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On the formation and evolution of triple SMBHs in the IllustrisTNG cosmology

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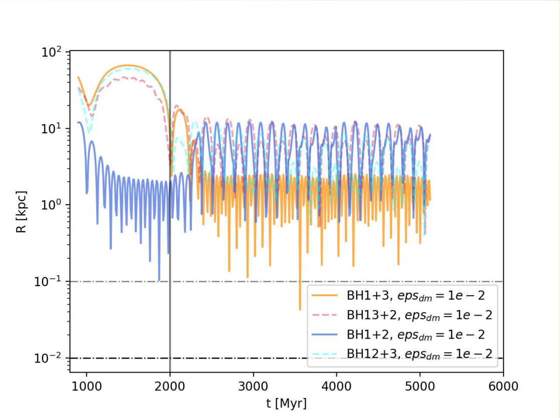
- **IllustrisTNG**
  - TNG-100 simulation
  - Selection of Triple systems
- **N-body simulations**
  - Initial conditions
  - Bonsai simulations
- **Results**



Project goals

- Broad goal: use cosmological simulation data as starting point for high-resolution N-body runs of SMBH triple evolution including Post-Newtonian effects and GW-induced coalescence
- Specific goal: Identify triple SMBH mergers in IllustrisTNG-100 and construct (spherical) galaxy models based on radial density profiles
- Then, follow the triple galaxy mergers and SMBH evolution using ~30 million particle runs

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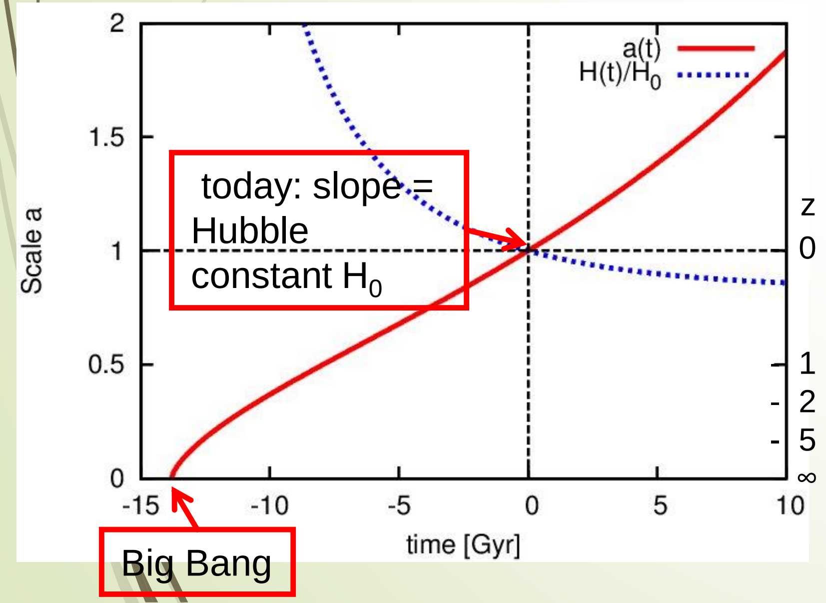
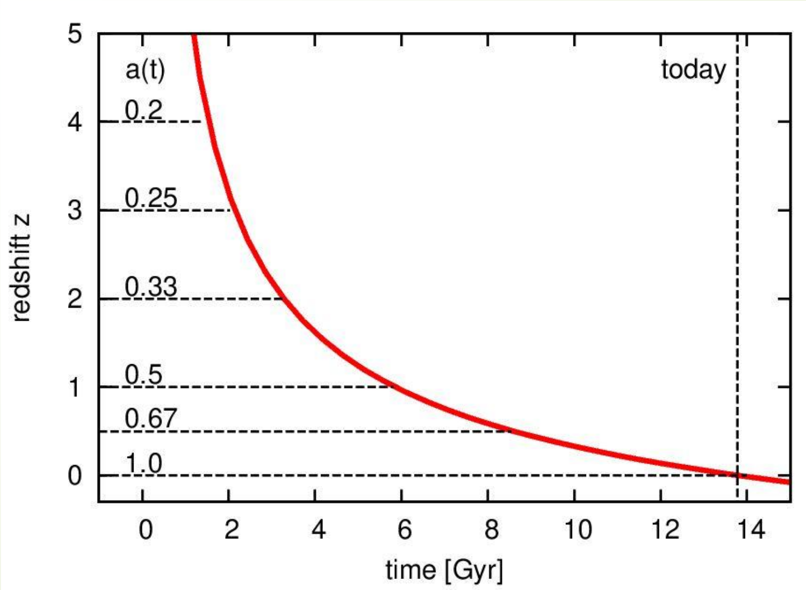
Cosmological simulations in standard ΛCDM

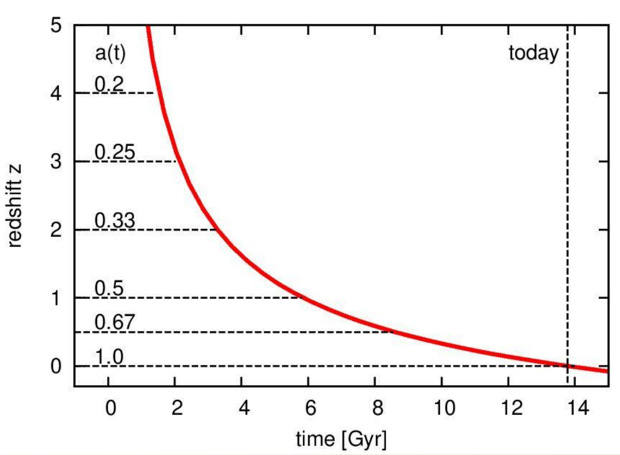
- Calculations done in co-moving coordinates
- Scaling to physical units using a(t) (distances, densities)
- z=5: t=1.2 Gyr; z=2: 3.3 Gyr; z=1: 5.9 Gyr





