Dynamical Evolution of Star Clusters with Varying IMF

Hosein Haghi

Institute for Advanced Studies in Basic Sciences (IASBS)-Zanjan, Iran

IPM, Spring Conference 2020

My research interests focus on

- **Dark Matter Problem:** Alternative theories of gravity, Modelling of dwarf galaxies, Rotation Curves of spirals, …

- **The Stellar Populations and Dynamics:**
  Nbody models of globular clusters

The dissolution rate of star clusters born with a top-heavy IMF

H. HAGHI,[1] G. SAFAEI,[1] A. H. ZONOOZI,[1] AND P. KROUPA[2,3]

[1]*Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan 45137-66731, Iran*

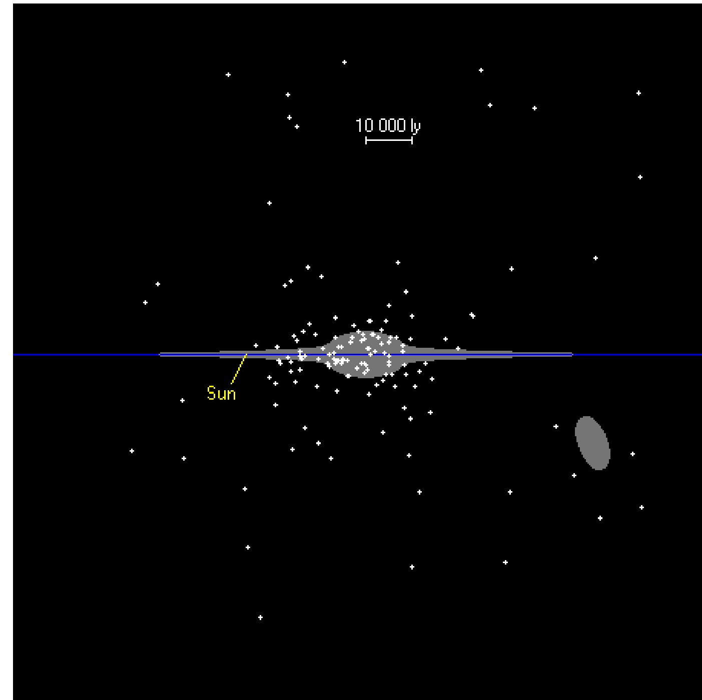
[2]*Helmholtz-Institut für Strahlen-und Kernphysik (HISKP), Universität Bonn, Rheienische Friedrich-Wilhelms Universität Nussallee 14-16, Bonn, D-53115, Germany*

[3]*Charles University in Prague, Faculty of Mathematics and Physics, Astronomical Institute, V Holesovickach 2, CZ-180 00 Praha 8, Czech Republic*

(Received .....; Revised .....; Accepted ....)

Submitted to ApJ

Globular clusters (GCs)



Median mass $\sim 3 \times 10^5 M_\odot$

Median Size: ~ 3 pc

ages ~ 10 – 12 Gyr

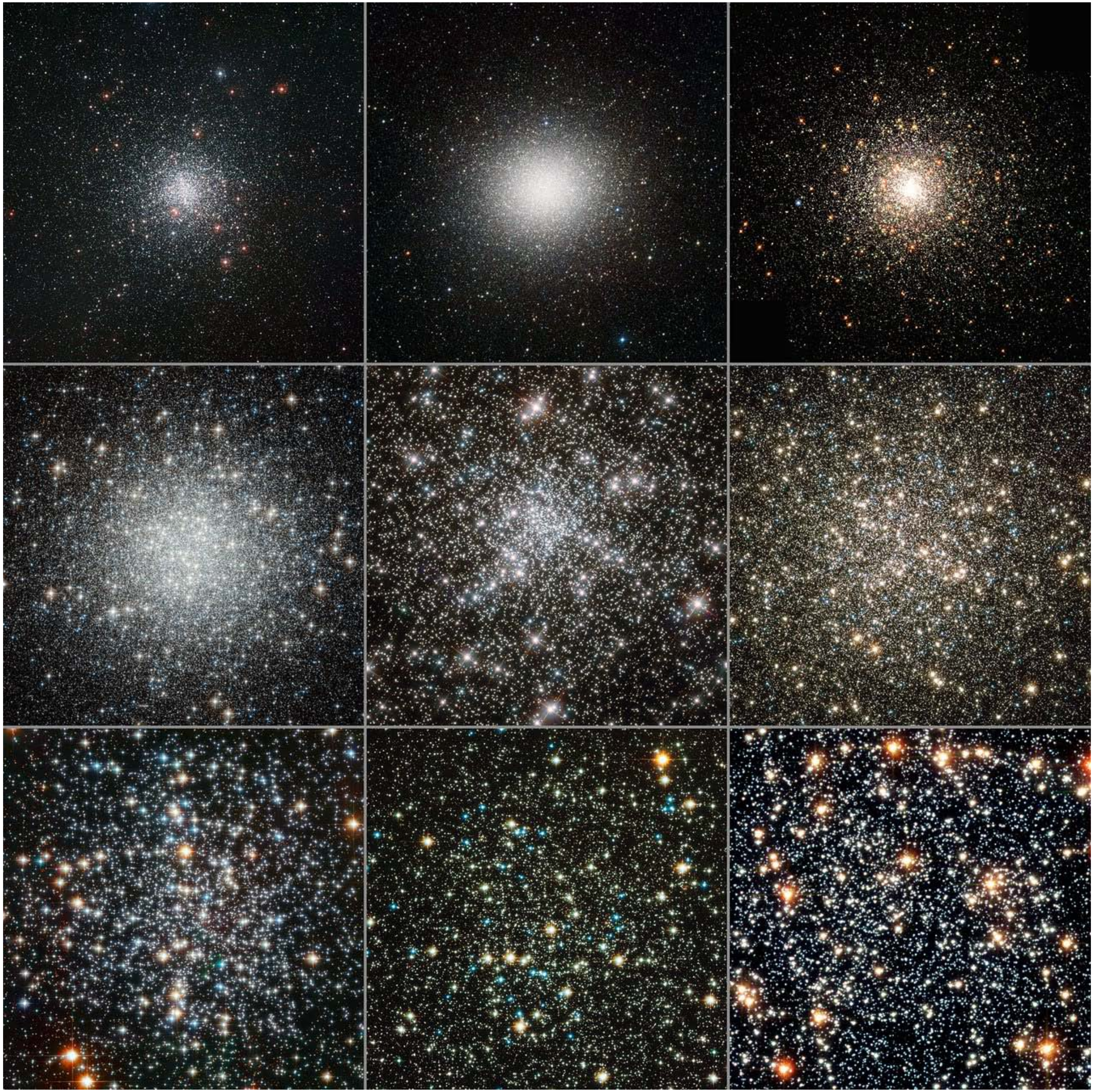
✓160 Milky Way satellites classified as GCs

✓They are distributed out to more than 100 kpc

✓Classical view: Contain coeval stars **??????**

✓ Multi-populations: age spread

✓Gas/dust-free systems.



Why GCs are important?

- Star formation and evolution
- Galaxy formation and evolution
- A perfect laboratory to explore the effects of 2-body encounters

Dynamic Evolutionary modeling of GCs

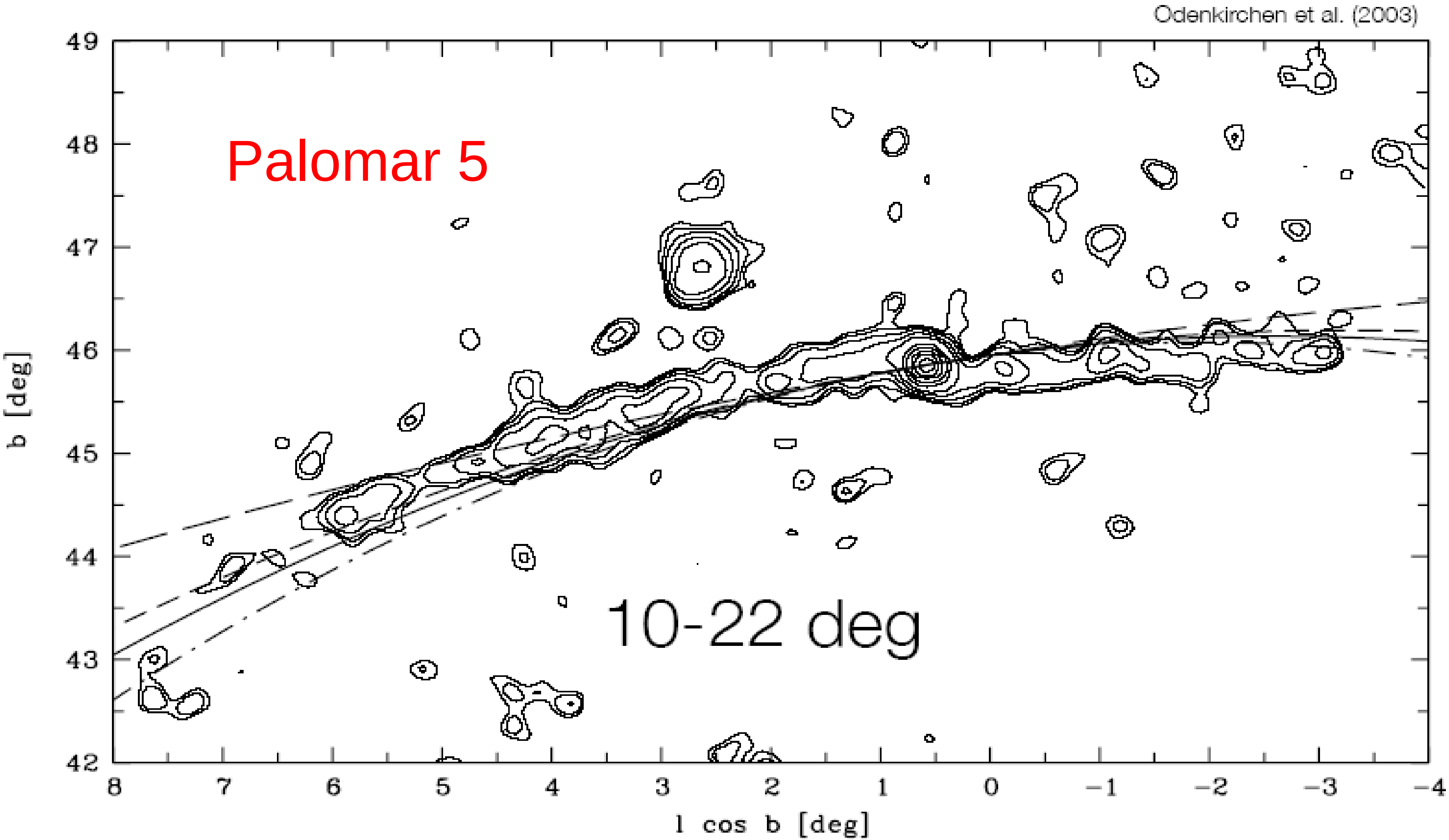
- Until the late 1970s, GCs were thought of to be relatively static stellar systems: fitted with equilibrium models like King (1966) profiles. This view has changed significantly over the last thirty years:

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



Dynamic Evolutionary modelling 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:

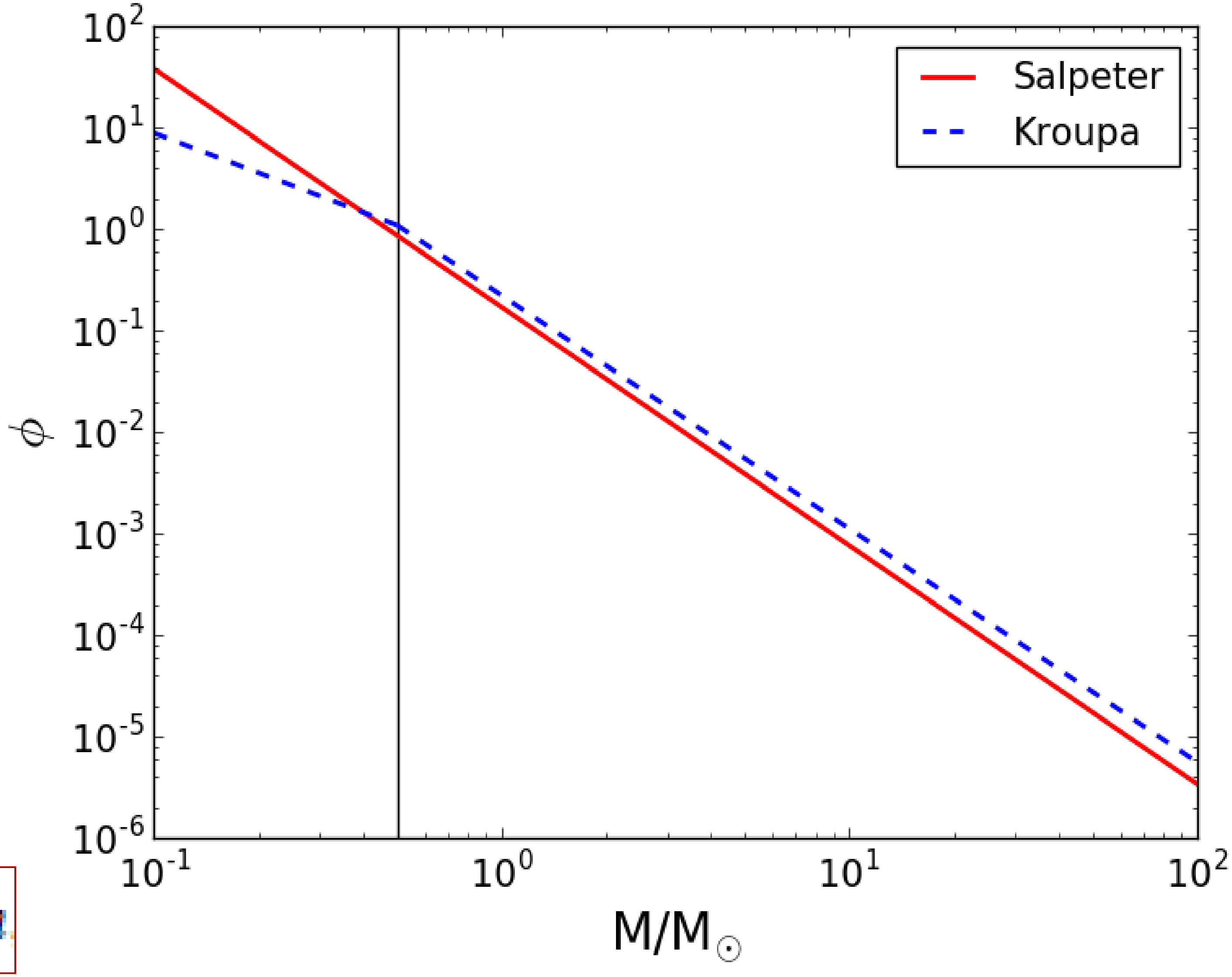
On the observational side:

Strong indications for the ongoing dynamical evolution:

