



Cosmology from Synergies Between SKAO Surveys and Gravitational Wave Observations

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Both radio surveys and gravitational wave observations have the potential to probe unprecedented volumes in the Universe with systematics independent of existing cosmological probes. This gives them the potential, especially in combination, to solve some of the outstanding issues in cosmology. Here we show how the use of radio observations as electromagnetic signals tracing large scale structures can be used to provide information on gravitational wave *standard sirens*. By providing a way to link luminosity distance to redshift, this combination can constrain the expansion history of the Universe, and provide information on the Hubble constant (H_0). We describe the utility of SKA-Mid neutral hydrogen (HI) intensity maps, HI galaxy redshift surveys, and continuum galaxy surveys compared to and in conjunction with large contemporaneous optical surveys. Such radio tracers provide a unique, large volume and high redshift information for gravitational wave source, capable of probing effectively the expansion history of the Universe $H(z)$.

1 Introduction

The discovery of the Universe's expansion by Hubble (Hubble, 1929) stands as a landmark achievement in astrophysics. Since then, determining the Hubble constant has remained a central objective in cosmology. As the measurements became increasingly precise, a persistent and unresolved discrepancy, known as the Hubble tension, emerged (Di Valentino et al., 2021).

This tension arises from the difference between two measurement approaches: indirect estimates derived from early-Universe Cosmic Microwave Background (CMB) observations and direct measurements based on local-Universe type Ia supernovae (SNe) data. These manifest a $\sim 5\sigma$ tension: we get $H_0 = 67.49 \pm 0.53 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from the CMB measurements (Planck Collaboration et al., 2020) and $H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ from SNe (Riess et al., 2022).

The first direct detection of gravitational waves (GWs) (Abbott et al., 2016) has opened the way to a new and independent probe of the expansion, which may someday shed light on the tension.

GWs from compact binary coalescences (CBCs), binary black holes (BBHs), binary neutron stars (BNSs), and neutron star - black holes (NSBHs) are the only astrophysical sources we measured so far for which we are able to access directly the luminosity distance, without having to rely on any calibration or distance ladder, representing one of the main shortcomings of the *standard candle* cosmology. The idea of GW cosmology dates back to the seminal paper by Schutz (1986). GWs, in fact, can be used as *standard sirens* (Holz and Hughes, 2005; Del Pozzo, 2012). Being cosmic rulers, GWs provide us with a self-calibrated measurement of the luminosity distance. Access to the redshift information, on the other hand, is not straightforward. Since in GW cosmology constraining the expansion rate of the Universe requires an independent measurement of both distance and redshift, alongside the luminosity distance derived from gravitational measurements, there is the need to develop methods to associate the redshift information.

The easiest and most informative approach requires the identification of an electromagnetic (EM) counterpart. When at least one of the two components of a CBC merger is a neutron star (NS), there is the possibility that part of the ejecta material fuels an EM counterpart, either in the form of a kilonova (KN) or a gamma-ray burst (GRB), or both. In such an event, the unique identification of the host galaxy, when the observation of the EM counterpart is feasible, allows easy access to the redshift association to the GW event. In such a case, we speak of *bright sirens*. So far, there has been only one bright siren measurement, coming from the merger of a BNS, for which we observed both the KN and the GRB, GW170817 (Abbott et al., 2017a). The H_0 constraint from GW170817, measuring $H_0 = 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (at 68% C.L. highest density interval), is in agreement with both the measurements from Planck 2018 data survey (Planck Collaboration et al., 2020) and Type Ia SNe constraints (Riess et al., 2022), although with large uncertainties. The H_0 measurement from GW170817 still prevent us from deeper insights into the Hubble, tension, but this type of events would allow, in principle, sub-percent precision in constraining H_0 (Chen et al., 2018).

Interestingly, it is possible to measure the Hubble parameter even without an EM counterpart: the increasing number of such CBC observations, most of them being BBHs, allows us to exploit *dark siren* methods. A particular version of this method, often referred to as the *catalogue* method, combines the information on luminosity distance and sky localisation available from the detected

GW waveform with the redshift information available from a galaxy catalogue (Holz and Hughes, 2005; Del Pozzo, 2012; Gray et al., 2022; Gair et al., 2023), with the combined redshift information across the catalogue used as a *redshift prior* for CBC events. For each GW source a probabilistic association is made with the galaxies as potential host locations, corresponding to a given redshift and a given H_0 . Though for a typical sky localisation regions for an individual GW event there will be many possible associated galaxy redshifts (and hence many possible H_0 values), the likelihoods for many individual GW events may be multiplied together, with the probability mass at the correct H_0 value being coherently reinforced and other noise-like associations being diminished. To date, this method has mostly involved photometric optical and near-Infrared galaxy surveys due to their relative depth and sky coverage, ensuring the greatest probability that the correct host galaxy is included.

Additionally, the *spectral sirens* method also uses dark sirens events, but instead of applying a redshift prior formed from the positions of detected potential host galaxies, it instead uses the expected joint mass-redshift distribution of CBC events determined from population modelling (e.g. Ezquiaga and Holz, 2022). Similarly, though this may lead to highly biased results for small numbers of GW events, the correct H_0 value may be increasingly isolated as orders of magnitude more sources are included. This prior information may also be combined with the prior information on CBC redshift from the catalogue method, with this often being referred to as a *line of sight redshift prior*.

This method comes with several complications, including the correct relative normalisation of host probability for each potential galaxy position. This involves not only the redshift probability distribution for the galaxy ($P_{\text{gal}}(z)$) but the probability that a particular galaxy is a host of a particular CBC (P_{host}). These two probabilities may depend on many of the same underlying variables (e.g. galaxy mass, metallicity) requiring a careful treatment to avoid biases on the cosmological inference (Mastrogiovanni et al., 2021). Another complication arises in the inclusion of completeness of the galaxy catalogue as a function of redshift as one needs to correctly account for the probability that the CBC has occurred in a galaxy which is not part of the galaxy catalogue (see e.g. Gray et al., 2020, for a description).

The LIGO-Virgo-KAGRA (LVK) Collaboration has reported constraints on the Hubble constant using either features in the mass spectrum alone, *spectral sirens*, or in combination with the information coming from statistical association with galaxy catalogs (Abbott et al., 2021, 2023, 2025).

Looking ahead, the future GW observatories, such as the Einstein Telescope (ET) (Punturo et al., 2010; Maggiore et al., 2020; Branchesi et al., 2023; Abac et al., 2026) and Cosmic Explorer (CE) (Reitze et al., 2019; Evans et al., 2021; Gupta et al., 2024), will open a new observational era. These third-generation (3G) detectors will provide an order-of-magnitude increase in sensitivity compared to the current LVK network, enabling the detection of sources out to very high redshifts and producing an order of $\sim 10^5$ CBC events per year. Such a wealth of data will make population-level studies and statistical approaches to cosmology with GWs increasingly powerful. They will also begin to detect CBC at increasing redshifts beyond the reach of optical galaxy catalogues.

In this context, a new synergy between GWs and other EM tracers of the large-scale structure (LSS) is emerging. Of particular interest here is the ability of neutral hydrogen (HI) intensity mapping (IM) (e.g. Battye et al., 2004; Santos et al., 2017; SKAO Cosmology SWG et al., 2020) to provide us with redshift information to be combined the luminosity distance measurement coming from GWs. We will describe two uses. First, the three dimensional map of the matter in the Universe offered by HI IM can be used, similarly to what is currently done with galaxy catalogues, to provide a line-of-sight (LoS) redshift prior. Secondly, the cosmological parameters are inferred from the cross-power spectrum of maps of the spatial distributions of HI and GW sources.

SKA Observatory (SKAO) will be capable of surveying large volumes of the Universe across much of the sky with redshift ideally spanning the range $0.35 < z \lesssim 3$ with SKA-Mid but also $3 \lesssim z \lesssim 20$ with SKA-Low, potentially providing redshift prior information for dark sirens analyses in regions unavailable to the traditional optical catalogues. The redshift ranges for the different SKAO telescope bands are shown as the purple regions of Fig. 1, along with the observable horizons of future GW observatories. This represents a unique opportunity, not only for increasing precision on H_0 , but also to probe the expansion history $H(z)$ at higher redshift, allowing to test models of modified gravity Ishak et al. (2025) and dynamical dark energy Lodha et al. (2025a,b). Compared to galaxy surveys, which typically become highly incomplete at redshifts above ~ 1 , IM from SKA-Mid could survey the entire southern sky up to $z \sim 3$ (SKAO Cosmology SWG et al., 2020), making IM an ideal complement which can provide redshift information for GW sources which would otherwise lie outside the informative part of the redshift prior. This use of HI information in dark sirens analysis is discussed extensively in Sec. 2.2.

