The long term dynamical evolution of Ultra Faint Dwarf Galaxies

CENTER FOR ASTROPHYSICS AND SPACE SCIENCE

جامعة نيويورك أبوظبي
NYU ABU DHABI

ff2415@nyu.edu

Francesco Flammini Dotti, Roberto Capuzzo-Dolcetta, Giovanni Carraro, Alessandro Alberto Trani, Rainer Spurzem

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Teaminar

the SILK ROAD PROJECT at NAOC / KIAA
丝绸之路计划
IN ANCIENT TIMES ... THERE WAS A BRIDGE BETWEEN CULTURES AND CONTINENTS ... TODAY THERE IS A PROJECT OF ASTROPHYSICS IN CHINA ON THE MOVE ... TO BUILD AN INTERNATIONAL BRIDGE FOR COMPUTATIONAL SCIENCE

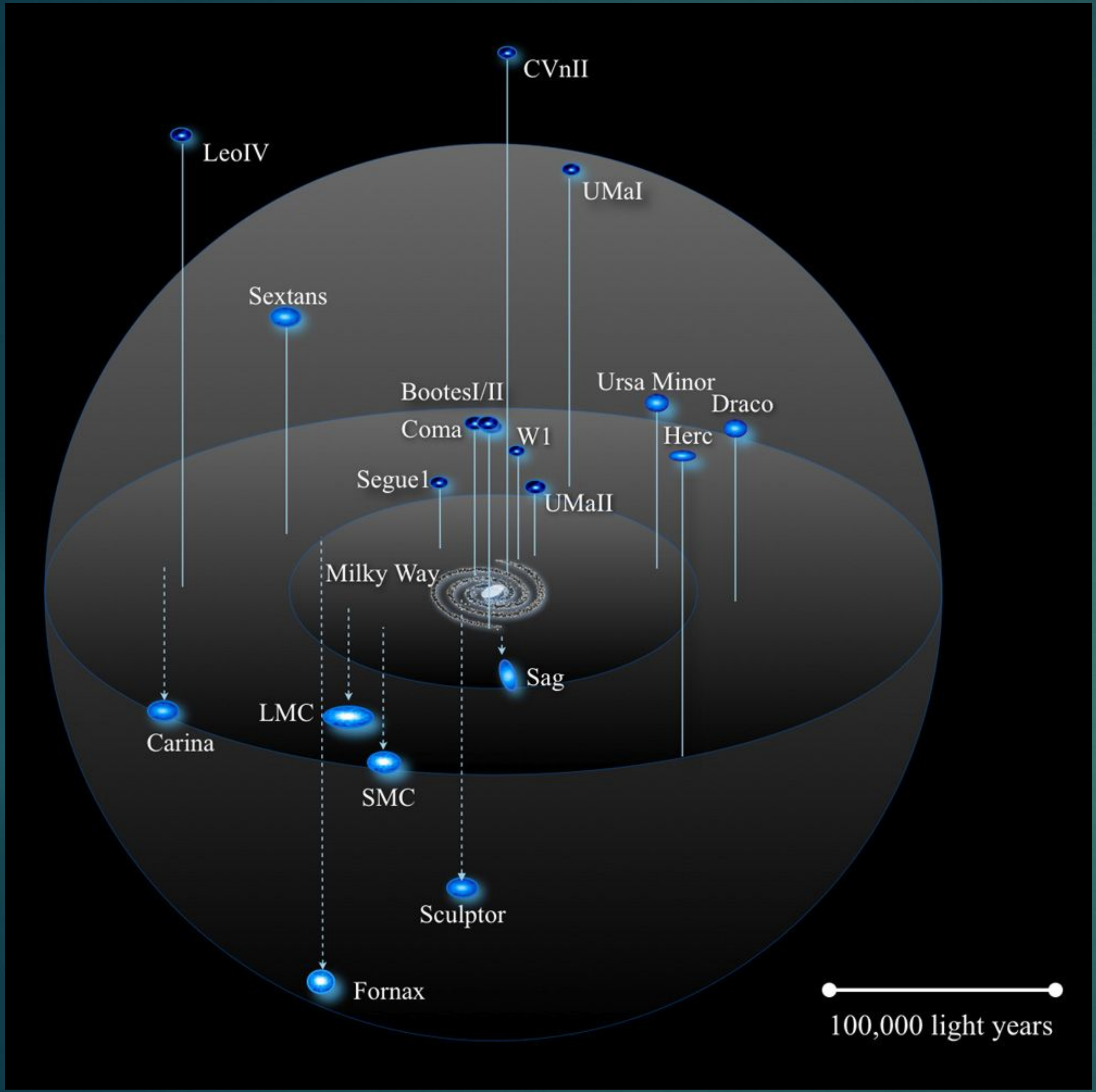
OUTLINE

1) Description and differences between Dwarf Galaxies and UFD

2) From observations to a numerical method

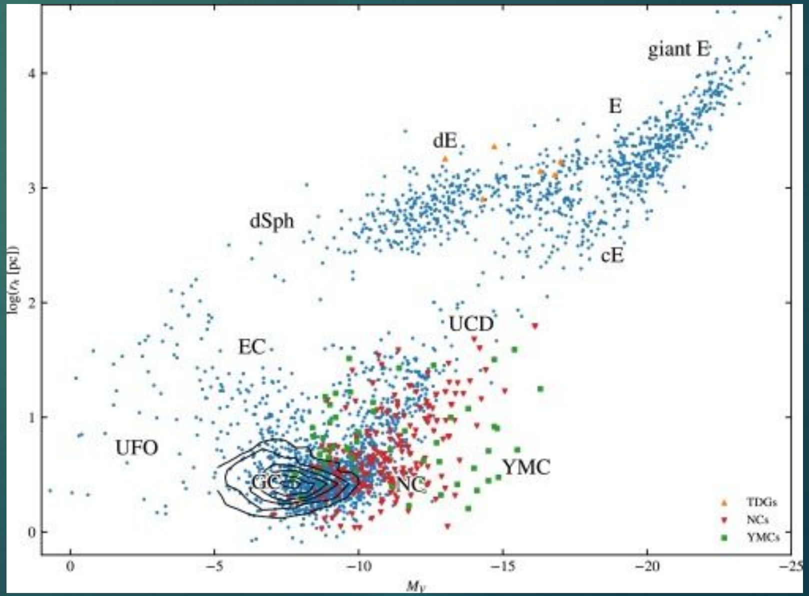
3) Dynamical evolution of UFD

4) Are UFD DM dominated?



Summary Table (Parsecs)

Classification	Typical Size (Diameter, pc)
dSph	90–900 pc
dE	300–3,000 pc
dIrr	300–9,000 pc
BCD	300–3,000 pc
UCD	20–180 pc
UFD	10–300 pc



Dwarf Galaxy

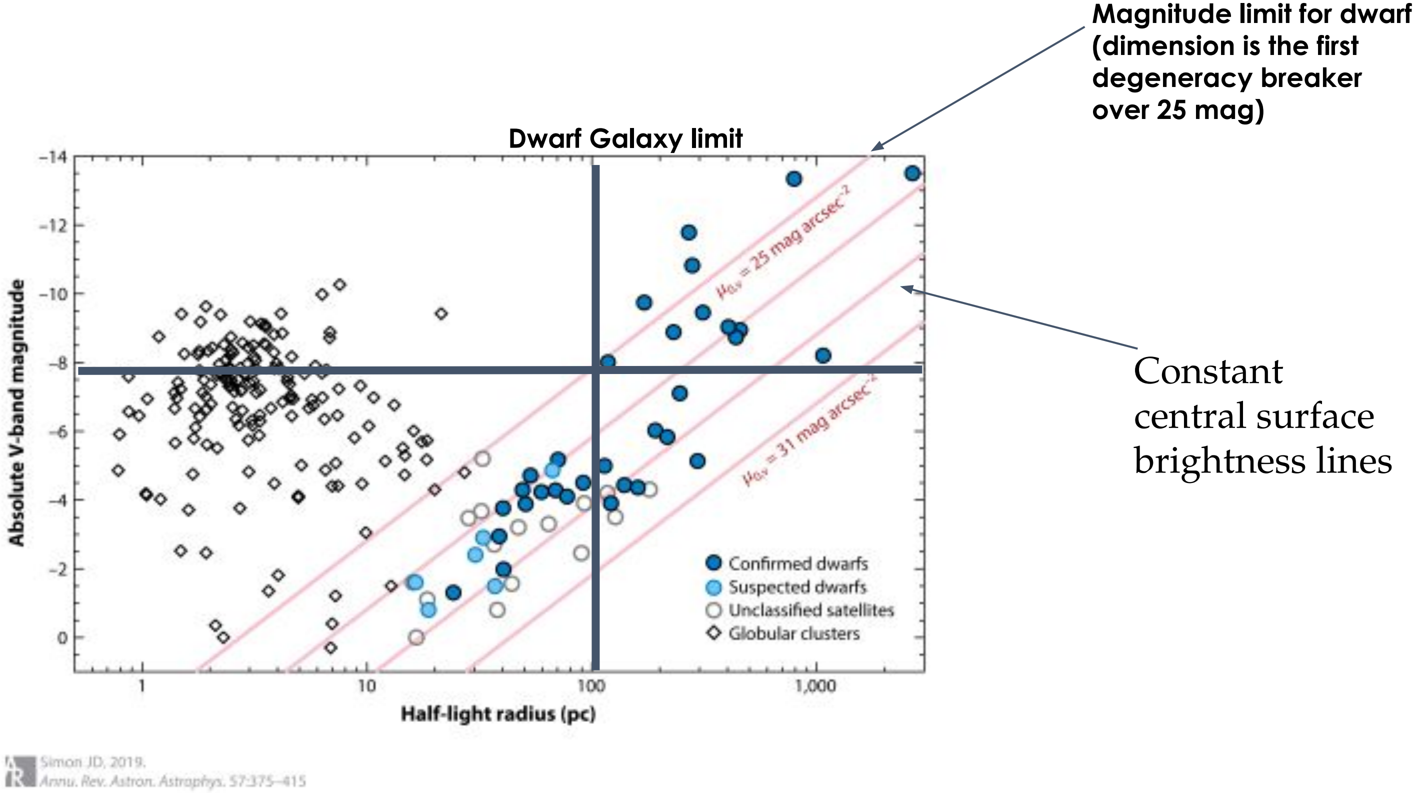
DM necessary
> 5 000 in z < 0.01
Generally very luminous

Dwarf Spheroidal galaxies (dSph) are the group of UFD

DM dominated
29 objects up to date
Very faint -> unresolved!

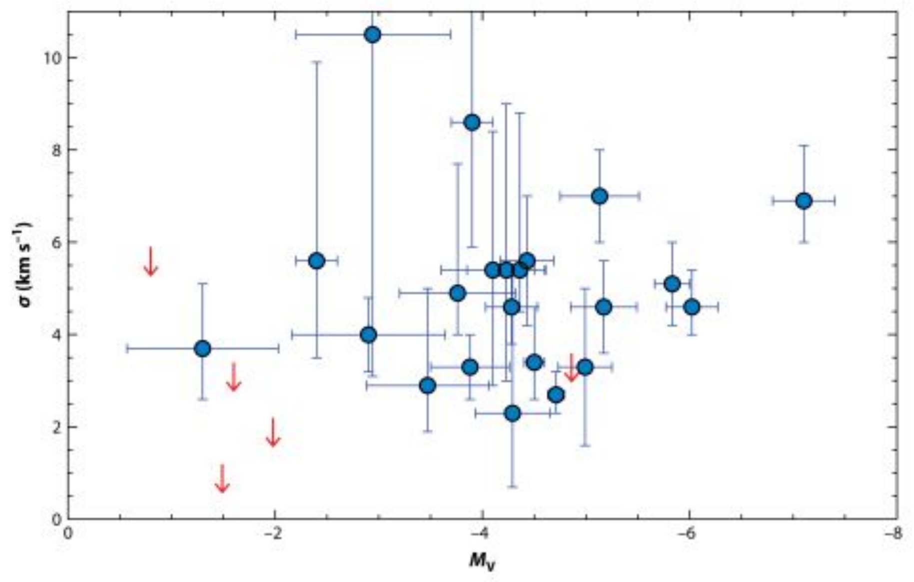
Ultra-Faint Dwarf Galaxy

We define UFD anything fainter than - 7.7 mag (that is also a galaxy)



Annual Reviews

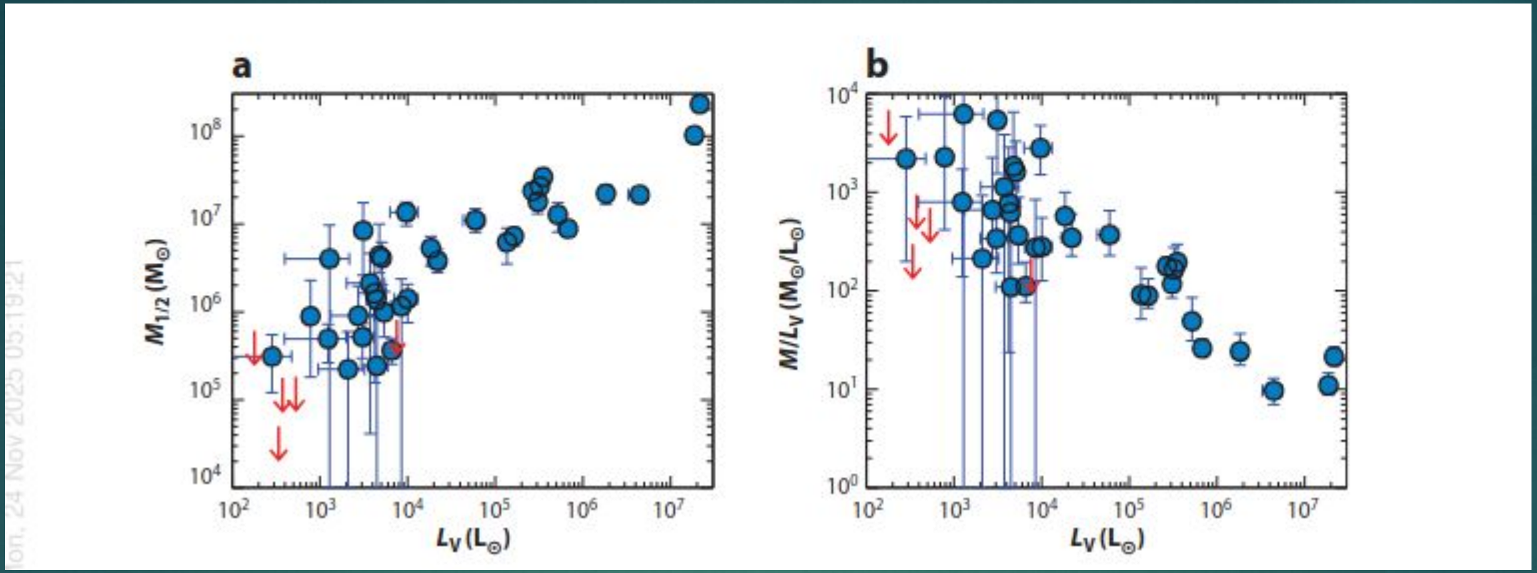
Dispersion velocity is extremely challenging. Error bars are gigantic….



Simon JD. 2019.
Annu. Rev. Astron. Astrophys. 57:375–415

But the brighter the source, the less big are the error bars!

Annual Reviews



(a) the velocity dispersion is independent of radius

(b) the velocity dispersion is isotropic

(c) the mass profile follows the light profile.

$M_{1/2} = 930\, \sigma_{1d}^2 R_{1/2}$ (Wolf 2010)

Simon 2019 selected those dispersion velocities and calculated the half mass… Half masses are not too large…

Can we do an N-body simulation?

Object	R (pc)	M ($M_\odot$)	t_{rh} (Gyr)	X	Y	Z	Age (Gyr)	L_{bol} ($L_\odot$)	L_V ($L_{V,\odot}$)	L_B ($L_{B,\odot}$)
dSph	3×10^3	10^7	1.79×10^5	0.747	0.252	0.001	13	1.35×10^8	1.38×10^7	1.67×10^7
UFD	50	5×10^4	43.07	0.747	0.252	0.001	13	6.72×10^5	6.88×10^4	8.37×10^4

In literature (Pianta et al. 2022 and references therein) dSph and UFD are similar in age and chemical composition (Salvadori et al 2009).

The main differences is the size of UFD (much smaller), mass (3 order of magnitude of difference) and luminosity (3 order of magnitude fainter).

Object	R (pc)	M ($M_\odot$)	t_{rh} (Gyr)	X	Y	Z	Age (Gyr)	L_{bol} ($L_\odot$)	L_V ($L_{V,\odot}$)	L_B ($L_{B,\odot}$)
dSph	3×10^3	10^7	1.79×10^5	0.747	0.252	0.001	13	1.35×10^8	1.38×10^7	1.67×10^7
UFD	50	5×10^4	43.07	0.747	0.252	0.001	13	6.72×10^5	6.88×10^4	8.37×10^4

How about star formation history?

UFD are considered single-stellar population as compared to the dSph, with possible multiple stellar populations (Vincenzo et al 2014)

Both are old, so we need to simulate at least an Hubble time to get today status!

