

Tracing Massive Black Hole evolution with Gravitational Waves and dual AGN

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Fabio Rigamonti, Rosa Valiante, Roberto Della Ceca and more!

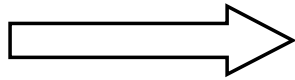


Background image credit: International Gemini Observatory / NOIRLab / NSF / AURA / M. Zamani, J. da Silva

Halo mergers to black hole mergers



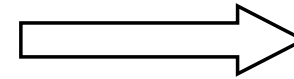
Halo merger



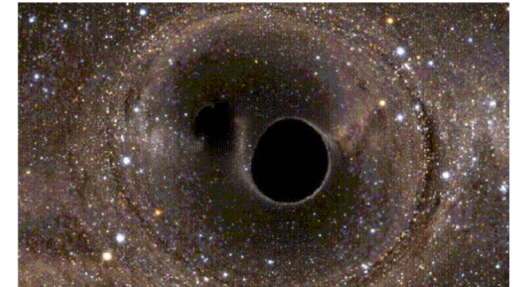
International Gemini Observatory/NOIRLab/NSF/AURA



Galaxy merger



<https://www.youtube.com/watch?v=hbmpe17fzA>



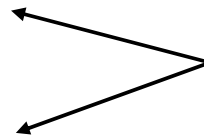
MBH merger



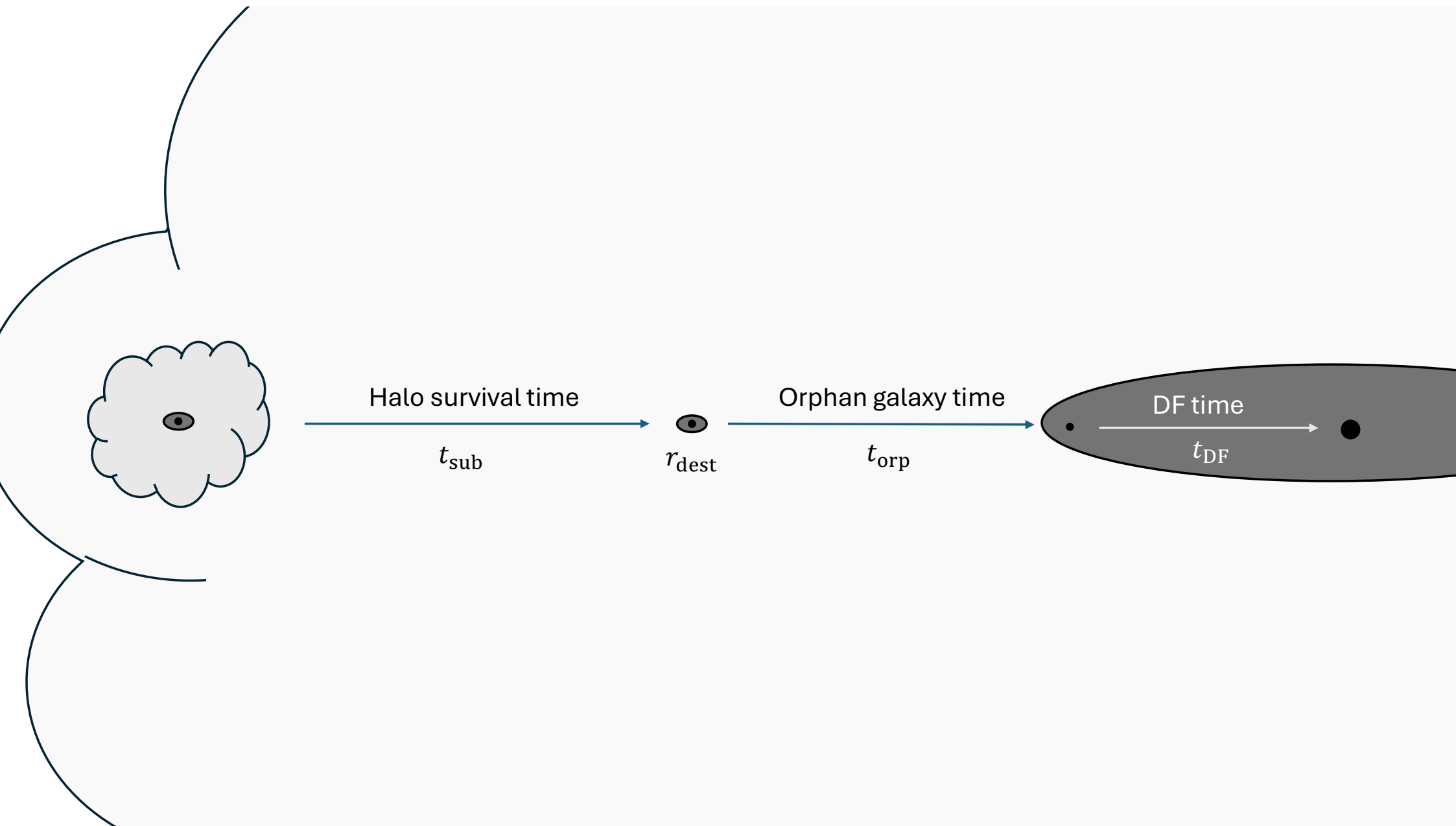
Dual/Binary AGN phase

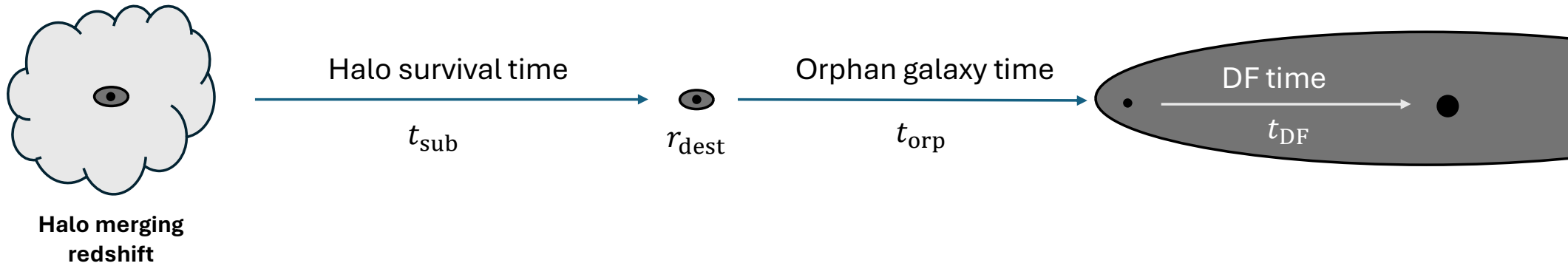
BH luminosity

Separation evolution



<https://cseligman.com/text/atlas/ngc37a.htm>





PINOCCHIO

