LISA MBHCatalogs

A large collaborative project
with a large dataset of massive black hole binaries

November, Garching 2024

How it started..

Astrophysics with the Laser Interferometer Space Antenna
Living Review, 2023

Theoretical predictions on the merger rates of MBHs span several orders of magnitude, across a large range of redshifts.
From <1 to 100s yr-1.

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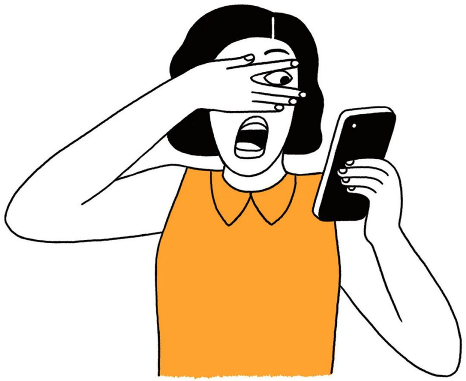

This is good news,
IF we can i) understand the global astrophysics uncertainties and ii) identify the robust model-independent predictions.

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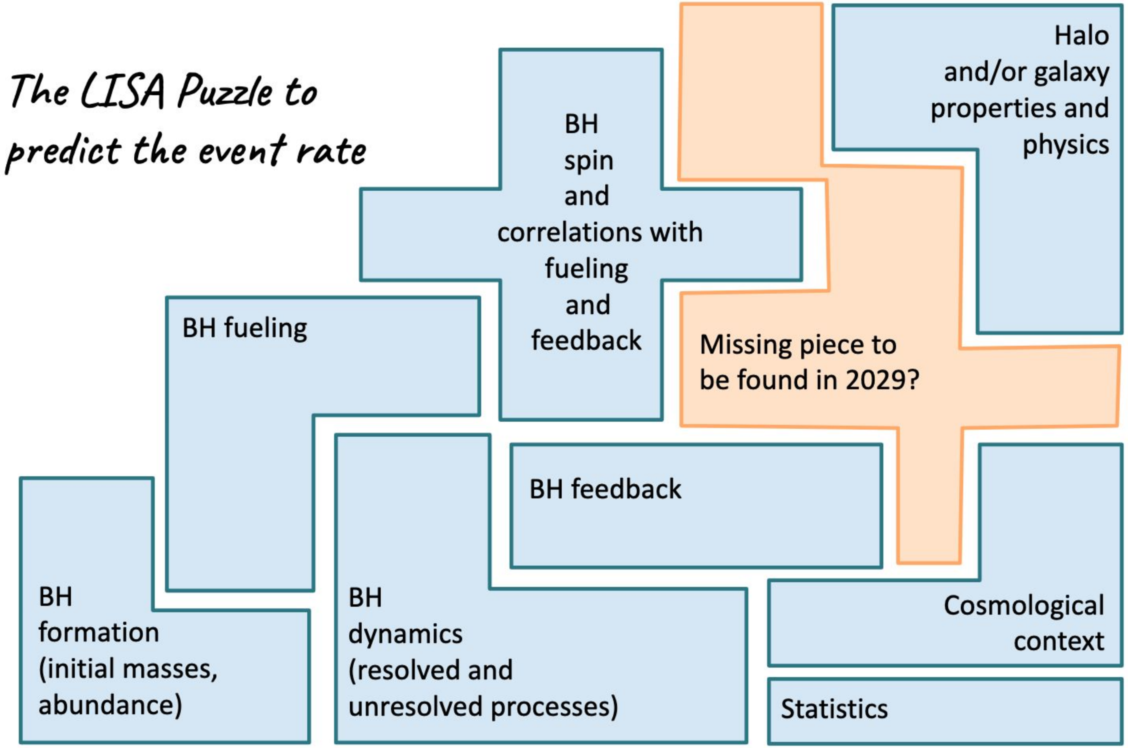

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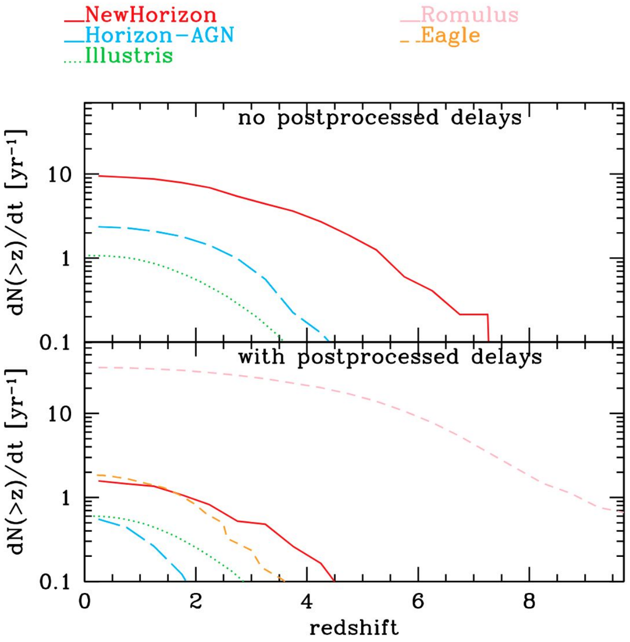
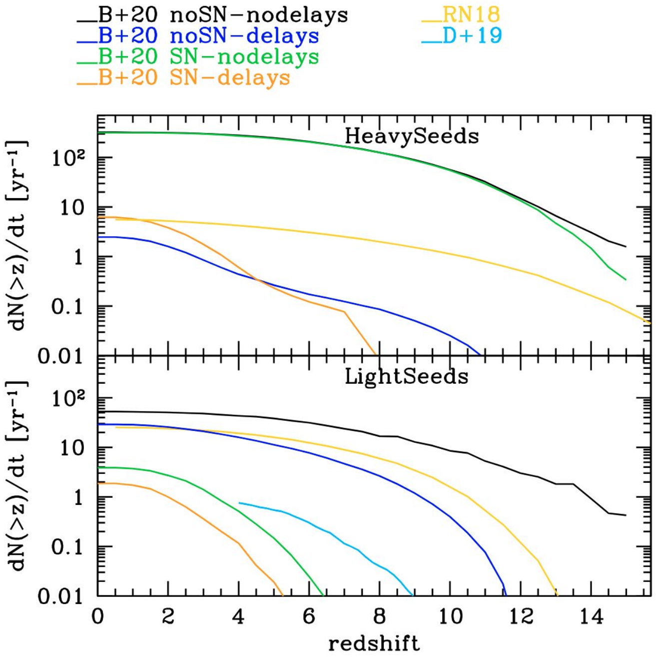
Cosmological simulations



Semi-analytical models



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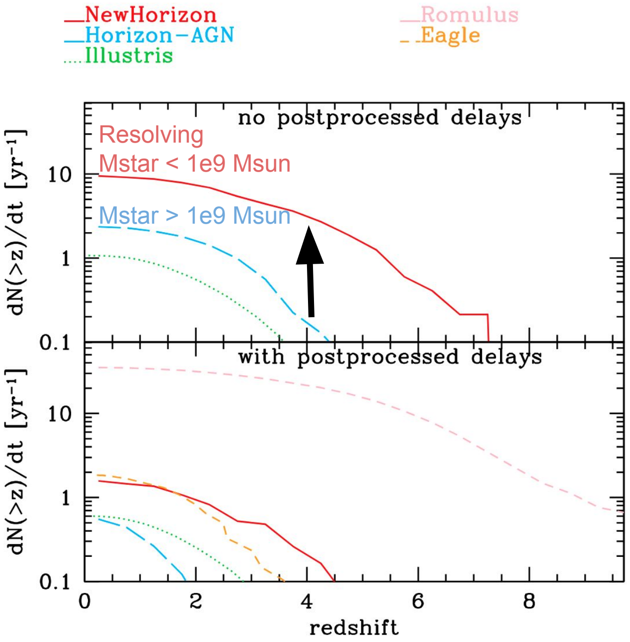

- ➢ Simulations which do not resolve galaxies with $M_{star} < 10^9\ M_{sun}$ can under estimate MBH merger rates (if MBHs exist in these galaxies).
- ➢ Decrease of MBH merger rates when accounting for post-processing delays.