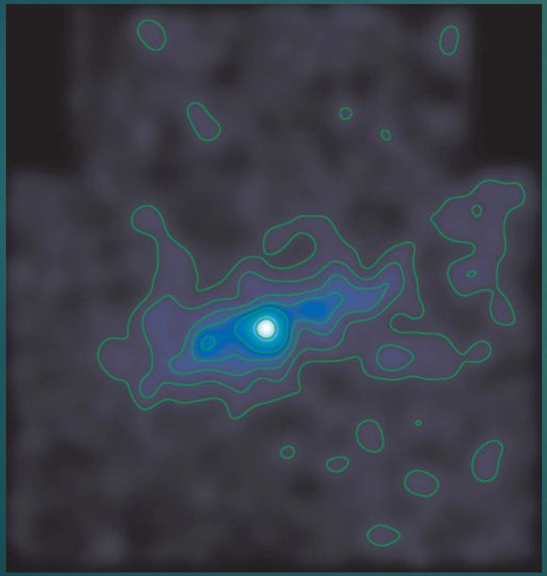
2 important issues:

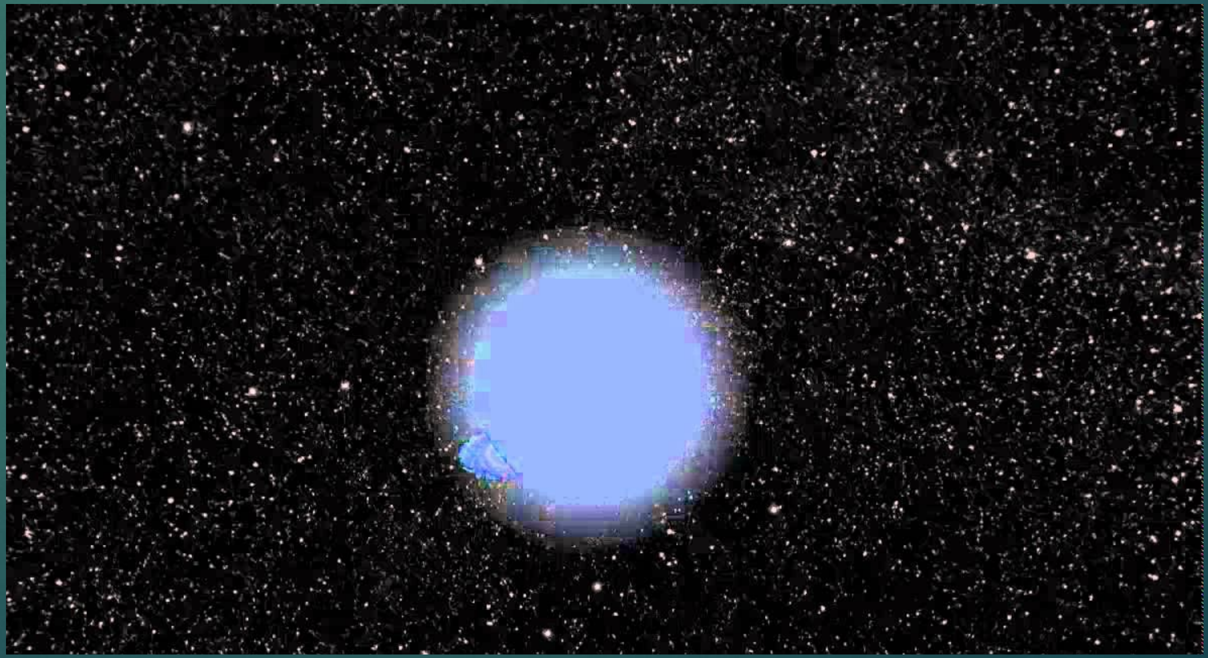
1) Virialised??

2) Large 1D velocity dispersions

Are UFD (and dSph) virialized? No definitive answers, but some examples (e.g., Ursa Major II, right) and counter-examples (e.g., Hercules, left) are present.

UFD are faint, so very difficult to identify dynamical parameters. Viral equilibrium is assumed from brighter dSph.





As for velocity dispersion, we use different % of binaries in our simulations.

<u>We DO NOT use DM density profiles, only stars!</u>

But before that…. Binaries are important!

By ROBERTO

The role of (unresolved) binaries.

$$M \le M_{vir} = \alpha \frac{R_{vir}}{G} \sigma^2_{com} < \alpha \frac{R_{vir}}{G} \sigma^2_{obs}$$

overestimate

$$\frac{\Delta M}{M} = \frac{\sigma^2_{obs} - \sigma^2_0}{\sigma^2_0}.$$

Given a binary fraction $0 < f_b < 1$ over a population of single stars

$$\sigma^2_{obs} = (1 - f_b)\sigma^2_s + f_b \sigma^2_b \Longrightarrow \frac{\Delta M}{M} \equiv \frac{M_{obs} - M}{M} = f_b \left[\left(\frac{\sigma_b}{\sigma_s} \right)^2 - 1 \right]$$

Being $\sigma^2_{com} \propto M$ while σ^2_b is not:

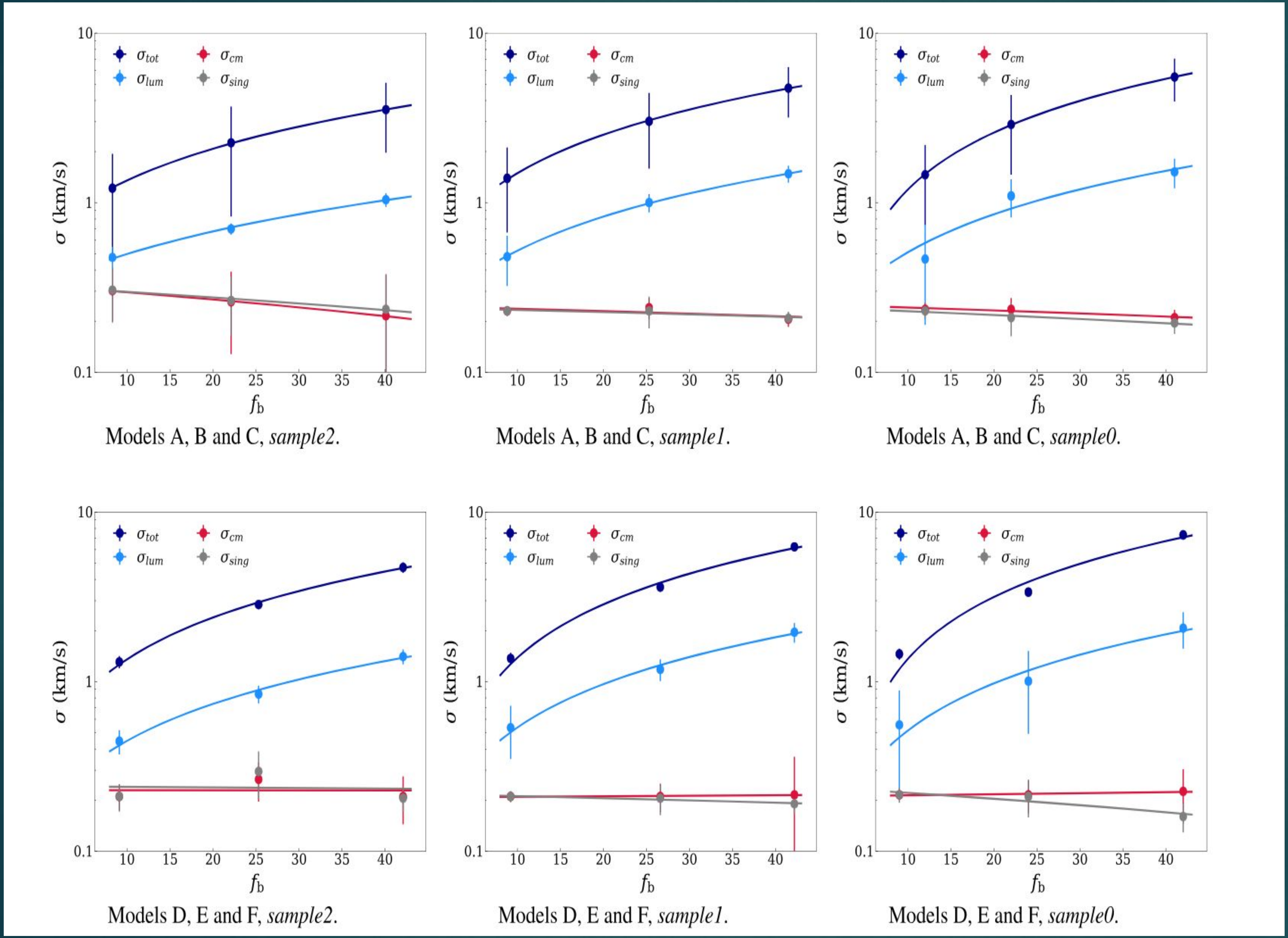
binaries affect more the *low mass* systems

M is real mass of the object.

Binaries dominates velocity dispersion in these systems.

Mass is over-estimated if the dispersion velocity is too!

What is the role of sigma for different binaries?

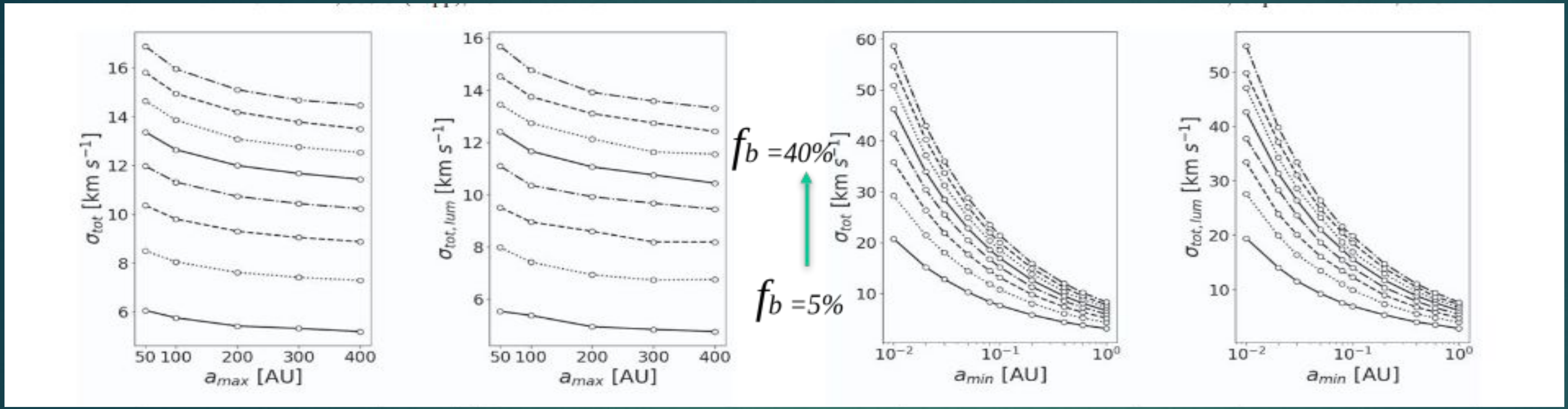


Models A, B and C, *sample2*. Models A, B and C, *sample1*. Models A, B and C, *sample0*.

Models D, E and F, *sample2*. Models D, E and F, *sample1*. Models D, E and F, *sample0*.

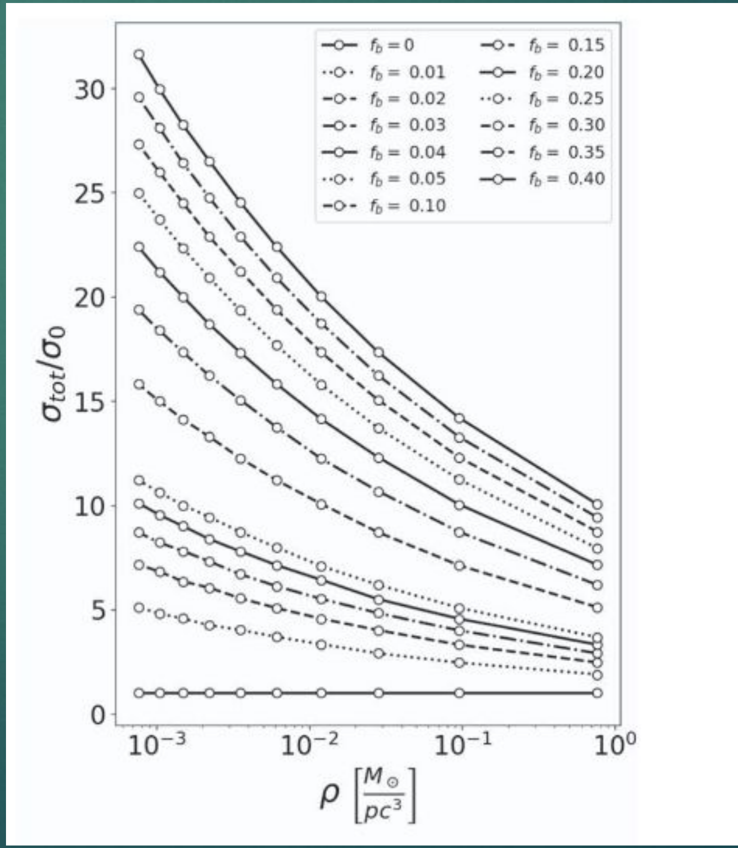
Although for open-cluster like models, Rastello 2020 already checked that large binary fraction has larger values for luminosity weighted dispersion velocity

Let’s see Pianta 2022 for dSph and UFD…



a_{min} is the minimal semi-major axis of Pianta 2022 analytical models, a_{max} the maximum.

Smaller densities have larger dispersion velocities.



Note that all these plots refers to initial conditions from observations and analytical considerations, not evolved systems like we will do!

Wider binaries reduce the dispersion velocity.

Smaller minimal semi-major axis enhance dispersion velocity.

Ultra Faint Dwarf Galaxy properties
N= 82 000 stars
Q = 0.5
r_{vir} = 50 pc
Plummer model, Kroupa 2001 IMF
No external tidal field
Simulation time = 13.7 Gyr
$t_{rel,c}$ = 6 Gyr ; $t_{df,c}$ = 1.98 Gyr
$t_{rel,hm}$ = 43 Gyr ; $t_{df,hm}$ = 14.19 Gyr
Binary properties
N_{bin} = 0,10,20,30,40,50 % of stars
model names: U0, U10, U20, U30, U40, U50
random coupling for binaries (Weidner et al. 2009; Wang et al. 2015)
a = 0.1-50 AU
Thermal distribution for eccentricity

This means that X % of the total number of stars are in binaries

$$t_{rel} = \frac{0.34\sigma^3}{G^2 m_* \rho \ln \Lambda},$$

$$t_{df} = 0.66 \frac{m_*}{m_{bin}} t_{rel} = 0.33\, t_{rel},$$

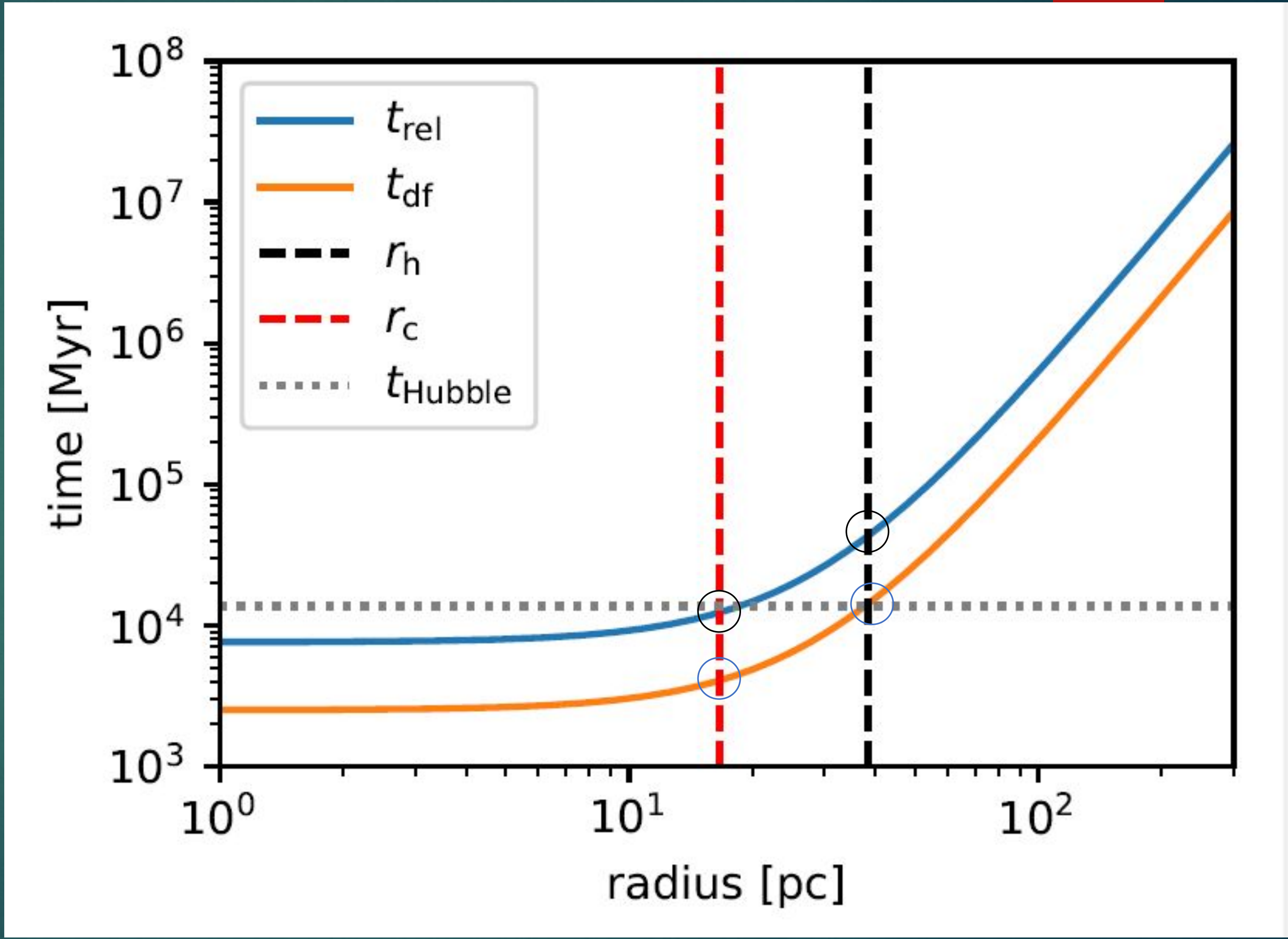
Relatively compact binaries augment the velocity dispersion (Pianta 2022)