In Fig. 1, we are showing a summary of the synergy between 3G GW observatories and observable with SKAO. We use the horizon as a metric for GW capabilities. This figure of merit shows, as a function of the total source-frame binary mass, the maximum redshift that such a system would be observed with a signal-to-noise ratio (SNR) threshold of eight under ideal conditions, i.e., equal-mass optimally oriented binaries. We show different network capabilities, in magenta, using different line styles. The *solid* line refers to the LVK network during the ongoing fourth observing run, using an optimistic-case simulated sensitivity curve. The *dashed* line refers to the future LVK upgrade comprising the LIGO India interferometer. The *dotted* one represents the leap achievable with a 3G detector like the ET¹. The current catalog of GW sources, comprising observations from 2015 till 2025, GWTC-4.0 (Abac et al., 2025) is represented with *purple triangles*.

Finally, as well as dark siren line of sight redshift priors, radio afterglows from CBC mergers can also be used to provide individual host identifications, giving z information for estimating H_0 . Expectations for these afterglows are also shown by the yellow stars in Fig. 1 and will be discussed in detail in Sec. 2.1.1. The wide redshift range covered with SKAO well matches the potential of future GW observatories, not only on the sheer gravitational detection side, but also for the potential radio emissions associated with some categories of GW sources, such as mergers involving NSs.

¹The sensitivity curves for the GW detectors are publicly available [here](#) for the LVK detectors and [here](#) for ET. In particular, we use *aligo_O4high.txt* for the LIGO O4 sensitivity and *AplusDesign.txt* for its O5 upgrade. We use *avirgo_O4high_NEW.txt* for the O4 stage of Virgo, and *avirgo_O5high_NEW.txt* for O5. Finally, for KAGRA O4 sensitivity, we employ the *kagra_10Mpc.txt* curve, and *kagra_128Mpc.txt* for the O5 stage. For ET, we employ the full cryogenic sensitivity for a 10 km-arm triangle shape as studied in Branchesi et al. (2023)

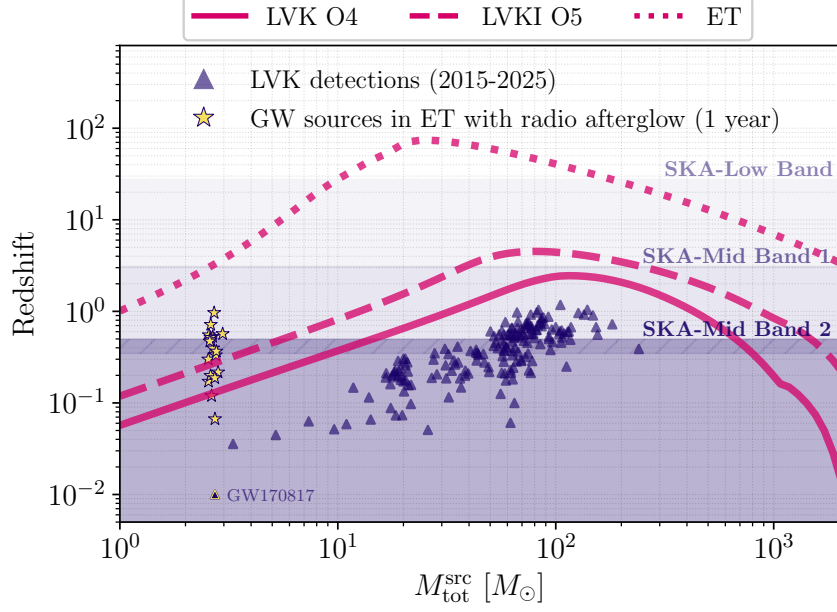


Figure 1: Horizon plots (*magenta* lines) for current and future GW observations compared to the SKAO reach in redshift. The horizon represents the maximum redshift for CBC equal-mass and optimally oriented GW sources observed with a SNR threshold of 8. On the x -axis is the total source-frame mass of the binary, while on y -axis is the redshift of the merger. The different line styles refer to different detectors' networks. The *solid* line refers to the LVK network during the ongoing fourth observing run, using an optimistic-case simulated sensitivity curve. The *dashed* line refers to the future LVK upgrade comprising the LIGO India interferometer. The *dotted* one represents the leap achievable with a 3G detector like the ET. The sensitivity curves for the GW detectors are publicly available [here](#) for the LVK detectors and [here](#) for ET (see footnote for details). The current catalog of GW sources, comprising observations from 2015 till 2025, GWTC-4.0 (Abac et al., 2025) is represented with *purple triangles*, while a simulation of one year of ET-detectable BNS sources with an associated afterglow in the radio band, detectable with SKAO, is marked with *yellow triangles*. We highlighted GW170817, our only bright siren event. The SKAO redshift ranges are highlighted horizontally in *purple*: there are the two bands of SKA-Mid, band 2 (950 – 1760 MHz) and band 1 (350 – 1050 MHz), and the high-redshift SKA-Low band (50 – 350 MHz). The intersection region of the two SKA-Mid bands is hatched.

This chapter is organized as follows. In Sec. 2, we introduce the general framework of the LoS cosmological approach, discussing both *bright* (Sec. 2.1.1) and *dark* (Sec. 2.1.2) sirens. The application of the H_I LoS method is then outlined in Sec. 2.2. In Sec. 2.3, we describe additional radio tracers relevant for the LoS approach, including continuum (Sec. 2.3.1) and H_I galaxies (Sec. 2.3.2). The cross-correlation analysis is presented in Sec. 3, and our main conclusions are summarized in Sec. 4.

2 GW sirens with line-of-sight redshift priors

2.1 Current Approaches

2.1.1 Bright Sirens

Mergers involving at least one neutron star, such as BNS and NSBH systems, can give rise to a variety of EM counterparts, including KNe and short GRBs with their associated prompt and afterglow emission. When such counterparts are detected, they enable the secure identification of the host galaxy and its redshift, providing the redshift information required to pair with the luminosity distance inferred directly from the GW signal. These events, commonly referred to as *bright sirens*, thus offer a completely self-calibrated distance–redshift relation that is independent of any external distance ladder.

As mentioned in the introduction, so far only one bright siren has been detected, GW170817, together with its KN and short GRB counterparts (Abbott et al., 2017b,a). The firm identification of its host galaxy, NGC 4993, provided a direct estimate of the Hubble constant. Since then, one additional BNS event has been detected but with insufficient sky localisation for meaningful EM follow-up, and none of the NSBH systems observed so far have shown detectable EM emission—likely due to limited mass ejection suppressing bright KN or GRB signatures.

The landscape is expected to change dramatically with the advent of 3G GW observatories, which will increase the detection rate of BNS and NSBH mergers by orders of magnitude. In parallel, the next generation of EM facilities will enhance our ability to identify their counterparts. Together, these advances will transform bright sirens from rare occurrences into a powerful and statistically rich probe of cosmic expansion, enabling precise cosmological measurements and the possibility of reaching sub-percent accuracy on H_0 with sufficiently large samples (Mancarella et al., 2024; Cozzumbo et al., 2025).

Radio observations will play a central role in this endeavour. As discussed in (Colombo et al., 2025), radio afterglows from short GRB can persist far longer than other EM bands, making radio follow-up a robust route for detecting and characterising GW-triggered transients. Radio observations provide unique insights into jet structure and energetics, constrain the viewing angle, and may reveal an afterglow even when a KN is too faint to be detected.

In this context, the capabilities of the SKAO are particularly significant. With its high sensitivity, large field of view, and broad frequency coverage, the SKAO will be ideally suited to discovering and monitoring radio afterglows from BNS and NSBH systems. Crucially, even when optical facilities fail to detect a counterpart, SKAO observations can still enable host-galaxy identification and improve constraints on source geometry, thereby refining the luminosity-distance measurement and strengthening the cosmological inference.

We perform here a cosmological-inference study to assess the potential of the bright siren method when combining 3G GW detectors and SKAO. Specifically, we simulate a population of BNS mergers as in Colombo et al. (2025), detected in GWs by ET and accompanied by radio afterglows observable with SKAO. Radio counterparts are generated at the central frequency of SKAO band 5a (6.55 GHz), and an event is considered detected if the afterglow peak flux exceeds $8.5 \mu\text{Jy}$. We find

18 detectable GW+radio afterglow events in one year of observations. This simulated population of one year of CBC sources with an associated afterglow in the radio band and detectable on the gravitational side with ET, is marked with *yellow triangles* in Fig. 1.

