The Formation of Early Supermassive Black Holes and Their Gravitational Wave Signatures

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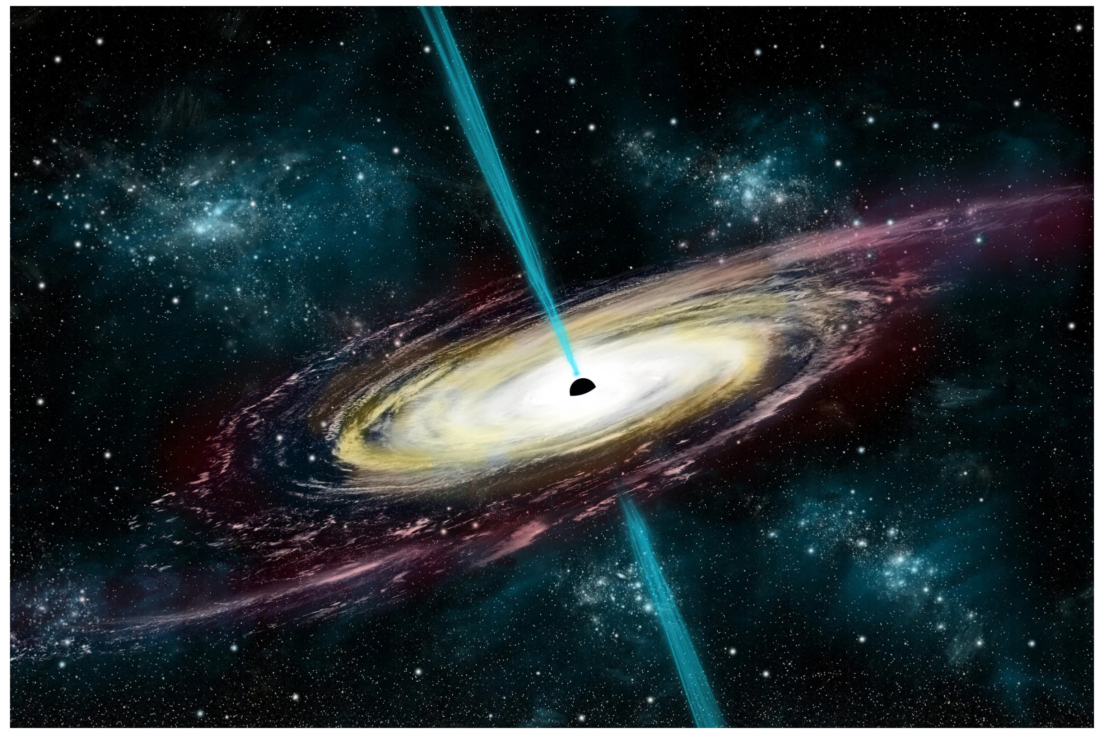

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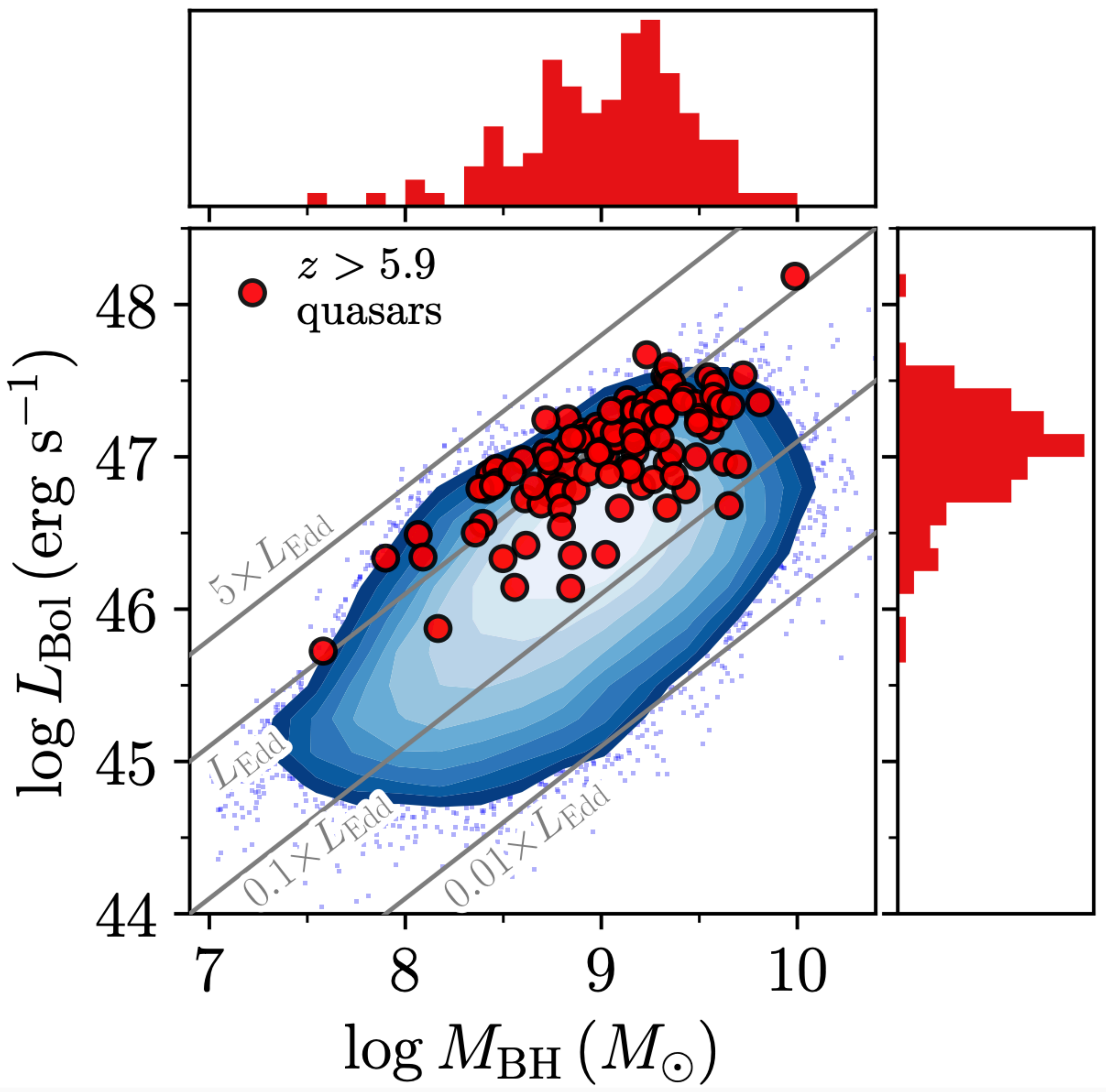
Observations of black holes at high z

- Currently, there are hundreds of known quasars at z > 6.
- Quasars are extremely bright and energetic objects found at the centers of distant galaxies.
- They are powered by supermassive black holes that consume surrounding gas and dust, releasing enormous amounts of radiation.
- The study of quasar luminosity function and black hole mass function over cosmic time has enriched our understanding of physical processes related to the growth history of SMBHs.

- This figure shows the bolometric luminosity and BH mass distribution for all quasars at z > 5.9.

- The median BH mass is $1.3 \times 10^9 M_\odot$, while the least and most massive quasars are J0859+0022 at z =6.39 ($\sim 4 \times 10^7 M_\odot$) and J0100+2802 at z = 6.33 ($\sim 10^{10} M_\odot$]), respectively.

- Most of them follow the line of the Eddington limit, but some of them are located both above and below.

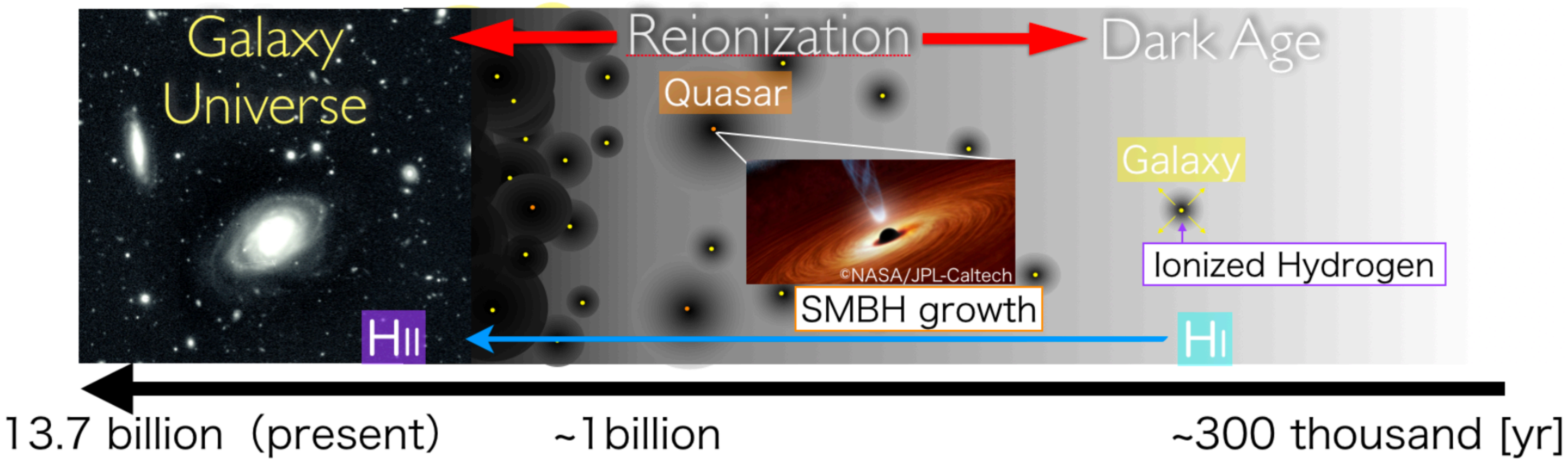


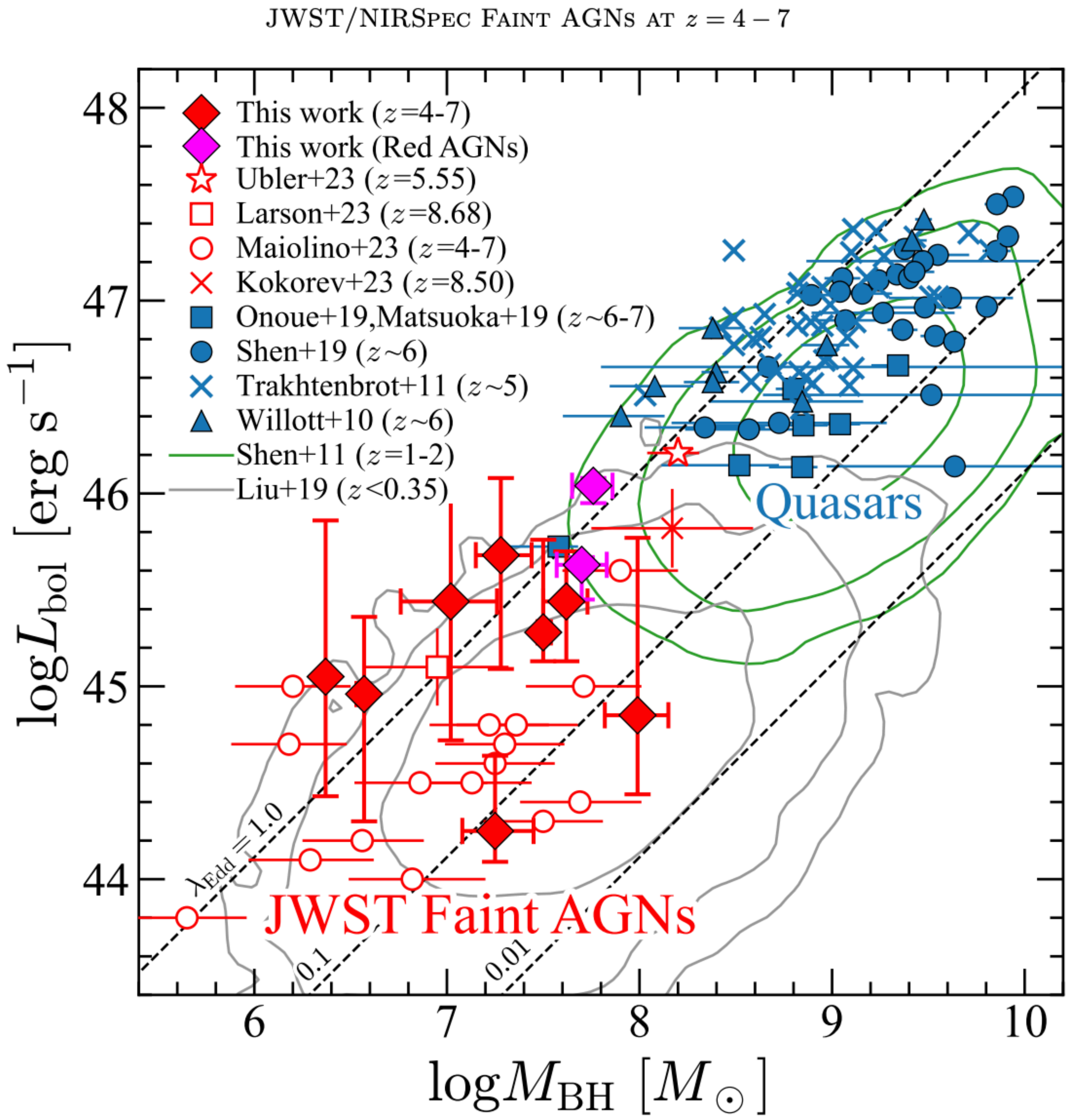
Fan et al. 2023

Observations of black holes at high z: JWST recent results

- All latest JWST discoveries are reported in this Figure.
- Relation between the bolometric luminosity (L_{bol}) and black hole mass (M_{BH}).

