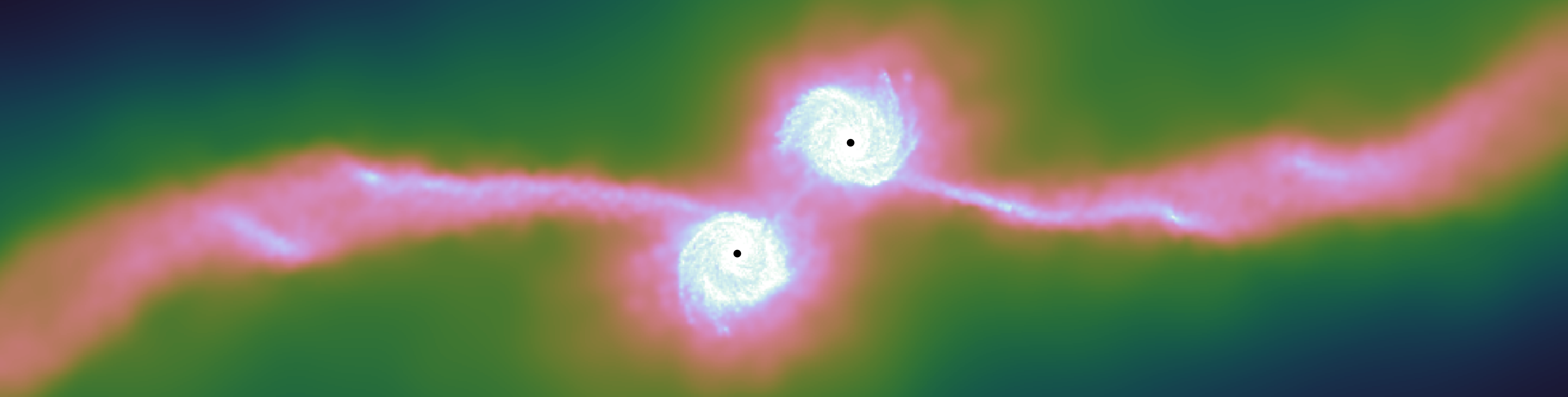
Resolving supermassive black hole binary evolution in galaxy formation simulations



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14 May, 2024 (Purple Mountain Observatory)

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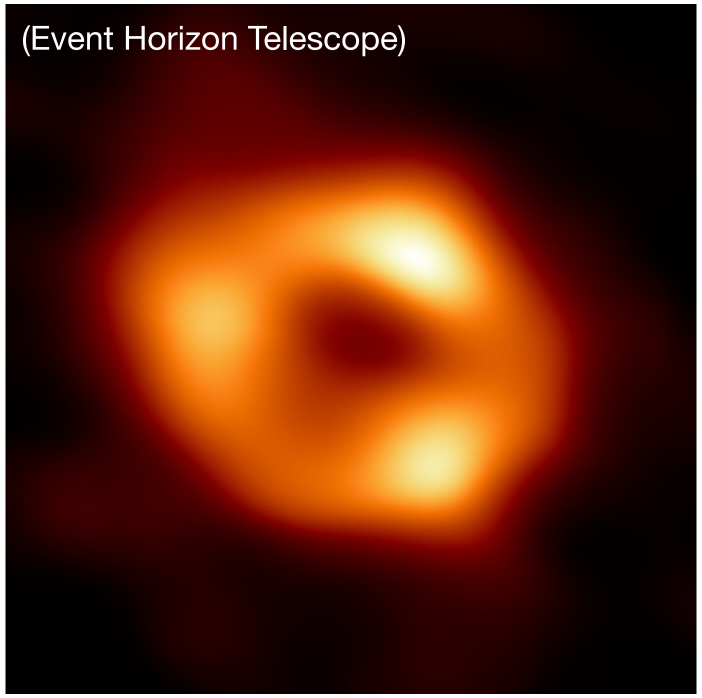
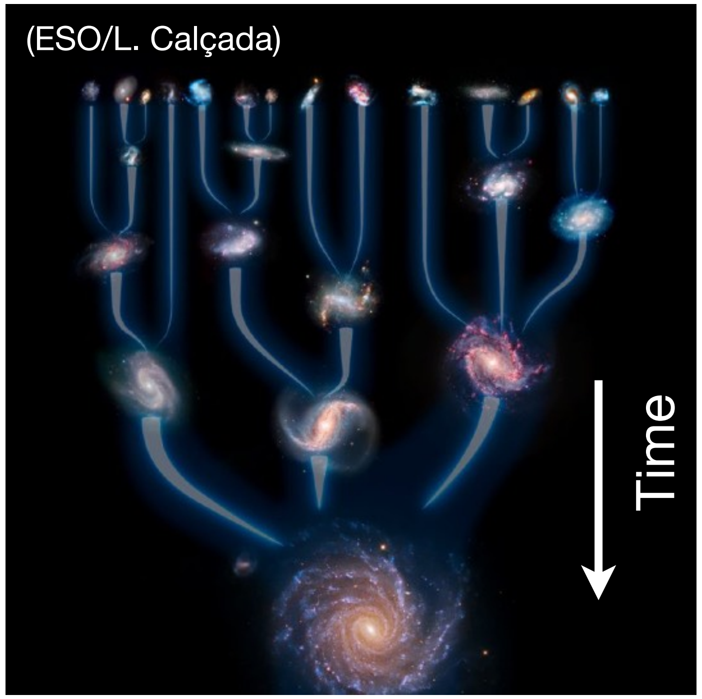
- Stuart McAlpine (Stockholm)

Galaxy mergers and SMBH binaries:
Ubiquitous in our Universe





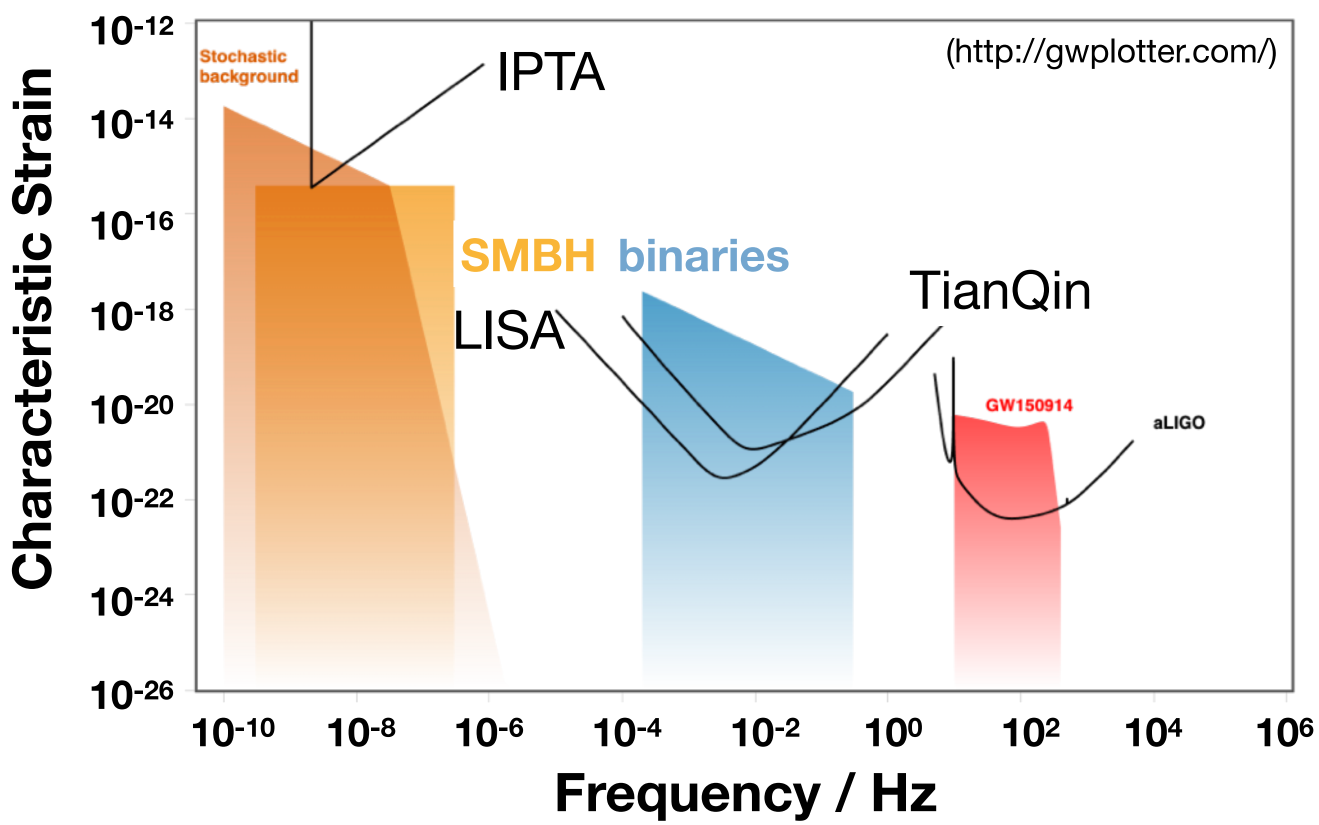
Every massive galaxy harbors a central supermassive black hole (SMBH)