(PINpointing Orbit Crossing Collapsed Hierarchical Objects)

Dark matter only code

Continuous time sampling of merger histories

60 Mpc side length box utilized

<https://github.com/pigimonaco/Pinocchio>

Minimum halo mass = $7.9 \times 10^7 M_{\odot}$

Arte e Vino, Castel Gandolfo
Photo taken during LGWA 2024 meeting

Halo 1

Halo 2

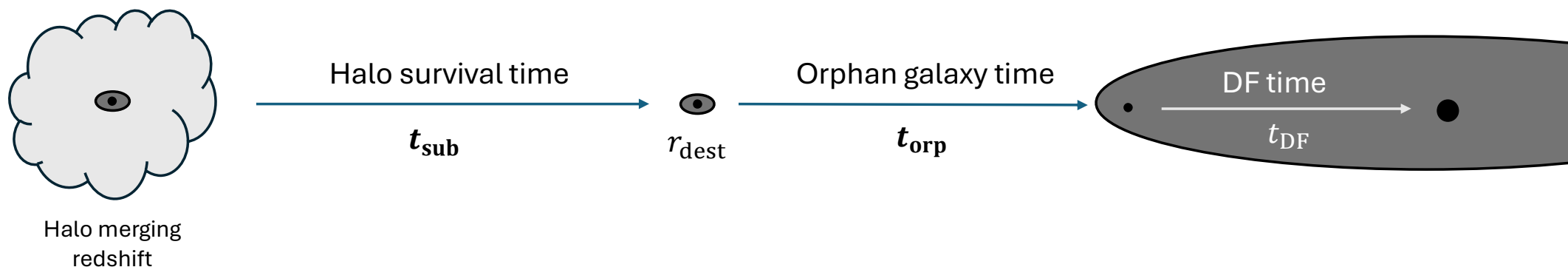
$D_i \approx R_{\text{virial},1}$

$$M_1 = \frac{4}{3} \pi R_{\text{virial},1}^3 \Delta \rho_c(z)$$

$$= \frac{4}{3} \pi R_{L_1}^3 \Delta \rho_c(z)$$

$$R_{\text{virial},1} = \left(\frac{3M_1}{4\pi \Delta \rho_c(z)} \right)^{\frac{1}{3}}$$

$\Delta \approx 200$



PinGAEA semi analytical model

Cammelli et al. (**JS** included), 2025

PINOCCHIO

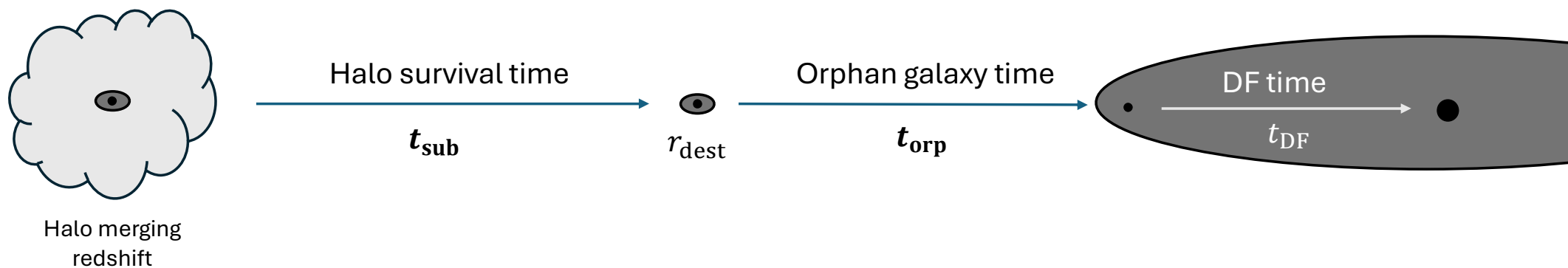
+

GAEA

GALaxy Evolution and Assembly model
(Hirschmann et al. 2016, Fontanot et al.
2020, De Lucia et al. 2024)

