COSMOLOGY FROM HOME 2022

EVOLUTION OF MASSIVE BLACK HOLE BINARIES IN MERGING NUCLEAR STAR CLUSTERS

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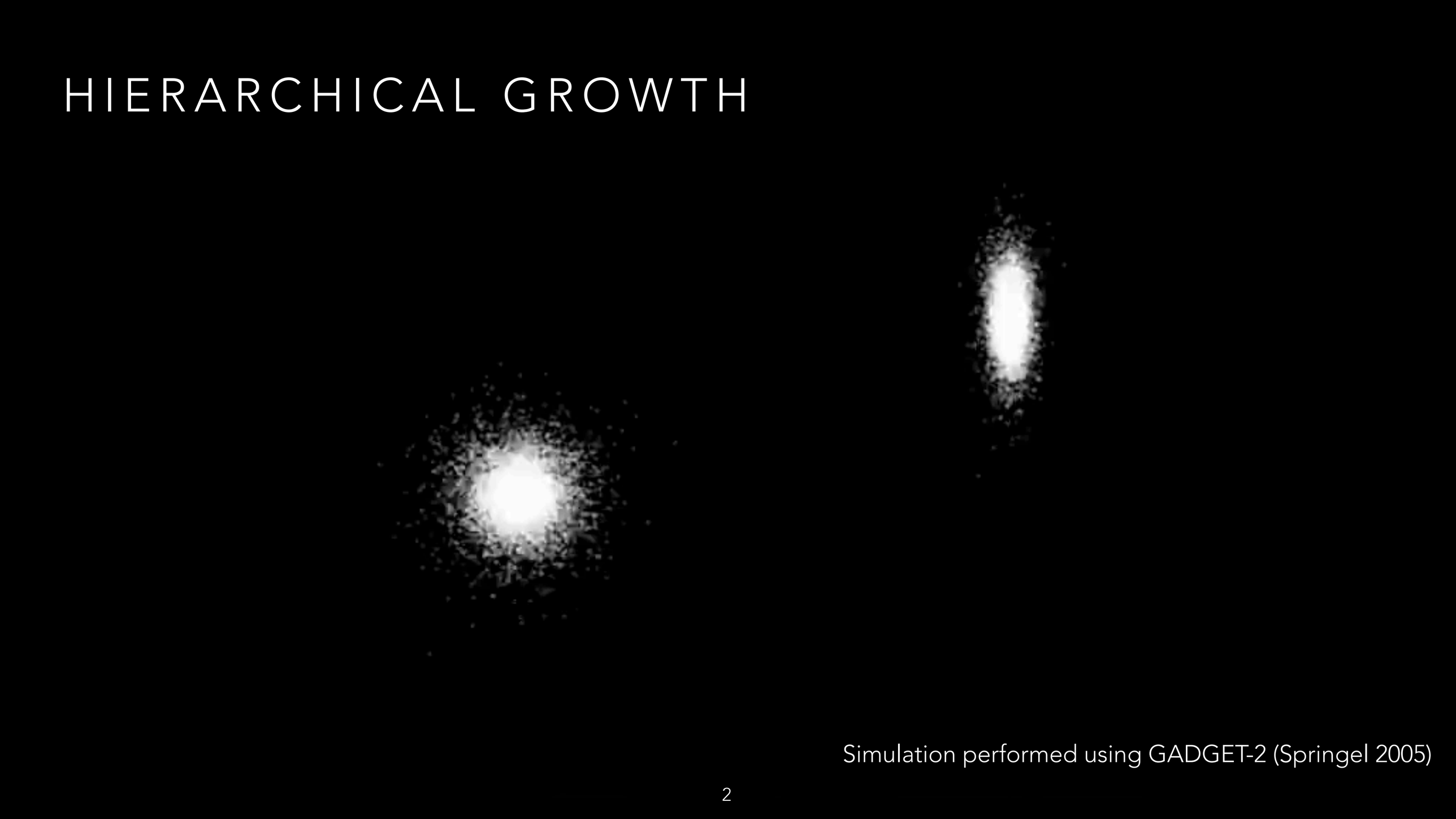
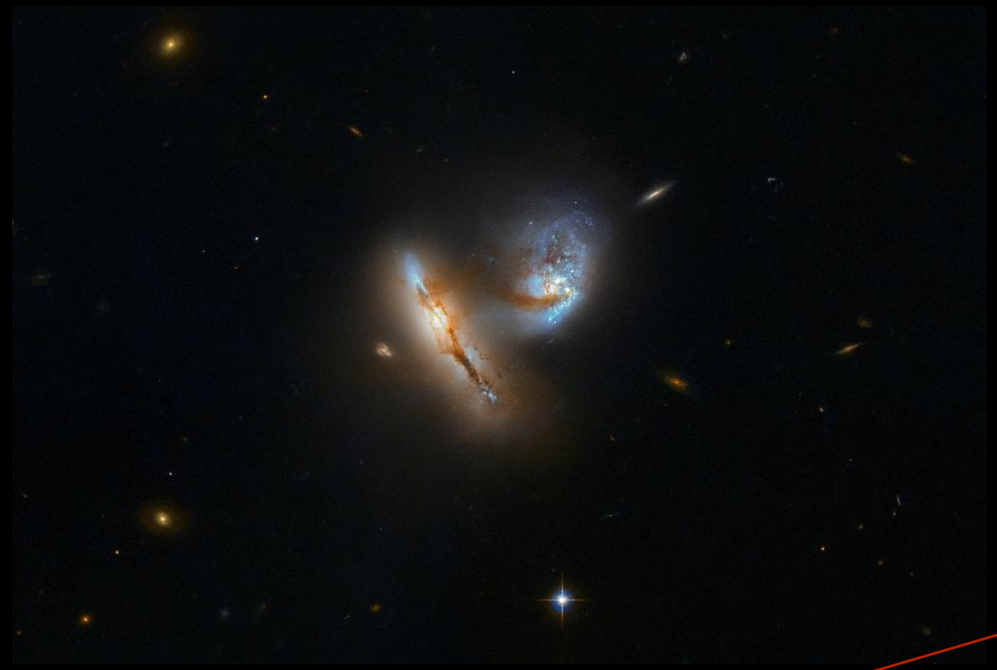
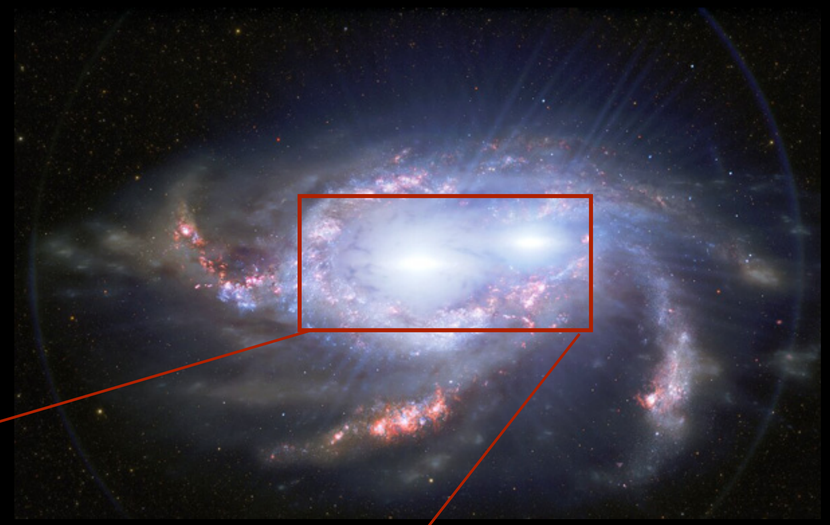
Image credit: NASA, ESA, and J. Olmstead (STScI)

