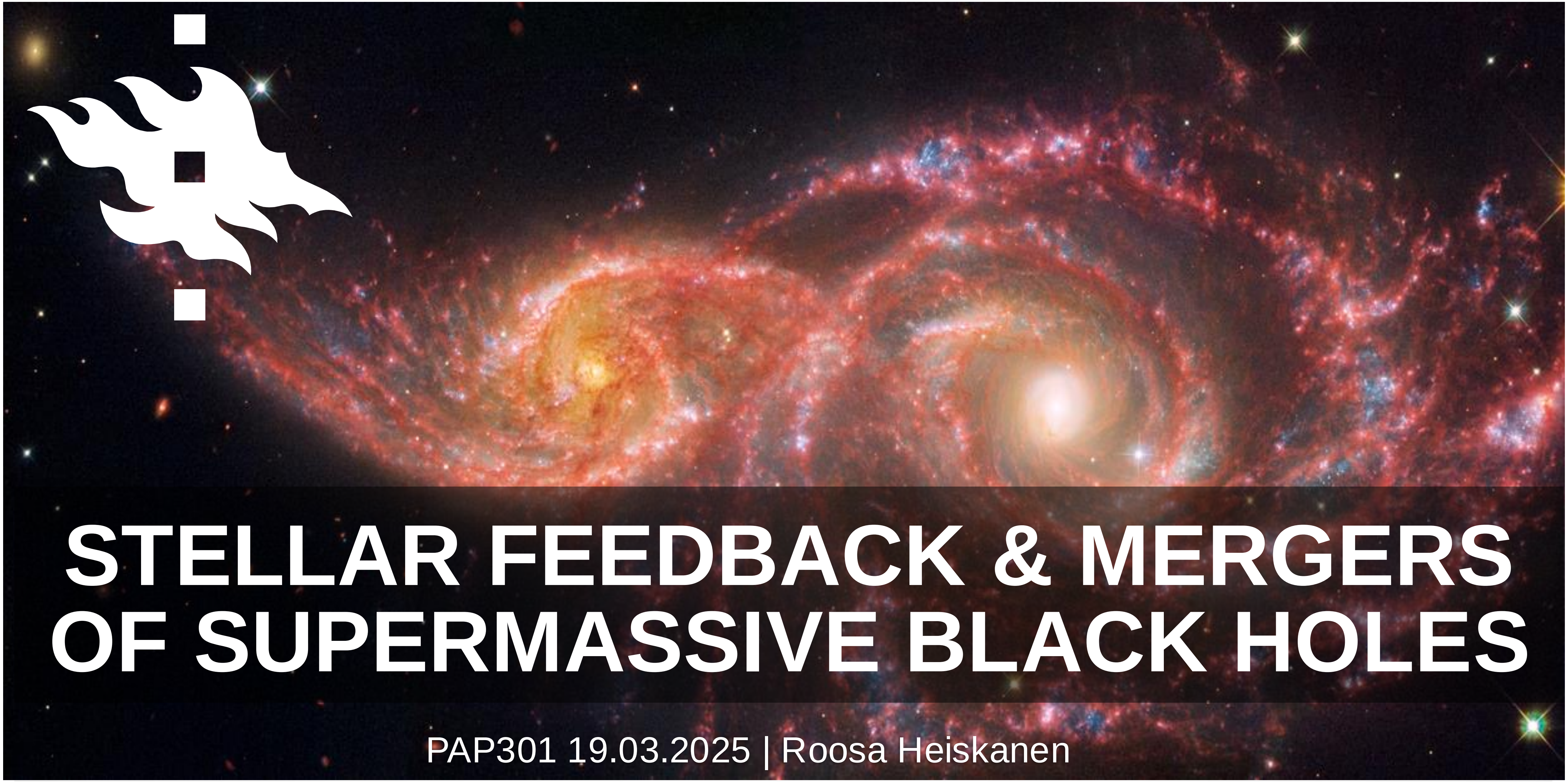

STELLAR FEEDBACK & MERGERS OF SUPERMASSIVE BLACK HOLES

PAP301 19.03.2025 | Roosa Heiskanen

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CONTENTS

INTRODUCTION

- Standard theory of structure formation: the *hierarchical structure formation*
  - Small structures form first and form the larger structures via mergers

- Nearly all massive galaxies harbour a supermassive black hole (SMBH) in the galactic centre
  - When galaxies merge their central SMBHs merge as well

INTRODUCTION – WHAT IS FEEDBACK?

- Energetic output that influences the surrounding environment
- Stellar feedback (e.g., stellar winds, supernovae)
- Active Galactic Nuclei (AGN) feedback
  - Feedback from accreting SMBH
  - In this work AGN feedback is not included into the simulation

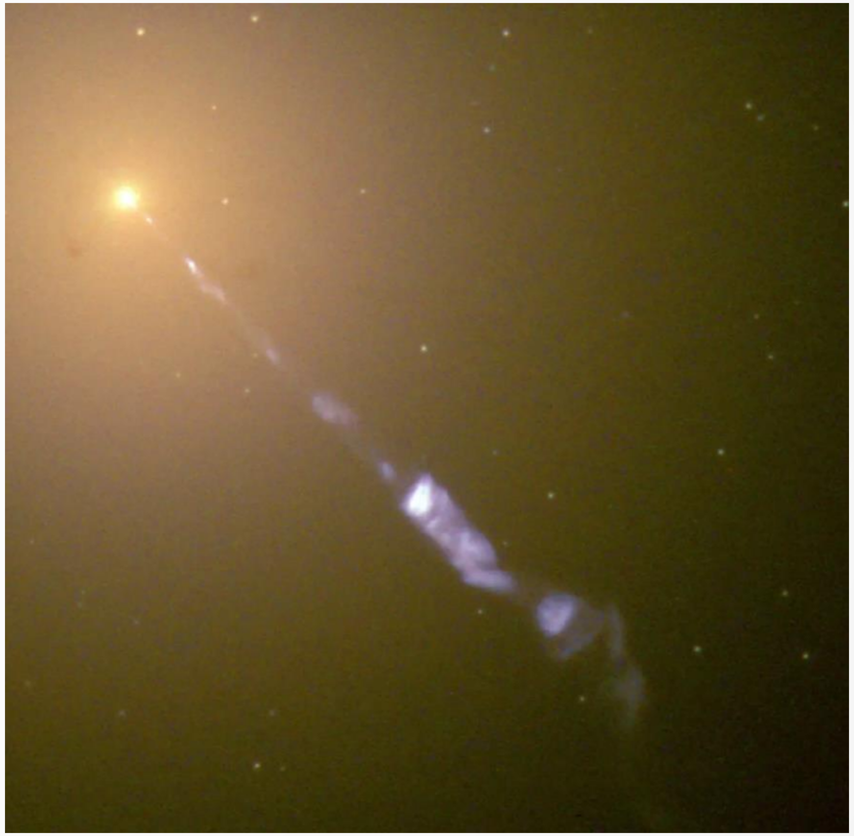


Figure 1: AGN feedback from M87. Image credit: NASA and the Hubble Heritage Team (STScl/AURA)

INTRODUCTION – MOTIVATION

- Numerical simulation studies of massive galaxies show that feedback from AGN influences the merging time-scales of SMBHs (e.g., Liao et al 2023, 2024a, 2024b)
  - Has not been studied for lower mass galaxies where stellar feedback is the dominant feedback mechanism

