

Gravitational Wave Astrophysics

Lecture 4

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In this lecture, you will learn

- Population-synthesis simulations
- Black holes from Population III stars
- Next generation detectors

Population synthesis

- Compact object mergers formed in the isolated formation channel are modelled through **population-synthesis** simulations
- These are fast codes that evolves millions of stars in binary systems where
 - Single stellar evolution is precomputed (fitting formulas or stellar tracks)
 - Binary stellar processes with analytic and semi-analytic methods
- **No hydrodynamics**

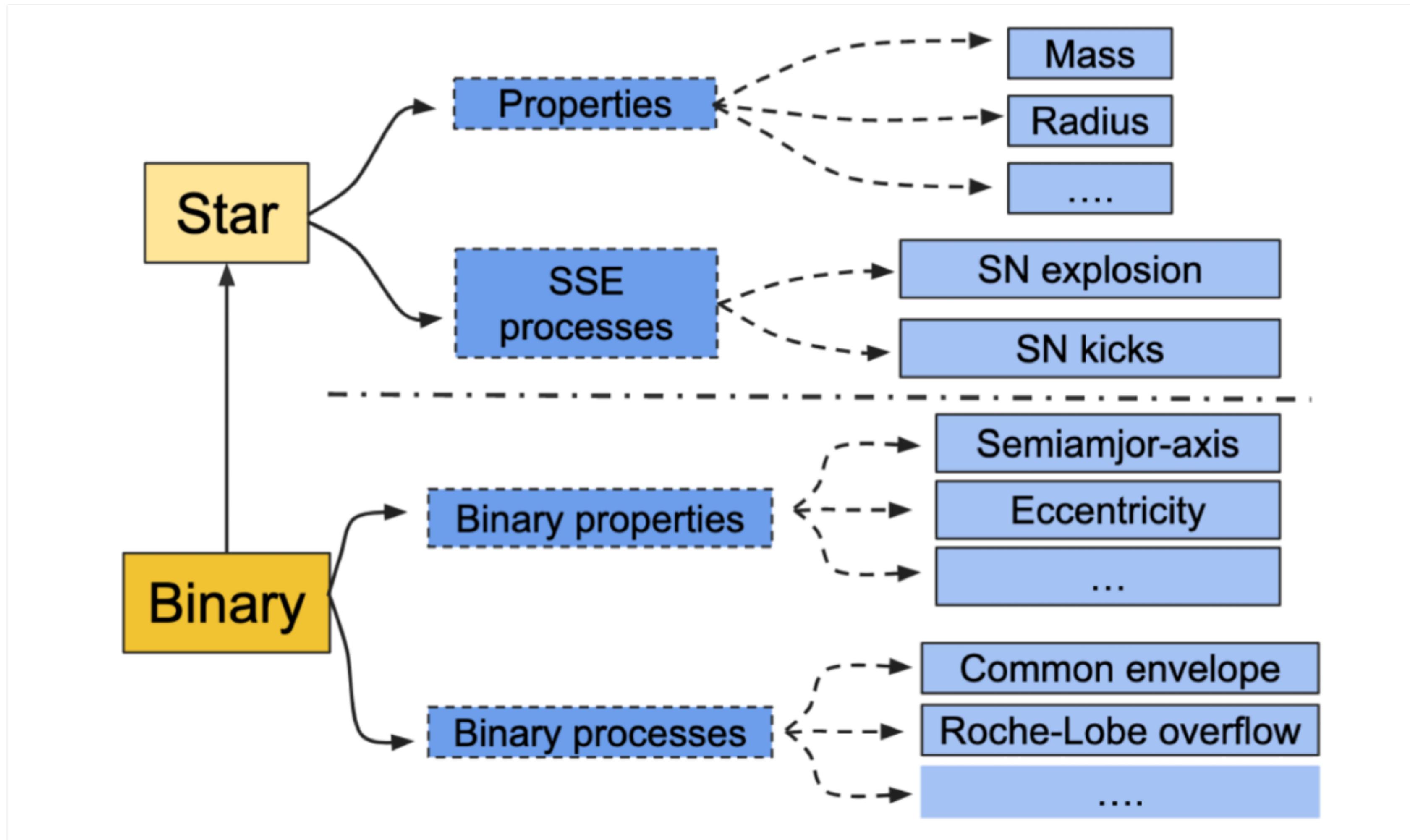
SEVN

- SEVN (Stellar EVolution N-body)
- Stellar evolution through interpolation of precomputed **stellar tracks**
- stellar tracks can be easily added to use **updated** stellar evolution models
- We will see an example applied to **Population III stars**

SEVNpy

- SEVN is written in C++ <https://gitlab.com/sevncodes/sevn>
- **SEVNpy** is a wrapper of SEVN, boosting its usability and application
- User guide and examples: [https://gitlab.com/sevncodes/sevn/-/tree/
SEVN/SEVNpy?ref_type=heads](https://gitlab.com/sevncodes/sevn/-/tree/SEVN/SEVNpy?ref_type=heads)

SEVN: input VS output



SEVN: input

- We need to define:
 - The properties of the **population of massive stars**, from which we expect compact object mergers to form (e.g., **mass** and **mass ratio distribution**, orbital period, etc.)
 - The (unknown) parameters governing single and binary evolution (e.g., the value of the **common envelope** ejection efficiency α , ...)
- An example

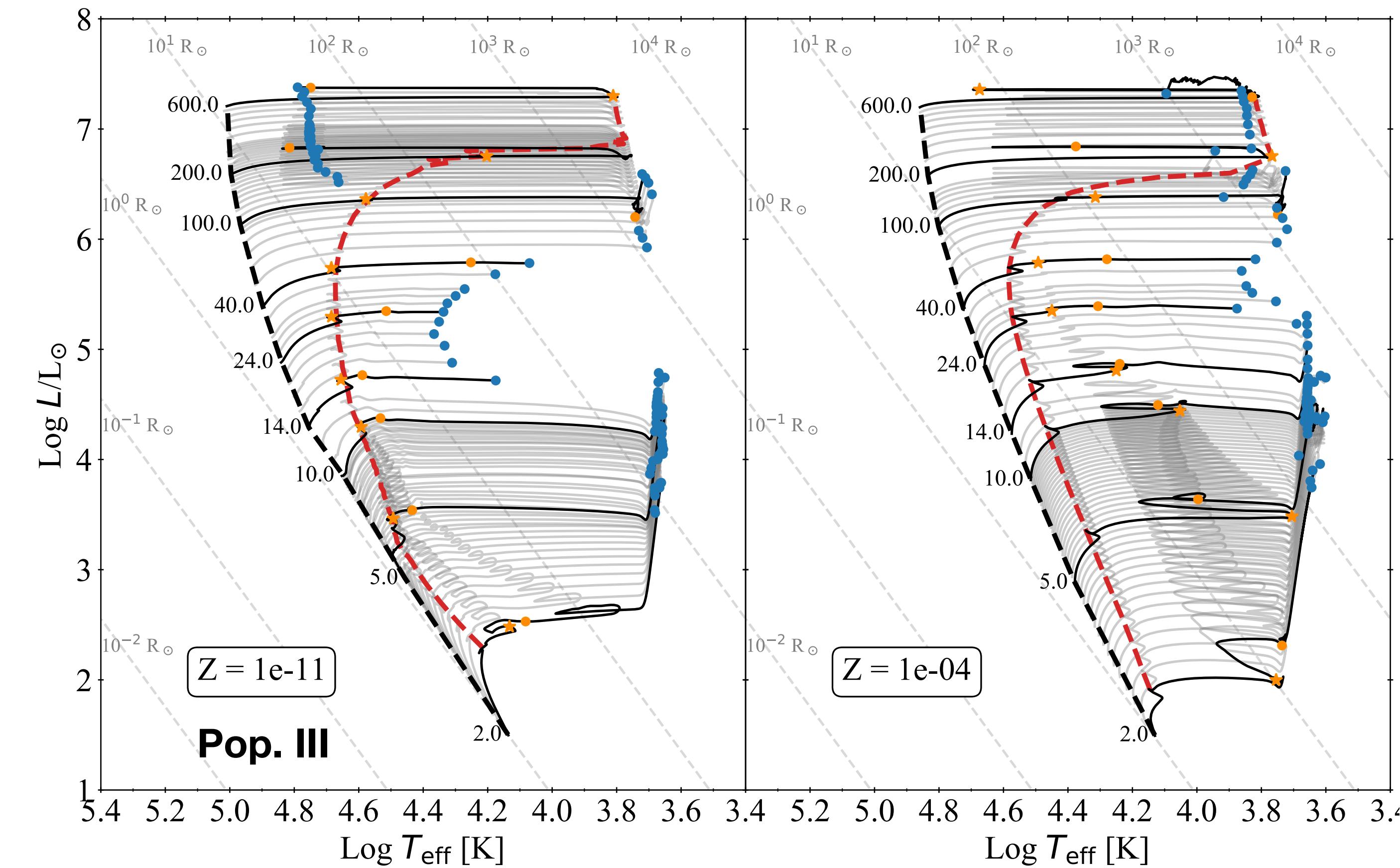
Population III stars

- Population III stars are believed to be the first generation of stars formed at **high redshift** ($z > 20$)
- They are massive and formed from pristine gas (i.e. **zero metallicity**)
- They are still undetected (*traces of their existence with JWST*)
- Modelled through cosmological simulations