$M_{\rm BH} \gtrsim 10^5\ {\rm M}_\odot$

Cold dark matter: hierarchical structure formation

SMBH binaries are ubiquitous

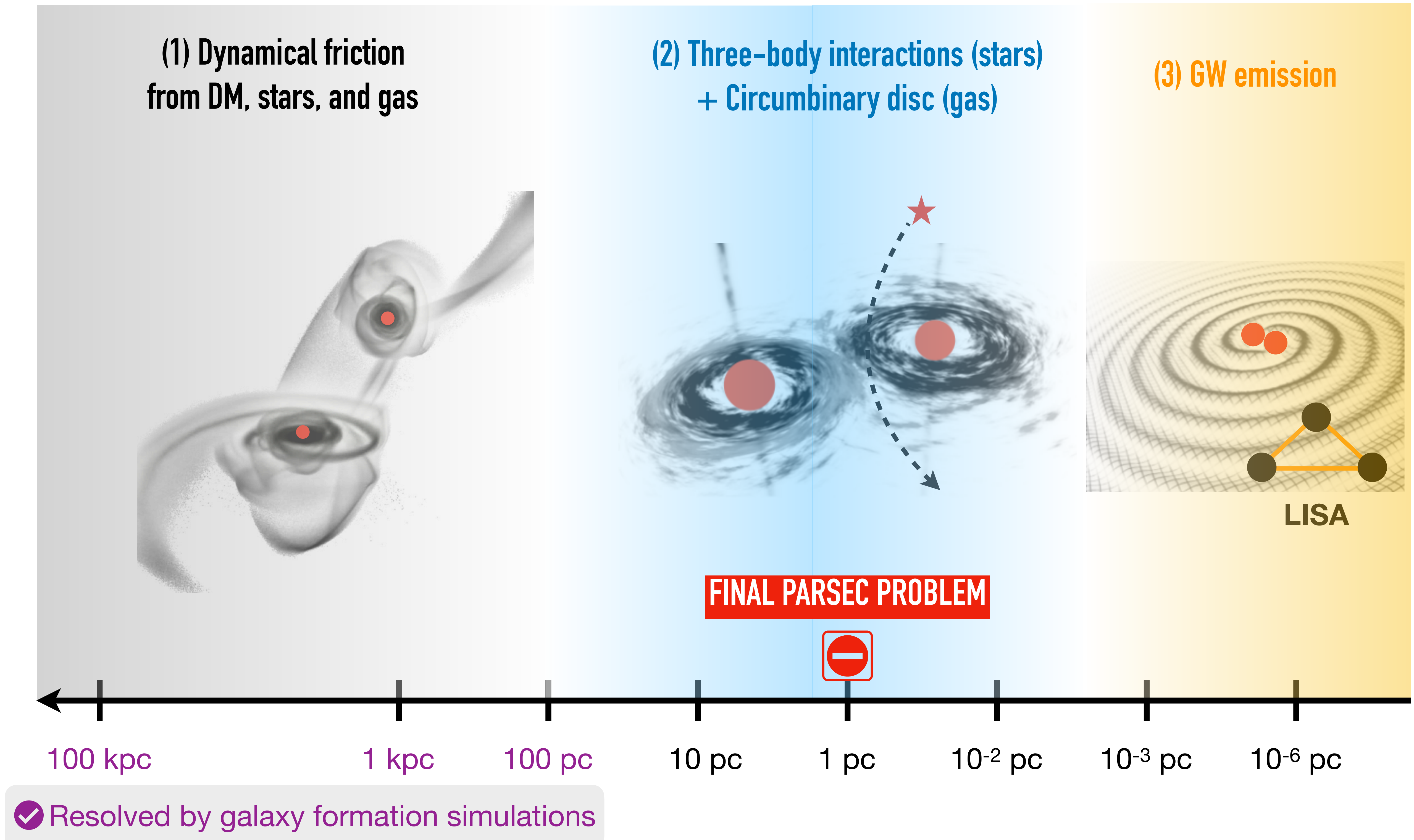
GRAVITATIONAL WAVE (GW) FROM SMBH BINARIES:
Targets for low-frequency GW detectors (LISA and PTA)



Understanding the coalescence process of two SMBHs in the cosmological framework is pivotal for accurate GW predictions

SMBH COALESCENCE:

A three-phase journey spanning over 10 orders of magnitude in space



TRADITIONAL GALAXY FORMATION SIMULATIONS:
Only resolve down to kpc or sub-kpc scales

Gravitational softening length (~kpc or ~0.1kpc) $\longrightarrow$ spatial resolution limit

$$\mathbf{F}_{ij} = G\frac{m_i m_j}{\left(|\mathbf{r}_i - \mathbf{r}_j|^2 + \epsilon^2\right)^{3/2}}(\mathbf{r}_i - \mathbf{r}_j)$$

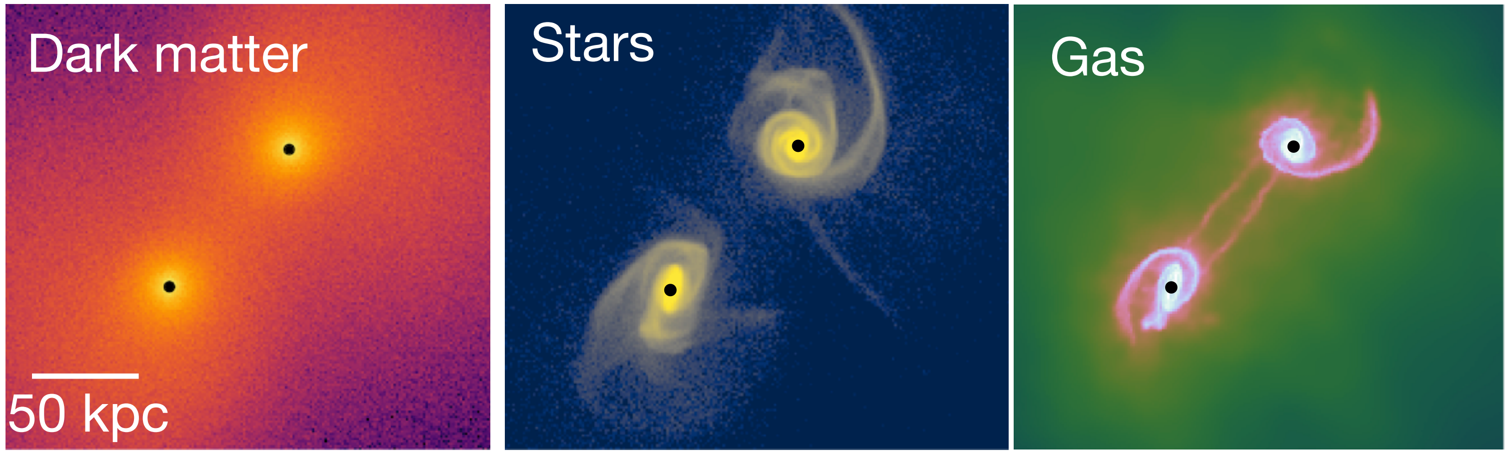
Two SMBHs are merged instantaneously once their separation is below the resolution limit