INTRODUCTION – MOTIVATION

- Gravitational waves (GWs) are emitted in the mergers of SMBHs
  - Primary targets for ongoing and future gravitational wave detectors such as LISA (the Laser Interferometer Space Antenna)
  - Important to provide theoretical predictions for these observational surveys

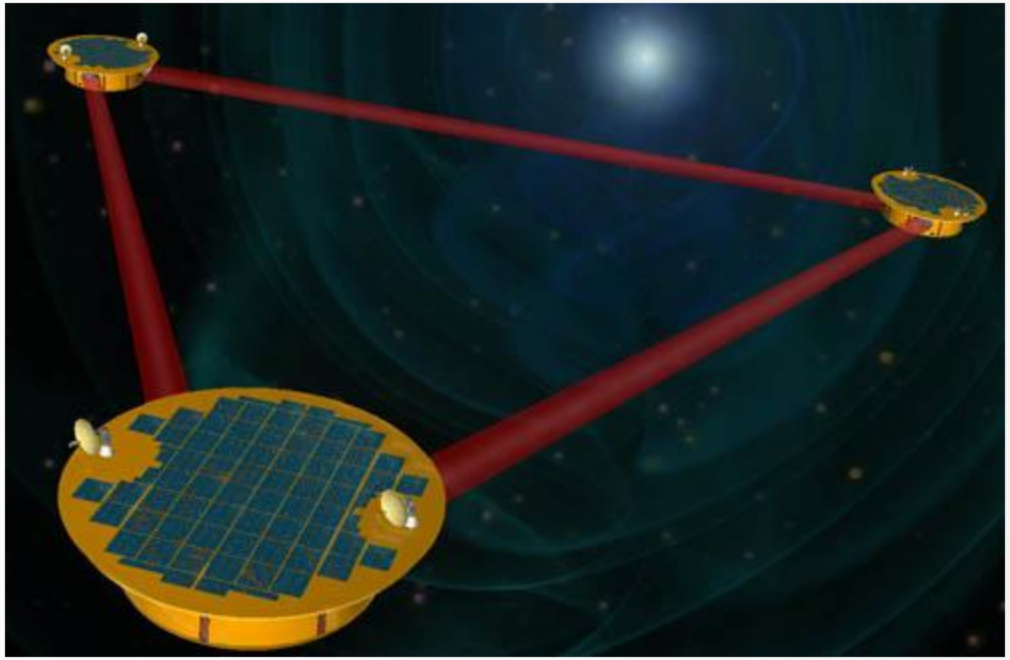
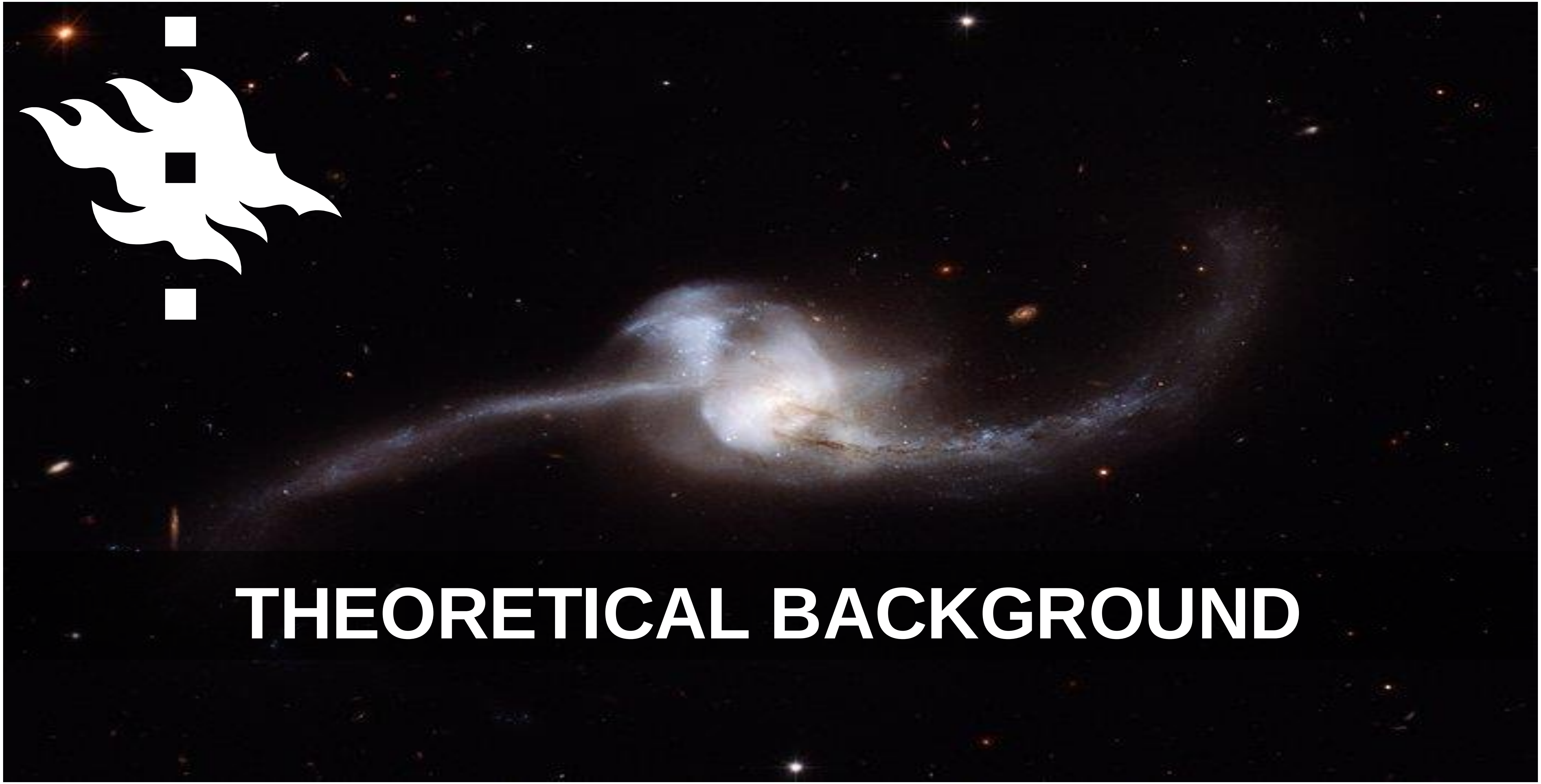


