



**Enter the ARCH-DEVIL:**

**Simulating supermassive black hole  
dynamics on galactic scales**

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**Antti Rantala, Pauli Pihajoki, Peter Johansson**

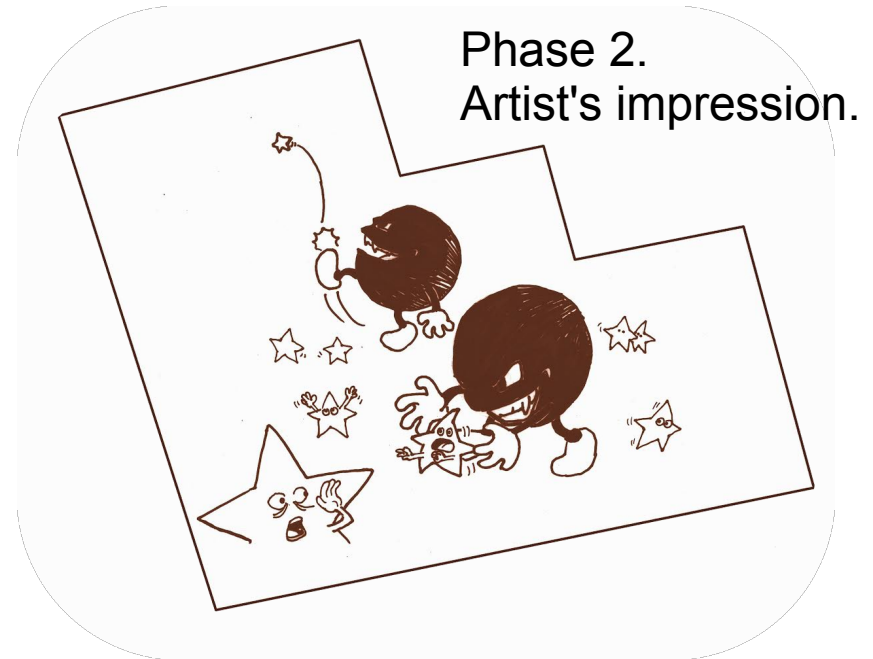


# Background: supermassive black hole binary (SMBH) evolution

The non-linear structure formation in our Universe is hierarchical: galaxies with SMBHs collide and form bigger galactic structures and SMBH binaries.

Three phases of binary evolution:

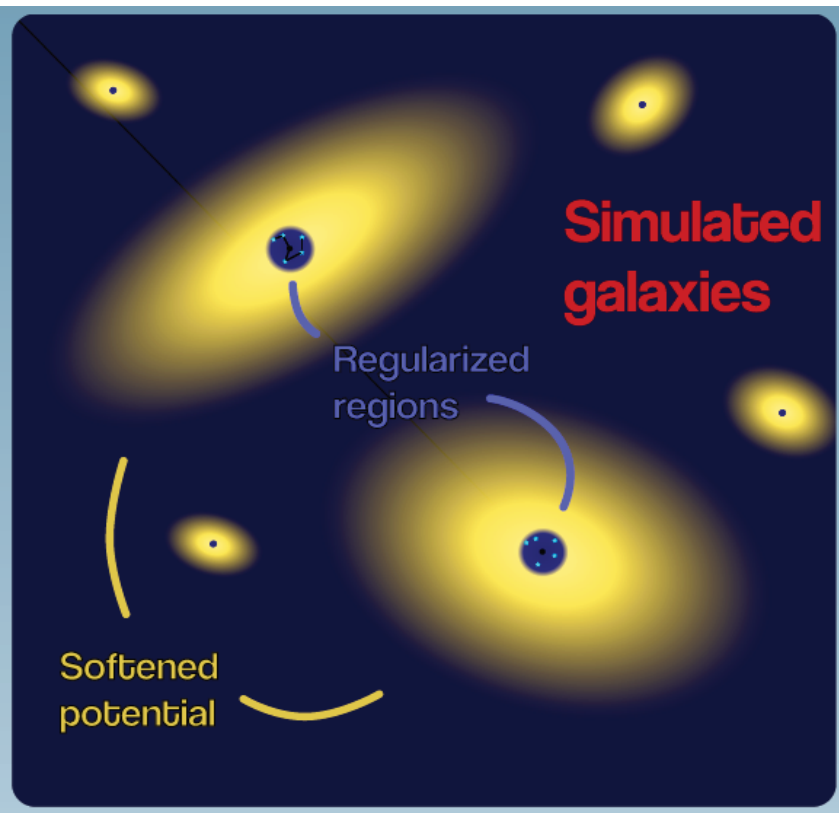
- 1) Dynamical friction from stars and gas diminishes the semi-major axis of the binary up to  $\sim 1$  pc.
- 2) The binary loses orbital energy via kicking out stars by three-body interactions. The slowest phase.
- 3) The binary emits the rest of its orbital energy as gravitational waves and forms a single SMBH.



# Regularized Post-Newtonian dynamics in Gadget-3

Gadget-3: a Newtonian tree code with hydrodynamics and state-of-the-art subresolution astrophysics.

Gravity is softened at small scales ( $< 10$  pc) for computational efficiency  $\rightarrow$  small-scale dynamics around SMBHs not resolved.



**SOLUTION:** Algorithmic Chain Regularization module (ARCH-DEVIL):

- 0) Select simulation particles nearby SMBHs.
- 1) Regularization: time transformation of the equations of motion:  $1/r$  – divergence avoided.
- 2) Usage of inter-particle vectors. Eliminates most round-off errors.
- 3) Bulirsch-Stoer extrapolation method: 'infinite' spatial and temporal resolution.

Post-Newtonian corrections from General Relativity as velocity / spin-dependent forces, and their cross terms up to  $(v/c)^7$ .



# Calibration and applications

Currently calibrating against a famous gravity-only code NBODY7

## Near-future applications:

Realistic SMBH merger time scales → merger rates → GW background from coalescing SMBHs.

Post-Newtonian dynamics in galactic scales: the corrections are small, but maybe cumulative?

Accurate simulations of galactic centers: NSCs and baryonic / dark density peaks.

