Milky Way nuclear star cluster on cosmological timescale:

Evolution of the orbital parameters in time-varying potentials. Interaction with the Galactic center.

Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

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PAN.BFB.S.BWZ.329.022.2023

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Formation and evolution of the Nuclear Star Cluster in the Milky Way and other spiral galaxies on the cosmological time scale.

PAN.BFB.S.BWZ.329.022.2023

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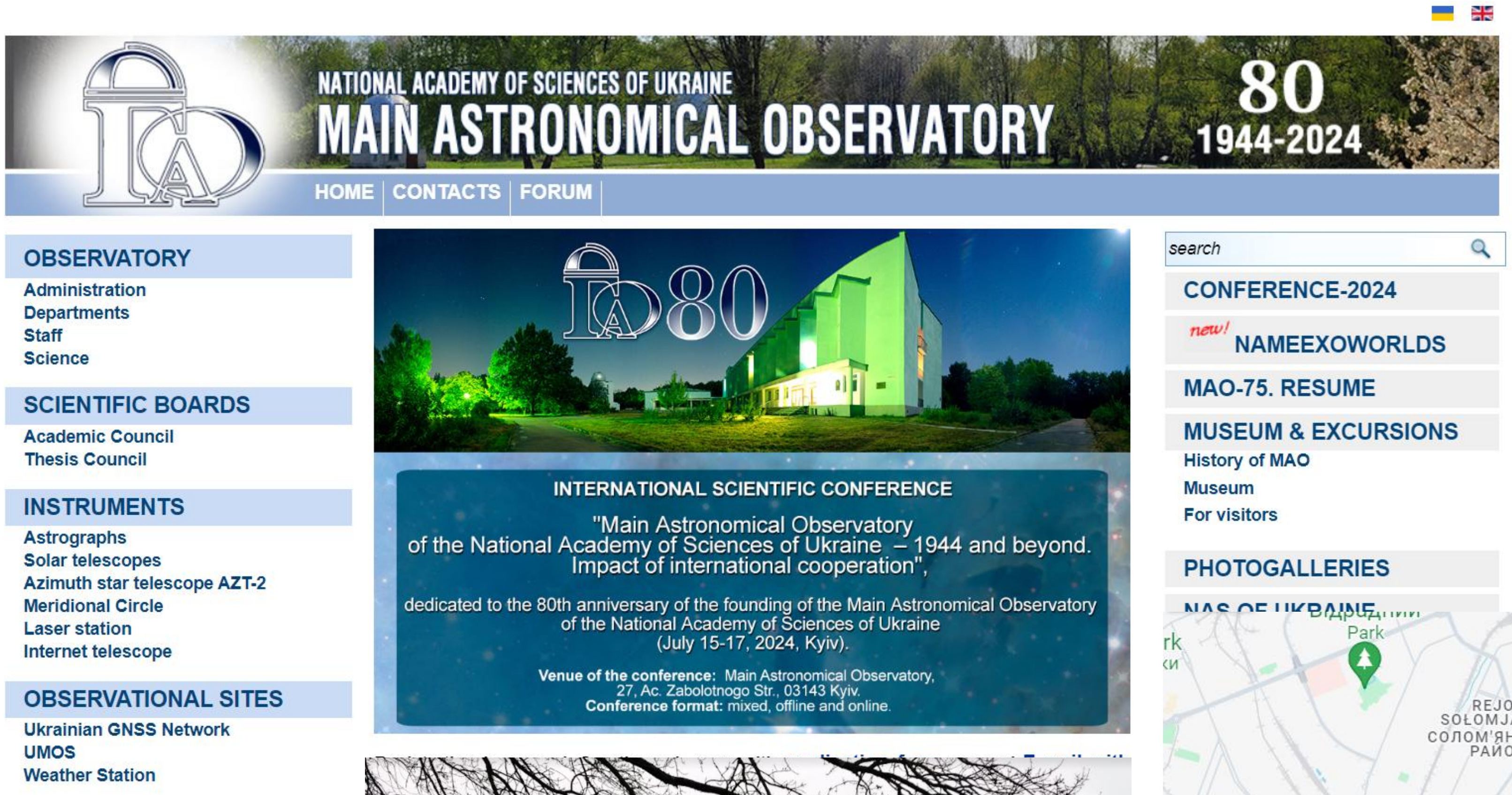
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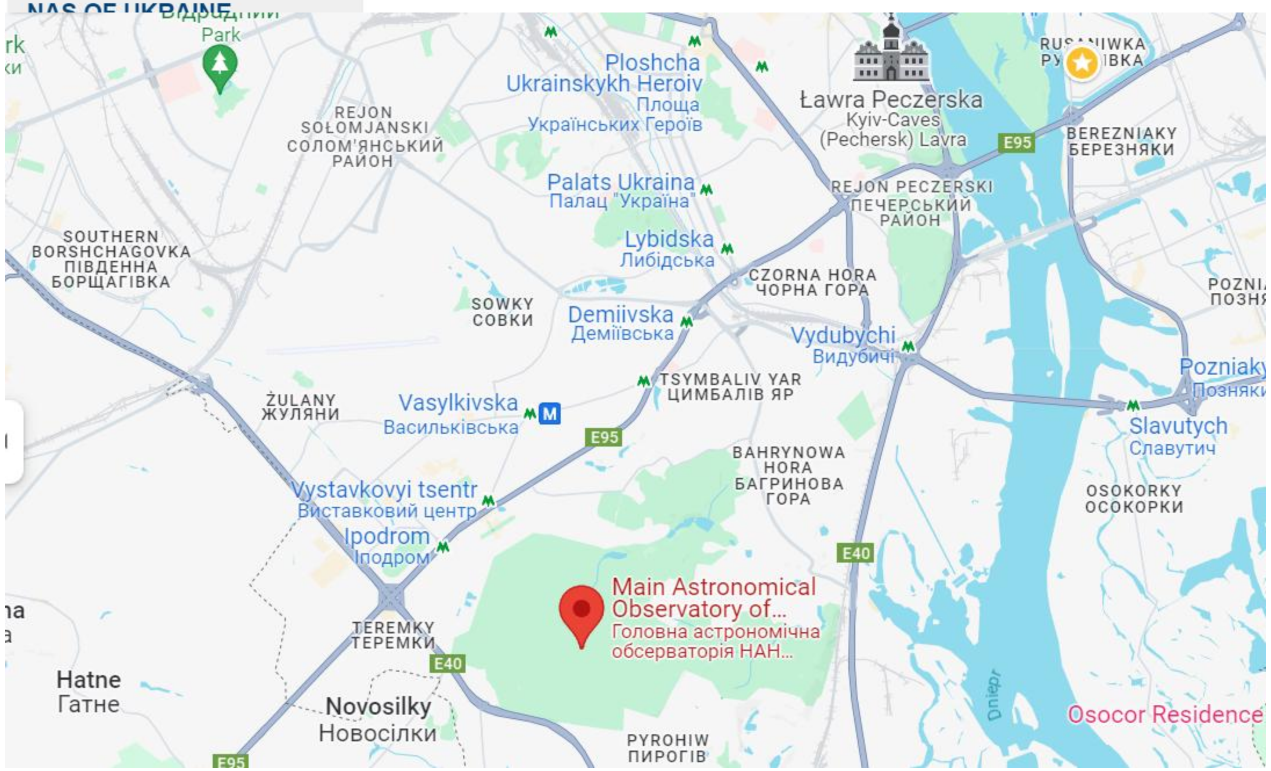
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GC evolution in MW TNG (Ishchenko – 3)

