PONT Avignon 2023

gwfast and the detection of high-redshift sources with third-generation gravitational-wave detectors

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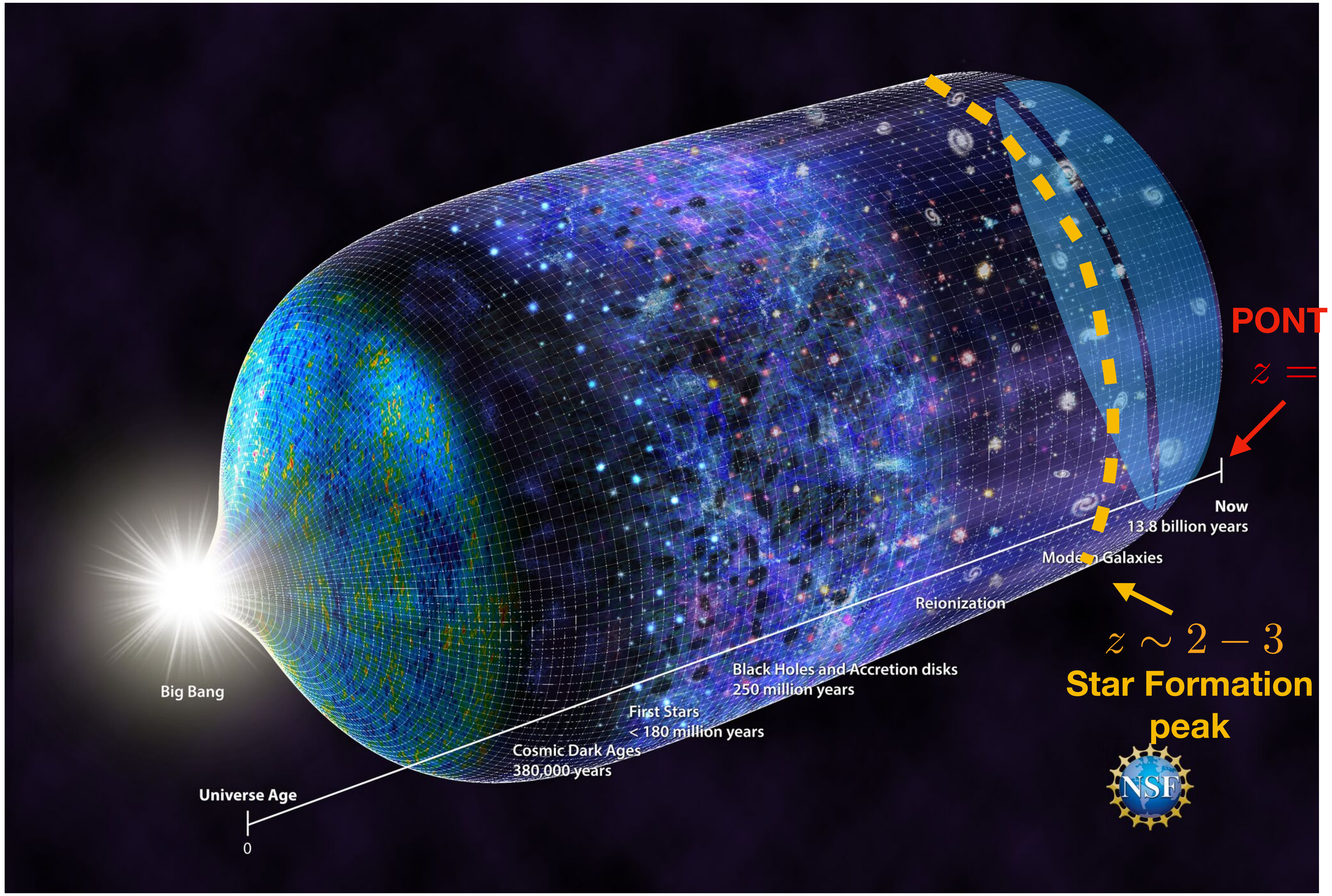
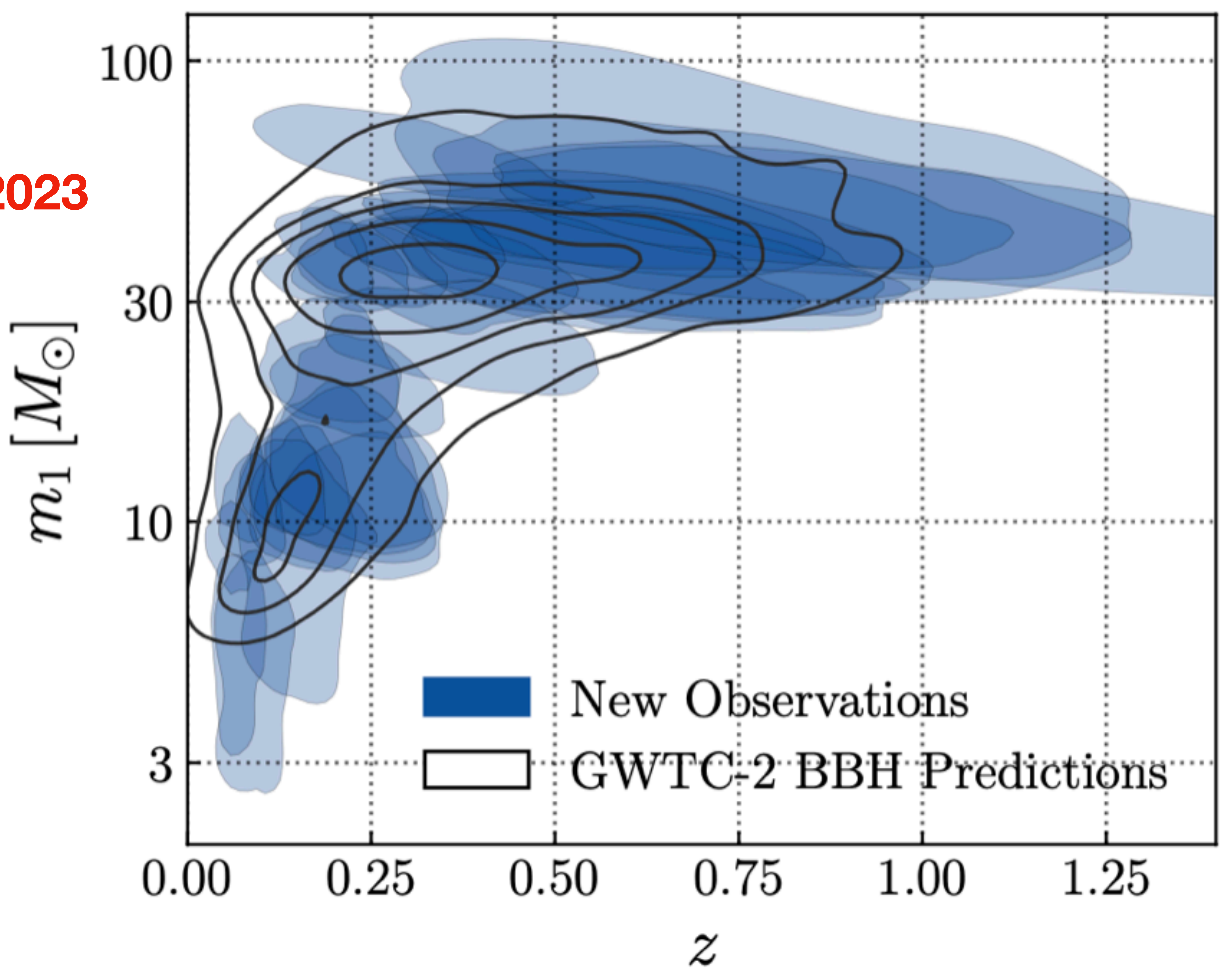
Cosmic history with GWs

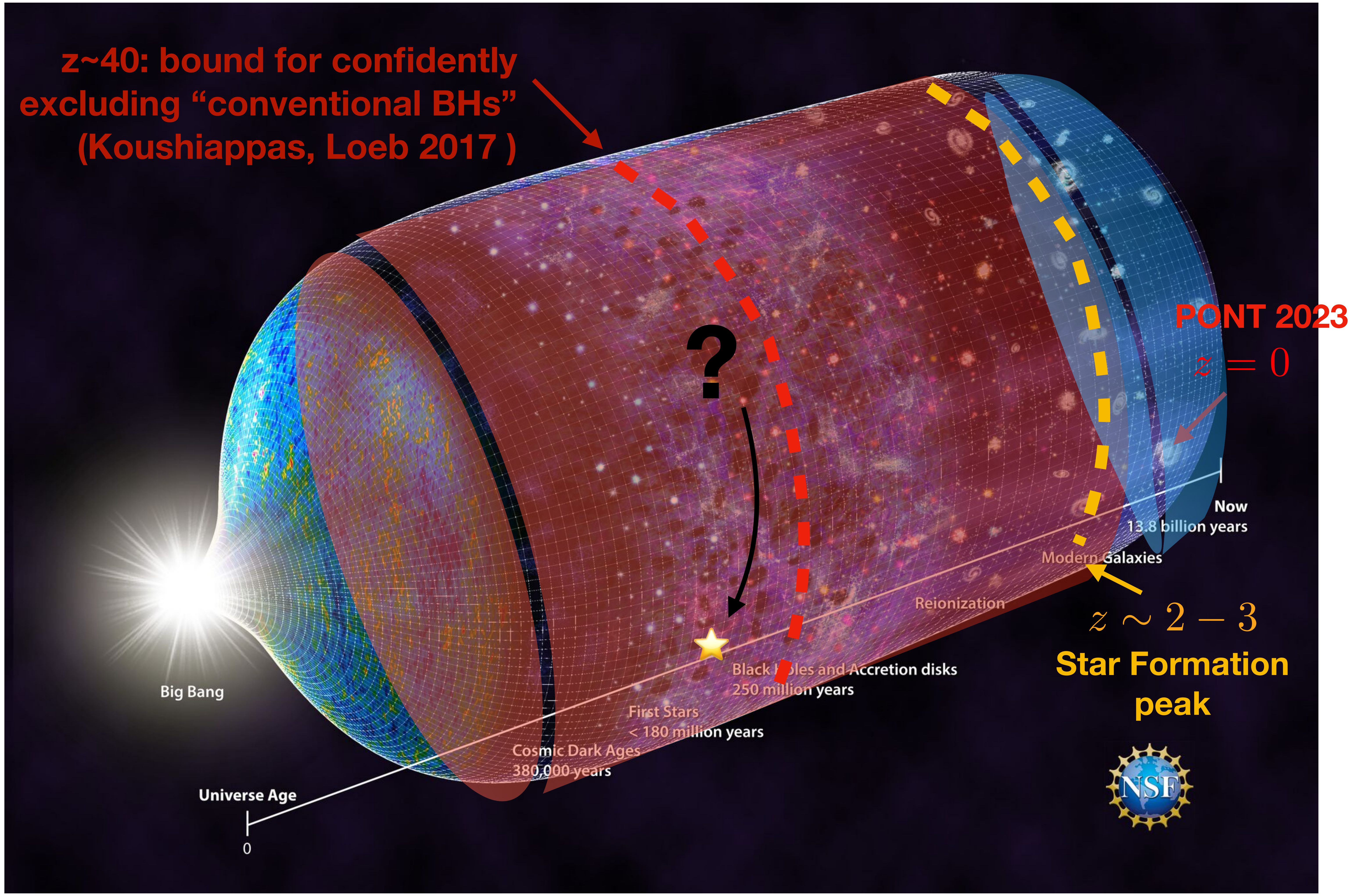


Redshift-mass distribution of new observations in GWTC-3 (LVK 2111.03634)