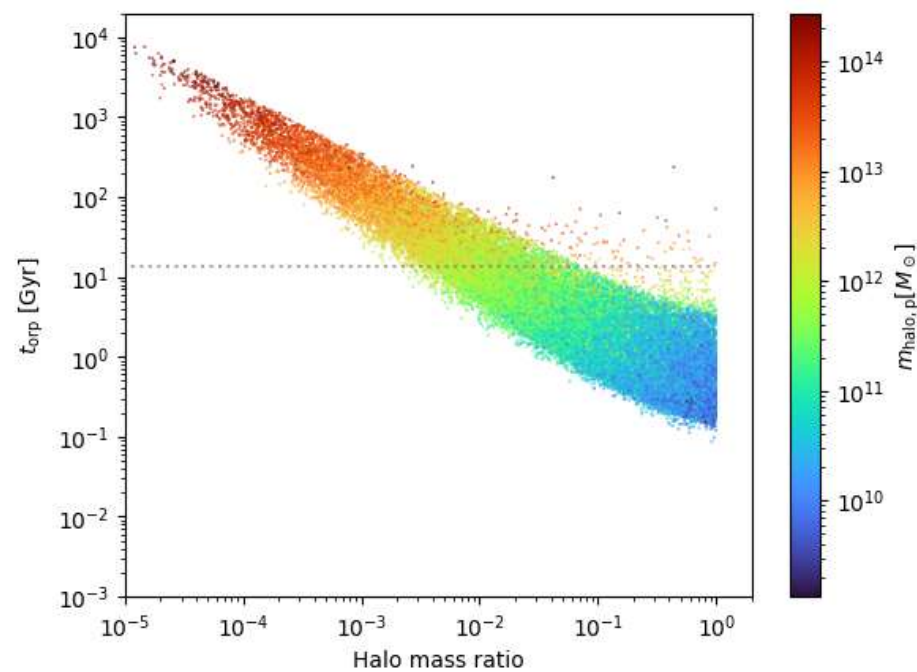
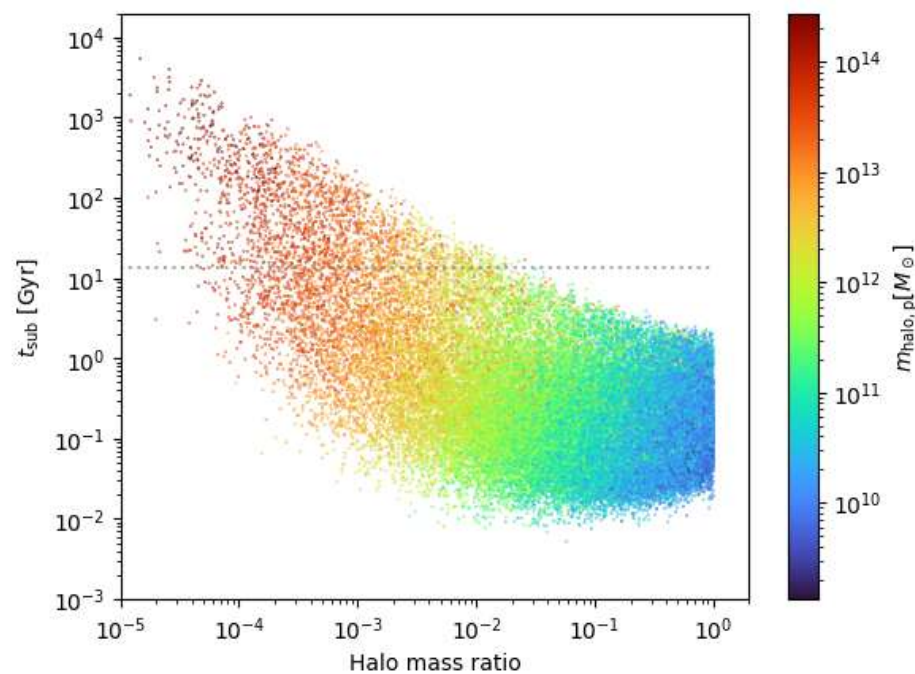
Light seed model

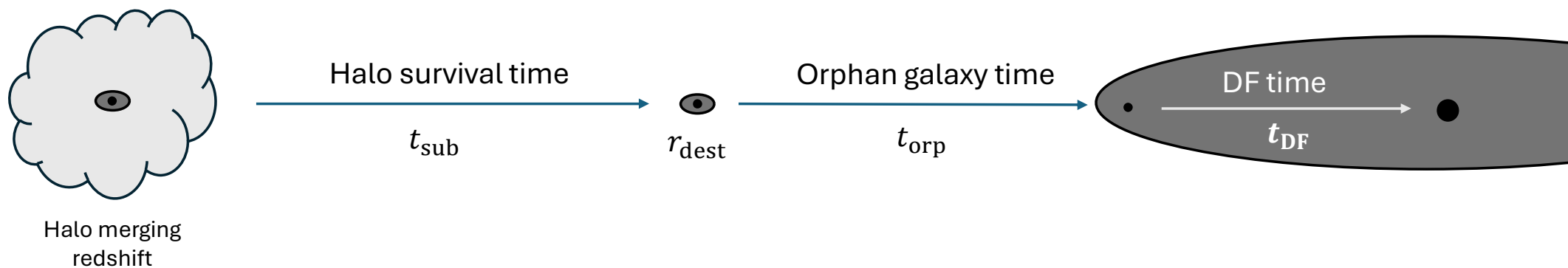
- Mimics black hole seeds formed from the collapse of Pop III stars in the early universe.
- **All Light Seeds (ALS)** (Volonteri+11, Xie+17, Cammelli+25)
- Seeding every dark matter halo with a light BH seed ranging from ~ 5 to $\sim 300 M_{\odot}$.