1) **Berczik, P., Ishchenko, M., Sobodar, O.,** Mardini, M., (2024). Cosmological insights into the early accretion of r-process-enhanced stars: II. Dynamical identification of lost members of Reticulum II. Astronomy and Astrophysics, 692, A130

2) **Ishchenko, M., Berczik, P., Sobolenko, M.,** (2024). Milky Way globular clusters on cosmological timescales. IV. Guests in the outer Solar System. Astronomy and Astrophysics, 683, A146

3) **Ishchenko, M., Berczik, P.,** Panamarev, T., Kuvatova, D., Kalambay, M., Gluchshenko, A., **Veles, O., Sobolenko, M., Sobodar, O.,** Omarov, C., (2024). Dynamical evolution of Milky Way globular clusters on the cosmological timescale: I. Mass loss and interaction with the nuclear star cluster. Astronomy and Astrophysics, 689, A178

GC internal evolution (Berczik – 2)
SC evolution in MW (Berczik – 1)

1) Bissekenov, A., Kalambay, M., Abdikamalov, E., Pang, X., **Berczik, P.,** Shukirgaliyev, B., (2024). Cluster membership analysis with supervised learning and N-body simulations. Astronomy and Astrophysics, 689, A282

2) Arca sedda, M., Kamlah, A. W. H., Spurzem, R., Rizzuto, F. P., Giersz, M., Naab, T., **Berczik, P.,** (2024). The DRAGON-II simulations - III. Compact binary mergers in clusters with up to 1 million stars: mass, spin, eccentricity, merger rate, and pair instability supernovae rate. Monthly Notices of the Royal Astronomical Society, 528, 5140-5159

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Galactic centre dynamical evolution with SMBH/BBH/TBH (Berczik – 3).

1) **Berczik, P., Sobolenko, M., Ishchenko, M.,** (2024). Dynamical evolution timescales for the triple supermassive black hole system in NGC 6240. Astronomy and Astrophysics, 687, L18

2) Khan, F. M., Javed, F., Holley-Bockelmann, K., Mayer, L., **Berczik, P.,** Macciò, A. V., (2024). The Potential for Long-lived Intermediate-mass Black Hole Binaries in the Lowest Density Dwarf Galaxies. The Astrophysical Journal, 976, 22

3) Hujeirat, A. A., **Berczik, P.,** (2024). The Origin of the Flat Rotation Curves in Spiral Galaxies: The Hidden Roles of Glitching SMDEOs and Emission of Gravitational Waves. Journal of Modern Physics, 15, 1523-1542

9 ref. publ. (2024):

A&A – 5, MNRAS – 2, ApJ – 1, JMP - 1

12 non. ref. publ. (2024):
EAS conf. – 9, IAU GA – 2, AAS – 1

1) **Ishchenko, M., Berczik, P., Sobolenko, M.,** (2024). NGC 6240: triple SMBH evolution with von Zeipel-Lidov-Kozai oscillation. IAU General Assembly, 1087

2) **Ishchenko, M., Berczik, P., Sobolenko, M.,** (2024). The Milky Way Globular Clusters: guests in the Oort cloud system on cosmological time scale.. IAU General Assembly, 1080

3) Bannikova, E., **Berczik, P.,** Akhmetov, V., Skolota, S., **Ishchenko, M.,** Capaccioli, M., (2024). N-body simulation of the innermost region of AGN with clumpy torus, wind, dissipation and accretion. EAS2024, European Astronomical Society Annual Meeting, 930

4) **Sobolenko, M., Berczik, P.,** Bannikova, E., Akhmetov, V., (2024). Can SMBHB explain the observed internal dynamics of the torus?. EAS2024, European Astronomical Society Annual Meeting, 858

5) **Sobolenko, M., Berczik, P.,** Polyachenko, E., **Ishchenko, M.,** (2024). Milky Way like potentials in TNG-50 and their application to GCs system evolution. EAS2024, European Astronomical Society Annual Meeting, 856

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7) **Sobodar, O.,** Kalambay, M., **Veles, O., Sobolenko, M., Ishchenko, M.,** (2024). Global dynamical evolution of the Globular Cluster high mass stellar remnants in Milky Way. EAS2024, European Astronomical Society Annual Meeting, 753

8) **Berczik, P., Ishchenko, M., Sobolenko, M.,** (2024). Formation and evolution of the Nuclear Star Cluster in the Milky Way and other spiral galaxies on the cosmological time scale.. EAS2024, European Astronomical Society Annual Meeting, 629

9) **Berczik, P., Sobolenko, M., Ishchenko, M.,** (2024). The impact of post-Newtonian effects on massive black hole binary evolution from 1000 to 10 Rsch separations.. EAS2024, European Astronomical Society Annual Meeting, 628

10) **Ishchenko, M., Sobolenko, M., Berczik, P.,** Omarov, C., **Sobodar, O.,** Kalambay, M., Yurin, D., (2024). A possibility of the Milky Way globular clusters interaction rates on cosmological timescales based on Gaia RD3. EAS2024, European Astronomical Society Annual Meeting, 389,

11) **Ishchenko, M.,** (2024). Star-by-star dynamical evolution of the physical pair of the Collinder 135 and UBC 7 open clusters based on Gaia RD3. EAS2024, European Astronomical Society Annual Meeting, 302

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A&A, 692, A130 (2024)
https://doi.org/10.1051/0004-6361/202451837

Cosmological insights into the early accretion of r-process-enhanced stars

II. Dynamical identification of lost members of Reticulum II

Peter Berczik[1,2,3,⋆], Maryna Ishchenko[1], Olexandr Sobodar[1,2], and Mohammad Mardini[4,5]