GWTC-3 reaches redshift ~1.2

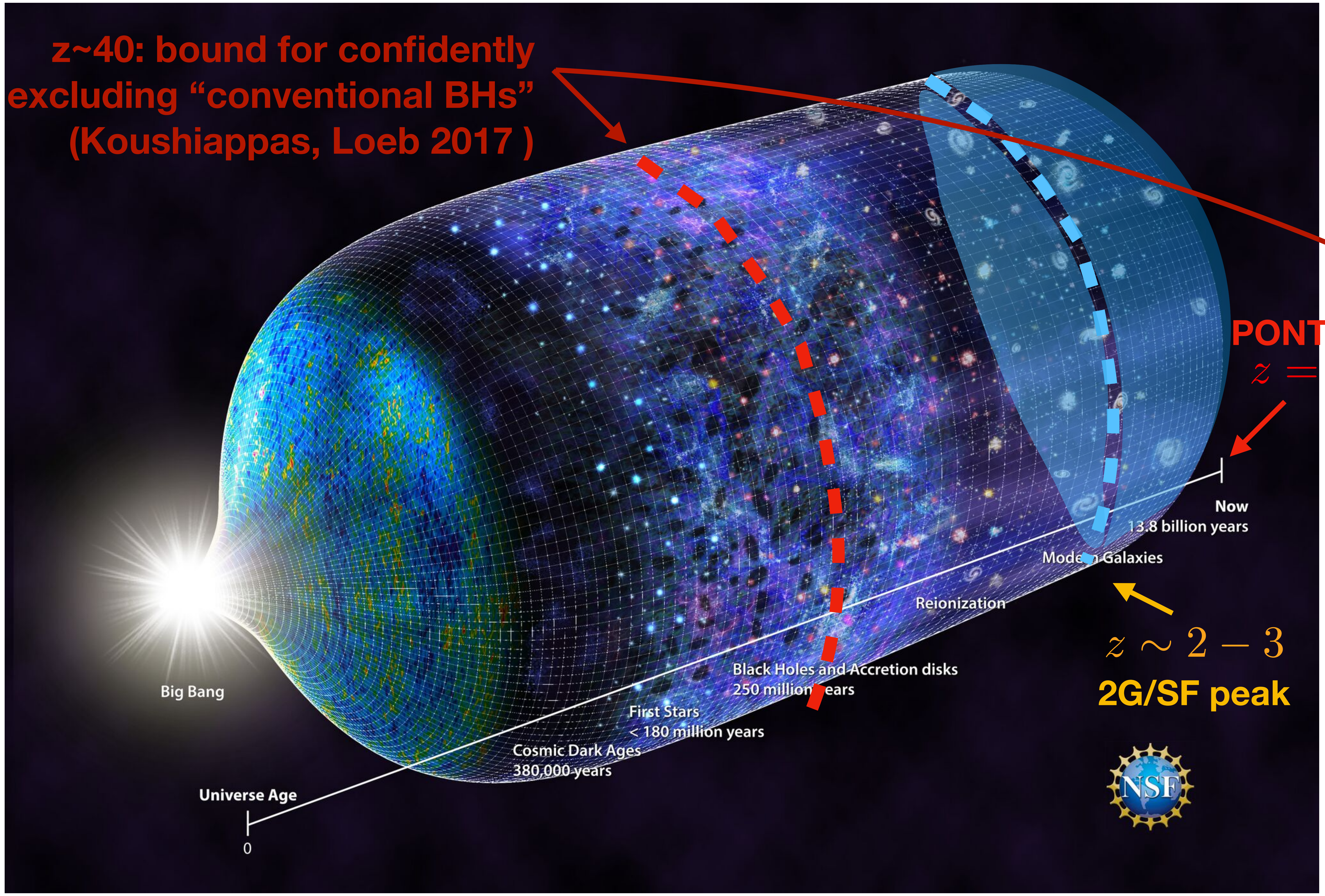
Cosmic history with GWs



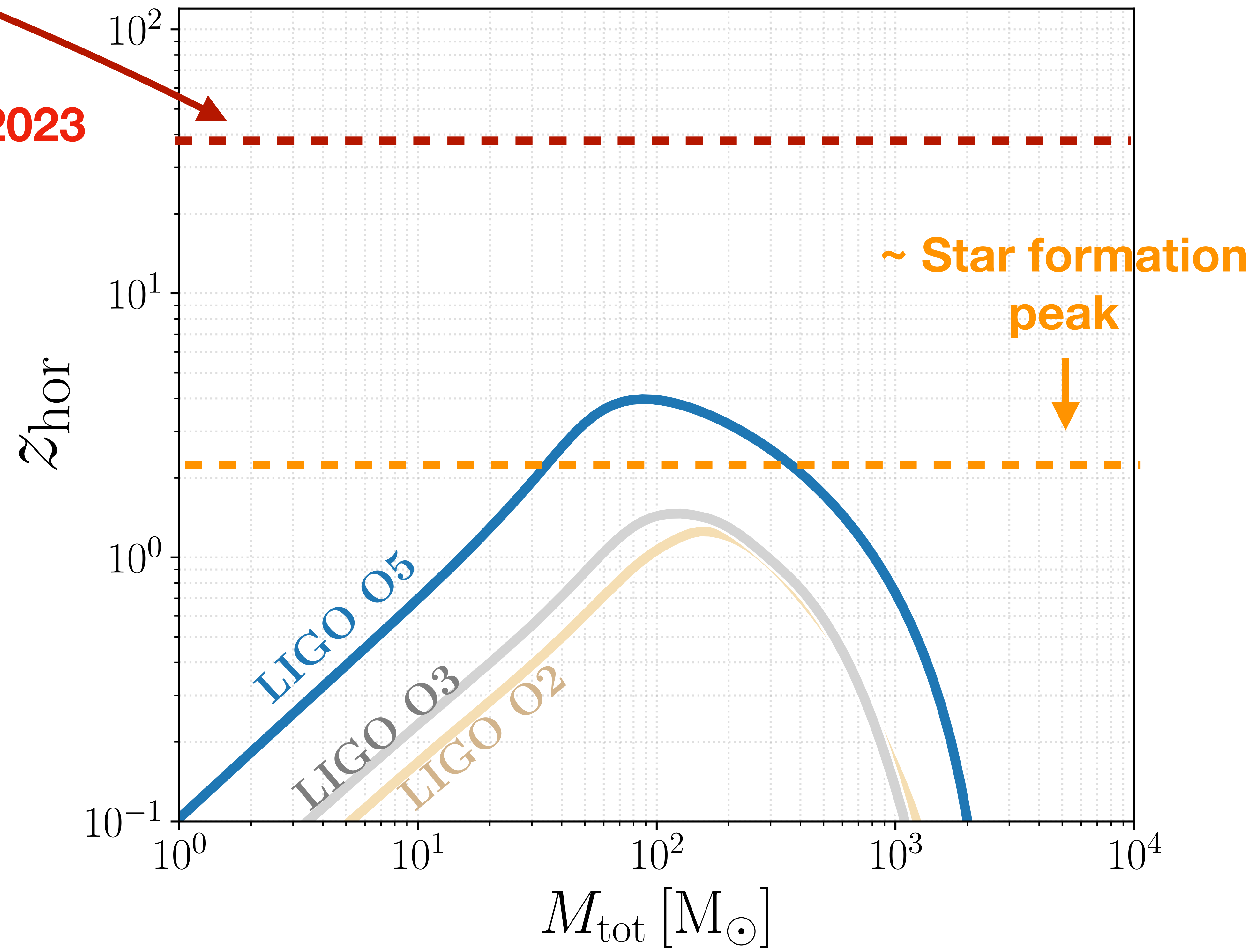
- The population of compact objects at high redshift is highly uncertain and provides a territory for potential revolutionary discoveries
  - Primordial Black Holes
  - Pop III stars
  - Origin of massive black holes
  - Cosmology
  - ?

What is the potential of GW observations of detecting and characterising sources at cosmological distances?

Cosmic history with GWs

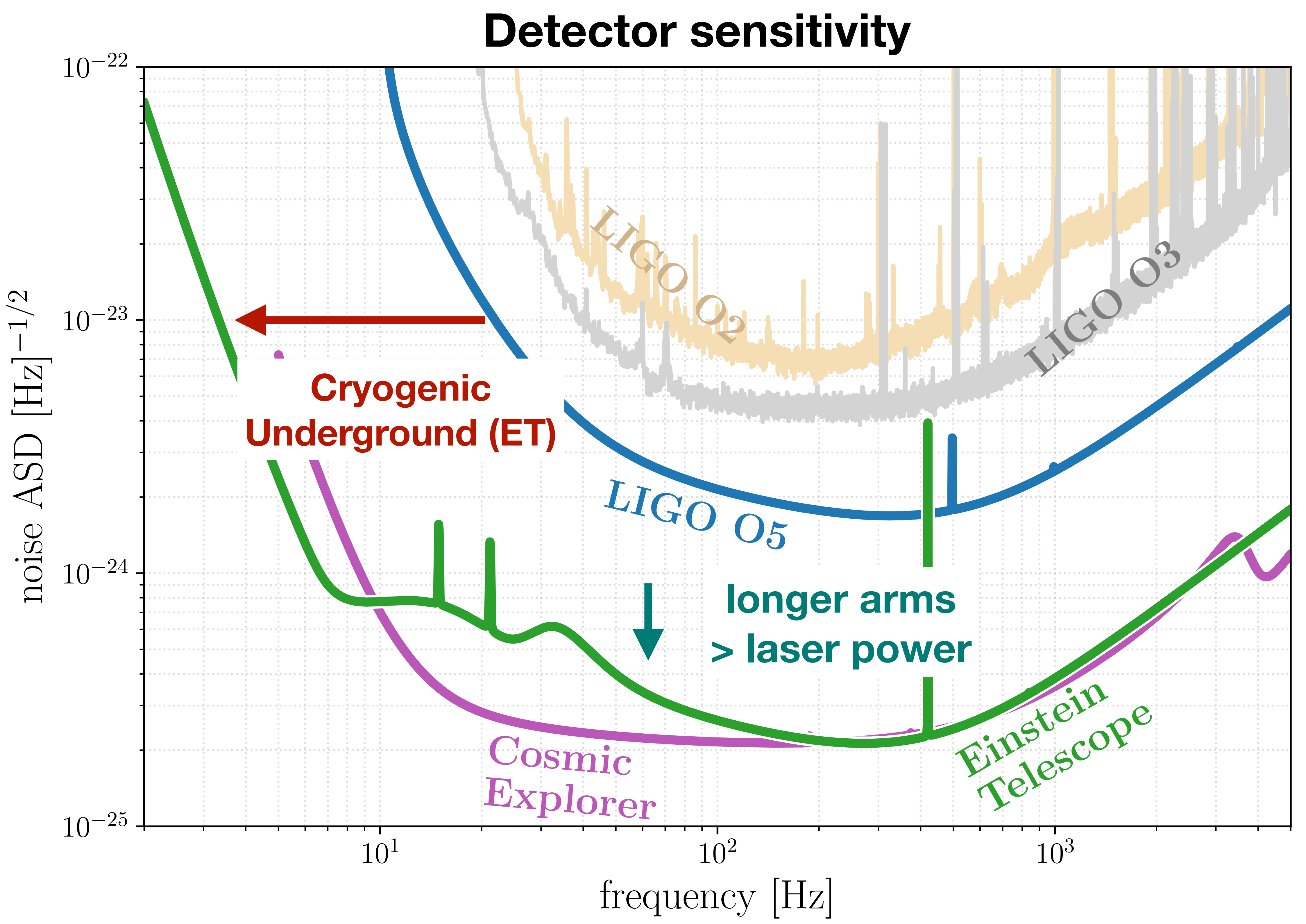


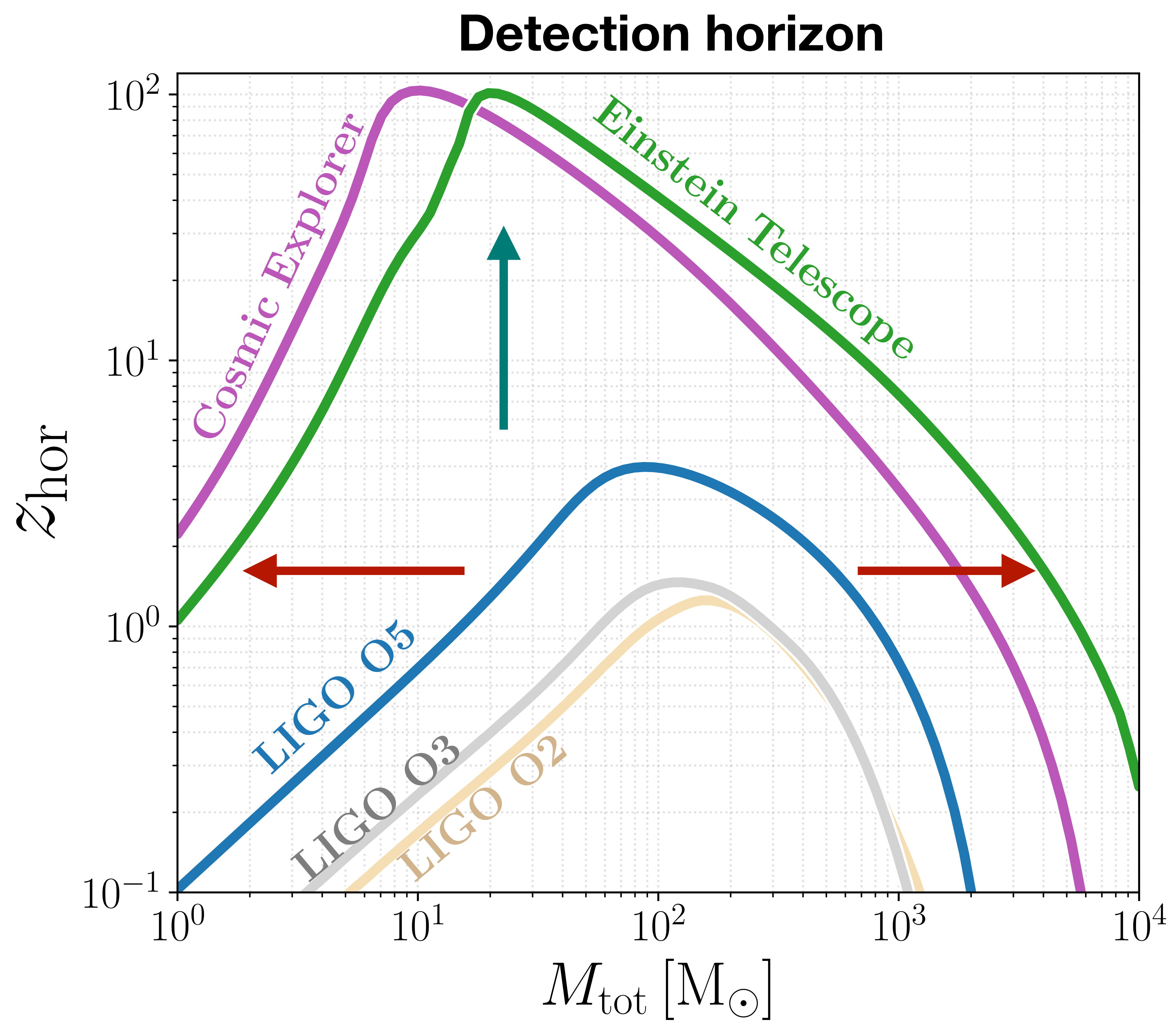
Detection horizon : largest redshift one could possibly detect a (equal mass, non-spinning, optimally-oriented, optimally-located) binary with given mass



