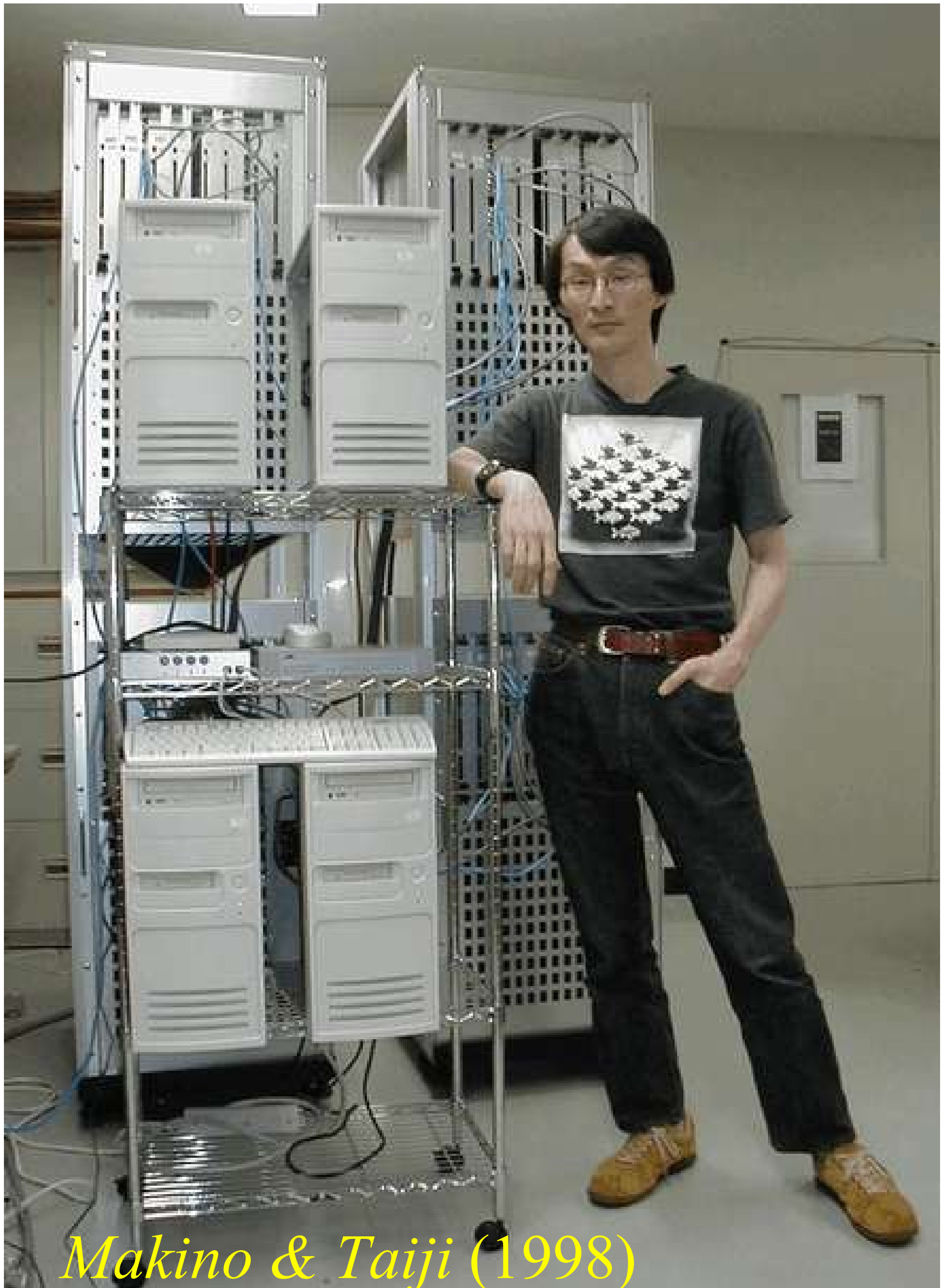
The slow progress of N-body simulations

N



Date

GRAPE



GRAPE 6 and Jun Makino, University of Tokyo (32 Tflops in 2001)
Project 5-year budget 500 M¥

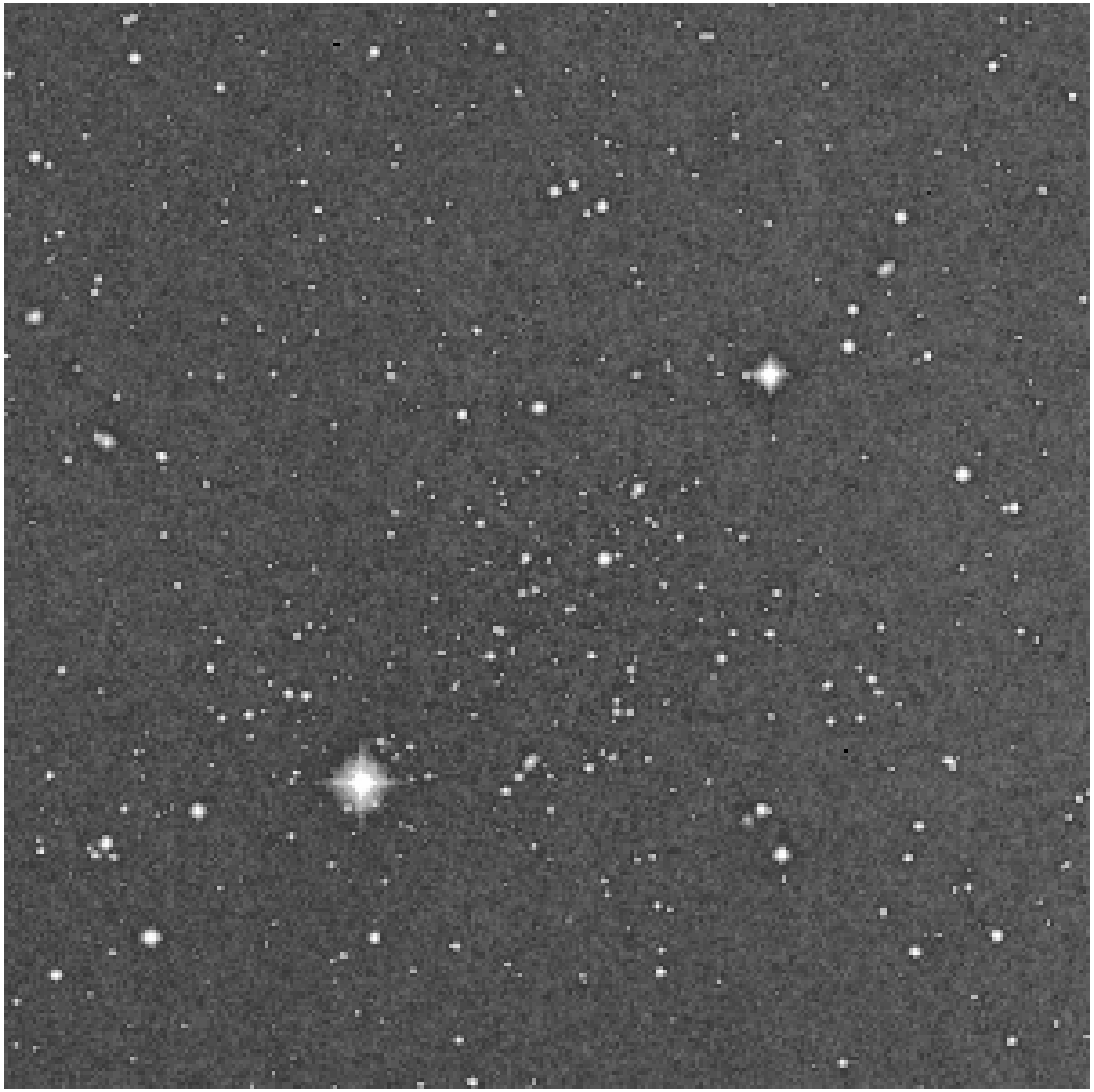
Baby GRAPE 6 with host, University of Edinburgh (100 Gflops in 2005)
Budget £4K

Some tools of the trade

or http://www.ids.ias.edu/~starlab/

2. The effects of tides

Pal 5: optical
(digitised sky survey)



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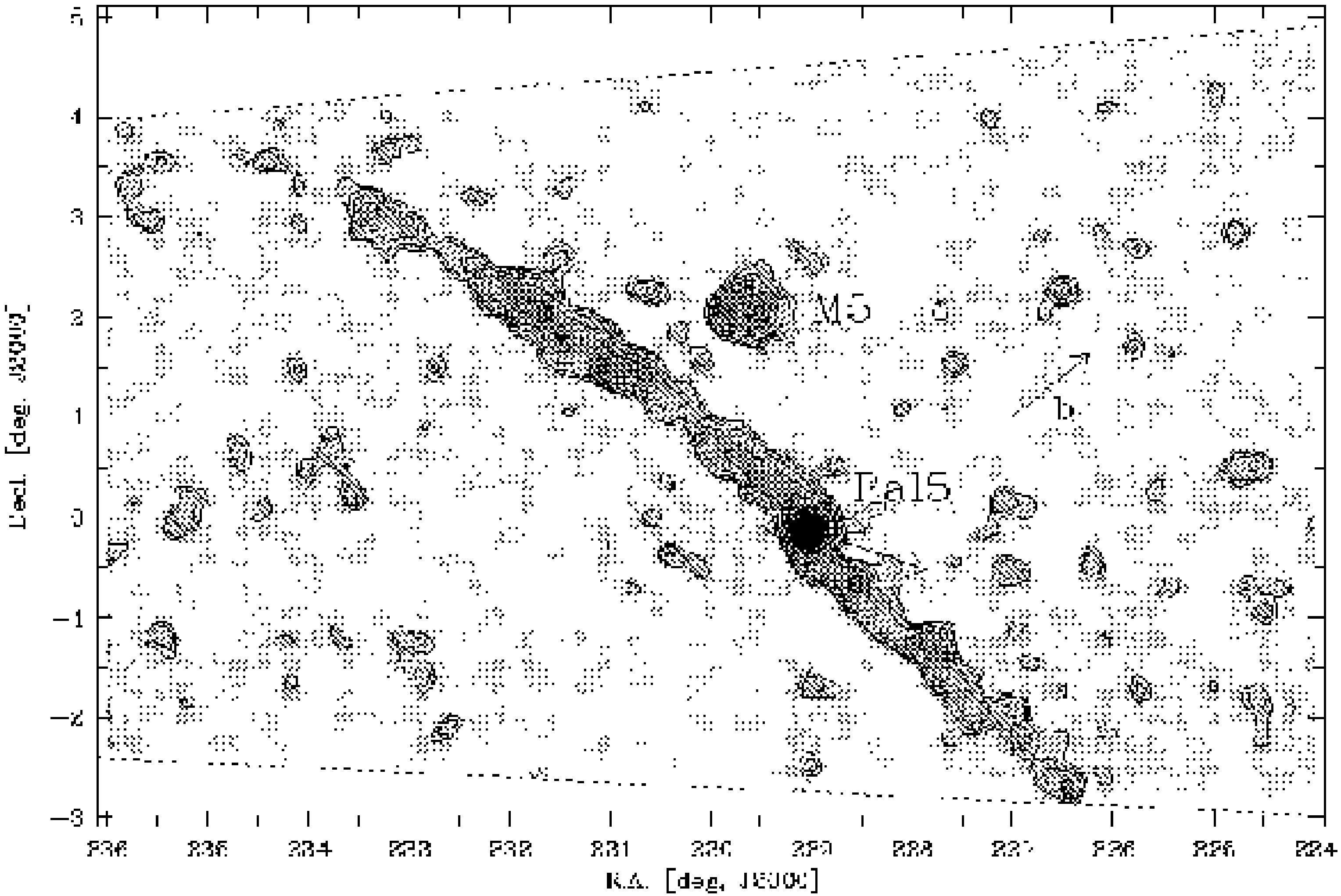
Pal 5: Sloan DSS (Odenkirchen et al)



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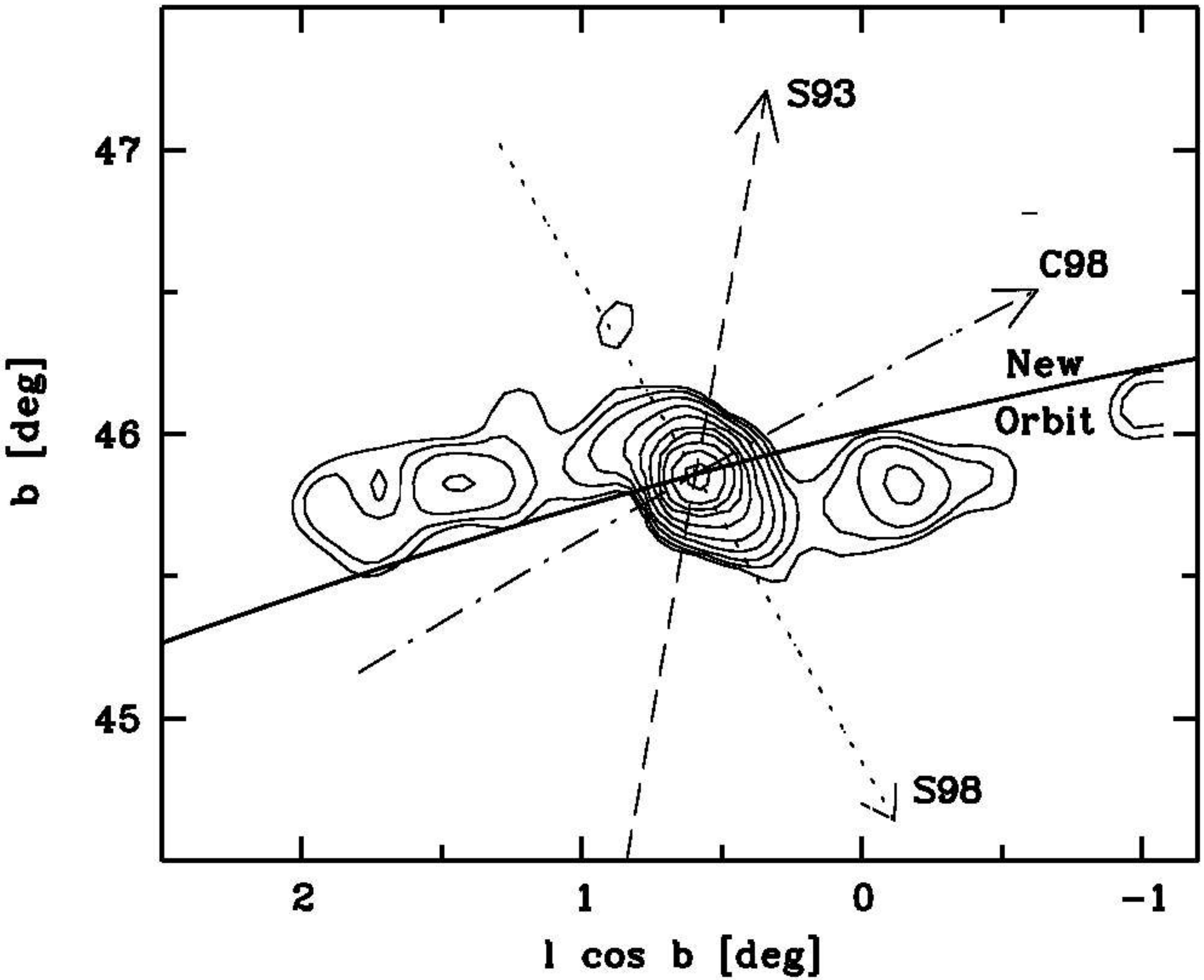
Pal 5