HIERARCHICAL GROWTH



Simulation performed using GADGET-2 (Springel 2005)





~kpc

< pc

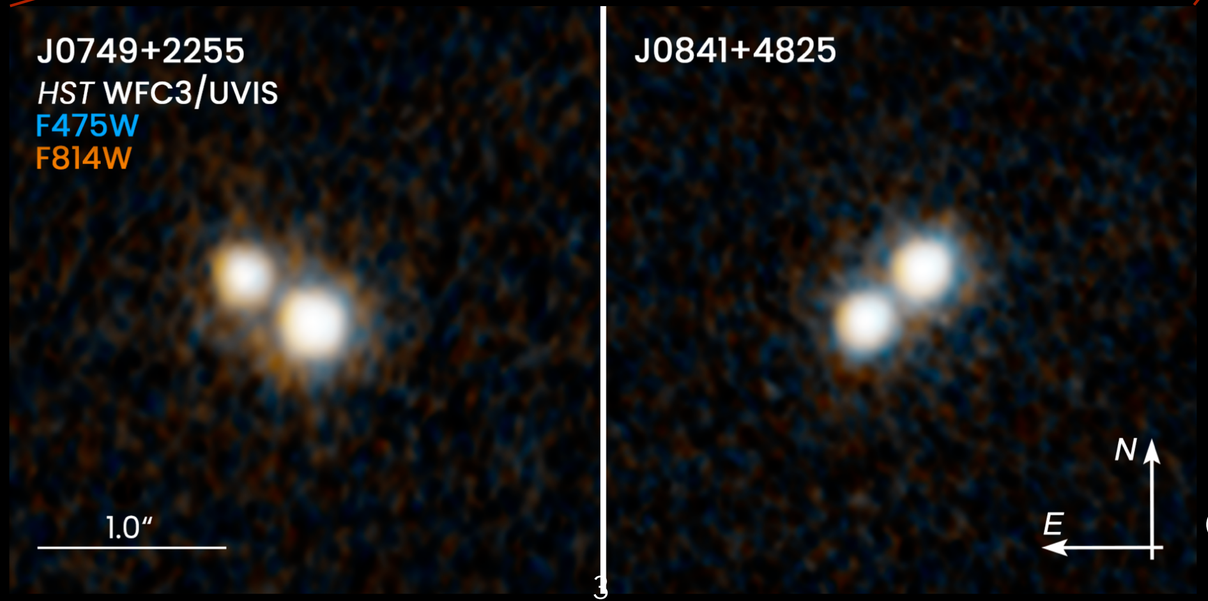
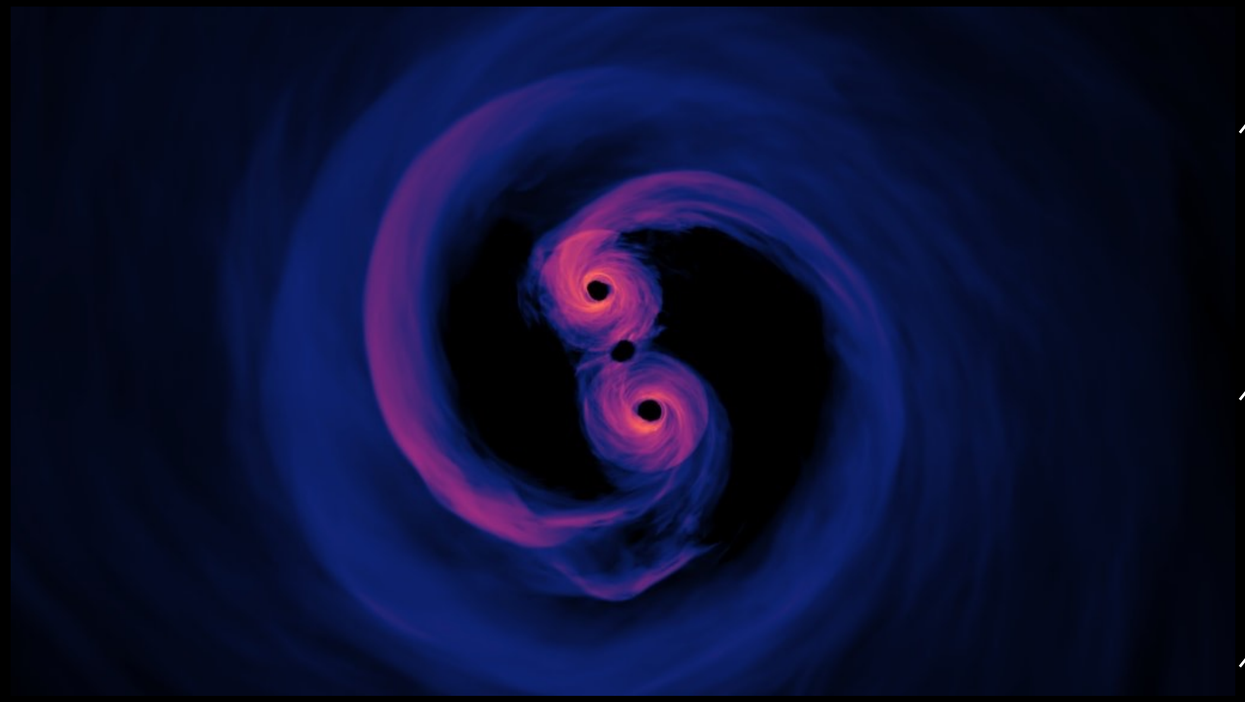


Image credits: NASA, ESA, Hsiang-Chih Hwang (JHU), Nadia Zakamska (JHU), Yue Shen (UIUC)