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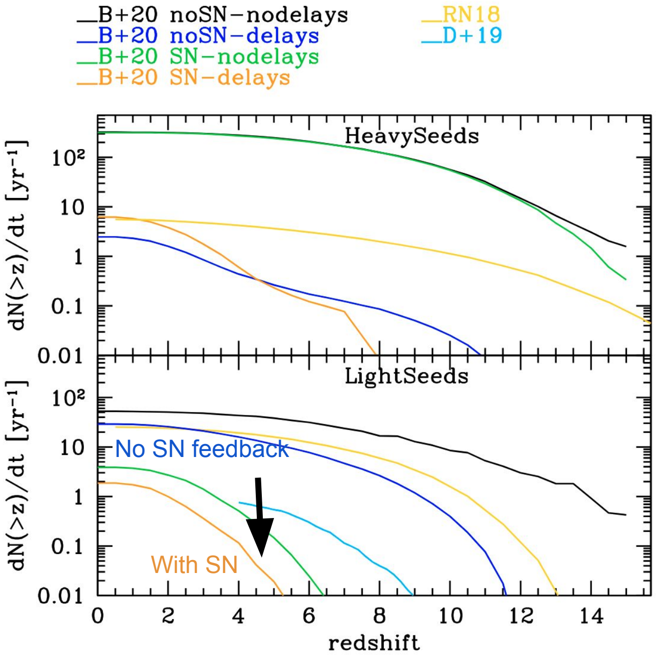

➢ Results suggest that different seeding models would impact LISA event rate differently.

<u>Light seeds</u>: 10 to 100s detections in 4 year mission duration.
<u>Heavy seeds</u>: less detections because rare.

➢ Event rate mostly driven by mergers of growing light seeds?

➢ Role of SN feedback?

Project overview

Project

Exhaustive comparison of **20 existing models** predicting MBH merger rates and LISA event rates.

Models span different techniques, resolution, physical assumptions on MBH seeding, growth, dynamics, galaxy formation models.

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Semi-analytical models

Cosmological simulations

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Goals

i) Evaluating the global astrophysical uncertainties on the LISA event rate.

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In practice

- About 100 participants with diverse expertise / skills and at different stages of career.
- 7 coordinators.
- Project divided in many tasks.
- Each participant expected to complete several tasks.
- Close monitoring of who is doing what.

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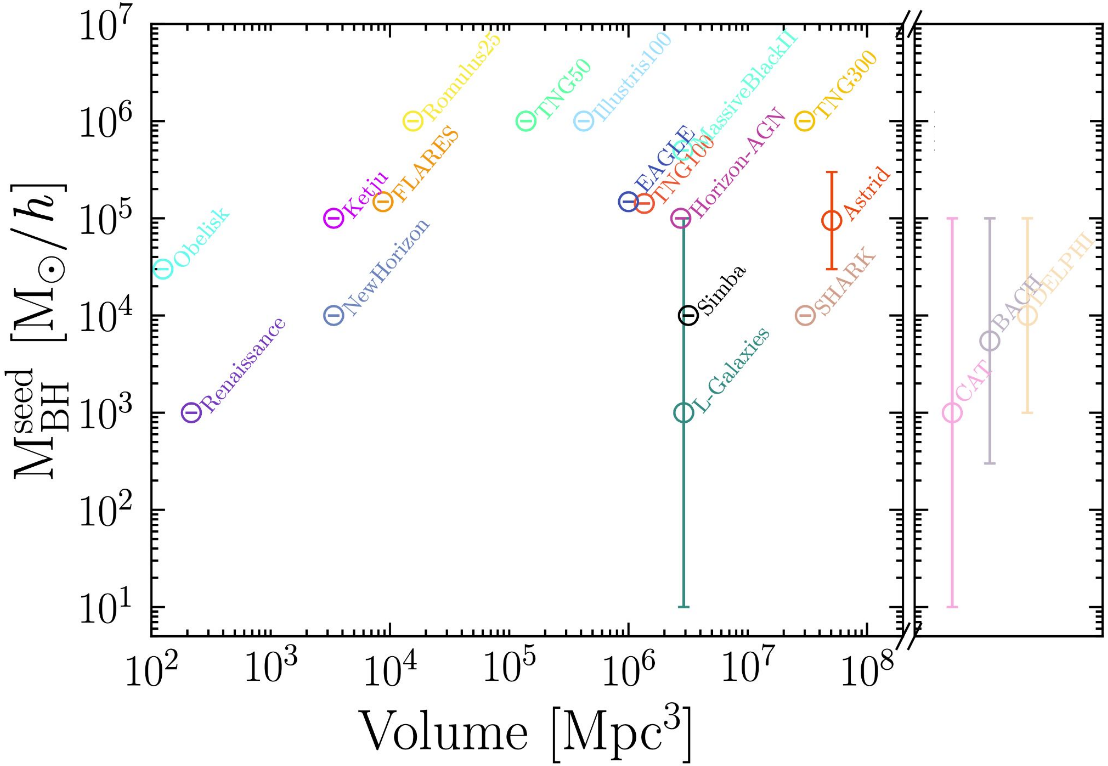
In practice

- Creating uniform templates & codes to produce the catalogs.
- Making catalogs
- Creating analysing pipeline & interpreting results
- Writing the paper

A landscape of models

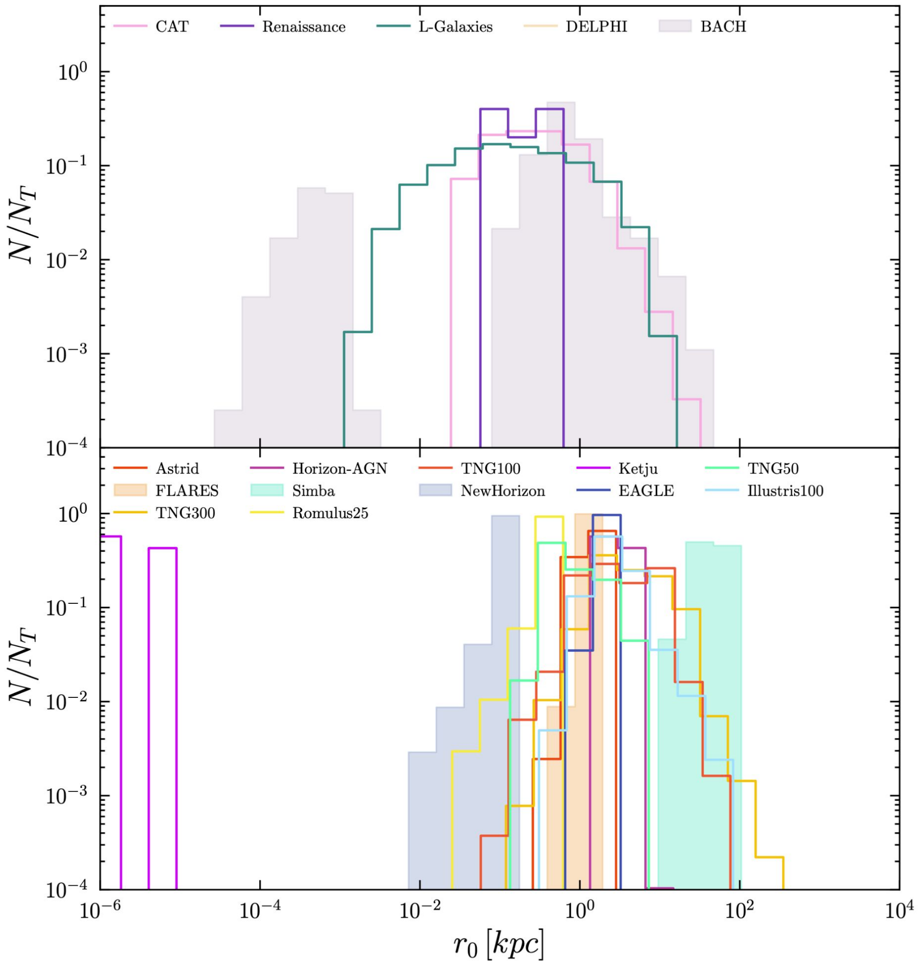
Cosmological simulations or SAMs with a volume

