Dynamical evolution of the Milky Way Globular Clusters in cosmological timescale: interaction with the central Supermassive Black Hole

Marina Ishchenko, Margaryta Sobolenko, Peter Berczik, Olexandr Sobodar, Oleksander Veles

Main Astronomical Observatory, National Academy of Sciences of Ukraine, Kyiv

Cosmology 2023 in Miramare, 28 Jul – 3 Aug, 2023

According to the ΛCDM model, the Milky Way globular clusters (GCs) are the first stellar associations that were formed in the early Universe as gravitationally bound systems. Their typical ages are >10−12 Gyr and the current masses are $\approx 10^5 M_\odot$.

According to our previous researches

- M. Ishchenko, M. Sobolenko, P. Berczik et al., A&A 673, A152 (2023),
- M. Ishchenko, M. Sobolenko, D. Kuvatova et al., A&A 674, A70 (2023),
- M. Ishchenko, M. Sobolenko, P. Berczik et al., KPCB, Vol. 39, No. 1 (2023),

we have found that the orbits of some MW GCs can pass close to the Galactic Centre (GalC).

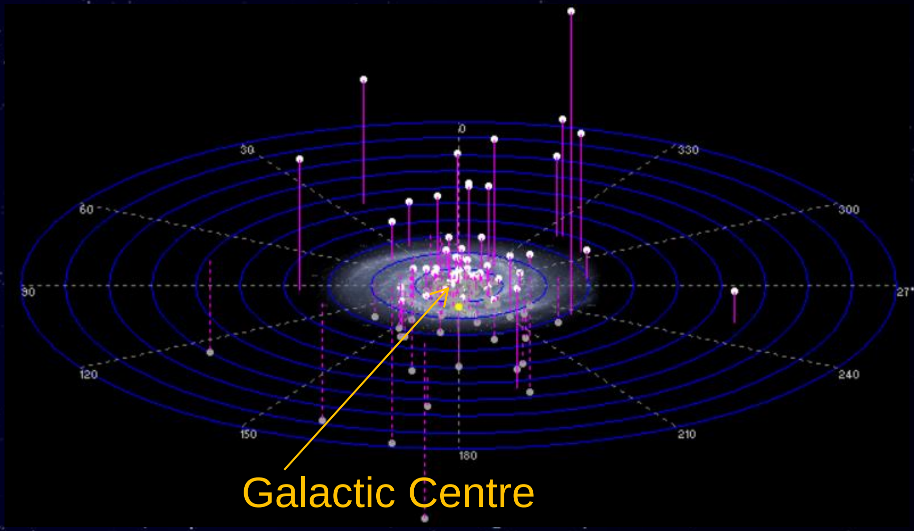
This idea is confirmed in the following papers:

- ✓ Burkert & Tremaine (2010),
- ✓ Harris & Harris (2011),
- ✓ González-Lópezlira et al. (2017),
- ✓ Harris et al. (2014),

where the authors show a correlation between the mass of the central Supermassive Black Hole (SMBH) and the number of GCs in elliptical and spiral galaxies.

Our aim is to carry out the dynamic evolution of the orbits of the GCs' subsystem sample in lookback time up to 10 Gyr with *Gaia* DR3 observations of the GCs positions, proper motions and radial velocities.

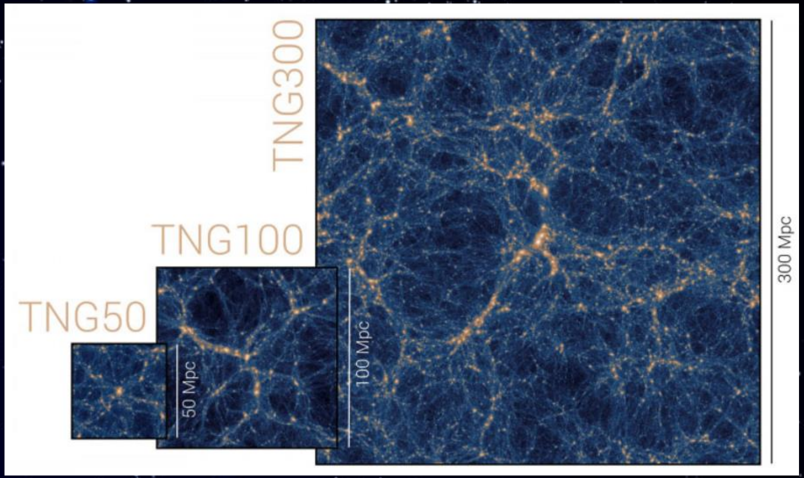
This allows us to estimate, in a common statistical way, the average probability and the possibility of close passages of GCs with the GalC including the possible gravity influence from the SMBH.



≈150 Globular Clusters within 200,000 LY of the GalC

To be more physically realistic, we performed our integration of GCs' evolution in time-varying MW-like potentials.

The IllustrisTNG-100 is characterized by a simulation box ~100 Mpc^3. In a box of such size we resolve a 54 MW-mass disk galaxies with the mass resolution of $7{,}5 \times 10^6\ M_\odot$ for dark matter and $1{,}4 \times 10^6\ M_\odot$ for the baryonic particles, respectively.



To obtain the spatial scales of the disks and dark matter haloes, we decomposed the mass distribution using the MN $\Phi_d(R, z)$ (Miyamoto & Nagai 1975) and NFW $\Phi_h(R, z)$ (Navarro et al. 1997) potentials:

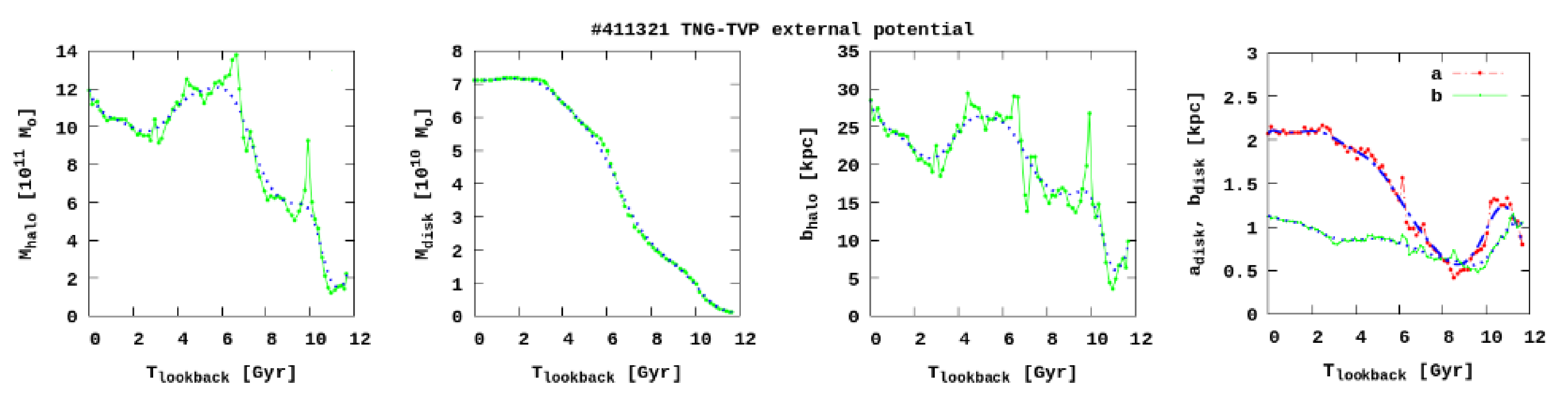
$$\Phi_{\rm tot} = \Phi_{\rm d}(R,z) + \Phi_{\rm h}(R,z) = = -\frac{GM_{\rm d}}{\sqrt{R^2 + \left(a_{\rm d} + \sqrt{z^2 + b_{\rm d}^2}\right)^2}} - \frac{GM_{\rm h} \cdot \ln\left(1 + \frac{\sqrt{R^2+z^2}}{b_{\rm h}}\right)}{\sqrt{R^2 + z^2}},$$

For our analysis, in the Illustris simulations, we identified the 4 MW-like galaxy candidates with at least 10^5 dark matter particles and at least 10^3 baryonic particles (stars and gas) at redshift zero and well reproduce MW parameters (disk and halo masses with the spatial scales) at present the best: **#411321**, **#441327**, **#451323**, and **#462077** (TNG-TVPs).

For more details, readers can refer (Ishchenko et al. 2023; Mardini et al. 2020).

Parameters of the time-varying potentials were selected from the IllustrisTNG-100 simulation at z = 0. The last column shows the parameters of the corresponding MW components according to Bennett et al. (2022) at present.

Parameter	Unit	#411321	#441327	#451323	#462077	Milky Way
Disk mass, M_{d}	10^{10} $M_\odot$	7.110	7.970	7.670	7.758	6.788
Halo mass, M_{h}	10^{12} $M_\odot$	1.190	1.020	1.024	1.028	1.000
Disk scale length, a_{d}	1 kpc	2.073	2.630	2.630	1.859	3.410
Disk scale height, b_{d}	1 kpc	1.126	1.356	1.258	1.359	0.320
Halo scale height, b_{h}	10 kpc	2.848	1.981	2.035	2.356	2.770



Evolution of halo and disk masses, and their characteristic scales for #411321 in time. Dotted and dash-dotted blue lines correspond to the values after the interpolation and smoothing with a 1 Myr time step that was used in the orbital integration.

