Probing the population of pop III remnants using gravitational wave observations

XV Einstein Telescope Symposium

Bologna, Italy

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Outline

- Introduction to pop III stars: current understanding and observational significance

- Electromagnetic probes and implications

- Gravitational wave (GW) probes: third-generation detector network

- Science capabilities and challenges of 3G detectors to probe the population properties of pop III star remnants

Universe forms roughly 13.8 billion years ago

“Recombination”: 380,000 years after Big Bang, first light (z ~1100)

“Reionization”: The first stars were form and complete within ~1 billion and started ~ 150 million years after big bang: cosmic dawn (z ~ 6-20)

About 9.8 billion years after big bang: formation of solar system (z~0.5)!

Opaque

As you probe higher redshifts you get to know the early Universe, pop III stars are the first stars in the Universe!

Pop III

- First stars: about 100-200 million years after big bang
- Entirely of Hydrogen/Helium (low metallicity environments)
- Very massive and short-lived
- No direct detection so far!

Pop II

- Older, younger than pop III stars
- Globular clusters and halo of galaxies
- Direct detections from 1920s

Pop I

- Younger stars with high metallicity
- Sun, Vega, and most stars in the Milky Way

How much we know about pop I, II and III stars?

Why we think pop III remnants exist: indirect evidences

Observation of Quasi-stellar objects: extremely luminous active galactic nuclei 'quasars'