Based on Press-Schechter formalism

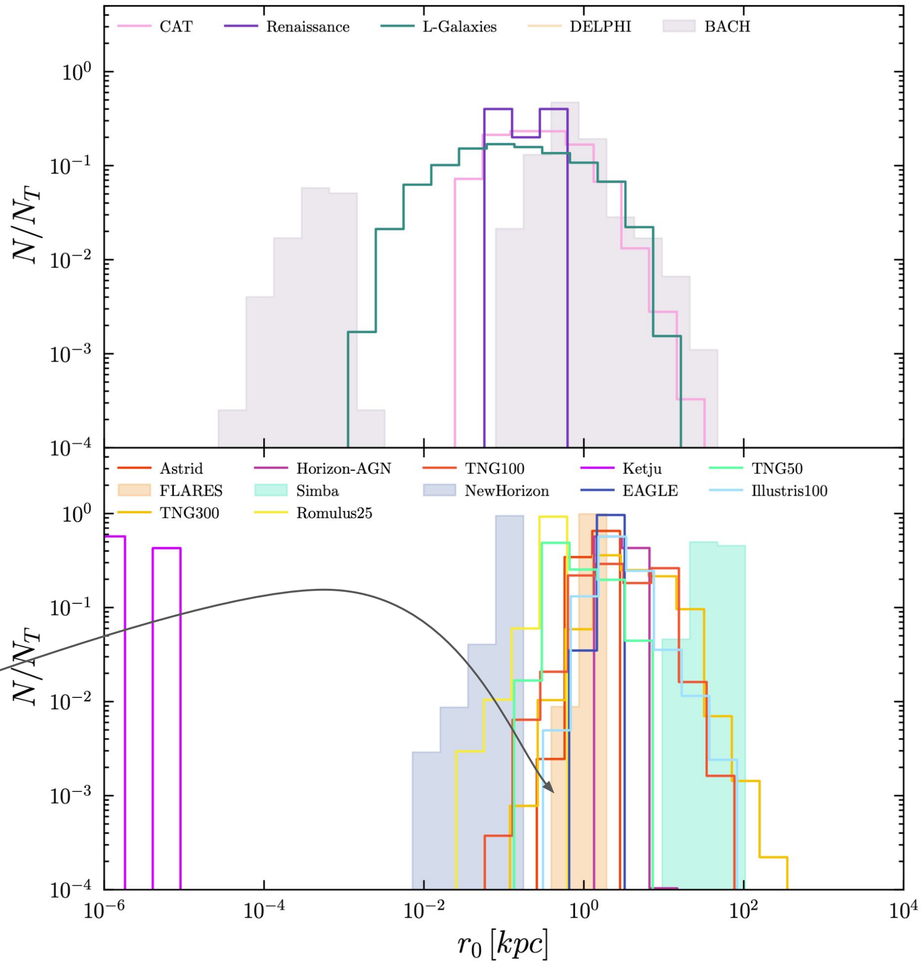


A landscape of models

Separations of the binaries at the last time step before numerical coalescence



A landscape of models



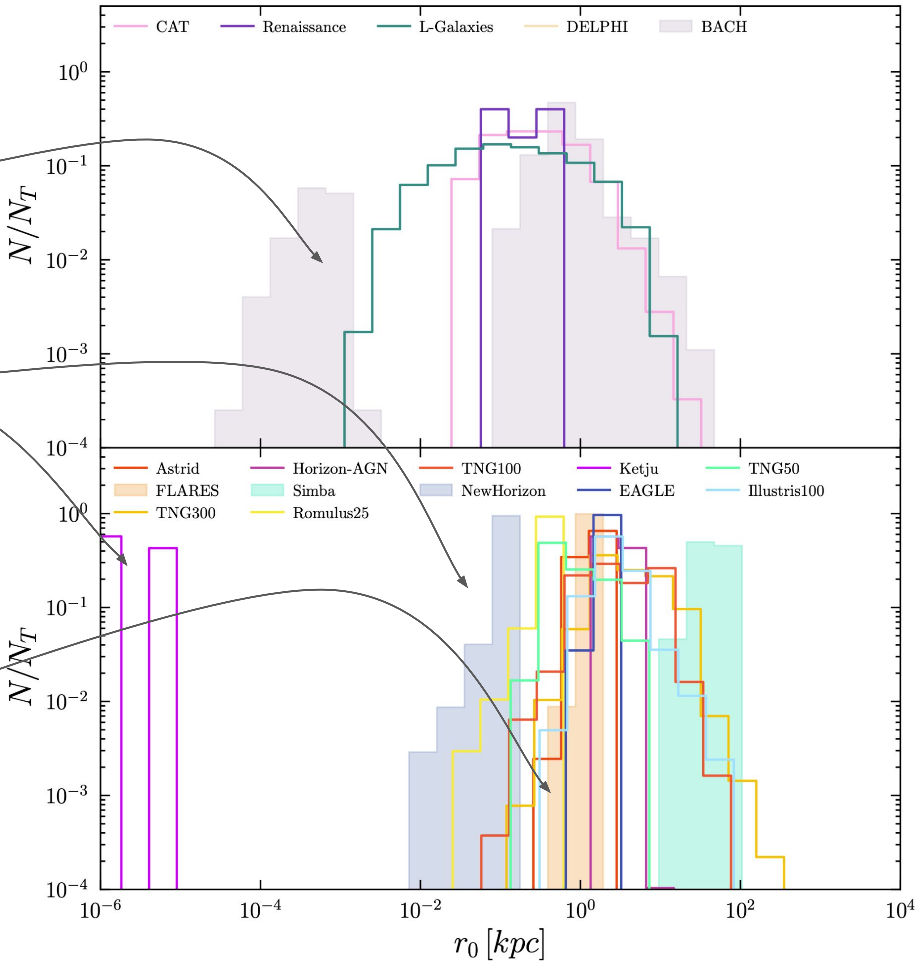
Large-scale cosmological simulations with resolution ~ 1 kpc

A landscape of models

The more flexible SAMs allow to explore smaller binary separation.

