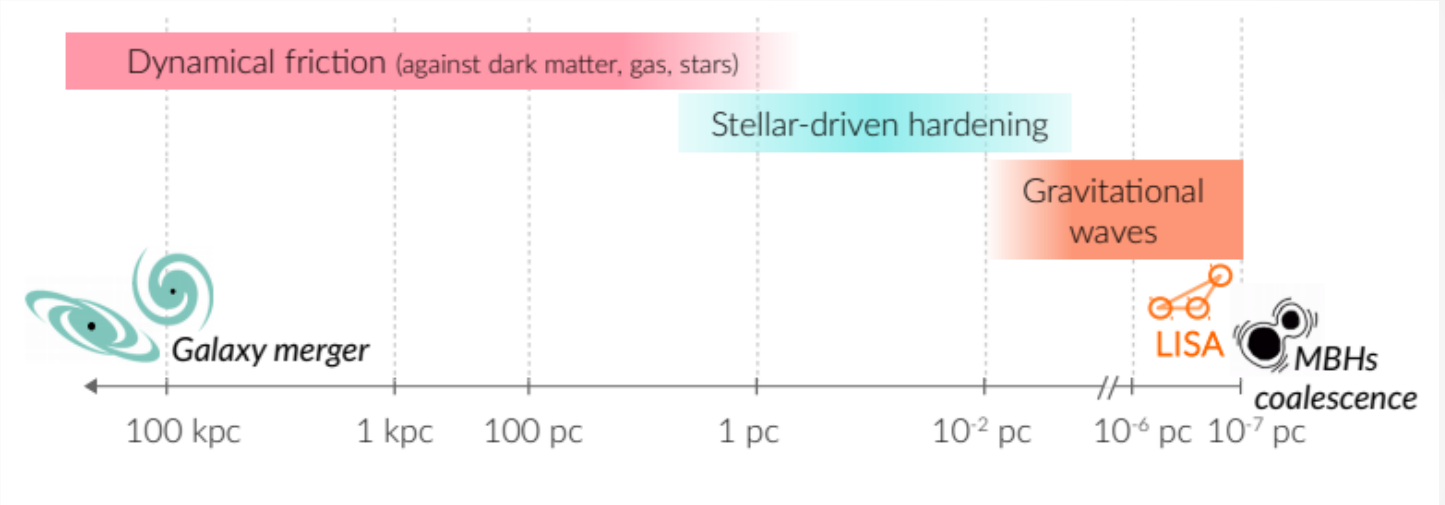
Supermassive black hole dynamics and evolution at redshifts ~~z>5~~ z>6 using KETJU

Atte Keitaanranta

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

The three phases of SMBH binary evolution

- Dynamical friction
- Three-body interactions, gas physics
- Gravitational wave emission

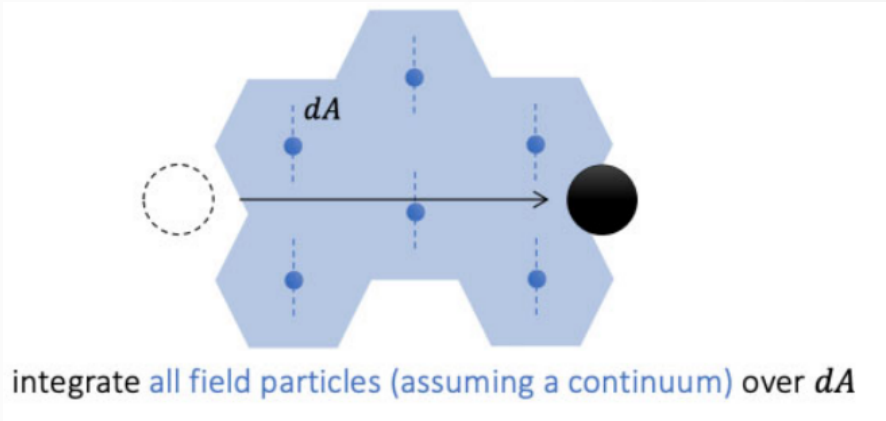


Adapted from Amaro-Seoane et al. 2023

SMBH dynamics in cosmological simulations

- The mass ratio $m_{\mathrm{BH}}/m_{\mathrm{star}}$ can be quite small, BH repositioning traditionally used
- Modern simulations often use a subgrid model to account for unresolved dynamical friction
- Tremmel et al. 2015 model: based on Chandrasekhar 1943 dynamical friction formula