IllustrisTNG-100

- Magnetohydrodynamics (Arepo)
- Improved AGN feedback
- Simple SMBH physics
  - Fixed at potential minimum
  - Seed BH mass: $1.8 \times 10^6 M_{sun}$ when $M_{gal} > 7.4 \times 10^{10} M_{sun}$
  - Growth by Bondi accretion
  - Immediate mergers of SMBHs at distances smaller than resolution limit of 250…750pc (z=5…0)



- Resolution
  - $M_{DM} = 7.5 \times 10^6 M_{sun}$
  - $M_b = 1.4 \times 10^6 M_{sun}$
  - $\varepsilon_{DM,*} = 1$ckpc/h (=750pc at z<1)
  - $\varepsilon_g = \varepsilon_{DM,*}/4$
  - 100 snapshots

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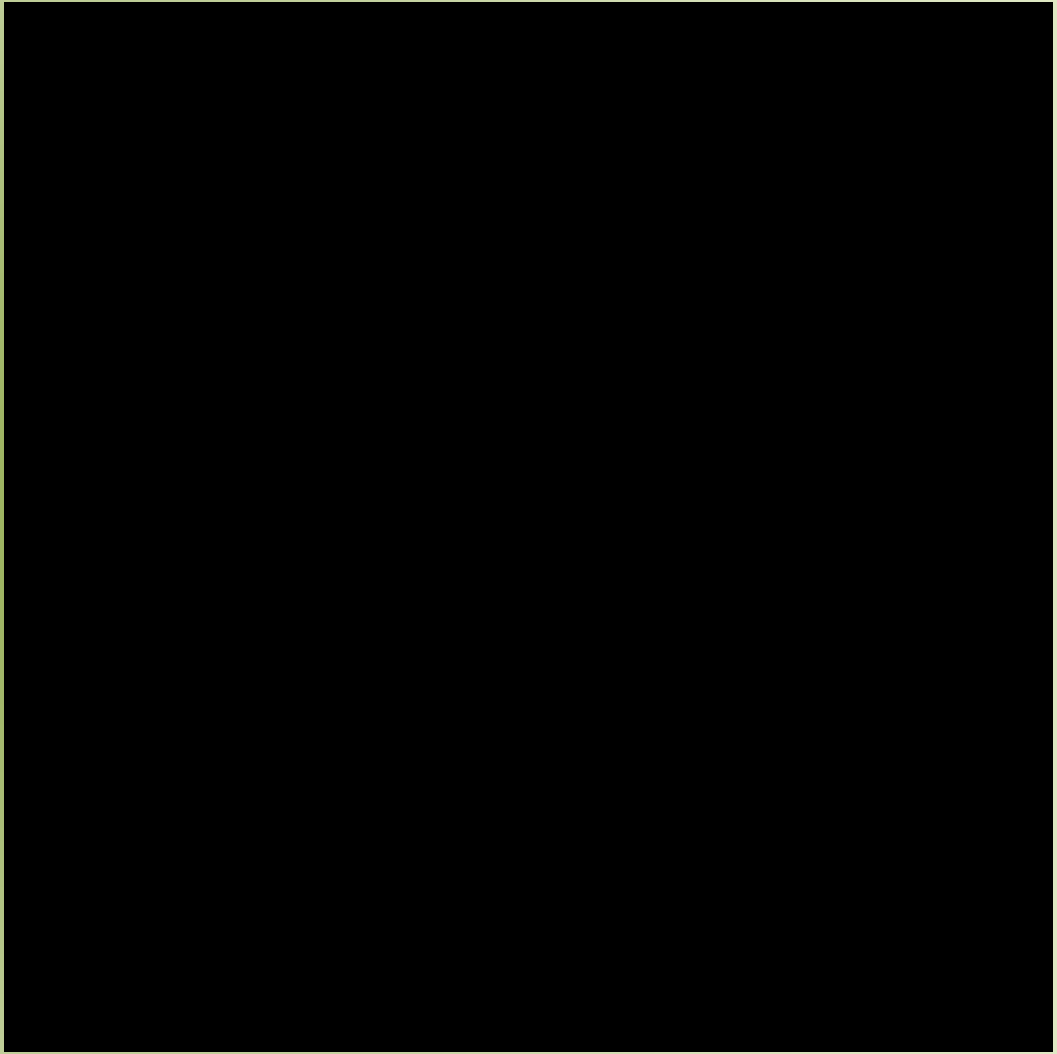
Movie: early type gal. Form.