PinGAEA semi analytical model

Cammelli et al. (**JS** included), 2025





Chandrasekhar timescale:

$$t_{\text{DF}} = 19 \left(\frac{r_0}{5 \text{ kpc}} \right)^2 \left(\frac{\sigma}{200 \text{ km/s}} \right) \left(\frac{10^8 M_{\odot}}{M_{\text{infall}}} \right) \frac{1}{\Lambda} \text{ Gyr}$$

$M_{\text{infall}} = M_{\text{BH,secondary}} \rightarrow$ Upper limits of t_{DF}

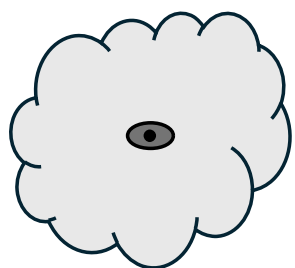
$M_{\text{infall}} = M_{\star,\text{secondary}} \rightarrow$ Lower limits of t_{DF}

r_0 - remnant galaxy radius

σ - velocity dispersion

M_{infall} - infalling object

$\Lambda = \ln(1 + M_{\star}/M_{\text{infall}})$



Halo merging
redshift

PINOCCHIO

Halo survival time

t_{sub}



r_{dest}

PinGAEA

Orphan galaxy time

t_{orp}

PinGAEA

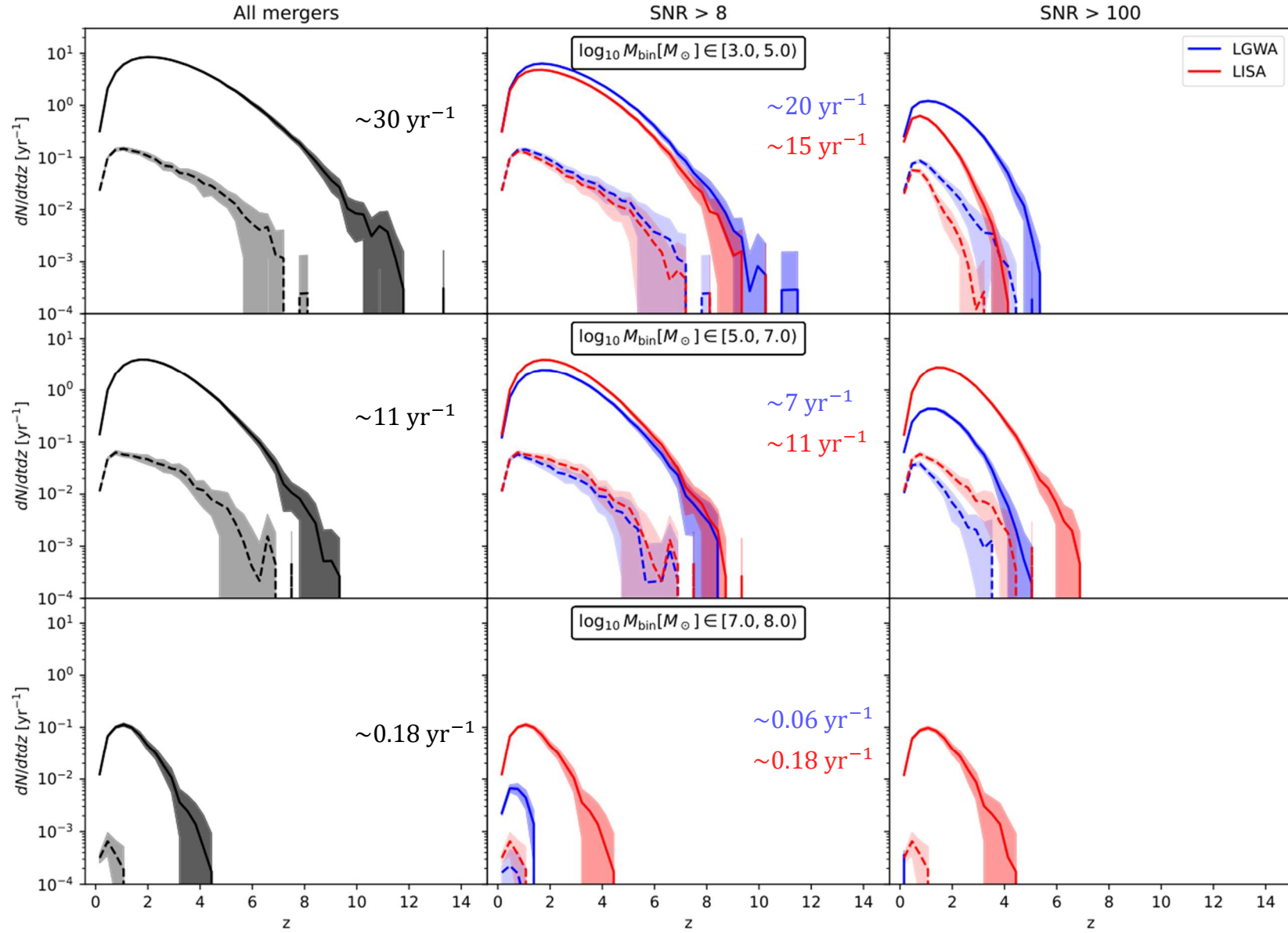
DF time

t_{DF}

Chandrasekhar
timescale

BH merging
redshift!