Orbital time integration – 10 Gyr lookback time

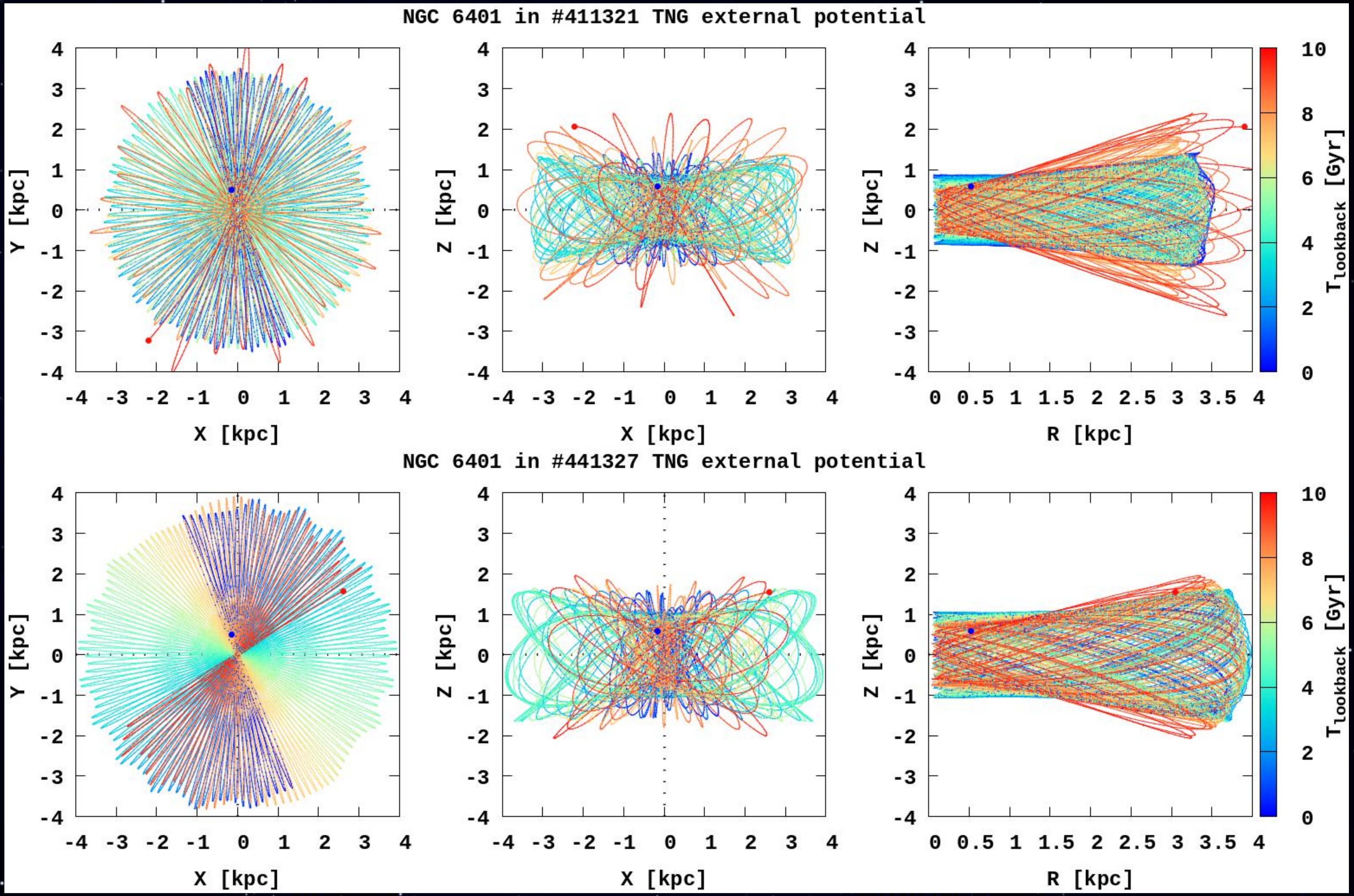
– a high-order parallel dynamical N-body φ-GPU code, based on the fourth-order Hermite integration scheme with hierarchical individual block time steps (Berczik et al. 2011, 2013),

– GCs initial positions, proper motions, velocities and heliocentric distances were taken from *Gaia* DR3,

– each GC was integrated as one physical particle with the fixed mass from the catalogue (Baumgardt & Vasiliev 2021),

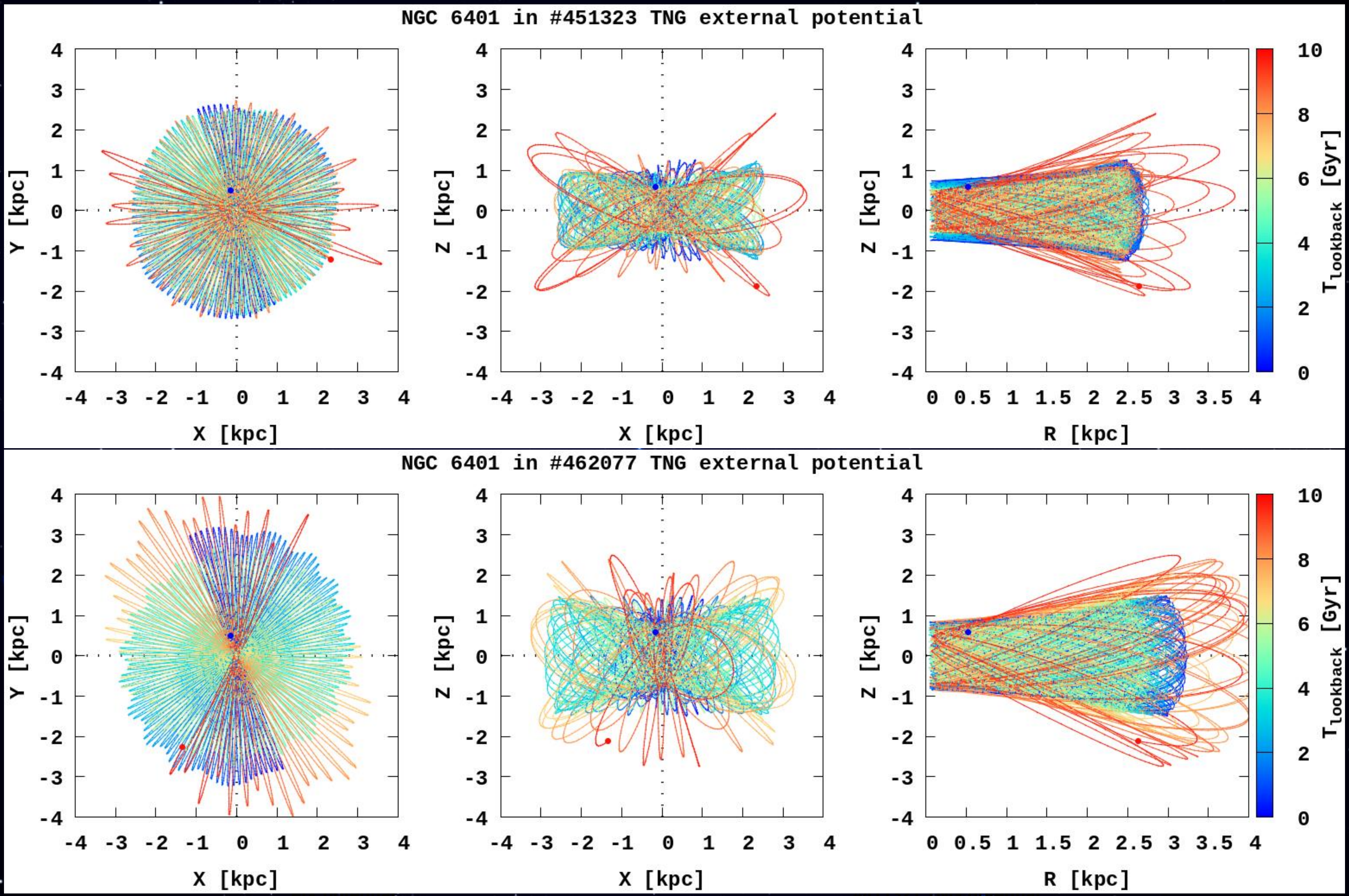
– 4 external time evolving potentials with variable dynamical masses and scales, were selected from IllustrisTNG-100,

– all GCs were integrated together taking into account the GCs self interactions and the interactions with the external potential.