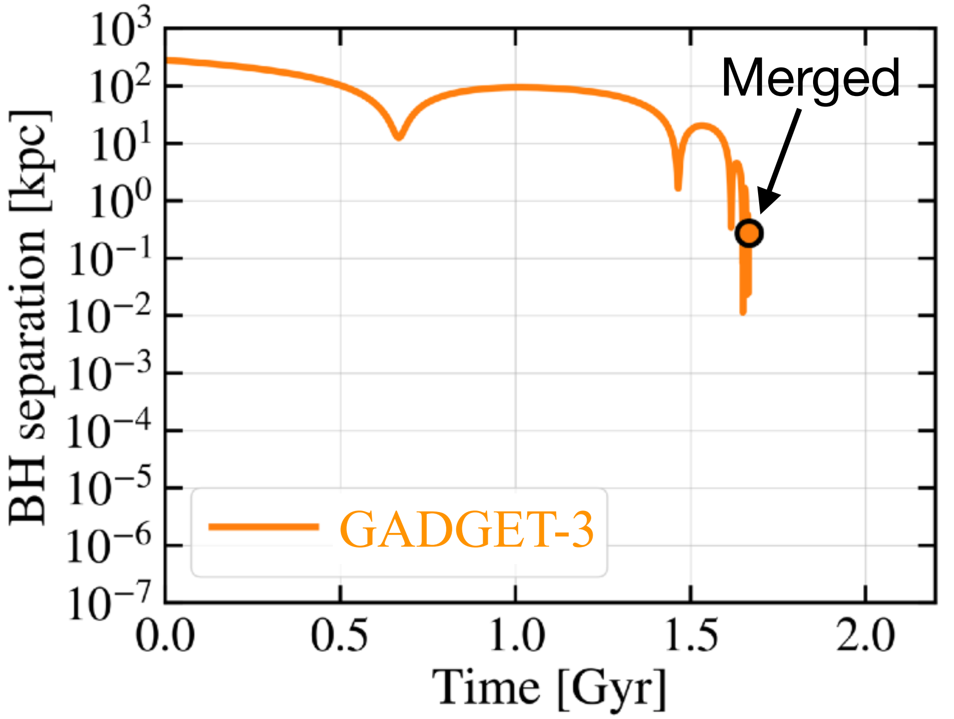
KETJU CODE:
Resolving BH dynamics in hydro galaxy formation simulations

GADGET-3:
galactic-scale physics

- Softened gravity (TreePM)
- Hydrodynamics (SPH)
- Galaxy formation processes (cooling, star formation, and stellar feedback)

(Springel 2005; Hu et al. 2014; Scannapieco et al. 2005, 2006; Aumer et al. 2013; Nunez et al. 2017)





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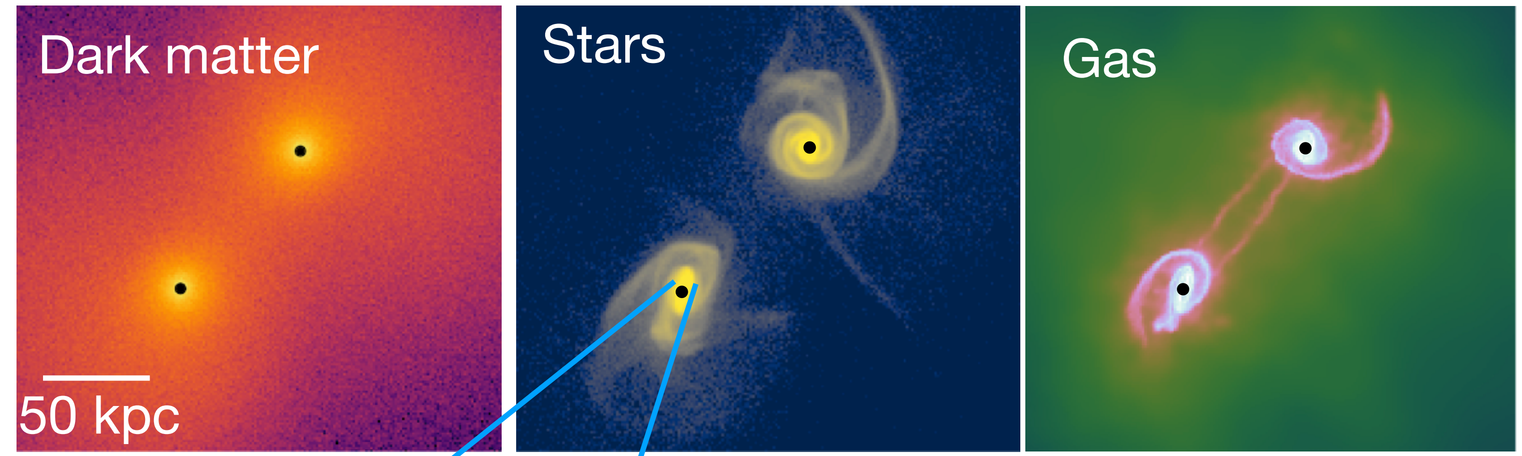
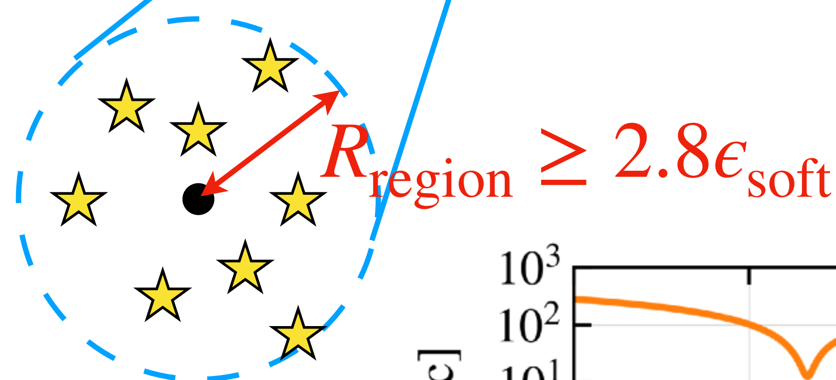
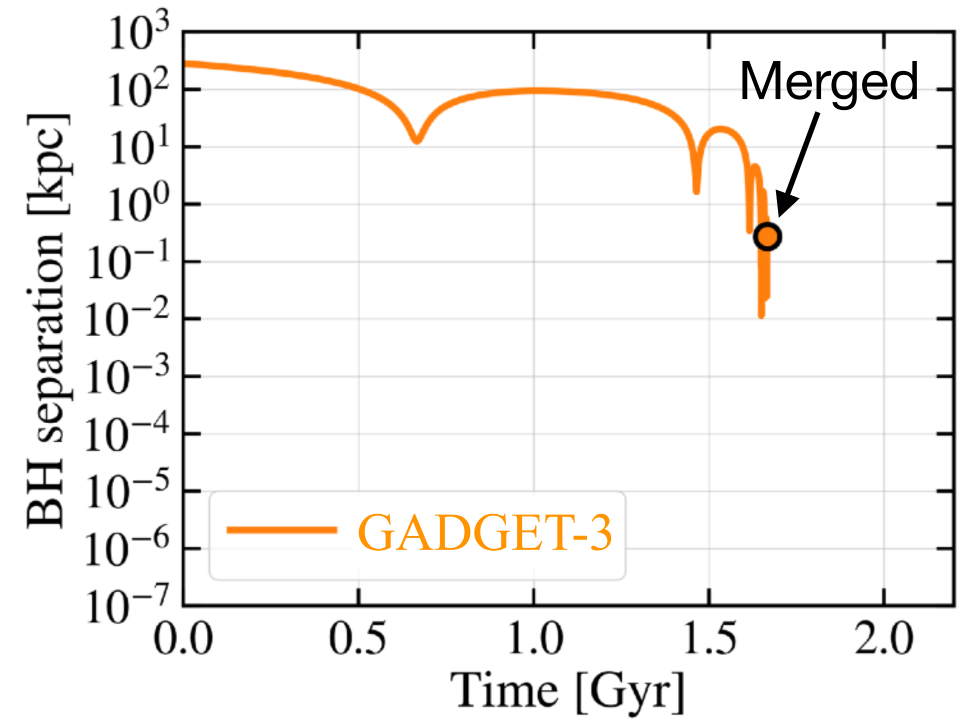