From Odenkirchen et al 2000

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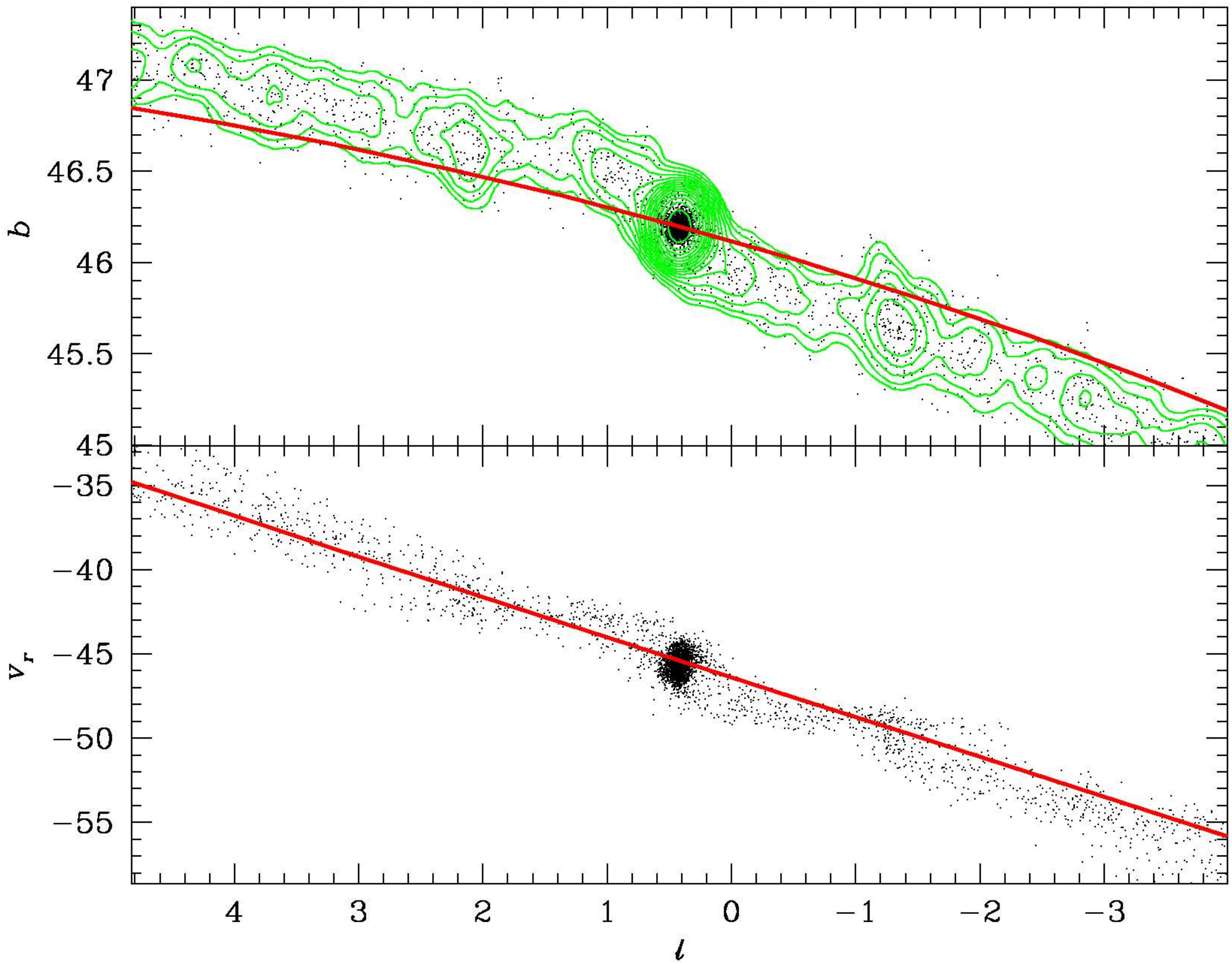
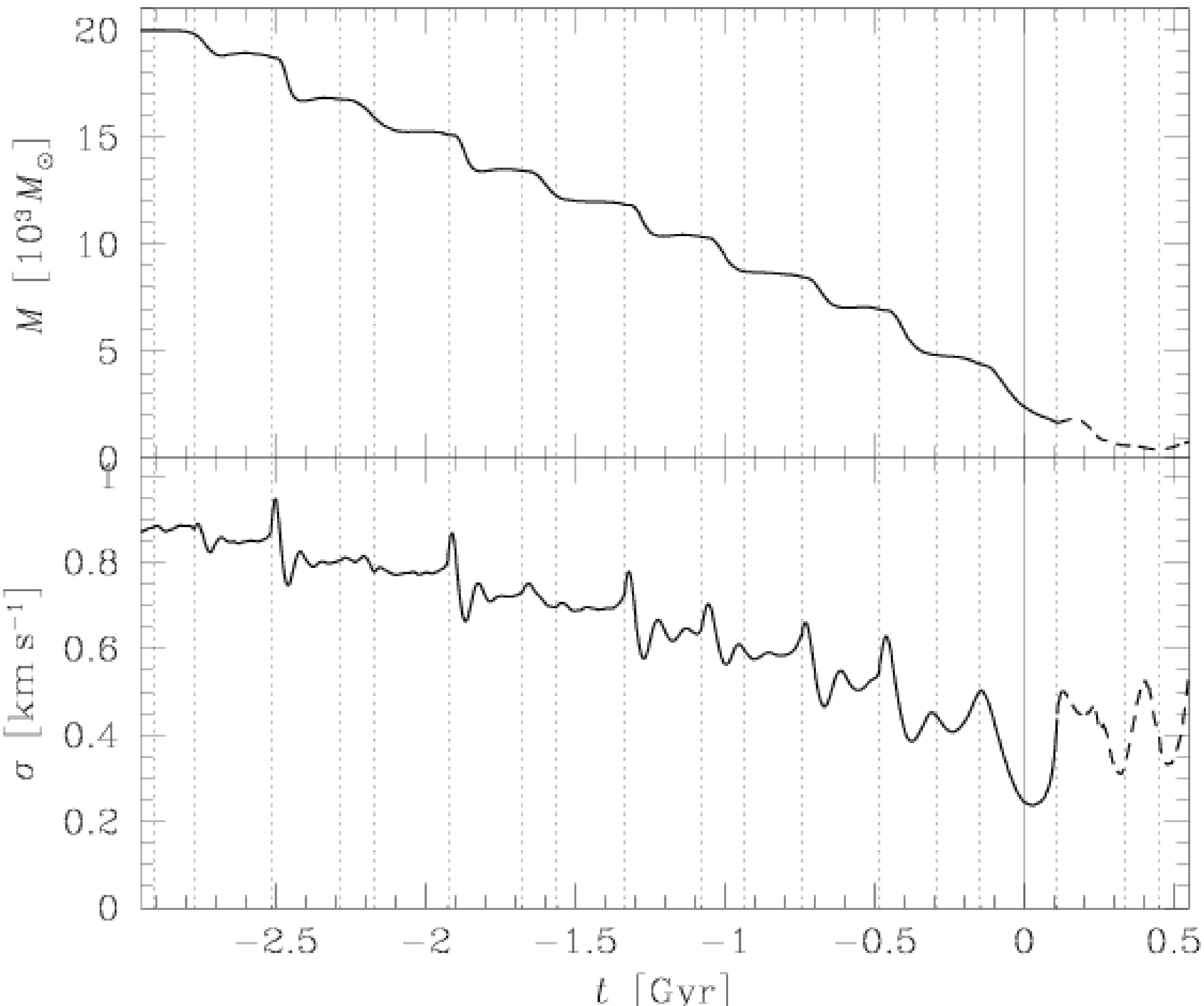
Pal 5: simulation (Dehnen)



Pal 5: simulation (Dehnen)

Mass

Velocity dispersion



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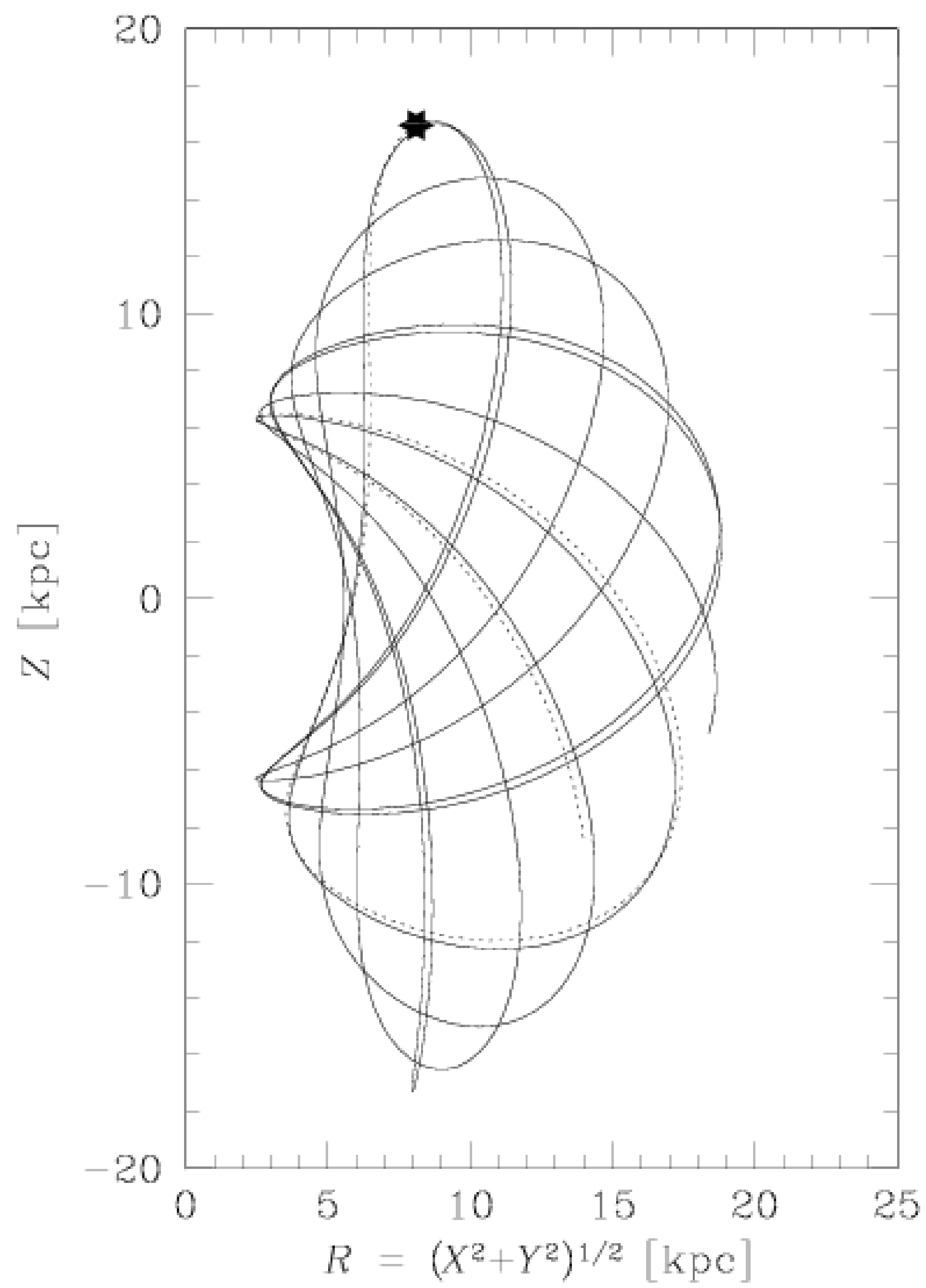
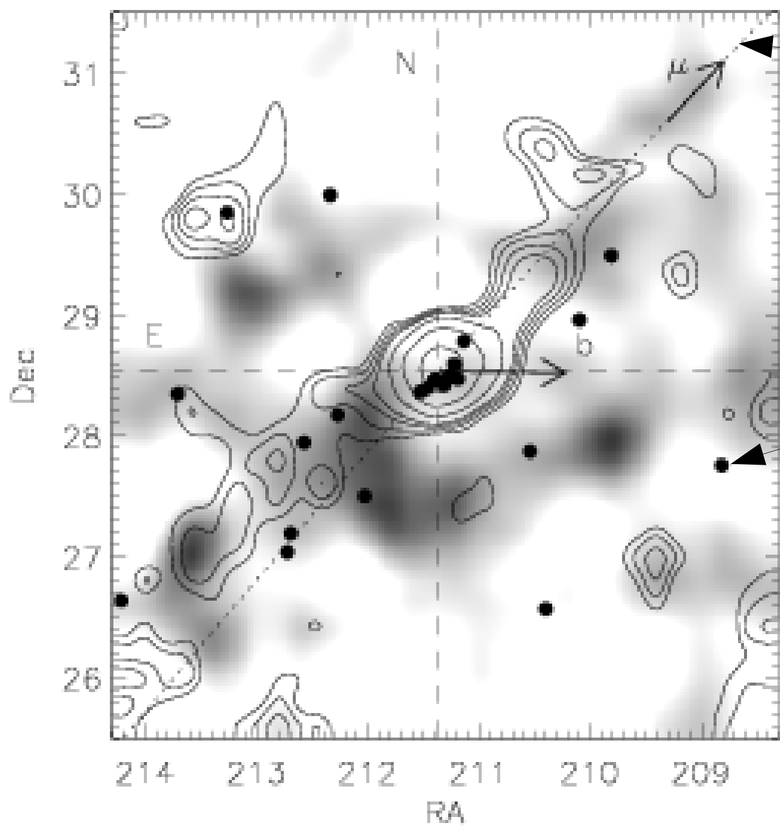
Pal 5: simulation (Dehnen)

The assumed orbit
in the meridional plane



A recent example: NGC 5466



orbit

BHB star

astro-ph/0511767
Belokurov et al

Contours of star density
(grey: background galaxy density)

