Probing Cosmology with Gravitational-Wave and Euclid data

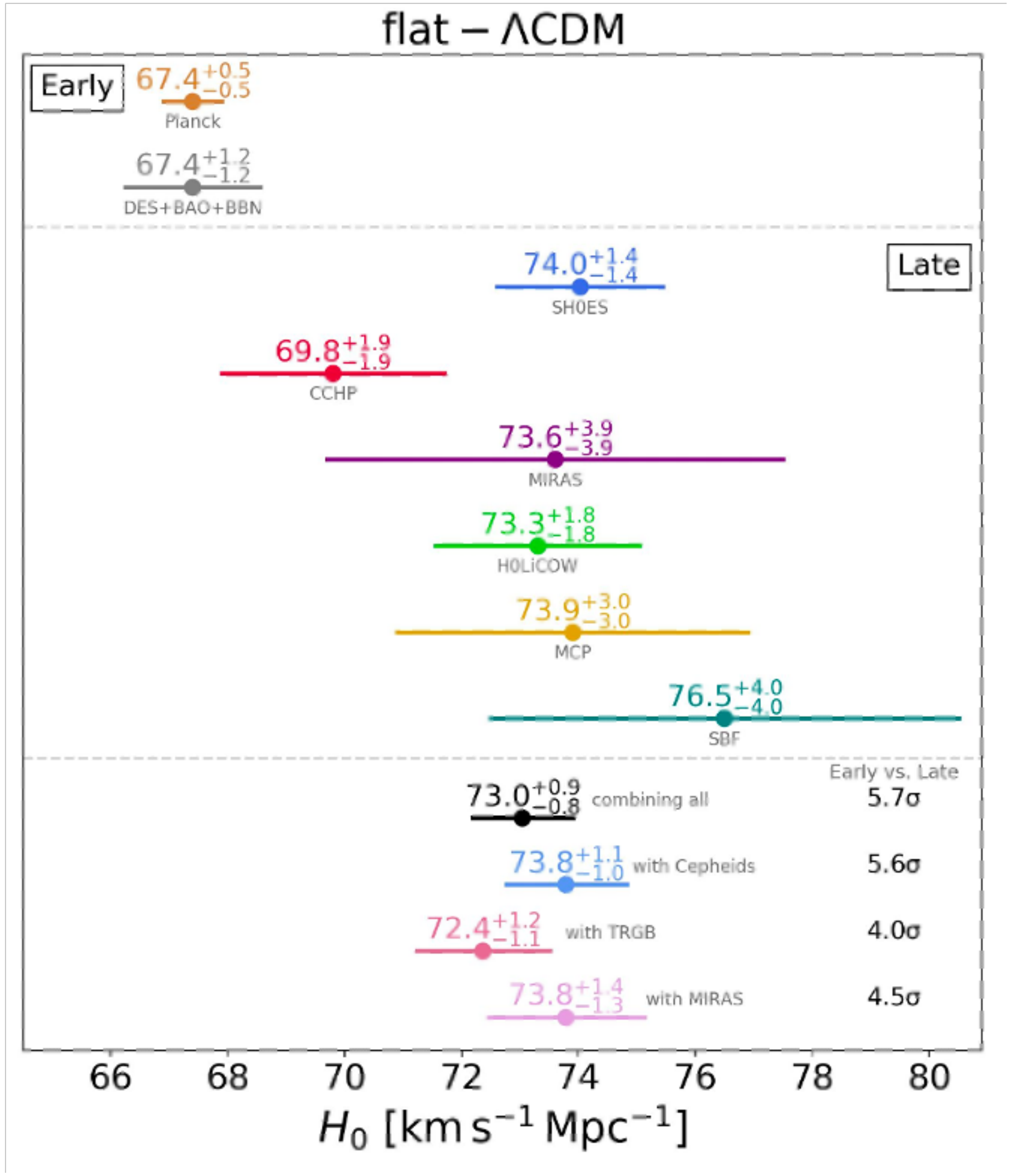
Sarah Ferraiuolo, CPPM seminar, 27/10/2025

Outline

- Introduction: Hubble tension and gravitational waves as standard sirens
- **First part**: Inferring astrophysics and cosmology with individual compact binary coalescences and their gravitational-wave stochastic background
- **Second part**: Cosmology with LVK Dark Sirens and Euclid latest catalogs available
- Conclusions

The Hubble tension

- There is a tension between direct and indirect measurements of the Hubble constant
- Although in-depth studies for hidden systematics the tension has not been yet alleviated
- We are required to directly measure the Universe expansion in all the observable Universe

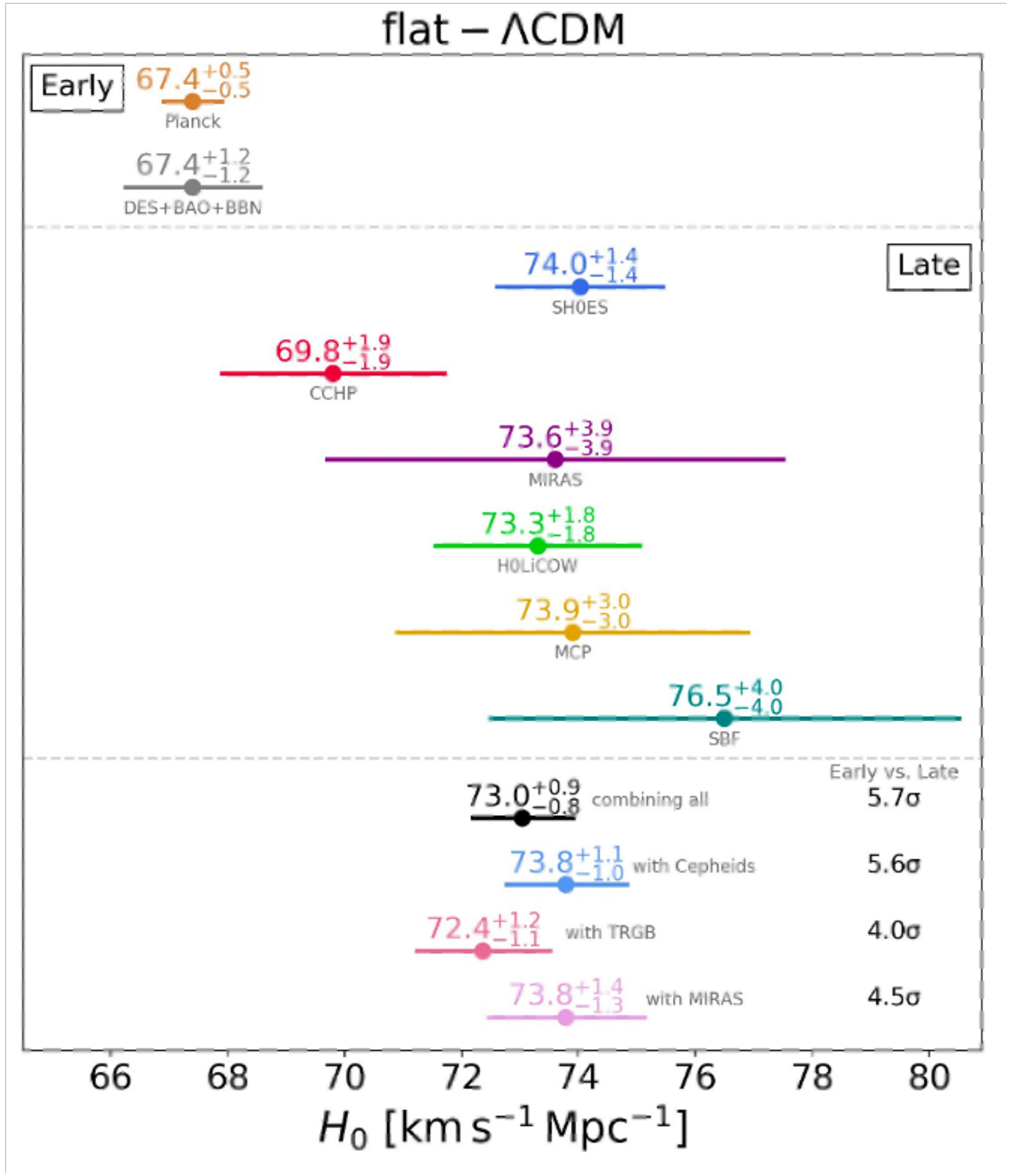


Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

The Hubble tension

- There is a tension between direct and indirect measurements of the Hubble constant
- Although in-depth studies for hidden systematics the tension has not been yet alleviated
- We are required to directly measure the Universe expansion in all the observable Universe

Gravitational Waves!



Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

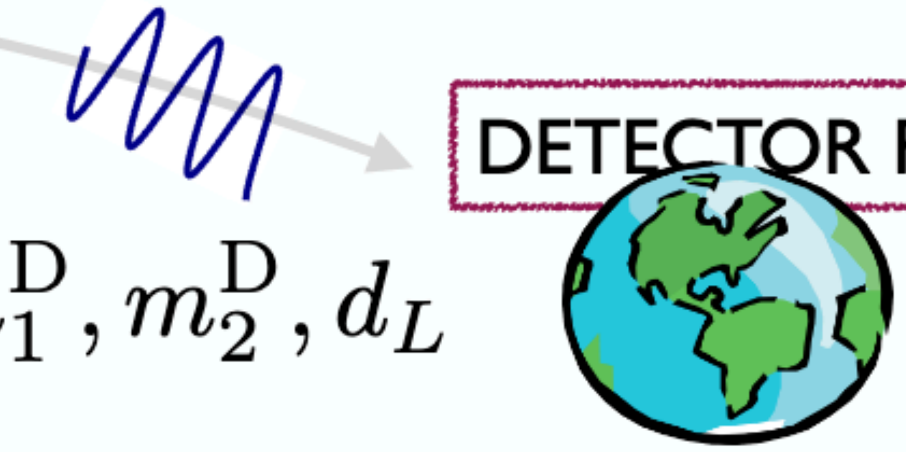
Standard Sirens with CBCs

SOURCE FRAME

m_1, m_2, z

PROPAGATION IN FLRW UNIVERSE

DETECTOR FRAME



$m_1^{\mathrm{D}}, m_2^{\mathrm{D}}, d_L$

Amplitude $h_{+,\times} \sim \frac{\mathcal{M}_c^{5/3} f_{gw}^{2/3}}{r}$ ⟶ Redshifting of frequency/time ⟶ $h_{+,\times} \sim \frac{\mathcal{M}_{c,D}^{5/3} f_{obs}^{2/3}}{d_L}$

Hubble friction

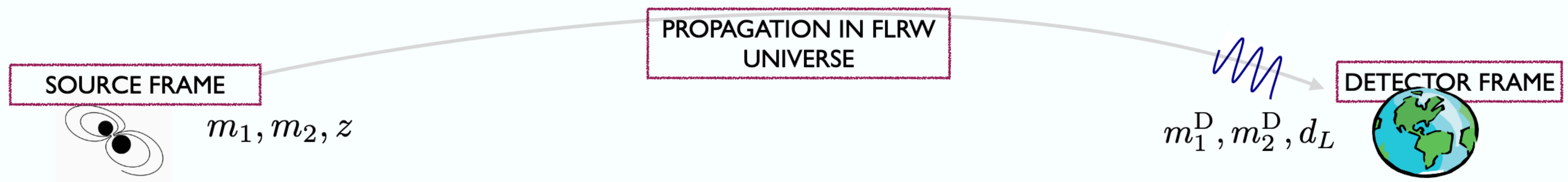
Phase $\dot{f}_{gw} \sim \mathcal{M}_c^{5/3} f_{gw}^{11/3}$ $\dot{f}_{obs} \sim \mathcal{M}_{c,D}^{5/3} f_{obs}^{11/3}$

NO ASTROPHYSICS, ONLY GR.

Hubble constant, redshift, luminosity distance relationship:

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_m + \Omega_\Lambda}}$$

Standard Sirens with CBCs



Amplitude $h_{+,\times} \sim \frac{\mathcal{M}_c^{5/3} f_{gw}^{2/3}}{r}$ $\longrightarrow$ Redshifting of frequency/time $\longrightarrow$ $h_{+,\times} \sim \frac{\mathcal{M}_{c,D}^{5/3} f_{obs}^{2/3}}{d_L}$

Hubble friction

Phase $\dot{f}_{gw} \sim \mathcal{M}_c^{5/3} f_{gw}^{11/3}$ $\qquad$ $\dot{f}_{obs} \sim \mathcal{M}_{c,D}^{5/3} f_{obs}^{11/3}$

NO ASTROPHYSICS, ONLY GR.

Hubble constant, redshift, luminosity distance relationship:

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_m + \Omega_\Lambda}}$$

Standard Sirens

Standard Sirens with CBCs

Amplitude $h_{+,\times} \sim \frac{\mathcal{M}_c^{5/3} f_{gw}^{2/3}}{r}$ ⟶ Redshifting of frequency/time ⟶ $h_{+,\times} \sim \frac{\mathcal{M}_{c,D}^{5/3} f_{obs}^{2/3}}{d_L}$

Hubble friction

Phase $\dot{f}_{gw} \sim \mathcal{M}_c^{5/3} f_{gw}^{11/3}$ $\dot{f}_{obs} \sim \mathcal{M}_{c,D}^{5/3} f_{obs}^{11/3}$

NO ASTROPHYSICS, ONLY GR.

Redshift: degenerate with mass in the GW signal. Must be found through other methods

Hubble constant, redshift, luminosity distance relationship:

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_m + \Omega_\Lambda}}$$

Standard Sirens

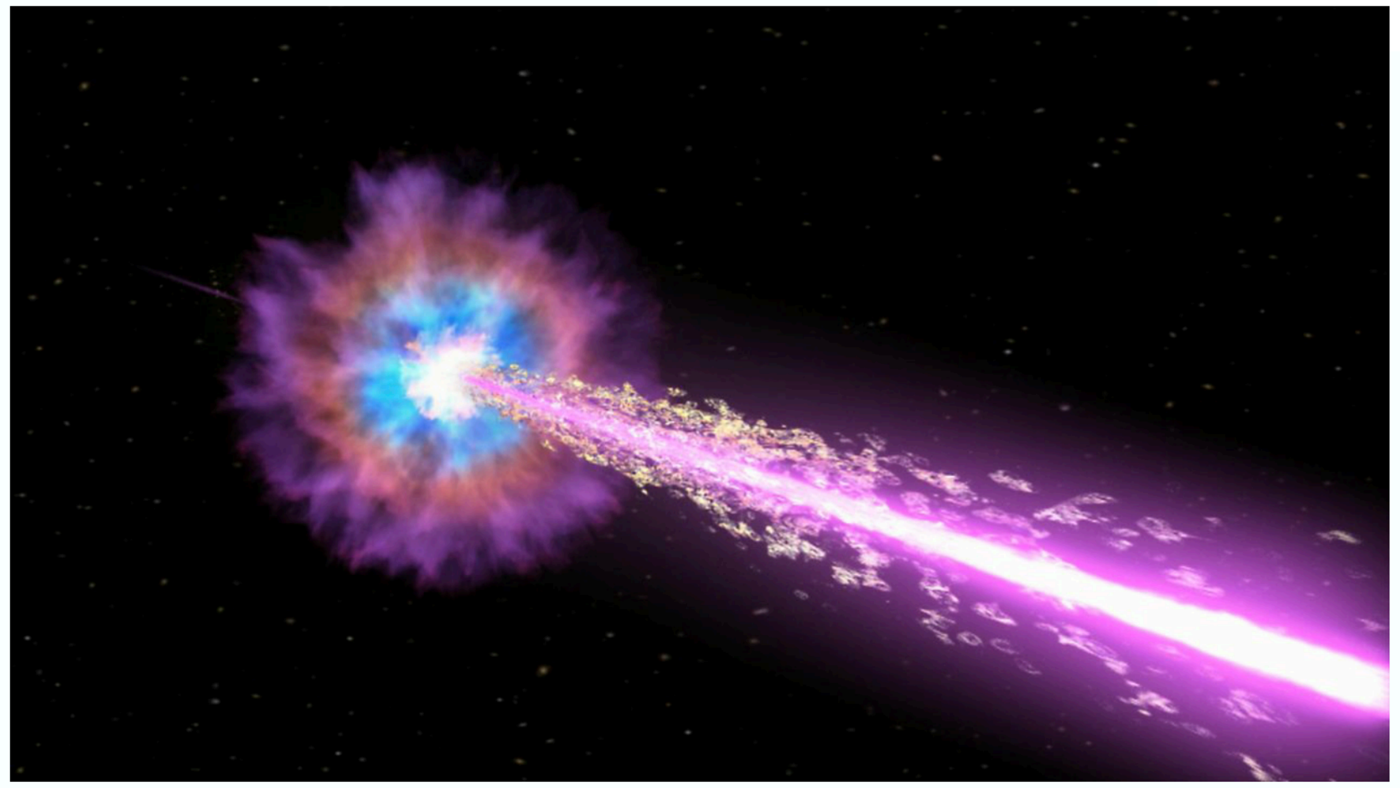
Standard Sirens with CBCs

'Sirens' methods = associate redshift information to distance measurement

Bright Sirens

- An EM counterpart is observed and used to obtain the host galaxy's redshift

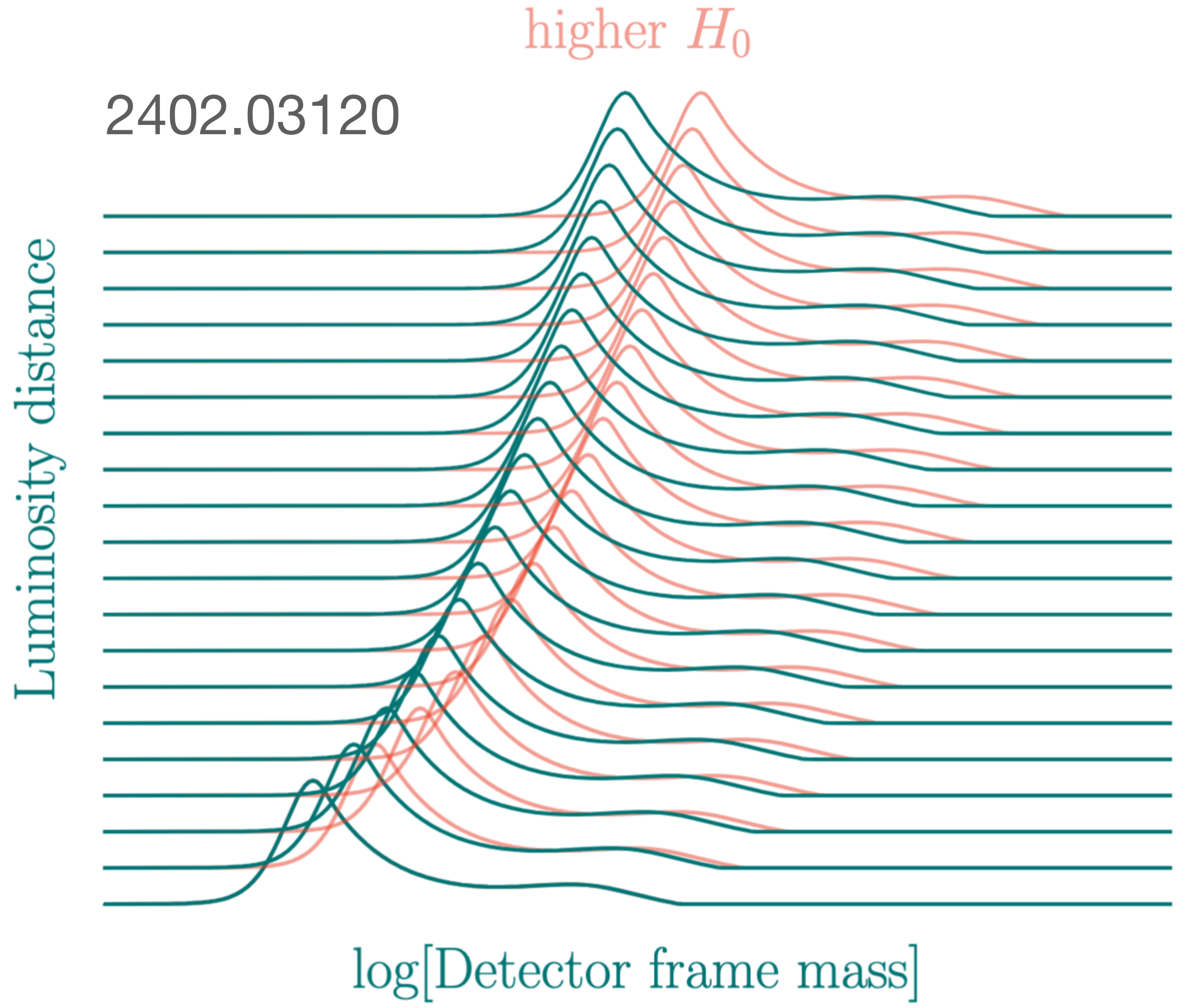
- E.g. GW170817 and NGC4993



Spectral Sirens

- Features in the mass distribution of the GW population break the mass-redshift degeneracy

$$m_{det} = m_{source}(1 + z)$$



Dark Sirens

- Galaxy surveys are used to provide redshift estimates for potential host galaxies → **the galaxy catalog method**

Inferring astrophysics and cosmology with individual compact binary coalescences and their gravitational-wave stochastic background

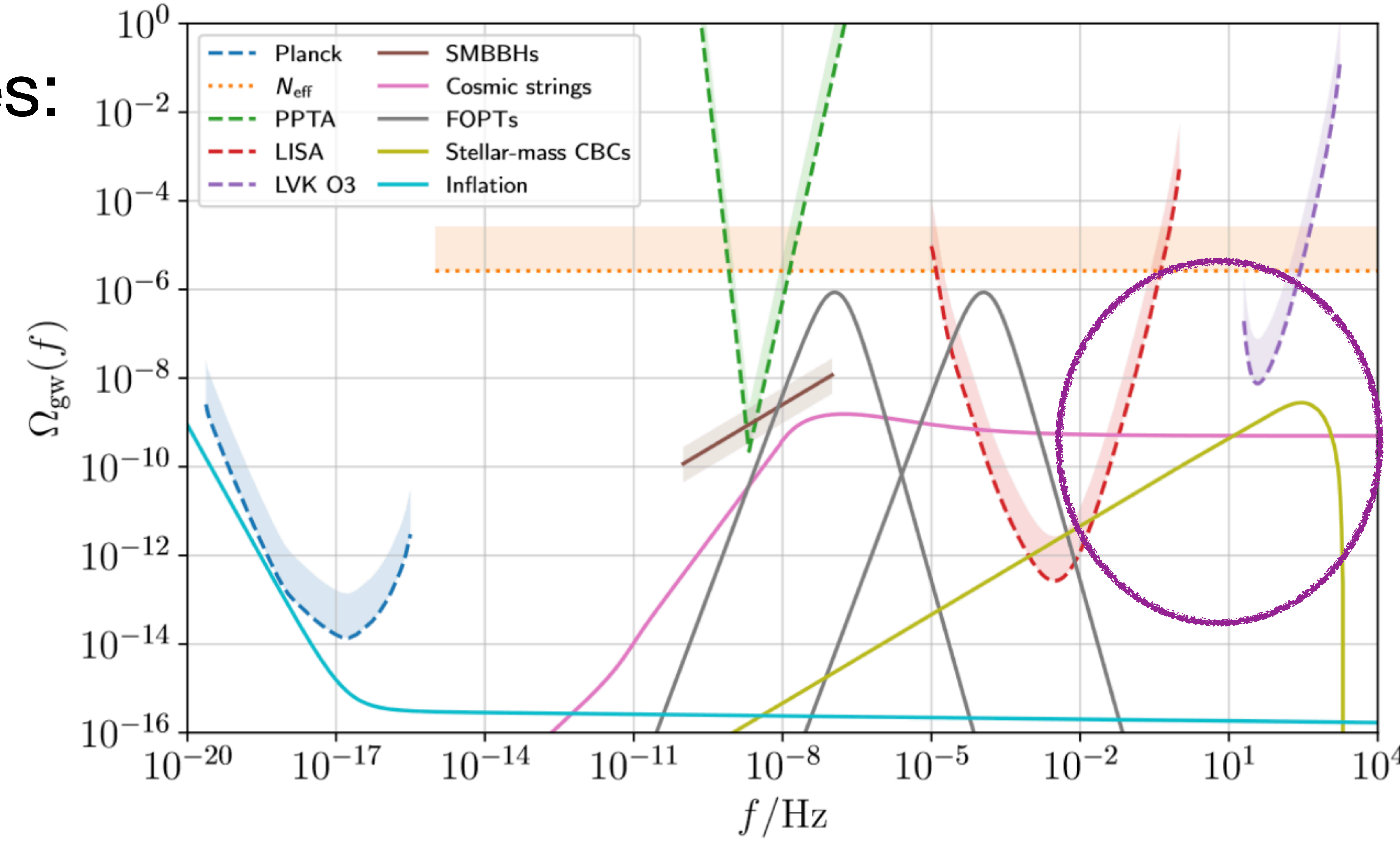
First part

Stochastic Gravitational Wave Background

The SGWB is a superposition of weak GW sources.

It can exist in many forms from two categories:

- **Astrophysical background**
- Cosmological background



Galaxies 2022,10(1), 34

For a BBH population

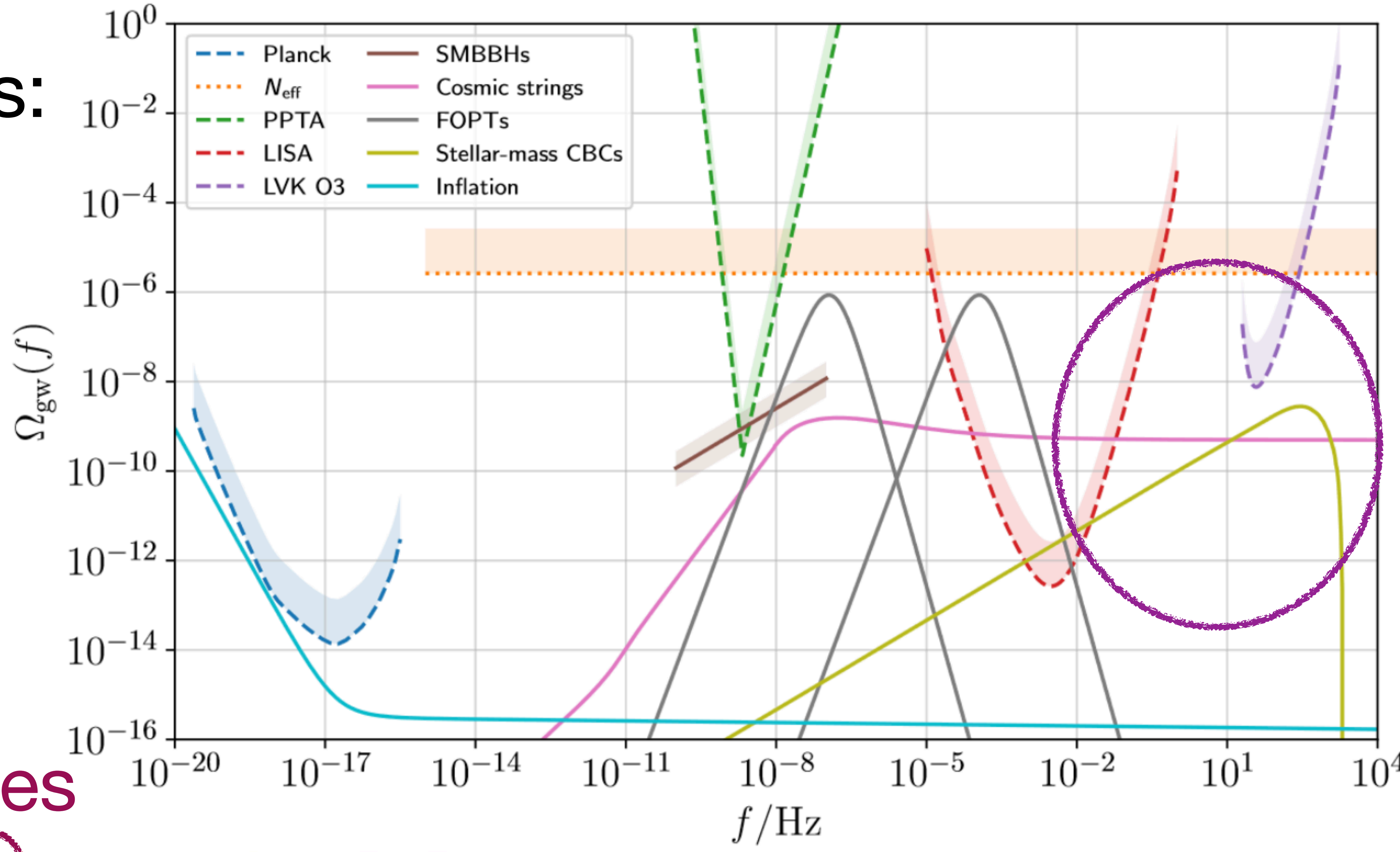
$$\Omega_{\rm GW} = \frac{f}{\rho_c}\int_0^{z_{max}} \mathrm{d}z \frac{R(z)}{(1+z)H(z)}\left\langle \frac{\mathrm{d}E_s}{\mathrm{d}f_s}\bigg|_{f(1+z)} \right\rangle$$

Stochastic Gravitational Wave Background

The SGWB is a superposition of weak GW sources.

It can exist in many forms from two categories:

- **Astrophysical background**
- Cosmological background



Galaxies 2022,10(1), 34

For a BBH population

Merger rate Source properties

$$\Omega_{\rm GW} = \frac{f}{\rho_c}\int_0^{z_{max}} \mathrm{d}z \frac{R(z)}{(1+z)H(z)} \left\langle \frac{\mathrm{d}E_s}{\mathrm{d}f_s}\bigg|_{f(1+z)} \right\rangle$$

Cosmology

Analysis Method

Turbang et al. 2020, Callister et al. 2023

Individual BBH detections

BBH events

↓

Likelihood on BBH and cosmology parameters (e.g., masses and H_0)

Stochastic Backgrounds

GW data from multiple detectors

↓

Optimal estimator for $\hat{C}$ GWB spectrum $\Omega_{\mathrm{GW}}(f)$

$$\mathscr{L}(d_i, \hat{C} \,|\, \Lambda) = \mathscr{L}_{\mathrm{BBH}}(d_i \,|\, \Lambda)\mathscr{L}_{\mathrm{GWB}}(\hat{C} \,|\, \Lambda)$$

We want to infer hyperparameters Λ consistent with the individual BBH events and the measurements on the GWB

Simulations for LVK at A+ design sensitivity

Framework

Resolved CBC

2 years of GW data only to detect resolved sources

- 5-detector network GW catalog (1200 BBH)
- 4-detector network GW catalog (600 BBH)

Combined SGWB and CBCs

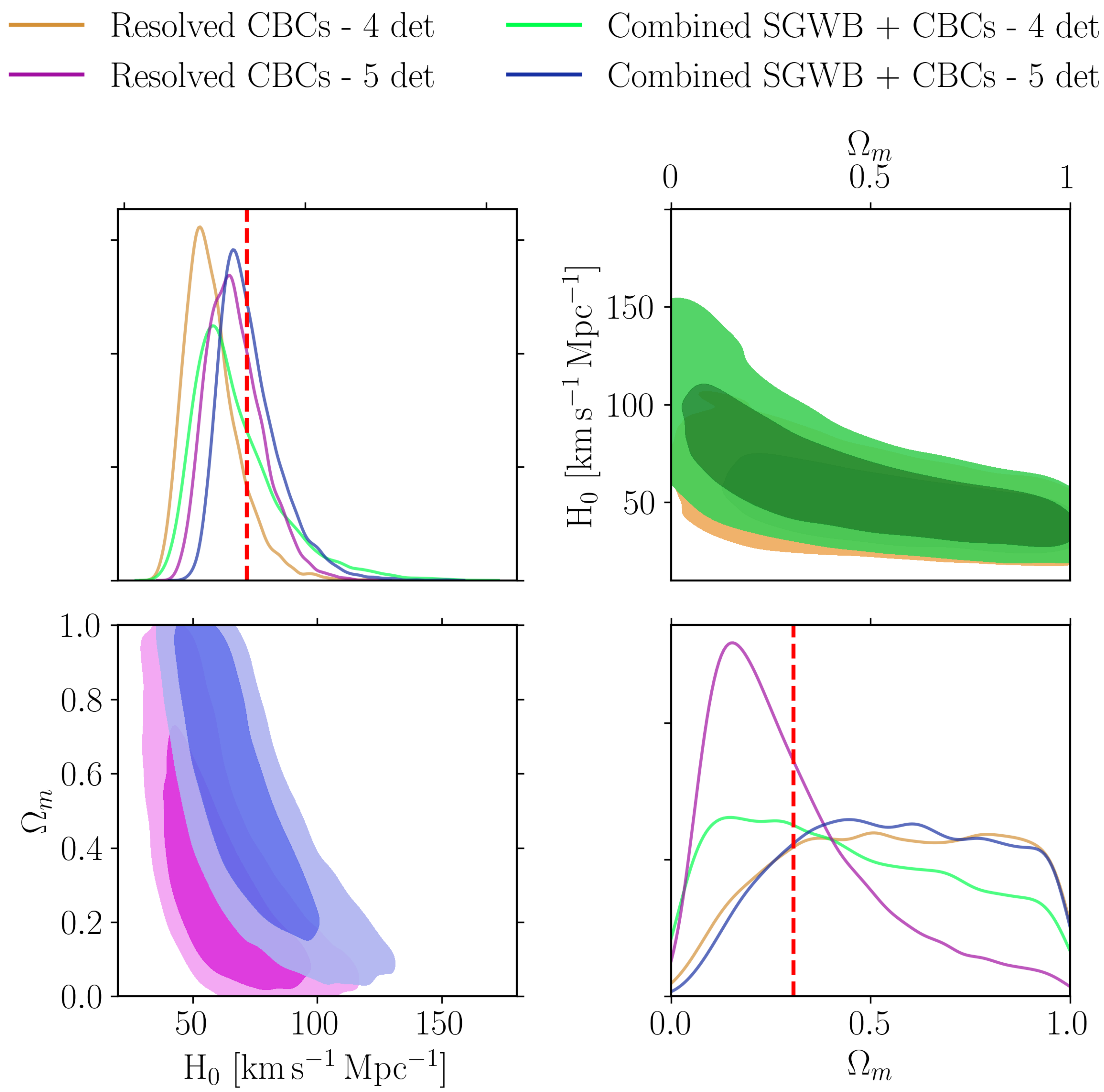
1 year of GW data used to collect resolved sources + 1 year used to detect the SGWB