Merger rates

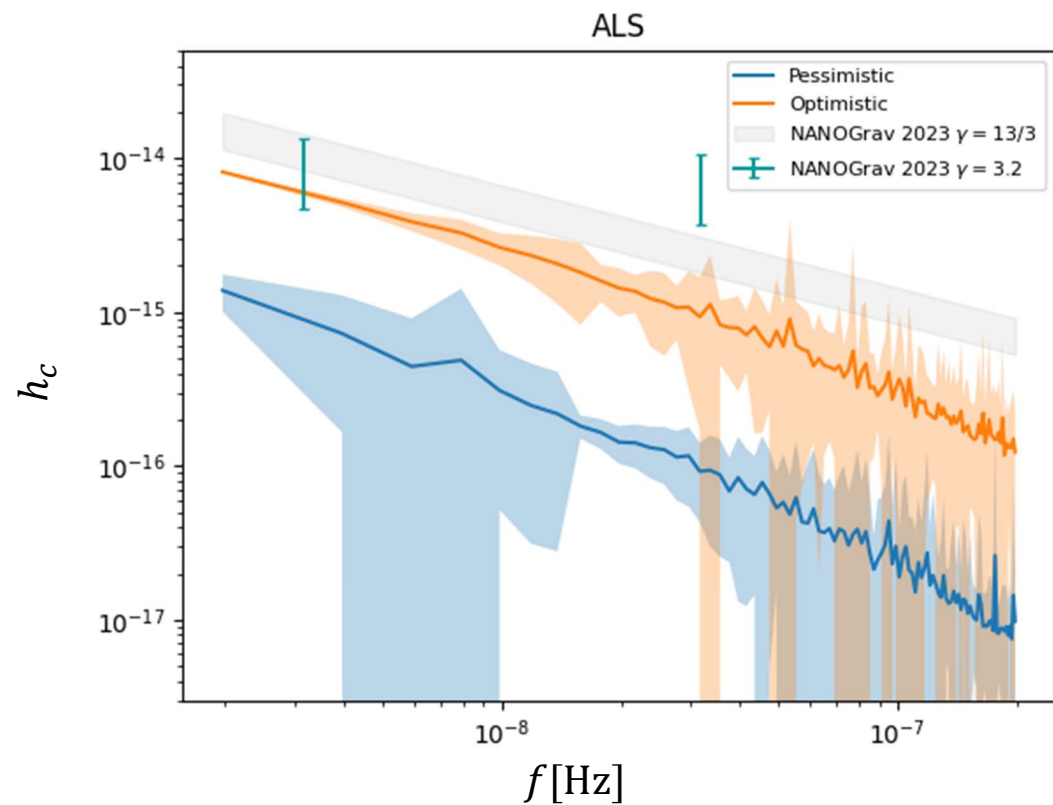
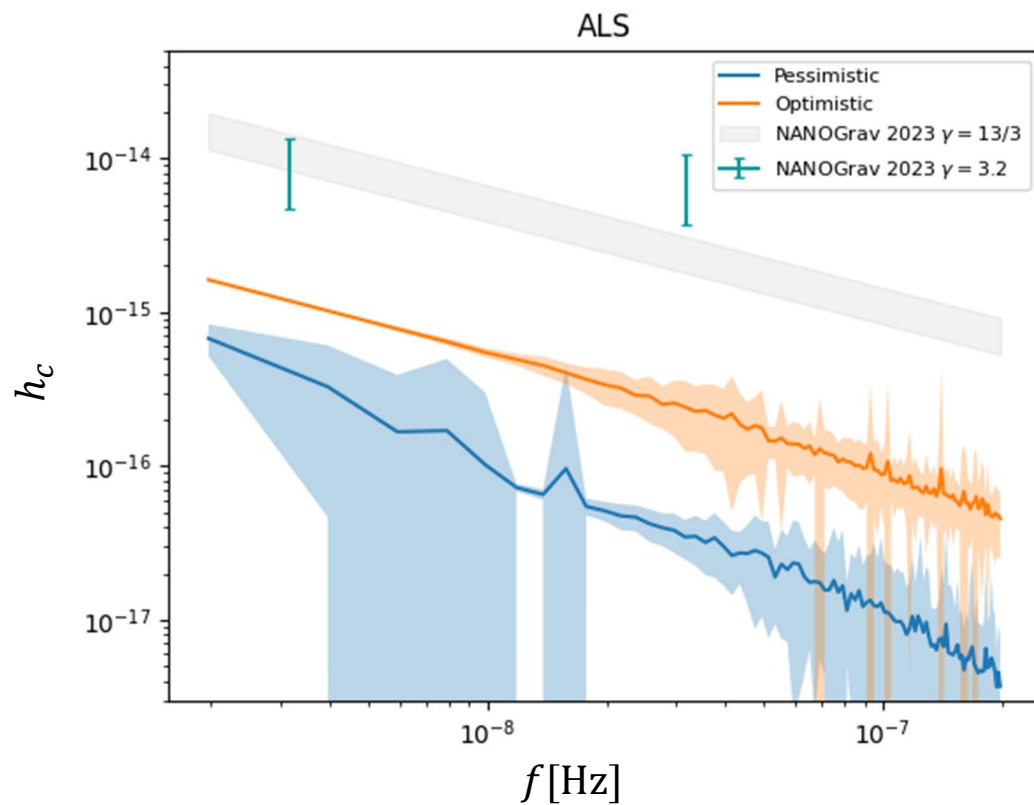


ALS

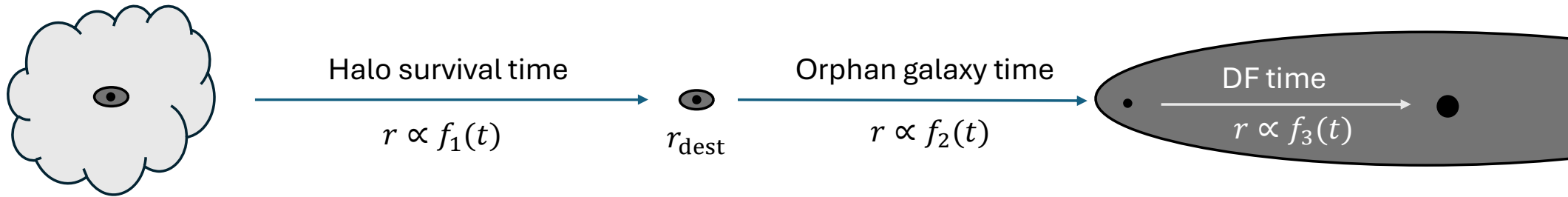
JS et al., 2026

S/N calculated using GWFish (Duplesta+23)