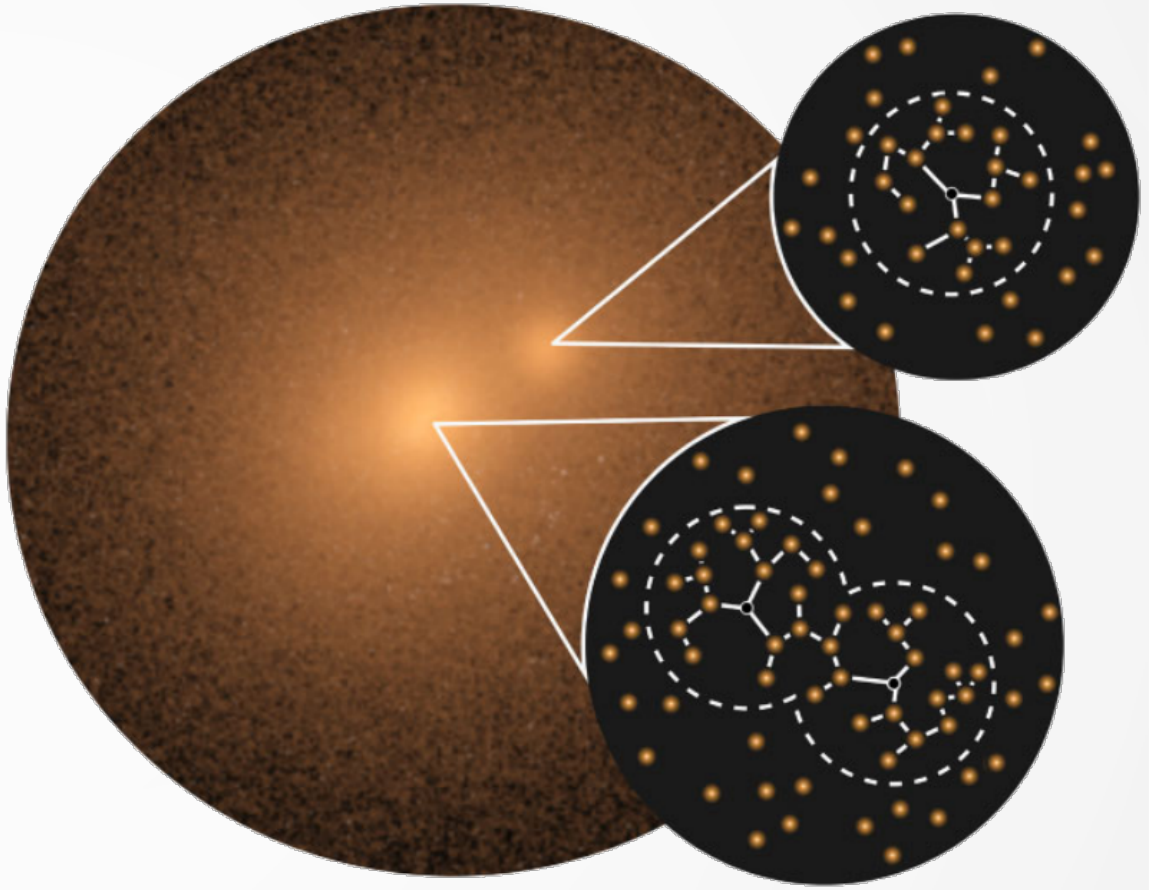
$$\boldsymbol{a}_{\mathrm{DF}} = -4\pi G^2 M_{\mathrm{BH}} \rho(<v_{\mathrm{BH}}) \ln\Lambda \frac{\boldsymbol{v}_{\mathrm{BH}}}{v_{\mathrm{BH}}^3}$$