Galaxy formation and merger trees

- FoF halo finder for DM
  - Baryons: next DM part.
- Parent subhalos merged, if $m_1/m_2>1/5$
  - Masses are maximum masses in the past
- BH merger tree useless
  - Parent galaxy ID missing
- Own search in snapshots
  - Subhalo finder

Credit: https://www.tng-project.org/



Selection of triple systems

- z=0: dominant halos, gas <20%, $M_{BH}>10^7 M_{sun}$
  - result: **8000 halos**
- Merger tree: all halos with particles of final halo
  - Maximum BH mass in the past, mass ratio $q>0.3$
  - Minimum 2 mergers at $z<6$
- Triples for LISA: $M_{BH}= 10^7\text{-}10^8 M_{sun}$
  - At least 2 mergers in 1 Gyr
  - Result: **20 candidates**
  - In 9 cases progenitor history not well defined
  - Finally: **6 cases** with progenitors $N_* > 1000$

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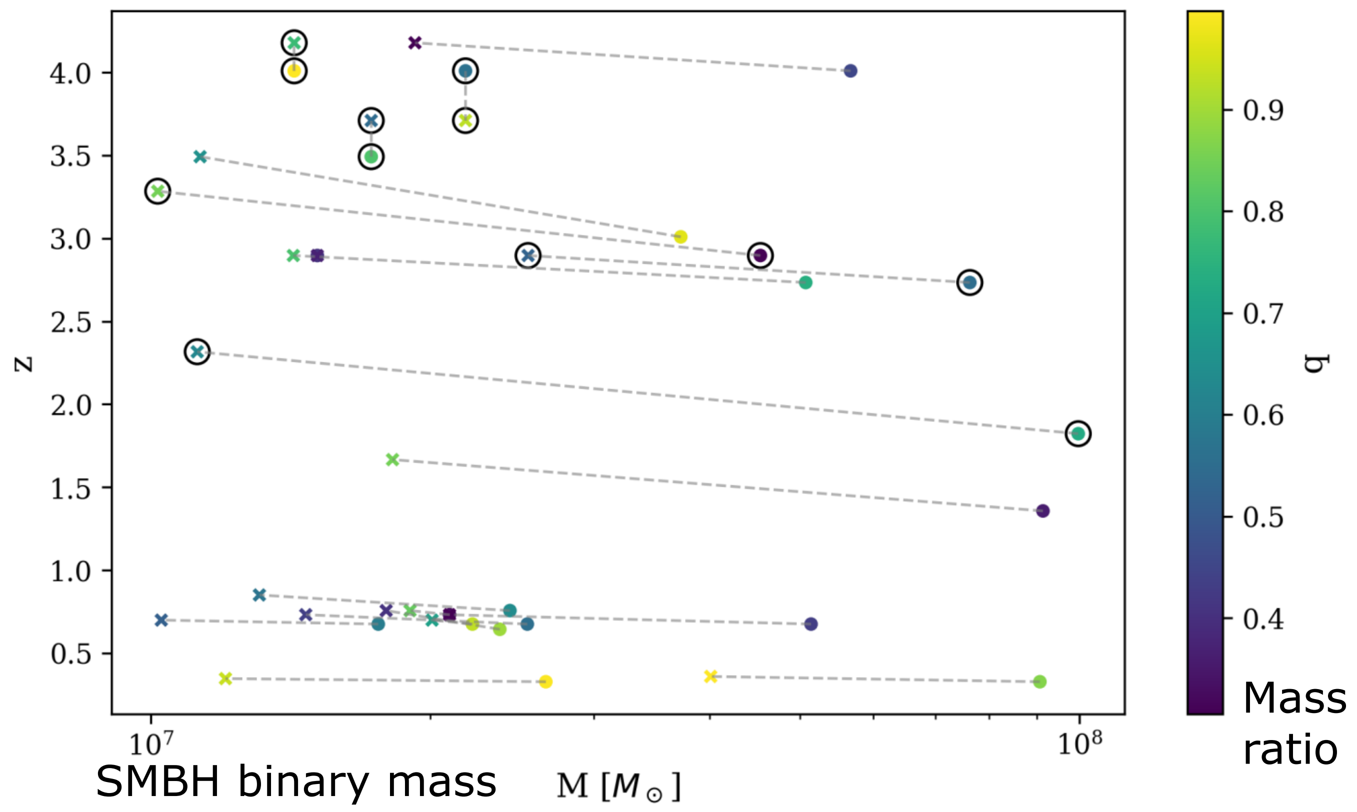
Triple candidates: **6 cases** with circles