Gravitational Wave Background



Masses boosted



Rate of change of angular momentum:

$$\frac{dL}{dt} = m(t)v_c \frac{dr}{dt}$$

v_c : circular velocity

$$\frac{dL}{dt} = -0.428\Lambda \frac{Gm(t)^2}{r}$$

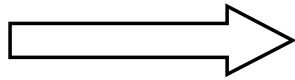
Chandrasekhar1943;
Binney & Tremaine 2008

$$\frac{dr}{dt} = -0.302\Lambda \frac{Gm(t)}{r\sigma}$$

Halo mergers to black hole mergers



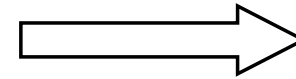
Halo merger



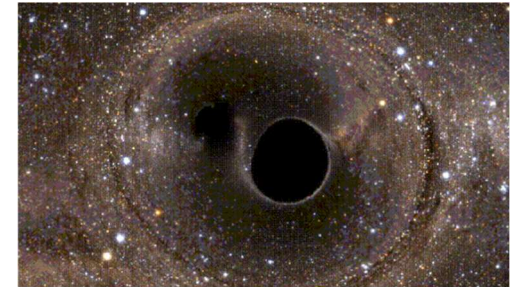
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Galaxy merger



<https://www.youtube.com/watch?v=hbbMpe17fzA>



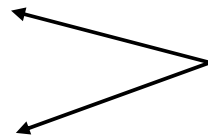
MBH merger



Dual/Binary AGN phase

BH luminosity

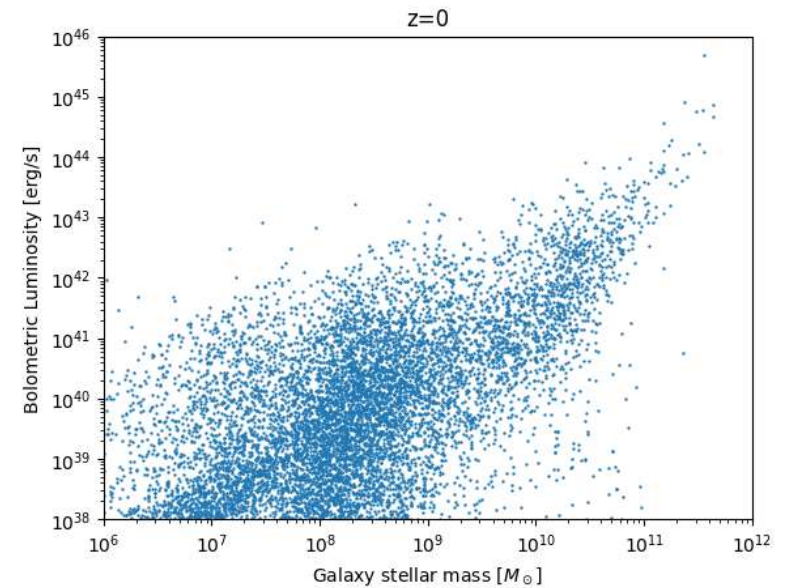
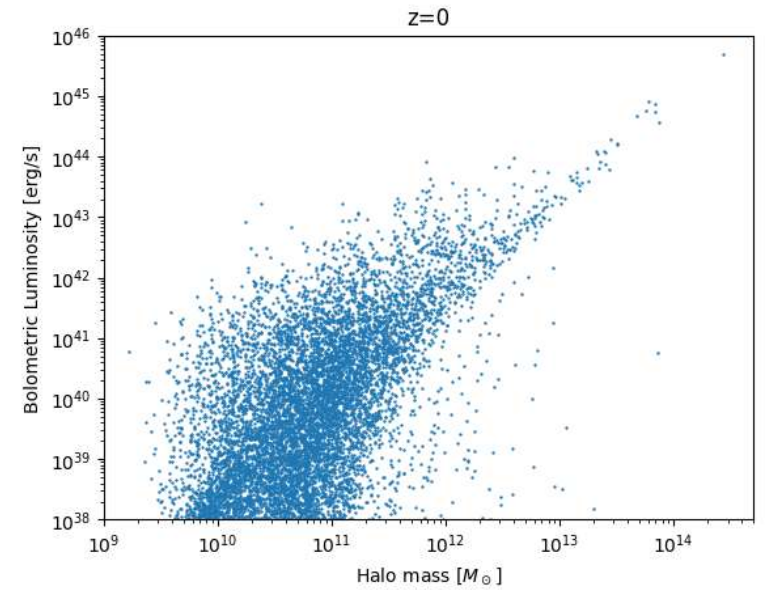
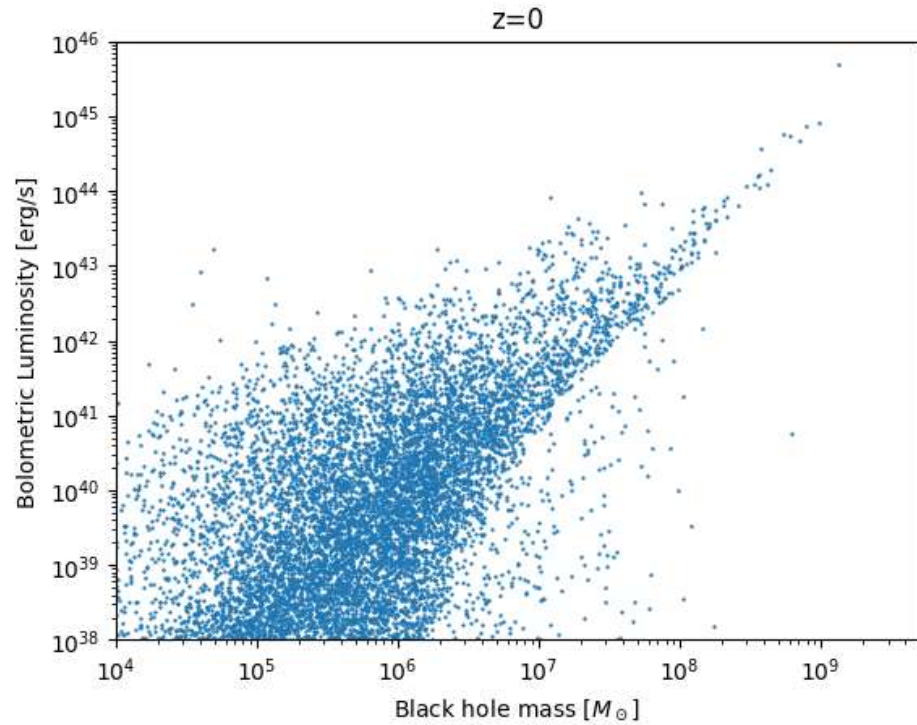
Separation evolution



<https://cseligman.com/text/atlas/ngc37a.htm>

Bolometric Luminosity

PinGAEA semi analytical model



Assigning luminosity to BH pairs



Main hurdle: PinGAEA snapshots do not contain the ID of PINOCCHIO halos.