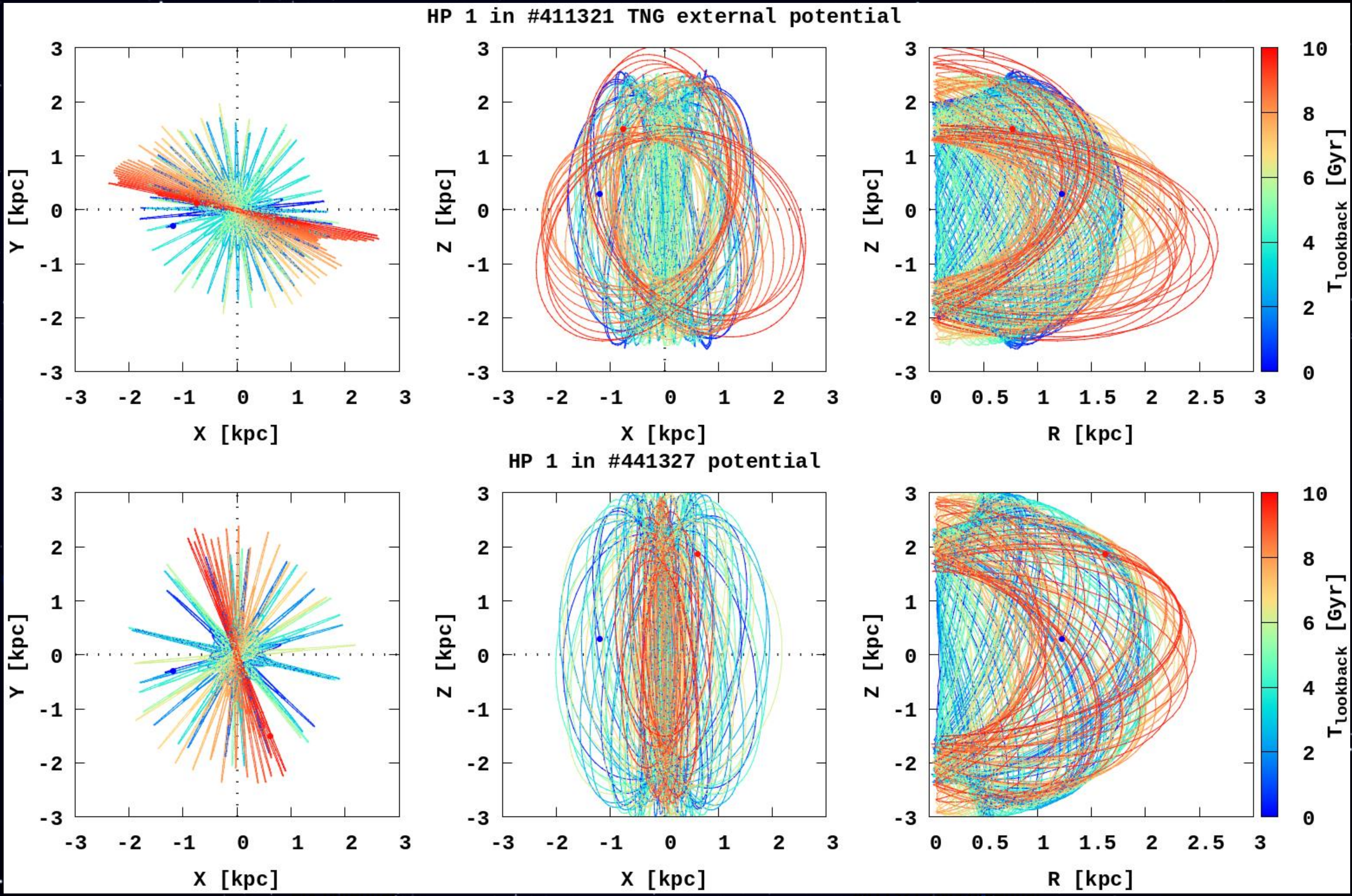


NGC 6401 orbital changes in three planes (X, Y), (X, Z) and (R, Z), where R is the planar Gal. radius.

The time of integration is 10 Gyr lookback time and represents by a colour line.

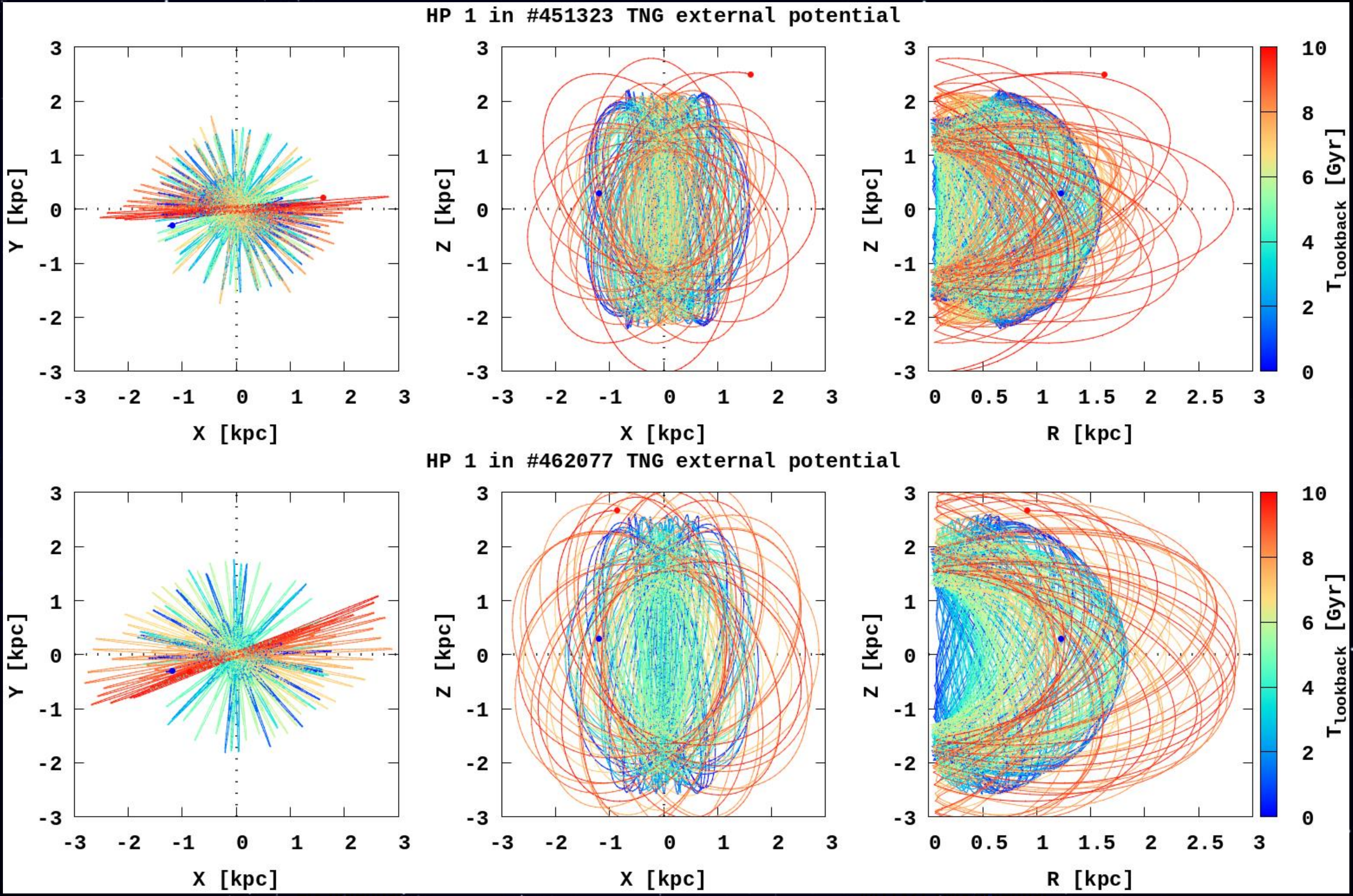


The same but for other potentials: #451323 and #462077

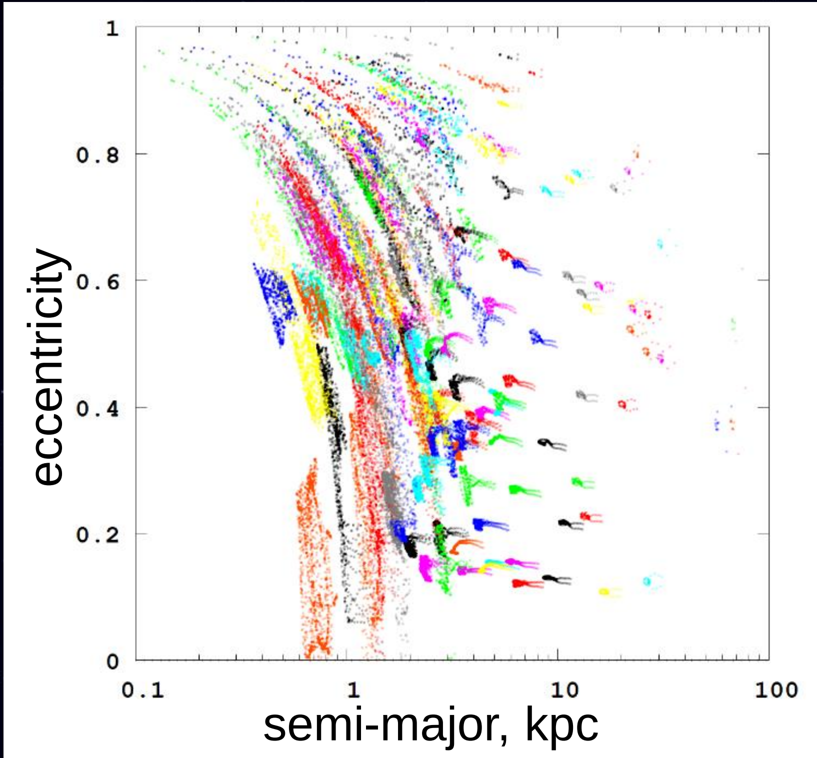


HP 1 orbital changes in three planes (X, Y), (X, Z) and (R, Z), where R is the planar Gal. radius.

The time of integration is 10 Gyr lookback time and represents by a colour line.



