IMBH Pair Evolution in Nuclear Star Clusters Featuring a Dark Stellar-Mass Black Hole Population

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Massive Black Hole Binaries

- ***Supermassive Black Holes*** ($10^6 - 10^9\ M_\odot$)

  bulges of spiral galaxies/elliptical galaxies

  (Kormendy & Richstone 1995; Haring & Rix 2004; Ferrarese & Ford 2005; Kormendy & Ho 2013; Graham 2016)

  SMBH Binaries via Galaxy Mergers

  dynamical friction, 3-body scattering, GW Emission (Begelmann et. al 1980)

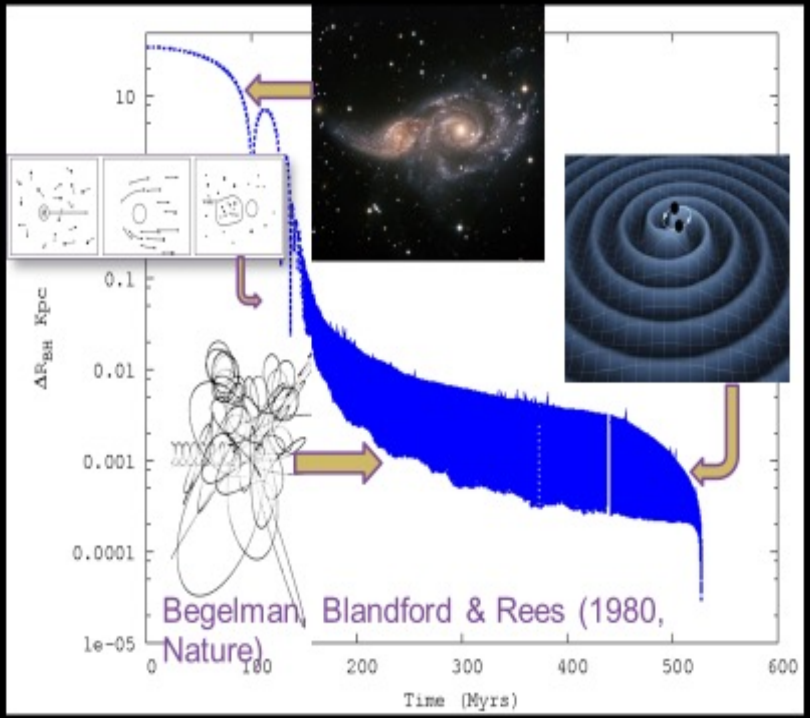
  Evolution and Merger Timescales

  $10^9\ M_\odot$: e → 0.9, Tcoal → 1-2 Gyr

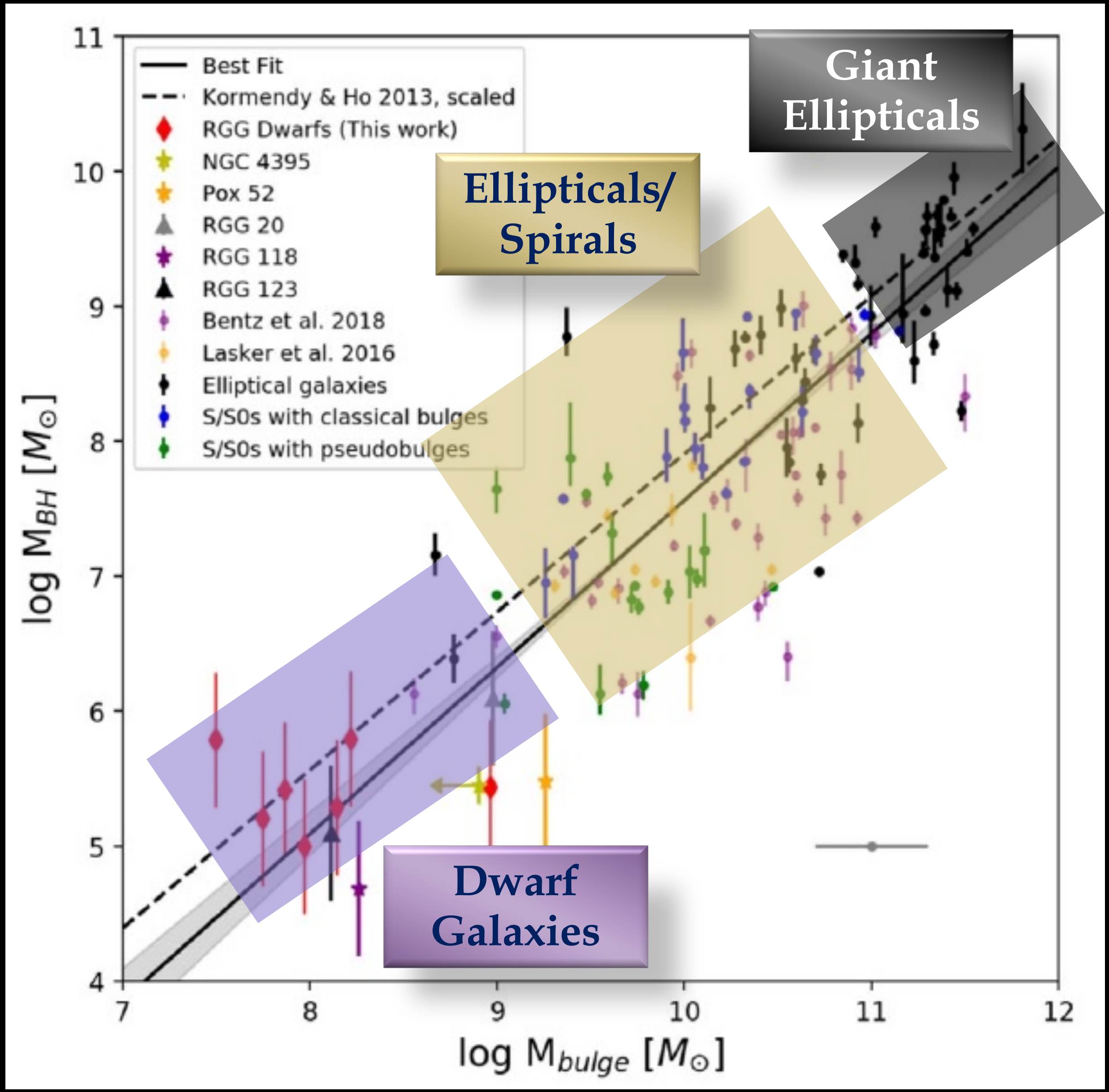
  $10^8\ M_\odot$: e → 0.7, Tcoal → ~ 1 Gyr

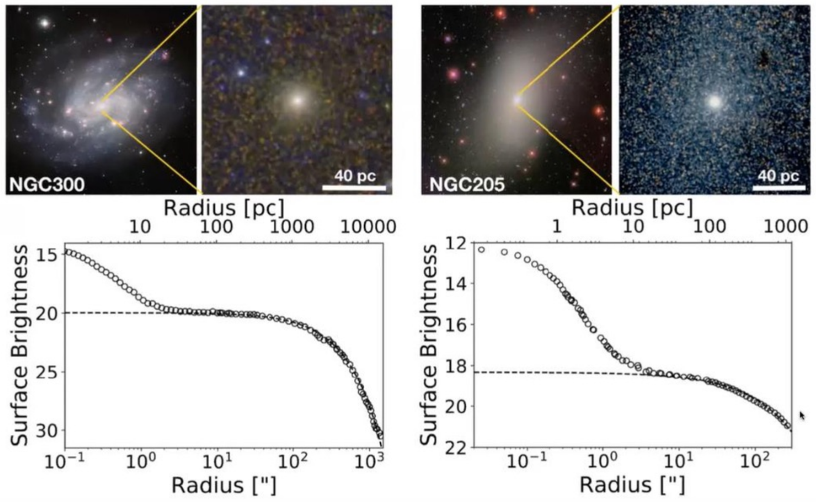
  $10^7\ M_\odot$: e → 0.3, Tcoal → ~ 0.5 Gyr

  (Khan+ 11,12,16,18, Gualandris & Merritt, 12, Vasiliev+15, Rantala+17)



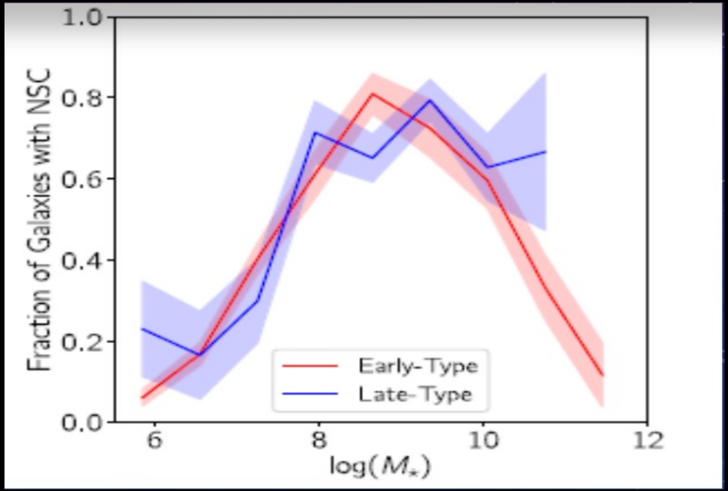
Dwarf Galaxies in Local Universe





NSCs as observed in a spiral (left) and elliptical (right) galaxy.

Luminous and compact sources that clearly 'stand out' above their surroundings.



Neumayer et al. 2020

IMBHs Dynamics in Nucleated Dwarf Galaxies

Table 2. M32 Galaxy Parameters

Component	n	$r_{\rm eff}/r_{\rm infl.}$(pc)	$M_\star$ (10^7 M$_\odot$)	a_2/a_1
IMBH	--	1.61	0.25	--
NSC	2.7	4.4	1.45	0.75
Bulge	1.6	108	79.4	0.79
Disk	1.0	516	19.3	0.79

Table 5. NGC 404 Galaxy Parameters

Component	n	$r_{\rm eff}$(pc)	$M_\star$ (10^7 M$_\odot$)	a_2/a_1
IMBH	--	0.35	0.007	--
NSC1	0.5	1.6	0.34	0.97
NSC2	1.96	20	1.1	0.95
Bulge	2.50	675	84.4	0.99

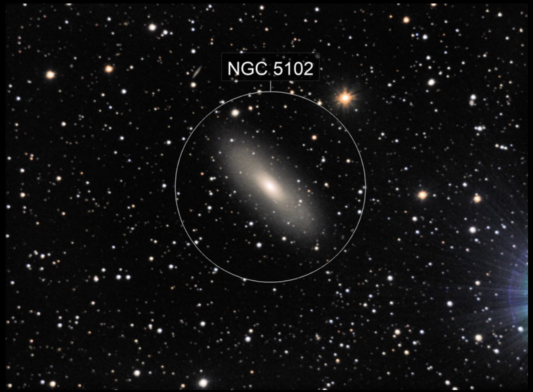


Table 6. NGC 205 Galaxy Parameters

Component	n	$r_{\rm eff}$(pc)	$M_\star$ (10^7 M$_\odot$)	a_2/a_1
IMBH	--	0.14	0.004	--
NSC	1.6	1.3	0.18	0.95
Bulge	1.4	516	97.2	0.90