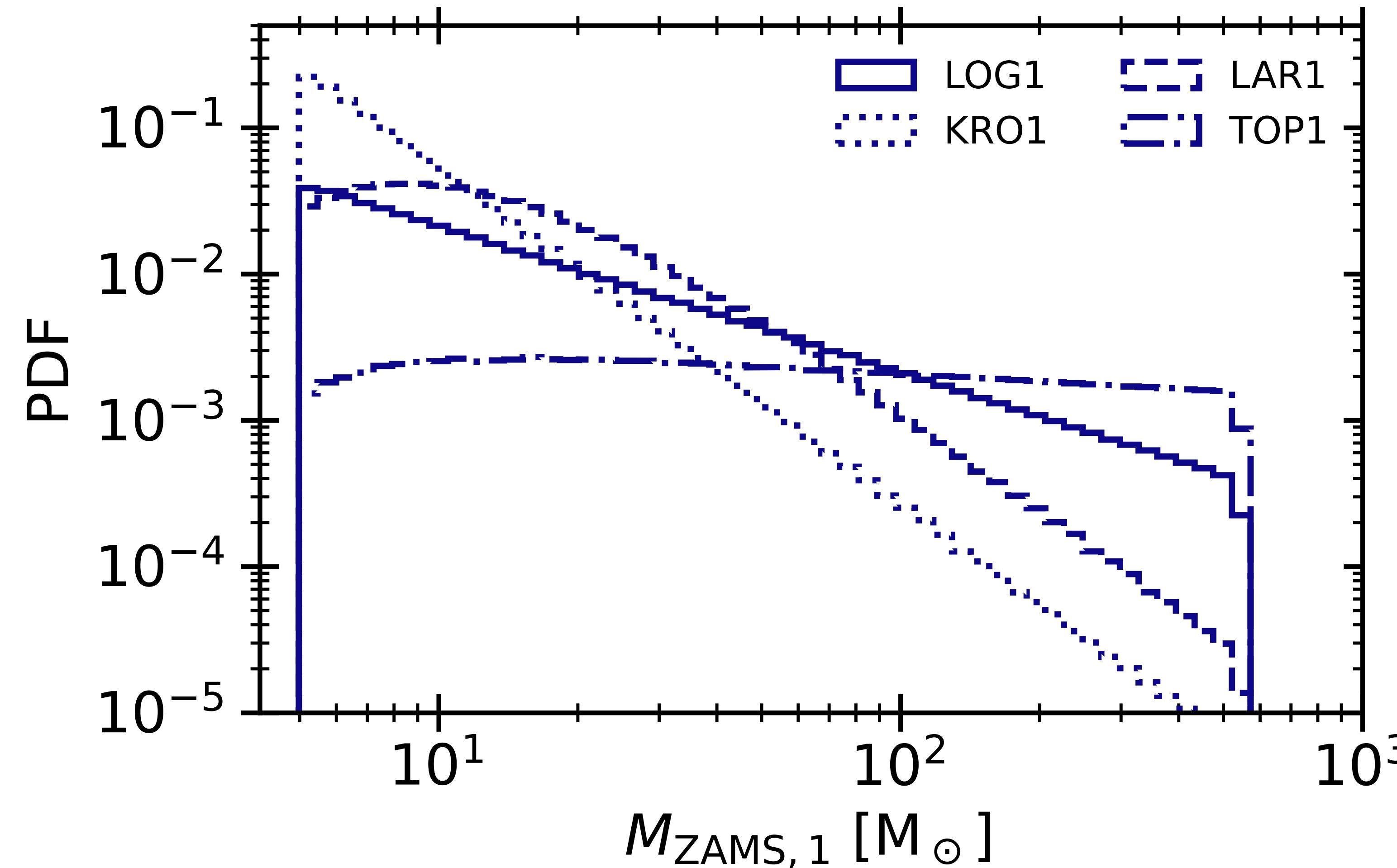
Refs: [Klessen and Glover 2023](#), [Zackrisson et al. 2023](#), [Maiolino et al. 2024](#)

Population III stellar tracks

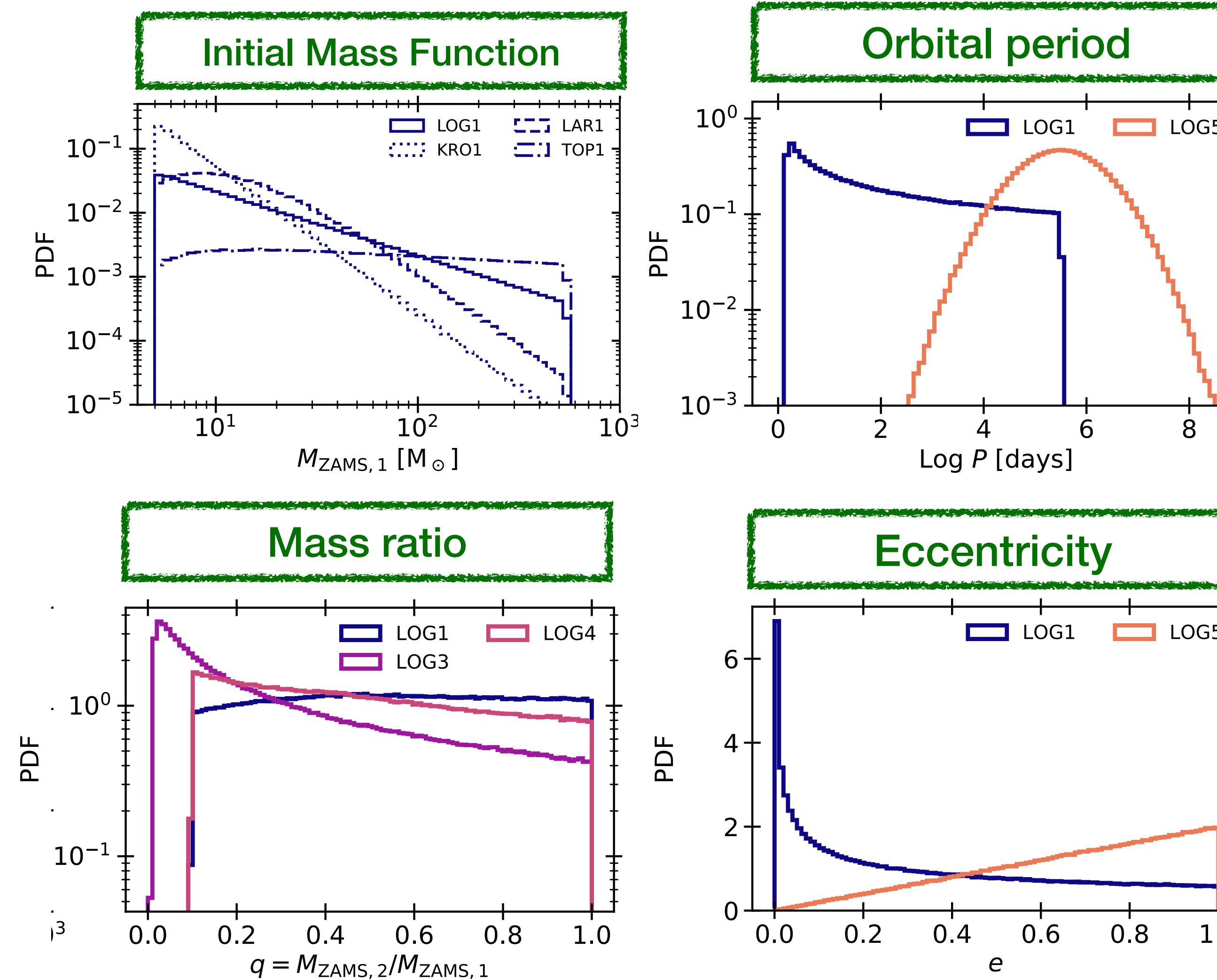
- Adding stellar tracks in SEVN
- Pop. III stars are more compact and hotter than Pop. II