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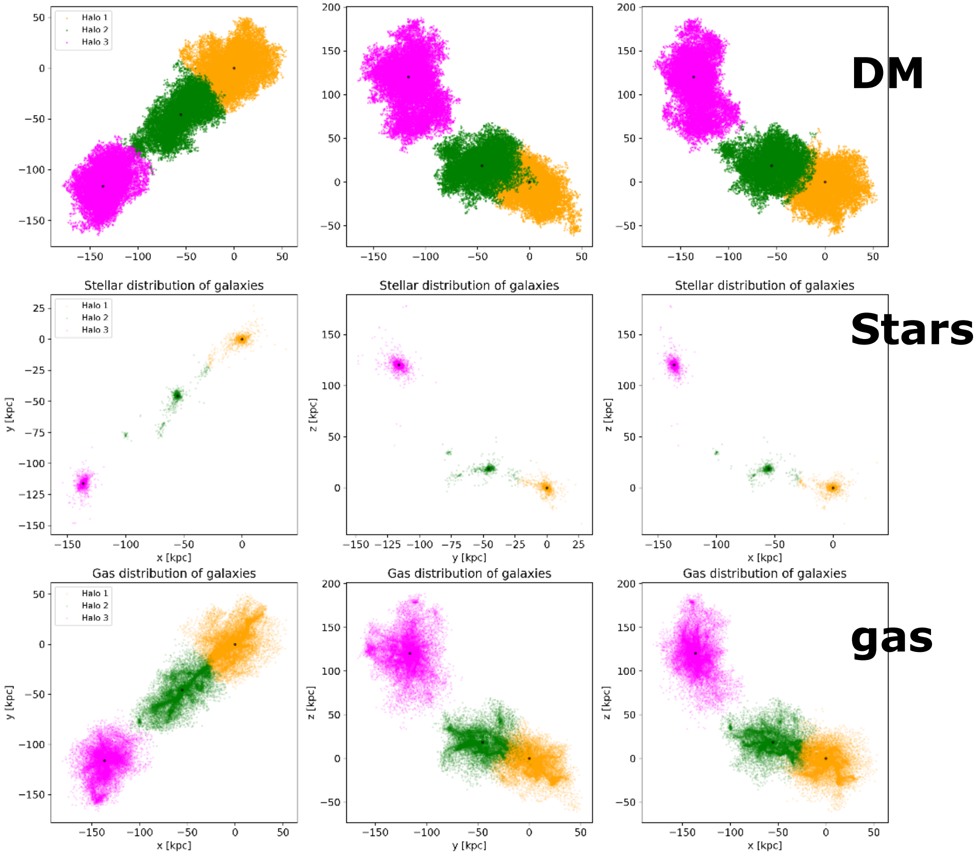
Initial conditions

- Data 4 snapshots before first merger
- Spherical components
  - DM, gas: Hernquist
  - Stars: Dehnen
  - Unresolved inner 1kpc ignored
  - AGAMA package
  - 30 million particles

Case C: X,Y,Z proj.; galaxy 1, 2, 3



Box size ~200kpc

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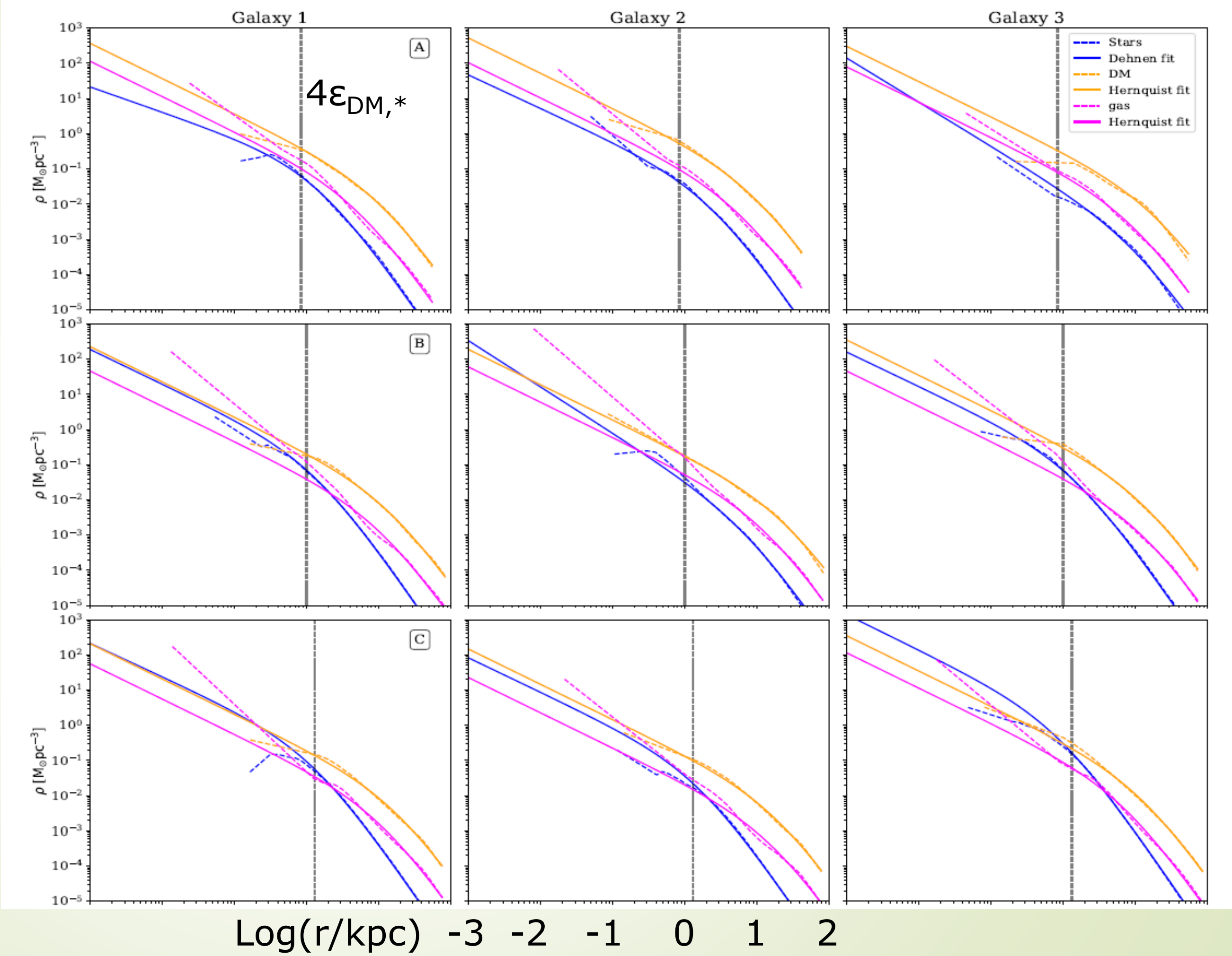
Profile fits
In log-log

