Post-Newtonian dynamical modelling of super-massive black holes in global large-scale simulations: First applications of the KETJU code

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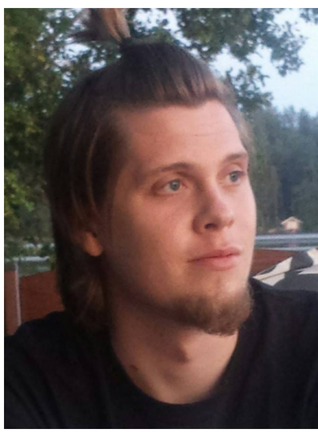

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Antti Rantala (Helsinki) **Matias Mannerkoski (Helsinki)**

Currently applying for postdoc positions!

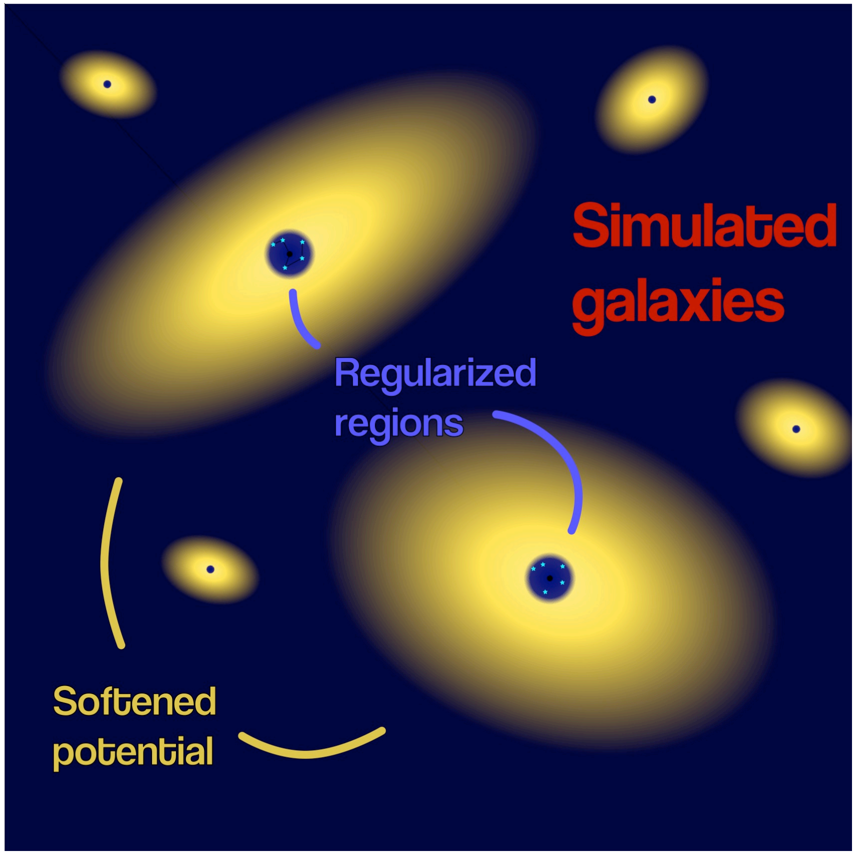
Rantala, Johansson, Naab, Thomas, Frigo, 2018, ApJL submitted, ArXiv: 1812.02732
Rantala, Johansson, Naab, Thomas, Frigo, 2018, ApJ, 864, 113
Rantala, Pihajoki, Johansson, Naab, Lahén, Sawala, 2017, ApJ, 840, 53

1. Motivation

- The dynamics of black holes in have traditionally been studied either with 10-100 million particle softened simulations (e.g. Gadget-3) or by unsoftened direct N-body simulations restricted to ~1 million particles (e.g. Nbody-7).

- We have added a submodule to GADGET-3 that employs algorithmically regularized dynamics and resolves the dynamics accurately near SMBHs with no softening.

- We can now resolve the dynamical friction, three-body interaction and gravitational wave phase self-consistently in one single simulation.



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KETJU - Regularized Gadget: Main features

1. KETJU (chain in Finnish): An extension of Gadget-3, which includes an algorithmically regularized chain (Mikkola & Merritt 2008) module that makes two-body collisions integrable by a simple leapfrog integrator.
2. Supports multiple regularized chains, where high-resolution regularized regions can be included around every BH in the simulation.
3. Includes Post-Newtonian corrections up to order 3.5 PN (or c^{-7}). Includes an explicit leapfrog that account for the fact that the PN correction terms depend on the particle velocities, and possibly spins, in addition to the particle coordinates. The PN approach is valid up to ~10 Schwarzschild radii.

$$\vec{a}_{2-\mathrm{body}} = \vec{a}_{\mathrm{New}} + \sum_{k=2}^{7} c^{-k}\vec{a}_{k/2PN} + \vec{a}_S$$