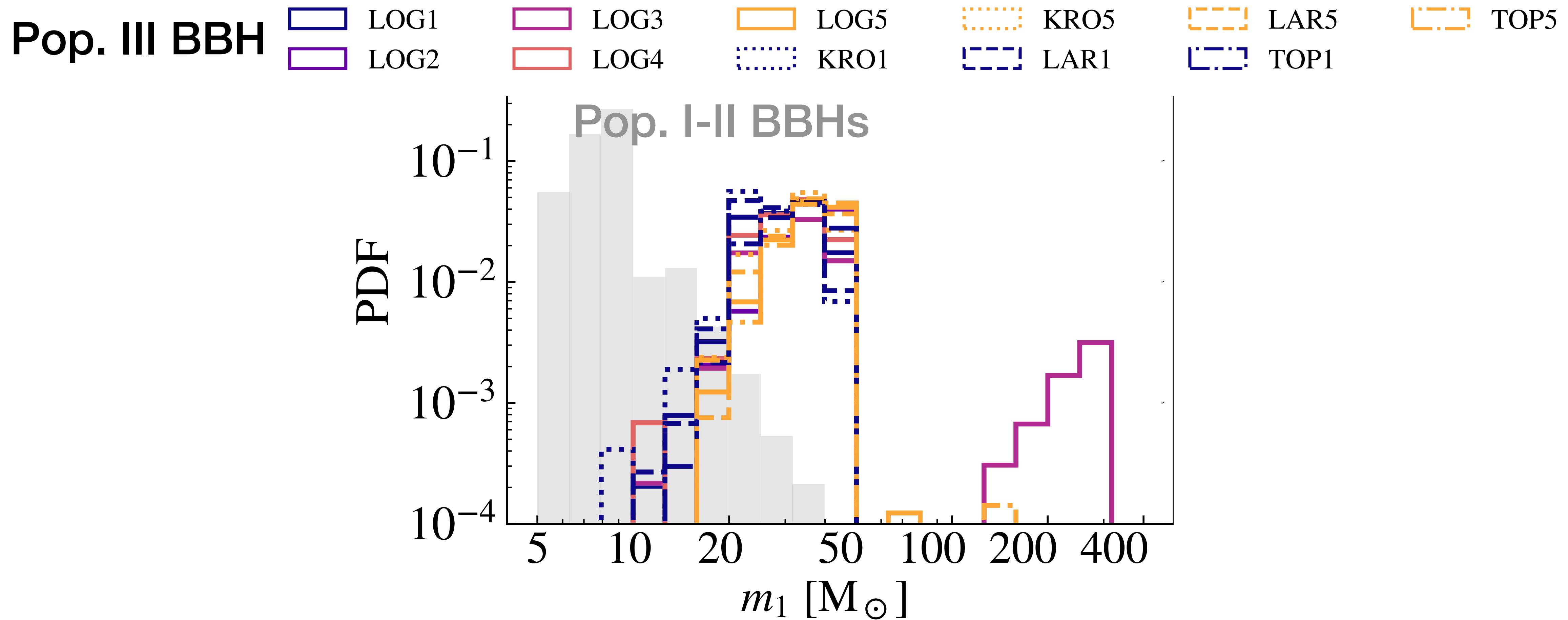
Pop. III Initial Mass Functions



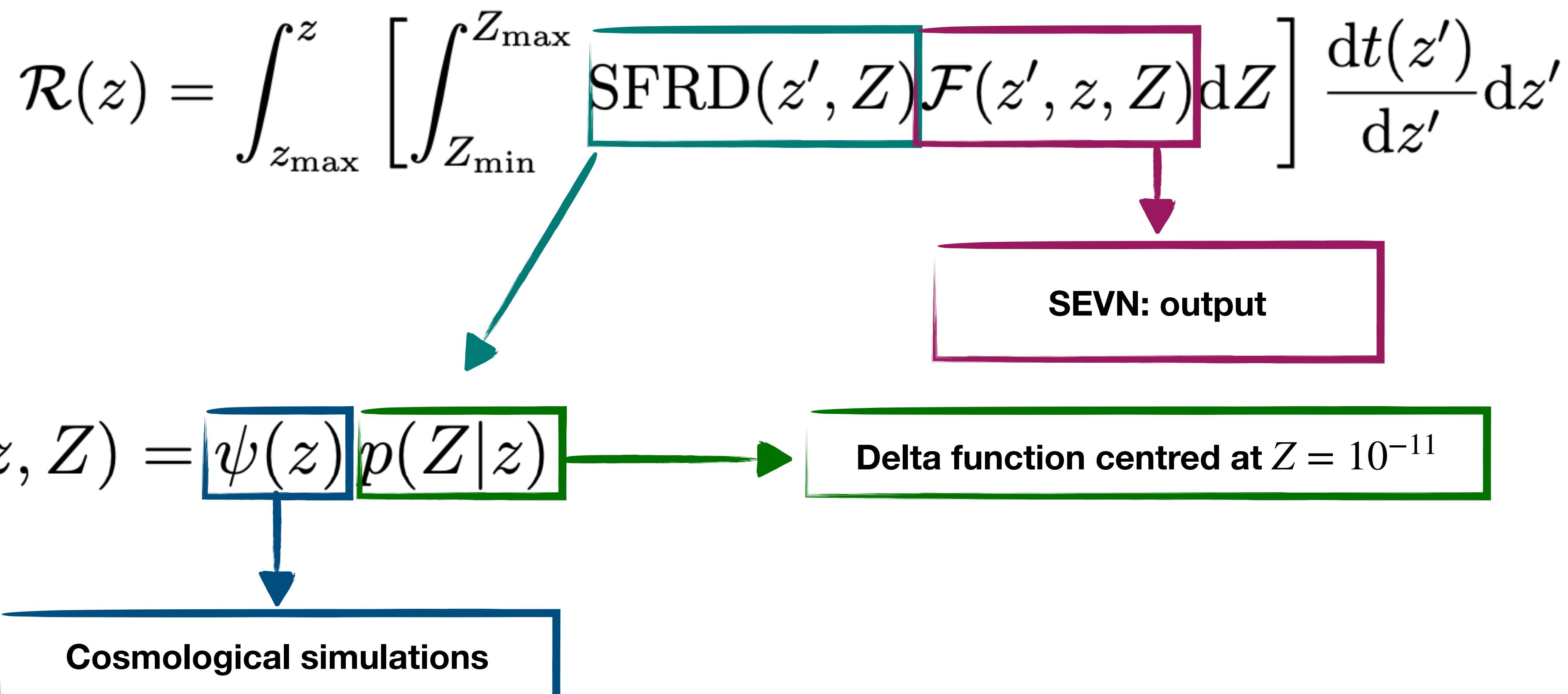
Pop. III initial conditions



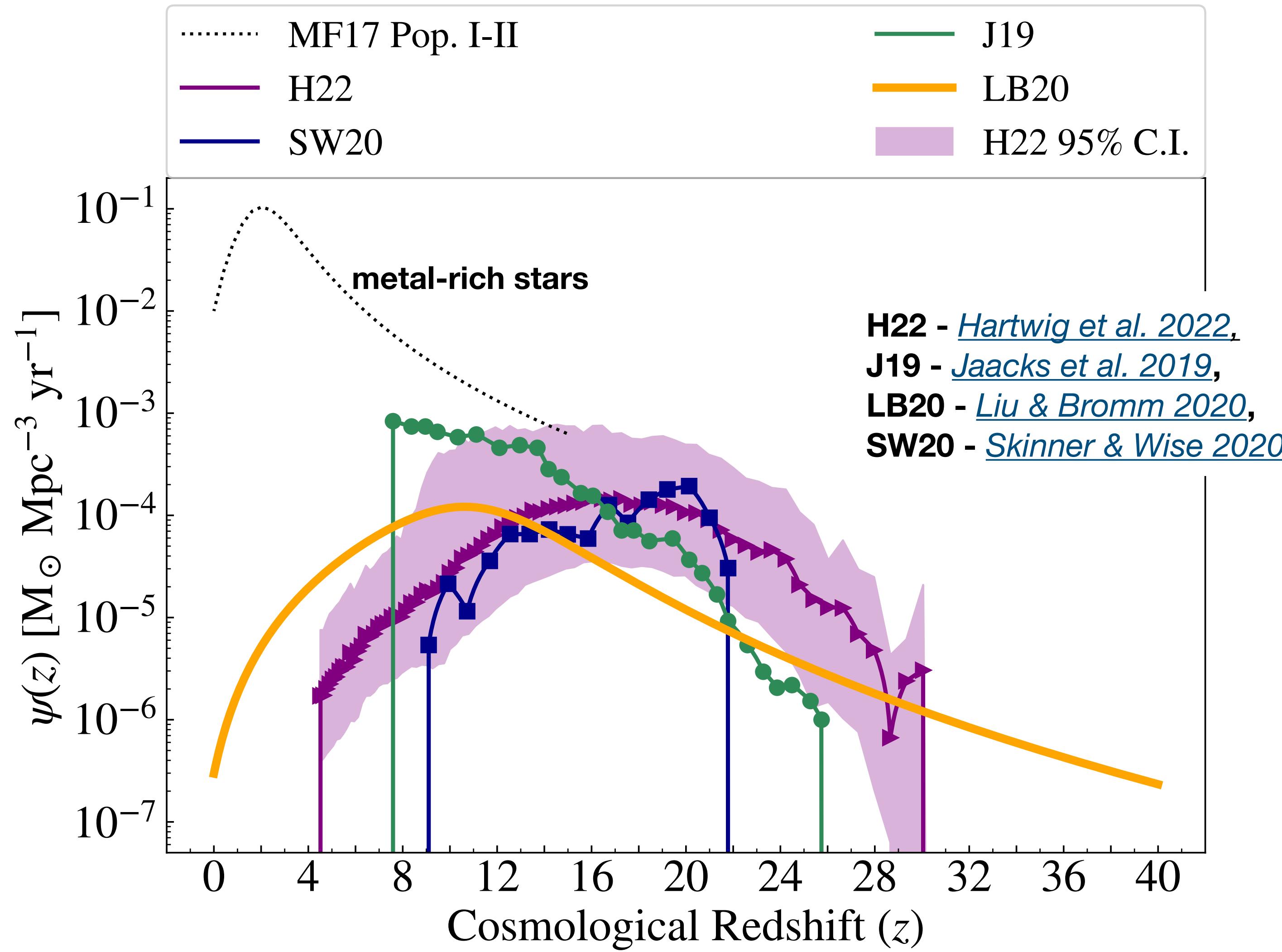
SEVN: output