Data: dashed
Fit: full lines

Rows: cases A,B,C: col: galaxy 1,2,3; stars, DM, gas



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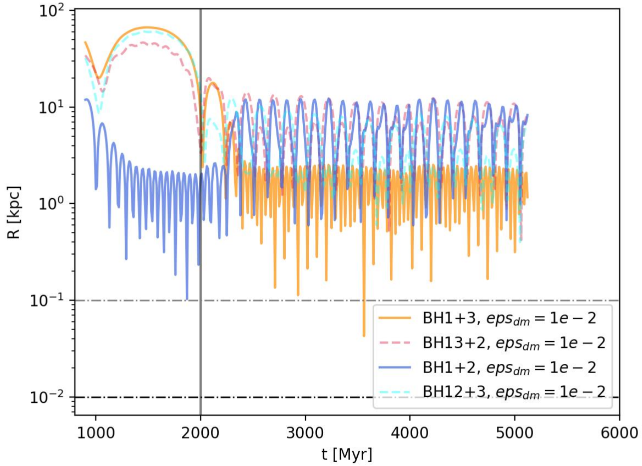
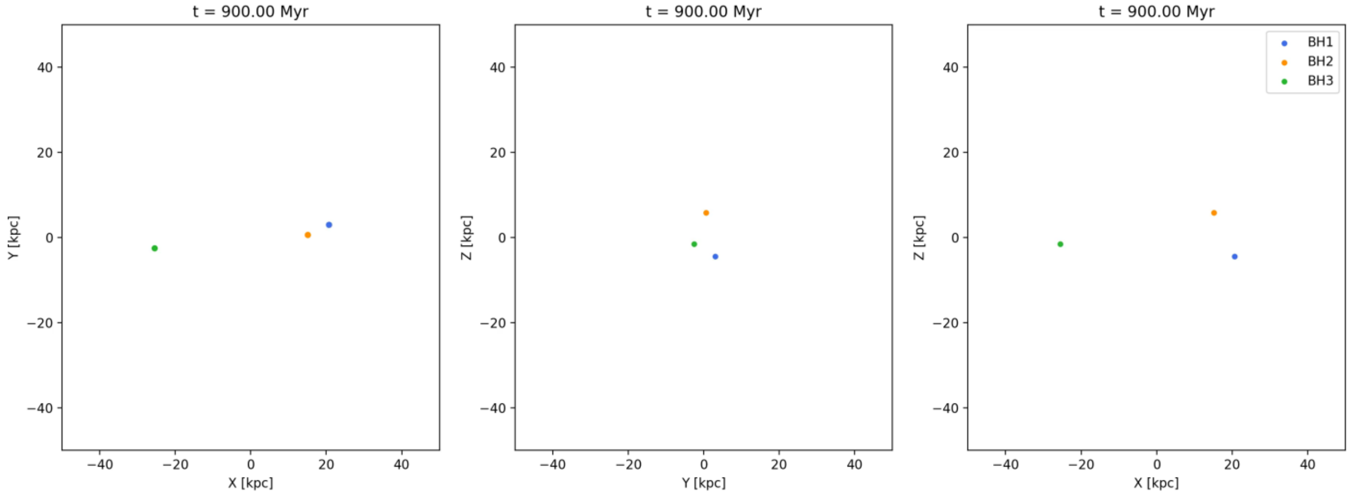
Results: case C

- Stalling at a=1kpc on eccentric orbit
- BH **2**+**3** exchange at t=2.4Gyr
- Then stalling BH **1**+**3**, still unbound



BH1
BH2
BH3



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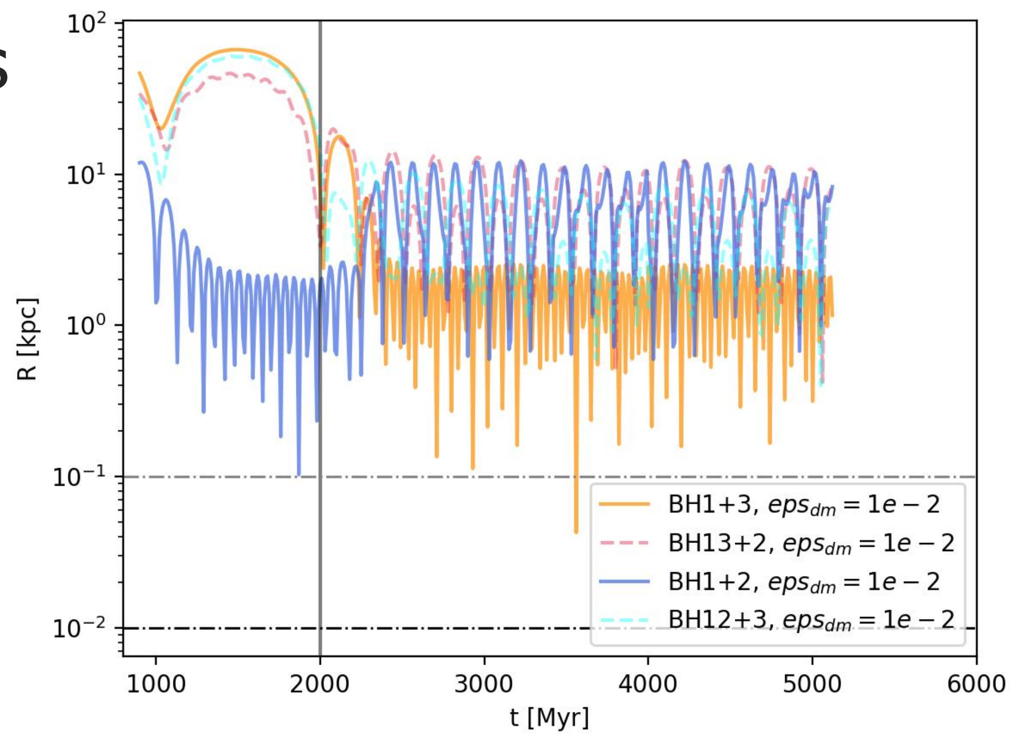
Results: checks