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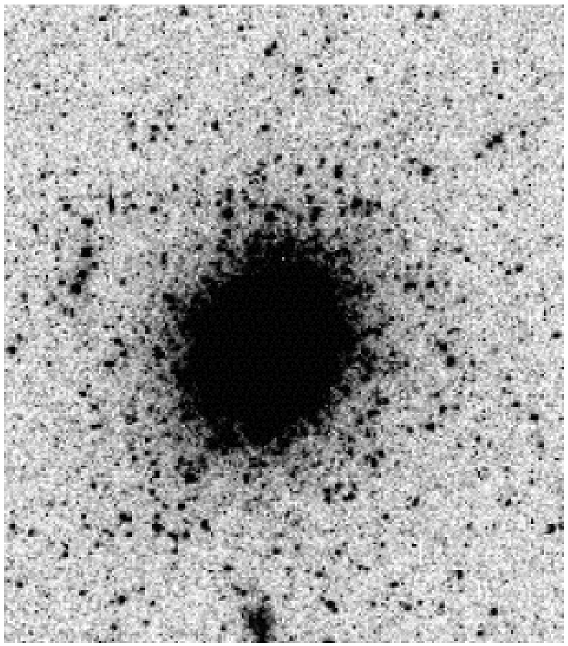
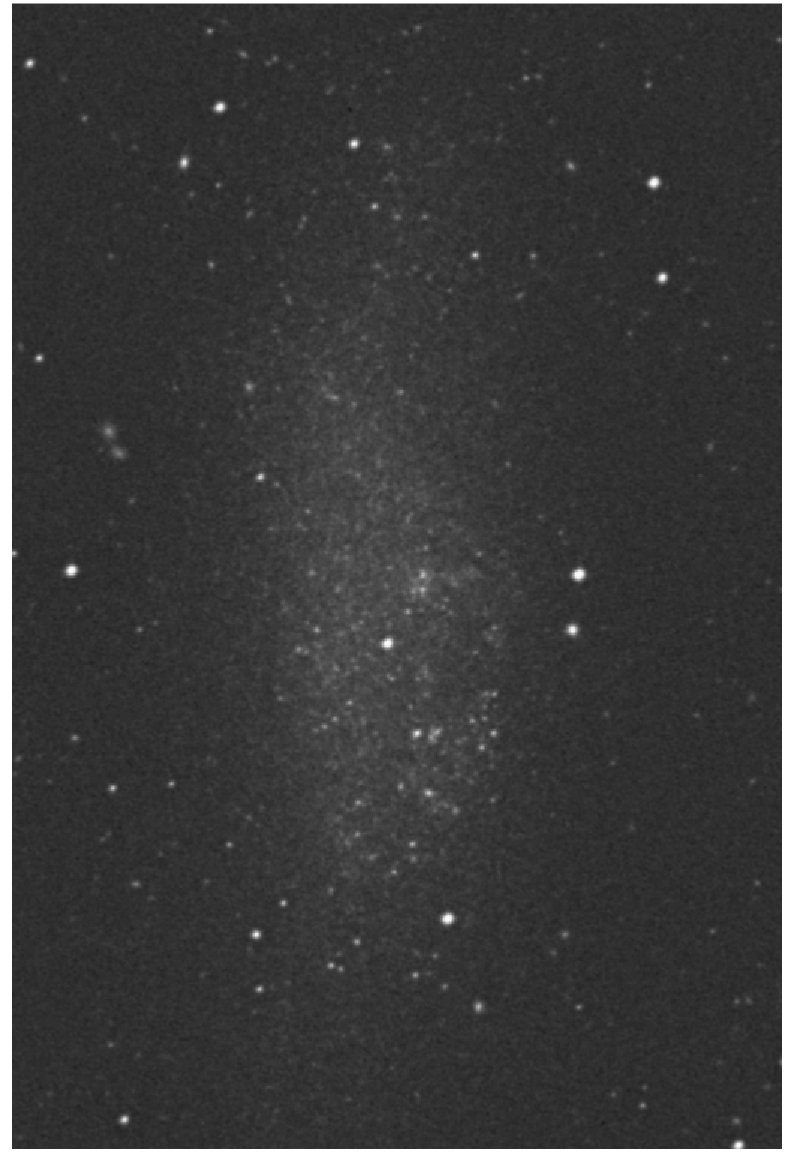
WLM-1: A globular cluster without tides?

Stephens et al, astro-ph/0511502

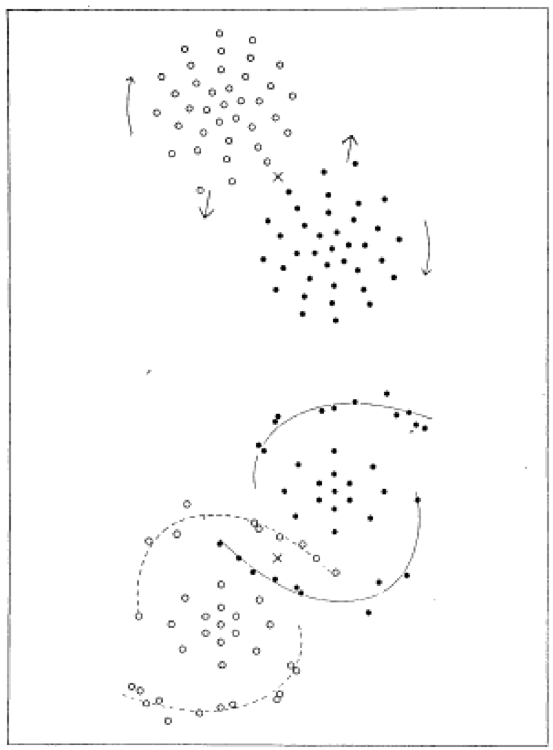


Hodge et al 1999

DSS



Holmberg's investigation



E. Holmberg (1941) ApJ, 94, 385

“On the Clustering Tendencies among the Nebulae. II. a Study of Encounters Between Laboratory Models of Stellar Systems by a New Integration Procedure.”

“Acknowledgement: ...The author also expresses his gratitude to the Luma Factory of Stockholm for valuable help in designing and manufacturing the special light-bulbs that were used in the present investigation.”

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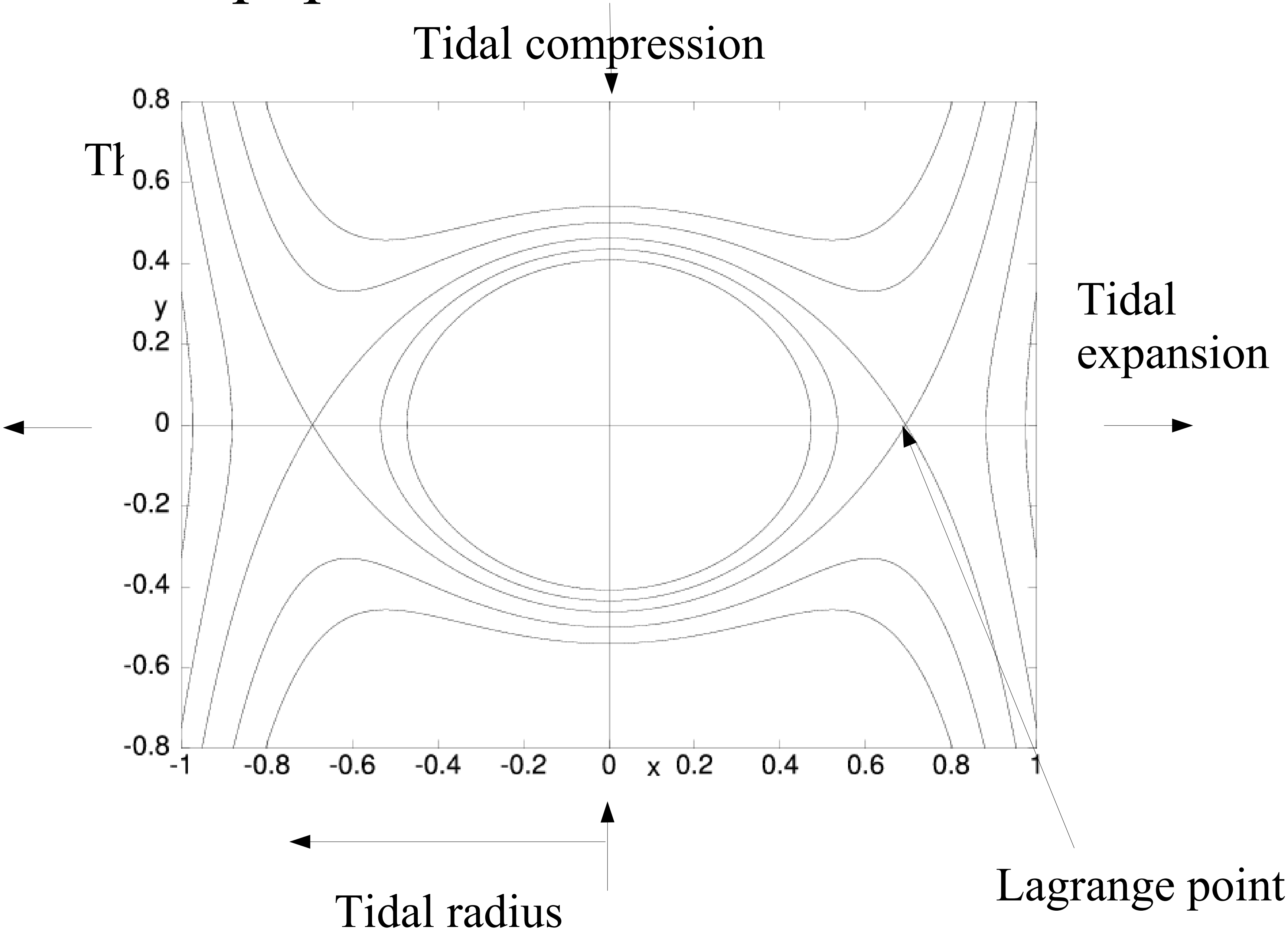
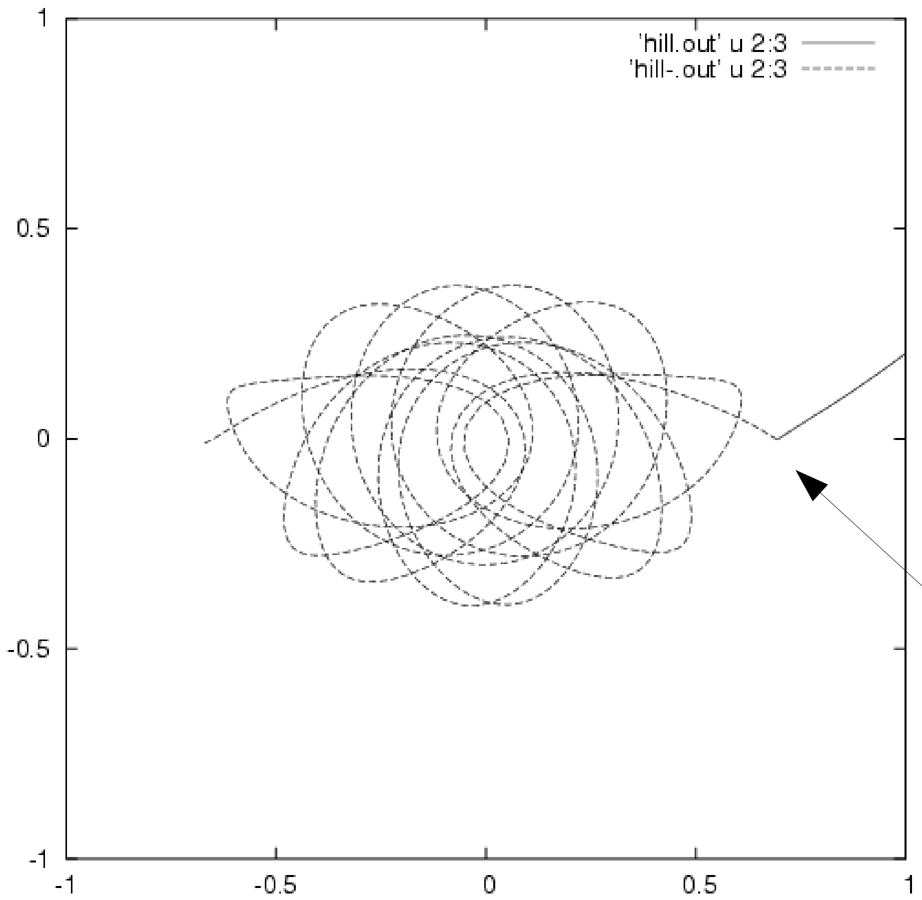
Effects of tides inside a cluster

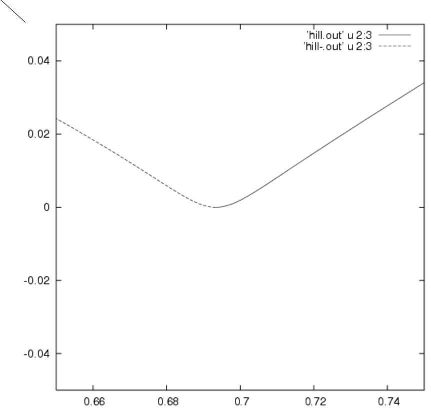
Equipotentials in the Cluster Frame



An orbit of an escaper

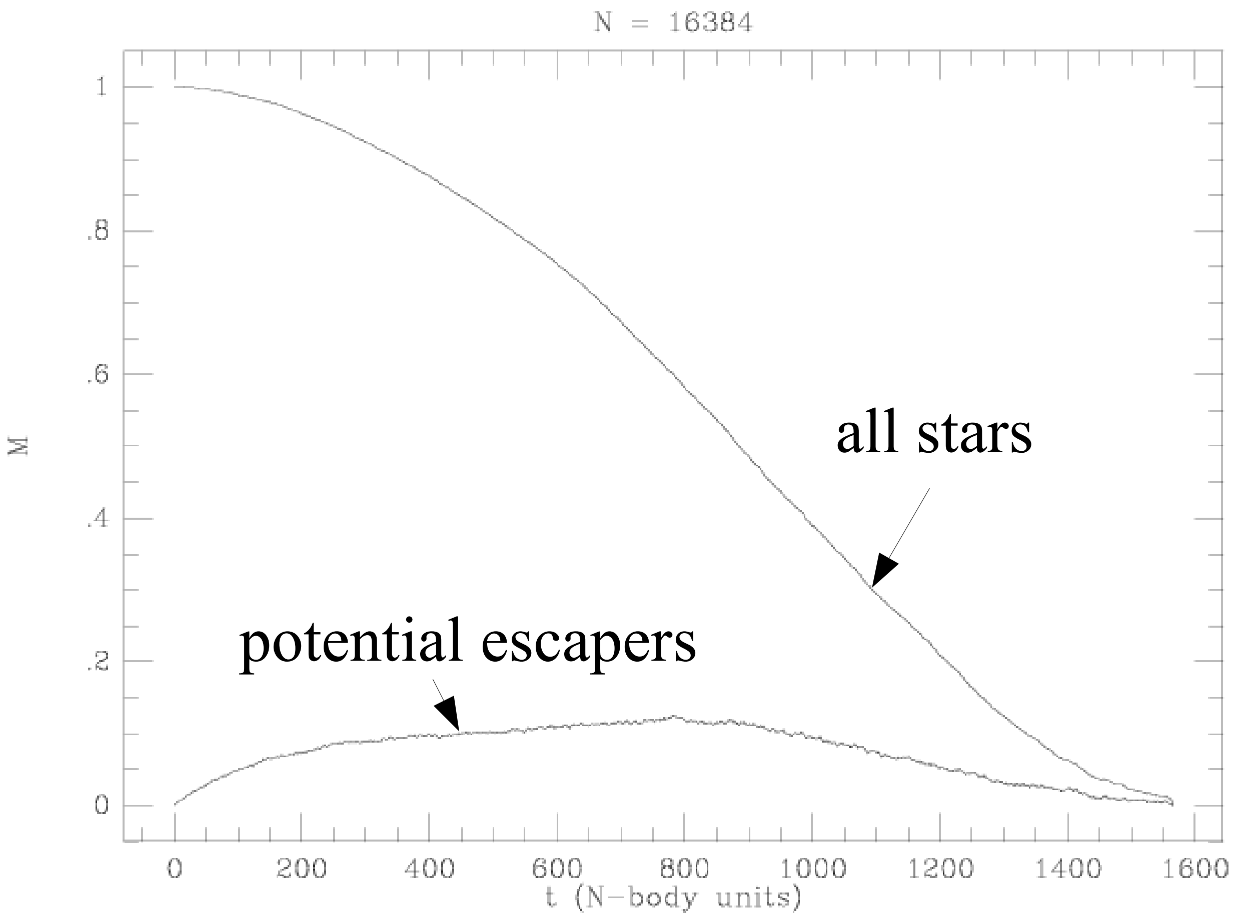


A star may remain inside the cluster for many crossing times even with enough energy to escape ("potential escaper")