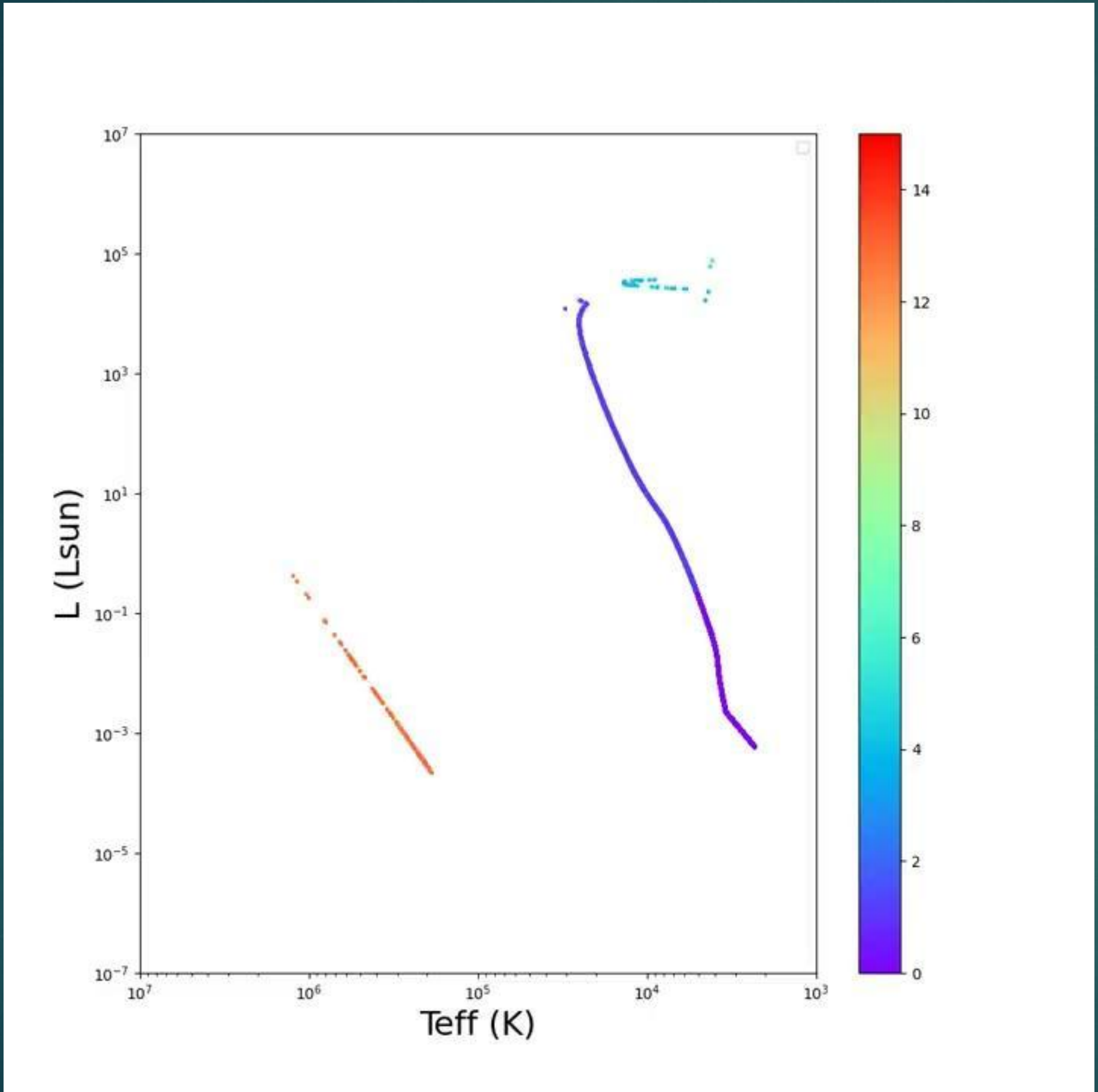
$$t_{\rm rel} = \frac{0.34\sigma^3}{G^2 m_* \rho \ln\Lambda},$$

$$t_{\rm df} = 0.66 \frac{m_*}{m_{\rm bin}} t_{\rm rel} = 0.33\, t_{\rm rel},$$

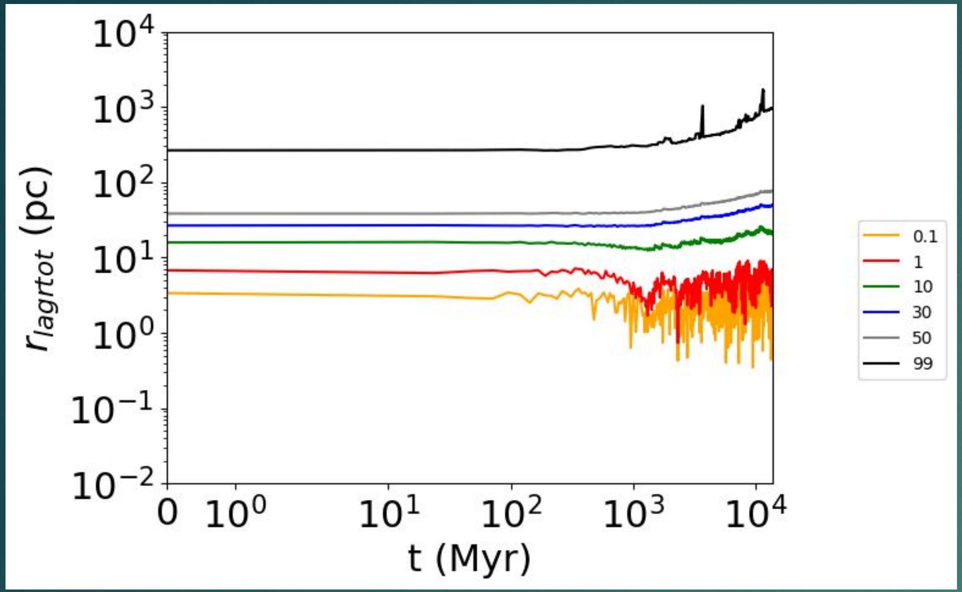
We assume the density from our initial conditions and m_* (average stellar mass) from our IMF.

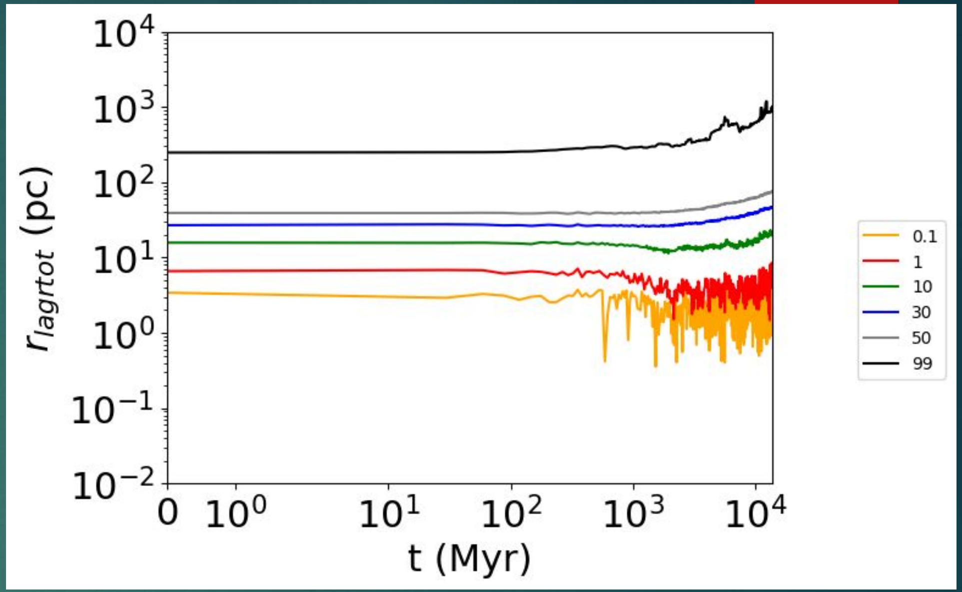
We assume the same dispersion velocity for both binaries and single stars in the dynamical friction timescale.





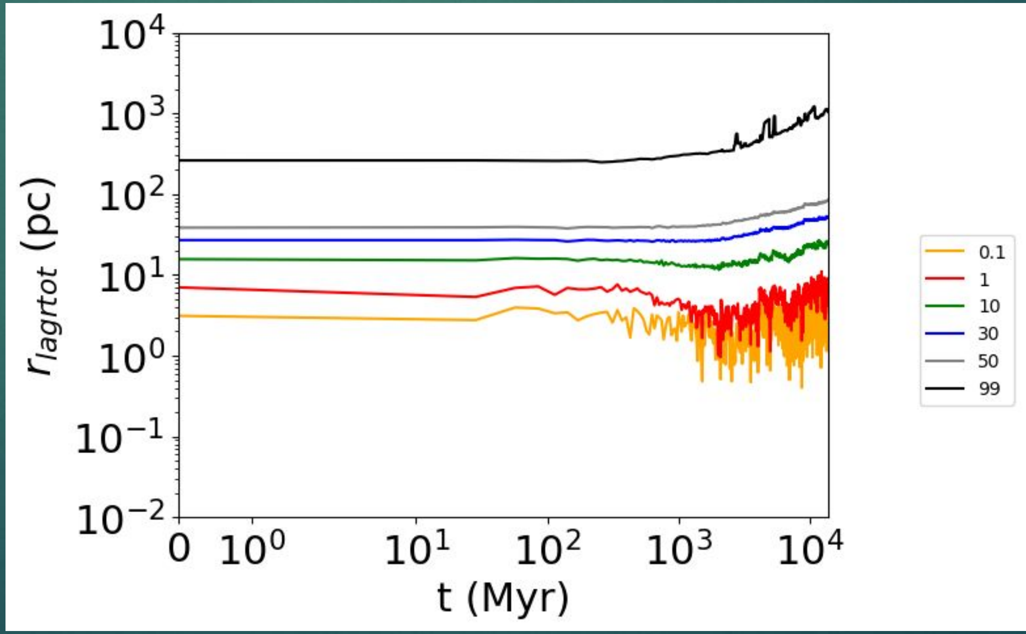
0: Low main sequence (M < 0.7)
1: Main sequence
2: Hertzsprung gap (HG)
3: Red giant (RG) branch
4: Core Helium burning
5: First Asymptotic giant branch (AGB)
6: Second AGB
7: Helium main sequence
8: Helium HG
9: Helium giant branch
10: Helium white dwarf
11: Carbon-Oxygen white dwarf
12: Oxygen-Neon white dwarf
13: Neutron star
14: Black hole
15: Massless supernova remnant

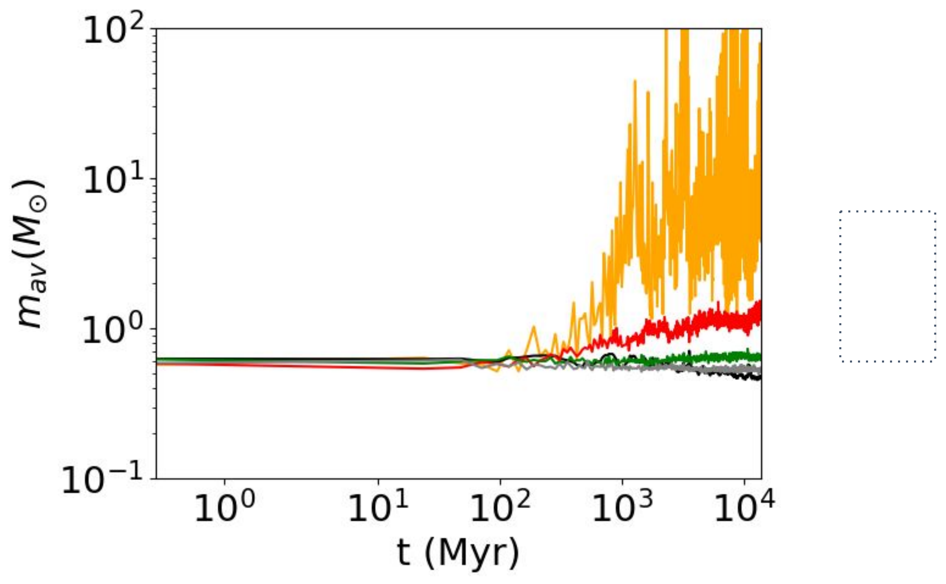


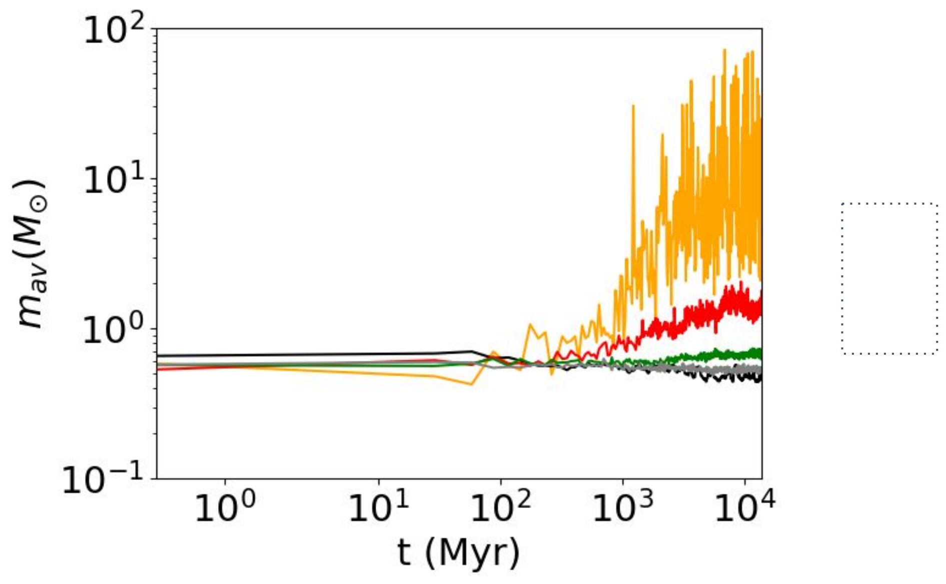


0, 20 and 40 % binaries…

No important differences in the overall dynamics. All system start to segregate around 1 Gyr.