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Algorithmic chain regularization

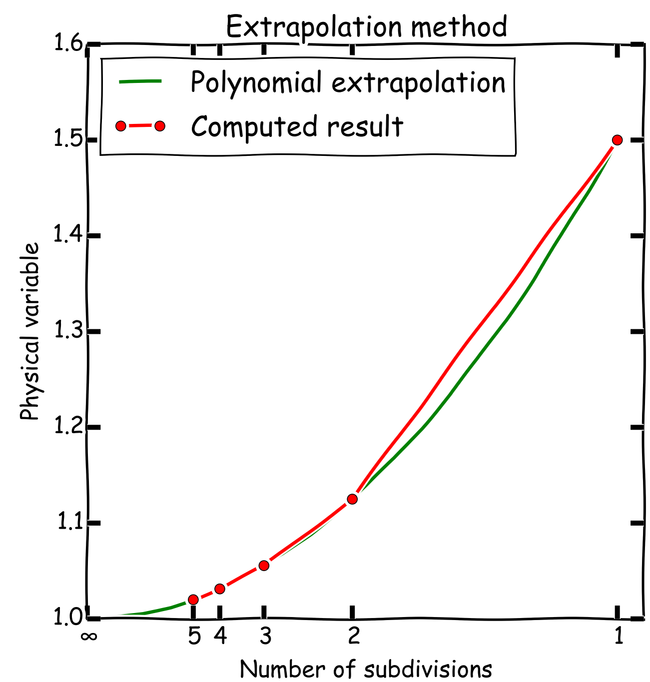
1. The dynamics in the high-resolution region is regularized through a time transformation that avoids force divergences and allows even for particle collisions (Mikkola & Tanikawa 1999, Preto & Tremaine 1999).
2. The particles are organized into a chain and in the calculation inter-particle vectors are used which significantly reduces round-off errors.
3. Particles in the chain are integrated using the Bulirsch-Stoer extrapolation method, in which a large number (~100) substeps are taken during a full Gadget timestep resulting in good convergence.

Define $t \mapsto s$ by

$$\mathrm{d}s = [\alpha(T + B) + \beta\omega + \gamma]\,\mathrm{d}t$$
$$= (\alpha U + \beta\Omega + \gamma)\,\mathrm{d}t,$$

where $\alpha, \beta, \gamma \in \mathbb{R}$, and

$$T = \sum_i \frac{1}{2} m_i \|\vec{v}_i\|^2 \quad \text{kinetic energy,}$$
$$U = \sum_i \sum_{j>i} \frac{G m_i m_j}{\|\vec{r}_{ij}\|} \quad \text{force function,}$$
$$B = -T + U \quad \text{binding energy,}$$
$$\Omega = \text{arbitrary function of } \vec{r}_i,$$
$$\dot{\omega} = \sum_i \nabla_{\vec{r}_i}\Omega \cdot \vec{v}_i.$$



Chain construction

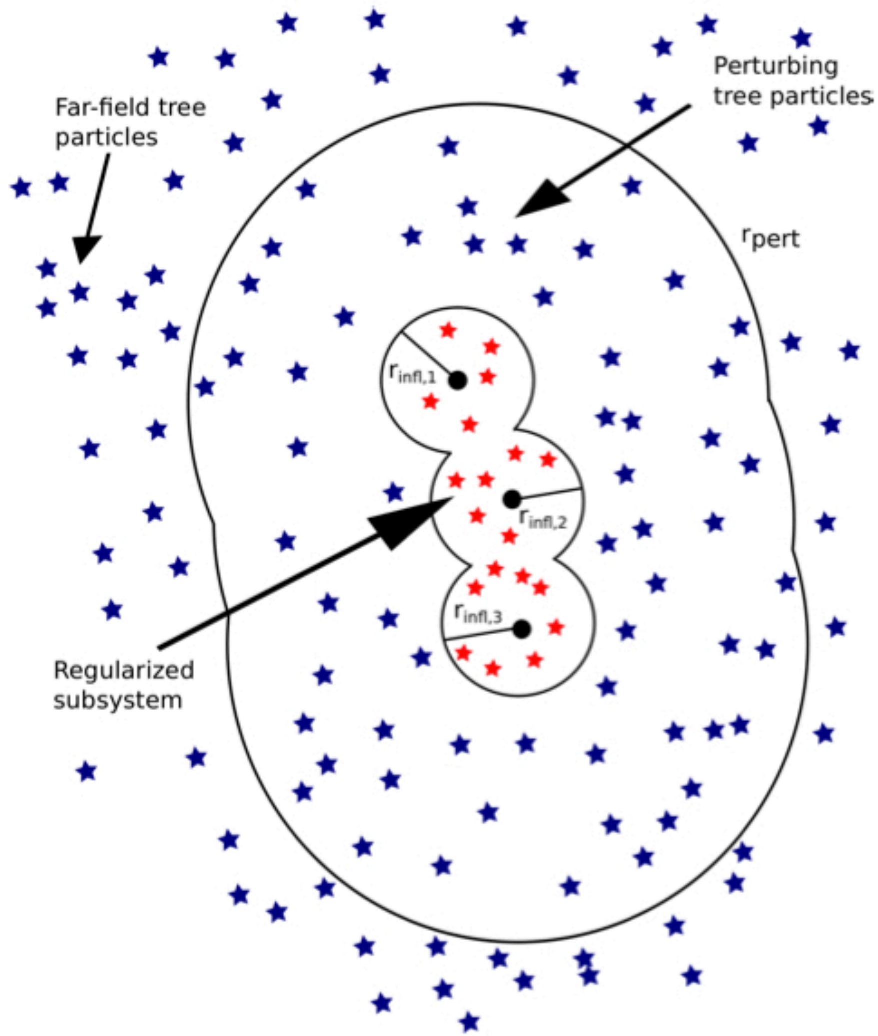
1. Chain particles: All the SMBH particles and stellar particles that lie within the influence radius of the SMBHs. Typically r_{infl}~10-30 pc.