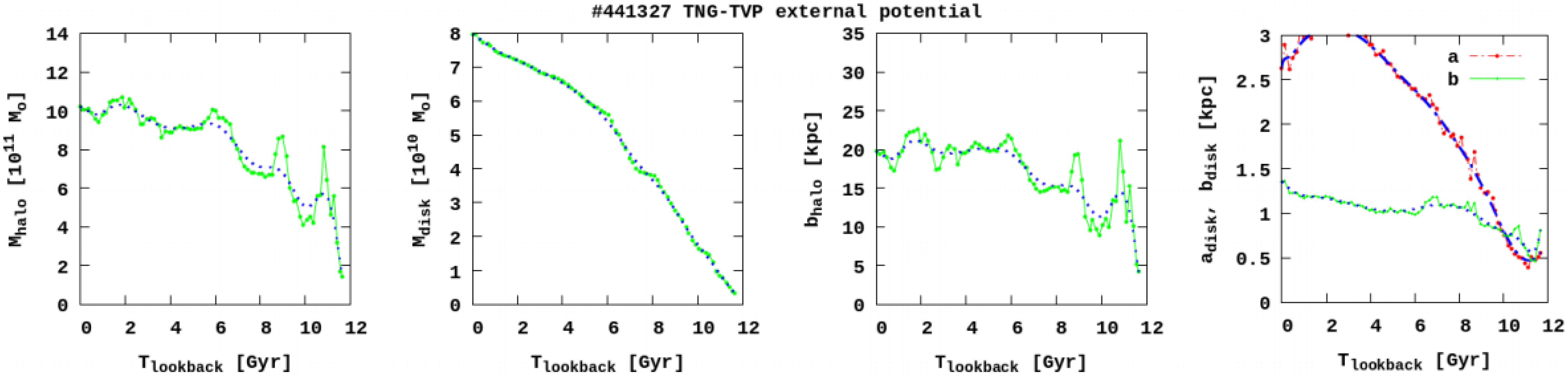


Fig. 1. Evolution of halo and disk masses, and their characteristic scales, for TNG-TVP 441327. The halo mass (M_h), disk mass (M_d), halo-scale parameter (b_h), and disk-scale parameters (a_d and b_d) are presented *from left to right*. Solid green lines with dots show the parameters derived from the IllustrisTNG-100 data. Dotted and dash-dotted blue lines correspond to the values after interpolation and smoothing with a 1 Myr timestep.

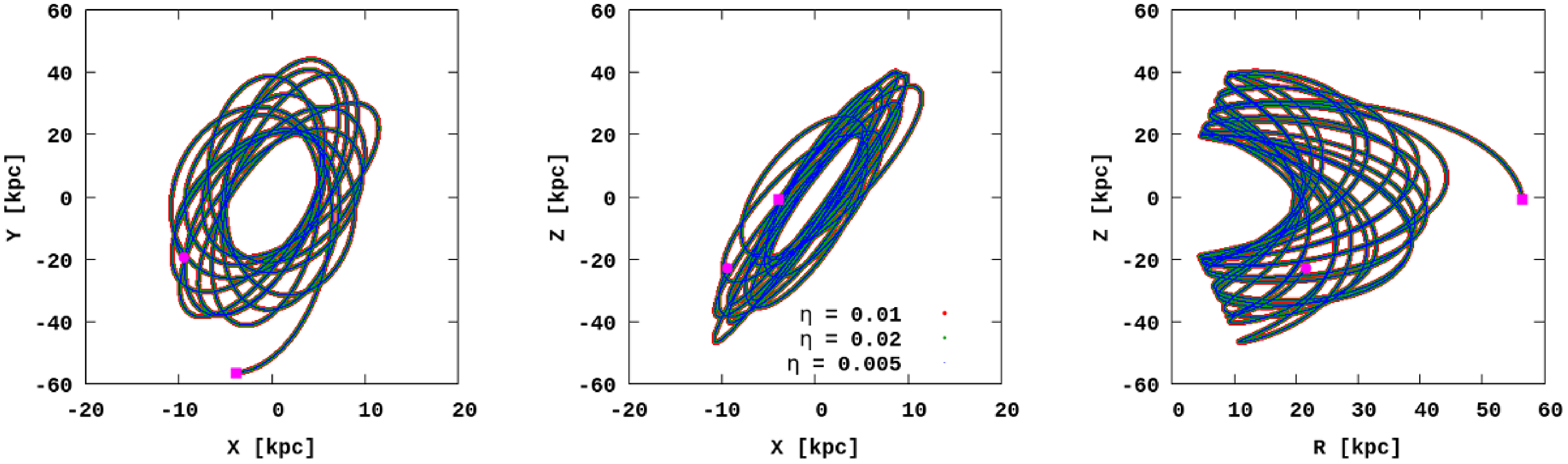


Fig. 2. Ret-II orbital reconstruction with 11.5 Gyr of lookback time integration with different η parameters. The magenta square shows the past position and the circle the present-day position.

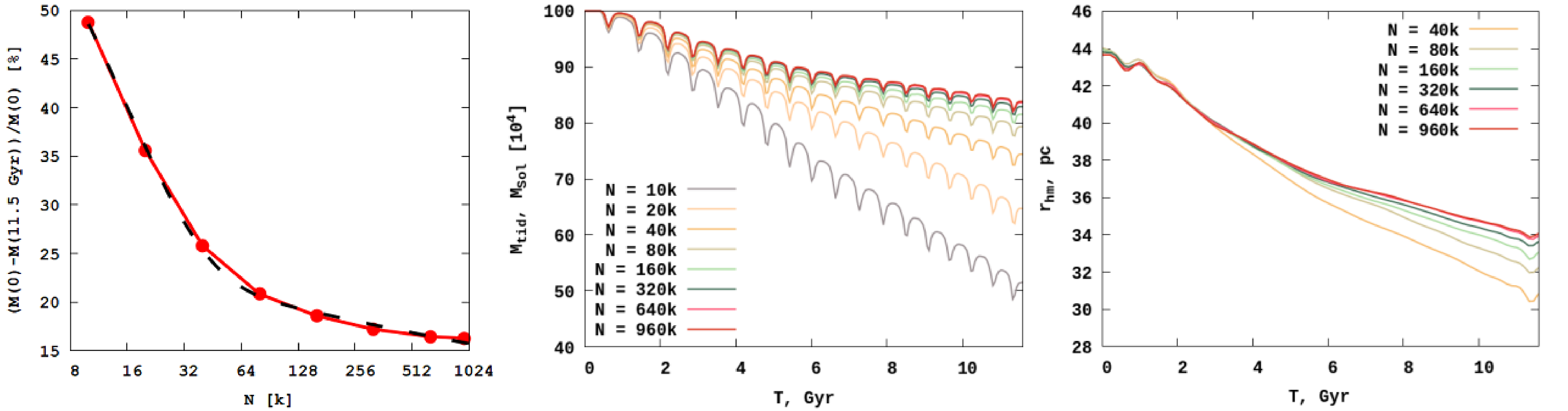


Fig. 5. Ret-II tidal mass and half-mass radius evolution for different models with different particle numbers. *Left panel*: global mass loss (red) in percent for different particle numbers. The dashed black line represents the exponential fitting of the mass-loss data for different N.