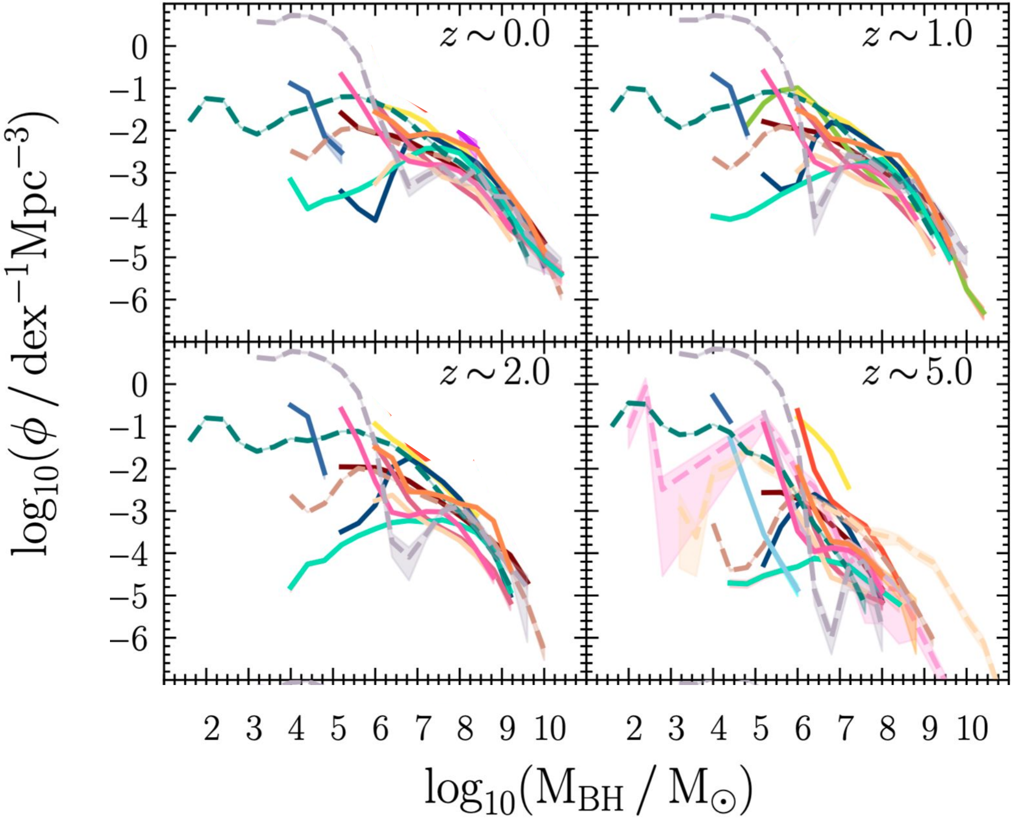
A few high-resolution simulations.

Large-scale cosmological simulations with resolution ~ 1 kpc



A landscape of models

Mass function of the entire MBH population produced in the models

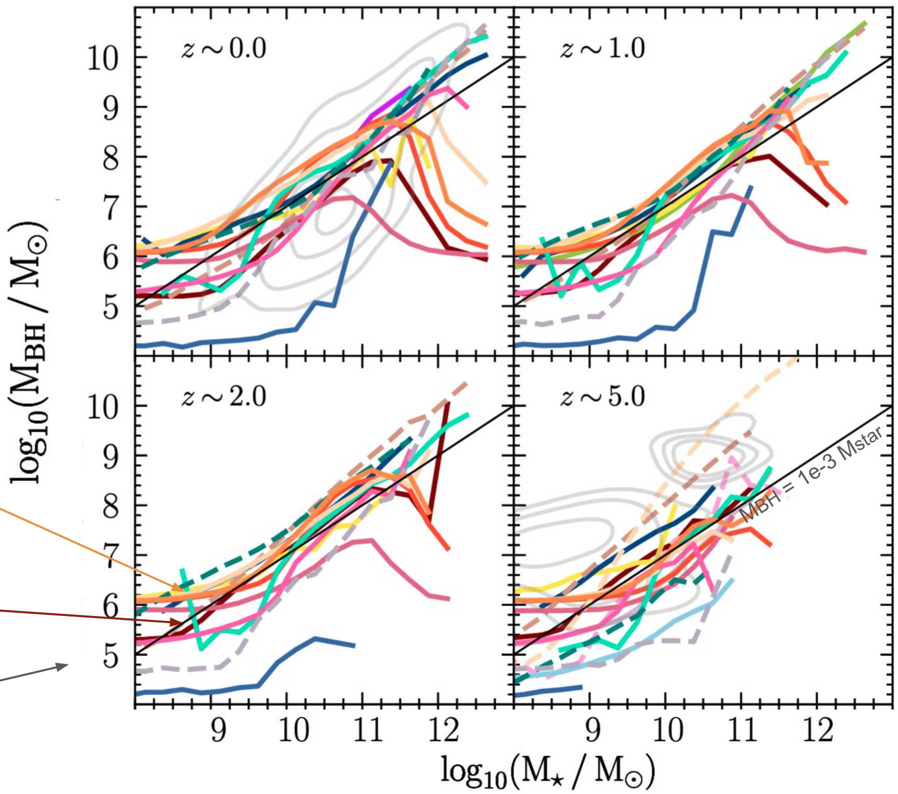


Convergence on the massive end,

large discrepancies at the low-mass end (seeding, accretion)

A landscape of models

MBH-stellar mass relation of the entire MBH population produced in the models



SN feedback preventing MBH growth (even for massive seeds for TNG)

More efficient MBH growth for weaker feedback strength (e.g., Illustris)