In this analysis, we do not explicitly incorporate afterglow-derived constraints on the viewing angle into the GW parameter estimation. Instead, radio observations are used to identify the subset of events with a detectable counterpart, for which a redshift measurement can be obtained and included in the bright-siren analysis. It is important to note that this approach is a simplification: we do not include sky-localization uncertainties or the impact of astrophysical contaminants that would inevitably affect a realistic EM follow-up campaign. Moreover, the results depend sensitively on the assumed local BNS merger rate and GRB afterglow model, so the predicted detection rate can vary significantly. Despite these caveats, these forecasts are important to underlying the possible role of SKAO for bright sirens.

In Fig. 2, we report the cosmological constraints obtained from our analysis for three models considered: Λ CDM (top left), w CDM (top right), and w_0w_a CDM (bottom). For each cosmology, we show the marginal posterior distributions and the joint contours for the relevant parameters: H_0 , Ω_m , and, where applicable, w_0 and w_a . Three datasets are used in this analysis to illustrate their complementarity: GW bright sirens from SKAO follow-up of ET events (blue), the uncalibrated type Ia SNe from Pantheon+ (pink) [Brout et al. \(2022\)](#), and DESI baryon acoustic oscillations (BAO) [Adame et al. \(2025\)](#) (orange). As we can observe from the figure, about 20 bright sirens detected in the SKAO/ET era will be able to constrain H_0 and the dark matter energy density Ω_m to a precision significantly better than, or equal to, the one of current measurements from SNe and BAO. Instead, in terms of the dark energy Equation of state parameters, we might expect GW bright sirens to provide a constraint on w_0 and w_a , but not as precise as the one currently available from SNe [Brout et al. \(2022\)](#). Another interesting aspect of bright sirens is that they do not share any systematic with SNe or BAO, as such, these two datasets can be combined to break some of the degeneracies present among cosmological parameters (H_0 and Ω_m , for example) and provide a per cent-level precision of some of the cosmological parameters.

2.1.2 Dark Sirens

Dark siren methods comprise both spectral and catalogue approaches. Spectral sirens rely on the information coming from the astrophysical model of the mass spectrum of CBCs in the source frame. The mass observed at the detector, in fact, is redshifted, and a model of the mass distribution in the source frame allows us to pinpoint the redshift of a given event:

$$(1 + z(d_L, H(z))) = \frac{m}{m_{\text{src}}}, \quad (1)$$

where m is the detector-frame measured mass, and m_{src} is the mass in the source frame. The presence of certain features in the mass spectrum, such as peaks and breaks, is crucial for inferring the redshift. Peaks indicate the most probable regions in the mass distribution, while breaks signify changes in the distribution. The reliability of this method increases as the amount of data grows.

The statistical framework for dark siren-like analysis is the hierarchical Bayesian inference ([Mandel et al., 2019](#); [Vitale et al., 2020](#)). The inference process operates on two levels. The first concerns the

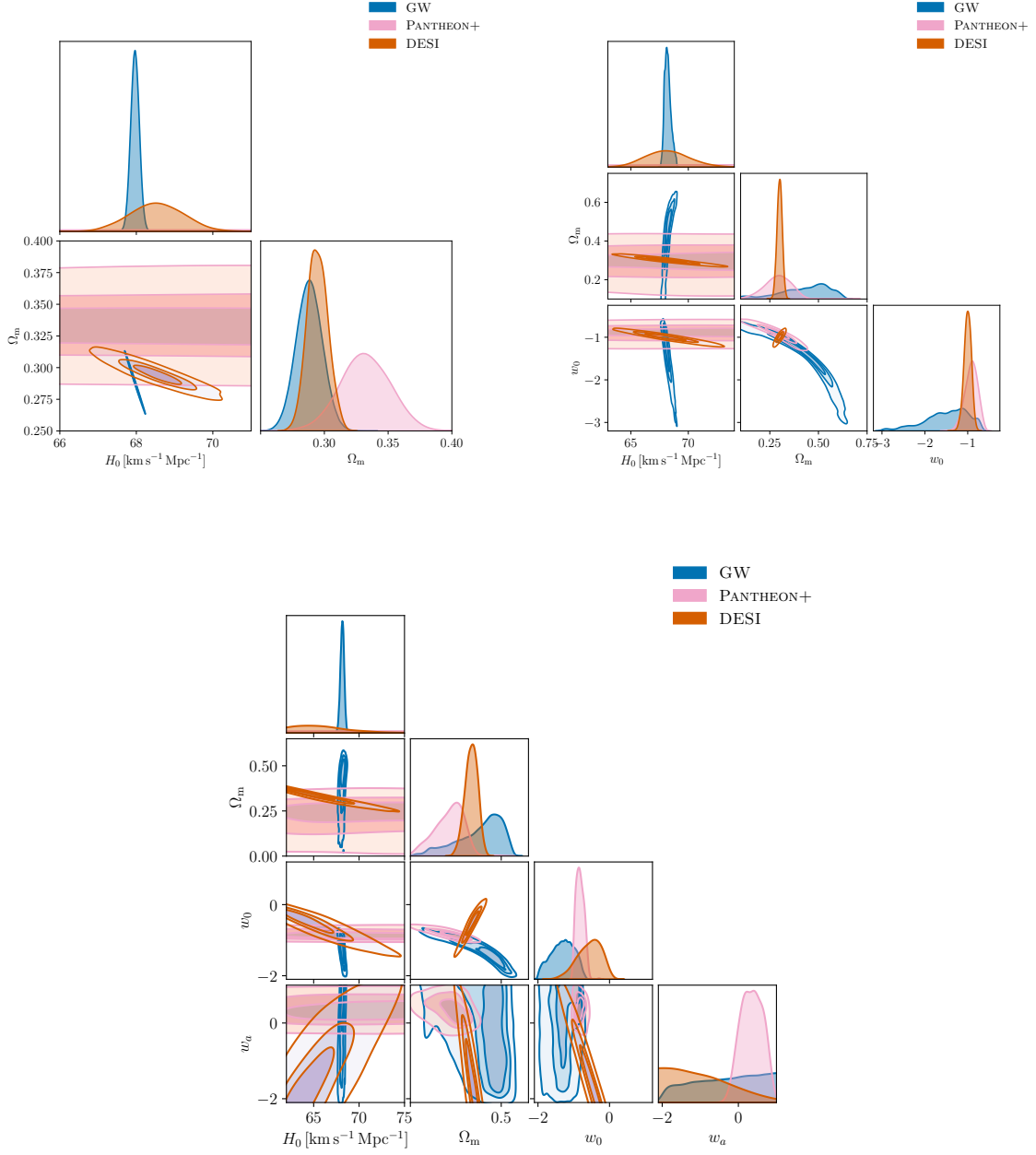


Figure 2: Corner plots of the cosmological constraints obtained from GW bright sirens (blue), Pantheon+ SNe (pink), and Dark Energy Spectroscopic Instrument (DESI) BAO (orange) for the Λ CDM model (top left), the w CDM model (top right), and the w_0w_a CDM model (bottom). For each model we show the one-dimensional marginal distributions and the two-dimensional posterior contours for the relevant cosmological parameters H_0 , Ω_m , and, when applicable, w_0 and w_a .

parameter estimation of individual GW events, while the second, known as population inference, aims to describe the collective set of observed GW events within a coherent framework governed by the mass spectrum, event rate, and cosmological parameters.

The detection of GWs is an inhomogeneous Poisson process, influenced by selection effects that stem from the finite sensitivity of the detectors. Given N_{obs} GW events, collectively specified as $\{x\}$, each of which is described by its own set of parameters θ , the hierarchical likelihood that describes the probability of observing the specific dataset in a given observation time T_{obs} , and given the set of population-level parameters Λ , is (Mandel et al., 2019; Vitale et al., 2020; Mastrogiovanni et al., 2021, 2023, 2024):

$$\begin{aligned} \mathcal{L}(\{x\}|\Lambda) &\propto \exp[-N_{\text{exp}}(\Lambda)] \prod_{i=1}^{N_{\text{obs}}} \int \mathcal{L}_{\text{GW}}(x_i|\theta, \Lambda) \frac{dN_{\text{CBC}}}{dt d\theta}(\Lambda) d\theta dt \\ &\propto \exp[-N_{\text{exp}}(\Lambda)] \prod_{i=1}^{N_{\text{obs}}} T_{\text{obs}} \int \mathcal{L}_{\text{GW}}(x_i|\theta, \Lambda) \frac{dN_{\text{CBC}}}{dt d\theta}(\Lambda) d\theta, \end{aligned} \quad (2)$$

where, passing from the first to the second line, we have integrated over the observing time, t , measured in the detector frame. There are two terms:

1. The individual GW event likelihood, $\mathcal{L}_{\text{GW}}(x_i|\theta, \Lambda)$, which accounts for how precisely we can measure the binary parameters from GW observations;
2. The differential number of GW sources $\frac{dN_{\text{CBC}}}{dt d\theta}(\Lambda)$ modelling the probability of the single event parameters θ given the population-level Λ . The set of population-level Λ comprises parameters modeling the rate Λ_{rate} , the source intrinsic parameters, as e.g. the masses, Λ_{pop} , as well as cosmological parameters like H_0 and Ω_m , referred to as Λ_c .
3. Selection effects enter into the evaluation of the expected number of events N_{exp} :

$$N_{\text{exp}}(\Lambda) = T_{\text{obs}} \int p_{\text{det}}(\theta) \frac{dN_{\text{CBC}}}{dt d\theta}(\Lambda) d\theta, \quad (3)$$

where p_{det} is the detection probability:

$$p_{\text{det}}(\theta) = \int_{x \in \text{detectable}} \mathcal{L}_{\text{GW}}(x_i|\theta) dx, \quad (4)$$

where the integration is carried out over all the individual GW events likelihood in the set $\{x\}$. Evaluating Eq.(4) is not straightforward. The customary approach is to use Monte Carlo simulations of a great number of injected GW events, which are simulated based on the chosen population-parameters Λ and evaluating the fraction of detected ones. We are using the SNR in the chosen detector network configuration as the metric to evaluate whether an event is detected or not.

The latter is the core term in hierarchical Bayesian inference. As we will specify in subsequent sections, is the one that can incorporate information of the LoS matter distribution, coming from tracer of the large-scale structure as optical galaxies or Hi.

In Fig. 3, we present a summary of GW cosmology measurements as from the LVK publications (Abbott et al., 2017a, 2021, 2023, 2025). The reported values show the median and the corresponding 68% symmetric credible interval. We summarize the methods employed for the measurements with different colors: *yellow* for bright sirens and either *magenta* (spectral) or *purple* (catalog) for the

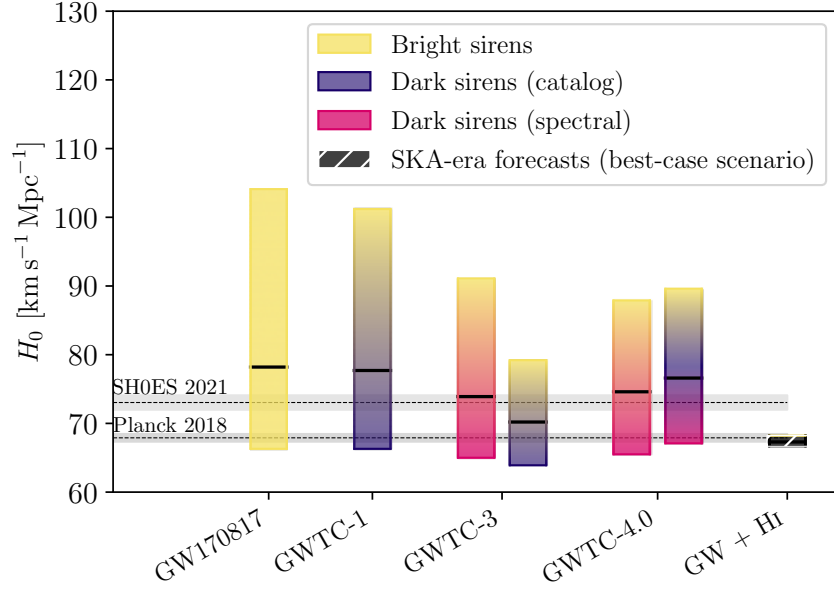


Figure 3: Summary plot of LVK H_0 measurements (Abbott et al., 2017a, 2021, 2023, 2025) in chronological order. The reported values show the median and the corresponding 68% symmetric credible interval. We summarize the methods employed for the measurements with different colors: *yellow* for bright sirens and either *magenta* (spectral) or *purple* (catalog) for the dark sirens. When more than one method is employed the colors are blended accordingly. We compare these measurements to results from Planck 18 (Aghanim et al., 2020) and SH0ES (Riess et al., 2022), for which we show the median value and the 1σ region. On the gravitational side, note that if the spectral siren method is not included, it means that the population model has been fixed. We compare the evolution of GW measurements to the SKAO era forecasts, in the most optimistic scenario. We report the Hubble constant constraint using perfectly measured GW as explained in detail in the subsequent Sec. 2.2. This figure is adapted from Fig. 11 of Abbott et al. (2025), to which we refer for more details.

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2.2 Neutral Hydrogen 21cm Intensity Maps as a Redshift Prior

An excellent source of complementary information for gravitational-wave cosmology will come from wide-area maps of the cosmic large-scale structure. The SKAO will deliver these through its 21cm intensity mapping surveys, which will trace the three-dimensional distribution of neutral hydrogen (Hi) across cosmic time. Intensity mapping exploits the fact that, on large scales, the aggregate 21cm emission from unresolved galaxies traces the underlying matter density field Bharadwaj et al. (2001); Battye et al. (2004); Chang et al. (2008); Wyithe et al. (2008). Instead of detecting individual sources, the telescope measures fluctuations in the collective brightness temperature of the redshifted 21cm line as a function of position and frequency. Each frequency channel directly maps to a cosmological redshift, yielding a tomographic view of the large-scale

structure over enormous cosmic volumes.

For this purpose, SKA-Mid will operate in auto-correlation, or *single-dish*, mode (Santos et al., 2017), where the total power detected by each antenna is used to construct sky maps of the integrated H_I emission. This observing mode is essential for accessing the largest angular scales, which are not captured by interferometric visibilities due to their limited baseline lengths. The measurements will use Band 1 of SKA-Mid (350-1050 MHz), corresponding to a redshift range of approximately $0.3 < z < 3$ encompassing much of the post-reionisation Universe where large numbers of binary black hole mergers detectable by the SKAO-era GW network are expected to occur.

Although the angular resolution of the single-dish observations is modest ($\sim 1^\circ$ at the centre of Band 1), the intensity maps provide exquisite radial precision through their spectroscopic frequency resolution. This radial information directly constrains redshift and hence distance, allowing detailed three-dimensional localisation when combined with GW measurements (Oguri, 2016; Mukherjee et al., 2024). The combination of wide-field angular coverage with high-fidelity redshift information will enable joint analyses that measure the cosmic distance–redshift relation and expansion rate, $H(z)$, using dark sirens calibrated against the large-scale structure traced by H_I.

The MeerKLASS single-dish survey with the SKA precursor MeerKAT has already started delivering the first results in the L-band (with a redshift range similar to Band 2) (Wang et al., 2021; Cunnington et al., 2022; MeerKLASS Collaboration et al., 2025) and is paving the way for a larger and deeper survey with the SKA-Mid. A review of the MeerKLASS observational strategy and results can be found in the chapter Cunnington&Wang et al. (2026), while the interested reader can find a summary of the SKA pathfinder results in the chapter Elahi et al. (2026).

An SKAO H_I intensity mapping campaign could ultimately survey up to 20,000 deg² of sky, making it the largest three-dimensional cosmological map ever constructed (SKAO Cosmology SWG et al., 2020). In chapter Spinelli et al. (2026), the challenges linked to foreground cleaning and the most common systematics of an 21cm intensity mapping survey are discussed. Wolz et al. (2026) instead discuss its constraining power for cosmology.

Covering a broad redshift range with precise radial resolution, this survey will provide the ideal counterpart to GW detections, offering the large-scale environmental context and statistical localisation information required to transform GW events into a powerful cosmological probe.

Both GW sources and the H_I field are assumed to follow the underlying dark matter (DM) field. Therefore, if BBHs, for which, on the gravitational side, we can measure the luminosity distance, are more likely to be found where there are H_I overdensities, we can use this information to pinpoint their redshift, which can be precisely measured with the upcoming radio surveys as SKA-Mid. This gives the luminosity distance-redshift pair for cosmological inference.