$$r_{\rm infl} = \lambda \times \frac{M_{\rm BH}}{10^{10} M_{\odot}} {\rm kpc}$$

2. Perturber particles: Simulation particles, which induce strong tidal perturbations on a chain system. Typically r_{pert}=2xr_{infl}

$$r < r_{\rm pert} = \gamma \times r_{\rm infl} \left(\frac{m}{M_{\rm BH}} \right)^{1/3}$$

3. Tree particles: Other particles that do not reside near any of the SMBHs act as ordinary GADGET-3 particles.



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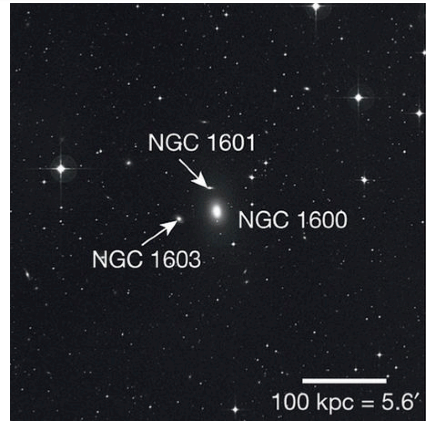
2. Formation of cored galaxies

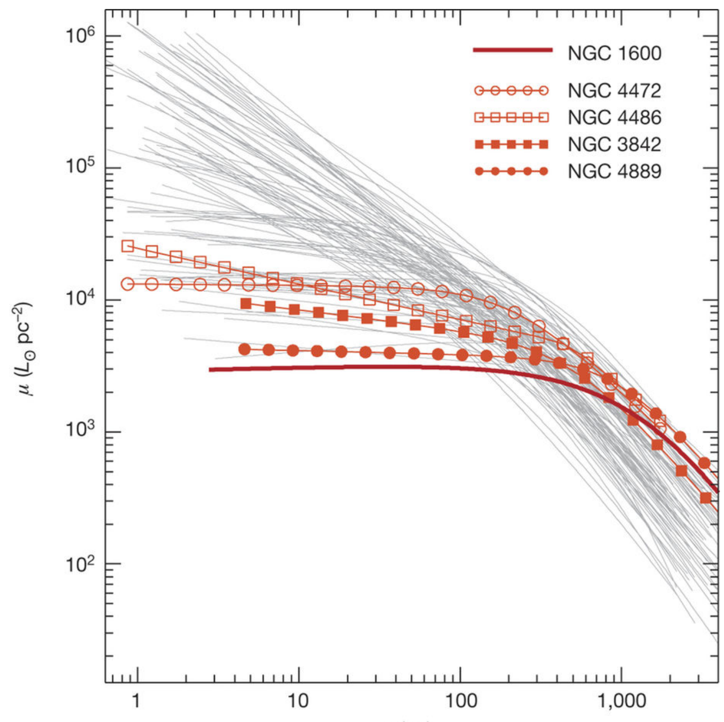
- Core ellipticals exhibit large cores with nearly constant surface brightness. Typically very massive, slowly rotating and have boxy isophotes.



- NGC 1600 is an extreme example of a cored galaxy. (Thomas et al. 2016).

$$M_{\mathrm{BH}} = (1.7 \pm 0.15) \times 10^{10} M_{\odot}$$

- Probably formed through a dry (gas-poor) merger between two massive early-type galaxies and scouring of the core by the dynamical evolution of a SMBH binary.



