Gravitational Wave Astrophysics

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Scuola Universitaria Superiore

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 hydrodynimcs**

SEVN

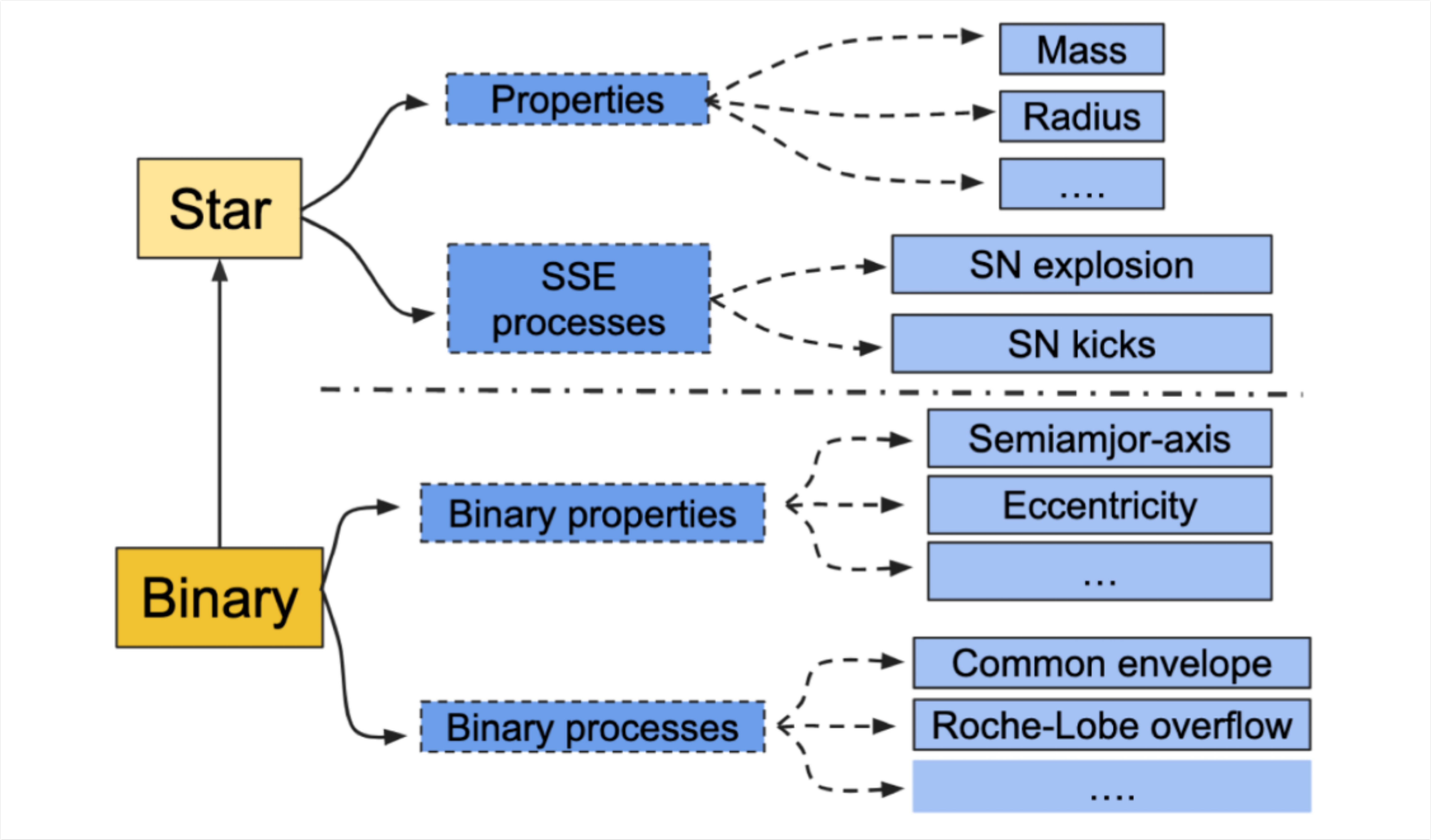
- SEVN (Stellar EVolution N-body)
- Stellar evolution through interpolation of precomputed **stellar tracks**
- Precomputed stellar tracks can be easily added to use **updated** stellar evolution models
- We will see an example applied to **Population III stars**

Credits: Spera et al. 2019, Mapelli et al. 2020, Iorio et al. 2023

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

SEVN: input VS oputput



Credits: Iorio et al. 2023

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, …)
- Let's see an example of this

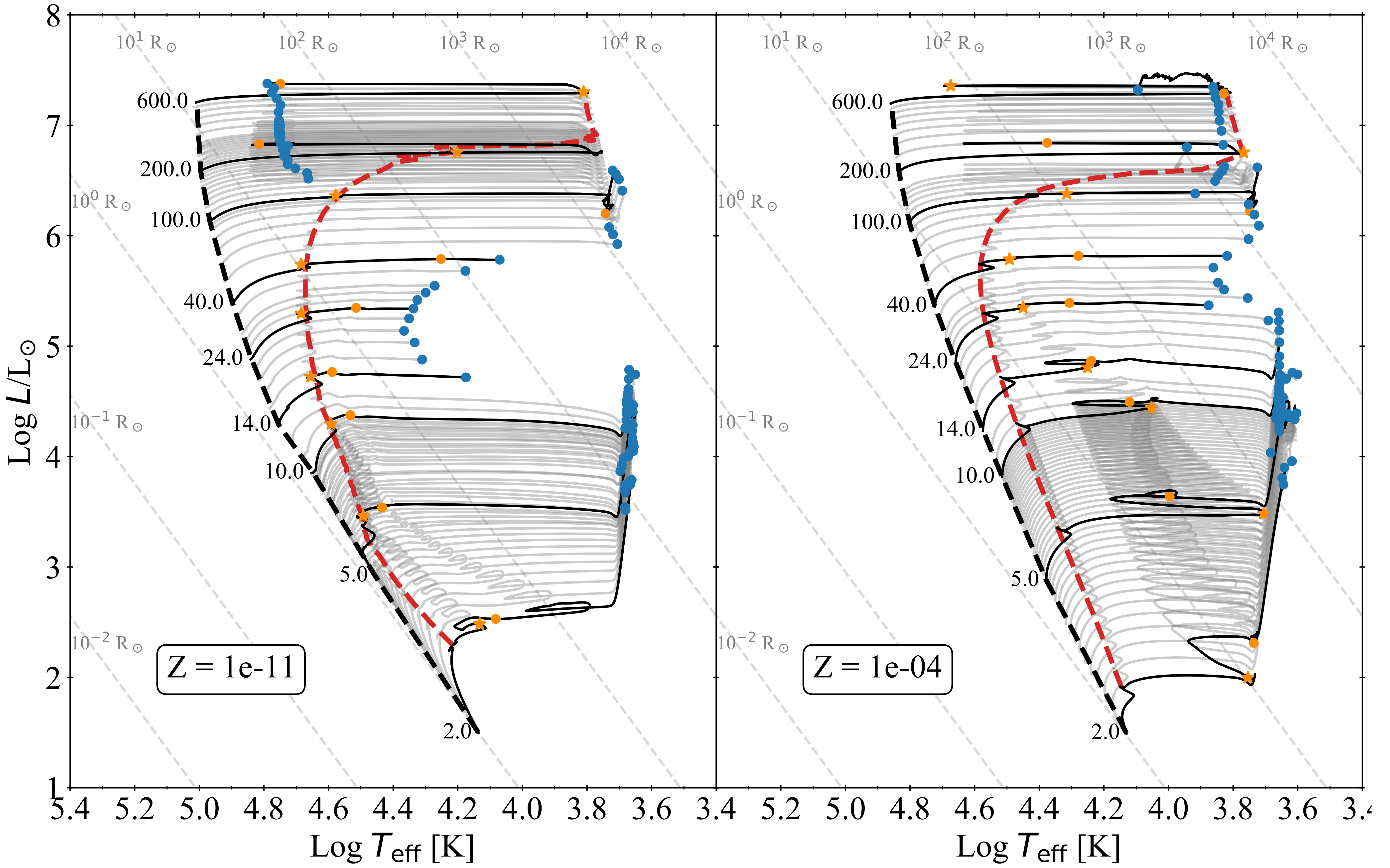
Population III stars

- 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 *(few 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

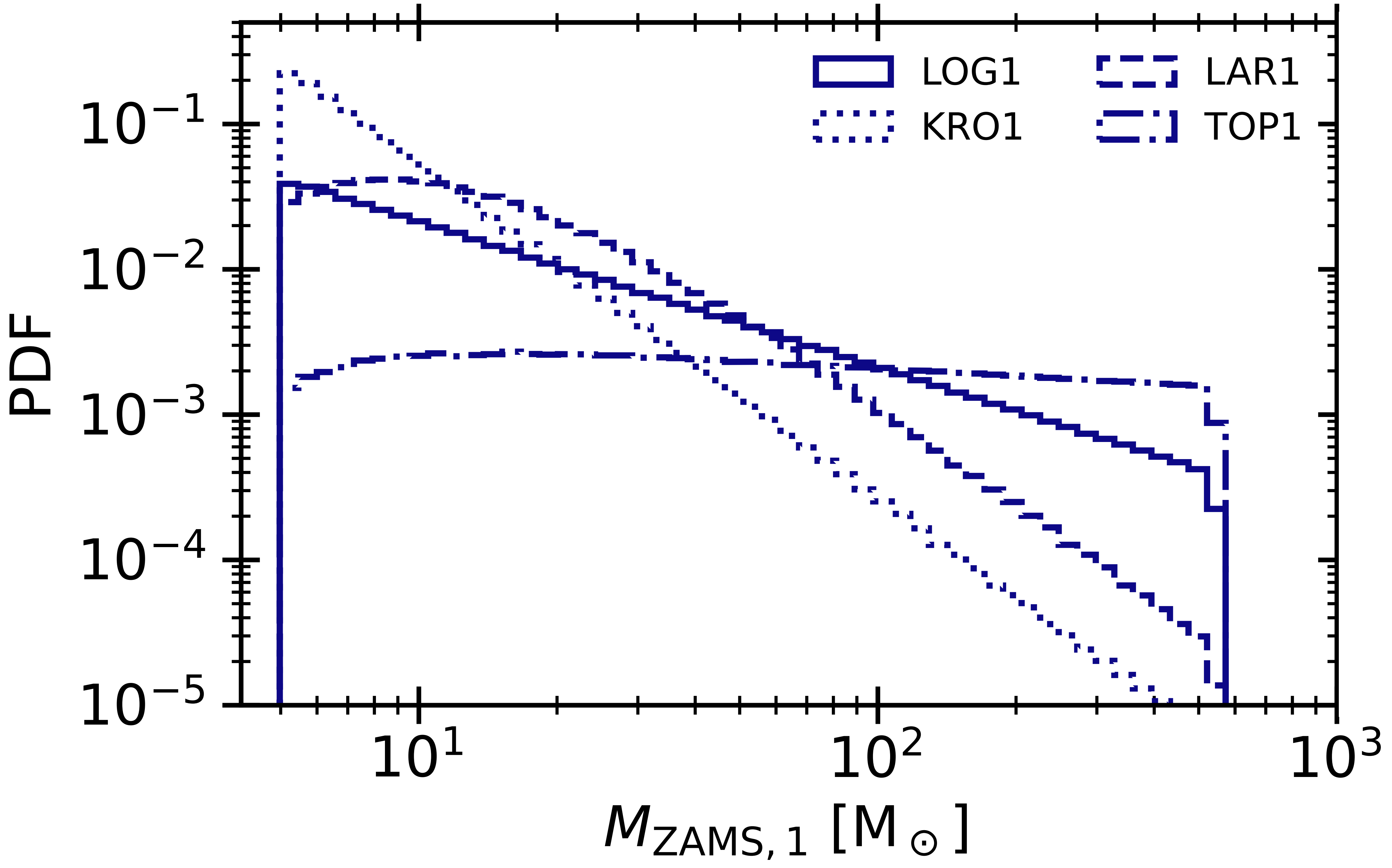
- Adding stellar tracks in SEVN
- Pop. III stars are more compact and hotter than Pop. II