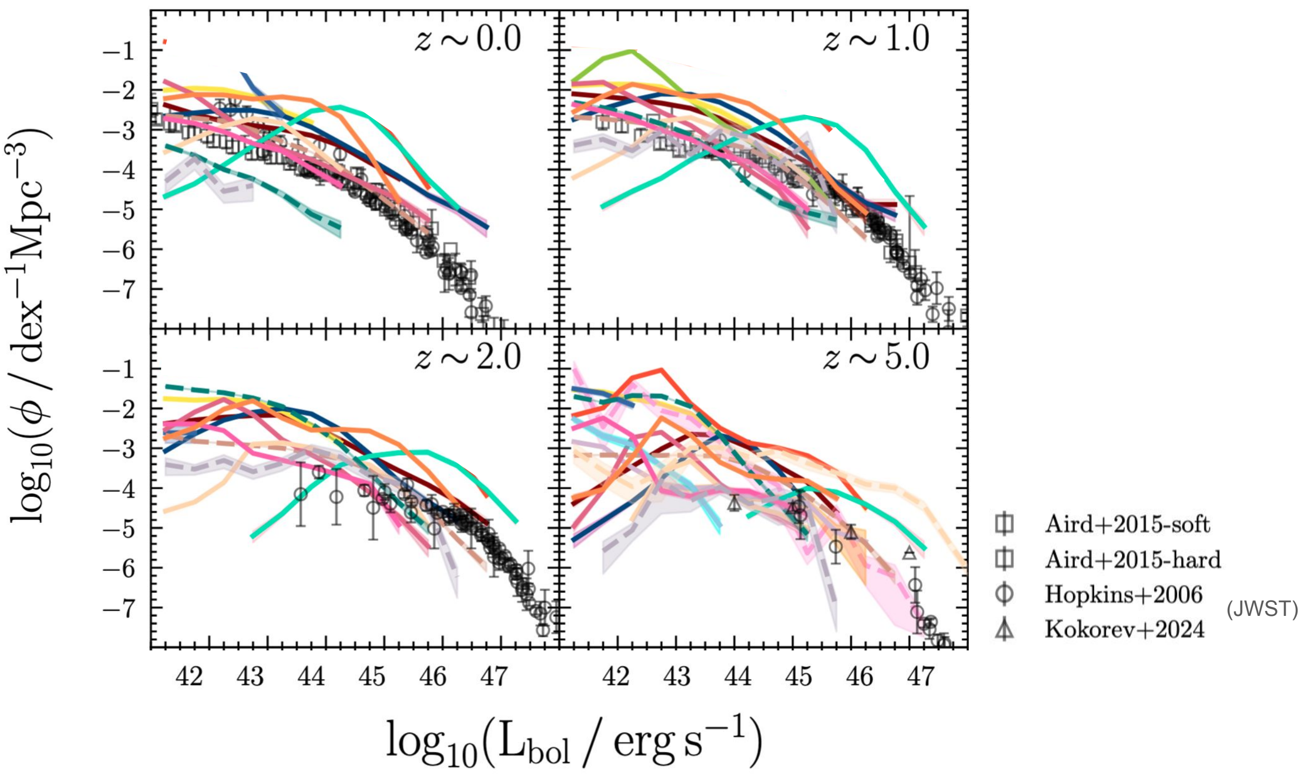
Ungrown MBH seeds

Convergence on the massive end,

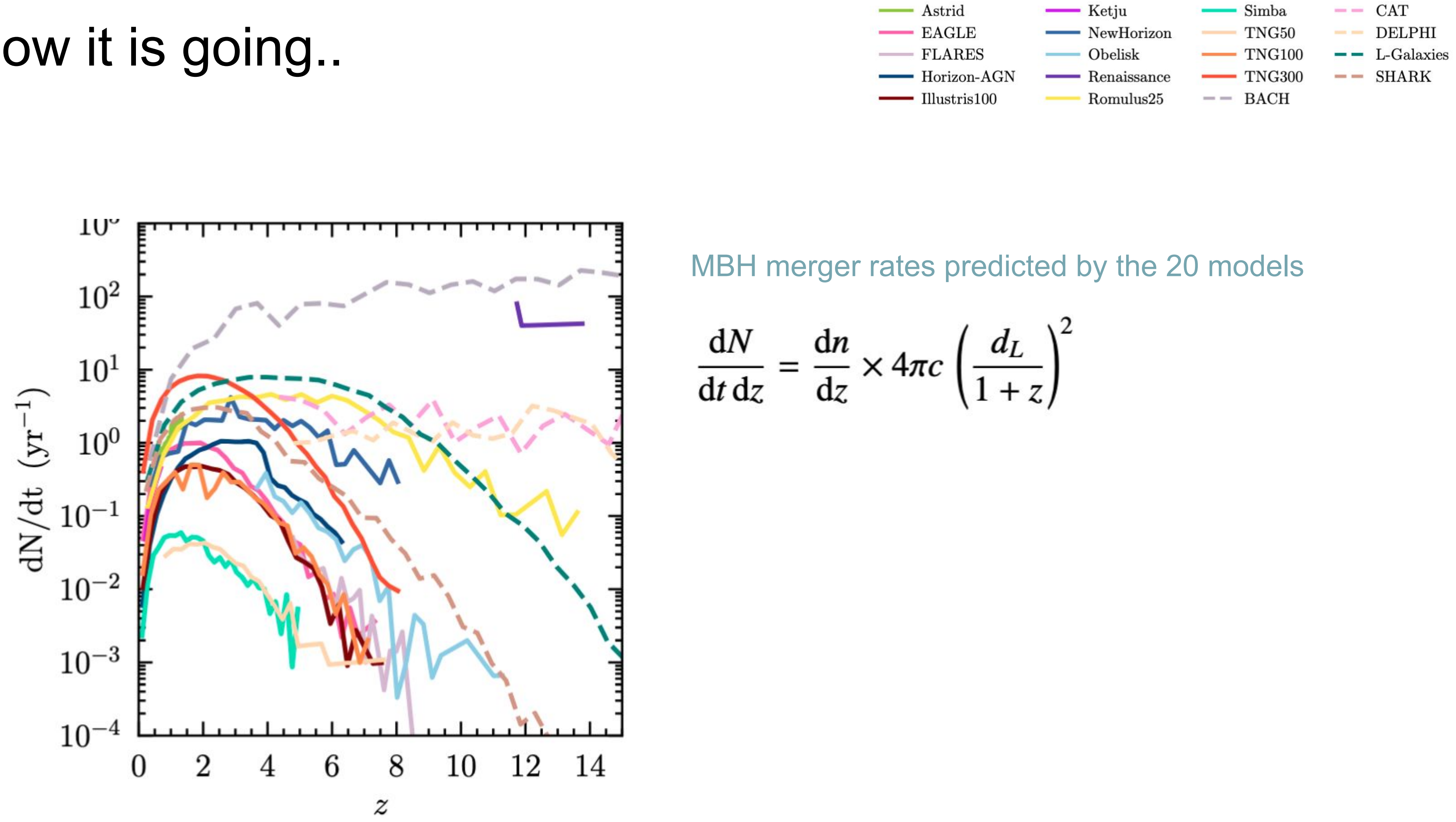
large discrepancies at the low-mass end (seeding, accretion, SN feedback)

A landscape of models

AGN luminosity function



How it is going..



MBH merger rates predicted by the 20 models

$$\frac{dN}{dt\,dz} = \frac{dn}{dz} \times 4\pi c \left(\frac{d_L}{1+z}\right)^2$$

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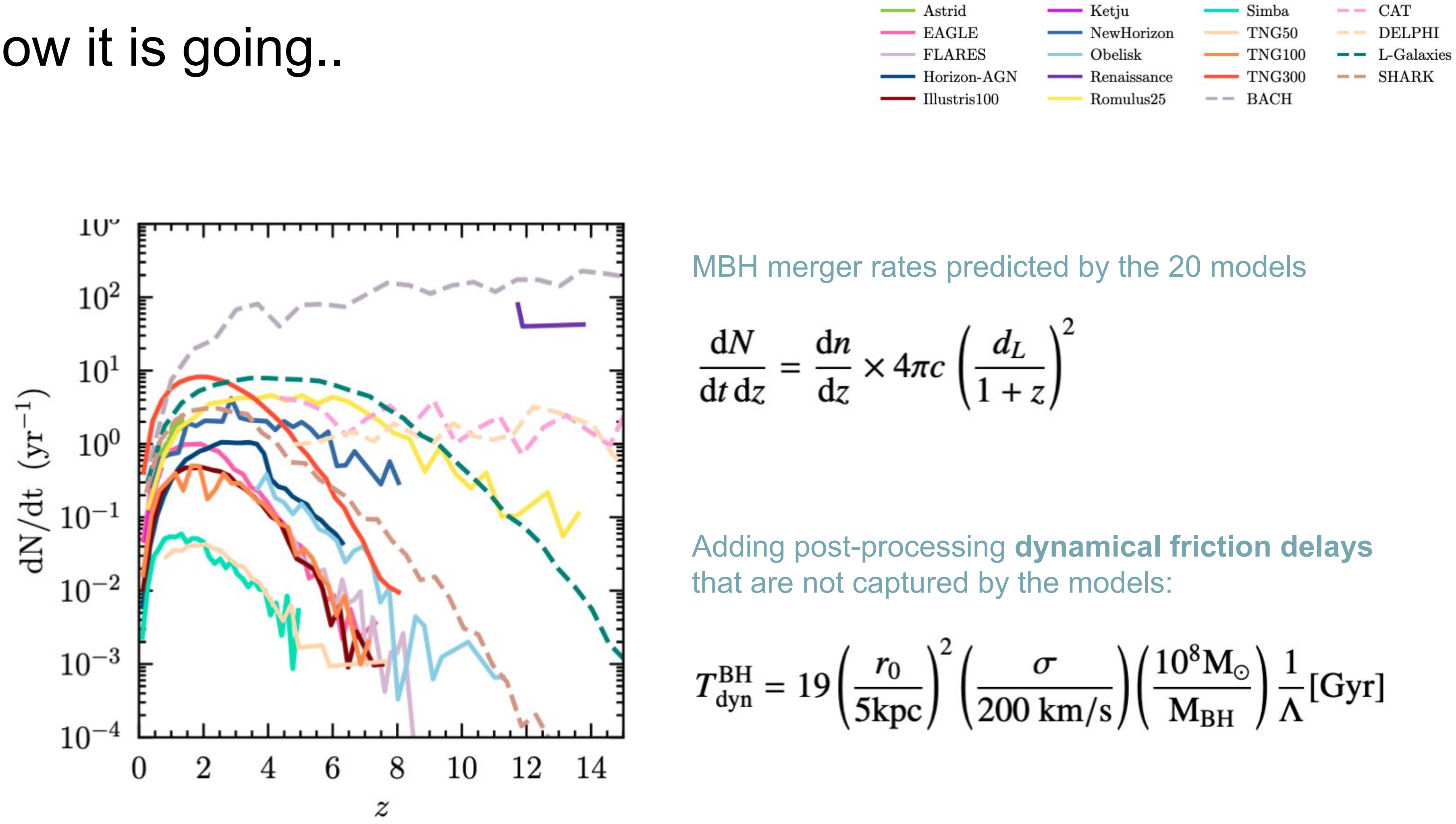


MBH merger rates predicted by the 20 models

$$\frac{dN}{dt\,dz} = \frac{dn}{dz} \times 4\pi c \left(\frac{d_L}{1+z}\right)^2$$