- 5-detector network GW (600 BBH) and stochastic catalog
- 4-detector network GW (300 BBH) and stochastic catalog

Results

O5 sensitivity simulated data

- Most of the precision on H_0 is determined by resolved spectral sirens
- For the 5-detector network, the inclusion of the SGWB significantly helps in excluding the region of the parameter space that covers low values of H_0 and Ω_m
- Instead the 4-detector network, we find that the population posterior is entirely dominated by resolved sources



In summary, so far

- With future detectors, the inclusion of the SGWB can help our understanding of astrophysical populations and cosmological parameters

- We apply this method to GWTC-3, and we obtain that with current sensitivities, the cosmological and population results are not impacted by the inclusion of the SGWB

- In this exploratory study, we made a few simplistic and conservative assumptions that can be revised for follow-up studies (ex. Likelihood, BNS and NSBH background…)

★ Paper and proceeding

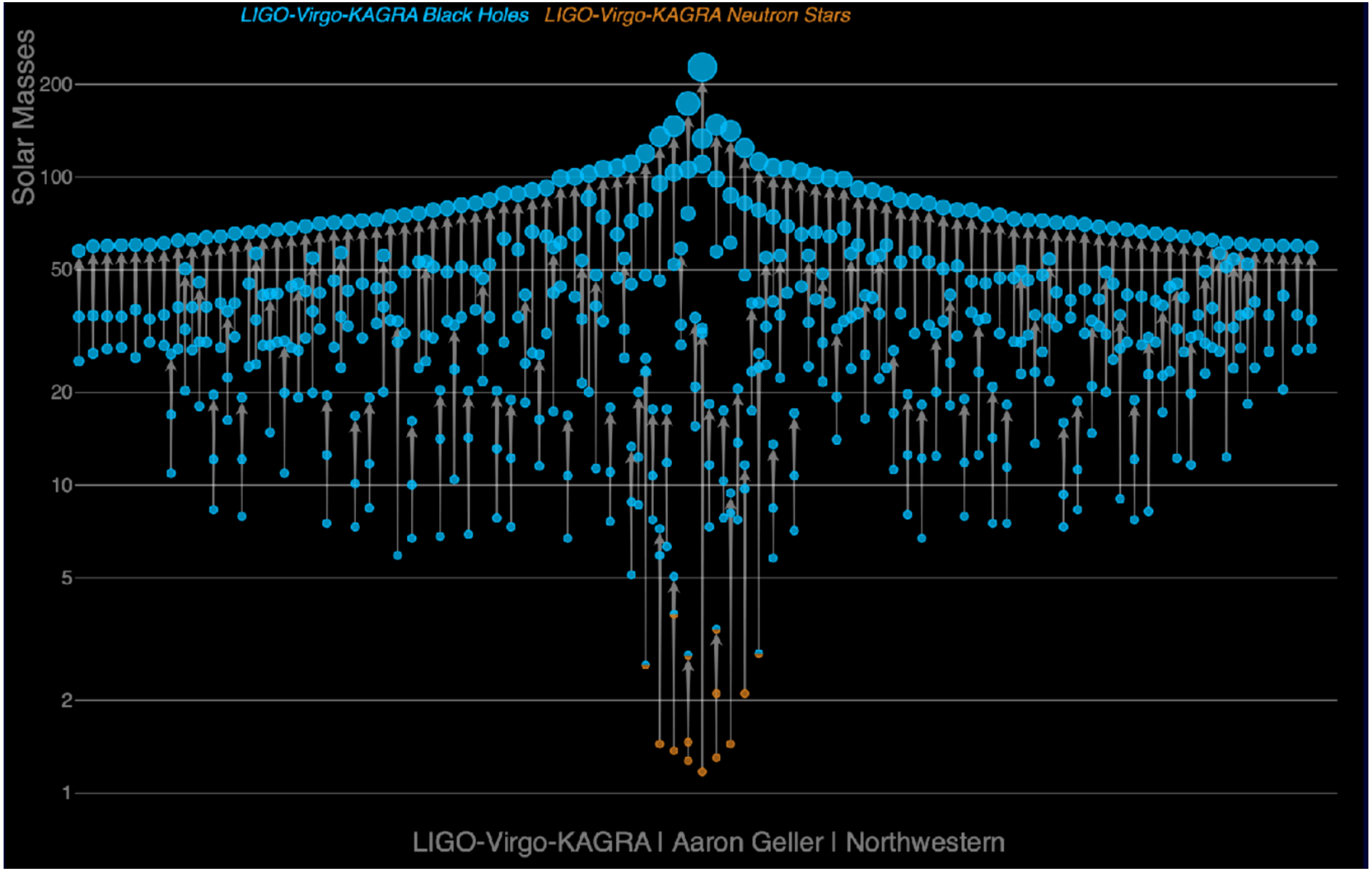
Ferraiuolo, S, Mastrogiovanni, S, Escoffier, S and Kajfasz, E 2025 A&A 701 A36 URL https: //doi.org/10.1051/0004-6361/202555124

Cosmology with LVK Dark Sirens and Euclid latest catalogs available

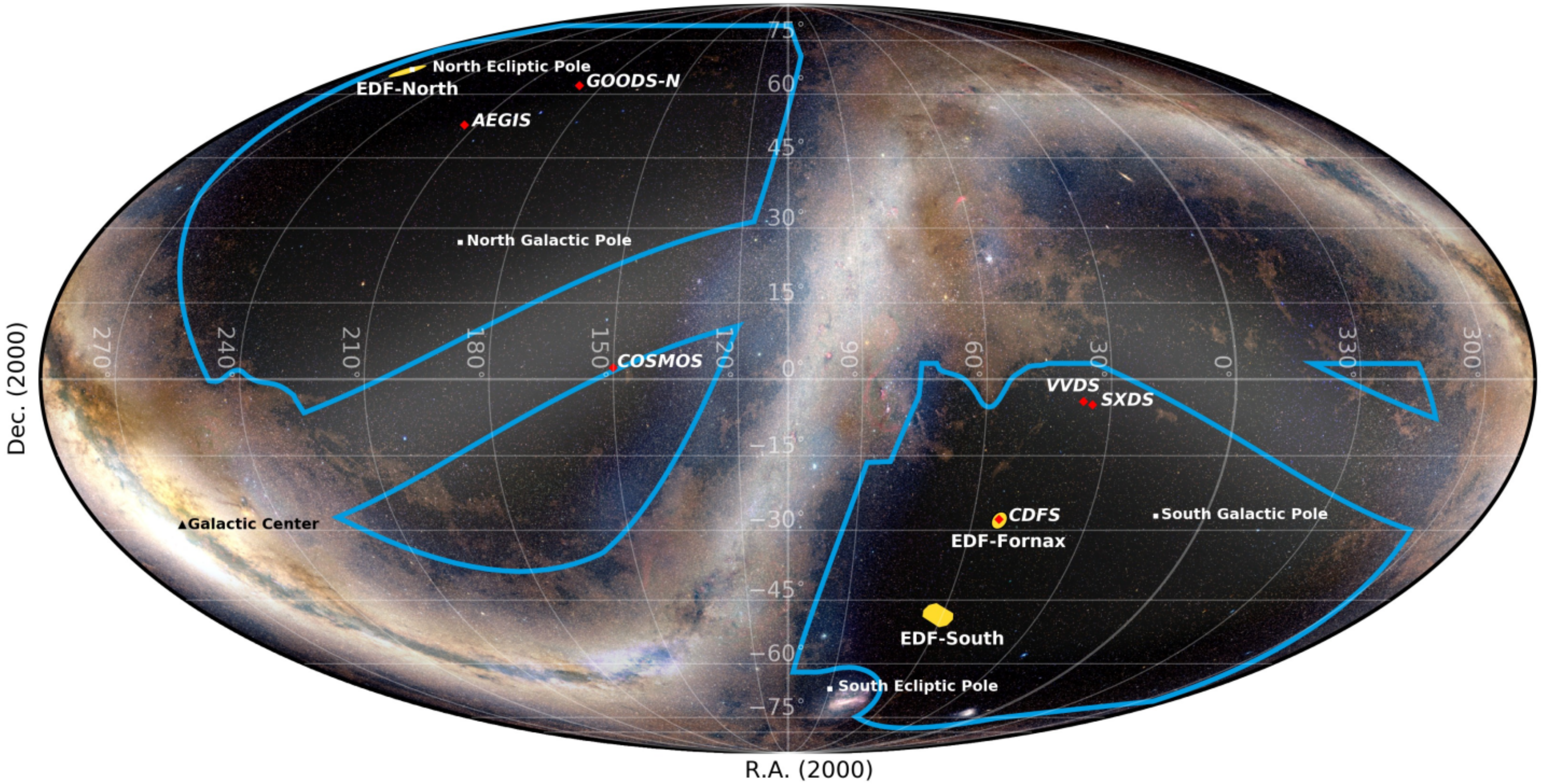
Second part

Gravitational wave sources in GWTC-4.0 (end of O4a)

O4a ran from 24th May 2023 to 16th January 2024



Euclid Region of Interest

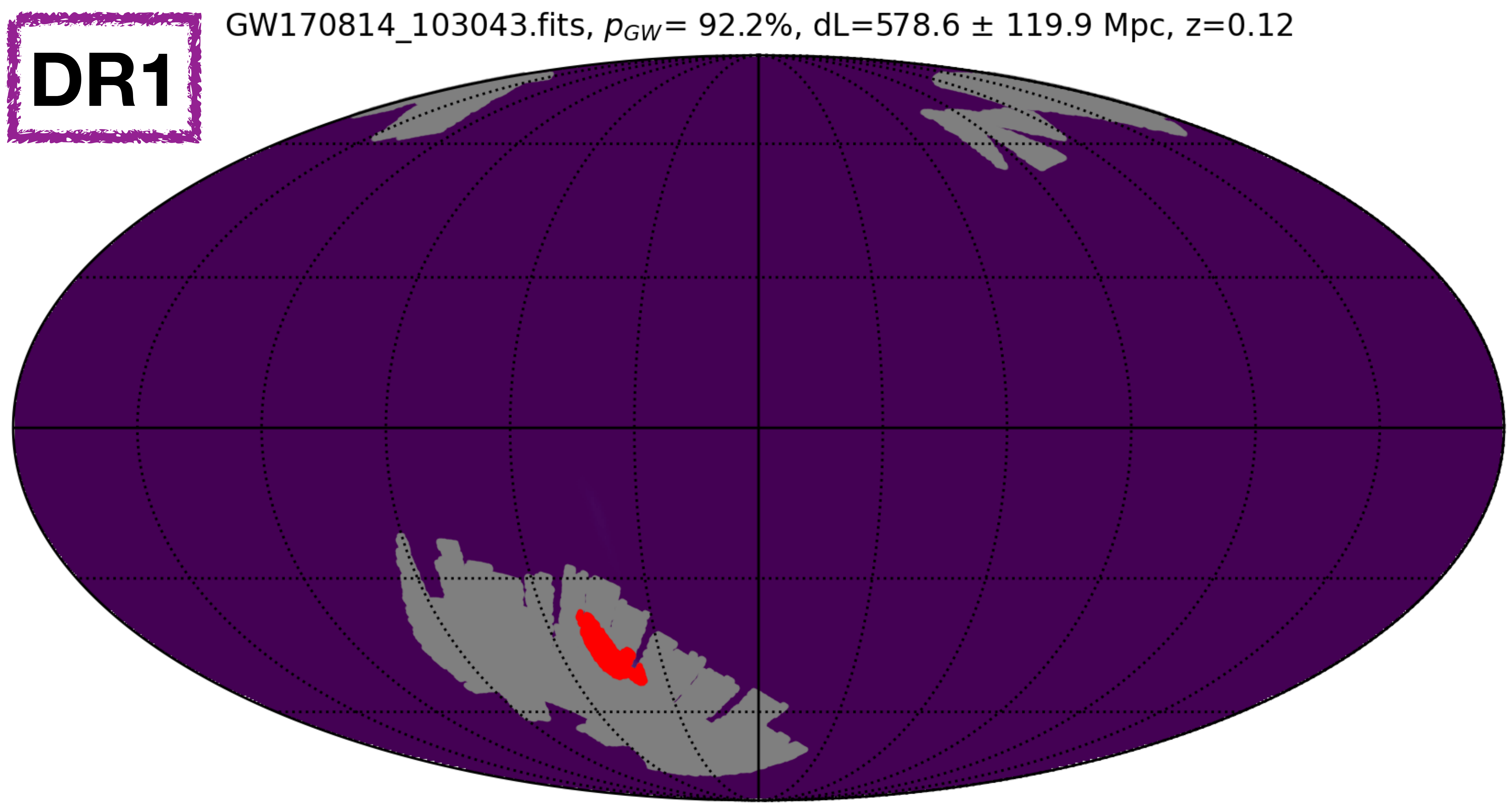


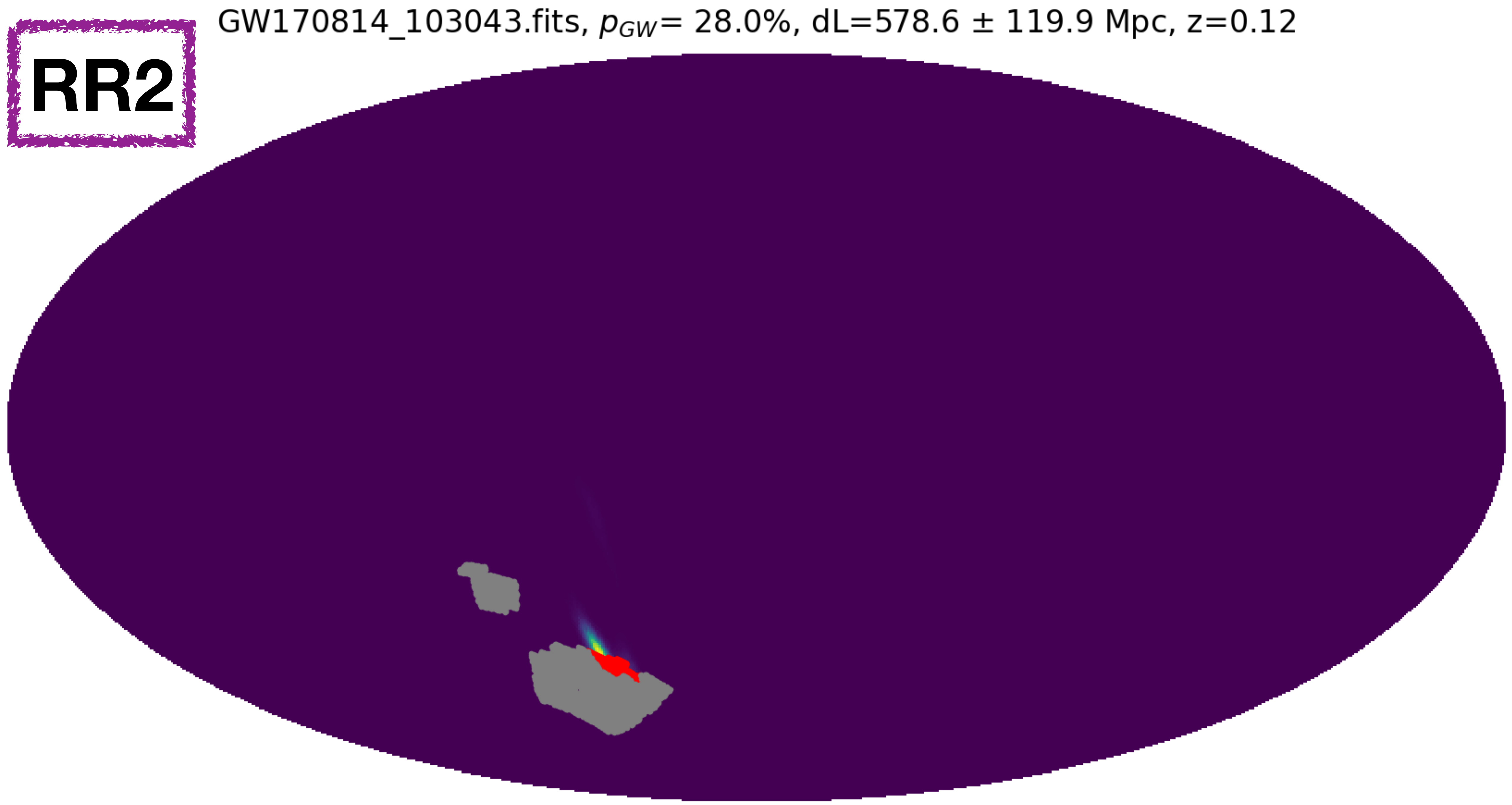
Euclid Catalogs

- **Euclid Q1** (First Data Release) – Contains VIS and NIR imaging from one pass over the three Euclid Deep Fields (North, South, Fornax) and LDN1641 (Orion) ≈ 63 square degrees
- **Euclid RR2 (Internal Release)** – An **internal validation dataset** used to test and refine analysis pipelines, involving reprocessing from multiple pipelines. Not publicly released, but essential for ensuring **DR1 data quality** ≈ 400 square degrees
- **Euclid DR1 Mask** – Defines the **survey footprint**, i.e., the specific **sky area observed** and used for scientific analysis in the first public data release ≈ 2000 square degrees

