Impact of astrophysics on cosmology forecasts for 21 cm surveys

Hamsa Padmanabhan*, Alexandre Refregier†, and Adam Amara‡
Institute for Particle Physics and Astrophysics, ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zurich, Switzerland

ABSTRACT

We use the results of previous work building a halo model formalism for the distribution of neutral hydrogen, along with experimental parameters of future radio facilities, to place forecasts on astrophysical and cosmological parameters from next generation surveys. We consider 21 cm intensity mapping surveys conducted using the BINGO, CHIME, FAST, TianLai, MeerKAT and SKA experimental configurations. We work with the 5-parameter cosmological dataset of \{\Omega_m, \sigma_8, h, n_s, \Omega_b\} assuming a flat \Lambda CDM model, and the astrophysical parameters \{v_c, \alpha, \beta\} which represent the cutoff and slope of the HI-halo mass relation. We explore (i) quantifying the effects of the astrophysics on the recovery of the cosmological parameters, (ii) the dependence of the cosmological forecasts on the details of the astrophysical parametrization, and (iii) the improvement of the constraints on probing smaller scales in the HI power spectrum. For an SKA I MID intensity mapping survey alone, probing scales up to \ell_{\text{max}} = 1000, we find a factor of 1.1 – 1.3 broadening in the constraints on \Omega_b and \Omega_m, and of 2.4 – 2.6 on h, n_s and \sigma_8, if we marginalize over astrophysical parameters without any priors. However, even the prior information coming from the present knowledge of the astrophysics largely alleviates this broadening. These findings do not change significantly on considering an extended HIHM relation, illustrating the robustness of the results to the choice of the astrophysical parametrization. Probing scales up to \ell_{\text{max}} = 2000 improves the constraints by factors of 1.5-1.8. The forecasts improve on increasing the number of tomographic redshift bins, saturating, in many cases, with 4 - 5 redshift bins. We also forecast constraints for intensity mapping with other experiments, and draw similar conclusions.

Key words: cosmology:observations – radio lines:galaxies – cosmology:theory

1 INTRODUCTION

Upcoming and future radio experiments aim to probe the distribution of neutral hydrogen with its redshifted 21-cm line, both during the dark ages and cosmic dawn (see, e.g., Madau et al. 1997) as well as in the post-reionization universe (e.g., Chang et al. 2010; Masui et al. 2013; Switzer et al. 2013). In the latter case, recent work aims to use the intensity mapping technique (e.g., Bharadwaj et al. 2001; Loeb & Wyithe 2008), for which the resolution of individual objects is not required and the power spectrum of the intensity fluctuations is directly measured. Many of the 21 cm experiments aim to measure fundamental physics parameters by placing constraints on e.g., dark energy (e.g., Bull et al. 2015), modified gravity (e.g., Hall et al. 2013) or inflationary models (e.g., Xu et al. 2016). In order to have a realistic estimate of the degree of cosmological information that can be extracted from these experiments, it is important to quantify the extent of astrophysical degradation in these studies. This is an important effect which can be called the ‘astrophysical systematic’, and has consequences for our derivation of cosmological forecasts from the knowledge of the HI power spectrum.

In Padmanabhan et al. (2015, hereafter Paper I), we provided a quantitative estimate of the degree of this uncertainty, by using a minimum-variance estimator applied to the key astrophysical quantities that influence the HI power spectrum. We found that the astrophysical uncertainties cause the order of 60 – 100% uncertainty in the measured power spectrum. This can be further expressed as a function of redshift and the resulting estimates are provided in Table 3 of that paper.

In follow-up analytical work to the theoretical and observational uncertainties above, we developed a halo model framework to understand the distribution and evolution of HI in the post-reionization universe, by considering the current data both from 21 cm intensity mapping and resolved emission, as well as from Damped Lyman-Alpha (DLA) systems (Padmanabhan et al. 2017, hereafter Paper II). The parameters of this halo model were astrophysical, and related to how HI populates haloes both in terms of the HI mass - halo mass relation, as well as the HI radial distribution profile. Five free parameters are used: (i) the concentration normalization parameter, cHI, (ii) the evolution of the concentration with redshift, specified by \gamma, (iii) the overall normalization for the MHI - \langle M HI \rangle relation, \alpha, and (iv) the slope of the relation, \beta, and
a lower cutoff in virial velocity, $v_{c,0}$. Constraints on these astrophysical parameters were possible using the combined set of the low- and high redshift observations, and the statistical uncertainties resulted in fairly tight error bars on the estimation of the free parameters.