LIGO/Virgo will cover cosmic history up to redshift ~a few

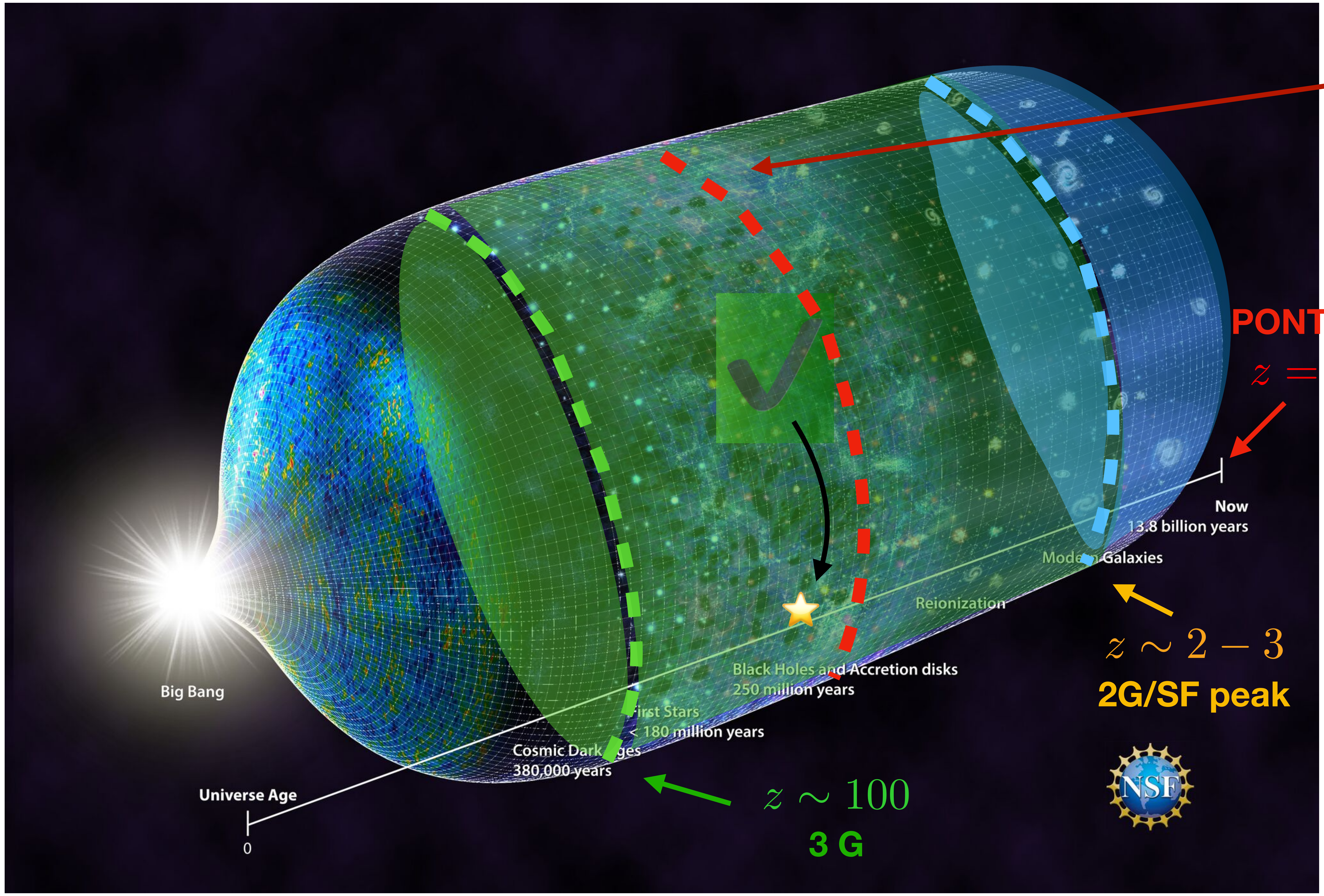
Larger horizons, larger bandwidths: 3G



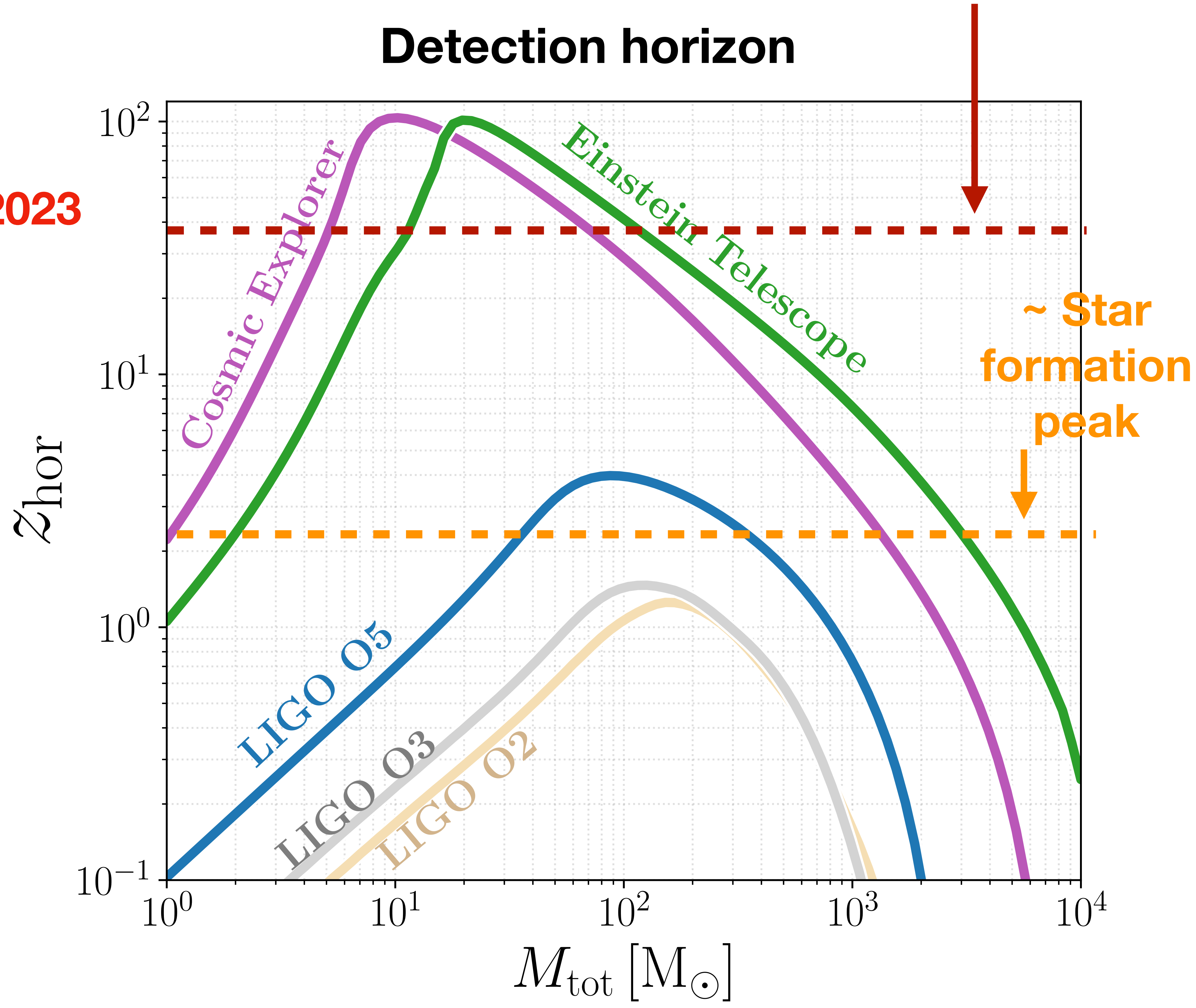


- Third-generation detectors: ~ 1 order of magnitude better sensitivity, larger frequency band. Larger horizons.
- **Einstein Telescope** in Europe. Pioneered the concept of 3G (Punturo + 2010). Conceived in 2010, included in the European Roadmap of Large Scientific Infrastructures in 2021. ET collaboration created in 2022.
- **Cosmic Explorer** in the U.S. CE white paper: Reitze + 2019

Cosmic history with GWs



z~40: bound for confidently excluding "conventional BHs" (Koushiappas, Loeb 2017)

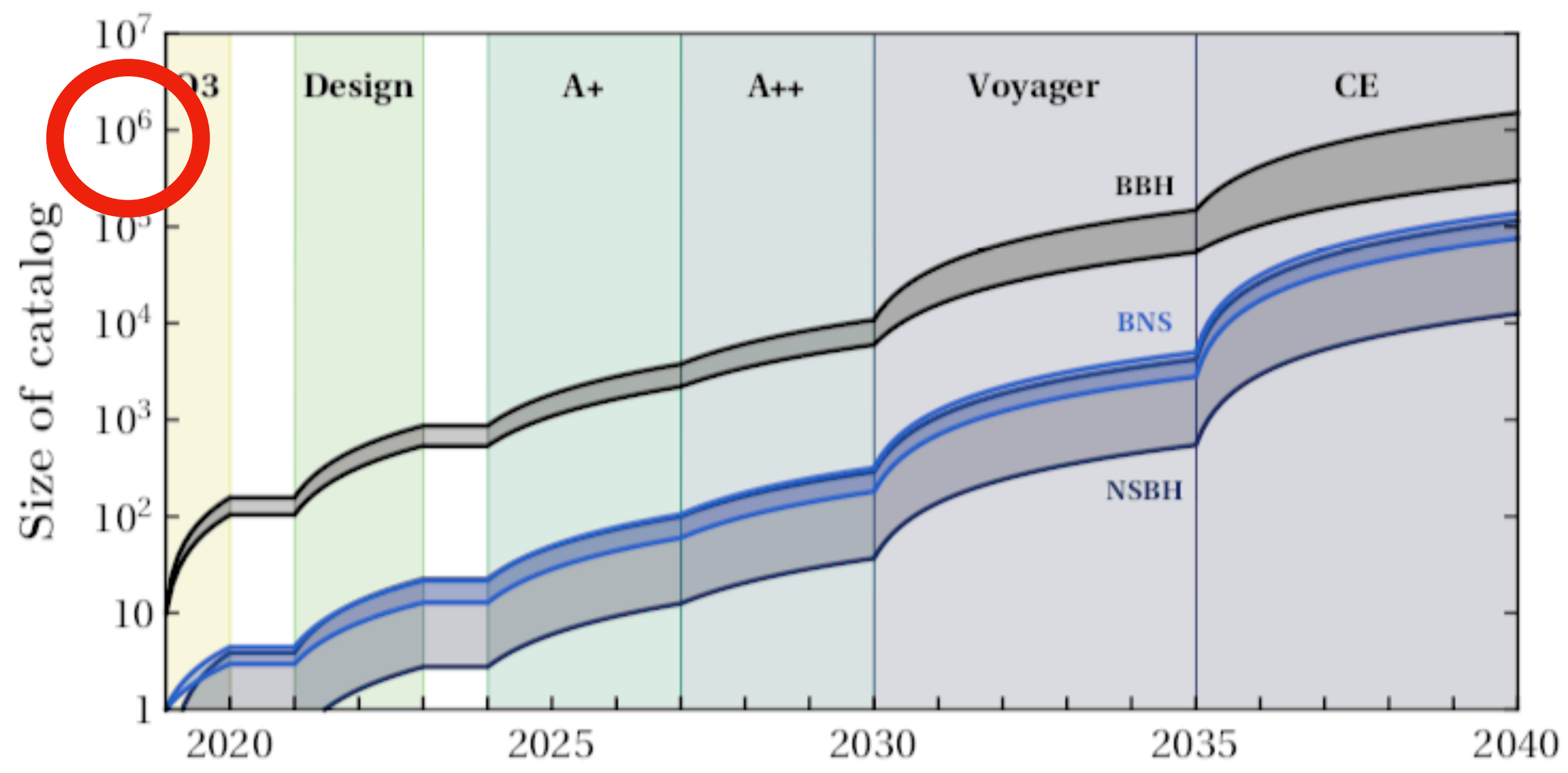


3G detectors can cover the entire star formation history and beyond

From great sensitivities come great challenges

Basic metrics for the 3G science cases:

- **Detection rates**: up to **10^5-10^6 detections/year** →
- Range and redshift distribution of detected events
- Accuracy in the reconstruction of the source parameters



- ~hrs to ~days for a single simulation (when feasible at all). Not affordable.
- **Fisher matrix** approximation = leading order expansion of the likelihood in 1/SNR (linear signal approximation)
- Covariance of the posterior probability: $\mathrm{Cov}_{ij} = \Gamma^{-1}_{ij}$

GW SIGNAL

$$\Gamma_{ij} \equiv \left(\frac{\partial h}{\partial \theta_i} \middle| \frac{\partial h}{\partial \theta_j} \right)_{\theta=\hat{\theta}}$$

PARAMETERS (MASS, DISTANCE, …)

- **Collective effort in the 3G community**: develop different Fisher codes. **Cross-validated** within ET

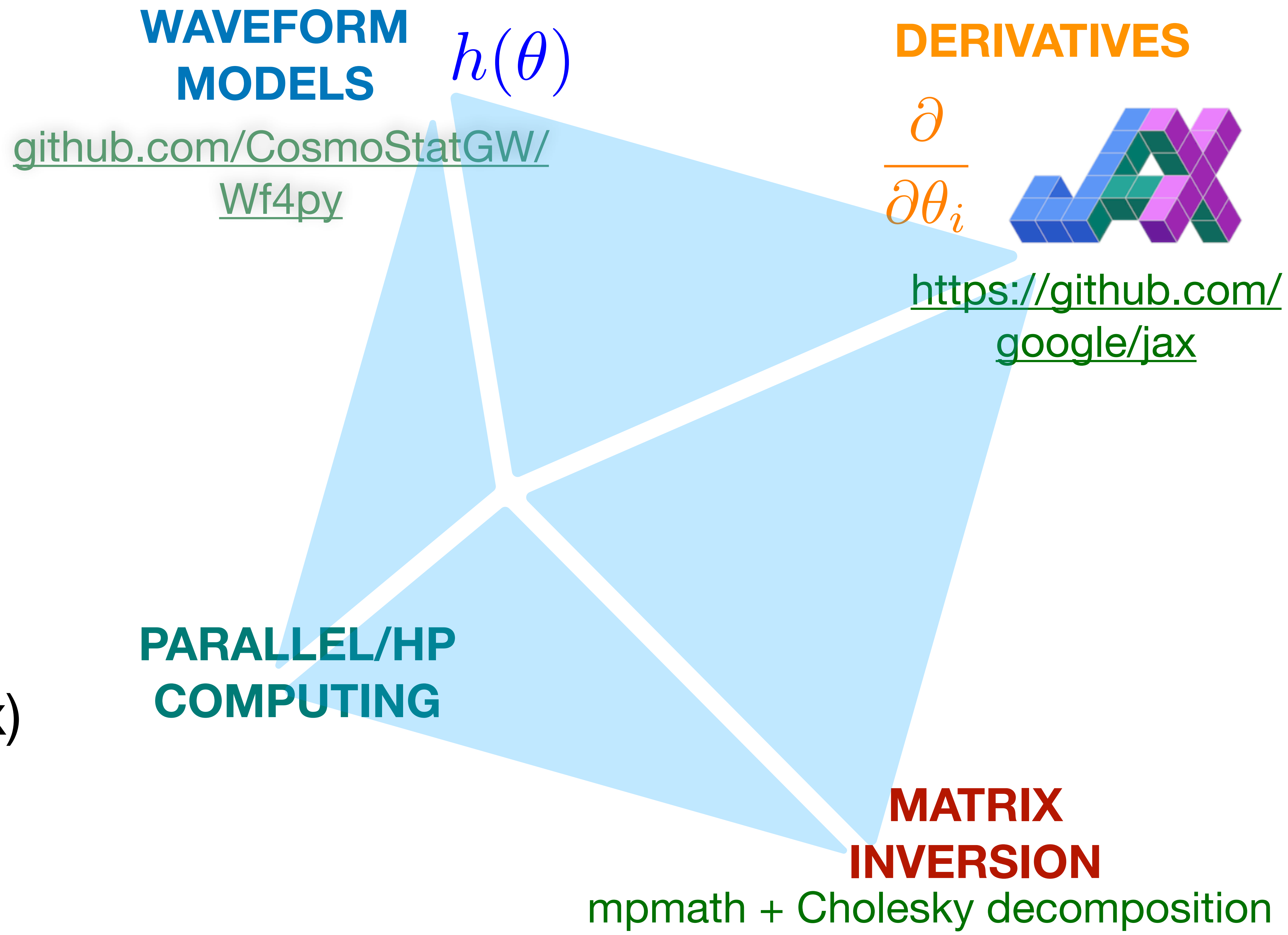
gwbench Borhanian 2021 (UPenn)	**gwfish** Harms + 2022 (GSSI)	**gwfast** Iacovelli + 2022 (Geneva)	**TiDoFM** Li + 2022	Pieroni + 2022

GWFAST

Iacovelli, Mancarella, Foffa, Maggiore APJS 2022

github.com/CosmoStatGW/gwfast

$$\mathrm{Cov}_{ij} = \Gamma^{-1}_{ij} \qquad \Gamma_{ij} = \left(\frac{\partial h}{\partial \theta_i} \middle| \frac{\partial h}{\partial \theta_j} \right)_{\theta=\theta_0}$$

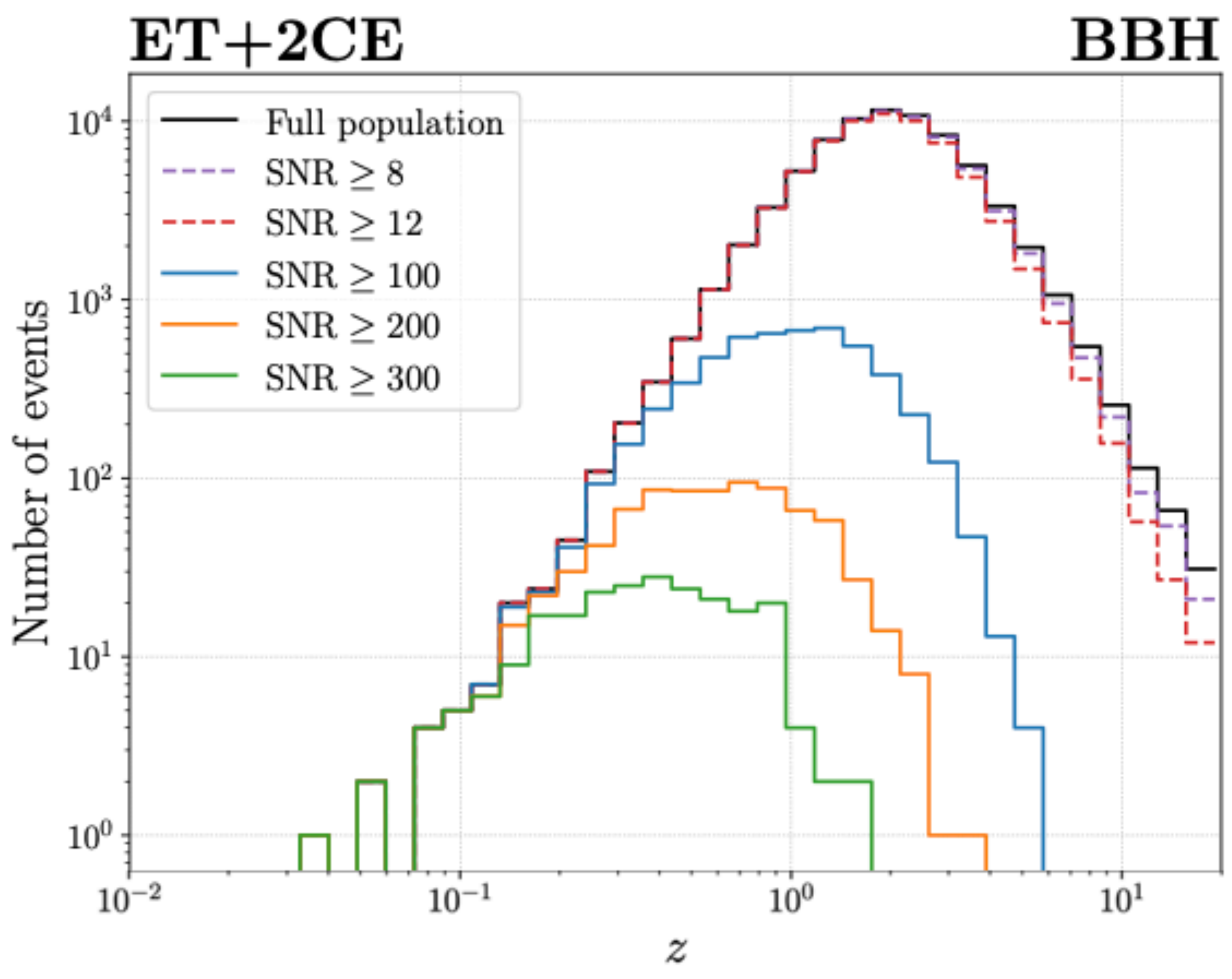


- **Differentiable waveforms** in *python*. Also useful for fast bayesian inference: full PE in ~minutes? see Wong+2023, “TurboPE"
- **Automatic differentiation with jax** (library from Google): derivatives at machine precision see Campagne+2023, "JAX-COSMO" for cosmology
- **Parallel computing + single-CPU vectorization**. Directly usable on GPUs with JIT compilation. (Not possible without jax)
- PE for 10^5 events in < 1 day

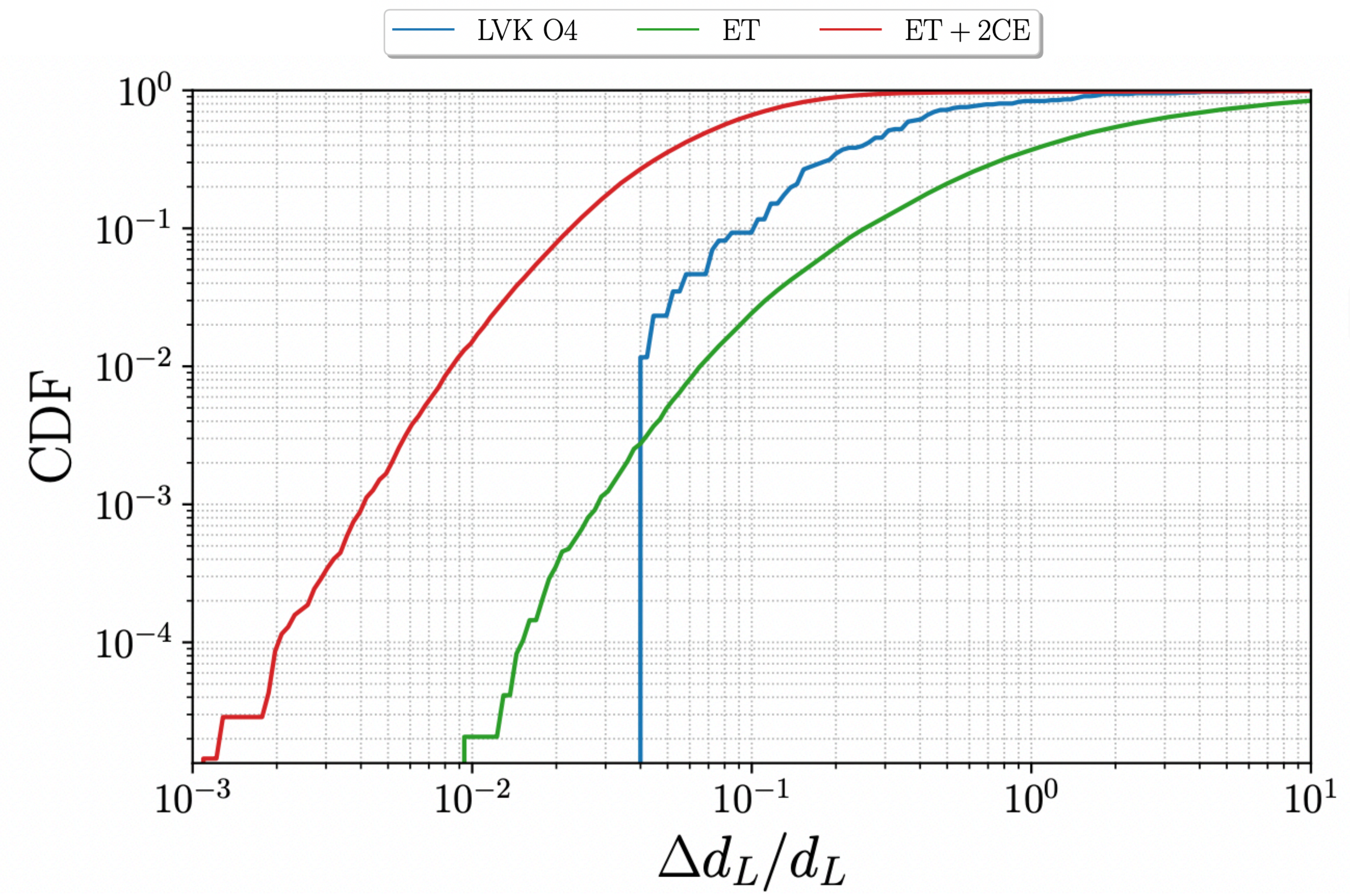
Detection prospects

Answer from the basic metrics for the 3G science cases:

~full population detected…



… with exquisite accuracy on distance reconstruction



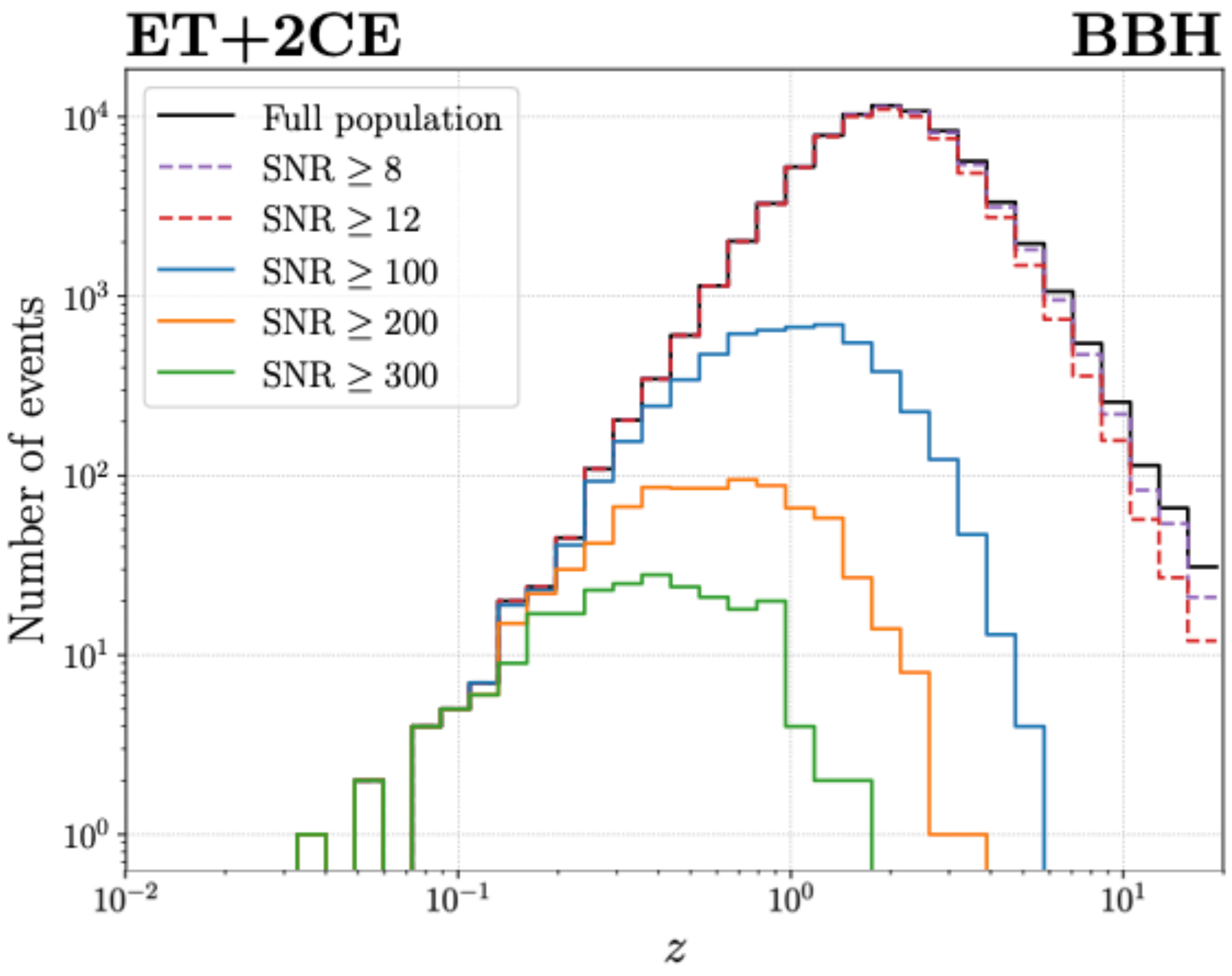
- Reference (triangular) ET design, BBH population = best-fit model from LVK — Iacovelli, Mancarella, Foffa, Maggiore APJ 2022
- For comparison of different designs and broad range of science cases see Branchesi, Maggiore et al. 2303.15923

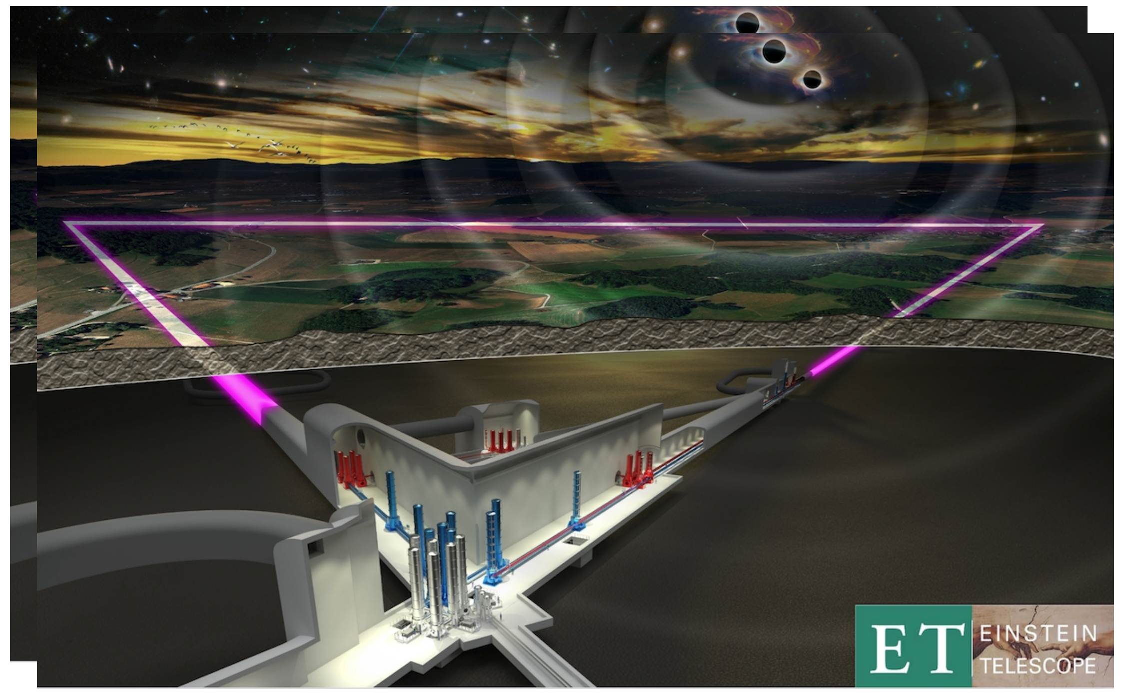
80+ authors, 200+ pages, 6 detector configurations, 3 noise curves, many specific science cases. Massive usage of *gwfast*

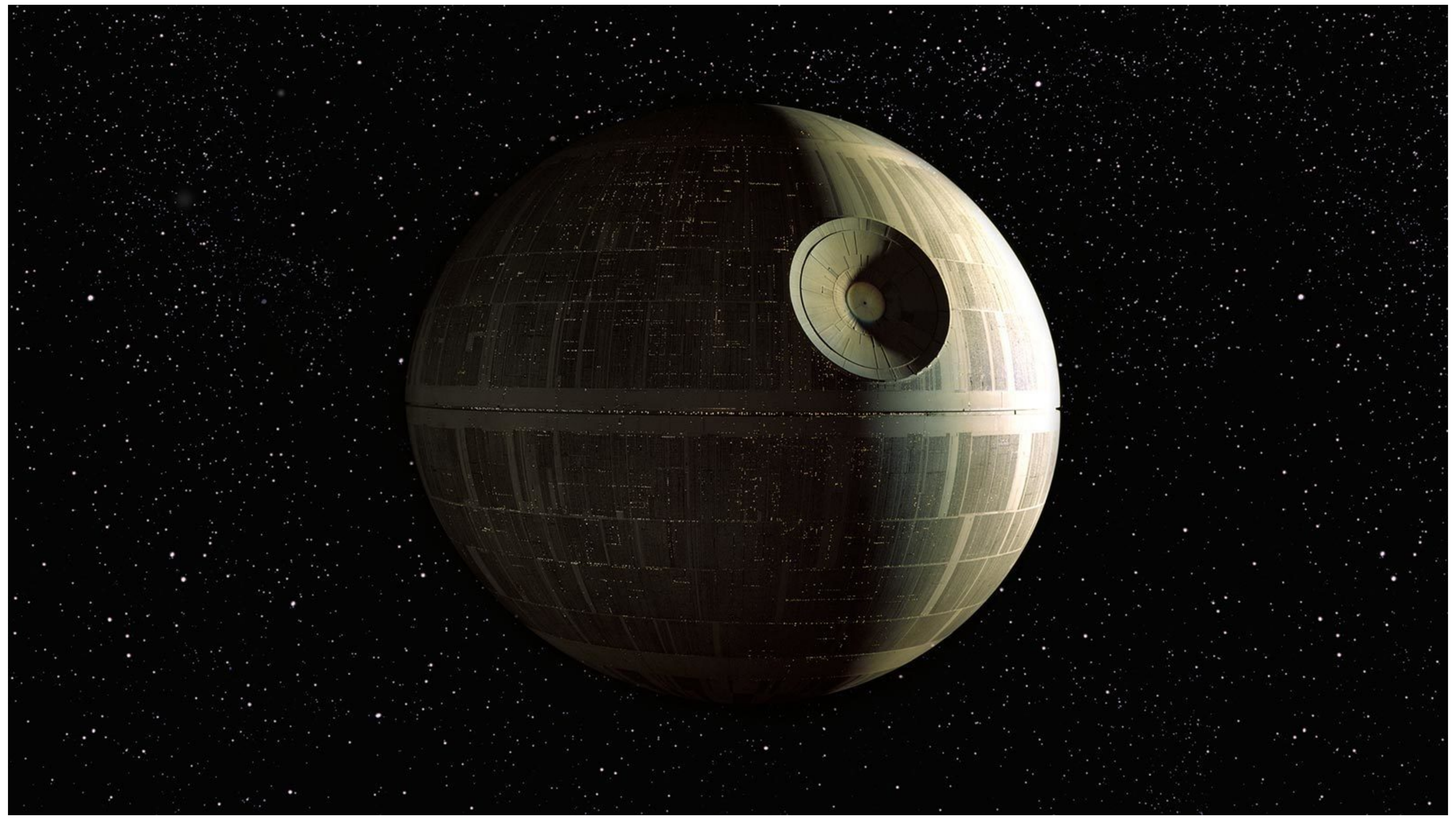
Detection prospects

“Is this the ultimate machine?”