- The James Webb Space Telescope has observed galaxies at high redshifts, offering a glimpse into the so called 'dark ages'.
- The enhanced sensitivity of the telescope is pushing observations to higher redshift and to lower BH masses, providing increased constraints on BH seeding and growth models.
- The blue symbols show previous measurement for quasars at z > 4 identified with the ground-based telescopes and red and magenta diamonds are CEERS results.



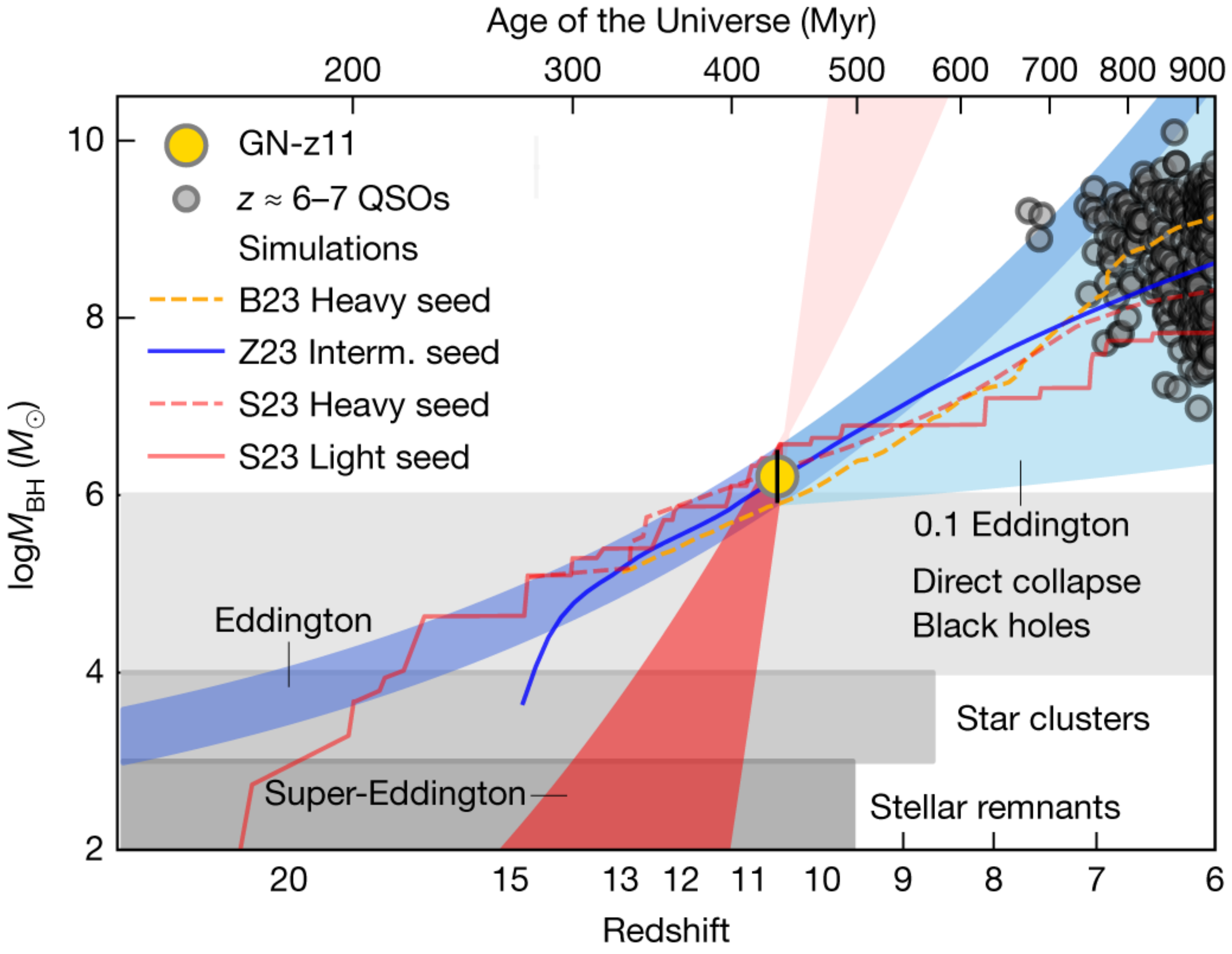


Harikane et al. 2023

Observations of black holes at high z: JWST recent results

- Numerous high-redshift BH candidates identified in JWST data: including low-mass AGNs at high redshift.
- The farthest SMBH ever detected, GN-z11, by the JWST at z = 10.6, i.e. only 440 Myr after the Big Bang.
- With a mass of only $\sim 10^6 M_{\odot}$,
- offering for the first time a glimpse of the lower end of the SMBH distribution at such redshifts.

✦ **Given all these new discoveries, it is even more important to test the different theories behind the formation of these objects.**



Maiolino et al. 2024

Accretion Models for BH Growth

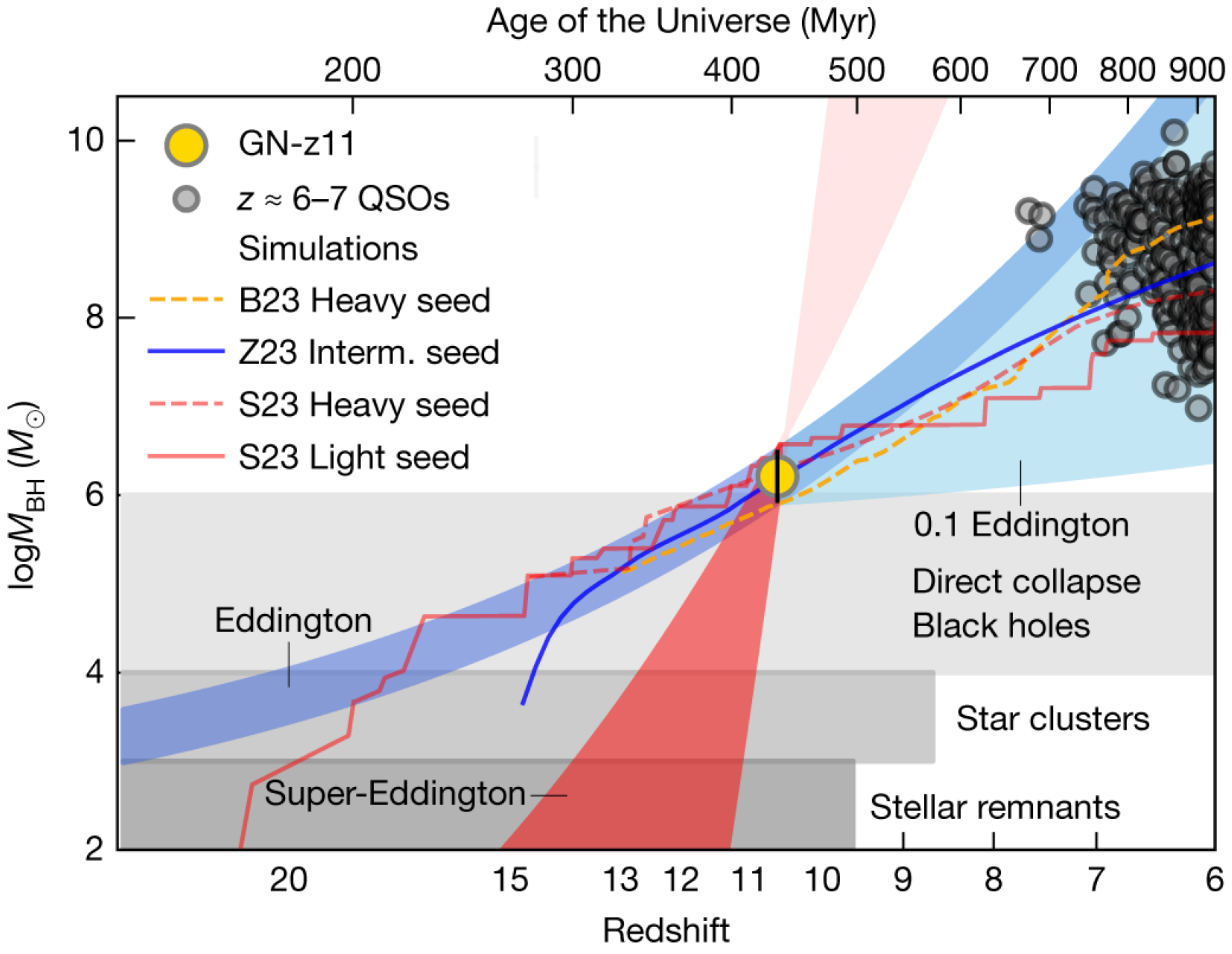
There are two main accretion models:

1. Bondi-Hoyle-Lyttleton (BHL) accretion with Eddington limit (standard model, capped at Edd limit)

$$\dot{M}_{BHL} = \frac{4\pi G^2 \rho_{gas}(r_A)}{c_s^3} M_{BH}^2$$

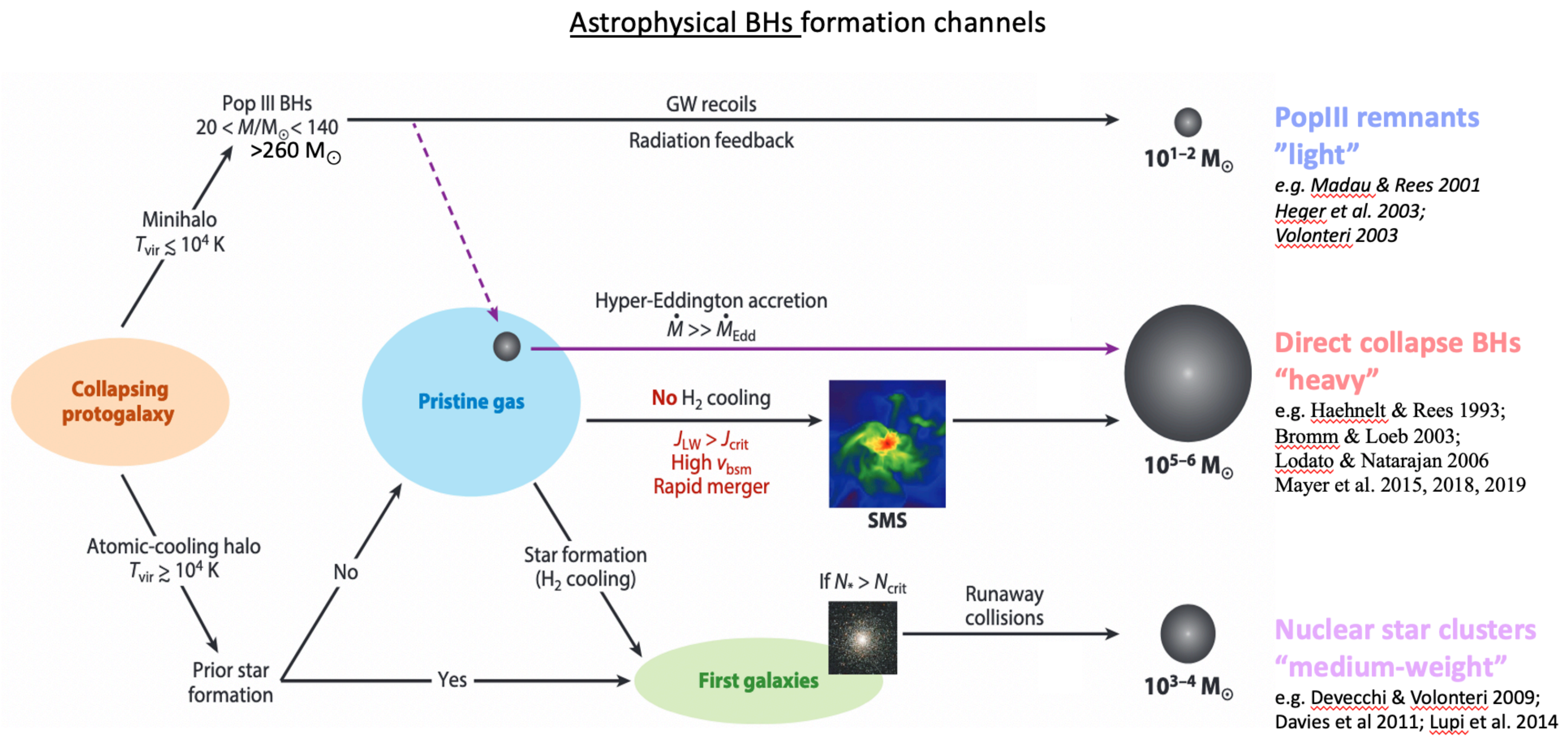
2. Super-Eddington accretion model (growth via slim disk accretion)

These models differ in how fast a BH can grow and how efficiently it converts accreted gas into radiation.