Nguyen+ 17,19

Table 3. NGC 5102 Galaxy Parameters

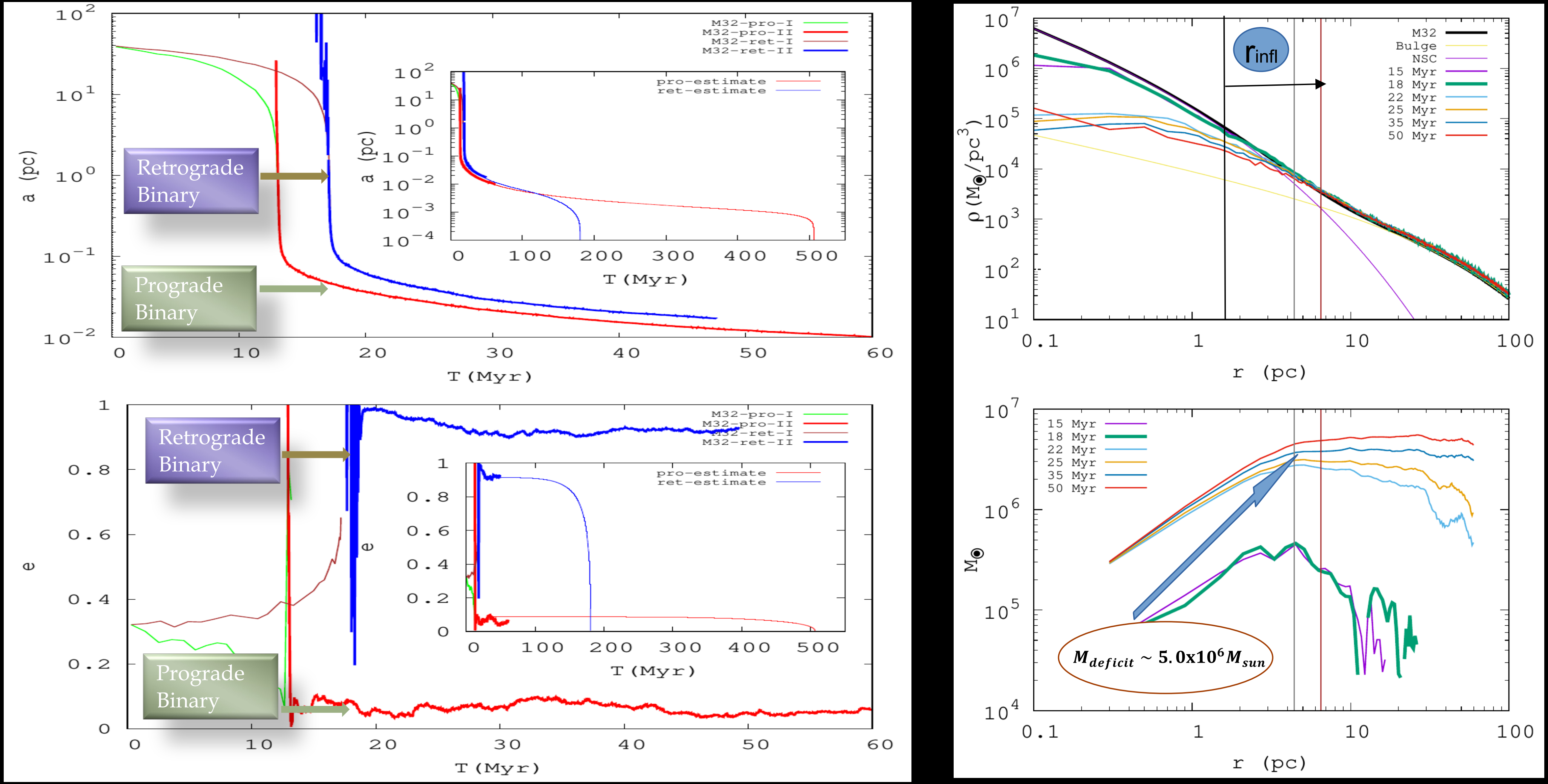
Component	n	$r_{\rm eff}$(pc)	$M_\star$ (10^7 M$_\odot$)	a_2/a_1
IMBH	--	1.2	0.088	--
NSC1	0.8	1.6	0.71	0.68
NSC2	3.1	32	5.8	0.59
Bulge	3.0	1200	592	0.60

Table 4. NGC 5206 Galaxy Parameters

Component	n	$r_{\rm eff}$(pc)	$M_\star$ (10^7 M$_\odot$)	a_2/a_1
IMBH	--	1.0	0.047	--
NSC1	0.8	3.4	0.17	0.96
NSC2	2.3	10.5	1.28	0.96
Bulge	2.57	986	241	0.98

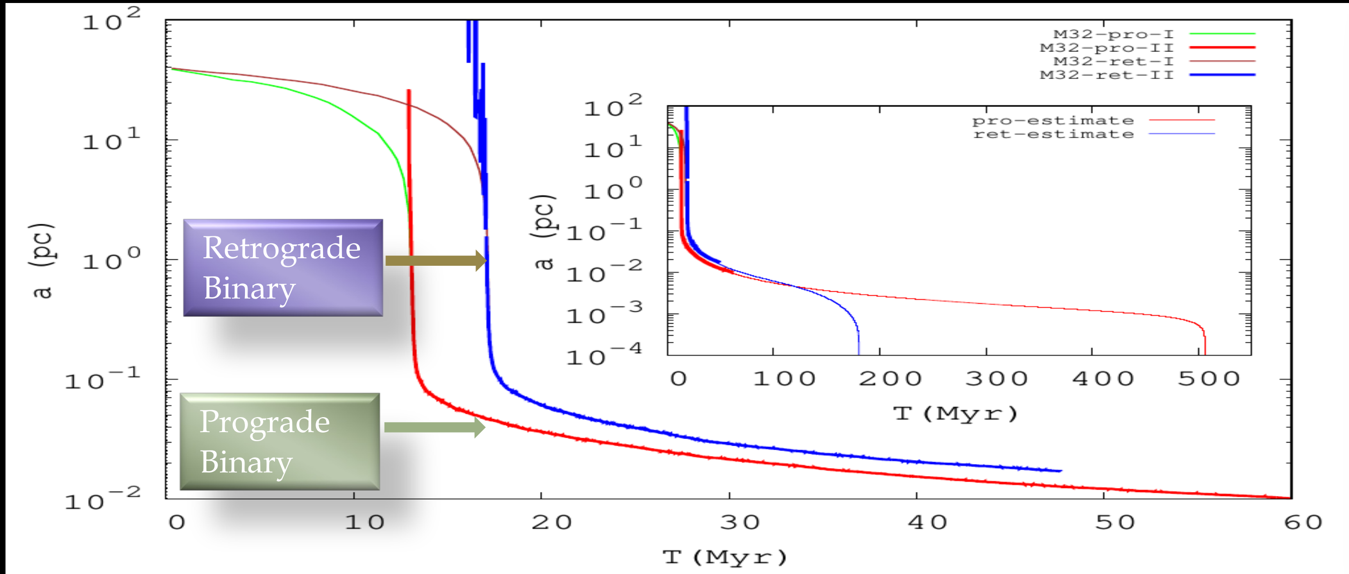
MBH Binary Evolution in M32

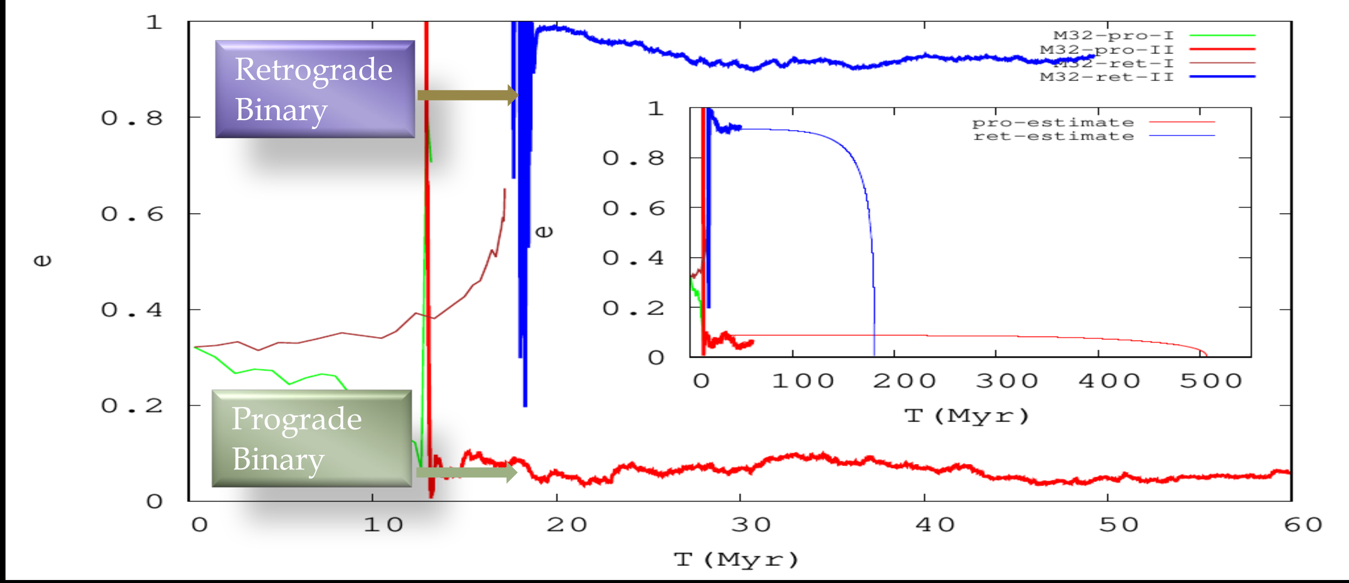
Khan & Holley-Bockelmann 2021, MNRAS, 508, 1174