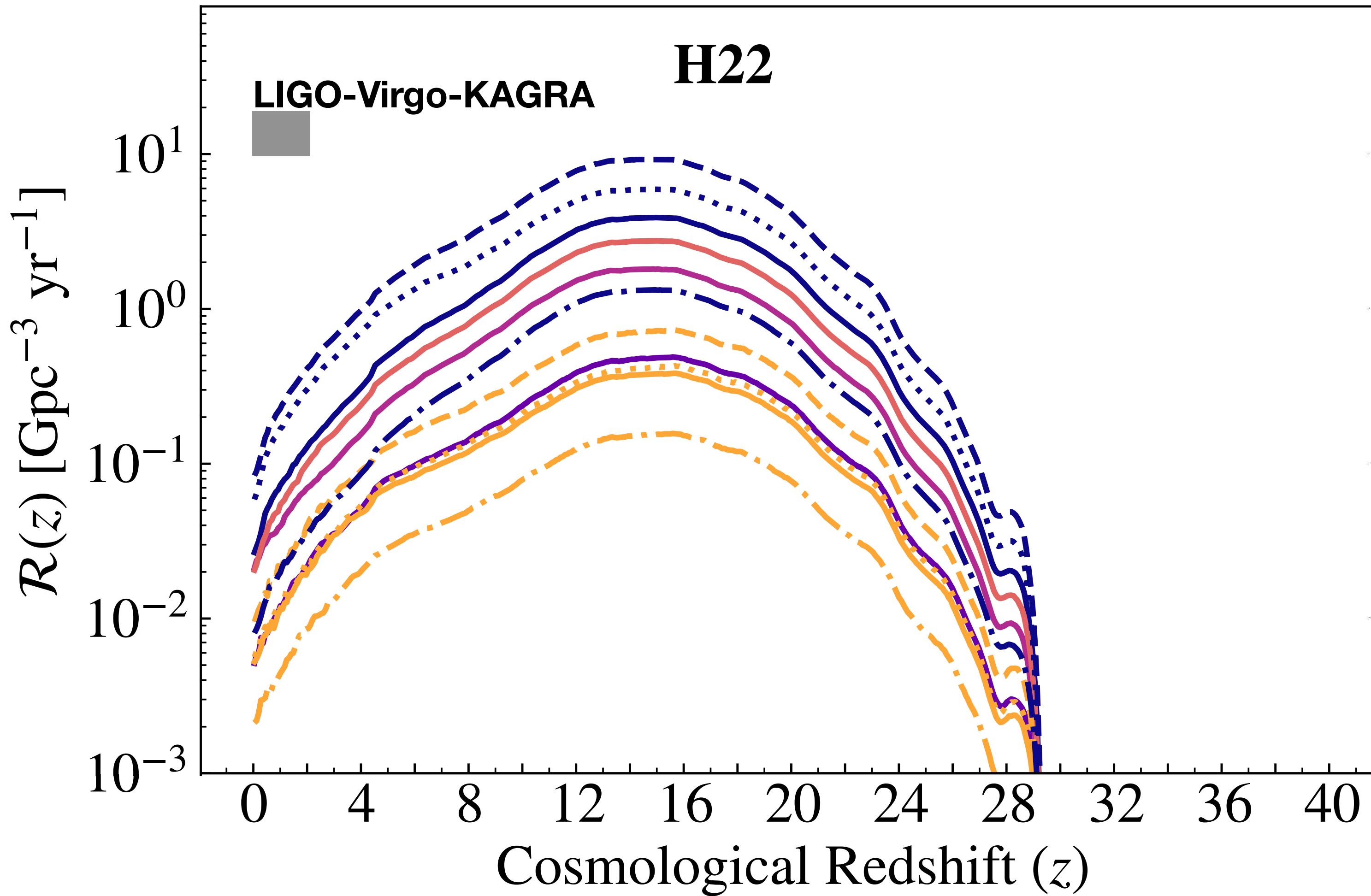
COSMORATE



$\psi(z)$: Pop. III SFRD



Rates of Pop. III BBHs

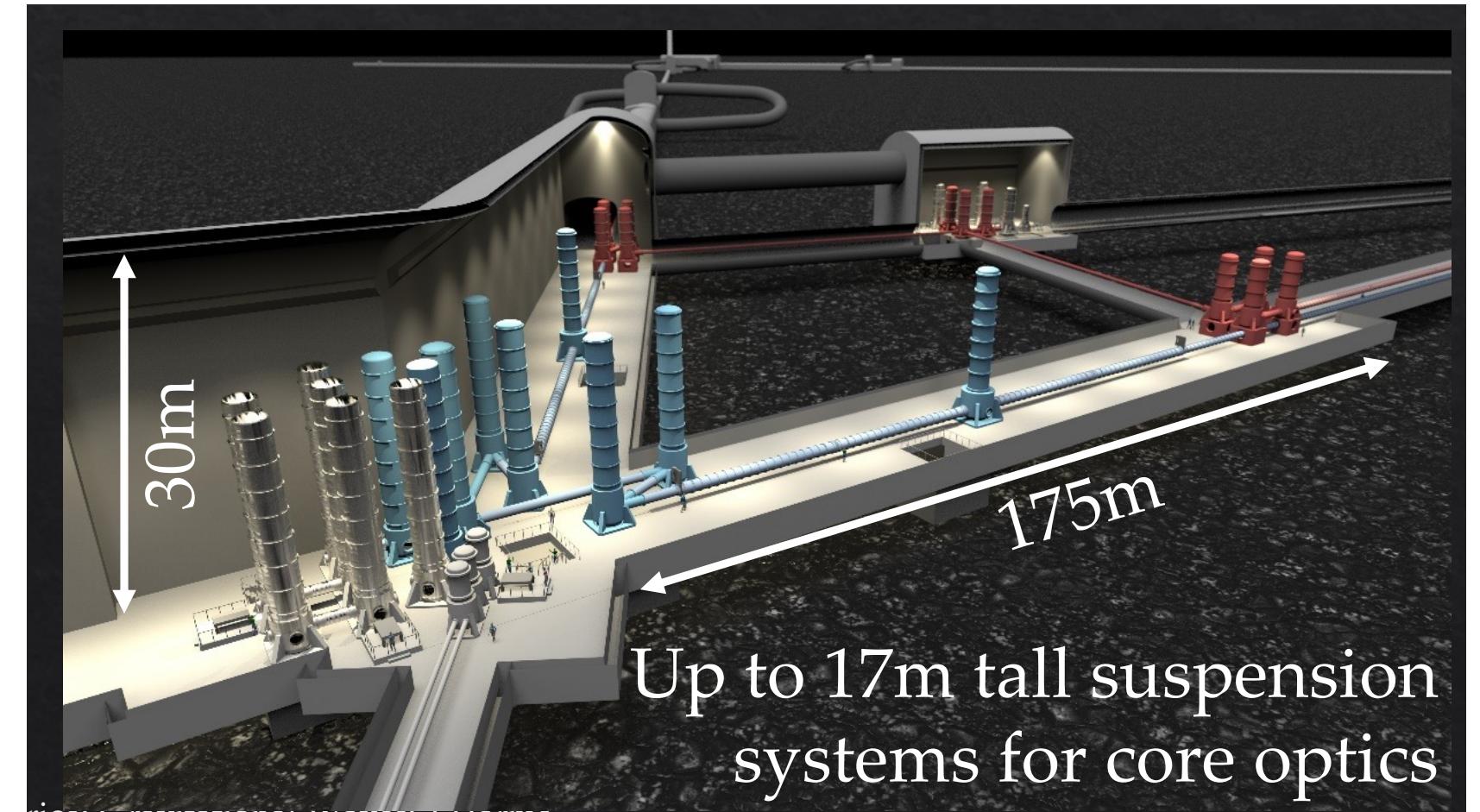
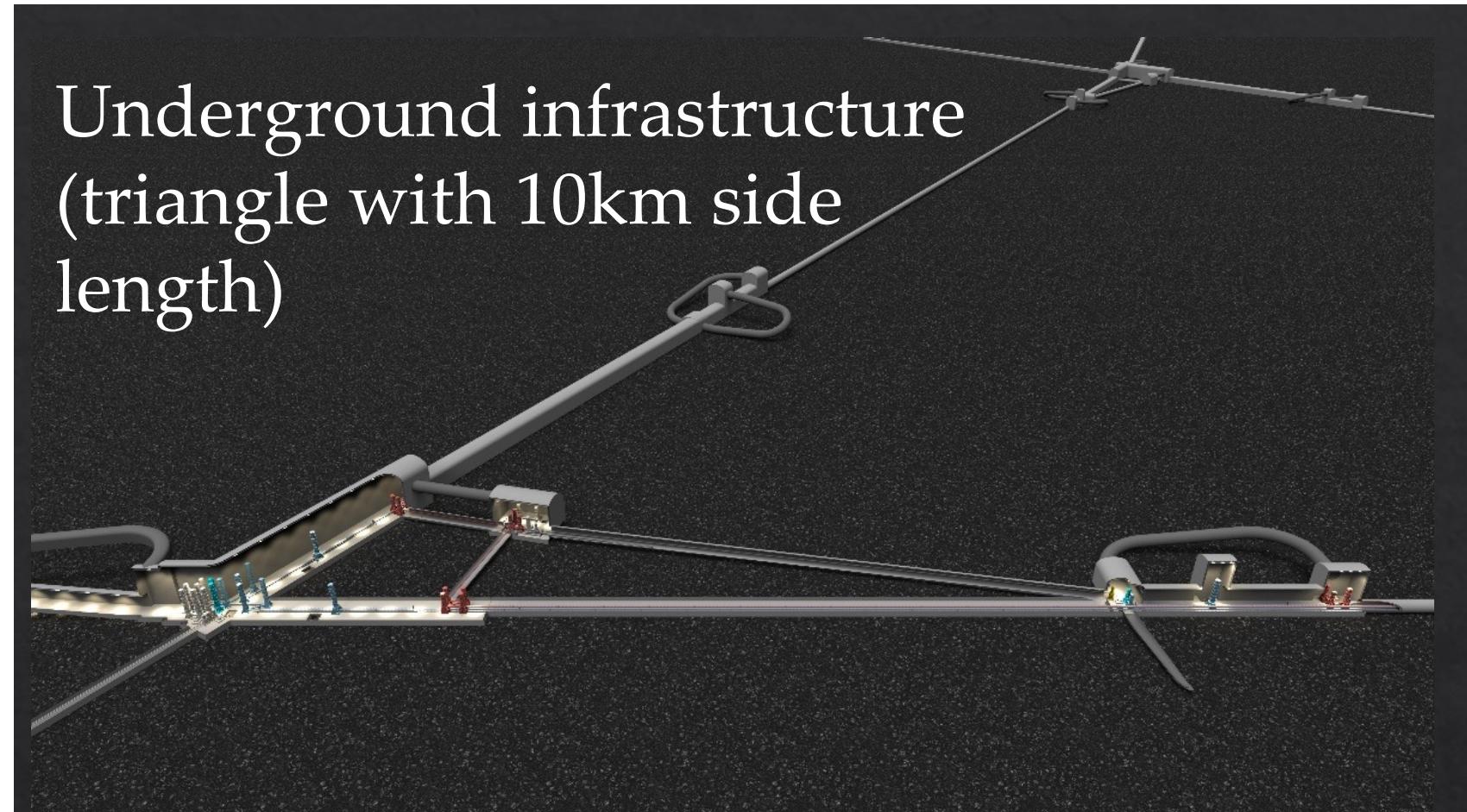


Are we able to detect these BBH mergers?