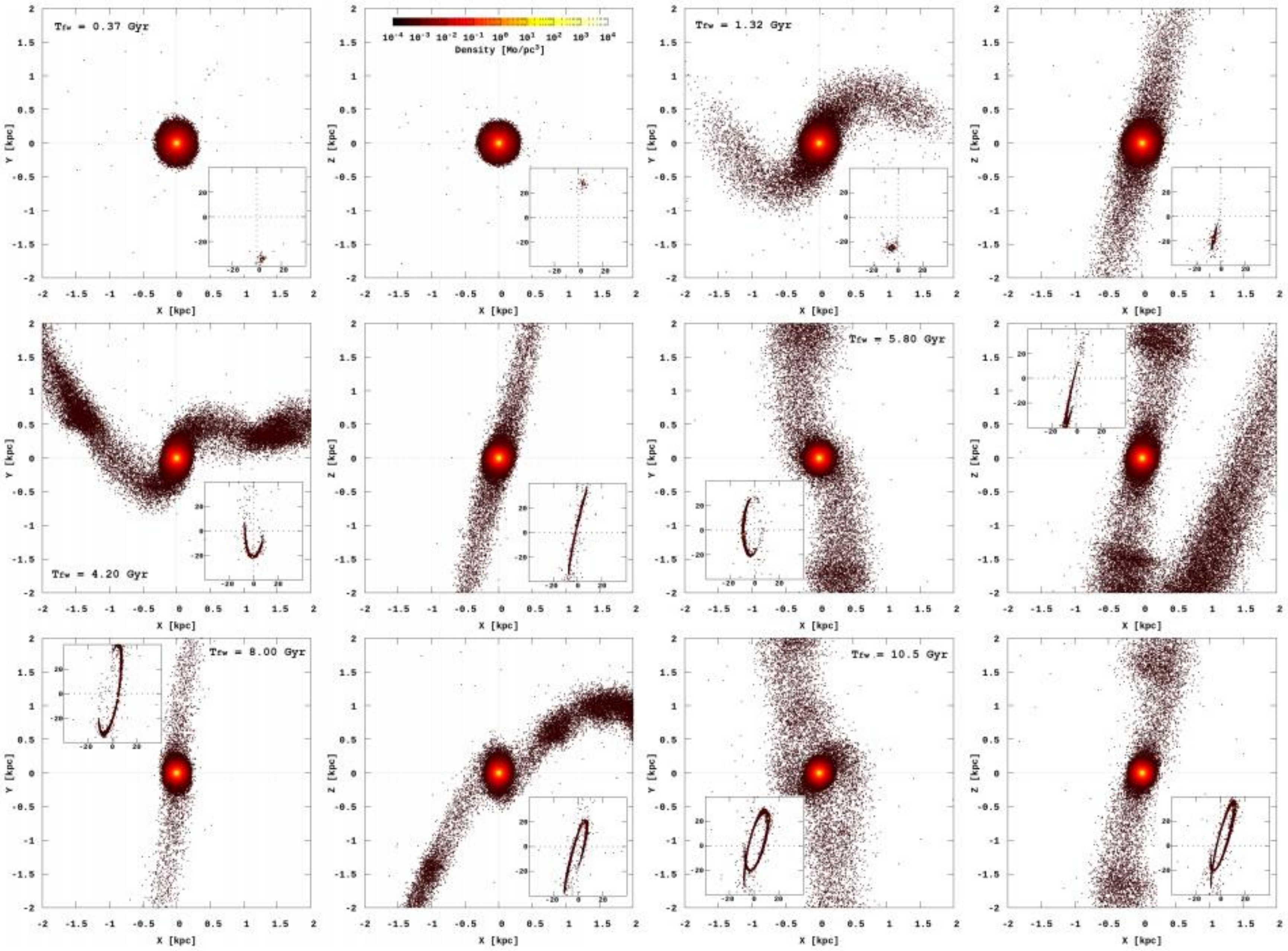


Fig. 6. Ret-II density distributions in 441327 TNG-TVP external potential for $N = 960k$. The central part in the local frame is presented in two projections, (X, Y) and (X, Z). The orbital global evolution is shown in the insets. The density distribution is presented for several moments of forward time integration: T = 0.37, 1.32, 4.20, 5.80, 8.00, and 10.5 Gyr from *left to right*.