KETJU regularized integrator:
small-scale BH dynamics

- Non-softened BH-star, BH-BH gravity in a small region around each BH (MSTAR)
- Post-Newtonian corrections (PN3.5)

(Rantala et al. 2017, 2020; Mannerkoski et al. 2021, 2022, 2023)





New BH subgrid model:
binary accretion & feedback

- Circumbinary disc accretion
- Thermal + kinetic AGN feedback

(Liao et al. 2023)

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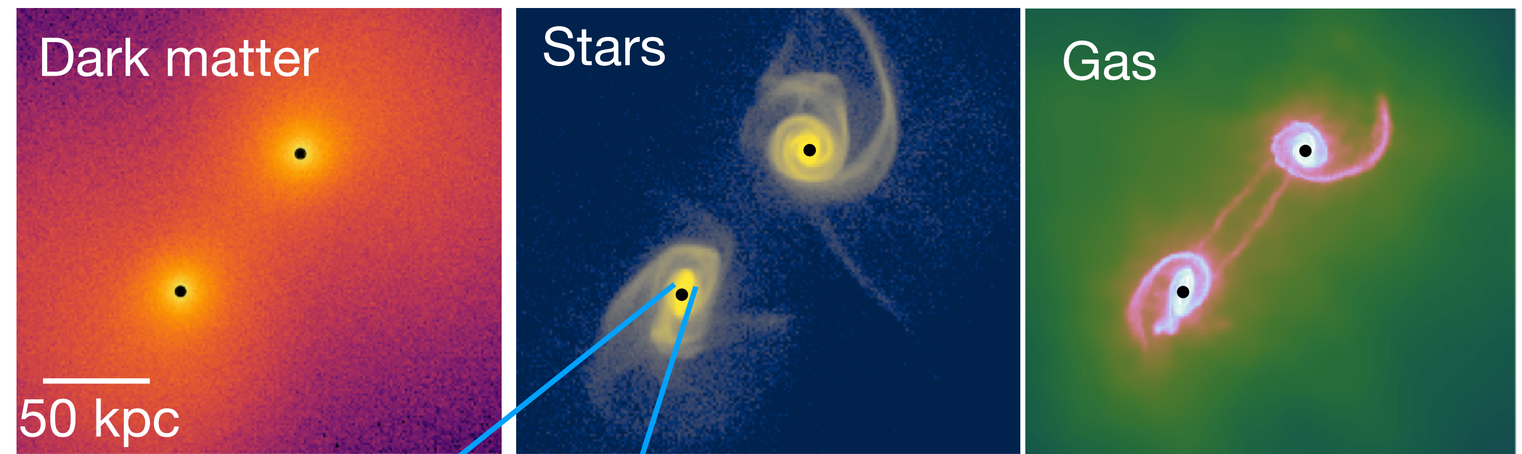
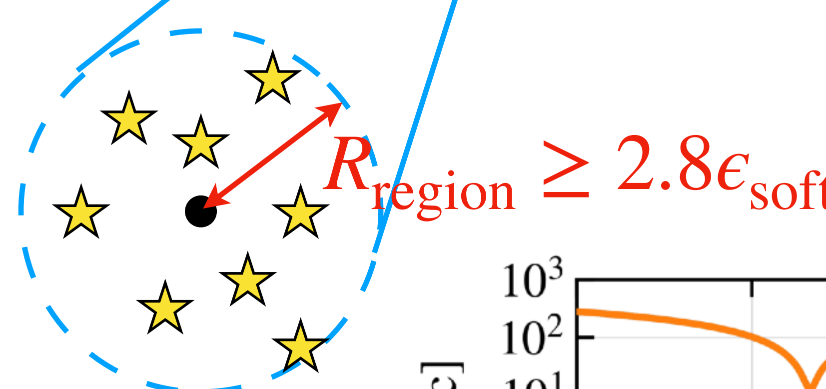
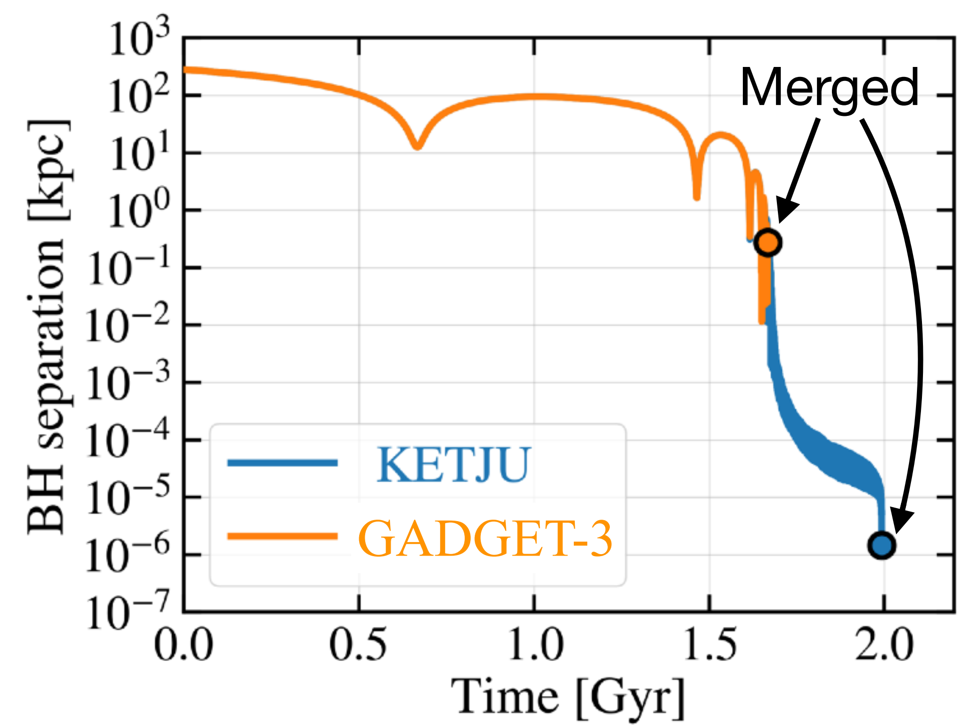
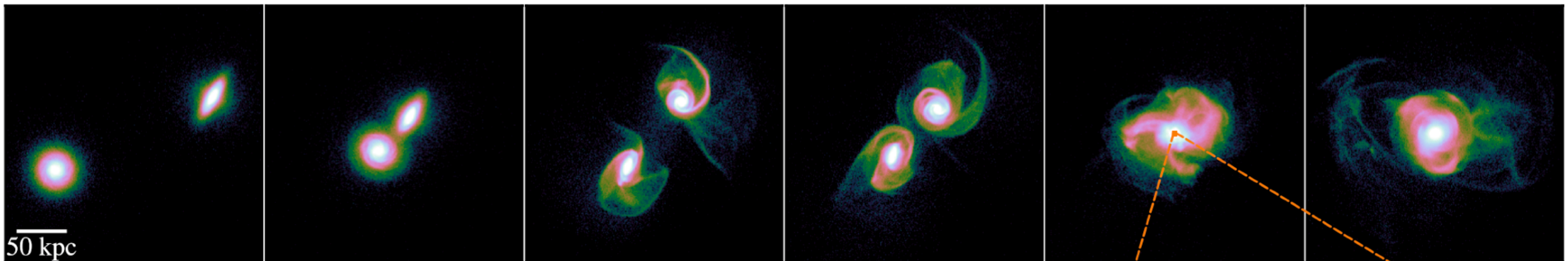