Solution:

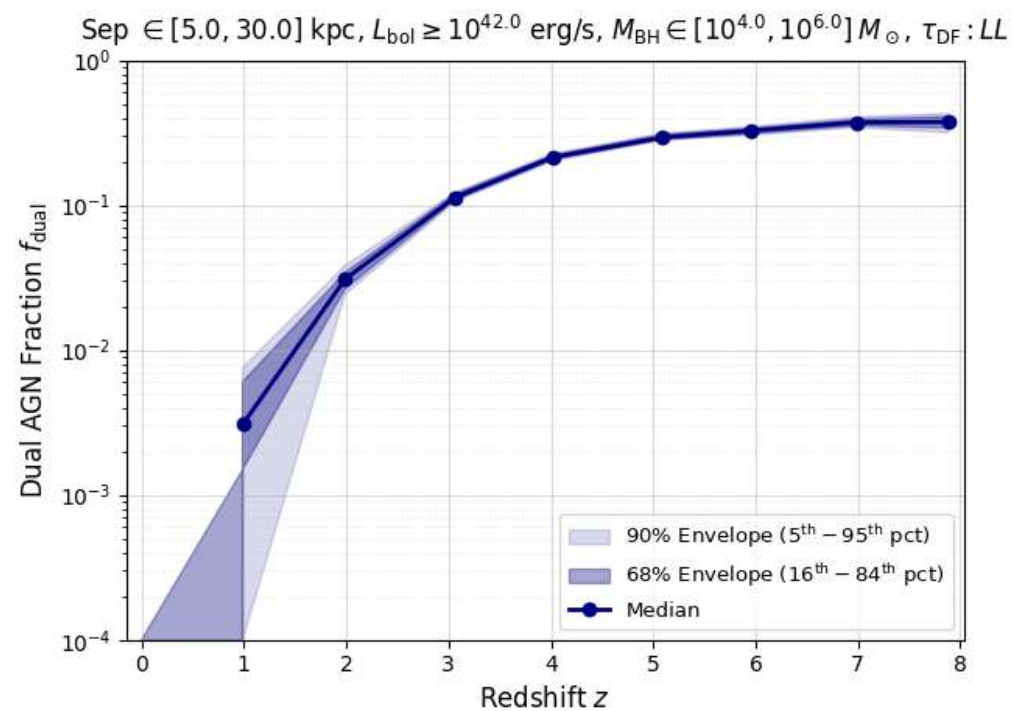
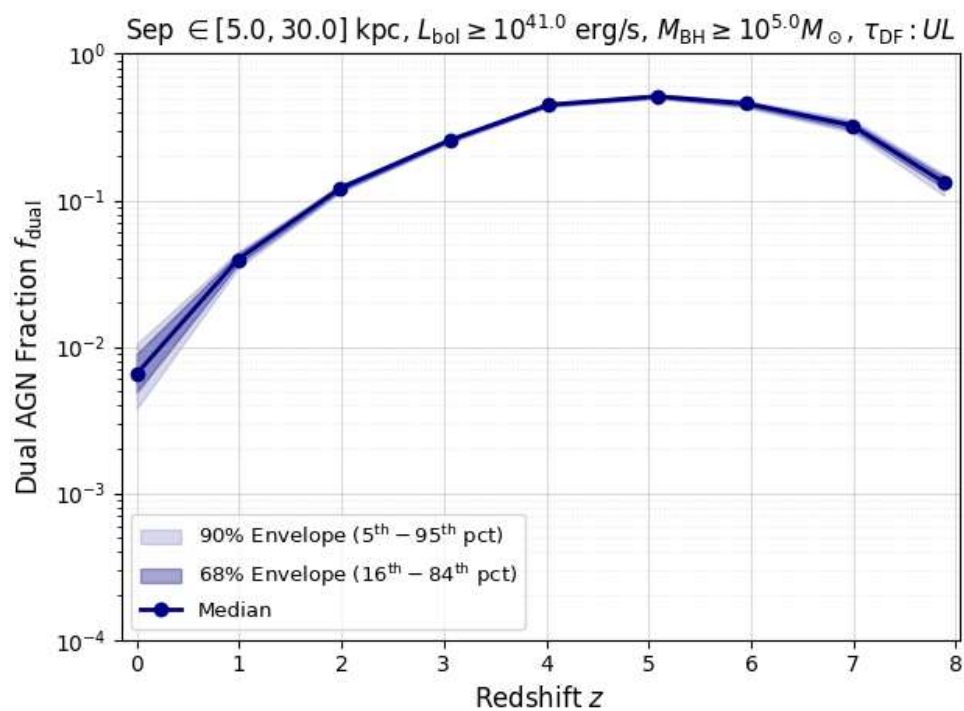
- Create a k -d tree with mass vectors ($\log_{10} M_{\text{halo}}$, $\log_{10} M_{\star}$, $\log_{10} M_{\text{BH}}$) at each snapshot redshift.
- For each BH (halo) of interest (merging or non-merging) identified using PINOCCHIO merger history, find n nearest neighbours from the tree at the snapshot redshift of interest.
- Draw a random neighbour from the n nearest to assign its bolometric luminosity, for S Monte Carlo realizations.