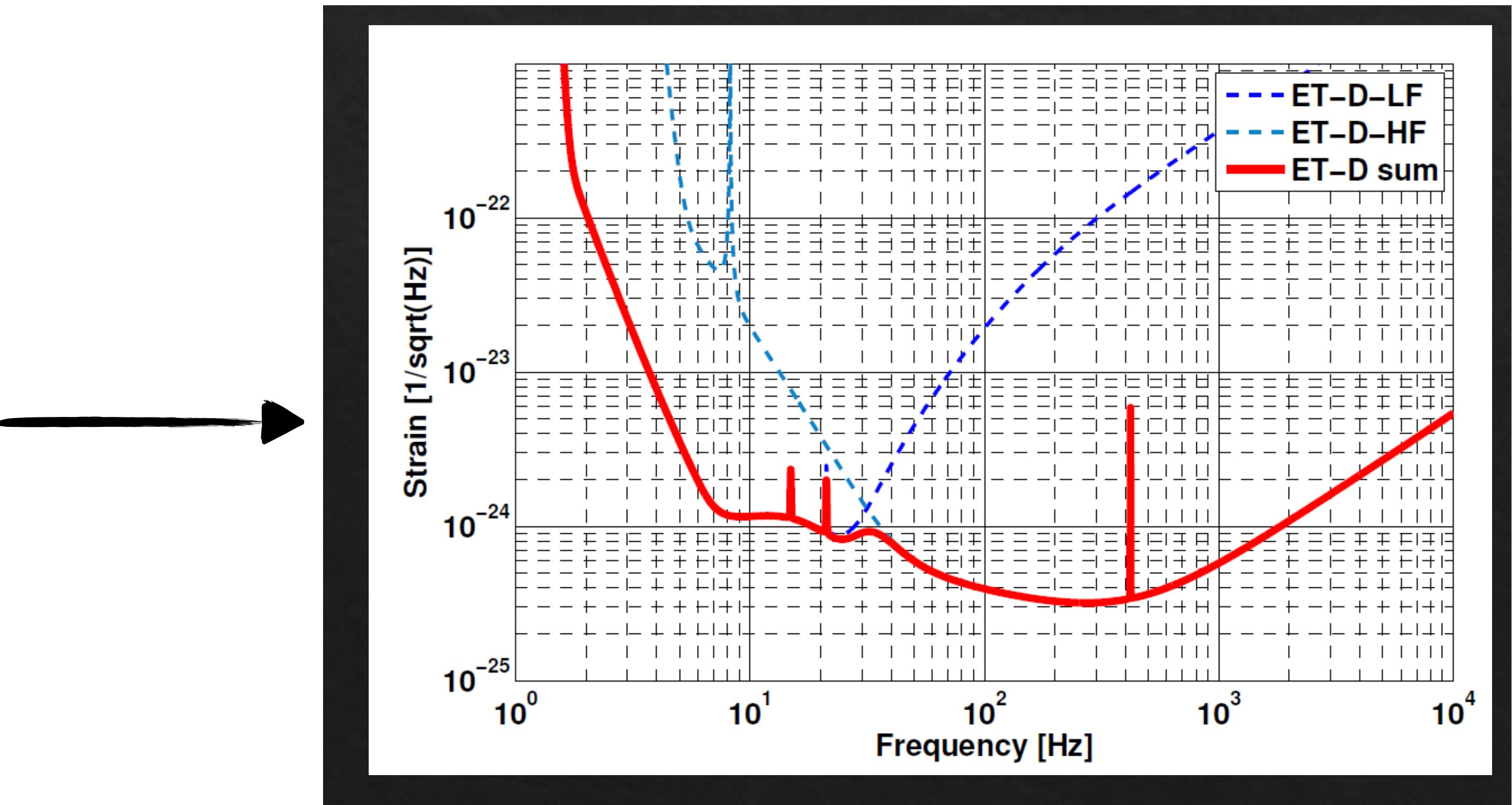
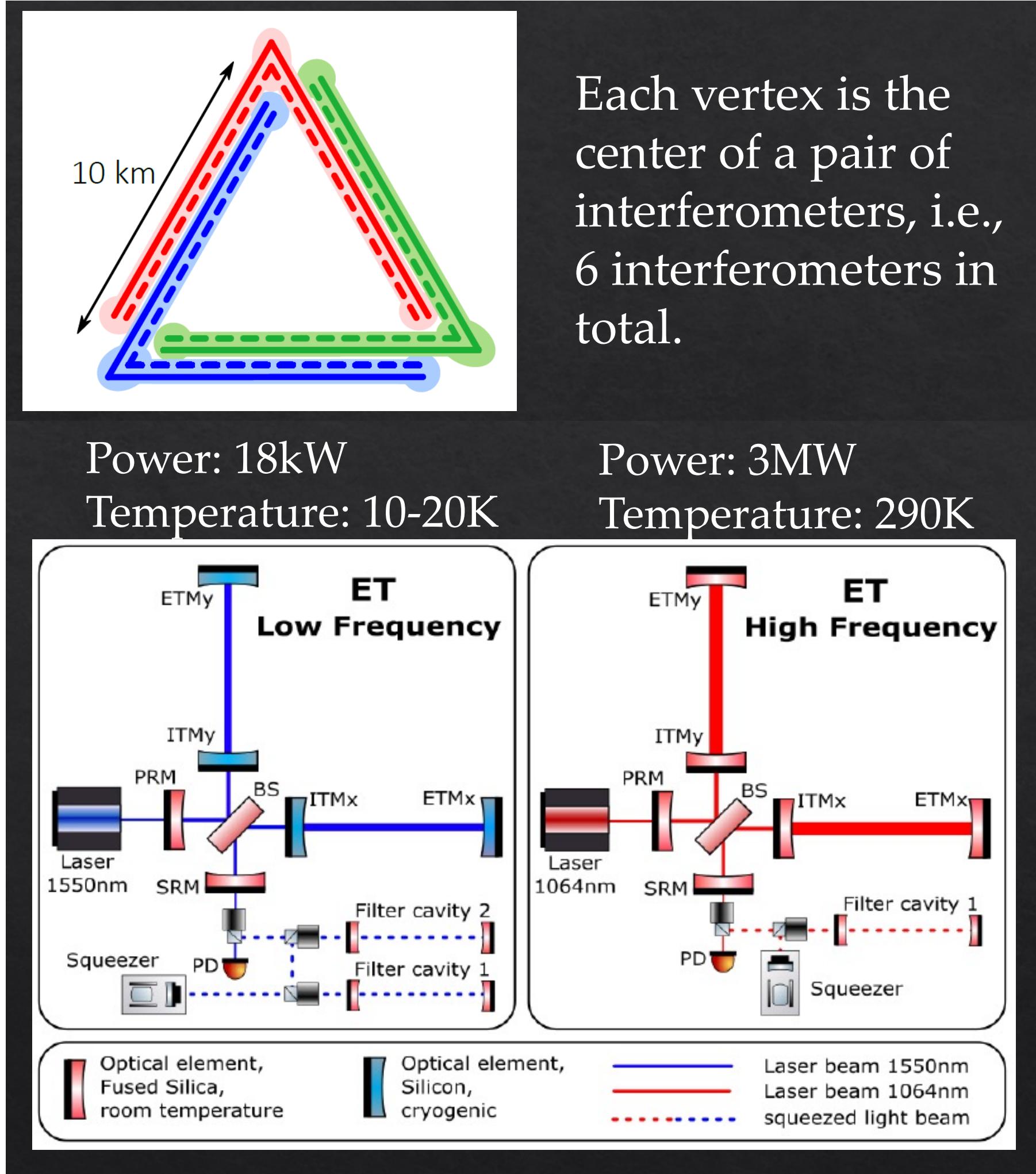
Are we able to detect these BBH mergers?