Adding post-processing **dynamical friction delays** that are not captured by the models:

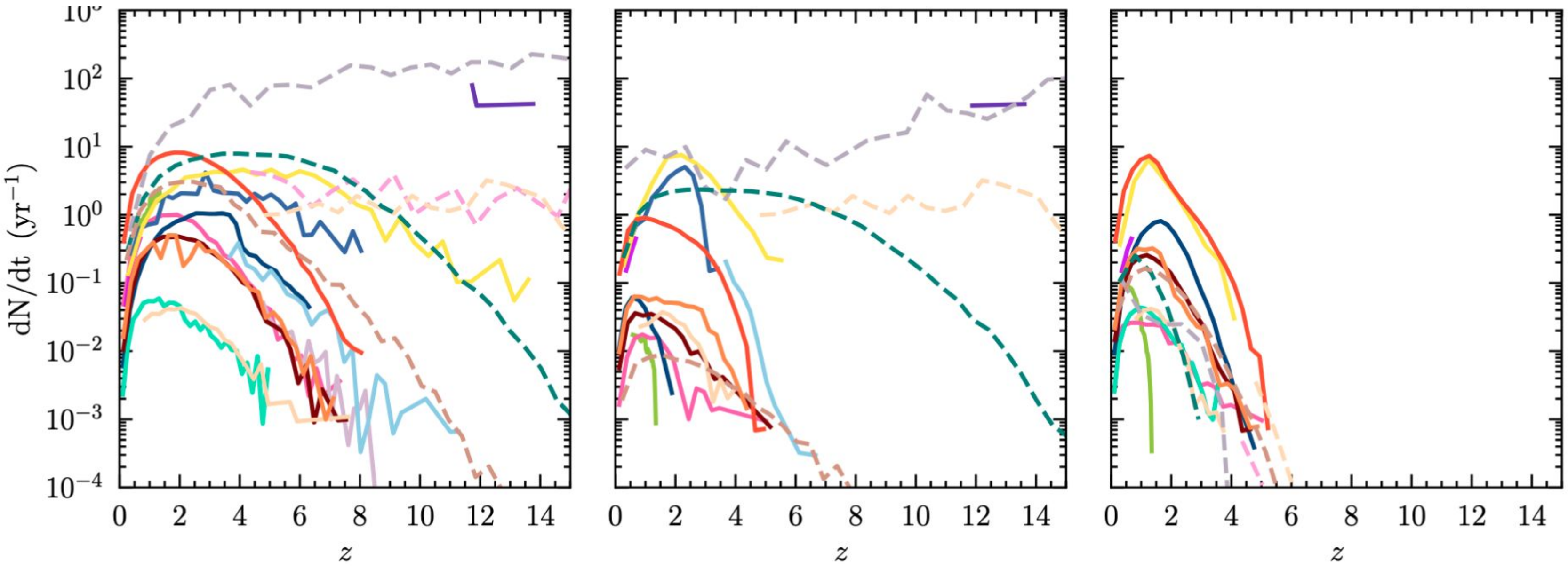
$$T_{\rm dyn}^{\rm BH} = 19\left(\frac{r_0}{5{\rm kpc}}\right)^2\left(\frac{\sigma}{200\ {\rm km/s}}\right)\left(\frac{10^8 {\rm M}_\odot}{{\rm M_{BH}}}\right)\frac{1}{\Lambda}[{\rm Gyr}]$$

How it is going..

No post-processing delays for Dynamical Friction

With delays for Dynamical Friction (binary separation at timestep before numerical merger)

With delays for Dynamical Friction (assuming separation is the effective radius from empirical size-mass relations)



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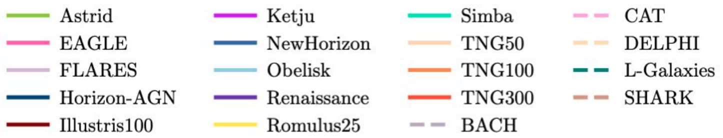

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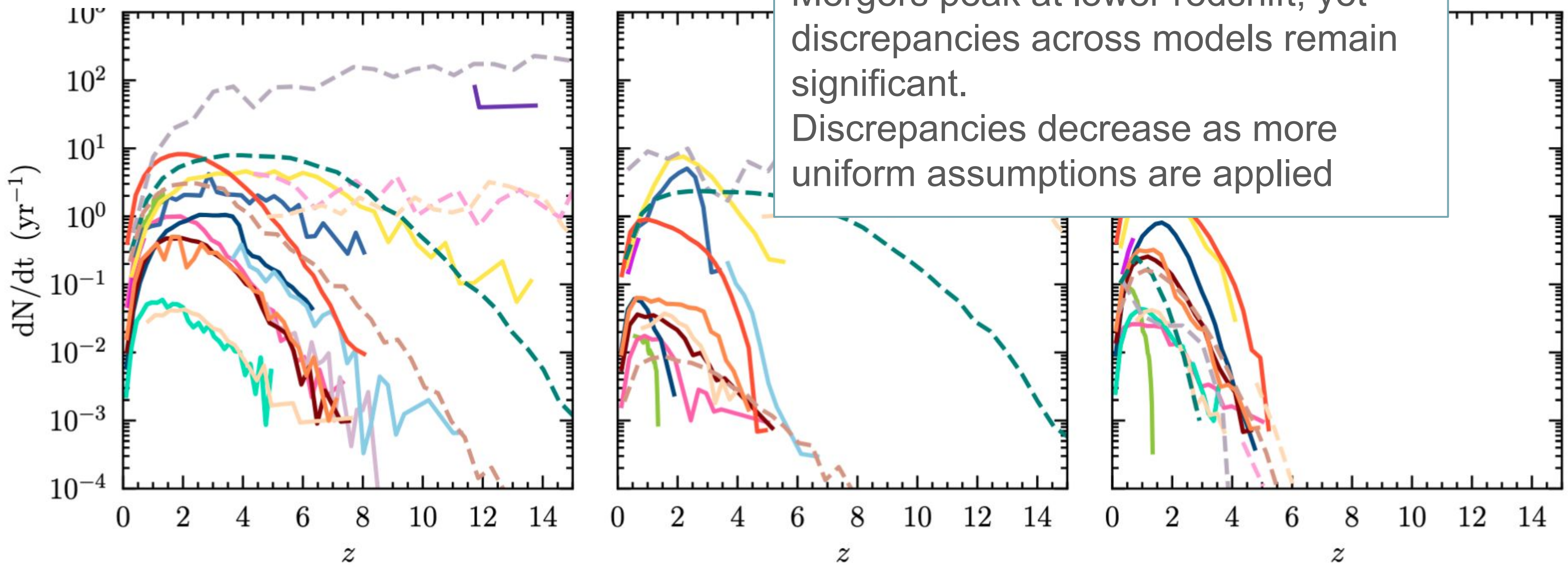
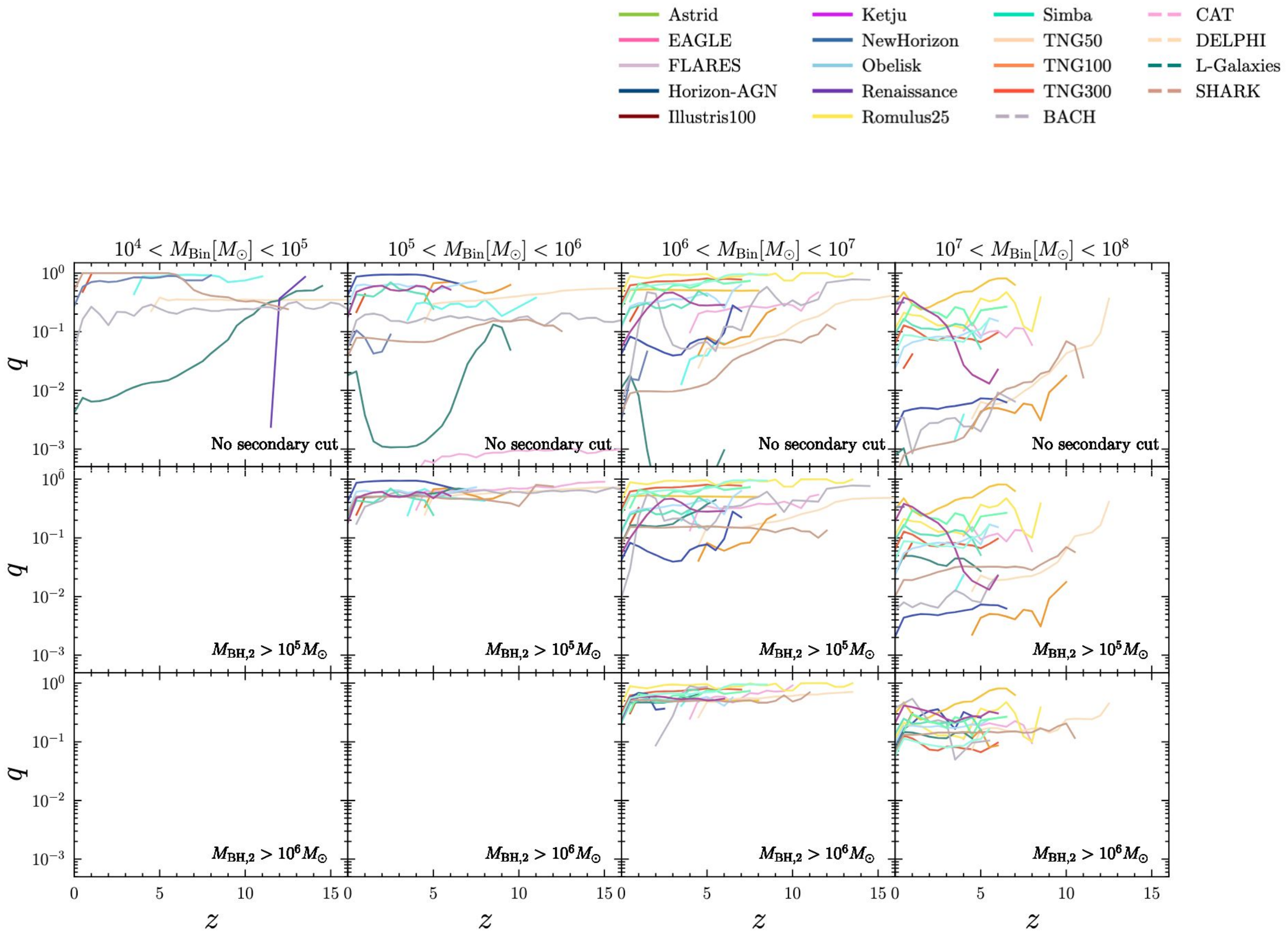