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

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

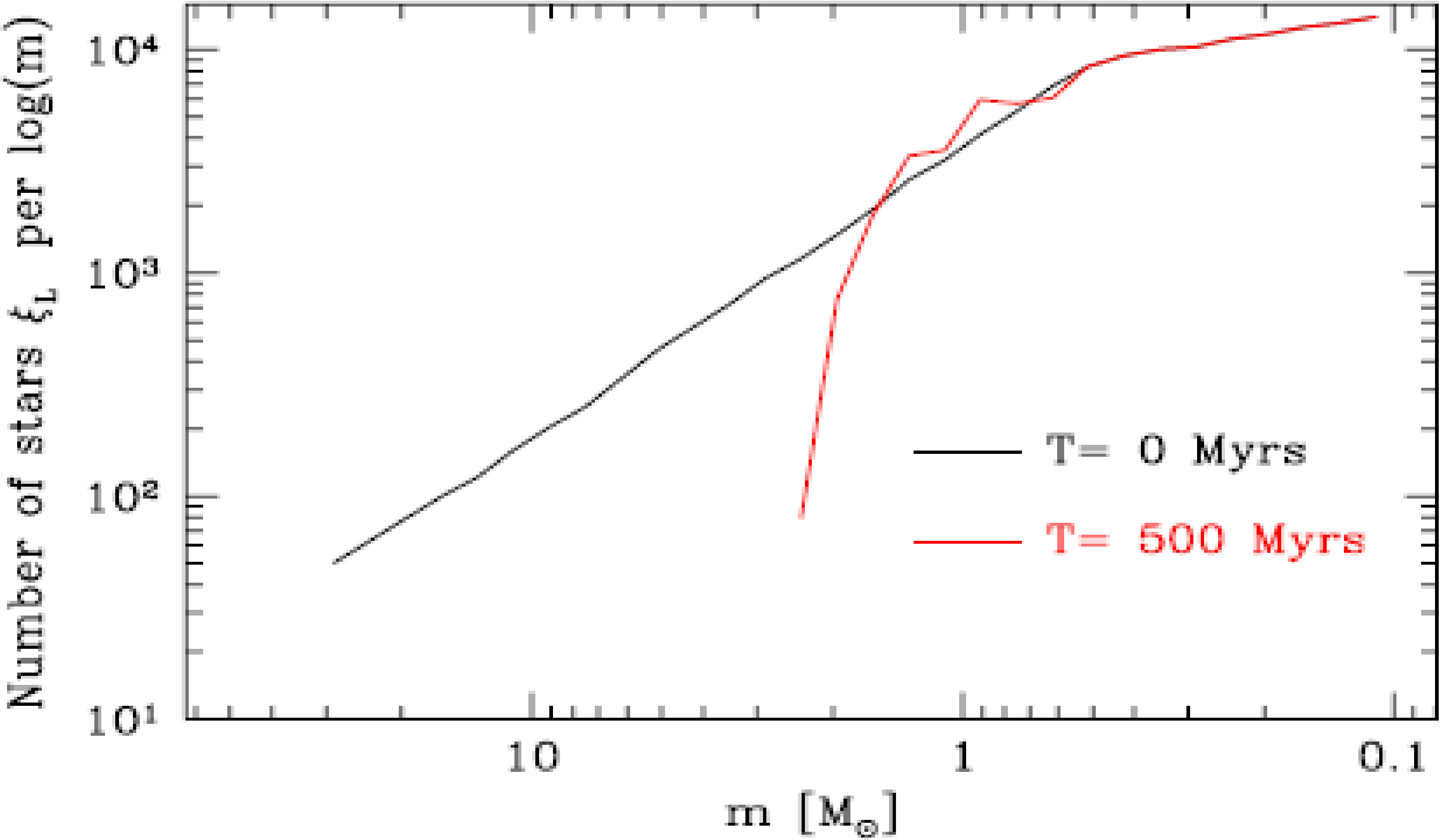
Stellar Initial Mass Function (IMF)



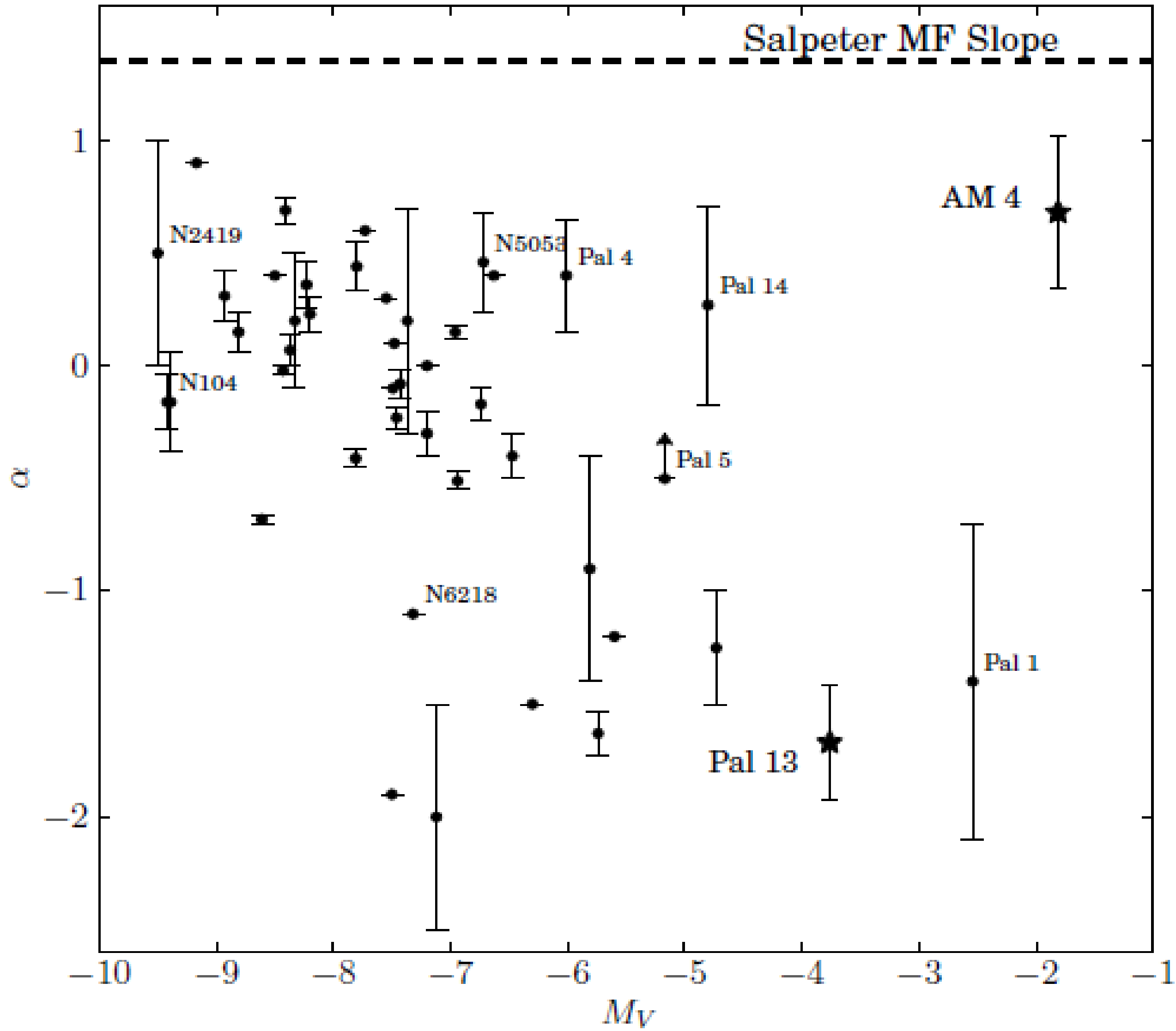
$$dN = \xi(m)dm$$

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

Dynamic Evolutionary modelling 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)

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

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.

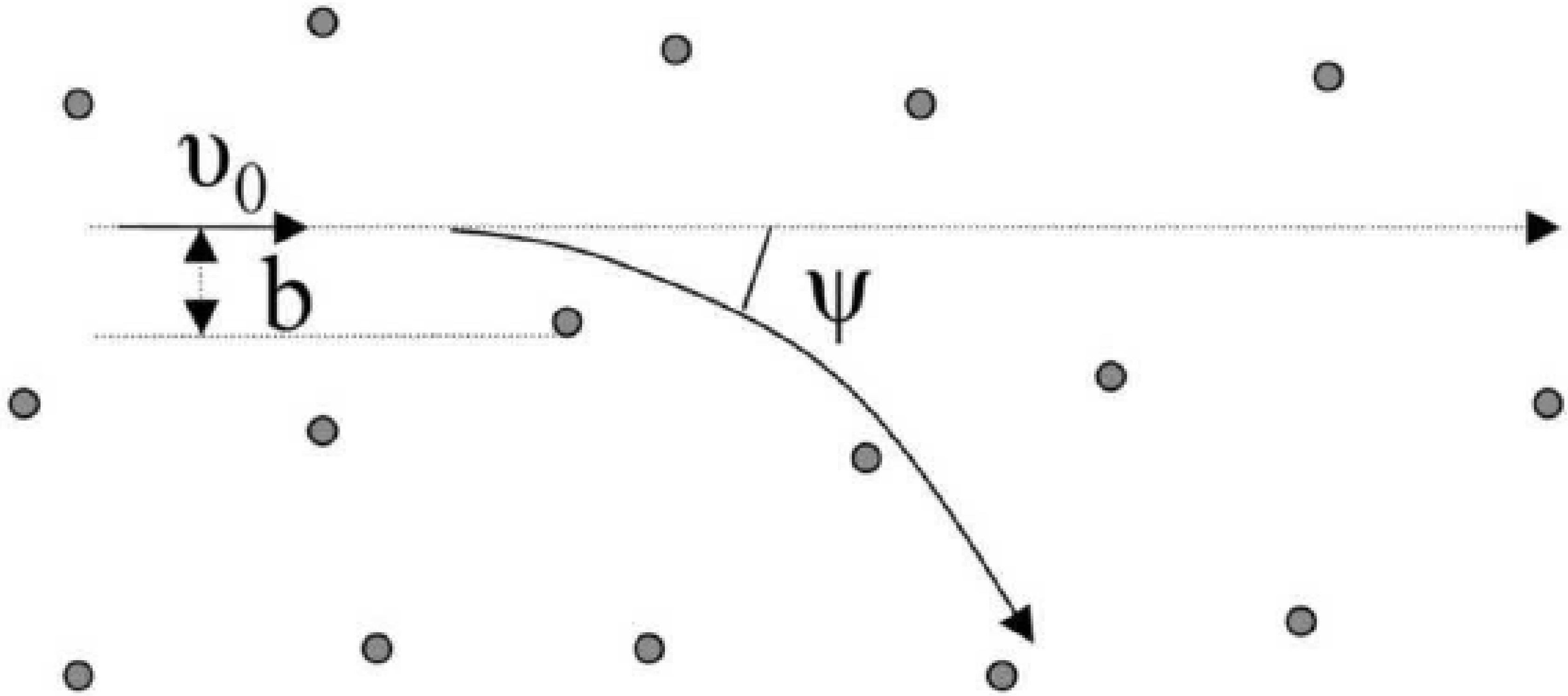
GCs are collisional systems

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

2-body Relaxation

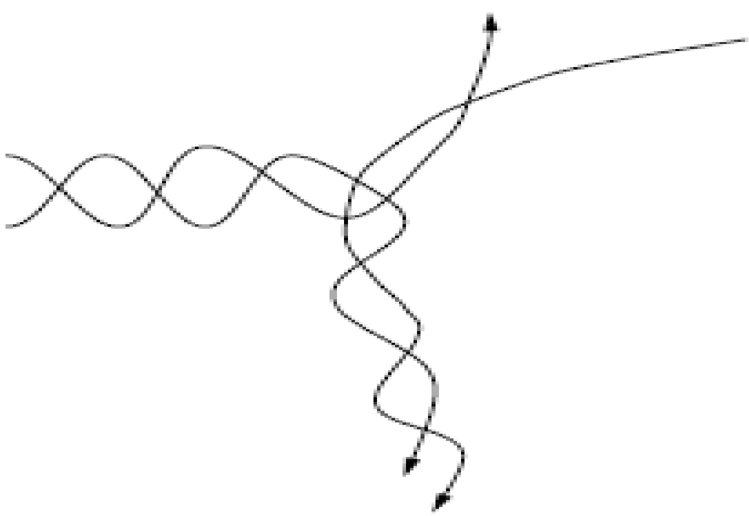


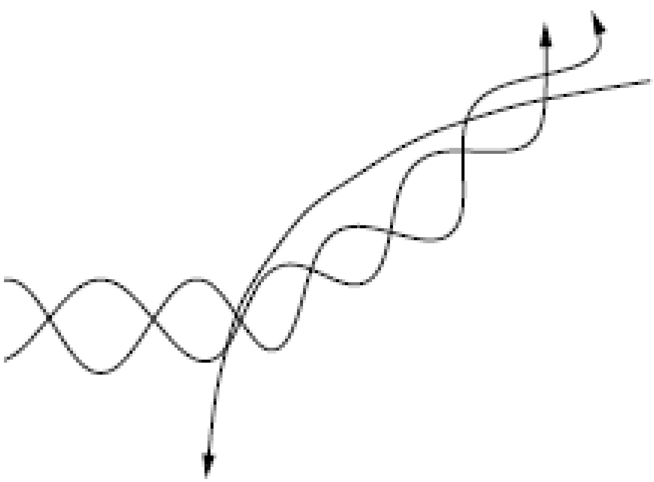
$$t_{\text{relax}} \approx \frac{2 \times 10^9\ \text{yr}}{\ln \Lambda} \left(\frac{V}{10\,\text{km}\,\text{s}^{-1}} \right)^3 \left(\frac{m}{\mathcal{M}_\odot} \right)^{-2} \left(\frac{n}{10^3\,\text{pc}^{-3}} \right)^{-1}$$