Euclid and O1-O2-O3 GW events

GW170814 → Golden Siren for GW cosmology





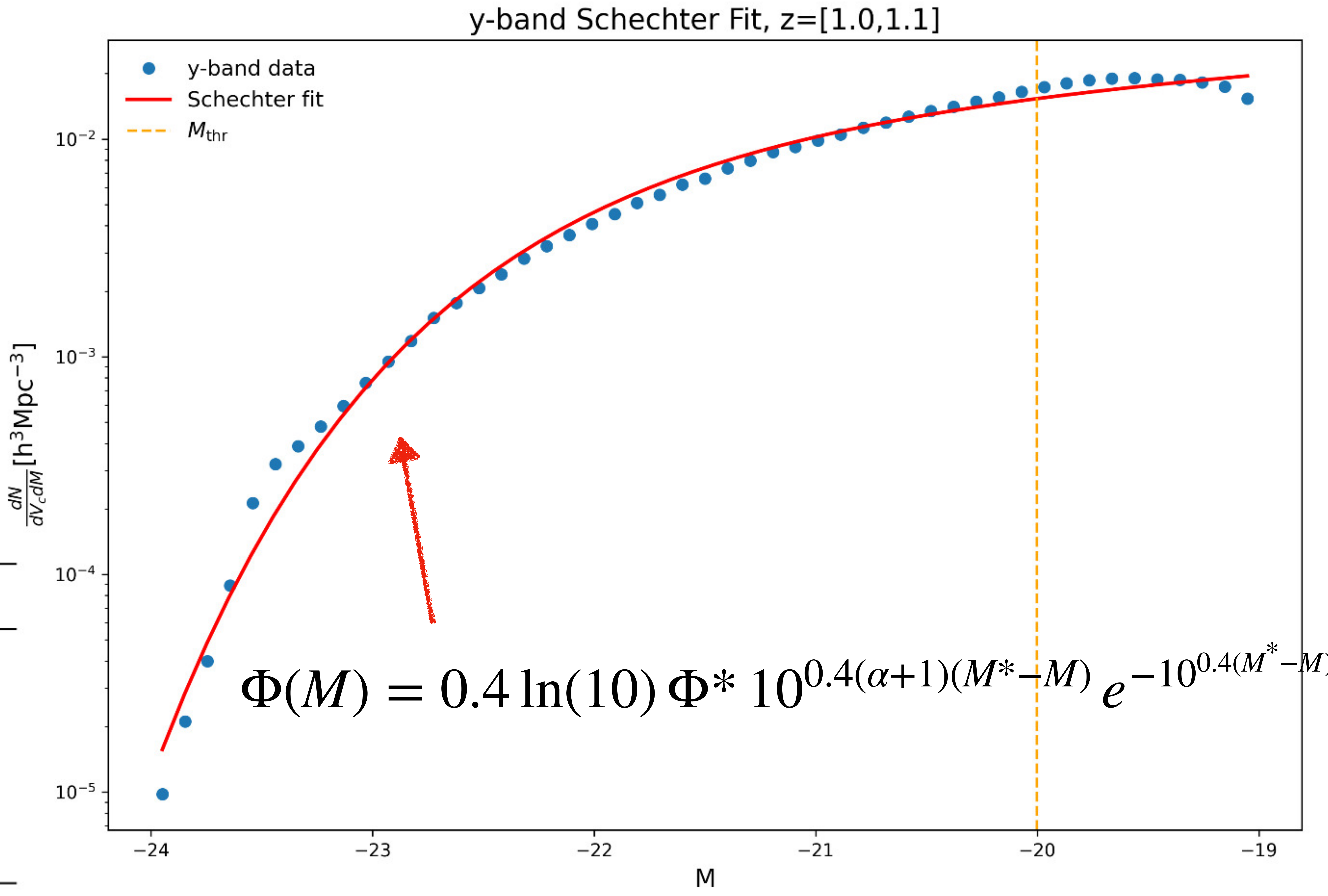
The overlapping region with Euclid DR1 has a significant probability (92.2%), making it an interesting dark siren candidate

Luminosity Function in Q1 Catalog

Y band example

Estimating the out-of-catalog part requires a distribution of galaxy luminosity in the Universe, usually given by Schechter funciton

Band	ϕ^* [Mpc^{-3}]	M^*	α
vis	9.13×10^{-4}	−22.05	−2.35
y	1.48×10^{-2}	−21.92	−1.16
h	8.10×10^{-3}	−22.98	−1.26
j	8.87×10^{-3}	−22.64	−1.29



$$\Phi(M) = 0.4\ln(10)\,\Phi^*\,10^{0.4(\alpha+1)(M^*-M)}\,e^{-10^{0.4(M^*-M)}}$$

Conclusions and future steps

- There are a few interesting events that are likely to fall within the Euclid footprint
- Fit the Schecter Function to account for galaxy completeness both for Q1 and DR1
- We can use these events for H_0 inference to test **icarogw** and check whether they provide any new information or differences compared to other galaxy catalogs

Thank you for your attention!

Backup slides

Hierarchical Bayesian inference

Prior

$$p(\lambda|\{\text{data}\}) \propto \frac{\pi(\lambda)}{\xi(\lambda)^{N_{\text{obs}}}} \prod_{i=1}^{N_{\text{obs}}} \int \mathrm{d}\theta_{D,i}\, p(\text{data}_i \mid \theta_{D,i})\, p_{\text{pop}}(\theta_i(\theta_D, \lambda_{\text{c}}) \mid \lambda_{\text{a}})\, \mathrm{J}(\lambda_{\text{c}})$$

H_0 here

Selection bias (depends on astrophysical assumptions)

GW mass-distance measurement

Astrophysical model of mass-redshift distribution

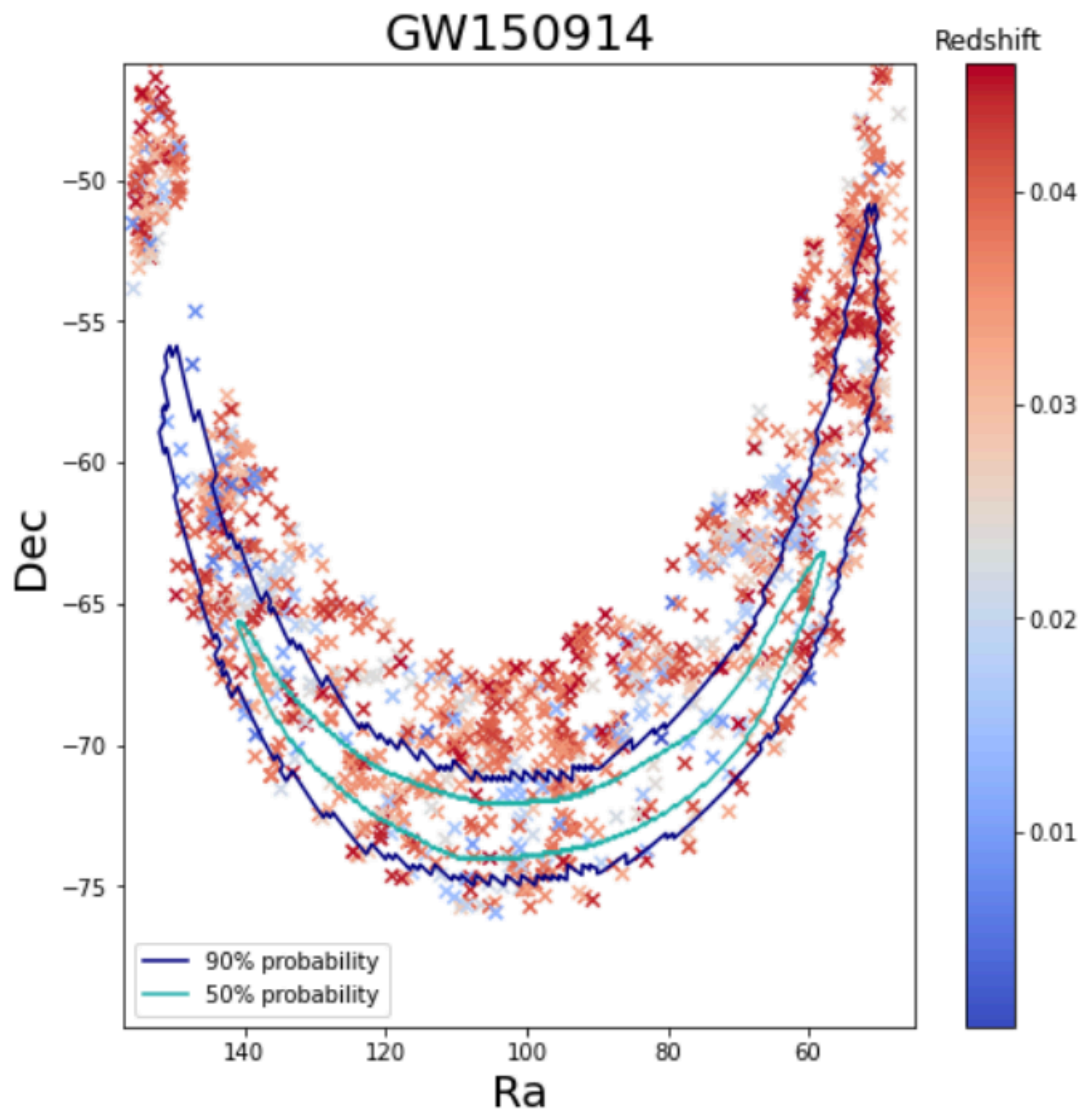
- **Dark sirens .** $p_{\text{pop}} \ni p(m_1, m_2|\lambda_{\text{astro}})$

Schutz 1986 $\times p(z|\text{galaxy catalog})$

Consider all galaxies in the GW localisation region

Marginalise over potential hosts.

$$p(z|\text{galaxy catalog}) \propto \sum_{gal} w_{gal}\, p(z|z_{\text{gal}})$$



Hierarchical Bayesian inference

Prior

$$p(\lambda|\{\text{data}\}) \propto \frac{\pi(\lambda)}{\xi(\lambda)^{N_{\rm obs}}} \prod_{i=1}^{N_{\rm obs}} \int \mathrm{d}\theta_{D,i}\, p(\text{data}_i \mid \theta_{D,i})\, p_{\rm pop}(\theta_i(\theta_D, \lambda_{\rm c}) \mid \lambda_{\rm a})\, \mathrm{J}(\lambda_{\rm c})$$

H_0 here

Selection bias (depends on astrophysical assumptions)