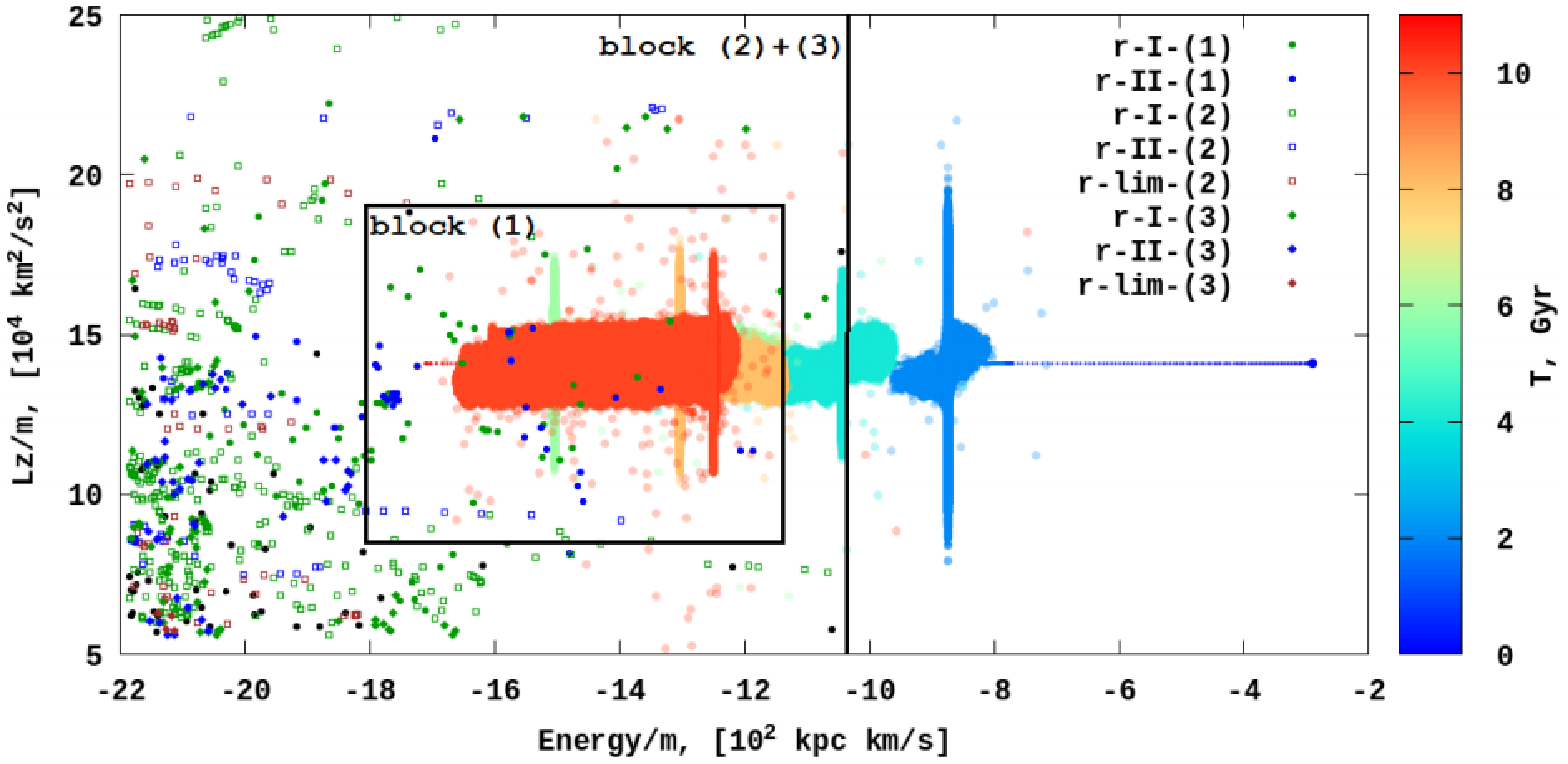


Fig. 7. Total specific energy (E/m) vs the z-th component of the specific angular momentum (L_z/m) for the Ret-II and r stars. The colours represent the time evolution of Ret-II from the past (blue) to today (red) based on a numerical simulation with N = 960k. The symbols (filled circle, unfilled square, and filled rhombus) represent the different types of r stars (r-I, r-II, and r-lim). For each individual r star, we generated ten random realisations inside their $\pm\,\sigma$ error box. Block (1) comprises the stars presented in Table A.1 as the 'most probable' candidates, overlapping in the E/m vs. L_z/m phase-space with the present-day Ret-II. Block (2)+(3) represents the stars with the moderate 'tentative' and low 'in question' probabilities.

r-I: $0.3 \leq$ [Eu/Fe] $\leq +1.0$ and [Ba/Eu] < 0.0;
r-II: [Eu/Fe] $> +1.0$ and [Ba/Eu] < 0.0;
r-lim: [Eu/Fe] < 0.3, [Sr/Ba] > 0.5, and [Sr/Eu] > 0.0.

A&A, 689, A178 (2024)
https://doi.org/10.1051/0004-6361/202450399

Dynamical evolution of Milky Way globular clusters on the cosmological timescale

I. Mass loss and interaction with the nuclear star cluster

Maryna Ishchenko[1,2,3,⋆], Peter Berczik[2,3,8,1], Taras Panamarev[7,3], Dana Kuvatova[3].

Table 1. Main kinematic and physical characteristics of the selected GCs at present.

GC	M (10^4 $M_\odot$)	dV (km/s)	Age (Gyr)	r_{hm} (pc)	Z_m (10^{-4})	TO	Pg.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 6401	12.10	331	13.20 [(a)]	3.17	0.85	TB	M-B
Palomar 6	8.60	340	12.40 [(b)]	2.91	2.46	TB	M-B
NGC 6681	10.50	410	12.80 [(c)]	3.04	0.46	LR	–
NGC 6642	3.90	262	13.80 [(d)]	1.73	1.10	TB	M-B
NGC 6981	8.10	545	10.88 [(c)]	5.79	0.66	LR	G-E
HP 1	14.00	304	12.80 [(e)]	4.19	2.00	IR	M-B

Notes. Masses and r_{hm} in columns (2, 3) is up to Oct. 2023 `https://people.smp.uq.edu.au/HolgerBaumgardt/globular/`; Column (4) – the GCs age in Gyr according to the: [(a)]Cohen et al. (2021), [(b)]Souza et al. (2021), [(c)]Forbes & Bridges (2010), [(d)]Balbinot et al. (2009), [(e)]Ortolani et al. (2011).

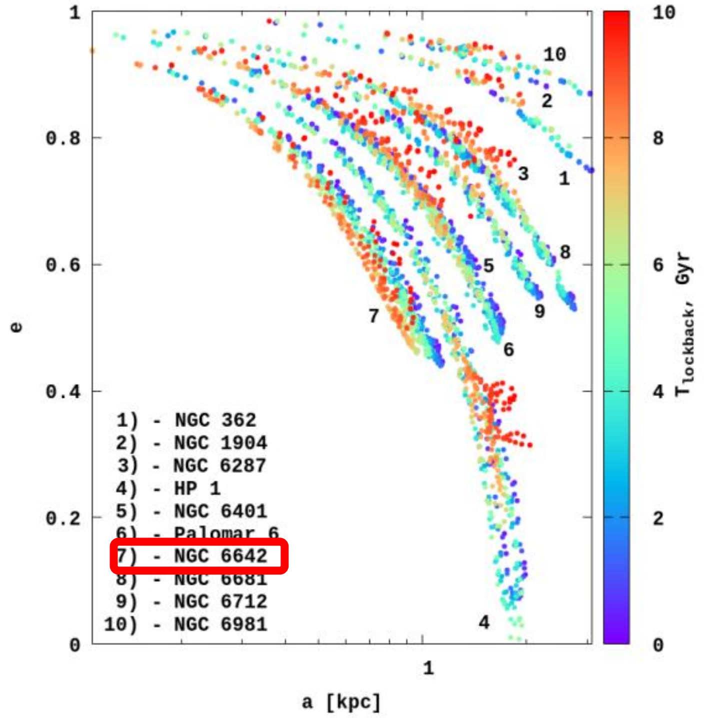


Fig. 2. Evolution of the semimajor axis and eccentricity during the whole forward-integration time for selected GCs in the 411321 TNG-TVP potential. Time is represented by the colour-coding.

Table 2. Initial kinematics and physical characteristics at a lookback time of eight billion years for the GCs.