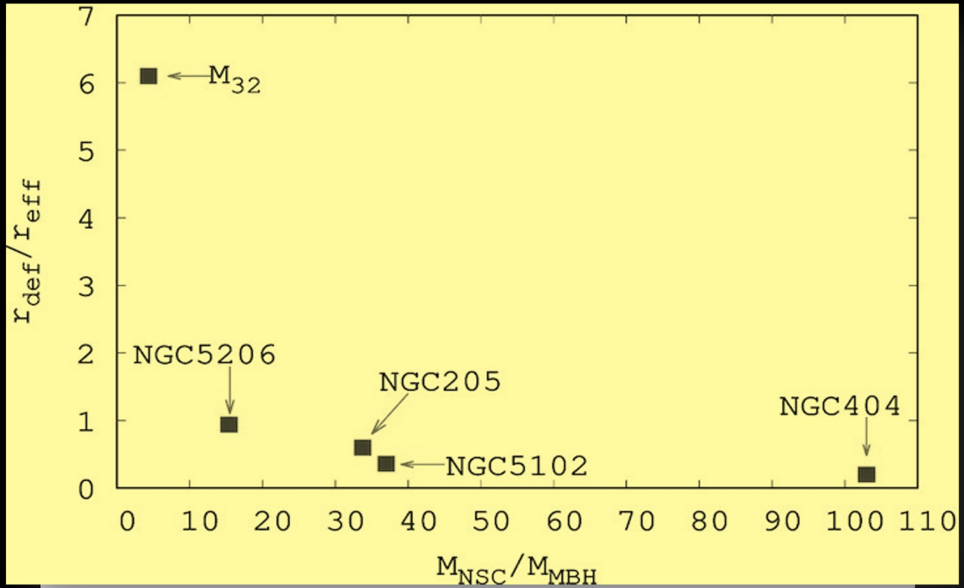


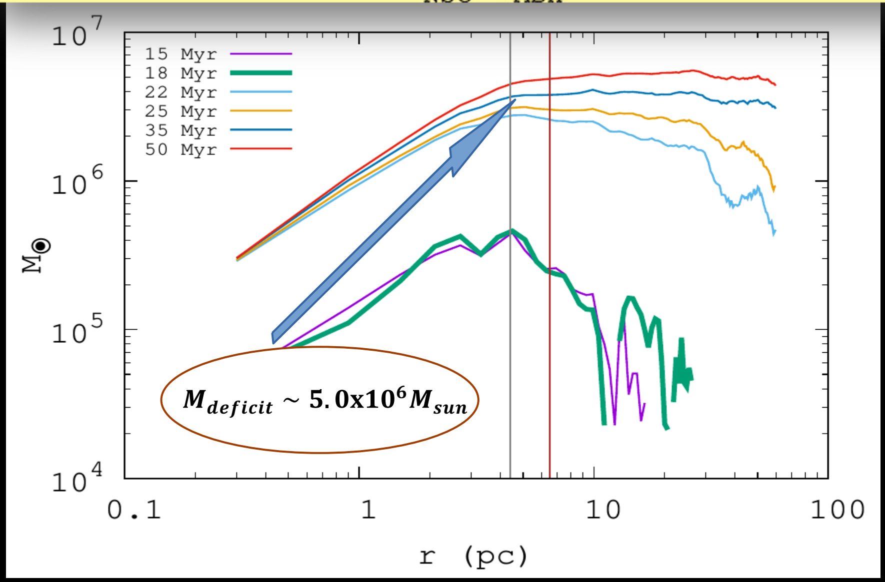
MBH Binary Evolution in Nucleated-Dwarfs

Khan & Holley-Bockelmann 2021, MNRAS, 508, 1174









MBH Binary Evolution in Nucleated-Dwarfs

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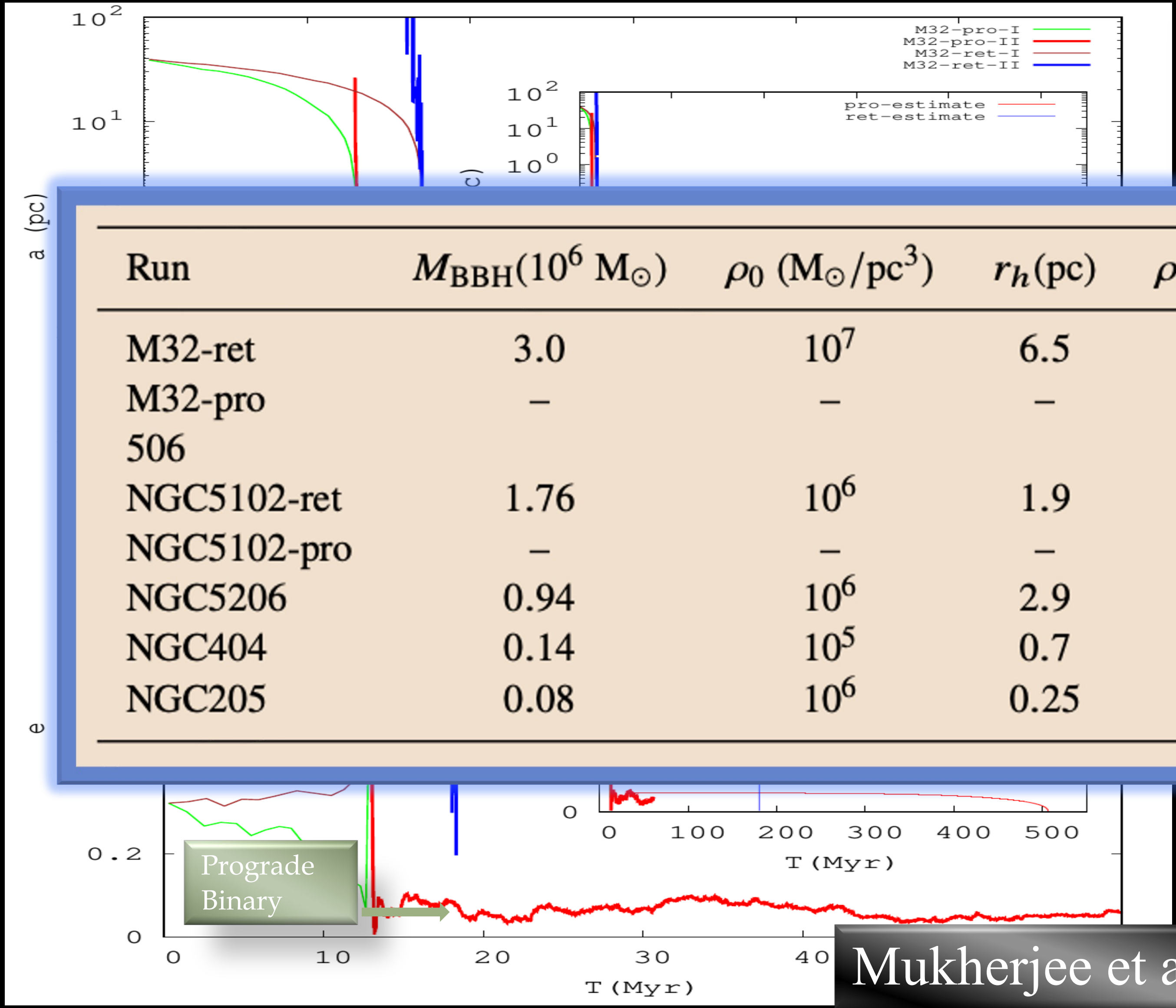
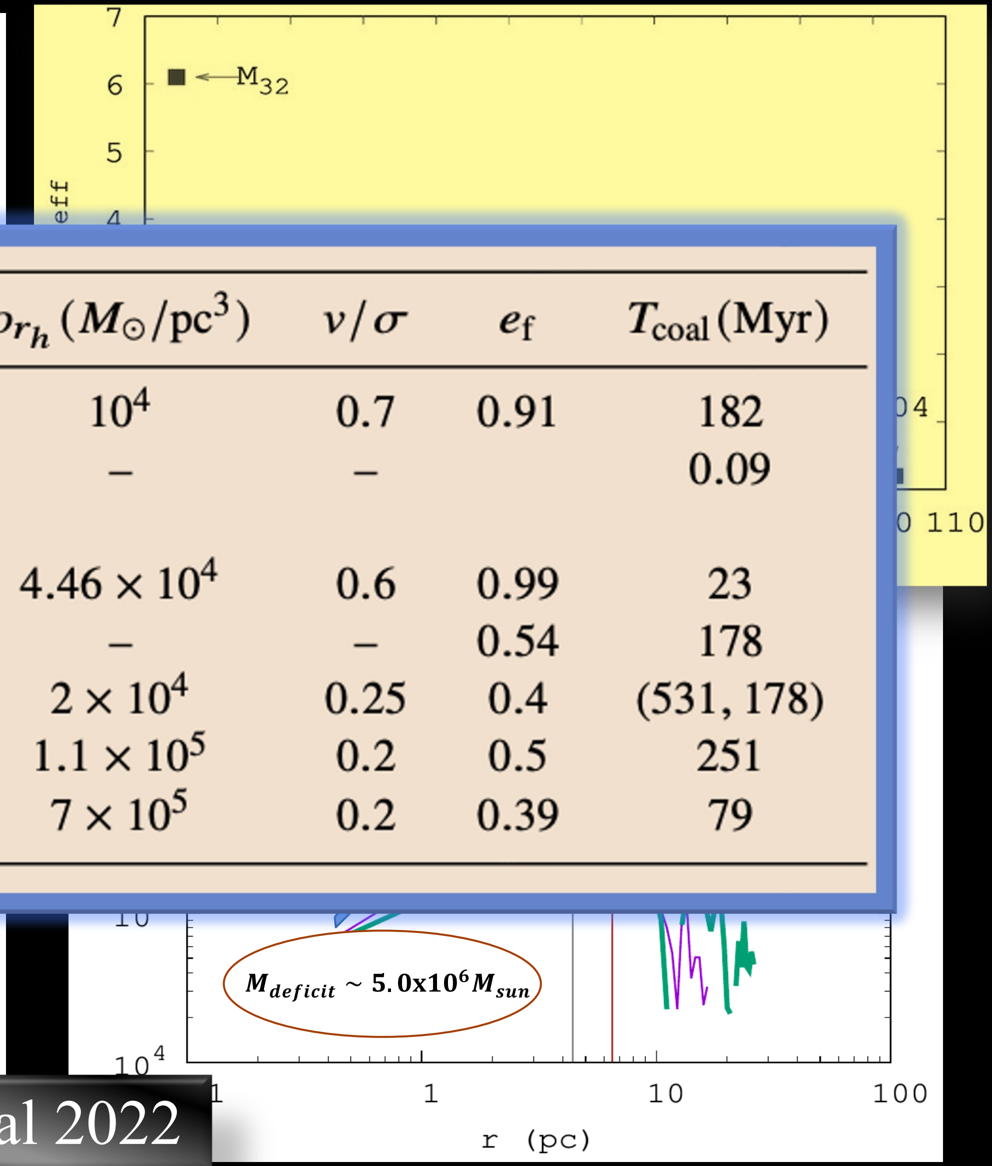