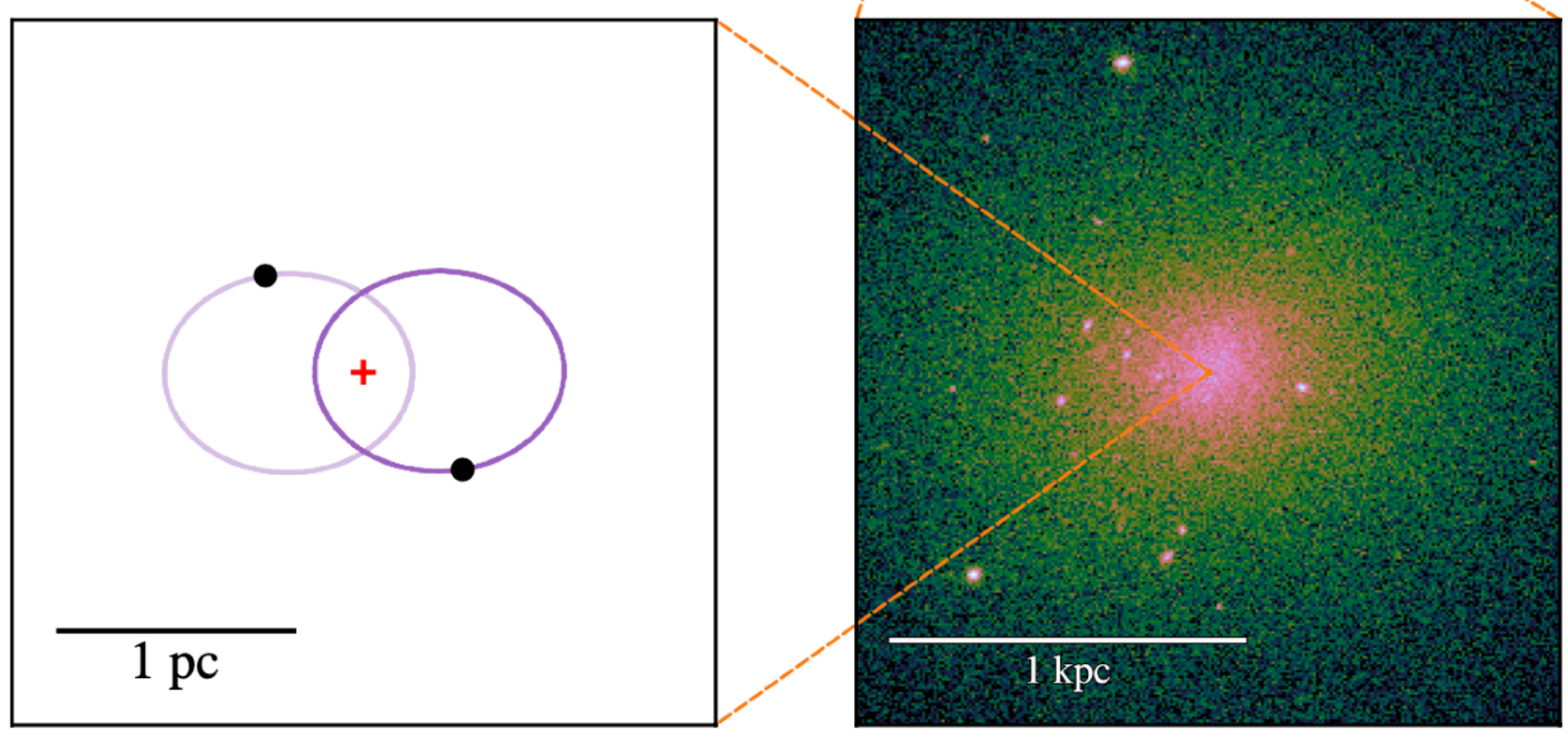
THE RABBITS PROJECT:

Resolving supermAssive Black hole Binaries In galacTic hydrodynamical Simulations



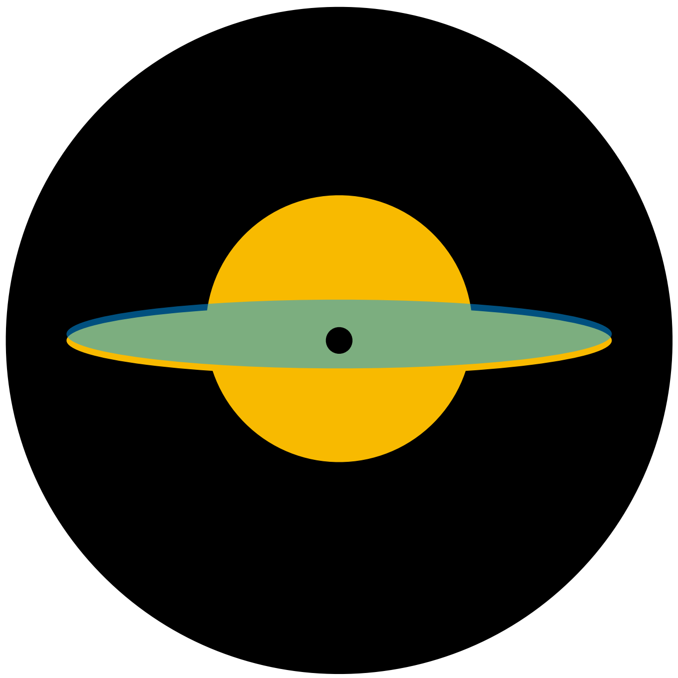
Scientific questions:

- How do *galactic-scale* physical processes affect *small-scale* SMBH coalescing process?
- How do SMBH merger time scales depend on galaxy properties?
- What are the predicted GW event rates and stochastic background for the LISA observatory?