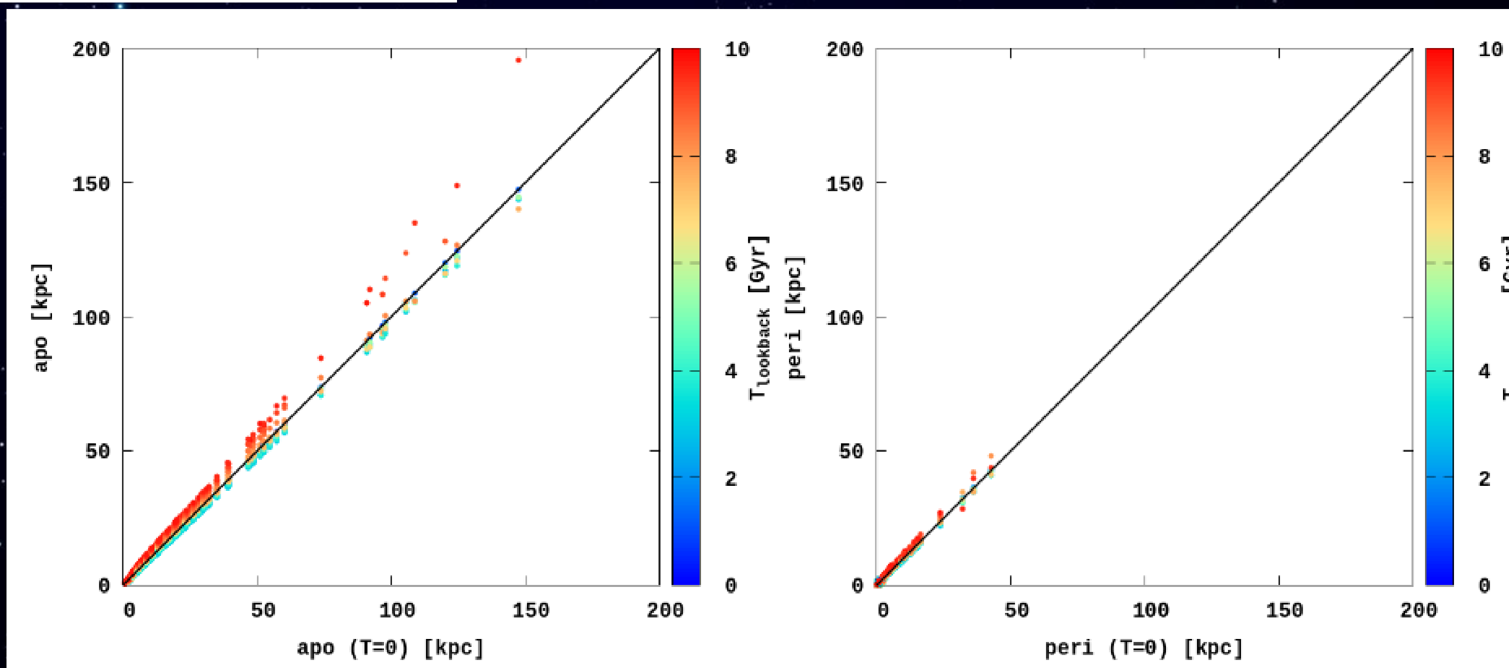
The same but for other potentials: #451323 and #462077

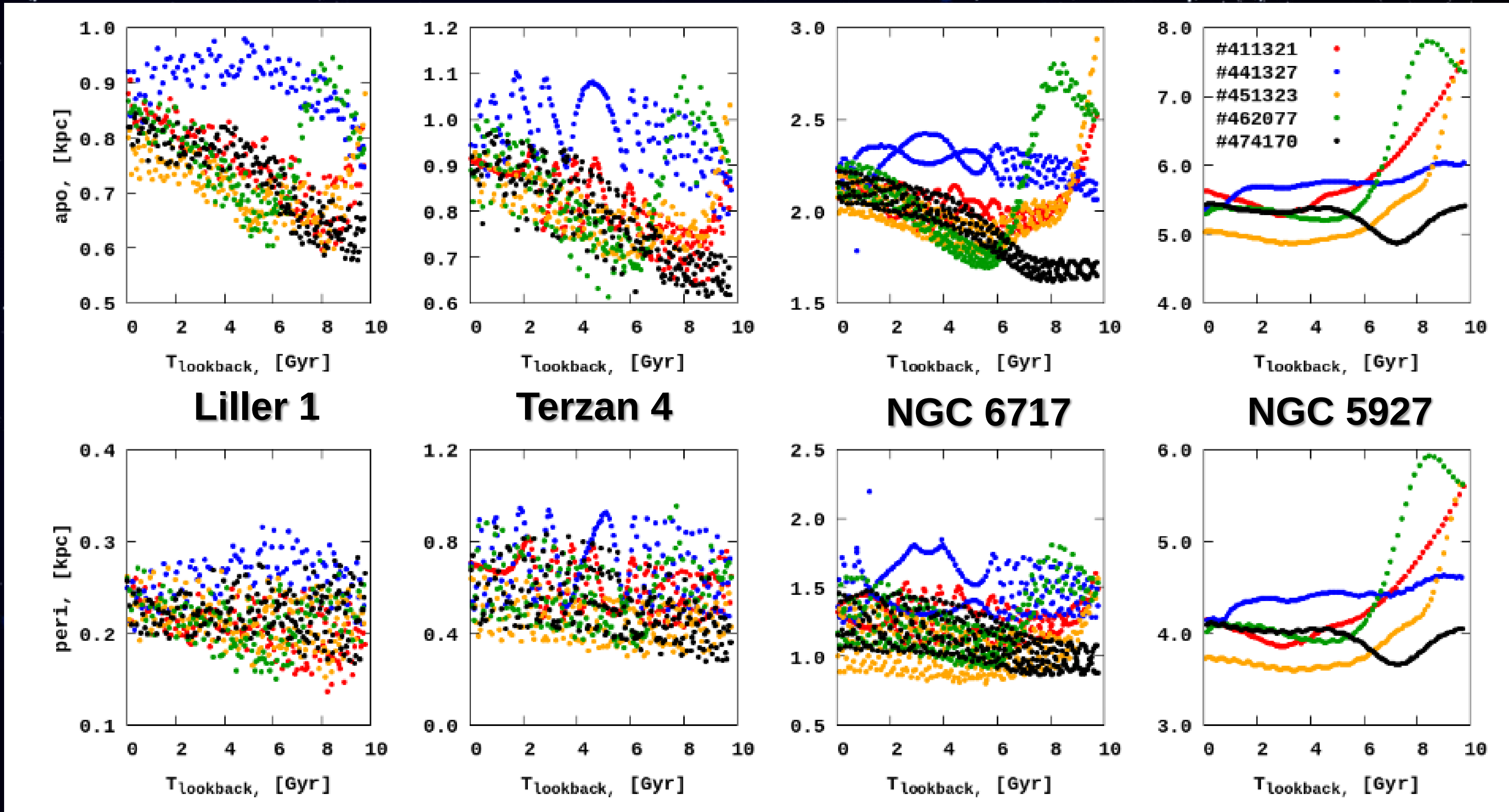


Evolution of the GC orbital **a** and **e** during the whole backward integration time.
The inner GCs ($a \leq 3$ kpc) have more regular and larger eccentricity changes during the evolution.
The outer GCs ($a > 3$ kpc) have much smaller eccentricity changes during the whole backward integration time.

 # 411321 TNG-TVP

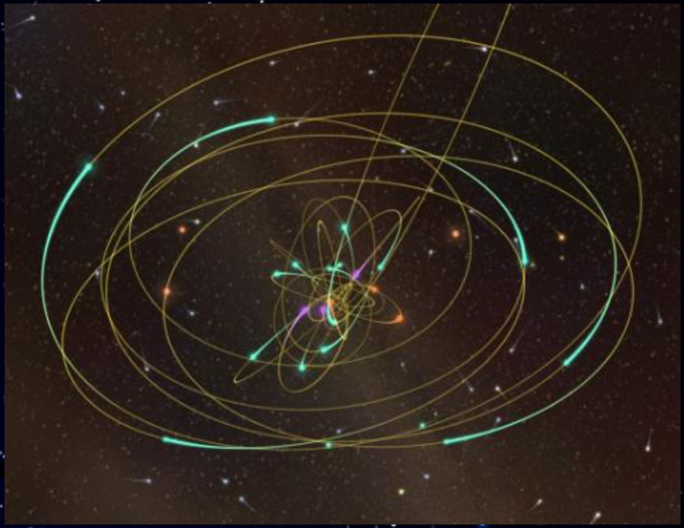
Evolution of the apocenters and pericenters for the 159 GCs. The colour-code corresponds to the lookback time.





Evolution of the apocenters and pericenters in five TNG-TVPs, where:
red – #411321, blue – #441327, orange – #451323,
green – #462077, and black – #474170.
The presented orbits were integrated for 10 Gyr lookback time.