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Initial conditions and simulations

- The collisionless initial conditions are modelled using isotropic Dehnen profiles (γ=1.5 or γ=1.0) for the stars and γ=1.0 for the dark matter, including a central SMBH.

$$\rho(r) = \frac{(3-\gamma)M}{4\pi} \frac{a}{r^{\gamma}(r+a)^{4-\gamma}}$$

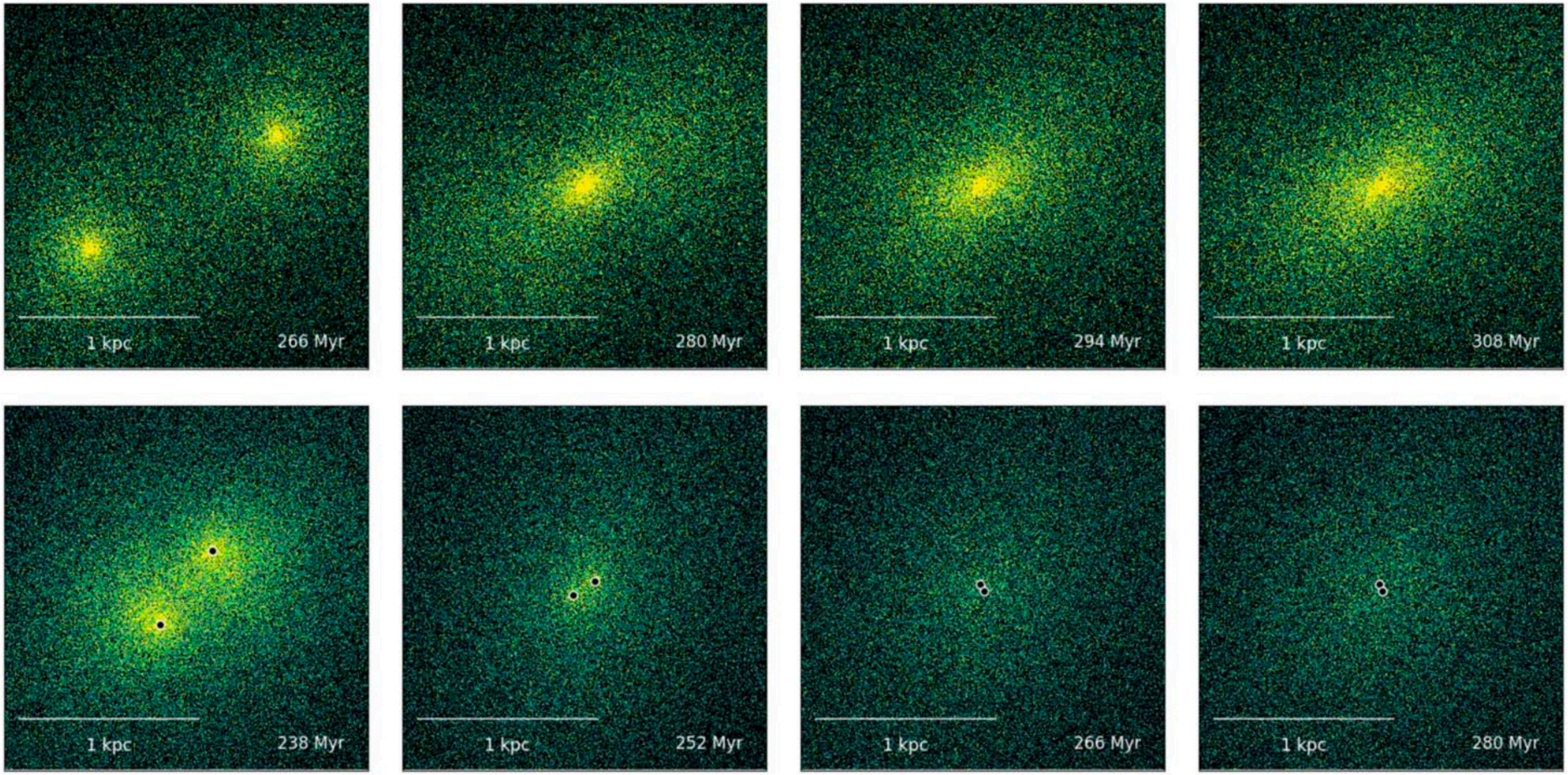
- We simulate major mergers to describe the final dry major merger that NGC 1600 likely experienced.
- High numerical resolution for N-body type of simulation.