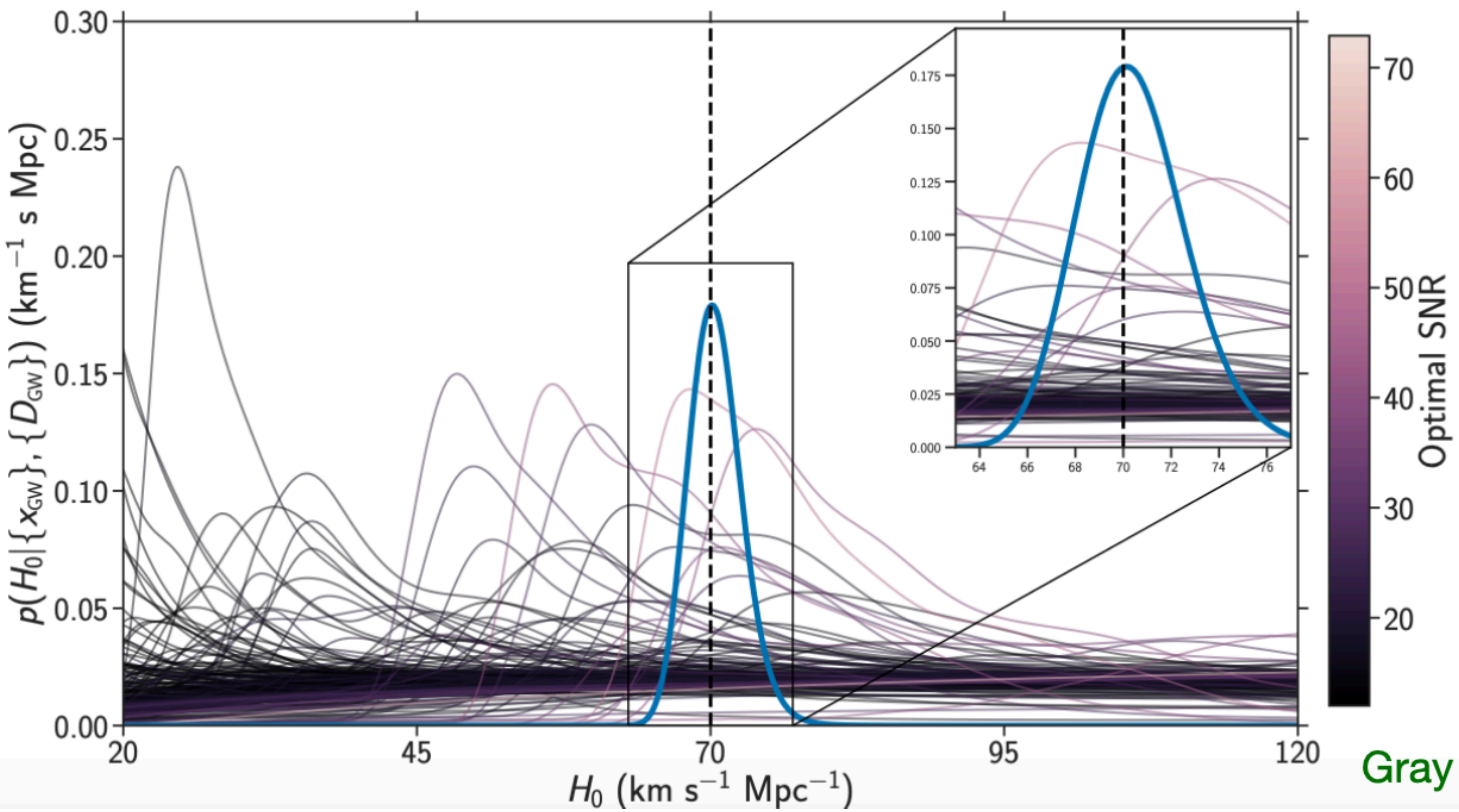
GW mass-distance measurement

Astrophysical model of mass-redshift distribution

- **Dark sirens .**

Each single event can lead to spurious peaks…

… which average out when combining many events

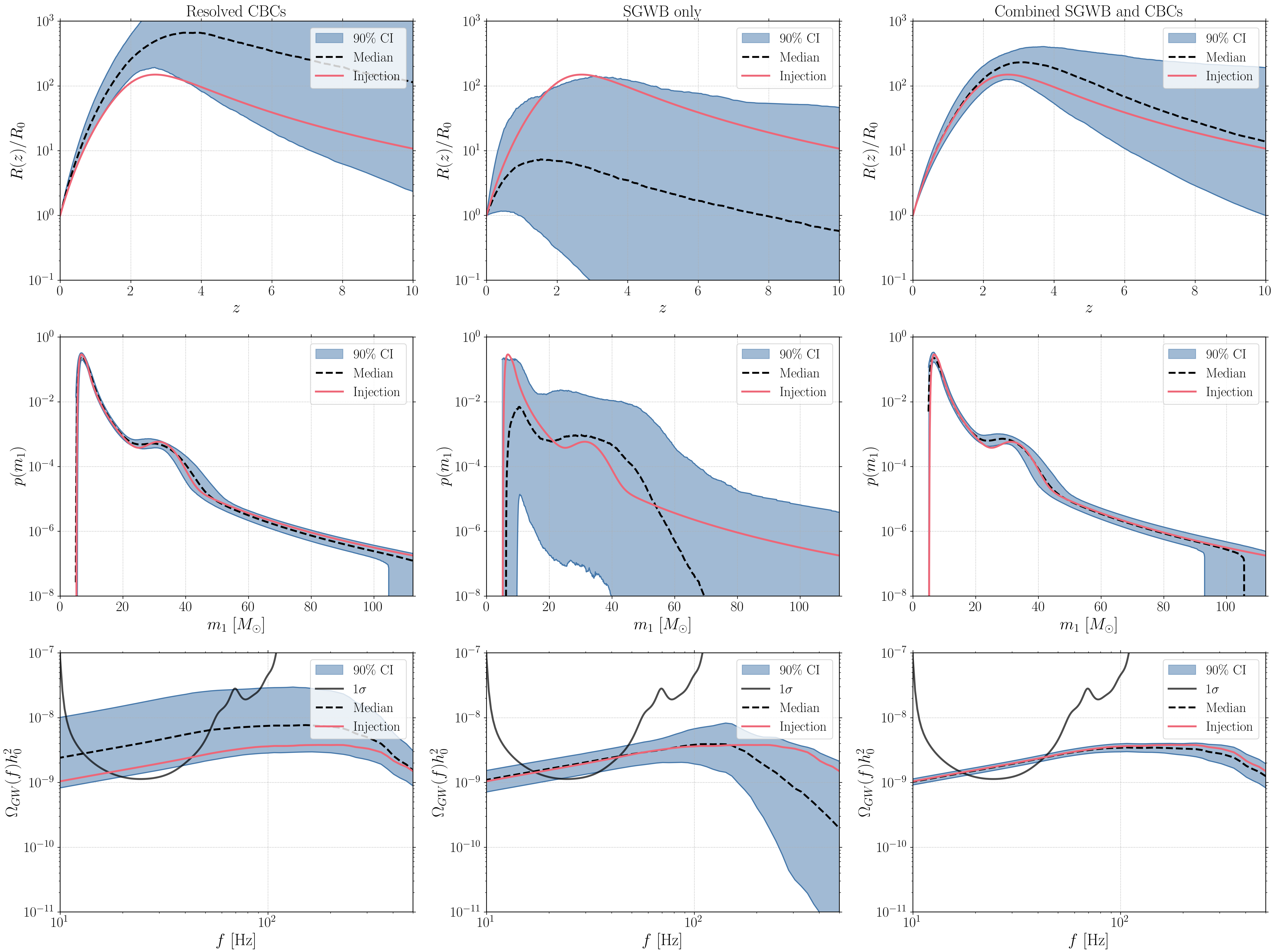


Gray + 2019

Results

Posterior predictive checks (PPC)

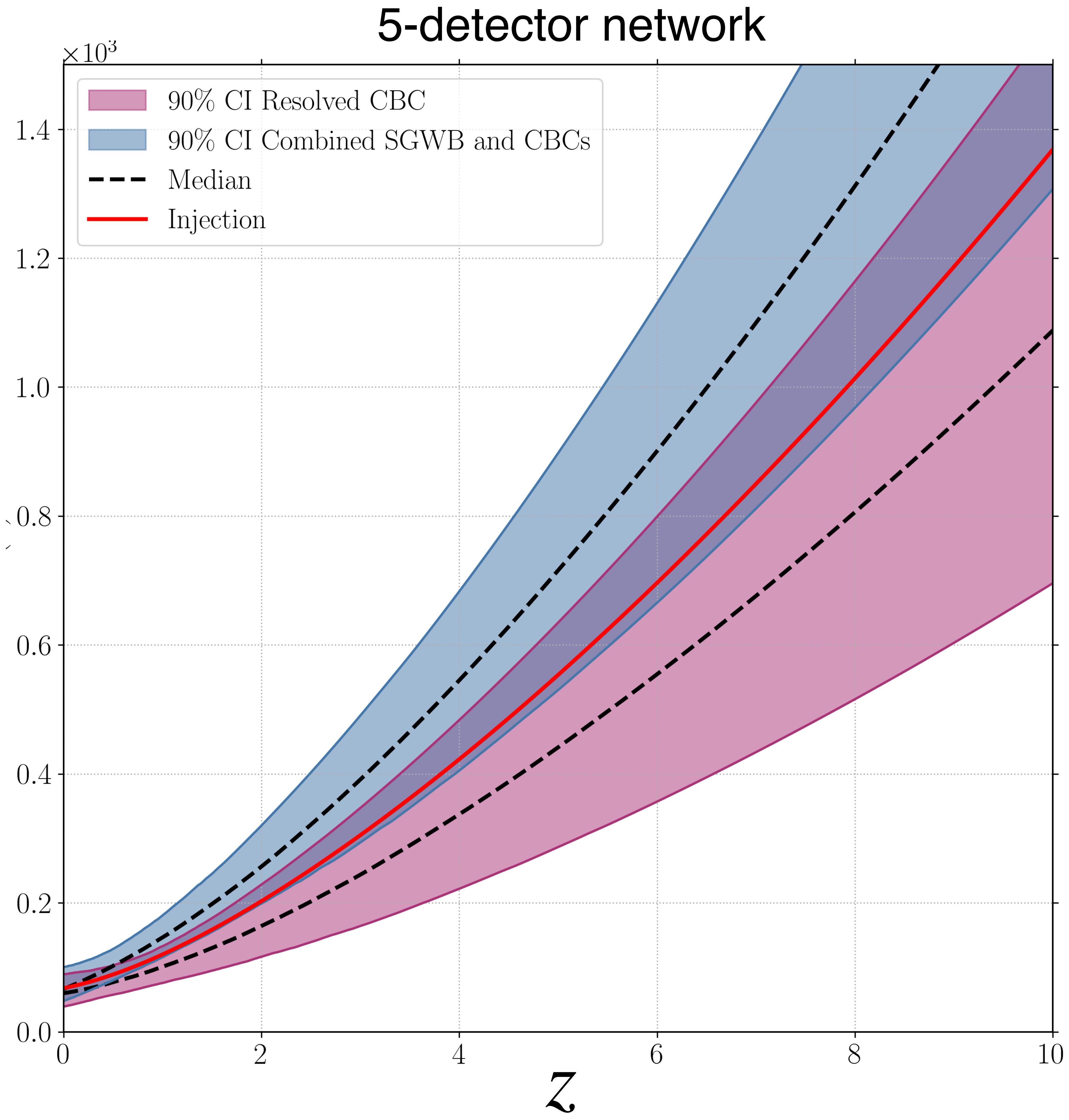
Only 5 detectors

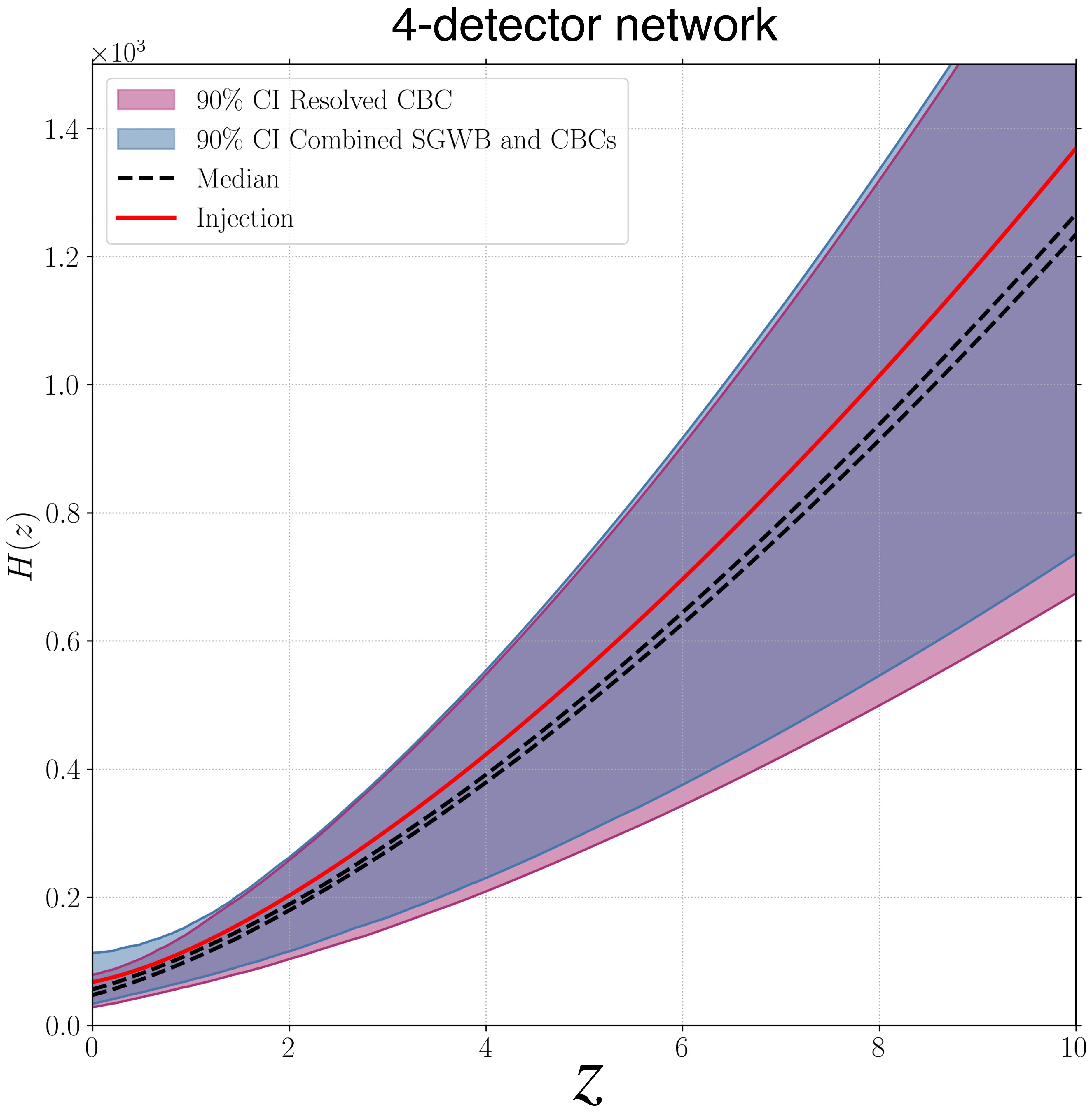


Results

PPC

- We observe an improvement in the measurement of the expansion rate $H(z)$ when including the SGWB in the 5-detector analysis



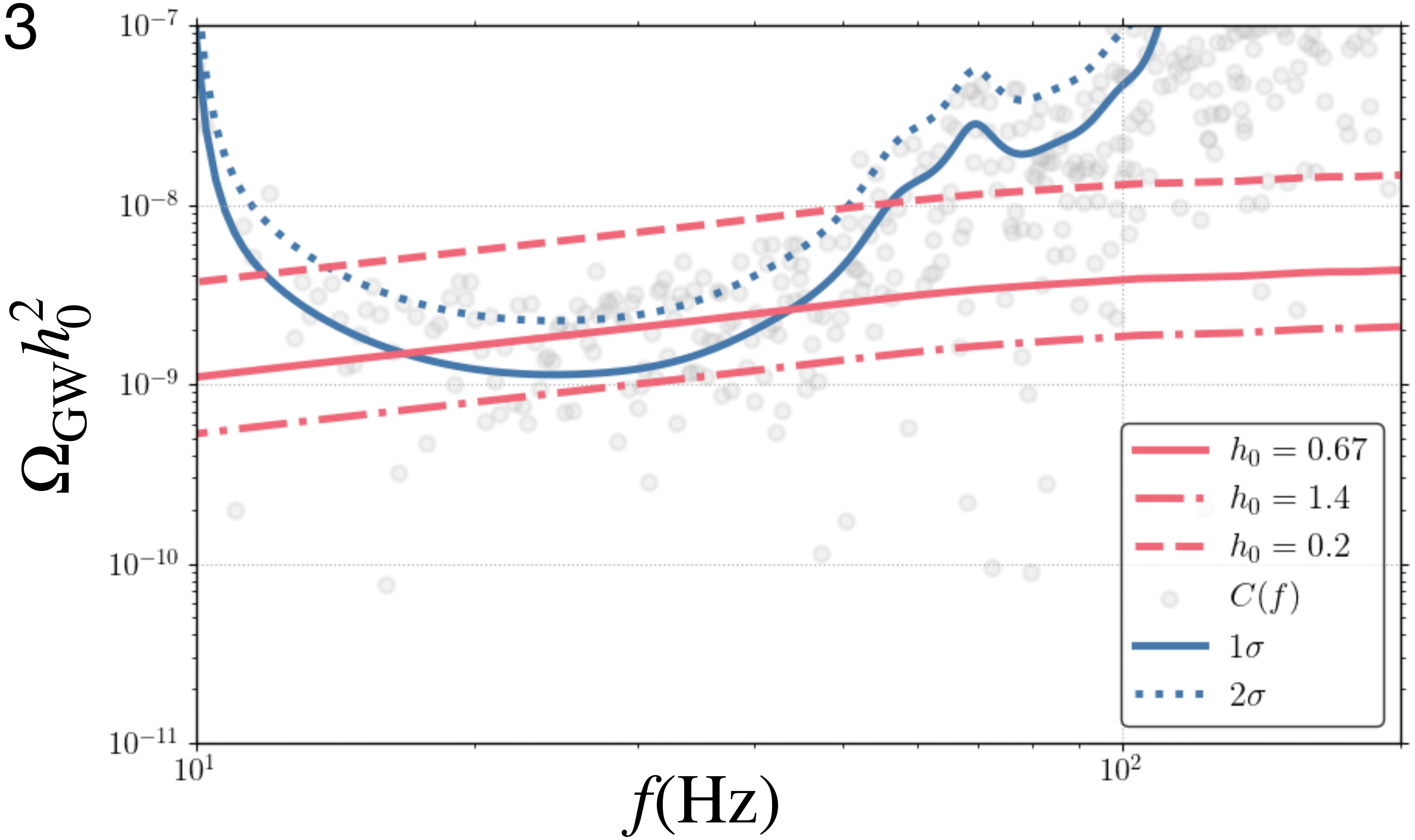


Simulations for LVK at A+ design sensitivity

SGWB Simulation

- We simulated $C(f)$ and $\sigma(f)$ based on A+ sensitivity

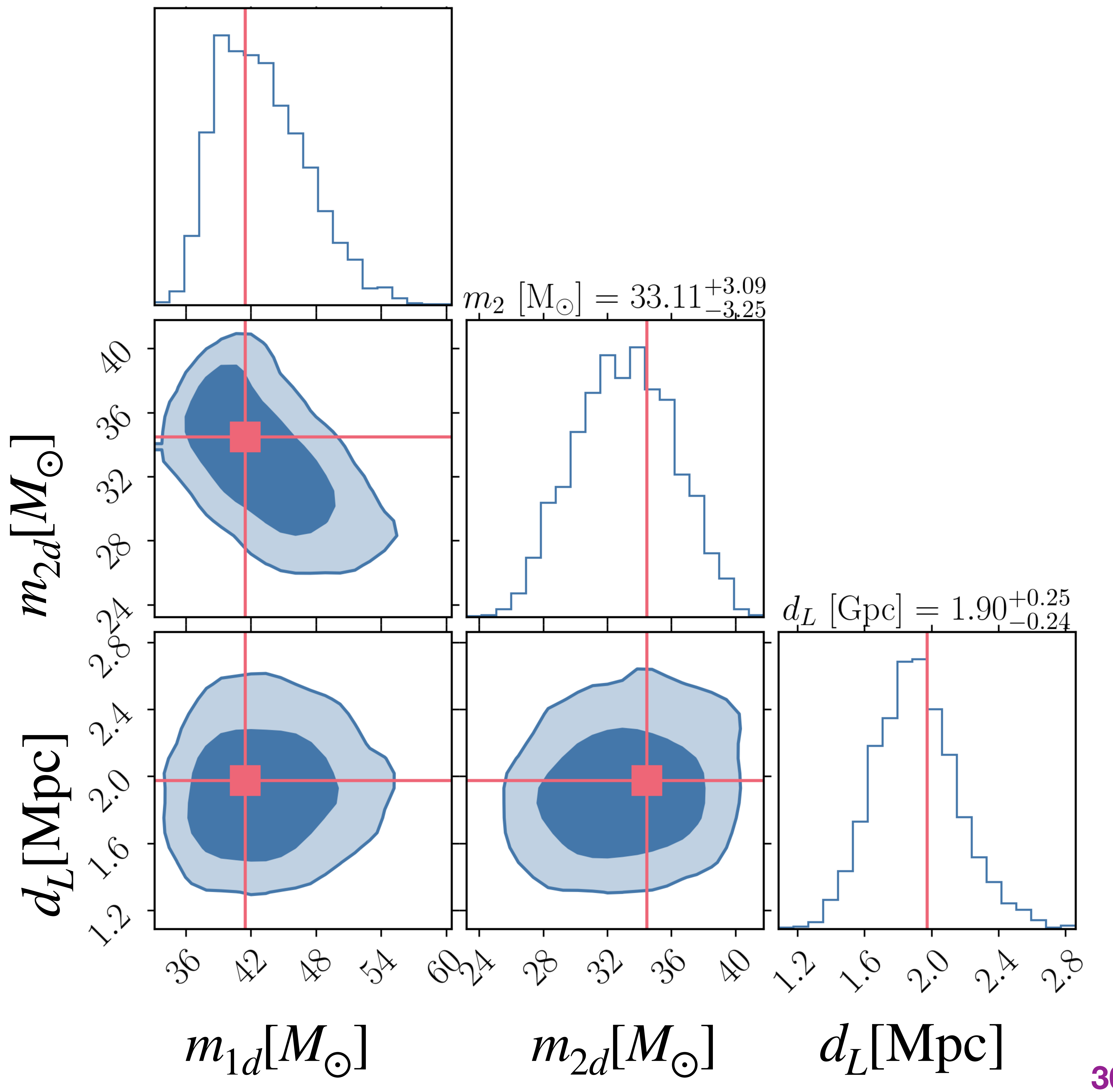
- The simulations rely on a population model of gravitational wave event rates as a function of redshift and source masses consistent with the latest measurements from GWTC-3