Figure 2: Artist's illustration of LISA. Image credit: NASA



THEORETICAL BACKGROUND

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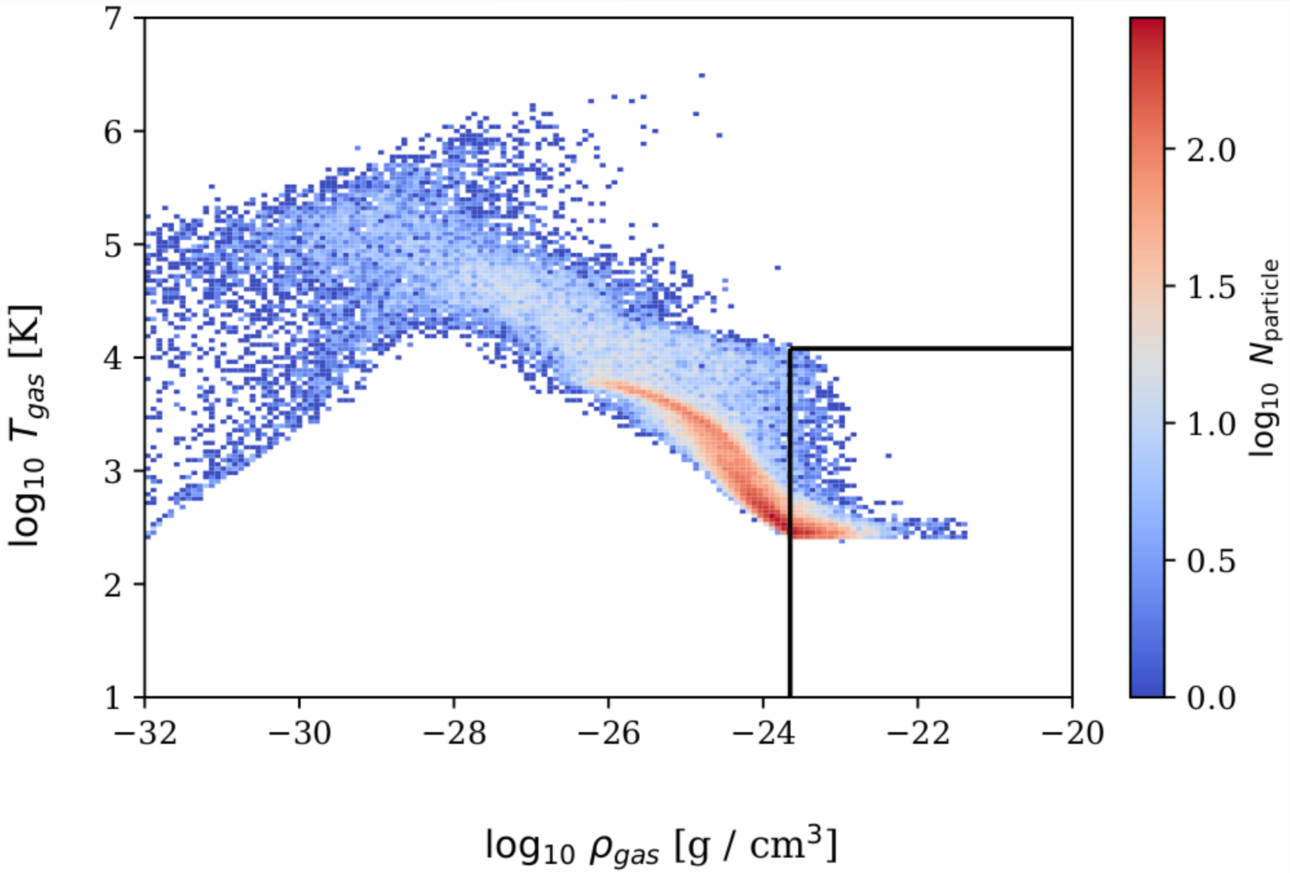
STAR FORMATION

- Stars form in cold (T ≤ 100 K), dense clouds of molecular hydrogen
  - Gravity surpasses internal pressure & gas clump collapses into a star
- In simulations:
  - If a gas particle is in the 'allowed star-formation region' it has a possibility of turning into a stellar particle of same mass



STELLAR FEEDBACK

- In this work: the focus is on supernova explosions
- Four feedback strengths, described by the ejecta velocity (V_{SN}):

Description	V_{SN} [km/s]	Colour
'weak'	2828	
'fiducial'	4000	
'strong'	5657	
'extra strong'	8000	

Table 1: The simulated supernova feedback strengths, descriptions and the associated plot colours.

Figure 3: Starburst galaxy M82. Image credit: NASA, ESA, Hubble Heritage Project (STScI, AURA)

MEGRERS OF SUPERMASSIVE BLACK HOLES

- SMBH coalescence is 3-phased process:
  1. Dynamical friction
  2. 3-body interactions
  3. Gravitational wave (GW) emission

- Purpose of each phase is to rid the binary of its orbital energy

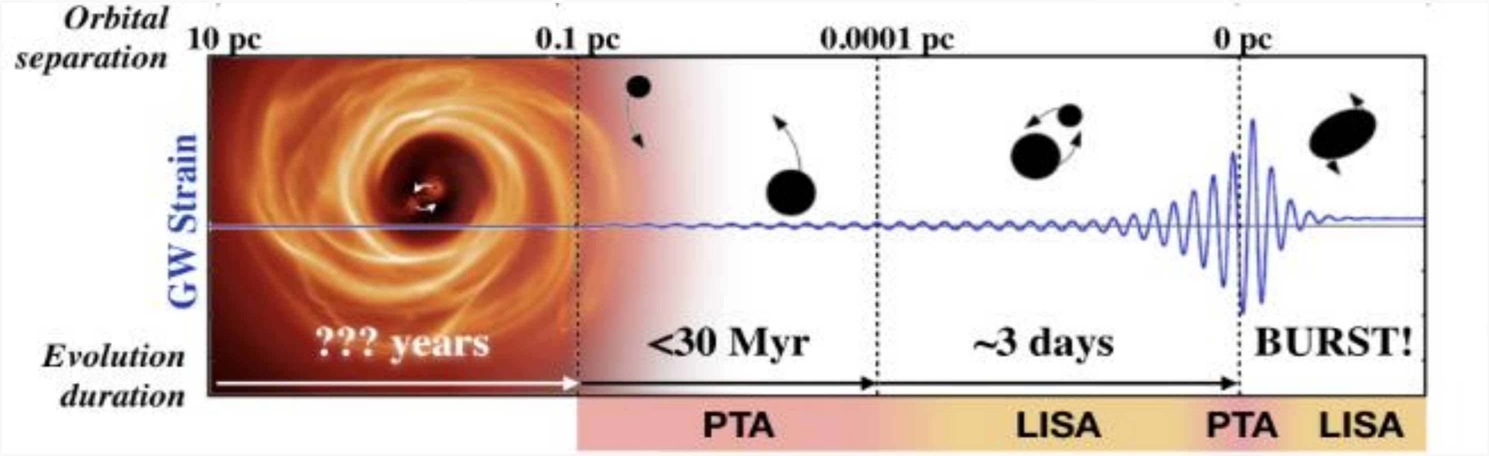
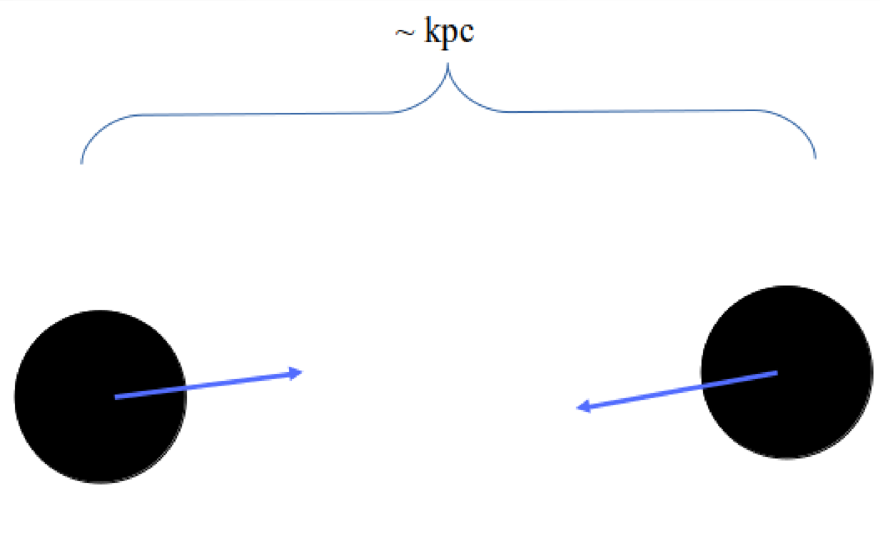
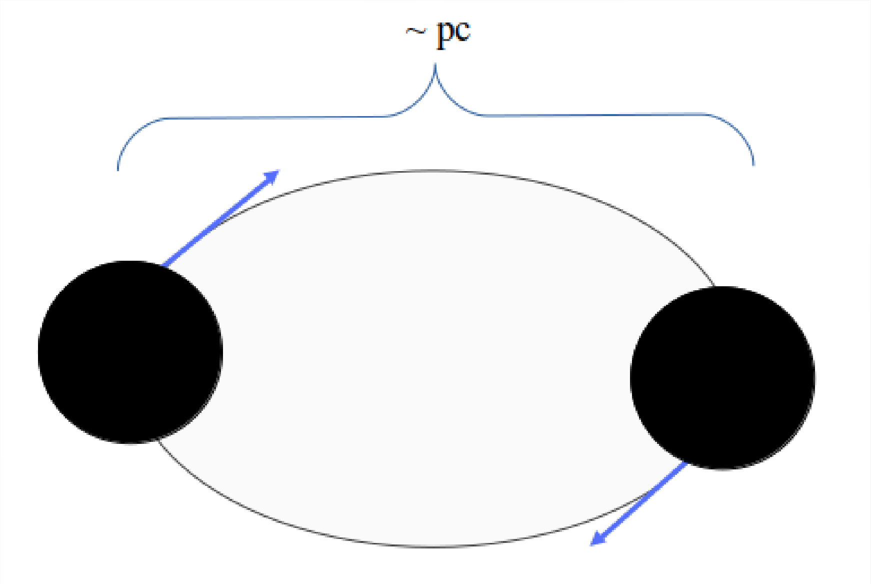