(question asked during a talk after seeing this plot)



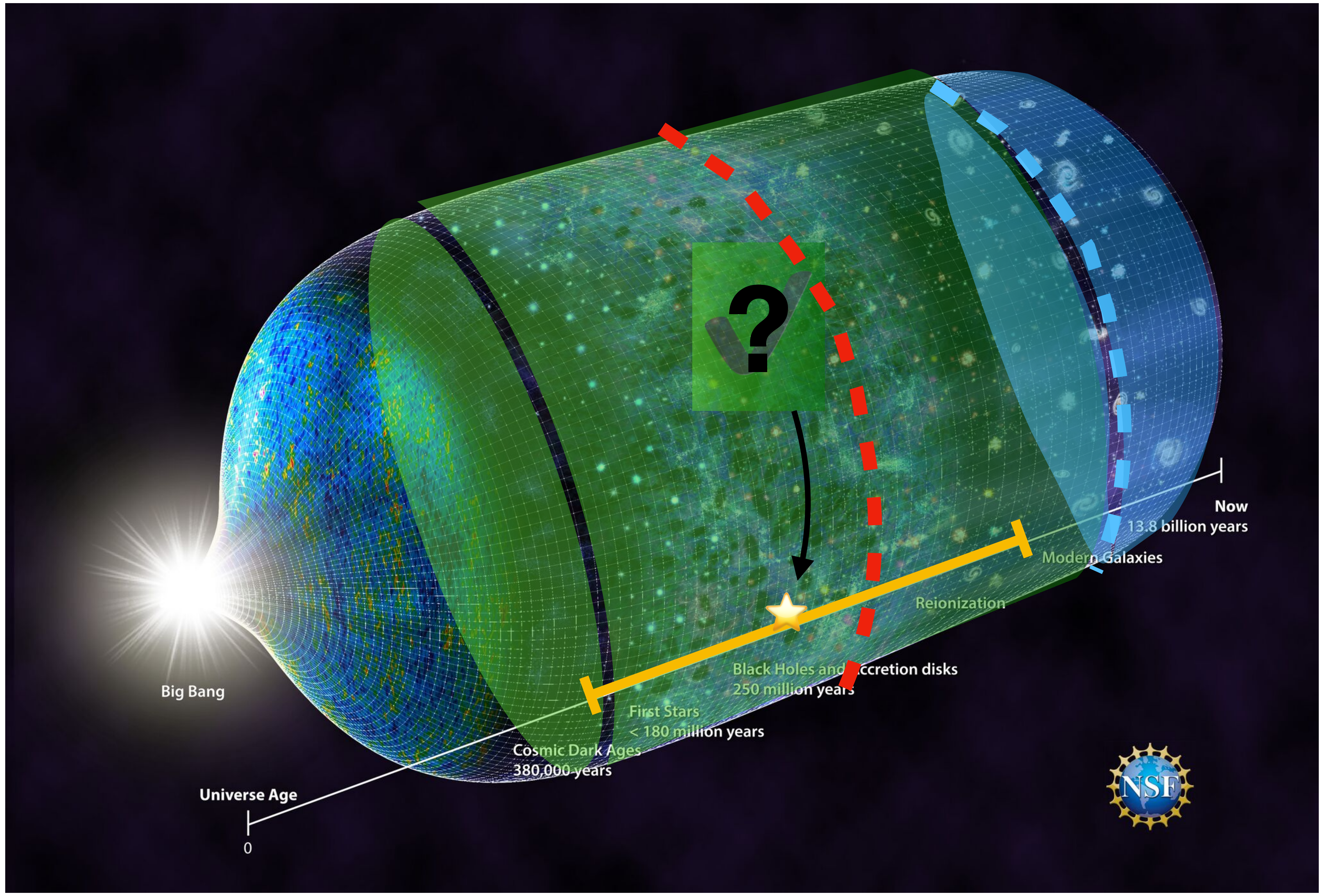




Inference prospects

- Basic metrics for the 3G science case :
  - Detection rates
  - Range and redshift distribution of detected events
  - **Accuracy in the reconstruction of the source parameters** →

Detecting does not mean **knowing** that the source is actually there



$$\text{Error} \propto \frac{1}{\text{SNR}} \propto \text{distance}$$

- Distant sources are most difficult to localise
- Simulations on single sources: unlikely to get constraints better than ~10% for sources at z>10

Ng et al. APJL 2022, 2108.07276
Ng et al. PRD 2023, 2210.03132

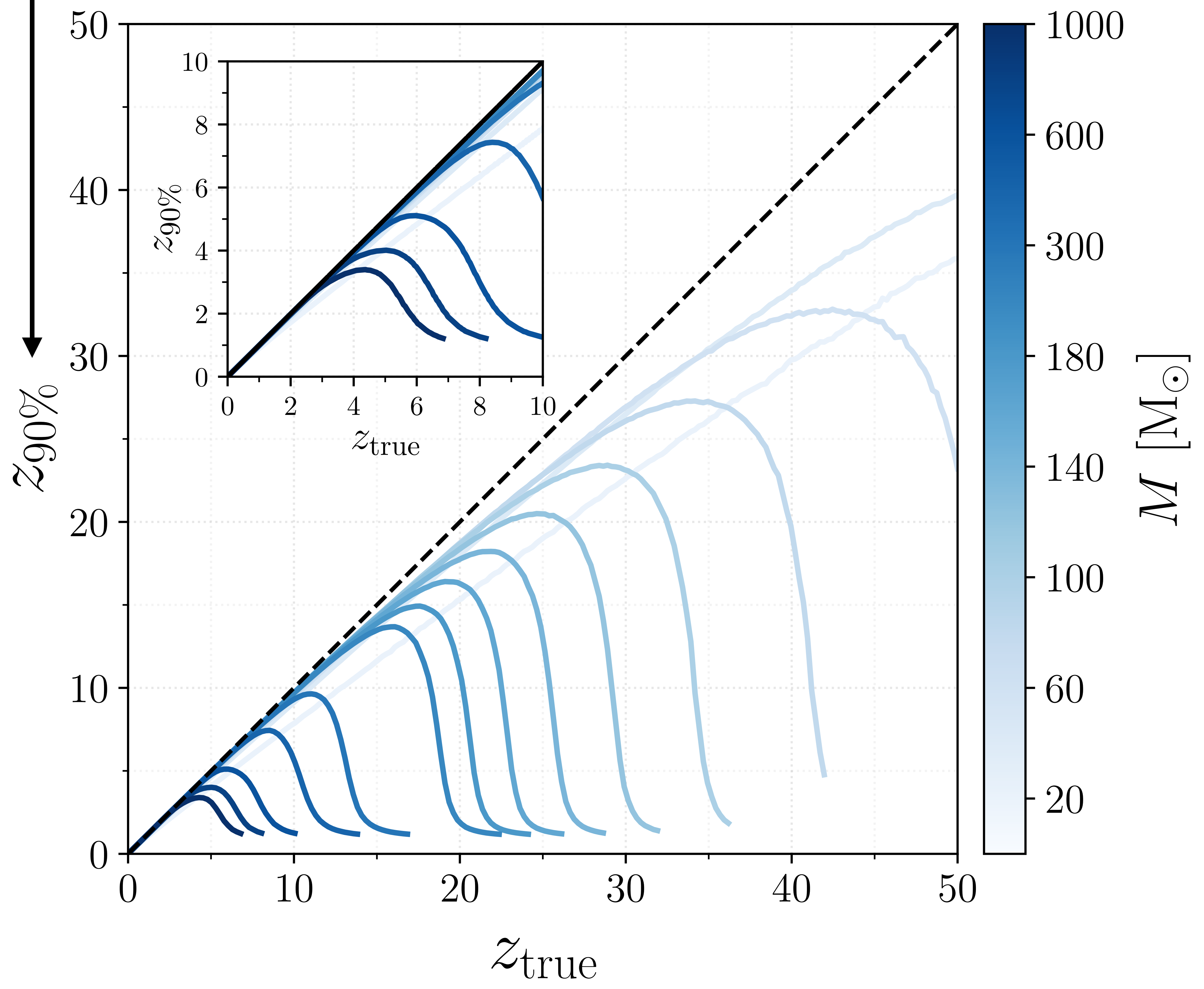
what is the correct figure of merit for the confidence of a high-redshift detection?

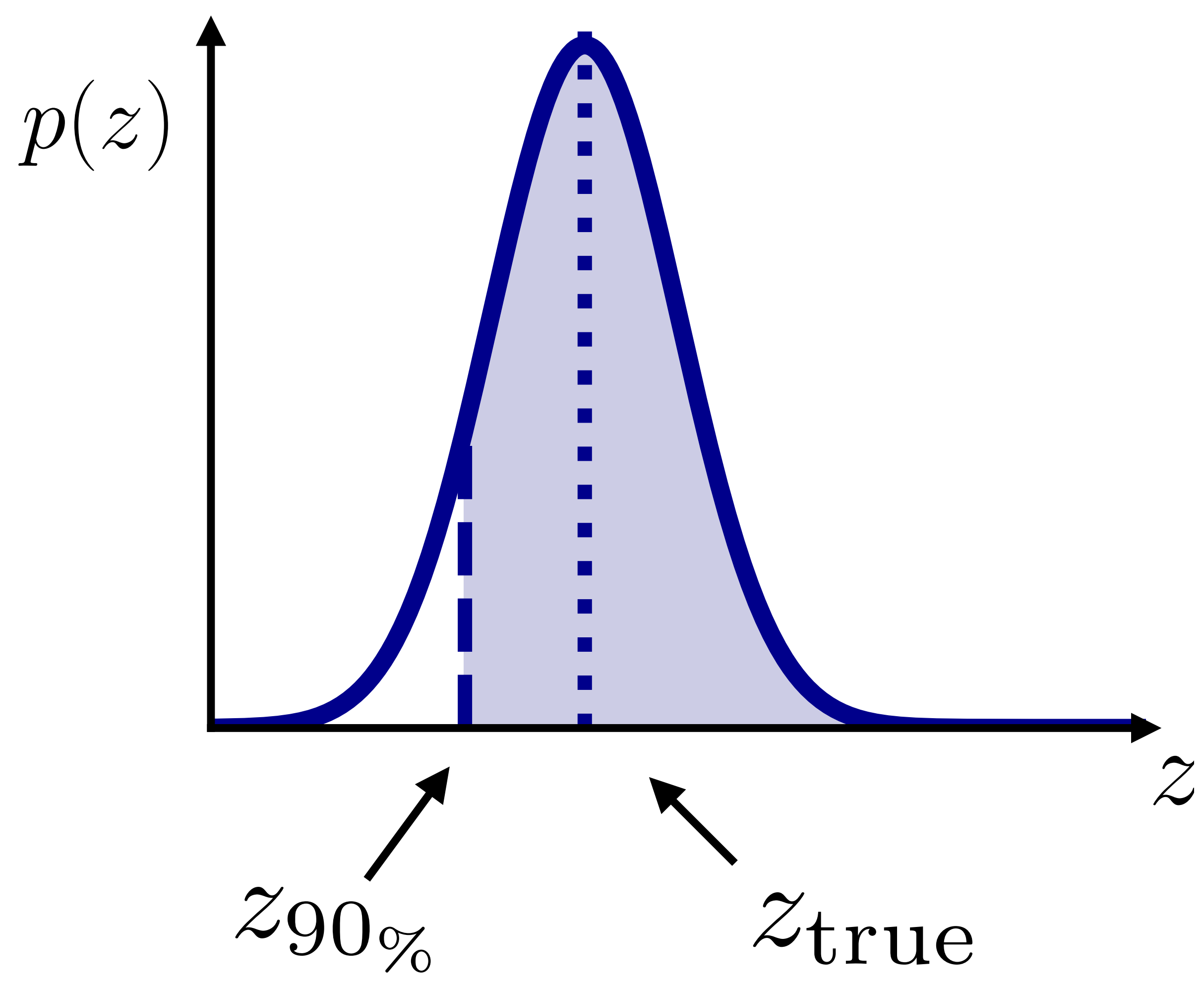
Inference metrics

Mancarella, Iacovelli, Gerosa, PRD Lett. 2023, 2303.16323

LOWER 90% BOUND ON THE REDSHIFT →

$$P\left(z \geq z_{90\%} | z_{\rm true}, \bar{\theta}\right) = \int_{z_{90\%}}^{\infty} p\left(z | z_{\rm true}, \bar{\theta}\right) {\rm d}z = 0.9$$