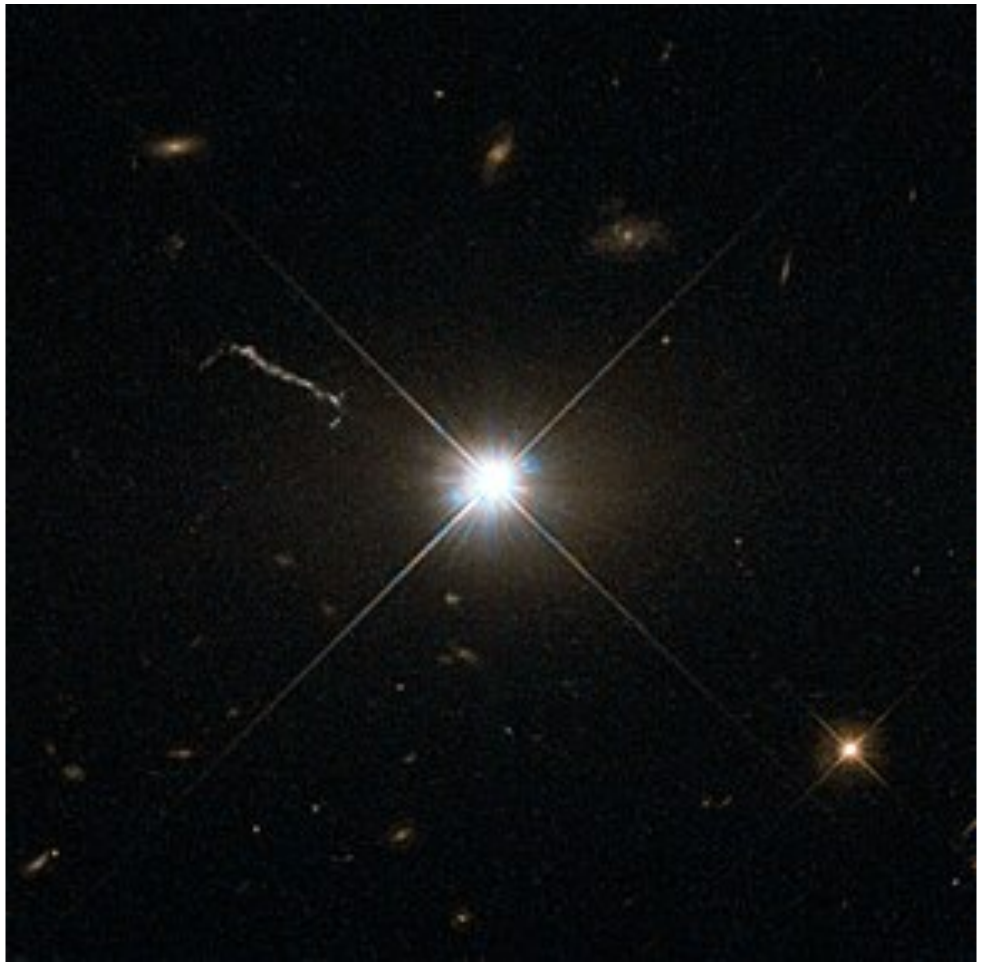
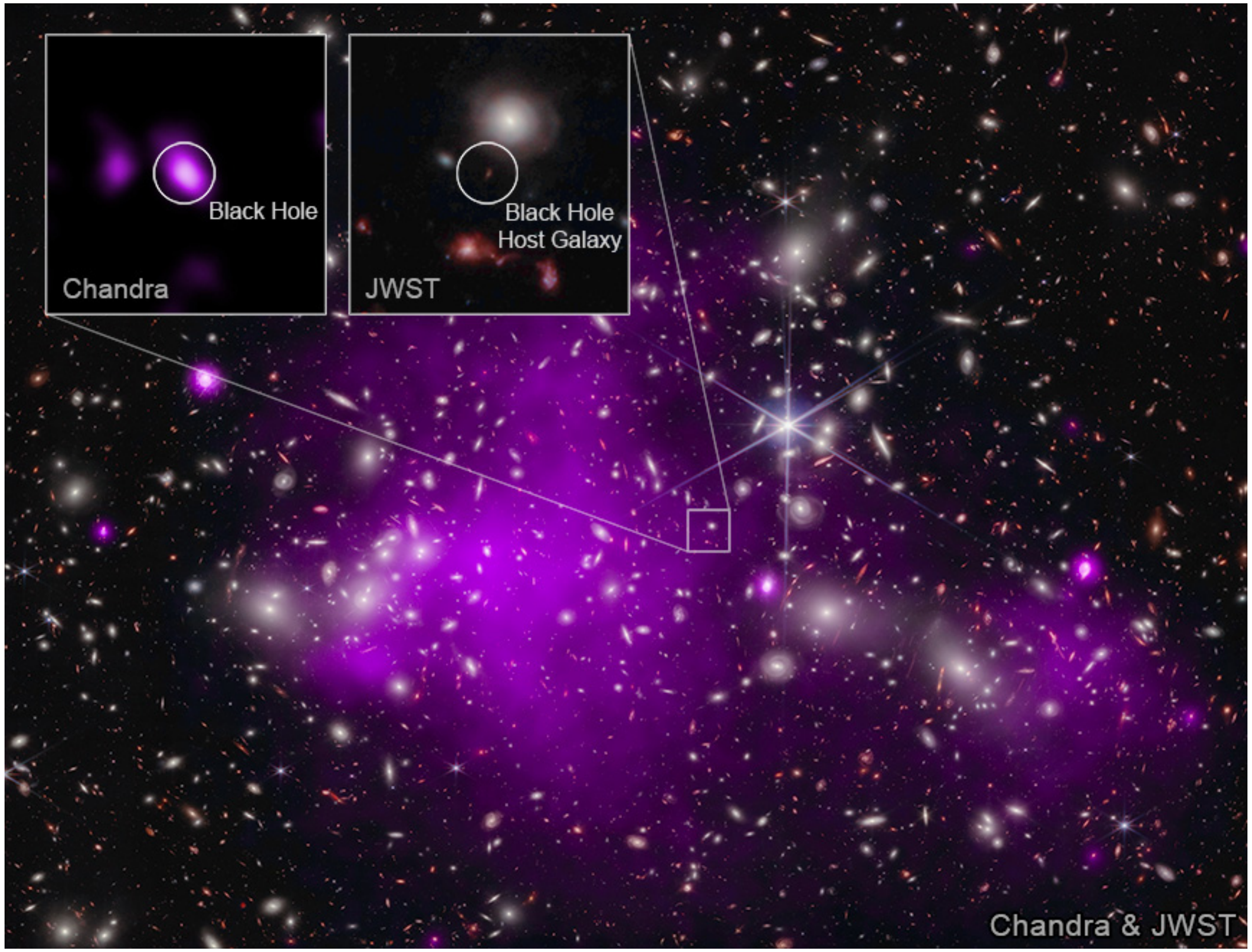