Figure 3: Schematic illustration of a SMBH merger. Image credit: NANOGrav, Sarah Spolaor

SMBH MERGER: DYNAMICAL FRICTION

- After the host galaxies have merged the two central SMBHs 'sink' to the galactic centre due to dynamical friction
  - Stars and gas create a decelerating force which brings the SMBH binary from kiloparsec to ~ parsec* scale separations

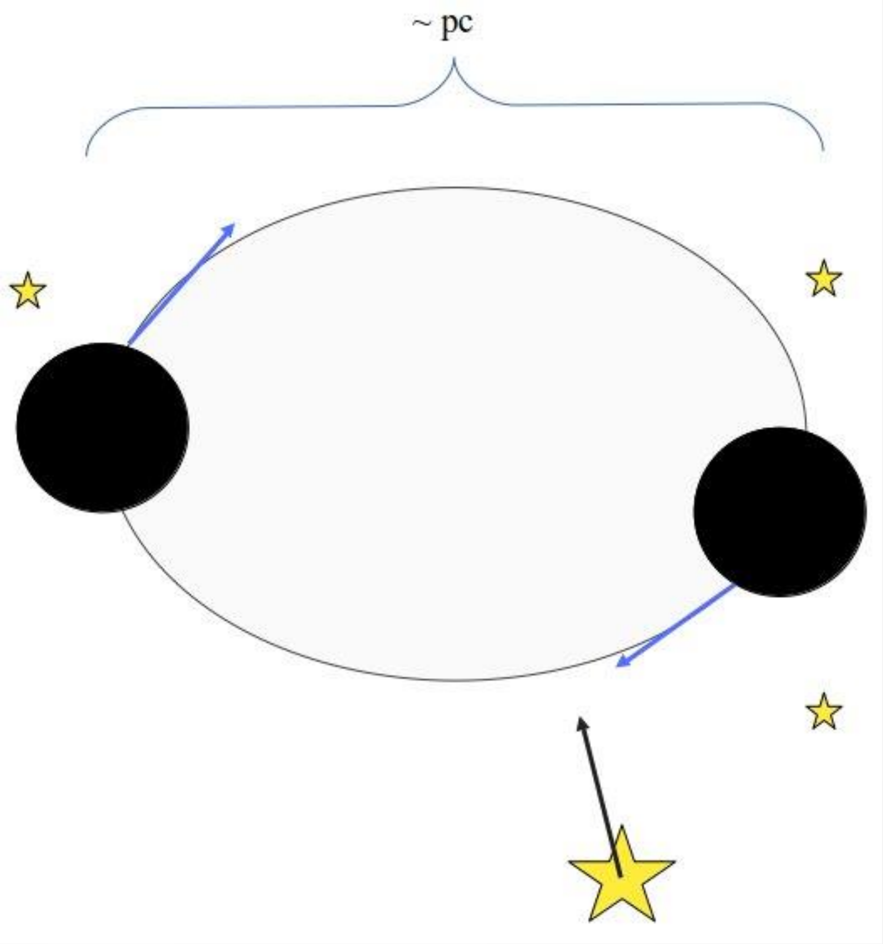




*1parsec [pc] = 3.086×10^{16} meters

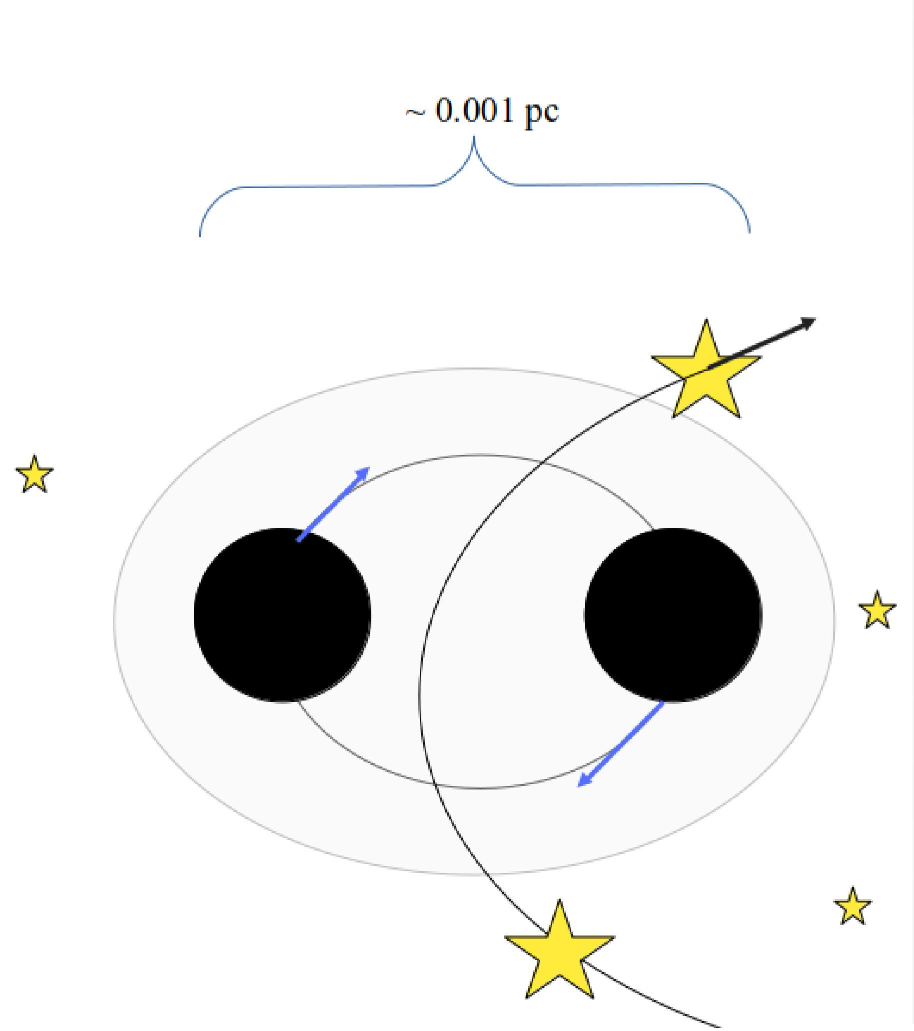
SMBH MERGER: 3-BODY INTERACTIONS

- The two SMBHs form a hard binary in the galactic centre
- In the galactic centre, the stellar number density is the highest
  - Stars can travel close to the SMBH binary



SMBH MERGER: 3-BODY INTERACTIONS

- If a star travels close enough to the binary it can get ejected
- Some of the binary orbital energy converts to kinetic energy for the star
    - As a result, the orbit shrinks



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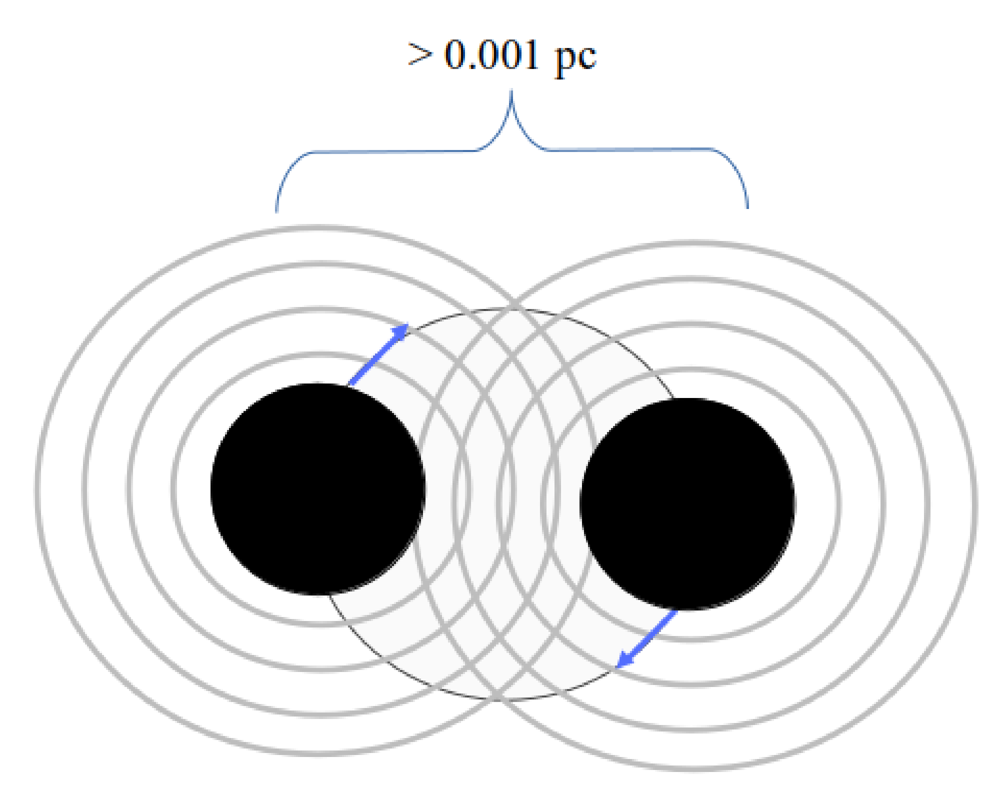
SMBH MERGER: GRAVITATIONAL WAVE EMISSION

- In the final phase the emission of gravitational waves is responsible in depleting the binary of its orbital energy
- From sub-pc separation to final coalescence



RESEARCH QUESTION: HOW DOES STELLAR FEEDBACK AFFECT THE MERGING TIME-SCALES OF THE SMBH BINARY?

RESEARCH: SIMULATION CODES

- GADGET-3: Smooth particle hydrodynamics (SPH) code
  - Used to model galaxy formation and evolution
  - For more see Springel 2005

- KETJU: extension to GADGET-3
  - Models the dynamics near a merging SMBH binary more accurately than GADGET-3 would alone
  - Utilizes post-Newtonian formalism
  - For more see Rantala et al. 2017, 2020