GC	X (pc)	Y (pc)	Z (pc)	V_x (km s^{-1})	V_y (km s^{-1})	V_z (km s^{-1})	E/m (10^4 km^2 s^{-2})	L_{tot}/M (10^2 kpc km s^{-1})	M (10^6 $M_\odot$)	N	r_{hm} (pc)	W_0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
NGC 6401	−1493	−3213	398	5	−3	−57	−18.8	2.03	1.2	2 249 640	6.5	9
Palomar 6	1499	465	−1655	140	51	−81	−18.8	1.14	1.0	1 751 970	3.5	9
NGC 6681	1392	−4638	4243	−0.7	−1	61	−16.6	2.9	1.3	2 265 380	3.0	8
NGC 6642	983	−897	545	−47	54	−117	−21.2	1.1	1.5	2 613 856	4.0	9
NGC 6981	1774	4001	−4943	70	159	−270	−11.5	3.7	1.0	1 742 560	7.0	9
HP 1	−580	242	1859	71	−36	128	−19.5	2.3	1.3	2 265 340	6.0	8

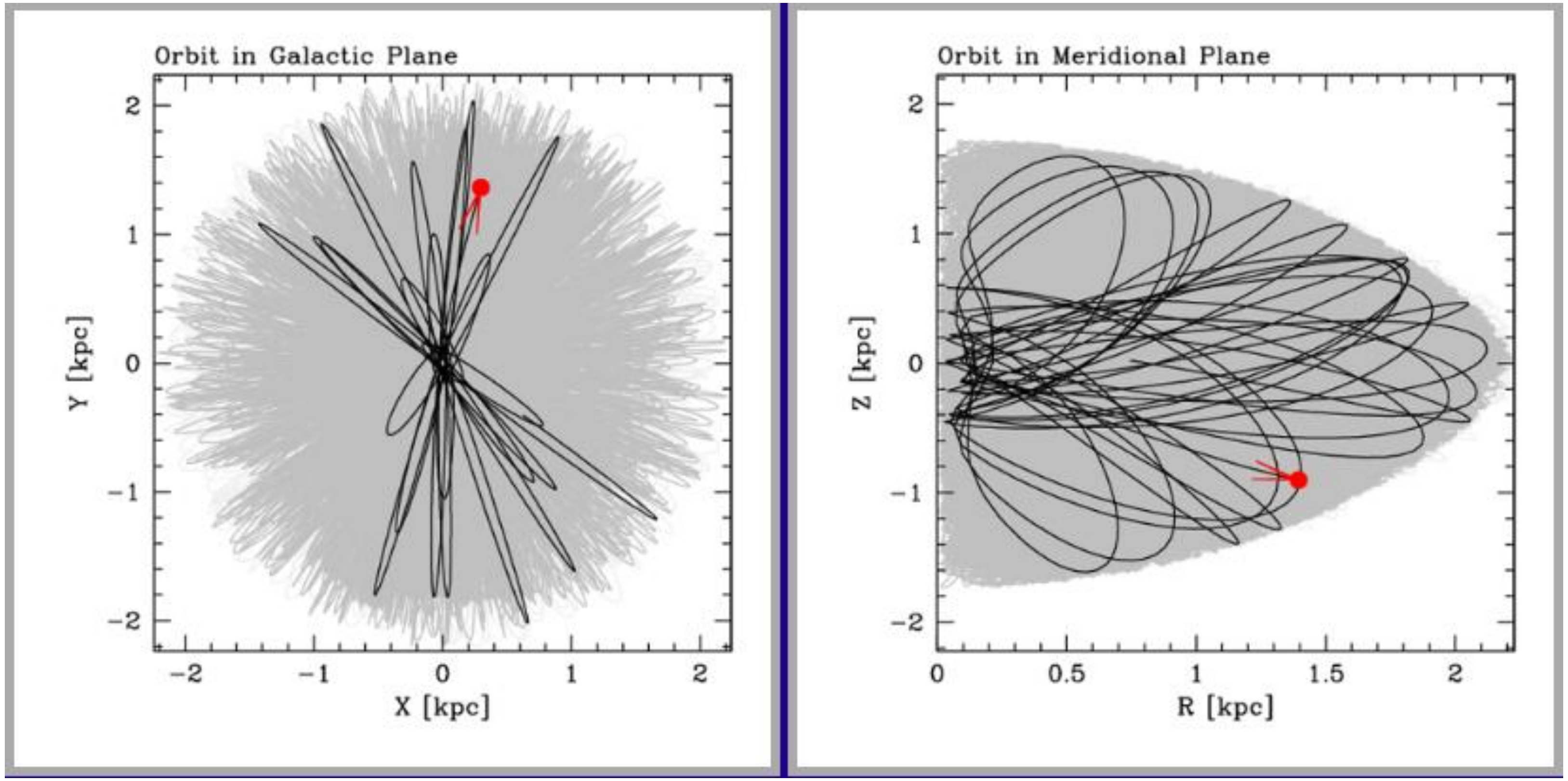
Notes. Column (1) – the GCs names; columns (2)–(4) – initial position in Cartesian galactocentric frame; columns (5)–(7) – initial velocities in Cartesian galactocentric frame; column (8) – total specific energy; column (9) – total specific angular momentum; column (10) – initial mass; column (11) – initial number of stars; column (12) – initial half-mass radius; column (13) – initial concentration of King profile.

NGC 6642

Image of NGC 6642 was created from visible and infrared images taken with the Wide Field Channel of the Advanced Camera for Surveys.

Observation data (J2000 epoch)	
Constellation	Sagittarius
Right ascension	$18^h\ 31^m\ 54.23^s$ [1]
Declination	−23° 28′ 34.1″
Distance	26.7 ± 2.3 kly (8.2 ± 0.7 kpc)[2]

Distance from Sun:	8050 ± 200 pc
Galactocentric distance:	1660 ± 10 pc
V-band magnitude:	9.65 ± 0.05
Mass:	$3.9 \cdot 10^4\ M_\odot$
M/L ratio:	$1.4 \pm 0.1\ M_\odot/L_\odot$
Half-mass radius:	1.73 pc
Power-law MF slope:	α = 1.00 ± 0.15



