Massive Black Holes Mergers at low-redshift Universe: predictions from cosmological simulation Astrid

Yihao Zhou
Carnegie Mellon University

Frontera LRAC AST20015

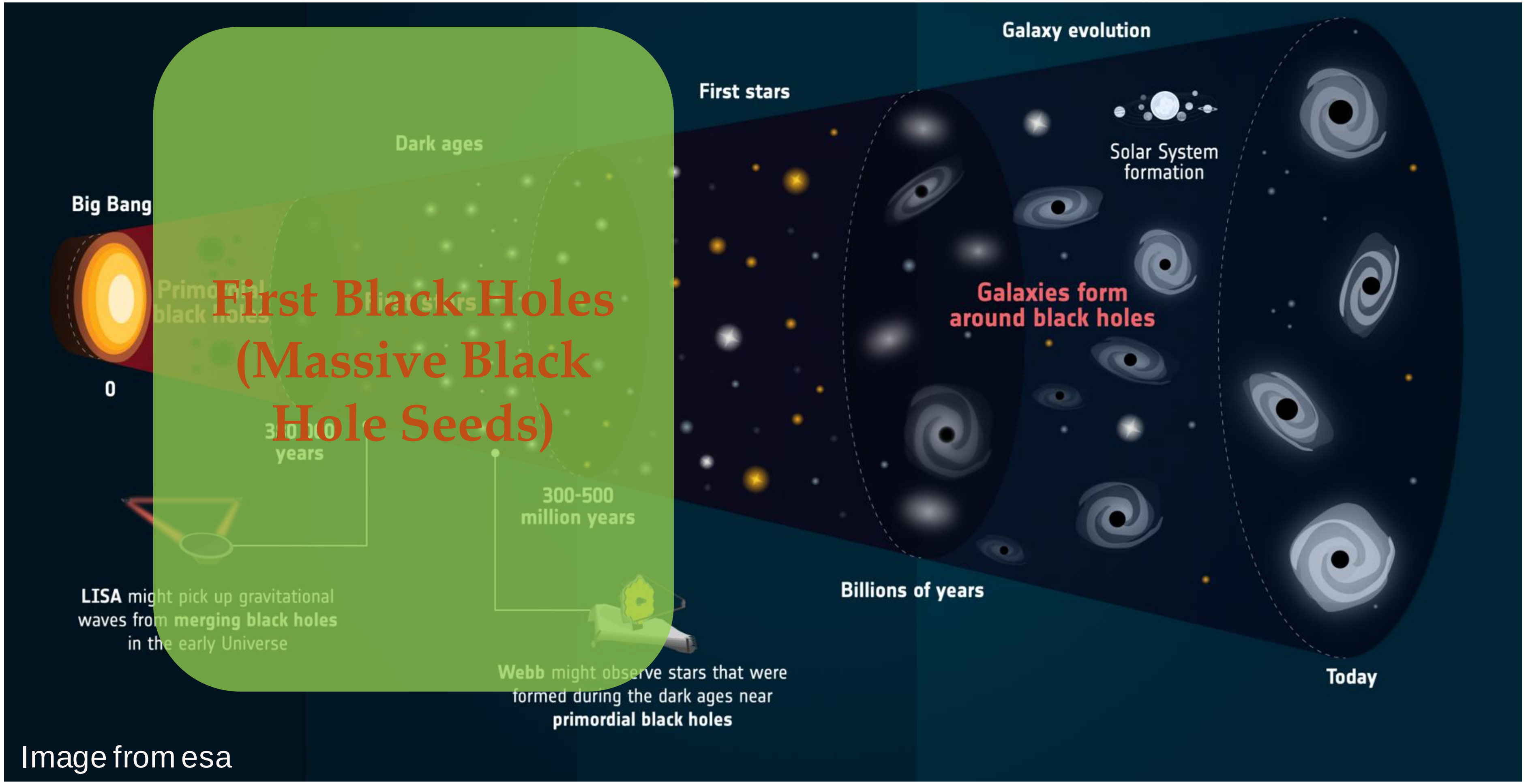
Team Members: Tiziana Di Matteo (PI; CMU), Simeon Bird (Co-PI; UCR)
Rupert Croft (CMU), Yueying Ni (Harvard)
Nianyi Chen (IAS), Patrick Lachance (CMU), Yu Feng (UCB)
Mahdi Qezlou (UCR), Mingfeng Ho (UCR), Yanhui Yang (UCR)

Growth of Massive Black Holes (MBHs) and Galaxies across cosmic history

Time Evolution

Big Bang → Today

t=0 t=13.8 Gyr



First Black Holes (Massive Black Hole Seeds)

Image from esa

Mysteries: over-massive MBH

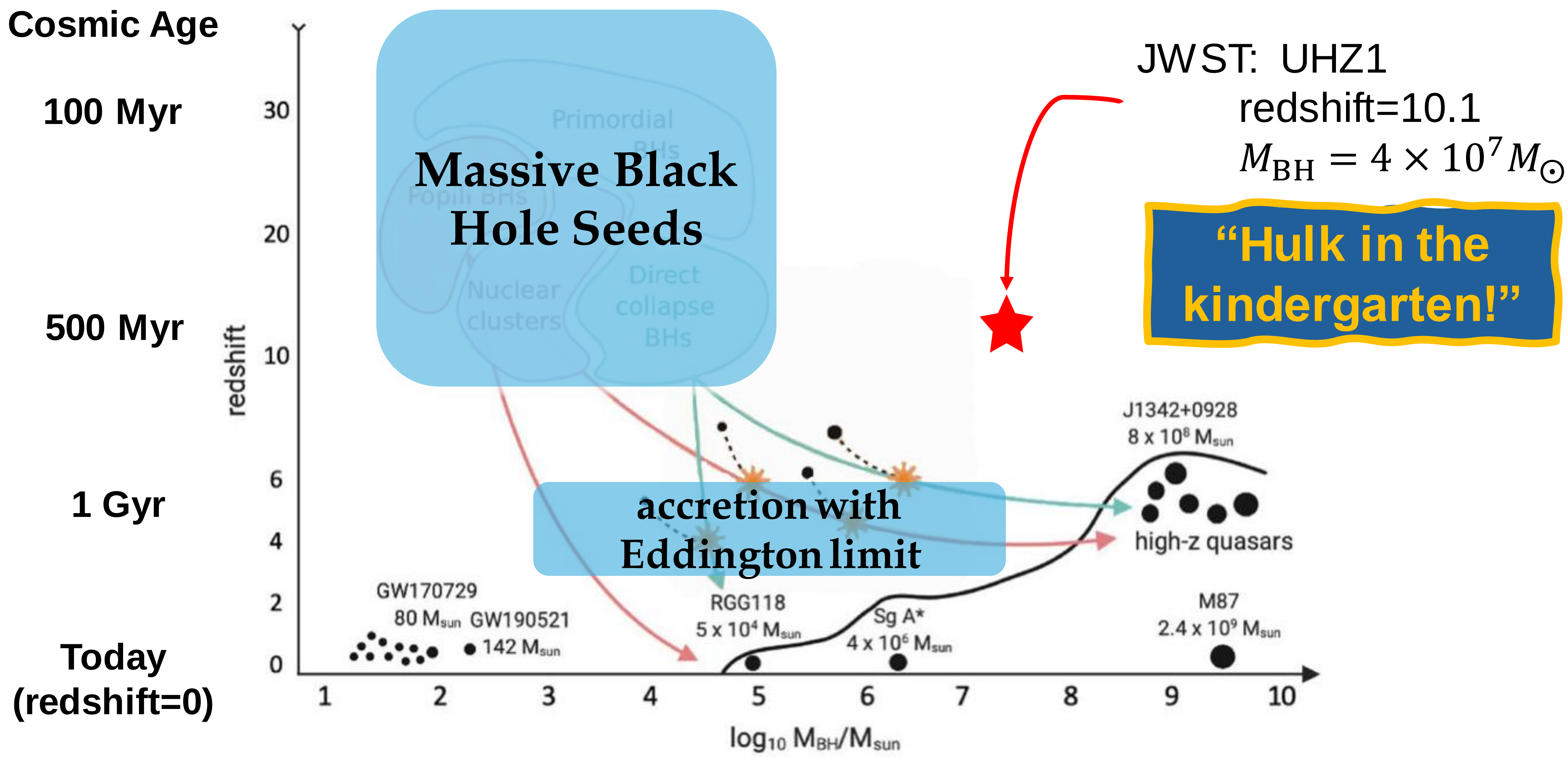
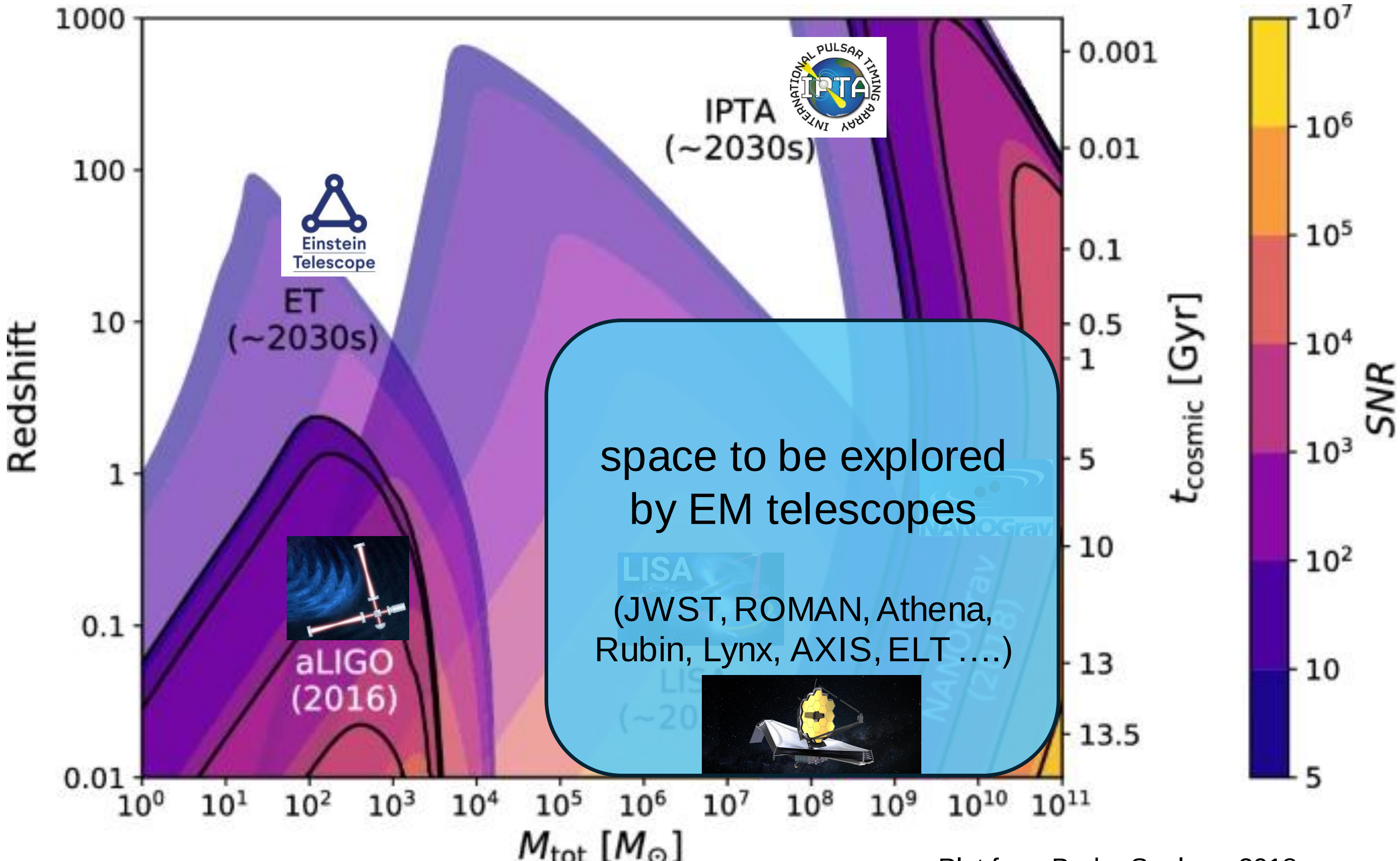


Image from: M. Habouzit

Discovery space for MBH

The parameter space to be explored by future GW detectors



Plot from Burke-Spolaor+2018

Asking for detailed and wide-ranging simulations to predict future observation data!