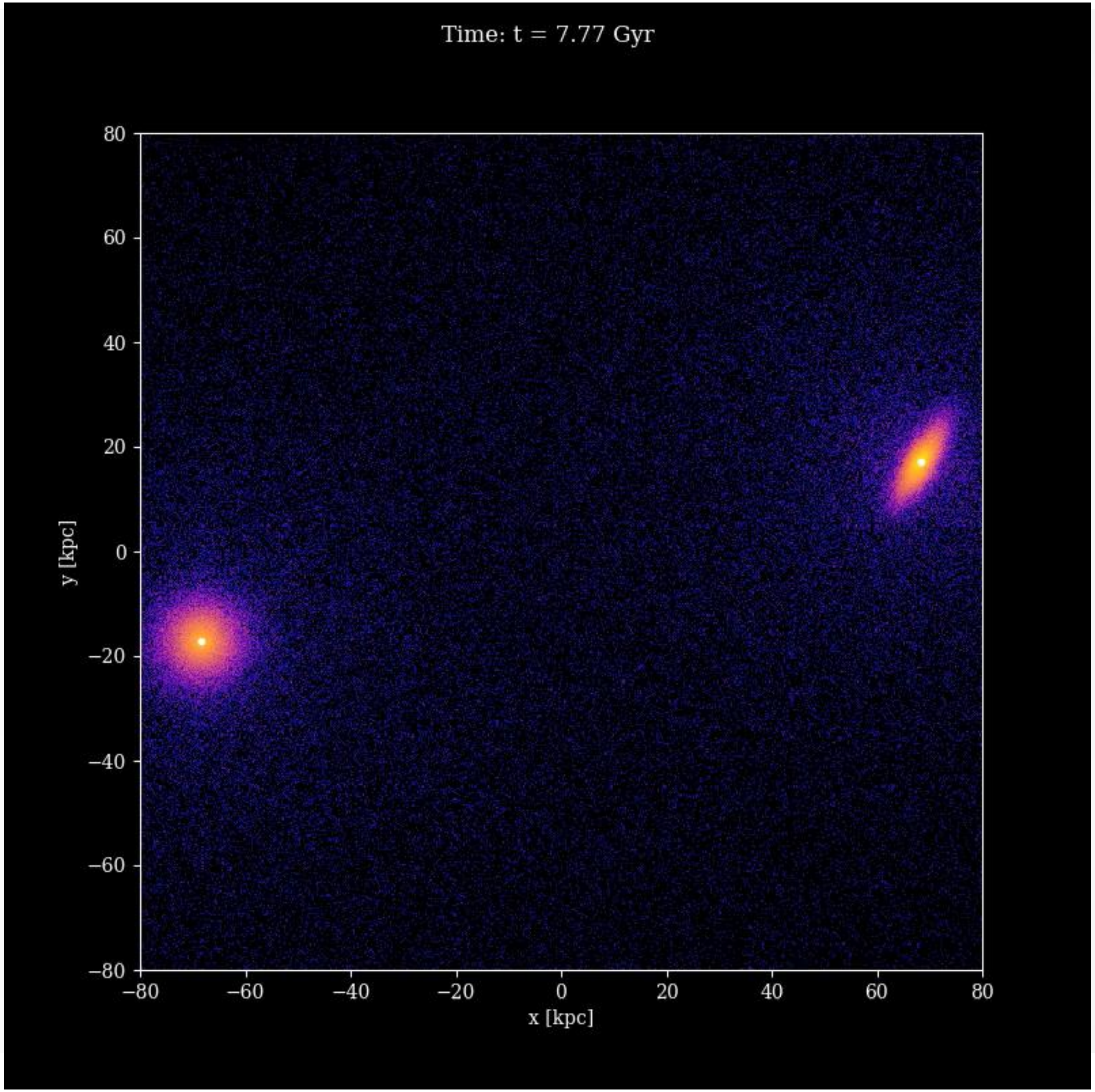
RESEARCH: SIMULATION INITIAL CONDITIONS

- The progenitor galaxies are gas-rich, disc galaxies, mass ratio 1:1
- The central SMBHs non-accreting particles

Stellar Mass (M_*)	SMBH Mass (M_{SMBH})	Baryonic particle resolution