MASSIVE BLACK HOLE BINARIES

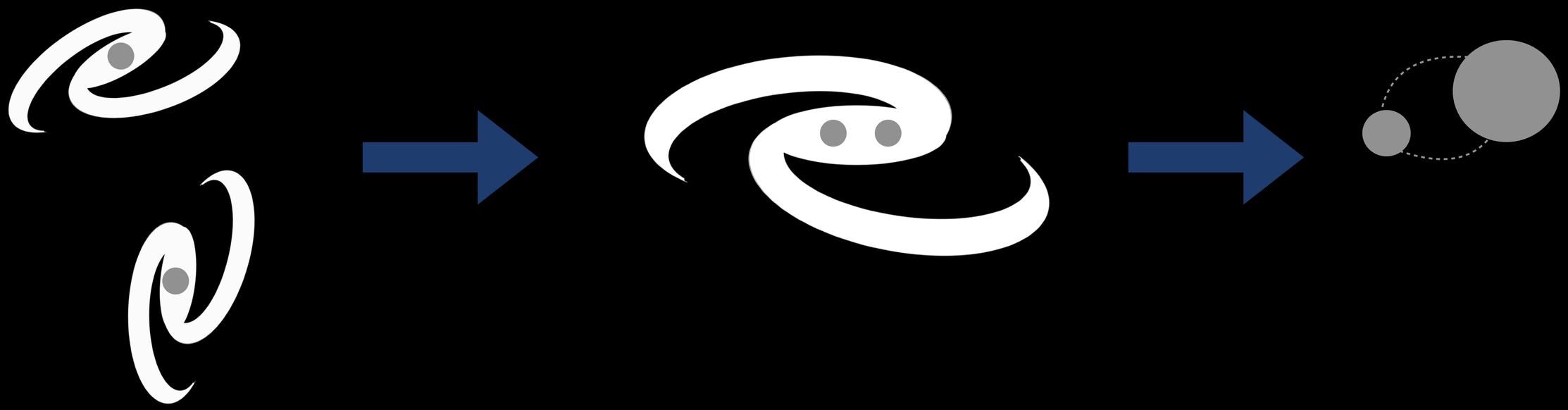


One of the most important LISA sources

Theories of formation and assembly uncertain

Dynamics sensitive to the surrounding environment

To maximize LISA science output, theoretical advances needed in dynamics and evolution!



~kpc

dynamical friction from surrounding media

~pc

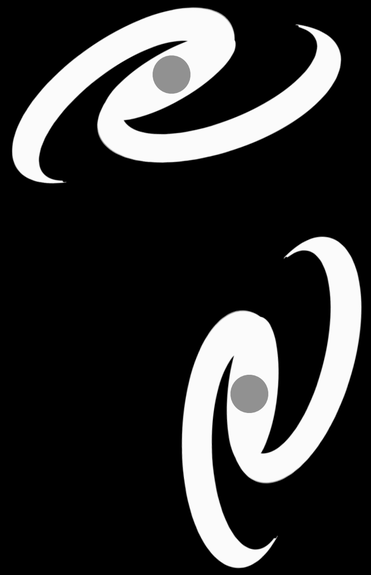
dynamical friction, stellar hardening dependent on host

~milli-pc

stellar hardening dependent on host, GW emission

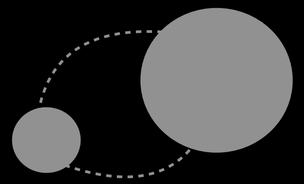
Uncertain timescales due to issues like final pc problem

Figures based on Amaro-Seoane+ (2022)



~kpc

~pc



~milli-pc

NEED HIGH RESOLUTION N-BODY SIMULATIONS

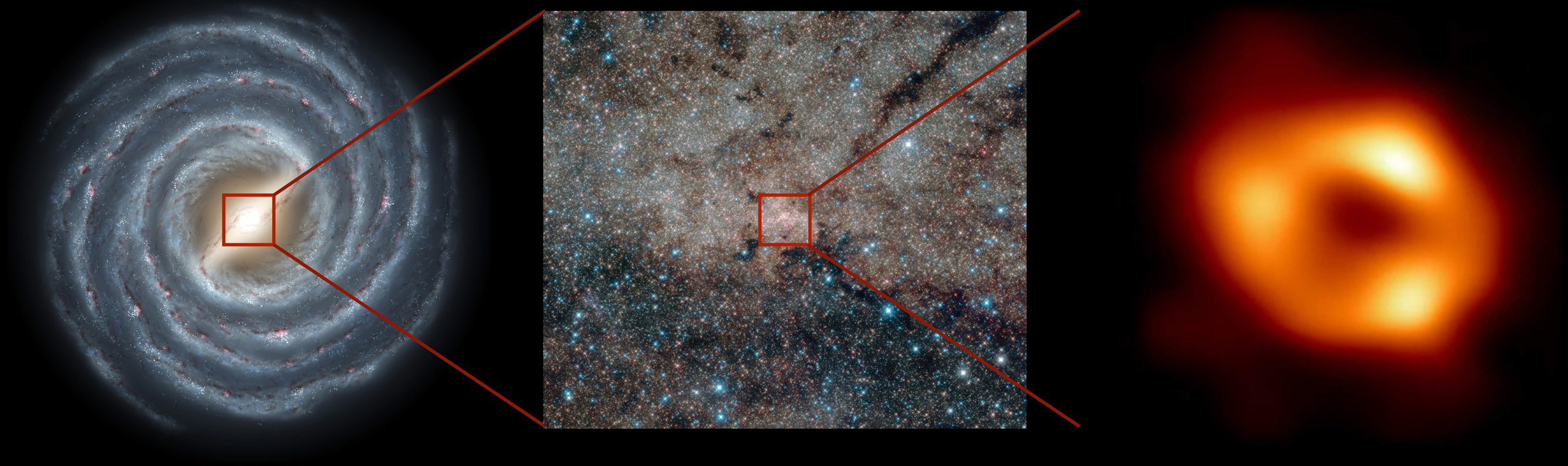
RESOLVED IN COSMOLOGICAL SIMULATIONS

UNRESOLVED IN COSMOLOGICAL SIMULATIONS

NUCLEAR STAR CLUSTERS

90% at $M_{\rm stellar} = 10^9 M_\odot$

50% of Milky Way sized galaxies



~kilo-pc

~pc

~milli-pc

Image credits: NASA/ESA & EHT collaboration

MBH BINARIES IN NUCLEAR STAR CLUSTERS

- Ogiya+ (2020) showed that NSCs greatly accelerate transition to GW dominated phase
- Robust and works better for lower mass ratio binaries
- Motivated to study how realistic models of NSCs with mass spectrum affect dynamics

