CBPF

A measurement of the Hubble constant using dark sirens from the first four LIGO/Virgo observing runs with galaxy information from DELVE and DESI Legacy Survey

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Introduction

The current and next observation seasons will detect hundreds of gravitational waves (GWs) from compact binary systems coalescence at cosmological distances. When combined with independent electromagnetic measurements, the source redshift will be known, and we will be able to obtain precise measurements of the Hubble constant H_0 via the distance–redshift relation. However, most observed mergers are not expected to have electromagnetic counterparts, which prevents a direct redshift measurement. In this scenario, one possibility is to use the dark sirens method that statistically marginalizes over all the potential host galaxies within the GW location volume to provide a probabilistic source redshift. In this work we perform the most precise H_0 measurement with the better localized dark sirens (well-localized and confident candidate events from O4a LIGO-Virgo-Kagra Observing run and other two, GW190924 021846 and GW200202 154313, from first three observing runs). We use the public photometric catalogs and imaging data, mainly by the Dark Energy Spectroscopic Instrument (DESI) Legacy Survey ([1-2]) and DECam Local Volume Exploration Survey (DELVE; [3-4]) , derived the photometric redshifts using a deep learning technique to estimated a full probability density of photo-z.

Methodology

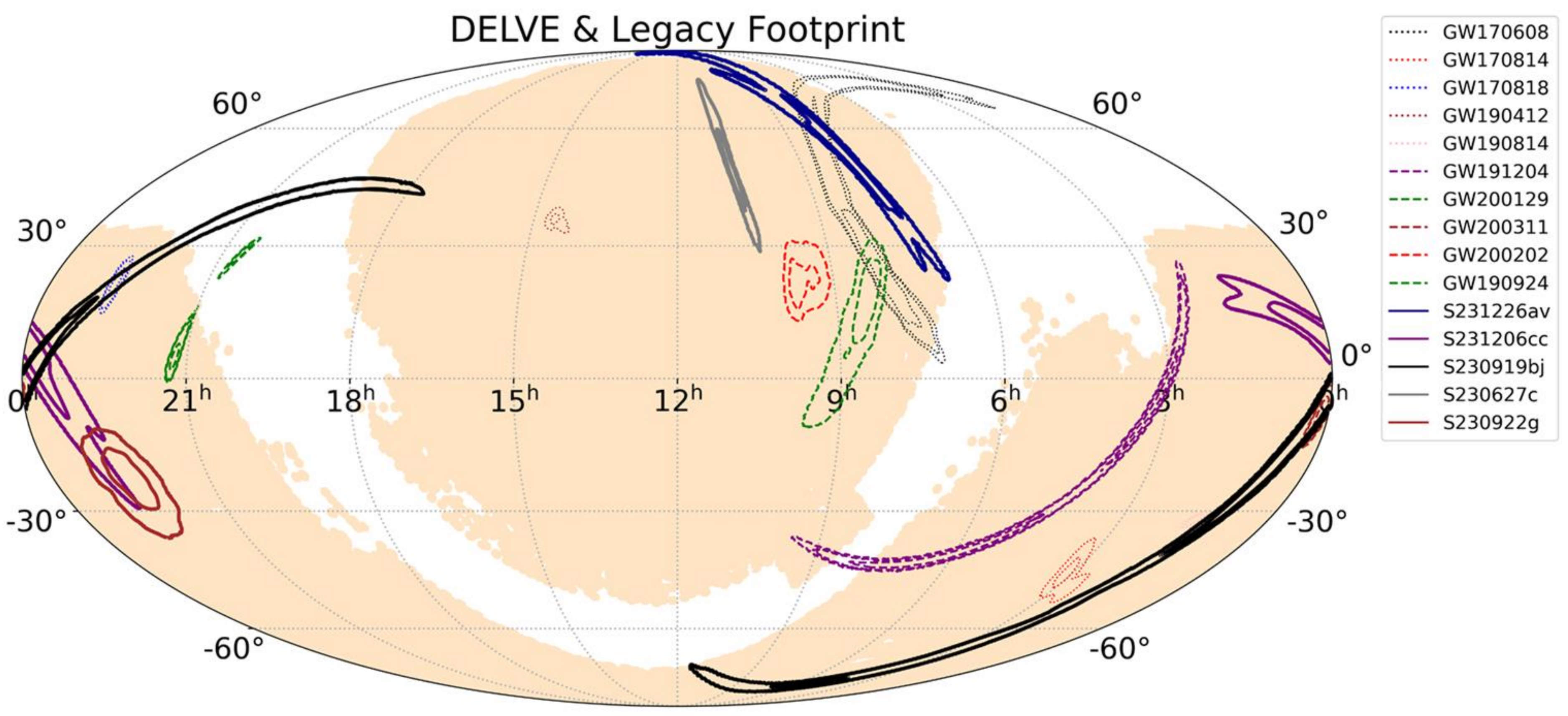
1) DATA:

a) The LIGO/Virgo GW data:

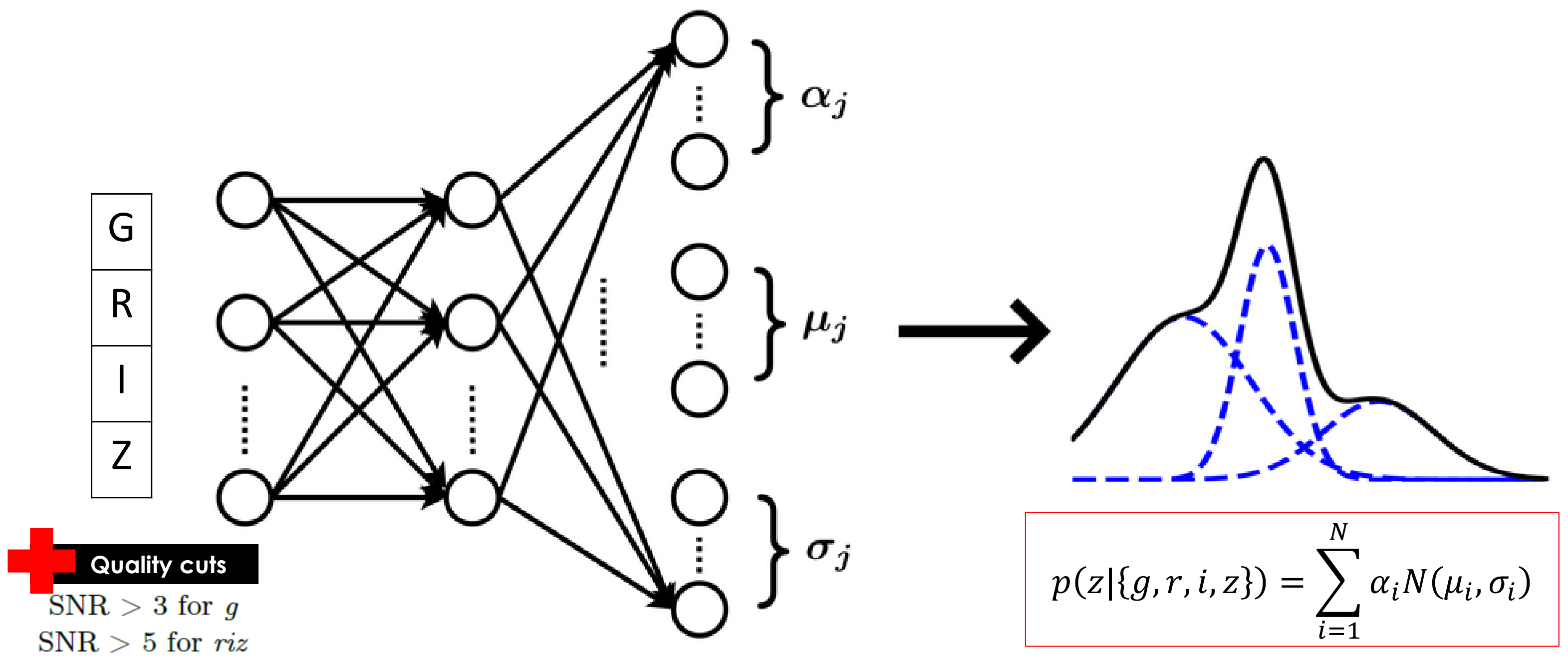
We expand the analysis upon the previous work with 8-events [5] by adding five novel sirens candidates events from O4a (S231226av, S231206cc, S230922g, S230919bj, and S230627c) and the two confirmed GW events from O3, GW190924 021846 and GW200202 154313. All the GW events satisfies the following selection criteria: > 70% of their probability is covered by the Legacy or DELVE surveys, and its luminosity distance is less than $d_L < 1500$ Mpc. We use the latest public skymaps produced by the python code Bilby (Ashton et al. 2019), that are available on the GraceDB event page (https://gracedb.ligo.org/).

b) **Optical Survey Data:**

We made use of publicly available catalogs from the DESI Legacy Survey [2] and DELVE survey ([3-4]). The combined footprint is presented in the figure below.