$4.9 \times 10^9 M_\odot$	$6.55 \times 10^6 M_\odot$	$10^4 M_\odot$

Table 2: Masses of the progenitor galaxies. Units are solar masses.

MERGER VIDEO



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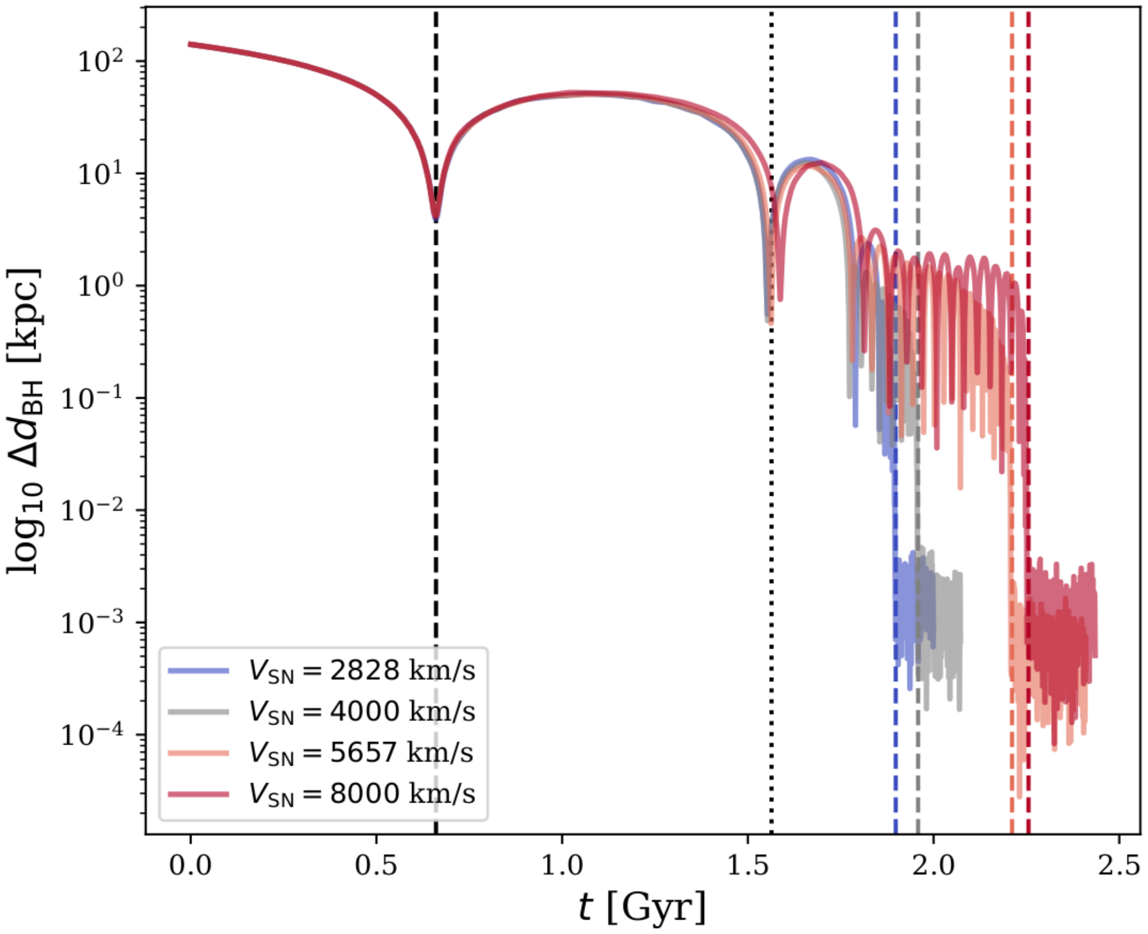
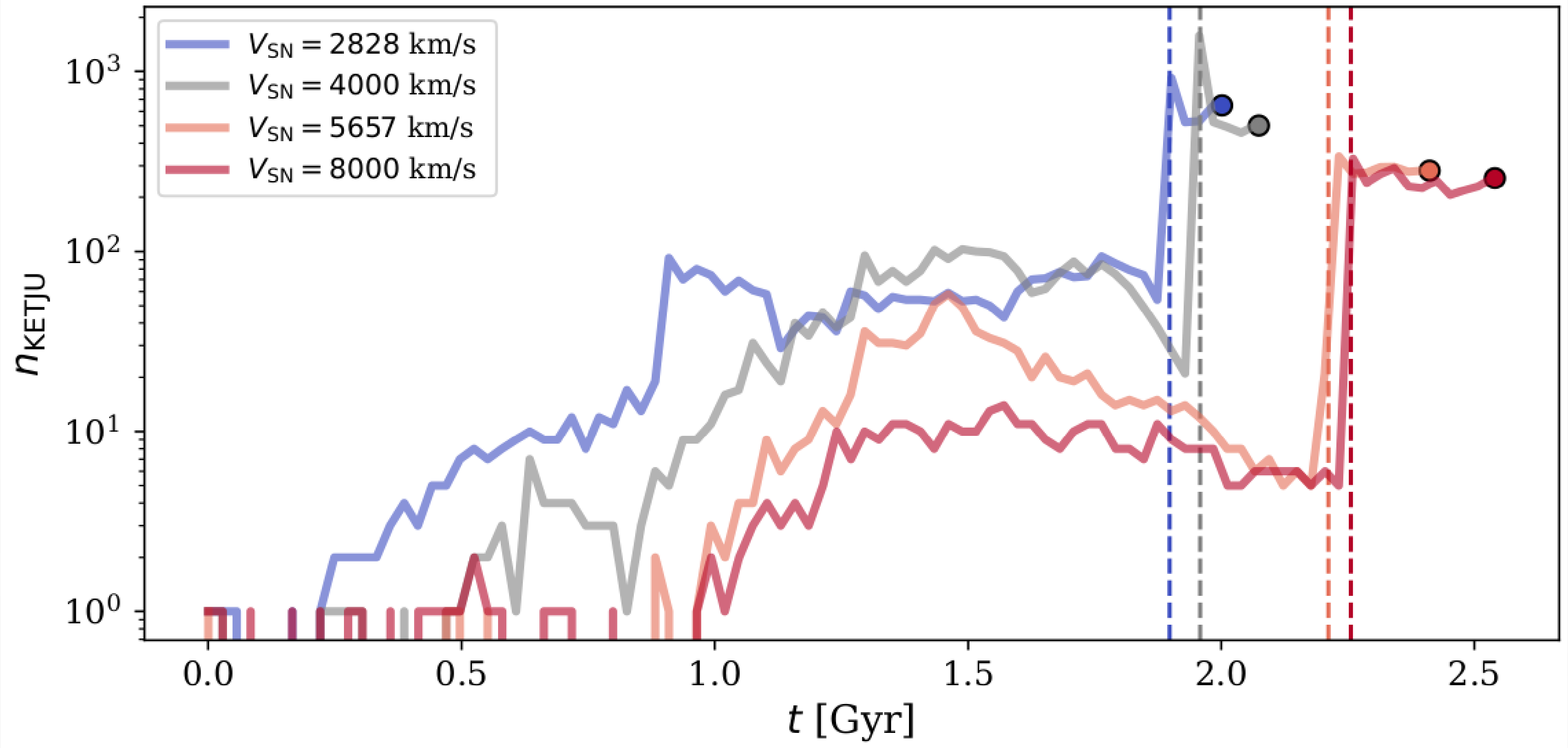
RESULTS