Adapted from Ma et al. 2023

KETJU

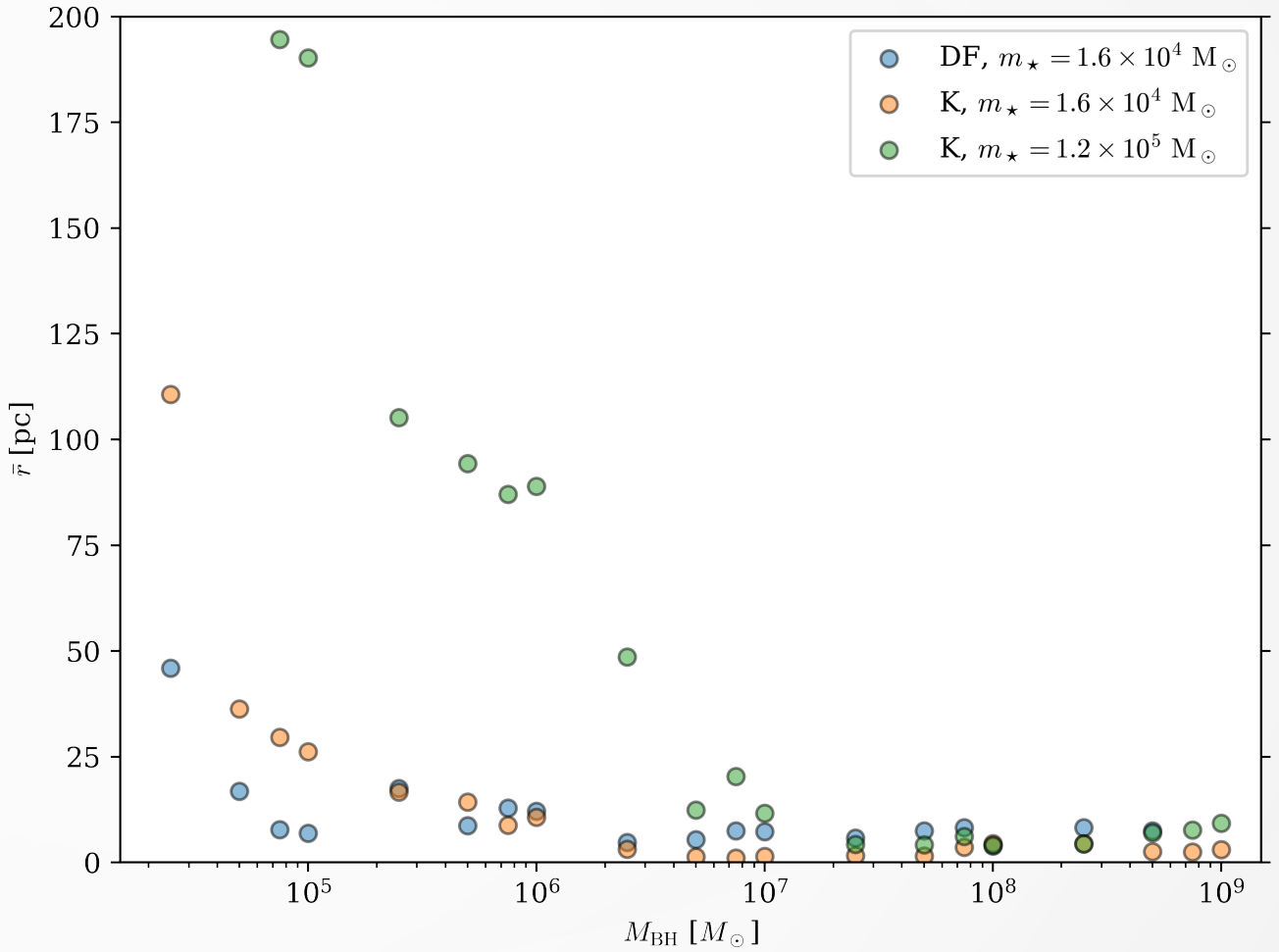
- Removes softening between SMBHs and stellar particles using a regularized integrator
- SMBH binaries also not softened, post-Newtonian corrections up to PN3.5
- Has been used in cosmological zoom-in simulations (Mannerkoski et al. 2021, 2022), but only at relatively low redshifts ($z \leq 0.815$), BH repositioning used before this redshift
- KETJU/GADGET-4 version publicly available
  https://www.mv.helsinki.fi/home/phjohans/group-website/research/ketju/



Mannerkoski et al. 2023

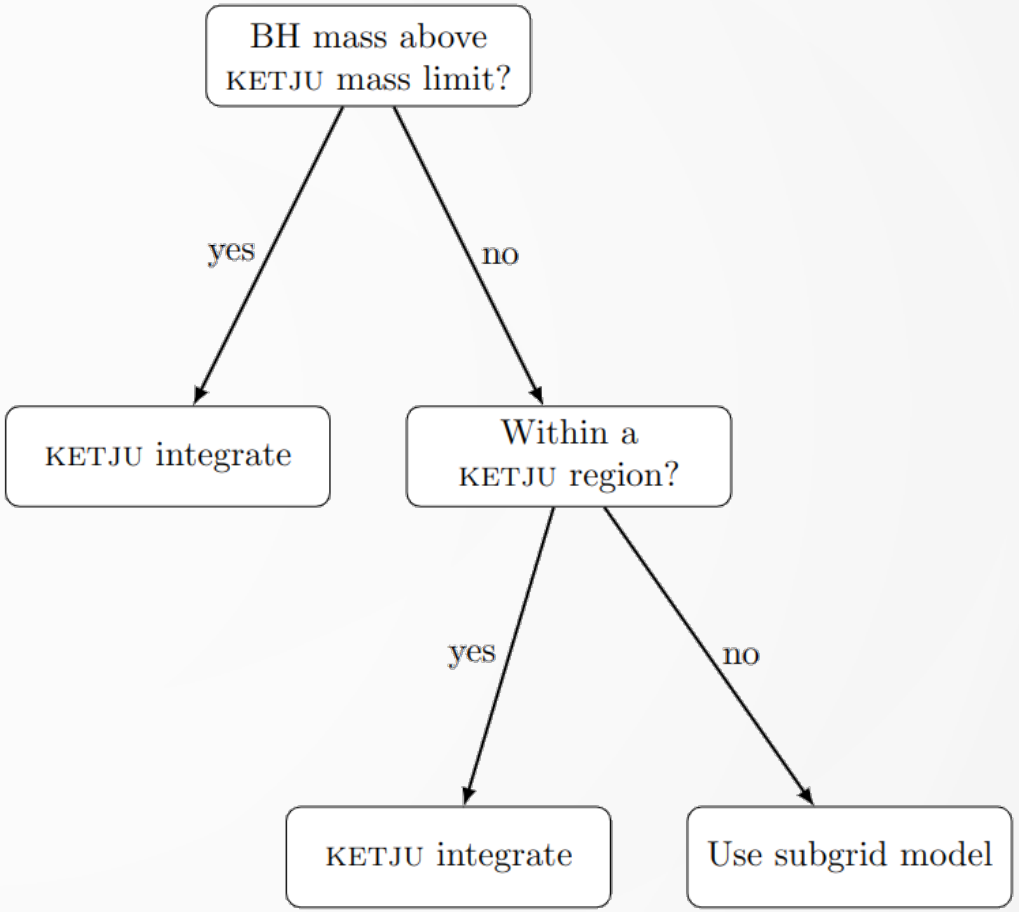
KETJU's Brownian motion strongly depends on the BH/stellar particle mass ratio