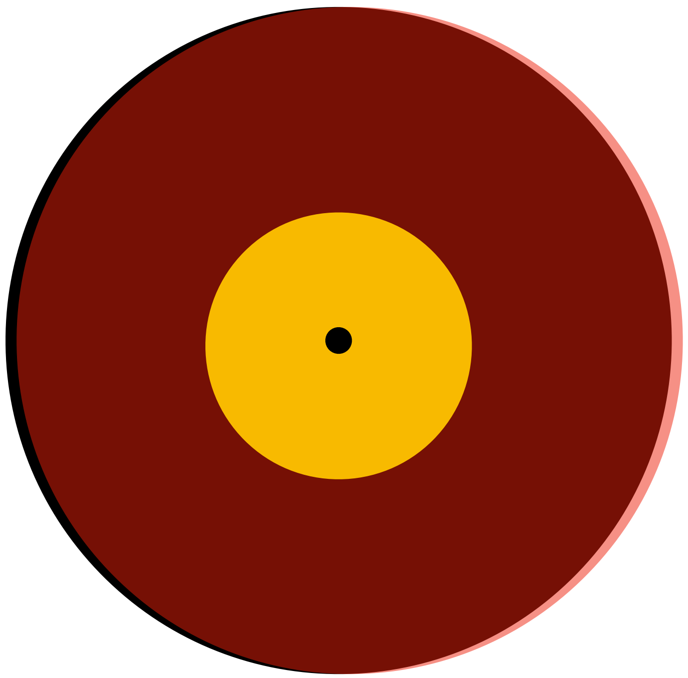
Idealized galaxy merger simulations:

Disc and elliptical galaxies, including different physical processes



Disc galaxy

= DM halo + stellar disc + stellar bulge + gas disc + SMBH



Elliptical galaxy

= DM halo + stellar bulge + gas halo + SMBH

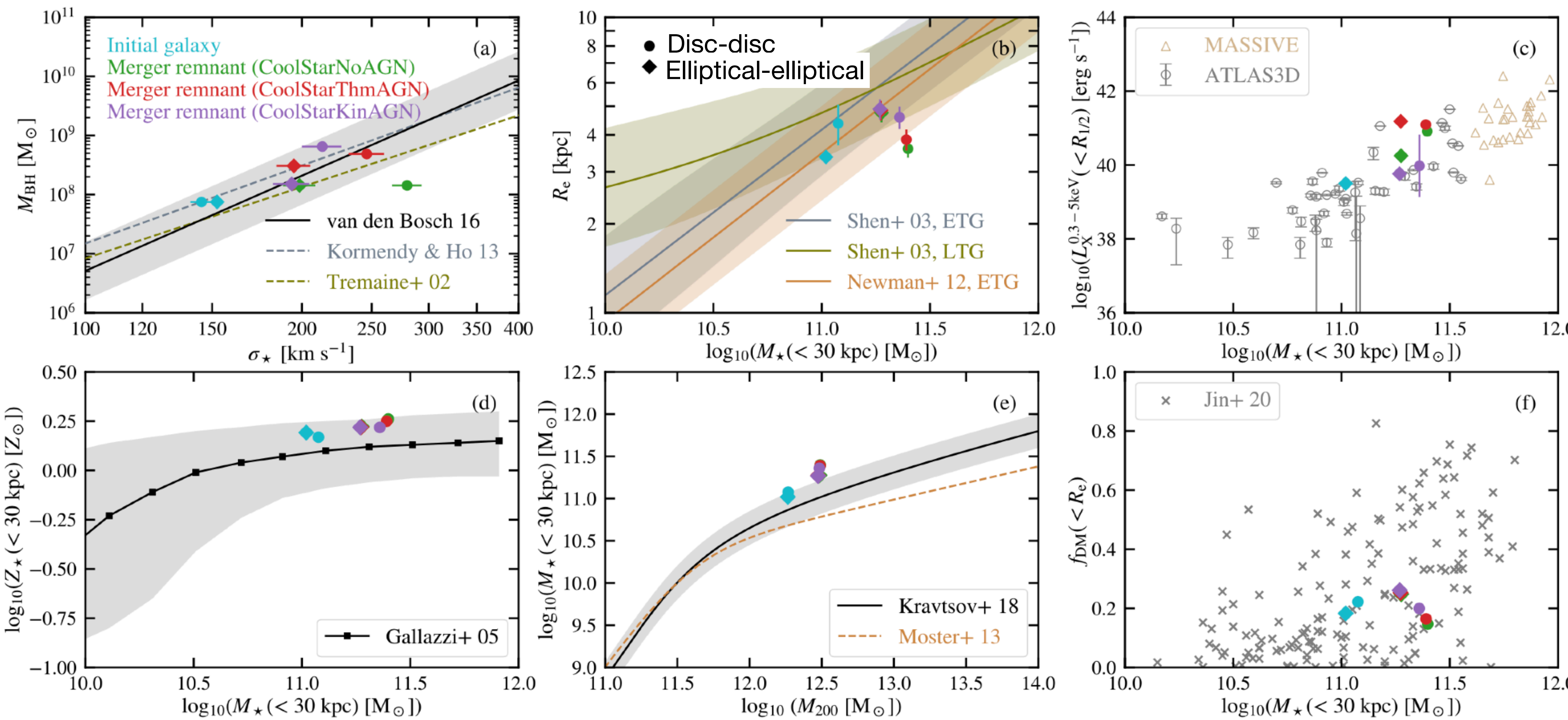
Name	Gravity & PN corrections	Hydrodynamics (SPH)	Radiative cooling	Star formation & stellar feedback	SMBH accretion	Thermal AGN feedback	Kinetic AGN feedback
NoGas	✓	✗	✗	✗	✗	✗	✗
NoCool	✓	✓	✗	✗	✗	✗	✗
CoolStarNoAGN	✓	✓	✓	✓	✗	✗	✗
CoolStarThmAGN	✓	✓	✓	✓	✓	✓	✗
CoolStarKinAGN	✓	✓	✓	✓	✓	✗	✓

(Liao et al. 2024b)

GALACTIC-SCALE PROPERTIES:

Well reproducing the observed galaxy scaling relations

BH mass—velocity dispersion | Galaxy size | X-ray luminosity from hot gas



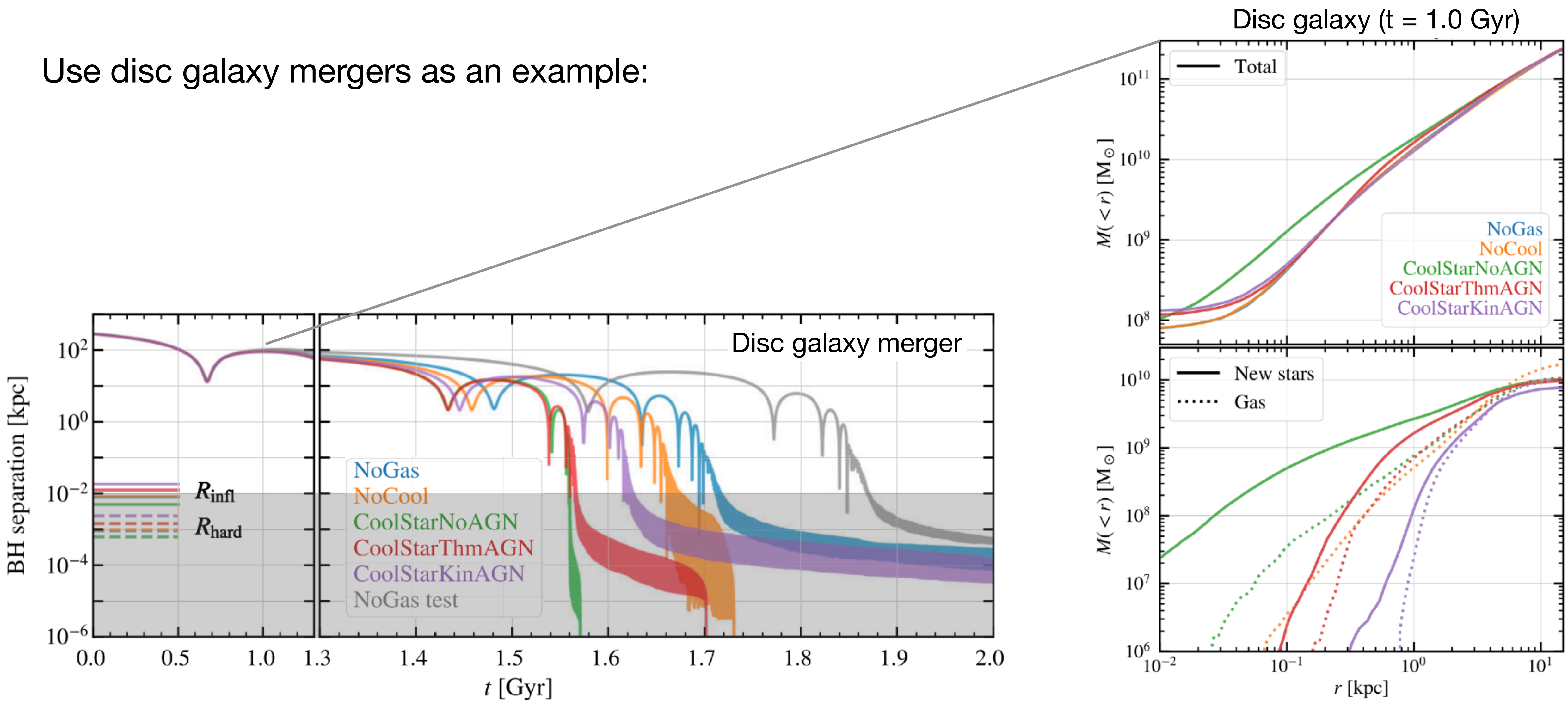
Stellar metallicity | Stellar mass—halo mass | DM fraction

(Liao et al. 2024b)

ORBITAL DECAY: DYNAMICAL FRICTION PHASE

Impact of AGN feedback

Use disc galaxy mergers as an example:



(i) Different AGN feedback models lead to different star formation and SMBH accretion histories.

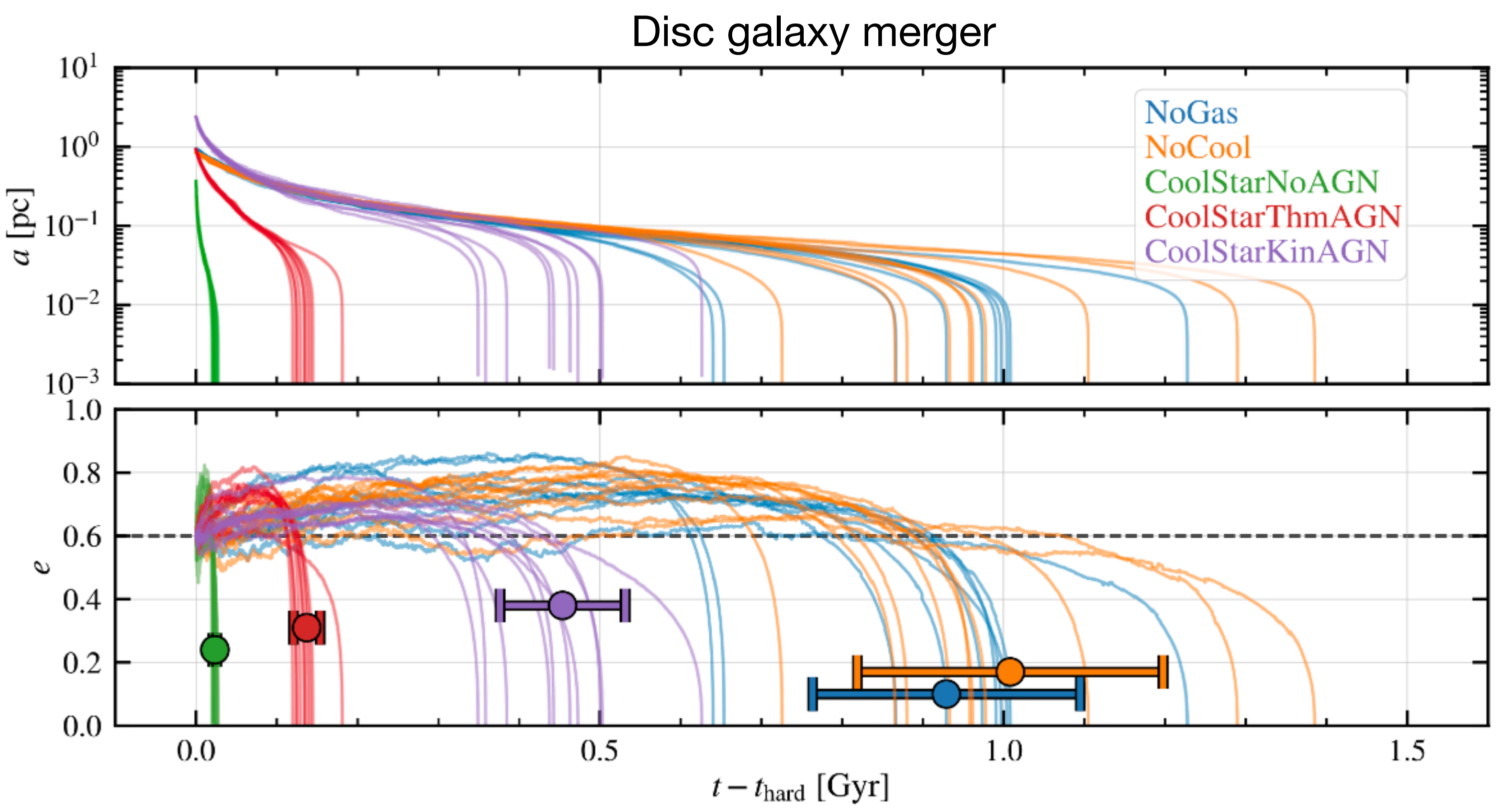
(ii) Galaxies with higher star formation and higher SMBH masses possess denser centers, become more resistant to tidal stripping, experience greater dynamical friction, and consequently form SMBH binaries earlier.

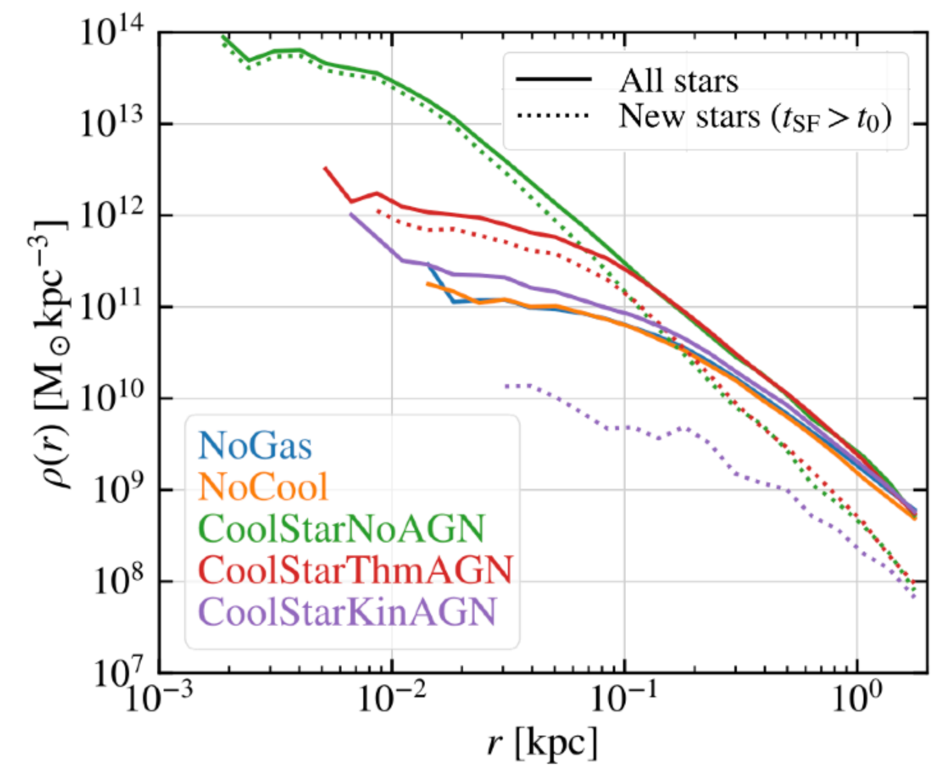
(Liao et al. 2024b)