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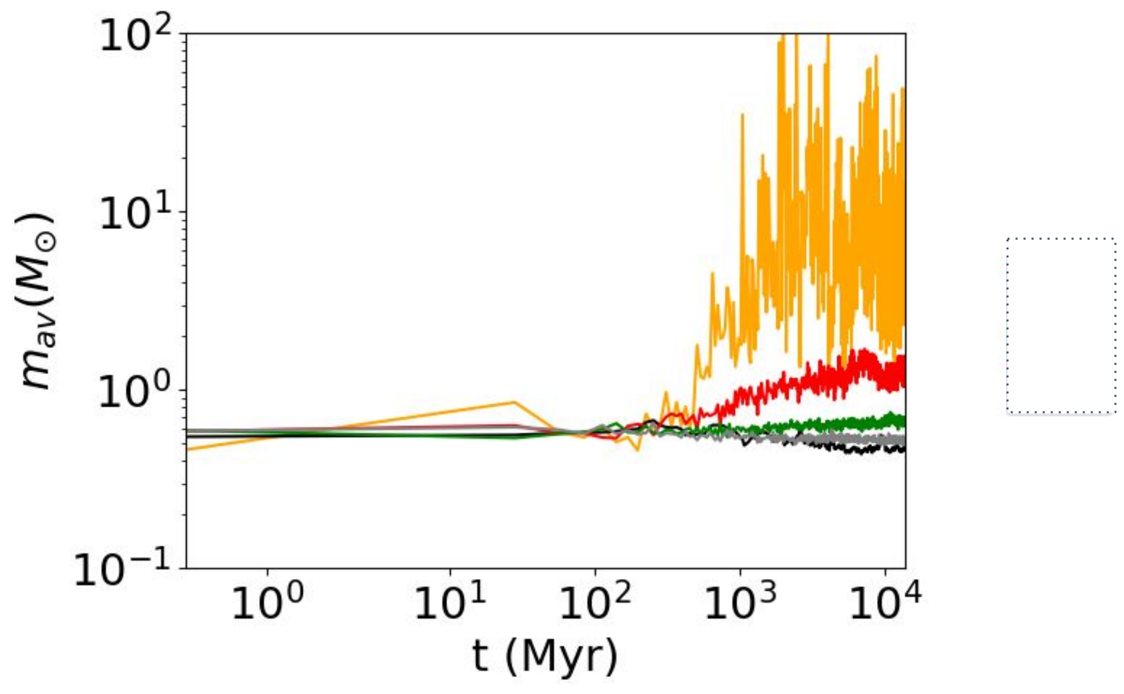
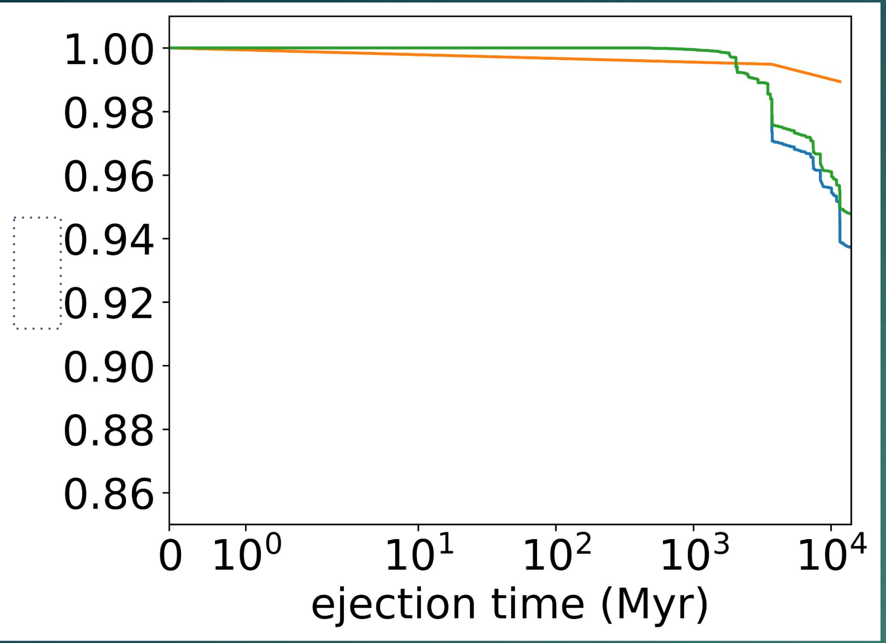
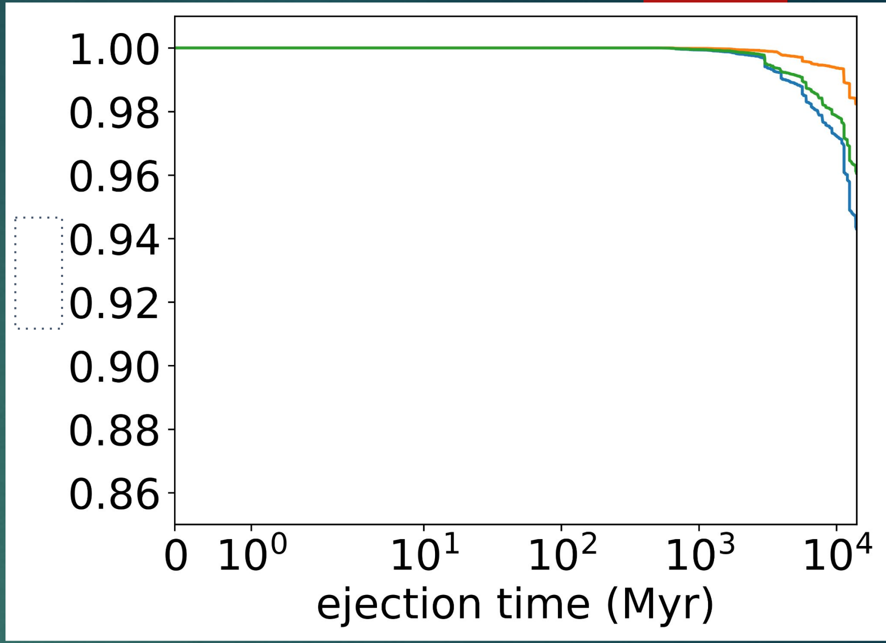


Orange 1 %
Red 10 %
Green 50 %
Grey 70 %
Black 99 %

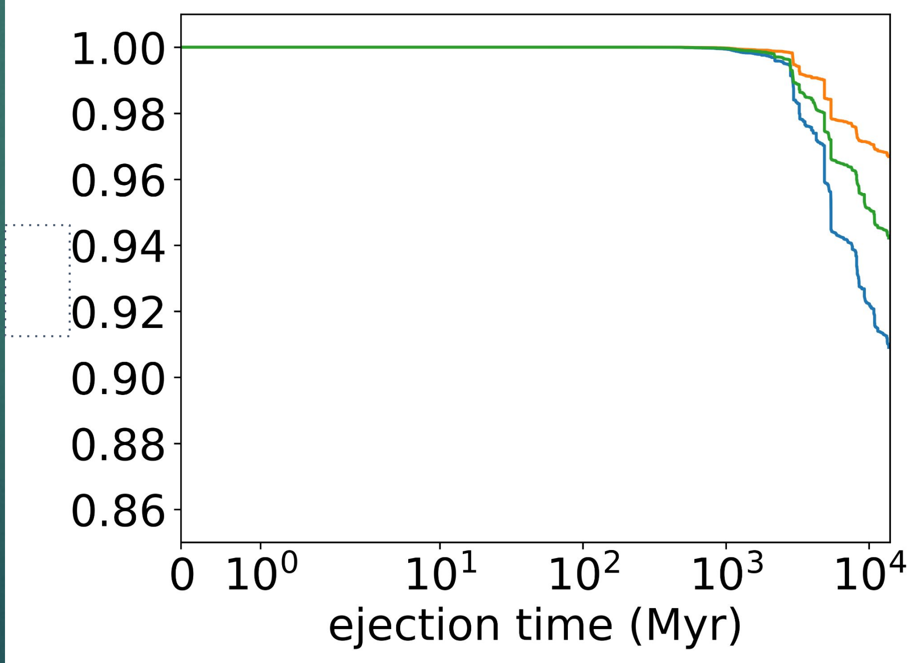


Orange is binaries
Green is single stars
Blue is overall

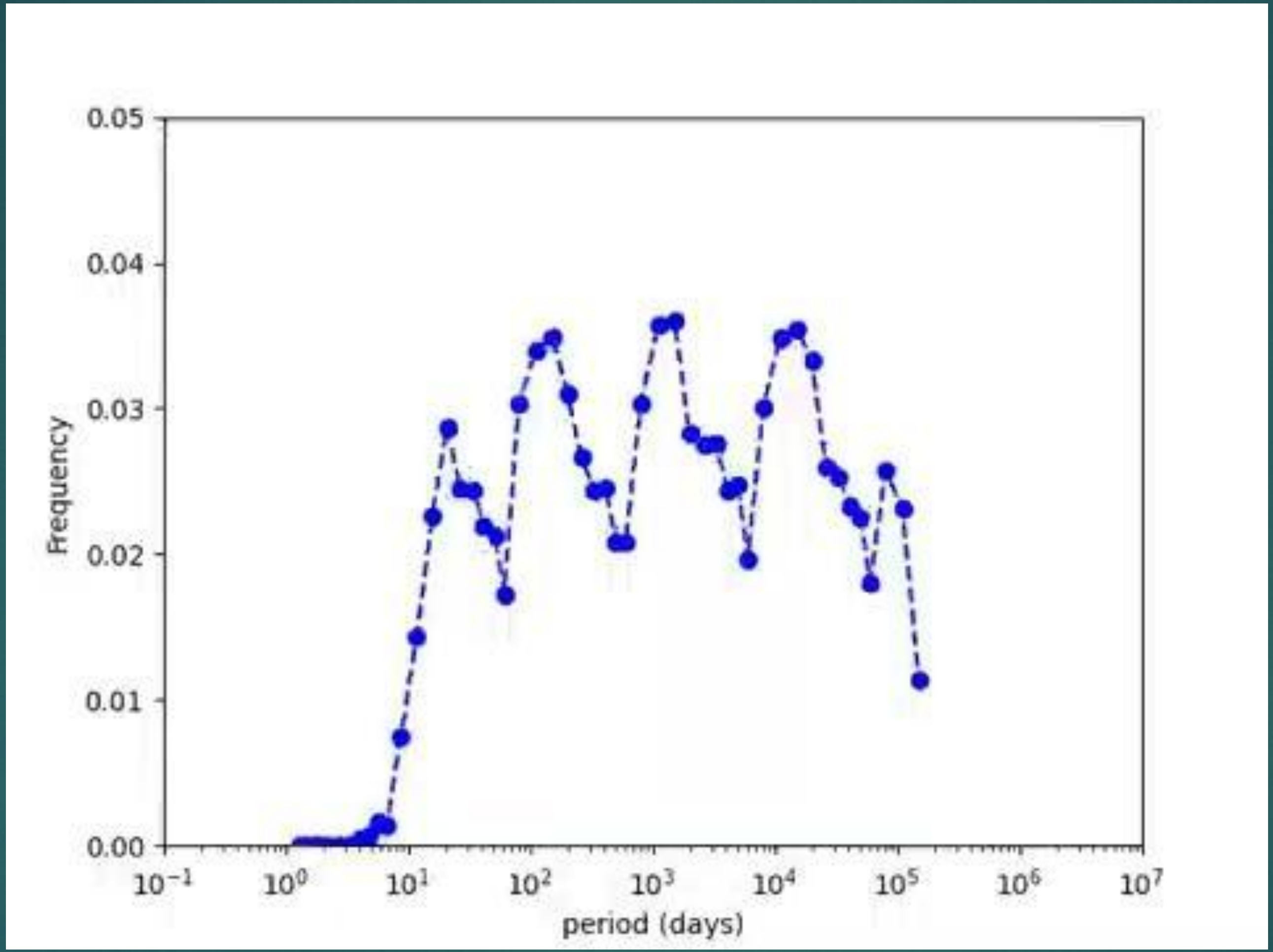


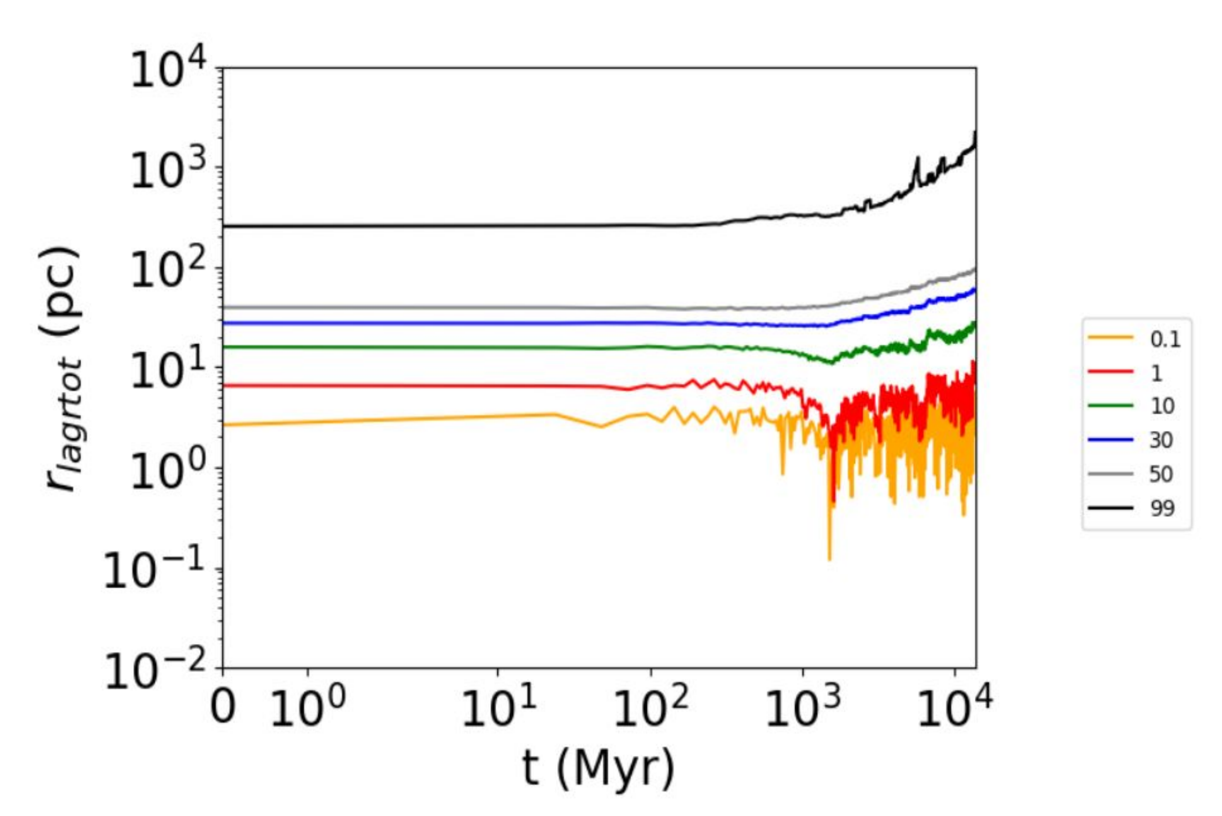
0, 20 and 40 % binaries…

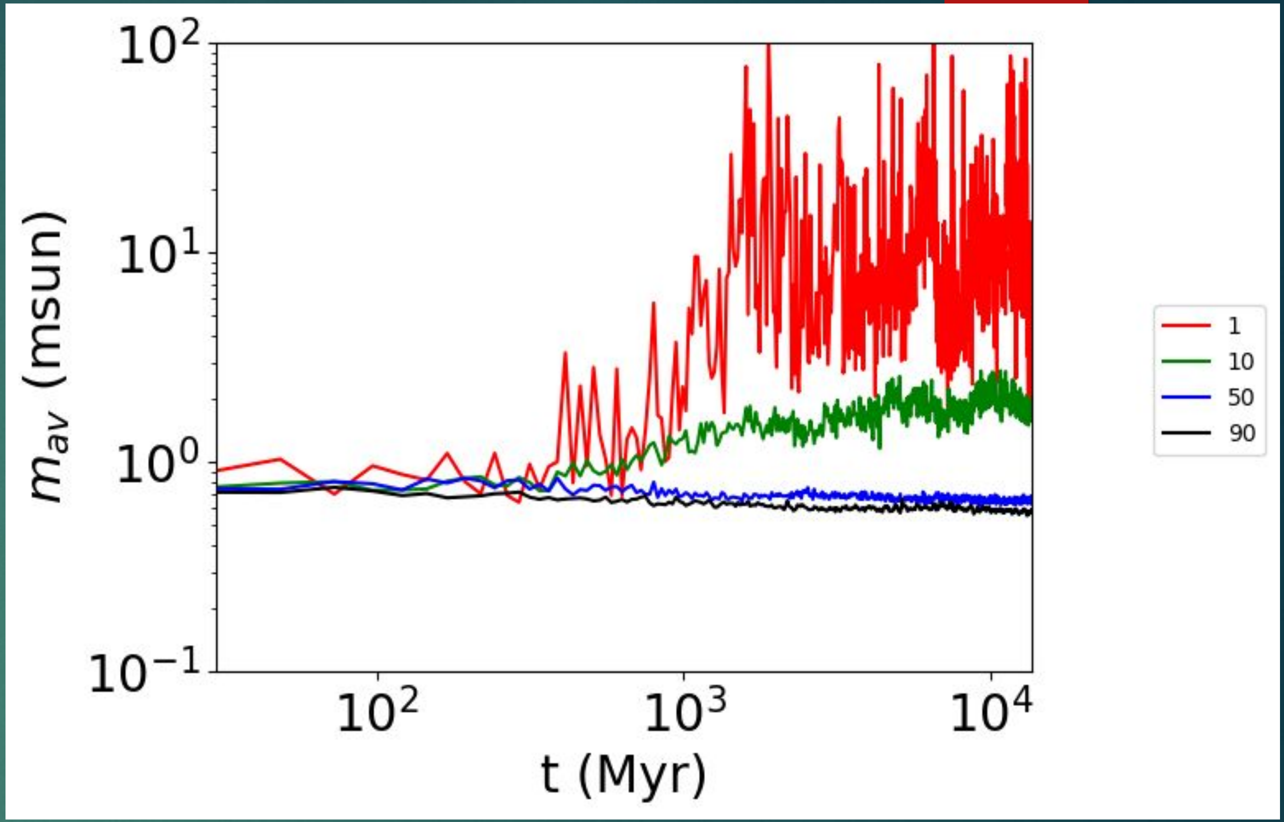
The surviving number of particles seems to be extremely similar, although slightly more particle are removed in the 40 % sim.