ASTRID:
from Cosmic Web to Massive Black Holes

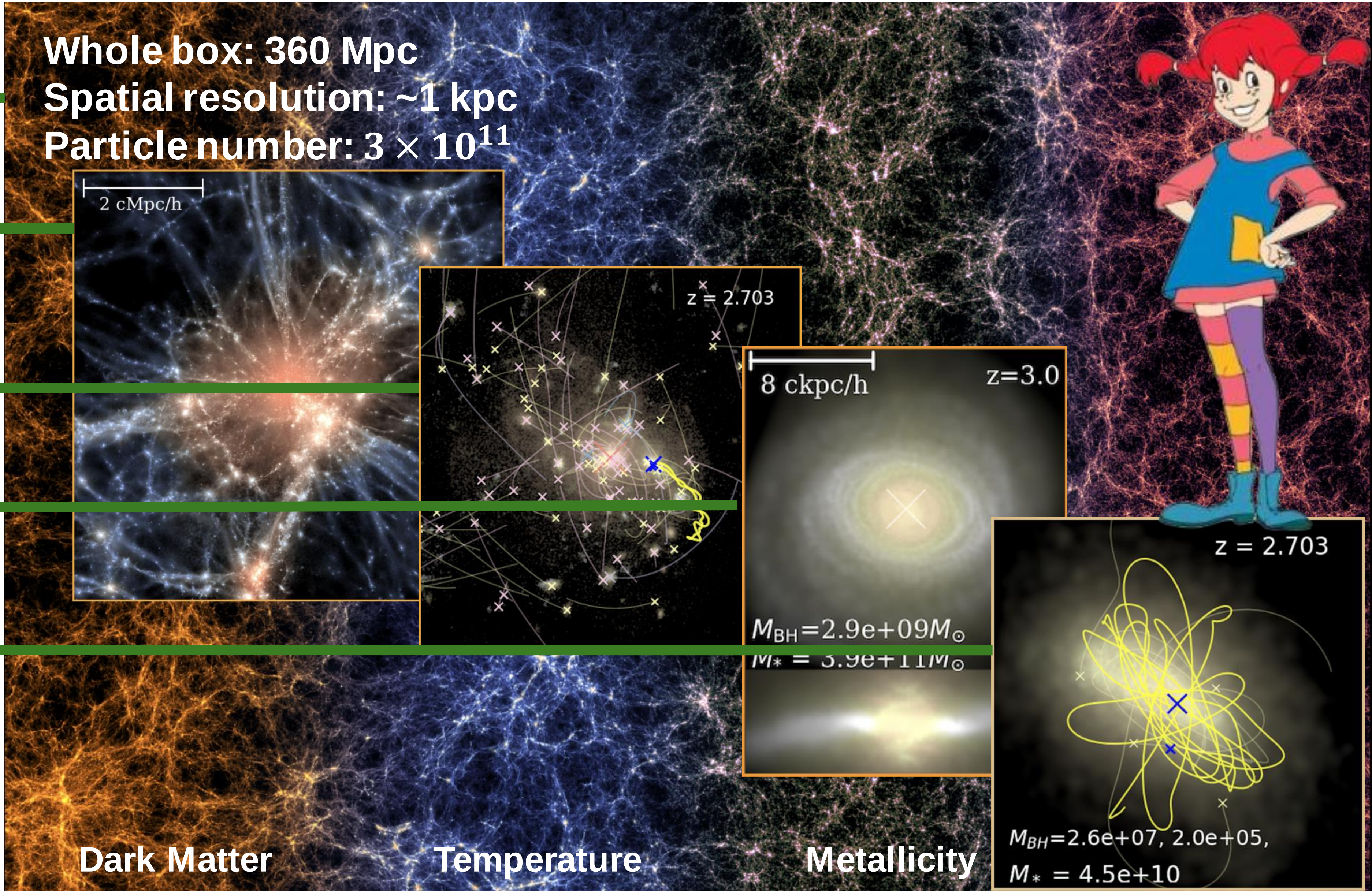
Cosmic Web:
>100 Mpc

Massive clusters
10 Mpc

Groups of galaxies
1 Mpc

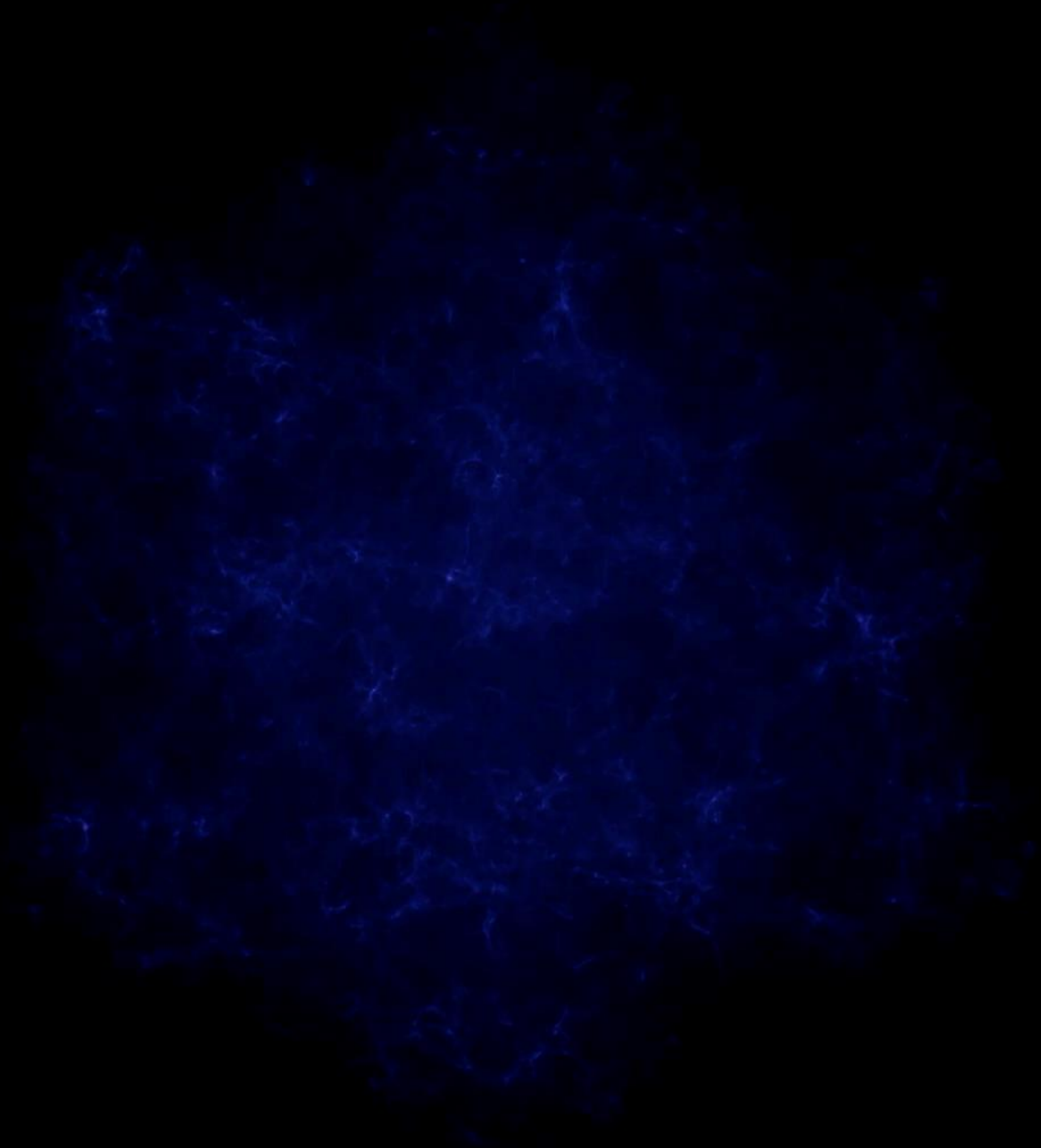
Interstellar Medium
10 kpc

Massive Black Holes:
kpc



1 pc ~ 3 light years

Image from Yueying Ni

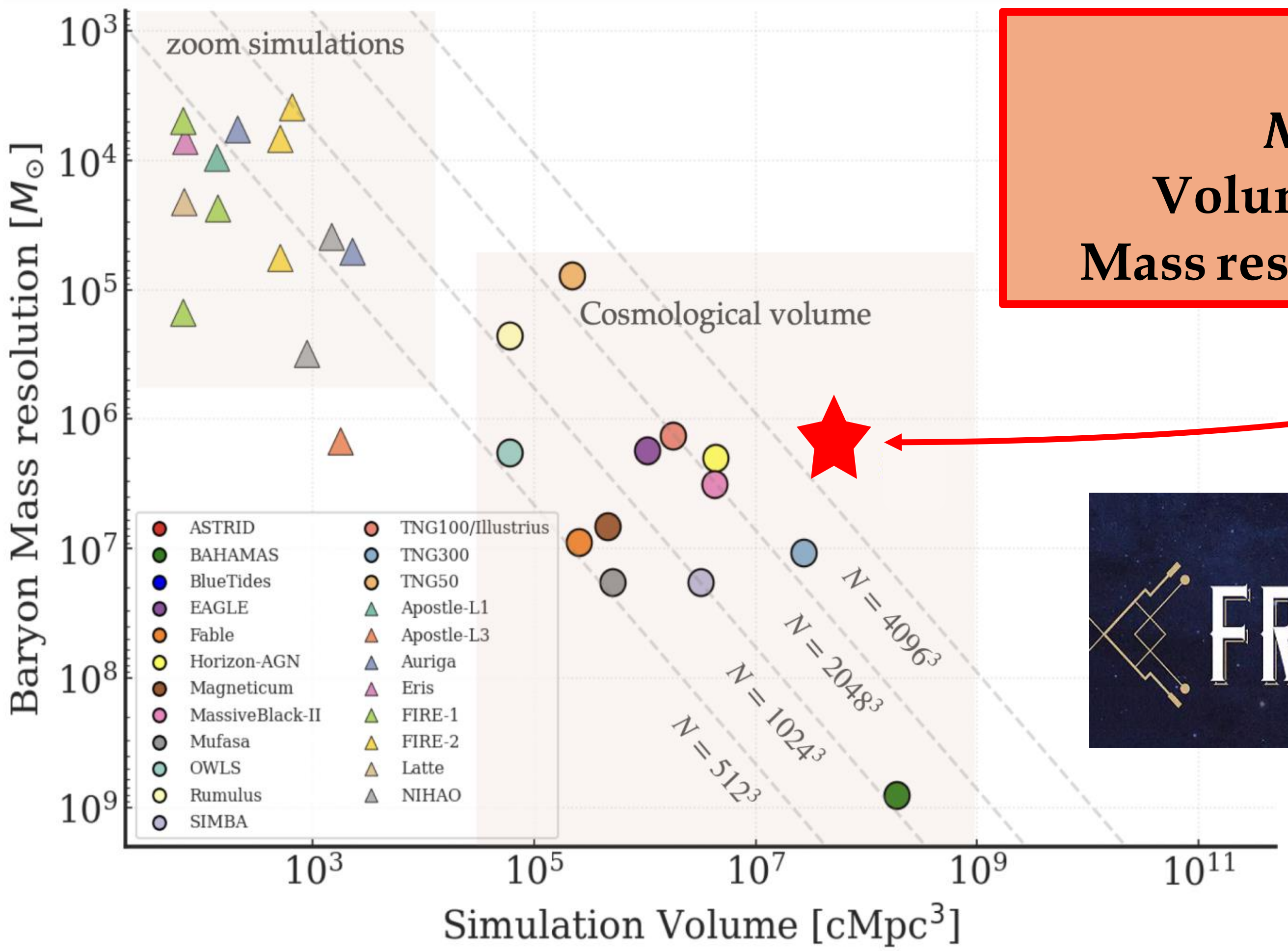


$z = 10.00$

ASTRID:

the uniquely large volume and resolution

Higher resolution: resolve physical process on smaller scales



ASTRID

$N = 2 \times 5500^3$

Volume $= 5 \times 10^7$ Mpc^3

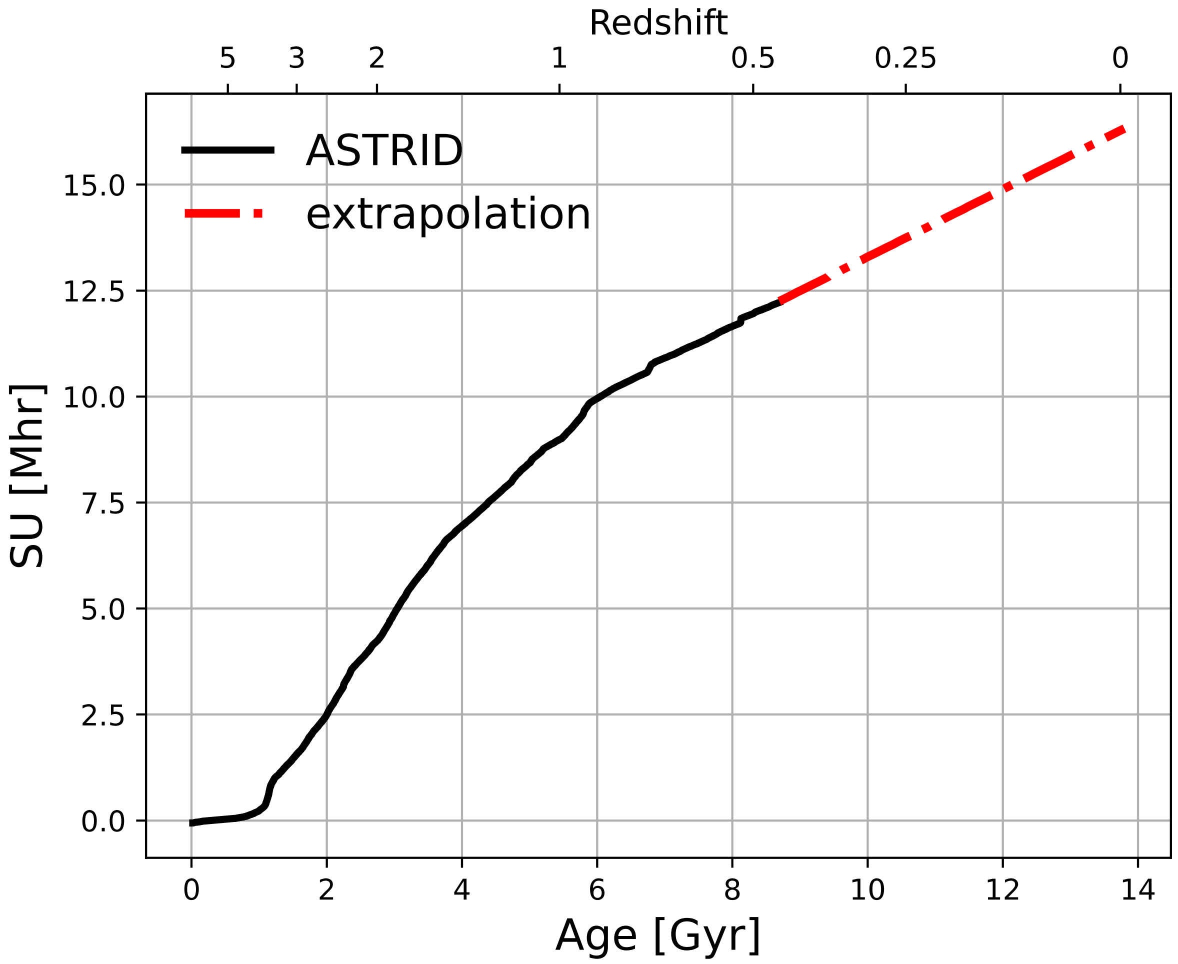
Mass resolution $= 2 \times 10^6\ M_\odot$