Maiolino et al. 2024

The seeds of the earliest SMBHs



Credit: Inayoshi et al. 2020

The Cosmic Archaeology Tool (CAT)

"The low-end of the black hole mass function at cosmic dawn" by **Trinca et. al 2022 MNRAS**

Fast Semi-analytical code:

- Tracks the evolution of a large statistical sample of the galaxy population during the first billion years of cosmic history
- Explores the early co-evolution of nuclear BHs and their host galaxies over a wide halo mass range $[10^6 - 10^{14} M_\odot]$ (down to the first "minihalos")

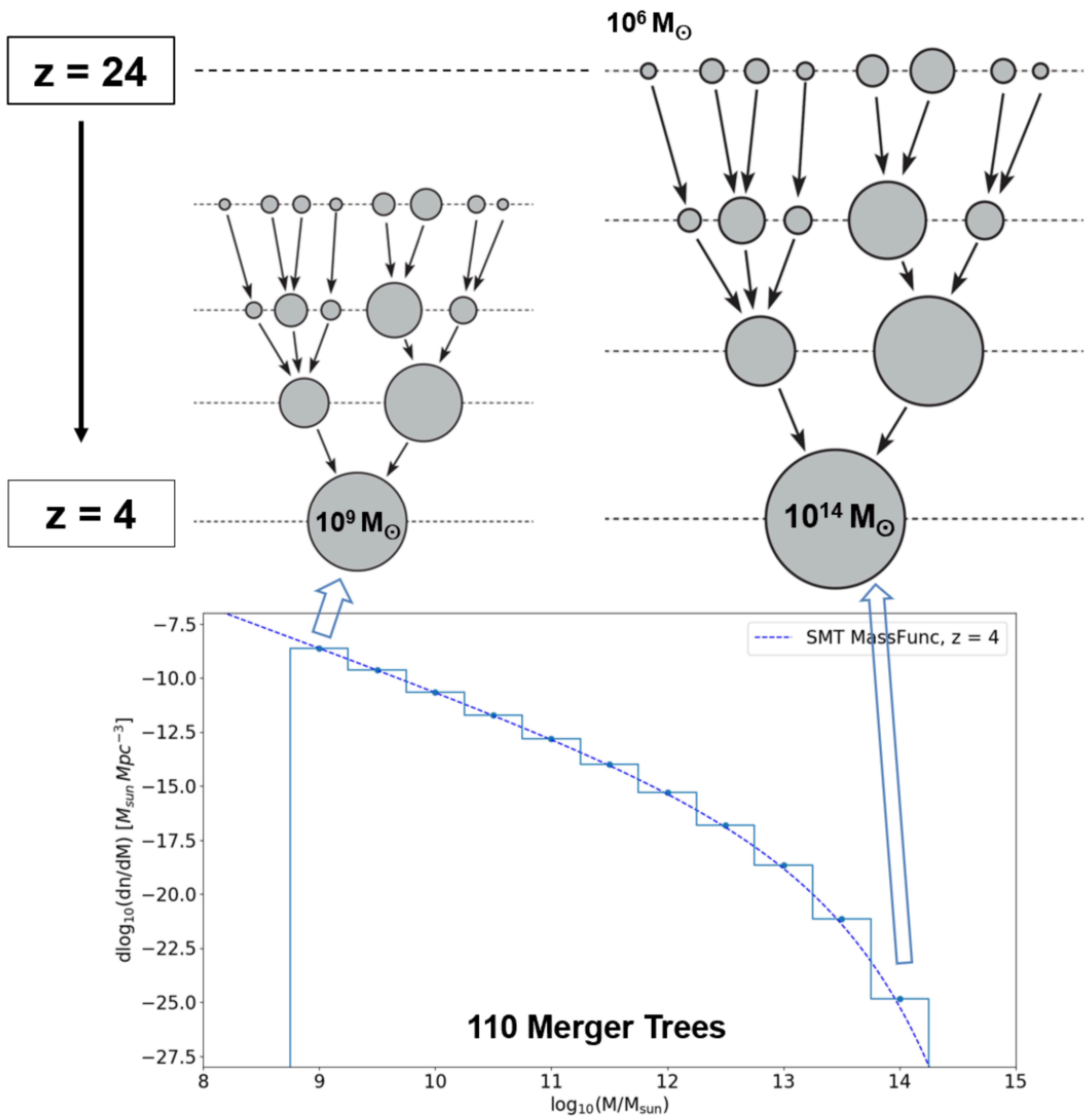


Figure Courtesy of A. Trinca

The Cosmic Archaeology Tool (CAT)

"The low-end of the black hole mass function at cosmic dawn" by **Trinca et. al 2022 MNRAS**

1. Evolution of dark matter halos: $[10^9 - 10^{14} M_\odot]$
   - Galaxy Formation Model (**GALFORM**) is adopted to reconstruct the hierarchical merger history of a given DM halo, based on the Extended Press Schechter theory (EPS).

as a starting point for the GALFORM:
this mass interval is divided into 11 logarithmically spaced bins with size 0.5.
For each bin, we consider a final halo of mass equal to the central bin value
we use it code to simulate10 independent halo merger trees.

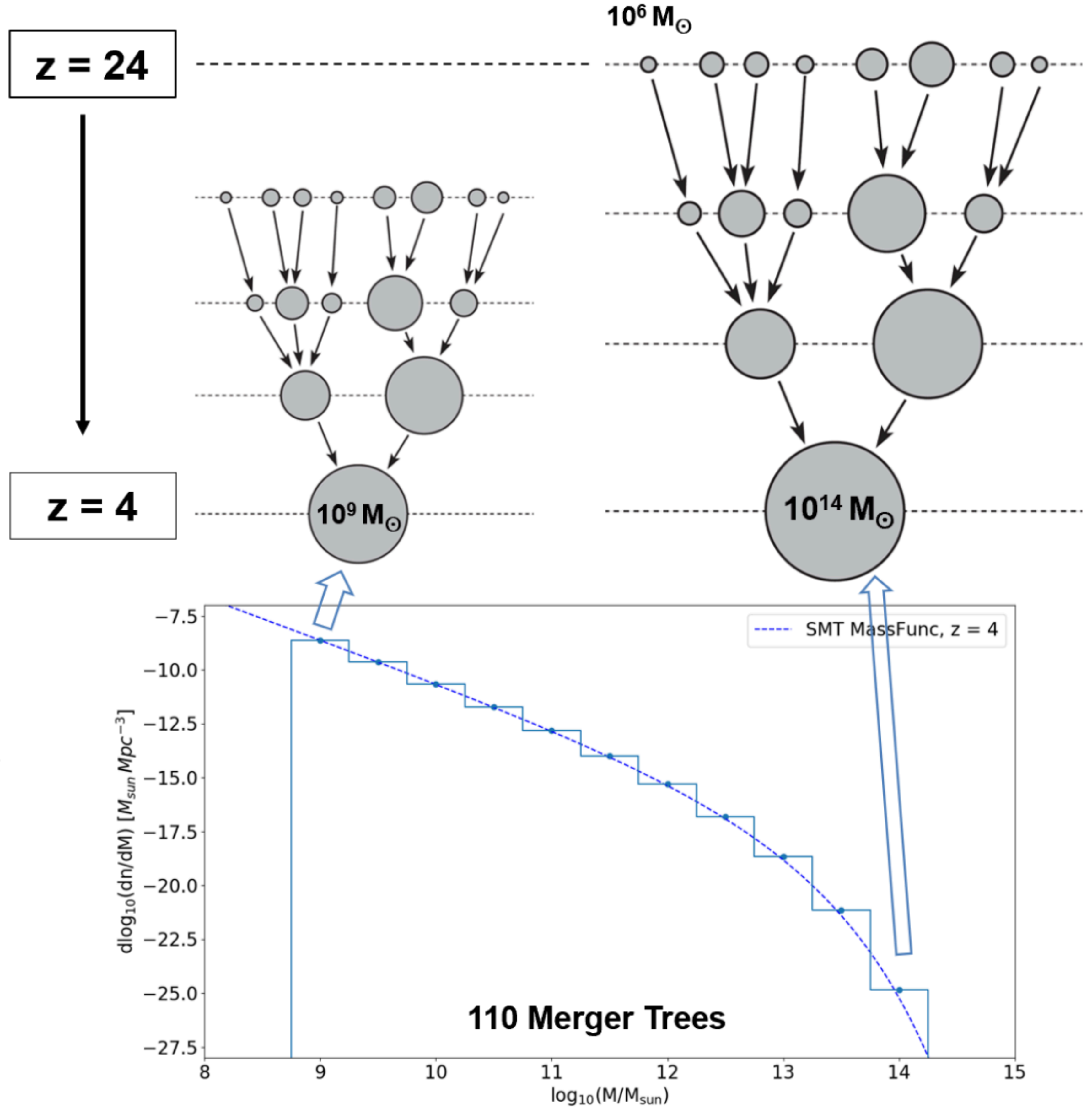


Figure Courtesy of A. Trinca

2. Baryonic Evolution (gas, stars, nuclear BHs):

- well tested GQd model (Valiante et al. 2011, 2014, 2016)
  - Star Formation and Feedback
  - Supernovae feedback

The Cosmic Archaeology Tool (CAT)

Multiple seed BH formation channels:

- Light ($[40-140], [260-300] M_\odot$), heavy ($10^5 M_\odot$) (**Trinca et al. 2022, 2023, 2024**)
- Light, medium-weight ($10^3 M_\odot$) and heavy (**Davari et al. in prep**)

Different BH accretion paradigms:

- Eddington-limited Bondi accretion
- Super-Eddington growth via slim disk accretion (**Trinca et al. 2022, 2023, 2024**)