Let us analyse the 30 % model, which is possibly the most realistic model

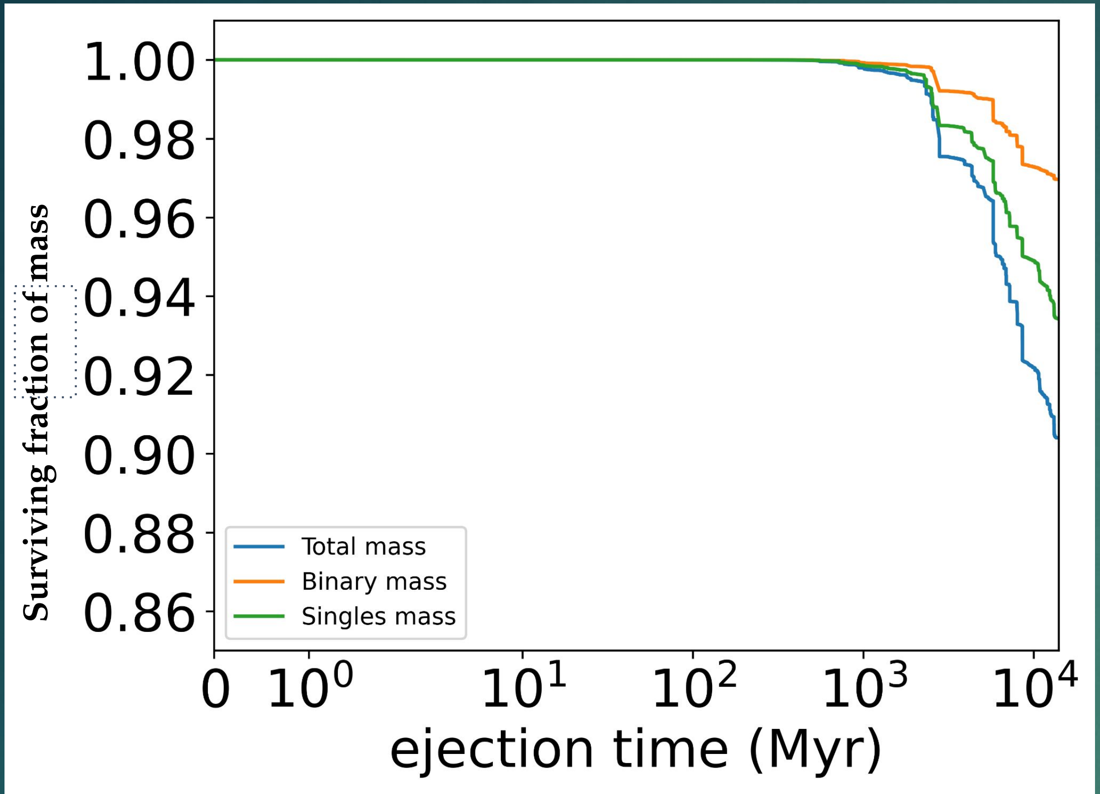

0.05
0.04
0.03
0.02
0.01
0.00
Frequency
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
period (days)

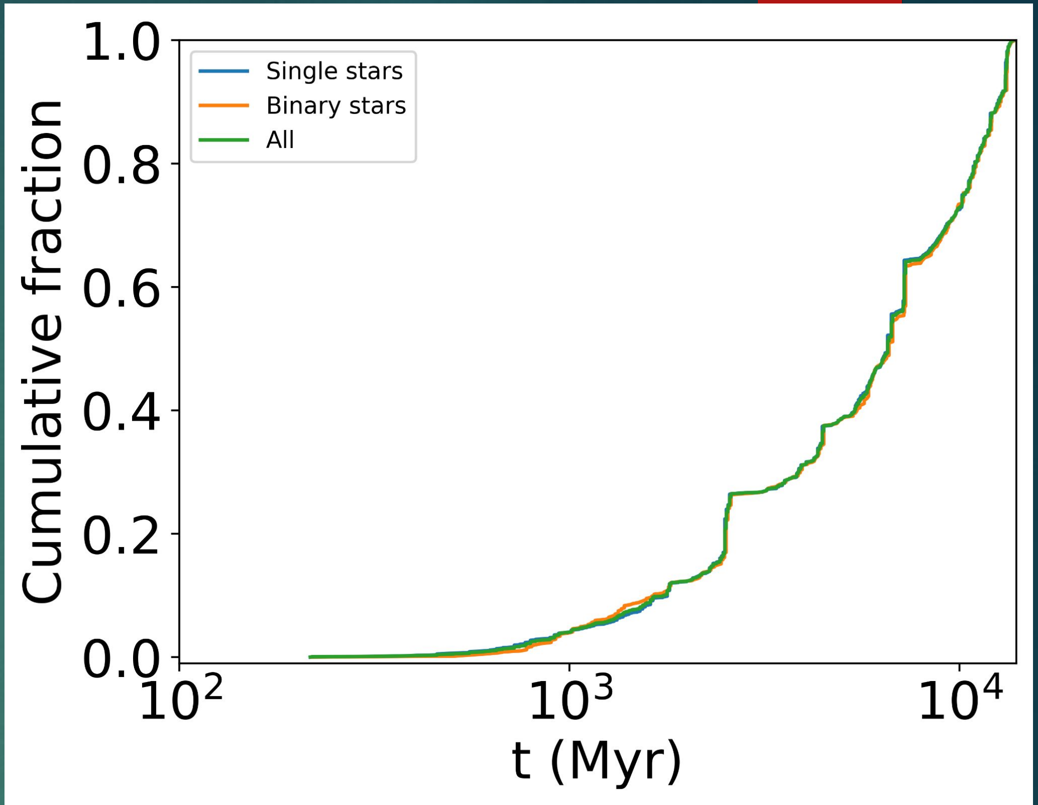




The lagrangian radii evolves similarly to the other models.

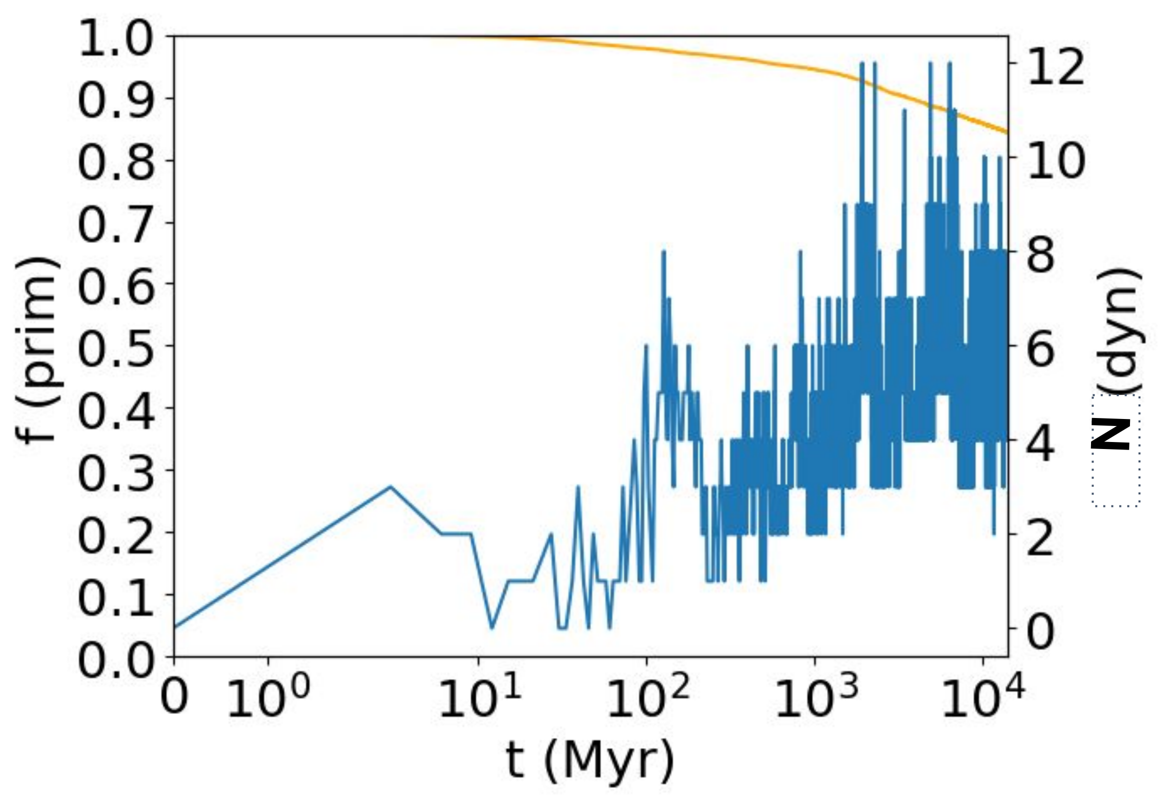
The segregation starts a little before 1 Gyr. Binaries are put in the core and giants are also formed around that time.

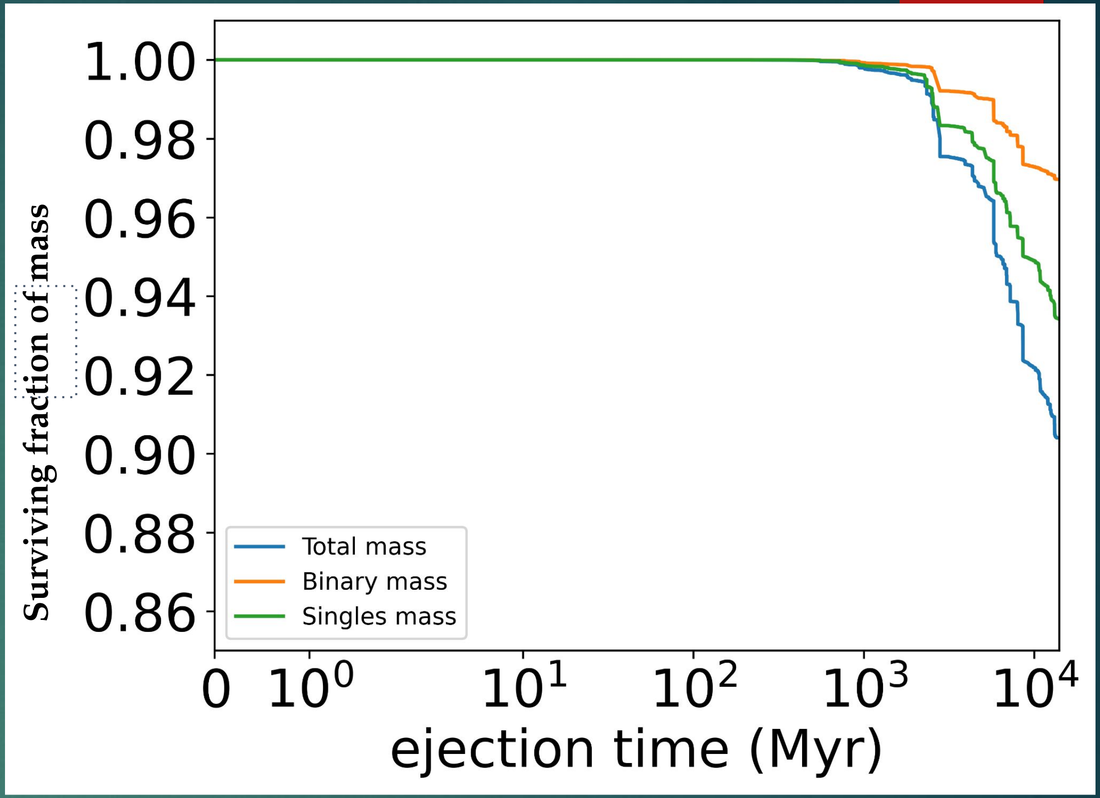




The system lose about 10 % of the total mass in an Hubble time. 6 % comes from single stars, 4 % from binaries.

The mass loss of the UFD grows during the segregation of stars and steady grows after 1 Gyr.
We lose just 20 % of total number of particles in the first 3 Gyr, and 80 % in the following 10.7 Gyrs.

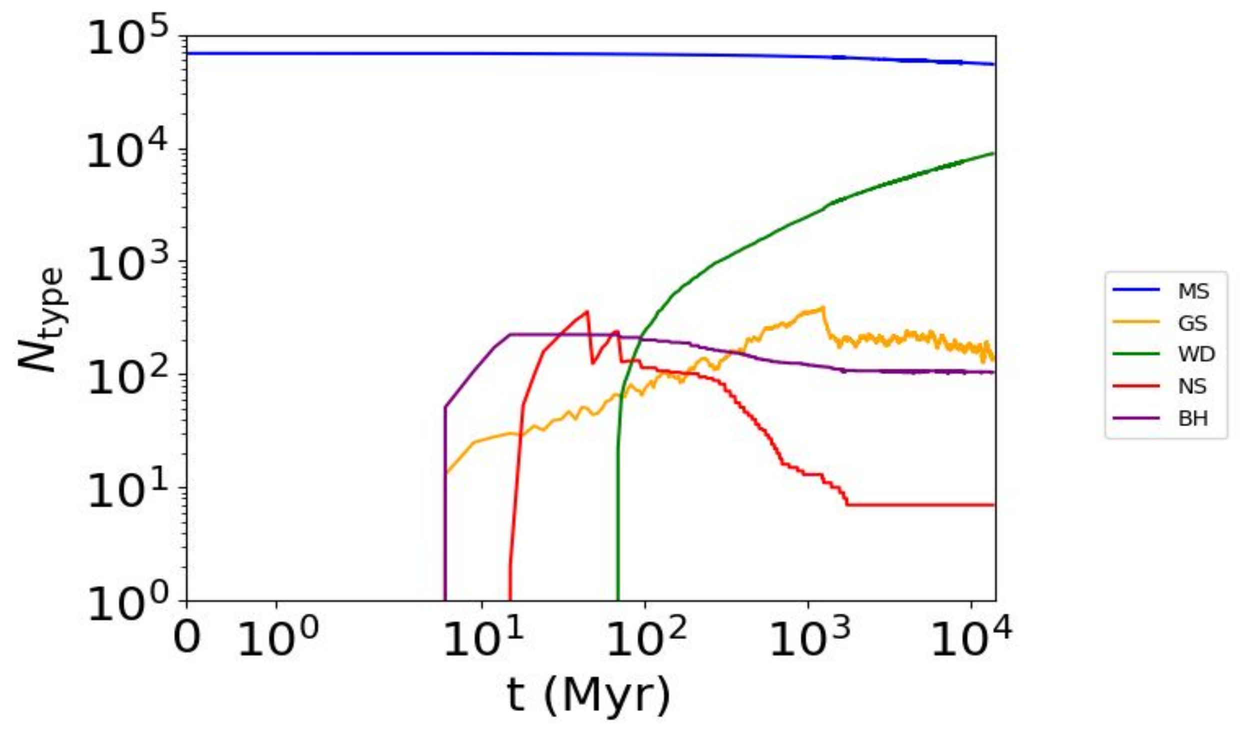


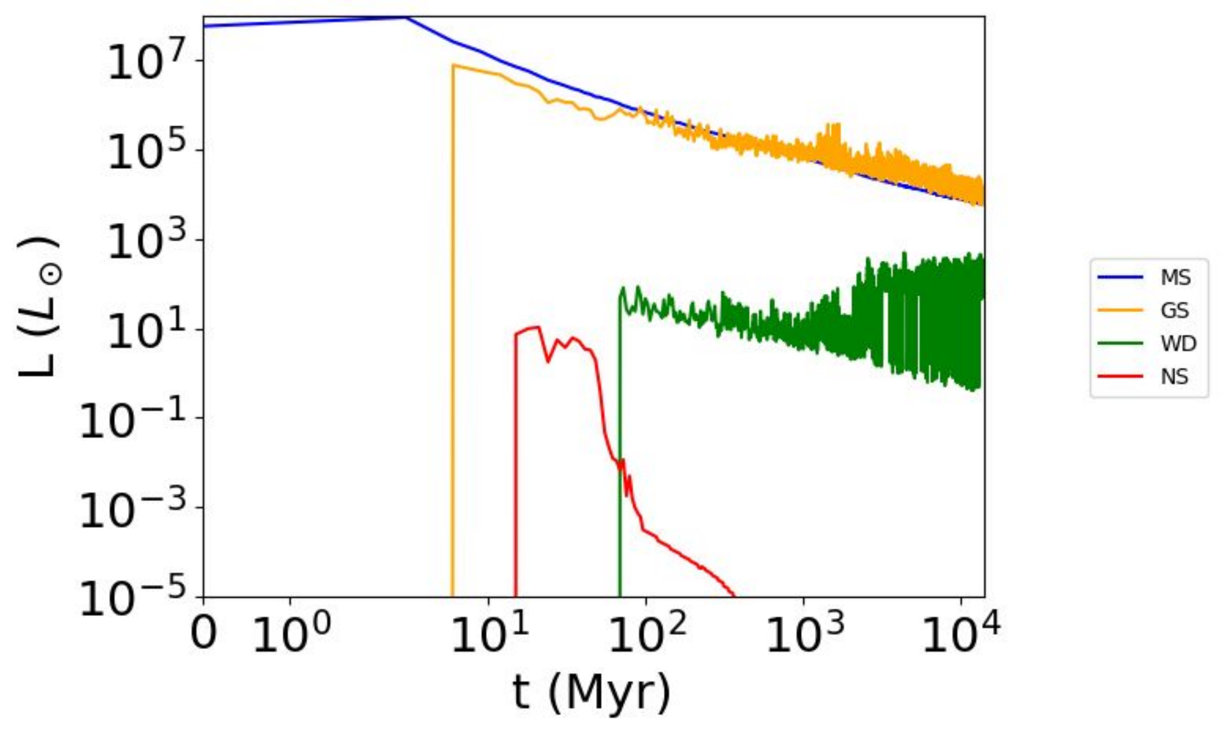


Dynamical binaries are too little and are destroyed quite quickly. All these binaries, in all models, are wide (> 10^3 AU).