FRONTERA

Larger volume: better statistics & more rare objects

Why Frontera is important for Astrid

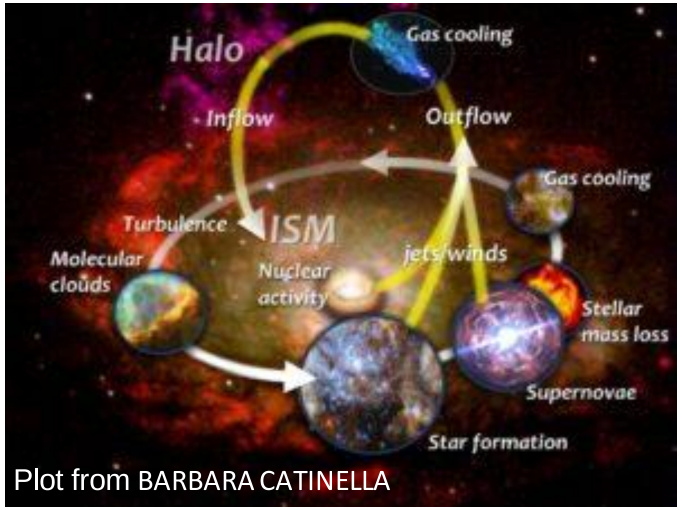
- Extreme memory request
- Over 10^{11} particles evolving almost the whole Universe Age
- 2048 CLX computer nodes
- 4096 MPI ranks × 28 threads per MPI rank
- Used ~ 12 M SU to z=0.5



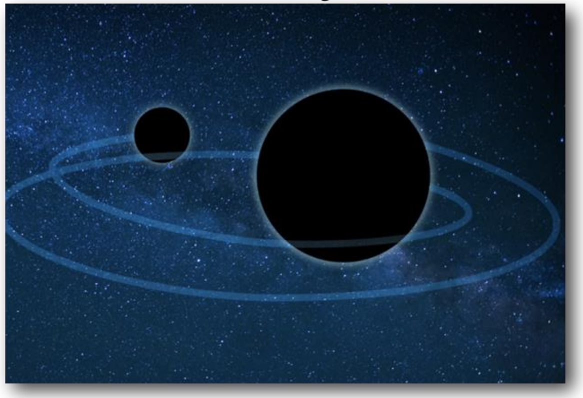
Physical Models in ASTRID

- Gravitational evolution: TreePM code
- Pressure-entropy SPH
- massive neutrinos
- Primordial cooling and metal-line cooling
- Multi-phase interstellar medium
- H2 based star formation
- Metal return from the massive stars
- Supernovae wind feedback
- Re-ionization models
- Inhomogeneous hydrogen reionization
- Helium reionization
- **Power-law seeding for BHs**
- **AGN accretion and feedback**
- **Wide MBH range: $10^4 \sim 10^{11}\ M_\odot$**
- **Accurate dynamics for BH mergers**

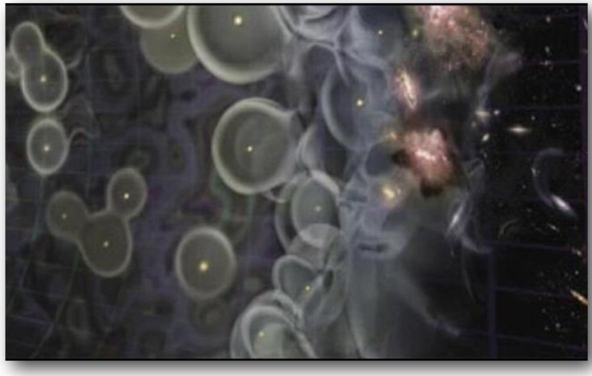
Star formation & Gas cooling



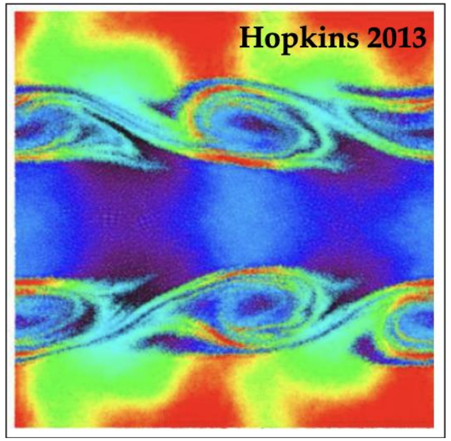
Black hole dynamics



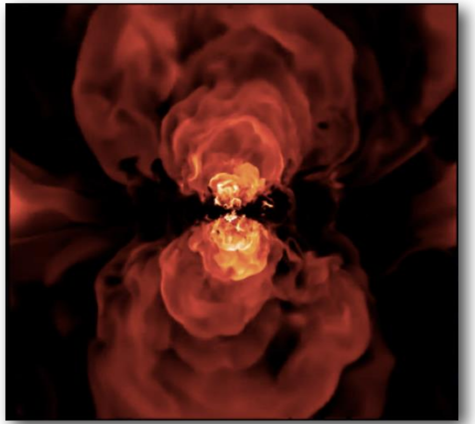
Reionization



pressure-entropy SPH



Supernova



AGN activity

Astrid scientific legacy

- **The formation of Massive Black Holes**

  Ni+2022, Chen+2022, DiMatteo+2023, Weller+2023, Hoffman+2023,

- **Massive Black Holes mergers and GW**

  Degraf+2023, Weller+2023, Hoffman+2023 Chen+2023, Chen+2024, Zhou+2024, Mukherjee+2024

- **AI-assisted Super-resolution simulation**

  Ni+2023, Zhang+2024

- **Large-scale clustering of quasars and galaxies**

  Dadiani+2023, Qezlou+2023

- **Cosmic Reionization**

  Bird+2022, Davies + 2023

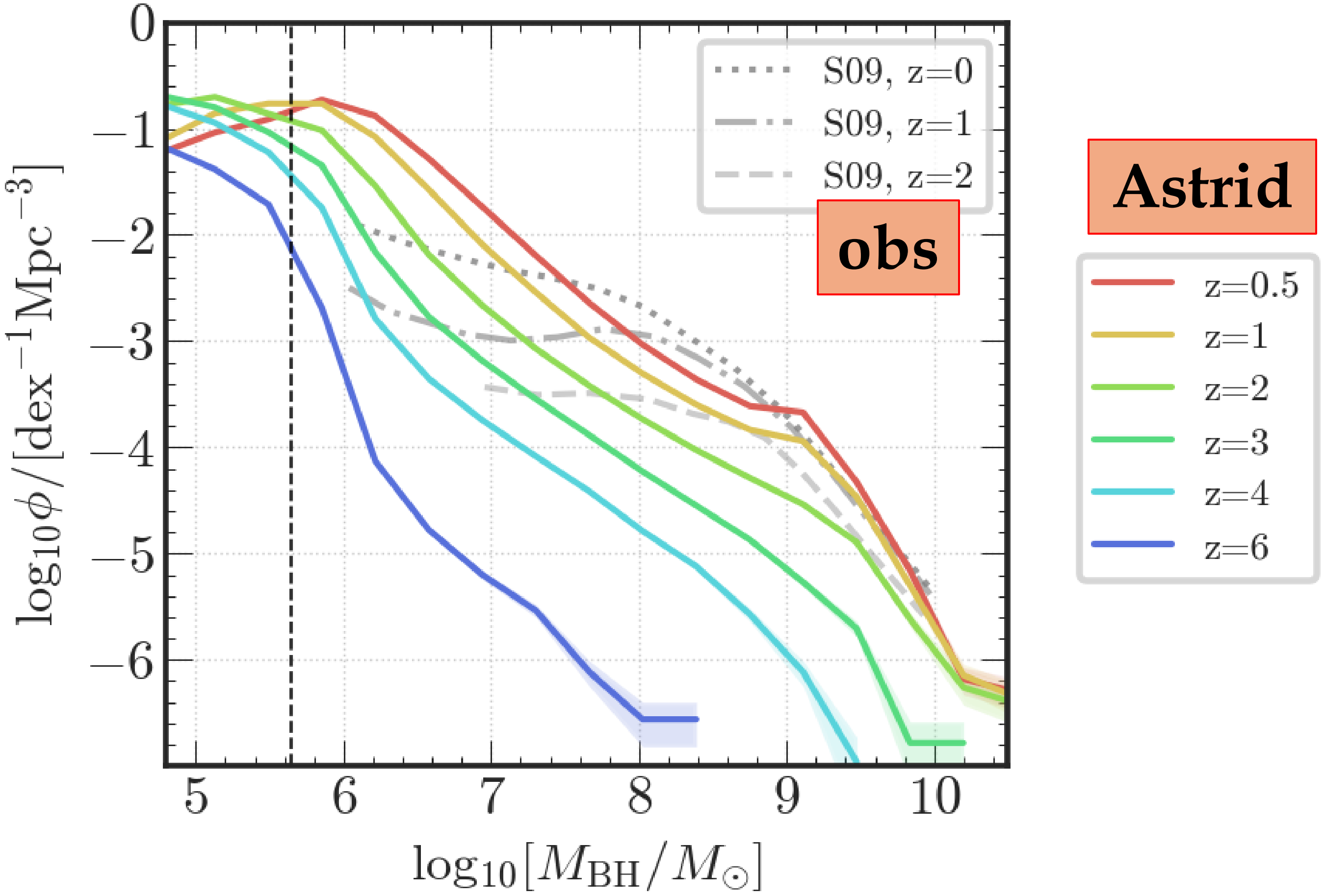
- **Mock Observations data**

  LaChance+2024

…

MBH Population in Astrid

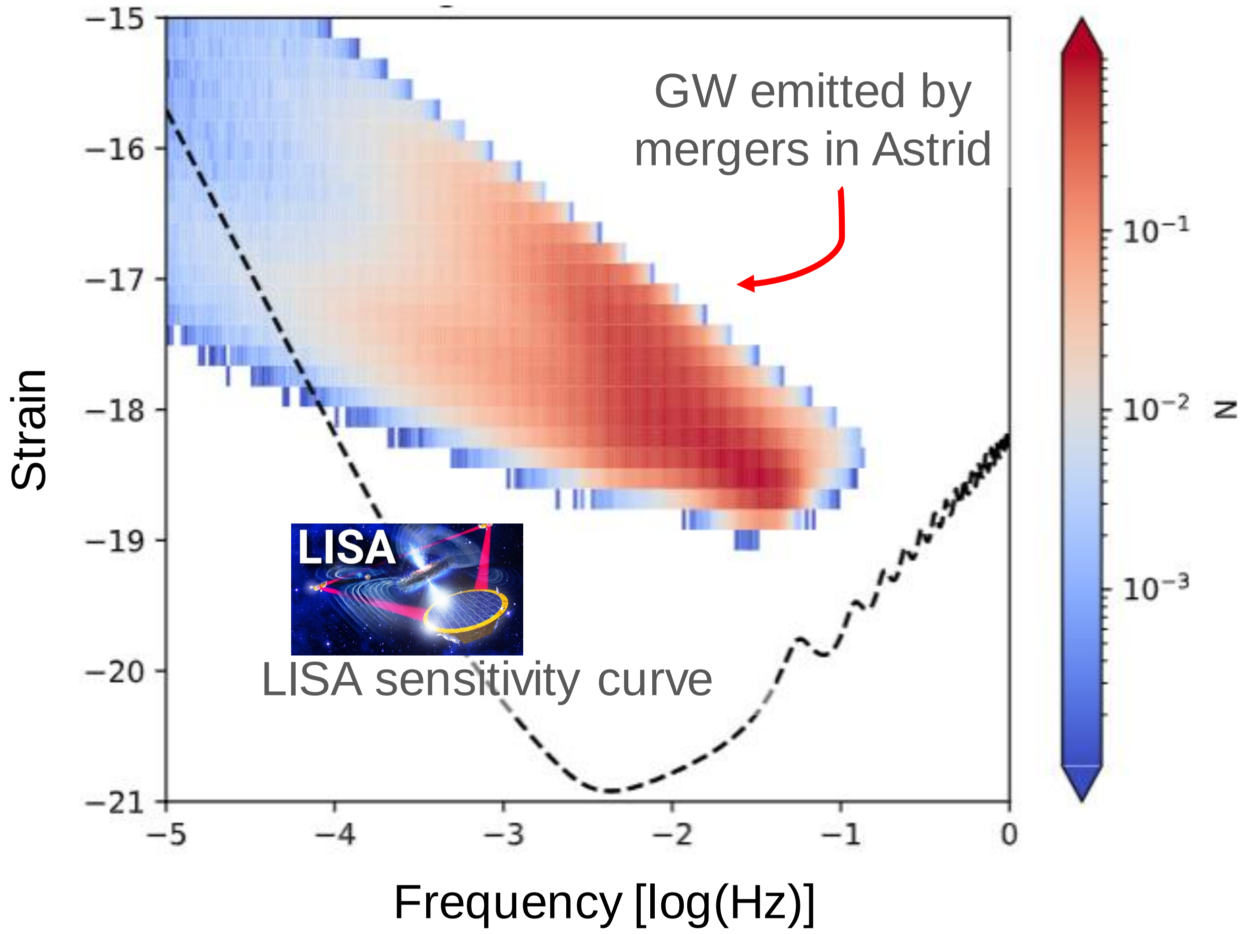
- **wide mass range**
- **consistent with observation**