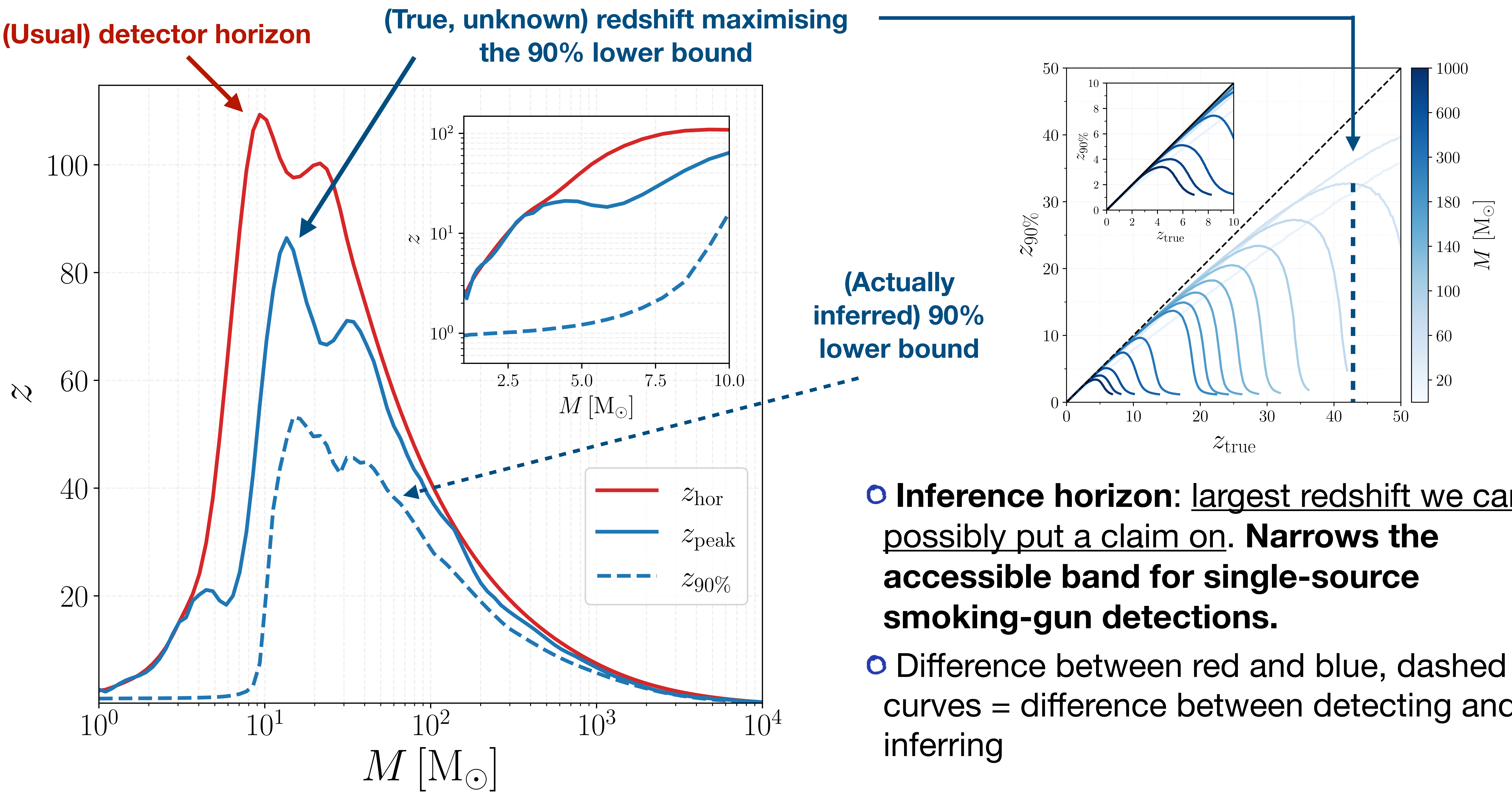




- The good quantity to look at is not the true (unknown!) redshift of the source, but the lower (e.g. 90%) credible interval, e.g. $z_{90\%}$

Inference horizon or detector horizon?

Mancarella, Iacovelli, Gerosa, PRD Lett. 2023, 2303.16323



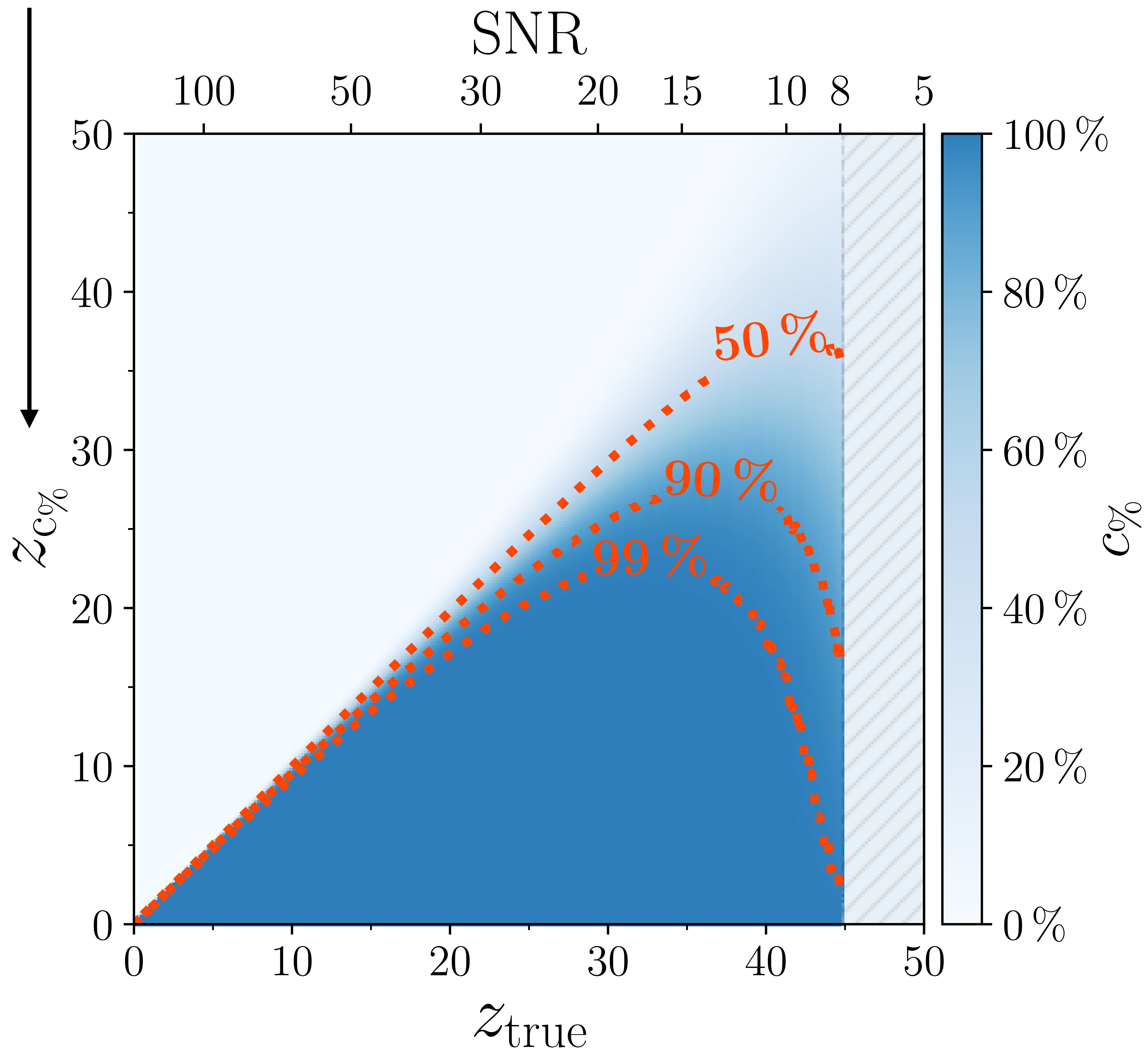
- **Inference horizon**: <u>largest redshift we can possibly put a claim on</u>. **Narrows the accessible band for single-source smoking-gun detections.**
- Difference between red and blue, dashed curves = difference between detecting and inferring

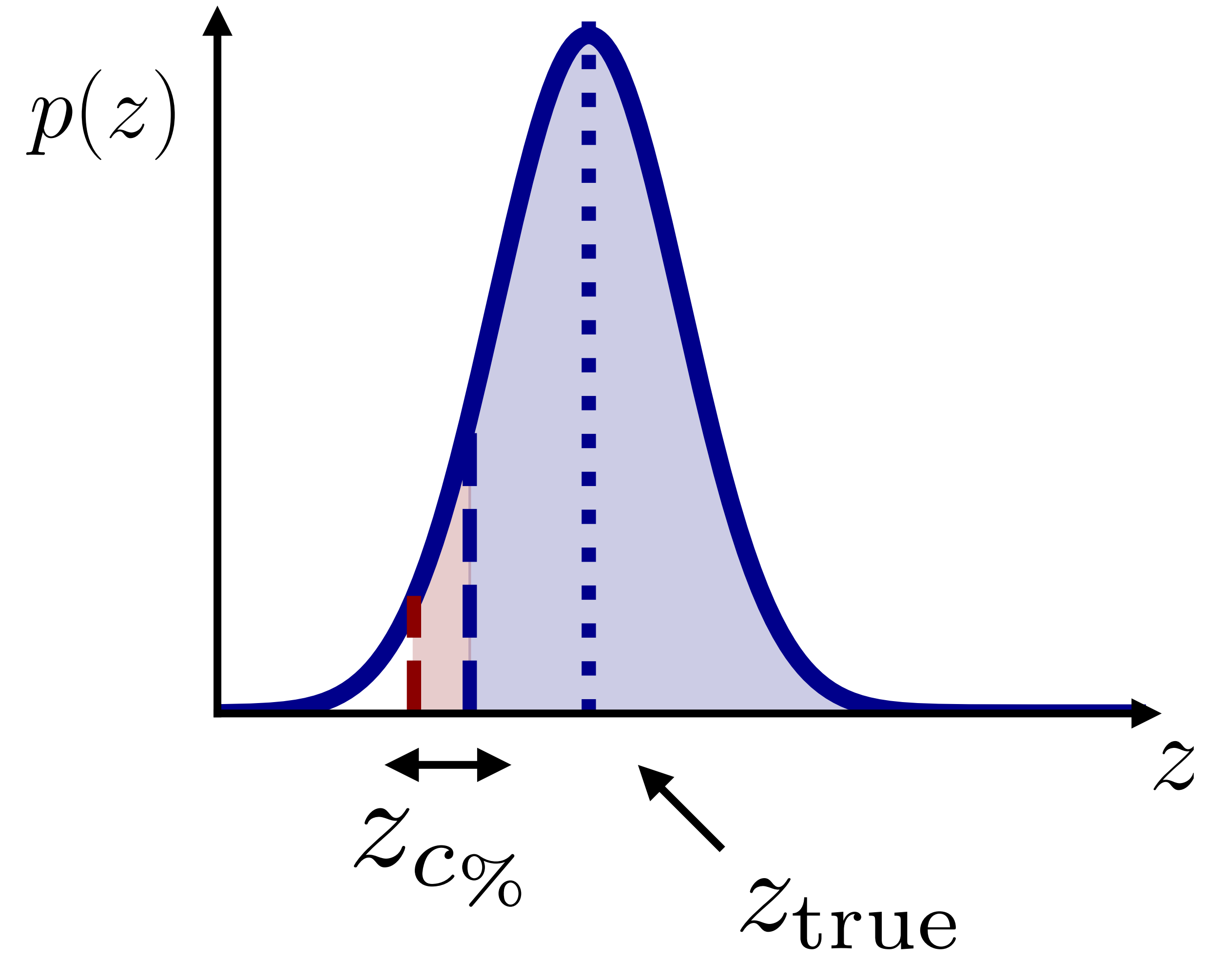
"z-z plots"

Mancarella, Iacovelli, Gerosa, PRD Lett. 2023, 2303.16323

LOWER BOUND ON THE REDSHIFT AT c% C.I. →

$$P\left(z \geq z_{c\%}\,|z_{\rm true}, \bar{\theta}\right) = \int_{z_{c\%}}^{\infty} p\left(z|z_{\rm true}, \bar{\theta}\right) \mathrm{d}z = \frac{c}{100}$$

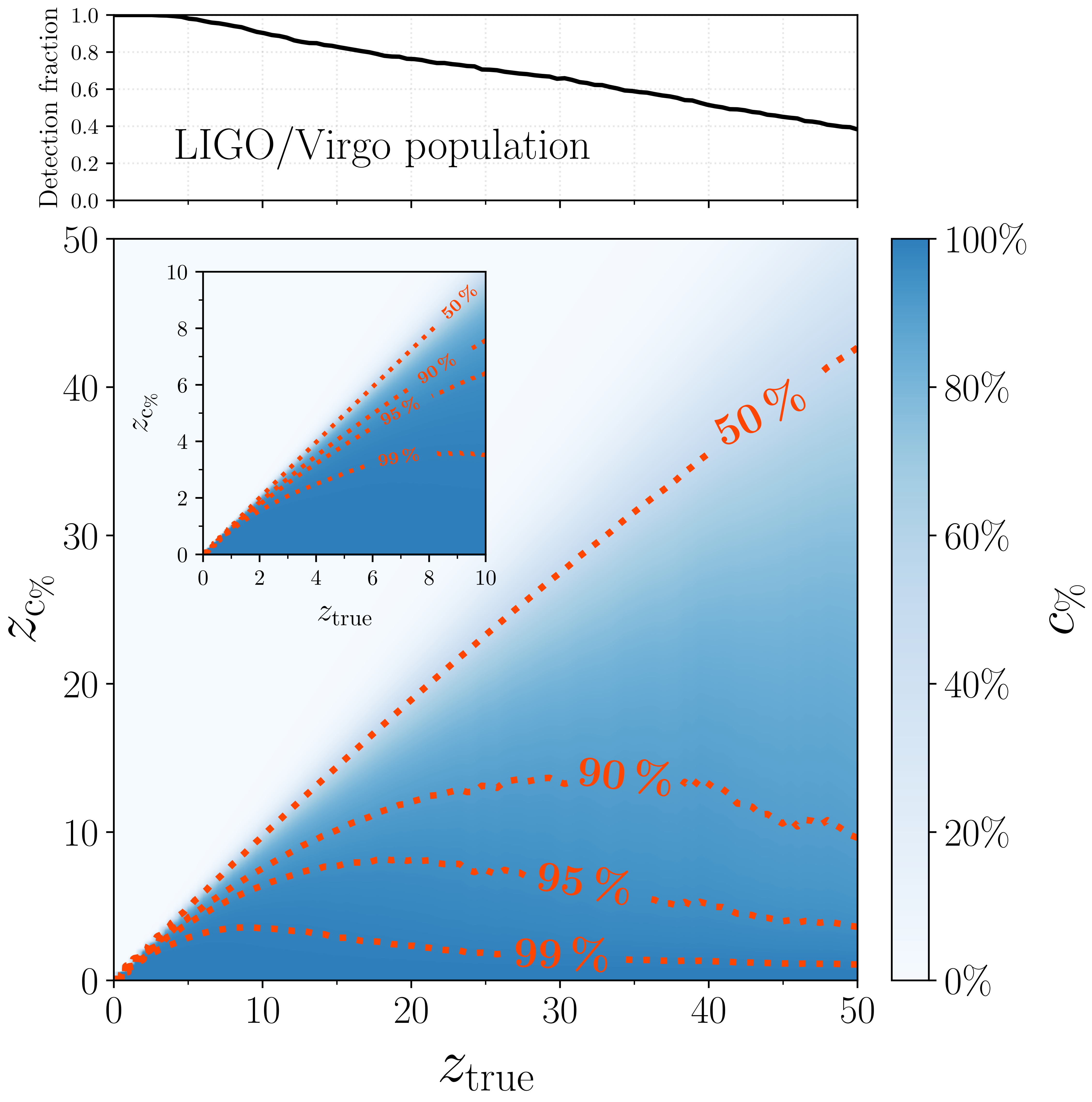




- GW150914-like source, fixed parameters
- Meaning: if the source was at z~35, ET+2CE would only be able to tell that it is at z > 20 at 99% C.L.