The population of potential escapers

M/M(0)



Time

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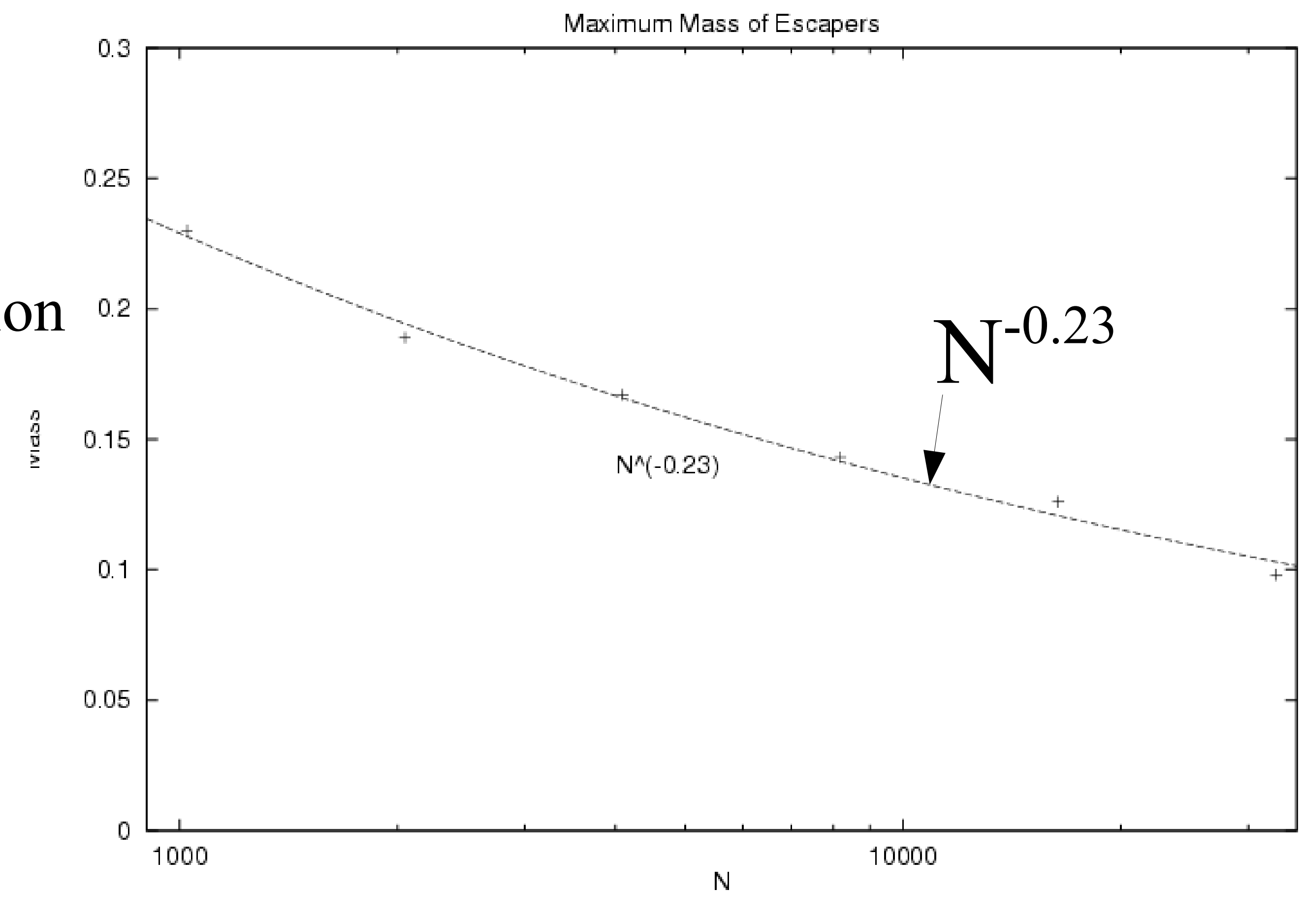
The maximum population of potential escapers as a function of N



Fraction

$N^{-0.23}$

N

High-velocity stars in globular clusters

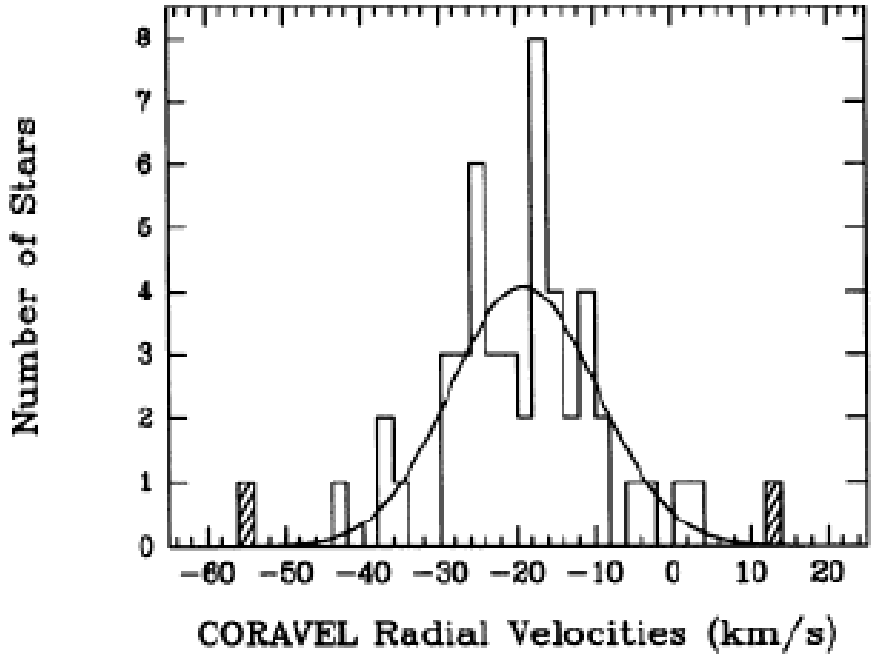


FIG. 3.—Histogram of the 50 radial velocities contained in Table 2, including the high-velocity star 74 found in CASPEC spectra and later observed with CORAVEL, and the high-velocity star 10 observed with CORAVEL.

Meylan et al (1991) ApJ, 383, 587

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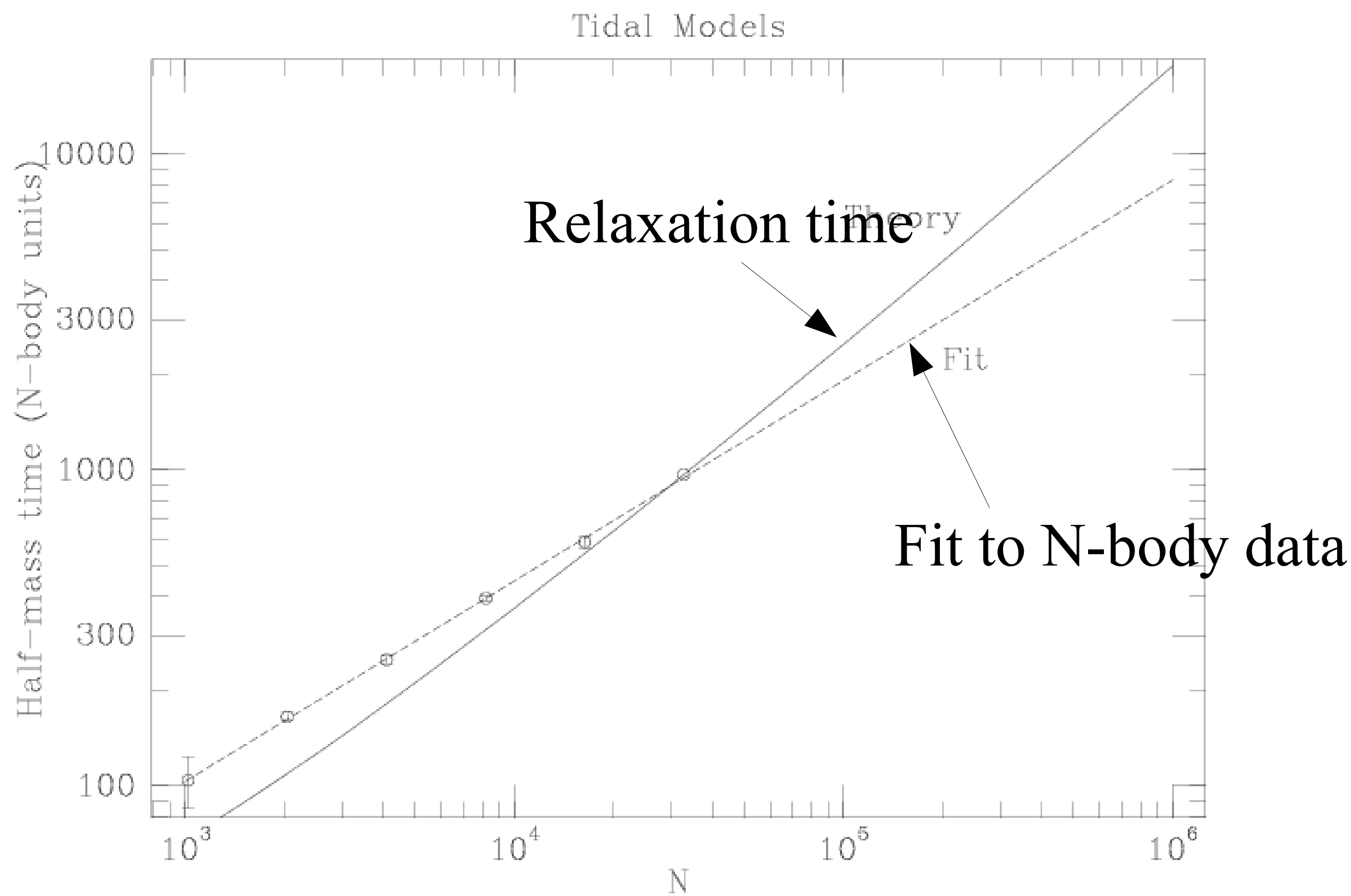
The effect of potential escapers on the lifetime of globular clusters