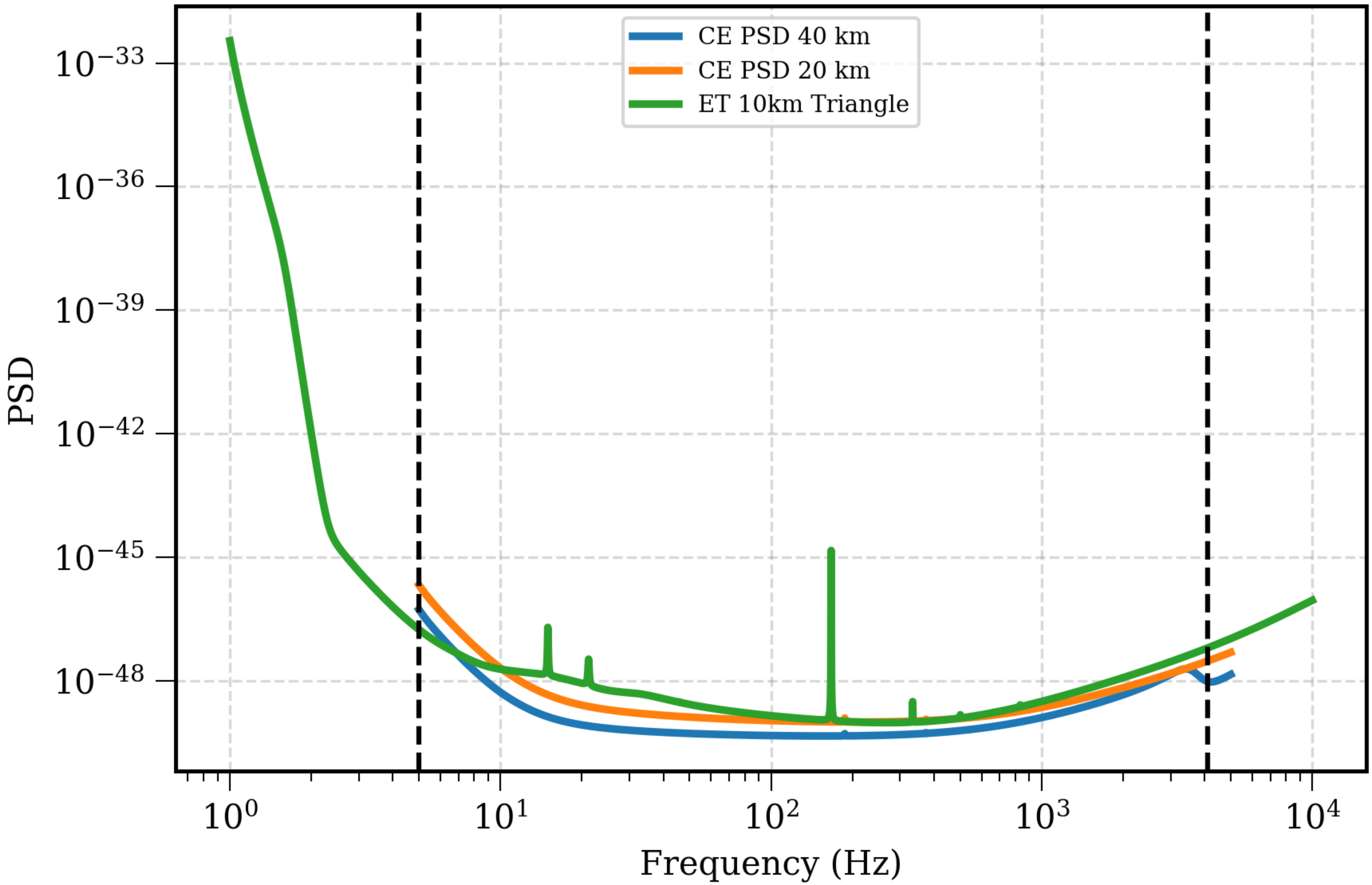
Image of the first quasar observed, 3C 273. Situated in the Virgo cluster ~749 Mpc (z~0.1). An extremely bright object, with a luminosity about 2 million times greater than that of the entire Milky Way galaxy. [image credit HST]

[Natarajan et al., ApJ Letters, 2023]