Simulations for LVK at A+ design sensitivity

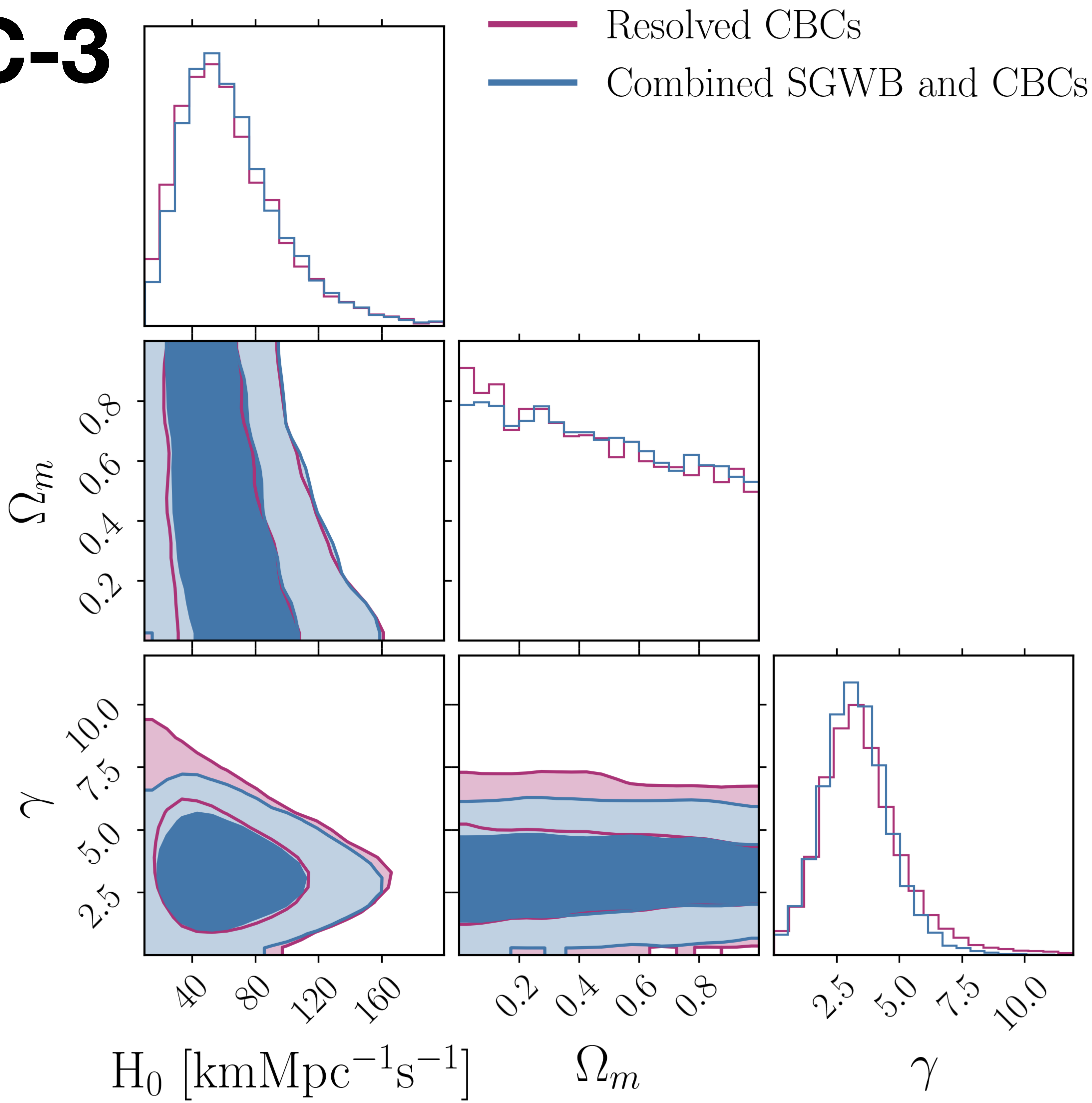
GWs Simulation

- A toy model simulates parameter estimation posteriors for BBHs
- The corner plot shows posterior distributions for detector-frame masses and luminosity distance



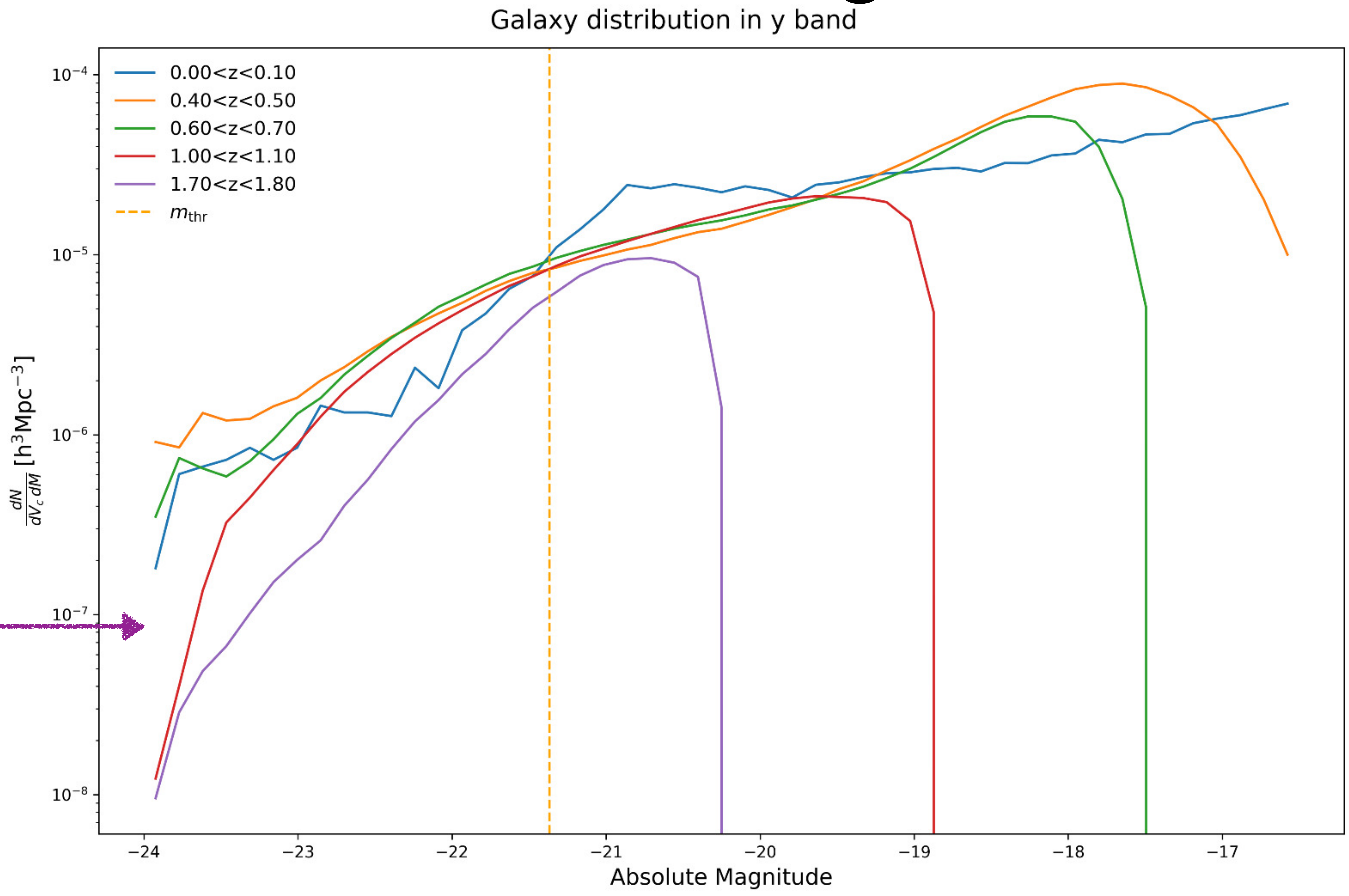
Reanalysis on GWTC-3

- We find that the constraints on the population and cosmological parameters are entirely given by the individual GW source
- We find that the inclusion of the SGWB weakly helps in excluding low values of H_0 and high values of γ from the 2σ CI areas