Ni+2024

MBH Merging Events in Astrid

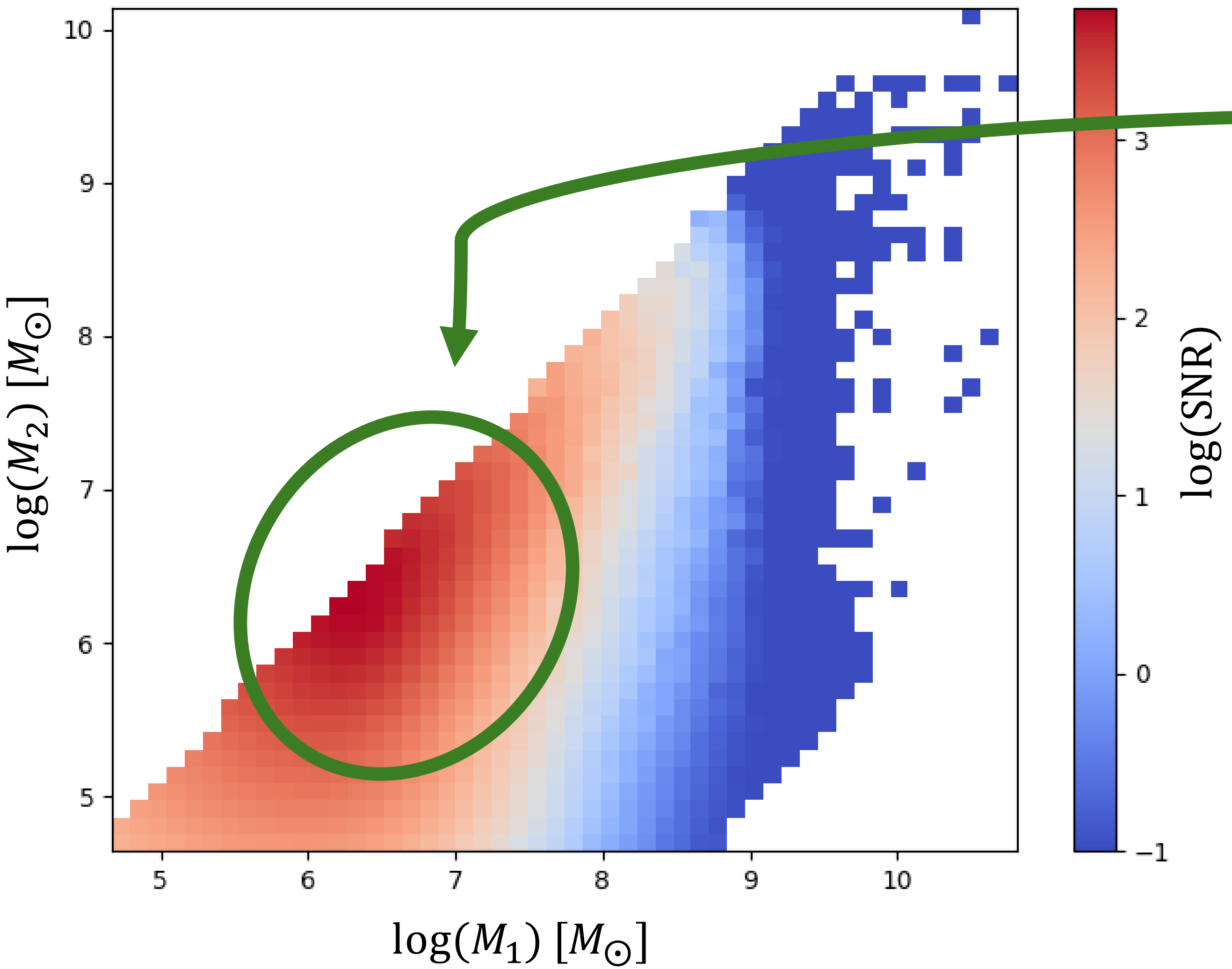
Mergers to be detected by LISA



~98% merging events are above the LISA sensitivity

MBH Merging Events in Astrid

Mergers to be detected by LISA

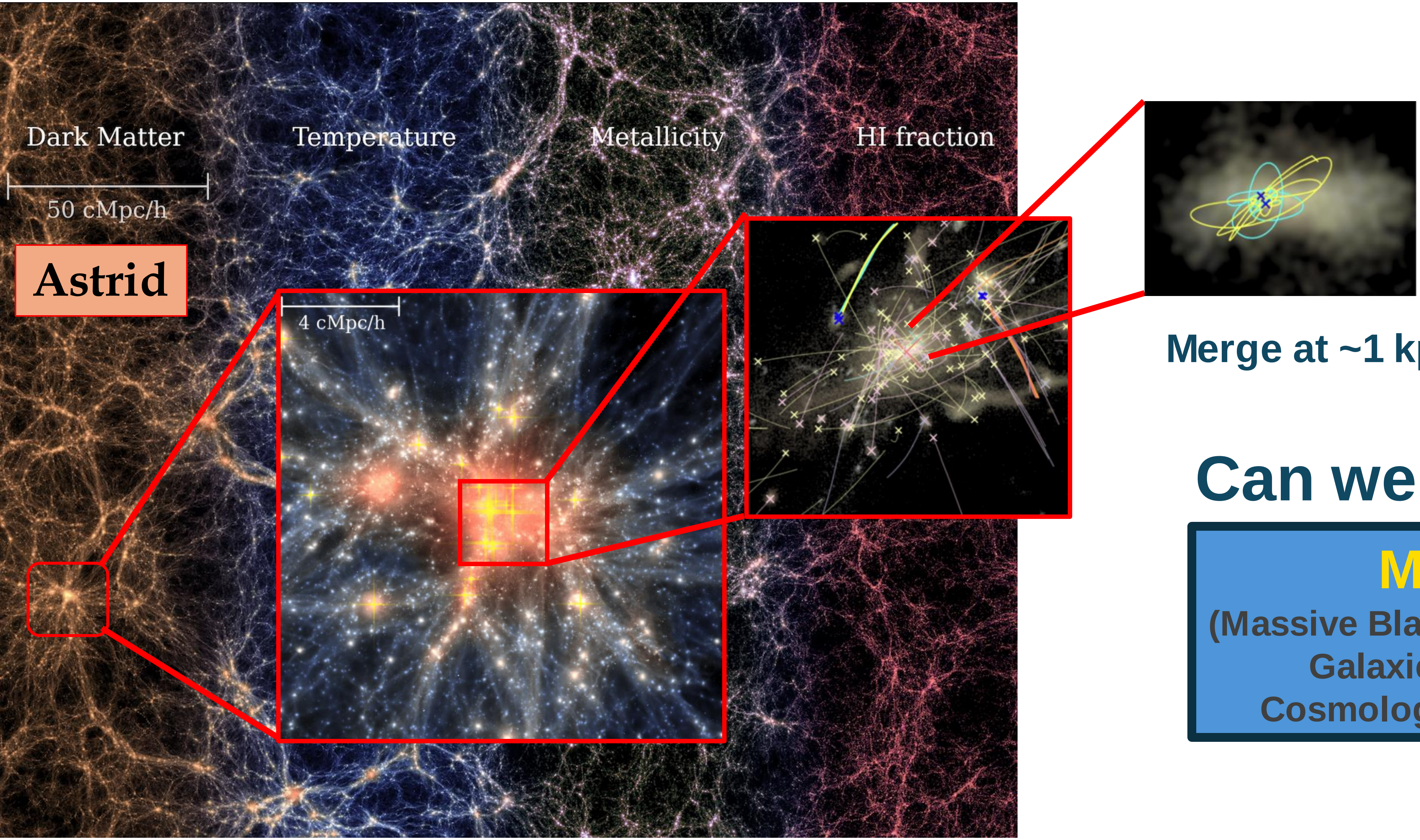


Event most likely to be detected:
MBH seeds ($10^6\ M_\odot$)
Equal-mass merger

MAGICS
Massive black hole Assembly in Galaxies Informed by Cosmological Simulation