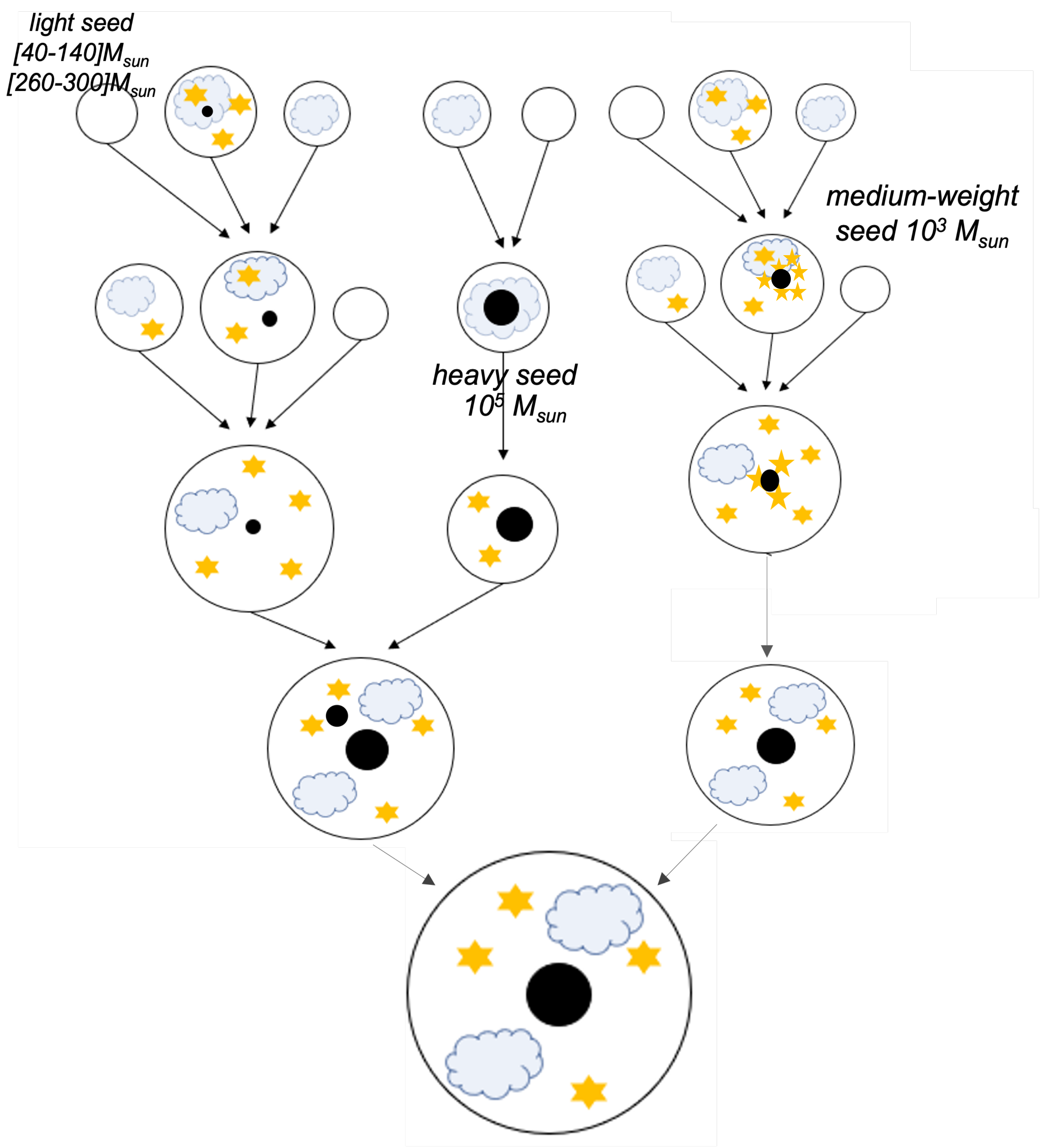
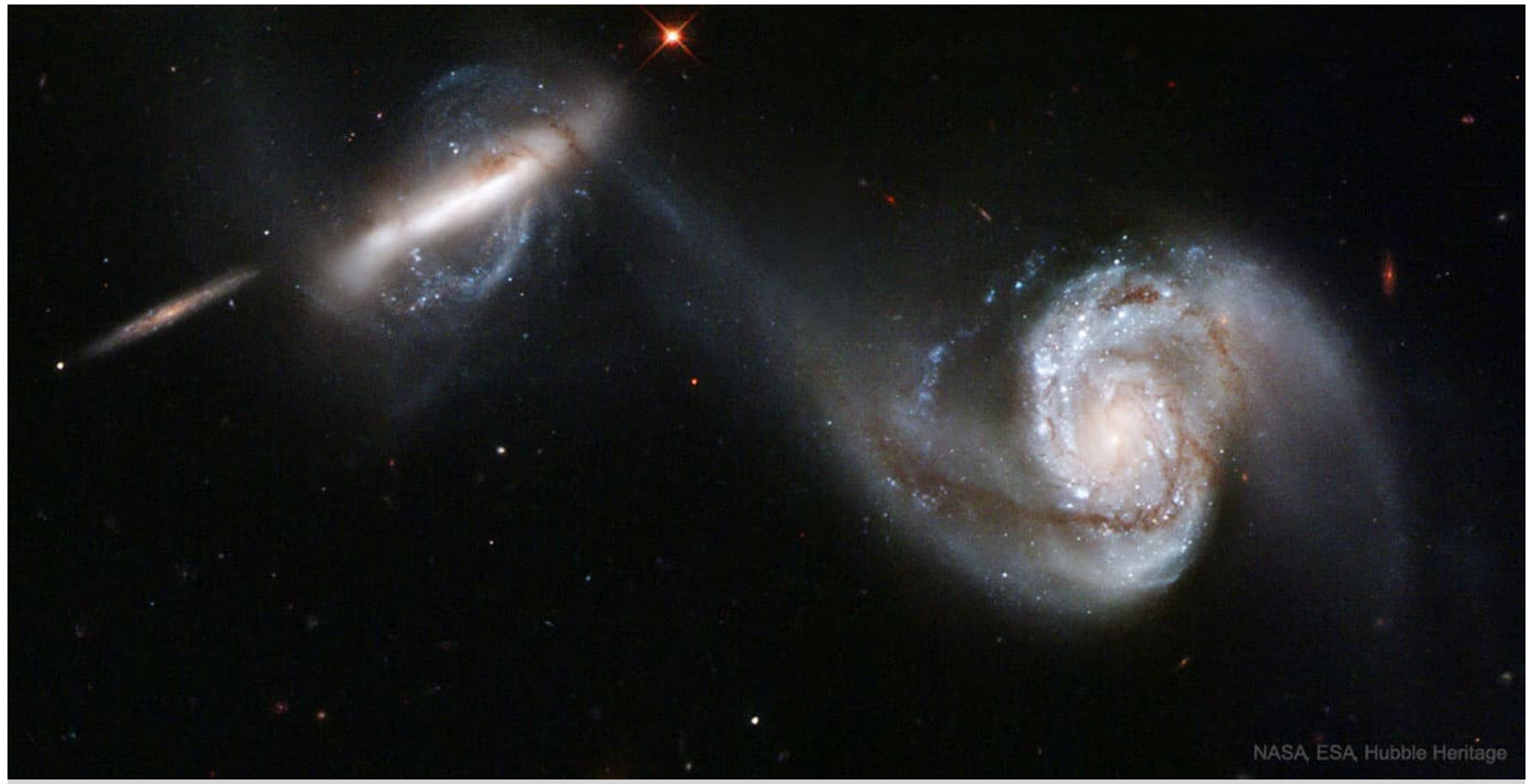


Figure Courtesy of Rosa Valiante

CAT: BHBs Dynamics

This study explores how dynamical friction timescales (the time it takes for a secondary BH to sink into the galaxy center) affect the overall evolution of BH binaries and their ability to merge.



What's Happening?

When galaxies merge, their central BHs also interact. The most massive BH (the **primary BH**) stays at the center of the newly formed galaxy. The smaller BH (the **secondary BH**) takes time to move toward the center due to **dynamical friction**—a force that slows it down as it moves through the surrounding matter.

BH-BH mergers

- **(instant mergers)** assumes BHs merge immediately during galaxy mergers $\tau_{delay} = \Delta t_{CAT}$ **(Trinca et al. 2022, 2023, 2024)**
- **(delayed mergers)** accounts for dynamical friction, meaning some BHs take longer to merge or don't merge at all $\tau_{delay} = t_{df}$ ***(Trinca et al. in prep; Davari et al. in prep)***

- **Some BHs remain "wandering" instead of merging, meaning their mass doesn't contribute to the central BH's growth.**

➡ Being a semi-analytical model, Cat is not able to give information on the physical distance between BHs at the time of merger of hosted galaxies.

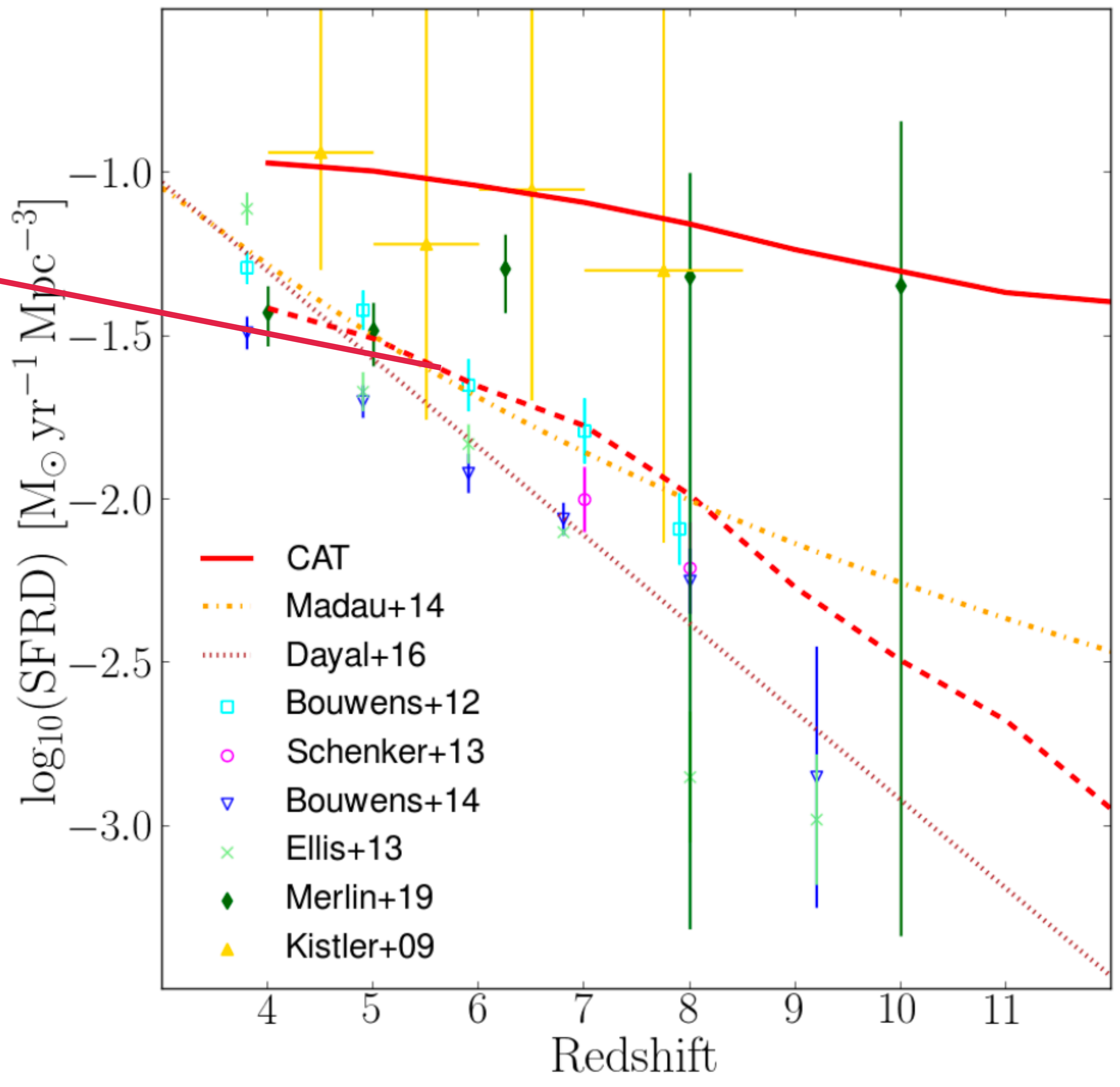
✓ Thus, in order to introduce the timescales in the model, we had to do a first calibration, comparing some of the quantities needed to compute the timescales with simulations.

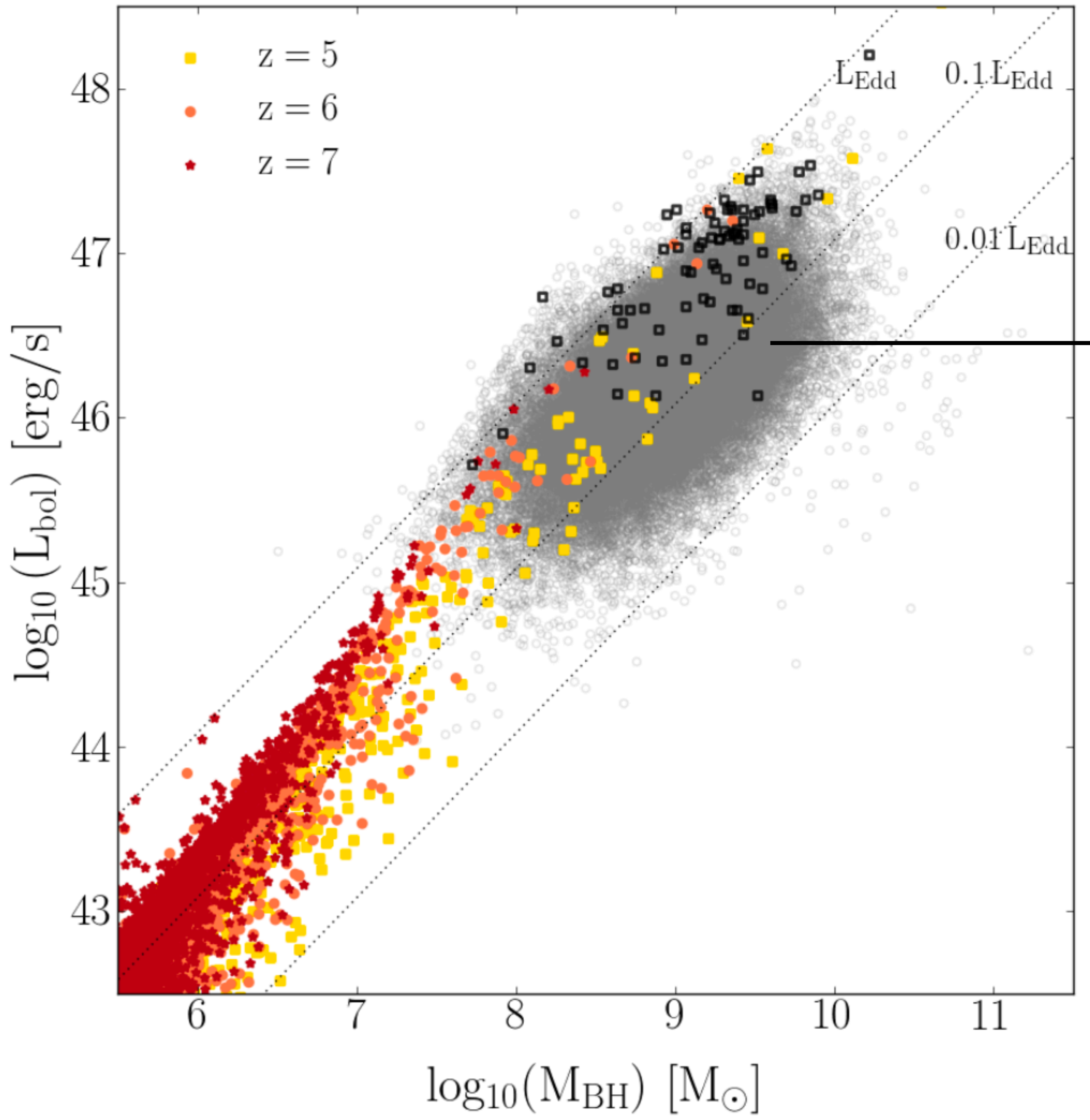
The Cosmic Archaeology Tool (CAT)

The model is calibrated to accurately reproduce the evolution of the cosmic star formation history (SFRD) and the properties of luminous quasars observed at z > 6 (L_{bol}, M_{BH}).