DELVE & Legacy Footprint

2) **Galaxies photo-z's: the Mixture density deep learning algorithm**



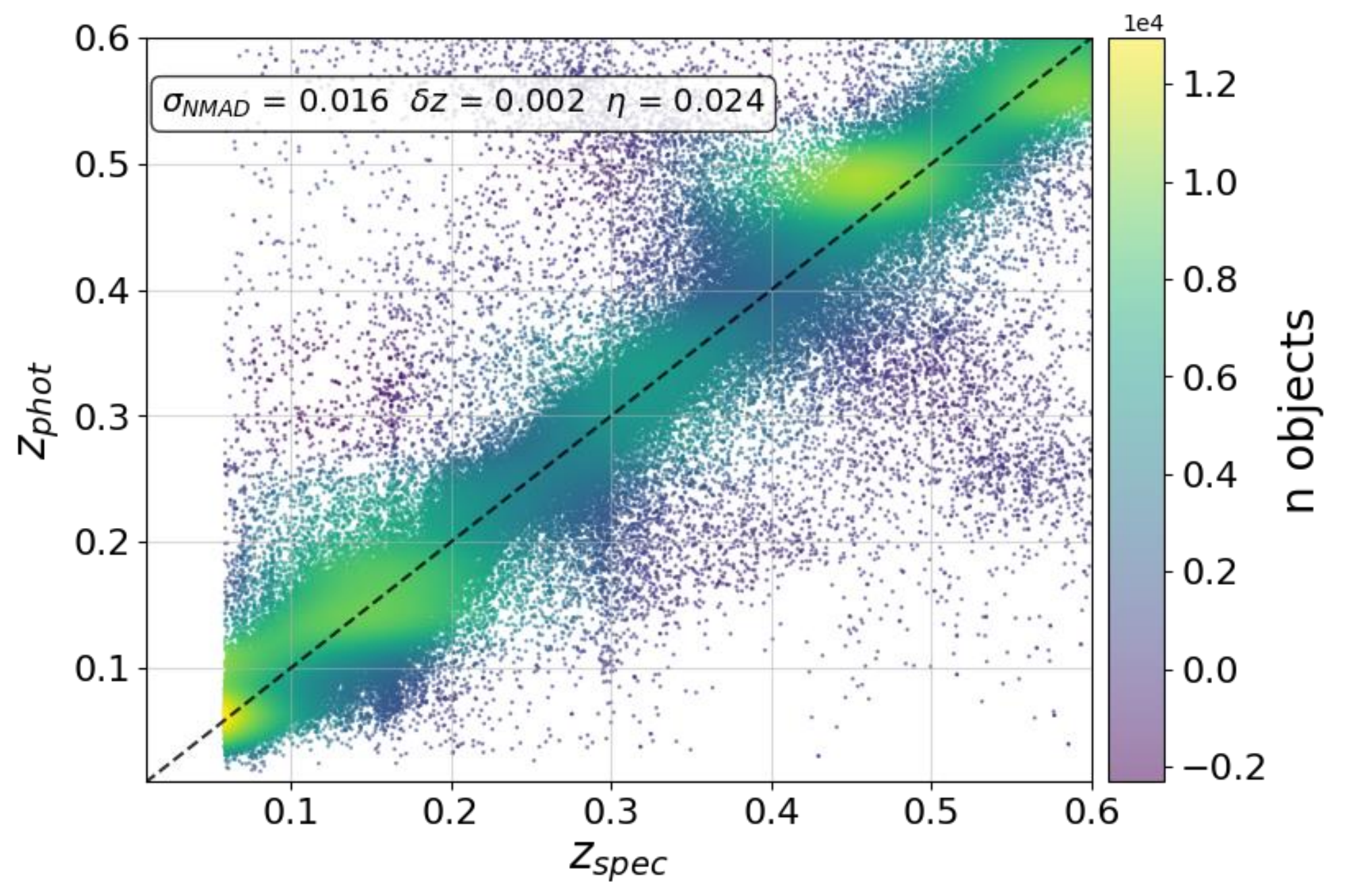
$$p(z|\{g,r,i,z\}) = \sum_{i=1}^{N} \alpha_i N(\mu_i,\sigma_i)$$