- LU = 1kpc
- TU = 10 Myr
- eps_dm = eps_g = 1e-2
- eps_st = 1e-3
- dt = 1e-3
- Runs with dt = 1e-4 show same result
- Result confirmed by Peter
  - N~15 million
  - different tree code
- phi-GPU runs also show stalling



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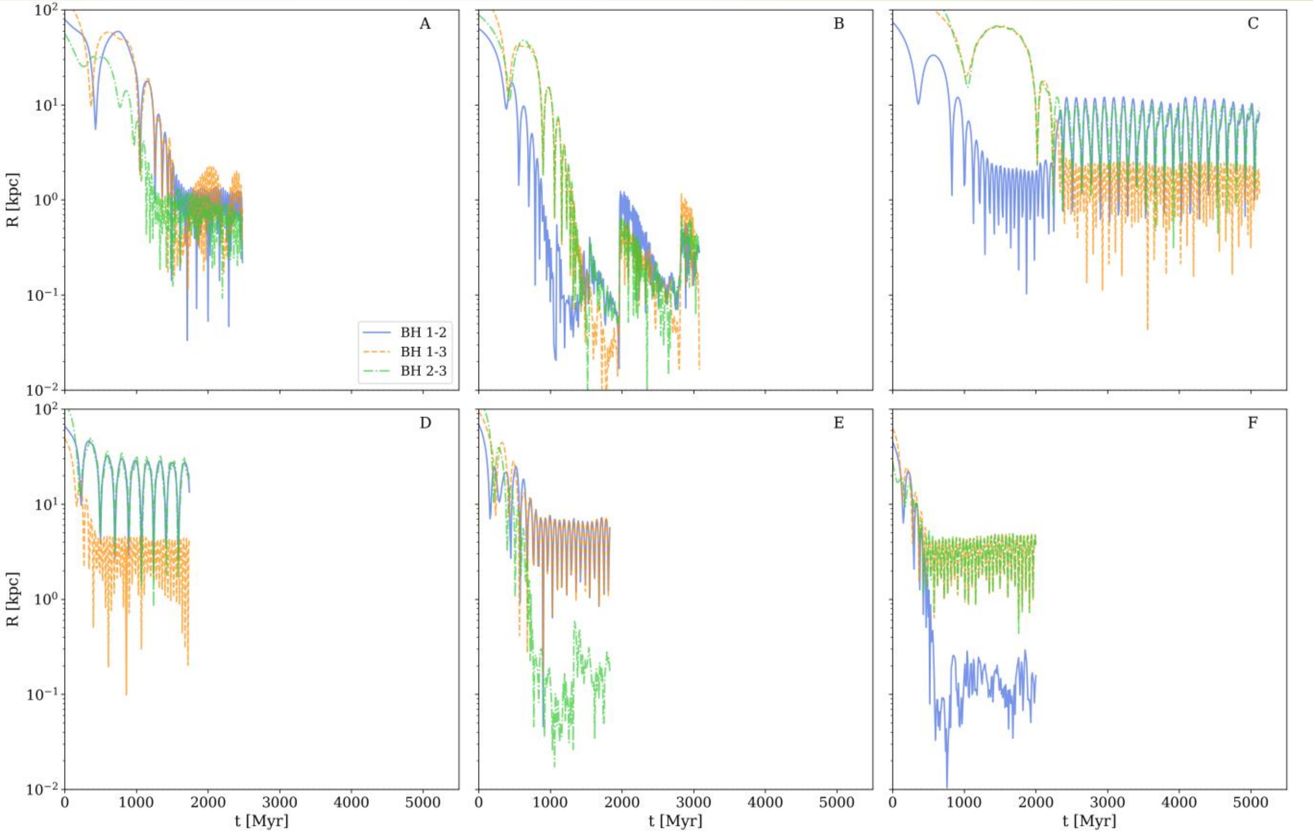
All 6 cases: similar results