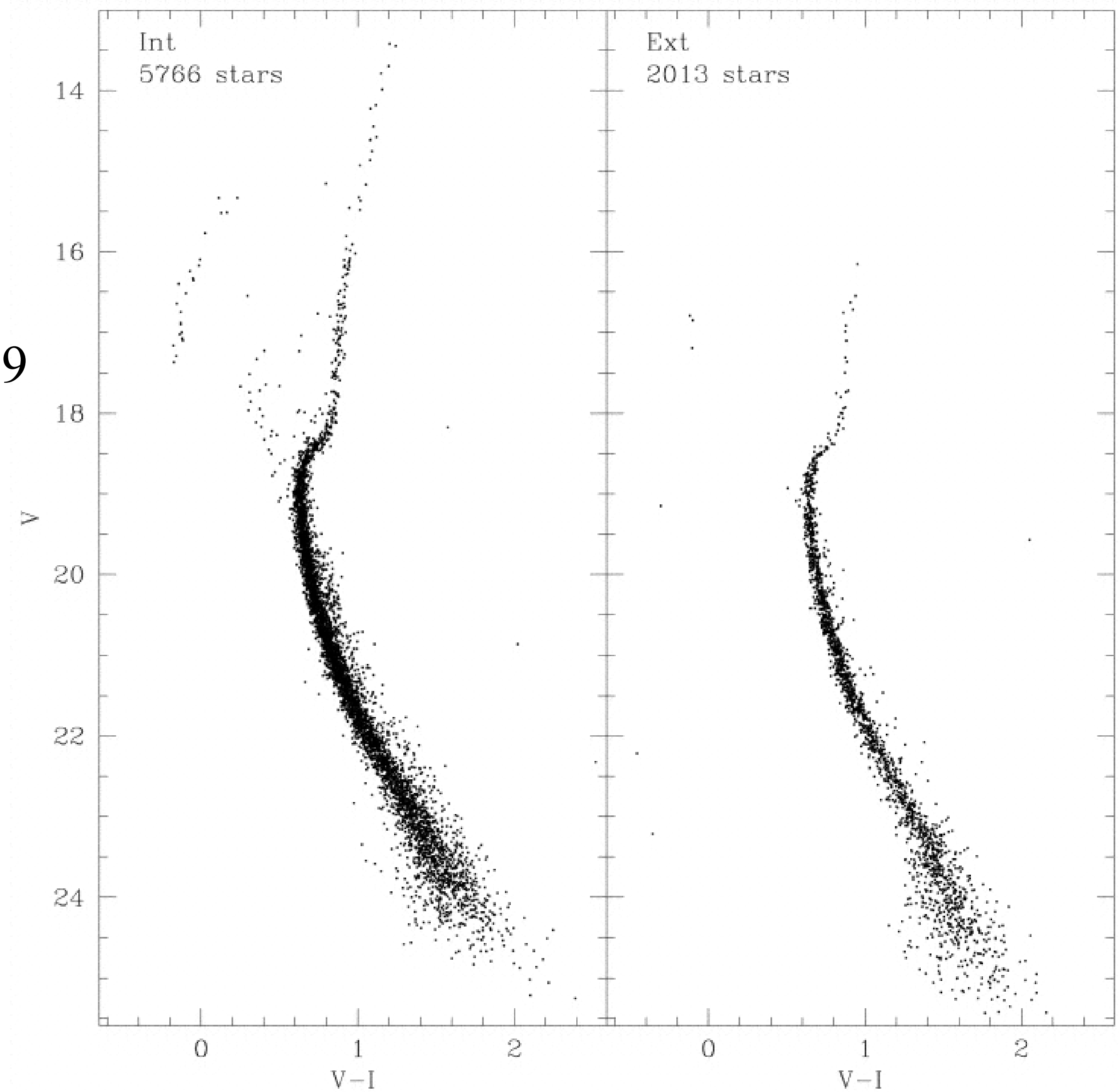
Time for half of the mass to escape



N

3. Binaries in globular clusters

NGC 288
(Bellazzini et al,
2002, AJ, 123, 1509



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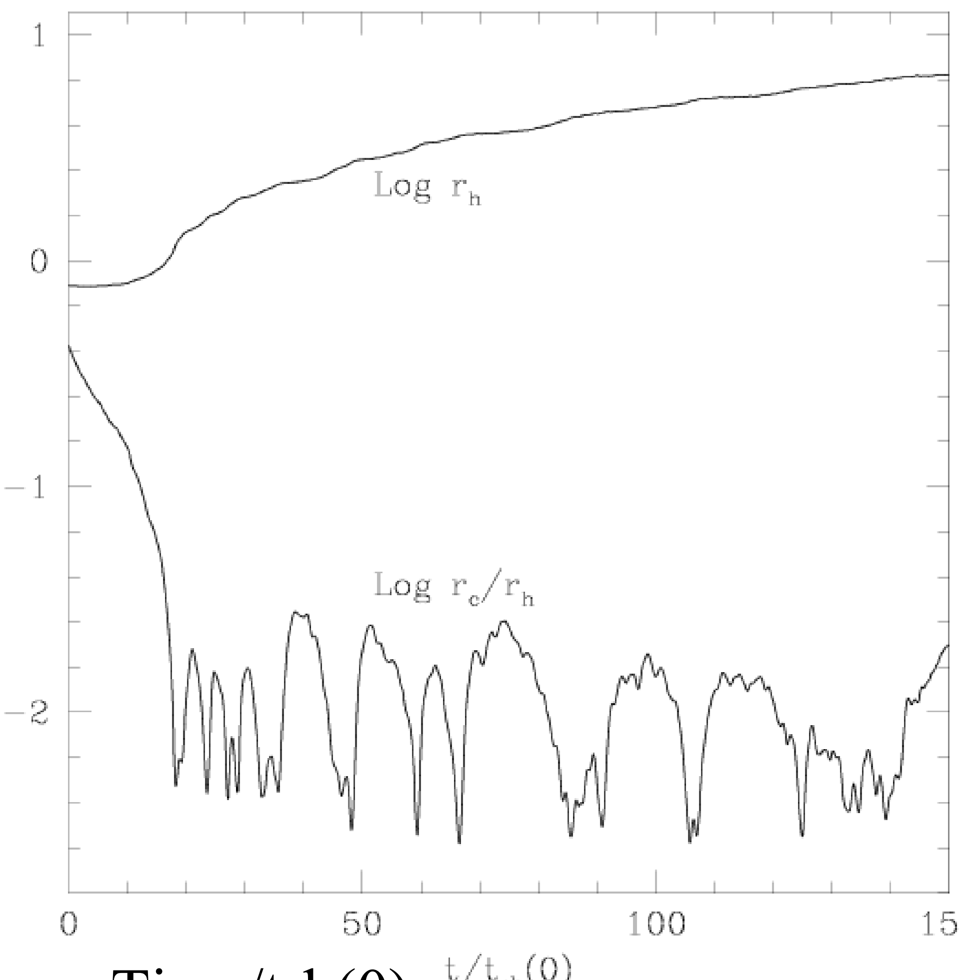
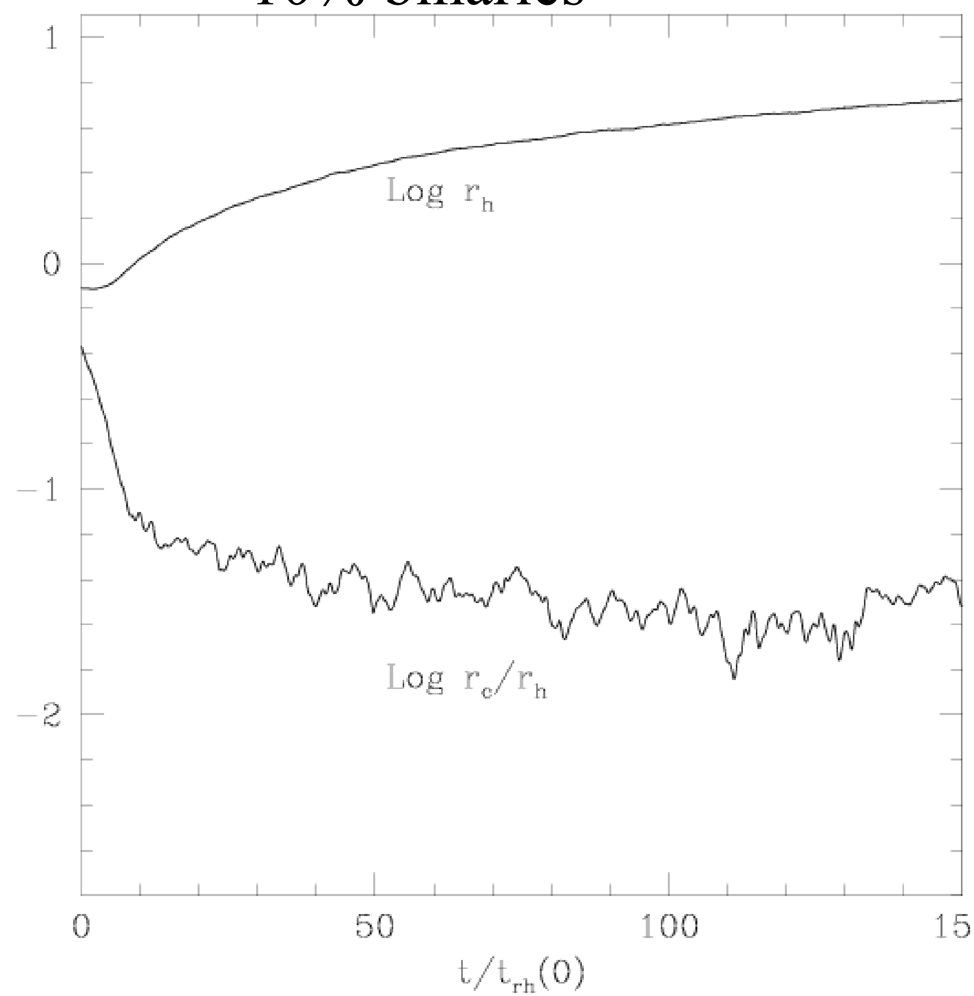
The idealised situation
No tide – equal masses

No binaries



10% binaries

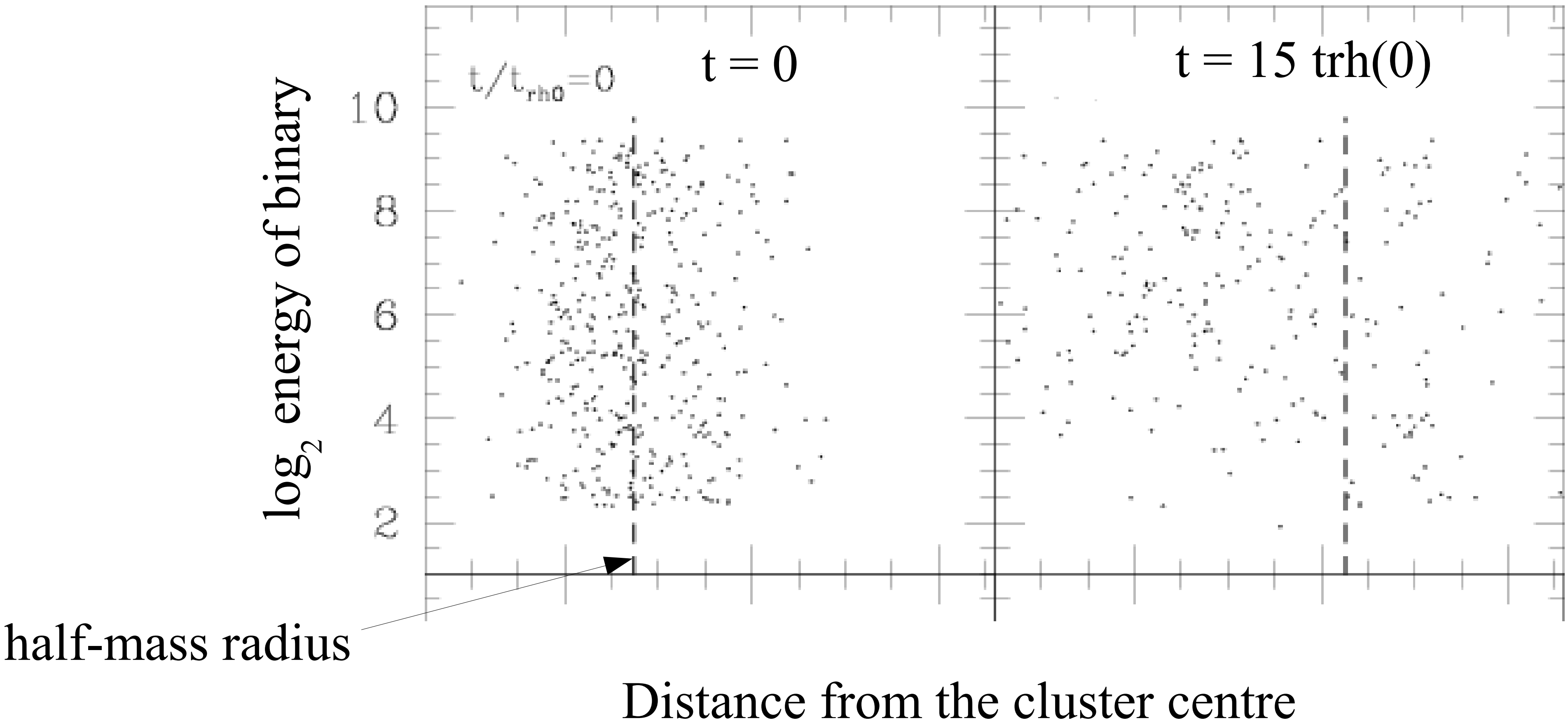


Core radius

Time/trh(0)

Trenti et al, MNRAS, soon to be accepted, I hope

No tide – equal masses (continued)



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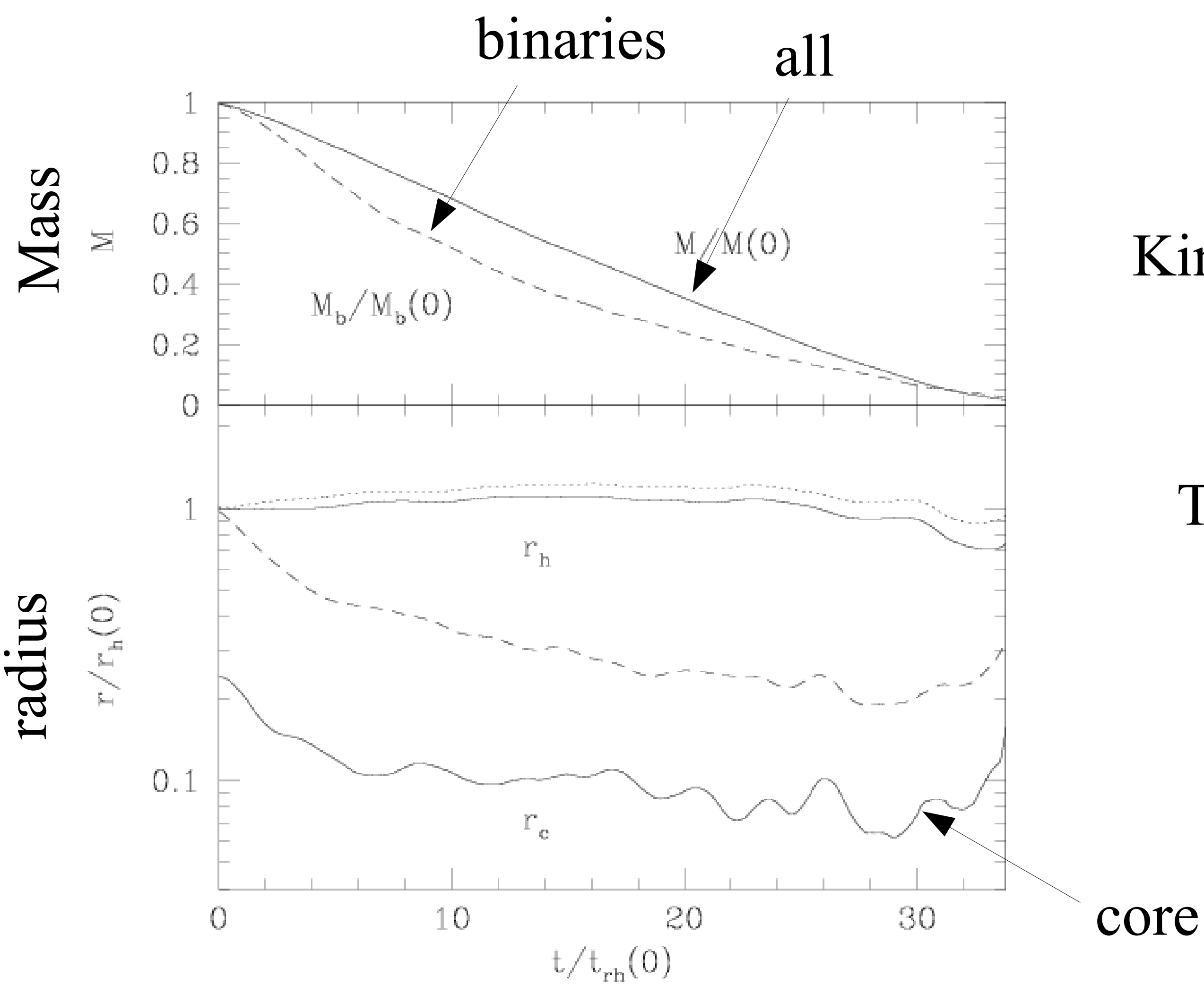
Effect of a tide