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

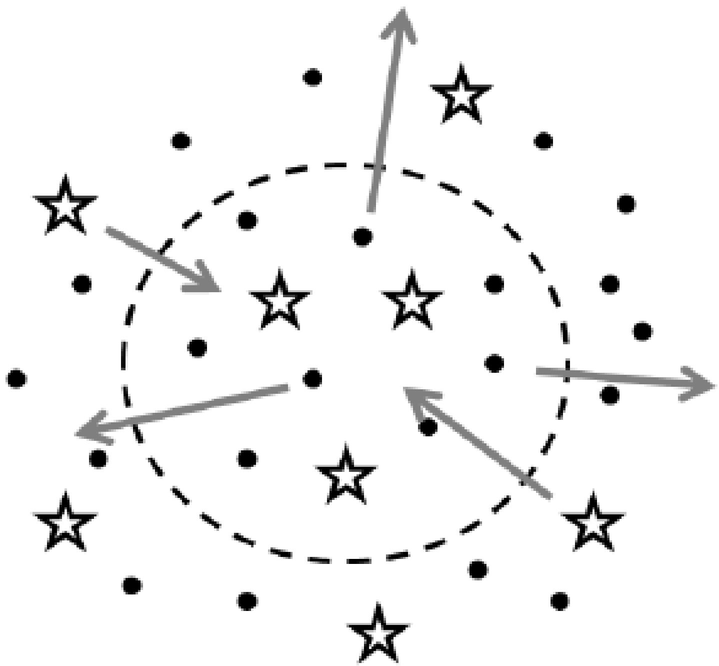
E_{bin} / kT_c



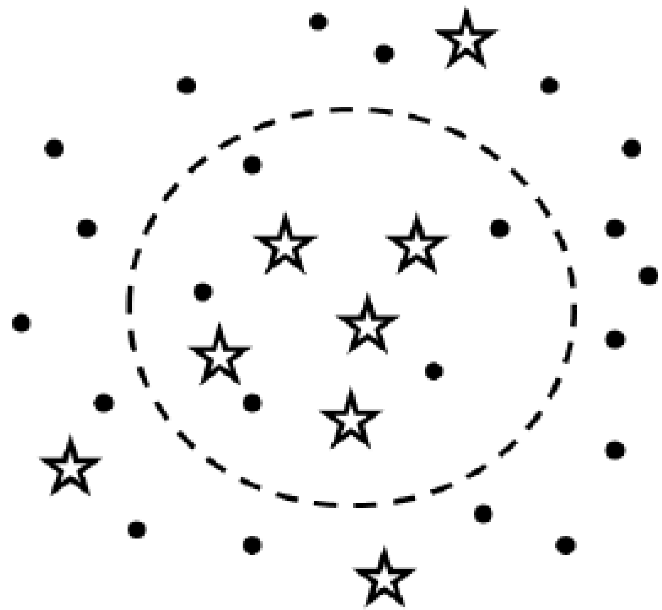


Dynamical Mass Segregation

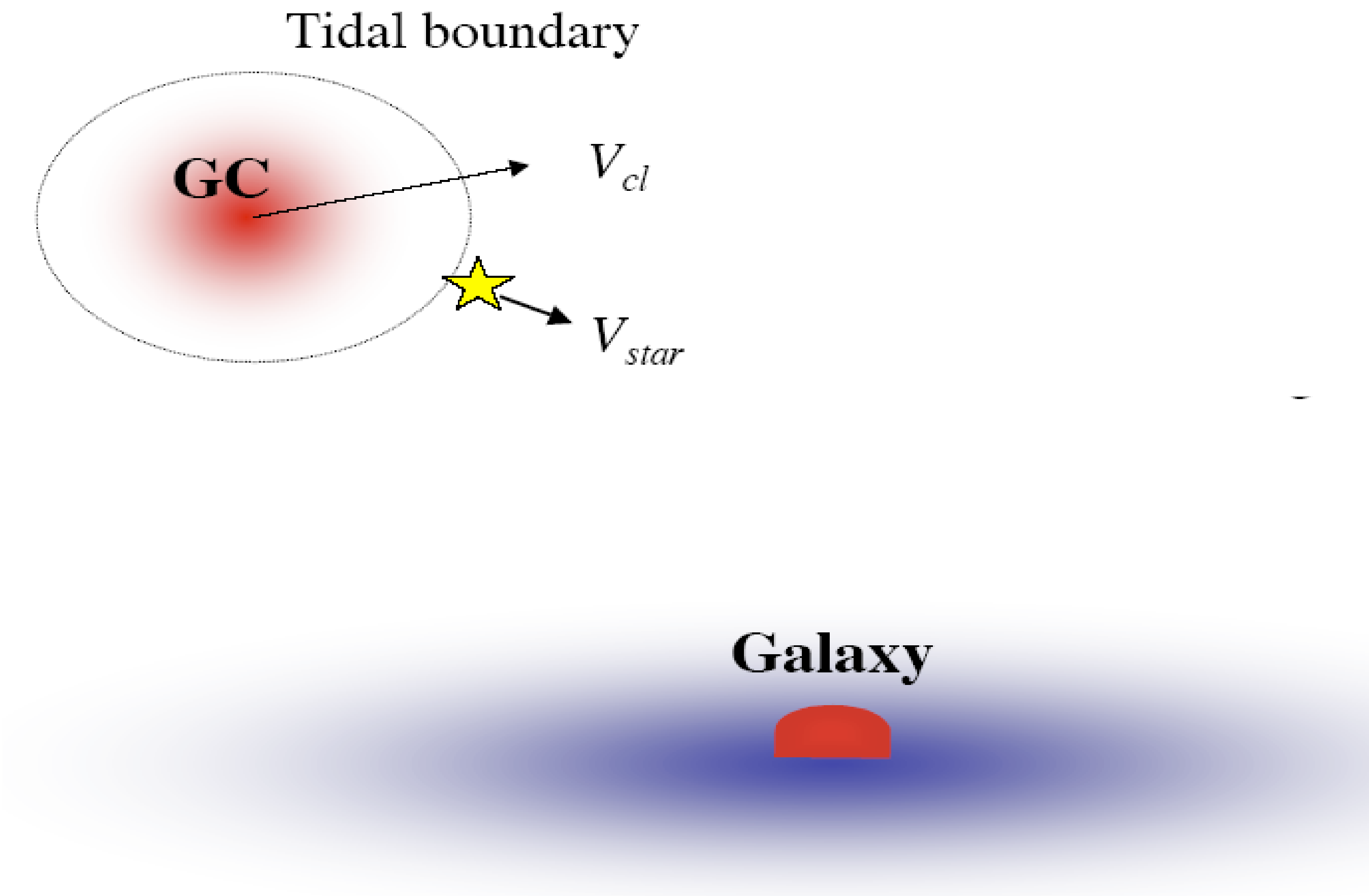
Energy equipartition



t = 0

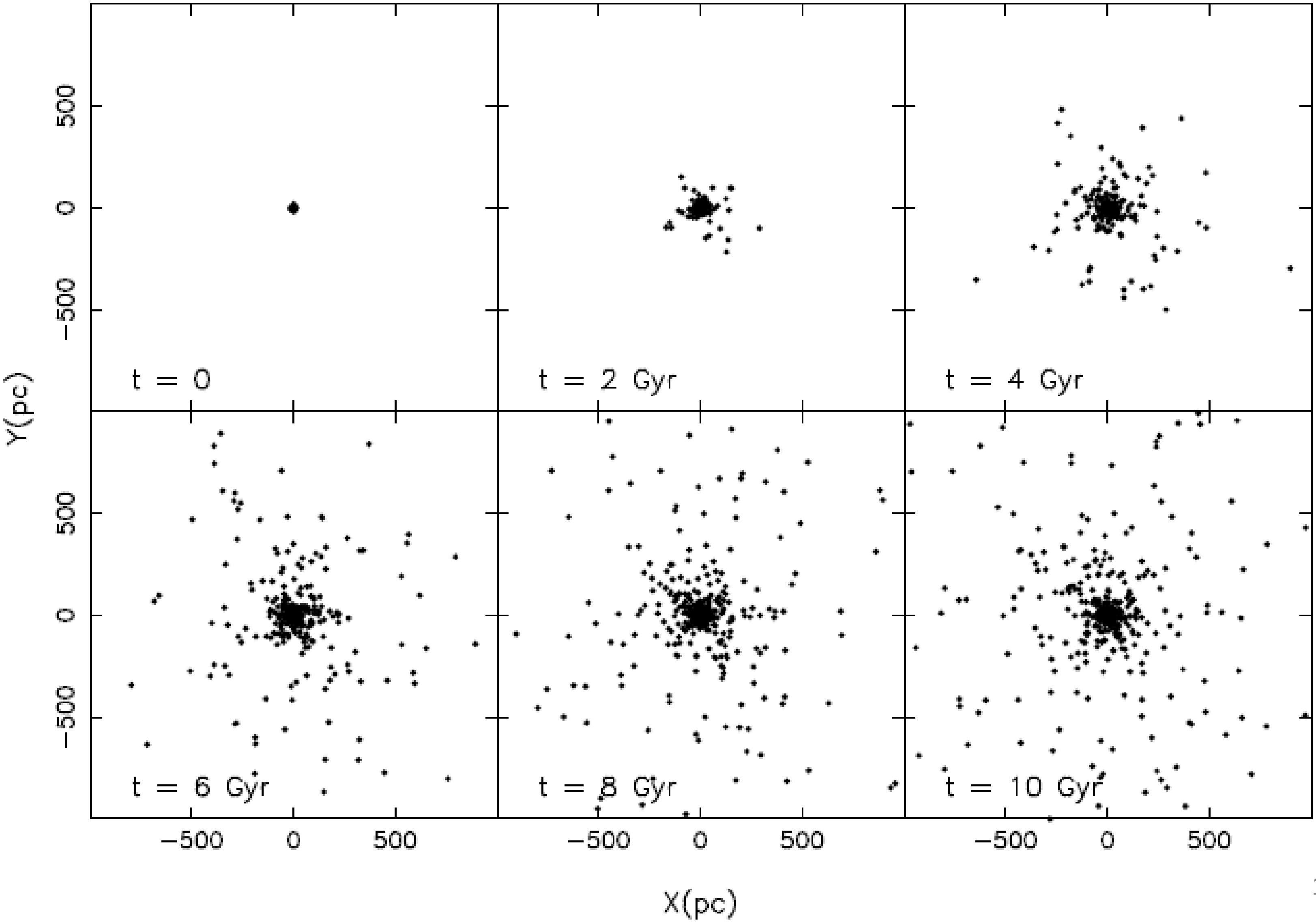


Star cluster modelling

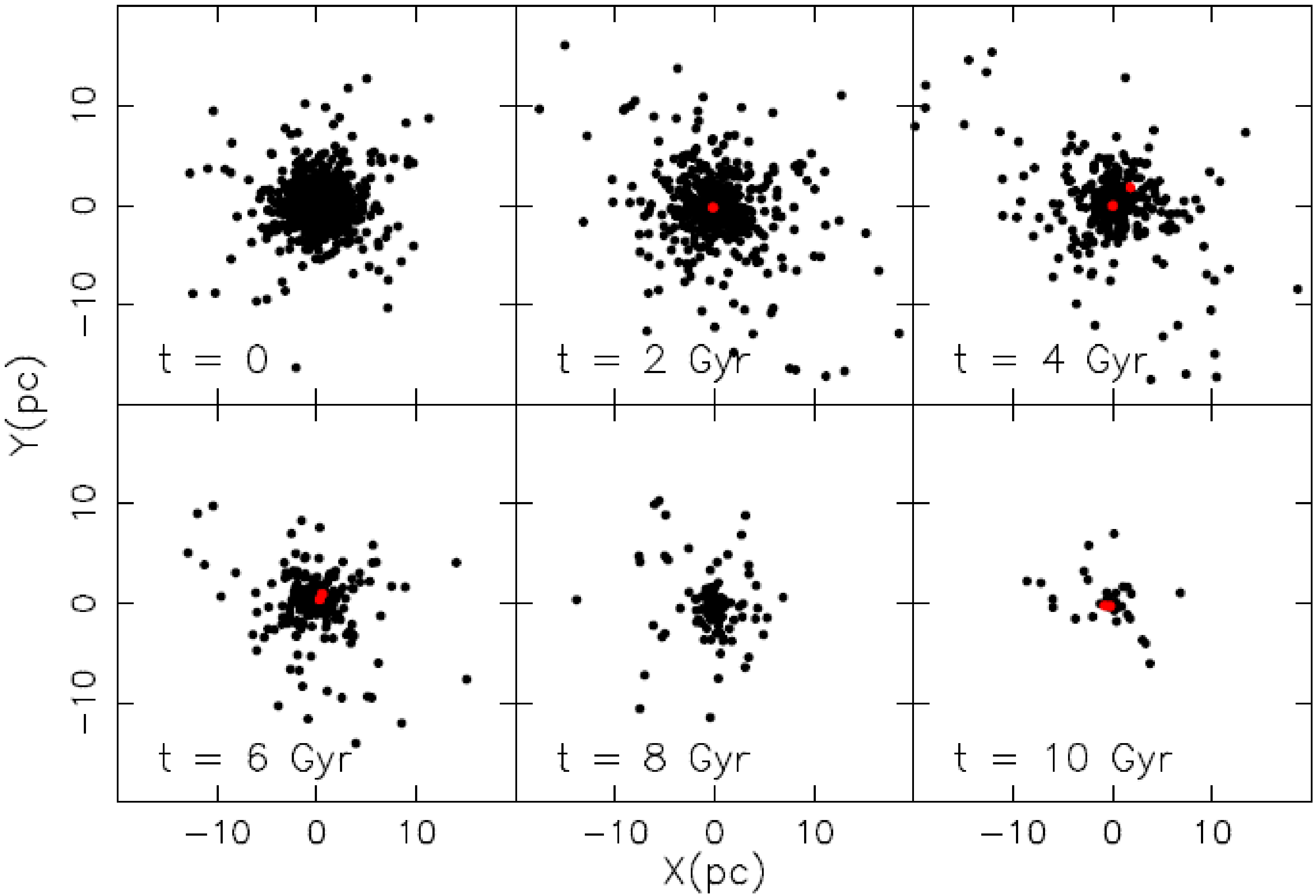


Isolated cluster

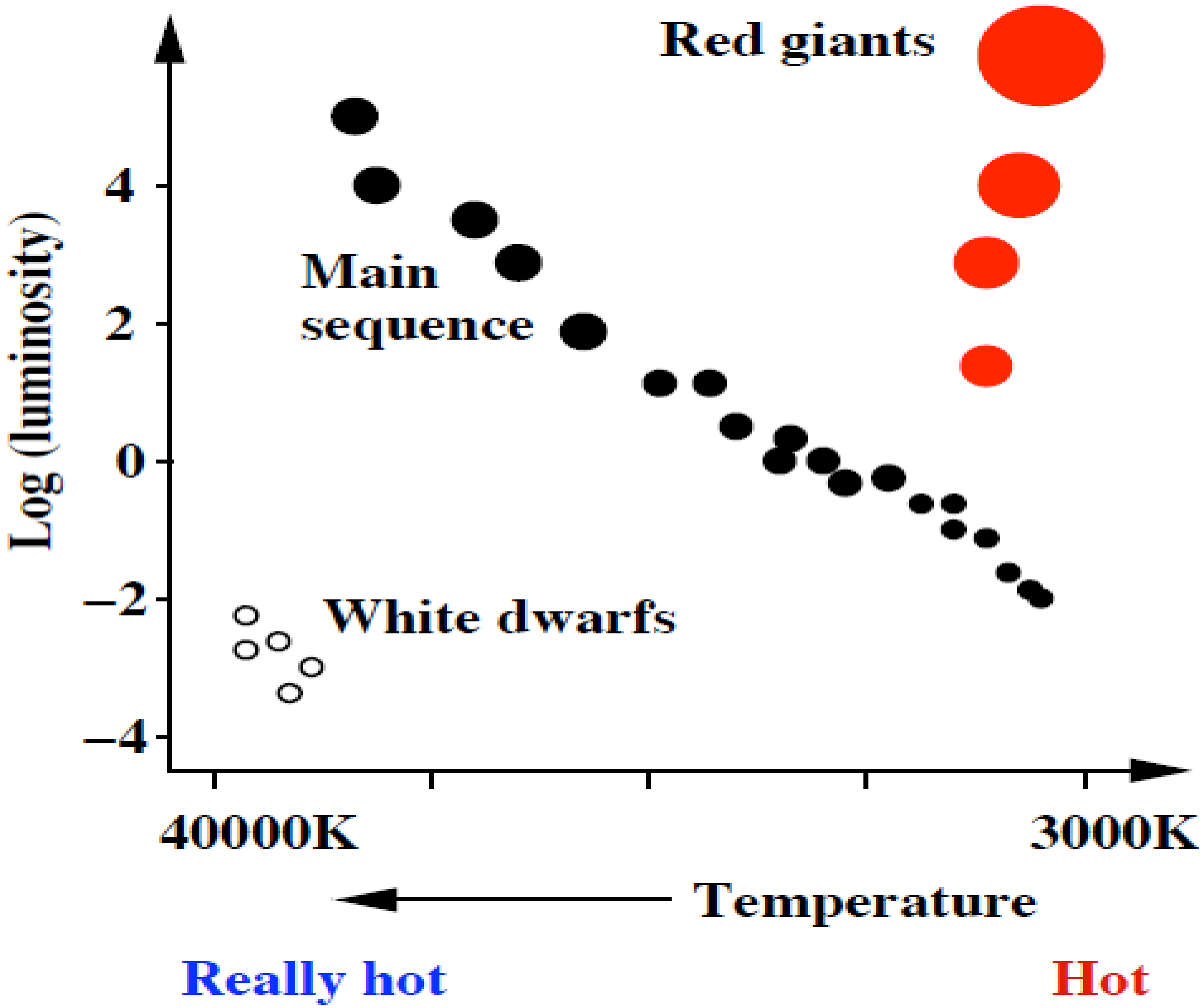
N=1000 equal mass, No Stellar Evolution



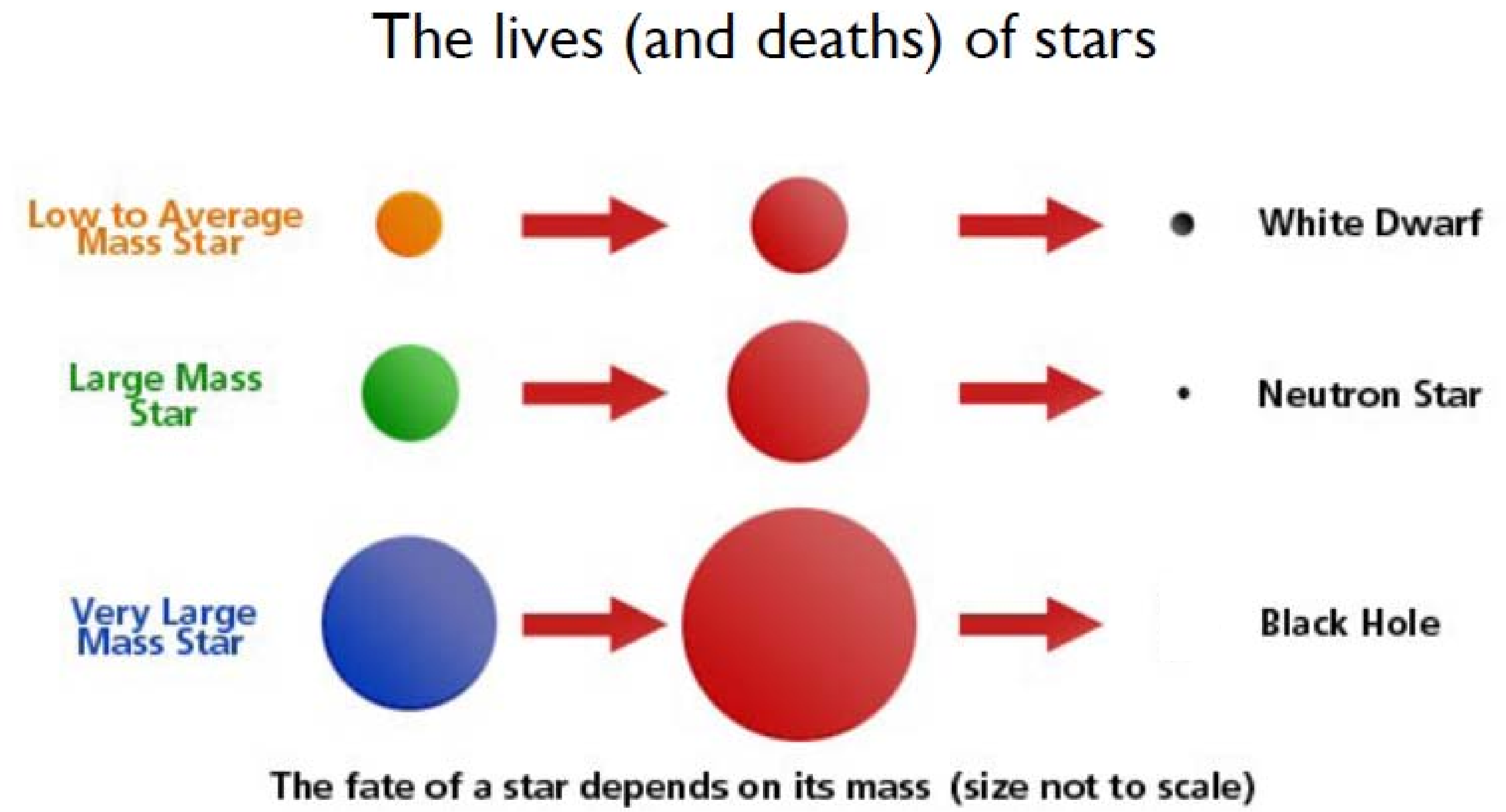
Tidal truncation



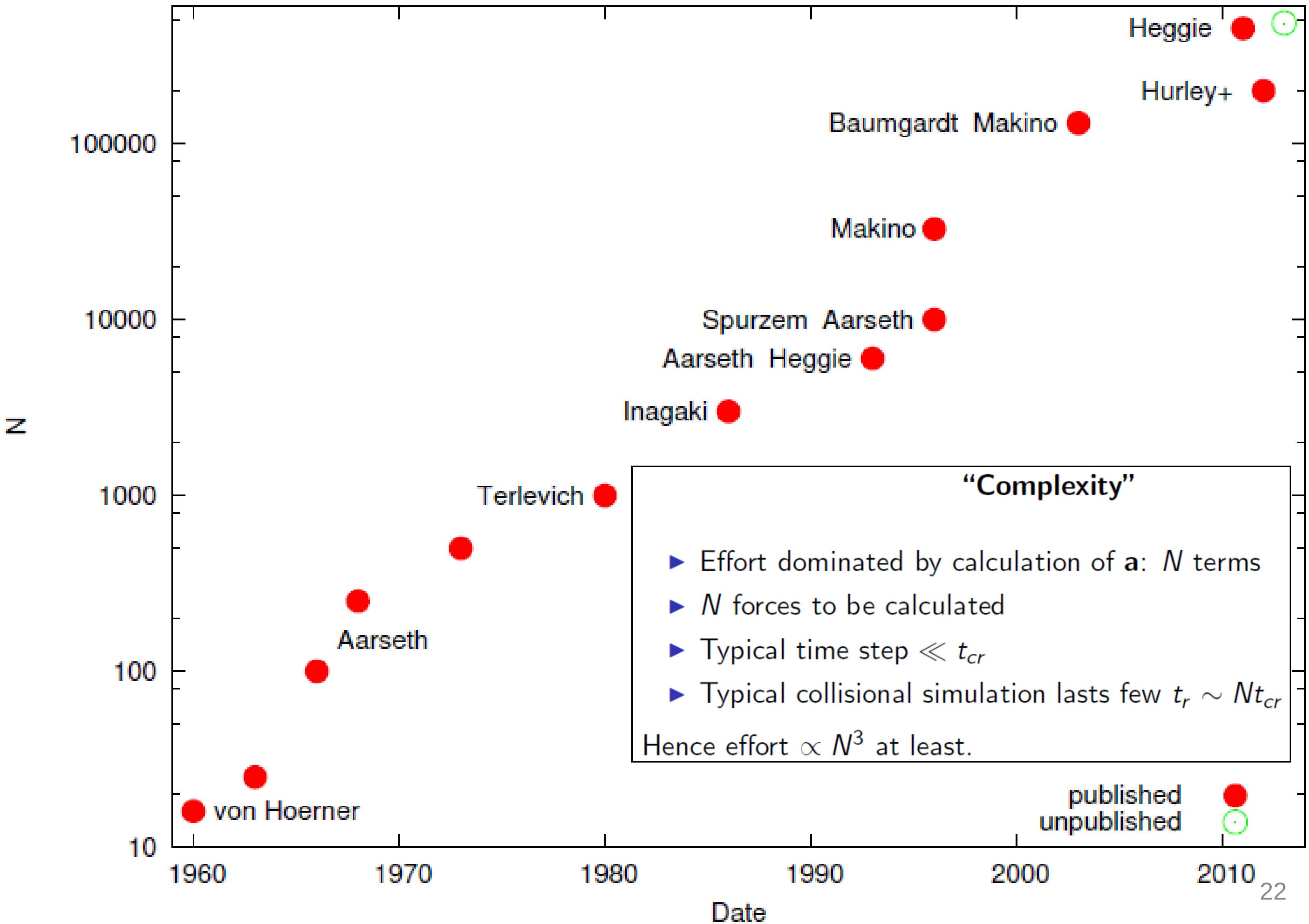
Particles evolve due to Stellar Evolution



Particles evolve due to Stellar Evolution



The slow progress of N-body simulations



Mass Loss From Star Clusters

Stellar & Dynamical Evolution