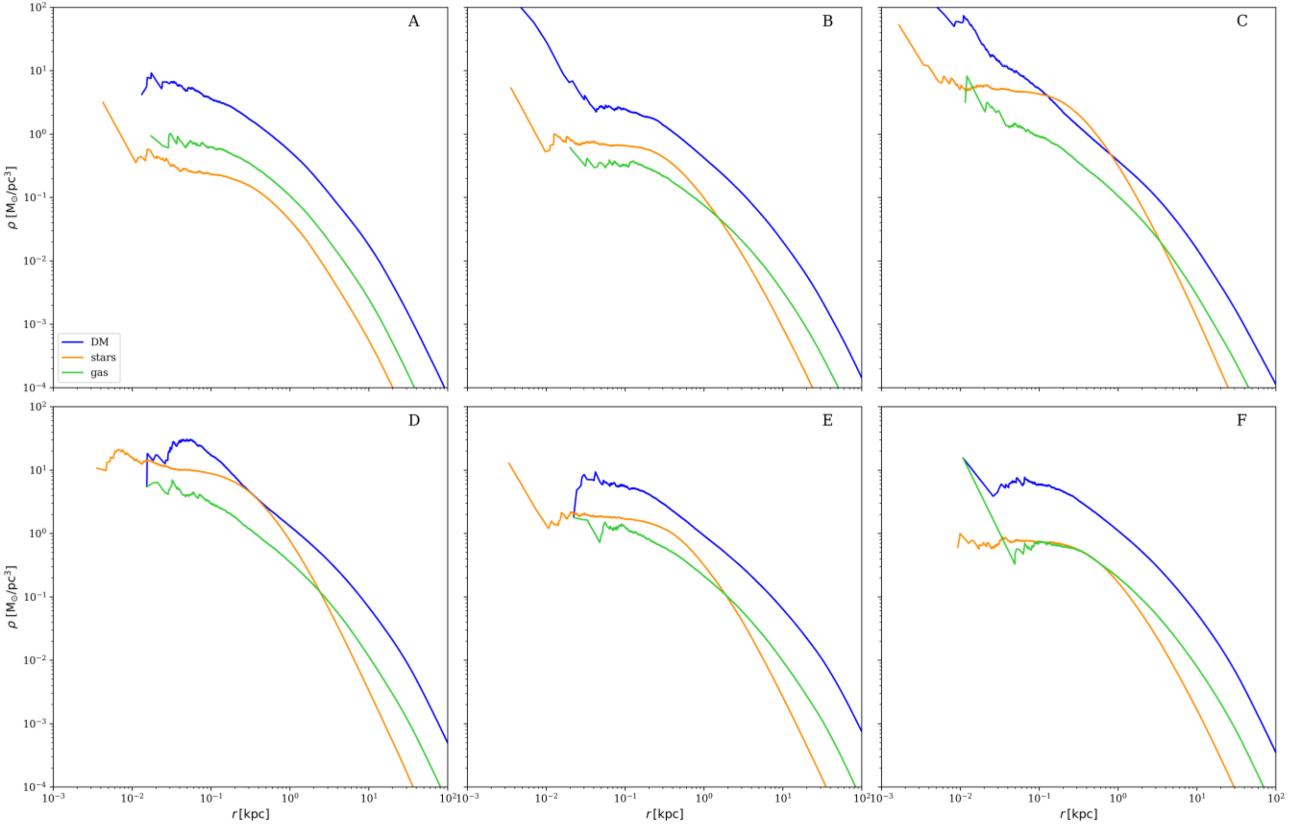
- Dynamical friction ineffective
- Resolution issue in TNG-100
  - density too low?
  - Harmonic core?



Density profiles at the end of simulations

- Constant density cores
  - Harmonic potential
  - All stars (DM) in resonance
  - Dynamical friction subpressed

DM
stars
gas



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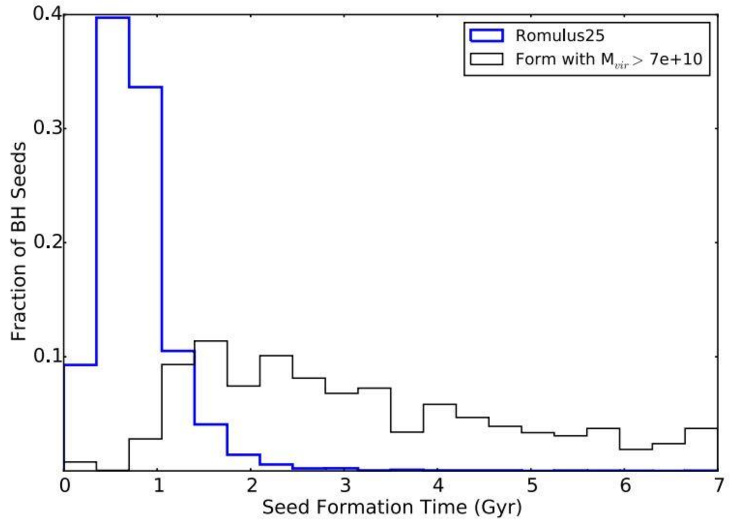
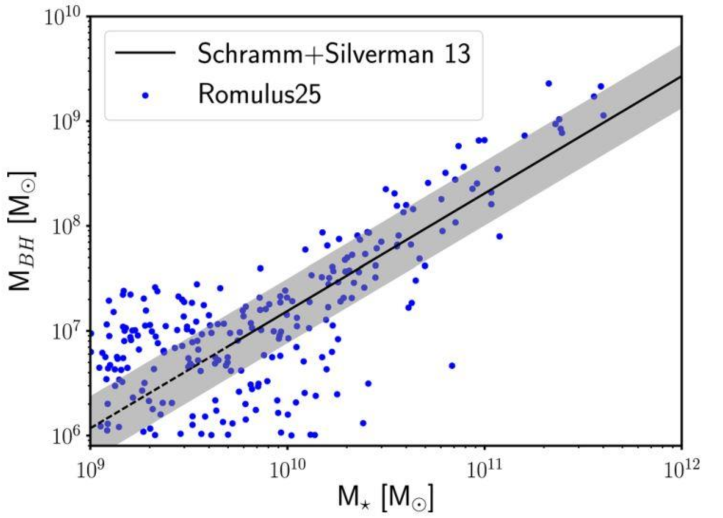
ROMULUS25 simulation