CAT predictions:

SFRD corrected for the observable galaxy population

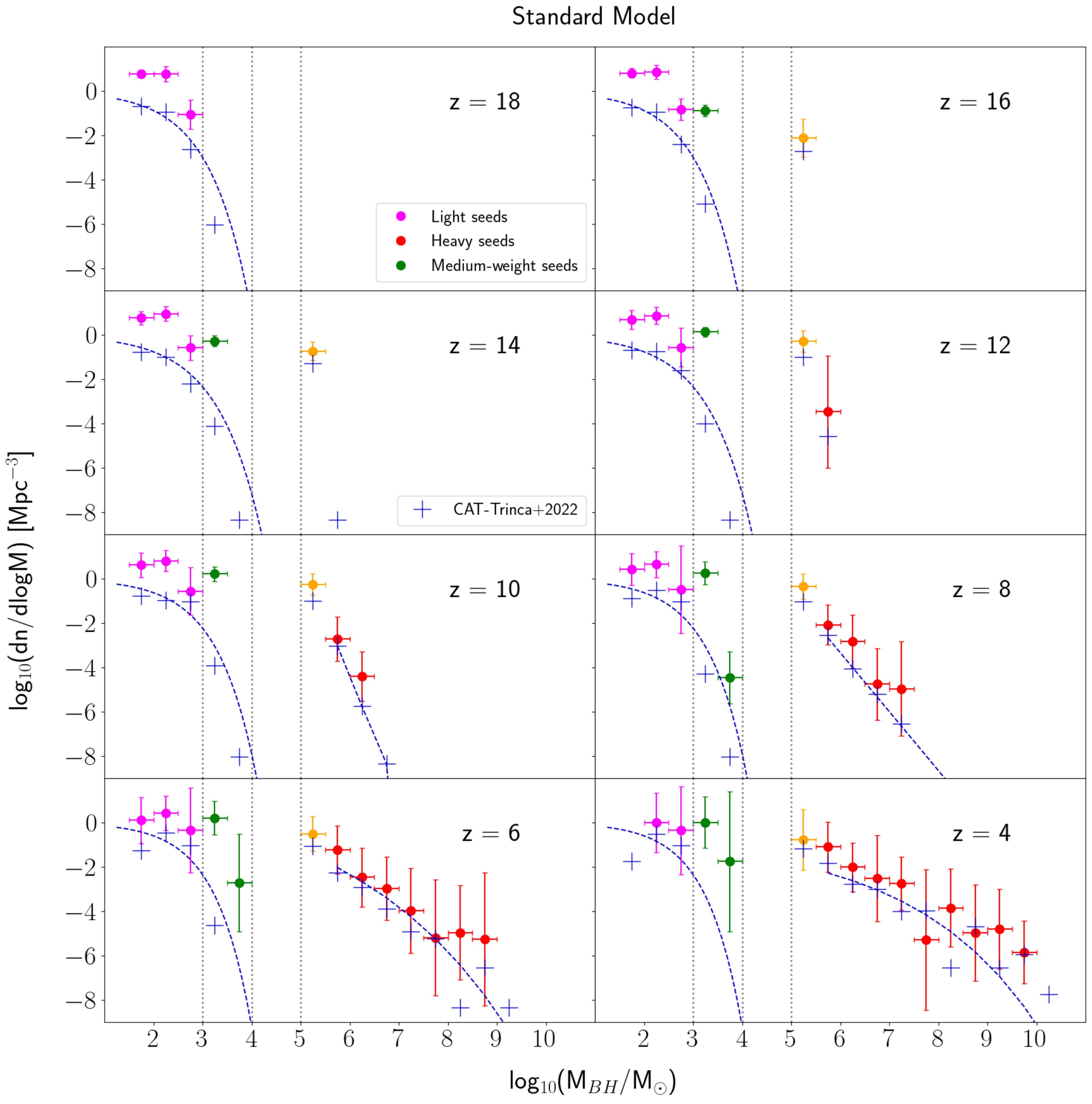


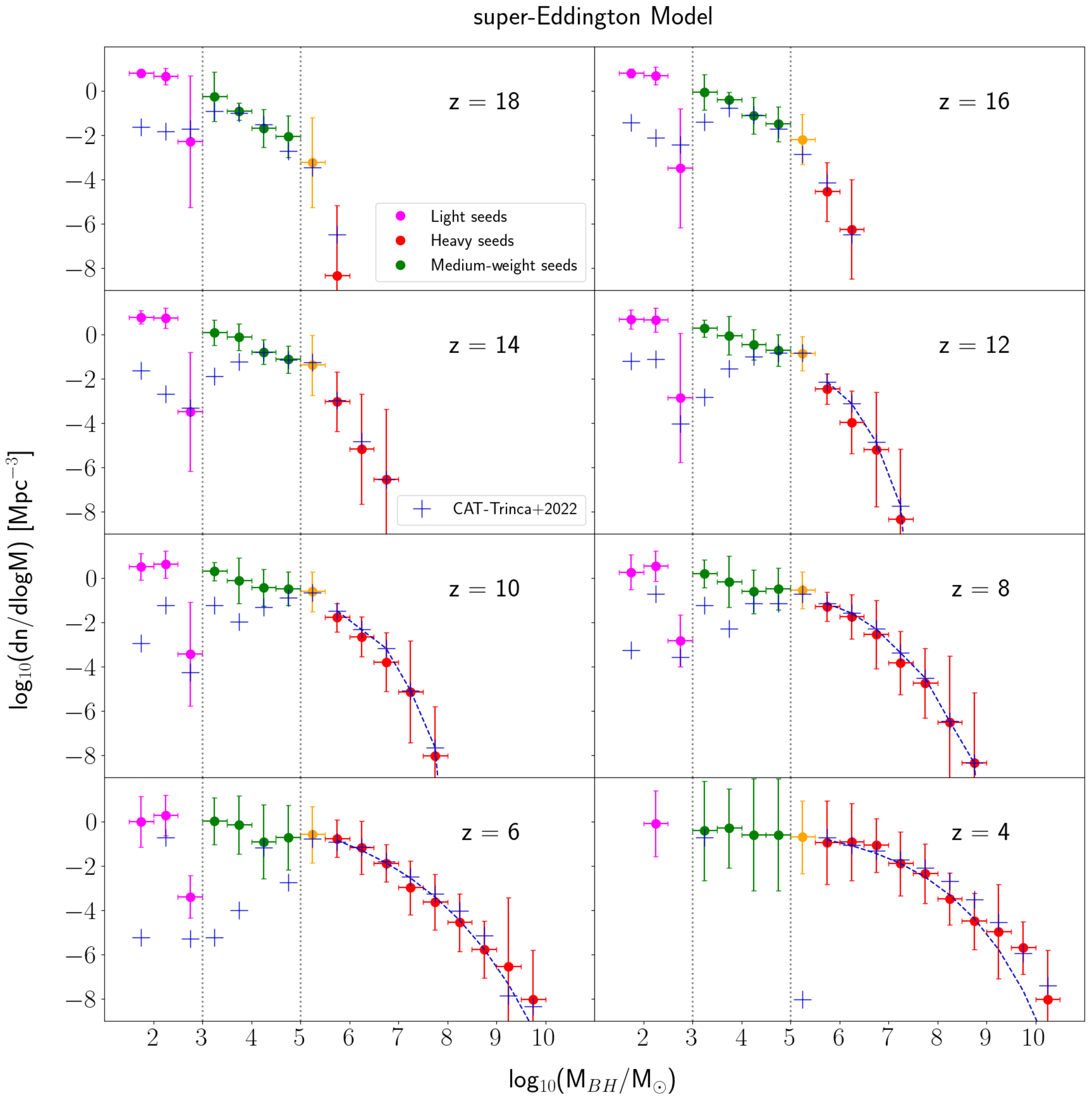


Some local observation for reference

Trinca et. al 2022

Results: Evolution of the BH Mass Function

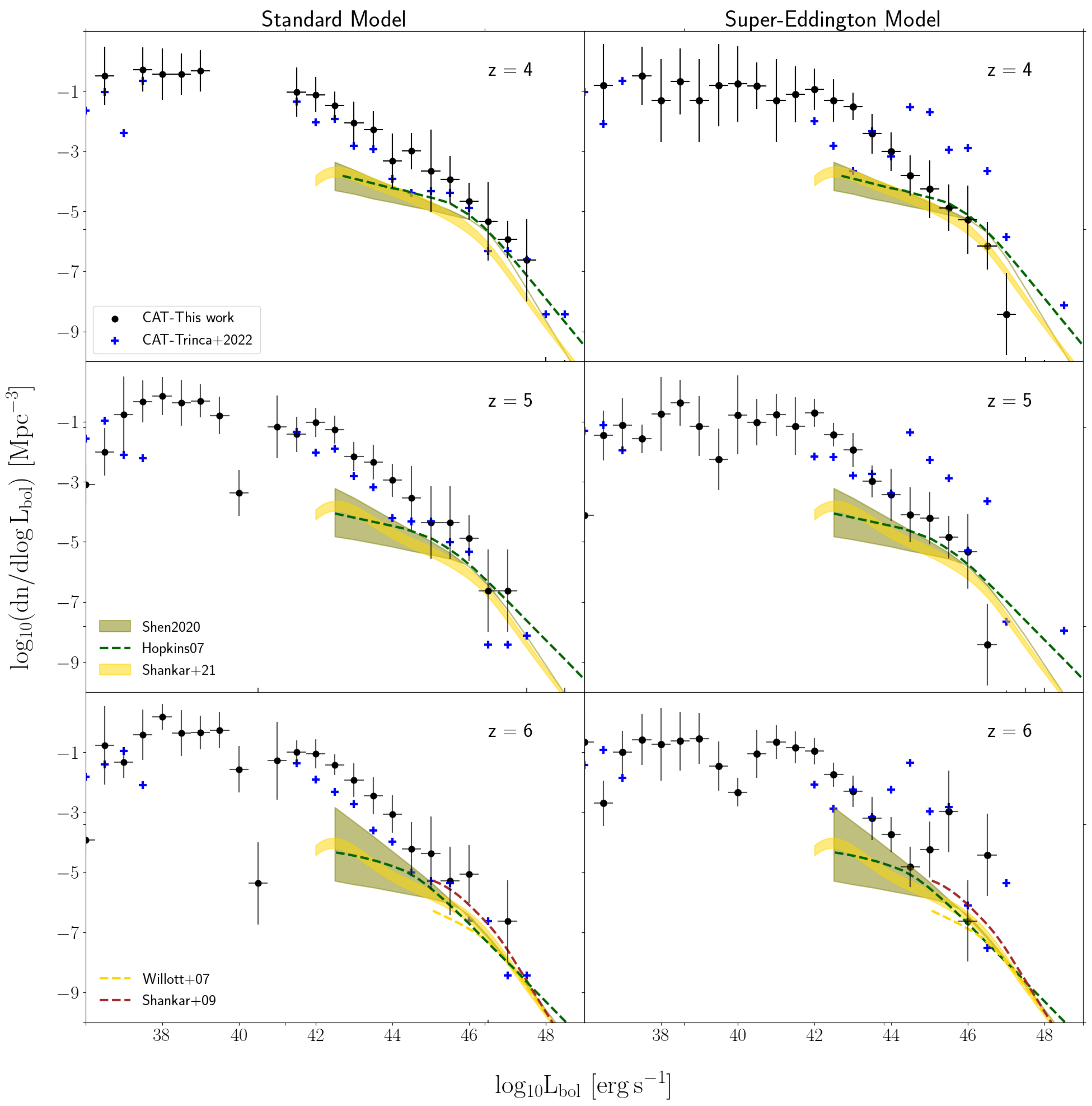




Results: Bolometric Luminosity Function of AGNs

Total Emitted light from black holes at redshifts z = 4, 5, 6 Compared with the previous CAT results with observational data from various studies as points or lines

Applying the bolometric correction proposed by Duras et al.(2020).