Characteristic parameters of star clusters change with time at early stages and also during the cluster long-term evolution

Vesperini & Heggie 1997; Giersz & Heggie 1996, **Baumgardt & Makino 2003**, Zonoozi et al. 2011, 2014, 2017, Haghi et al. 2015, Bianchini et al. 2017, webb et al 2017 .....,

MC method : Giersz et al. , Rasio et al., ...

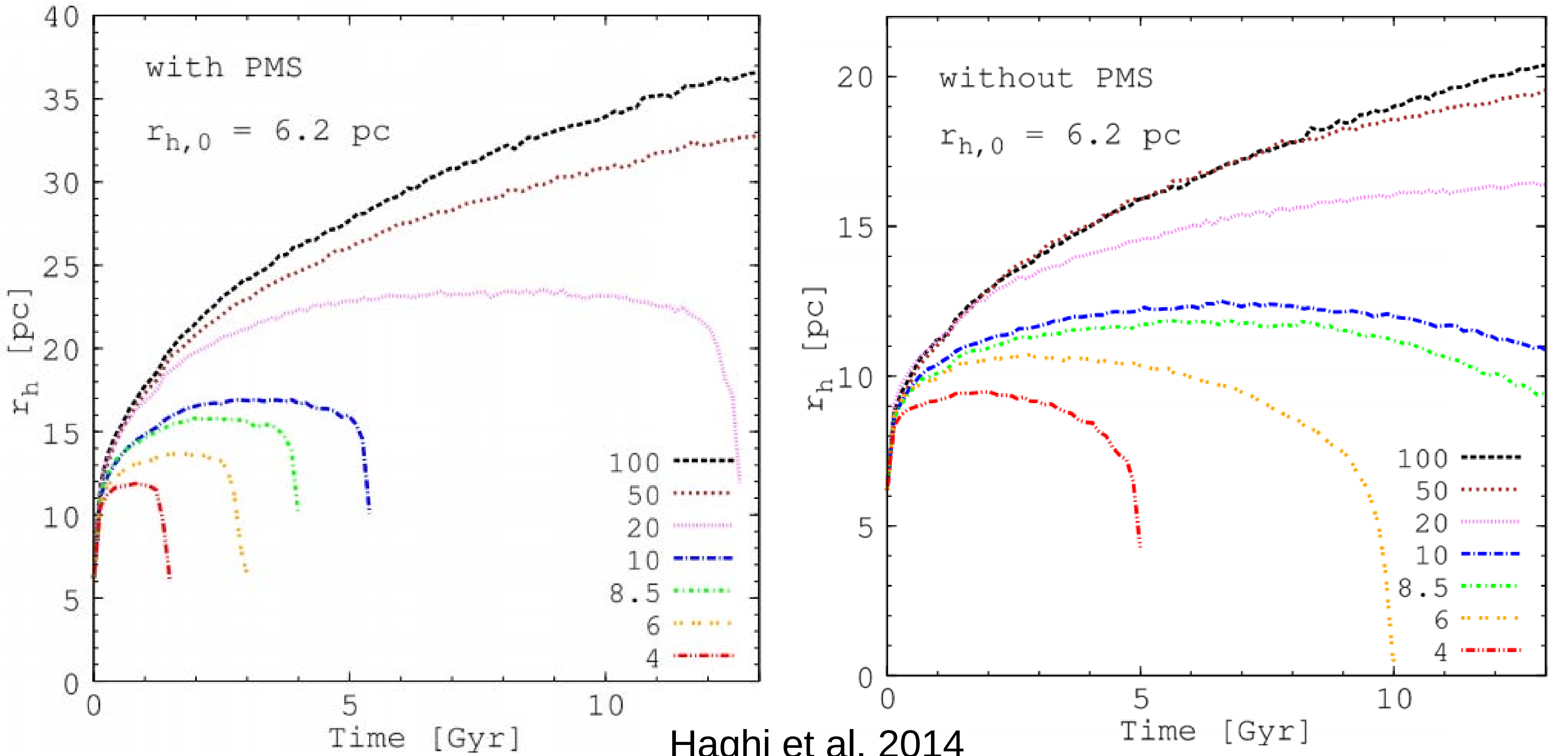
Internal and External Mechanisms:

- Stellar evolution

- Two body (collisional) relaxation: energy equipartition and mass segregation, binary heating, 3 and 4-body encounters, core evolution

- Violent relaxation: Tidal interactions, dynamical friction, bulge/disk shocking, tidal stripping

Primordial Mass Segregation (PMS)



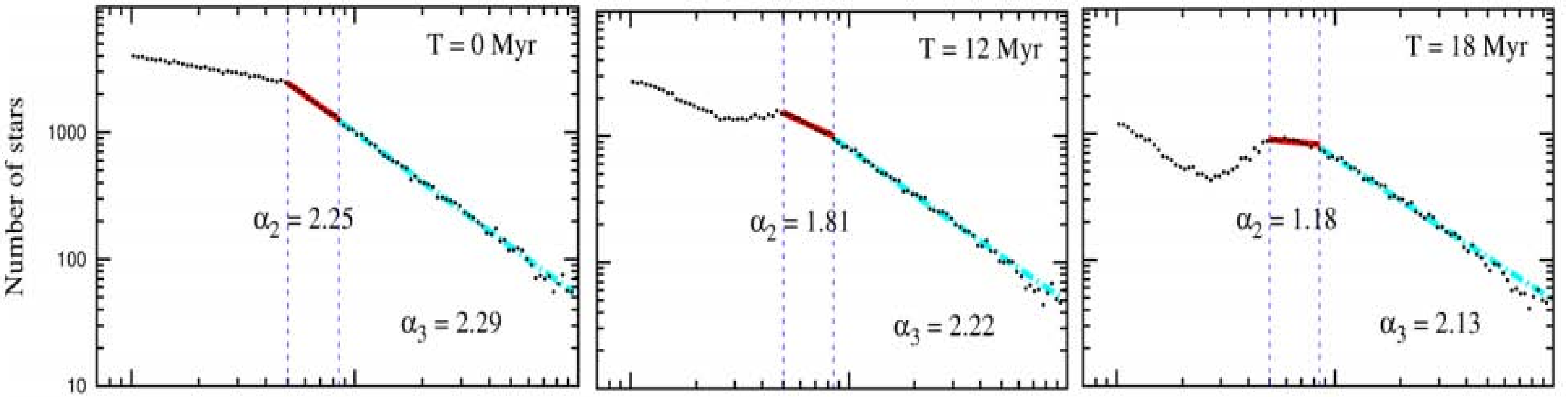
Haghi et al. 2014

Primordially segregated clusters, leads to a stronger expansion than for initially non-segregated clusters.