Result:

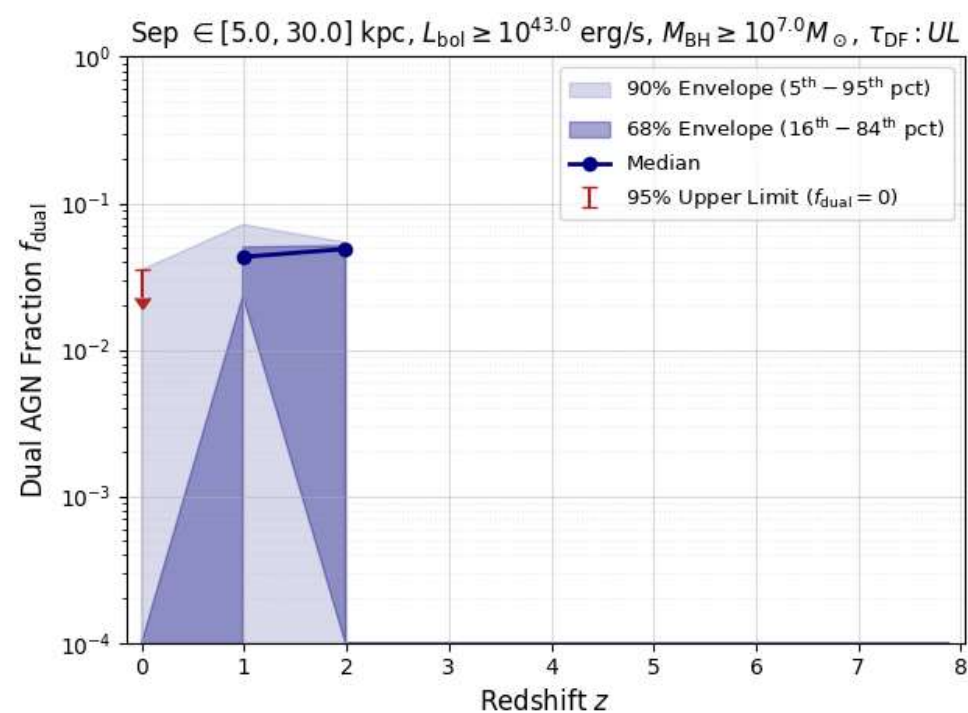
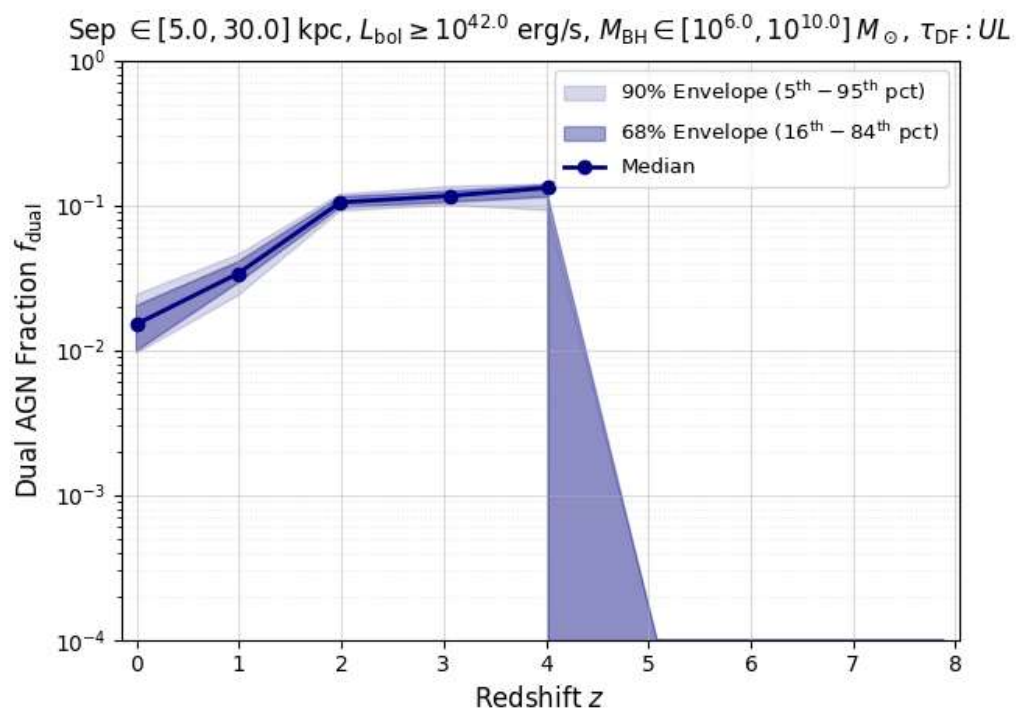
- Each realization contains a sampled luminosity of each BH, merging or non-merging at a particular redshift.
- By setting a minimum luminosity definition for an AGN, the dual AGN fraction for each realization is computed by:

$$f_{\text{dual}} = \frac{\text{number of AGN in pairs}}{\text{total number of AGN}}$$

Dual AGN fractions



Dual AGN fractions



Summary

- Using PinGAEA semi-analytical model, various properties of the galaxies and black holes can be calculated.
- Merger rates of more than 25 yr^{-1} expected of events with $\text{SNR} > 8$ in both LGWA and LISA detectors in the optimistic scenario for light seed scenario.
- The GWB amplitude is lower than observed but is consistent after mass enhancement.
- Modelling the separation evolution of MBH pairs with simple prescriptions allows quick predictions for dual AGN fraction.
- Next steps involve implementing the SAM on a larger volume and to compare with other simulations and observations.