“Including” the Supermassive Black Hole into TNG external potential



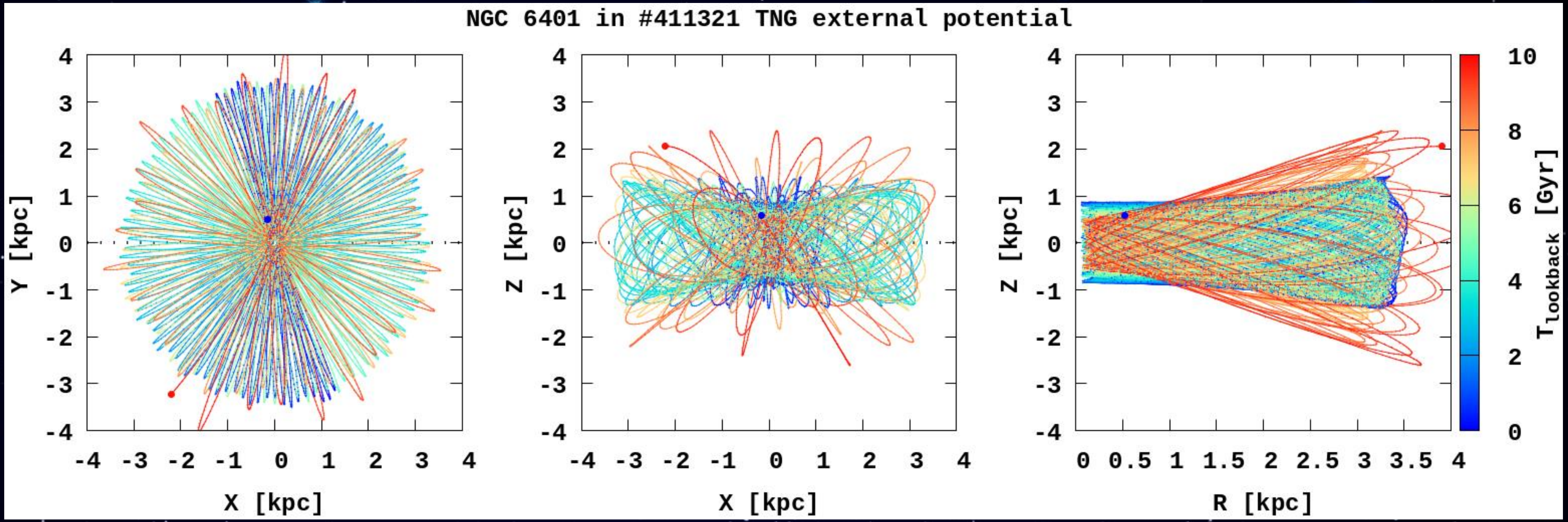
The morphology central region in TNG-TVPs, obtained from large-scale cosmological simulations, cannot be accurately resolved since these simulations are focused on large-scale structure.

Taking into account these numerical limitations of our external potentials, we intentionally added the extra SMBH into simulations. A SMBH was added as one special particle with a fixed position and mass equal to 4.1×10^6 $M_\odot$ (Ghezet al. 2008).

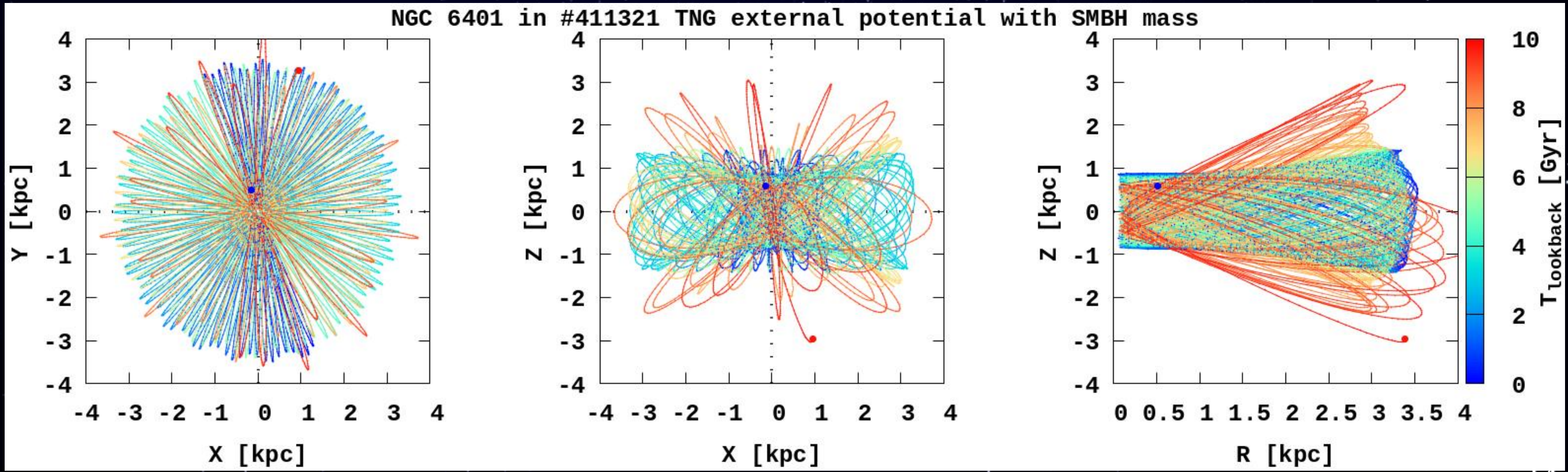
.

The SMBH mass was fixed throughout the entire time of the integration. So, in total, we got four TNG-TVPs plus one modified potential #411321 #411321-m.

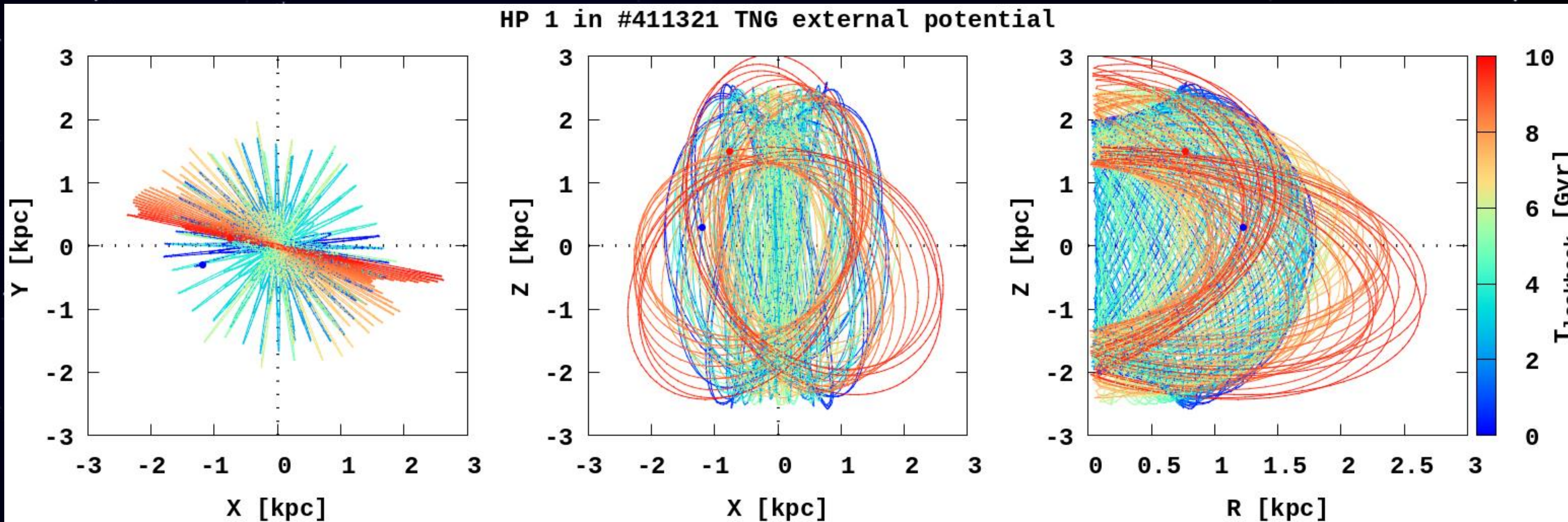
NGC 6402 in #411321 without SMBH in the Gal Center



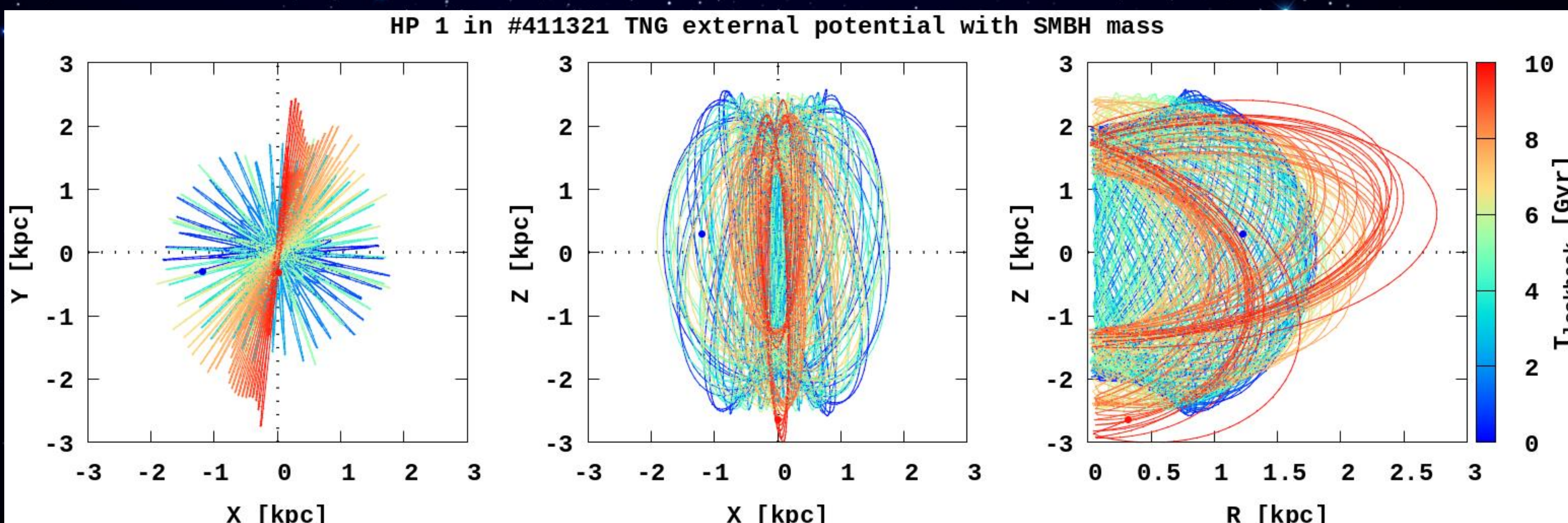
NGC 6402 in #411321 with SMBH in the Gal Center