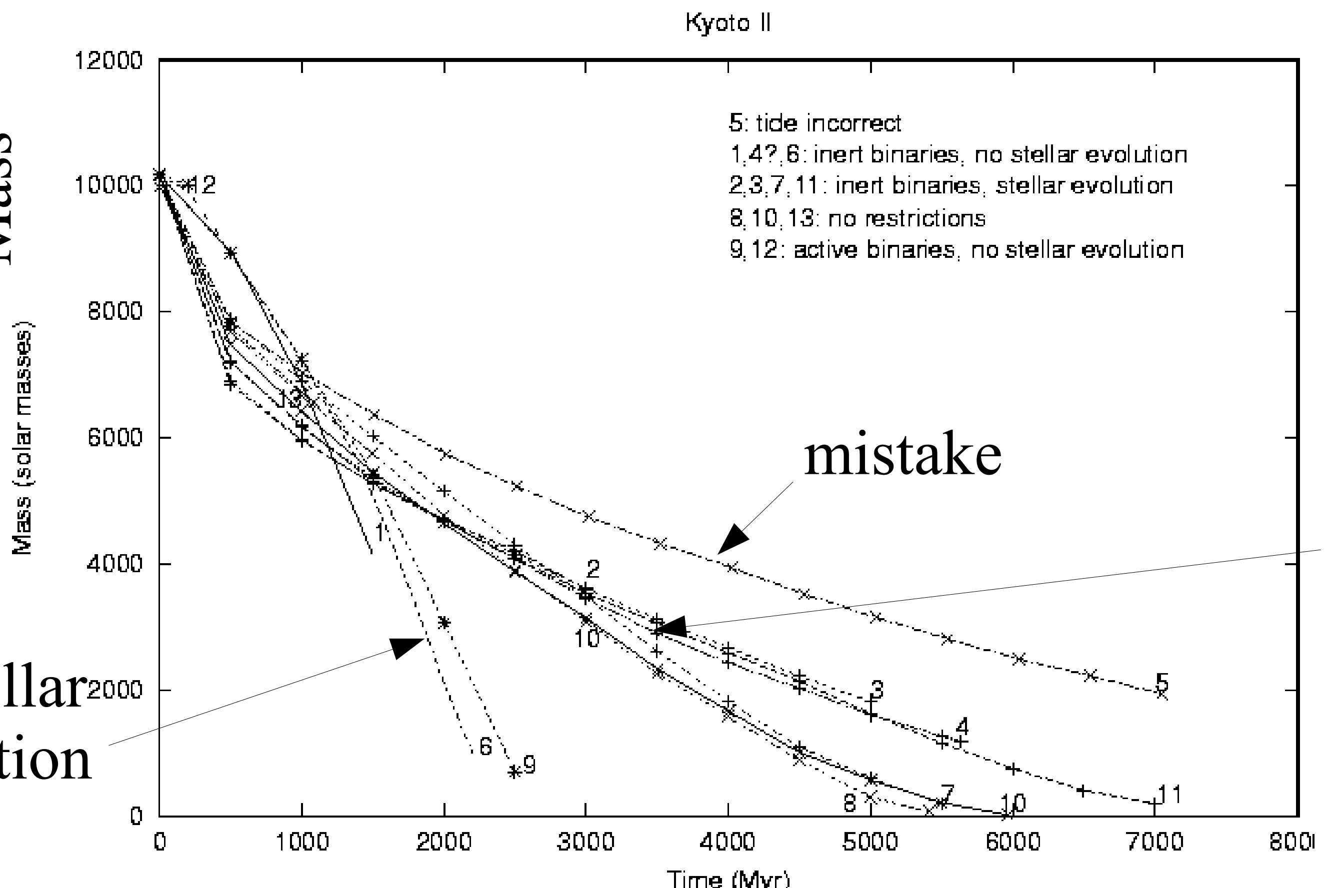
t/trh(0)

King, W_0 =3, 10% binaries

Trenti et al, in preparation

The effect of a mass function and stellar evolution

Mass



mistake

inert/active binaries and stellar evolution

no stellar evolution

Time

Kyoto II collaborative experiment

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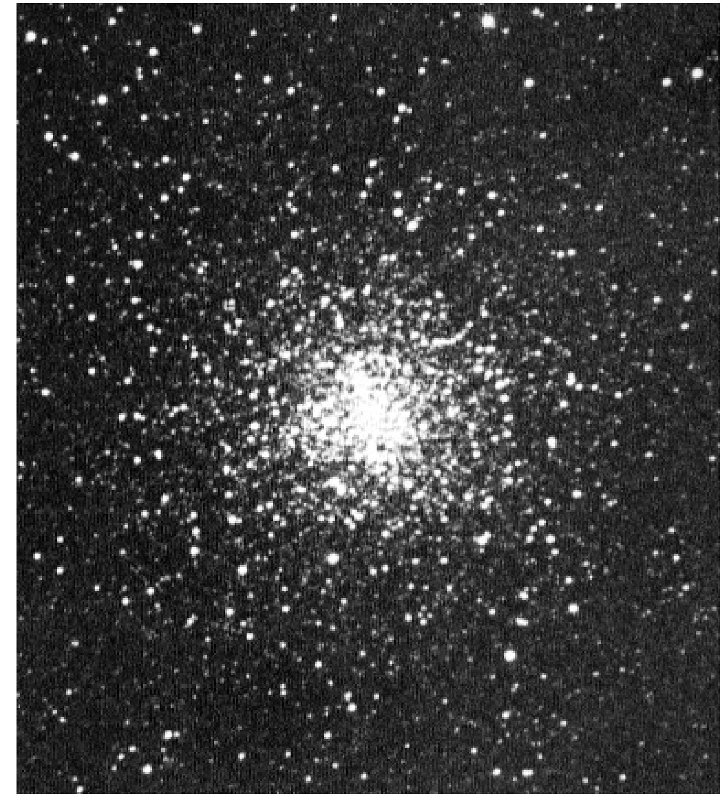
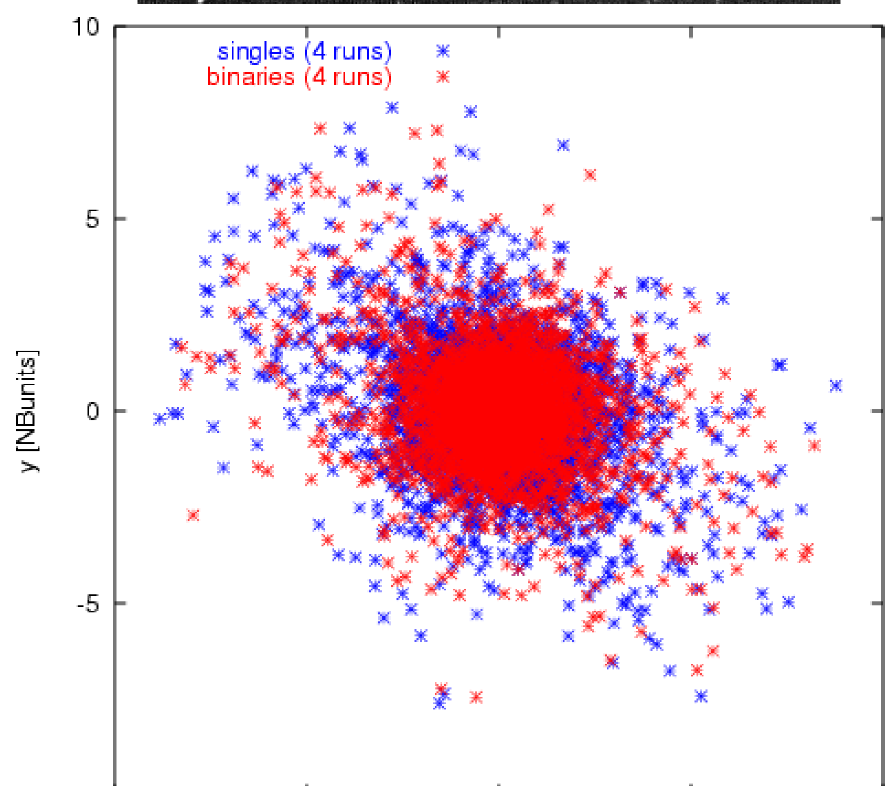
An example: a miniature M4

$W_0 = 7$
KTG mass function
50% binaries, 1-100 kT
Tidal field
Stellar evolution
$N \leq 12000$
NBODY6
Kristin Warnick (now at Potsdam)
$t_{rh}(\text{now}) \approx 600$ Myr





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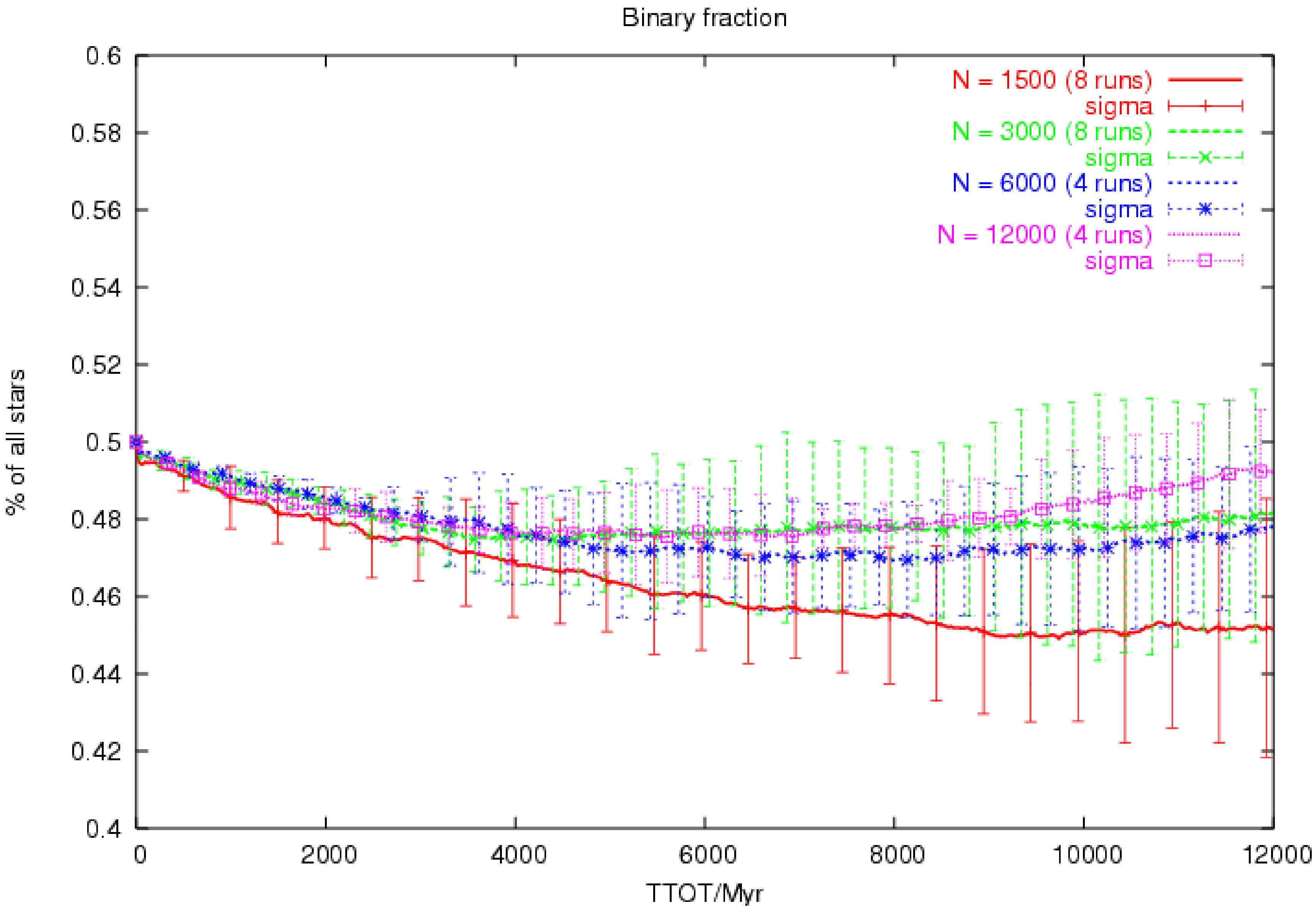
Evolution of the binary fraction



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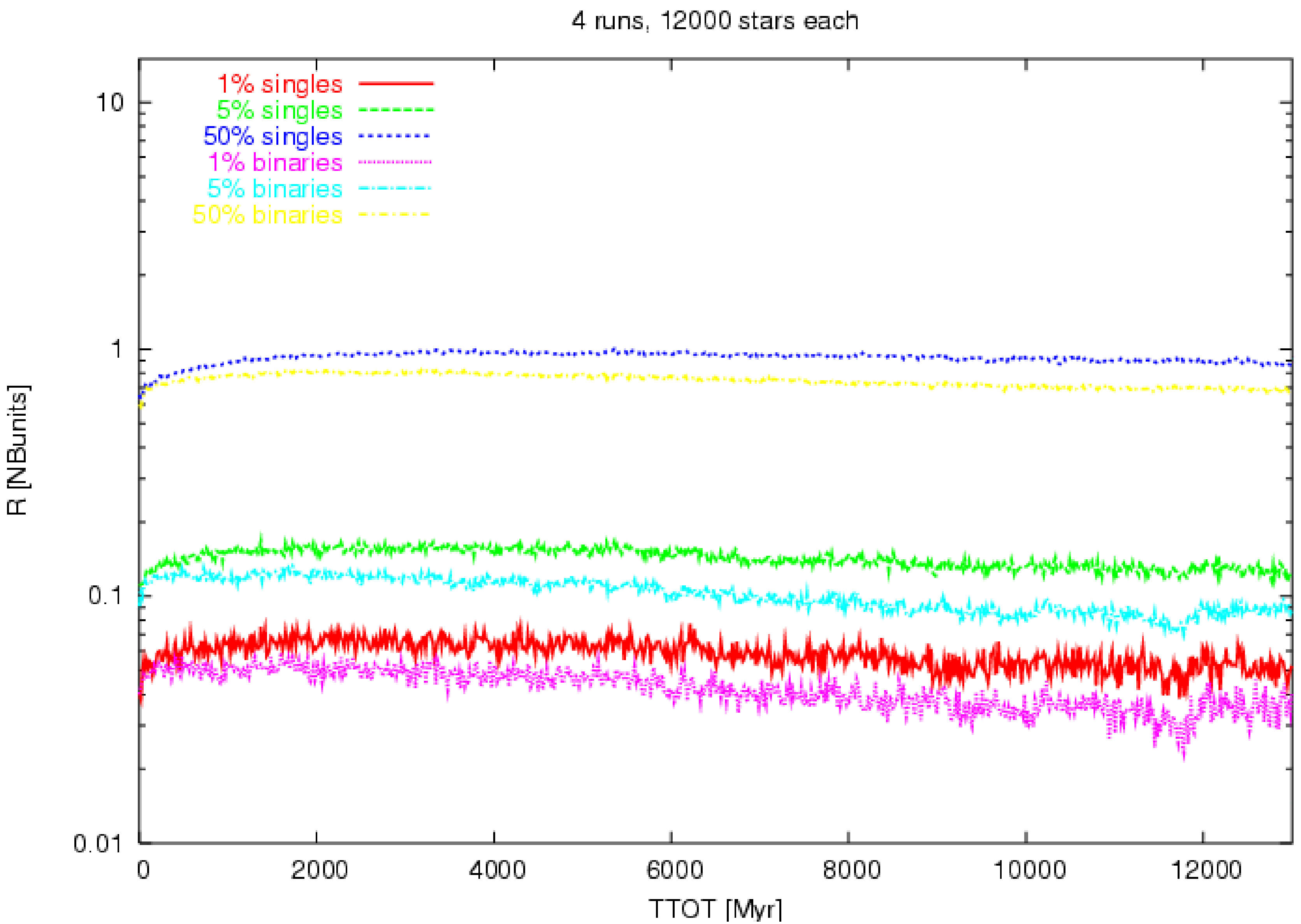
Spatial distribution by Lagrangian radius