Refs: Costa et al. 2023

Pop. III initial conditions

Initial Mass Function



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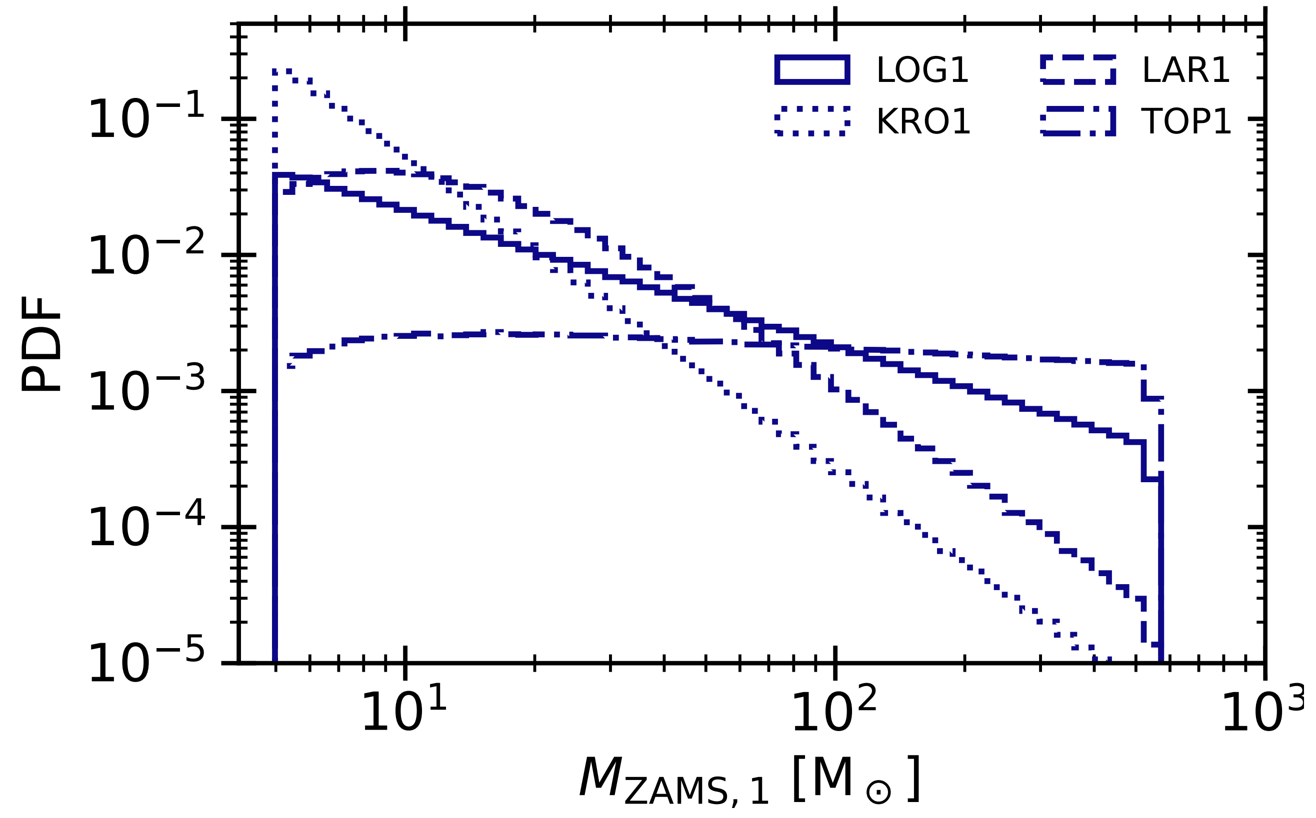
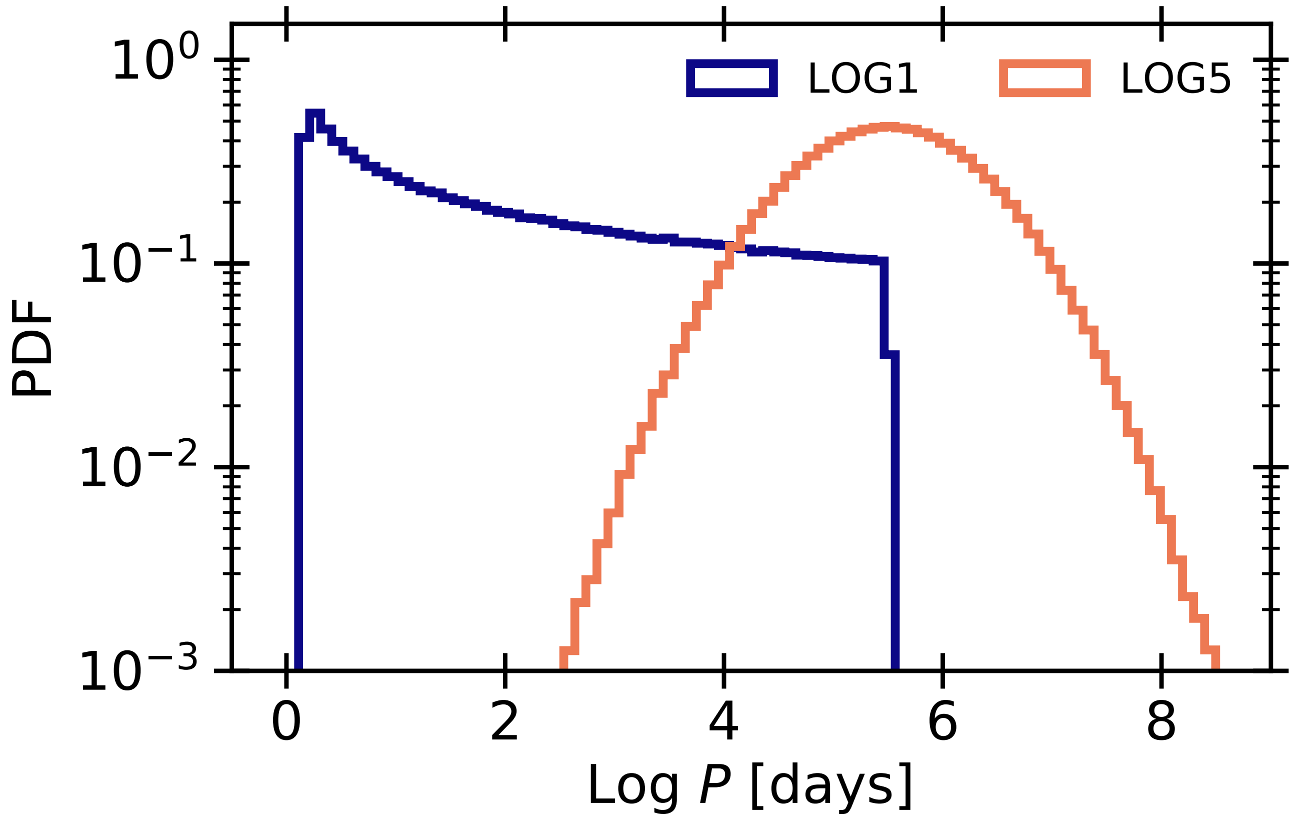
Pop. III initial conditions