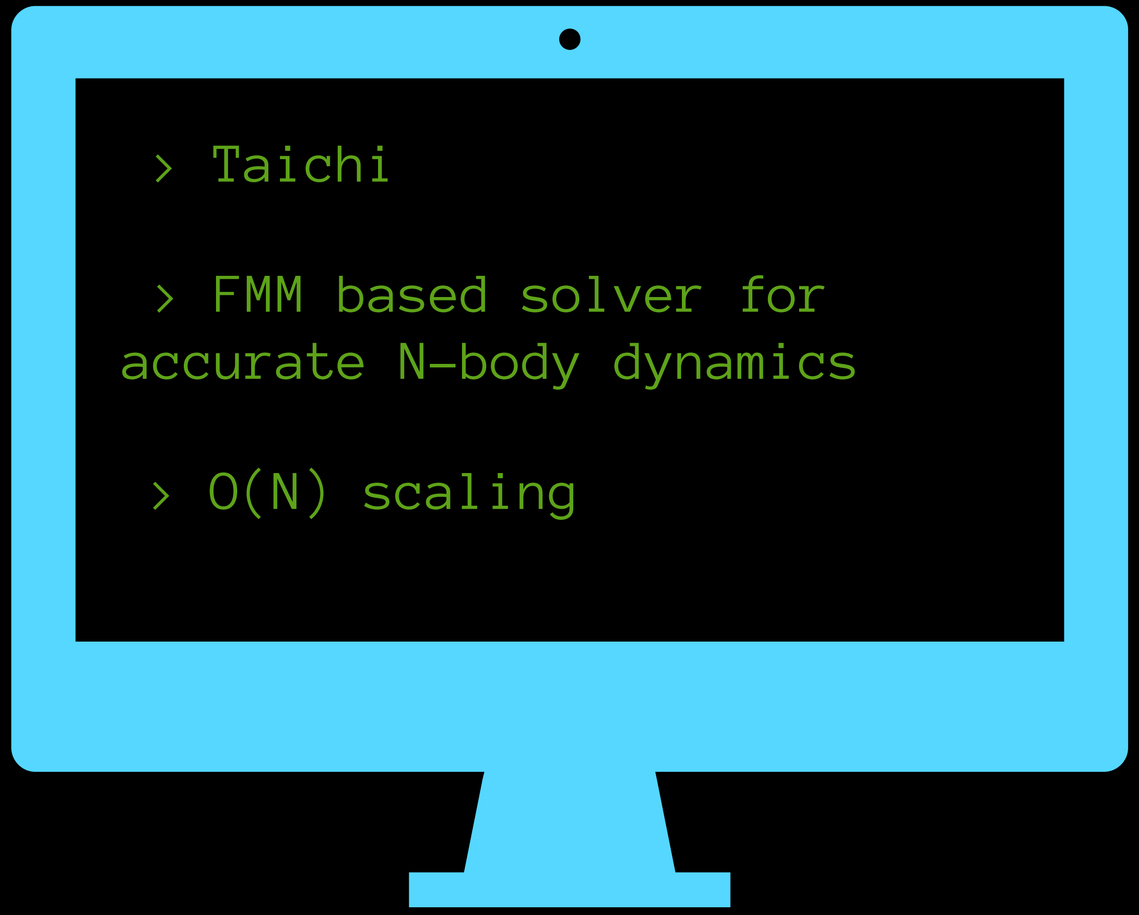
SIMULATING PC SCALE DYNAMICS

High-resolution →

Can resolve three body scattering →

Accurate →

Fast →



Mukherjee+ (2021)