- Isolated Hernquist sphere, SMBH starting at the center
- Decreasing $m_{\mathrm{BH}}/m_{\mathrm{star}}$ increases median distance from the center
- Wander away from the center → delayed BH binary formation in galaxy mergers



Combining KETJU with a subgrid model

- KETJU used if the SMBH mass is above a mass limit
- The Tremmel et al. 2015 subgrid model used until the mass limit is reached



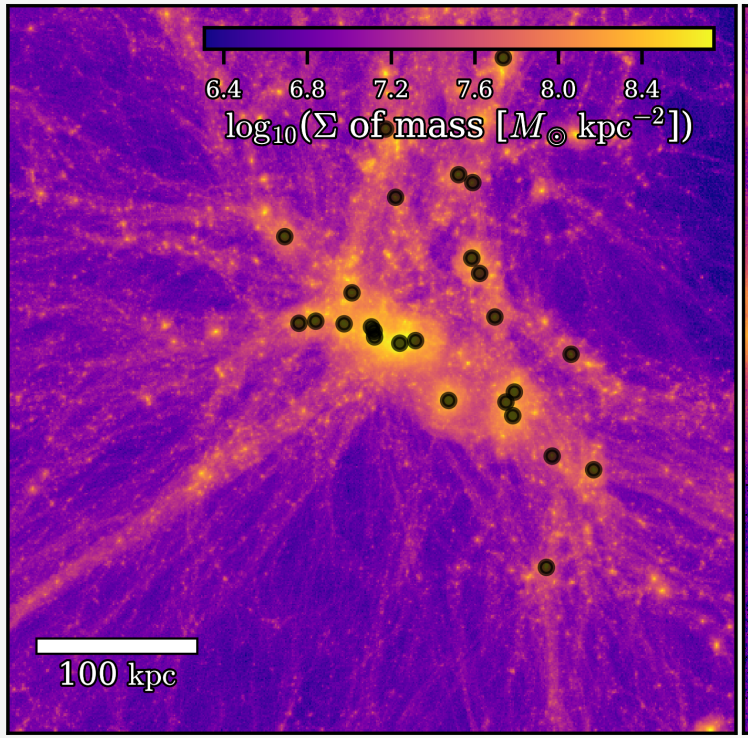
Cosmological zoom-in setup

V_{zoom}	m_{ketju}	m_{seed}	r_{ketju}	m_{bar}	m_{dm}
$(4\ \mathrm{cMpc}/h)^3$	$1.3 \times 10^6\ \mathrm{M}_\odot/h$	$3.2 \times 10^5\ \mathrm{M}_\odot/h$	$3\ \mathrm{pc}/h$	$1.0 \times 10^4\ \mathrm{M}_\odot/h$	$5.7 \times 10^4\ \mathrm{M}_\odot/h$

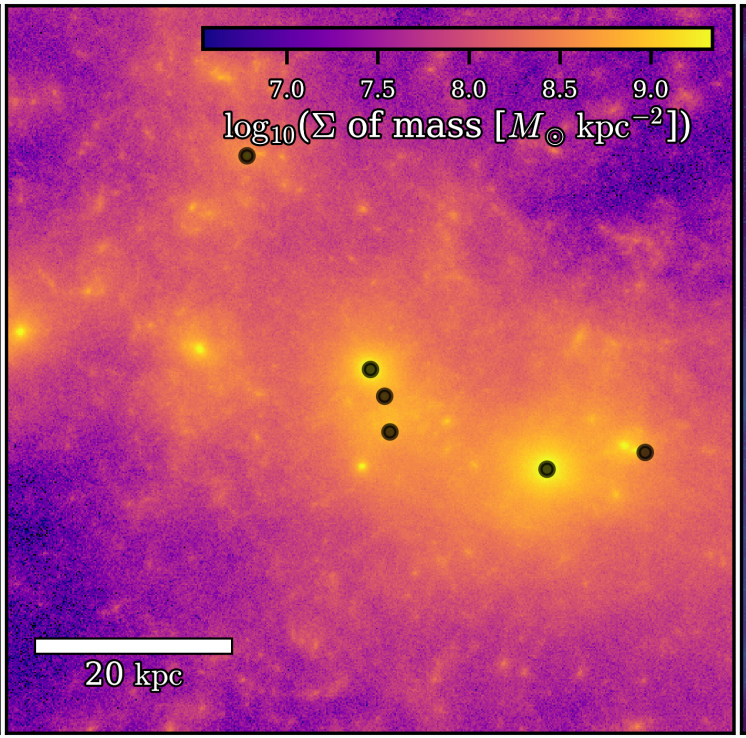
- 3 different simulations: Both with and without Ketju, one with Ketju allowing super-Eddington accretion