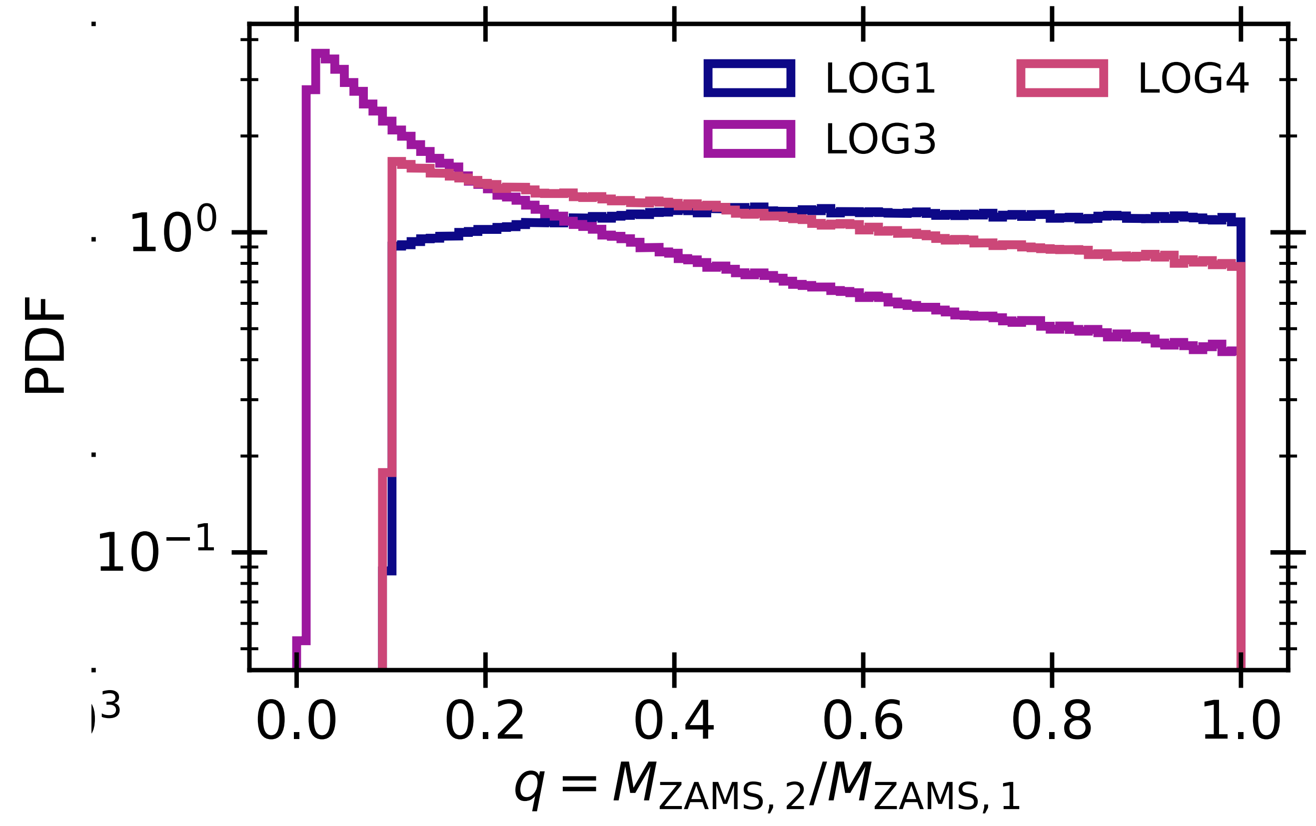
Initial Mass Function



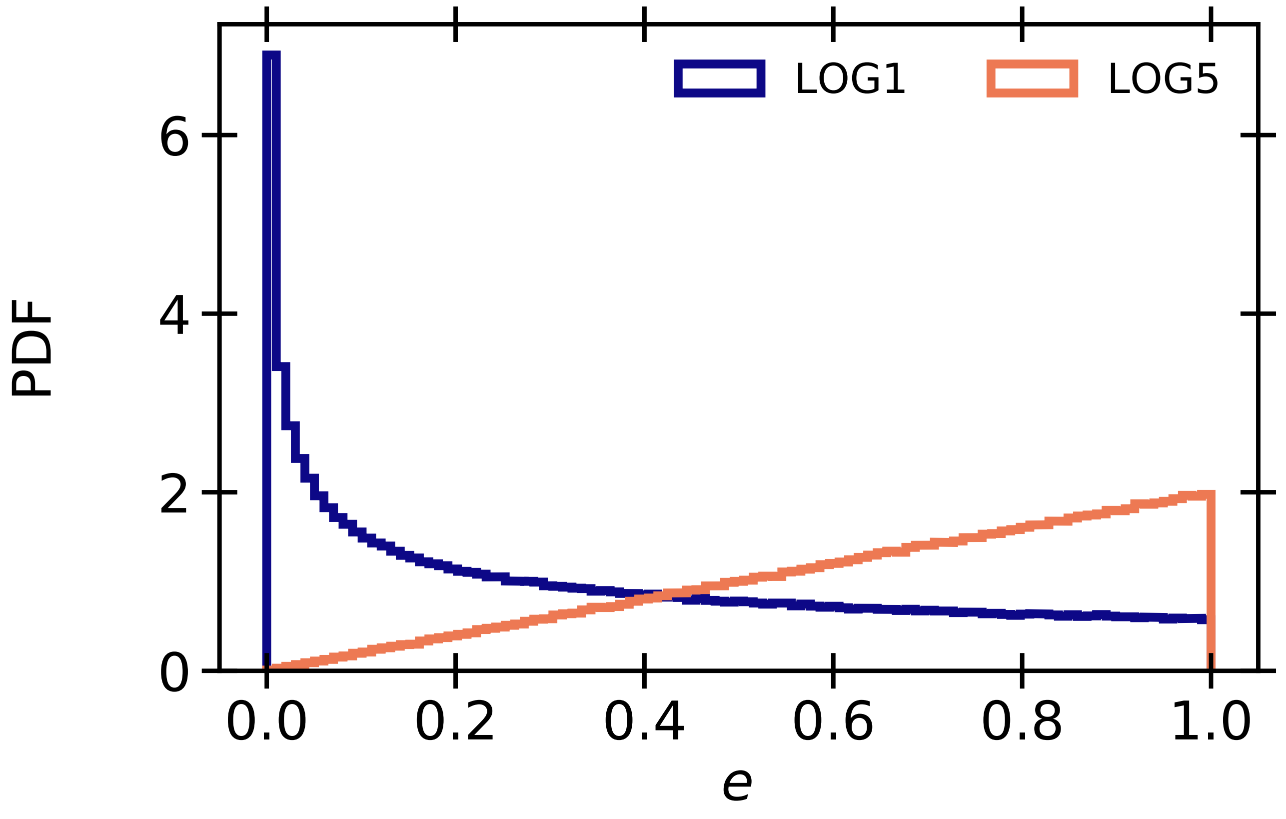
Orbital period



Mass ratio

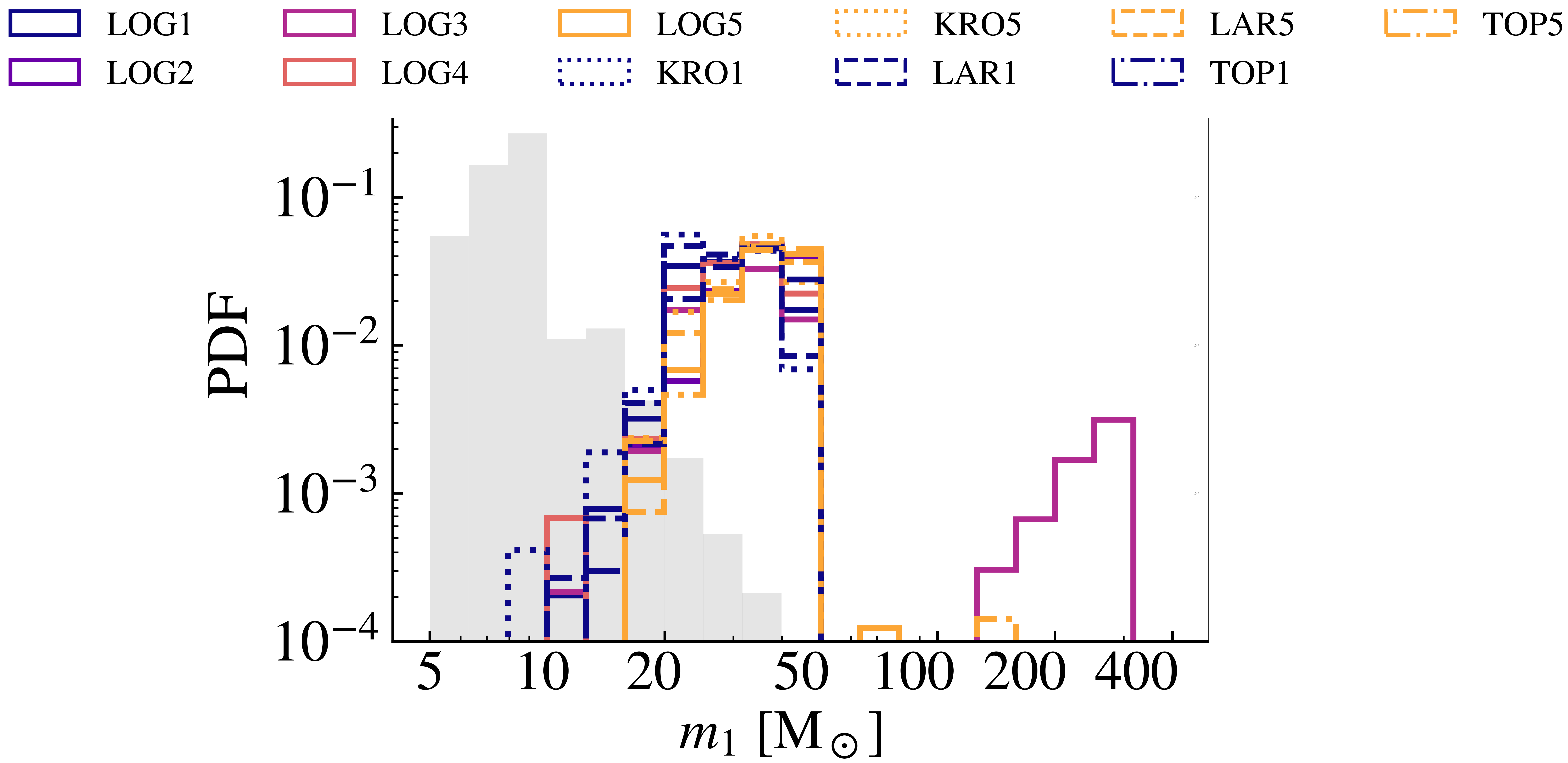


Eccentricity



Credits: Costa et al. 2023

Result: Population III BBH



Ref: Santoliquido et al. 2023

COSMORATE

$$\mathcal{R}(z) = \int_{z_{\max}}^{z} \left[\int_{Z_{\min}}^{Z_{\max}} \boxed{\mathrm{SFRD}(z', Z)} \boxed{\mathcal{F}(z', z, Z)} \mathrm{d}Z \right] \frac{\mathrm{d}t(z')}{\mathrm{d}z'} \mathrm{d}z'$$

catalogs from SEVN

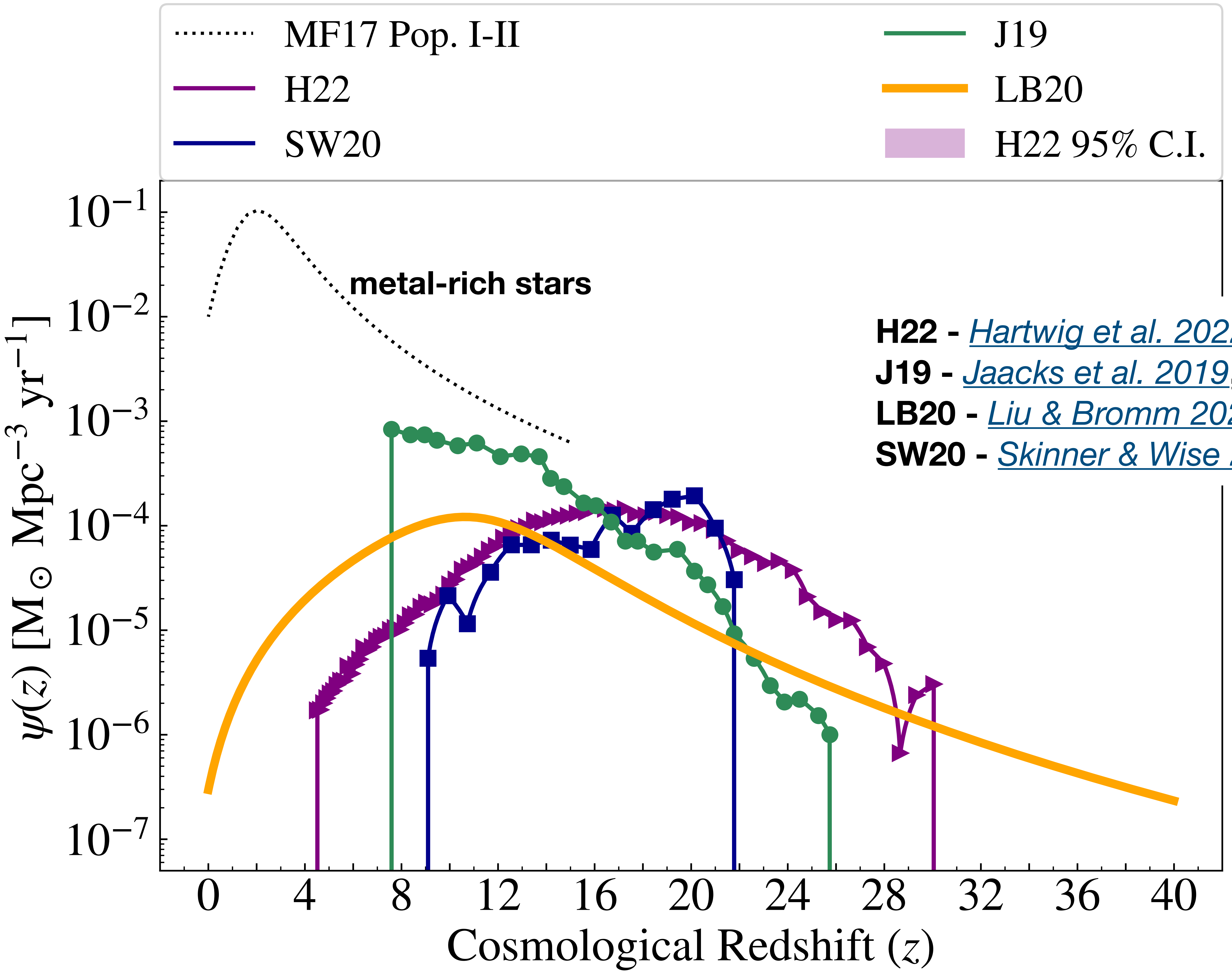
$$\mathrm{SFRD}(z, Z) = \boxed{\psi(z)} \boxed{p(Z|z)}$$