Chen+ 2023
Zhou+ 2024
Mukherjee+ 2024

MAGICS



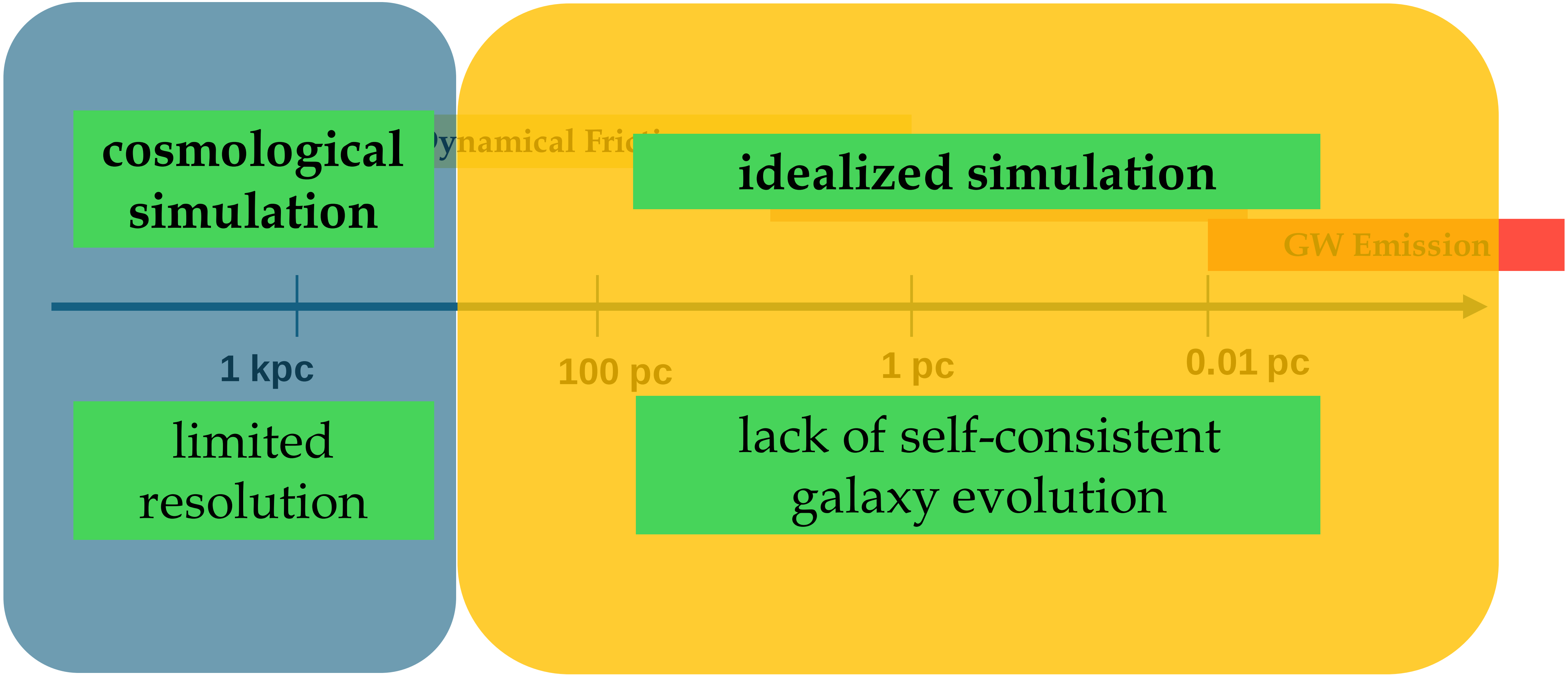
Merge at ~1 kpc

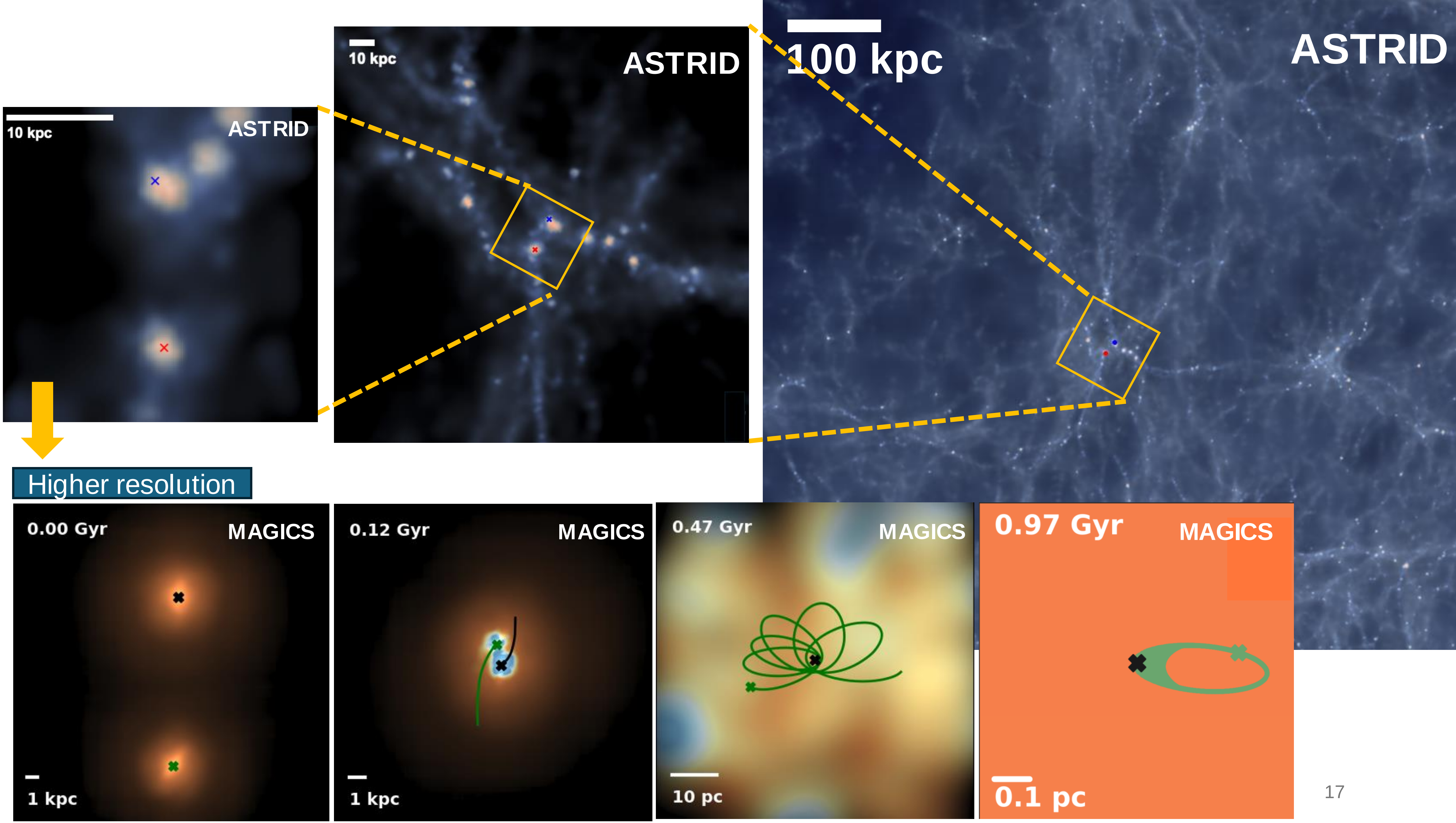
Can we go further ?

MAGICS

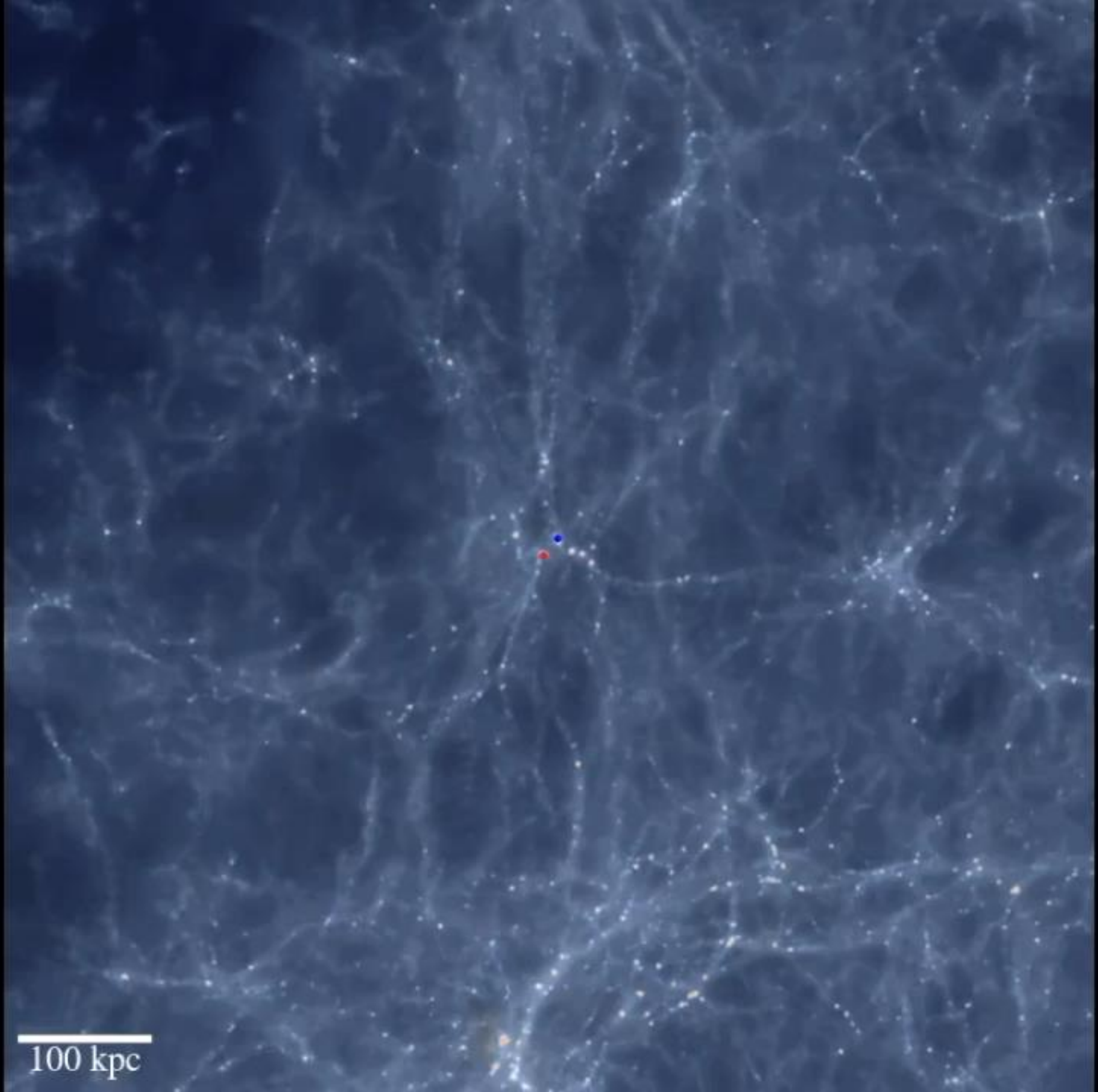
(Massive Black Hole Assembly in Galaxies Informed by Cosmological Simulations)

MBH Binary Dynamics



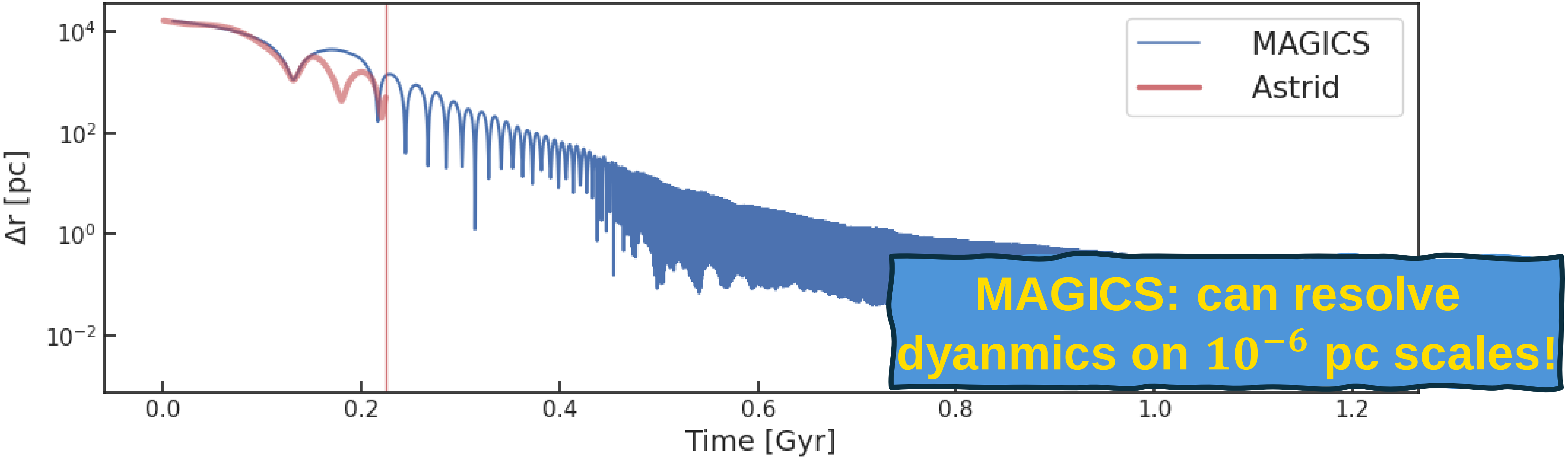


100 kpc
ASTRID
10 kpc
ASTRID
10 kpc
ASTRID
Higher resolution
0.00 Gyr
MAGICS
1 kpc
0.12 Gyr
MAGICS
1 kpc
0.47 Gyr
MAGICS
10 pc
0.97 Gyr
MAGICS
0.1 pc


100 kpc

MAGICS: Separation between the MBH binary

- **consistent evolution with Astrid**
- **resolve dynamics on smaller scales**



Summary

- **ASTRID simulation:**
  - **100 Mpc ~ 1 kpc**
  - Largest cosmological hydrodynamic simulations
  - Host the largest population of low-redshift MBH
  - A powerful tool to predict the sources of GW for upcoming LISA mission
- **MAGICS**
  - **10 kpc ~ 10^{-6} pc (for MBH)**
  - Bridge the gap between ASTRID and MBH dynamics on smallest scales (near MBHs)