HP1 in #411321 without SMBH in the Gal Center

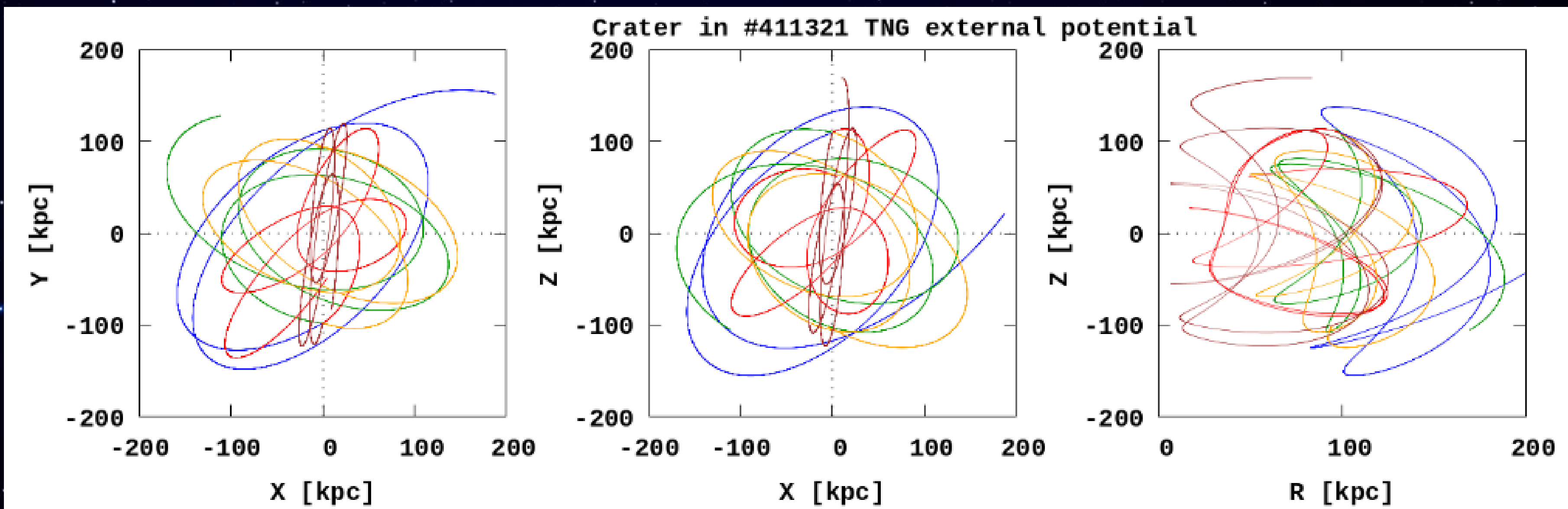


HP1 in #411321 with SMBH in the Gal Center



As example: Milky Way Globular Cluster Crater in Gaia DR3 database as a “bad” GC

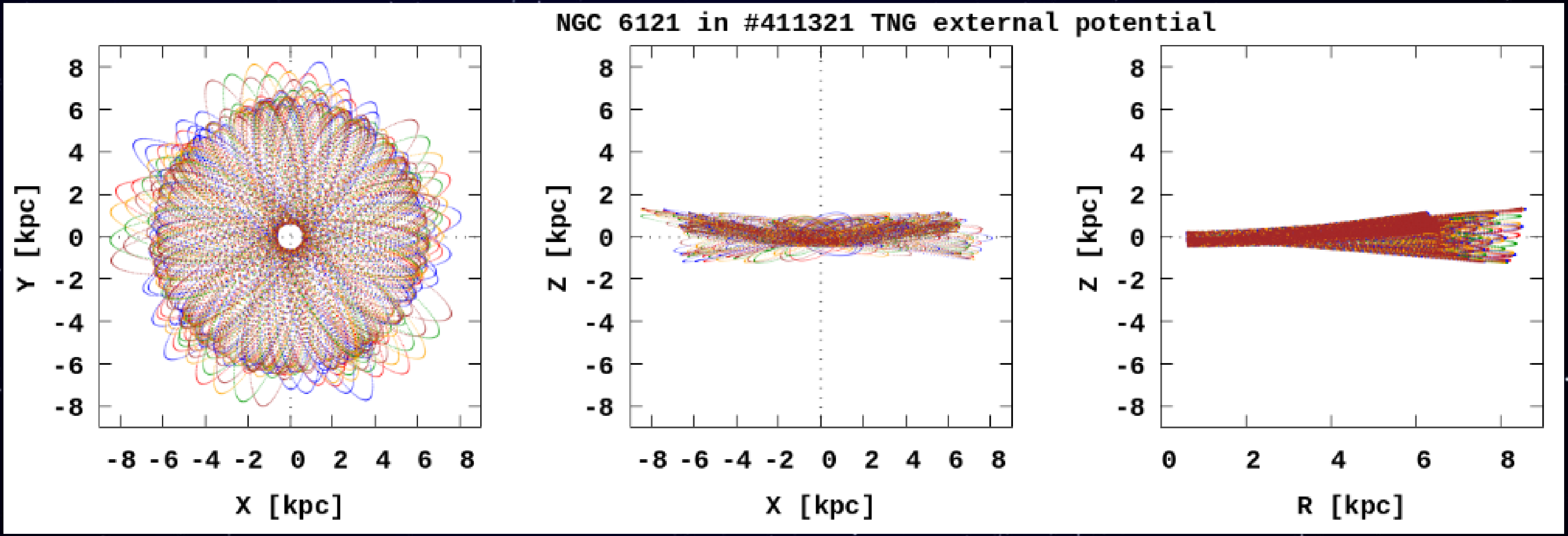
RA	DEC	PMRA	ePMRA	PMDEC	ePMDEC	RV	eRV
174.069	-10.877	-0.059	0.125	-0.116	0.116	148.10	0.65



The velocity uncertainties significantly change the orbital characteristics in the case of Crater. Colour lines – different realizations.

As example: Milky Way Globular Cluster NGC 6121 in Gaia DR3 database as a “good” GC

RA	DEC	PMRA	ePMRA	PMDEC	ePMDEC	RV	eRV
245.897	-26.526	-12.514	0.023	-19.022	0.023	71.21	0.15



For NGC 6121, which parameters are well measured, the orbit is weakly affected by the velocity uncertainties. Colour lines – different realizations.

Orbital time integration – 10 Gyr lookback time

– a high-order parallel dynamical N-body φ-GPU code. This code is based on the fourth-order Hermite integration scheme with hierarchical individual block time steps (Berczik et al. 2011, 2013),
– GCs initial positions, proper motions, velocities and heliocentric distances were taken from *Gaia* DR3,
– each GC was integrated as one physical particle with the fixed mass from the catalogue (Baumgardt & Vasiliev 2021),
– 4 external time evolving potentials with variable dynamical masses and scales, selected from IllustrisTNG-100,
– all GCs were integrated together taking into account the GCs' self interactions and the interactions with the external potential,