Delta function centred at $Z = 10^{-11}$

Cosmological simulations

Ref: Santoliquido et al. 2020

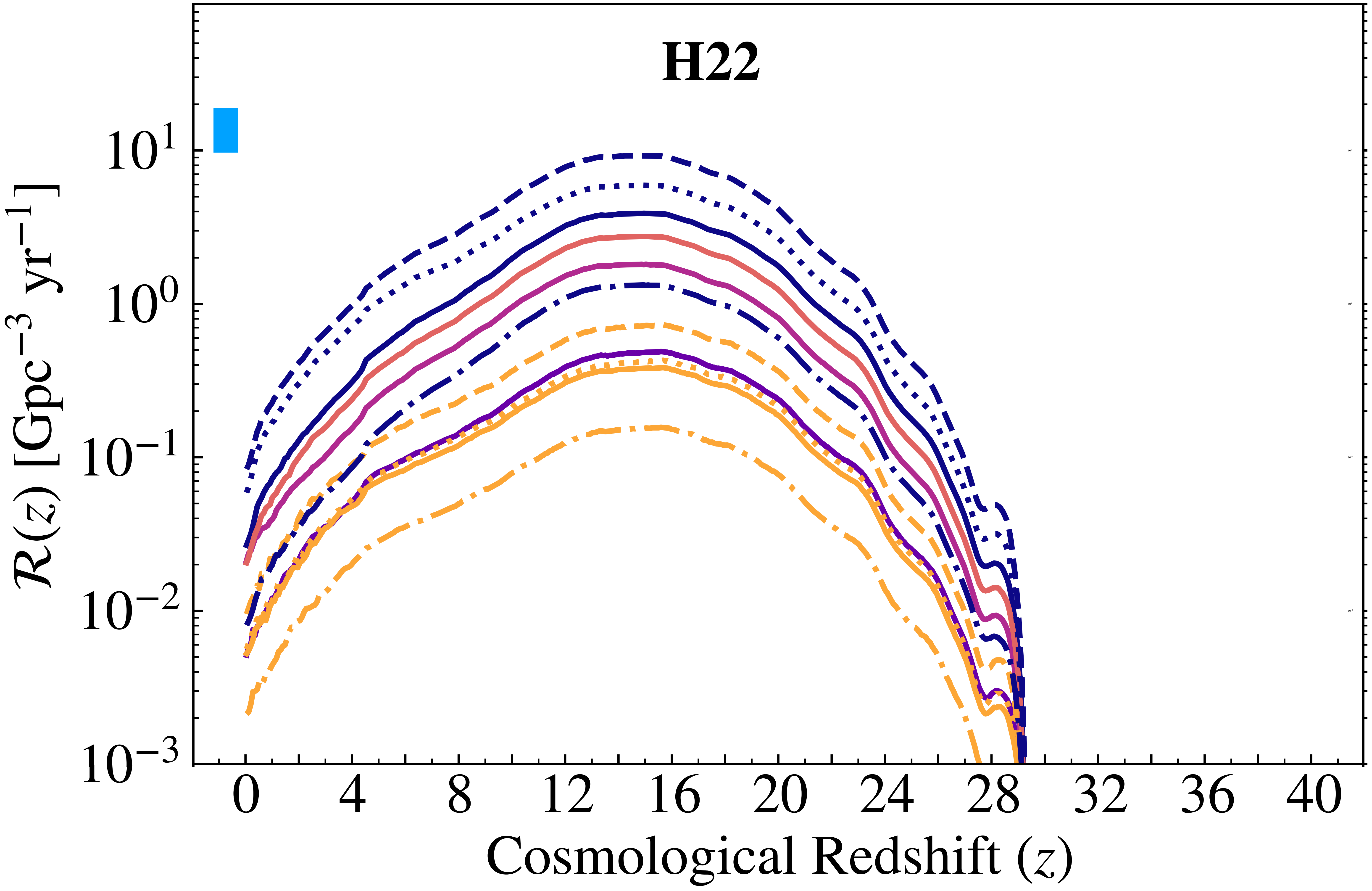
Pop. III SFRD



H22 - *Hartwig et al. 2022*,
J19 - *Jaacks et al. 2019*,
LB20 - *Liu & Bromm 2020*,
SW20 - *Skinner & Wise 2020*