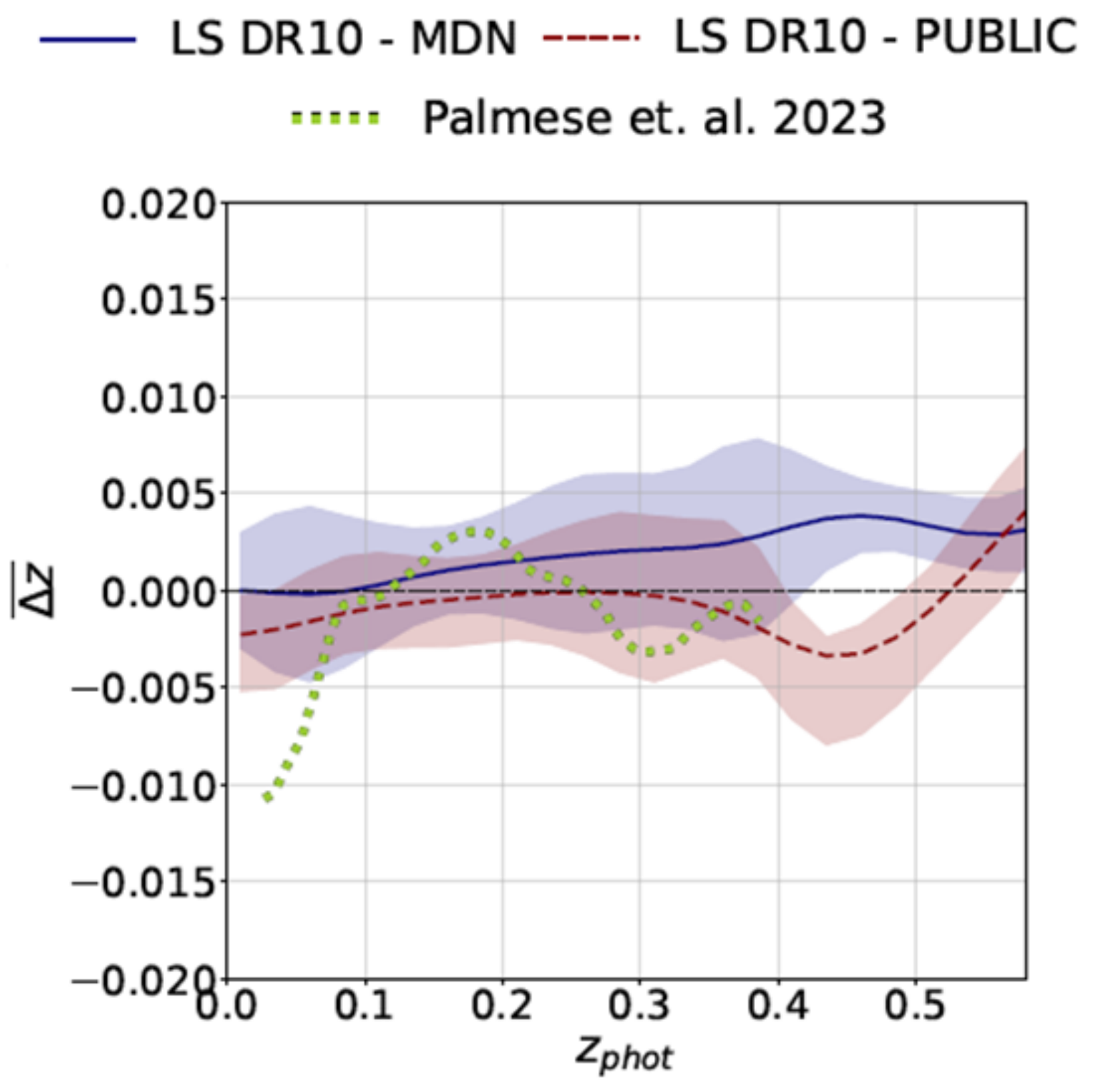
Quality cuts

$\mathrm{SNR} > 3$ for g
$\mathrm{SNR} > 5$ for riz
$-1 < g - r < 4$
$-1 < r - i < 4$
$-1 < i - z < 4$
$g < 22.5$
$0.01 < z_{spec} < 1$

Credit: Zoutendijk, M. & Mitici, M., Aerospace 2021, 8(6), 152.