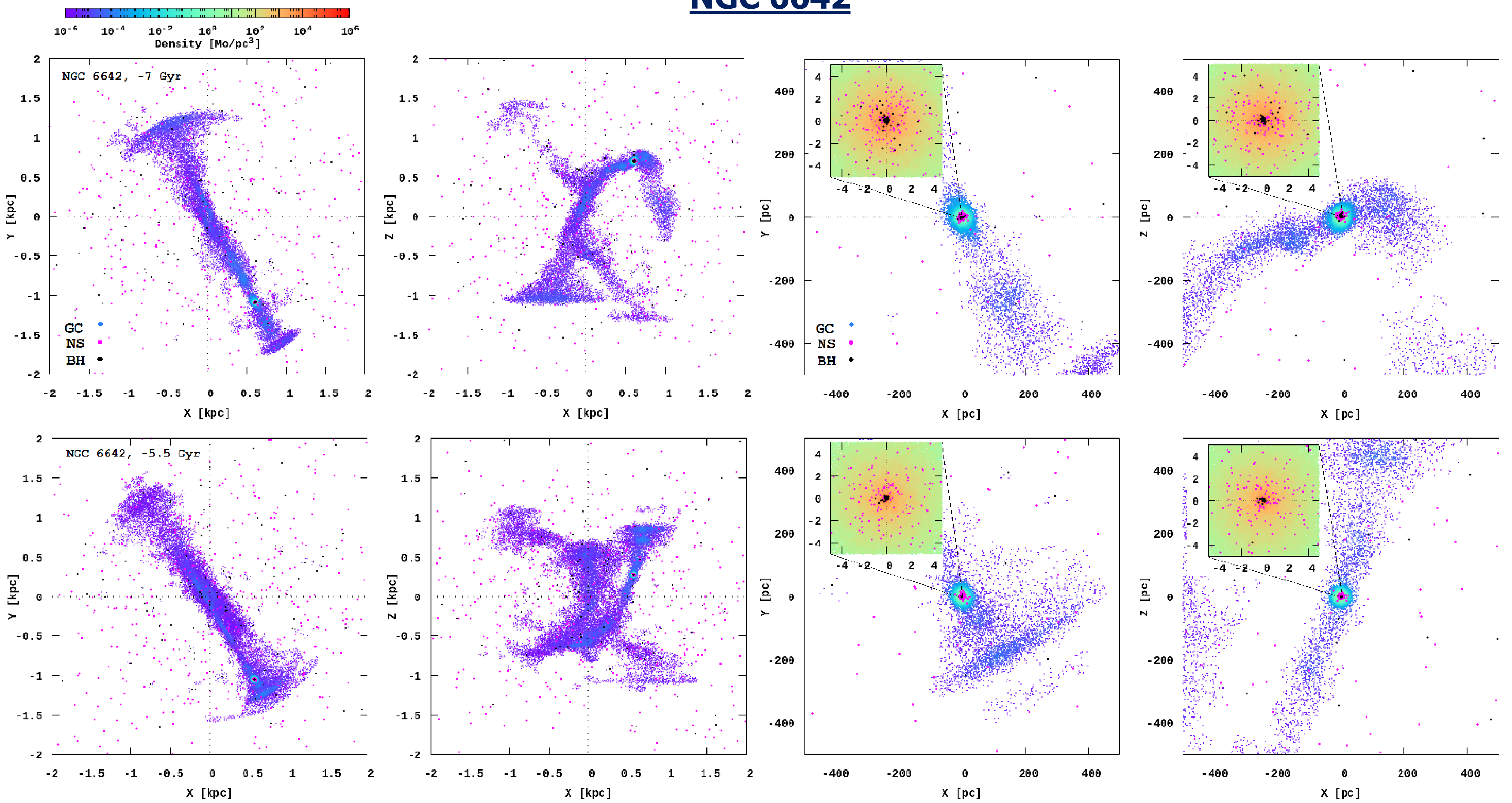
$$E^*_{\text{bound}} = -(M_{\text{NSC}} + m_*)/R_* + V_{\text{red}} \cdot 0.5 \cdot V_*^2,$$

Table 5. Total amount of the bound particles with the NSC and their masses with different velocity redaction during 8 billion years evolution in units of 10^3.

Vel_{red}	NGC 6642			NGC 6401			NGC 6681			HP 1		
	Tot.	Unq. / in %	$M_\odot$	Tot.	Unq. / in %	$M_\odot$	Tot.	Unq. / in %	$M_\odot$	Tot.	Unq. / in %	$M_\odot$
$V_{\text{red}=1.00}$	9.8	2.6 / 0.1	0.1	0.2	0.1 / 0.01	0.01	0	0	0	0	0	0
$V_{\text{red}=0.80}$	22	8 / 0.3	0.4	1.2	0.1 / 0.01	0.01	0	0	0	0	0	0
$V_{\text{red}=0.75}$	72	29 / 1.1	1.2	1.7	0.1 / 0.01	0.01	0	0	0	0	0	0
$V_{\text{red}=0.60}$	4 550	1 066 / 41	40.7	2.6	0.1 / 0.01	0.01	0	0	0	0	0	0
$V_{\text{red}=0.50}$	14 534	1 984 / 76	73.5	3.9	0.2 / 0.7	0.03	0	0	0	0	0	0
$V_{\text{red}=0.40}$	–	–	–	20	1.4 / 0.6	0.7	0	0	0	0	0	0
$V_{\text{red}=0.35}$	–	–	–	–	–	–	0	0	0	2 760	813 / 35	28.5
$V_{\text{red}=0.30}$	–	–	–	–	–	–	0.37	0.17 / 0.01	0.01	5 127	1 504 / 66	56.5
$V_{\text{red}=0.25}$	–	–	–	–	–	–	6.73	4.7 / 0.2	0.02	5 128	1 518 / 67	56.6
$V_{\text{red}=0.20}$	–	–	–	–	–	–	5 820	199 / 88	7.1	–	–	–