Ref: Santoliquido et al. 2023

Pop. III BBHs MRD

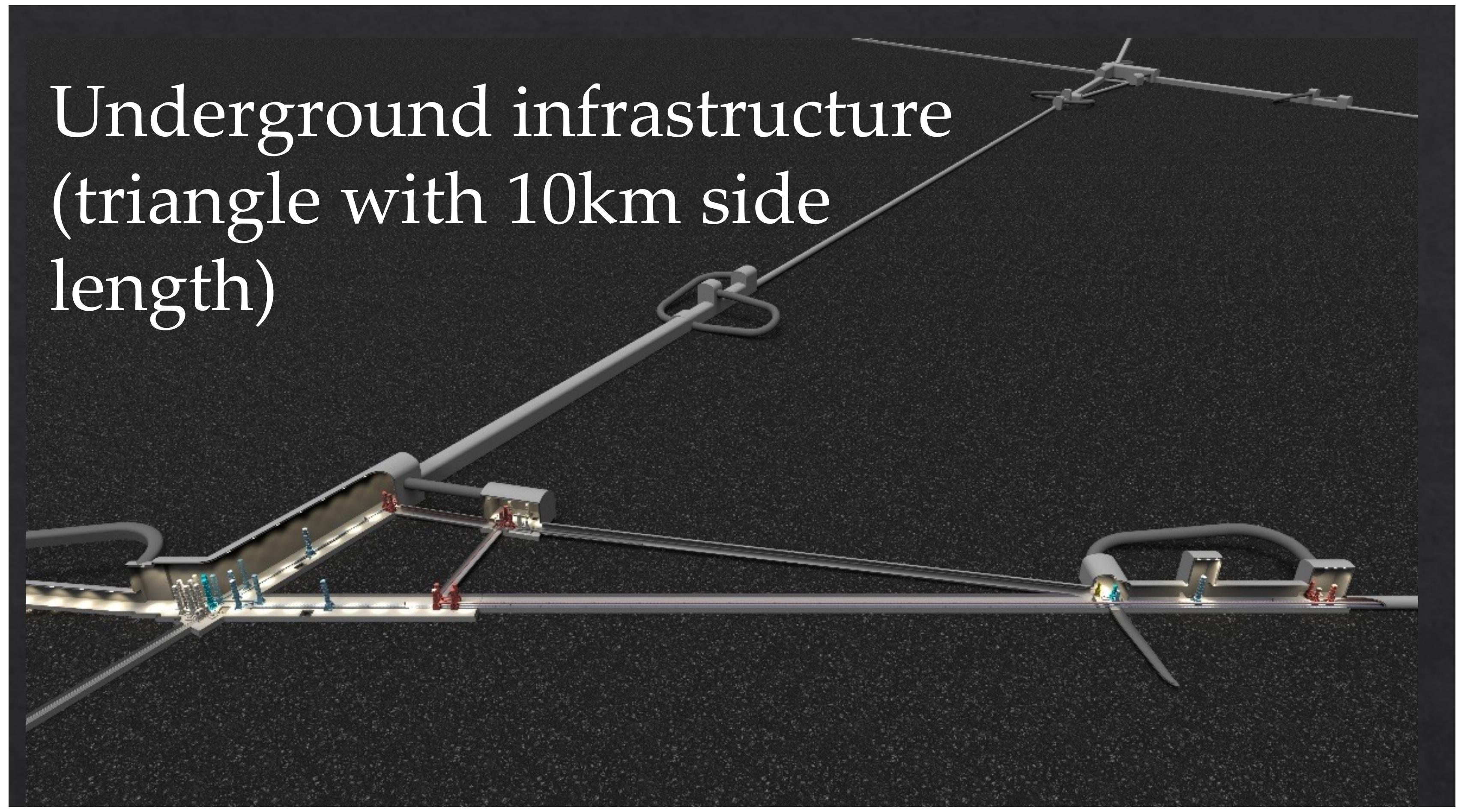


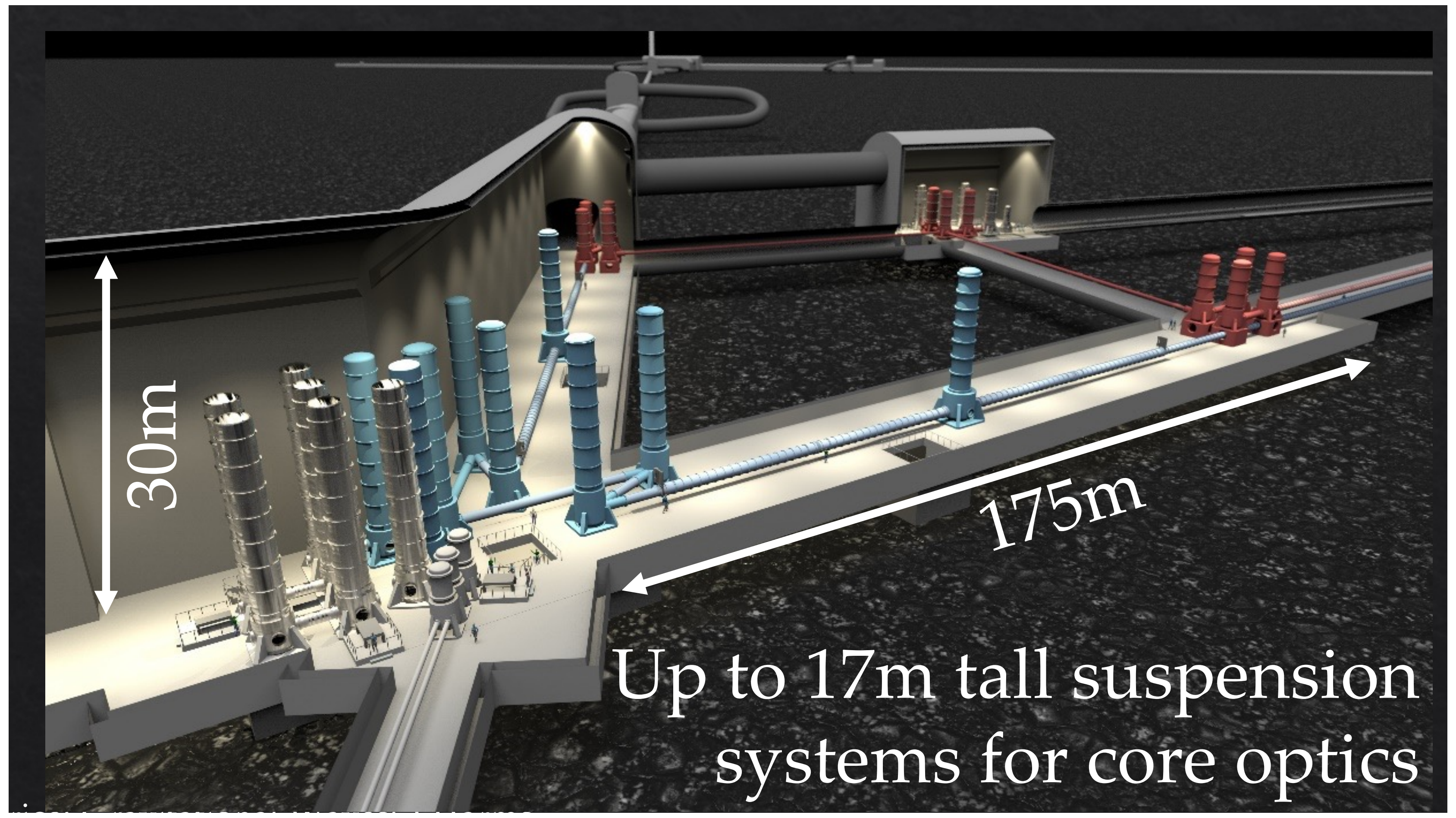
Ref: Santoliquido et al. 2023

Are we able to detected these BBH mergers?

Next generation GW detectors

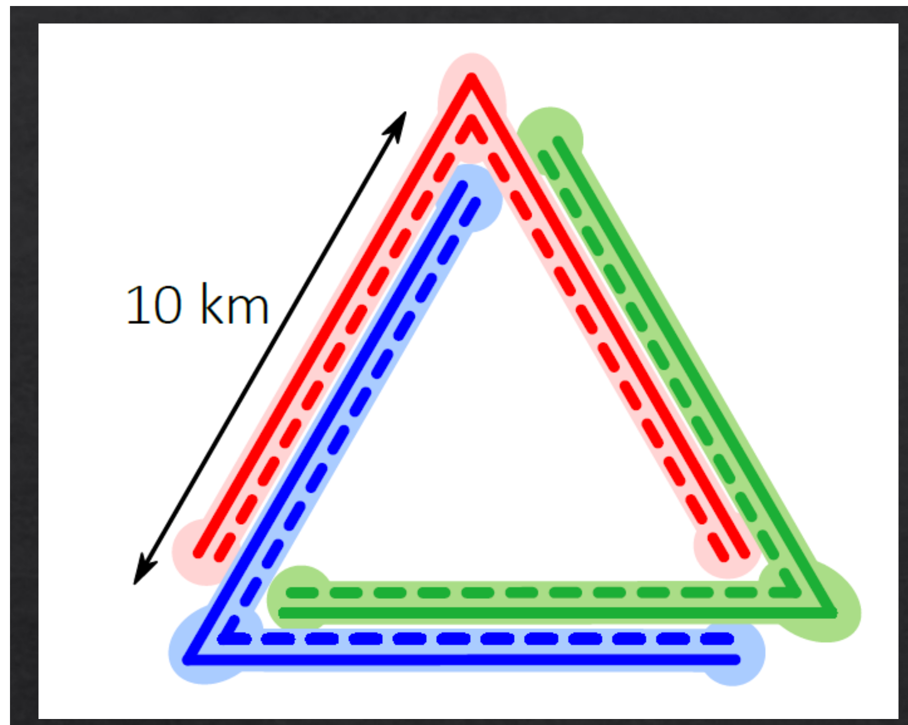
The Einstein Telescope: 3 facts





Credits: Jan Harms

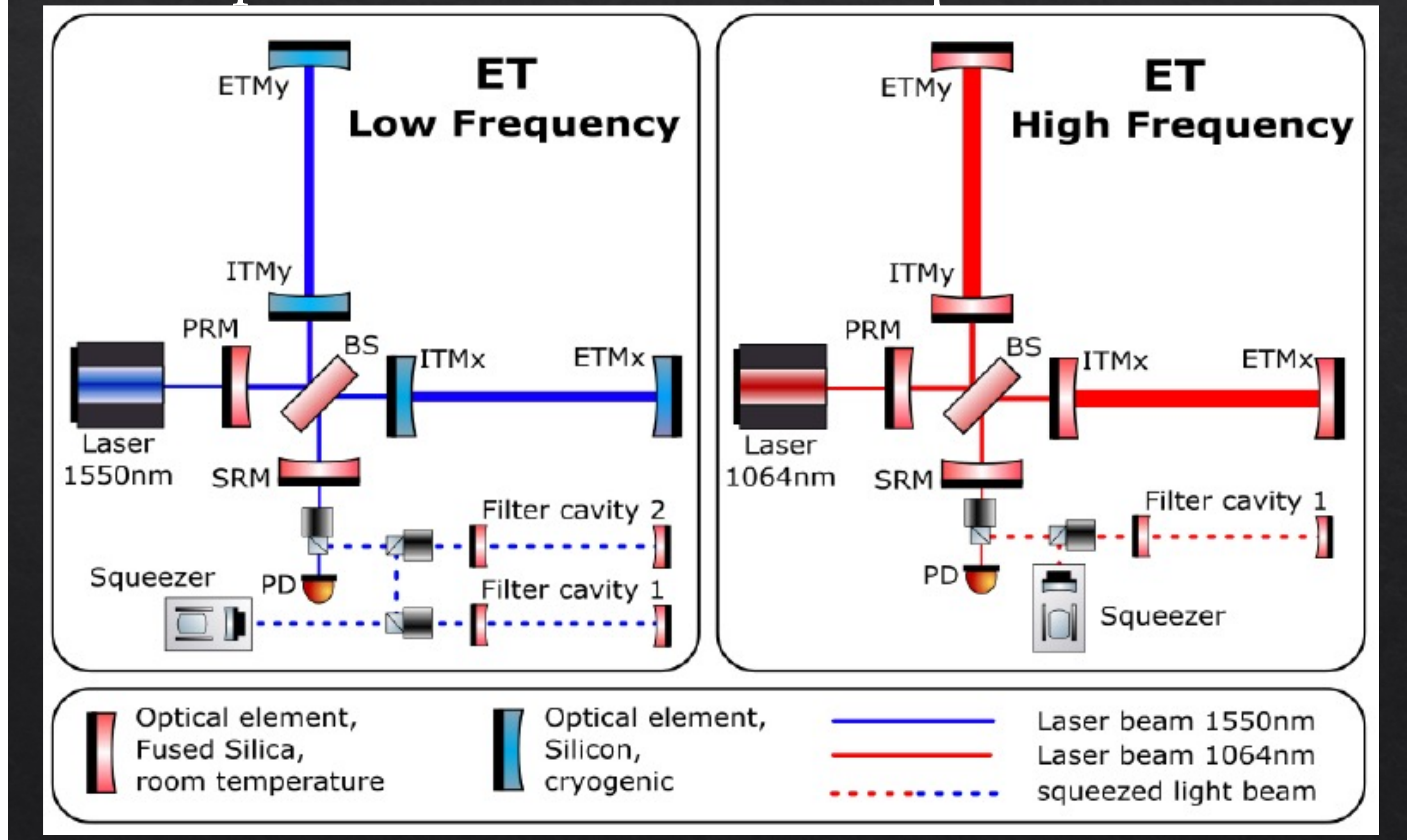
The Einstein Telescope: design

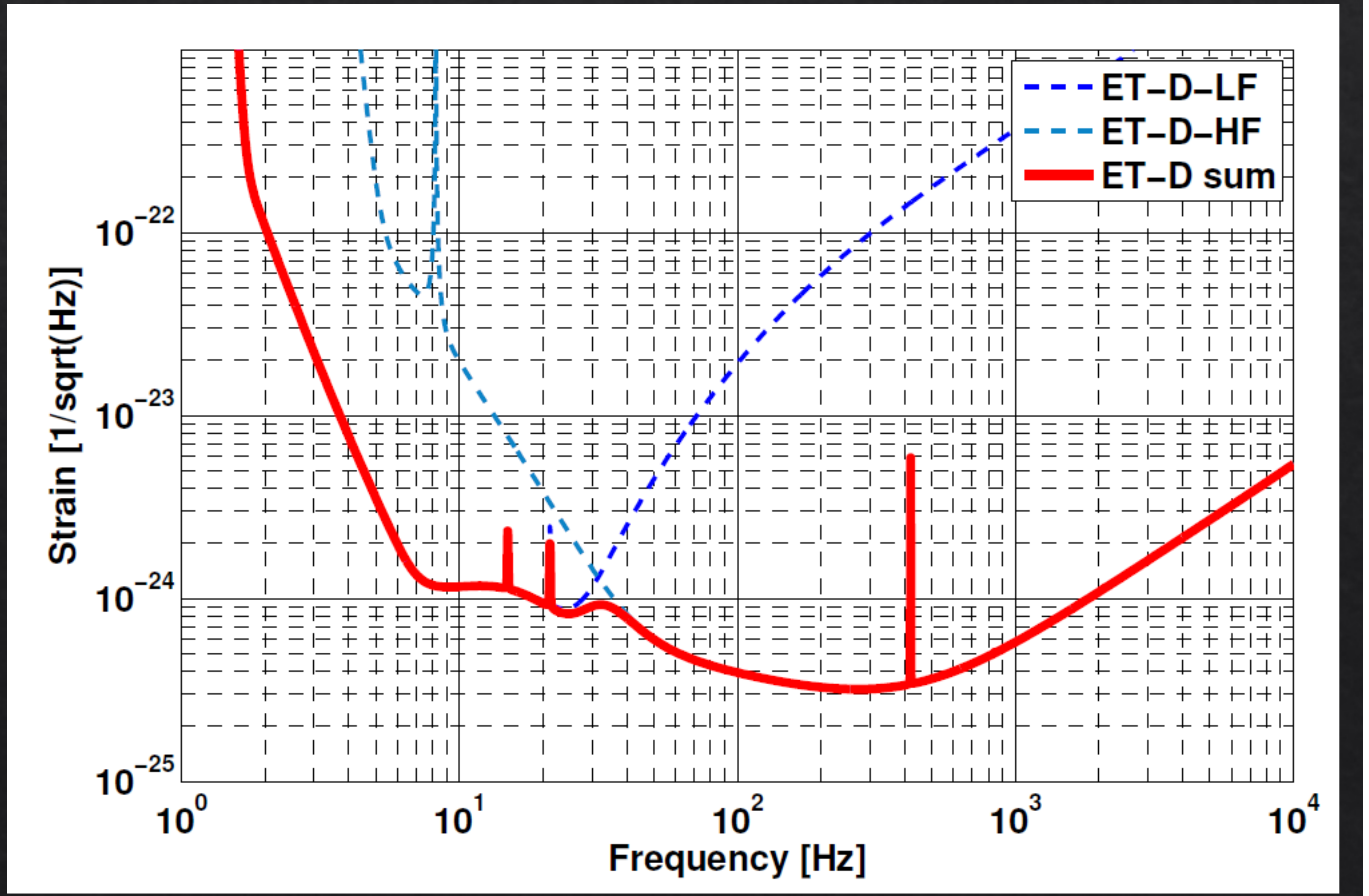


Each vertex is the center of a pair of interferometers, i.e., 6 interferometers in total.