In other words, the redshift of GW detections can be constrained by building a LoS redshift prior describing the probability that there is a compact binary merger, as proportional to the distribution of neutral hydrogen on that LoS. For simplicity, we assume that neutral hydrogen and merging compact binaries both trace the underlying dark matter and that their distributions are related by a scale- and redshift-independent bias. These assumptions will need to be refined when moving to

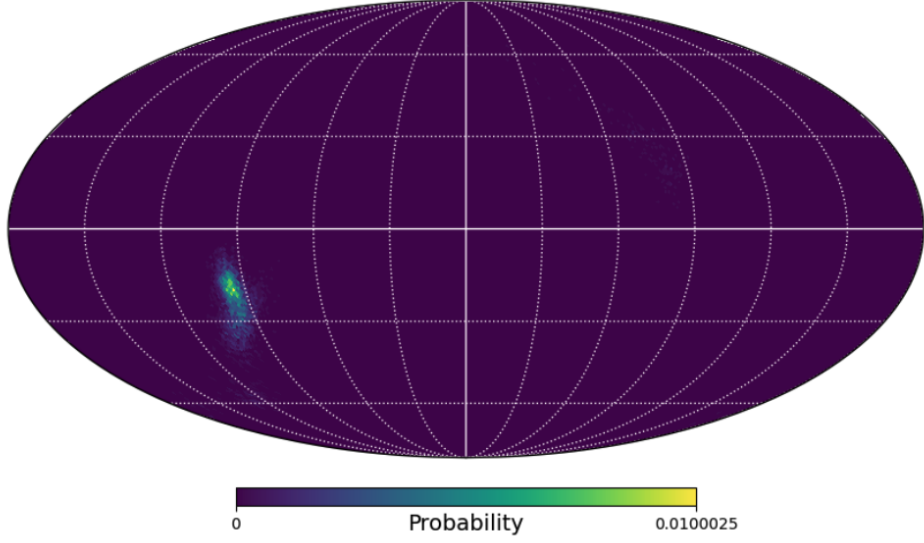


Figure 4: Pixelated sky map for a mock GW event with 90% sky area $A_{sky}^{90\%} = 94\text{deg}^2$.

real data analysis, where additional parameters will need to be included in the model. The required refinements can in principle concern both our assumptions on the physical relation between the presence of H_I and GW events and also the effect that realistic systematics can have in "masking" the real H_I distribution. Such systematics can be the presence of residual foregrounds contamination after foreground cleaning, mis-calibration effects, non-uniform mapping of the structure and the incompleteness due to unobserved regions of the sky.

This approach is explored in both (Dupletsa et al., 2026) and (Nanadoumgar-Lacroze et al., n.d., *in preparation*), with independent underlying modelling. Dupletsa et al. (2026) make use of N-body simulations to model the underlying dark matter tracers, which provided high fidelity simulations, whilst (Nanadoumgar-Lacroze et al., n.d., *in preparation*) make use of log-Normal simulations of the density fields, which have lower accuracy on small scales but can be rapidly generated, allowing the easier exploration of different physical cosmological, source and telescope models.

The sky localisation of GW events is given as pixelated sky probability maps as shown in Fig. 4. For a two-dimensional pixel Ω_i , we construct a line-of-sight redshift prior, $P(z|\Omega_i)$, which summarizes the probability of a CBC merger for each redshift bin z_j , $P(z_j|\Omega_i)$. For each pixel in the sky map, a redshift prior can be built by looking at the variation of H_I density along the redshift direction, defining $\mathbb{P}(z|\Omega_i)$, the CBC merger probability as a function of z . We have:

$$\mathbb{P}(z|\Omega_i) = \sum_{j=1}^{N_z} f(z; z_j, \sigma_j) \mathbb{P}(z_j|\Omega_i) = \frac{1}{\mathbb{P}(\Omega_i)} \sum_{j=1}^{N_z} f(z; z_j, \sigma_j) \mathbb{P}(\Omega_i|z_j) \mathbb{P}(z_j), \quad (5)$$

where:

- $f(z; z_j, \sigma_j)$ is the redshift grid function, it is equal to $\delta(z - z_j)$ when the redshift coordinate z_j is perfectly measured

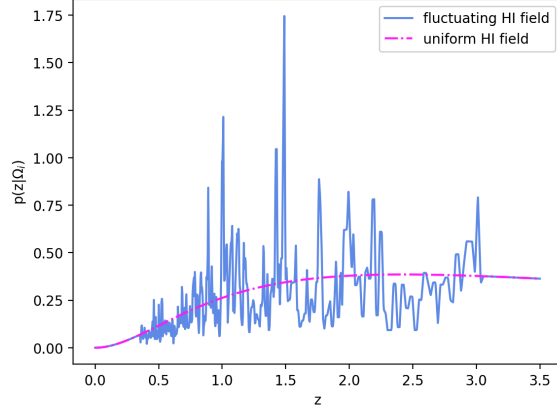


Figure 5: Line-of-sight redshift prior for a single pixel with $n_{\text{side}}=128$ in the GRIDIMP intensity maps. We compare the redshift prior from a fluctuating HI field with that of a uniform HI field.

- $\mathbb{P}(\Omega_i|z_j)$ is the probability that a pixel with coordinates (Ω_i, z_j) hosts a compact binary merger. It is directly computed from the HI density fluctuations as given by the HI intensity map.
- $\mathbb{P}(z_j)$ is the probability that there is a compact binary merger at redshift z_j based on considerations such as the star formation rate, assuming a uniform co-moving volume and taking into account time dilation.
- $\mathbb{P}(\Omega_i)$ corresponds to the probability that the GW is in pixel Ω_i , as described by its sky map.

Eventually, the HI-informed redshift prior for a single GW event, $\mathbb{P}(z)$, is defined by summing over the redshift prior of all pixels that form part of the GW event’s sky map:

$$\mathbb{P}(z) = \sum_{i=0}^{N_{\Omega}} \mathbb{P}(z|\Omega_i). \quad (6)$$

It is possible to define those probabilities with respect to various quantities such as the HI mass M_{HI} , HI density ρ_{HI} , or HI temperature T_{HI} . Fig. 5 shows an example of such a redshift prior along a single line-of-sight Ω . For comparison, when using galaxies as the EM tracer, they are defined as functions of the galaxy number density and the galaxy luminosity or magnitude.

In addition to being fundamental to the construction of a HI-informed redshift prior, Equation 5 is essential to the generation of a mock GW catalogue when using simulated data. For both cases here where N-body simulations and log-Normal simulations are used, the rationale is the following:

- We simulate HI intensity maps produced following the observational characteristics of studied HI IM surveys.
- We create a mock GW catalogue with parameters $\{m_1, m_2, z, \text{RA}, \text{Dec.}\}$. Given the dark matter distribution of our simulations, the spatial location of GW sources is drawn for each redshift shell with a probability $\mathbb{P}(\Omega_i|z_j)$ while the redshift distribution is drawn following $\mathbb{P}(z_j)$. Fig. 6 shows an example of the distribution of GW events drawn from a given dark matter map, superposed to our HI simulated sky.

- We simulate the GW parameters in detector-frame, assuming a waveform model and a GW interferometer-network.
- We use the spectral siren method to infer cosmological parameters with the hierarchical Bayesian inference pipeline `icarogw` (Mastrogiovanni et al., 2024), adapted to allow the use of H_I intensity maps.

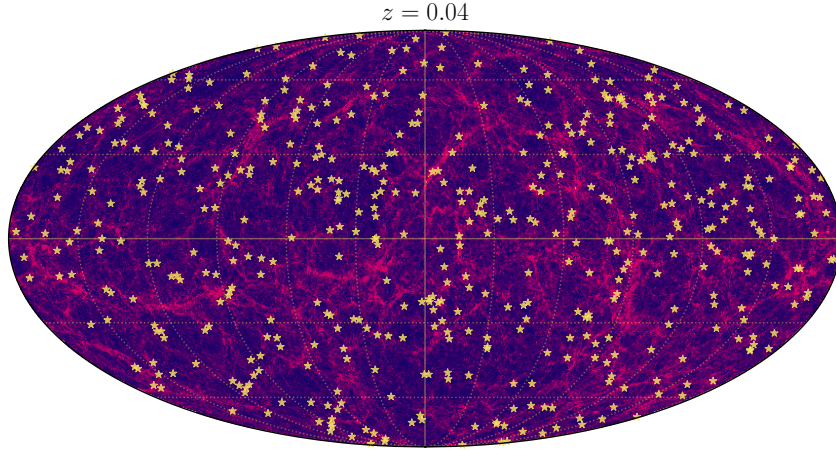


Figure 6: Illustrative example of 500 GW events (*yellow stars*) on H_I number density map at $z \sim 0.4$ as from the Dark Energy and Massive Neutrino Universe (DEMNUi) N-body simulation.

The work in Dupletsa et al. (2026) uses density maps. The starting point is the simulation of the DM distribution at different redshift bins. Given that SKA-Mid frequency coverage will allow tomography of the 21 cm line of H_I up to $z \sim 3$, and with ET we will be able to detect BBH mergers much further, the analysis is set in $z \in [0, 3]$. The DM maps come from an N-body simulation, where more realistic features, e.g., non-Gaussianities, are included.