MODELS

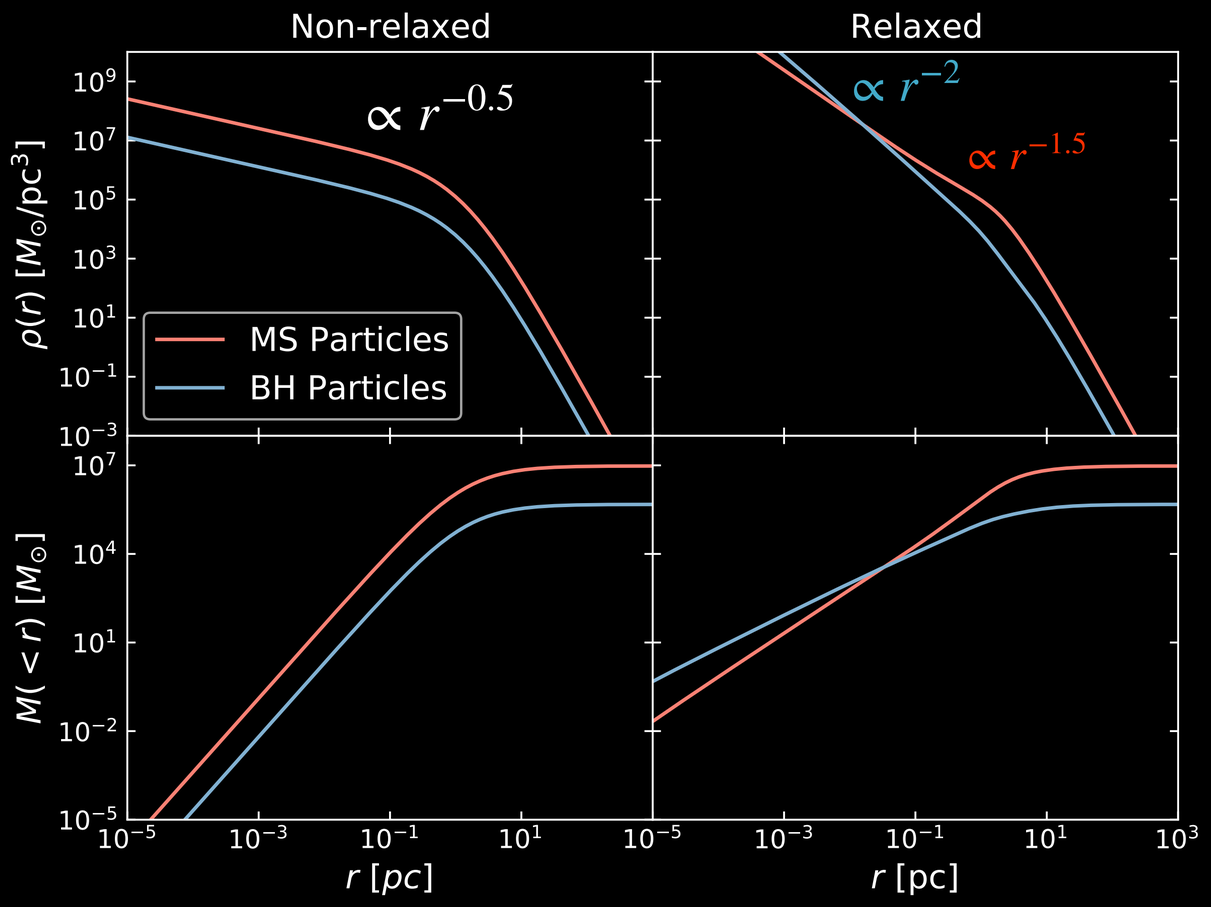
- Masses of MBHs in LISA band

$$M_{\rm primary} = 10^6 M_\odot \qquad q = 1.0, 0.1, 0.01$$

- Realistic NSCs with a two-component mass spectrum

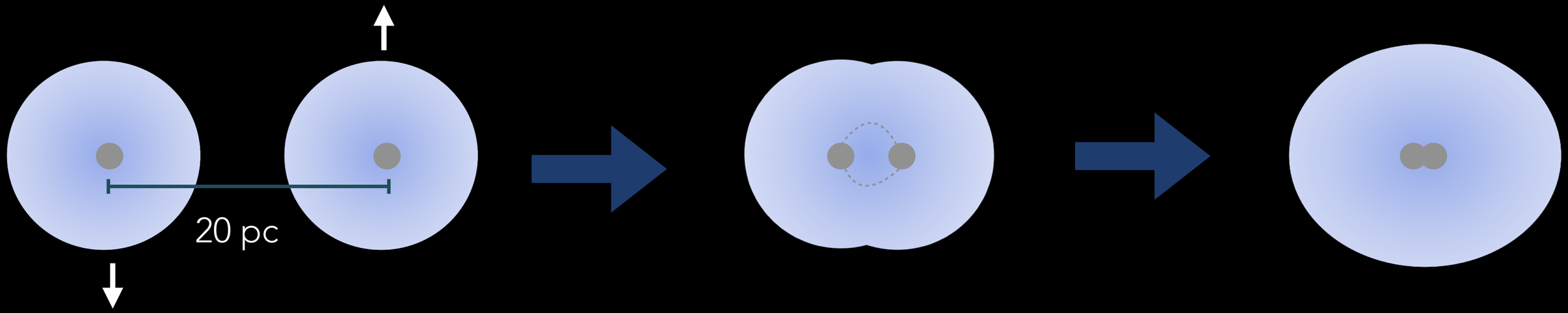
$$M_{\rm NSC} = 10^7 M_\odot \qquad N_{\rm MS} : N_{\rm BH} = 1 : 0.005$$

- Collisional relaxation: segregated vs. non-segregated



Mukherjee+ (2022)