Mergers peak at lower redshift, yet discrepancies across models remain significant.
Discrepancies decrease as more uniform assumptions are applied

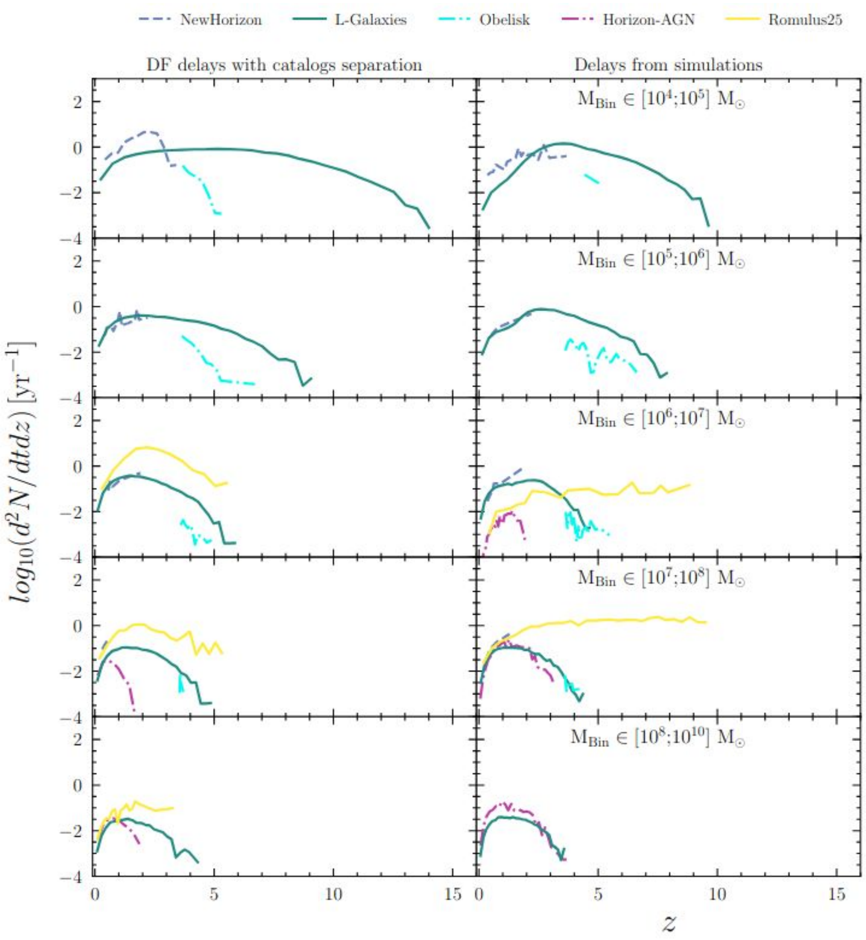
How it is going..

Mass ratios of the binaries

- Large distributions for most of the models.
- Discrepancies across models largely due to seeding and fraction of ungrown MBHs.
- Reduced discrepancies when accounting for DF delays.
- Models converge for mergers of massive MBHs.



Comparing our DF delay modeling to existing delays in some models.



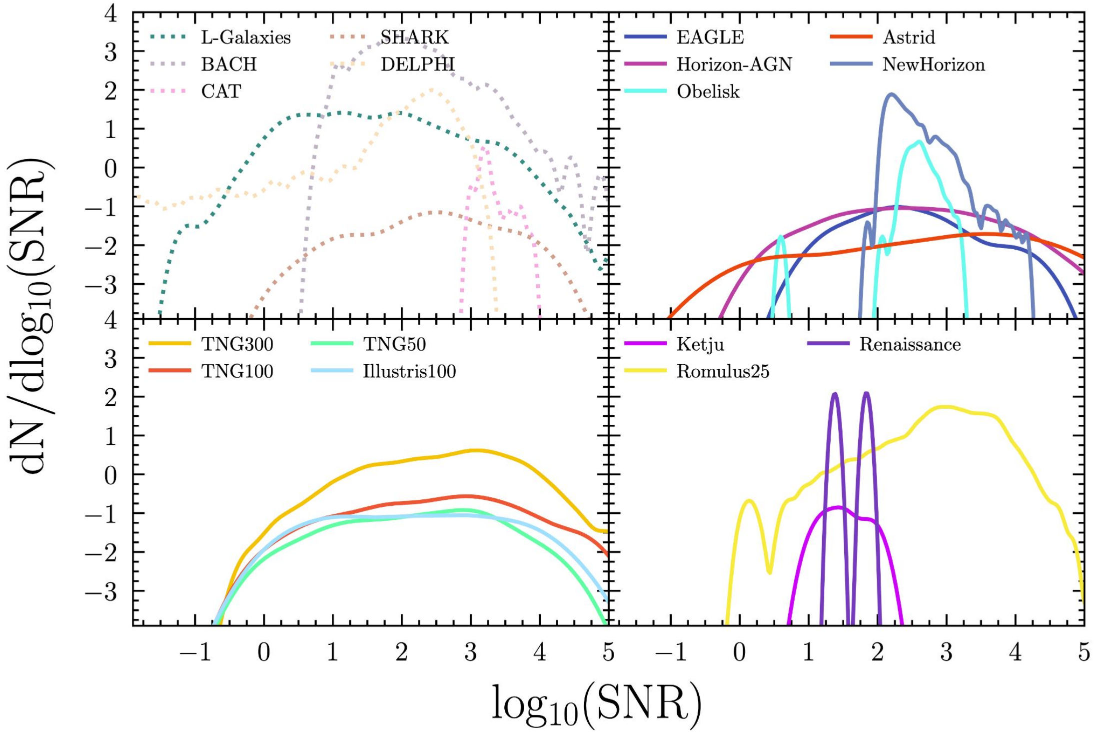
Catalogue project	Models with self-consistent delays
Dynamical friction ✓	Dynamical friction ✓
Stellar/Gas Hardening ✗	Stellar/Gas Hardening ✓
GW emission ✗	GW emission ✓

The main differences are seen at high redshift.