Primordial binaries, are ejected up to 16 % compared to the initial number of binaries, resulting in the mass loss on the right.

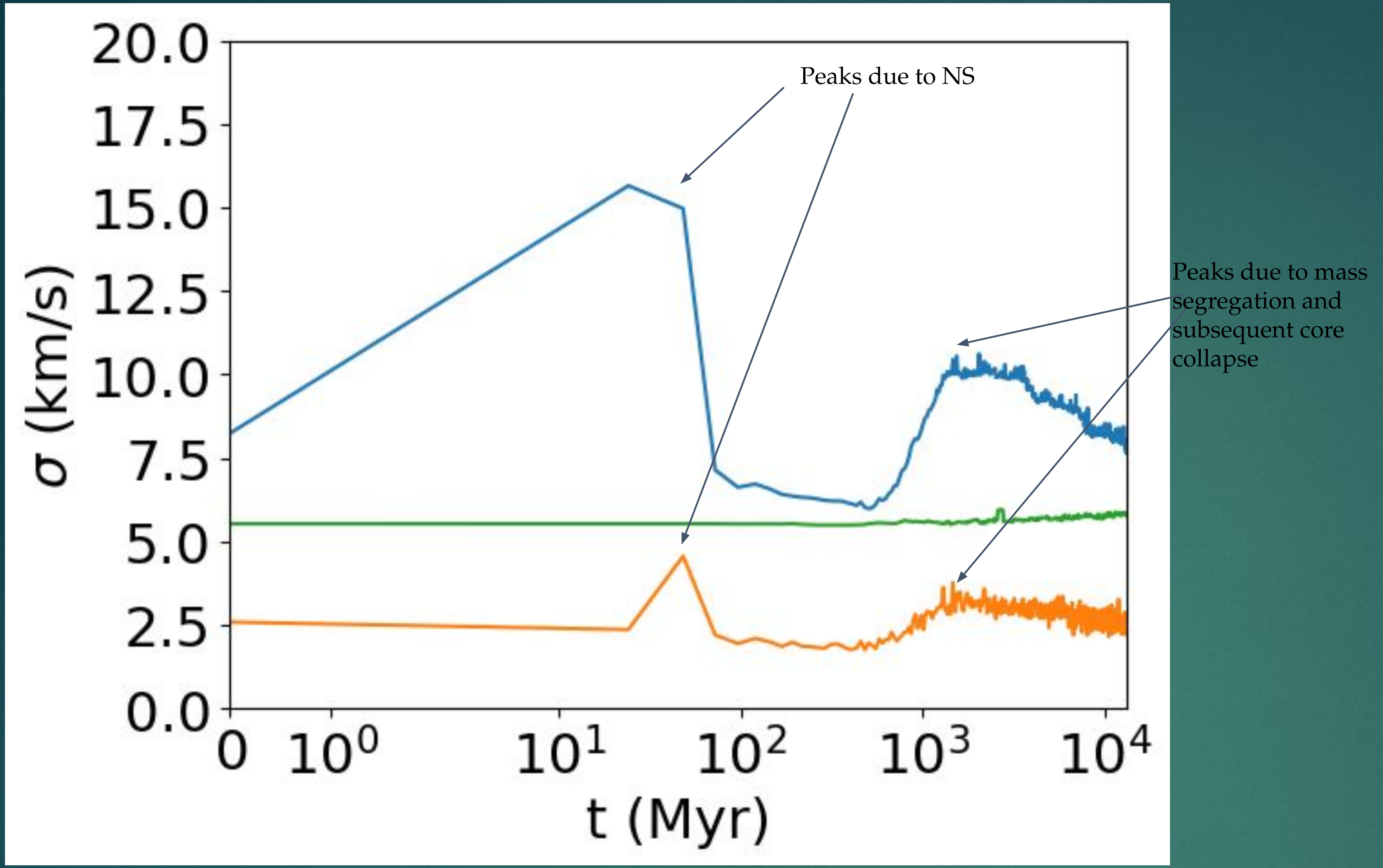
And what about luminosity?





Numerically, as expected MS stars dominates. Although isolated, the system losses some NS. WD and GS are the two other more common objects.

Luminosity-wise, RG becomes the more luminous objects after 1 Gyr.



1. Method 1: the total velocity dispersion (hereafter, denoted with $\sigma_{\rm tot}$) is estimated accounting for all the stars of the cluster as if "they were all single stars," i.e., independently of possible binarity. In practice, given N velocity vectors, $\boldsymbol{v}_i$ ($i = 1,2, \ldots, N$), we scaled them to the proper rest frame to evaluate the total velocity dispersion

$$\sigma_{\rm tot} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2}, \qquad (1)$$

where v_i is the absolute value of $\boldsymbol{v}_i$.

2. Method 2: here we make a distinction between the N_s single stars and the N_b binaries, in that, in the velocity dispersion calculation, we consider for every jth ($j = 1,2, \ldots, N_b$) binary composed by the two masses $m_{A,j}$ and $m_{B,j}$, only its center of mass velocity,

$$\boldsymbol{v}_{{\rm cm},j} = \frac{m_{A,j}\boldsymbol{v}_{A,j} + m_{B,j}\boldsymbol{v}_{B,j}}{M_j}, \qquad (2)$$

where $M_j = m_{A,j} + m_{B,j}$ is the binary mass, to evaluate the cluster velocity dispersion as

$$\sigma_{\rm cm} = \sqrt{\frac{1}{N_s + N_b}\left(\sum_{i=1}^{N_s} v_i^2 + \sum_{j=1}^{N_b} v_{{\rm cm},j}^2\right)}. \qquad (3)$$

3. Method 3: here we keep a distinction between single and binary stars but, in this case, for every binary we consider a luminosity averaged velocity

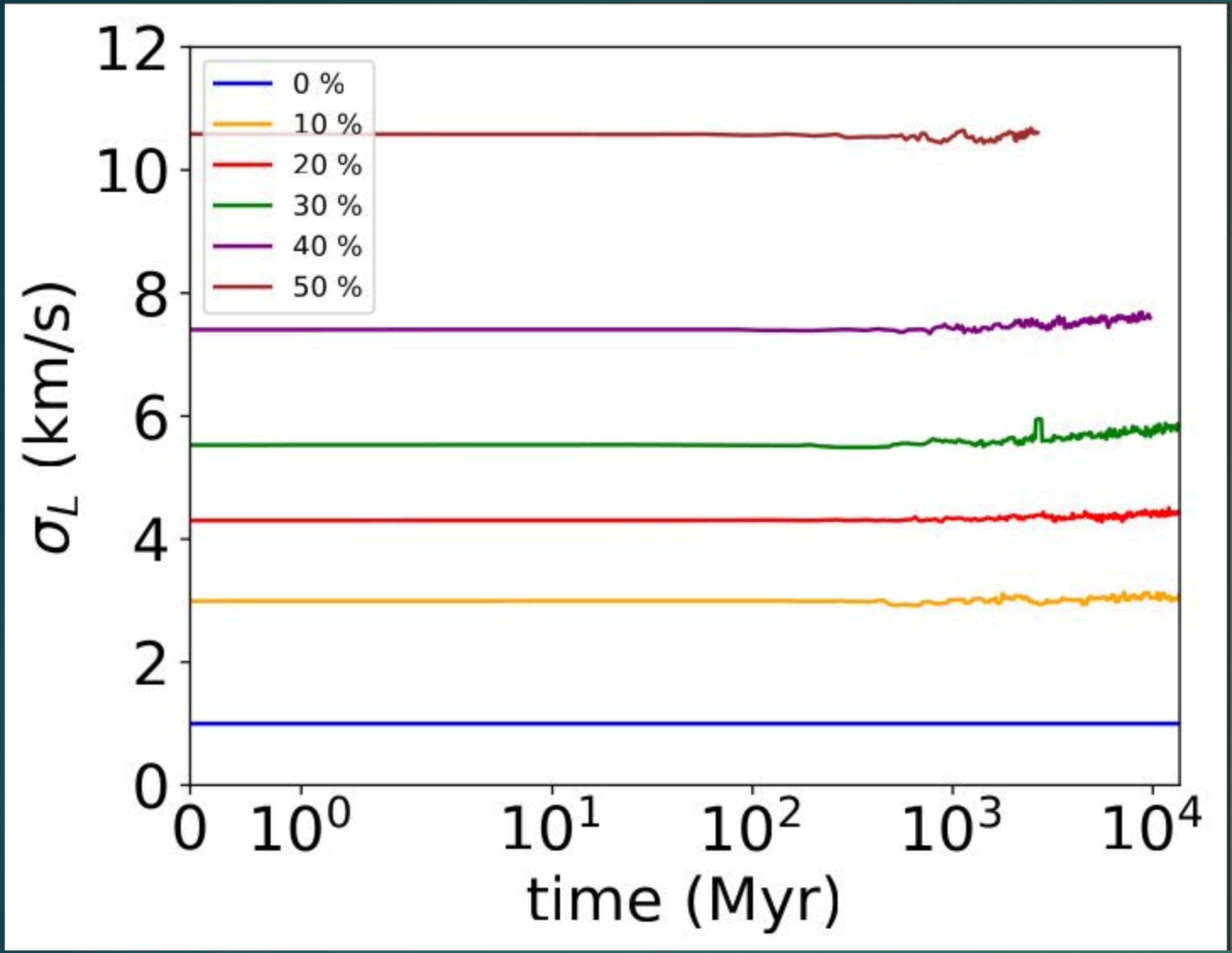
$$\boldsymbol{v}_{{\rm lum},j} = \frac{L_{A,j}\boldsymbol{v}_{A,j} + L_{B,j}\boldsymbol{v}_{B,j}}{L_j},$$

where $L_j = L_{A,j} + L_{B,j}$ is the binary total bolometric luminosity, so to have a dispersion, $\sigma_{\rm lum}$, defined as

$$\sigma_{\rm lum} = \sqrt{\frac{1}{N_s + N_b}\left(\sum_{i=1}^{N_s} v_i^2 + \sum_{j=1}^{N_b} v_{{\rm lum},j}^2\right)}. \qquad (4)$$

Orange is center of mass velocity dispersion
Green is luminosity weighted velocity dispersion
Blue is total velocity dispersion

The luminosity depends on the sources. MS luminosity is constant, and it is altered only when the RG contribution to luminosity grows.



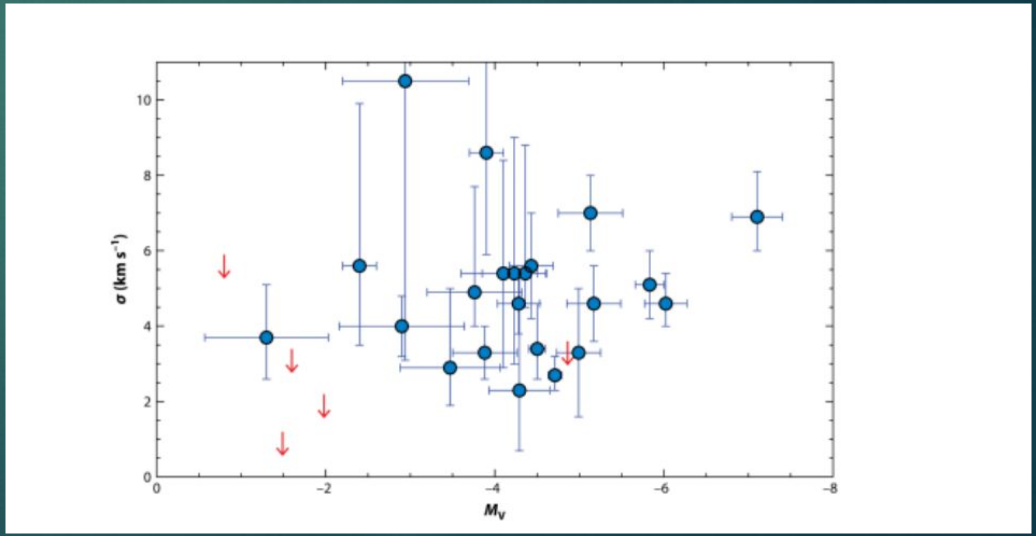
More binaries larger dispersion velocity.

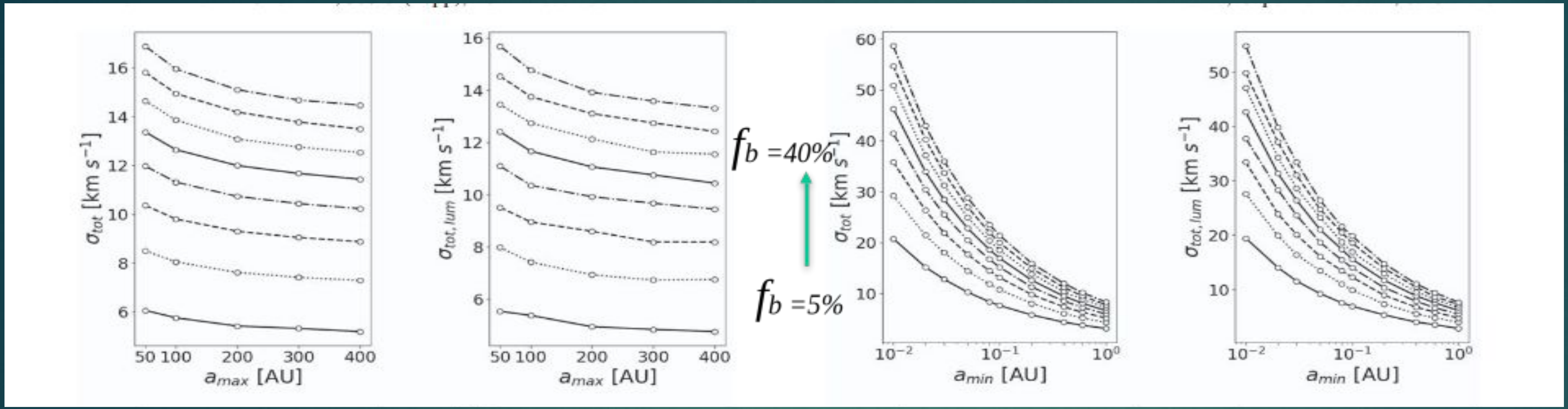
We can estimate roughly, the binary percentage.

20-30 % seems a good estimation… ***but we didn't account for DM!!!!!***

And how about the estimation on DM dominated UFD?
These results tell us that there is an overestimation of DM, as our system have comparable dispersion velocity to observational ones!

No need for large DM abundance if there are undetected binaries!

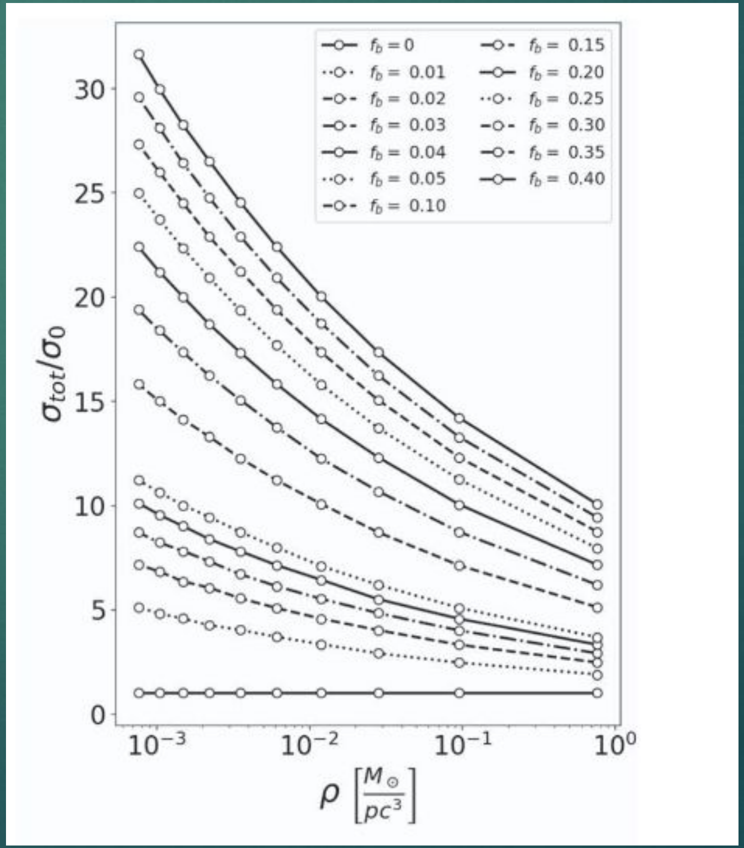




a_{min} is the minimal semi-major axis of Pianta 2022 analytical models, a_{max} the maximum.