- <u>**Photometric redshift quality assessment:**</u>





Results

The H_0 posterior within a Bayesian formalism for a gravitational wave measurement d_{GW} and electromagnetic data d_{EM} for a galaxy survey is

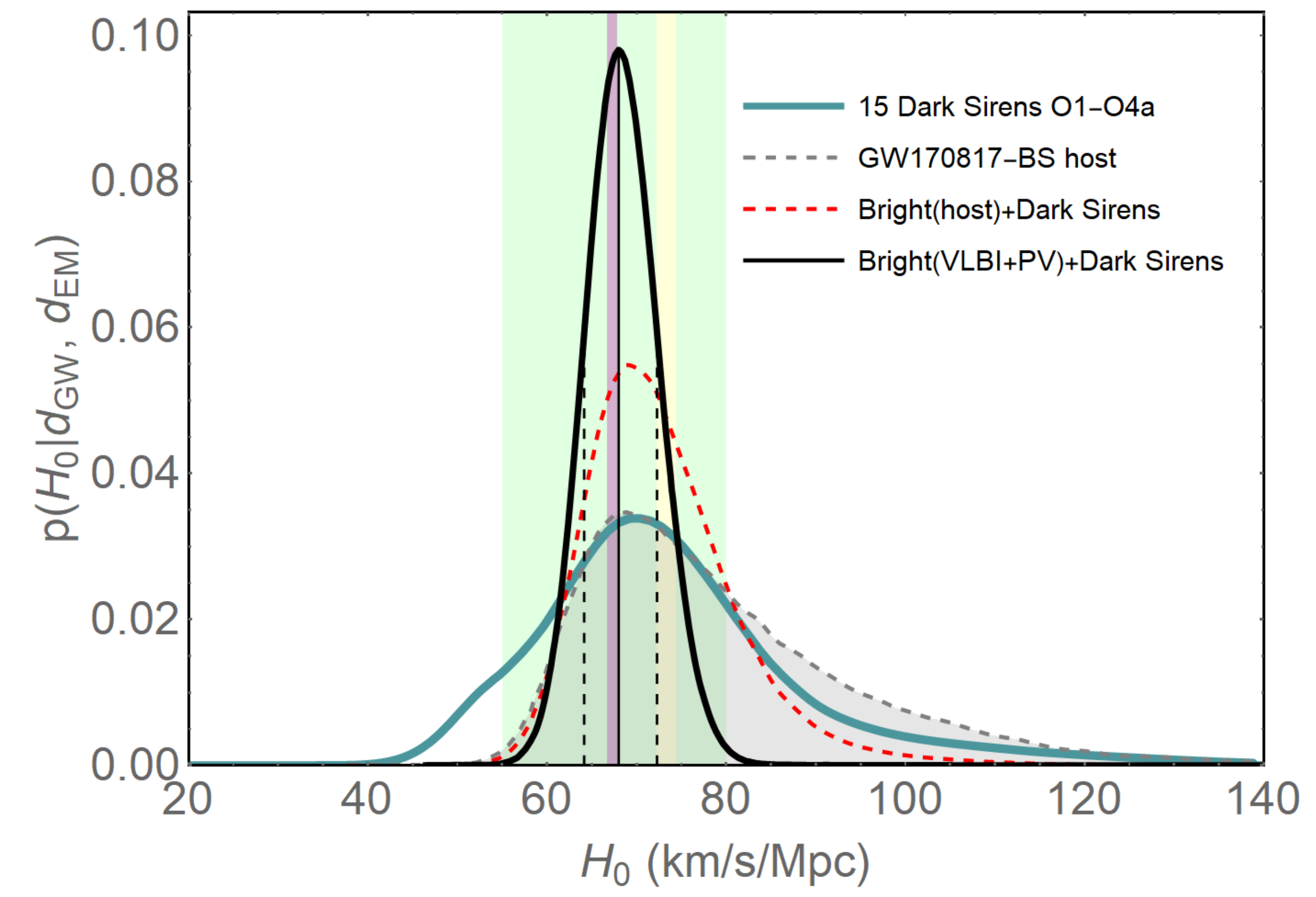
$$\boxed{p(H_0|d_{GW},d_{EM}) \propto \frac{p(H_0)}{\beta(H_0)} \sum_i \frac{1}{\mathcal{Z}_i} \int dz d\Delta z\, p\big(d_{GW}|d_L(z,H_0),\widehat{\Omega}_i\big) p_i(d_{EM}|z,\Delta z) p(\Delta z) \frac{r^2(z)}{H(z)}}$$