Parameter	Symbol	Value
Stellar mass	$M_\star$	$4.15 \times 10^{11}\ M_\odot$
Effective radius	R_e	7 kpc
DM halo mass	M_{DM}	$7.5 \times 10^{13}\ M_\odot$
DM fraction	f_{DM}	0.25
Number of stellar particles	$N_\star$	4.15×10^6
Number of DM particles	N_{DM}	1.0×10^7

Progenitor	γ	$M_\bullet$	Progenitor	γ	$M_\bullet$
γ-1.0-BH-0	1.0	-	γ-1.5-BH-0	1.5	-
γ-1.0-BH-1	1.0	$8.5 \times 10^8\ M_\odot$	γ-1.5-BH-1	1.5	$8.5 \times 10^8\ M_\odot$
γ-1.0-BH-2	1.0	$1.7 \times 10^9\ M_\odot$	γ-1.5-BH-2	1.5	$1.7 \times 10^9\ M_\odot$
γ-1.0-BH-3	1.0	$3.4 \times 10^9\ M_\odot$	γ-1.5-BH-3	1.5	$3.4 \times 10^9\ M_\odot$
γ-1.0-BH-4	1.0	$5.1 \times 10^9\ M_\odot$	γ-1.5-BH-4	1.5	$5.1 \times 10^9\ M_\odot$
γ-1.0-BH-5	1.0	$6.8 \times 10^9\ M_\odot$	γ-1.5-BH-5	1.5	$6.8 \times 10^9\ M_\odot$
γ-1.0-BH-6	1.0	$8.5 \times 10^9\ M_\odot$	γ-1.5-BH-6	1.5	$8.5 \times 10^9\ M_\odot$

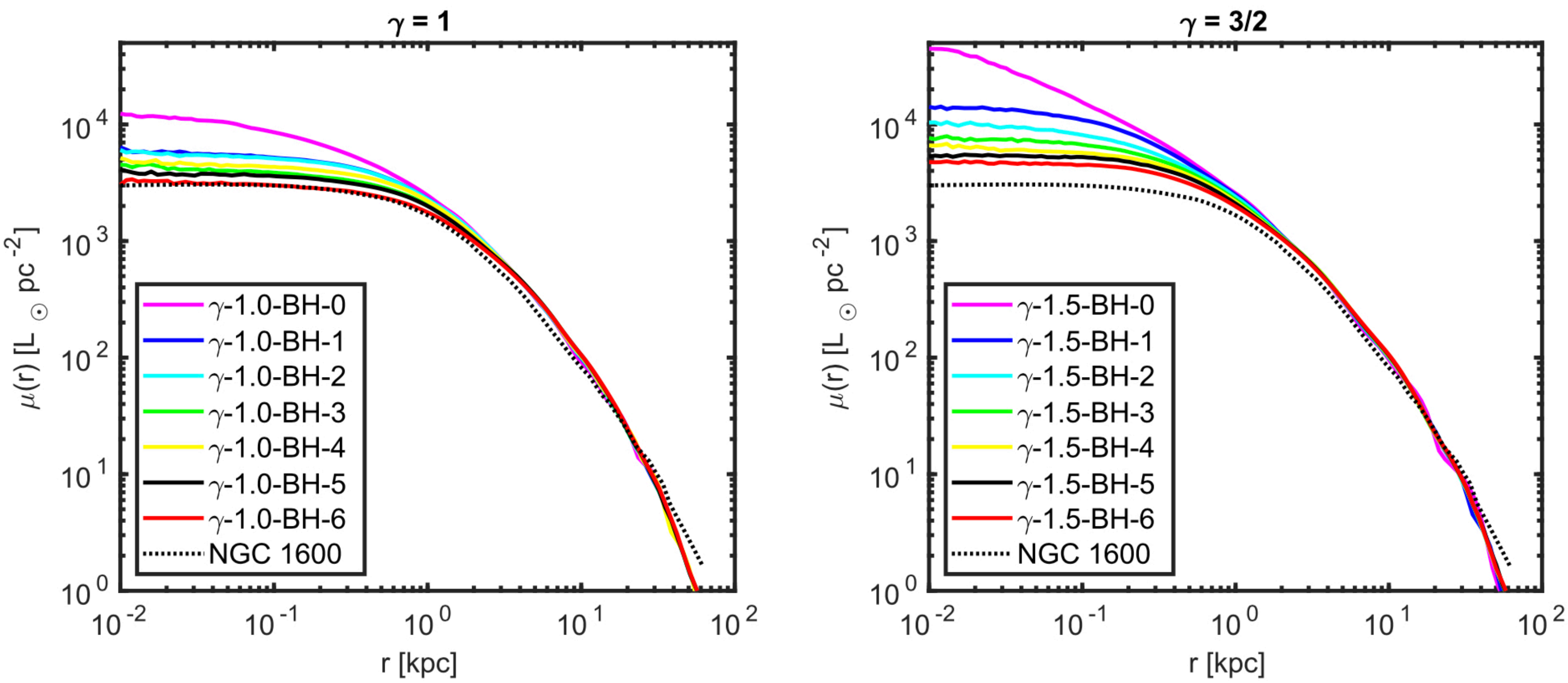
BH-0: no SMBHs and BH-6: Observed SMBHs

Stellar surface densities



- Top: Merger without SMBHs. Bottom: Merger with massive SMBHs.
- The effect of core scouring by the SMBHs can clearly be seen in the surface density plot.