Combined Effect of Gas Expulsion and Primordial Mass Segregation

Flattening of the stellar mass function (MF) of outer halo GCs: Pal 4 and Pal 14 (**Zonoozi et al 2011, 2014, 2017)**

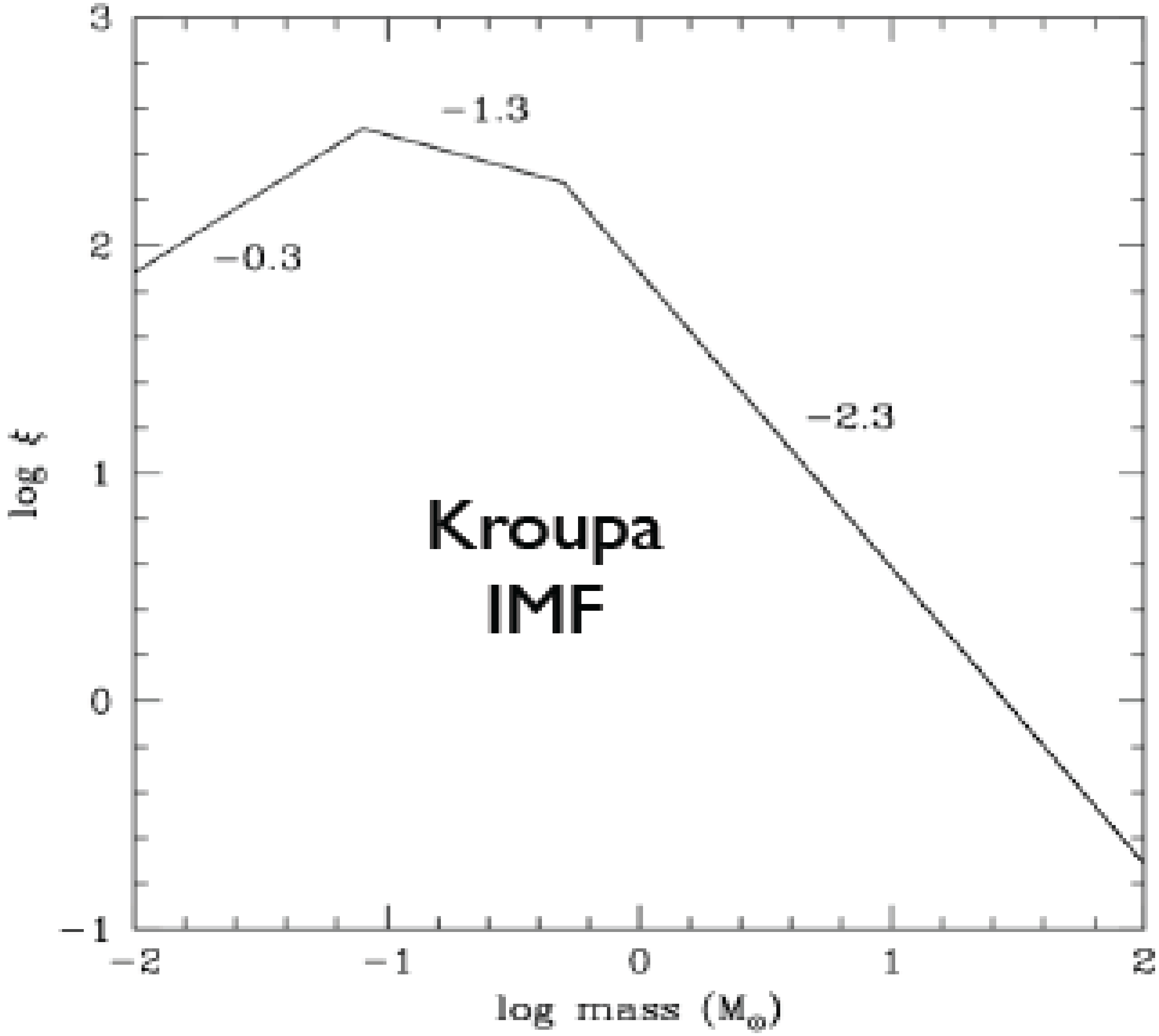
Ri=10 pc, S=0.9, SFE=0.33



The flattening of the MF-slope driven by a violent early phase of gas-expulsion (GE) of an embedded cluster with primordial mass segregation

(Haghi et al. 2015)

Stellar IMF



The stellar IMF

- Is the stellar IMF a universal probability distribution function?
- It is expected that the IMF varies and for example becomes top-heavy for high density and metal-poor star-forming regions
- For active galaxies with high SFRs, the top-heavy IMF is expected
- Kroupa & Weidner (2003) introduced integrated galactic IMF (IGIMF) theory to formulate the galaxy-wide IMF.

The IMF depends on environment

Observational evidences in UCDs and GCs show that the IMF is top-heavy in **metal-poor** and **dense** environment

Dabringhausen et al. 2009, 2010, 2012: Evidence from UCDs
Marks et al. 2012 : Evidence from GCs
Kroupa et al. 2013, Weidner & Kroupa 2013: Theoretical evidence

$$\xi(m) \propto m^{-\alpha} : \begin{cases} \alpha_1 = 1.35 \quad , \quad 0.08 < \frac{m}{M_\odot} < 0.50 \\ \alpha_2 = 2.35 \quad , \quad 0.50 < \frac{m}{M_\odot} < 1.00 \\ \alpha_3 \quad\quad\quad , \quad 1.0 < \frac{m}{M_\odot} < 100.0 \end{cases}$$

Top-heavy IMF $\alpha_3 = \begin{cases} +2.3, & x < -0.87 \\ -0.41 \times x + 1.94, & x \geqslant -0.87 \end{cases}$

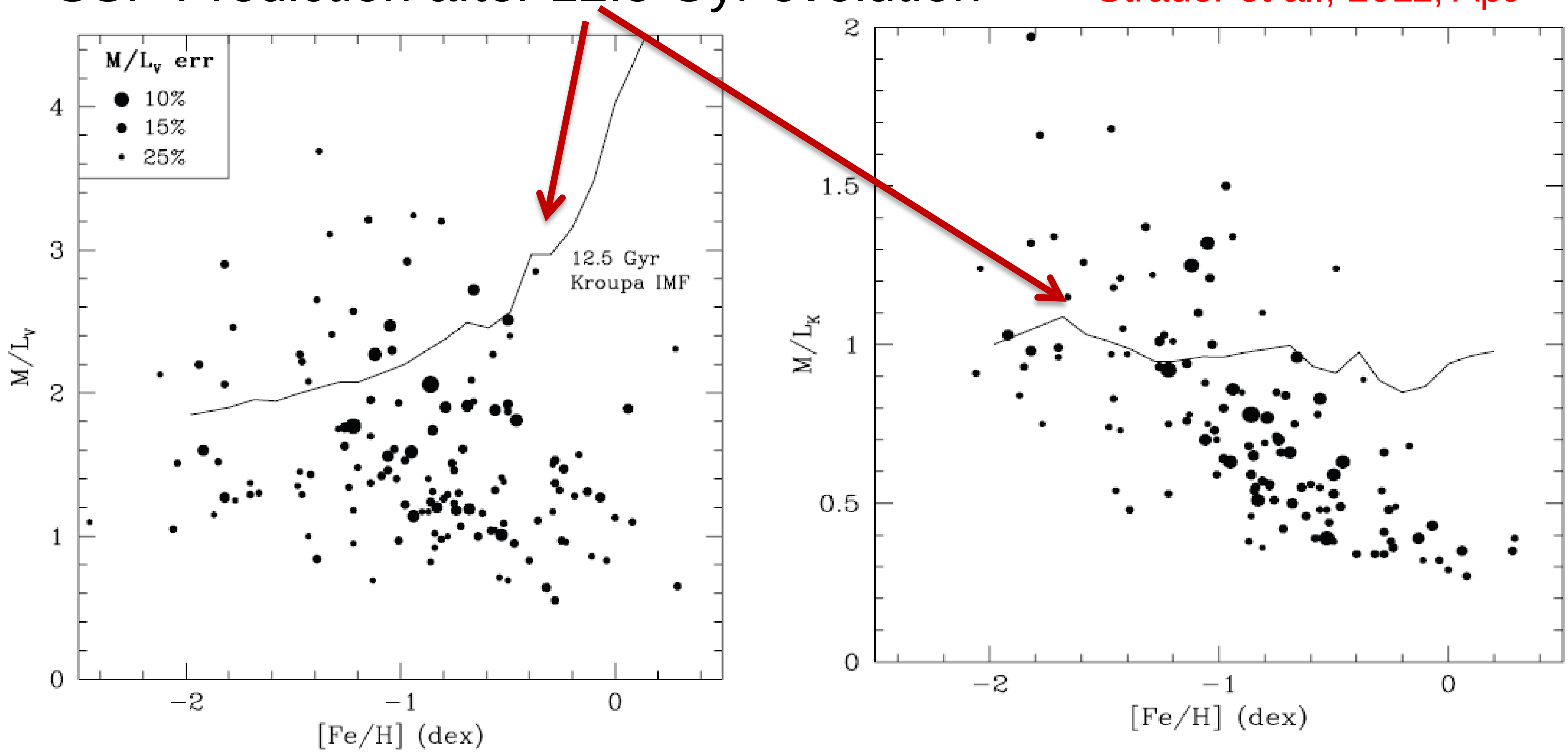
$$x = -0.14[\mathrm{Fe/H}] + 0.99 \log_{10}(\rho_{\mathrm{cl}}/(10^6 M_\odot \mathrm{pc}^{-3}))$$

Indirect evidence for top-heavy IMF:

M/L – [Fe/H] correlation of GC population in M31

SSP Prediction after 12.5 Gyr evolution

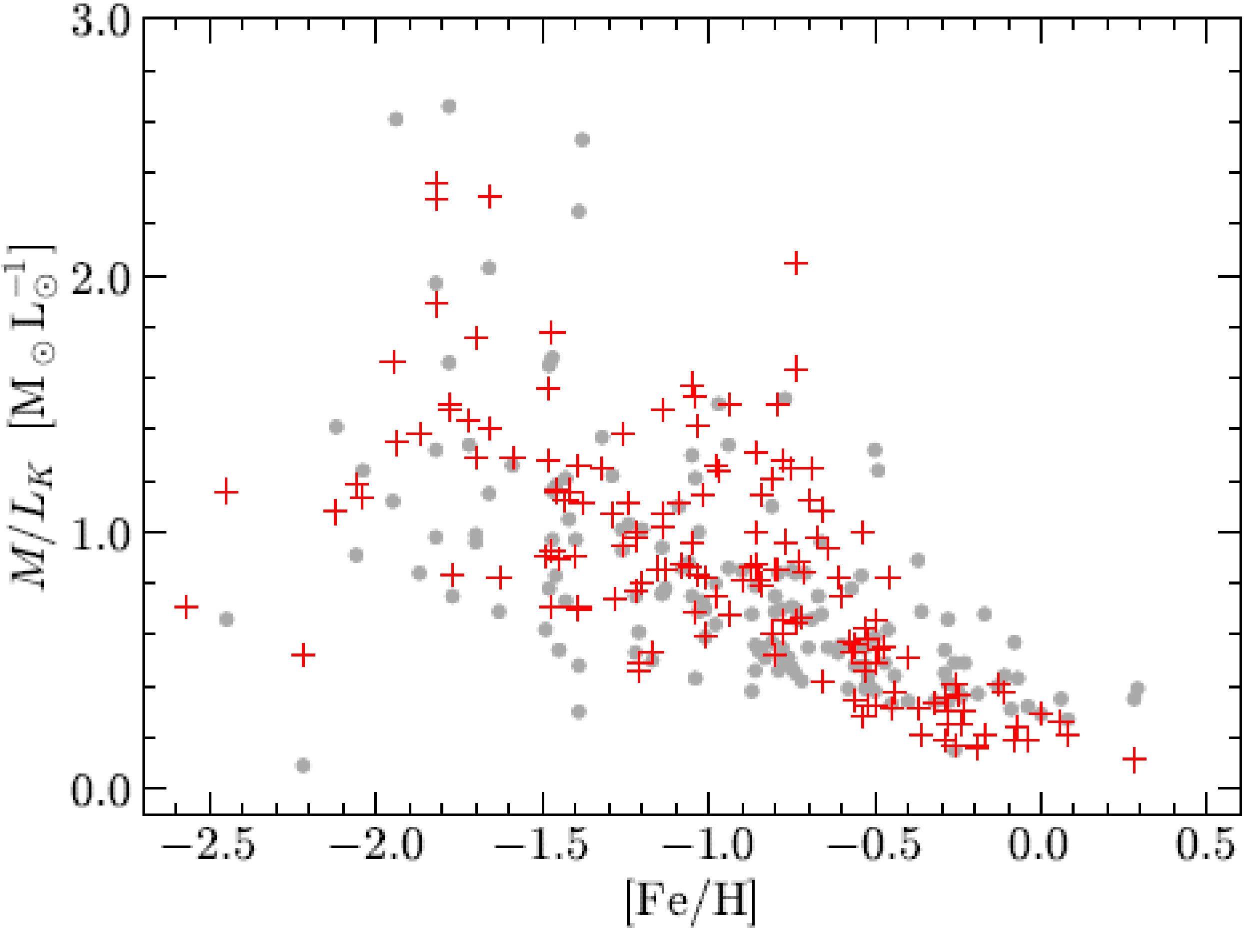
Strader et al., 2011, ApJ



The Stellar Evolution raises the M/L ratio of a cluster **with time**

The Dynamical Evolution leads to a decrease in the M/L ratio

Incorporation of the Stellar/Dynamical evolution and top-heavy IMF can explain the correlation.



Haghi et al 2017, Zonoozi et al. 2016

The evolution of star clusters starting with a top-heavy IMF

N-body models: Initial conditions

Top-heavy IMF

$$\xi(m) \propto m^{-\alpha} : \begin{cases} \alpha_1 = 1.35 \quad , & 0.08 < \frac{m}{M_\odot} < 0.50 \\ \alpha_2 = 2.35 \quad , & 0.50 < \frac{m}{M_\odot} < 1.00 \\ \alpha_3 \quad , & 1.0 < \frac{m}{M_\odot} < 100.0 \end{cases}$$

$$(\alpha_3 = 1.5, 1.7, 1.9, 2.1, 2.3)$$

Initial Mass- radius relation of Marks-Kroupa (2012)

$$\frac{r_\mathrm{h}}{\mathrm{pc}} = \sqrt[3]{\frac{3\,(M_\mathrm{ecl}/M_\odot)^{1-a}}{8\pi \times 10^b}} = 0.10^{+0.07}_{-0.04} \times \left(\frac{M_\mathrm{ecl}}{M_\odot}\right)^{0.13 \pm 0.04},$$