where $r(z,H_0)$ is the comoving distance, $H(z) = H_0(\Omega_{m0}(1+z)^3+1-\Omega_{m0})^{1/2}$ is the Hubble parameter in a Flat ΛCDM model, p(z) is the prior on the photometric redshift bias), $\beta(H_0)$ is the selection function responsible for normalizing the likelihood, and $\mathcal{Z}$ is the evidence term defined as $\mathcal{Z} = \int dz_i p(d_{EM}|z_i) r^2(z_i)/H(z_i)$. The first term inside the integral, $p\big(d_{GW}|d_L(z,H_0),\widehat{\Omega}_i\big)$, is the marginal GW likelihood and the second represents the marginal EM likelihood of the galaxy shifted by the photo-z bias Δz.

- **The H_0 posterior distributions of the 15 dark sirens of O1-O4 observations:**

Event(s)	Method(s)	H_0 (km/s/Mpc)	σ_{H_0} (km/s/Mpc)
O1-O3a [1]	Catalog	$67.3^{+27.6}_{-17.9}$	22.5 (34%)
O1-O3 – 8 dark sirens [2]	Catalog	$79.8^{+19.1}_{-12.8}$	15.8 (20%)
O1-O3 – 47 dark sirens [3]	Catalog + BBH population	67^{+13}_{-12}	12.5 (18%)
O1-O3 – 47 dark sirens [3]	BBH population	67^{+14}_{-13}	13.5 (20%)
O1-O3 - 10 dark sirens [4]	Catalog	$76.00^{+17.6}_{-13.4}$	15.6 (20%)
GW170817 [5]	Bright (v_p corrected)	$68.80^{+17.3}_{-7.6}$	12.5(18%)
GW170817 [6]	Bright (Chandra+HST+VLA)	$75.46^{+5.34}_{-5.39}$	5.36(7%)
GW170817 [7]	Bright (v_p+VLBI)	$68.3^{+4.6}_{-4.5}$	4.6(7%)
O1-O4a – 15 dark sirens [8]	Catalog	$69.9^{+13.3}_{-12.0}$	12.6 (18%)
O1-O4a – 15 dark + 1 bright sirens [8]	Bright (host) + Catalog	$69.2^{+9.0}_{-5.8}$	7.4 (11%)
O1-O4a – 15 dark + 1 BS (EM) [8]	Bright (Chandra+HST+VLA) + Catalog	$74.3^{+5.0}_{-5.0}$	5.0 (7%)
O1-O4a – 15 dark + 1 BS (EM) [8]	Bright (v_p+VLBI) + Catalog	$68.0^{+4.3}_{-3.8}$	4.0 (6%)

Table 1: Hubble constant measurements using gravitational wave standard sirens from this work and previous works. H0 values and uncertainties are given in km s−1 Mpc−1, and H0 priors are flat, unless otherwise stated. The uncertainty from the flat prior only is derived by assuming the same H0 maximum found in the analysis. Quoted uncertainties represent 68% HDI around the maximum of the posterior. The "σH0/σprior"column shows the 68% CI from the posterior divided by 68% CI of the prior width. (1) Finke et al. (2021), (2) Palmese et al. (2023), (3) Abbott et al. (2023a), (4) Alfradique et al. (2024), (5) adapted from Nicolaou et al. (2020), (6) Palmese et al. (2024), (7) Mukherjee et al. (2021), and (8) this work.



Conclusion

- We presented a new measure of H_0 provided by the current best localized and covered GW events from LVK O1-O4a observing run with the galaxy catalog method and precise photometric redshift. The combination of the 15 dark sirens leads to a H_0 measurement found is $\mathbf{69.9^{+13.3}_{-12.0}}$ **km/s/Mpc**, a **-18% uncertainty of H_0. This is, at the best of our knowledge, an unprecedented precision for the catalog method and for the dark siren approach.**

- In addition, we combine the H_0 posterior from the 15 dark sirens with recente constraints over the one bright standard siren available, GW170817, considering the constraints to the viewing angle from VLBI and the host galaxy peculiar velocity [12] and obtained H_0 = $\mathbf{68.00^{+4.28}_{-3.85}}$ km/s/Mpc, a **relative precision of 6%**, reducing the previous constraint **uncertainty in ~ 10%.**

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