Specifically, we use the DEMNUi set of N-body simulations (Castorina et al., 2015; Carbone et al., 2016; Parimbelli et al., 2021). They are characterized by a Planck 2013 (Ade et al., 2014) baseline flat Λ Cold Dark Matter (Λ CDM) cosmology with a box with side length of $500 \text{ Mpc } h^{-1}$ in comoving coordinates, with 2048^3 DM particles and no neutrino particles. A full-sky lightcone from redshift $z = 0$ to redshift $z \approx 8$ is then built, corresponding to a total comoving volume of approximately $3 \times 10^3 \text{ Gpc}^3 h^{-3}$. Around 39 billion haloes are identified through the Friends-of-Friends (FoF) algorithm. The DM haloes are used as a biased tracer of the underlying continuous DM distribution. Dupletsa et al. (2026) explores, in particular, the interplay between the H_I redshift prior and the uncertainties in the GW parameters measured with ET, and the role of the GW population parameters in the H_0 constraint.

The work in (Nanadoumgar-Lacroze et al., n.d., *in preparation*) uses temperature maps generated with the python package GRIDIMP (Cunnington and Wolz, 2024), by drawing log-Normal realisations from the H_I matter power spectrum, itself derived from the DM power spectrum. Two observational scenarios are studied:

- SKA-Mid Band 1, covering $z \in [0.3, 3]$ (SKAO Cosmology SWG et al., 2020);

- MeerKLASS UHF-Band, covering $z \in [0.4, 1.4]$ (Santos et al., 2017).

The resulting H_I intensity maps are pixelated with `healpix` `nside=128` and a frequency resolution of 1MHz. The forecasts are made realistic by leveraging the observational and instrumental effects that are expected to most impact the quality of the maps: 1. The redshift error associated with each bin of the map; 2. The limited sky coverage of the surveys; 3. The smoothing effect of the telescope beam, which further limits the angular resolution; 4. The noise introduced by the telescope receiver that reduces the signal-to-noise ratio of the H_I signal; 5. The signal loss or foreground residuals, dependent on the performance of foreground cleaning technique. The differences in observational characteristics such as the diameter and number of dishes, observational time and sky coverage influence the noise level and the angular resolution achieved by the surveys. Using the GRIDIMP maps, the H_I temperature $T_{\text{H}_I}(\Omega, z) = \delta T_{\text{H}_I}(\Omega, z) + \bar{T}_{\text{H}_I}(z)$ is used as an observable for the analysis, where $\delta T_{\text{H}_I}(\Omega, z)$ represents the temperature fluctuation at sky angle Ω and redshift z in the simulated map with respect to the mean temperature $\bar{T}_{\text{H}_I}(z)$. The observational incompleteness, both in sky coverage and redshift, is mitigated by $\bar{T}_{\text{H}_I}(z)$, defined in the GRIDIMP simulations.

Both studies modify the CBC merger rate parametrization, essential to the cosmological inference with `icarogw`. We define the CBC merger rate, $\frac{dN_{\text{CBC}}}{dt dz d\Omega}$, as the rate of CBC mergers in detector-frame per unit redshift and unit solid angle. It can be written such as

$$\frac{dN_{\text{CBC}}}{dt dz d\Omega} = \mathcal{R}_0 \psi(z|\gamma, \kappa, z_p) f_{\text{H}_I}(z, \Omega) \frac{1}{1+z} \frac{dV_c}{dz d\Omega}, \quad (7)$$

where \mathcal{R}_0 is the CBC merger rate at $z = 0$, $\psi(z|\gamma, \kappa, z_p)$ is the Madau-Dickinson star formation rate (Madau and Dickinson, 2014). $f_{\text{H}_I}(z, \Omega)$ is the function encoding the H_I information proportional to the H_I density contrast as a function of redshift. Further details about the derivation of this expression can be found in Dupletsa et al. (2026) and (Nanadoumgar-Lacroze et al., n.d., in preparation).

In Fig. 7, we show the H_0 posterior obtained with ~ 3000 GW events, with the H_I distribution as from the N-body maps using the pipeline described in Dupletsa et al. (2026), marginalizing over all the other population-level parameters. We can see that under the simplified analysis, using the H_I maps, not only we manage to recover the injected H_0 value (the one from Planck 2013 (Ade et al., 2014) used for the N-body maps simulations), but we also recover it with great precision. For comparison, we report the measurement from Planck 2013, which estimate of H_0 is at the percent level.

A similar analysis is presented in (Nanadoumgar-Lacroze et al., n.d., in preparation), where the marginal H_0 posterior is obtained with about 160 GW events drawn from the LVK zero-noise O5 sensitivity curve with a SNR threshold of 12, and a SKA-Mid-like temperature map generated with log-Normal simulations from GRIDIMP. Cosmological and GW population parameters are inferred jointly leveraging on the interplay of the source-frame mass distribution with cosmology to avoid biases (Mastrogiovanni et al., 2021) and marginalise the H_0 posterior from the other parameters. Please note that in this case the procedure use also the information from the mass spectrum, in particular a broken power law plus a two peaks model is considered. In this framework, it is possible to recover the fiducial cosmological and population parameters, including H_0 which is measured with a 19 % error (pink curve in Fig. 8). This corresponds to a 10% improvement with respect to

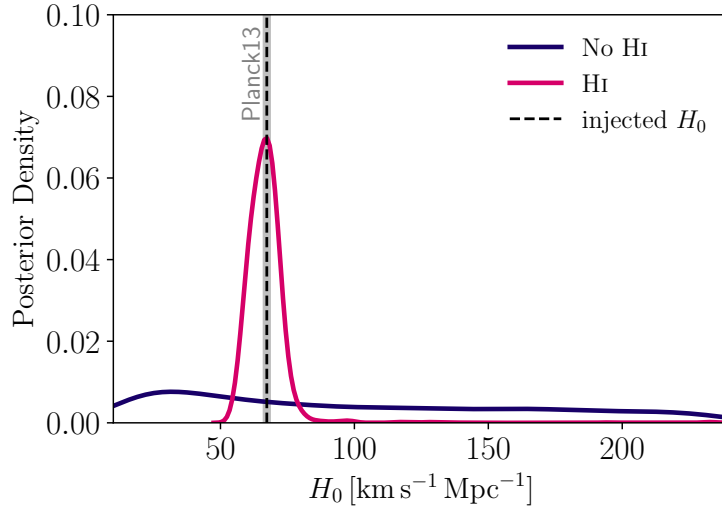


Figure 7: Reconstruction of the H_0 posterior using the N-body simulations and modified `icarogw` code (as described in the pipeline presented in Dupletsa et al. (2026) with ~ 3000 GW events with an SNR greater than 150. We present the results using the N-body HI maps from the DEMNUni simulation to model the GW rate, in *magenta*, and results from assuming a sky-averaged distribution of HI, in *purple*.

performing an identical analysis without relying on HI maps (blue curve in Fig. 8). These results show, in particular, how observational and instrumental limitations introduced by the SKA-Mid (Band 1) and MeerKLASS (UHF-band) surveys are expected to impact the constraining power of the method. Anticipating the challenges that may arise with real data, these results show that HI intensity maps could allow us to measure H_0 with a precision that matches and maybe exceeds the current estimate from LVK GWTC-4 (Abbott et al., 2025), and therefore provide a valuable data set, complementary to galaxy surveys. The use of the information from the mass spectrum explains why even for the no HI case there is constraining power. This information is instead not used in Fig. 7, justifying why there is no constraining power there despite considering more GW events.

2.3 Other Radio Tracers as a Redshift Prior

2.3.1 Continuum Galaxies

SKA-Mid will also perform large area surveys of continuum radio galaxies; a sample which can provide information on the hosts of dark siren events. Though these surveys will contain large numbers of sources compared to optical surveys, and may have redshift distributions which peak at higher redshifts, they will likely not be directly usable for line of sight prior information due to their intrinsic lack of redshift information. Such redshift information will come either from cross-matching with surveys in optical and near-InfraRed bands, or other approaches such as clustering redshifts. Nonetheless, radio continuum information may provide useful information on the host probability for each galaxy through enhancing the multi-wavelength view of star formation and evolution (as discussed elsewhere in this volume e.g. Asorey&Hale et al. 2026).