MODELS



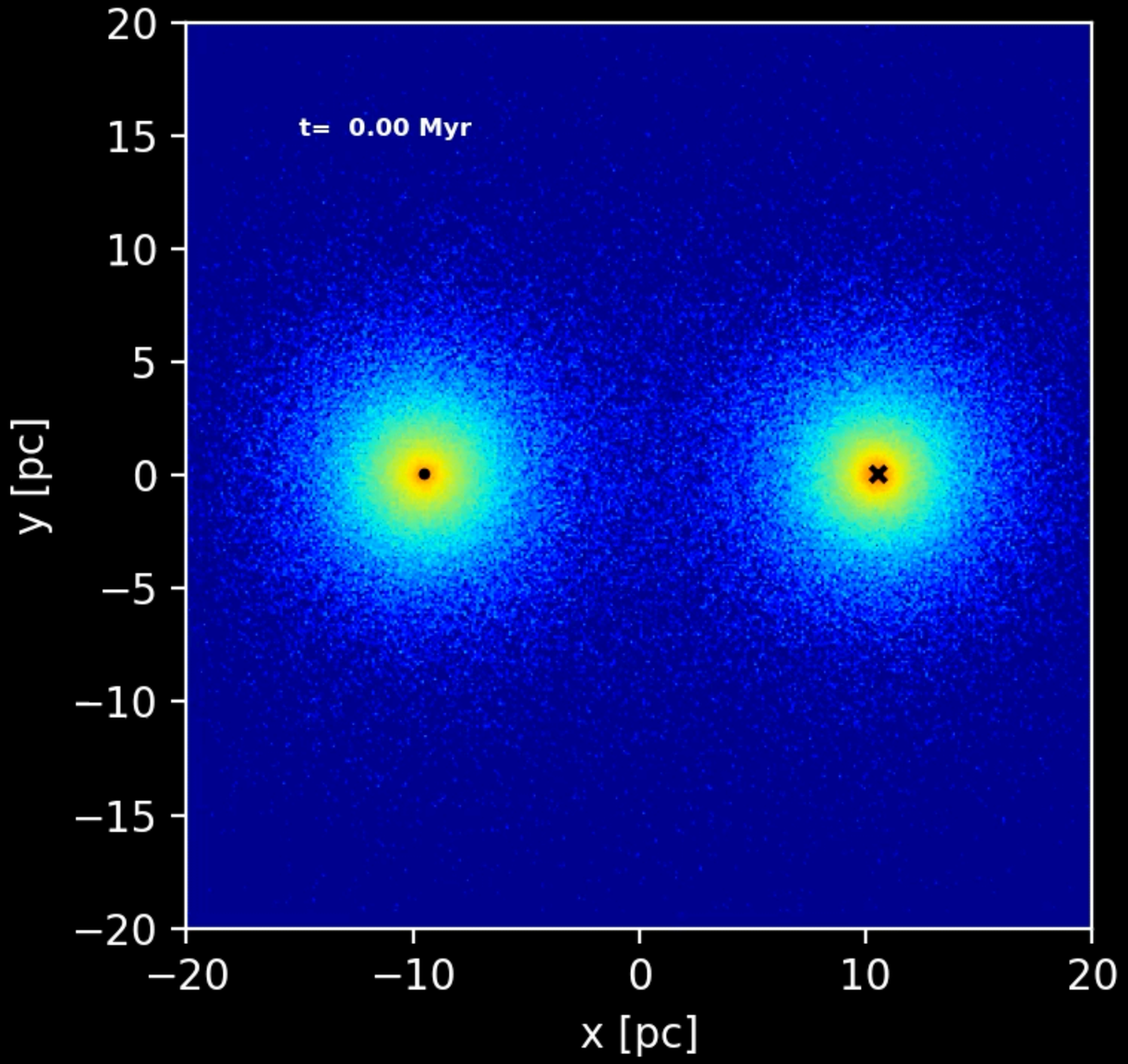
Pre-binary stage

Middle stage

Hard-binary stage

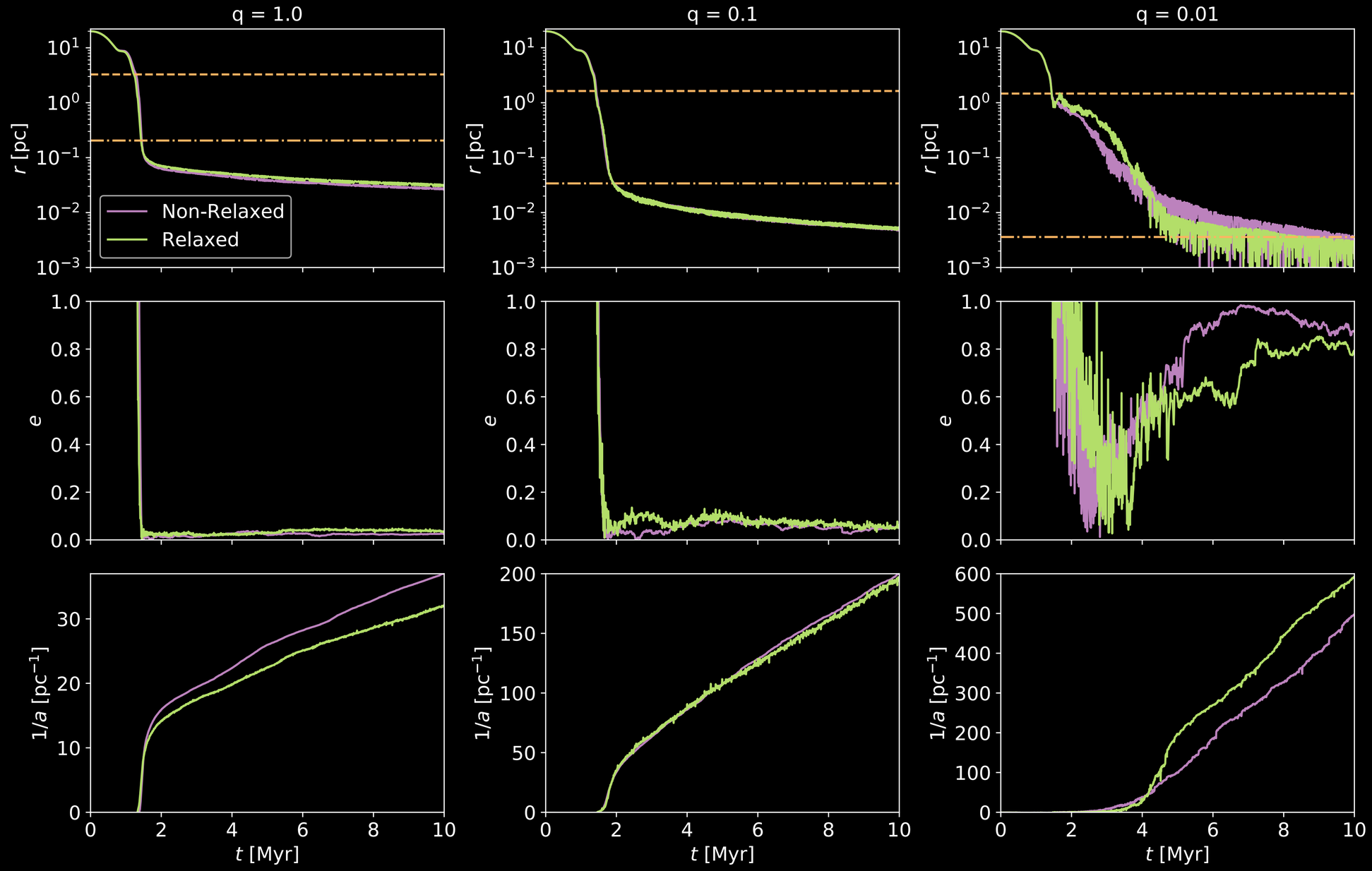
Begelman+ (1980), Merritt (2013), Ogiya+ (2020)

VISUALIZING THE MERGER PROCESS



Mukherjee+ (2022)