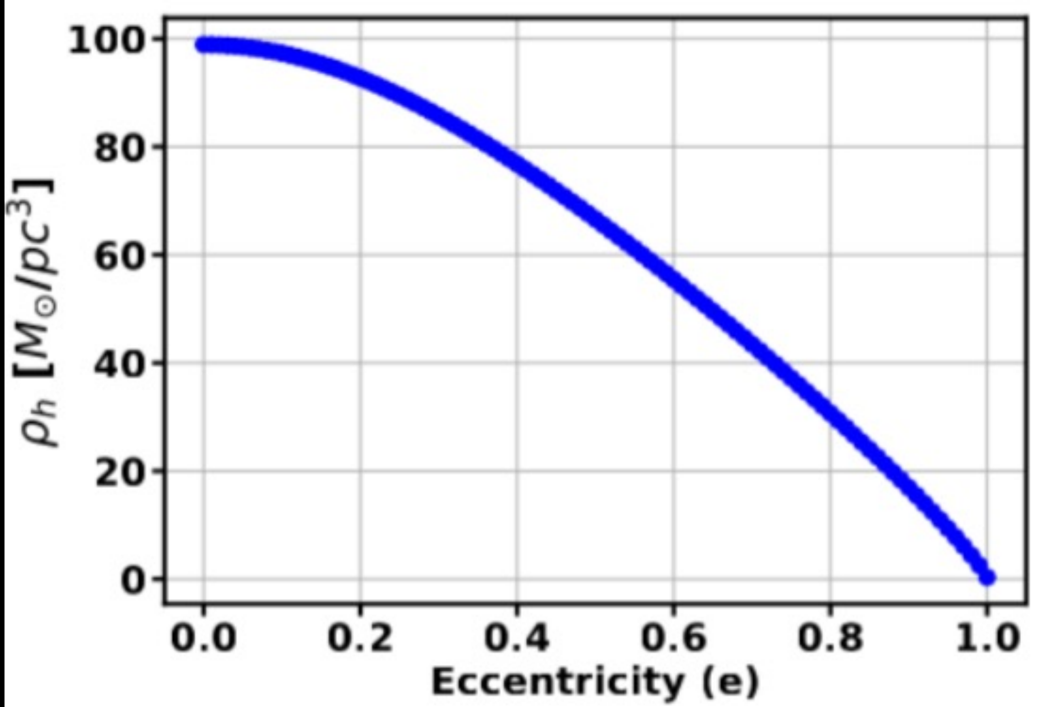


Run	$M_{\rm BBH}(10^6\ {\rm M}_\odot)$	$\rho_0\ ({\rm M}_\odot/{\rm pc}^3)$	r_h(pc)	$\rho_{r_h}\ (M_\odot/{\rm pc}^3)$	v/σ	$e_{\rm f}$	$T_{\rm coal}$ (Myr)
M32-ret	3.0	10^7	6.5	10^4	0.7	0.91	182
M32-pro	–	–	–	–	–		0.09
506							
NGC5102-ret	1.76	10^6	1.9	4.46×10^4	0.6	0.99	23
NGC5102-pro	–	–	–	–	–	0.54	178
NGC5206	0.94	10^6	2.9	2×10^4	0.25	0.4	(531, 178)
NGC404	0.14	10^5	0.7	1.1×10^5	0.2	0.5	251
NGC205	0.08	10^6	0.25	7×10^5	0.2	0.39	79

Mukherjee et al 2022

IMBHs Dynamics in Non-Nucleated Dwarf Galaxies

- Dwarfs in Next Generation Fornax Survey (NGFS) (Muñoz et al. 2015; Eigenthaler et al. 2018; Ordenes-Briceño et al. 2018).
- The masses of dwarf galaxies in Fornax cluster are between $9.5 \geqslant \log M_\star/M_\odot \geqslant 5.5$ (Eigenthaler et al. 2018).
- We adopt 10^8 $M_\odot$ for the stellar mass and ~ 10^5 $M_\odot$ for IMBH mass.



Run	$R_{\rm eff}$ (pc)	ρ_0 ($M_\odot/pc^3$)	r_h(pc)	ρ_{r_h}($M_\odot/pc^3$)	s(pc^{-1}/Myr)	e_f	$T_{\rm coal}$(Gyr)	$T_{\rm coal}(e_{0.95})$	$T_{\rm coal}(e_{0.99})$
D0.8	560	4.5×10^{-1}	59	1.7×10^{-1}	0.00025	0.93	No	600	224
D1.0	560	1.7×10^{0}	40	1.9×10^{-1}	0.0003	0.76	No	500	180
D1.5	560	1.8×10^{1}	36	1.3×10^{0}	0.004	0.83	No	70	24
D1.5c	200	1.9×10^{2}	13	2.6×10^{1}	0.055	0.92	No	13	3.2
D2.0	200	5.7×10^{2}	8	9.1×10^{1}	0.2	0.17	No	3.45	1.3

Khan et al 2024

Biava+2019

Nuclear Star Clusters in NGC205 & NGC404

Table 6. NGC 205 Galaxy Parameters

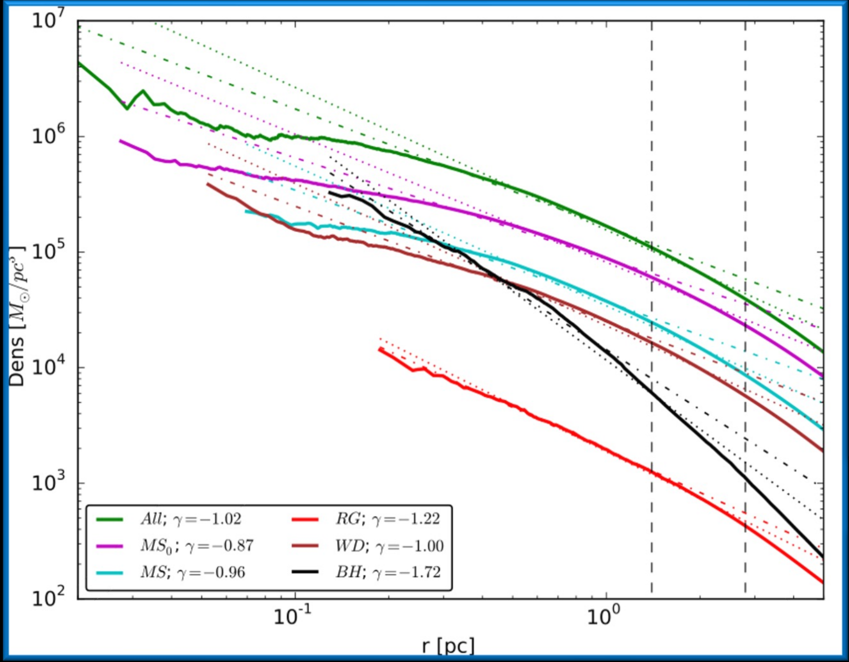
Component	n	$r_{\rm eff}$(pc)	$M_\star$ (10^7 $M_\odot$)	a_2/a_1
IMBH	−−	0.14	0.004	−−
NSC	1.6	1.3	0.18	0.95
Bulge	1.4	516	97.2	0.90

Table 5. NGC 404 Galaxy Parameters

Component	n	$r_{\rm eff}$(pc)	$M_\star$ (10^7 $M_\odot$)	a_2/a_1
IMBH	−−	0.35	0.007	−−
NSC1	0.5	1.6	0.34	0.97
NSC2	1.96	20	1.1	0.95
Bulge	2.50	675	84.4	0.99

Nguyen+ 17,19

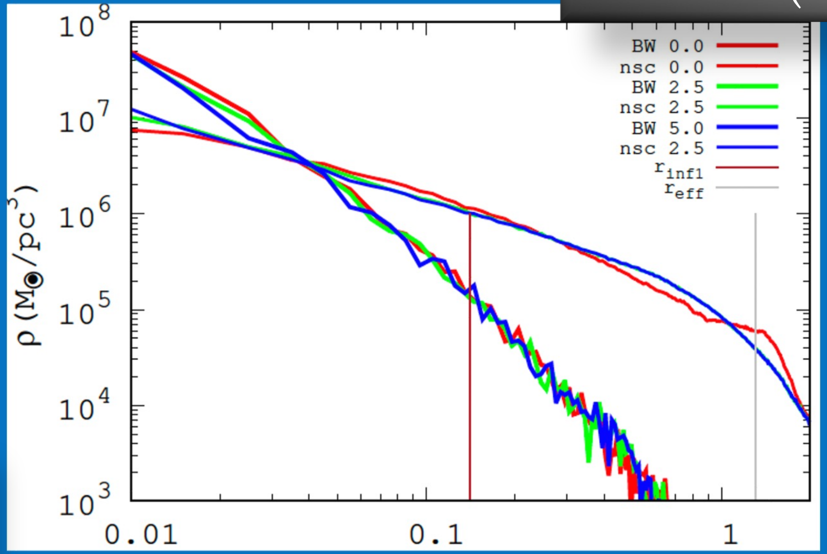
Nuclear Star Cluster Models

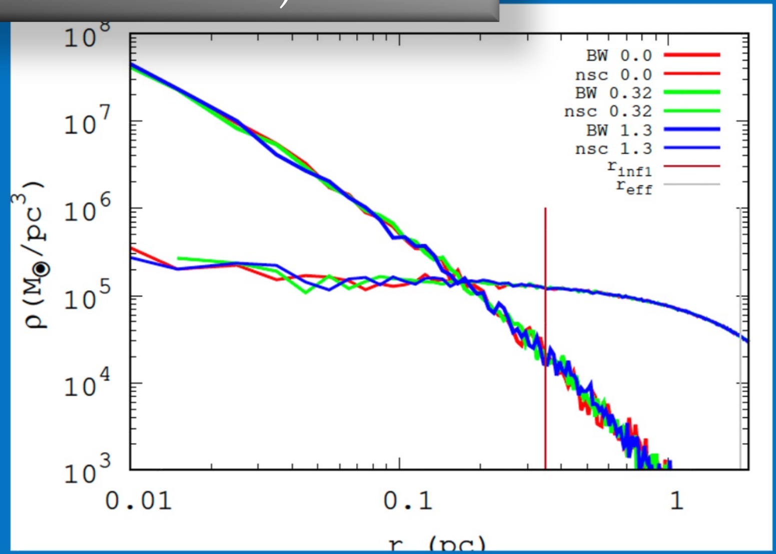


Panamarev et al. 2019

NSC Component	N	Mass (10^6 $M_\odot$)	R_{eff}, R_{infl} (pc)	n or γ	$b/a, c/a$
NGC205					
Stars	1.84×10^6	1.84	1.3	1.6	0.95, 0.85
BW Cusp	1.8×10^3	0.018	0.14	1.75	0.95, 0.85
IMBH	1	0.022	0.14	−−	−−
NGC404					
Stars	4.25×10^6	4.25	1.85	0.65	0.95, 0.85
BW Cusp	4.25×10^3	0.0425	0.35	1.75	0.95, 0.85
IMBH	1	0.027	0.35	−−	−−

Galaxy models built using AGAMA (Vasiliev - 2019)





Bhacall & Wolf Cusp of stellar mass black holes with 1% of NSC mass

N-body Simulations - Phi-GPU (hybrid)

Phi-GPU (Berczik et al.):

- parallel direct summation N-body code (GPU supported).