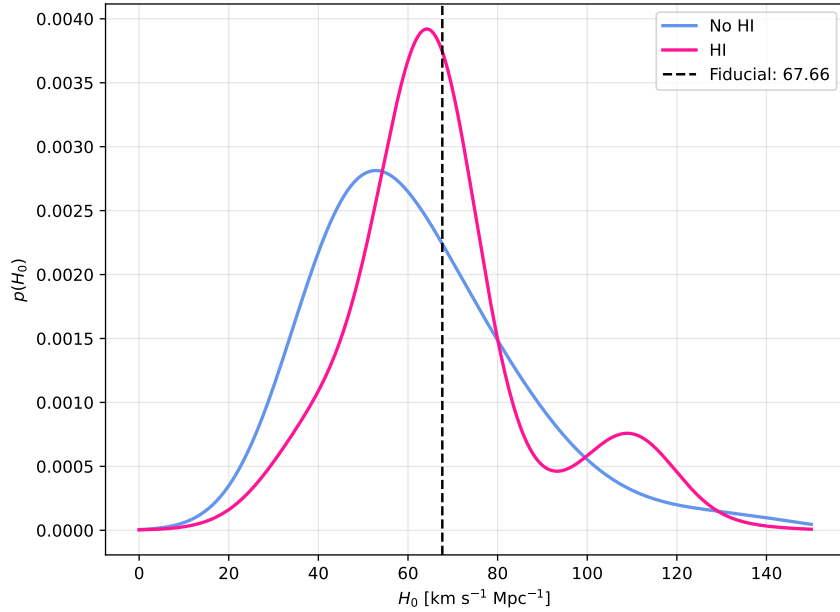


Figure 8: H_0 posterior distribution marginalised over cosmological and population parameters obtained using the pipeline with log-Normal simulations presented in (Nanadoumgar-Lacroze et al., n.d., in preparation). We show preliminary results using `icarogw` with ~ 160 O5-like GW events and compare the constraint on H_0 achieved with and without using the corresponding SKA-Mid-like $H\text{I}$ temperature map. For this analysis, the information from the mass spectrum, in particular a broken power law plus a two peaks model is also considered.

2.3.2 $H\text{I}$ Galaxies

Similarly, large scale SKA-Mid surveys of $H\text{I}$ line emission in galaxies could also provide a line of sight redshift prior. As discussed in Yahya et al. (2015); Nasirudin et al. (2026) these surveys could contain $\mathcal{O}(10^6)$ galaxies with spectroscopic redshifts in the range $z < 0.5$, highly competitive with the optical spectroscopic surveys often considered for dark sirens analyses. Such surveys will also have a distinct advantage of cleaner selection functions than many optical surveys, bypassing a key systematic uncertainty in their use for dark sirens.

3 Angular Cross-Correlations

In addition to the map-space information used in the above sections on dark sirens, the angular cross-correlation between any pair of matter tracers, can be calculated via the angular power spectra $C_{\ell s}$ of such tracers. This technique is particularly powerful in this context for some key reasons. First, given the lack of electromagnetic counterparts for BBH mergers, it allows for the calibration of the redshift distribution of GW events thanks to the high redshift precision of $H\text{I}$ IM. Secondly, the cross-correlation of two independent cosmological probes provides intrinsic robustness to instrumental and observational systematics, as uncorrelated errors between the datasets of the different tracers naturally vanish in the cross-spectrum. Additionally, by taking advantage of being a multi-tracer method, cross-correlation cancels the cosmic variance from the analysis, thus improving the overall constraining power of the datasets. Lastly, it helps to constrain the linear clustering bias of GW with

respect to the underlying DM distribution, which would provide hints on the formation and evolution of the BBH population. This formalism is well established within the cosmological community, with its first applications presented in Regos and Szalay (1989); Scharf et al. (1992); Lahav et al. (1994); Fisher et al. (1994).

For a given tracer X , its matter fluctuations δ^X at a generic position in the sky (θ, ϕ) and radial distance x can be described as:

$$\delta^X(\theta, \phi, x) = \frac{\rho^X(\theta, \phi, x) - \langle \rho^X \rangle(x)}{\langle \rho^X \rangle(x)} \quad (8)$$

where $\rho^X(\theta, \phi, x)$ is the matter density and $\langle \rho^X \rangle(x)$ is the average matter density on the entire sky at radial distance x . By projecting it onto the sky surface, it is possible to expand the matter fluctuations in spherical harmonics, as:

$$\delta^X(\theta, \phi, x) = \sum_{\ell=0}^{+\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m}^X(x) Y_{\ell m}(\theta, \phi) \quad (9)$$

where $a_{\ell m}^X(x)$ and $Y_{\ell m}(\theta, \phi)$ represent, at each angular scale ℓ and mode m , the harmonic coefficients and the spherical harmonics, respectively. The observed angular power spectrum $\tilde{C}_\ell^{XY}(x_i, x_j)$ between tracers X and Y , at radial distances x_i and x_j , is defined as the covariance of their angular harmonics coefficients:

$$\langle a_{\ell m}^X(x_i), a_{\ell' m'}^{Y*}(x_j) \rangle = \delta_{\ell \ell'} \delta_{m m'} \tilde{C}_\ell^{XY}(x_i, x_j) \quad (10)$$

with δ denoting Kronecker deltas. Crucially, since the harmonic coefficients encode the decomposition onto spherical harmonics of the matter fluctuations, the angular power spectrum \tilde{C}_ℓ directly measures the covariance of these projected fluctuations on the sky.

To explicitly describe the observed angular power spectrum, we can decompose the harmonic coefficients into two separate terms, one including the signal contribution $s_{\ell m}$ and one including the noise contribution $n_{\ell m}$:

$$a_{\ell m}^X(x_i) = s_{\ell m}^X(x_i) + n_{\ell m}^X(x_i) \quad (11)$$

thus, by assuming that:

$$\langle s_{\ell m}^X(x_i), s_{\ell' m'}^{Y*}(x_j) \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell^{XY}(x_i, x_j) \quad (12)$$

$$\langle n_{\ell m}^X(x_i), n_{\ell' m'}^{Y*}(x_j) \rangle = \mathcal{N}_{\ell m}^{XY}(x_i, x_j) \quad (13)$$

where $C_\ell^{XY}(x_i, x_j)$ is the theoretical angular power spectrum and $\mathcal{N}_{\ell m}^{XY}(x_i, x_j)$ is the noise spectrum and represents the covariance of the projected noise fluctuations on the sky; it is then possible to write the observed angular power spectrum as:

$$\tilde{C}_\ell^{XY}(x_i, x_j) = C_\ell^{XY}(x_i, x_j) + \mathcal{N}_{\ell m}^{XY}(x_i, x_j) \quad (14)$$

Assuming the Limber approximation, the theoretical power spectrum, describing the correlation between two tracers (X, Y) at any distance (x_i, x_j) , is defined as:

$$C_\ell^{XY}(x_i, x_j) = \frac{2}{\pi} \int_{z_{min}}^{z_{max}} \frac{cdz}{H(z)\chi^2(z)} W^X(z, x_i) W^Y(z, x_j) \mathcal{P} \left(k = \frac{\ell + 1/2}{\chi(z)}, z \right) \quad (15)$$

where k is the comoving wavenumber, $\chi(z)$ is the comoving distance at redshift z , $H(z)$ is the Hubble parameter at z , $W^X(z, x_i)$ and $W^Y(z, x_j)$ are the observational window functions for each tracer at their corresponding redshift bin, $\mathcal{P}(k, z)$ is the primordial power spectrum, and $[z_{min}, z_{max}]$ represents the redshift range of the survey. The window functions depend on the specific experiments of the different tracers and include contributions from the observed redshift distribution of each tracer, redshift and distance measurement errors, and tracer biases. Note that, to track how the signal evolves with redshift, in equation (15) a tomographic approach has been applied, i.e. evaluating the distribution of each source at different redshift bins. Crucially, equation (15) provides only a schematic baseline which includes only spatial density fluctuations. As such, the forecasts summarized below do not rely on this approximation, as a fully relativistic, non-Limber approach, computed via `Multi_CLASS` (Bellomo et al. (2020)), is adopted.

Given that the noise is intrinsically linked to the observational setup for each source, the noise spectrum has also to be discussed separately for each tracer. In the specific case of discrete sources, such as GW signals, the noise spectrum can generally be defined as:

$$\mathcal{N}_\ell^{XY}(x_i, x_j) = \frac{4\pi f_{\text{sky}}^X}{N^X(x_i)} \frac{\delta_{ij}}{[\mathcal{W}_\ell^X(x_i)]^2} \quad (16)$$

where f_{sky}^X is the fraction of the sky covered by the observation of tracer X , $N^X(x_i)$ represents the number of events of tracer X in the i -th redshift bin, δ_{ij} are Kronecker deltas, and $\mathcal{W}_\ell^X(x_i)$ is the beam window function, which accounts for the localization errors due to the instruments for a given multipole ℓ at the i -th redshift bin. In contrast, hydrogen IM measurements do not resolve each source individually, but instead observe the overall emission, thus not allowing for the application of equation (16). Due to the nature of these unresolved observations, strictly linked to the observational setup, the noise spectrum must be discussed on a tracer-by-tracer basis.