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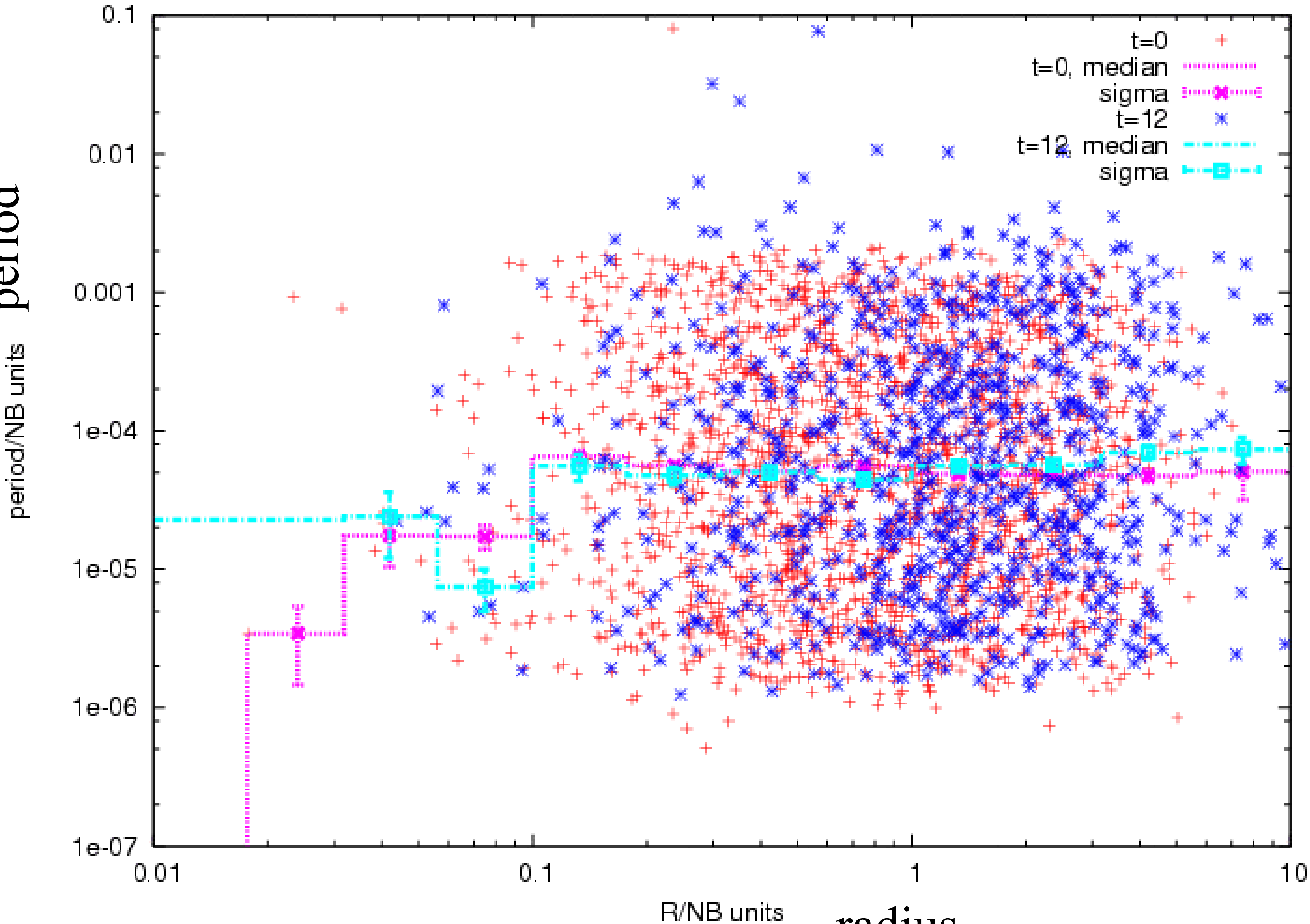
Evolution of the period distribution

period



radius

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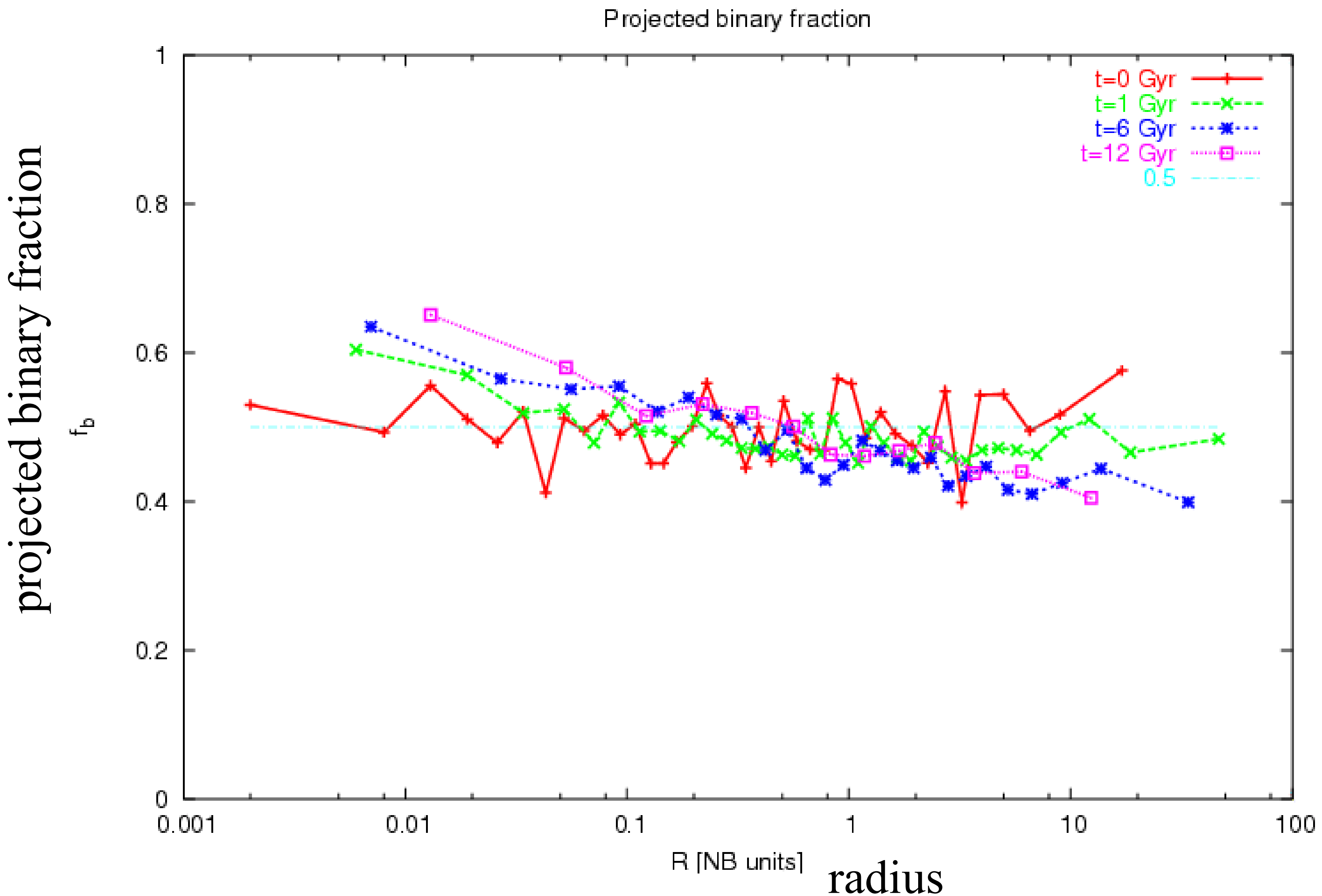
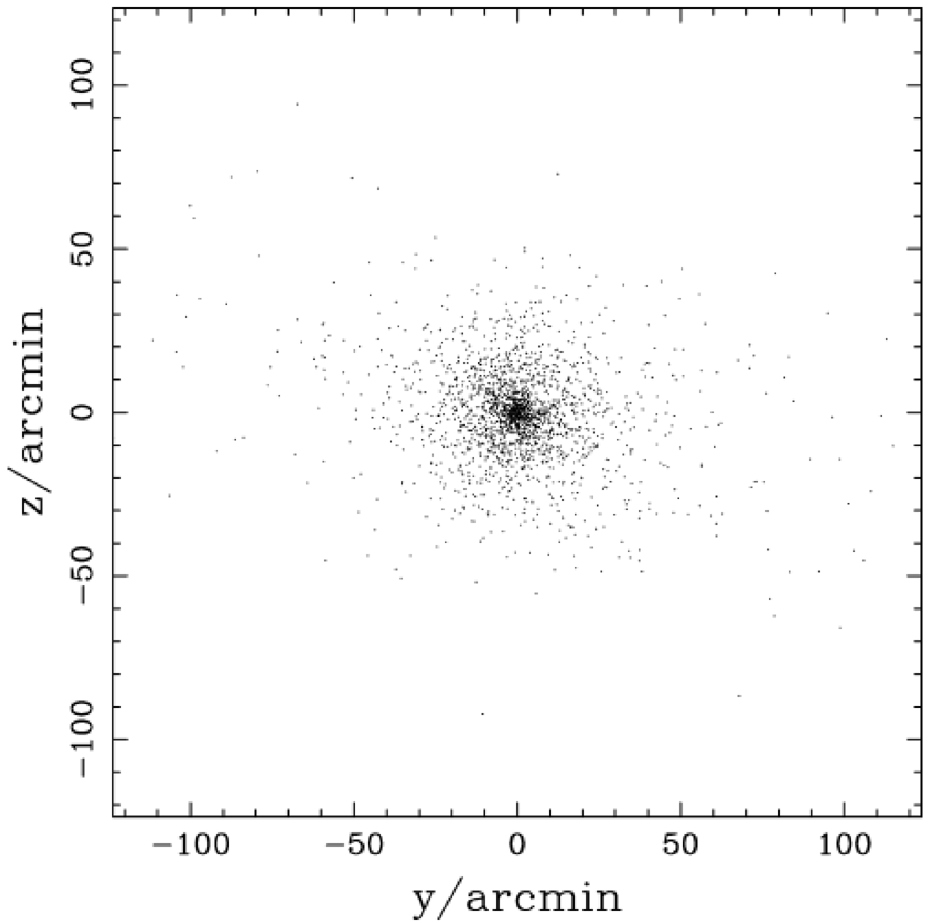
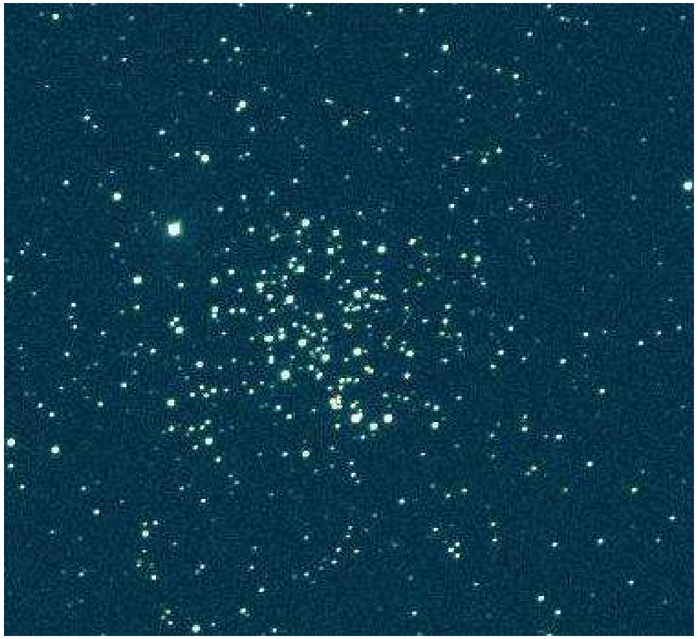
The binary fraction as function of projected radius



Kitchen-sink calculations: the example of M67

Hurley et al, 2005, MNRAS, 363, 293;
http://www.maths.ed.ac.uk/~stefan/MODEST-5a/talks/hurley.pdf