Backup Slides

Discovery space for MBH

Gravitational Wave (GW) Detectors

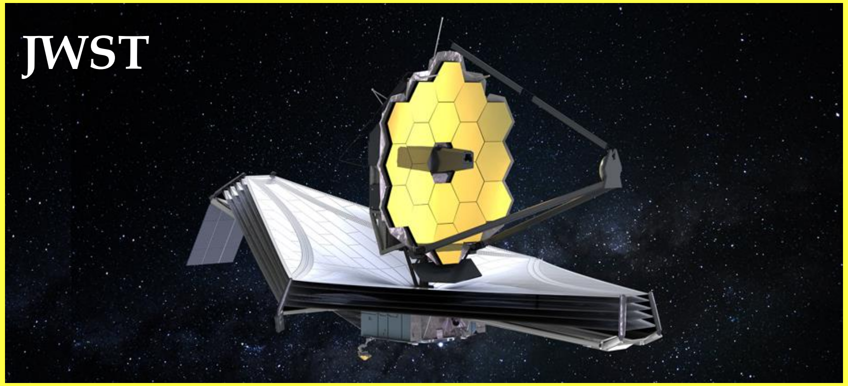
NANOGrav

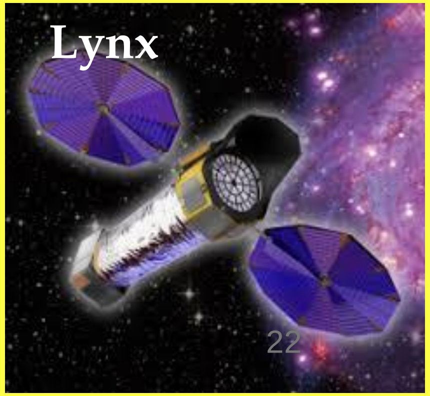
INTERNATIONAL PULSAR TIMING ARRAY
IPTA

EPTA

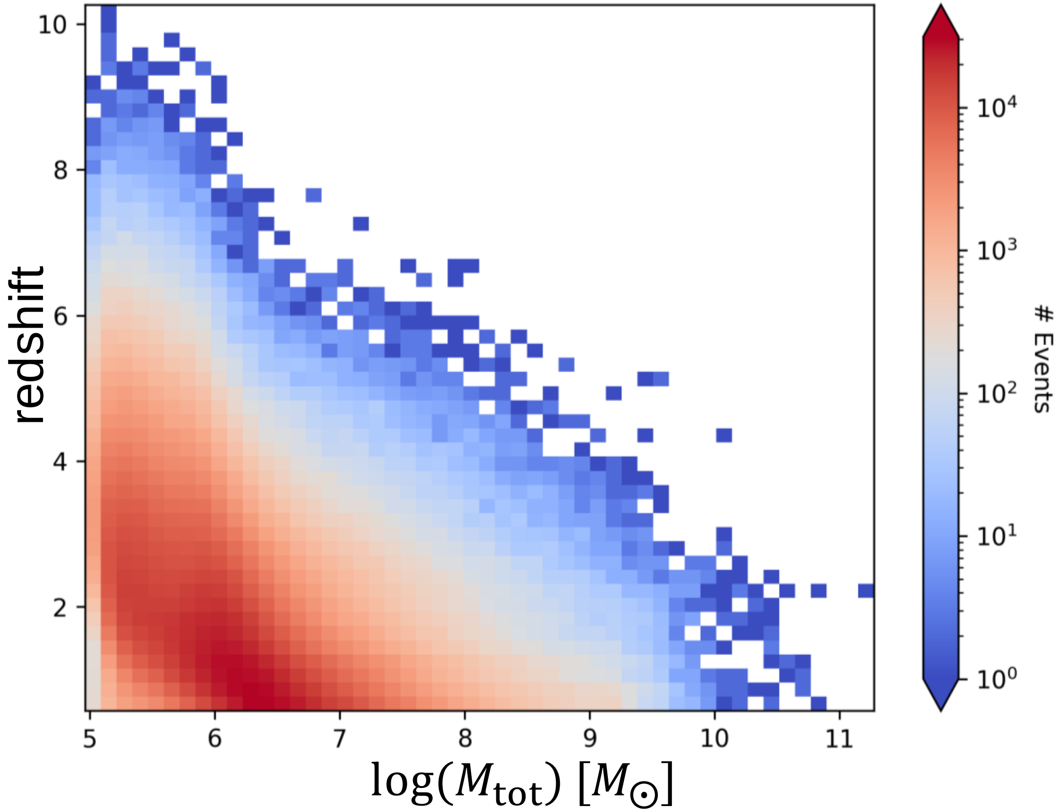
Electromagnetic (EM) Detectors

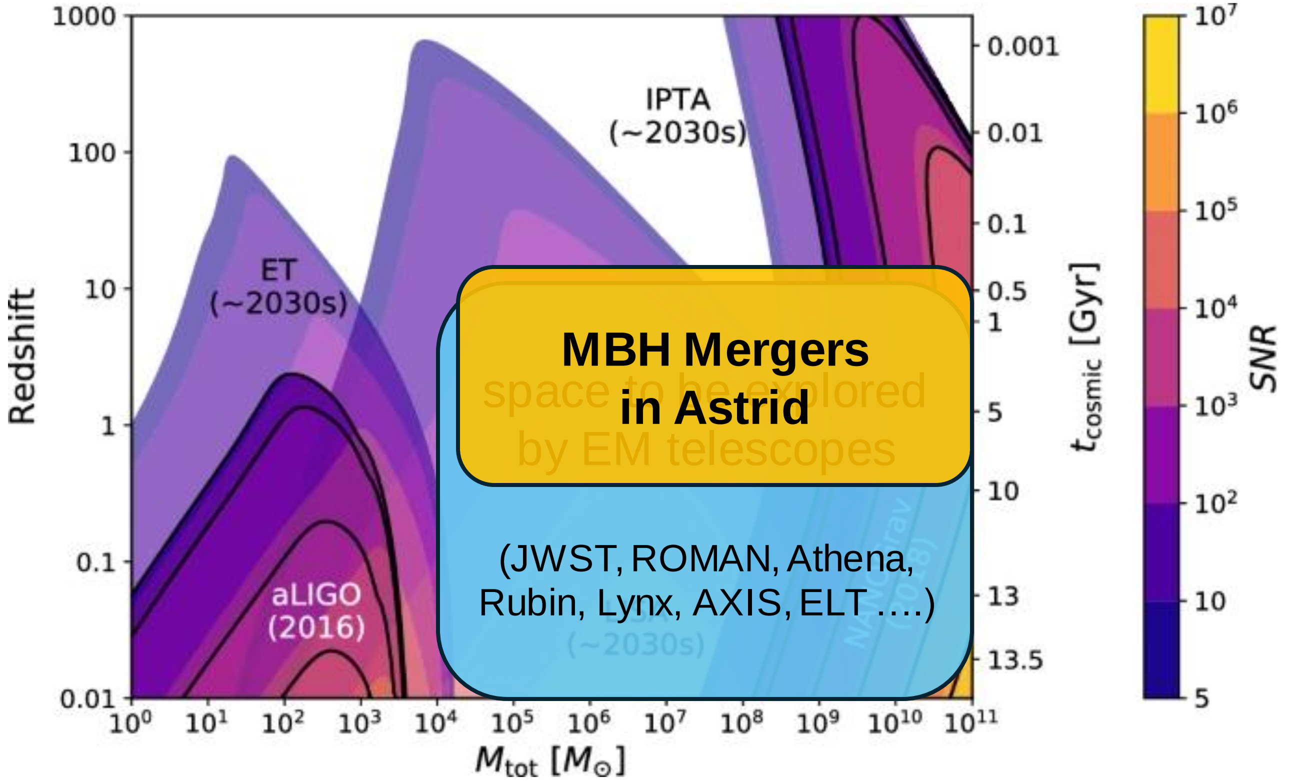
Optical Survey





MBH Merging Events in Astrid

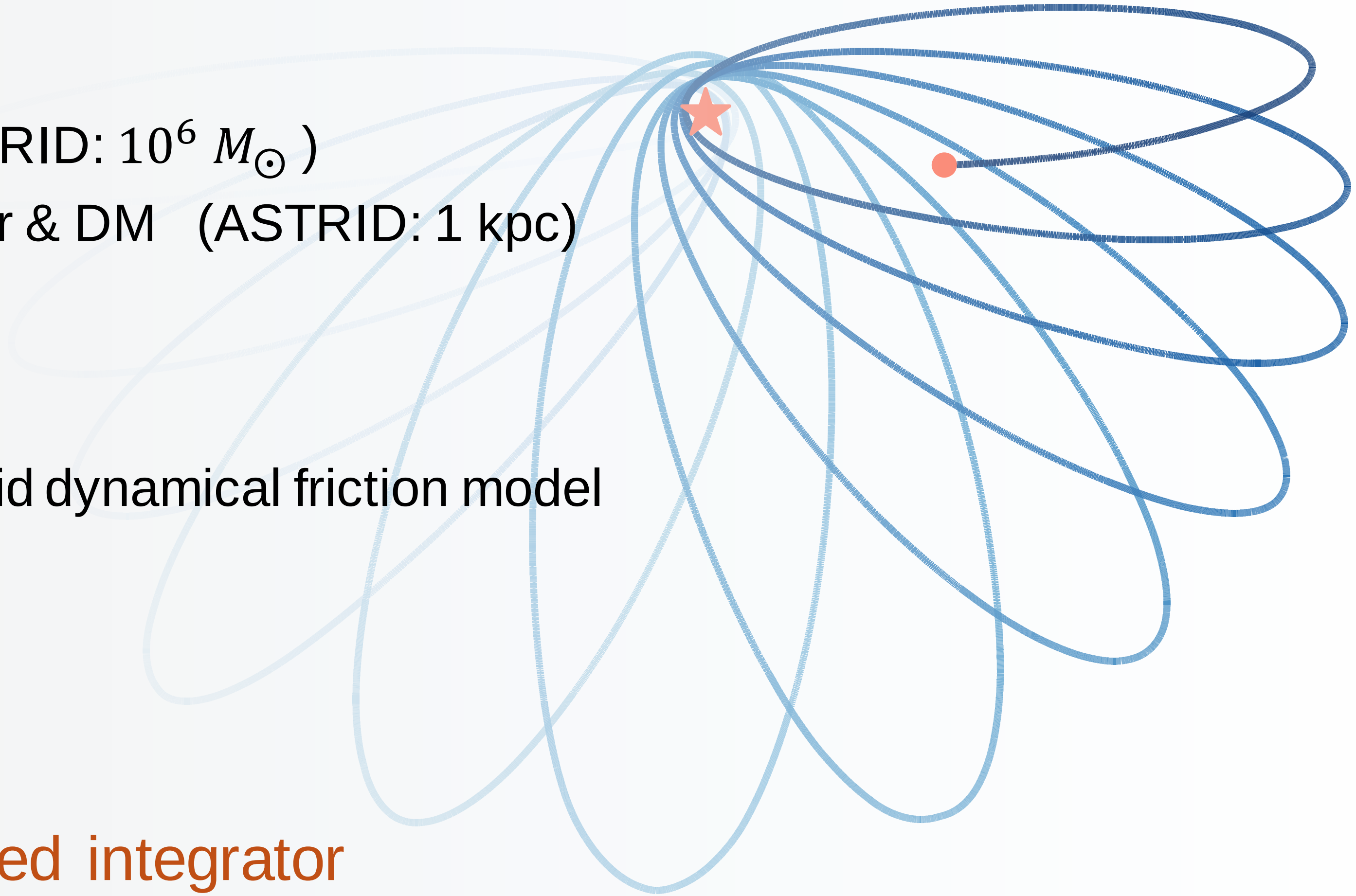




Plot from Burke-Spolaor+2018

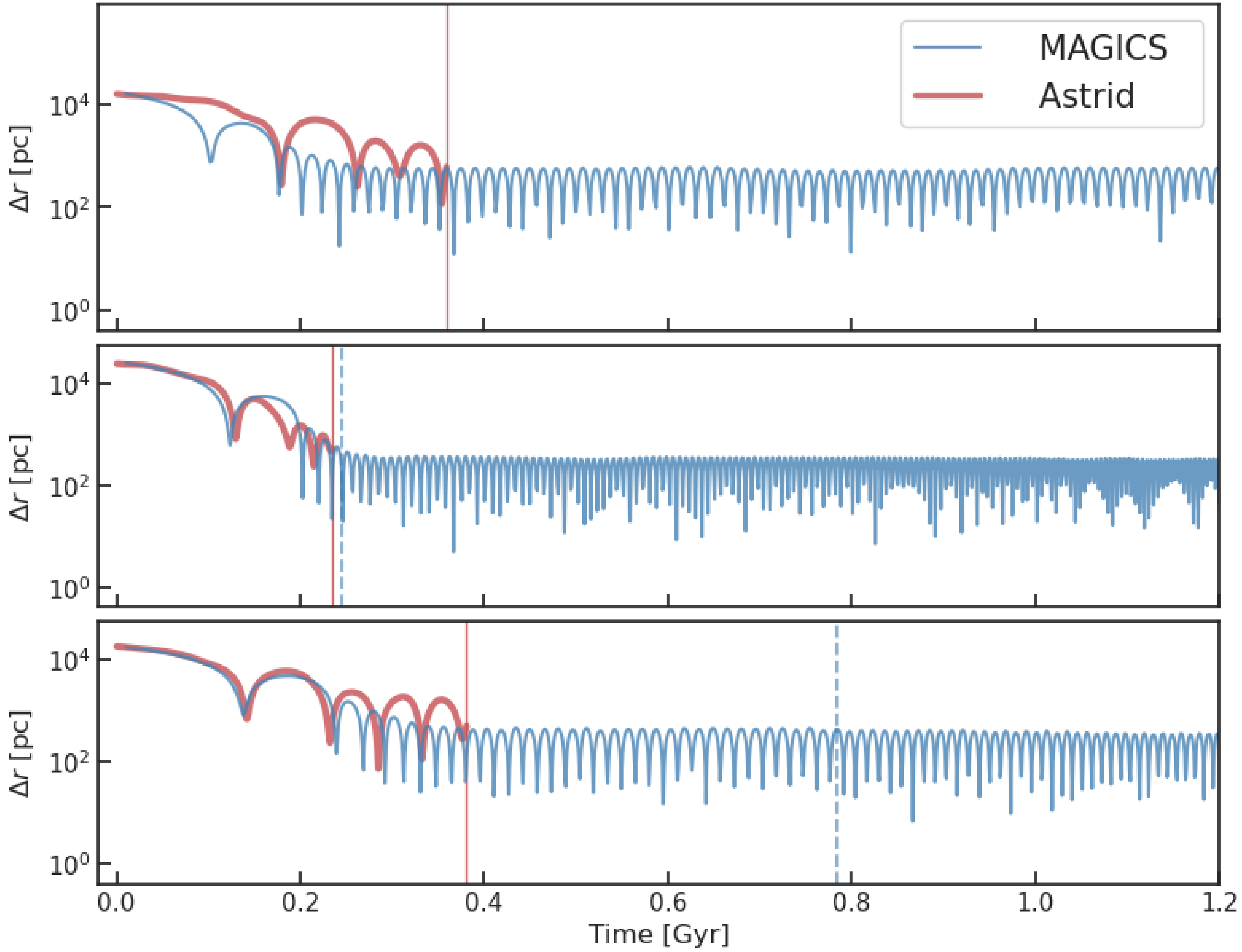
Improvements in **MAGICS**

- Resolution
  - Better mass resolution: 500 $M_\odot$ (ASTRID: 10^6 $M_\odot$)
  - Better spatial resolution: 5 pc for stellar & DM (ASTRID: 1 kpc)
- Hydro models
  - No need for the semi-analytical sub-grid dynamical friction model
  - Circumbinary accretion
- **Gravity integrator:**
  - KETJU: Algorithmically regularized integrator
  - **→ able to trace the MBH down to scales of 10^{-6} pc !**