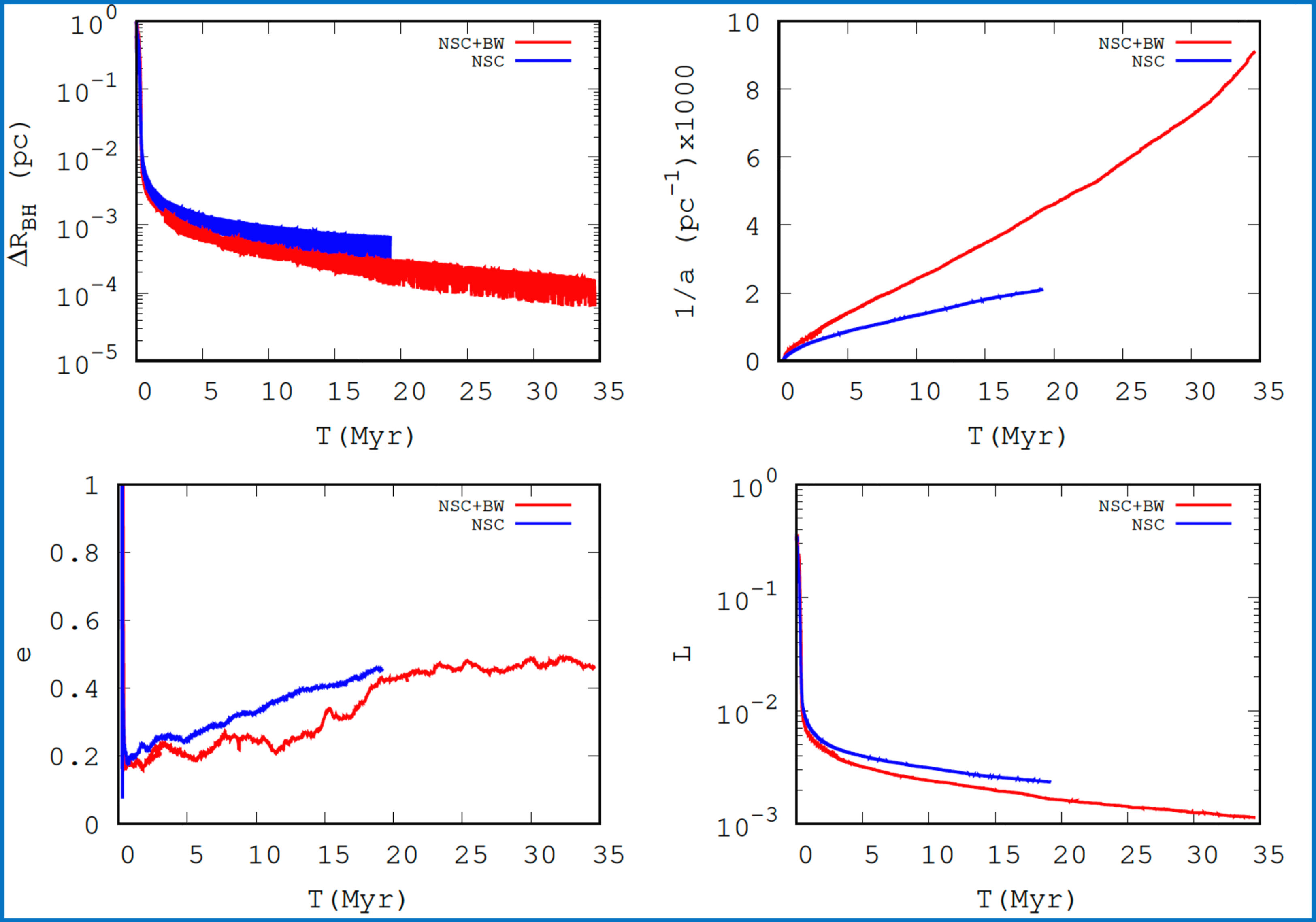
$$\mathbf{F}_i = -m_i \sum_{j=1,j\neq i}^{N} \frac{m_j(\mathbf{r}_i - \mathbf{r}_j)}{(|\mathbf{r}_i - \mathbf{r}_j|^2 + \epsilon^2)^{3/2}}$$

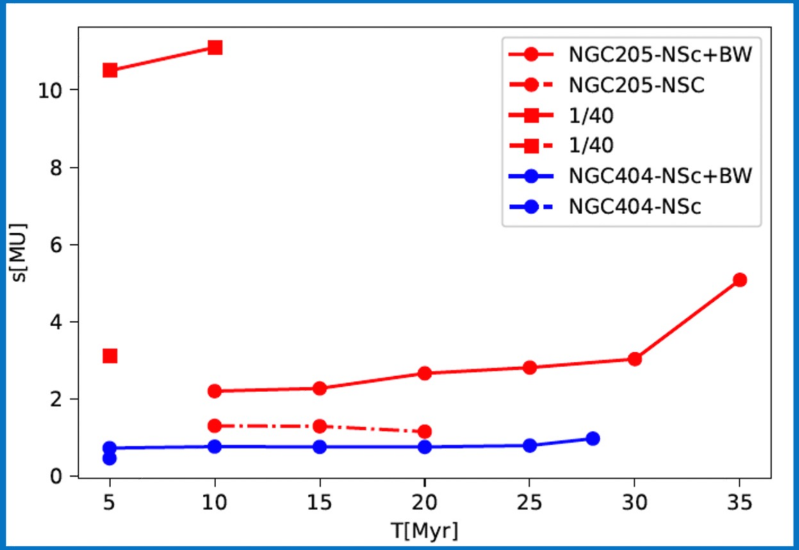
$\epsilon_{*,*} = 10^{-4}\ pc$
$\epsilon_{bh,bh} = 0\ pc$
$\epsilon_{bh,*} = 10^{-6}\ pc$

-Fourth-order Hermite integrator with individual block time steps (PN terms upto 3.5).

-The N-body integrations were carried on ACCRE cluster at Vanderbilt University & JUWELS @ Juelich.

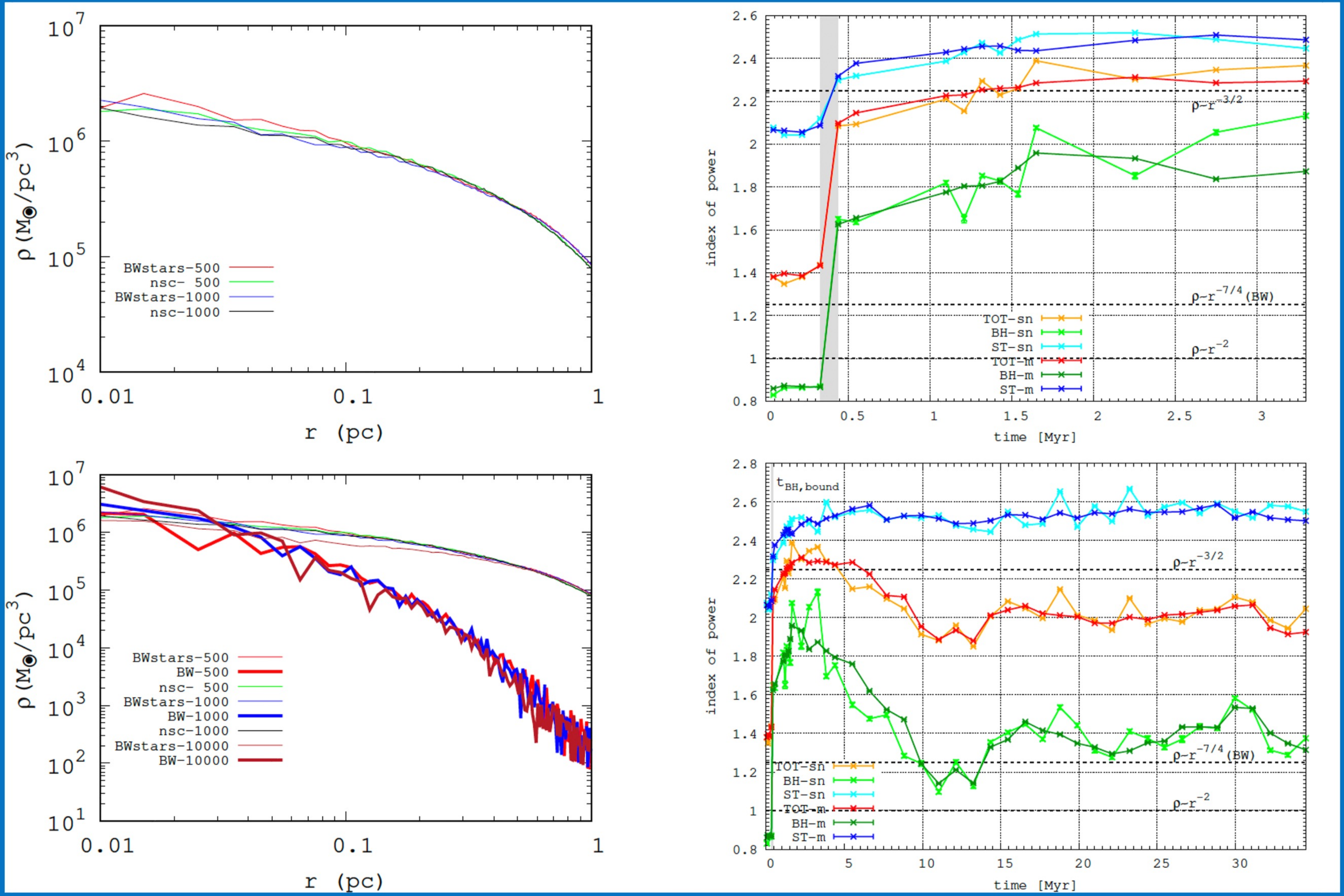
IMBHs Dynamics in NGC205





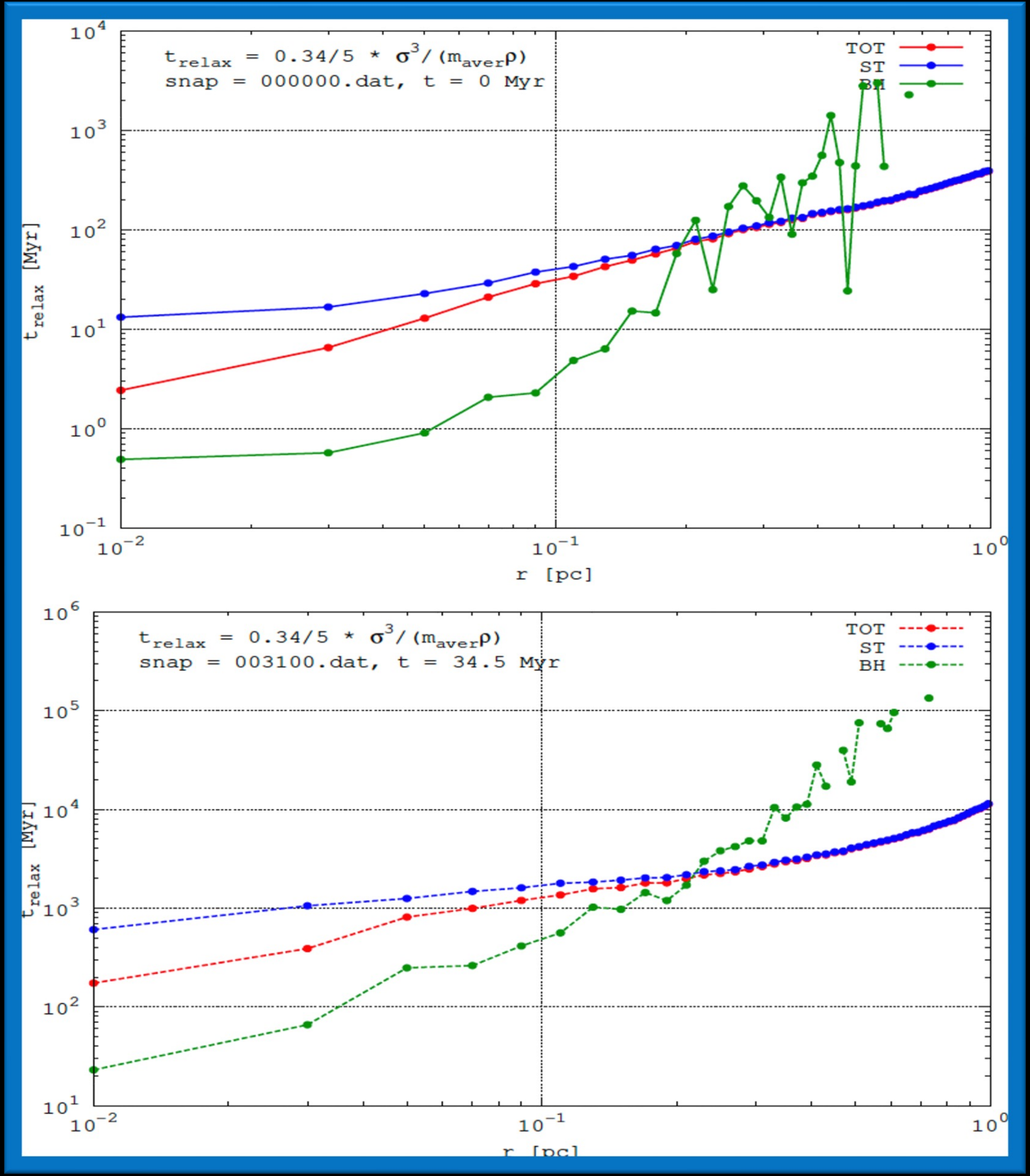
- BH component- IMBH binary evolves faster
- Hardening rate – 2x
  - increase with T
- e similar evolution