Power: 18kW
Temperature: 10-20K

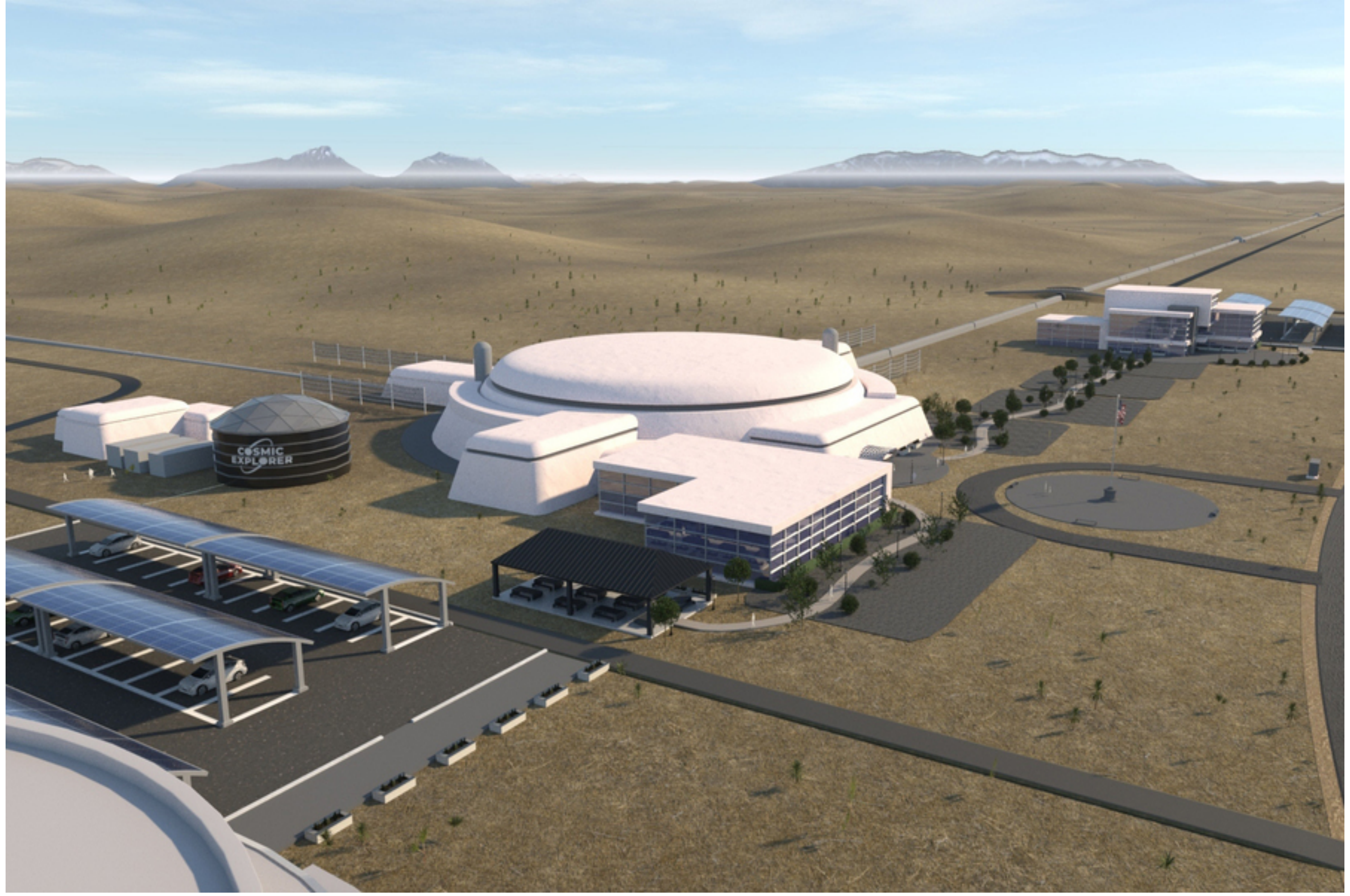
Power: 3MW
Temperature: 290K





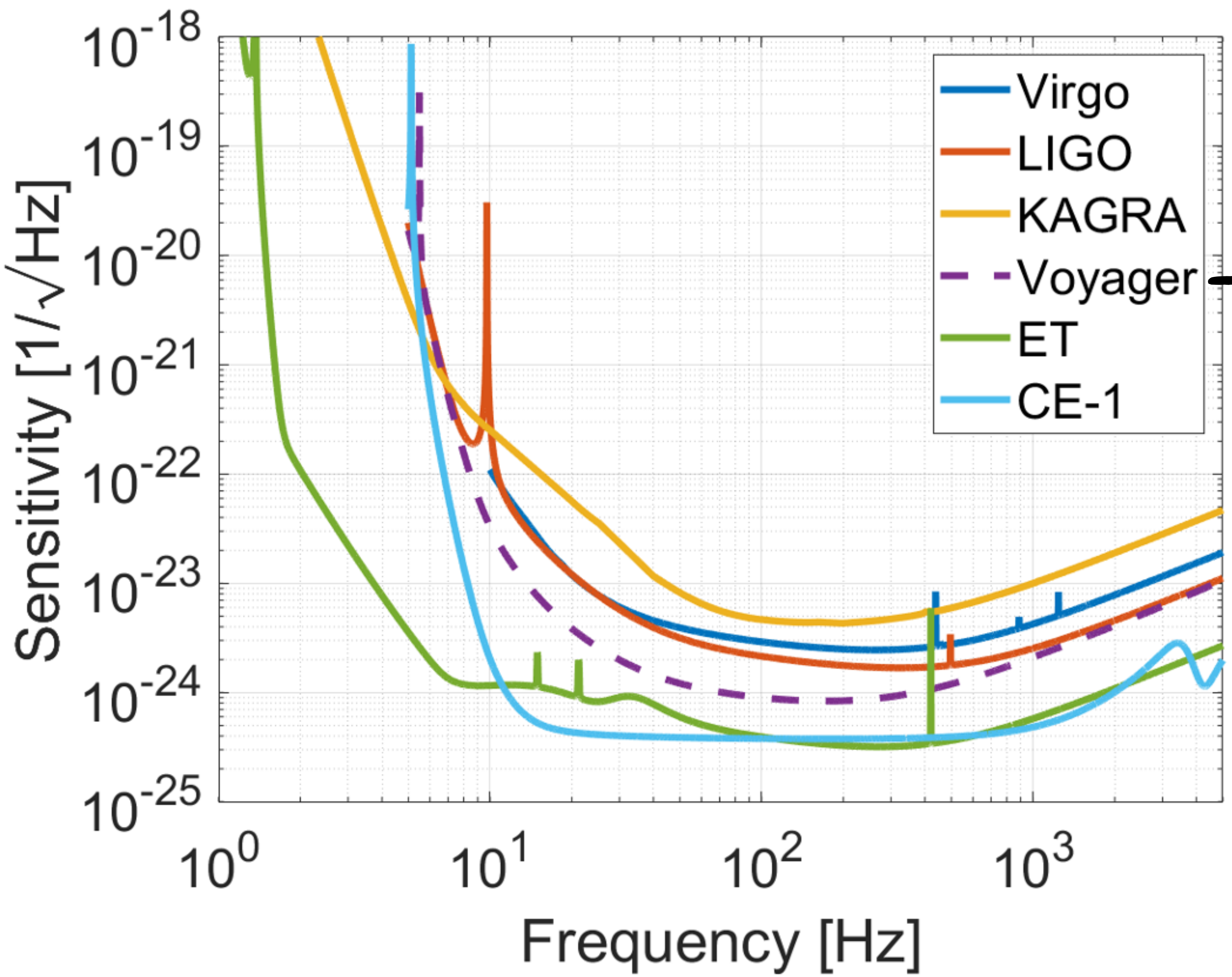
Credits: Jan Harms

Cosmic Explorer



Credits: MIT

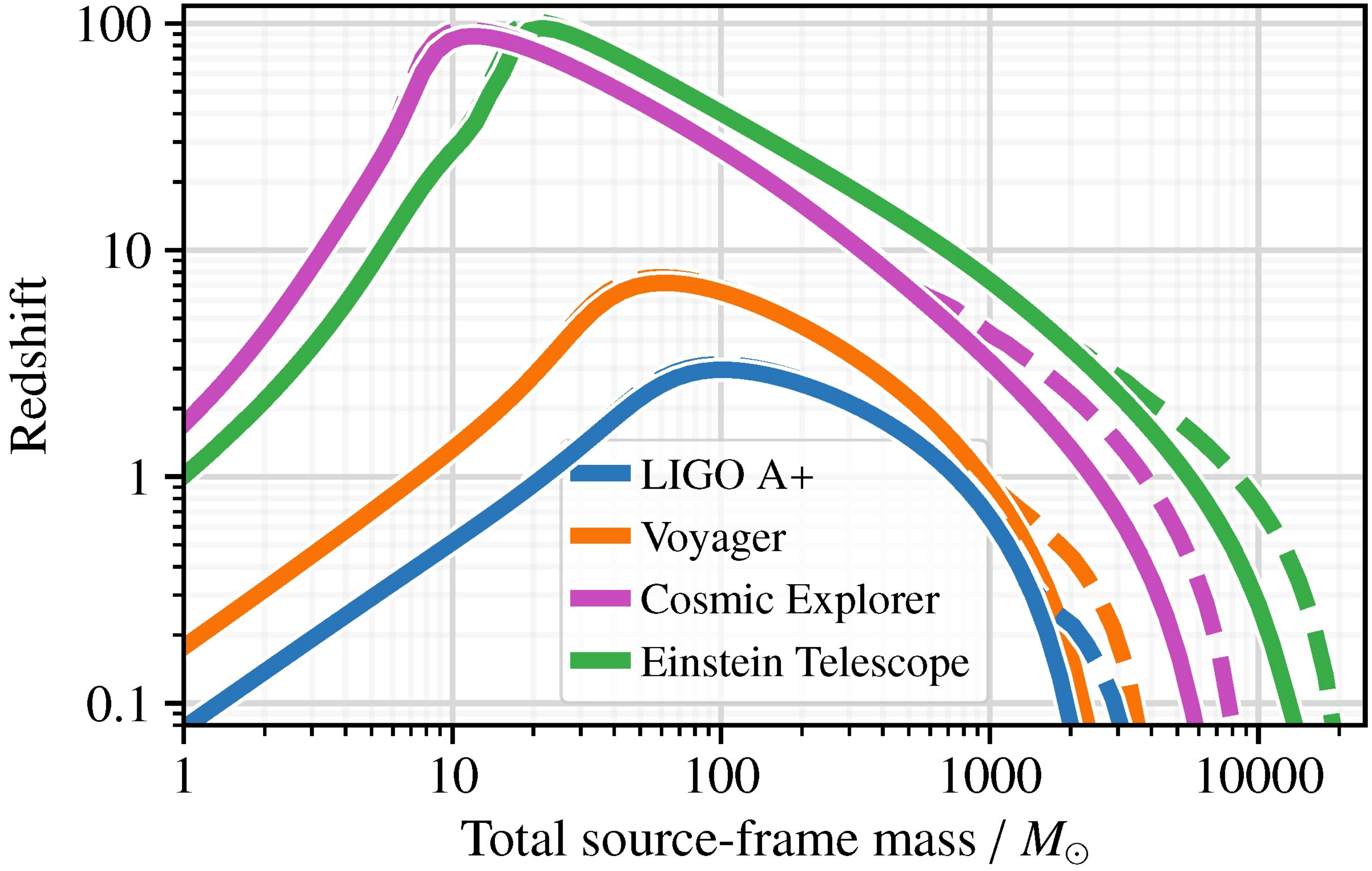
Sensitives



Substantial upgrade of LIGO

Credits: Rosati et al. 2021

Redshift horizon



Credits: Hall 2022

Detecting Pop. III BBHs

- $p(\Lambda \mid \{d\}) \propto \mathscr{L}(\{d\} \mid \Lambda) p(\Lambda)$
- $\mathscr{L}(\{d\} \mid \Lambda) \propto \prod_{i}^{N_{obs}} \frac{\int \mathscr{L}(d_i \mid \theta) \pi(\theta \mid \Lambda)}{\xi(\Lambda)}$