"z-z plots"

Mancarella, Iacovelli, Gerosa, PRD Lett. 2023, 2303.16323

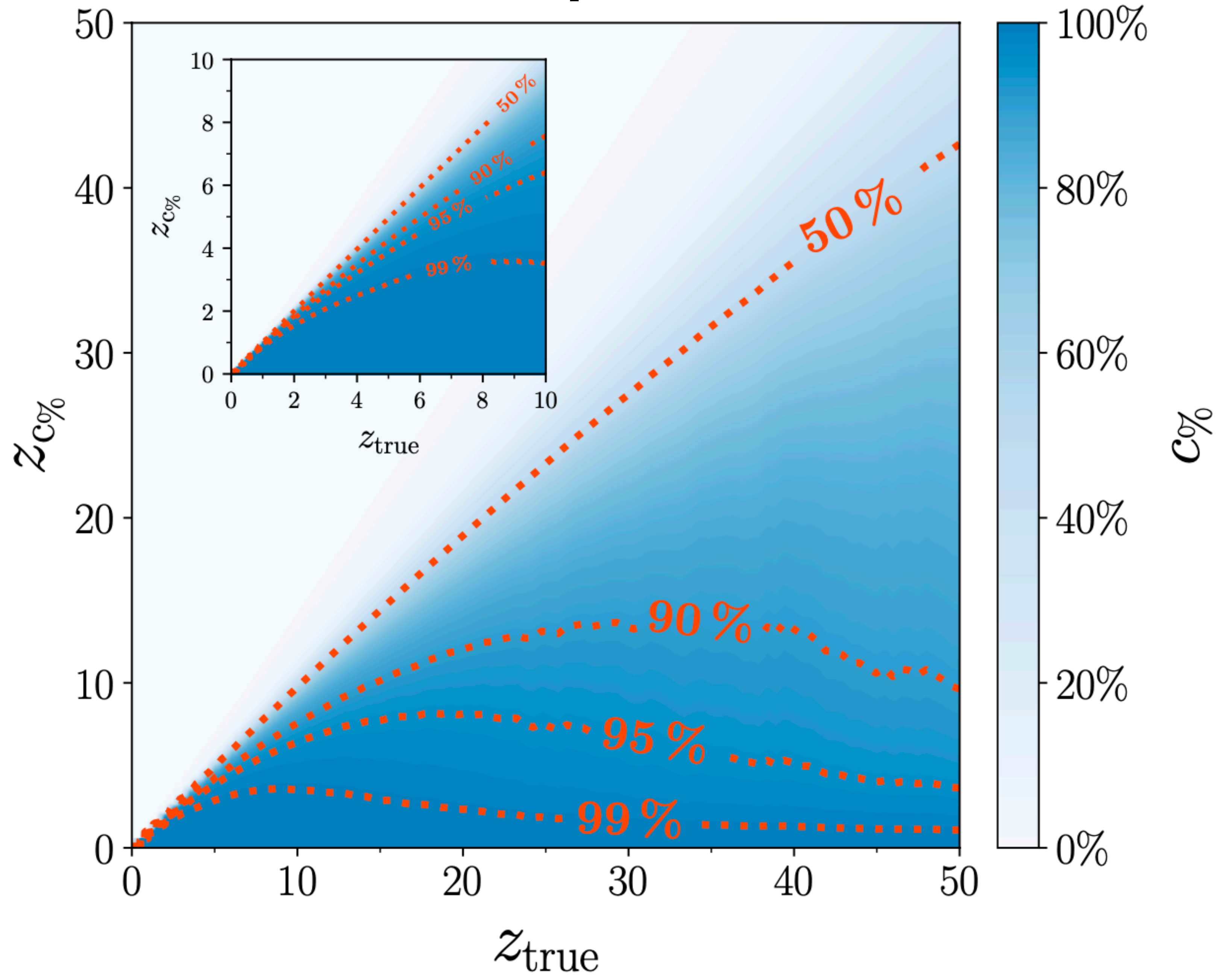


- Averaged on detected population, extrapolating LVK constraints (robust to variations)
- On average, it will be **challenging to put a claim on the primordial origin with single-event detections**. Population studies might be the way?

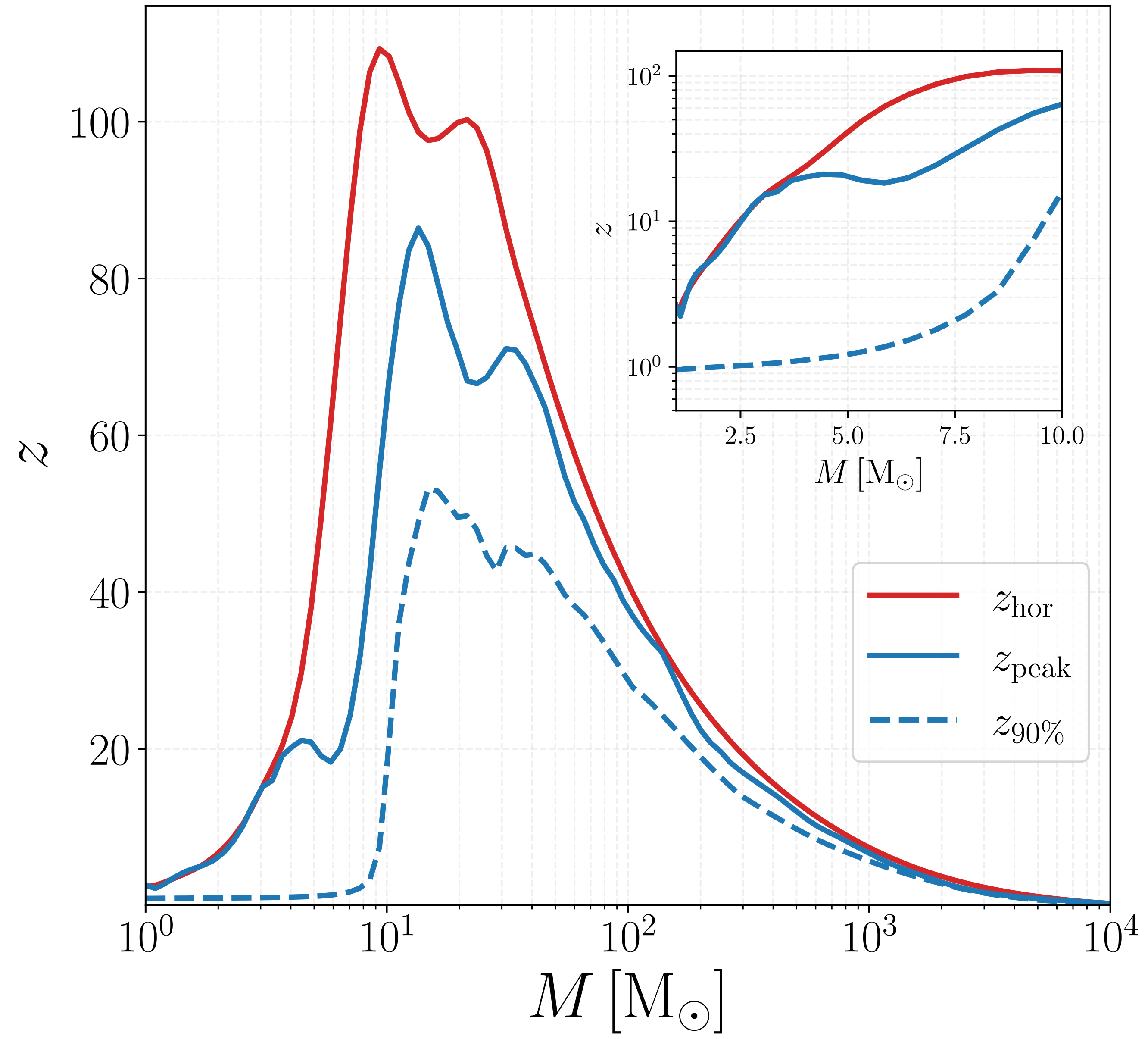
Summary

github.com/CosmoStatGW/gwfast

z-z plot

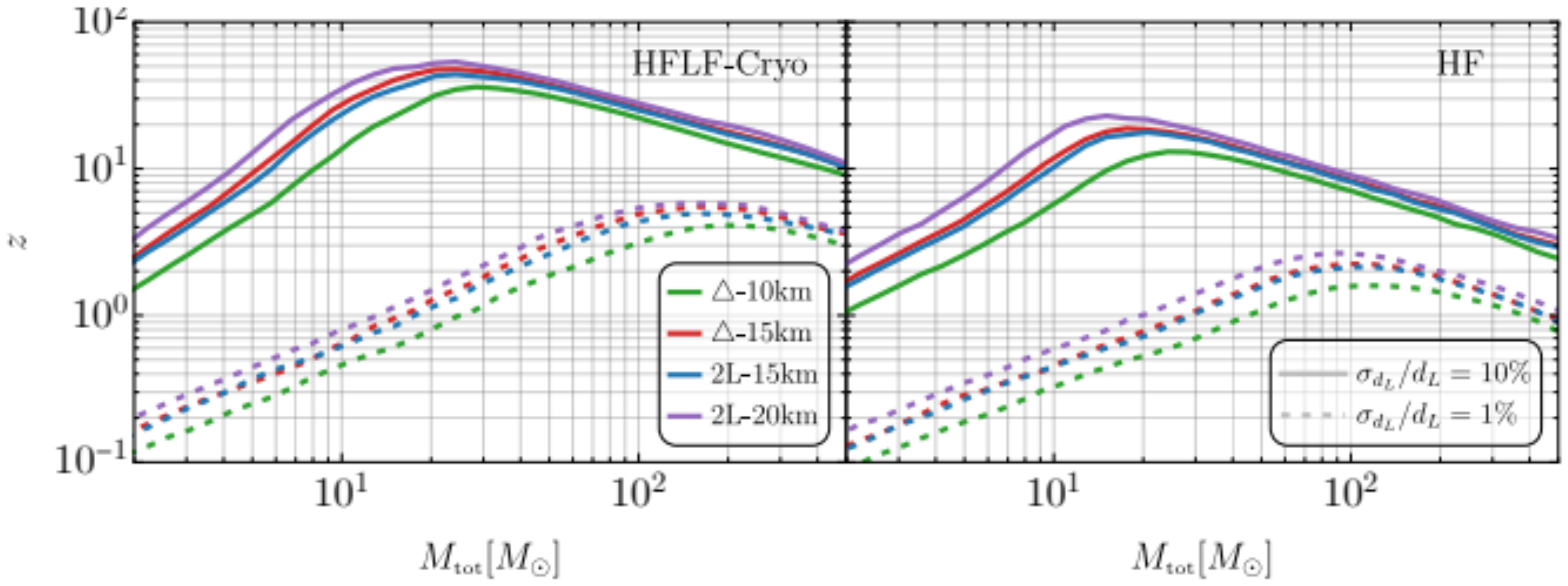


Inference horizon



- Detecting the full population of compact objects = science driver of 3G detectors
- *gwfast*: a forecast tool at the interface with other active research domains in GW data analysis (WF models in python, GPU, fast inference). Recent extensive study by the ET OSB.
- Detecting does not mean inferring that the source is actually there: *z-z* plots and inference horizon as realistic metrics. Confidently ruling out “conventional" star formation scenarios will be challenging with single sources

Horizon for well-localised sources



Franciolini, Iacovelli, Mancarella, Maggiore, Pani, Riotto, 2304.03160