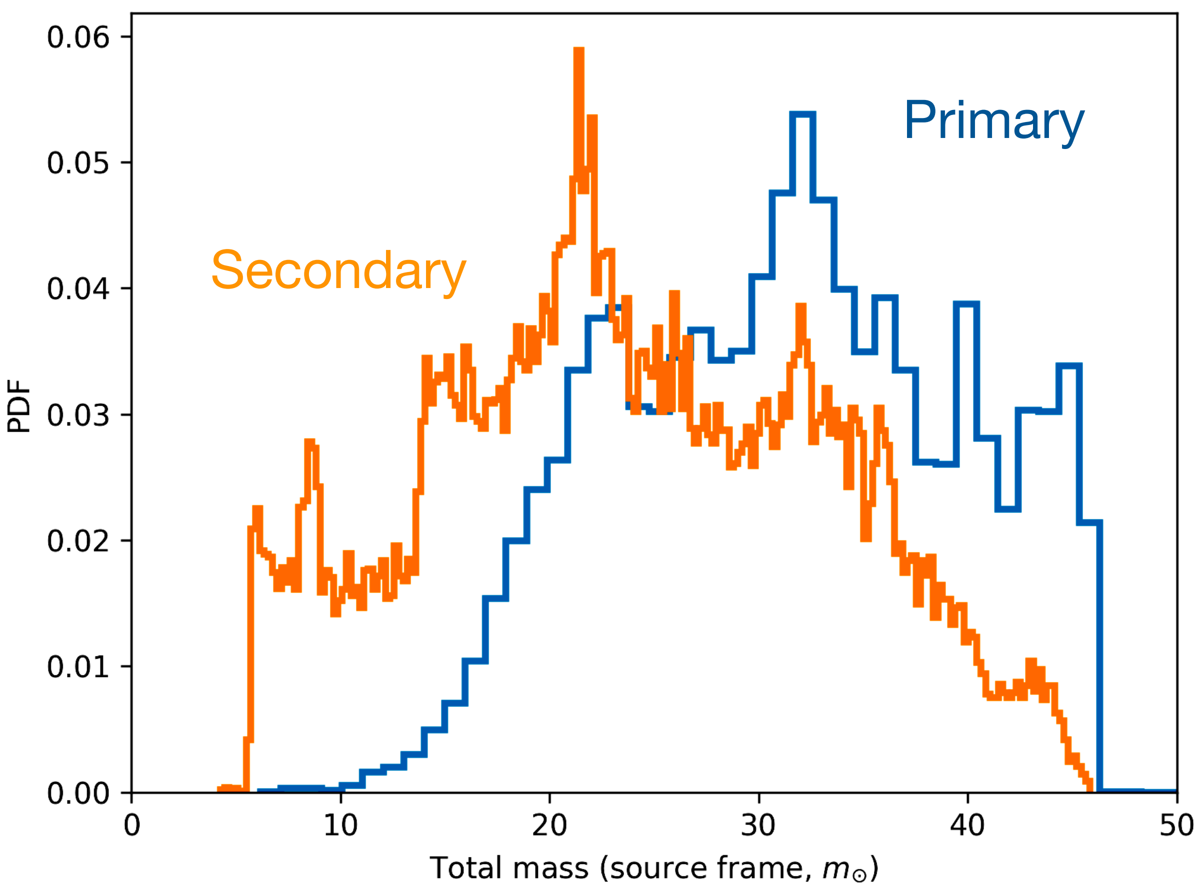


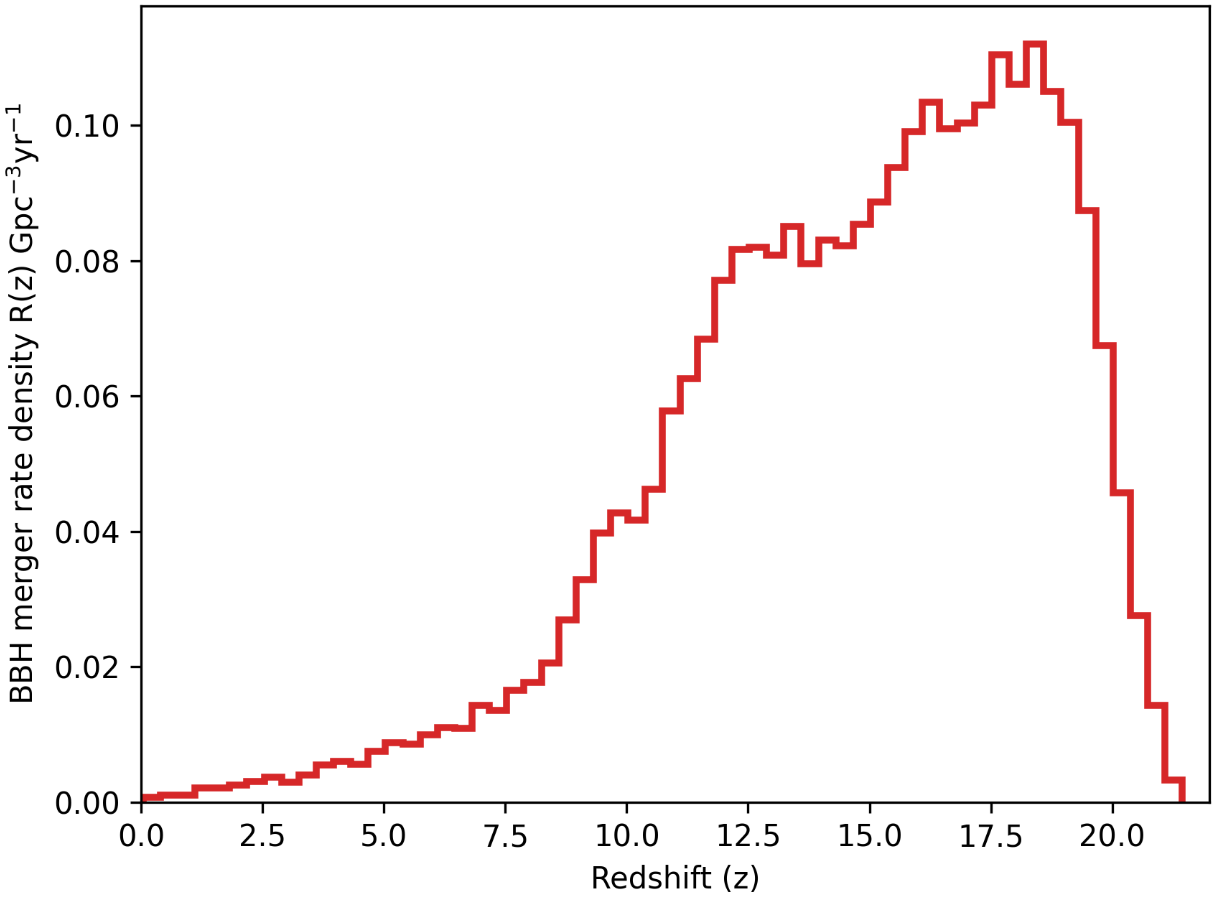
AGN of mass $4 \times 10^7 m_\odot$ in galaxy UHZ1 at 4.047 Gpc (z ~ 10.1, 470 million years after big bang), observed using X-rays from NASA's Chandra X-ray Observatory (purple) and infrared data from NASA's James Webb Space Telescope (red, green, blue)