z= 5.93

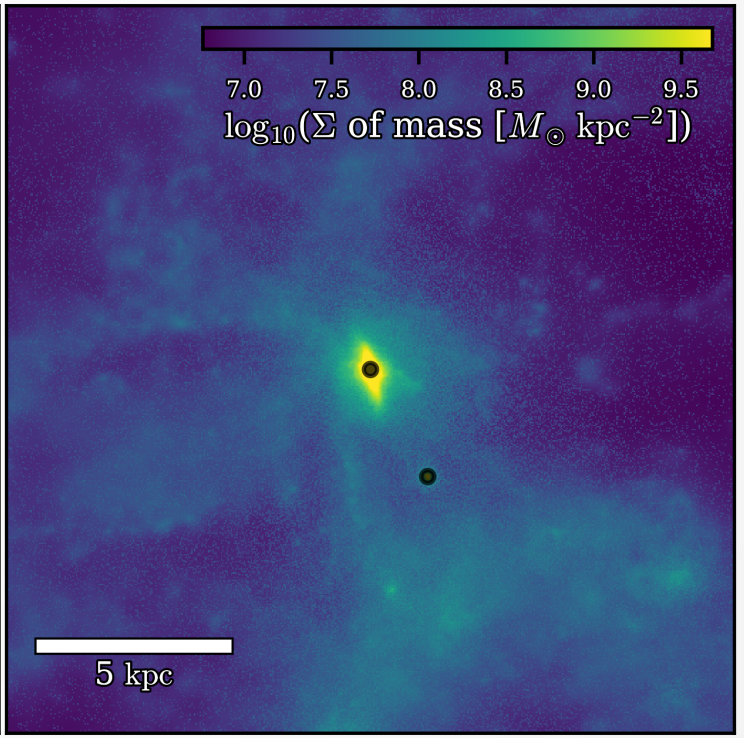
Dark matter



Dark matter



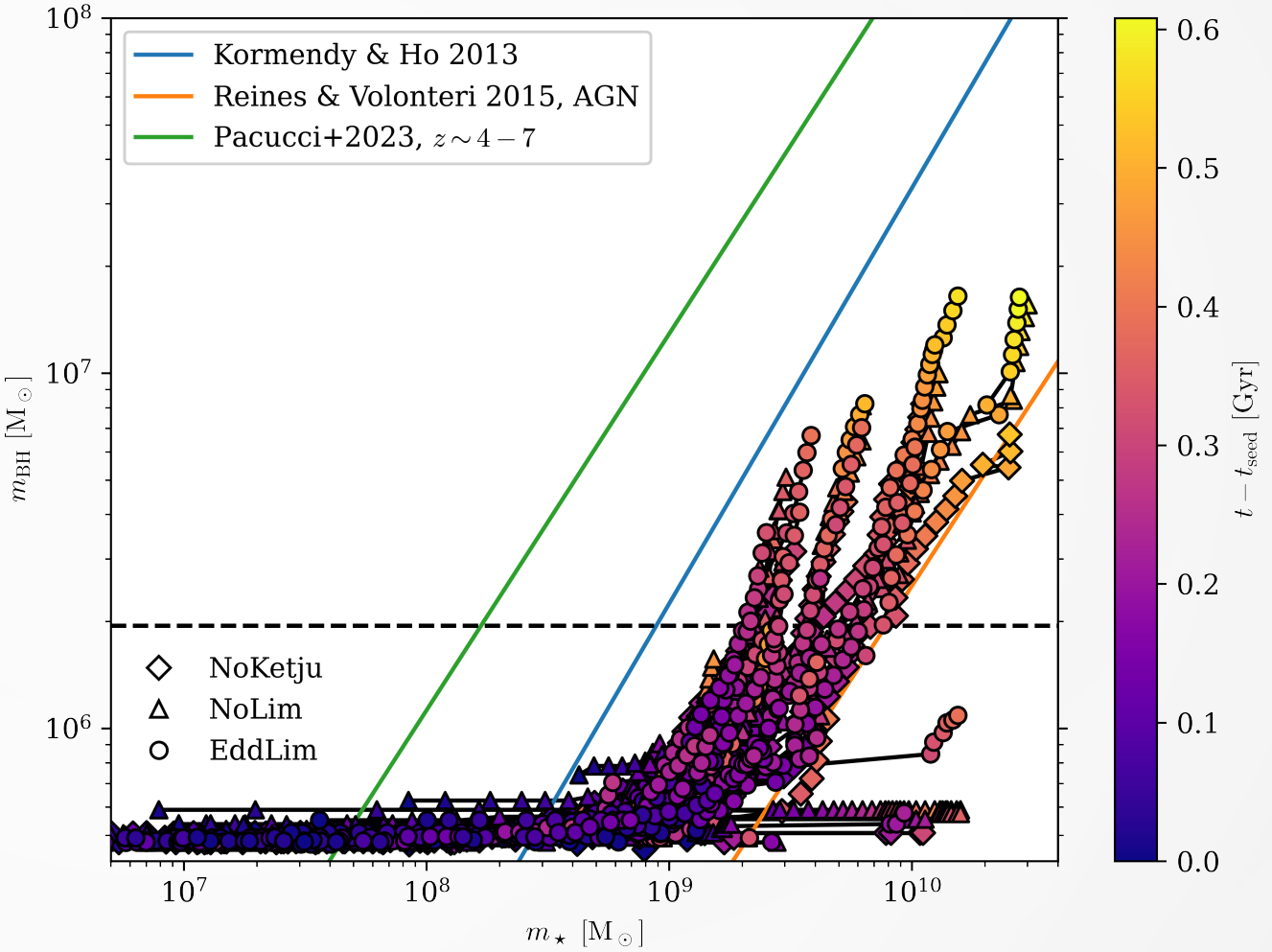
Baryons



No large effect on BH mass when allowing super-Eddington accretion

PRELIMINARY

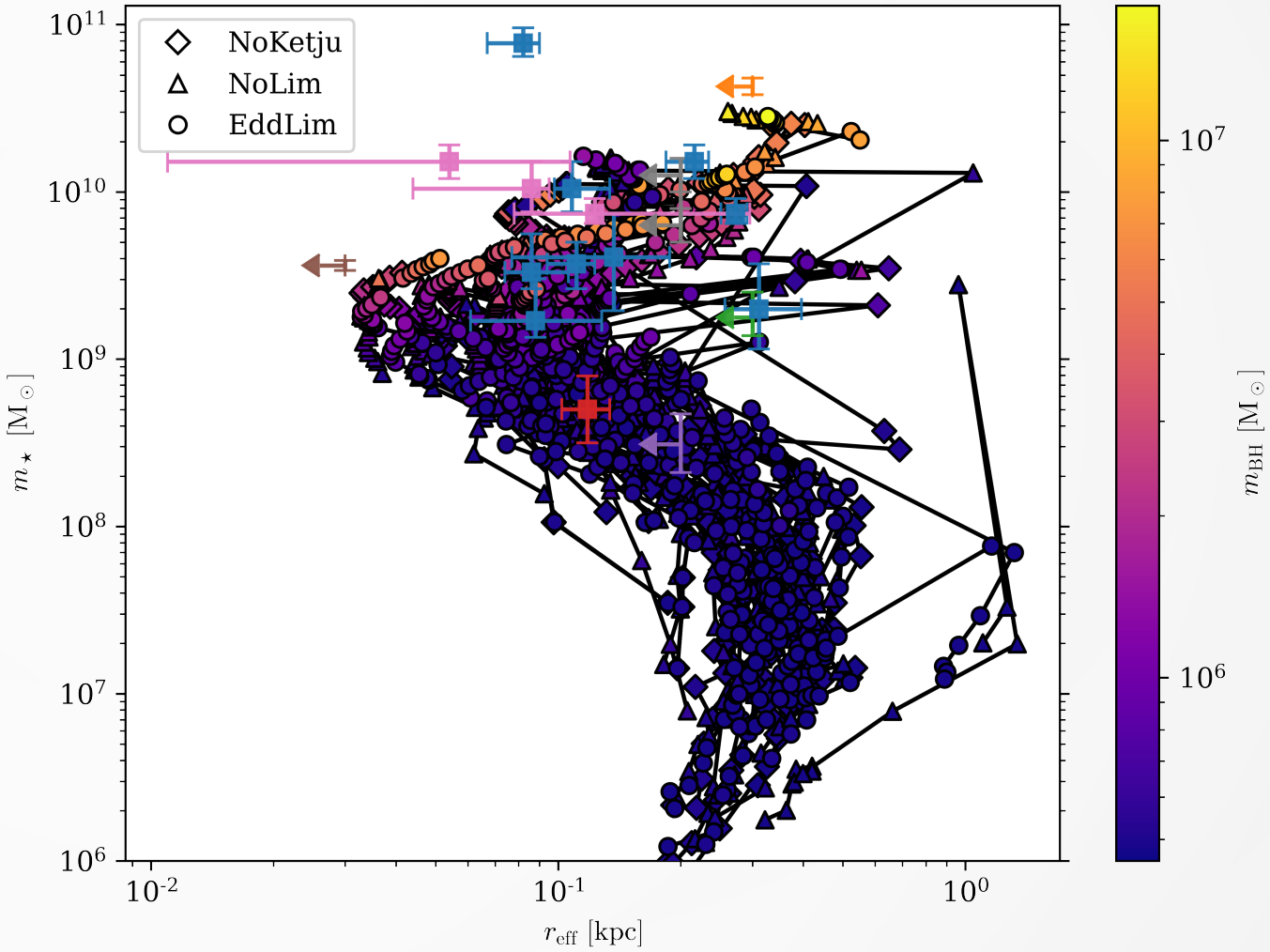
- Galaxies grow in stellar mass before SMBHs, which starts to grow efficiently at stellar masses $\sim 10^9 \mathrm{M}_\odot$
- No large differences between super-Eddington and Eddington-limited accretion
- No overmassive black holes