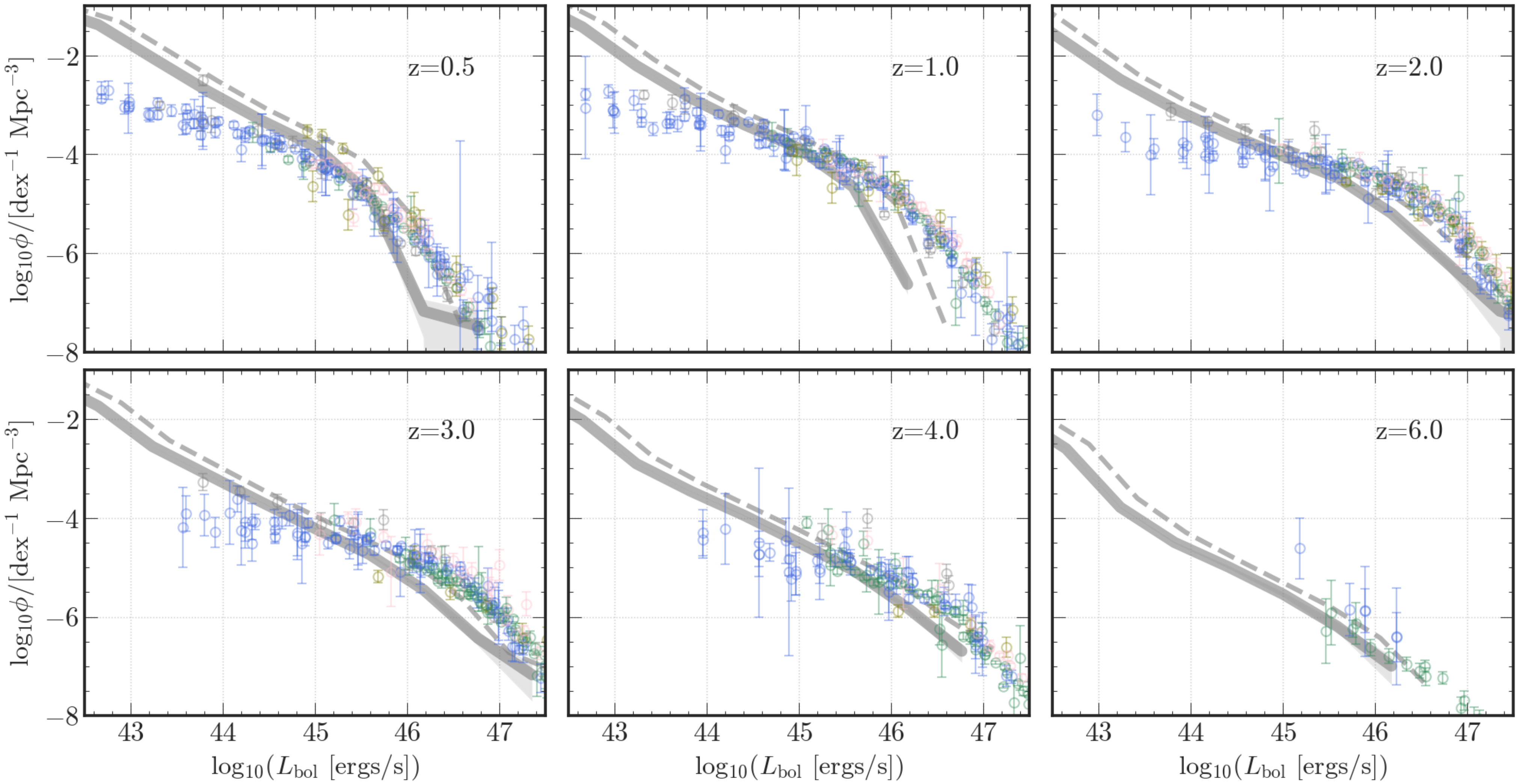
Different fate of MBH pairs

stalling or merging?



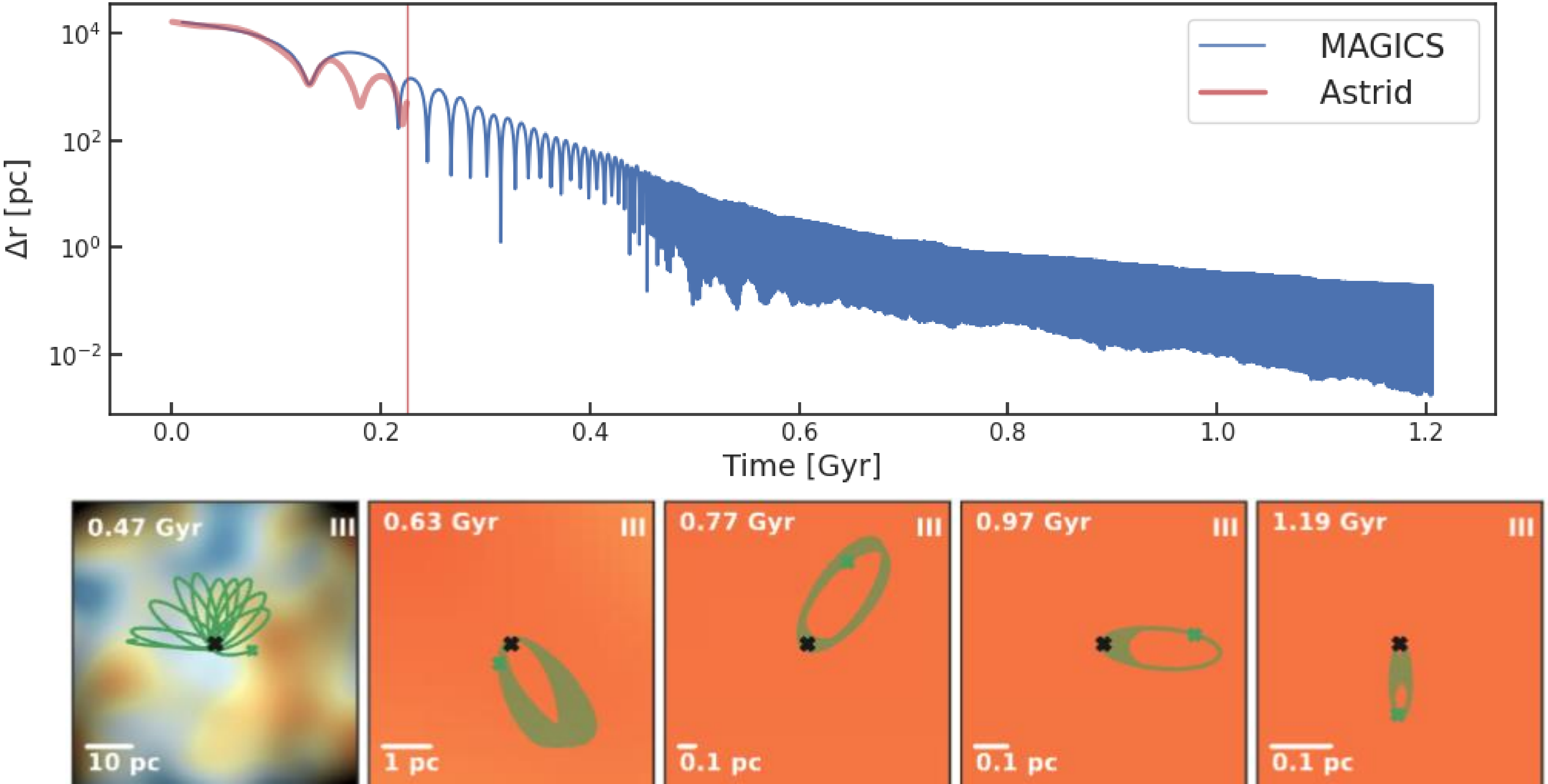
MBH Population in Astrid：

Prediction for MBH population: luminosity function



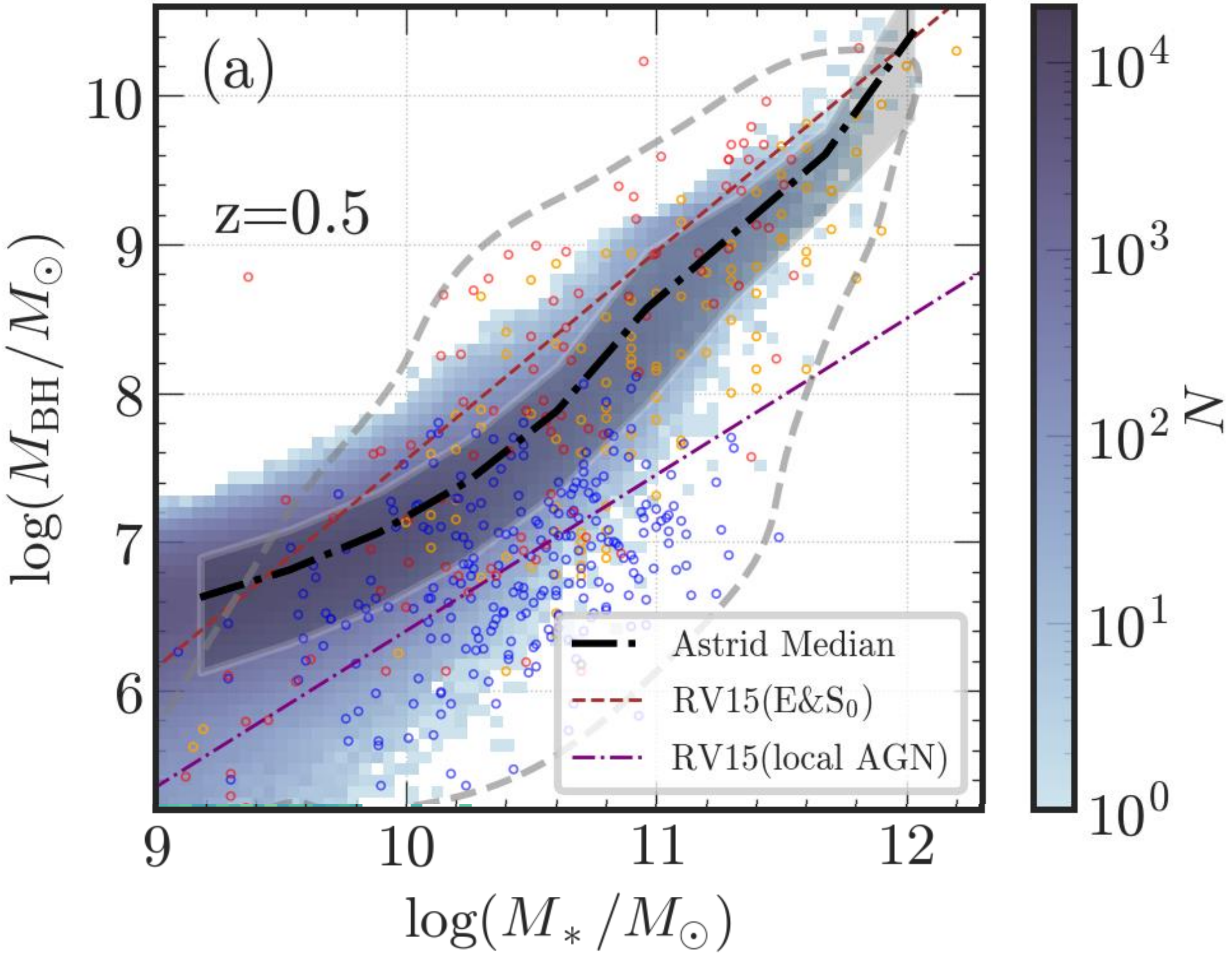
Ni+2024

Separation between the MBH binary



MBH Population in Astrid

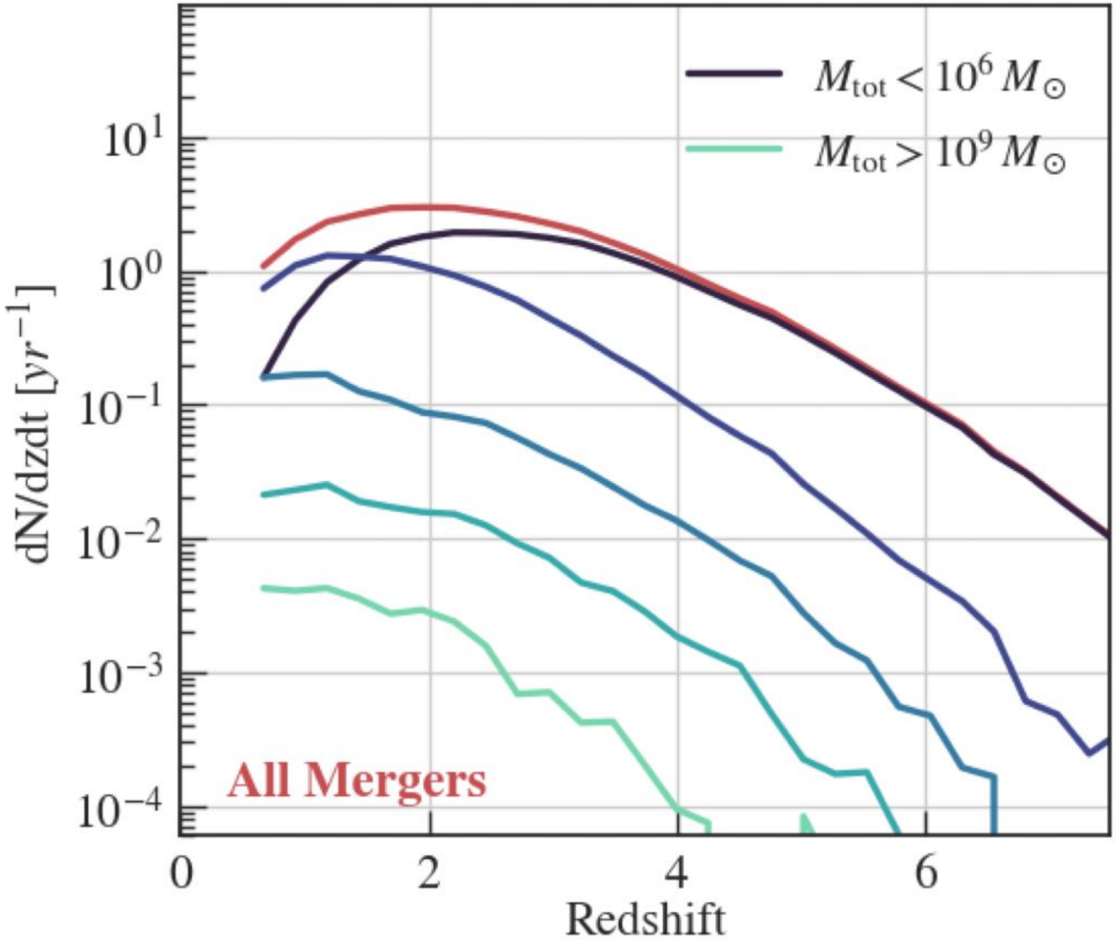
- **capture the coevolution of MBH and galaxy**