Surface brightness profiles



- Similarly to the Thomas et al. (2016) observations we assume a constant mass-to-light ratio of $M_*/L=4.0$.
- As expected we find a systematic decrease in the surface brightness as a function of increasing BH mass (e.g. Merritt 2006).

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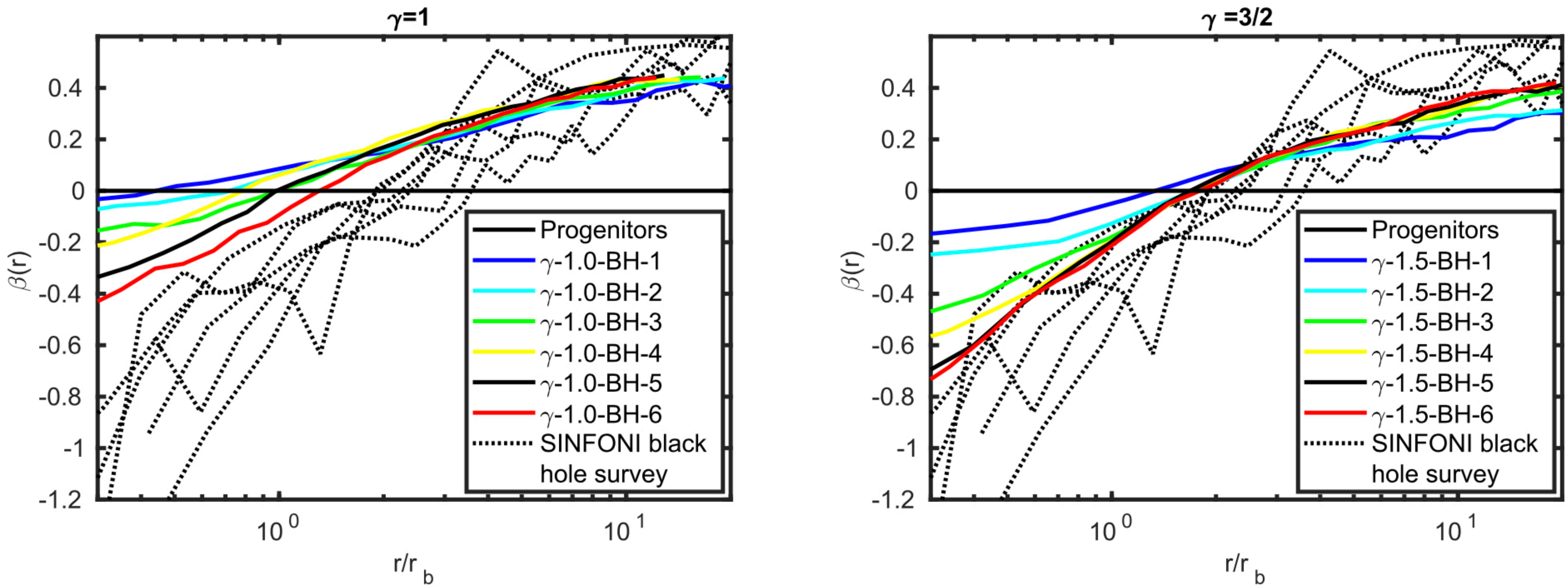
Velocity anisotropy profiles



- We find a monotonic decrease in the central β-parameter, meaning an increasingly more tangentially biased stellar population in the core region.
- More massive BHs have larger spheres of influence -> lower β.

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_\mathrm{r}^2} = 1 - \frac{\sigma_\mathrm{t}^2}{\sigma_\mathrm{r}^2}.$$