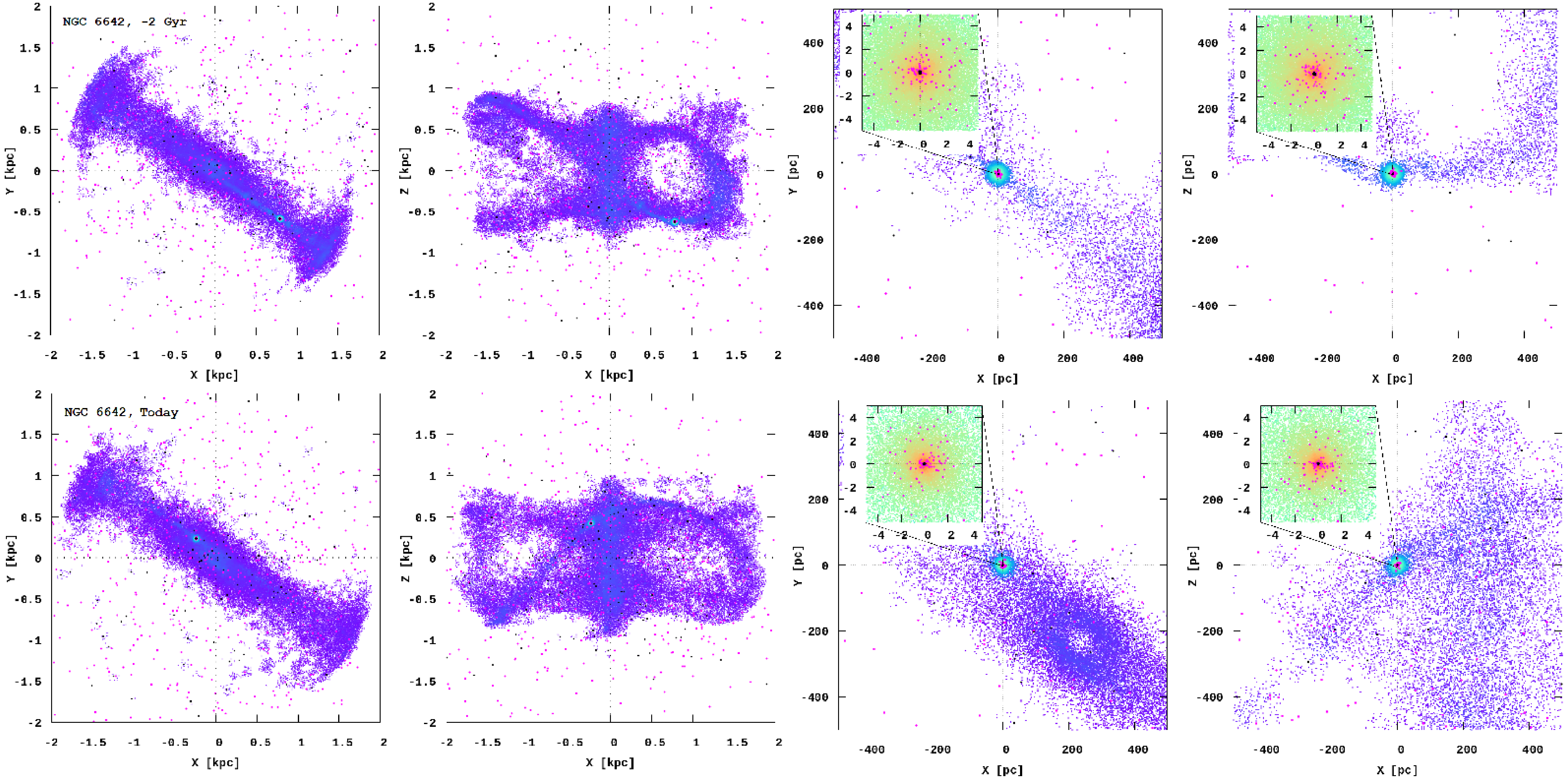
Notes. – indicates, that no calculations were carried out for these V_{red}.

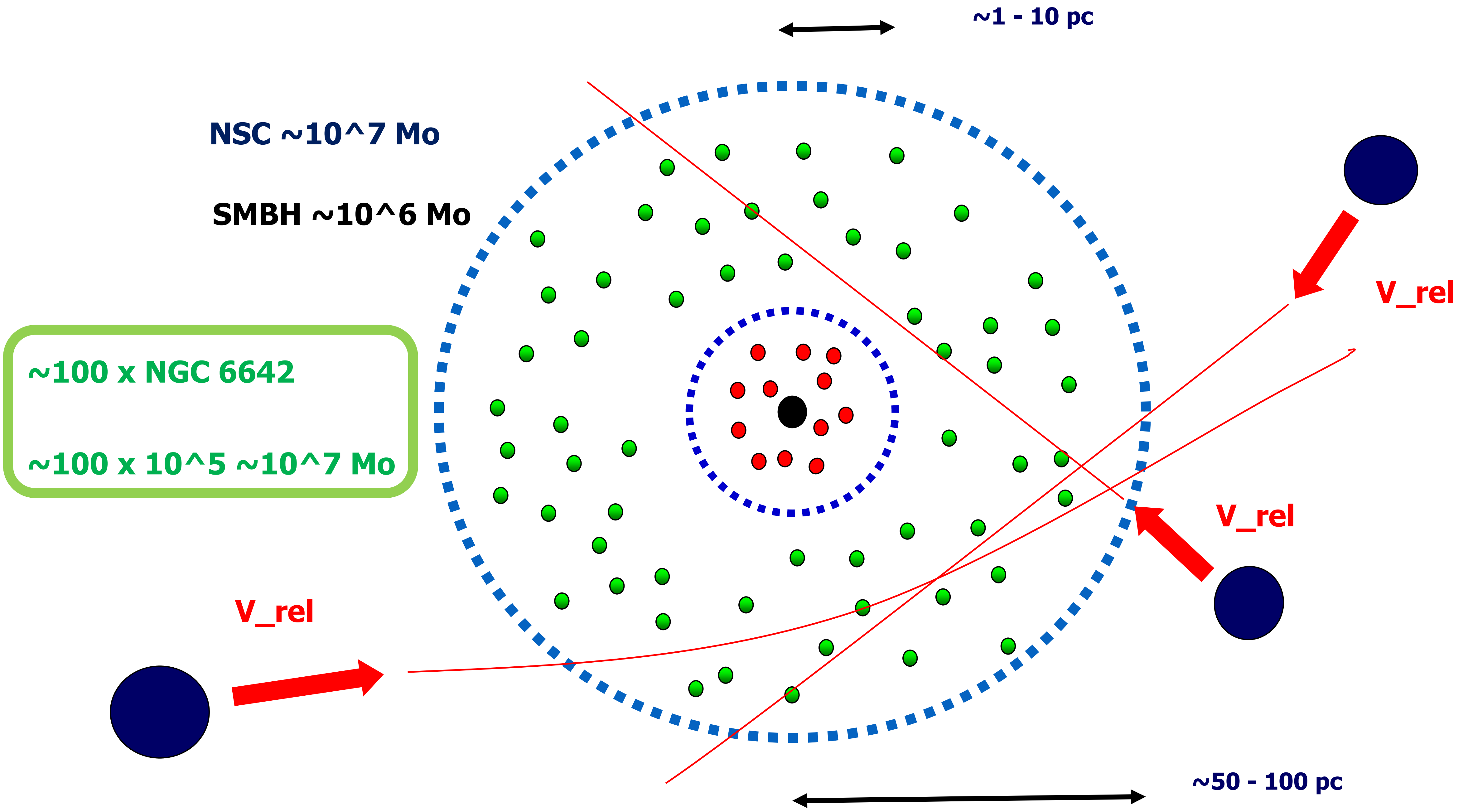
NGC 6642



Density [Mo/pc³]
NGC 6642, -7 Gyr
NGC 6642, -5.5 Gyr
GC
NS
BH
X [kpc]
Y [kpc]
Z [kpc]
X [pc]
Y [pc]
Z [pc]

NGC 6642




~1 - 10 pc
NSC ~10^7 Mo
SMBH ~10^6 Mo
~100 x NGC 6642
~100 x 10^5 ~10^7 Mo
V_rel
V_rel
V_rel
~50 - 100 pc

Thank you for your attention...

☺