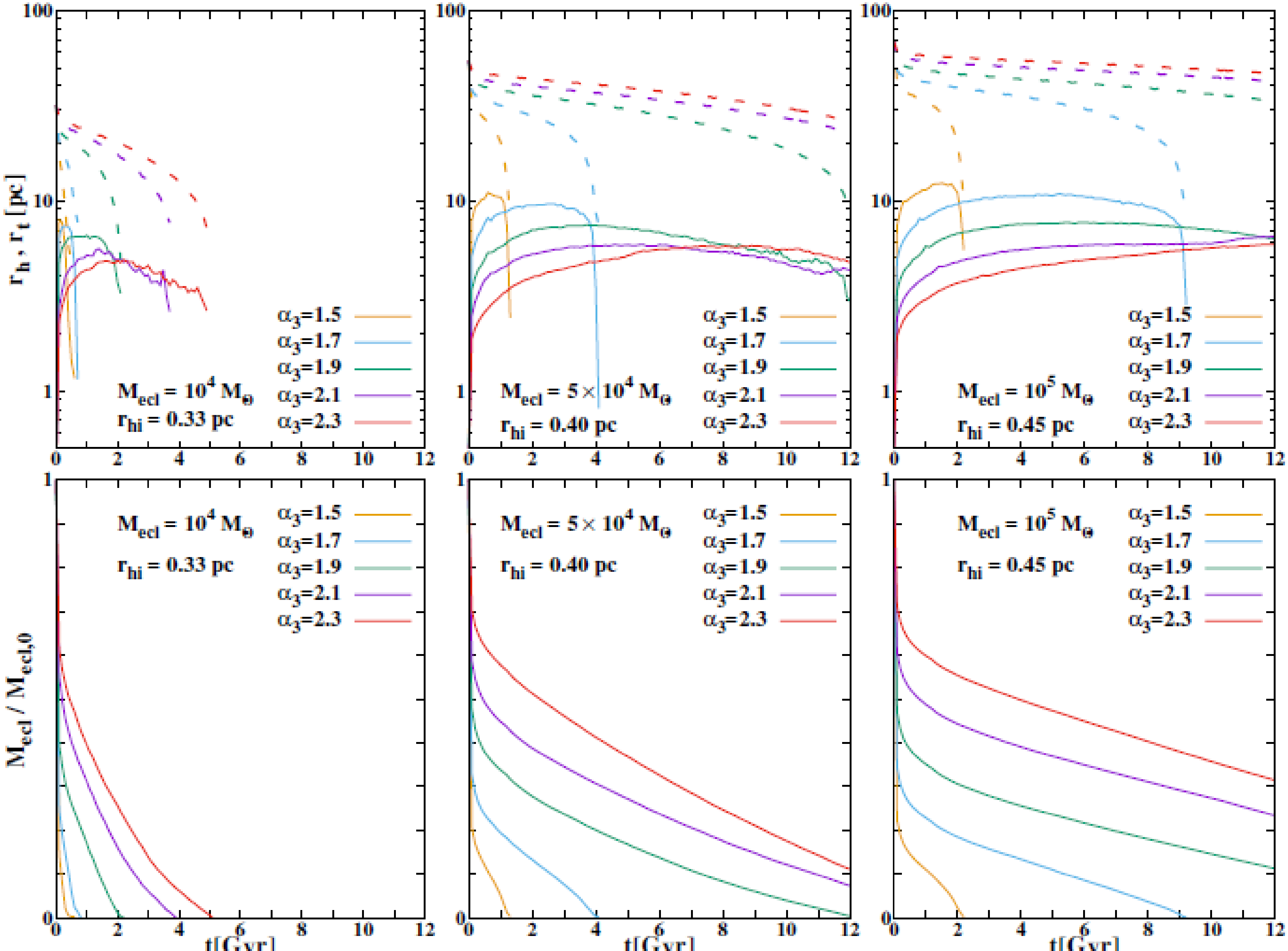
Modeled clusters

1 day

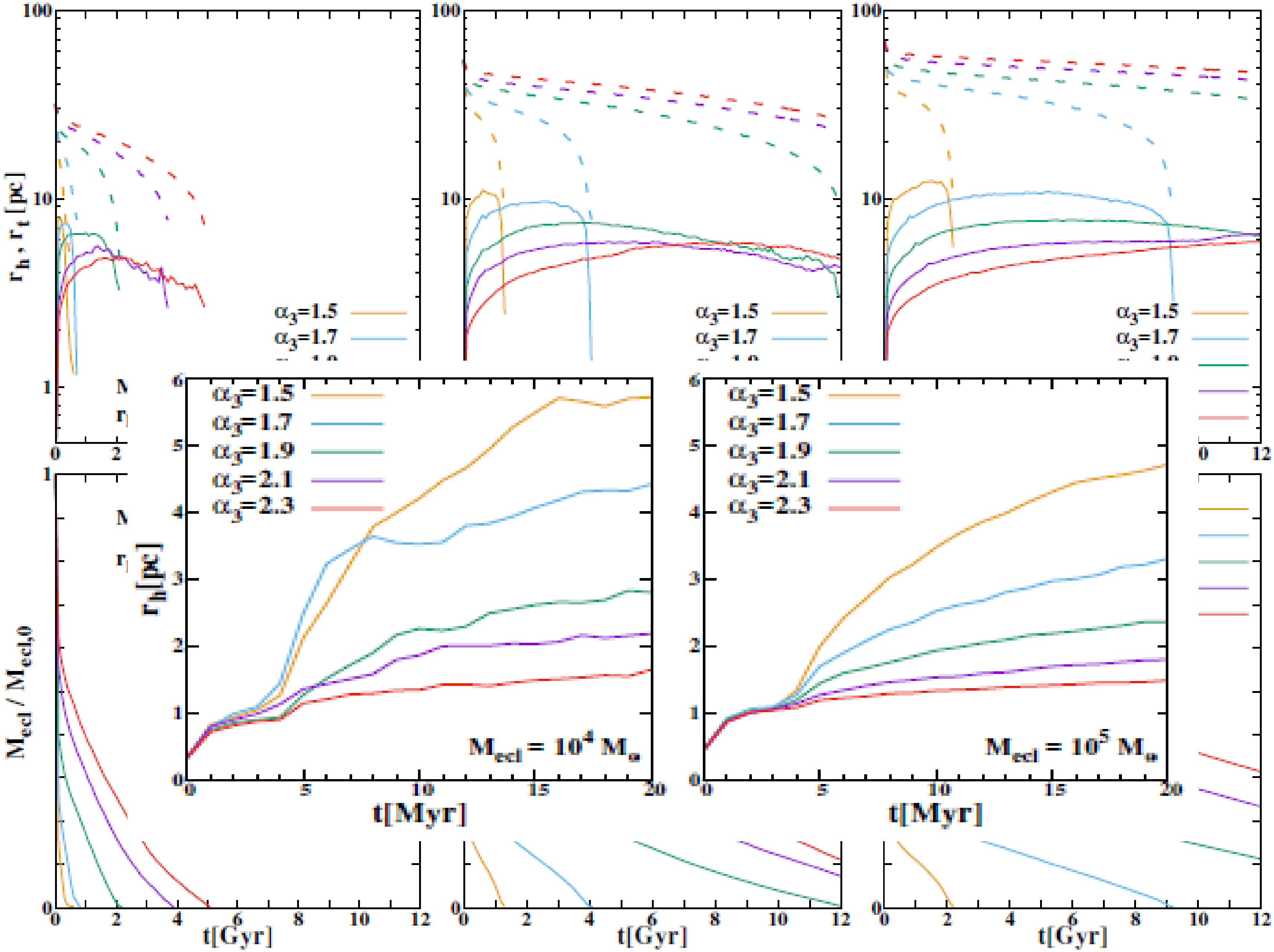
$M_{cluster}$ ($\times 10^3 M_\odot$)	α_3				
	1.5	1.7	1.9	2.1	2.3
	The initial number of Stars				
10	4379	7646	10473	14869	17337
20	9857	14832	21754	29713	38132
30	13970	21465	34072	44247	55594
40	18726	30297	43493	58750	72728
50	24589	36889	57012	73043	91113
60	28281	44614	66636	79579	111158
70	32323	51366	78889	102966	126627
80	37074	58745	86008	119240	147388
90	41750	65973	100596	132773	165458
100	46328	75236	110149	146424	182453

200 days

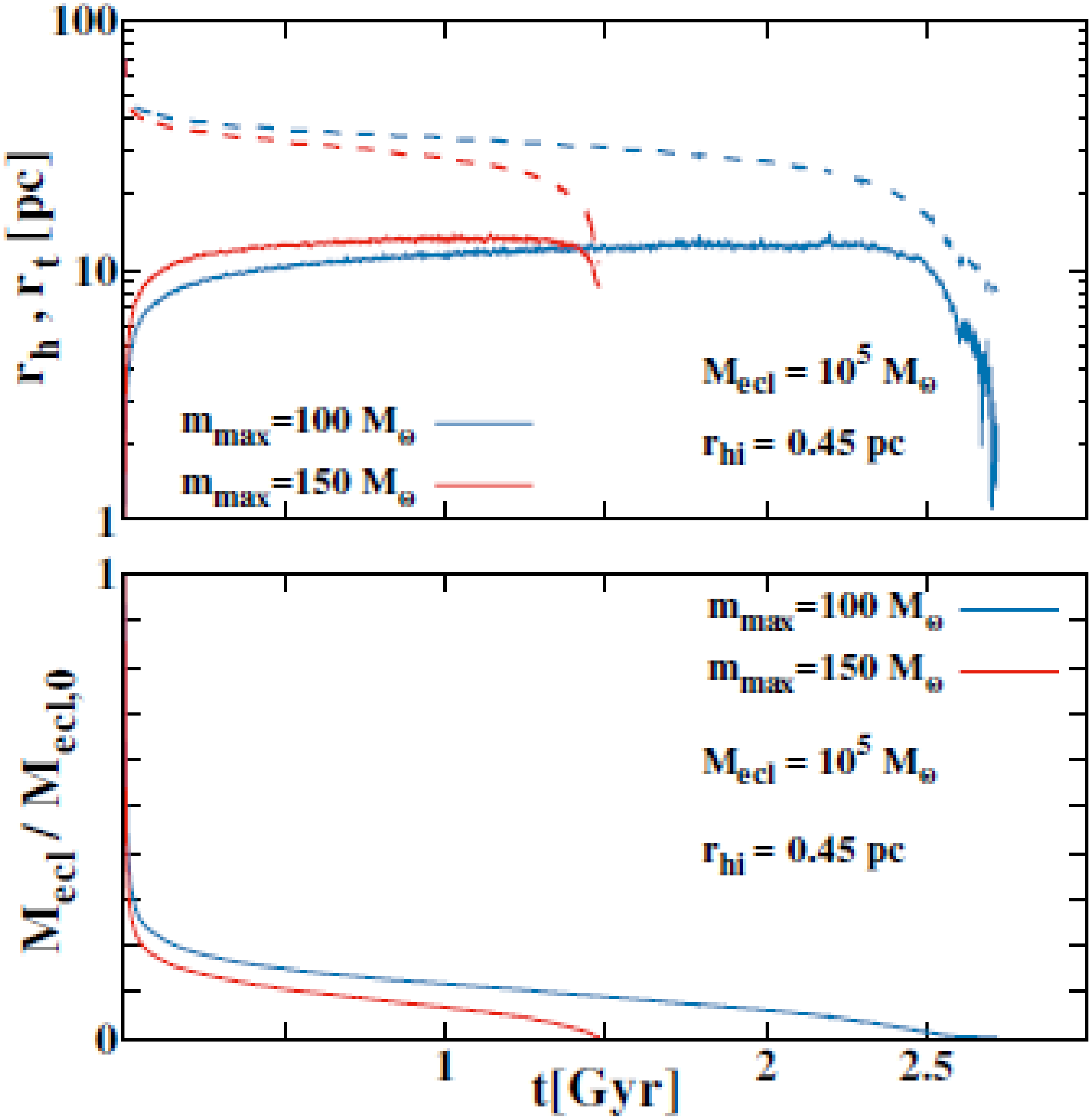
Evolution of cluster mass and size



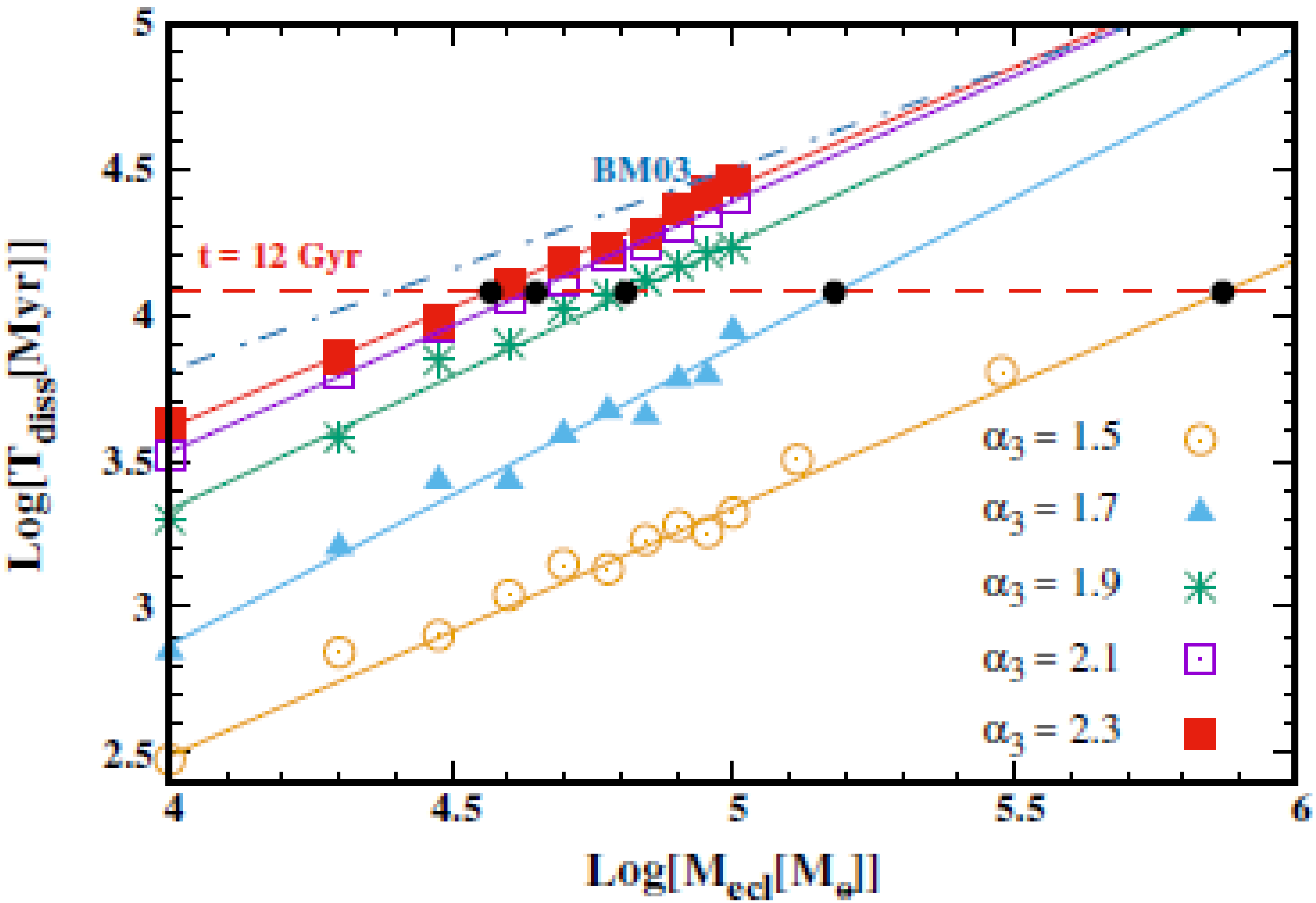
Evolution of cluster mass and size



The effect of upper stellar mass limit in the IMF



Dissolution time



$$log_{10}\left[T_{diss}(\alpha_3)\right] = a(\alpha_3)\, log_{10}\left[M_{ecl}\right] + b(\alpha_3).$$