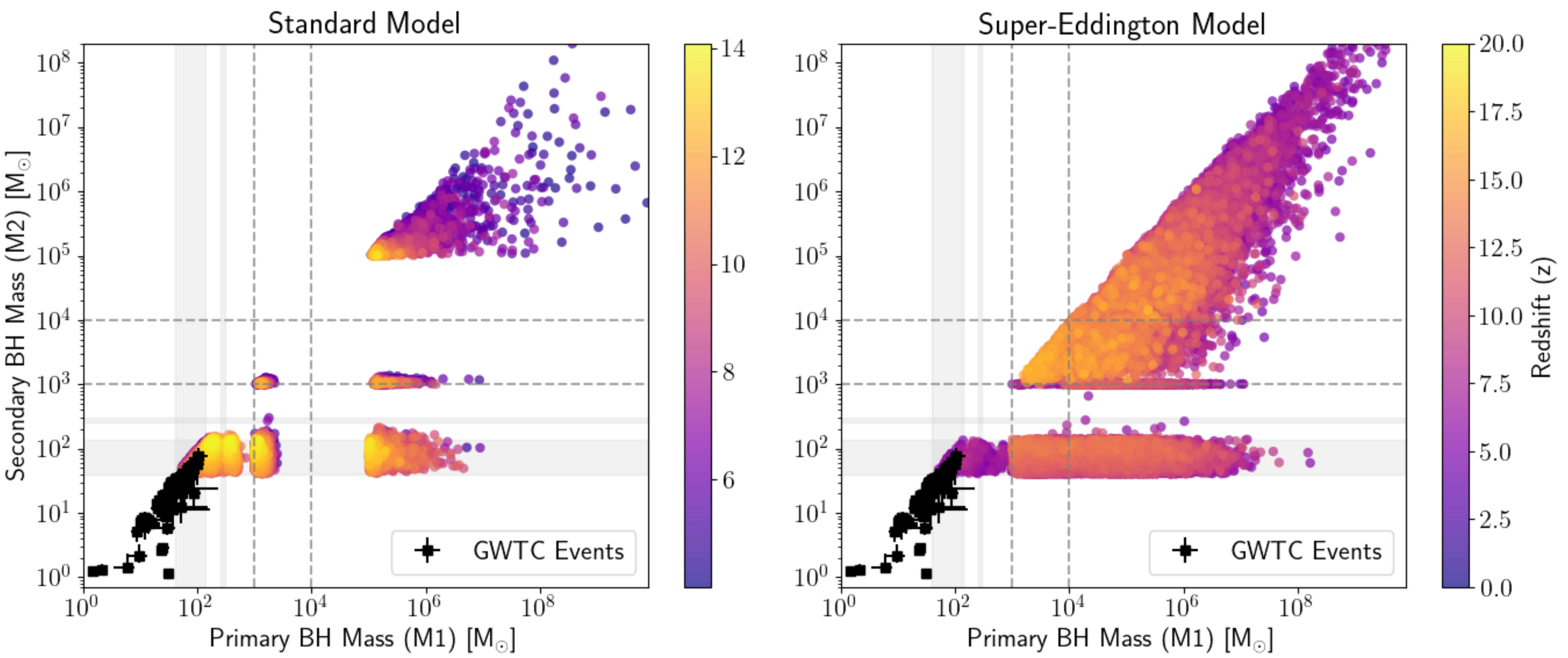
The gap in the LF in the Edd reflects the behaviour of the BH mass functions shown previously slides, and it is a consequence of the failed growth of light black hole seeds that characterize this model.

- Bright quasars (at the high-luminosity end) are rare
- This is because the BH seeds grow quickly at first, using up surrounding gas and stopping the black holes from growing as large as the extreme quasars we observe.
- while faint black holes (at the low-luminosity end) are more common.

Both models predict a lot of low-luminosity sources but not enough very bright ones at early times (like z ~ 6).

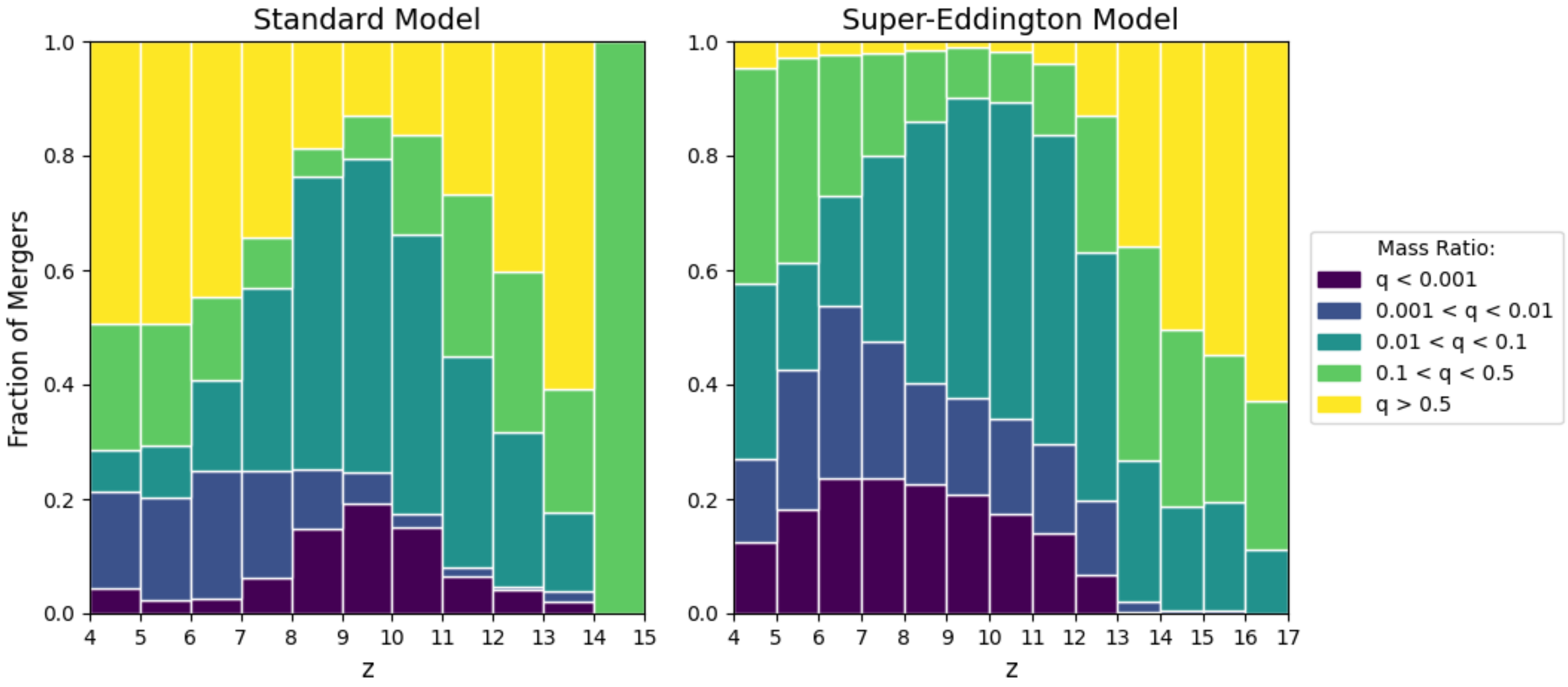
Results: GW Detections of BBHs

Mass distribution at different redshifts



Light BH seeds: [40, 140] & [260, 300] M⊙
Medium BH seeds: [10^3 – 10^5] M⊙
Heavy BH seeds: [10^5] M⊙

Results: GW Detections of BBHs



Results: GW Detections of BBHs

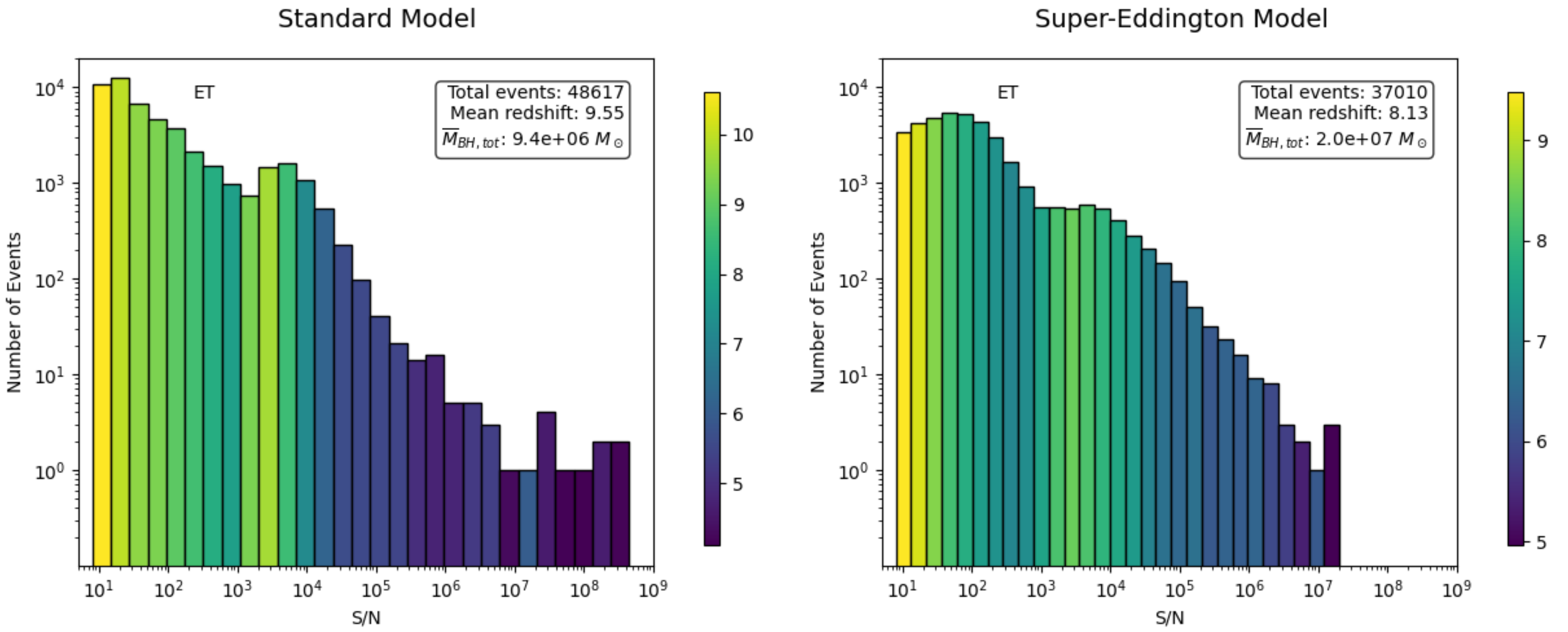
Dupletsa+2022

GWFish is a Fisher matrix code and is able to provide estimates of the signal-to-noise ratio and of the errors on our estimates of the parameters, for a signal as it would be seen by one or more future detectors, among:

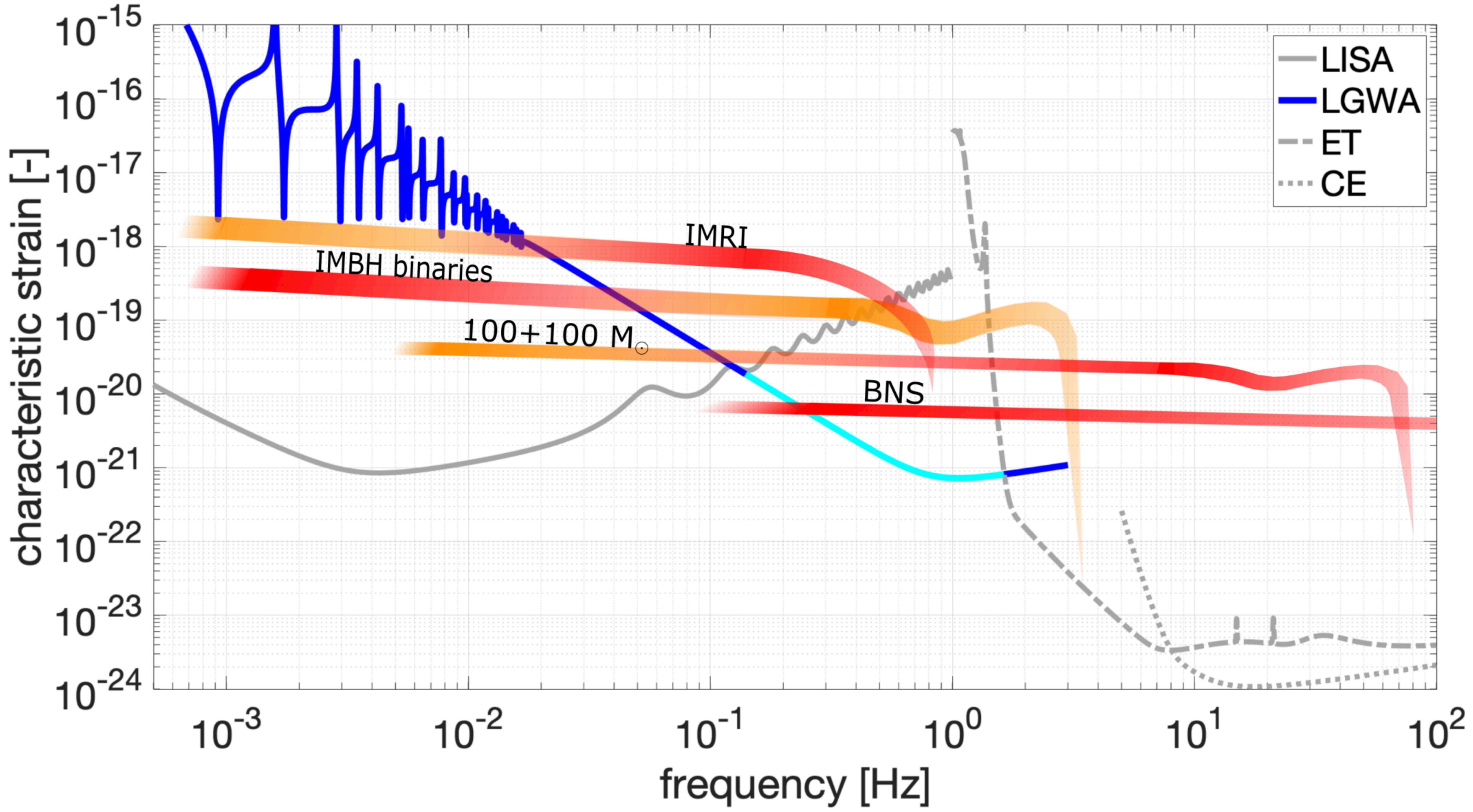
- LIGO / Virgo in their fifth observing run;
- Kagra;
- Einstein Telescope;
- Lunar Gravitational Wave Antenna;
- Cosmic Explorer;
- LISA;
- Voyager.