EVOLUTION OF ORBITAL PARAMETERS

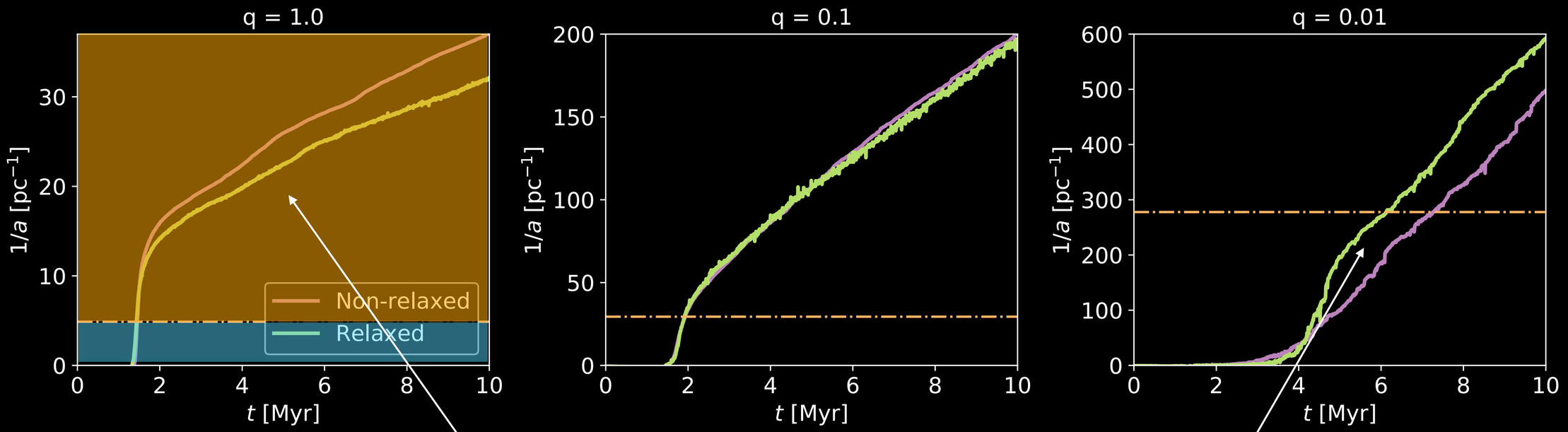


EVOLUTION OF MBH BINARY

HARD BINARY PHASE

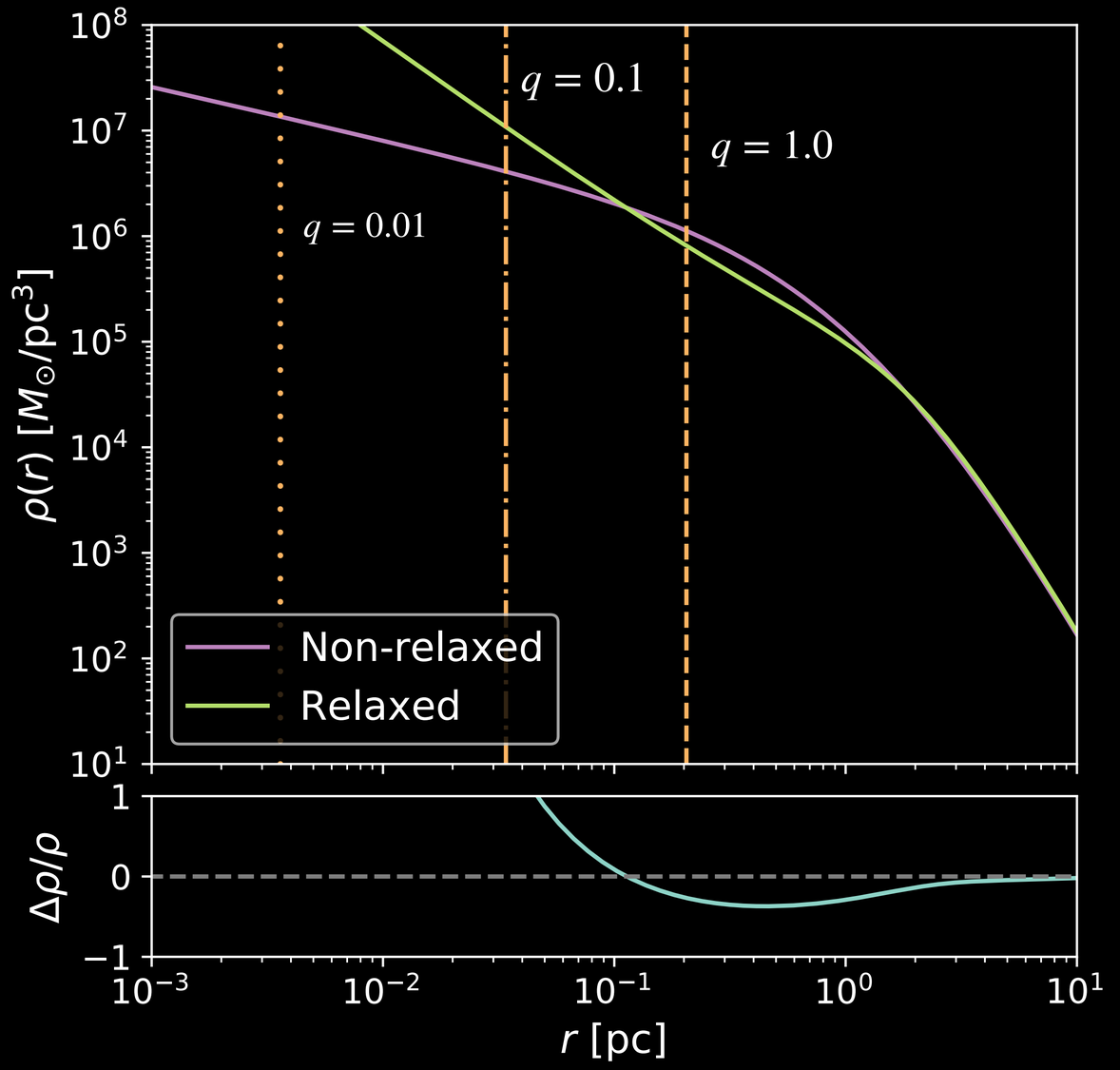
PRE-HARD BINARY PHASE

$$E_{\mathrm{binary}} = -\frac{GM_1M_2}{2a}$$



Why does the trend change over the mass ratio?

EVOLUTION OF THE MBH BINARY

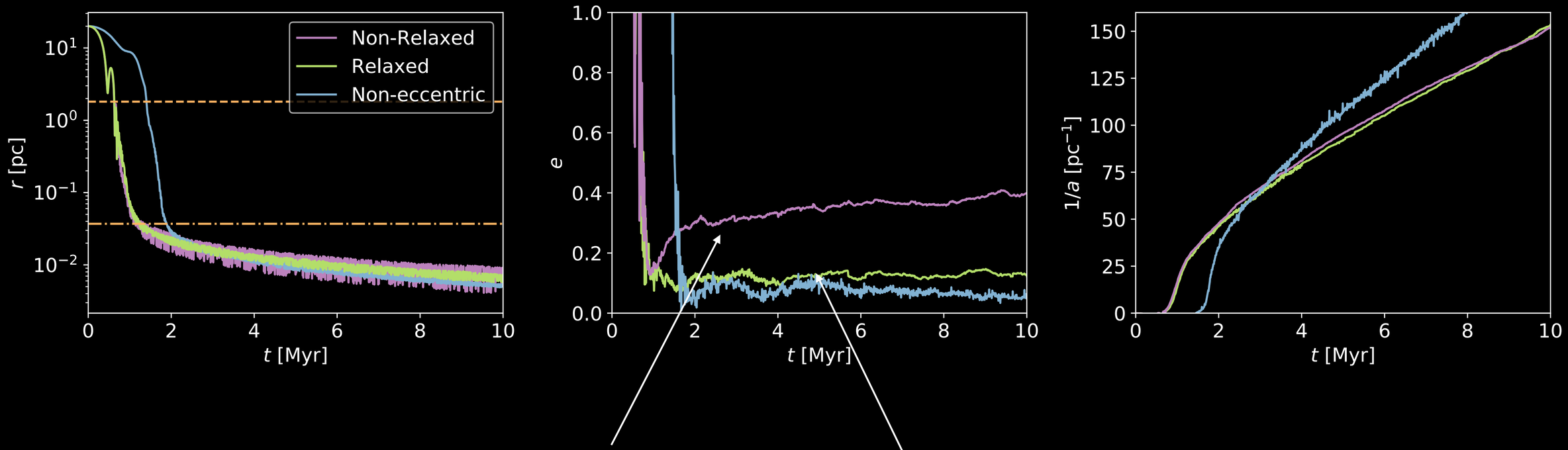


$$\left.\frac{dE}{dt}\right|_{\rm df} \approx -4.4\frac{G^2M_2^2\rho(r)\ln(\Lambda)}{\sigma}$$

$$\left.\frac{dE}{dt}\right|_{\rm s} = -\frac{H(a)}{2q}\frac{G^2M_2^2\rho(r)}{\sigma}$$