Growth of AGNs and popIII remnants as possible seeds: possibility of gravitational wave observations as probes


CE PSD 40 km
CE PSD 20 km
ET 10km Triangle
10^{-33}
10^{-36}
10^{-39}
10^{-42}
10^{-45}
10^{-48}
PSD
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)

Population Model for POP III stars



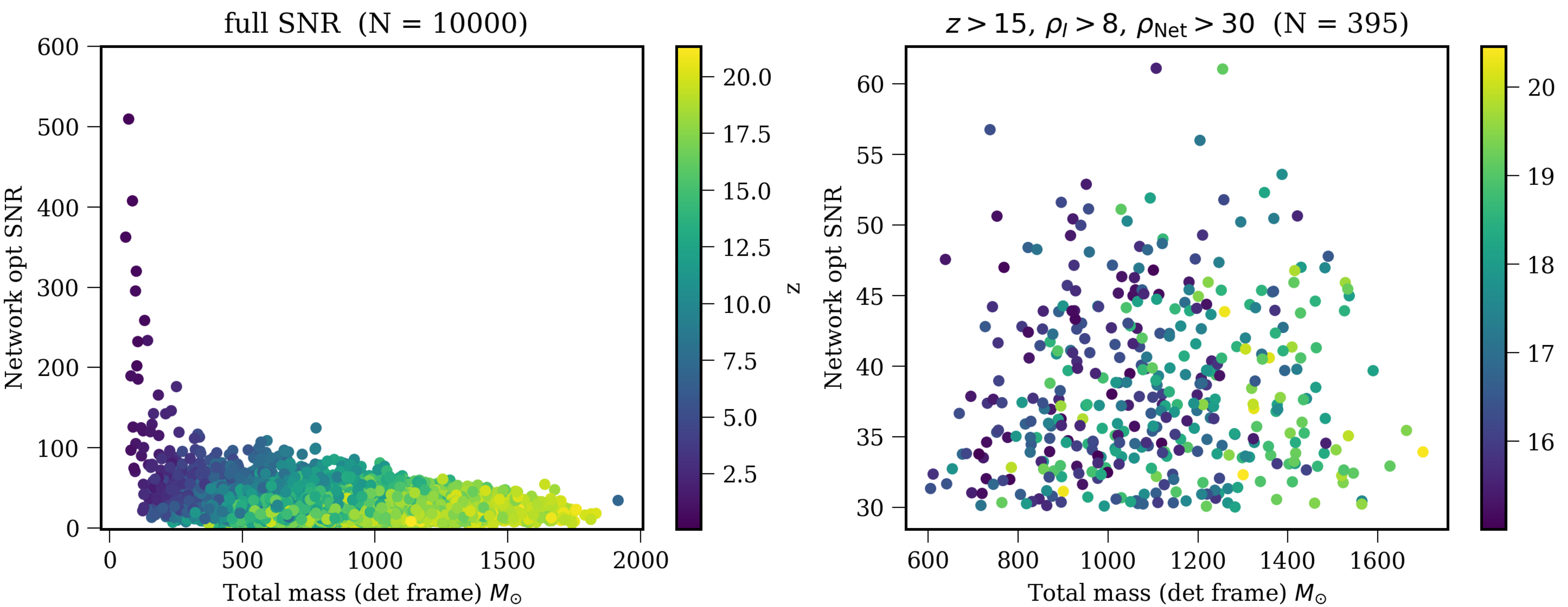


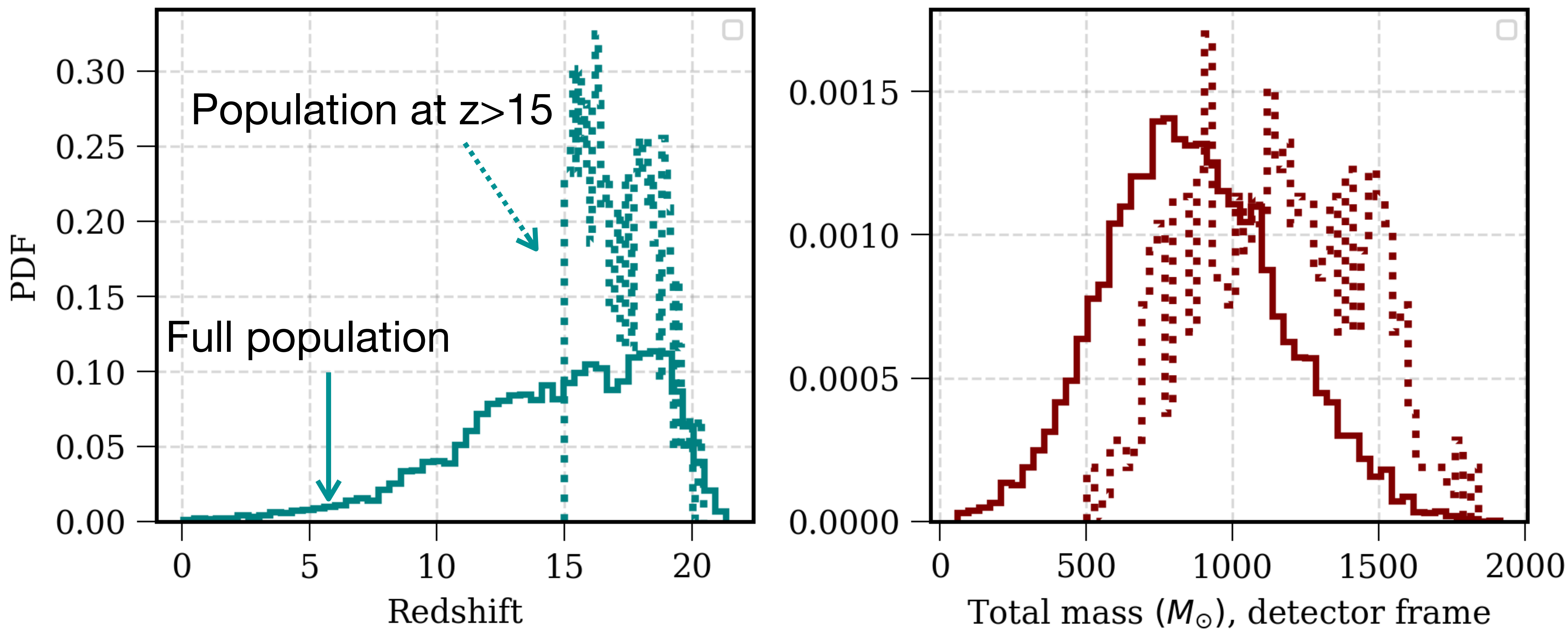
Details of this model:

- Provides a total of 44 different models considering various initial mass functions of the stars, their orbital properties including the orbital period and eccentricity distributions, super novae models, and star formation rate density estimates
- Estimate the merger rate density of these sources
- Let us choose one case: A flat-in-log for the initial mass function with mass ratio following a power law with index -0.1 (LOG1), power law for orbital period and orbital eccentricity, and a particular star formation rate density model

[Filippo Santoliquido 2024 (a) and Filippo Santoliquido 2024 (b)]

What are the high redshift sources with significant signal-to-noise ratios?