Dissolution time

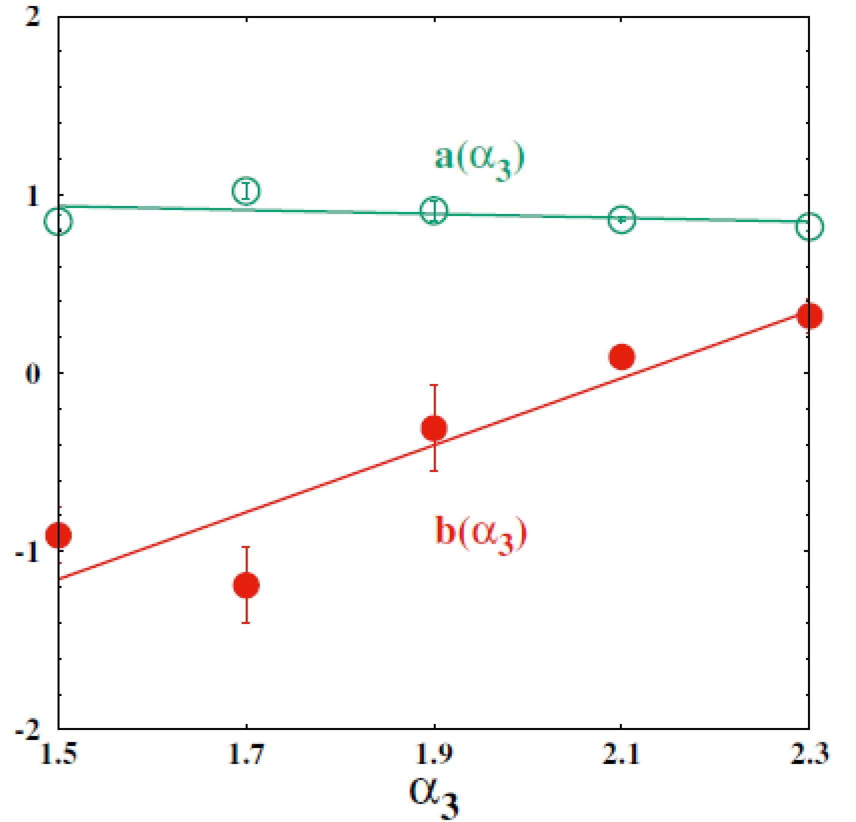
$$log_{10}\left[T_{diss}(\alpha_3)\right] = a(\alpha_3)\, log_{10}\left[M_{ecl}\right] + b(\alpha_3).$$

$$a(\alpha_3) = (-0.11 \pm 0.13)\,\alpha_3 + (1.10 \pm 0.25),$$

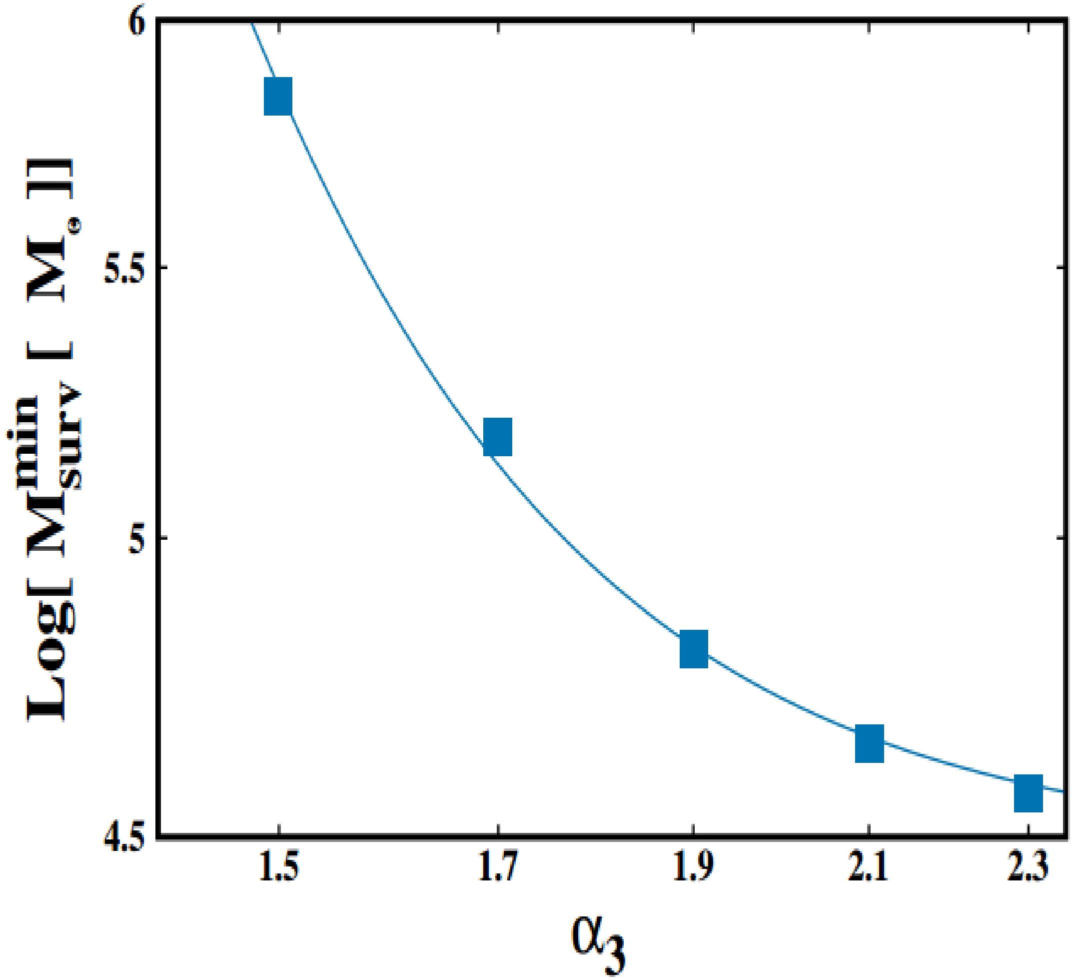
$$b(\alpha_3) = (1.88 \pm 0.47)\,\alpha_3 - (3.98 \pm 0.91).$$

α_3	$a(\alpha_3)$	$b(\alpha_3)$	M_{surv}^{min} $[10^3 M_\odot]$
1.5	0.85 ± 0.04	-0.91 ± 0.16	700
1.7	1.01 ± 0.05	-1.19 ± 0.21	150
1.9	0.91 ± 0.05	-0.31 ± 0.24	65
2.1	0.86 ± 0.01	0.09 ± 0.07	45
2.3	0.82 ± 0.02	0.32 ± 0.10	38
2.3*	0.82*	—	—

*Denotes the value for BM03

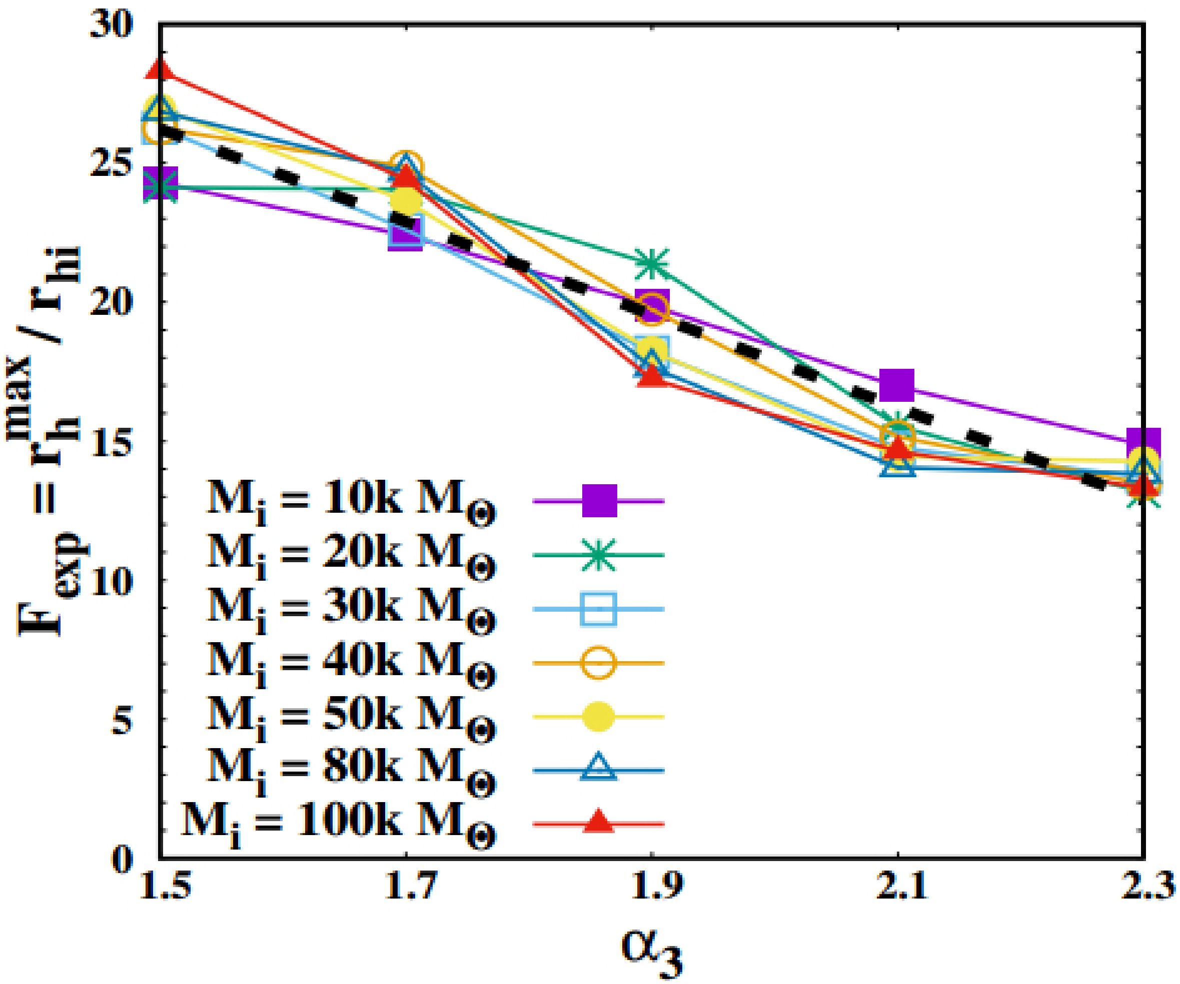


Minimum Survived mass of clusters vs. MF-slope



$$log_{10}(M_{surv}^{min}) = A\,(\alpha_3)^{-\eta} + B,$$ where $A = 15.7 M_{\odot}$, $\eta = 6$ and $B = 4.5 M_{\odot}$.

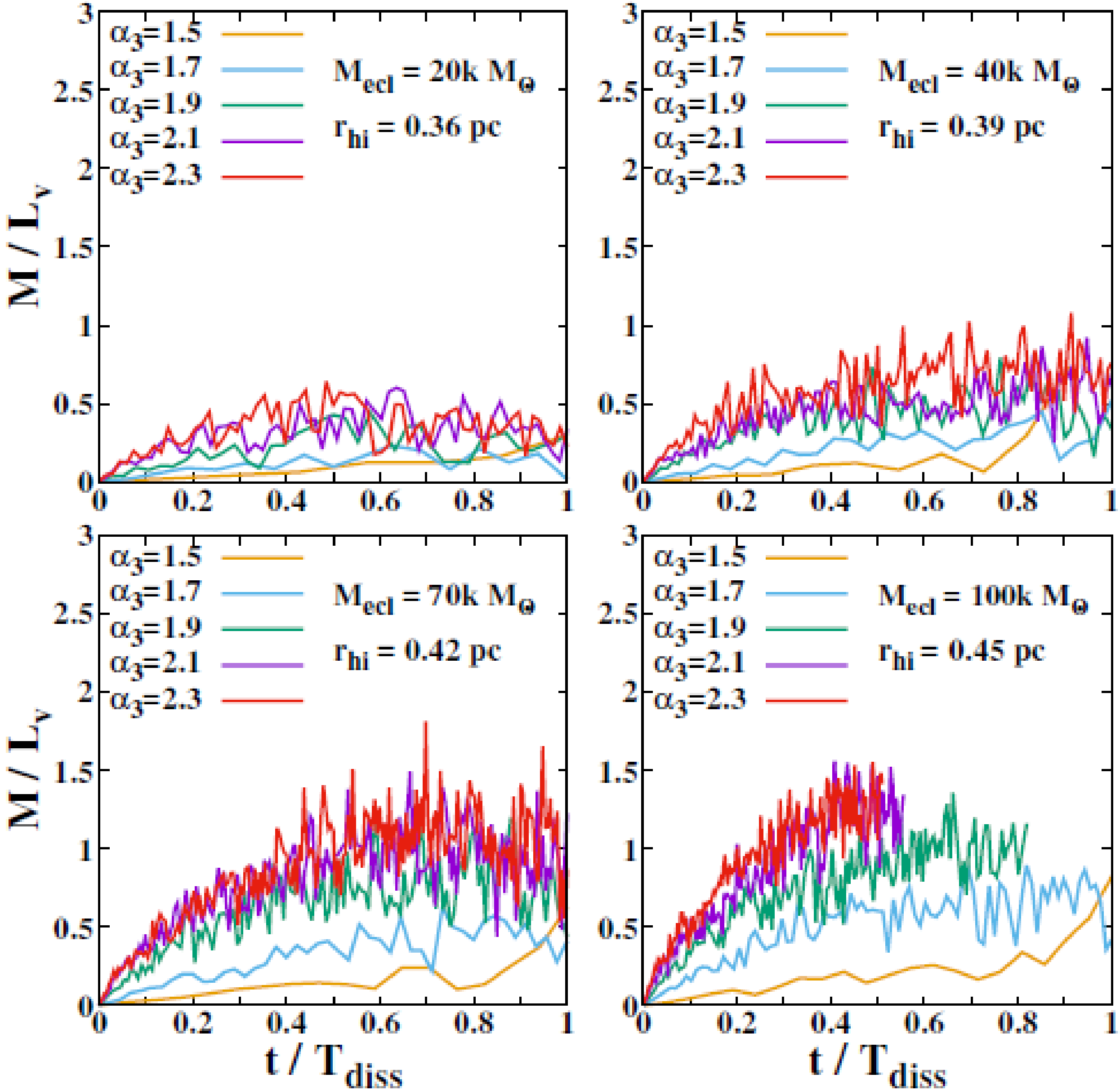
Expansion rate



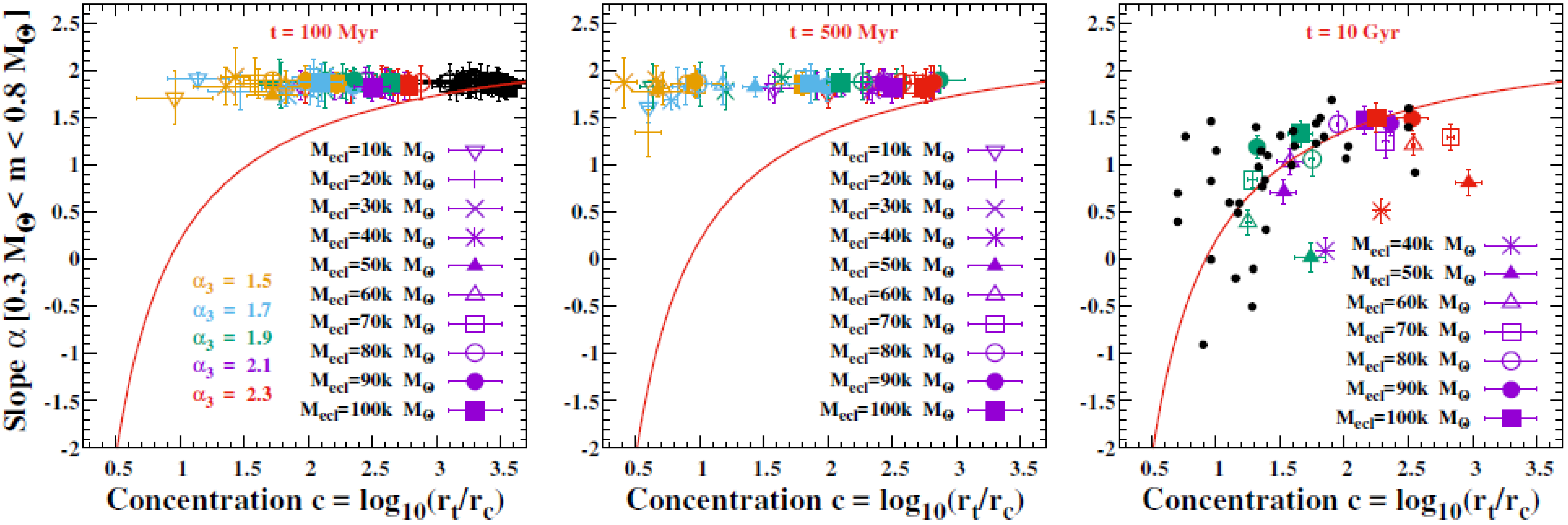
$$F_{exp}(\alpha_3) = e\,(\alpha_3) + f$$