Smaller densities have larger dispersion velocities.

Note that all these plots refers to initial conditions from observations and analytical considerations, not evolved systems like we will do!



Wider binaries reduce the dispersion velocity.

Smaller minimal semi-major axis enhance dispersion velocity.

Conclusions

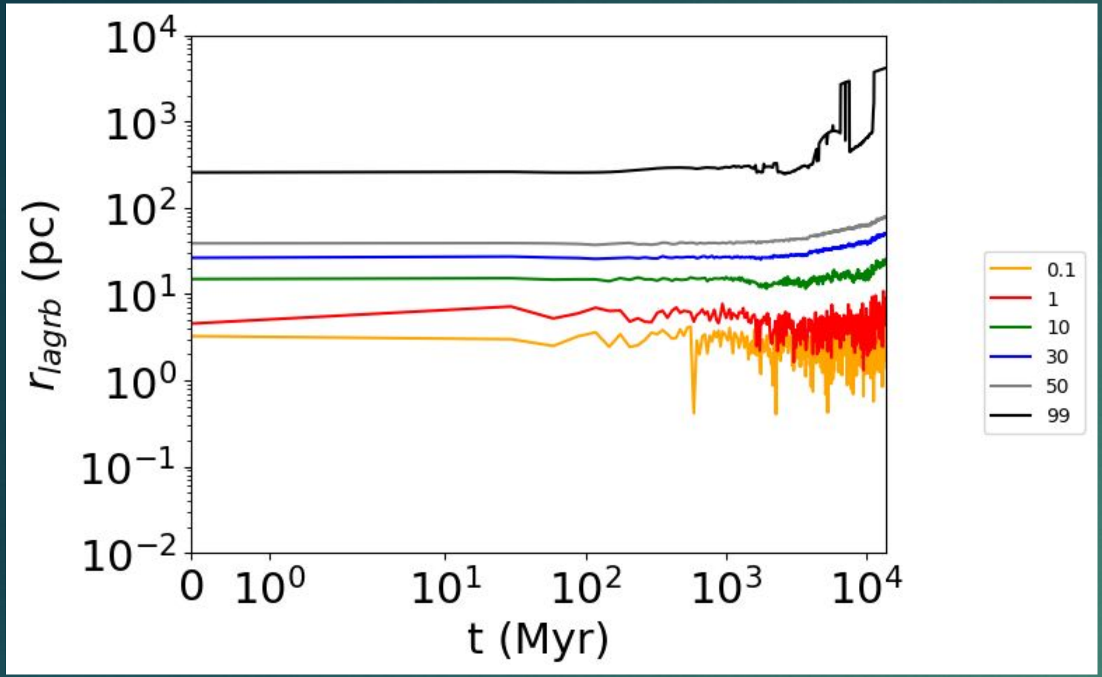
1. The dynamical evolution of an UFD is basically collisionless until 1 Gyr. The presence of binaries, at a dynamical friction time, result in segregation and collisions.

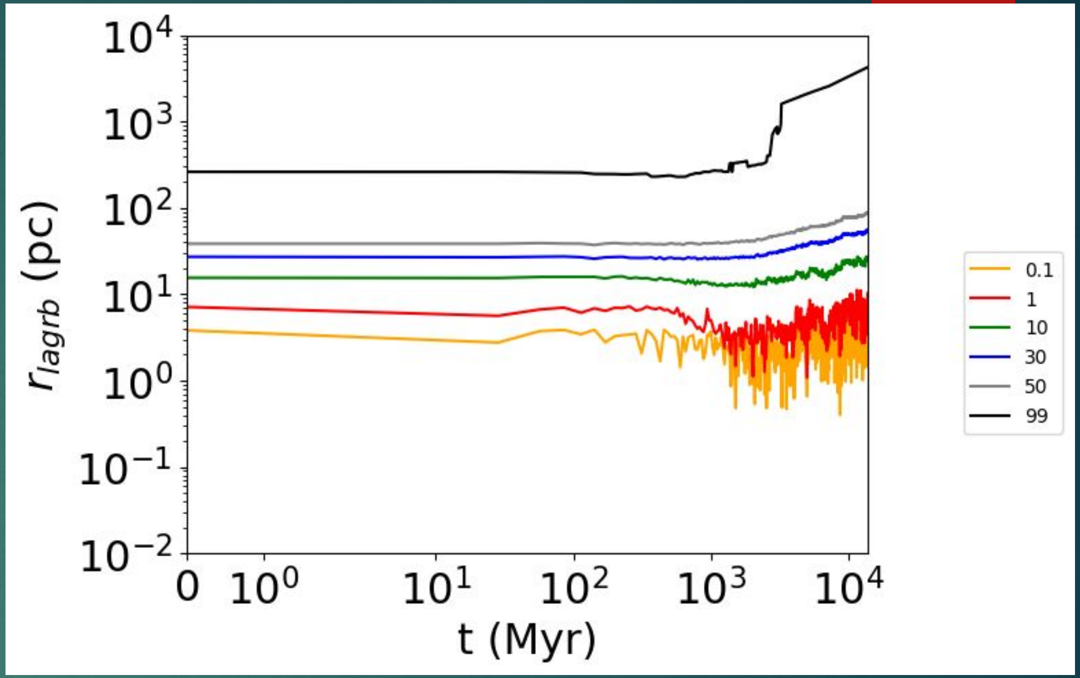
2. The mass loss is small in the span of an Hubble time, thus these objects are possibly still massive and lost a small percentage of binaries.

3. The dispersion velocity in UFD is overestimated if we don’t account for undetected binaries. Their roles is fundamental for an accurate understanding of this objects.

Future perspectives

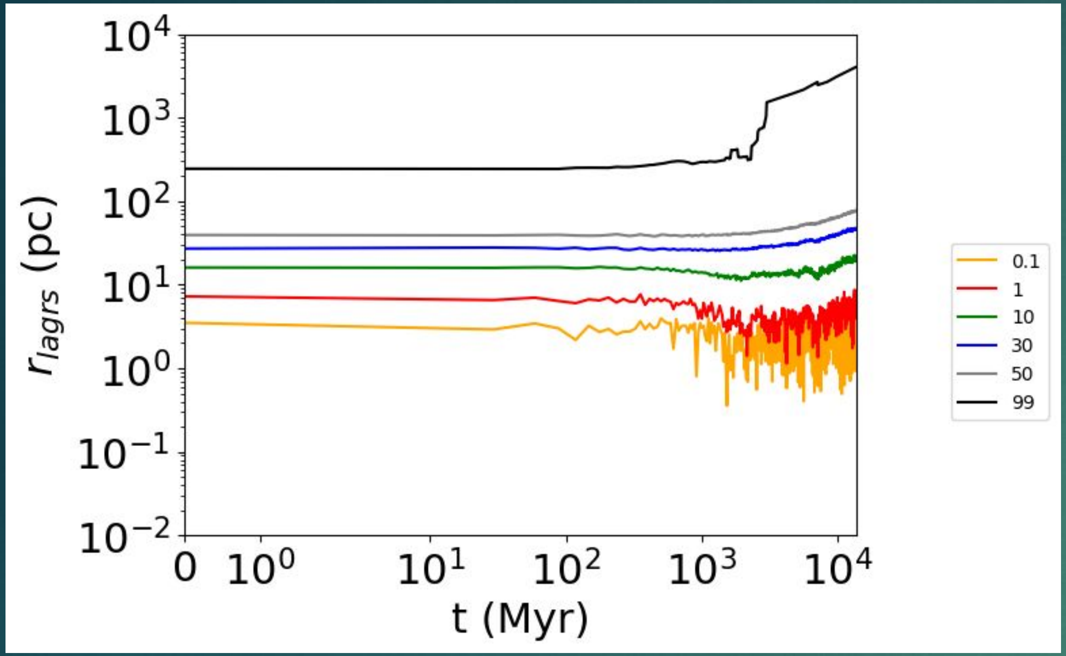
1. Finding exotic or strange objects in our UFD, and continuing the 50 % simulation
2. Analysing the mass segregation observed in these objects, and considering using different types of density profiles
3. Analyse different UFDs with our new knowledge!

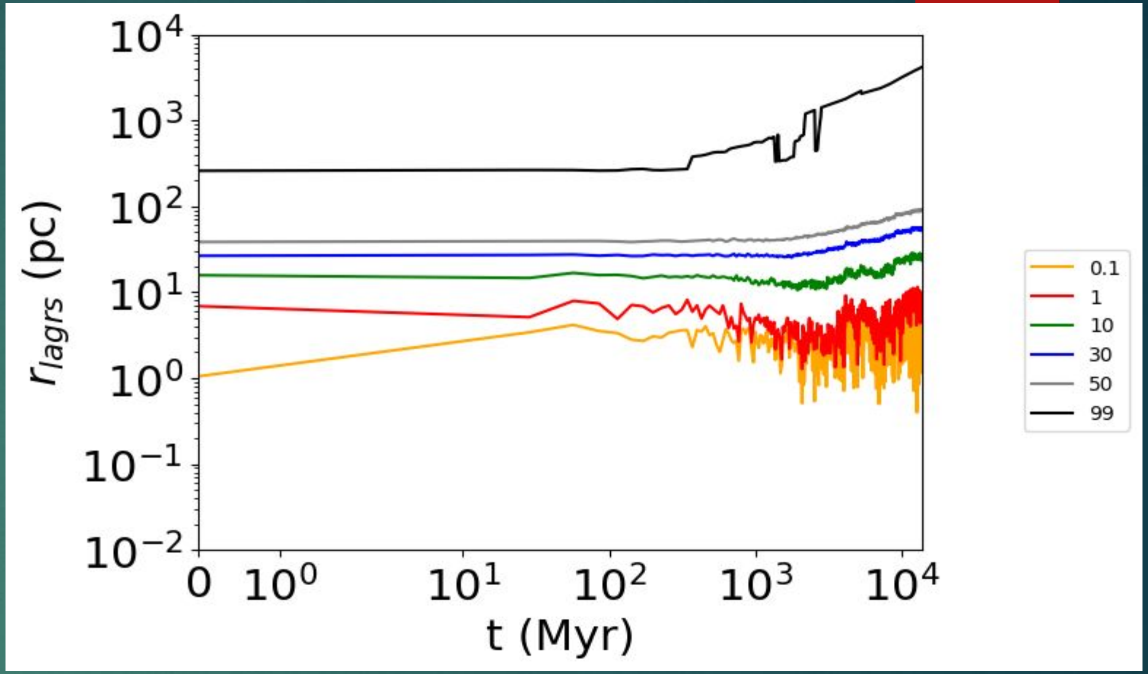




20 % and 40 %, for 0 % the plots there is just a few dynamical binaries.

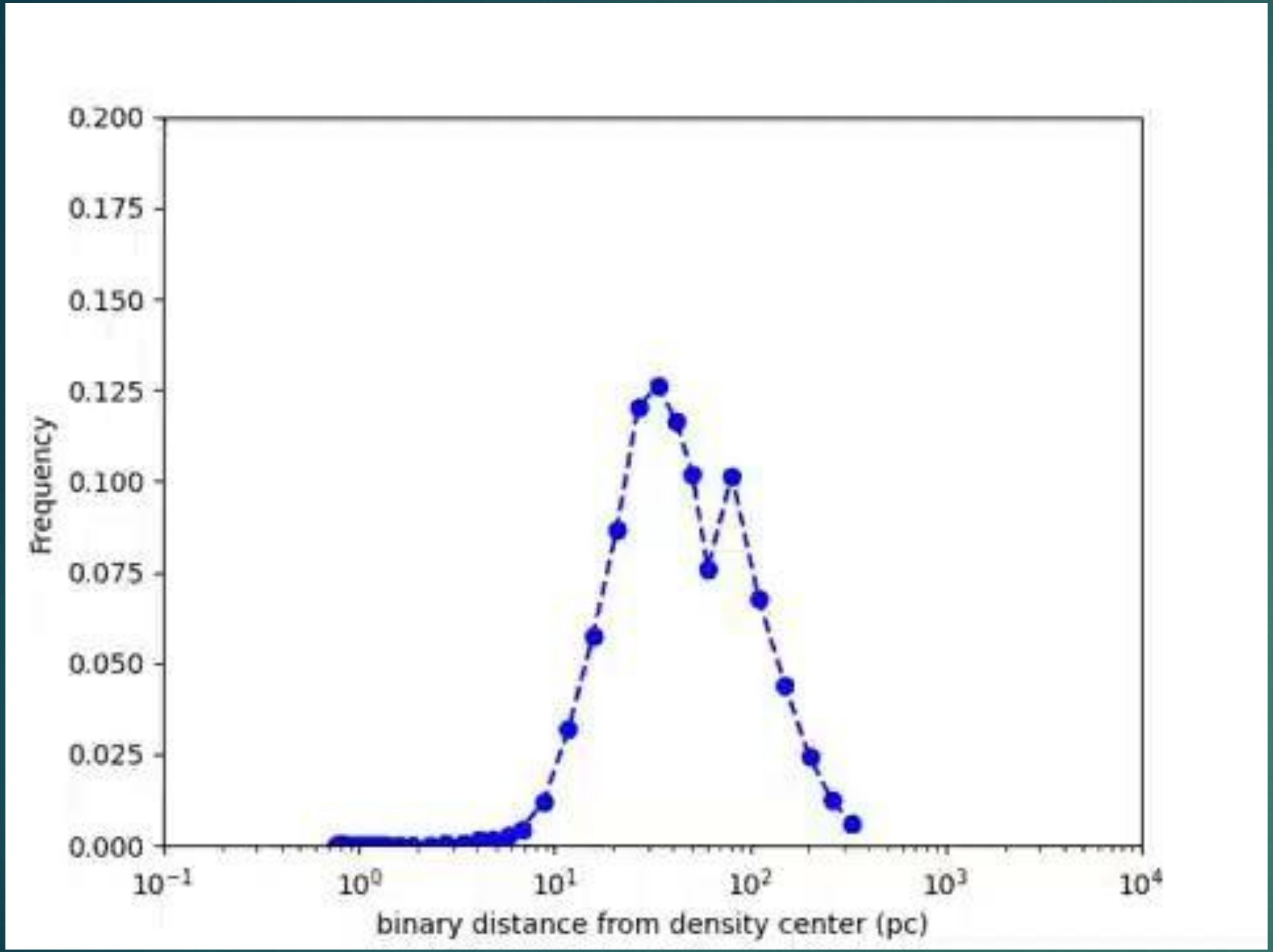
The binary component behaves similarly, except the inner regions are initially more compressed for single stars in the 40 % model. This eventually affects the overall evolution of the outer stars near the segregation time at 1 Gyr.



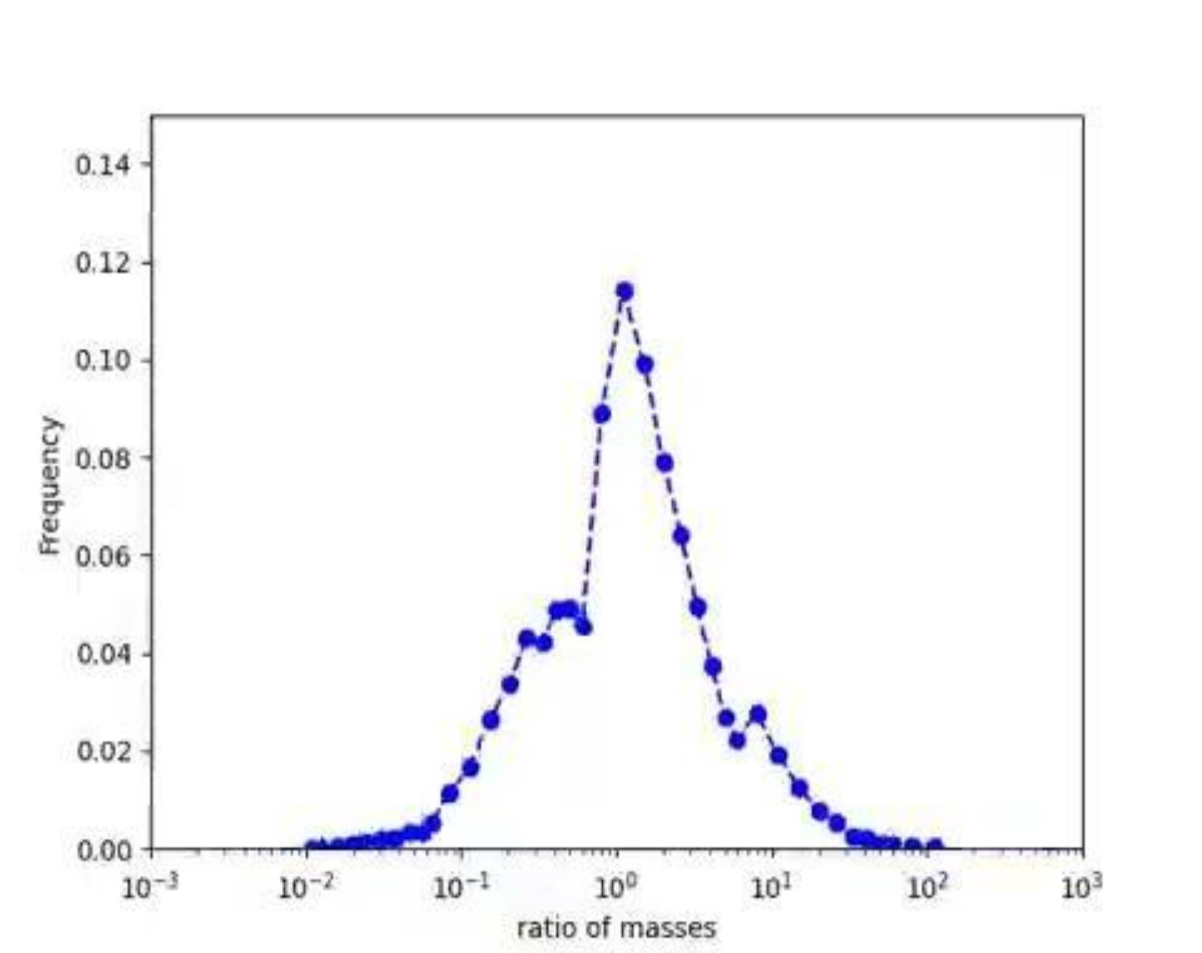


20 % and 40 %, for 0 % the plots are going to be extremely similar.