Population at z>15
Full population
PDF
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
Redshift
0.0015
0.0010
0.0005
0.0000
0
500
1000
1500
2000
Total mass ($M_\odot$), detector frame

Pop III remnant population properties from observations

Initial population properties of compact objects in the Early Universe

Population synthesis

Detectability of the network configuration plus detector selection effects

Waveform and data analysis

Obtain detector frame and source frame properties

(Parametric/non-parametric models to reconstruct the properties)

Obtain astrophysically motivated models

How the population properties of black holes formed in the very early Universe differ from the ones we observed? How these objects formed and evolved? To answer these questions, what is the accuracy requirement on individual binary parameters?

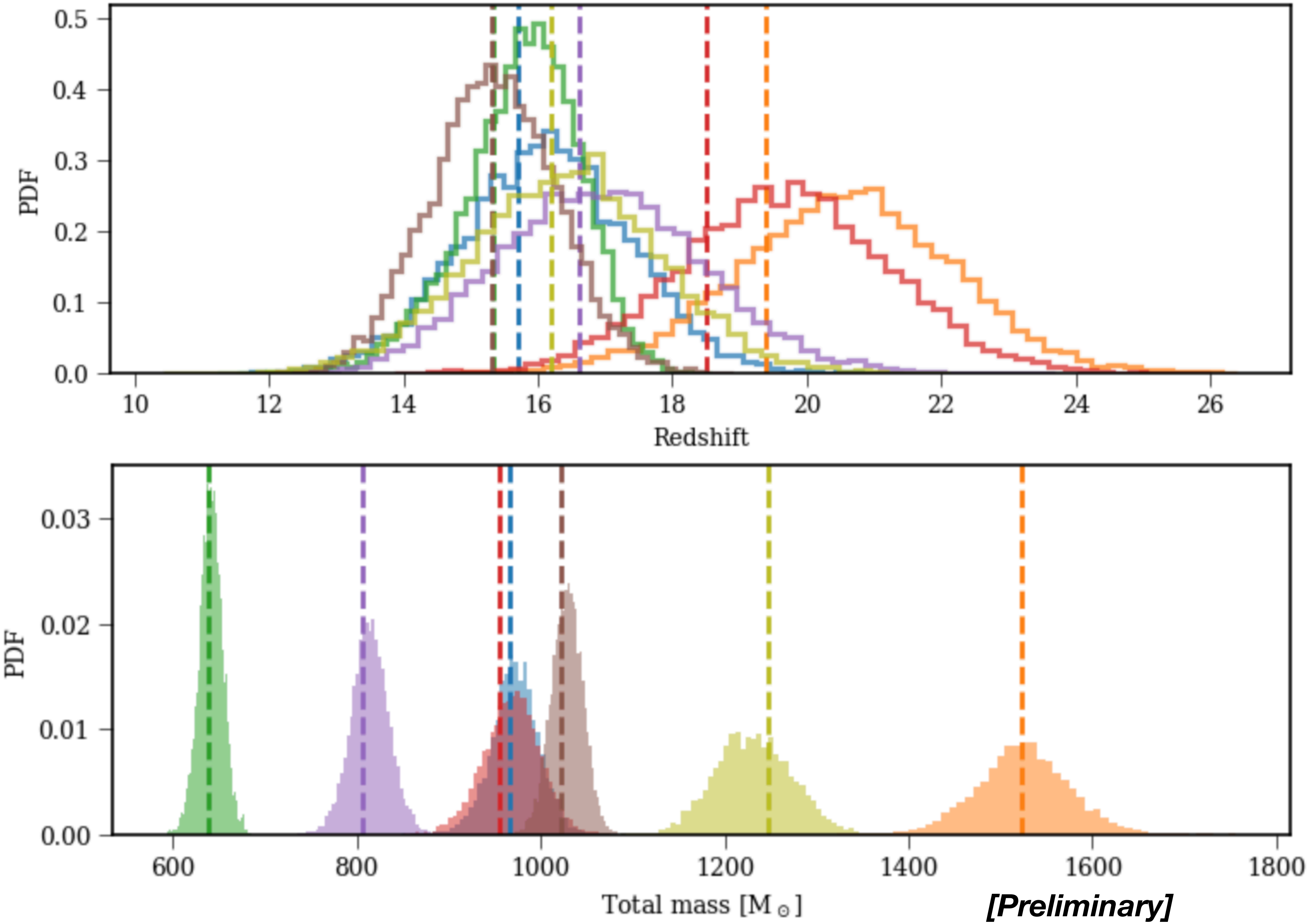
Plunkett et al., Arxiv: 2504.18615

- If we analyse the selected sources at large redshift using Bayesian inference, how well we can measure the individual binary properties, such as the masses, spins, redshift and then the intrinsic properties of the binary?