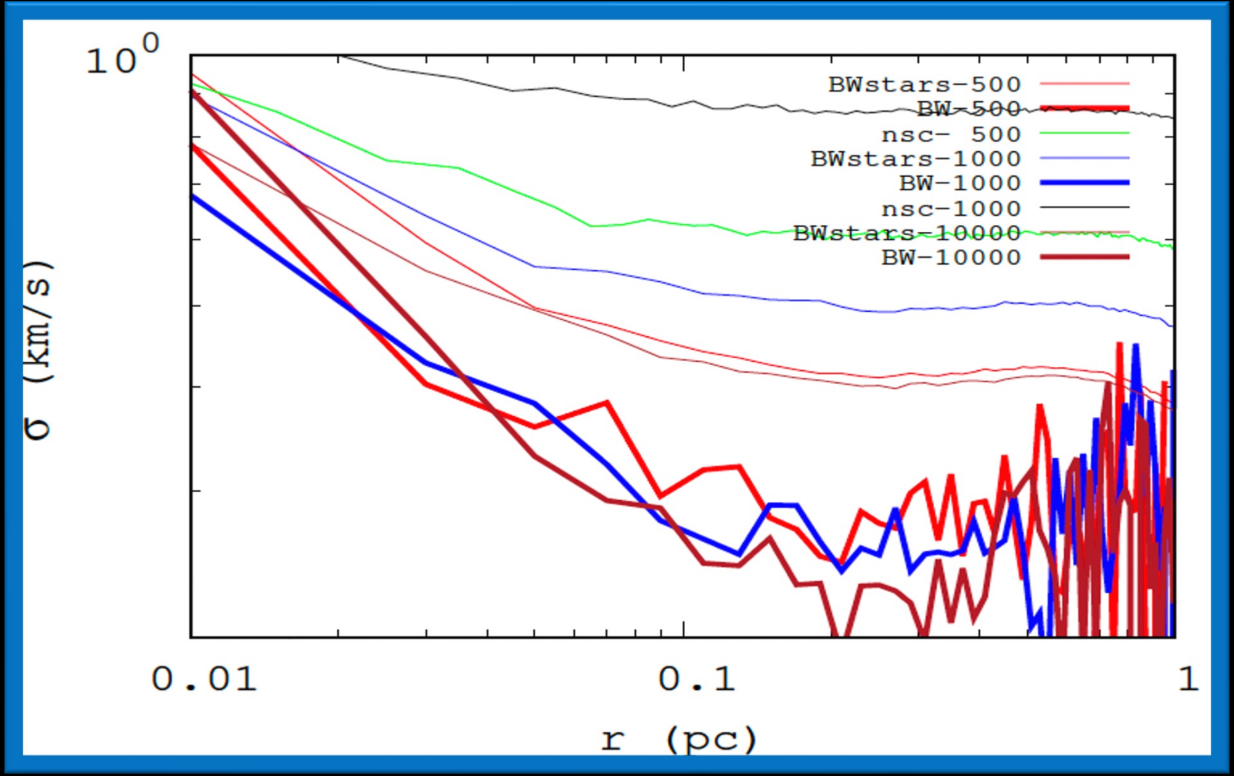
Density Profile Evolution for NGC205



- ❑ Similar density for both the stellar and BH components.
- ❑ Density slopes flattens for both the components as binary scour the central region of NSC.
- ❑ BH component re-establishes Bhacall & Wolf cusp after ~ 10 Myr.