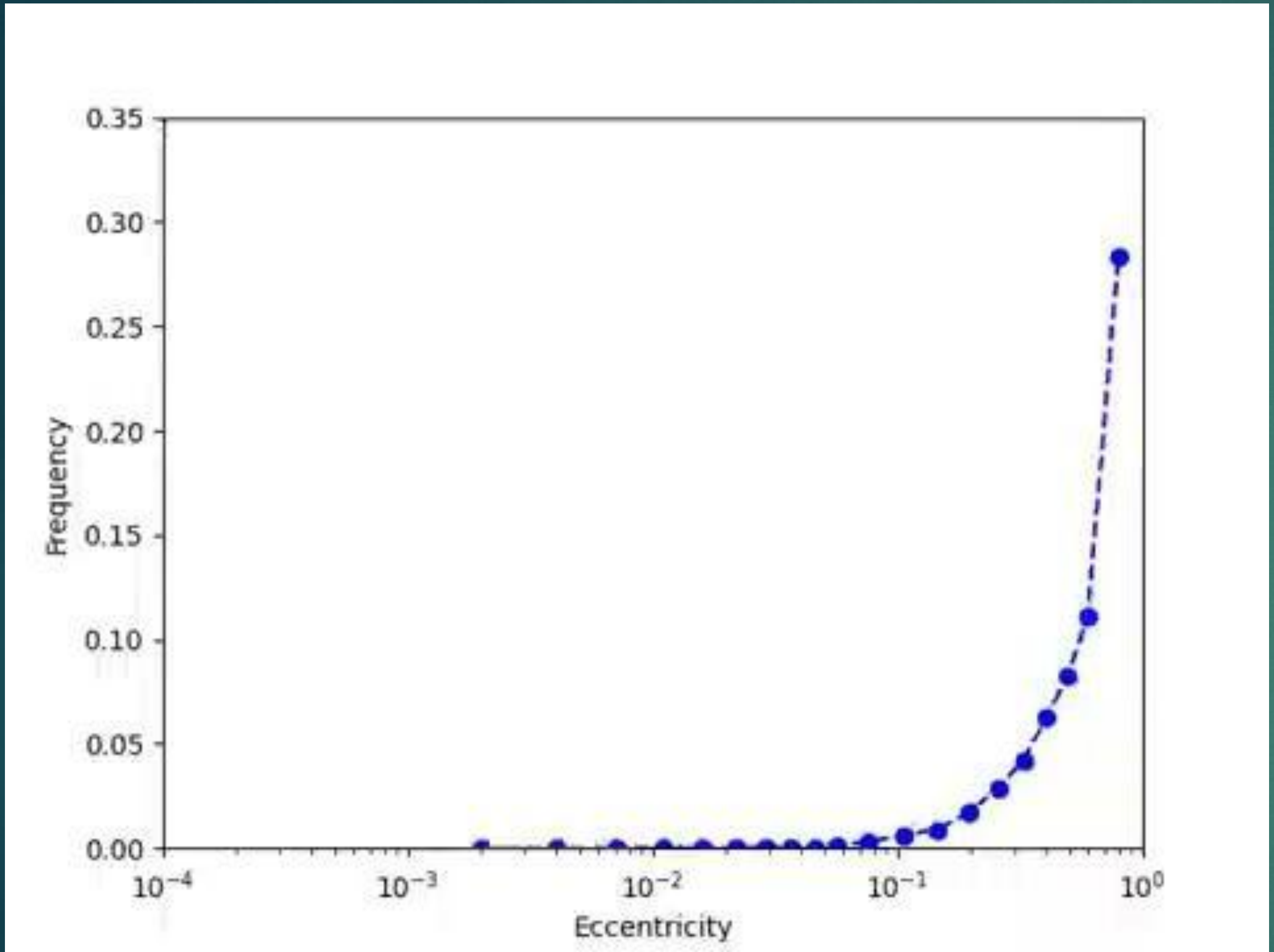
The single component behaves similarly, except the inner regions are initially more compressed for single stars in the 40 % model. This eventually affects the overall evolution of the outer stars near the segregation time at 1 Gyr.

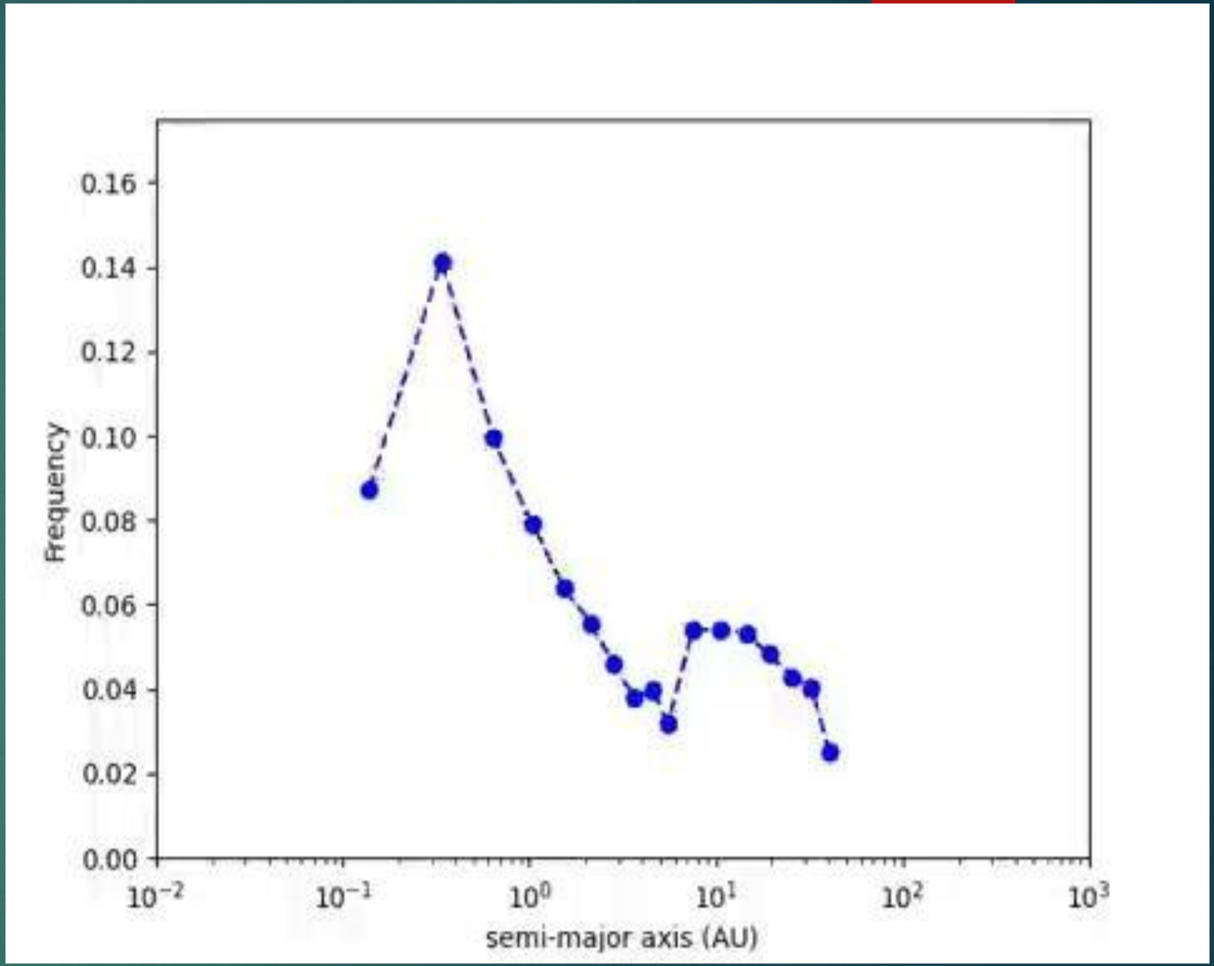


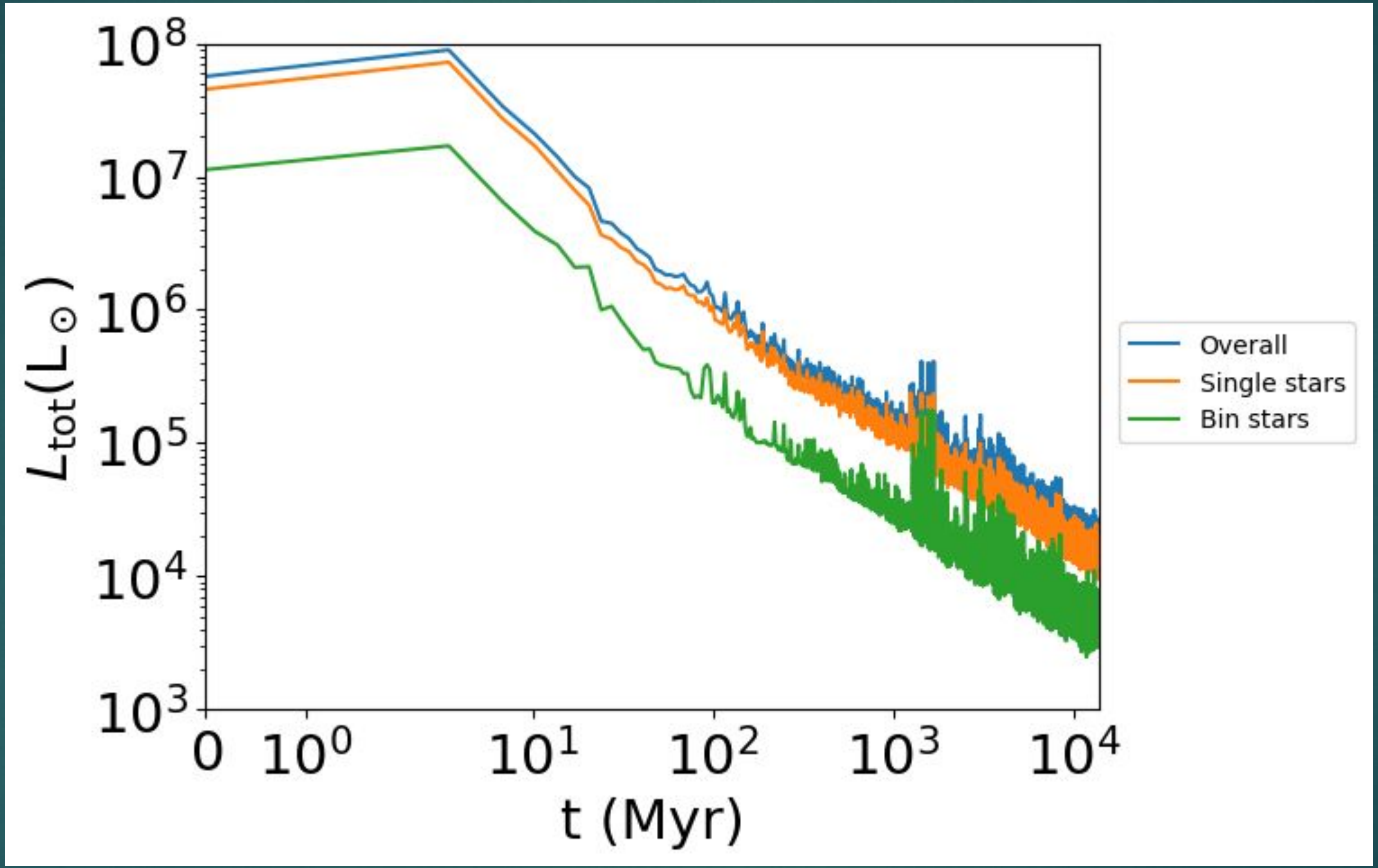
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
Frequency
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
binary distance from density center (pc)

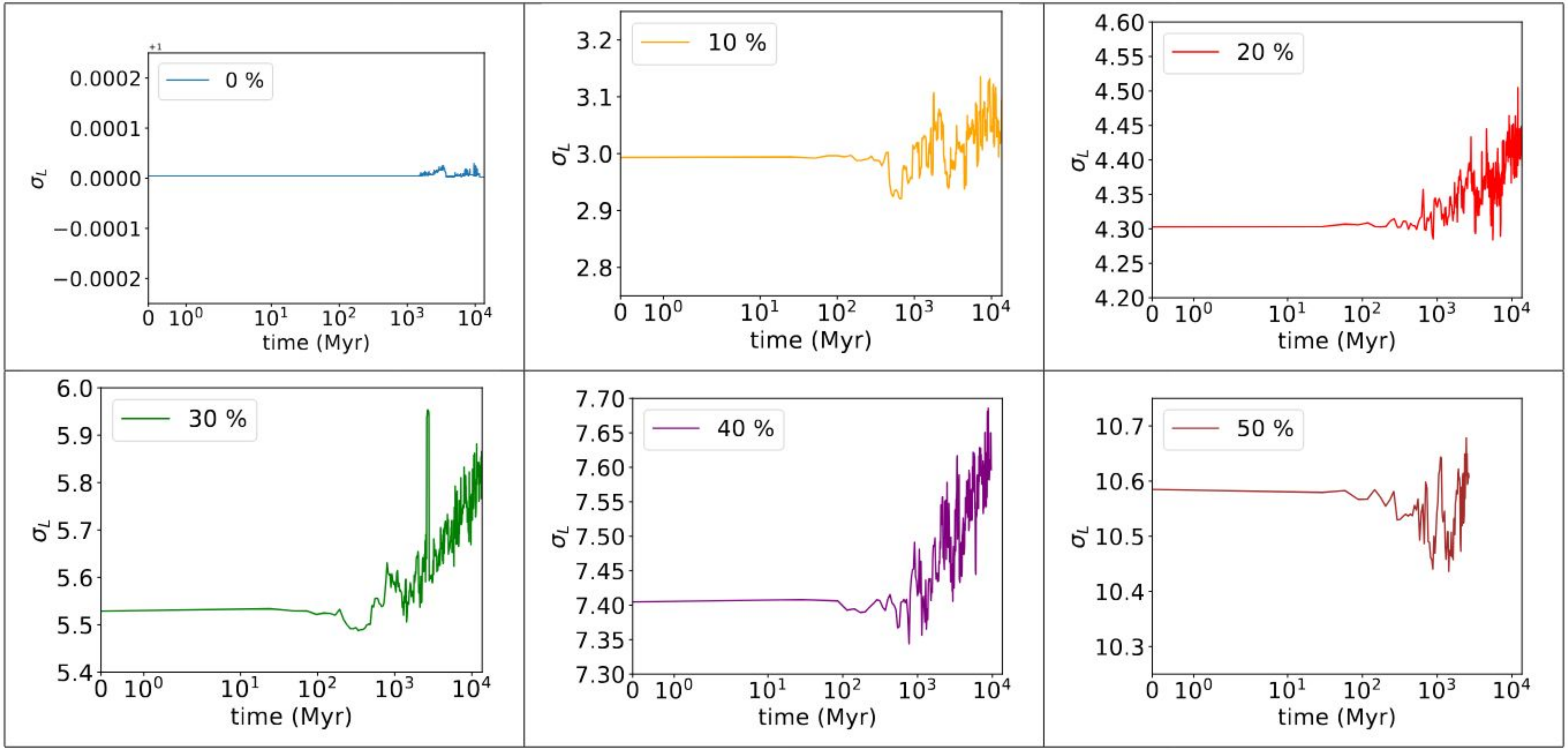


0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Frequency
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
ratio of masses


0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Frequency
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Eccentricity


0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Frequency
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
semi-major axis (AU)


$L_{tot}(L_\odot)$
10^8
10^7
10^6
10^5
10^4
10^3
0
10^0
10^1
10^2
10^3
10^4
t (Myr)
Overall
Single stars
Bin stars



0 %
10 %
20 %
30 %
40 %
50 %
σ_L
time (Myr)