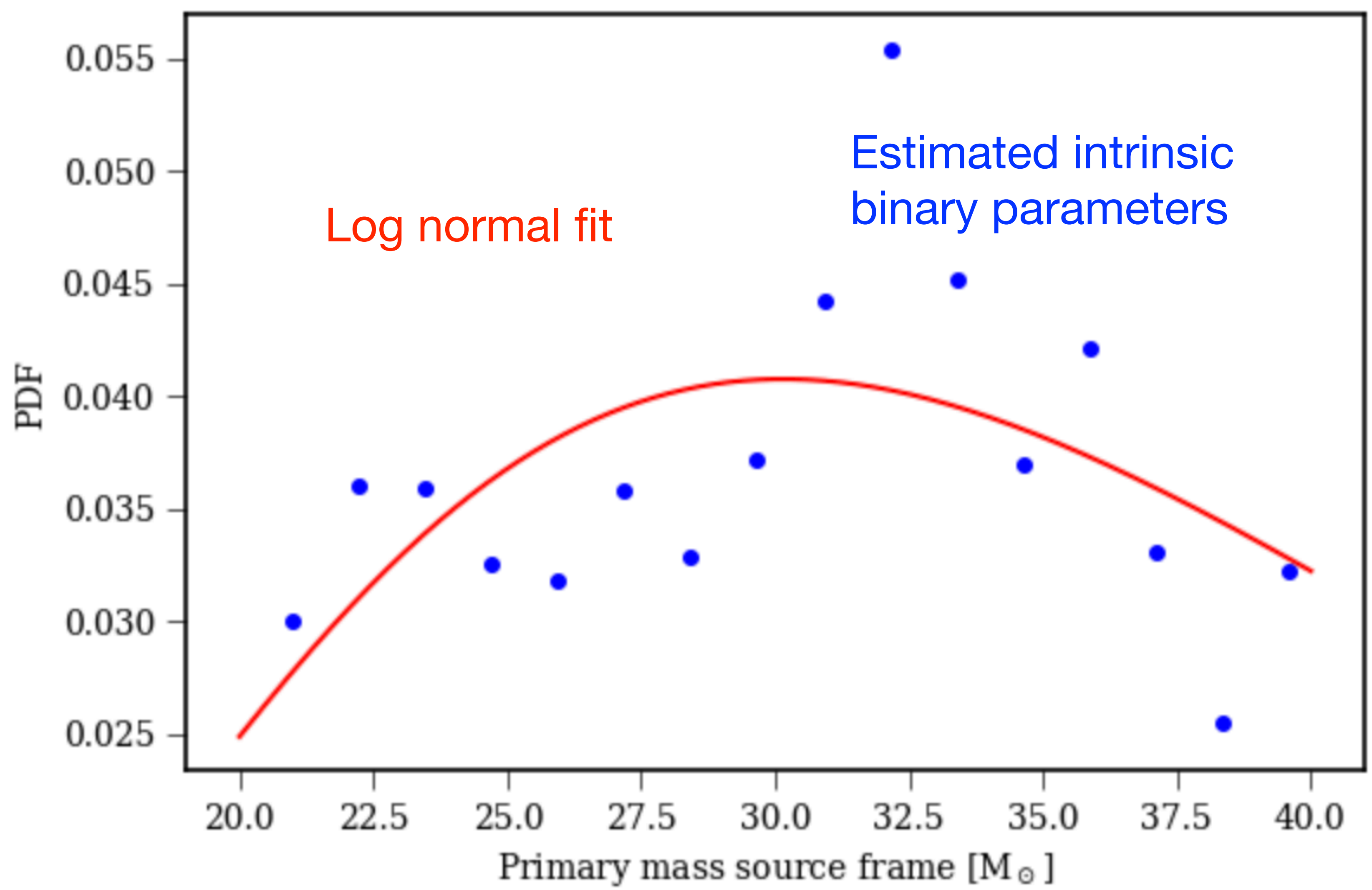
- The implementation is based on dynesty sampler from Bilby and IMRPhenomXPHM waveform model

G. Ashton et al., The Astrophysical Journal Supplement Series (2019) 241, 27; G. Pratten et al. Phys. Rev. D 102, 064001 (2020)

High redshift binary black hole parameter estimation



[Preliminary]



[Preliminary]

Estimate the intrinsic population properties of binaries from the Bayesian analysis and assess the capabilities of third-generation GW detector network

- Ongoing work
  - How accurately we can construct the population properties of pop III star remnants considering different detector configurations and networks.
  - Implications to star formation rate density models and merger rate density models.

Thank You!