ORBITAL DECAY: BINARY HARDENING PHASE

Impact of nuclear star formation

Use disc galaxy mergers as an example:





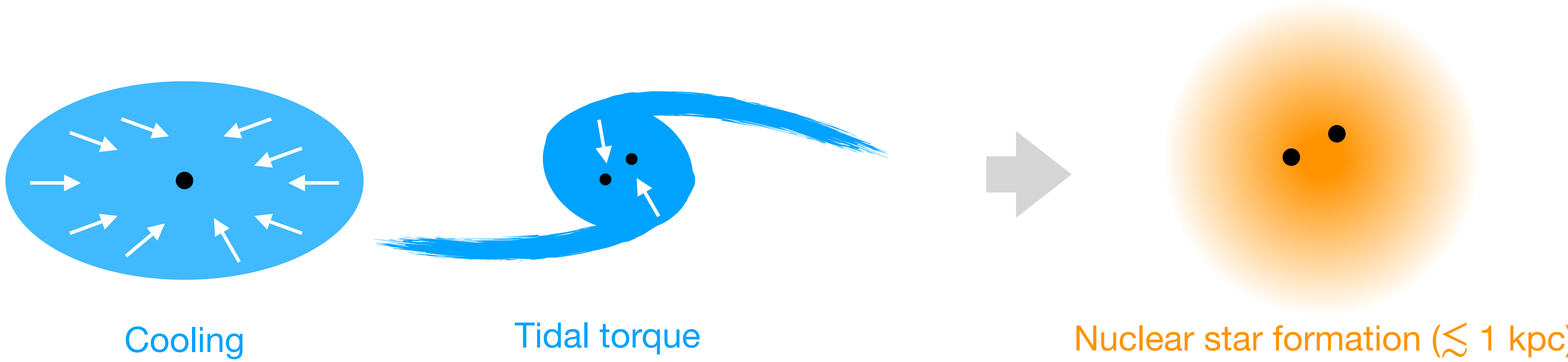
We find a strong correlation between the SMBH merger time-scales and the presence of nuclear star formation.

(Liao et al. 2024a)

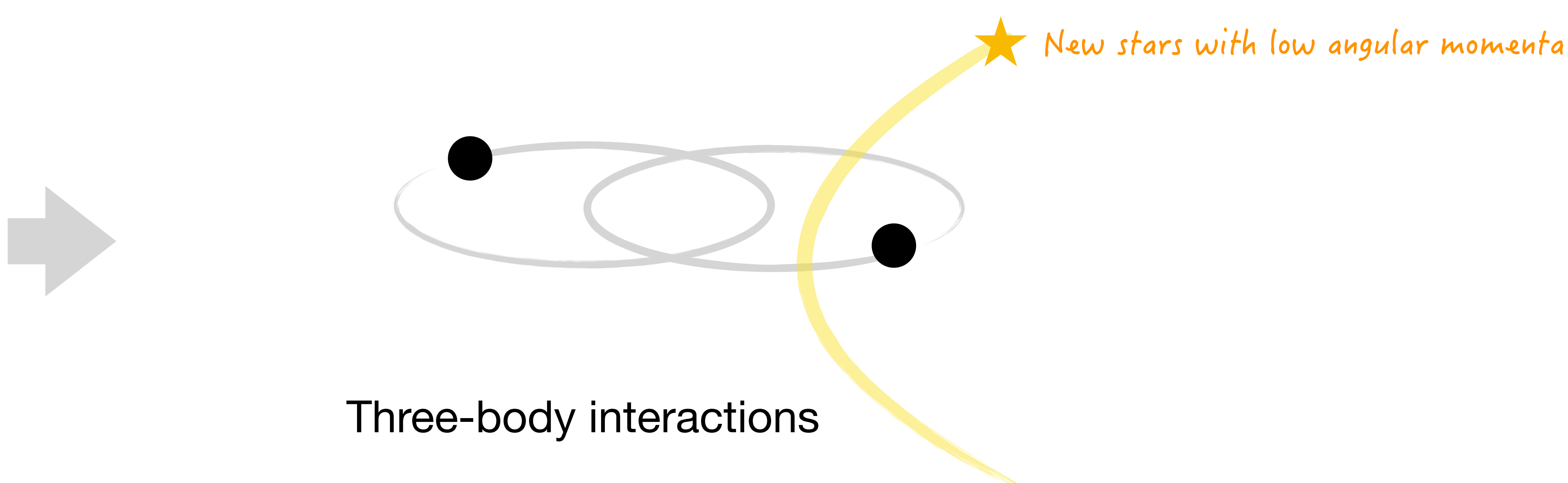
Orbital decay: Binary hardening phase

Nuclear star formation: another mechanism to avoid the Final-Parsec Problem

(i) Throughout the galaxy merging process, gas condenses at the centre due to cooling and tidal torques, leading to nuclear star formation.



(ii) These recently formed stars, which inherit low angular momenta from the gas, contribute to the loss cone and assist in the SMBH hardening via three-body interactions.



SMBH MERGER TIME-SCALES

Disc V.S. elliptical galaxy mergers

Simulation set	Disc galaxy mergers $T_{\rm m}$ [Myr]	Elliptical galaxy mergers $T_{\rm m}$ [Myr]
NoGas	929.2 ± 165.7	2390.0 ± 507.4
NoCool	1008.3 ± 189.3	2655.3 ± 457.9
CoolStarNoAGN	23.2 ± 2.5	537.3 ± 87.0
CoolStarThmAGN	137.0 ± 16.5	1412.5 ± 137.0
CoolStarKinAGN	453.8 ± 77.5	2107.2 ± 424.1

(Liao et al. 2024a)

Disc galaxy mergers (gas-rich): 100 ~ 500 Myr
Elliptical galaxy mergers (gas-poor): 1 ~ 2 Gyr

Implications: the exact SMBH merger time-scales depend on the detailed galaxy properties.

SUMMARY

- **KETJU code (based on GADGET-3):** a numerical tool capable of simultaneously following *galactic-scale* galaxy (hydro-)dynamics and resolving *small-scale* SMBH dynamics
- **RABBITS project:** resolve SMBH binaries in galaxy formation simulations, improve the estimation of SMBH merger time-scales and the GW predictions

- **Galactic-scales:** agree with the observed galaxy properties
- **Small-scales:** *AGN feedback* and *nuclear star formation* have an important impact on the SMBH coalescing process

- **Future plan:**

2. How do SMBH merger time-scales depend on galaxy properties?
3. What are the predicted GW event rates and stochastic background for the LISA observatory?