Detecting Pop. III BBHs

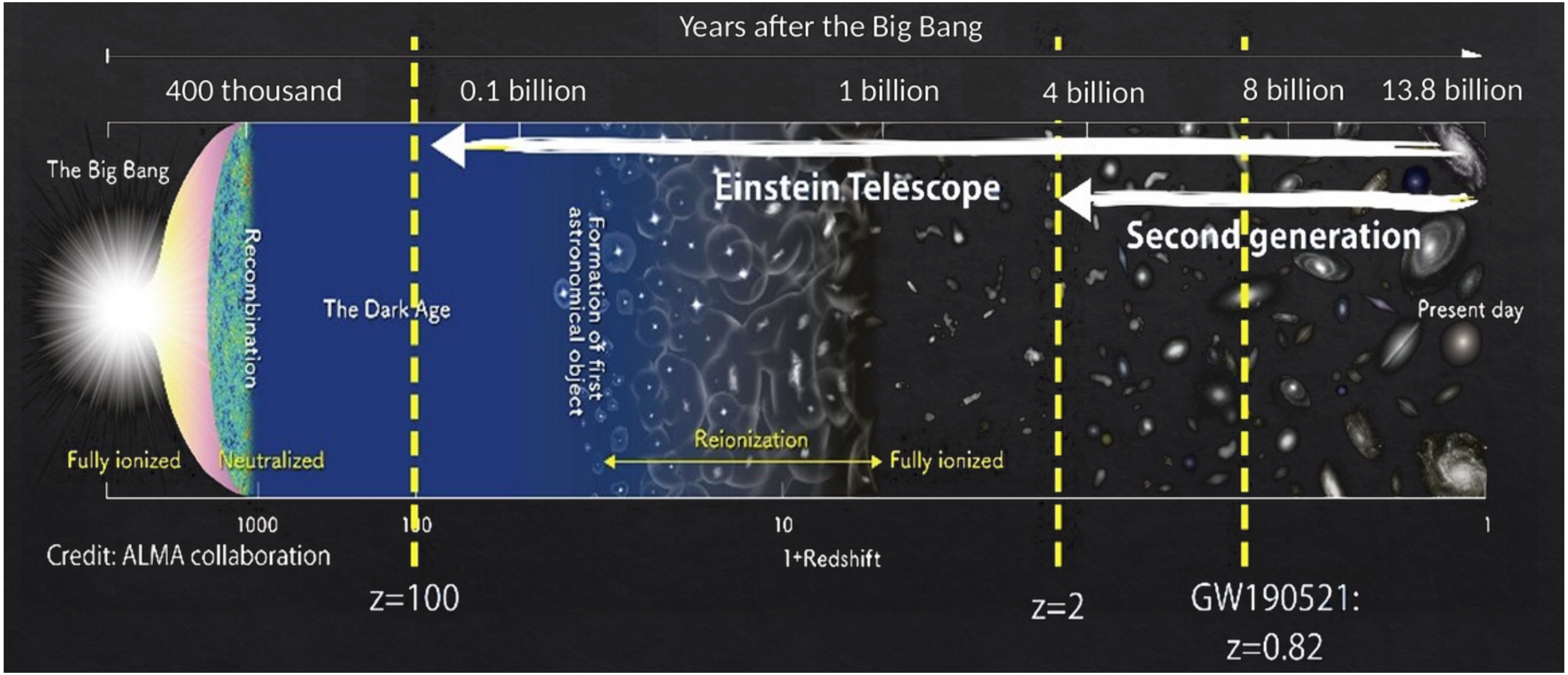
- $p(\Lambda \,|\, \{d\}) \propto \mathscr{L}(\{d\} \,|\, \Lambda) p(\Lambda)$
- $\mathscr{L}(\{d\} \,|\, \Lambda) \propto \prod_{i}^{N_{obs}} \frac{\int \mathscr{L}(d_i \,|\, \theta) \pi(\theta \,|\, \Lambda)}{\xi(\Lambda)}$
- $\xi(\Lambda) = \int p_{\mathrm{det}}(\theta) \pi(\theta \,|\, \Lambda) \quad \Lambda = \mathrm{LOG1,\ KRO1,\ \ldots}$

Detecting Pop. III BBHs

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

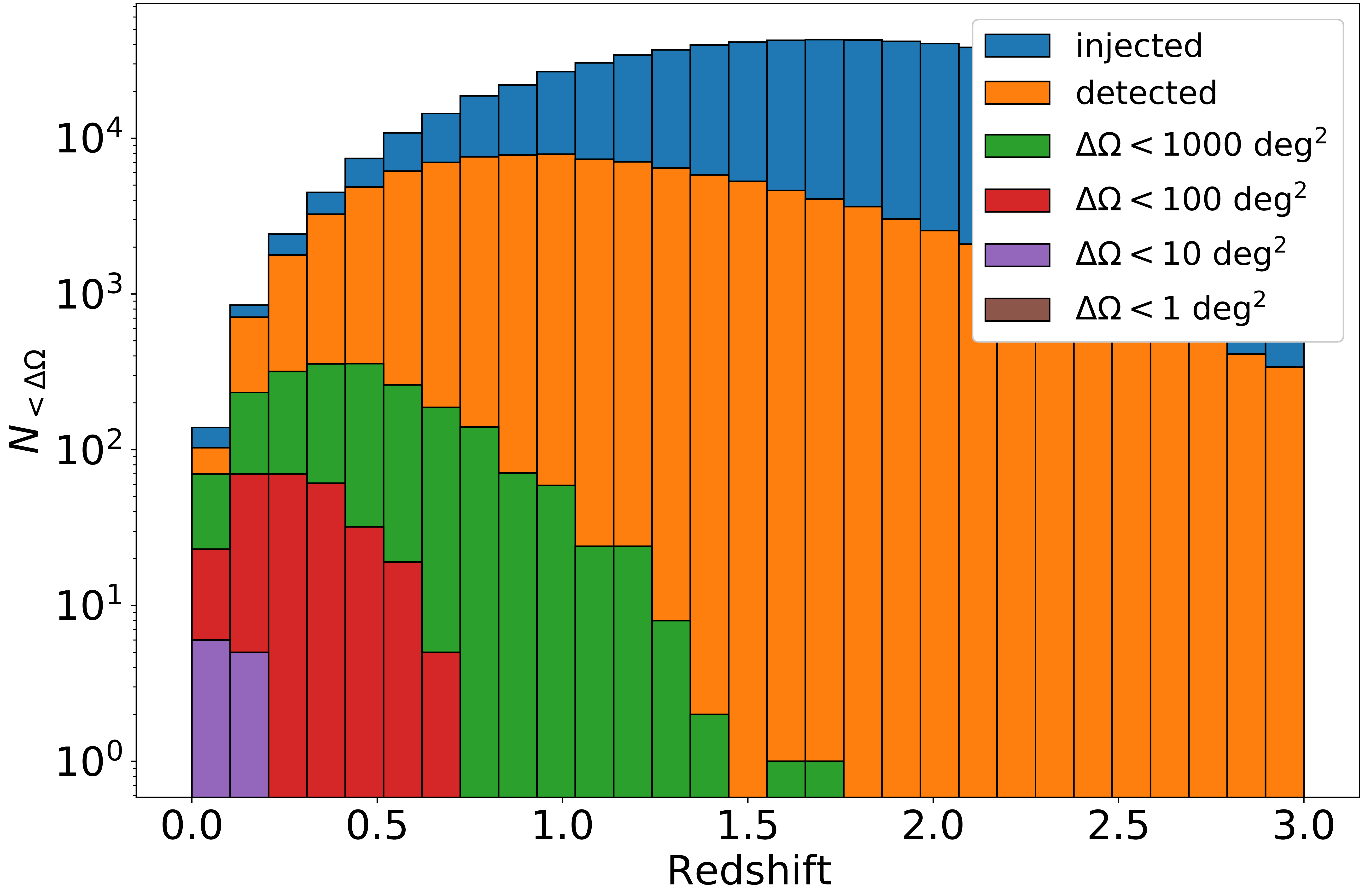
- $\rho^2 \sim \int \frac{|\tilde{h}(f)|^2}{S_n(f)} \mathrm{d}f$