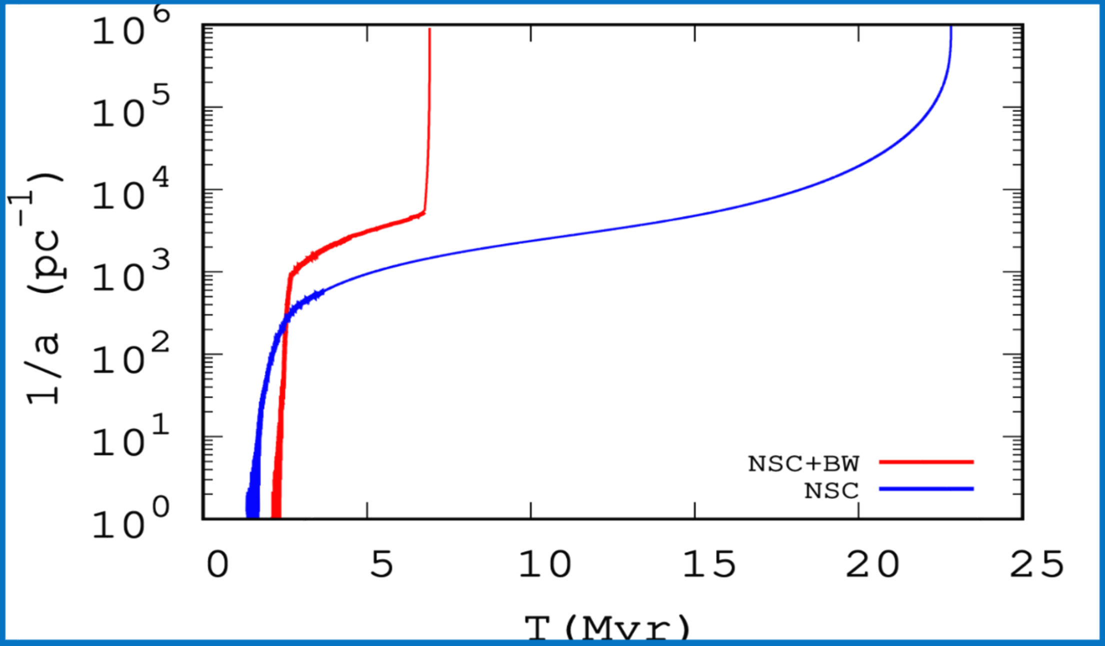
Relaxation Time & Velocity Dispersion

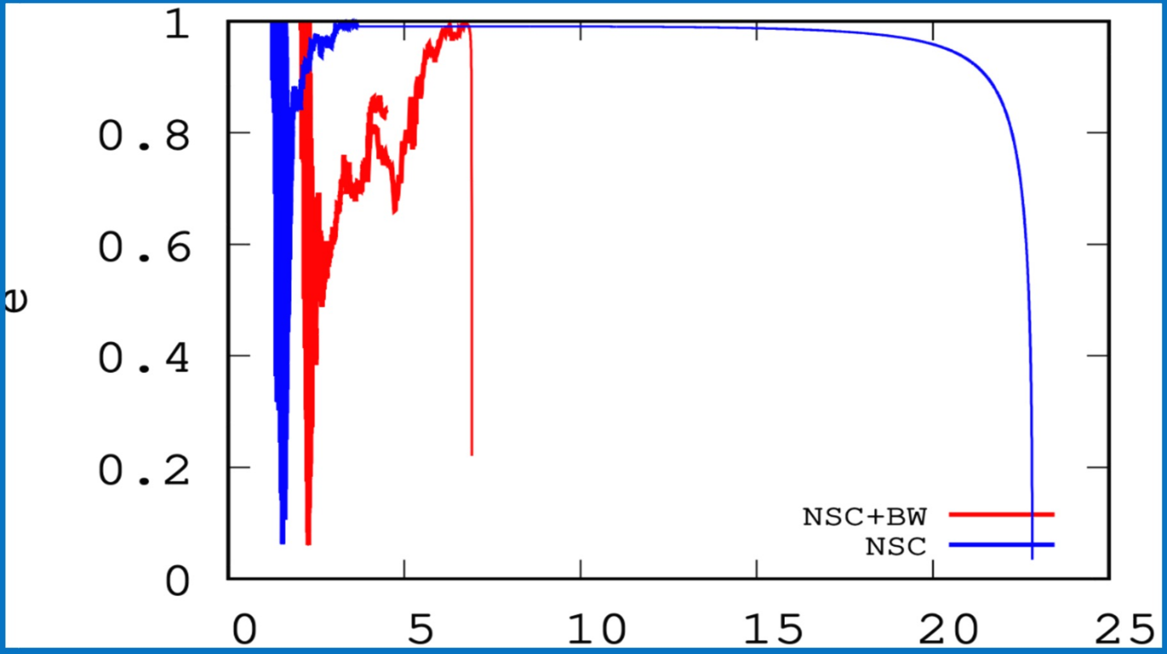


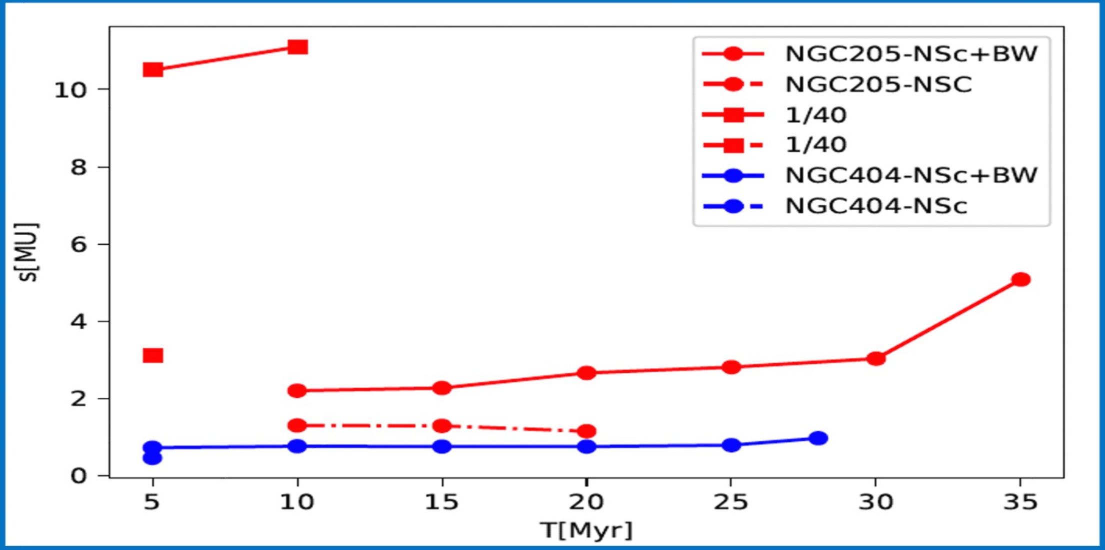


$$s = \frac{GH\rho}{\sigma}$$

IMBHs Dynamics (q =1:40) NGC205

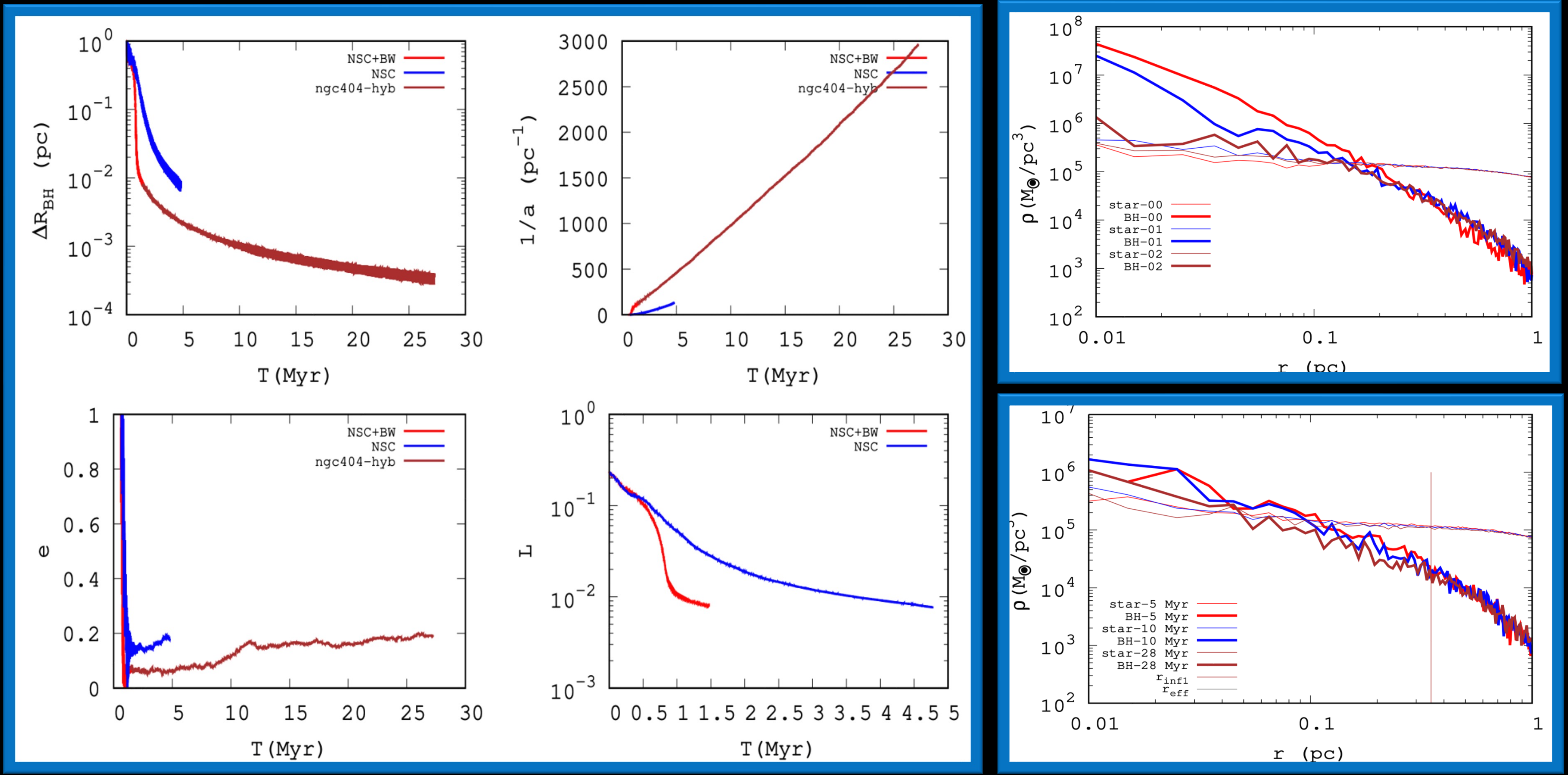




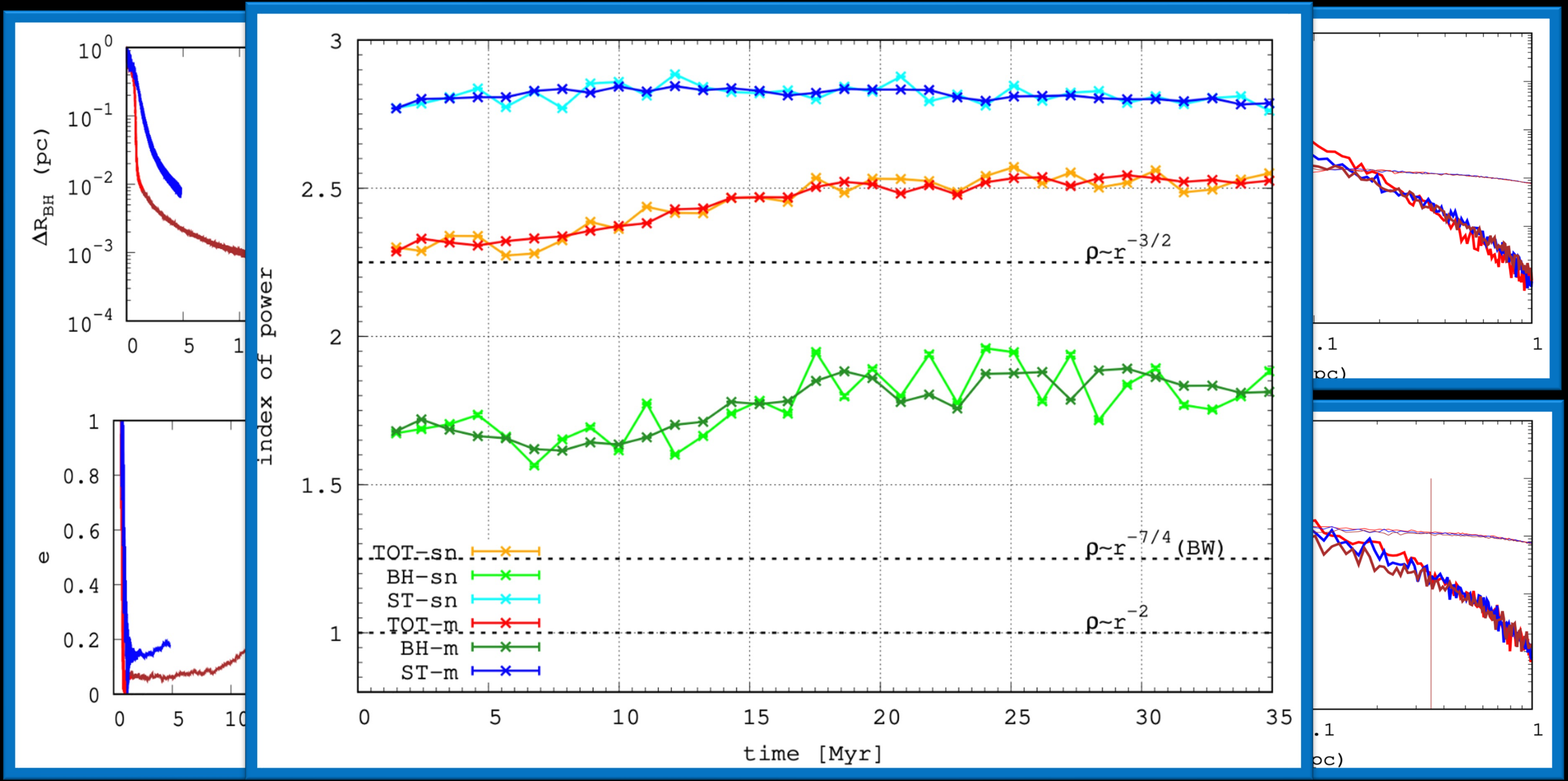


- Eccentricity → 1
- Higher hardening rates
- Very short binary merger times

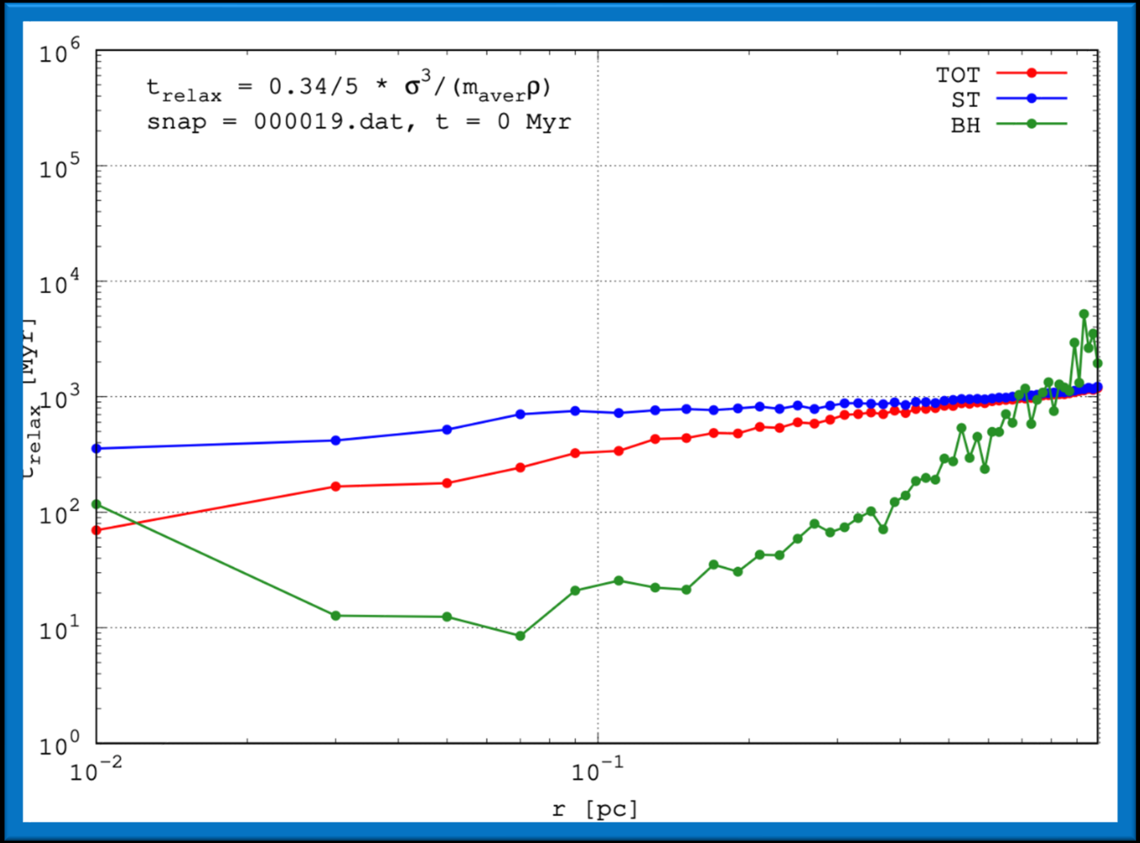
IMBHs Dynamics in NGC404

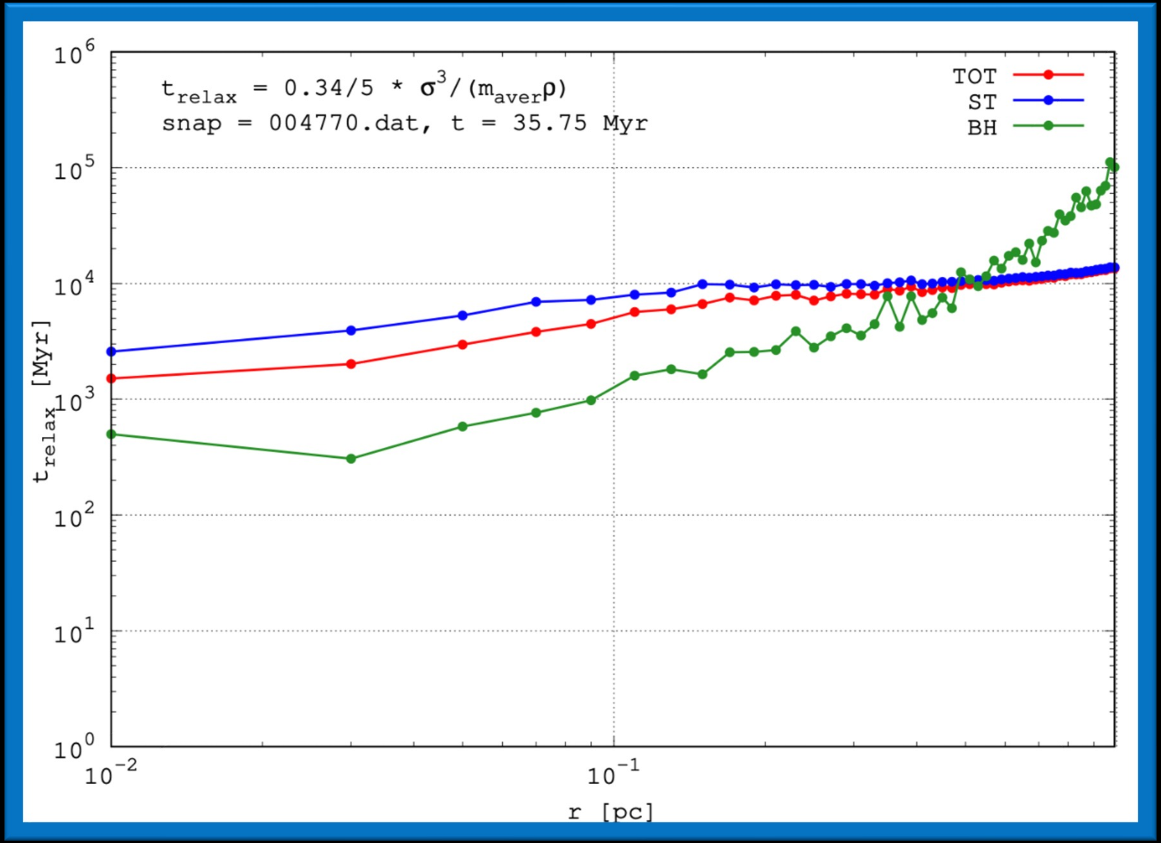


IMBHs Dynamics in NGC404



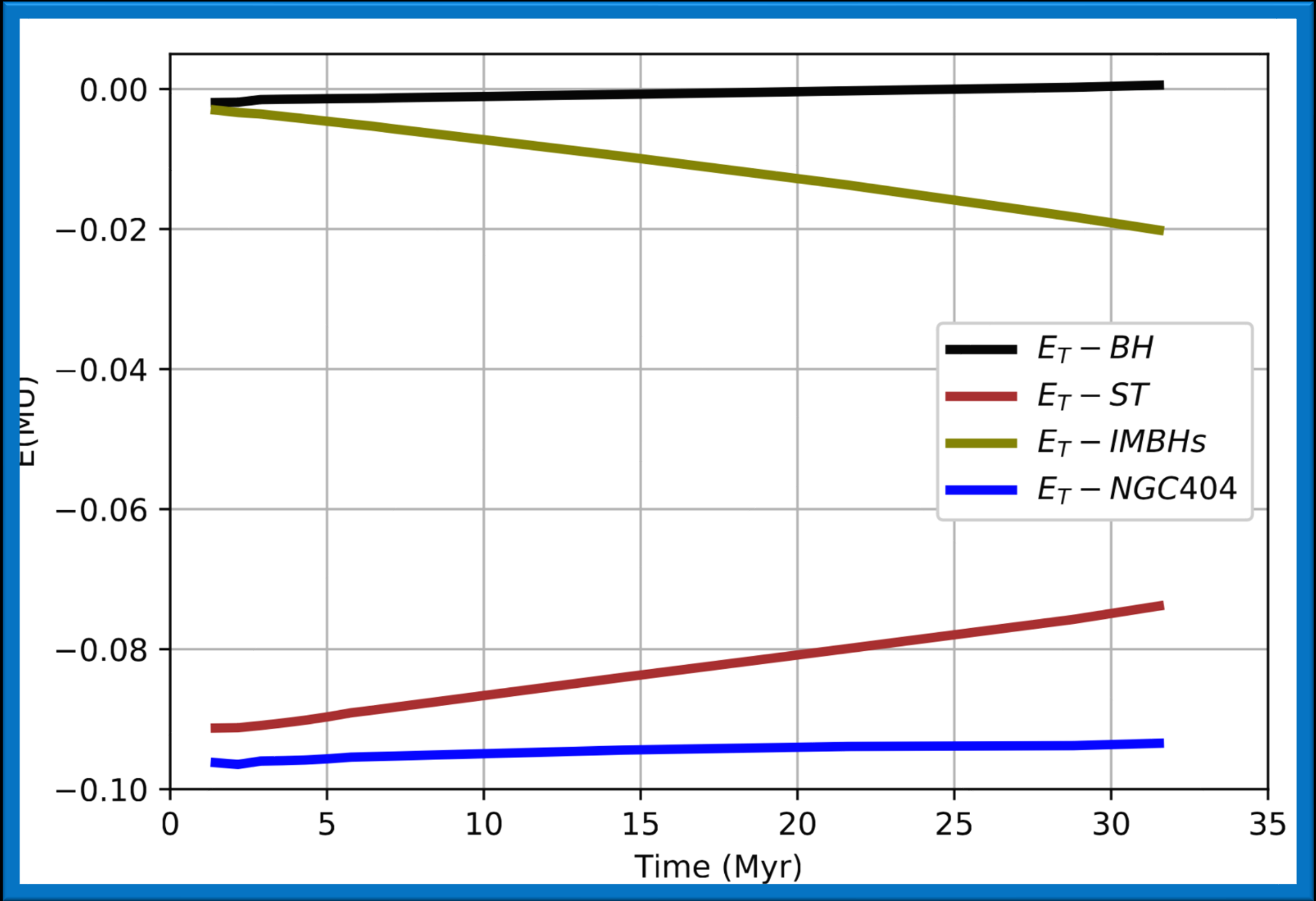
Relaxation Time – NGC404

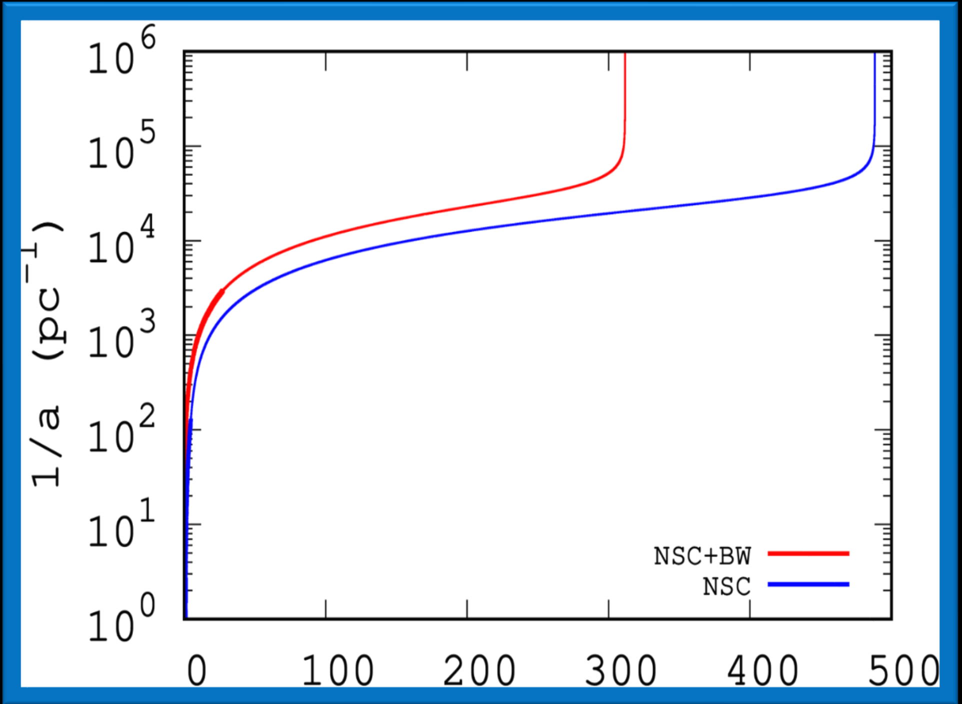




$T_{relax.}$ ~ few hundred Myr after core scouring by IMBH binary >> duration of the simulation

Energy Exchange & Merger Time – NGC404





- Energy Loss by IMBH binary is balanced by energy gain of stars.
- Total E is conserved.
- BH component shortens the merger time by a factor of 2.

Conclusions

- BH component - significantly influences the dynamics of the IMBH binary, nearly doubling the sinking rate and halving the merger time.
- During the initial phase of inspiral, the IMBH binary disrupts both the stellar and BH cusps.
- BH cusp quickly regains its steep slope due to its shorter relaxation time.
- BH component continues to dominate the evolution of the IMBH binary, despite being much less massive compared to the stellar component.
- IMBH binary transfers its energy to the BHs , which quickly dissipates to stellar component due to relaxation/mass-segregation.
- For a high mass ratio of 1:40, IMBHs in binary achieve coalescence in very short time almost falling on radial orbits – high eccentricity.

Thank You