Next-generation GW detectors

The Einstein Telescope: 3 facts

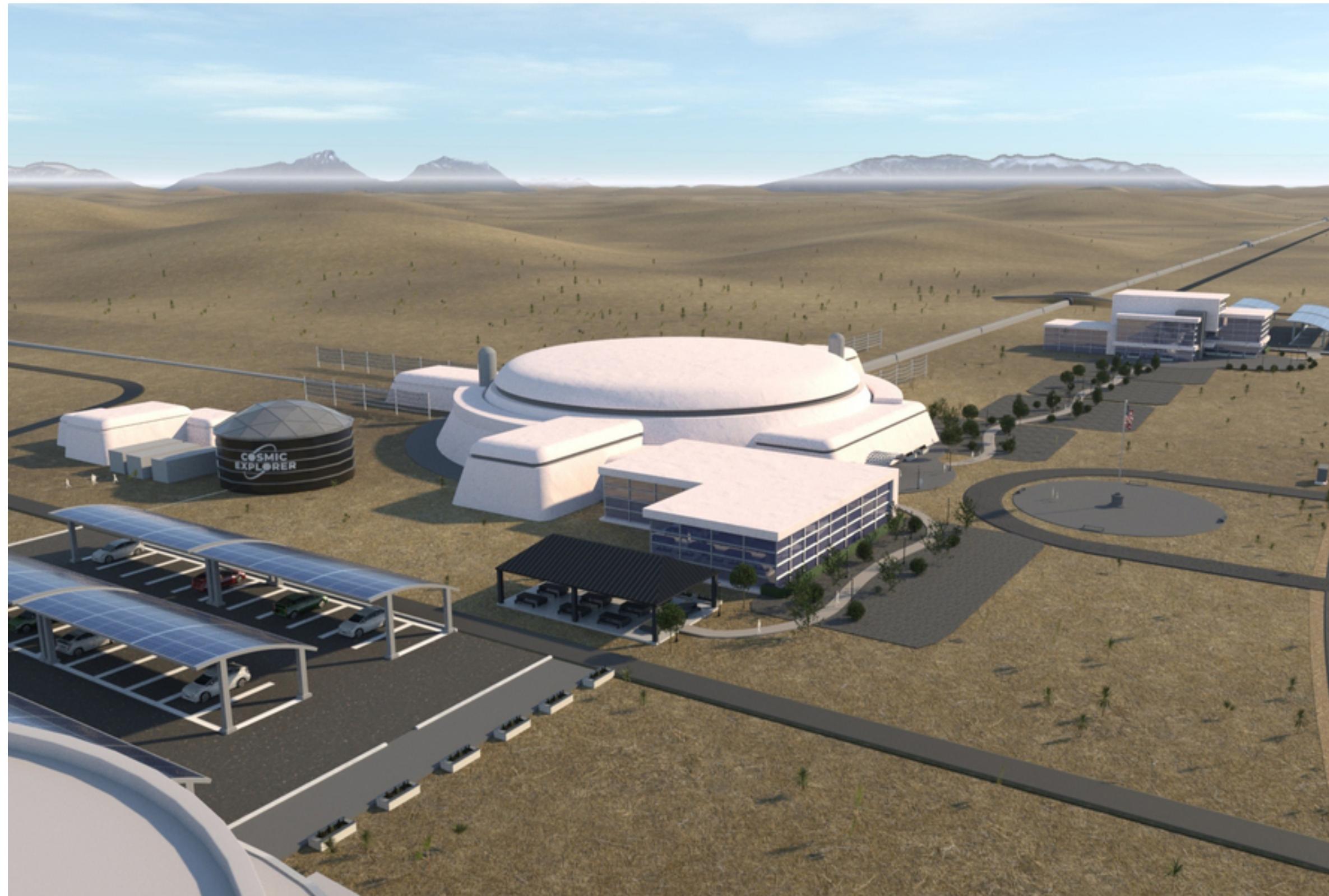


The Einstein Telescope: design



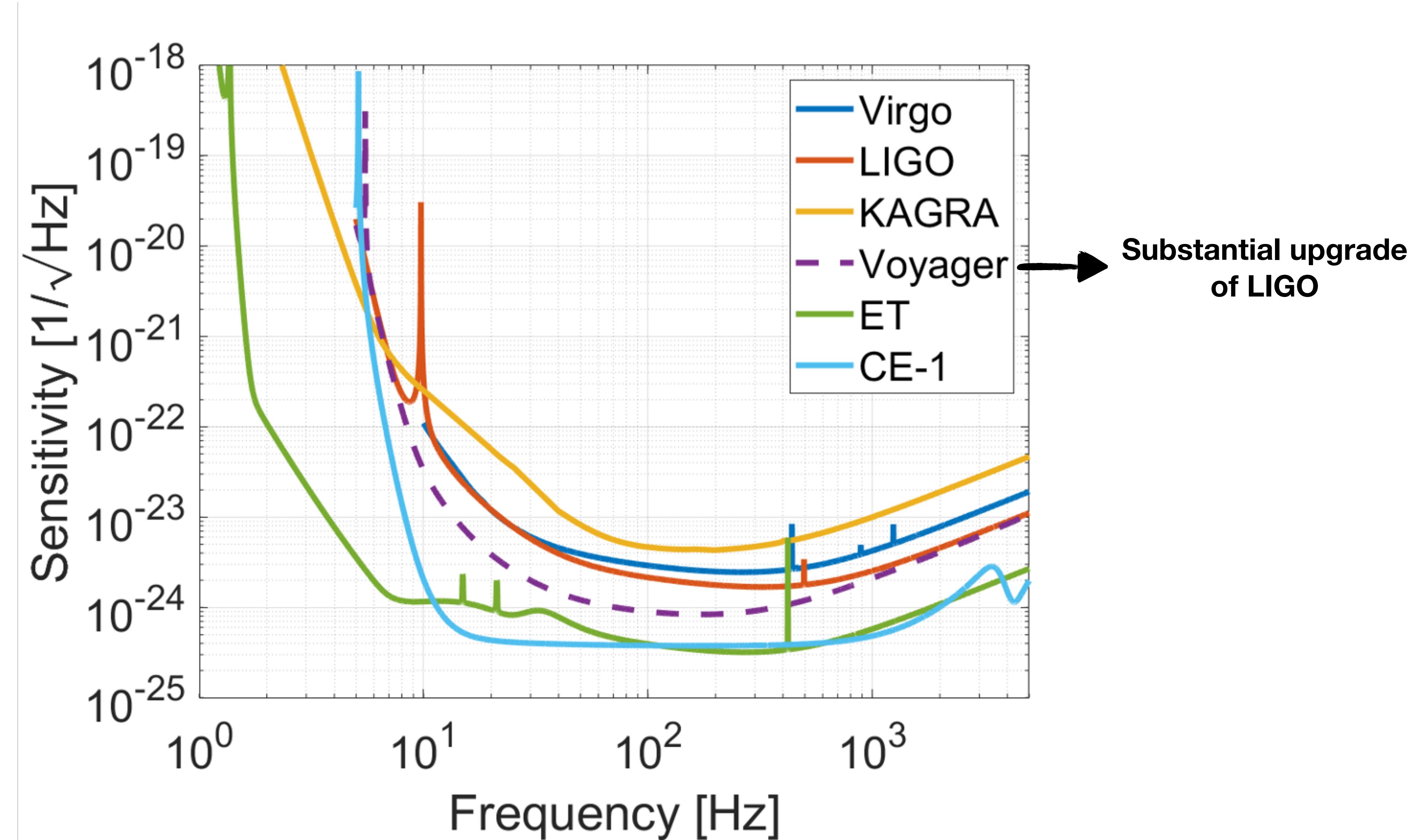
Credits: Jan Harms

Cosmic Explorer

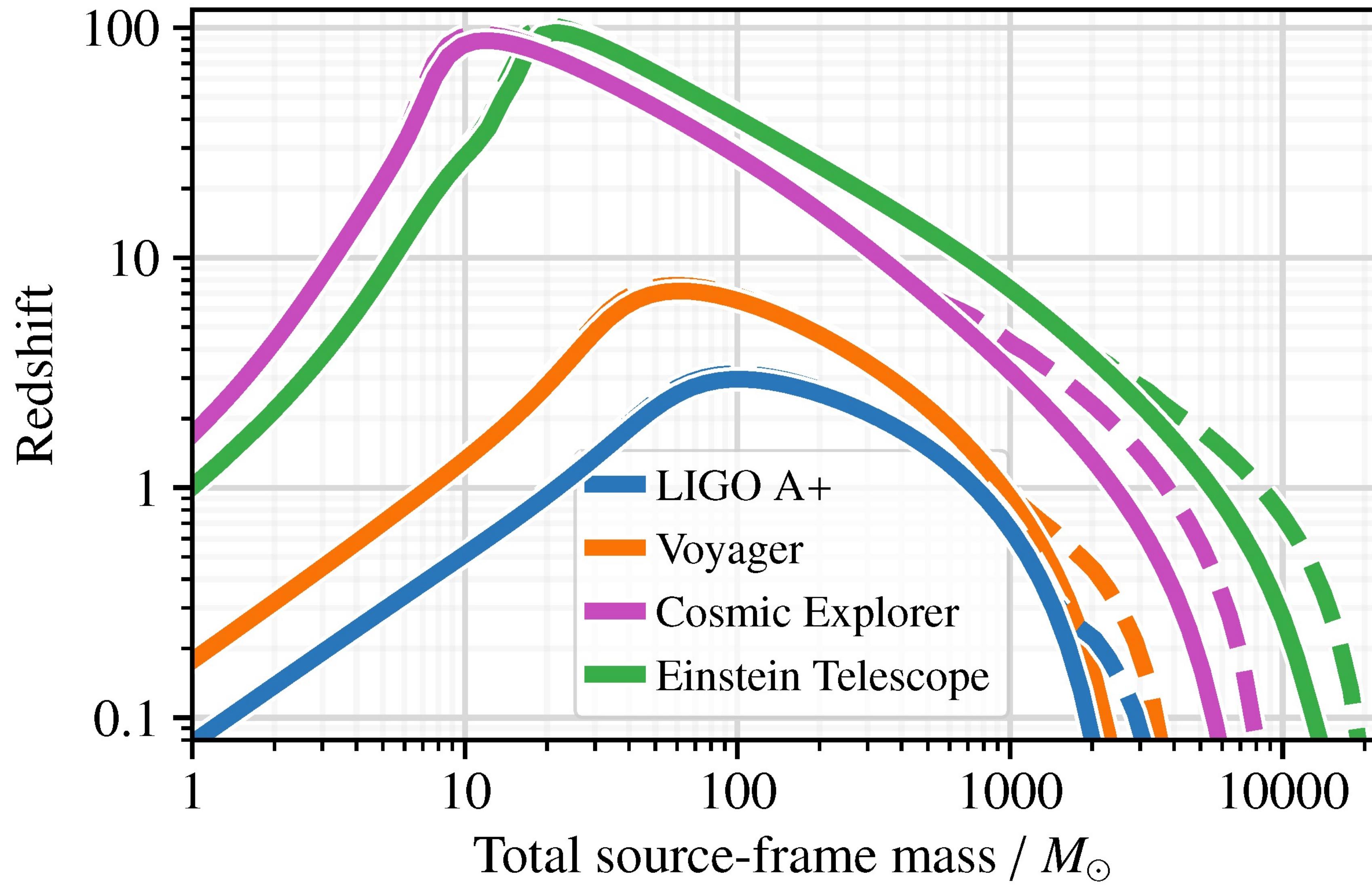


Credits: [MIT](#)

Sensitives

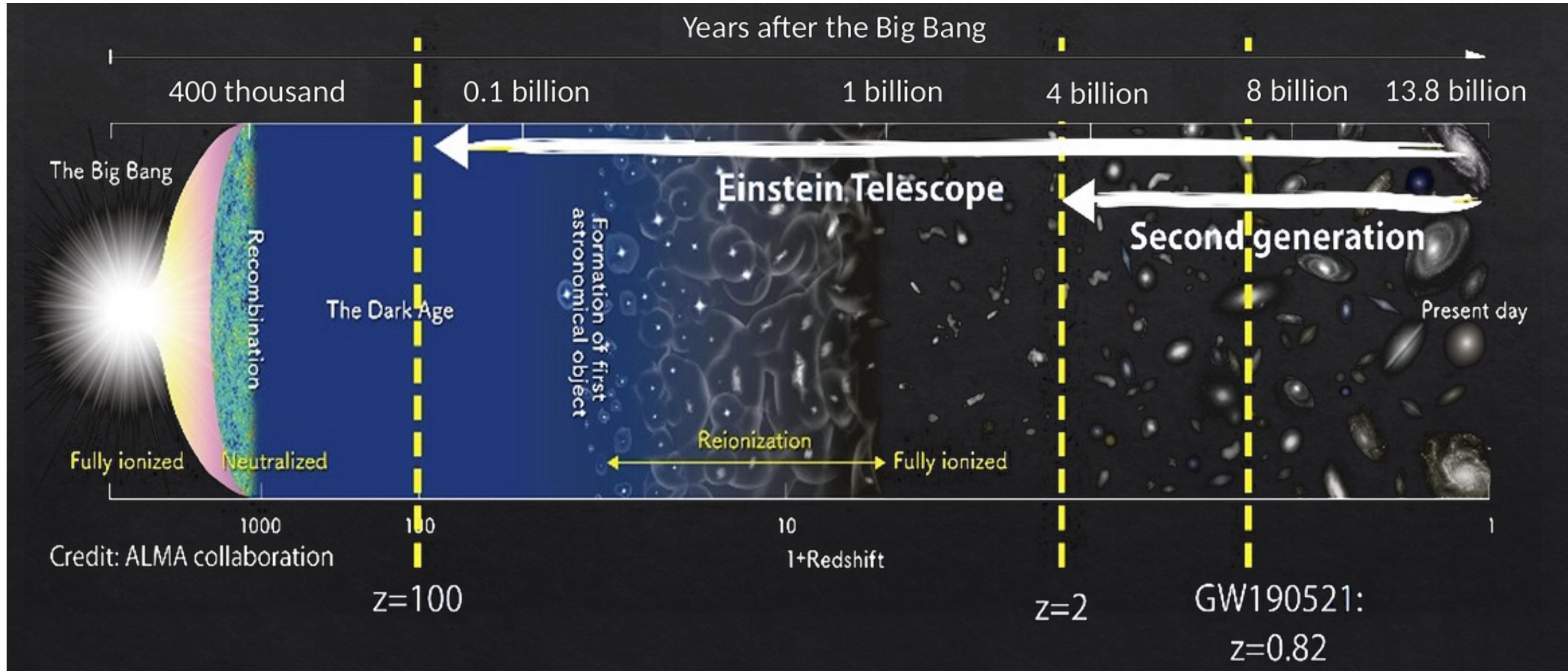


Redshift horizon



Credits: Hall 2022

Early Universe with 3G detectors



Detecting Pop. III BBHs

- $p(\Lambda | \{d\}) \propto \mathcal{L}(\{d\} | \Lambda) p(\Lambda)$
- $\mathcal{L}(\{d\} | \Lambda) \propto \prod_i^{\text{N}_{obs}} \frac{\int \mathcal{L}(d_i | \theta) \pi(\theta | \Lambda)}{\xi(\Lambda)}$

Detecting Pop. III BBHs

- $p(\Lambda | \{d\}) \propto \mathcal{L}(\{d\} | \Lambda) p(\Lambda)$
- $\mathcal{L}(\{d\} | \Lambda) \propto \prod_i^N \frac{\int \mathcal{L}(d_i | \theta) \pi(\theta | \Lambda)}{\xi(\Lambda)}$
- $\xi(\Lambda) = \int p_{\text{det}}(\theta) \pi(\theta | \Lambda) d\theta \approx \left\langle p_{\text{det}}(\theta_j) \right\rangle_{\theta_j \sim \pi(\theta | \Lambda)} \quad \Lambda = \text{LOG1, KRO1, ...}$