Luminosity Function in Q1 Catalog

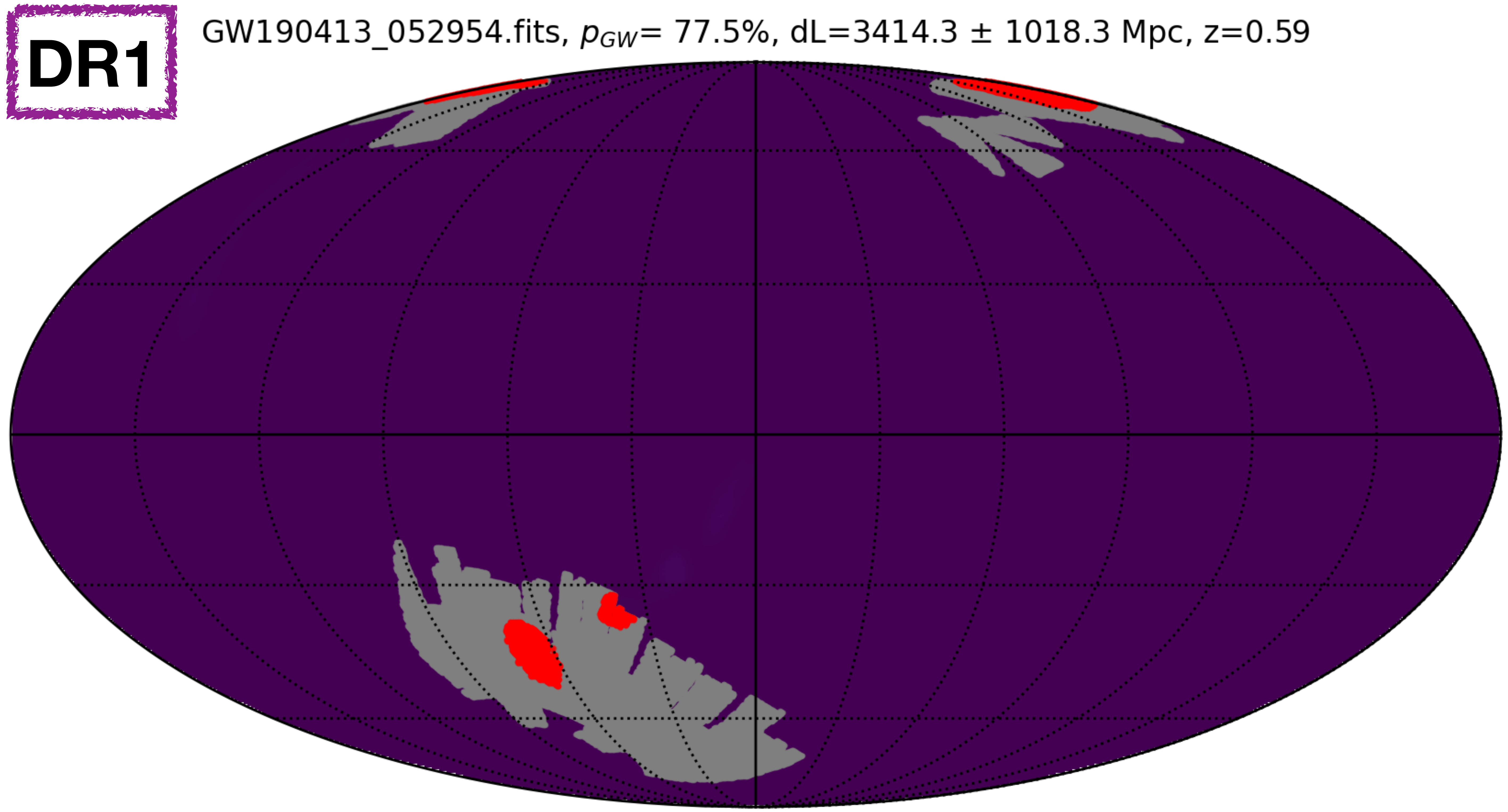
Y band example

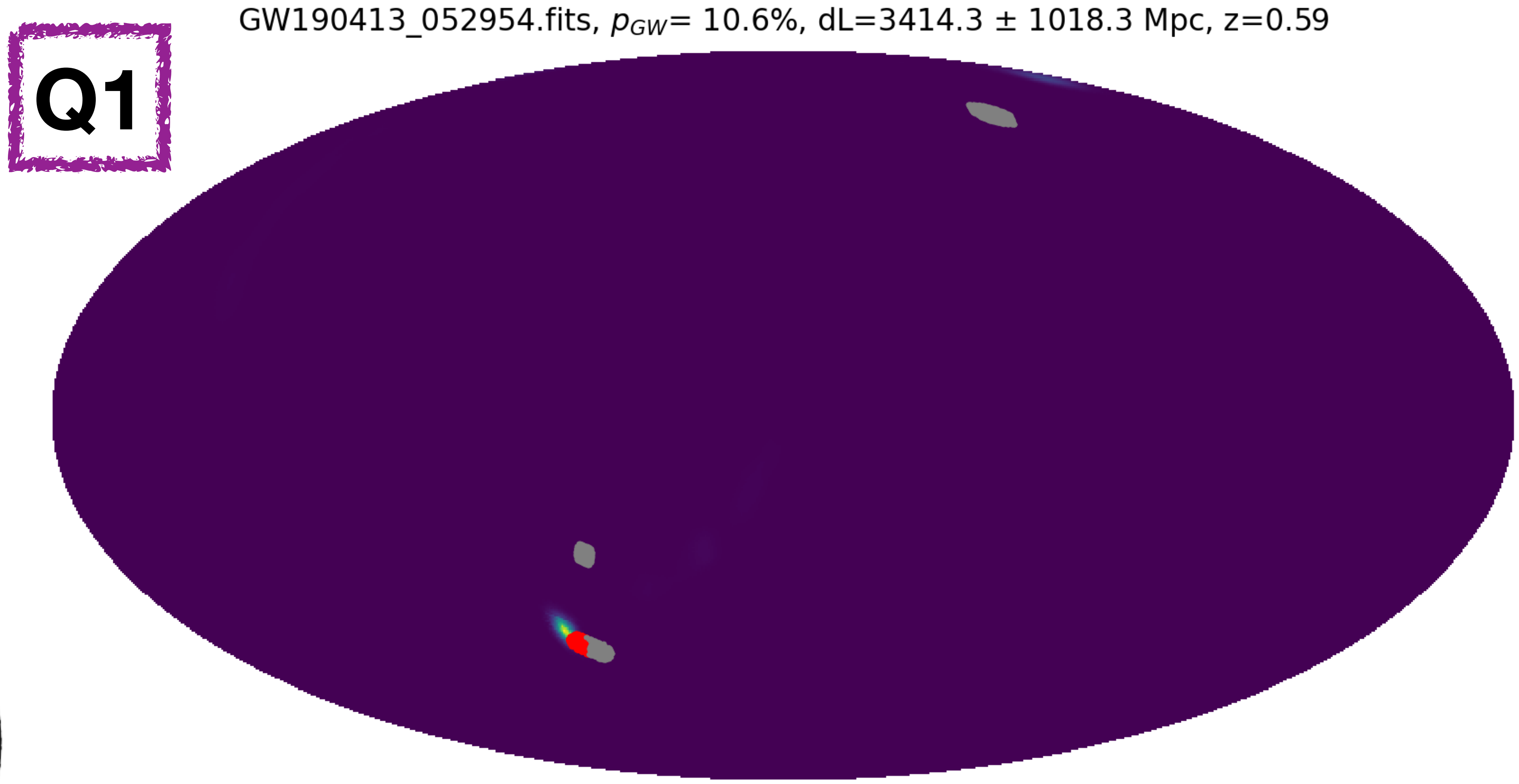


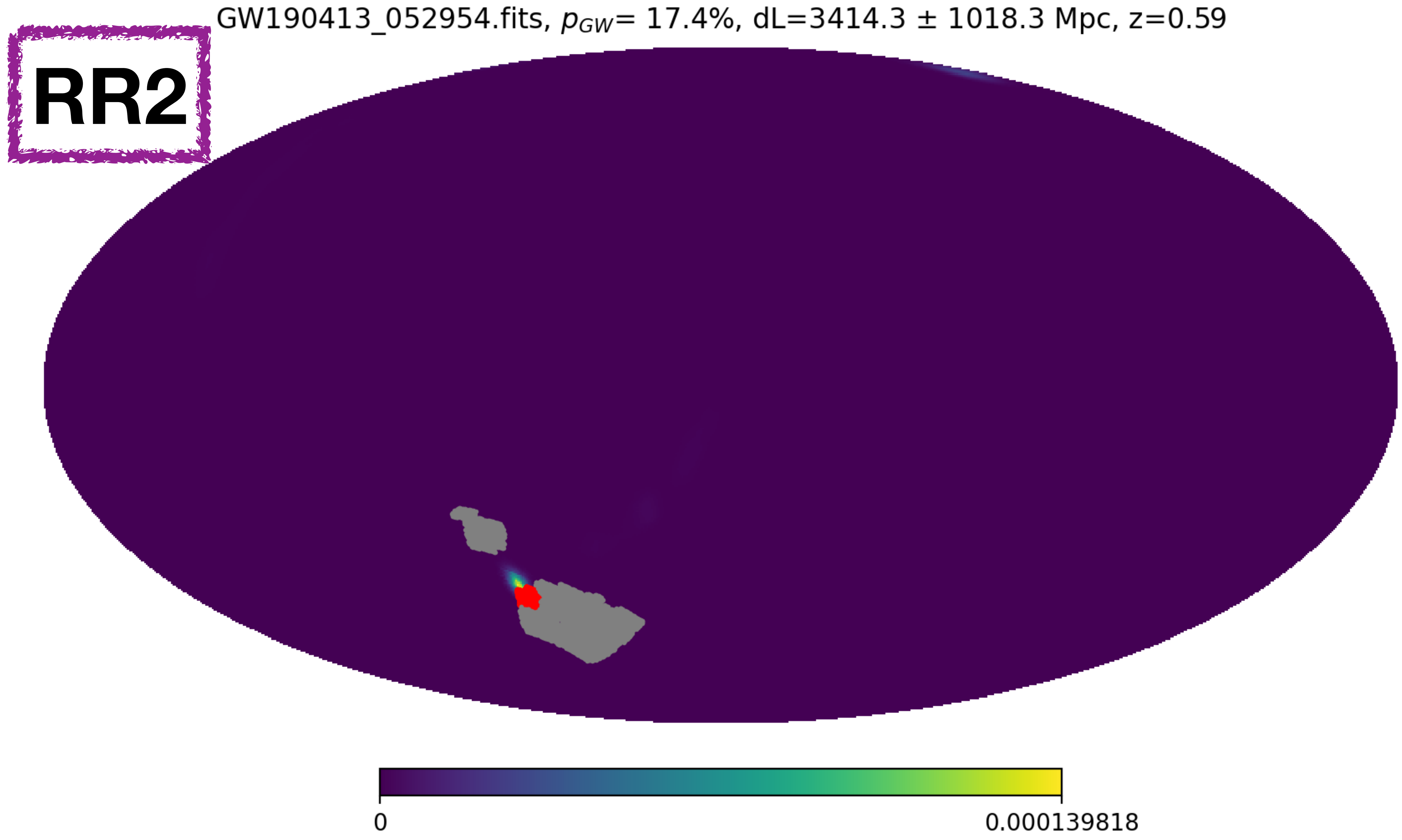
At z>1 the distribution look cleaner

Euclid and O1-O2-O3 GW events

GW190413



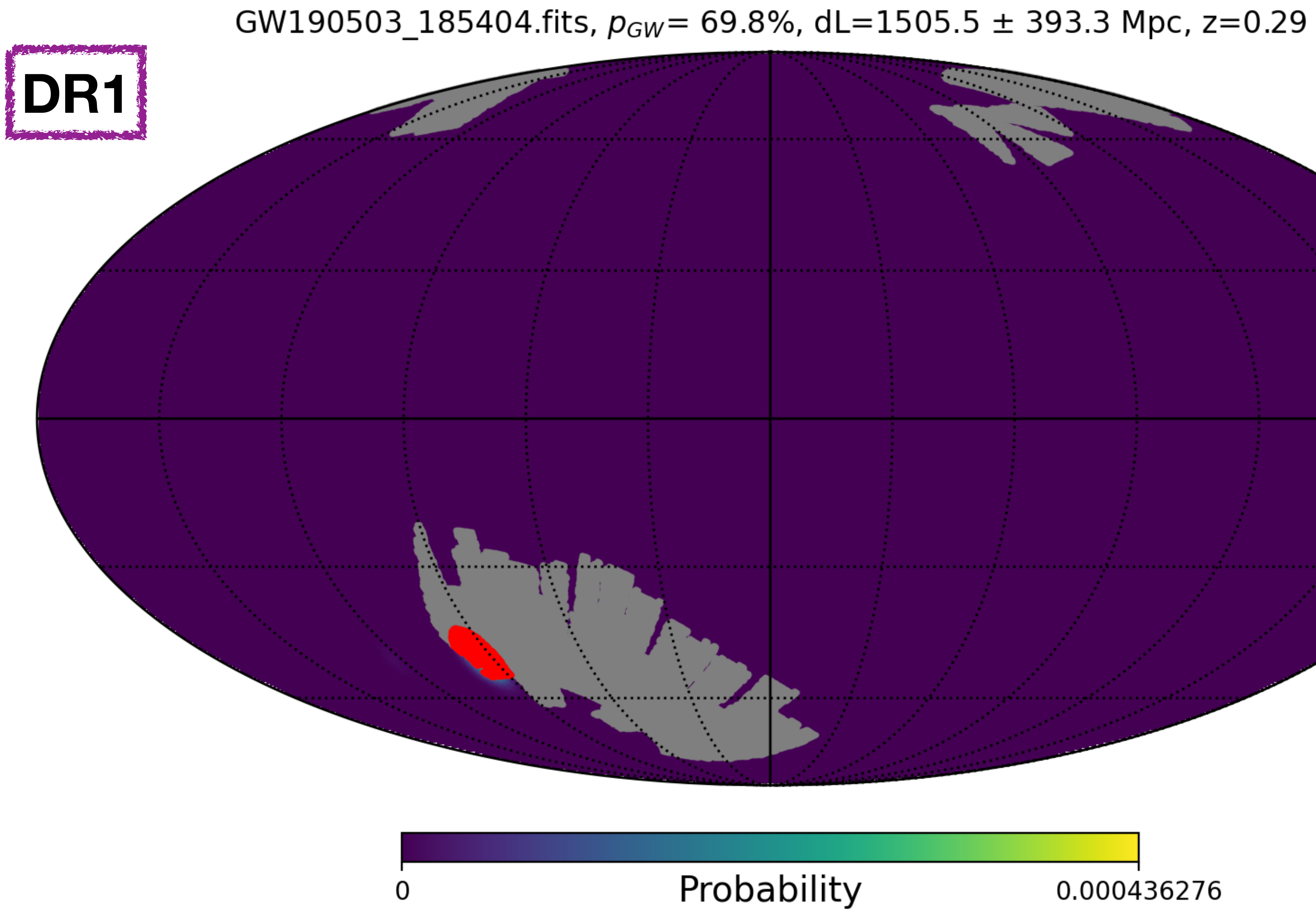




GW190413 is shown across three sky maps. The overlapping region with Euclid DR1 has a significant probability (77.5%), making it an interesting dark siren candidate

Euclid and O1-O2-O3 GW events

GW190503



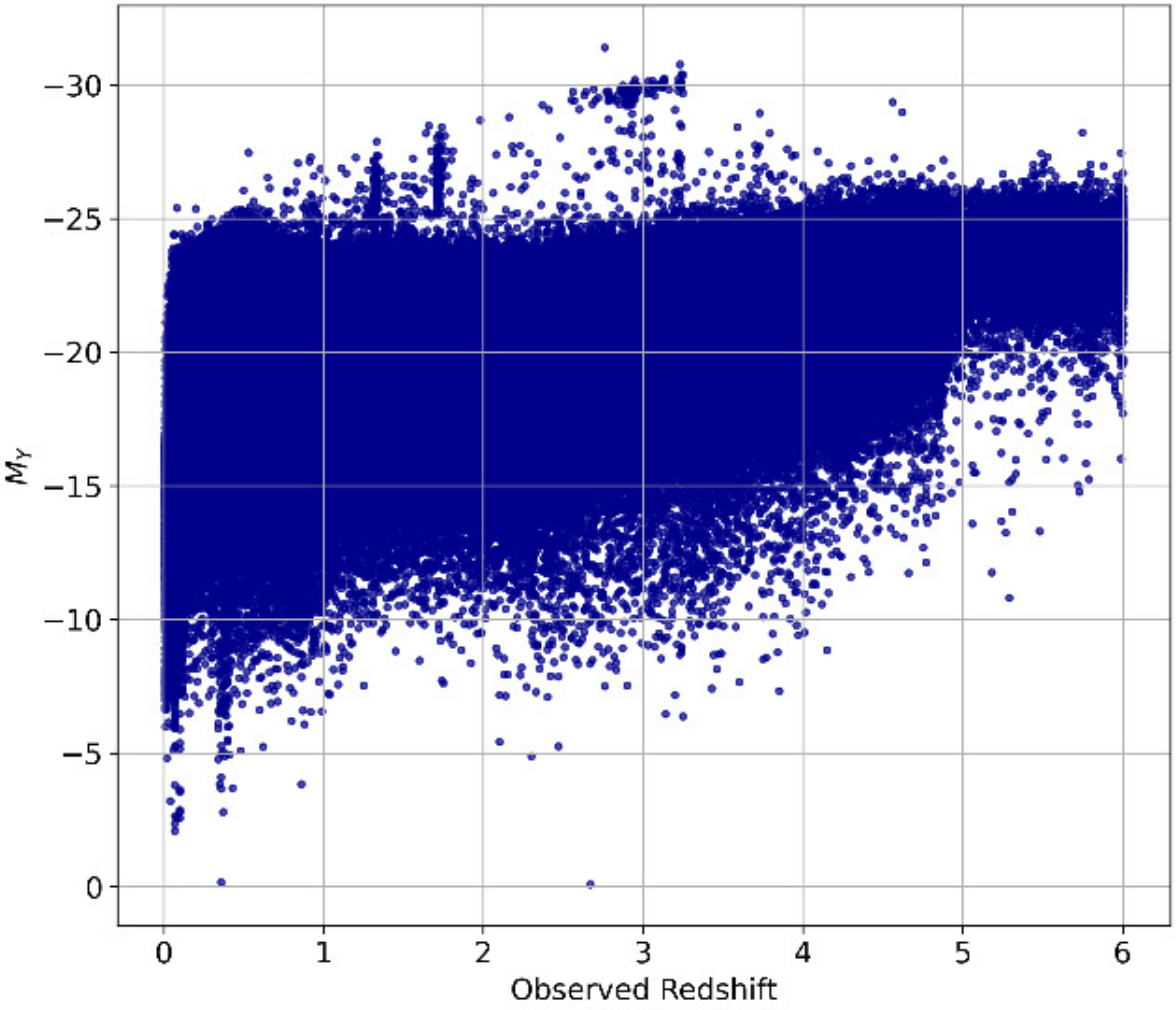
The overlapping region with Euclid DR1 has a probability of 69.8%. This event presents a moderate but viable opportunity for dark siren analysis