Early Universe with 3G detectors



Credits: Einstein Telescope Steering Committee

Network of 3G detectors

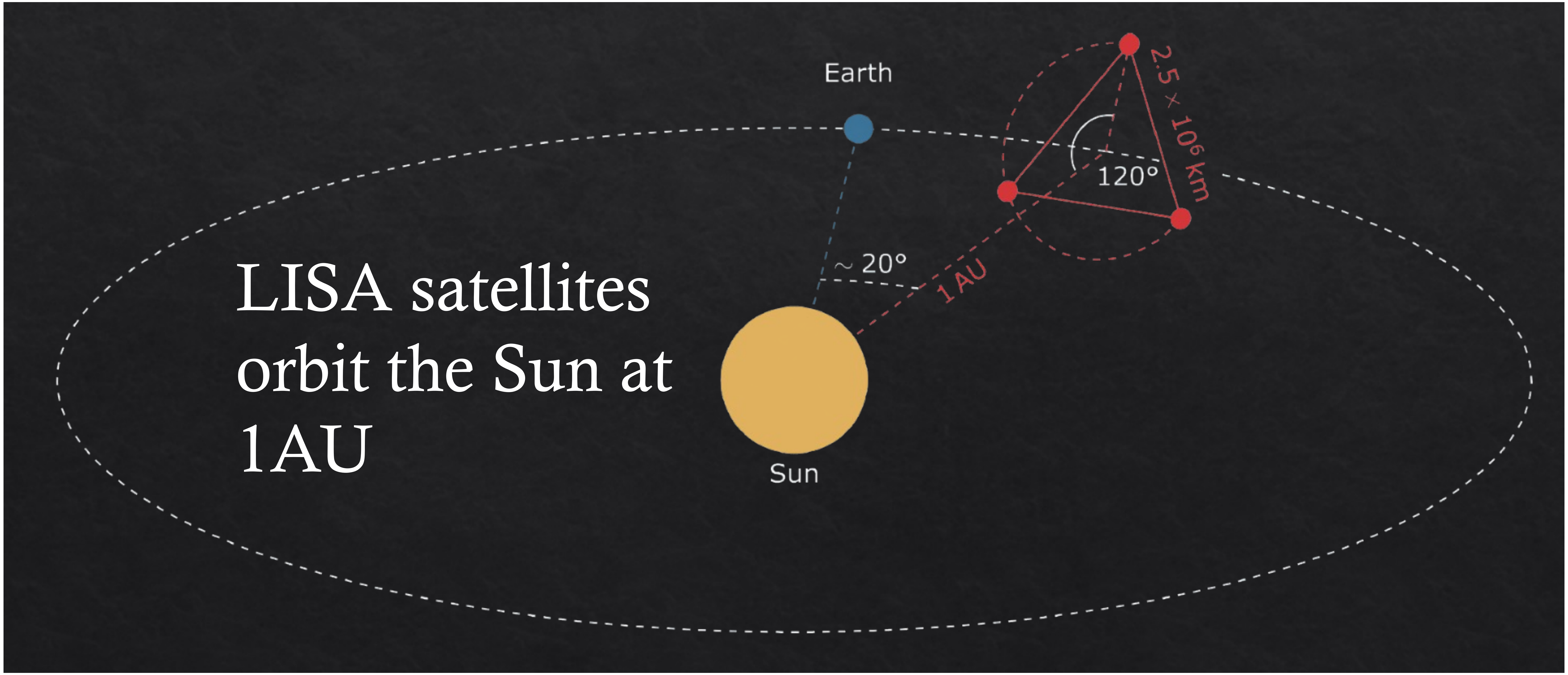


- ~ 10 detections per year with sky localisation $< 10\ \mathrm{deg}^2$
- Different designs (Δ 10 km)
- Let's check **https://gracedb.ligo.org/superevents/public/O4/#**

Ref: Branchesi et al. 2023

Let’s go space

LISA



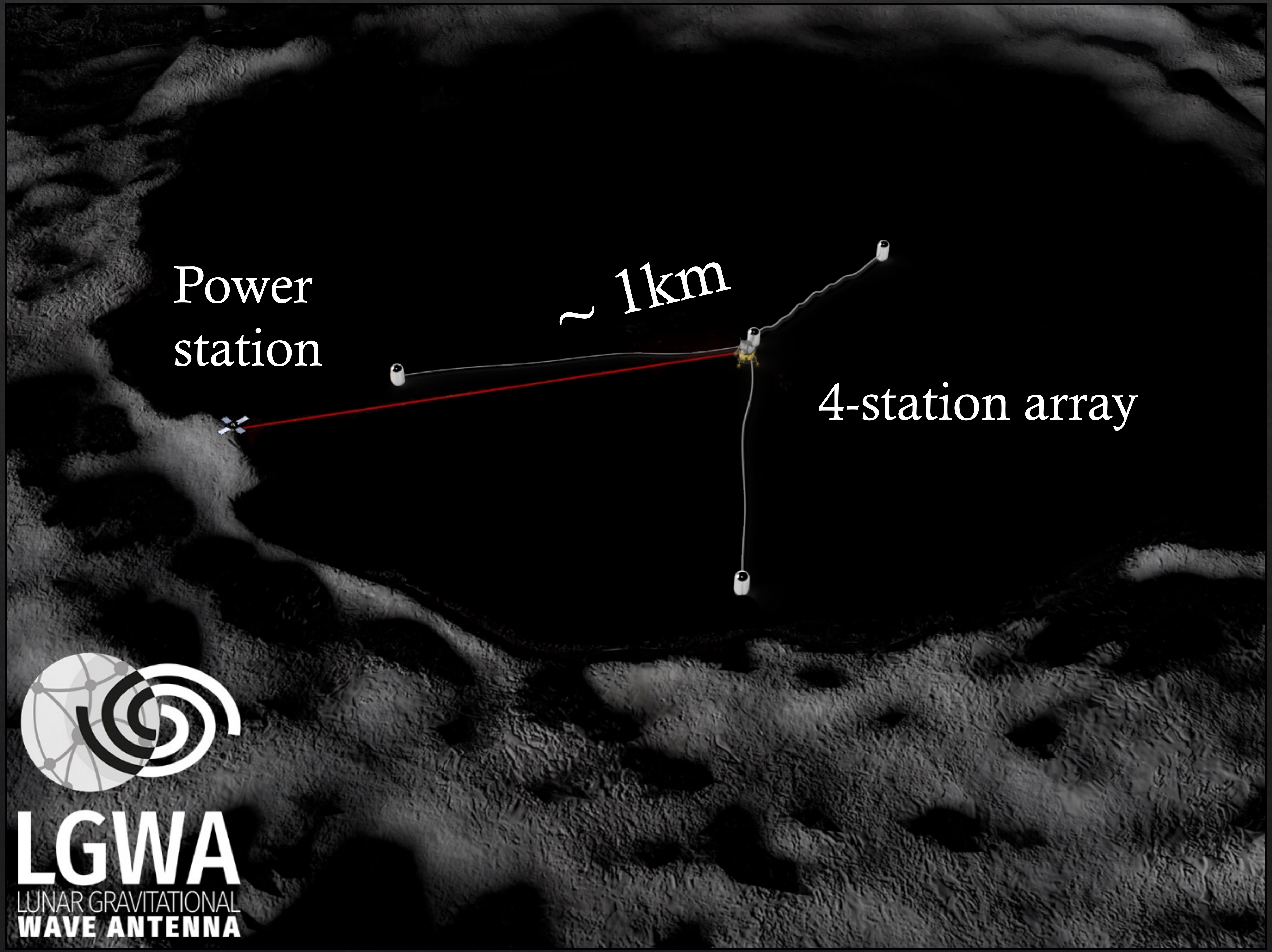
LISA technology developed in LISA pathfinder: https://www.youtube.com/watch?v=Y-CT4wxEOBA

Credits: Jan Harms

LGWA

Apollo 17 – Lunar Surface Gravimeter

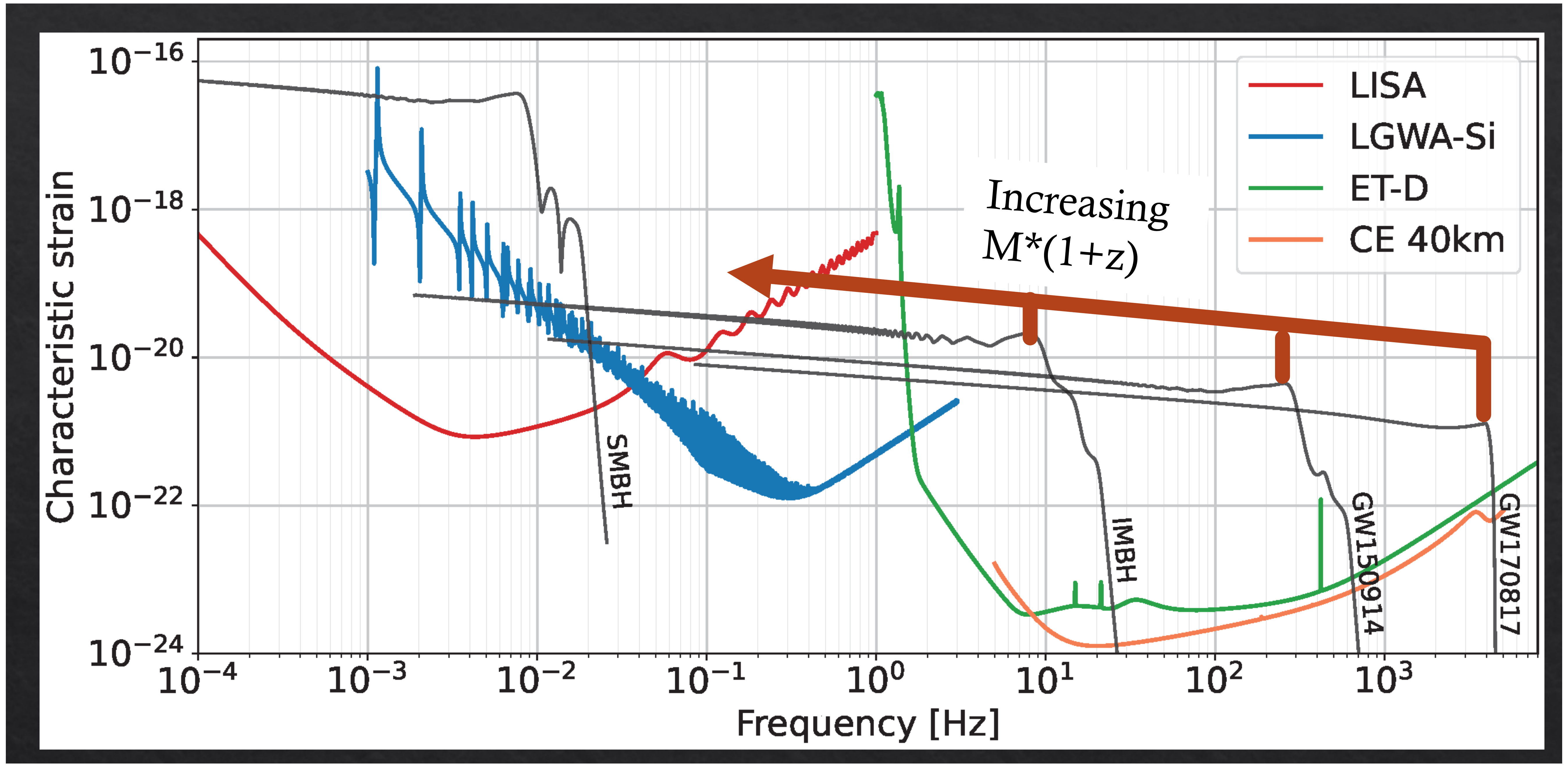
ESA 2020 – Lunar GW Antenna



Credits: Jan Harms

Multiband observations

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



Credits: Jan Harms

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

What you learnt in these lectures

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