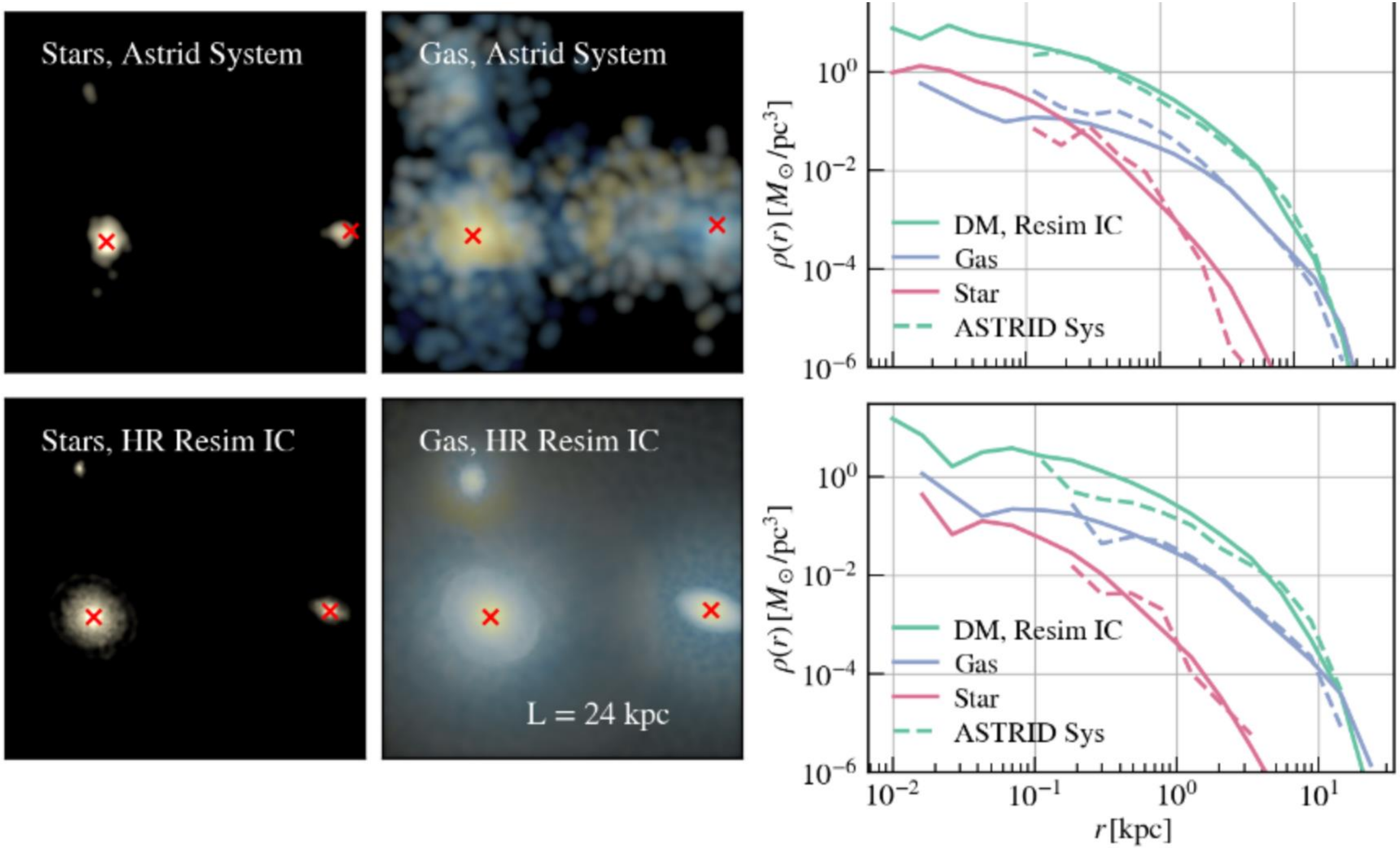
Ni+2024

MBH Merging Events in Astrid

MBH merging rates

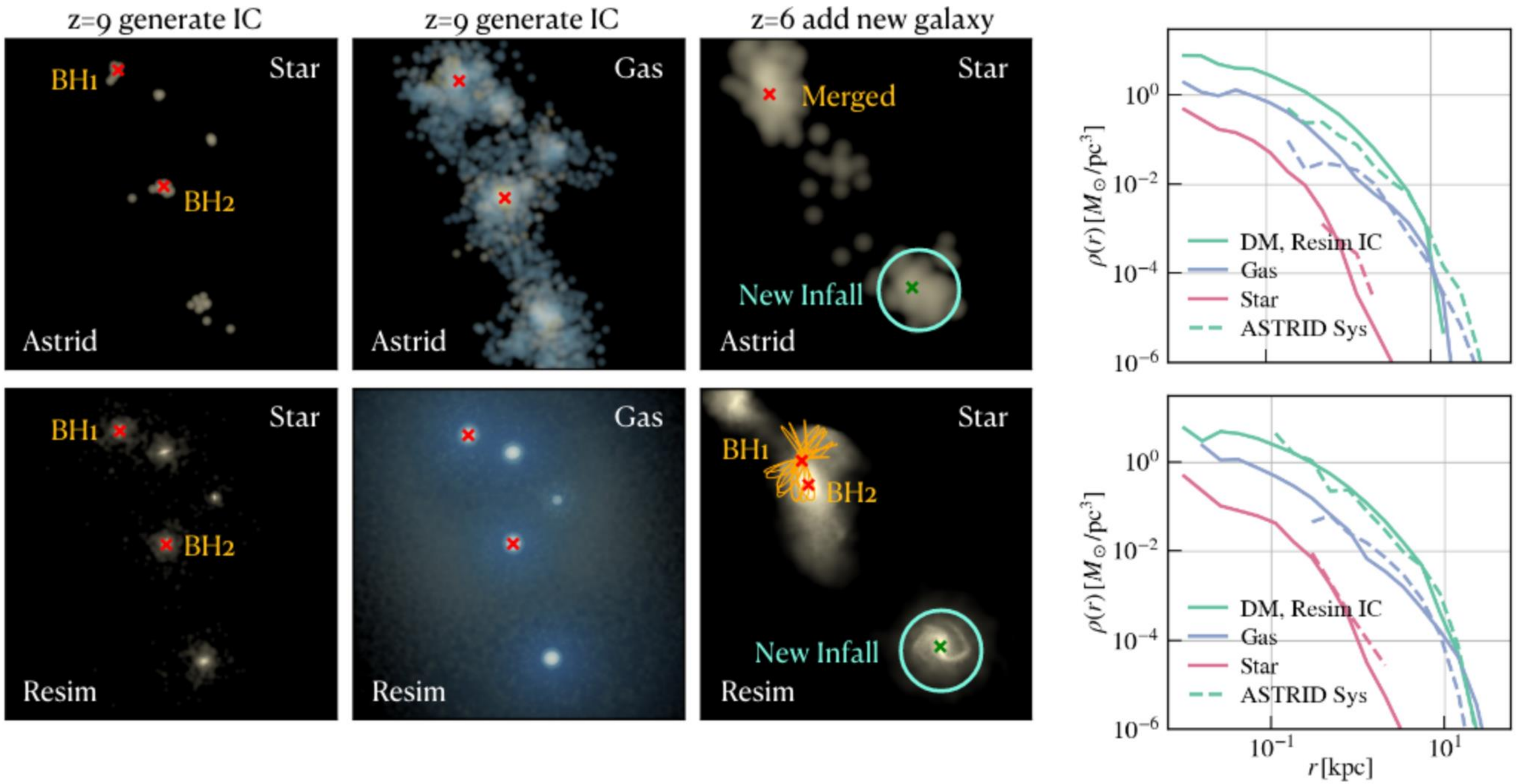


MAGICS



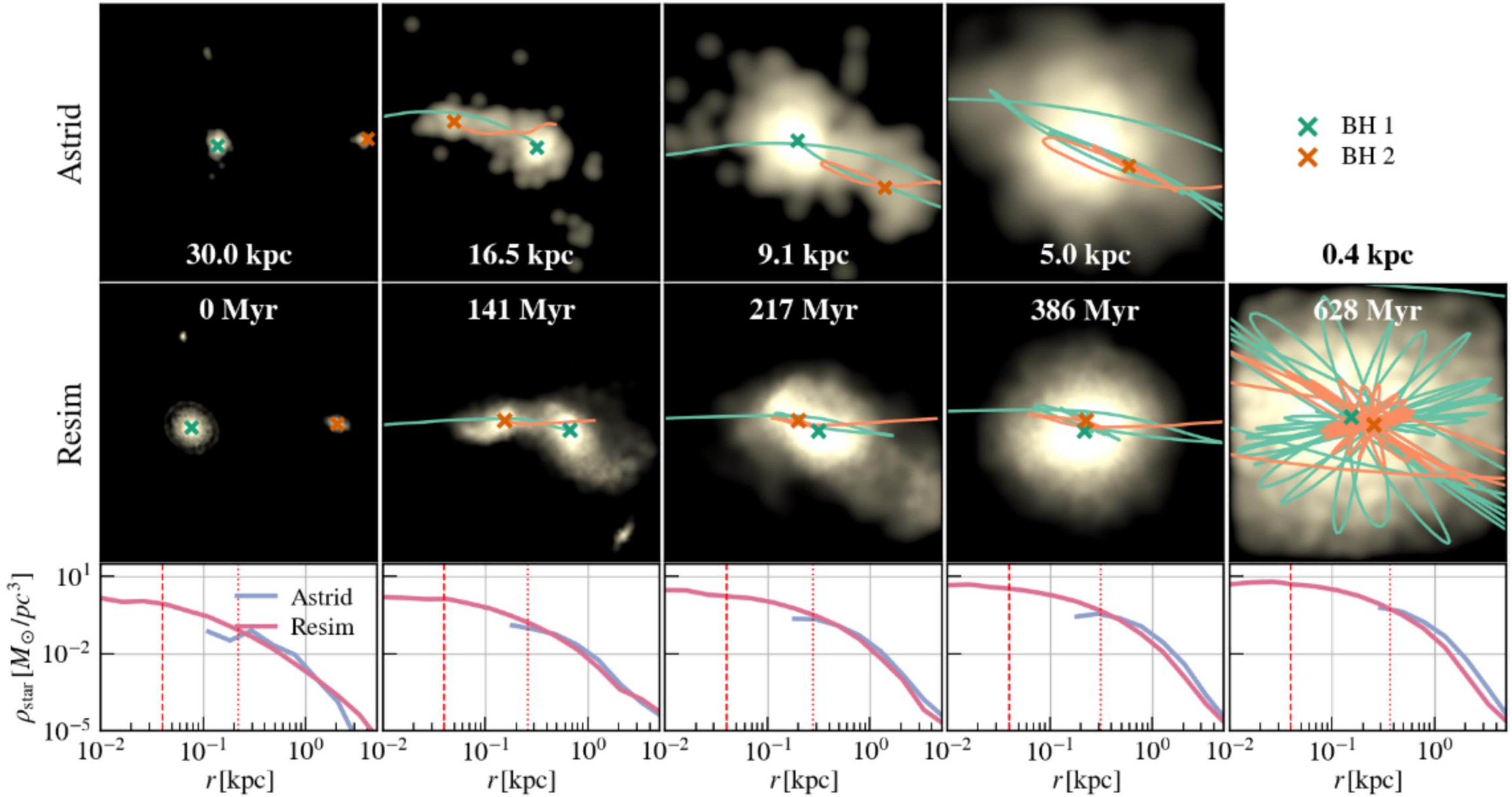
Stars, Astrid System
Gas, Astrid System
Stars, HR Resim IC
Gas, HR Resim IC
L = 24 kpc
$\rho(r)\,[M_\odot/\mathrm{pc}^3]$
10^0
10^{-2}
10^{-4}
10^{-6}
DM, Resim IC
Gas
Star
ASTRID Sys
10^{-2}
10^{-1}
10^0
10^1
$r\,[\mathrm{kpc}]$

MAGICS



z=9 generate IC
z=9 generate IC
z=6 add new galaxy
BH1
BH2
Star
Astrid
Gas
Astrid
Merged
New Infall
Star
Astrid
BH1
BH2
Star
Resim
Gas
Resim
BH1
BH2
Star
New Infall
Resim
$\rho(r)\,[M_\odot/\mathrm{pc}^3]$
10^0
10^{-2}
10^{-4}
10^{-6}
DM, Resim IC
Gas
Star
ASTRID Sys
10^{-1}
10^1
$r\,[\mathrm{kpc}]$

MAGICS



Astrid
Resim
30.0 kpc
16.5 kpc
9.1 kpc
5.0 kpc
0.4 kpc
0 Myr
141 Myr
217 Myr
386 Myr
628 Myr
BH 1
BH 2
Astrid
Resim
$\rho_{\rm star}\,[M_\odot/pc^3]$
$r\,[\rm kpc]$