SMBHs begin to grow in very compact galaxies

PRELIMINARY

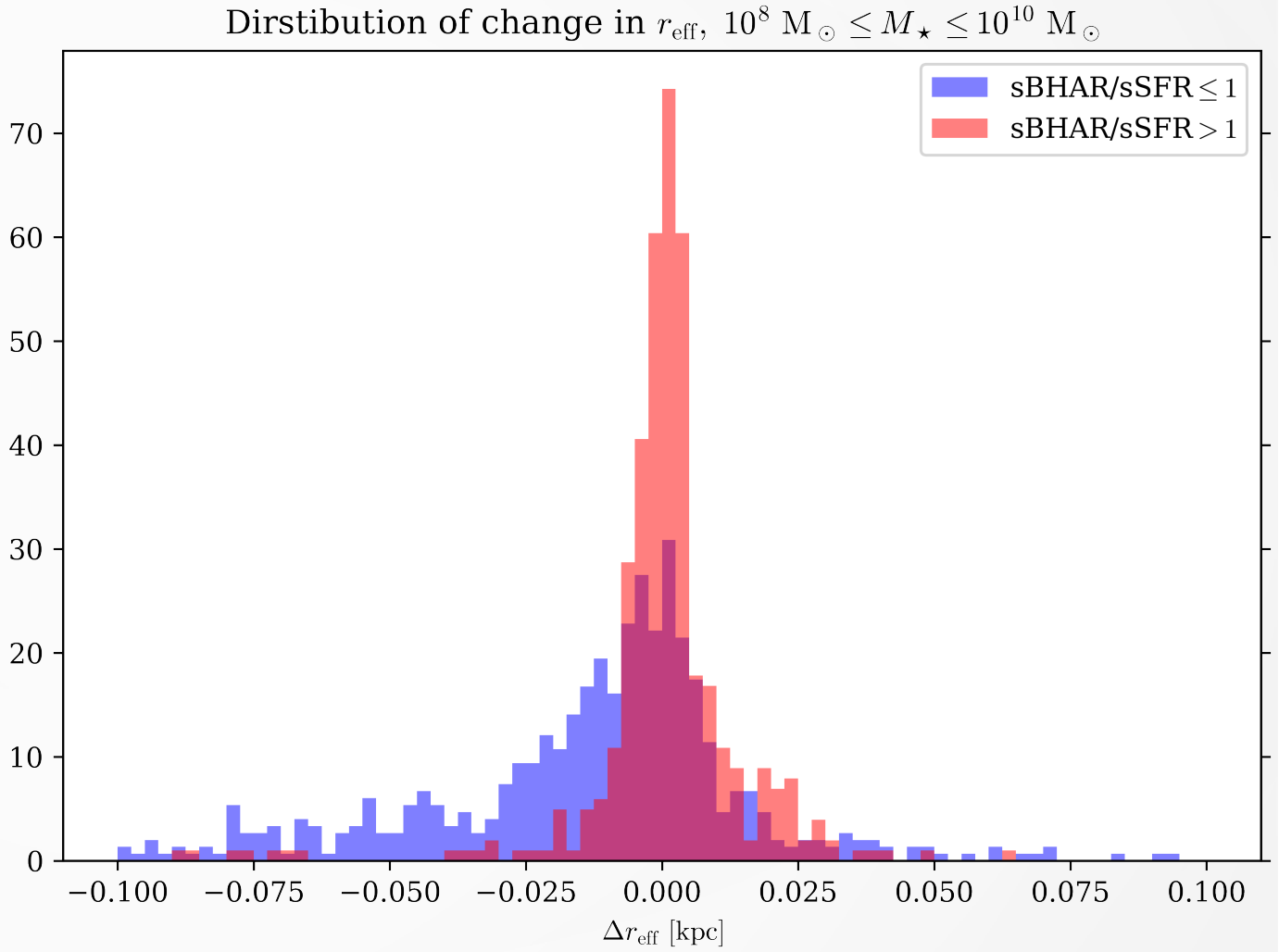
- Forming galaxies seem to grow in stellar mass and decrease in half-mass radius
- SMBHs start to grow ~at the same time as half-mass radius begins to decrease
- Most compact sizes agree well with the sizes of LRDs