- Tremmel et al. 2017 (MNRAS 470, 1121)
- TREE+SPH code ChaNGa
- Improved SMBH physics
  - SMBHs form in high density, low metallicty, 10K gas cells
  - subgrid dynamics by analytic dynamical friction eq.
  - Density dependent and rotation corrected Bondi-Hoyle accretion
  - Mergers, if closer then resolution and dynamically bound





Conclusions and outlook

- Is stalling in SMBH pairs the normal case and the formation of hard binaries the exception?
  - As a consequence triple and multiple SMBH systems as well as free floating SMBHs should be frequent
- Is the low central density still a caveat of cosmological simulations?
  - Enhanced densities by cusps and nuclear star clusters are not resolved in cosmological simulations
- Next step: test with different cosmology: ROMULUS
  - SMBH physics better modeled

A. Just

- Redshift and fitting parameters

id	j	z_0	M_{bh} [$10^6 M_\odot$]	M_{st} [$10^9 M_\odot$]	γ_{st}	a_{st} [kpc]	M_{dm} [$10^{11} M_\odot$]	a_{dm} [kpc]	M_g [$10^{10} M_\odot$]	a_g [kpc]
A	1	5.23	1.37	1.54	0.71	1.47	1.98	11.31	1.45	5.5
A	2	5.23	1.31	1.61	0.95	2.36	2.04	9.66	1.71	6.27
A	3	5.23	2.3	6.2	1.25	10.27	5.06	19.99	3.1	9.67
B	1	4.18	1.45	1.71	0.98	1.39	2.27	15.51	2.58	11.6
B	2	4.18	1.55	4.89	1.31	7.52	5.21	25.78	4.59	13.56
B	3	4.18	1.53	1.91	0.98	1.55	2.63	13.46	3.36	13.27
C	1	2.9	1.9	2.15	0.95	1.29	2.97	18.49	3.25	11.81
C	2	2.9	2.13	1.03	0.98	1.58	2.42	19.9	2.71	16.92
C	3	2.9	2.8	4.55	1.00	0.89	2.53	13.18	2.70	7.54
D	1	4.7	1.7	13.32	1.00	1.09	11.17	18.46	10.99	8.6
D	2	4.7	1.29	2.05	1.31	3.82	6.78	25.96	10.56	28.53
D	3	4.7	1.64	8.67	1.49	5.88	11.27	23.82	13.87	16.88
E	1	3.71	1.69	7.81	1.12	3.88	25.41	41.49	17.65	20.17
E	2	3.71	1.35	5.02	0.98	1.49	8.61	19.01	6.43	9.26
E	3	3.71	1.6	9.10	0.98	1.61	20.23	31.64	11.92	12.21
F	1	5.00	1.65	7.91	1.31	4.20	8.91	18.79	11.04	13.60
F	2	5.00	1.62	3.38	0.97	1.63	4.25	13.85	5.04	9.32
F	3	5.00	1.79	2.51	0.89	2.67	5.48	17.32	4.68	10.94

A. Just

- Particle masses and numbers

id	j	N_{tot} [$\times10^6$]	m_{st} [$M_\odot$]	N_{st} [$\times10^6$]	m_{dm} [$M_\odot$]	N_{dm} [$\times10^6$]	m_g [$M_\odot$]	N_g [$\times10^6$]
A	1	7.0105	1030	1.5048	41,200	4.8032	20,600	0.7025
A	2	7.3415	1030	1.5596	41,200	4.9507	20,600	0.8312
A	3	19.809	1030	6.0153	41,200	12.290	20,600	1.5037
B	1	8.4419	1030	1.6613	41,200	5.5283	20,600	1.2623
B	2	19.625	1030	4.7512	41,200	12.645	20,600	2.2287
B	3	9.883	1030	1.8574	41,200	6.3952	20,600	1.6304
C	1	10.867	1030	2.0911	41,200	7.1986	20,600	1.5778
C	2	8.1909	1030	1.0016	41,200	5.8717	20,600	1.3176
C	3	11.865	1030	4.4162	41,200	6.1357	20,600	1.3128
D	1	13.226	2060	6.4680	206,000	5.4233	82,400	1.3343
D	2	5.5686	2060	0.9935	206,000	3.2939	82,400	1.2812
D	3	11.364	2060	4.2079	206,000	5.4721	82,400	1.6839
E	1	18.266	2060	3.7905	206,000	12.334	82,400	2.1417
E	2	7.3996	2060	2.4386	206,000	4.1806	82,400	0.7805
E	3	15.687	2060	4.4170	206,000	9.8231	82,400	1.4471
F	1	9.5089	2060	3.8419	206,000	4.3273	82,400	1.3396
F	2	4.3166	2060	1.6404	206,000	2.0647	82,400	0.6115
F	3	4.4472	2060	1.218	206,000	2.6612	82,400	0.5681