Completeness study

Q1 Euclid Catalog

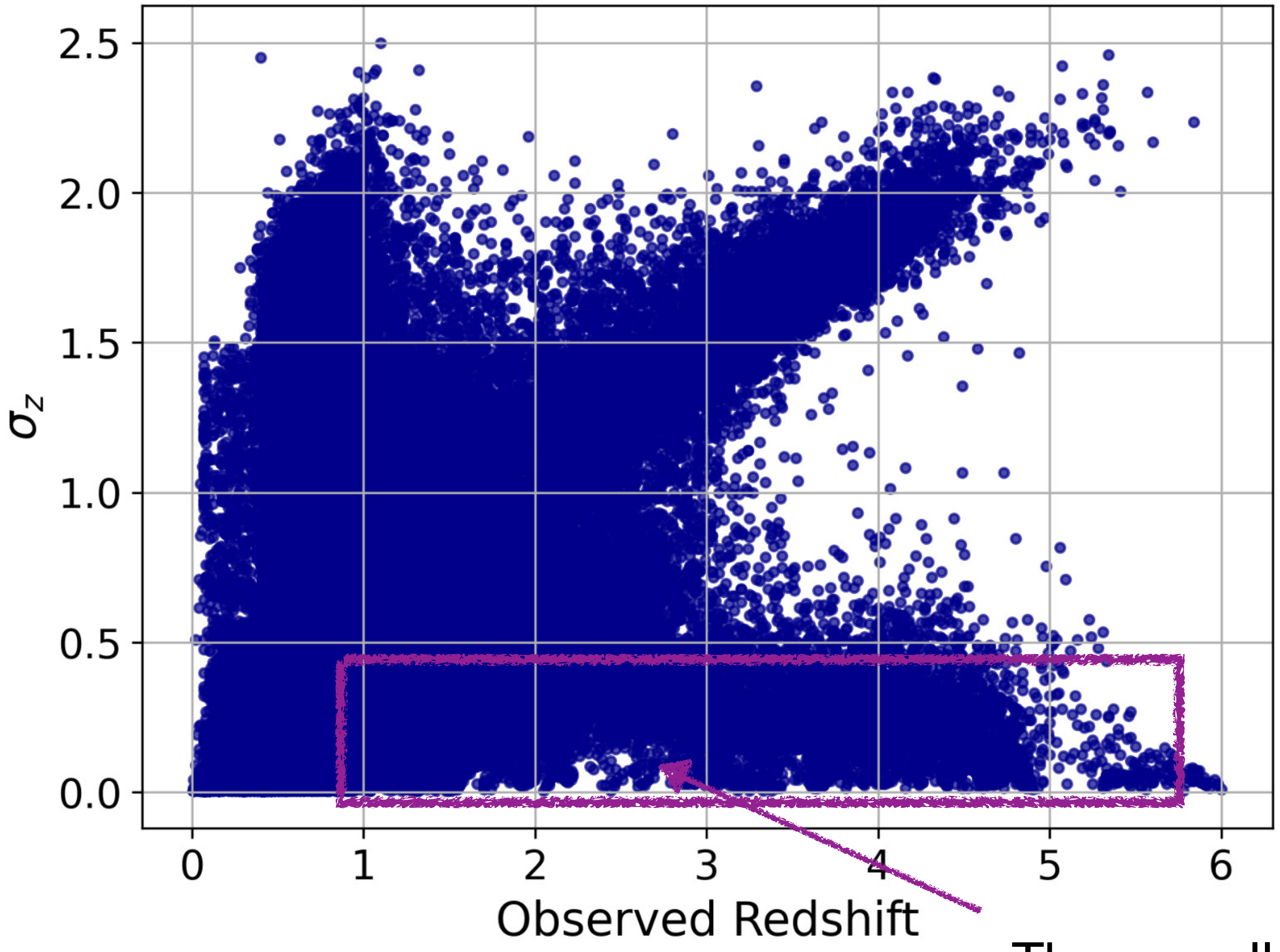
Y band example

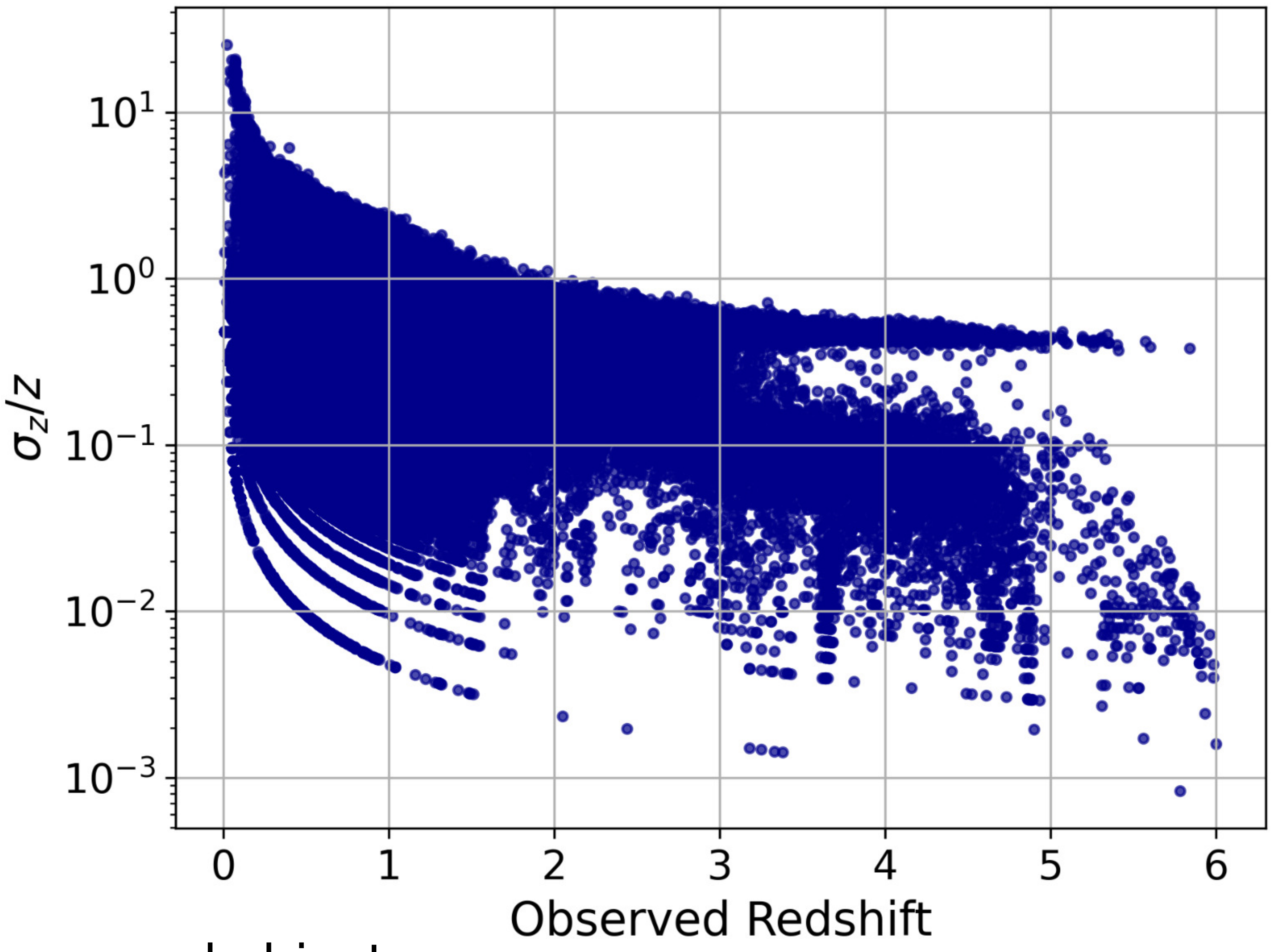
The catalog requires cleaning, as it contains numerous artifacts and sources of contamination



Completeness study

Q1 Euclid Catalog





These well-measured objects are important for the analysis

Luminosity Function

Schechter function

characteristic magnitude

In magnitude form : $\Phi(M) = 0.4 \ln(10)\, \Phi^* \, 10^{0.4(\alpha+1)(M^*-M)}\, e^{-10^{0.4(M^*-M)}}$

normalization (number density scale)

faint-end slope

LIGO-Virgo-KAGRA (LVK) sky maps

LVK distributes gravitational-wave event data in HEALPix .fits.gz files.

1. They use the HEALPix projection for all-sky imaging

2. Each pixel contains the probability that the source lies within it

```
# HDU 1 in bayestar.fits.gz,0:
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                   32 / length of dimension 1
NAXIS2  =             50331648 / length of dimension 2
PCOUNT  =                    0 / number of group parameters
GCOUNT  =                    1 / number of groups
TFIELDS =                    4 / number of table fields
TTYPE1  = 'PROB    '
TFORM1  = 'D       '
TUNIT1  = 'pix-1   '
TTYPE2  = 'DISTMU  '
TFORM2  = 'D       '
TUNIT2  = 'Mpc     '
TTYPE3  = 'DISTSIGMA'
TFORM3  = 'D       '
TUNIT3  = 'Mpc     '
TTYPE4  = 'DISTNORM'
TFORM4  = 'D       '
TUNIT4  = 'Mpc-2   '
PIXTYPE = 'HEALPIX '           / HEALPIX pixelisation
ORDERING= 'NESTED  '           / Pixel ordering scheme: RING, NESTED, or NUNIQ
COORDSYS= 'C       '           / Ecliptic, Galactic or Celestial (equatorial)
NSIDE   =                 2048 / Resolution parameter of HEALPIX
INDXSCHM= 'IMPLICIT'           / Indexing: IMPLICIT or EXPLICIT
OBJECT  = 'MS181101ab'         / Unique identifier for this event
REFERENC= 'https://example.org/superevents/MS181101ab/view/' / URL of this even
INSTRUME= 'H1,L1,V1'           / Instruments that triggered this event
DATE-OBS= '2018-11-01T22:22:46.654437' / UTC date of the observation
MJD-OBS =    58423.93248442613 / modified Julian date of the observation
DATE    = '2018-11-01T22:34:49.000000' / UTC date of file creation
CREATOR = 'BAYESTAR'           / Program that created this file
```

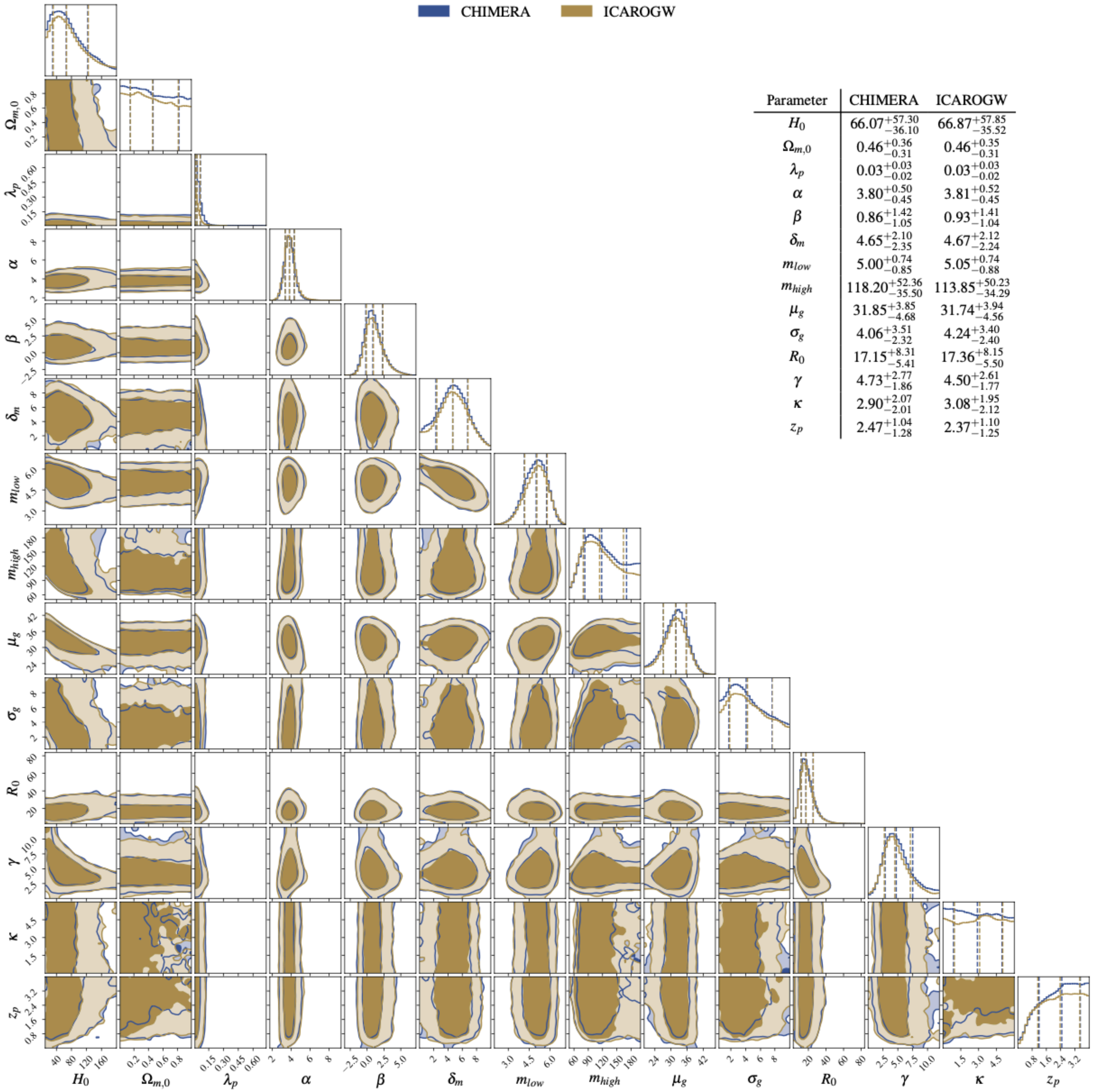
Blinded Mock Data Challenge for ET

Collaboration project with **Matteo Tagliazzucchi** (UniBo), Michele Moresco (UniBo), Michele Mancarella (CPT), and Alessandro Agapito (CPT), Simone Mastrogiovanni (INFN Rome)

Mock Data Challenge

We compare icarogw 2.0 and CHIMERA 2.0 in a joint population and cosmological parameters inference using 42 BBH from GWTC-3

.



Parameter	CHIMERA	ICAROGW
H_0	$66.07^{+57.30}_{-36.10}$	$66.87^{+57.85}_{-35.52}$
$\Omega_{m,0}$	$0.46^{+0.36}_{-0.31}$	$0.46^{+0.35}_{-0.31}$
λ_p	$0.03^{+0.03}_{-0.02}$	$0.03^{+0.03}_{-0.02}$
α	$3.80^{+0.50}_{-0.45}$	$3.81^{+0.52}_{-0.45}$
β	$0.86^{+1.42}_{-1.05}$	$0.93^{+1.41}_{-1.04}$
δ_m	$4.65^{+2.10}_{-2.35}$	$4.67^{+2.12}_{-2.24}$
m_{low}	$5.00^{+0.74}_{-0.85}$	$5.05^{+0.74}_{-0.88}$
m_{high}	$118.20^{+52.36}_{-35.50}$	$113.85^{+50.23}_{-34.29}$
μ_g	$31.85^{+3.85}_{-4.68}$	$31.74^{+3.94}_{-4.56}$
σ_g	$4.06^{+3.51}_{-2.32}$	$4.24^{+3.40}_{-2.40}$
R_0	$17.15^{+8.31}_{-5.41}$	$17.36^{+8.15}_{-5.50}$
γ	$4.73^{+2.77}_{-1.86}$	$4.50^{+2.61}_{-1.77}$
κ	$2.90^{+2.07}_{-2.01}$	$3.08^{+1.95}_{-2.12}$
z_p	$2.47^{+1.04}_{-1.28}$	$2.37^{+1.10}_{-1.25}$

Mock Data Challenge

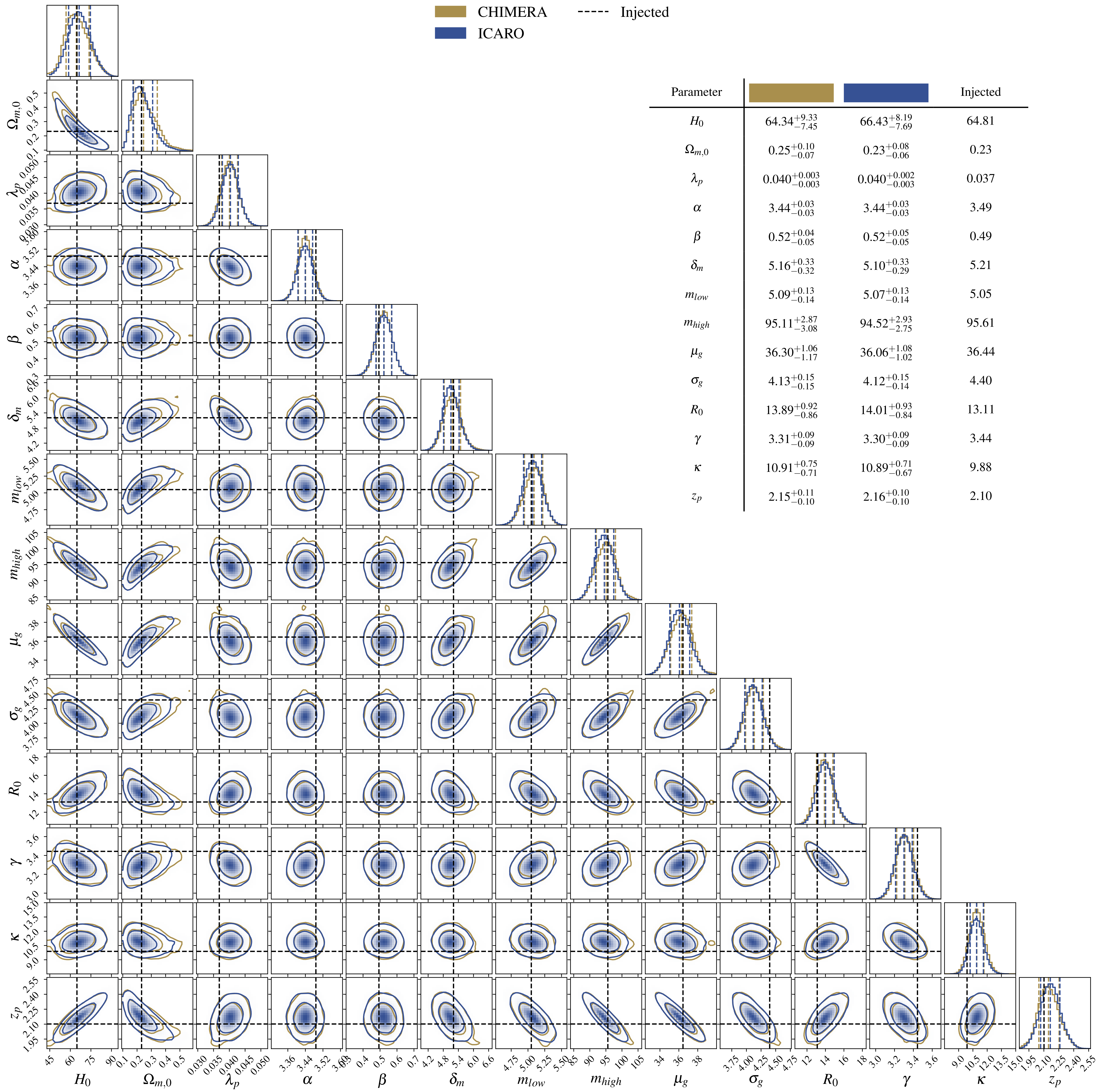
- Test using 6500 simulated events with SNR = 75 using 2 ET

- Chimera e Icarogw are giving similar results

Next steps:

- Test systematic effects of ICAROGW and CHIMERA

- This project is expected to result in a co-authored publication by the end of the year



Parameter	CHIMERA	ICARO	Injected
H_0	$64.34^{+9.33}_{-7.45}$	$66.43^{+8.19}_{-7.69}$	64.81
$\Omega_{m,0}$	$0.25^{+0.10}_{-0.07}$	$0.23^{+0.08}_{-0.06}$	0.23
λ_p	$0.040^{+0.003}_{-0.003}$	$0.040^{+0.002}_{-0.003}$	0.037
α	$3.44^{+0.03}_{-0.03}$	$3.44^{+0.03}_{-0.03}$	3.49
β	$0.52^{+0.04}_{-0.05}$	$0.52^{+0.05}_{-0.05}$	0.49
δ_m	$5.16^{+0.33}_{-0.32}$	$5.10^{+0.33}_{-0.29}$	5.21
m_{low}	$5.09^{+0.13}_{-0.14}$	$5.07^{+0.13}_{-0.14}$	5.05
m_{high}	$95.11^{+2.87}_{-3.08}$	$94.52^{+2.93}_{-2.75}$	95.61
μ_g	$36.30^{+1.06}_{-1.17}$	$36.06^{+1.08}_{-1.02}$	36.44
σ_g	$4.13^{+0.15}_{-0.15}$	$4.12^{+0.15}_{-0.14}$	4.40
R_0	$13.89^{+0.92}_{-0.86}$	$14.01^{+0.93}_{-0.84}$	13.11
γ	$3.31^{+0.09}_{-0.09}$	$3.30^{+0.09}_{-0.09}$	3.44
κ	$10.91^{+0.75}_{-0.71}$	$10.89^{+0.71}_{-0.67}$	9.88
z_p	$2.15^{+0.11}_{-0.10}$	$2.16^{+0.10}_{-0.10}$	2.10