RESULTS: DYNAMICAL EVOLUTION OF SMBH BINARY

- SMBH binary separation over time
  - Binary in weak feedback run merges first
  - Binary in extra strong run merges last



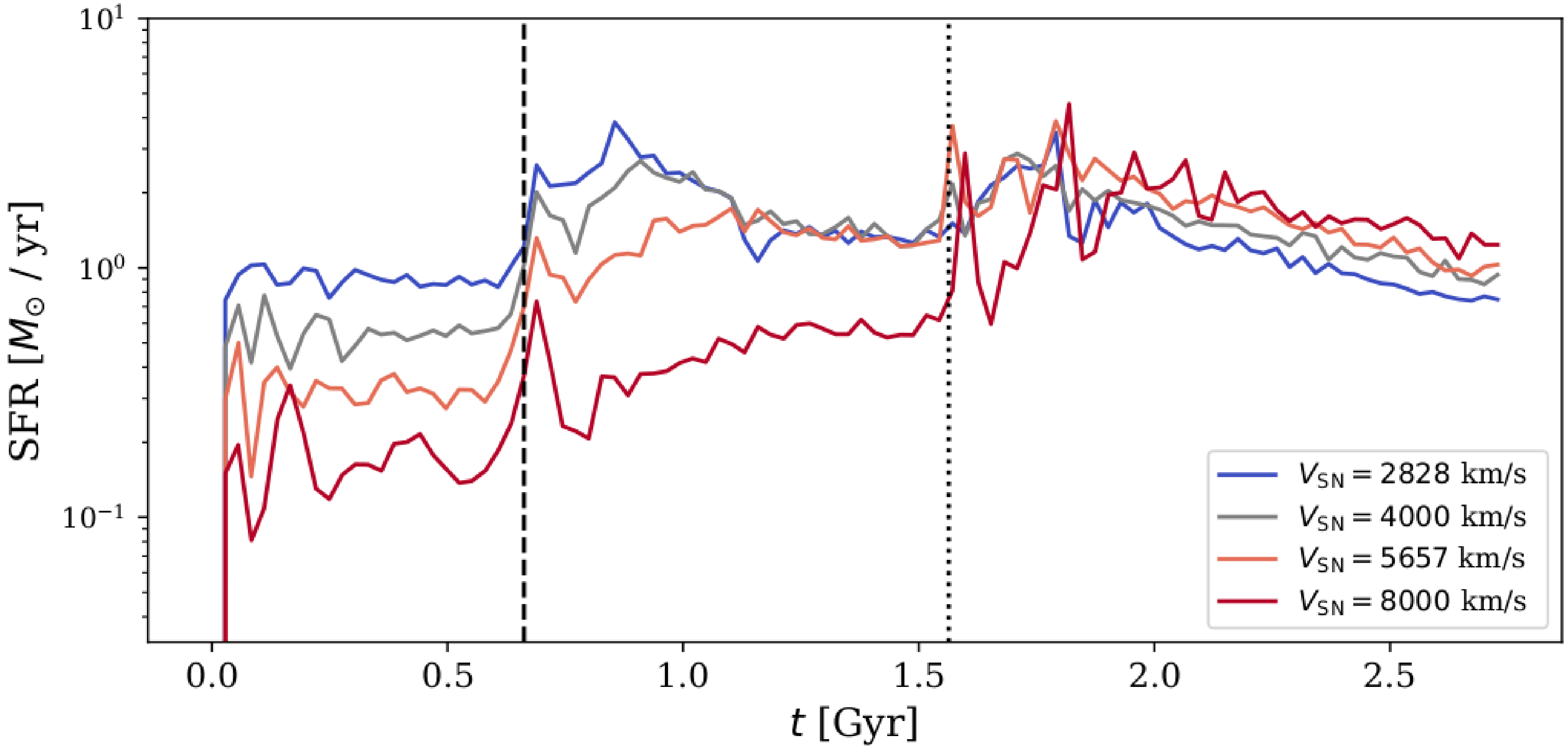
RESULTS: PHYSICAL DRIVERS OF SMBH COALESCENCE



- Number of stellar particles near the SMBH binary over time

RESULTS: PHYSICAL DRIVERS OF SMBH COALESCENCE

- Star formation rate (SFR) over time
  - High in weak feedback run
  - Decreases as the feedback strength increases