✳Waveform model: '**IMRPhenomXHM**', a tuned high-order approximant for black hole binaries also including higher order modes (especially important for high-mass and off-axis events).

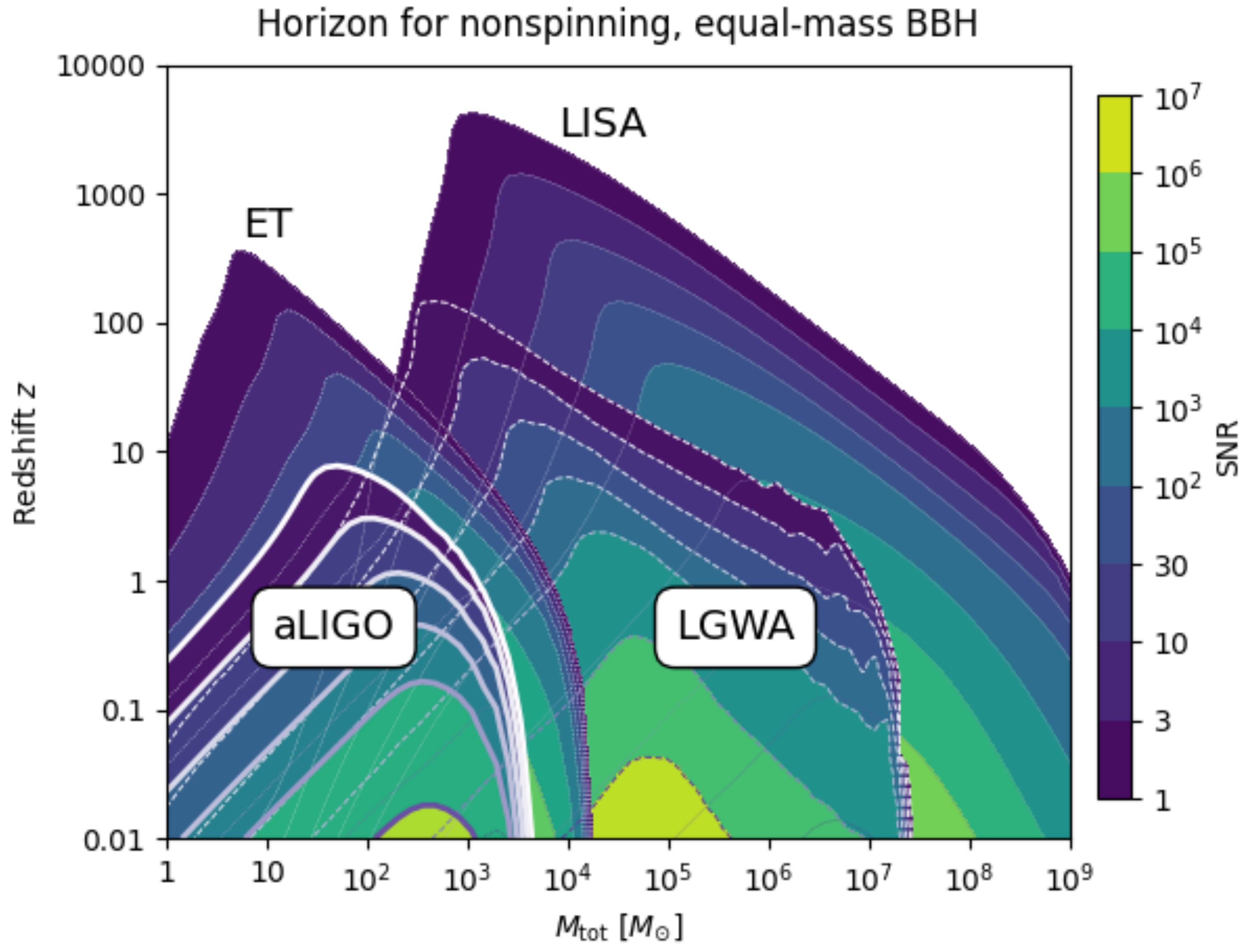
q>0.001



Multi-band GW Observation



Harms et al. 2021



➡The Lunar Gravitational-wave Antenna (LGWA)

➡Its observation band reaches from 1mHz to several Hz, with peak sensitivity in the decihertz (0.1 Hz) band.

➡It will therefore provide the “missing link”.

Results: Multi-band GW Observation

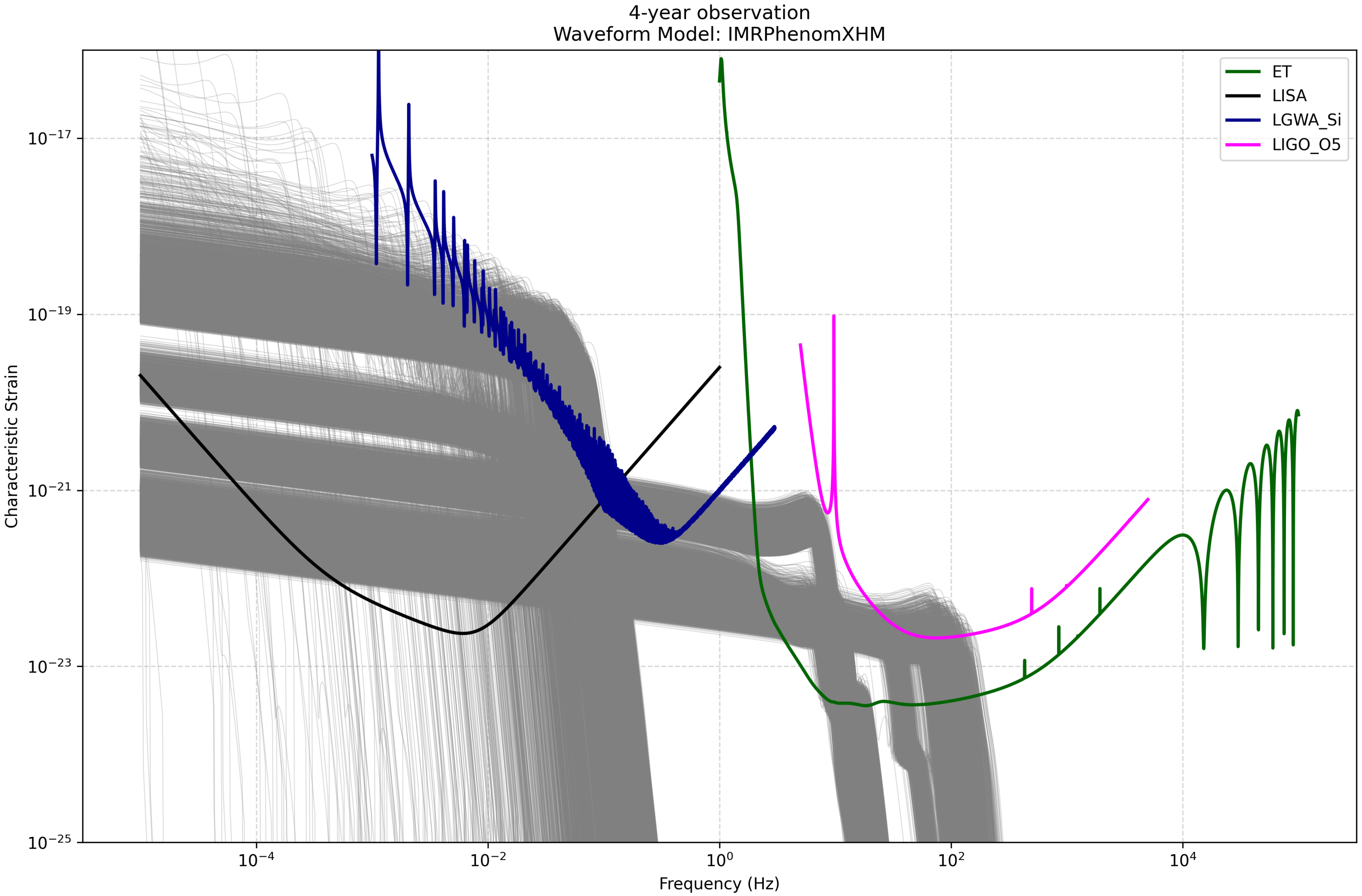
✤ A measurement of the binary's evolution in both the ground- and space-based detectors is what we define as a multiband observation.

- The multiband detection of BBHs: the measurement of their inspiral in LISA throughout the 4-year mission lifetime (0.001 – 0.1 Hz) , and at least the merger or ringdown in the ground-based detectors (ET, CE, VOY: 1 – 250 Hz).

- For binaries with IMBHs in the lower and medium-range ($10^2 - 10^4 M_\odot$), LISA-like space-based detectors will measure only their early inspiral, from 1 – 100 milli-Hz.

- This inspiral could last months to years depending on the mass of the black holes.

- However, the loudest gravitational wave signature - the merger of IMBHs - would occur in the frequency range accessible to ET/LIGO-like ground-based detectors, ~ 1 – 250 Hz.



IMRPhenomXHM not valid at mass ratios below 0.001 (q < 0.001)

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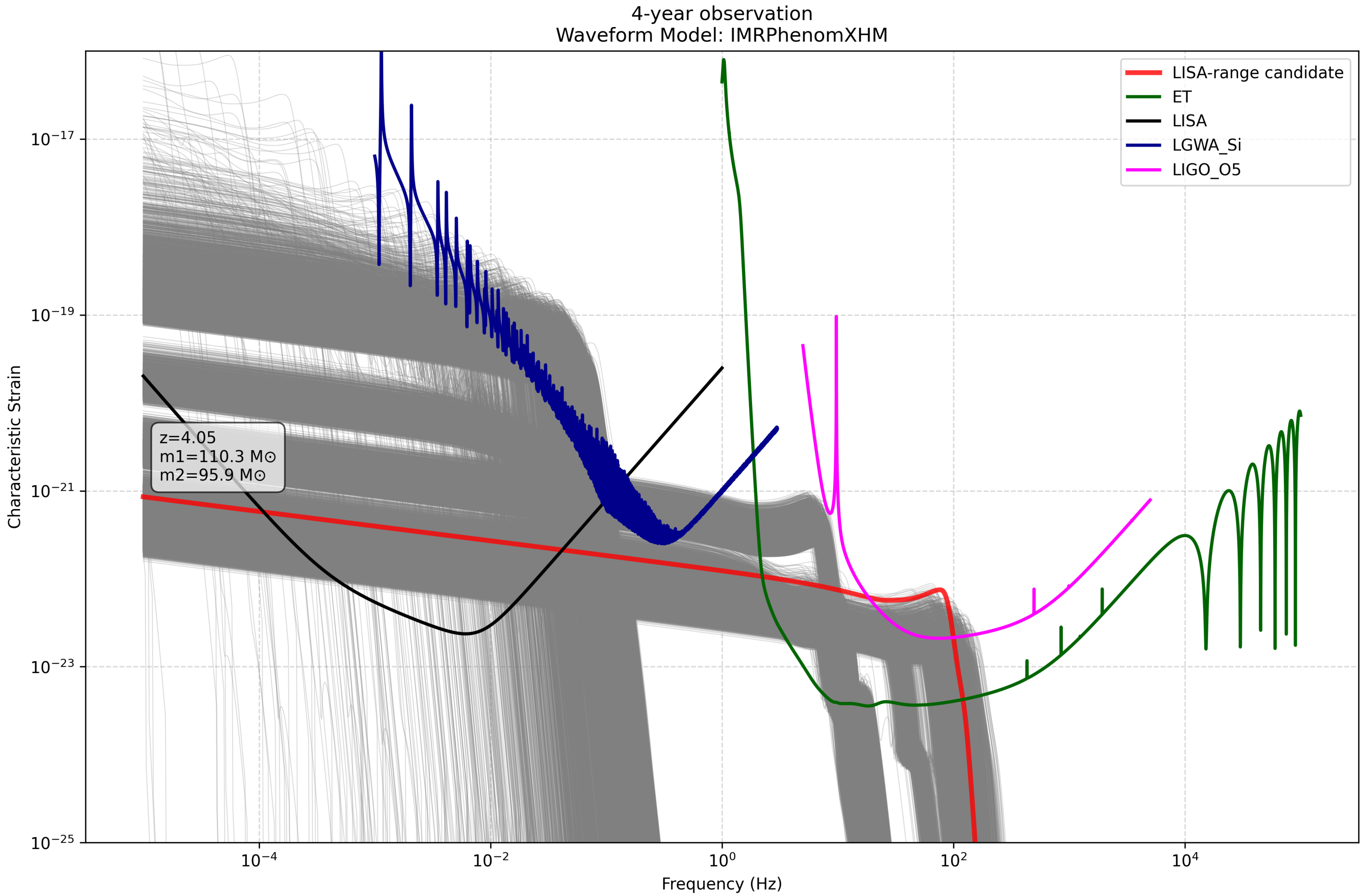