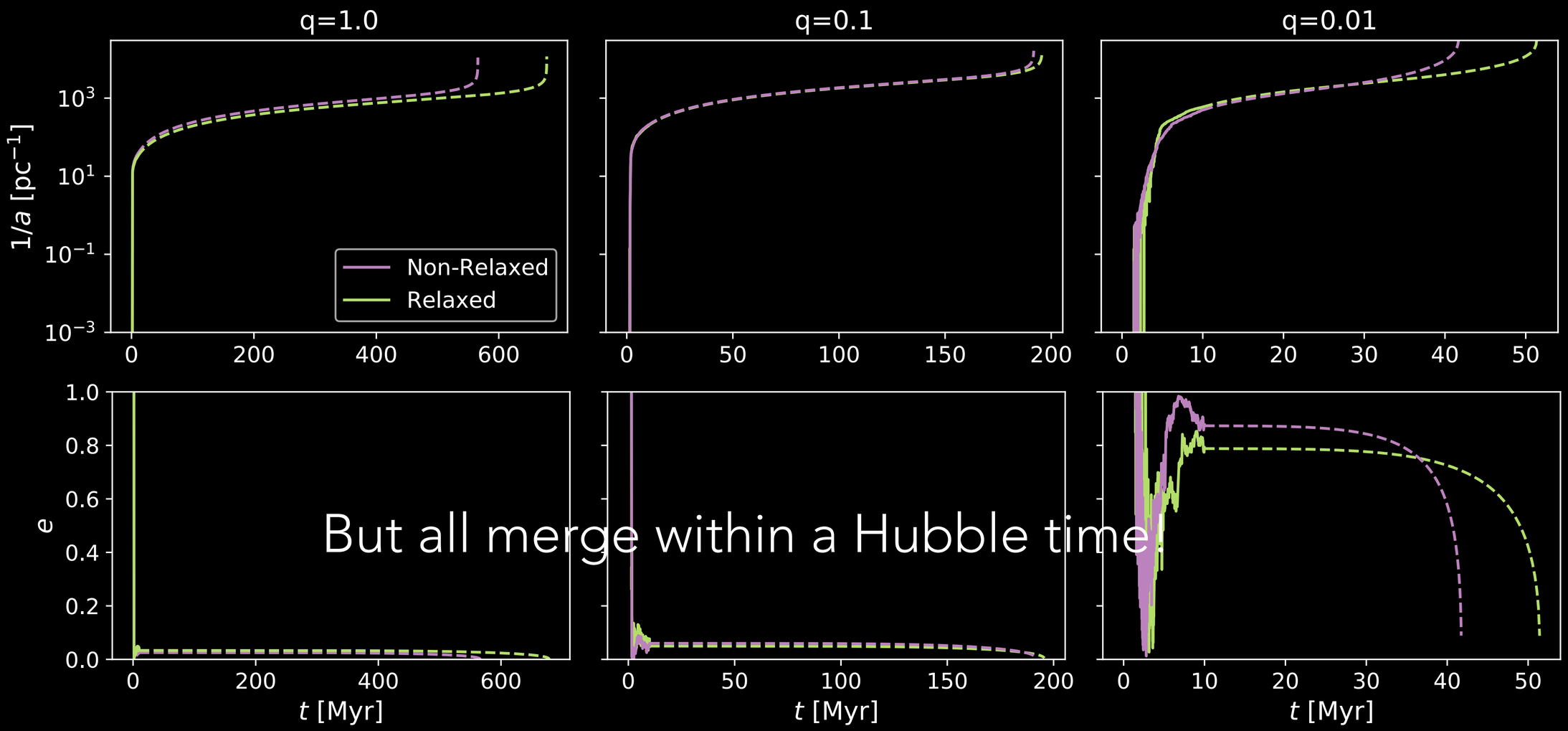
Relaxed models have a lower density than non-relaxed models until a certain radius!

ECCENTRIC ORBITAL PARAMETERS



Non-relaxed models demonstrate higher eccentricities

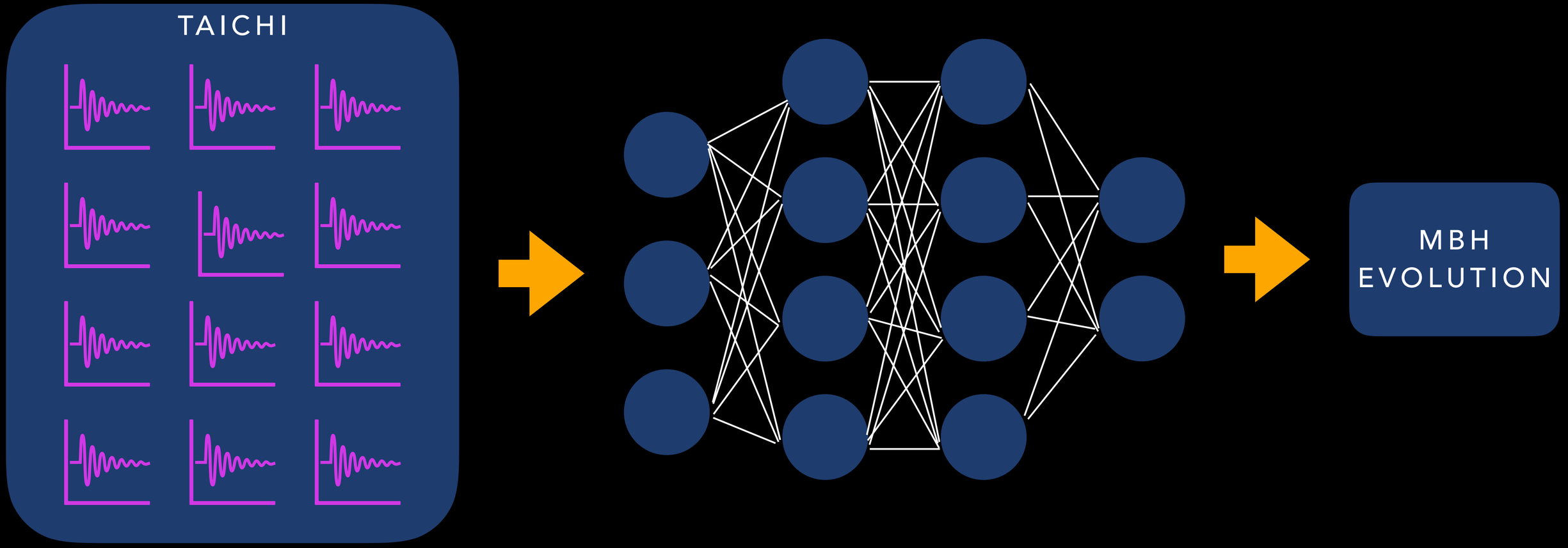
GRAVITATIONAL WAVE TIMESCALES



But all merge within a Hubble time!

Non-relaxed models merge faster in all cases

IMPROVING COSMOLOGICAL SIMULATIONS



CONCLUSIONS

- Able to ascertain the differences in evolution of MBHs in relaxed and non-relaxed NSCs
- Showed that NSCs are extremely robust and efficient at merging MBHs, especially lower mass MBHs
- Presented Taichi as an effective N-body code to solve problems of this scale
- Discussed potential improvements to future cosmological simulations