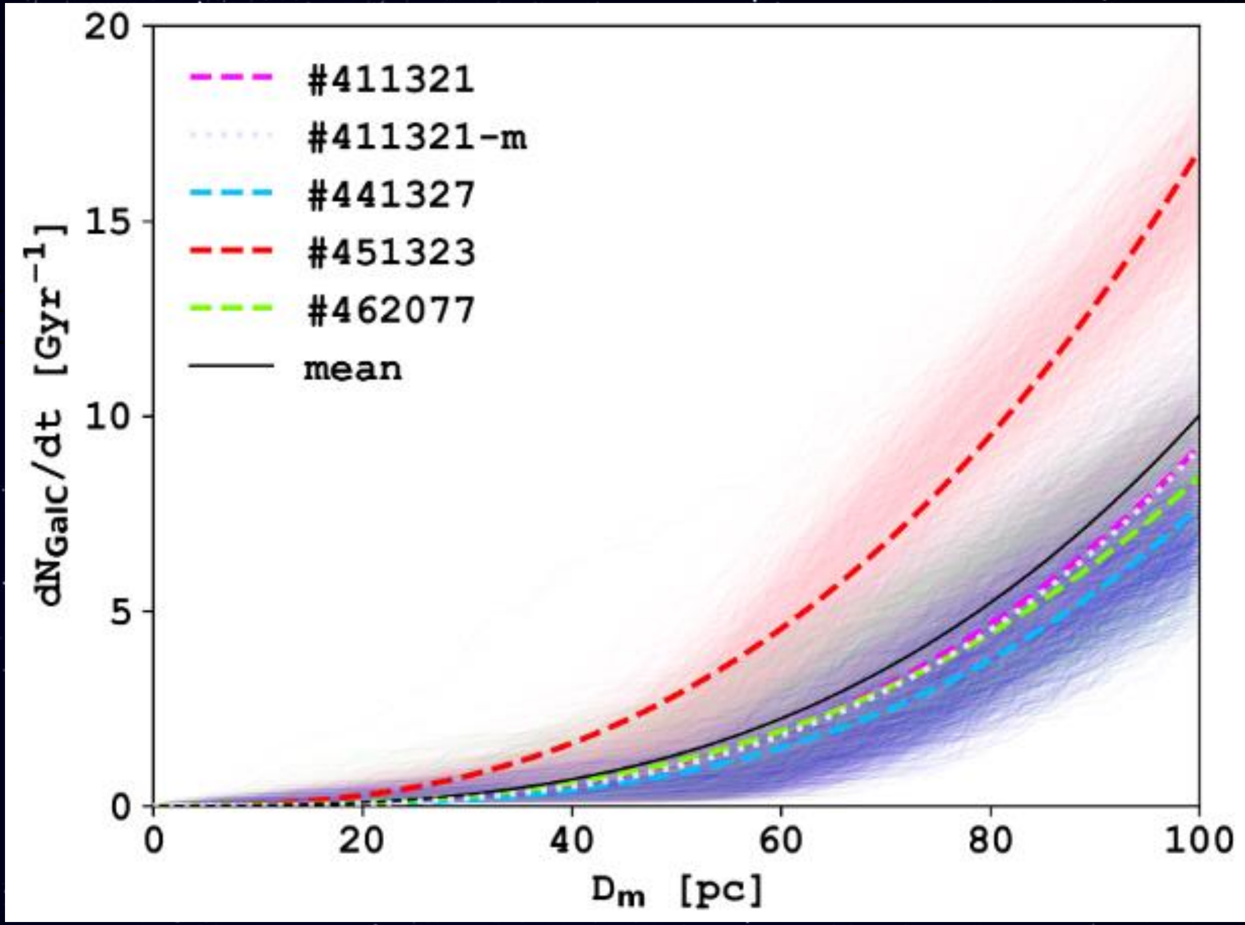
+

– selected the GCs with relative errors in proper motions and velocities of less than 30%,

– performed 1000 simulations varying initial velocities of the GCs within ±1σ of the measurement errors taken from the normal distribution,

– criteria for the GCs selection is 100 pc between GCs and GalC,

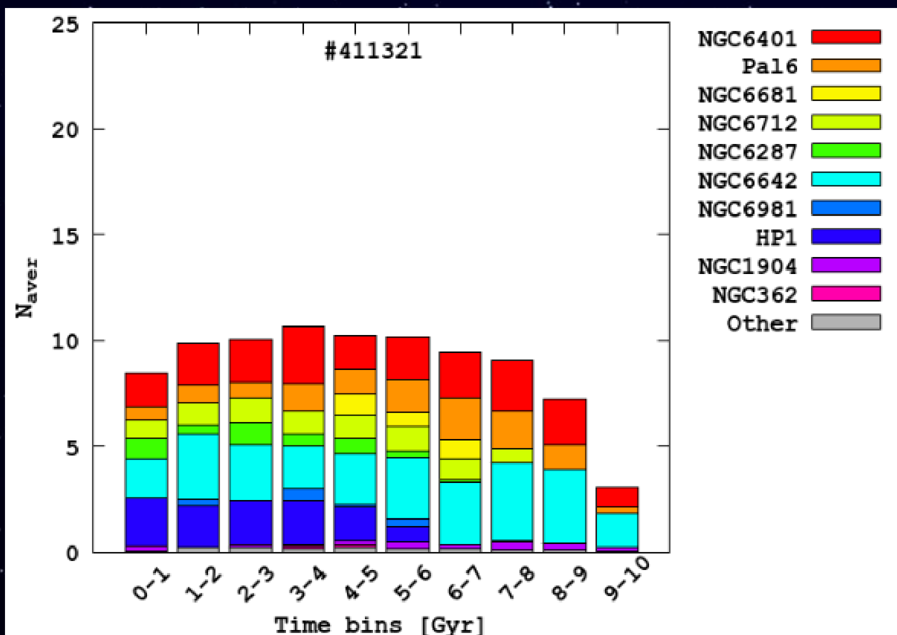
– carried out 5000 simulations: 4000 for the four TNG-TVPs and 1000 for the #411321-m potential (with SMBH).



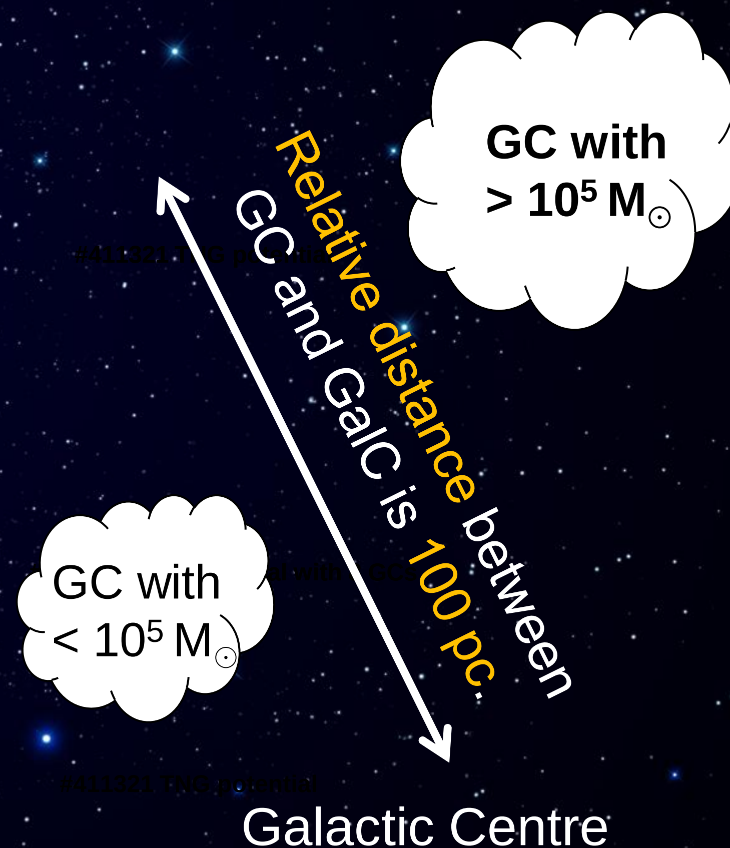
Passages numbers / dt [Gyr^{-1}] between GCs and GalC as a function of the relative distance dR.

At a relative distance between the GC and GalC:
– in 50 pc we get 4 close passages / Gyr,
– in 80 pc – 6 close passages / Gyr.

We found 10 GCs: NGC 6401, Palomar 6, NGC 6681, NGC 6712, NGC 6287, NGC 4462, NGC 6981, HP 1, NGC 1904, and NGC 362



Contribution of individual GCs into global collision rate at different time ranges for #411321 TNG external potential.



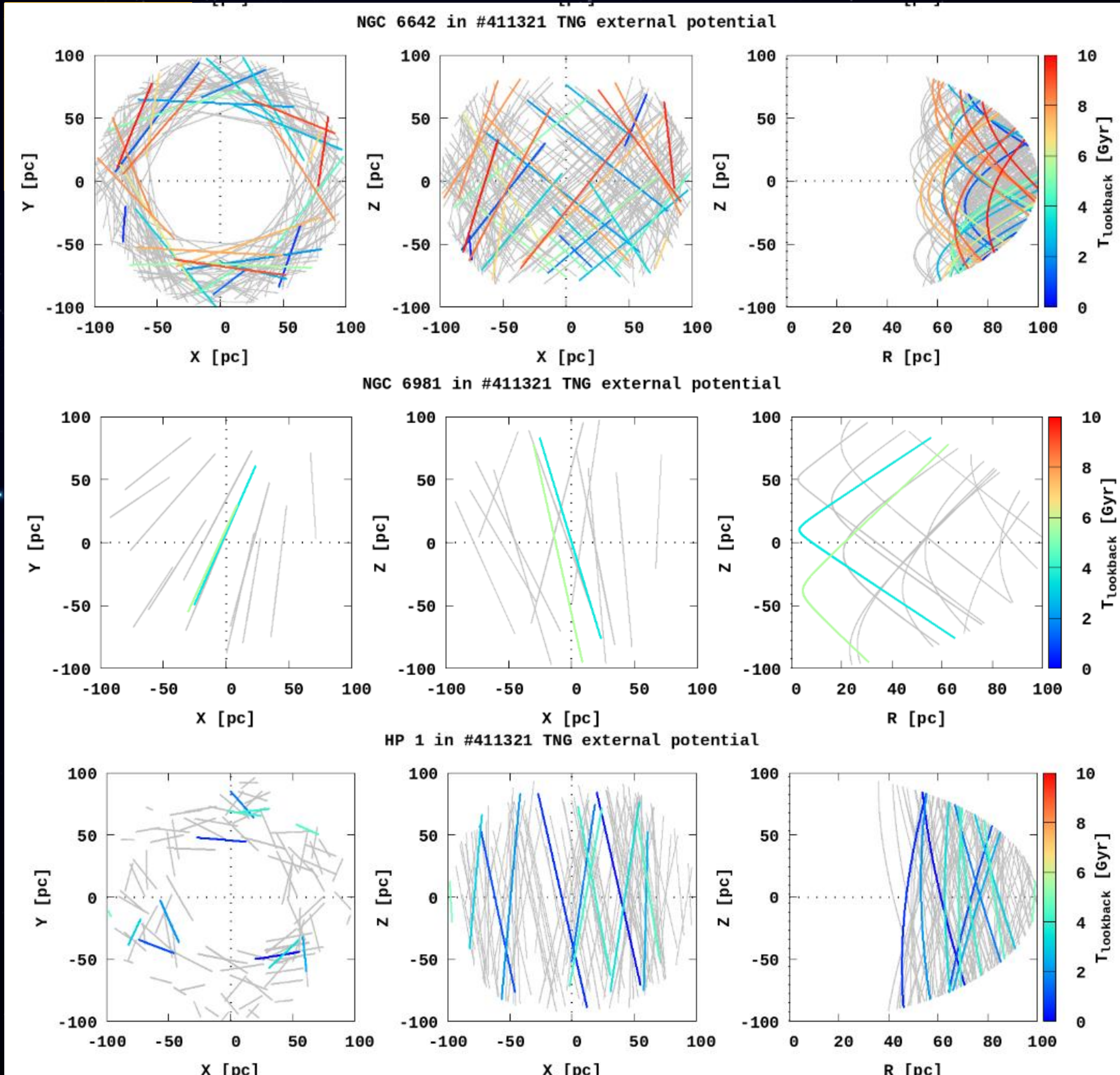
Percent of probability of the GCs' interaction with the GalC in all 1000 sets of randomization for four TNG TVPs + one with SMBH.