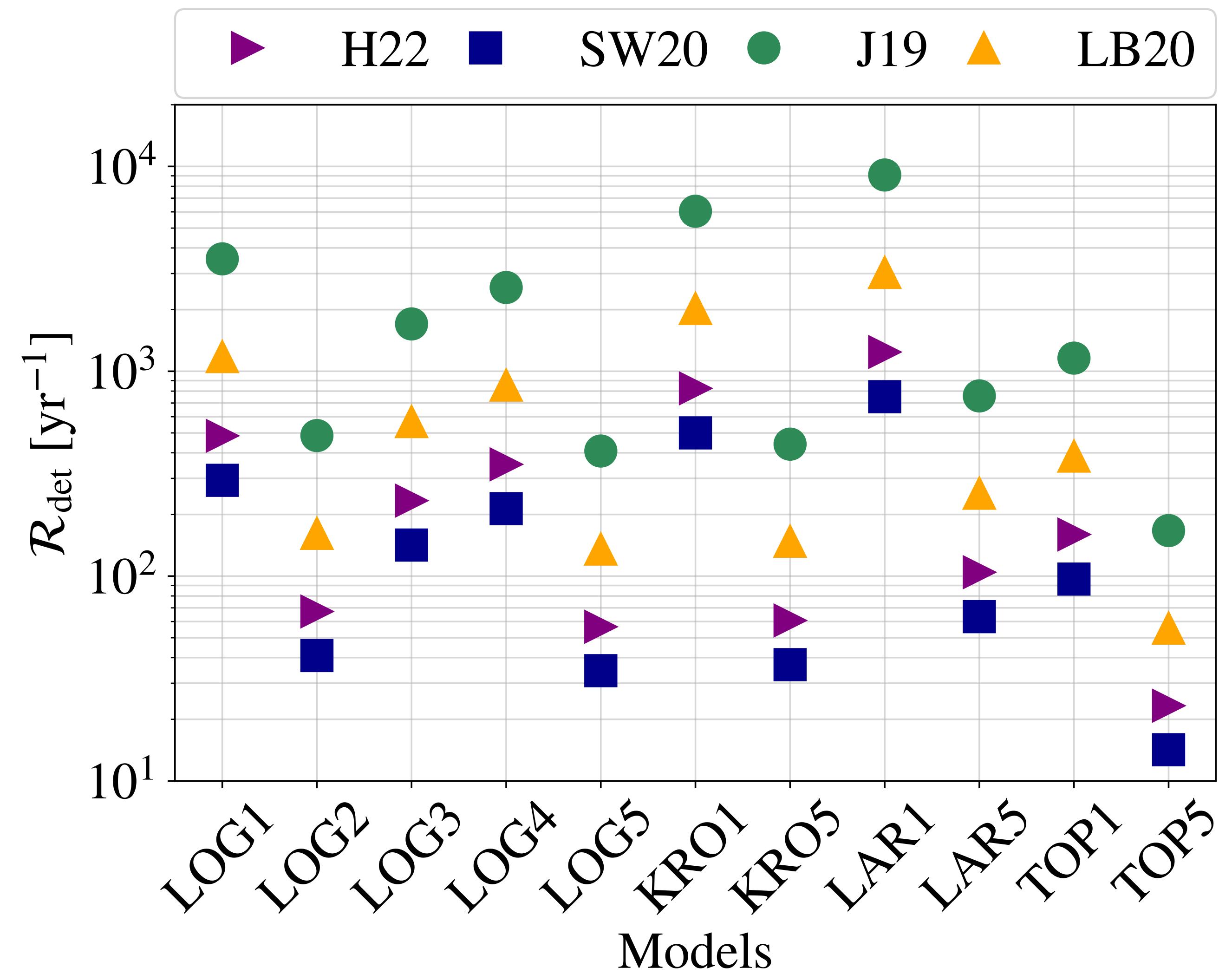
Detecting Pop. III BBHs

- $p_{\text{det}}(\theta) = \begin{cases} 1, & \text{if } \rho \geq \text{thr} \\ 0, & \text{otherwise} \end{cases}$

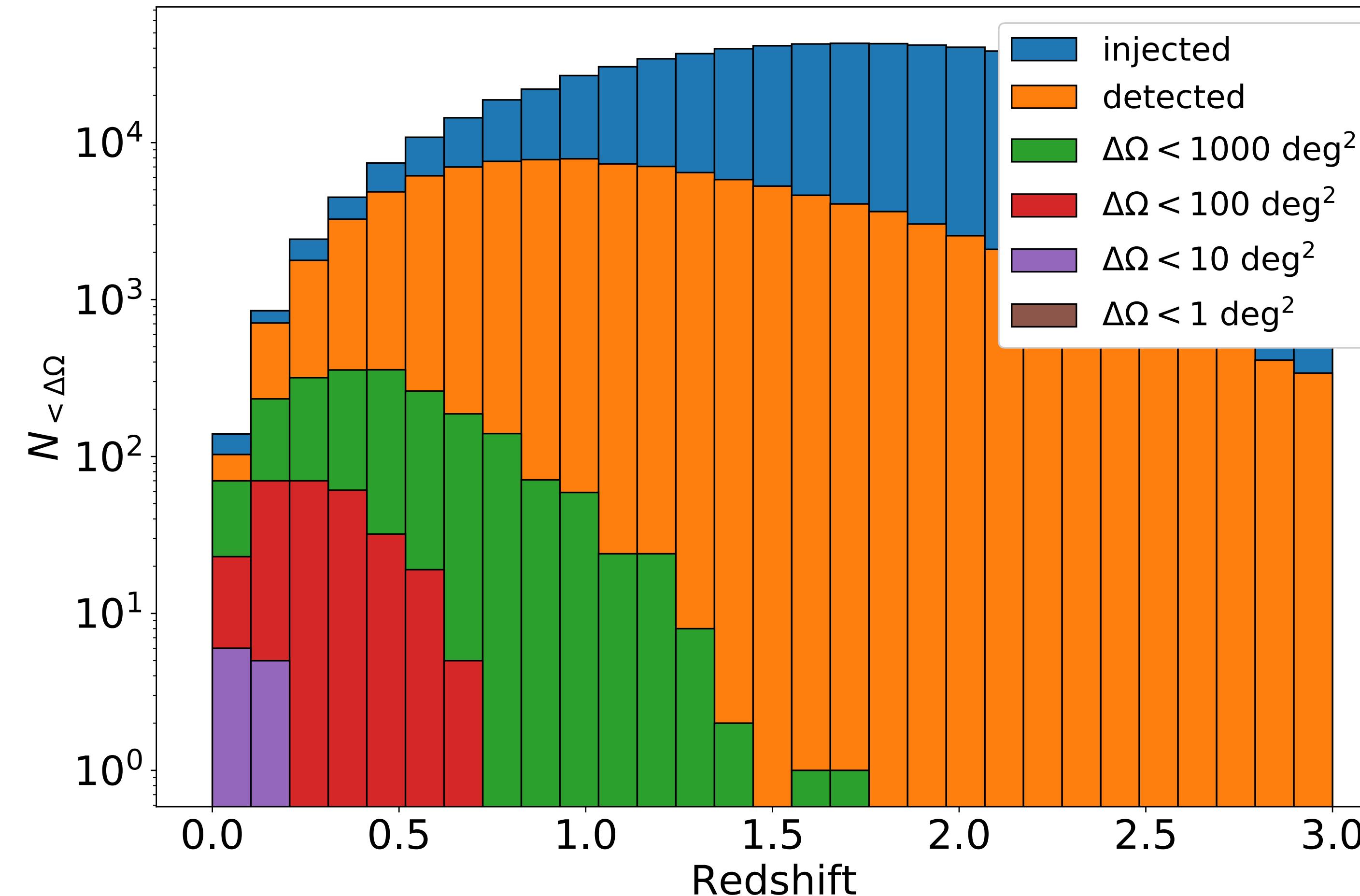
- $\rho^2 \sim \int \frac{|\tilde{h}(f)|^2}{S_n(f)} df$

Detecting Pop. III BBHs

- Einstein Telescope will detect $10 - 10^4$ Pop. III BBH mergers per year
- We expect between 23% and 73% of detections to occur at redshift $z > 8$