where $e = -16.7 \pm 1.7$ and $f = 51.3 \pm 3.3$

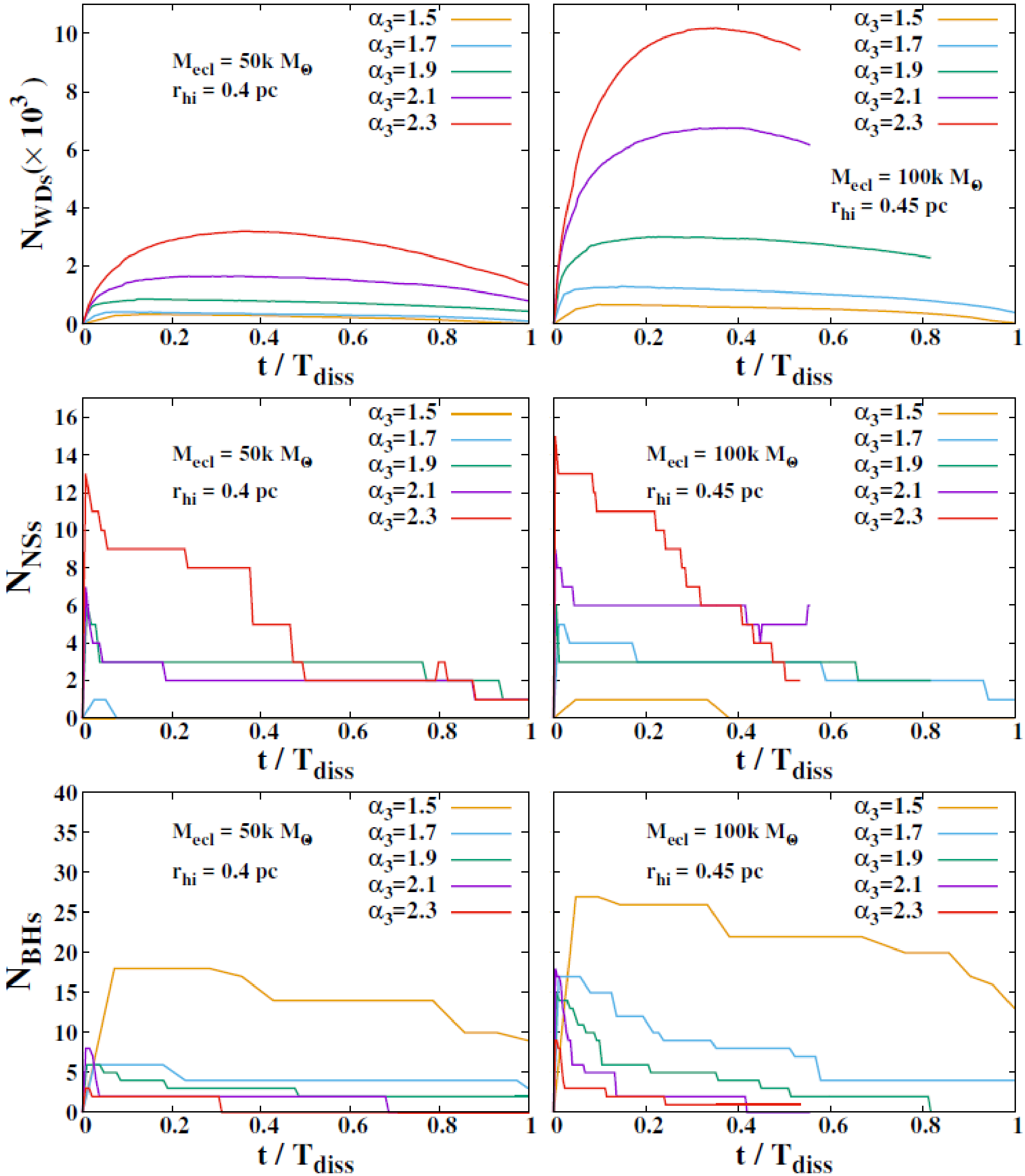
The evolution of mass-to-light ratio



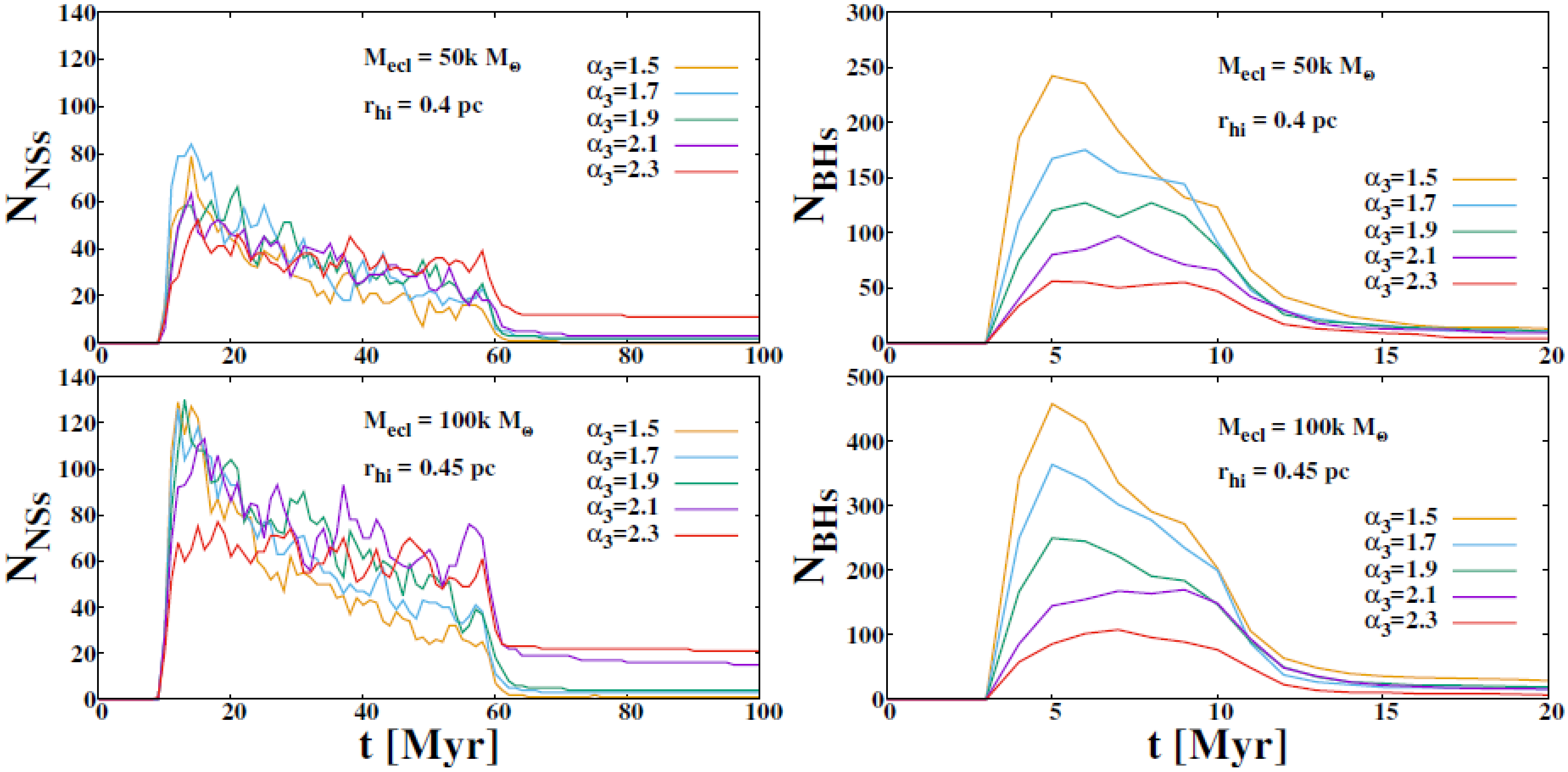
MF_slope – concentration relation



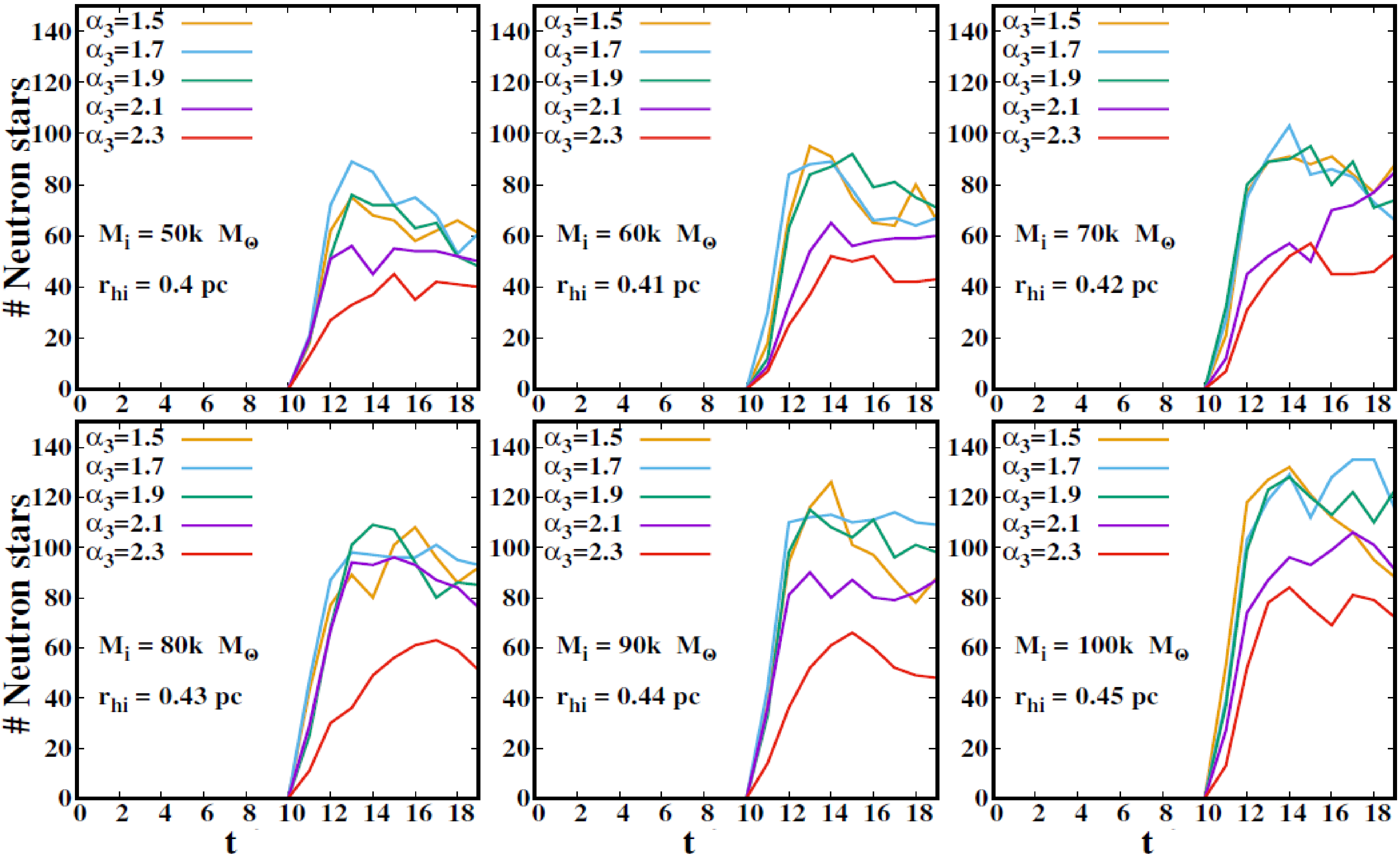
The number of WDs, NSs, BHs



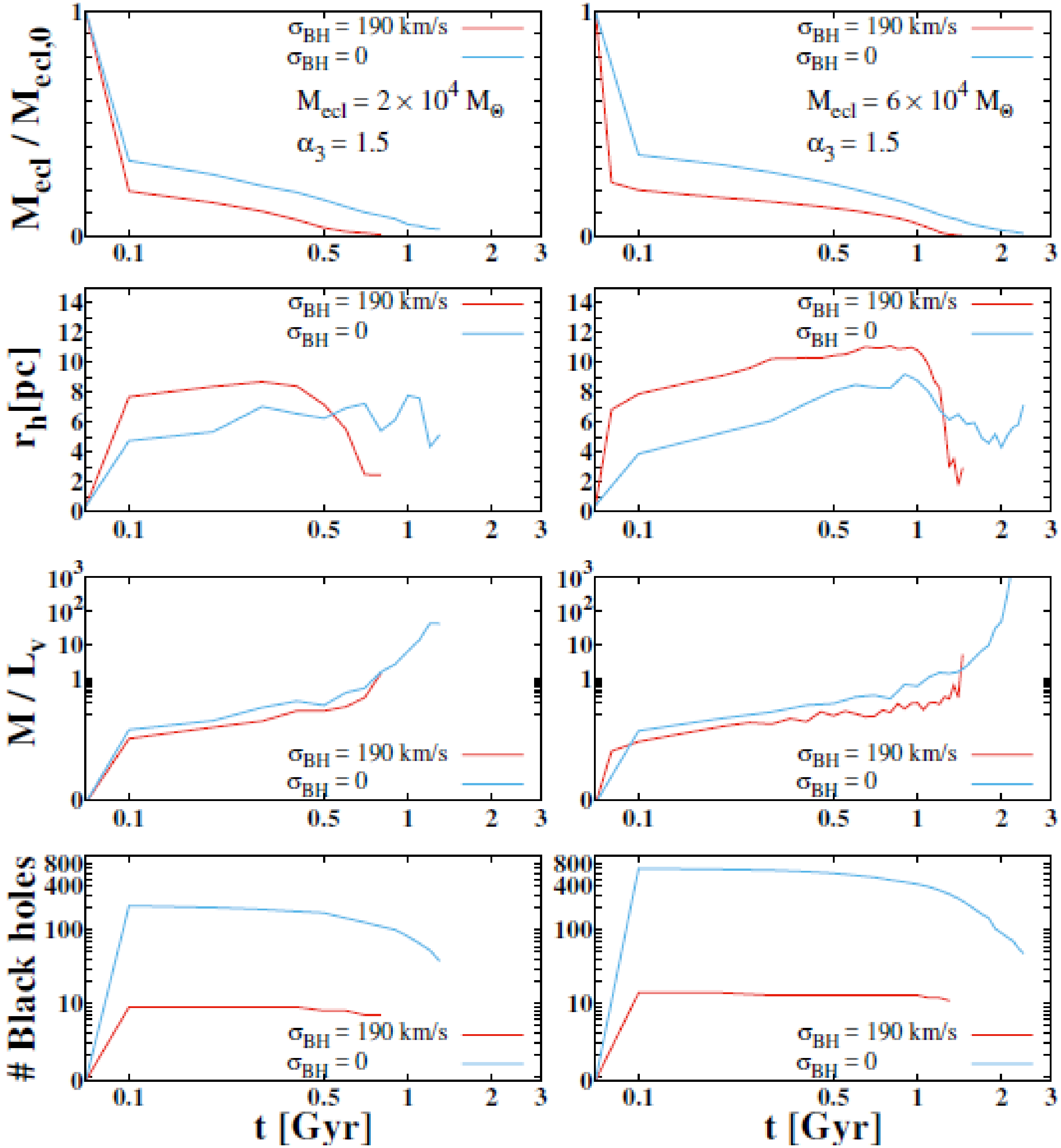
Zoom in the first 100 Myr evolution



Zoom in the first 20 Myr evolution



The effect of BHs retention fraction



The effect of BHs retention fraction