GC	#411321	#411321-m	#441327	#451323	#462077	Mean
(1)	(2)	(3)	(4)	(5)	(6)	(7)
NGC 6401	100.0	99.9	100.0	100.0	100.0	100.0
Pal 6	100.0	99.6	99.9	100.0	100.0	99.9 ± 0.1
NGC 6681	99.9	99.9	100.0	100.0	100.0	99.9 ± 0.1
NGC 6712	99.9	100.0	99.9	99.8	100.0	99.9 ± 0.1
NGC 6287	100.0	100.0	100.0	97.0	92.1	97.3 ± 3.7
NGC 6642	99.8	99.8	99.3	100.0	99.5	99.7 ± 0.3
NGC 6981	83.9	84.9	90.2	93.5	87.8	88.9 ± 4.0
HP 1	98.7	99.0	70.7	99.5	83.0	89.9 ± 13.8
NGC 1904	72.4	73.0	73.6	83.2	76.7	76.5 ± 4.8
NGC 362	24.4	27.9	30.7	41.2	12.9	27.3 ± 11.8

Statistics example of the characteristics of the GCs' interaction with the GalC in #411321 and #411321-m (with SMBH) TNG-TVP external potentials

	GC \ Pot	#411321			#411321-m		
		$< D_{\rm m} >$ pc	$< dV >$ km s^{-1}	$< N_{\rm int} >$	$< D_{\rm m} >$ pc	$< dV >$ km s^{-1}	$< N_{\rm int} >$
TB	NGC 6401	56 ± 10	331 ± 18	19 ± 2	58 ± 10	333 ± 17	18 ± 4
TB	Pal 6	58 ± 12	340 ± 10	11 ± 6	58 ± 13	341 ± 10	10 ± 5
IR	NGC 6681	42 ± 16	410 ± 4	3 ± 1	45 ± 17	411 ± 1	3 ± 1
TB	NGC 6712	52 ± 8	379 ± 10	8 ± 2	53 ± 8	380 ± 10	8 ± 2
TB	NGC 6287	82 ± 5	405 ± 10	4 ± 1	81 ± 4	398 ± 11	4 ± 1
TB	NGC 6642	62 ± 16	262 ± 19	27 ± 10	63 ± 14	260 ± 19	28 ± 9
LR	NGC 6981	57 ± 24	545 ± 8	2 ± 1	57 ± 24	547 ± 8	2 ± 1
IR	HP 1	50 ± 21	304 ± 10	11 ± 4	50 ± 22	306 ± 11	16 ± 4
LR	NGC 1904	53 ± 25	517 ± 17	3 ± 2	54 ± 24	518 ± 18	3 ± 1
LR	NGC 362	88 ± 10	484 ± 6	1 ± 1	87 ± 10	481 ± 5	1 ± 1

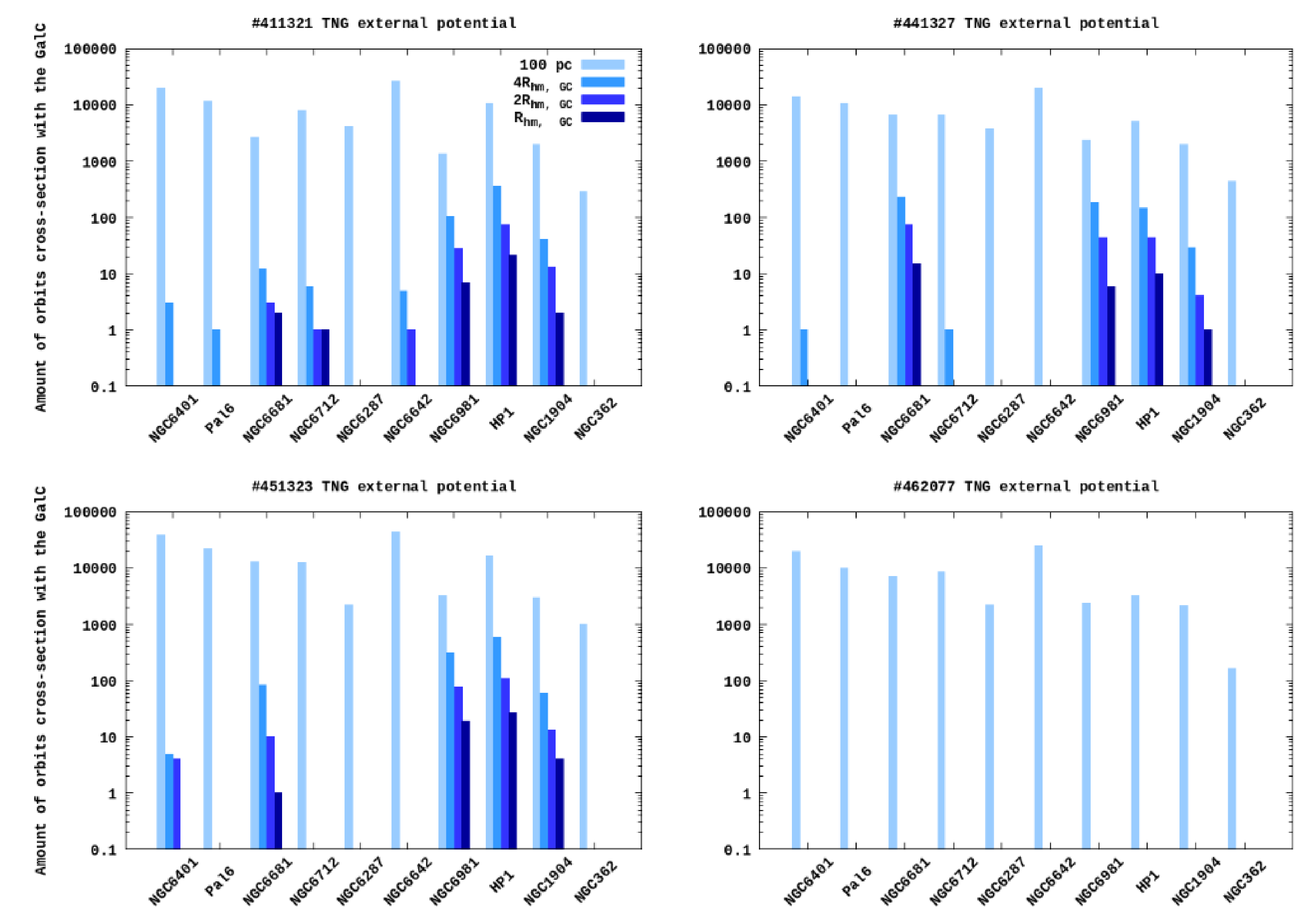
< Dm > - the minimum distance in parsec between the GC and GalC,
< dV > - the corresponding value of the relative velocity,
< Nint > - the average number of individual interactions for each randomization ,
± values - the standard deviation from these average values based on our 1000 random realisations.



NGC 6642
has **tube** orbit

NGC 6981
has **long radial** orbit

NGC HP1
has **irregular** orbit



Amount of orbits cross-section with the GalC for selected GCs for four different distance criteria for #411321, #441327, #451323 and #462077 TNG-TVP external potentials.

What is next?

For the selected Globular Cluster we try to find initial conditions such as mass in $M_{\odot}$, half-mass radii in pc and King profile, including stellar evolution.

By finding and adopting initial conditions we will integrate the GC up to one million particles on cosmological time scale for today to get parameters which are observed.

We estimate the SMBH influence (with Nuclear Star Cluster) by analyzing particles distribution due to orbital and stellar evolution on these particles .

Thanks for your attention