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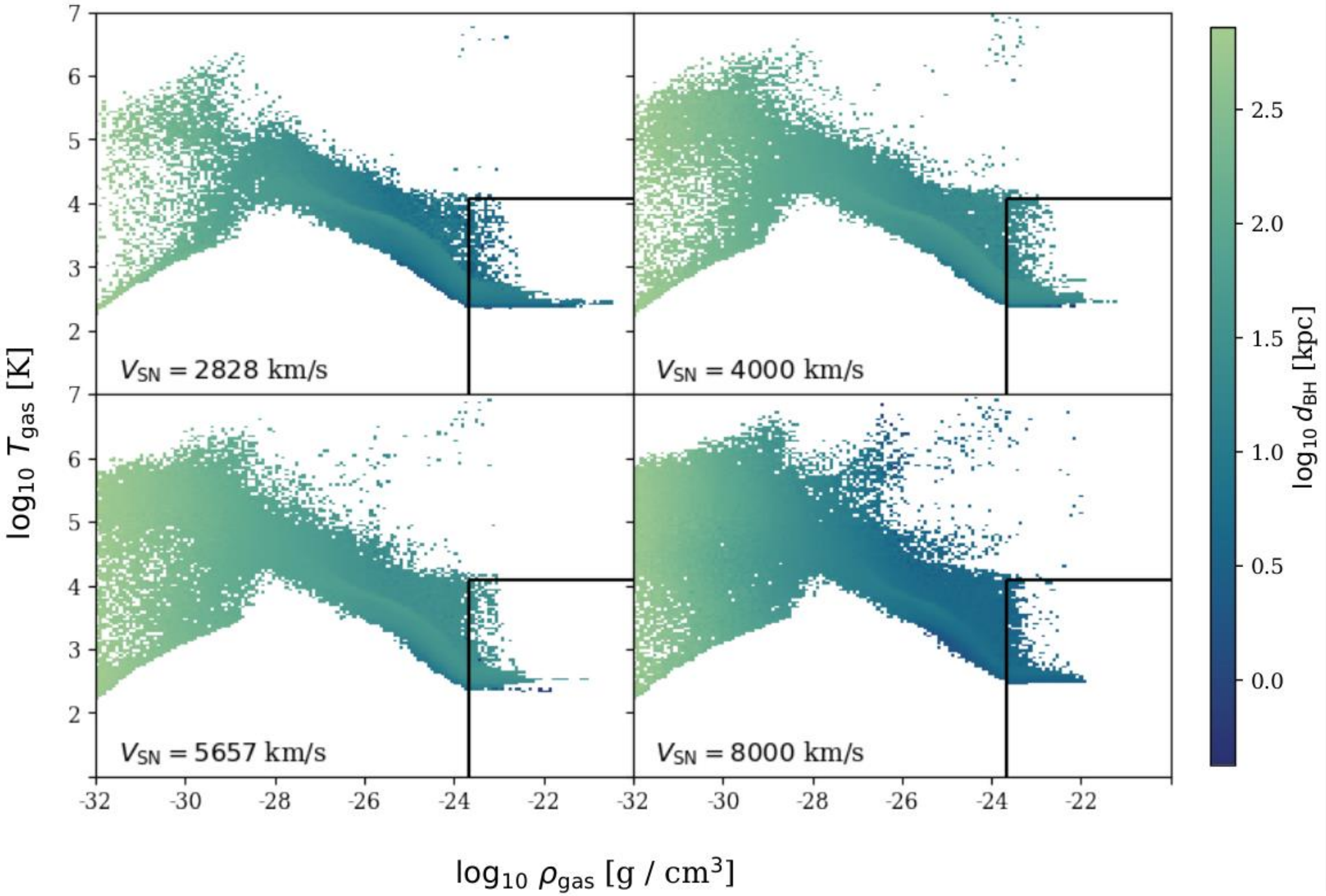
RESULTS: PHYSICAL DRIVERS OF SMBH COALESCENCE

- Temperature-density phase diagram of the simulation gas particles
- As the feedback strength increases the gas particles are driven to hot, low-density region



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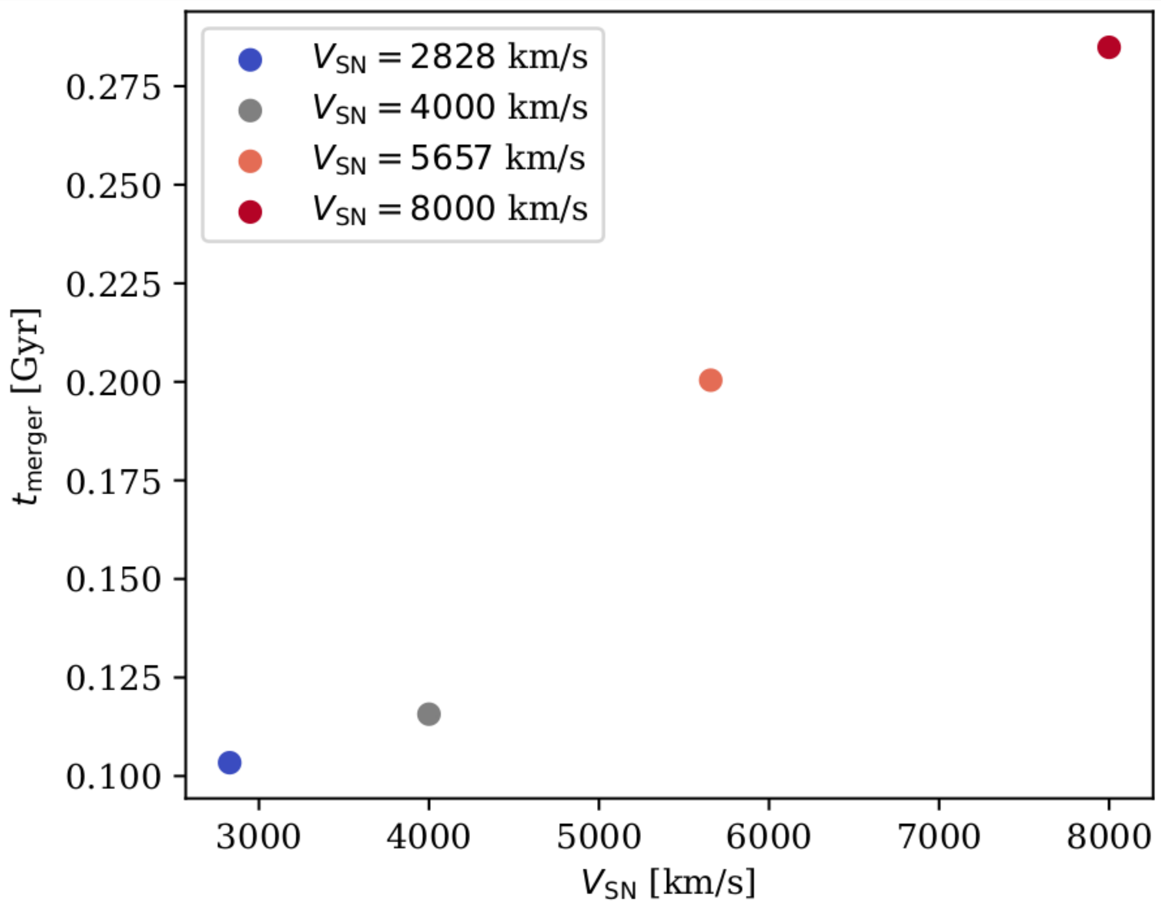
RESULTS: MERGING TIME-SCALES

- When the strength of stellar feedback increases the SMBH merging time-scale increases!

Description	V_{SN} [km/s]	t_{merger} [Myr]
'weak'	2828	103.4
'fiducial'	4000	115.7
'strong'	5657	200.4
'extra strong'	8000	284.9

Table 3: The simulated feedback strengths, descriptions and merging times.



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CONCLUSIONS

- As stellar feedback strength increases, the merging time-scales increase
- LISA will be most sensitive to SMBH mergers of this mass range
- The merging time of SMBH binary affects LISA's ability to detect the source

- Future work:
  - In an upcoming paper we include more simulation runs to move forwards with statistically stronger results

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THANK YOU!
QUESTIONS?

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