The authors of (Scelfo et al., 2022) investigate the cross-correlation signal between resolved GW BBHs sources and H α intensity mapping, focusing on the combined capabilities of ET (Sathyaprakash et al., 2012; Maggiore et al., 2020; Branchesi et al., 2023; Abac et al., 2026) and SKA-Mid respectively, tackling three main topics (listed below). The study adopts a fully relativistic tomographic approach based on the angular power spectra $C_\ell^{\text{GW} \times \text{H}\alpha}(z_i, z_j)$ of equation (15), including density, redshift-space distortions, lensing magnification and potential (GR) terms. The main noise contributions included in the analysis are the shot noise for the GW sources, and the single-dish thermal instrumental noise together with residual foregrounds for the H α IM. The angular spectra are computed using `Multi_CLASS` (Bellomo et al. (2020)) and forecasts are obtained through a Fisher matrix approach covering the redshift range $0.5 < z < 3.5$ with a binning of $\Delta z_{\text{GW}} = 1.0$ and $\Delta z_{\text{IM}} = 0.1$, assuming ET in its Δ configuration and different observational campaigns from 1 year up to 10 years. In the following, details on the three applications explored in Scelfo et al. (2022) are provided:

- i) *Statistical redshift calibration of GW events.* In the absence of electromagnetic counterparts, GW luminosity distances yield poorly constrained redshifts. The GW \times H α cross-correlation provides a tomographic mapping between the poorly localized GWs and the precisely localized

H_I IM field, allowing to infer the overall statistical redshift distribution dN_{GW}/dz . Modeling dN_{GW}/dz as a piecewise function with a different amplitude A_i at each H_I bin, Fisher forecasts show relative errors $\sigma_{A_i}/A_i < 1$ up to $z \approx 2$ for $f_{\text{sky}} \geq 0.5$ and multi-year ET operativity $T_{\text{obs}}^{\text{GW}}$, enabling GW sources calibration without any assumption on cosmology or astrophysics (see e.g. left panel of Fig. 9).

- ii) *Constraints on dynamical dark energy.* As an example of cosmological application, extending the parameter space to a total of 10 (cosmological, bias and IM foreground parameters), the authors forecast errors on the (w_0, w_a) parameters describing the dark-energy equation of state (see central panel of figure 9) to be comparable with BOSS-Planck constraints. Cross-correlations help decorrelating degeneracies and overcome systematics, also providing a fundamental validation of IM-only results, which could be affected by unknown systematic errors.
- iii) *Probing the nature of BBH progenitors.* The clustering bias of resolved GW sources encodes crucial information on BHs origins. Astrophysical BBH mergers are linked to stellar populations in massive star-forming and high-bias halos, highly cross-correlating with H_I too. Primordial black holes (PBH) are theorized to be formed in the early universe (Hawking (1971); Carr and Hawking (1974)) and are expected to trace the dark matter field with a lower bias (Bird et al. (2016); Scelfo et al. (2018); Bosi et al. (2023)) whose value depends on the time of binary capture. Forecasts show that GW \times H_I measurements could detect a PBH merger fraction (Γ_{PBH}) down to $\sim 10\%$, corresponding to a measurable deviation in the cross-bias amplitude of $C_\ell^{\text{GW,HI}}$ (see right panel of figure 9).

Finally, the authors of Scelfo et al. (2023) have shown that with a similar approach, focusing mainly on lensing and angular clustering, the ET \times SKAO cross-correlation can shed light on beyond-GR signatures and Modified Gravity.

An extension to the Fisher-matrix approach presented in Scelfo et al. (2022) and Scelfo et al. (2023) is explored in (Schulz et al., n.d., *in preparation*), where a likelihood-based Bayesian analysis has been carried out. This extension allows for a more robust cosmological inference from the combined observations of ET and SKAO.

In the previous works listed here it is assumed that either the redshift of the GW is known via the host galaxy or a photometric redshift-like distribution can be built from the potential host galaxies in the field where the event came from. The authors in Fonseca et al. (2023) take a different approach and consider the only distance that can be inferred from GW events, the luminosity distance. They then compute the full number counts expression in luminosity-distance space and adapt CAMB² to allow for luminosity-distance space tracers of dark matter. They also show that the C_ℓ can be up to 30% different from the redshift space expression. The same authors recently looked at the angular power spectrum of correlations between radio tracers and GW events (Zazzera et al., 2025). Their focus was on synergies with future third-generation GW detectors like the Einstein Telescope (ET) and Cosmic Explorer (CE) which are expected to detect millions of BBH mergers. For the SKAO they considered H_I intensity mapping, an H_I galaxy surveys and a radio continuum galaxy catalogue.

²<https://github.com/cmbant/CAMB>

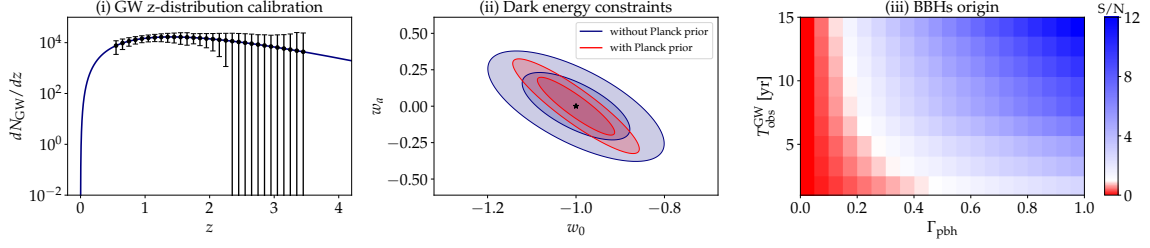


Figure 9: Summary results from Scelfo et al. (2022), assuming $f_{\text{sky}} = 0.5$. (i) *Left panel:* constraints (absolute error bars) on the statistical z -distribution dN_{GW}/dz of resolved BBHs merger events, without any assumption on the underlying cosmology or astrophysical models. Assuming $T_{\text{obs}}^{\text{GW}} = 15\text{yr}$. (ii) *Center panel:* $1\sigma - 2\sigma$ Fisher contours on dark energy parameters $\{w_0, w_a\}$, either with and without a Planck prior on the other cosmological parameters considered in the analysis. (iii) *Right panel:* S/N ratios for the detection of a fraction Γ_{pbh} of BBH mergers of primordial origin (assuming binary formation of PBHs binaries at late time, and astrophysical BBHs as ground truth fiducial model). Different observation times $T_{\text{obs}}^{\text{GW}}$ for ET are considered. See main reference for a full treatment of different scenarios.

The authors take a full multi-tracer approach and conclude that such synergies can greatly inform about GW astrophysical parameters, namely their clustering bias. Of all, synergies with the H I IM band 1 wide area survey is the one which can provide the tightest constraints on GW parameters as well as on standard cosmological parameters. Additionally, they explored a triple cross-correlation using GWs, IM, and photometric galaxies. The three multi-tracer method enhances constraints on the magnification lensing effect, achieving percent-level precision, and allows for a measurement of the Doppler effect with approximately 15% uncertainty. Such uncertainty can only be attained when adding the radio information and will give a new stage to perform null tests of GR in cosmological scales.

4 Conclusions

In this chapter, we highlighted the synergy between radio surveys and GW observations in the context of cosmological analyses. With the increase in the number of detections of BBHs, BNSs, and NSBHs expected from third-generation GW observatories, the role of radio observatories will become more and more central. In particular, the SKAO will provide valuable support for a wide range of redshifts, going potentially beyond the reach of the optical galaxy surveys.

The identification of a variety of EM counterparts will provide the redshift information necessary to use bright sirens efficiently for cosmology. In an idealised scenario, we found that, with a few tens of events, it will be possible to constrain H_0 and Ω_m with comparable precision of current SNe and BAO surveys and even to explore evolving dark energy scenarios.

In the context of dark sirens, neutral hydrogen intensity mapping (H I IM) observations of the large scale structure will provide a unique opportunity to improve the priors of hierarchical Bayesian inference and to explore angular cross-correlation analyses. H I IM, with its relative low resolution but high survey speed and very precise redshift information, is already mapping large volume of the universe and will provide, thanks to the SKAO, competitive and complementary measurements to optical galaxies. Combining it with current and next-generation GW detector networks using

the spectral siren method, will allow us to measure cosmological parameters such as the Hubble constant H_0 with great accuracy, even including uncertainties arising from the detection of GWs and SKAO instrumental limitations.

For future surveys, using cross-correlations will also be crucial to constrain cosmological parameters: cross-correlation methods have the potential to probe the nature of BBH progenitors and to shed light on dynamical dark energy.

Author List Ordering

The authors of this chapter have contributed equally to the conception and the writing, and are listed alphabetically.

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