Sky localisation

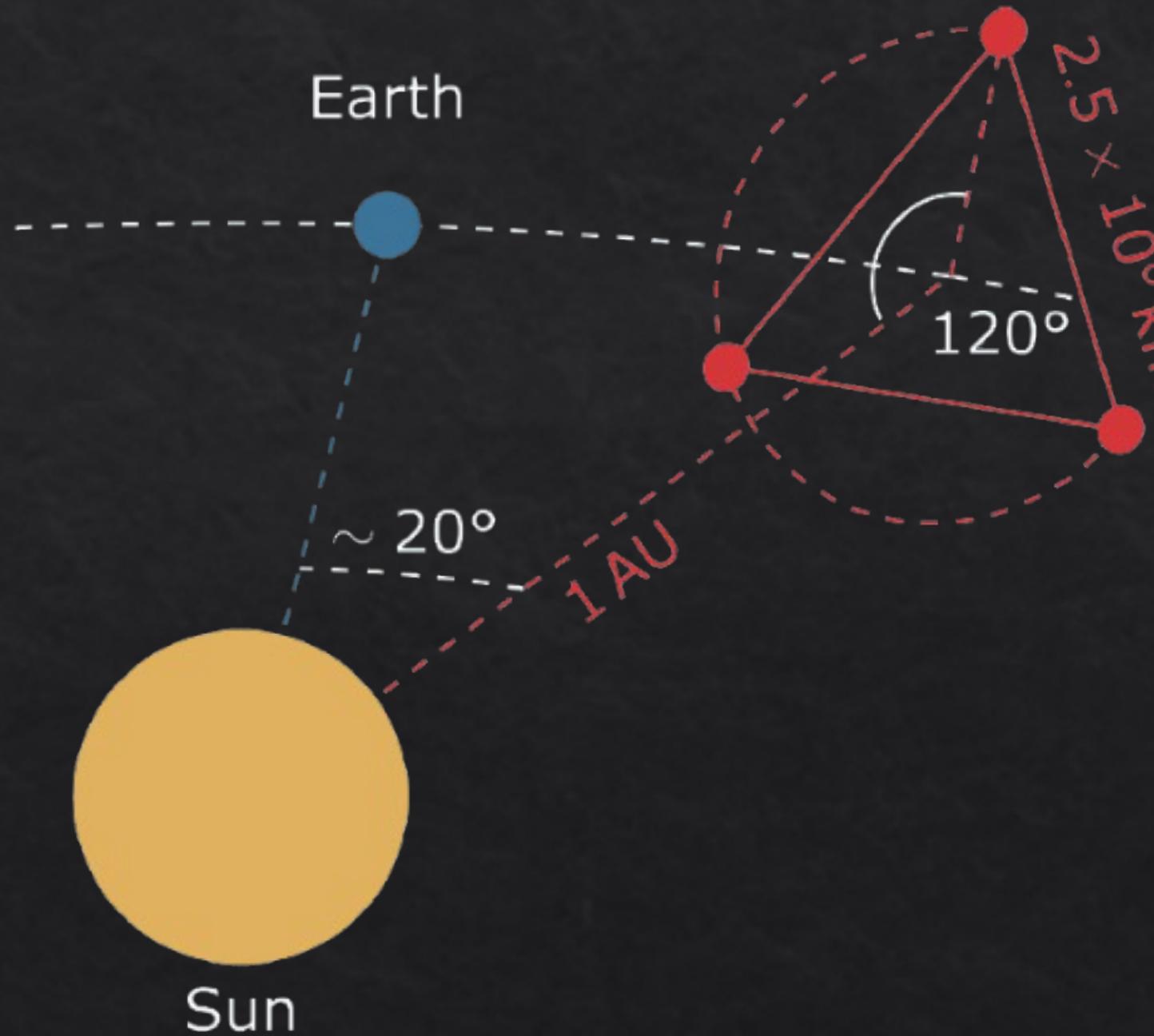


- **GWFish**
- ~ 10 detections per year with sky localisation $< 10 \text{ deg}^2$
- Different designs ($\Delta 10 \text{ km}$)
- Compare with current GW detectors

Let's go space

LISA

LISA satellites
orbit the Sun at
1AU



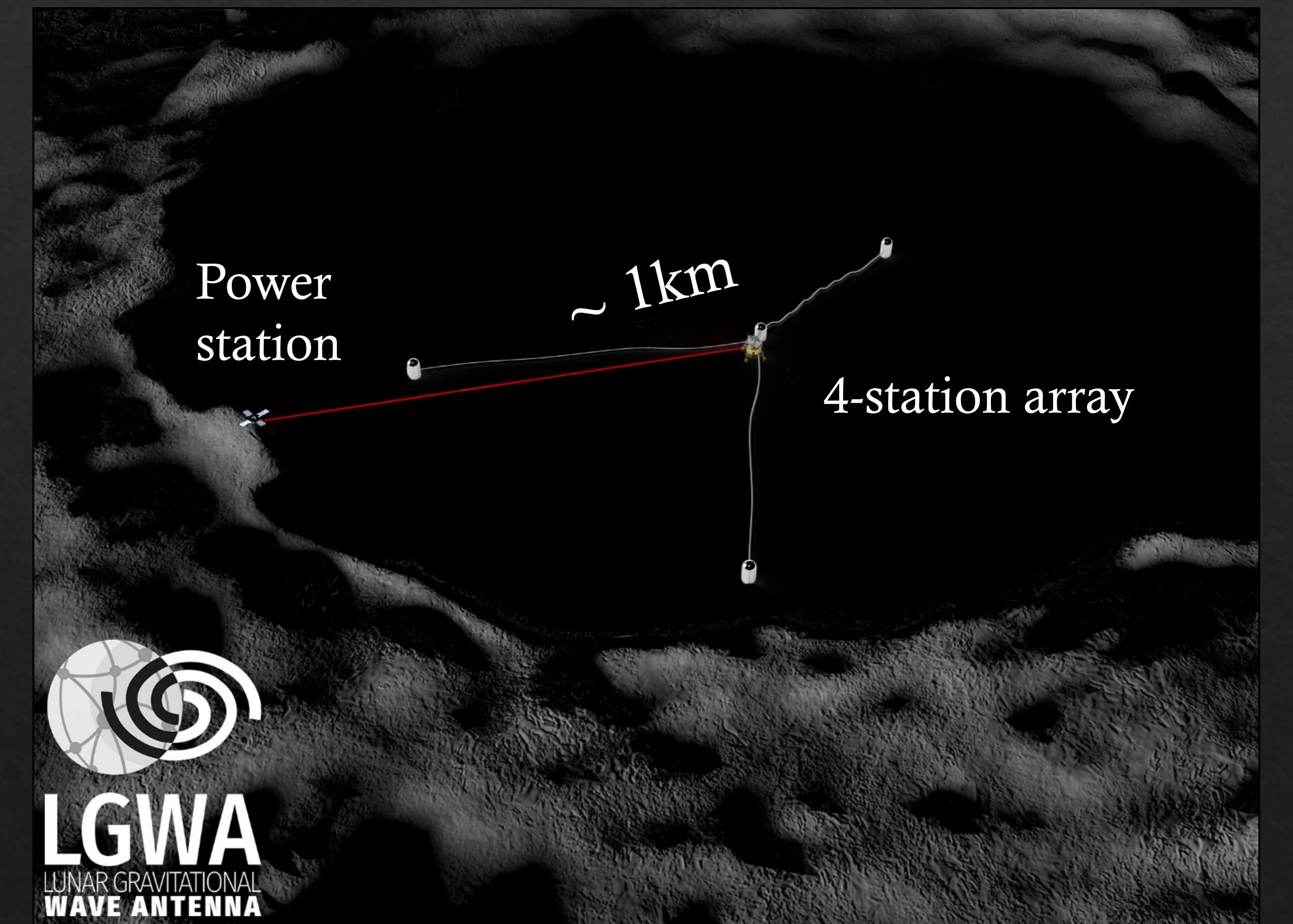
LISA technology developed in LISA pathfinder

LGWA

Apollo 17 – Lunar Surface Gravimeter

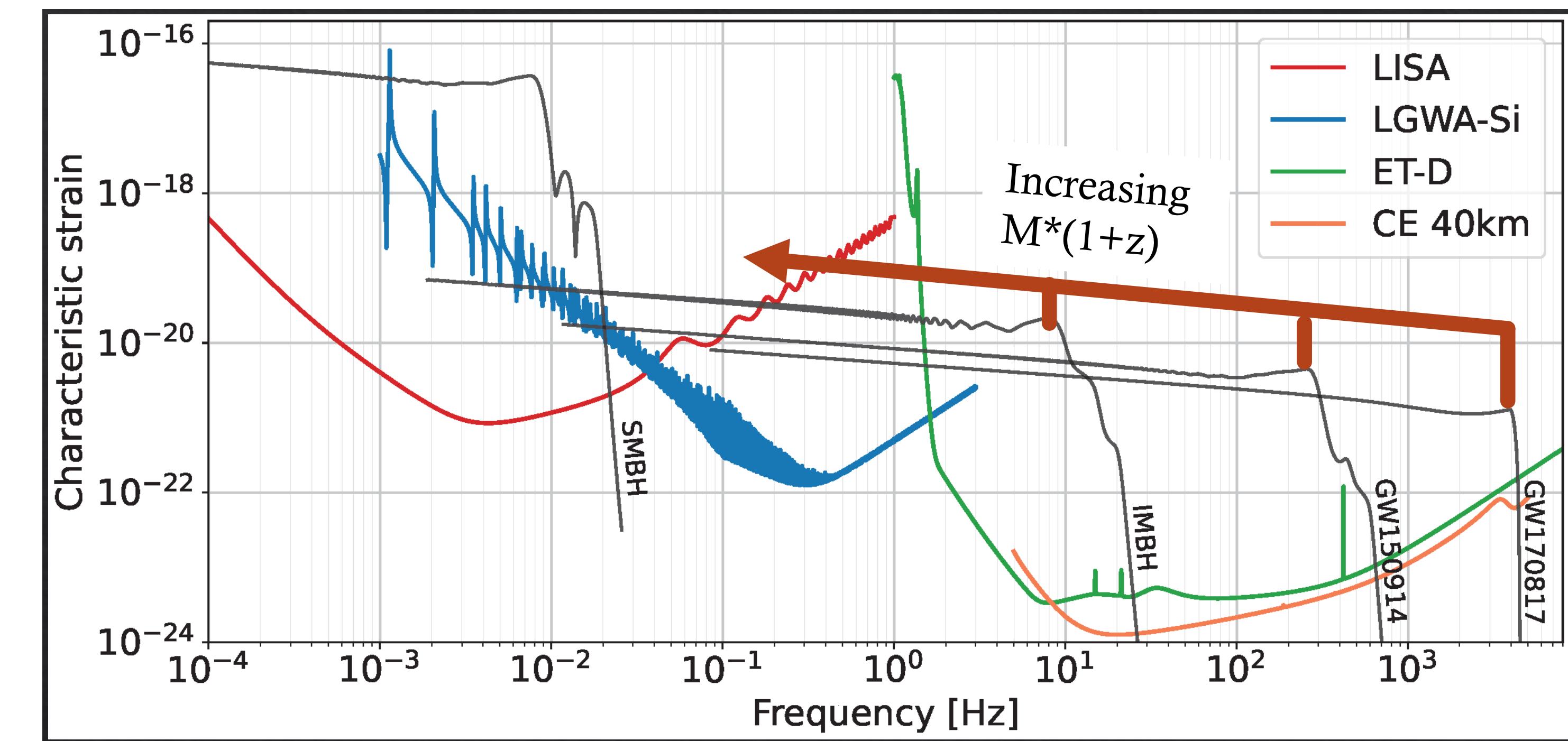


ESA 2020 – Lunar GW Antenna



Multiband observations

- You can observe the **same signal** during different phases of its inspiral with **different detectors** (in the order: LISA, LGWA, ET/CE)
- Multiband observations enable high-precision waveform analysis



What you did learn today

- Population-synthesis simulations: input VS output
- Black holes generated from Population III stars
- Future of GW astrophysics with next generation detectors

Further reading

- This is based on lecture materials of Marica Branchesi, Jan Harms, Tito Dal Canton, Michela Mapelli, Eleonora Loffredo, Giuliano Iorio and Gaston Escobar
- References:
 - **Pop-synth:** [Iorio et al. 2023](#), [Fragos et al. 2023](#)
 - **3G detectors:** [Reitze et al. 2019](#), [Maggiore et al. 2020](#), [Branchesi et al. 2023a](#), [Branchesi et al. 2023b](#)

What you learnt in these lectures

- In your toolbox:
 - Basics of detecting GW signals
 - Parameter Estimation
 - Astrophysics of compact objects
 - Multimessenger astrophysics and host galaxies
 - Next-generation detectors