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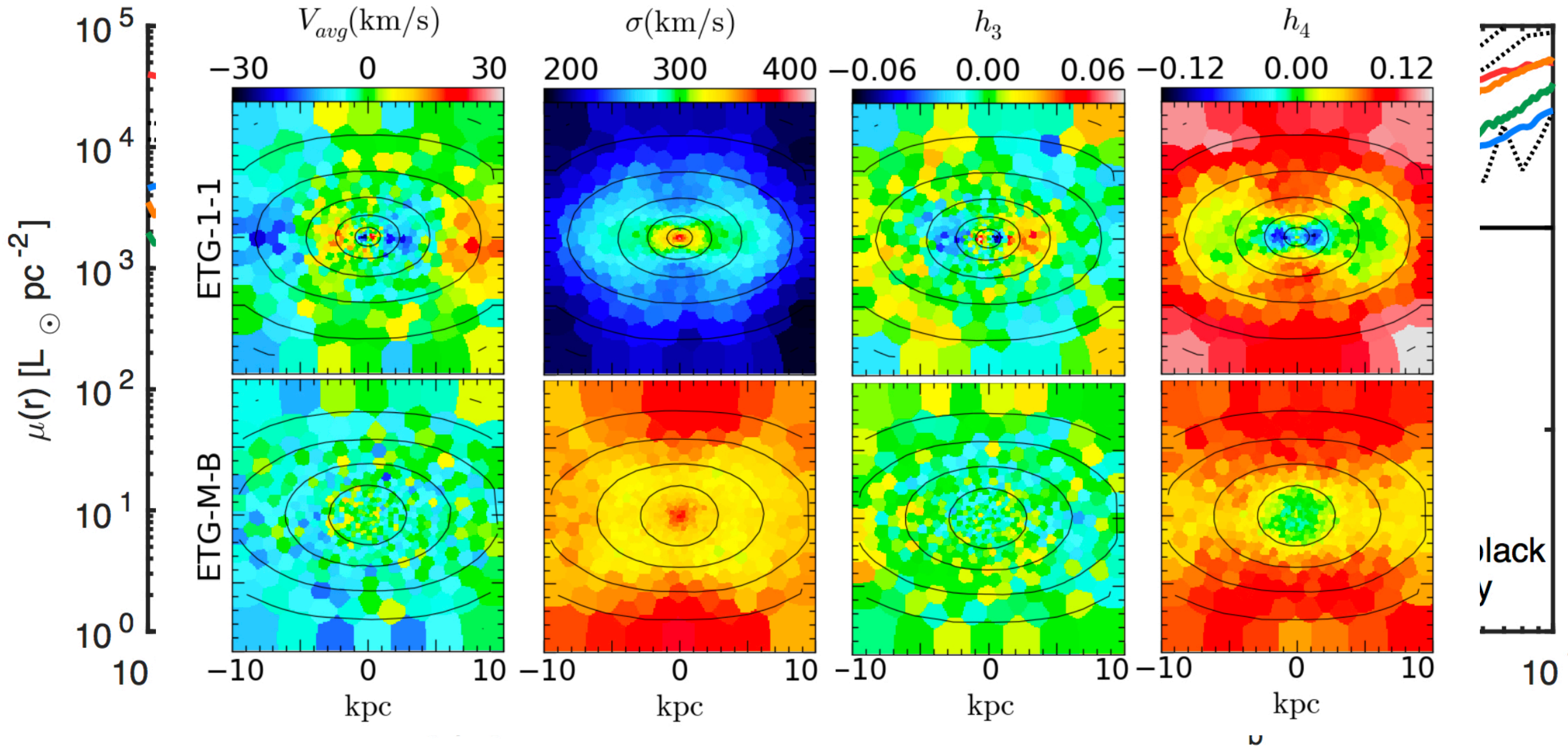
3. Multiple merger generations and remergers



- ETG-1-1-nobh no SMBH, ETG-1-1 merger, ETG-M-A remerger of ETG-1-1 merger remannts, ETG-M-B 5 generations of 5:1 mergers.
- Repeated mergers (green and orange lines) render the central velocity dispersion closer to isotropic, confirmed also by velocity maps.
- Very large cores are probably formed in multiple minor mergers.