LISA detection rate (Signal-to-noise ratios)

Input: Sampling of N binaries from each model (for given $M_{primary}$, $M_{secondary}$, redshifts).
SNR averaged over location on the sky, inclination, polarisation.

$$\mathrm{SNR}^2 = \int_{f_{\min}}^{f_{\max}} \frac{h_c^2}{f^2 S_n(f)} df.$$



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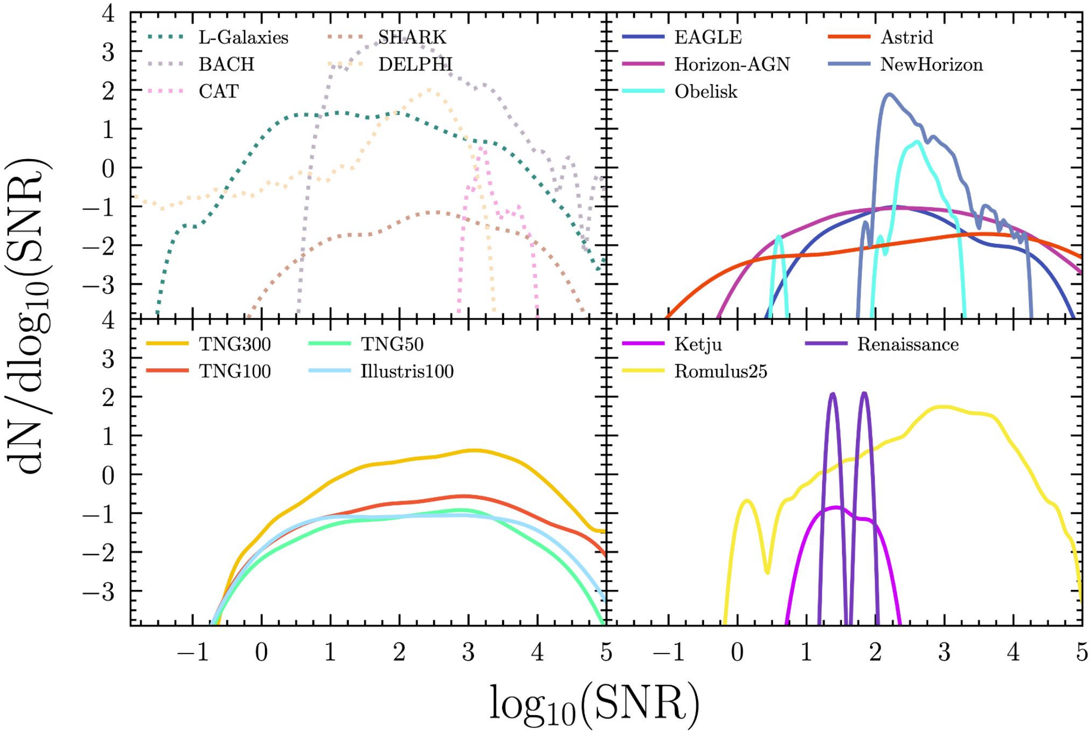

Large SNR.
LISA will detect a large fraction of the mergers predicted by the models.
(Keeping in mind unresolved low-mass galaxies and BHs in some models)

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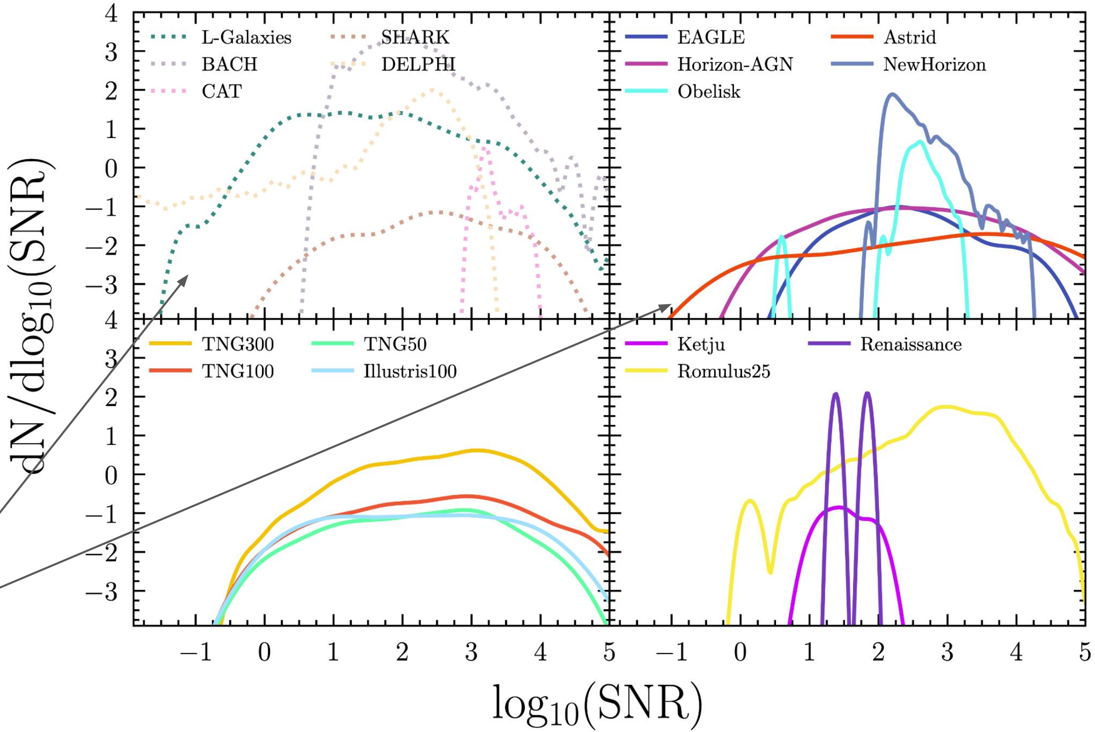

Lower SNRs for models with MBH mergers <1e4 Msun.

Our conclusions

i) Understand global astrophysics uncertainties

- MBH merger rate, event rate, MBHB mass ratios, strongly shaped by MBH formation modeling.
- Assembly of low-mass galaxies (and their MBHs) not captured by many models.
- Parameters in Dynamical Friction delay modeling.

ii) Identify the robust model-independent predictions

- Larger discrepancies across models occurs in the LISA mass band.
- Expected mergers with low mass ratios while not accounting for DF delays; reduced to ~0.1 with delays.
- Discrepancies more nuanced at the massive end, due to models being more anchored to existing observational constraints and signatures of seeding being washed out.

We did not tackle interesting aspects:

- The galactic and large-scale environments fostering MBH mergers (e.g., galaxy morphologies?, filaments or clusters?) and evolution with redshift.
- EM counterparts of the systems from dual AGN stage to coalescence.

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Community value

1. Evaluation of the global astrophysical uncertainties on the LISA event rate.
2. Provide simulated catalogs to test pipelines.
3. Provide simulated catalogs to validate LISA catalogs.