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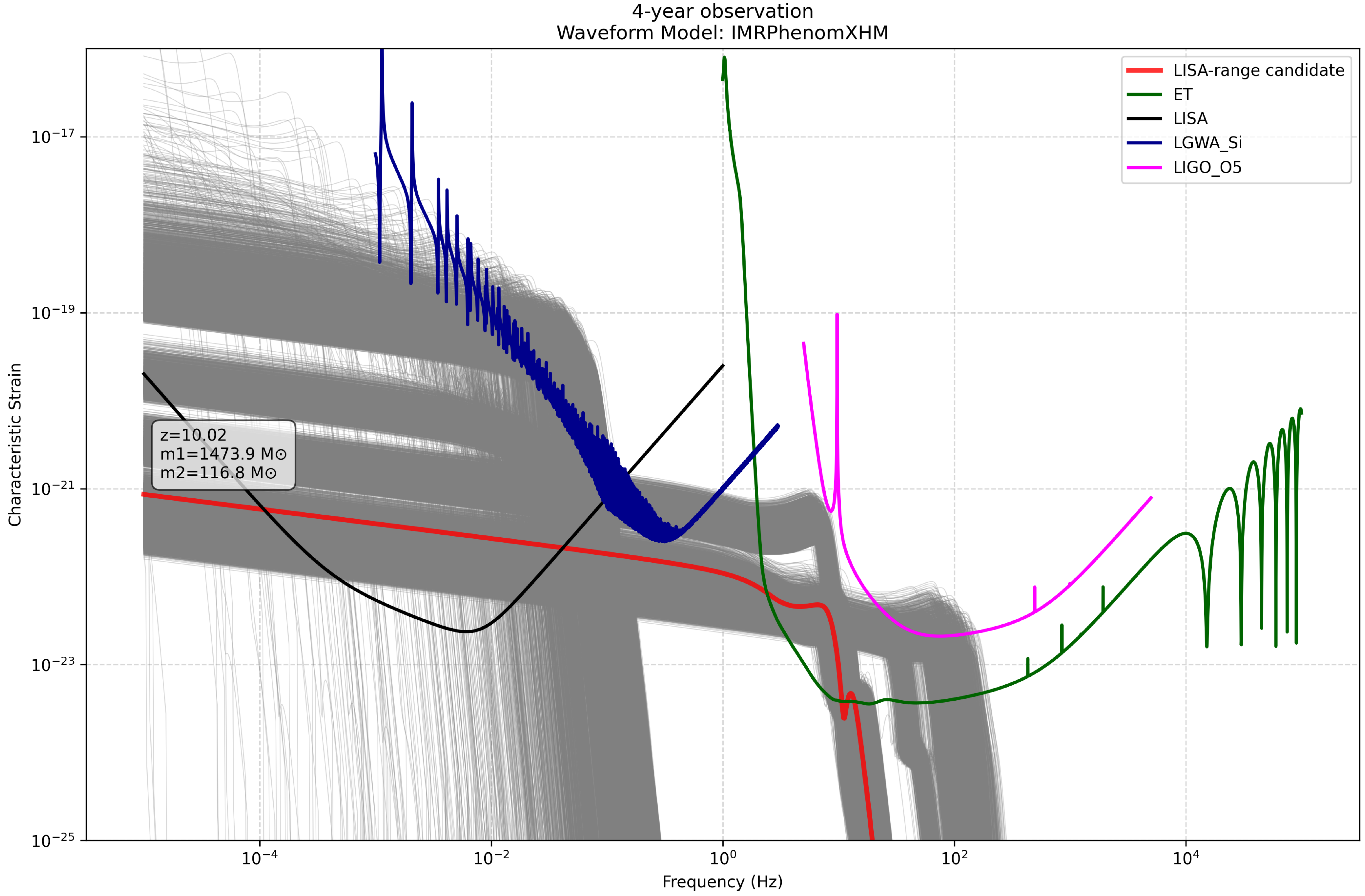

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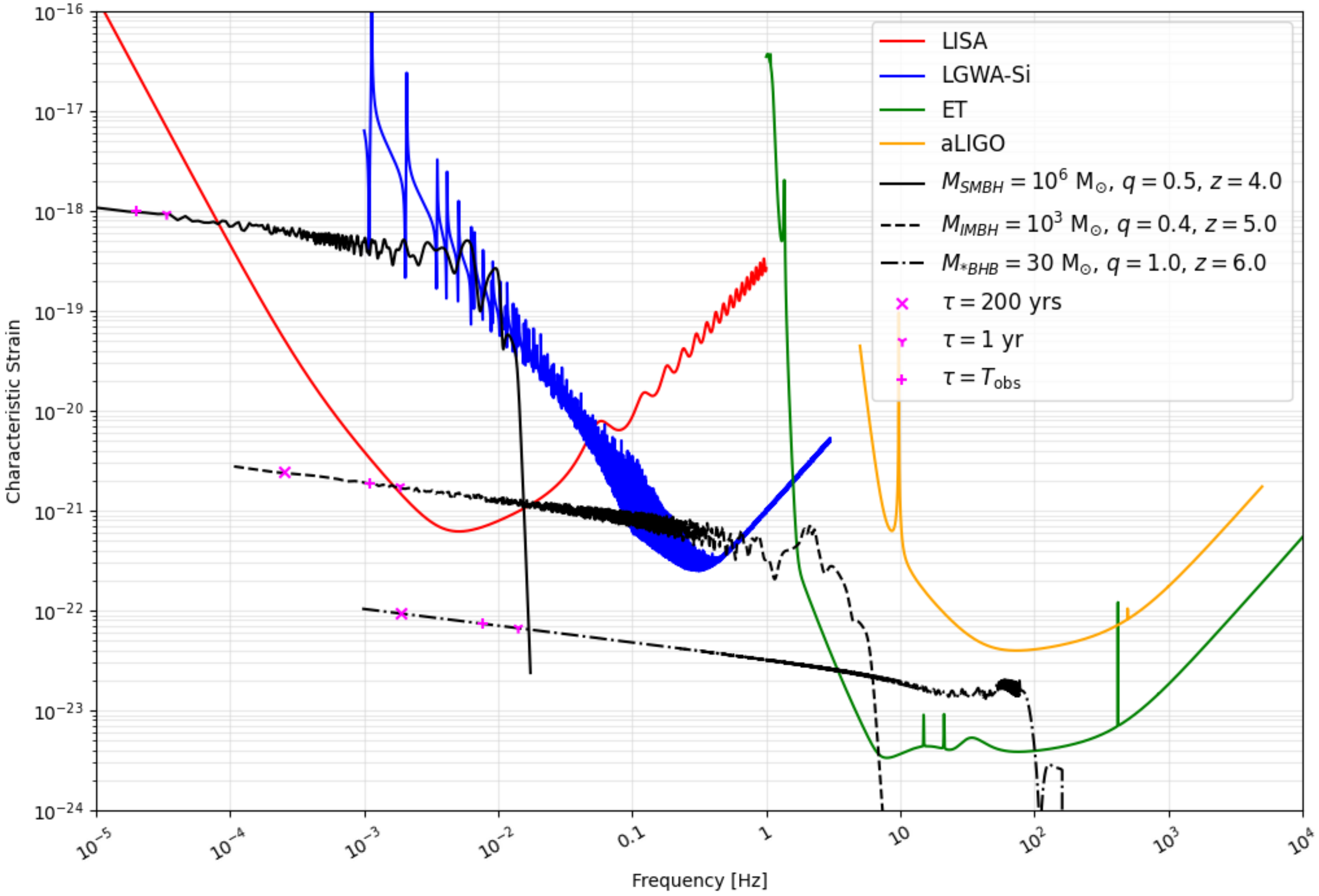
GWFISH

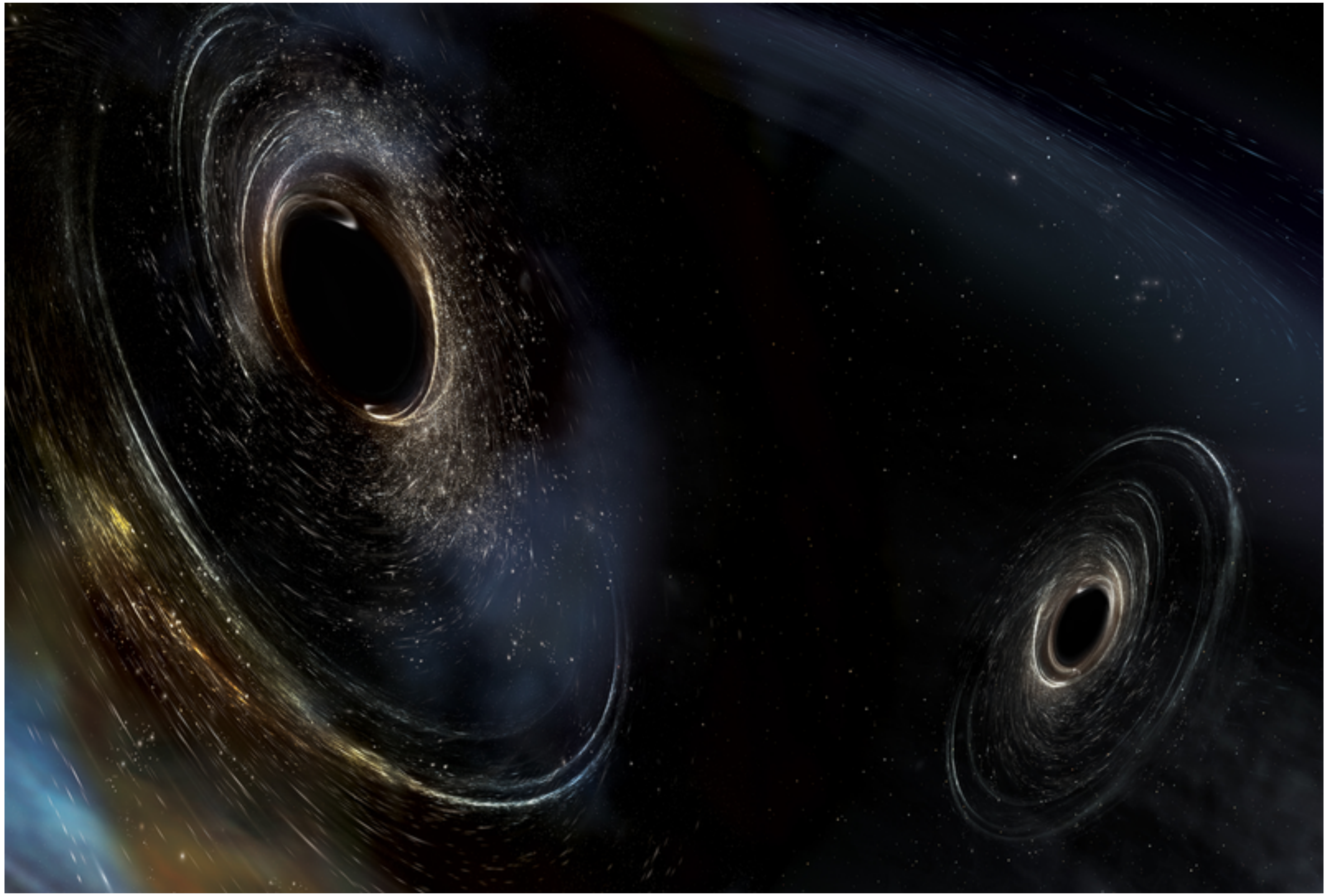
Results: Multi-band GW Observation

An illustration of multi-band GW sources.
we show the LISA, LGWA, ET and aLIGO sensitivity curves together with GW candidates from different classes of compact objects.

Three different moments, namely 200 years before the coalescence, at the detector’s (typical) observation time Tobs and 1 year before the coalescence.



IMBHs >> Their potential is high since they could accumulate a high enough SNR in LISA, LGWA and ET during the inspiral, merger and ringdown.
A combined measurement could then allow a joint analysis.
A system such as the one in figure emits at~0.003 Hz around 1 year before the merger. This makes imaginable an early warning by LISA to both LGWA and ET, with the subsequent detection in all the three bands.



Thank you for your attention!