N=24000, 50% binaries

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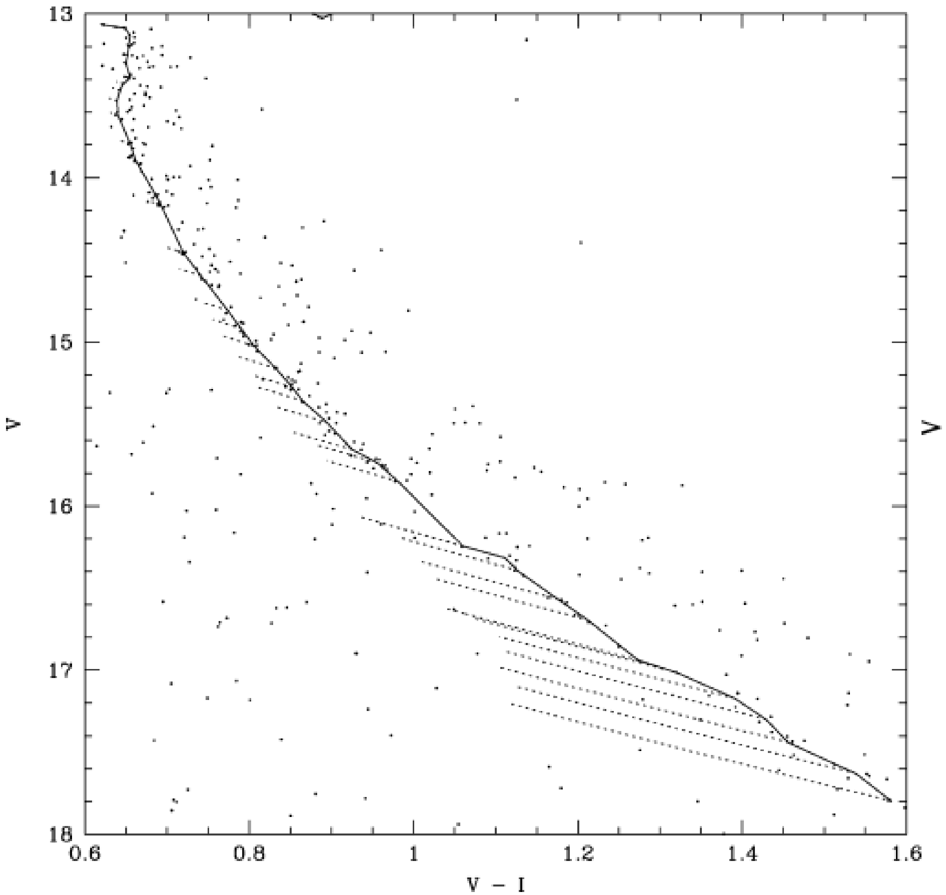
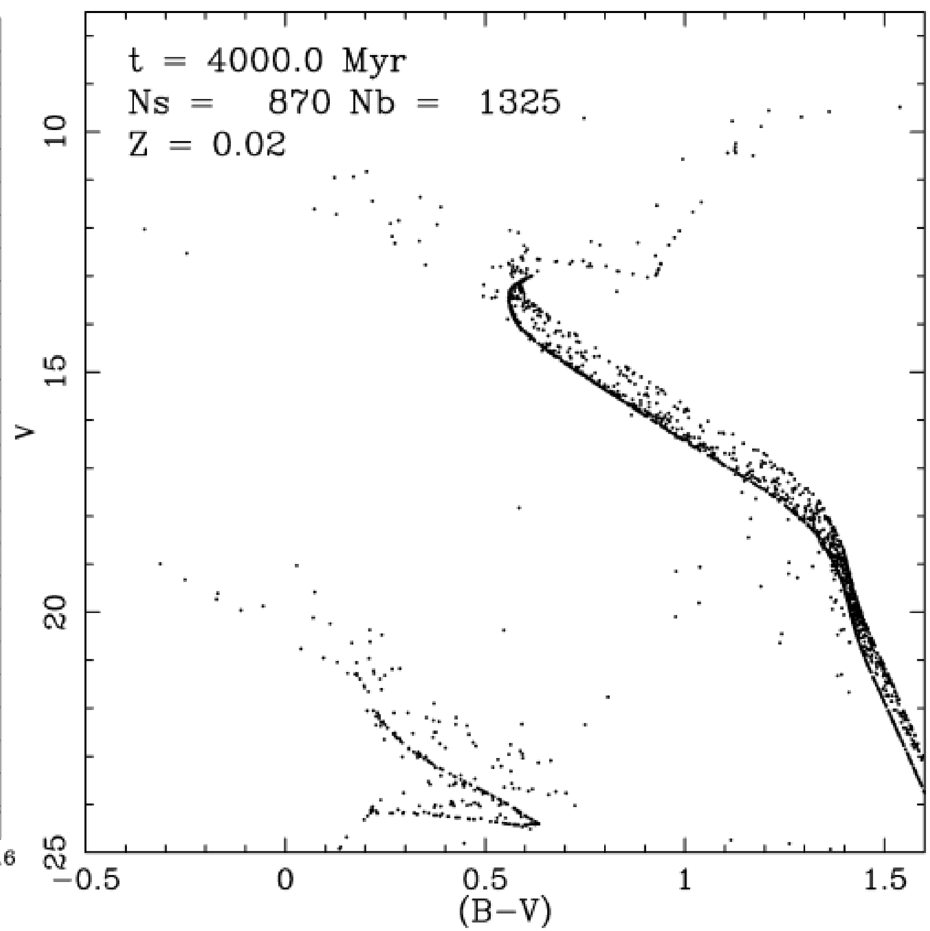
Colour-magnitude diagram





Sandquist, 2004, MNRAS, 347, 101

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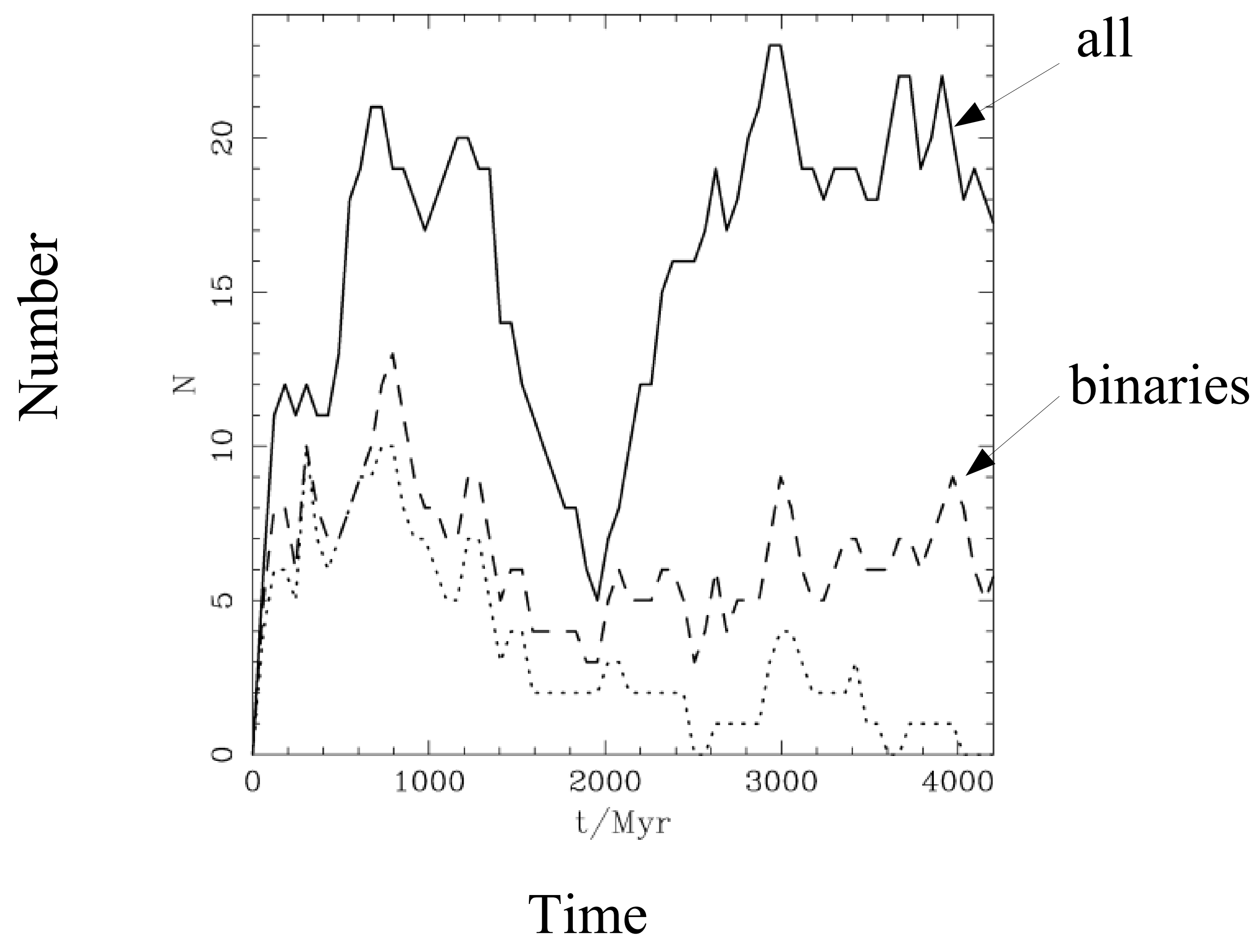
Evolution of the number of blue stragglers



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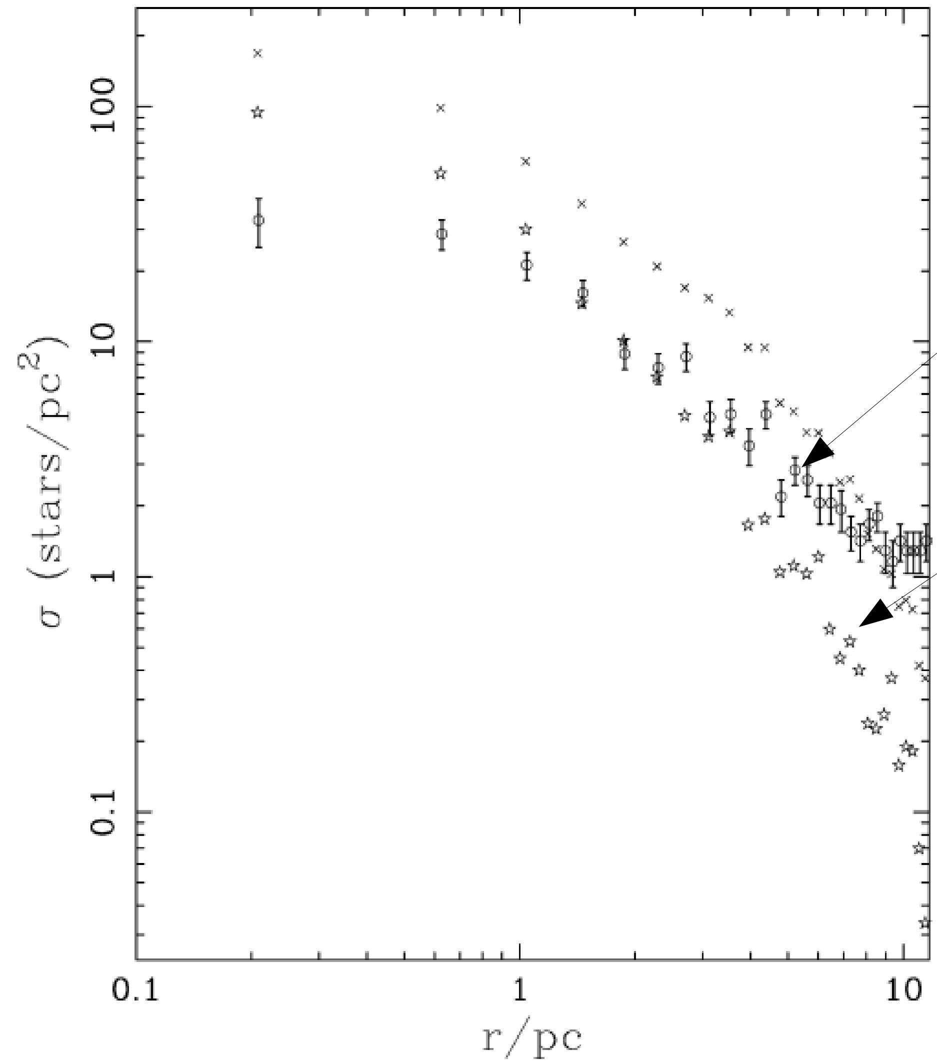
The surface density profile



SDSS data

model

surface density

radius

Where we are now

Open clusters

Kitchen-sink N-body modelling of all open star clusters is now feasible

Finding the right initial conditions is done by trial and error:
we could do better

Some basic observational data not well known

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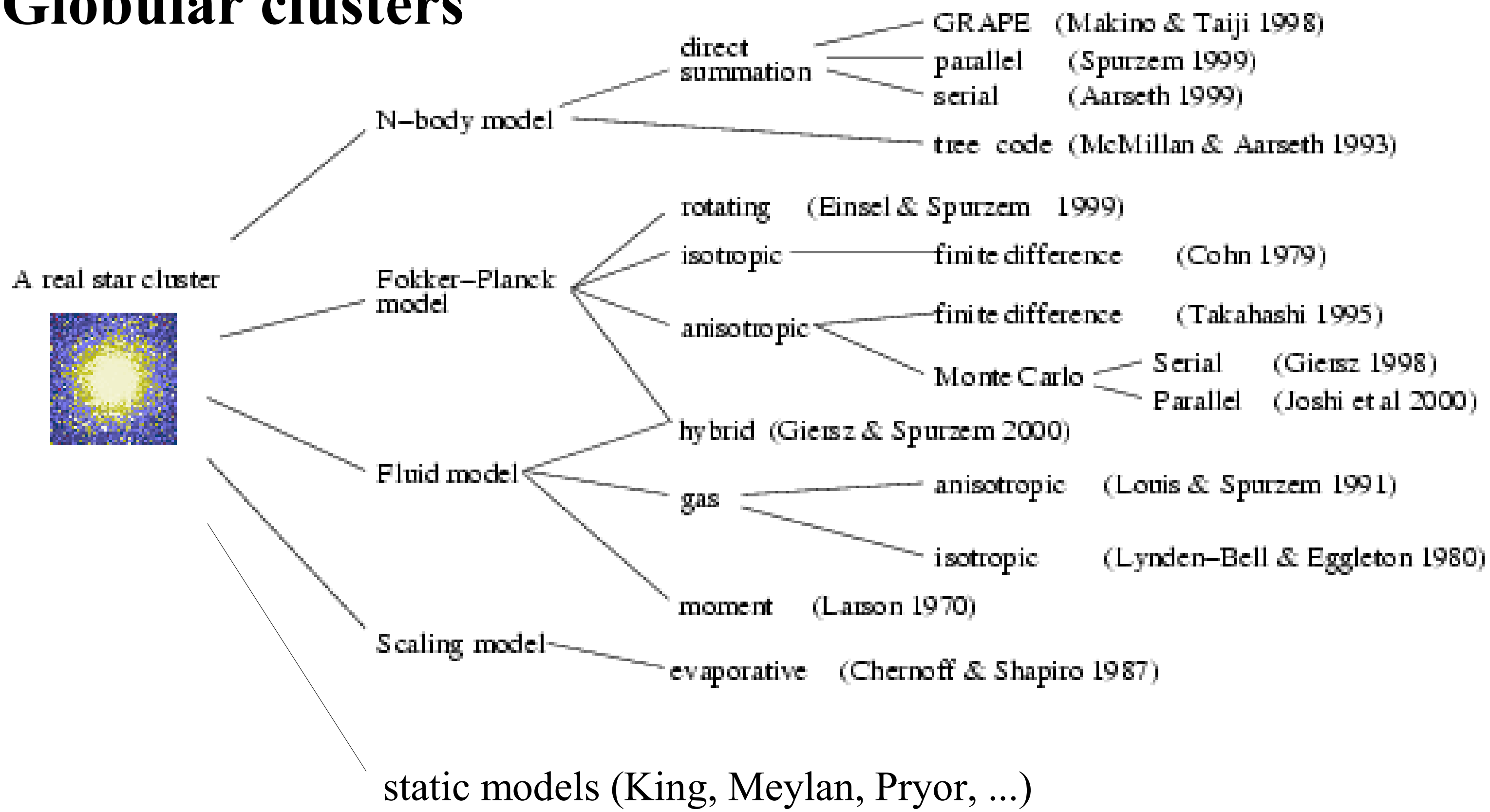
Where we are now - II

Globular clusters



We don't yet have a comparable tool for evolutionary modelling of globular clusters, even non-rotating ones

Finding the right initial conditions is done by trial and error: we could do better