BH feedback prevents further size decrease

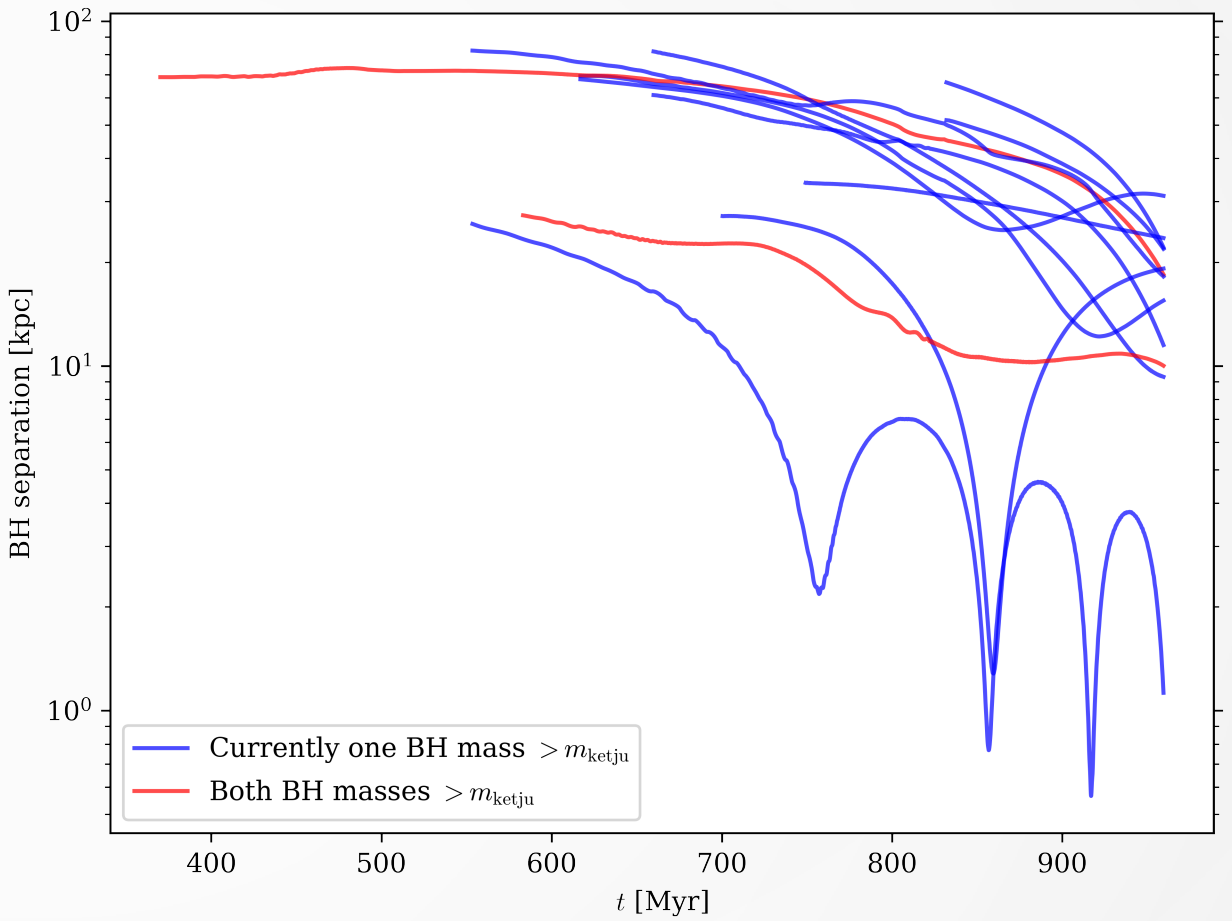
PRELIMINARY

- Very recently, Shashank et al. (2024) discussed how the ratio sBHAR/sSFR reflects how gas is used between star formation and BH accretion
- Ratio sBHAR/sSFR<1 → skewed towards making galaxy more compact, ratio above 1 prevents further size shrinking
- BH feedback causes star formation to be more spread out



Summary

- With low mass ratios, Brownian motion of a BH can be large with KETJU
- Combining KETJU with a dynamical friction subgrid model allows the use of KETJU in a cosmological setting without picking the KETJU integration start time by hand
- At high redshifts, our simulation produces SMBHs that start to grow in very compact galaxies, with BH accretion increasing the size of the stellar component
- KETJU integrated mergers coming soon!



Thank you!