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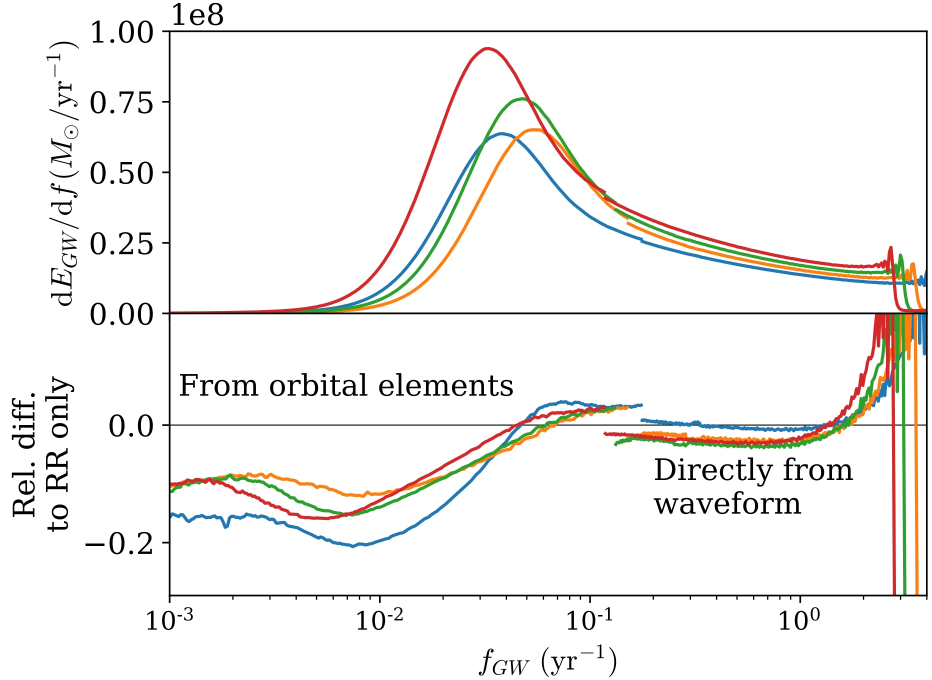
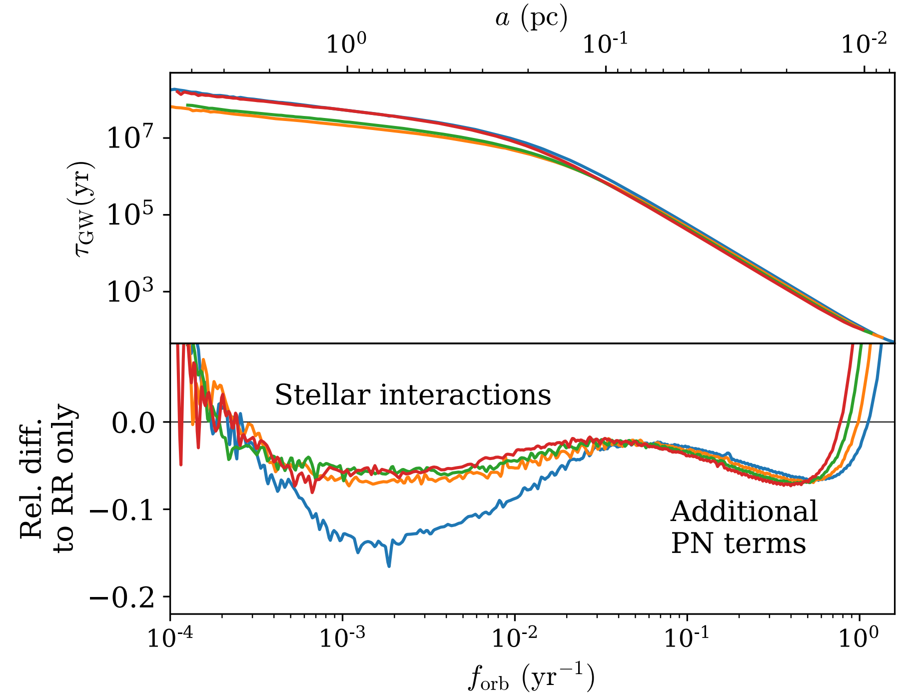
4. First GW calculations with KETJU

4 merger generations: 5:1, 6:1, 7:1, 8:1, each mergers adds the same SMBH mass.





- The emitted total gravitational energy (left) and GW timescale (right) as a function of frequency can be calculated from the KETJU orbital elements and during the final KETJU timestep directly from the SMBH positions and velocities using a fast Fourier transform algorithm.
- Differences to the Peters & Mathews (1963) PN2.5 radiation reaction only term are given in the bottom panels.

$$\left|\frac{da}{dt}\right| = \frac{64}{5}\frac{G^3 M_1 M_2 (M_1+M_2)}{c^5 a^3}\frac{1+\frac{73}{24}e^2+\frac{37}{96}e^4}{(1-e^2)^{7/2}}$$

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Summary/Connection to LISA

- The KETJU code is a version of Gadget includes an algorithmically regularized chain module that makes two-body collisions integrable by a simple leapfrog integrator.
- Cores form rapidly on the order of the crossing timescale by SMBH binary evolution and the velocity distribution becomes increasingly more tangential over a longer timescale.

- Thus far all published KETJU papers have been used simulations without a gas component, but as KETJU is built on Gadget running simulations with gas and feedback should be relatively straightforward.
- LISA will be most sensitive to GW signals from SMBHs with masses in range 10^6-10^7 $M_\odot$, thus modelling the accurate small-scale dynamics simultaneously with the gas physics will be important.
- We are planning to make the KETJU code publicly available, not just for Gadget, but also other simulation platforms such as AREPO, RAMSES and GASOLINE.
- In Helsinki a KETJU related ERC project will start next summer and we are looking to hire dynamics/GW experts also from within the larger LISA community.

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