In this paper, we combine the understanding of the uncertainties in the astrophysics as described in Paper I, with the modelling framework for these as presented in Paper II, towards building realistic forecasts for current and future 21 cm experiments. In this work, we concentrate on the intensity mapping observations, in which the individual systems are not resolved. This constrains the power spectrum of HI, $P_{\text{HI}}(k, z)$ as a function of scale and redshift. In an intensity mapping survey, the angular power spectrum, $C_{\ell}(\ell, z)$ is the quantity that is typically constrained.

We first work with a ‘fiducial’ configuration, taken to be the SKA I MID (using bands B1 and B2) and explore both (i) how the astrophysical uncertainties cause a degradation (‘systematic’) in the cosmological forecasts, and the extent to which this can be alleviated through tomography or the combining of redshift bins, and (ii) the constraints on the astrophysical parameters themselves, achievable with an intensity mapping survey. In this work, we consider the cosmology to be given by the flat LCDM model with the free parameters $\{\Omega_{\text{m}}, \sigma_8, h, n_s, \Omega_{\text{b}}\}$. We use the astrophysical parameters $\beta$ and $v_{c,0}$ for describing the HI-halo mass relation.

We next investigate the impact of extending the multipole range from $\ell_{\text{max}} = 1000$ to $\ell_{\text{max}} = 2000$, thereby probing more non-linear scales for the fiducial configuration. We then investigate the effects of an extended parametrization of the HI-halo mass relation, beyond that favoured by the current data, on the forecasts obtained. We also explore the cases of other upcoming HI intensity mapping experiments, namely the CHIME, BINGO, TianLai, MeerKAT and FAST configurations. We discuss how the astrophysical effects influence the recovery of the cosmological parameters in each case. We summarize our conclusions and discuss future prospects in the final section.

### 2 Fisher Matrix Forecasts

Here, we present the formalism for forecasting the constraints on astrophysics and cosmology with the Fisher matrix.

In the halo model framework for HI, developed in, e.g., Padmanabhan & Refregier (2017); Padmanabhan et al. (2017), the average HI mass associated with a dark matter halo of mass $M$ at redshift $z$ is given by:

$$M_{\text{HI}}(M, z) = \alpha f_{\text{HI}} c M \left( \frac{M}{10^{11} M_\odot} \right)^{\beta} \exp \left[ - \left( \frac{v_{c,0}}{v_c(M, z)} \right)^3 \right]$$

where the three free parameters are (i) $\alpha$, the overall normalization factor, (ii) $\beta$, the slope of the HI - halo mass relation, and (iii) $v_{c,0}$, which is a lower virial velocity cutoff for the dark matter halo of mass $M$ to be able to host HI.  

The distribution of HI in the dark matter halo is described by a radial profile function, of the form:

$$\rho(r, M) = \rho_0 \exp(-r/r_s) \quad (2)$$

which contains the scale radius, $r_s$ which is calculated from the virial radius, $R_v(M)$ of the dark matter halo, and the concentration parameter of the HI, $c_{\text{HI}}(M, z)$, as:

$$r_s = R_v(M, z)/c_{\text{HI}}(M, z) \quad (3)$$

where the concentration parameter can be expressed as:

$$c_{\text{HI}}(M, z) = c_{\text{HI},0} \left( \frac{M}{10^{11} M_\odot} \right)^{-0.109} \frac{4}{(1 + z)^7} \quad (4)$$

The constant $\rho_0$ in the Eq. (2) is fixed by normalizing the HI profile within the virial radius $R_v$ to be equal to $M_{\text{HI}}$. Hence, the two free parameters in the HI density distribution are $c_{\text{HI},0}$ and $\gamma$. Using the above formalism for the HI - halo mass relation and the HI profile, we can compute the power spectrum of the HI intensity fluctuations by defining the Fourier transform of the density profile:

$$u_{\text{HI}}(k|M) = \frac{4\pi}{M_{\text{HI}}(M)} \int_0^{R_v} \rho_{\text{HI}}(r) \sin kr r^2 dr \quad (5)$$

where the profile is assumed truncated at the virial radius of the host halo. From this, we can compute the one- and two-halo terms of the HI power spectrum as:

$$P_{\text{HI}}(k, z) = P_{1h, \text{HI}} + P_{2h, \text{HI}} \quad (6)$$

where

$$P_{1h, \text{HI}}(k, z) = \frac{1}{\rho_{\text{HI}}} \int dM n(M) M_{\text{HI}}^2 |u_{\text{HI}}(k|M)|^2 \quad (7)$$

and

$$P_{2h, \text{HI}}(k, z) = P_{1h}(k) \left\{ \frac{1}{\rho_{\text{HI}}} \int dM n(M) M_{\text{HI}}(M) b(M) |u_{\text{HI}}(k|M)|^2 \right\} \quad (8)$$

In the above expressions, $n(M)$ denotes the dark matter halo mass function [taken to have the Sheth-Tormen (Sheth & Tormen 2002) form in the present study], and $b(M, z)$ (Scoccimarro et al. 2001) is the corresponding halo bias. From the above expression for the power spectrum, we can define the the angular power spectrum, denoted by $C_{\ell}$’s (e.g., Battye et al. 2012; Seehars et al. 2016) which is calculated from the

$$C_{\ell}(z, z') = \frac{2}{\pi} \int d\tilde{z} W(\tilde{z})D(\tilde{z}) \int d\tilde{z}' W'(\tilde{z}')D'(\tilde{z}') \times \int k^2 dk P_{\text{HI}}(k, z) jj(kR(\tilde{z})) jj(kR(\tilde{z}')), \quad (9)$$

where the $W, W'$ are the window functions at the redshifts $z$ and $z'$, taken to be uniform across the redshift bin considered, $R(z)$ is the co-moving distance to redshift $z$, and $D(z)$ is the growth factor for the dark matter perturbations. The calculation of the angular power spectrum can be simplified on using the Limber approximation (Limber 1953) which is a good approximation in the large $\ell$ ($\ell \gtrsim 50$) limit. The expression can be shown to reduce to:

$$C_{\ell} = \frac{1}{c} \int dz' \frac{W(z')^2 D(z')^2 H(z) H(z)}{R(z')^2} P_{\text{HI}}(\ell/R(z), z) \quad (10)$$

An example angular power spectrum calculated using the above formula is plotted in Fig. 1.

As can be seen from the above equation, both the astrophysical and cosmological parameters enter the expression for the power spectrum.
Intensity mapping forecasts

by $D_{\text{dish}}$, the expression for $N_t$ can be written as (e.g., Battye et al. 2012; Bull et al. 2015):

$$N_t = \left( \frac{\sigma_{\text{pix}}}{T} \right)^2 \left( \frac{\Omega_{\text{pix}}}{W_t} \right)$$

with $W_t = e^{-2\sigma_{\text{beam}}^2/N}$, $\sigma_{\text{beam}} = \theta_{\text{beam}}/\sqrt{8\ln 2}$ and $\theta_{\text{beam}} = \lambda_{\text{obs}}/(N_{\text{dish}}D_{\text{dish}})$, and the $T(z)$ is the mean brightness temperature at redshift $z$ defined by:

$$T(z) \approx 44 \mu K \left( \frac{\Omega_{\text{HI}}(z) h}{2.45 \times 10^{-4}} \right) (1+z)^2$$

where $E(z) = H(z)/H_0$ is the normalized Hubble parameter at that redshift. The $\Omega_{\text{pix}}$ is defined through $\Omega_{\text{pix}} = \theta_{\text{beam}}$, and the $\sigma_{\text{pix}}$ is defined by:

$$\sigma_{\text{pix}} = \frac{T_{\text{sys}}}{\sqrt{4\pi \sigma_{\text{pix}}^2}}$$

where $T_{\text{sys}}$ is the system temperature, calculated following $T_{\text{sys}} = T_{\text{inst}} + 60$ K ($\nu/350$ MHz)$^{-0.5}$ where $T_{\text{inst}}$ is the instrument temperature and $\nu$ is the observing frequency. The integration time per beam is $t_{\text{pix}}$ (taken to be 1 year for all the surveys considered here) and the $\Delta t$ denotes the frequency band channel width, which is connected to the tomographic redshift bin separation $\Delta z$. For the purposes of the noise calculation, we assume $\Omega_{\text{HI}}(z) h = 2.45 \times 10^{-4}$, independent of redshift. The fraction of sky probed by the survey, $f_{\text{sky}}$ is given by:

$$f_{\text{sky}} = \frac{S_A}{4\pi (180/\pi)^2}$$

where the survey area $S_A$ is in square degrees. Thus, given an experimental configuration specifying the values of $N_{\text{dish}}$, $D_{\text{dish}}$, the survey area, redshift coverage and instrument temperature, it is possible to compute the Fisher information matrix for a set of cosmological and astrophysical parameters. We now apply this to the various experiments. For completeness, we also study the comparison between the forecasts derived using the Fisher matrix framework and from a Markov Chain Monte Carlo (MCMC) approach for a few cases in Appendix A.

We consider six of the forthcoming experiments in the present work: (i) The Canadian Hydrogen Intensity Mapping Experiment (CHIME)\(^2\), (ii) BAO In Neutral Gas Observations (BINGO; Battye et al. 2012), (iii) TianLai (Chen 2012), (iv) the Five hundred metre Aperture Spherical Telescope (FAST; Smoot & Debono 2017), (v) the Meer-Karoo Array Telescope (MeerKAT; Jonas 2009) and (vi) the Square Kilometre Array (SKA) Phase 1 MID\(^3\) (using both bands, B1 + B2). Table 2 gives the configurations used [for more details on the experiments, see Bull et al. (2015)]. More details of the configurations of the BINGO and SKA as regards the noise properties etc. are provided in Olivari et al. (2018).

### 3 FIDUCIAL CONFIGURATION: SKA - I MID: B1 + B2

In this section, we analyze the effects of the astrophysical uncertainties on the cosmological forecasts in some detail for a particular configuration, namely the SKA I MID, with both Bands 1 and 2\(^4\).

We compute the noise term as defined by Eq. (13) in the preceding section. We consider equal sized redshift bins of width

---

**Figure 1.** Angular power spectrum $C_\ell$ from Eq. (10) at redshift 0.35, using the fiducial astrophysical and cosmological parameters from Table 1. The error bars shown in red represent the standard deviation $\Delta C_\ell$, calculated following Eq. (12) for the SKA I MID configuration.

**Table 1.** Fiducial values of astrophysical and cosmological parameters considered.

| Astrophysical | Cosmological |
|---------------|-------------|
| log $v_{c,0}$ | $h$         | 0.71       |
| $\beta$       | $\Omega_m$  | 0.28       |
| $\alpha$      | $\Omega_b$  | 0.0462     |
| $\sigma_{\text{HI}}$ | $\sigma_s$  | 0.81       |
| $\gamma$      | $n_s$       | 0.963      |

* spectrum. For forecasting the magnitude of the constraints, we adopt a Fisher matrix formalism considering both the mean and variance of the $C_\ell$. For the comparisons between the various experiments, the following parameters go into the computation of the power spectrum of HI:

(i) The astrophysical parameters include $v_{c,0}$, $\alpha$, and $\beta$ used in estimating $M_{\text{HI}}(M)$, and the normalization $c_0$ and the evolution parameter $\gamma$ used in the HI profile.

(ii) The cosmological parameters are the Hubble parameter $h$, the baryon density $\Omega_b$, the spectral index $n_s$, the power spectrum normalization parameter $\sigma_s$ and the matter density of the universe, $\Omega_m$.

Throughout, the cosmology adopted is flat, so that we assume that $\Omega_A = 1 - \Omega_m$. The fiducial values of the parameters are listed in Table 1.

The Fisher matrix for forecasts on the parameters is computed as follows:

$$F_{ij} = \sum_\ell \frac{1}{(\Delta C_\ell)^2} \frac{\partial C_\ell}{\partial p_i} \frac{\partial C_\ell}{\partial p_j}$$

where the sum is over the range of $\ell$’s probed, and

$$(\Delta C_\ell)^2 = \frac{2(C_\ell + N_t)^2}{(2\ell + 1)f_{\text{sky}}}$$

where the noise term is denoted by $N_t$ and depends on the particulars of the experiment. If the observing wavelength is denoted by $\lambda_{\text{obs}}$, the number of dishes by $N_{\text{dish}}$ and the diameter of the dish

---

\(^2\) [https://chime-experiment.ca/]

\(^3\) [http://www.ska.ac.za/]

\(^4\) This leads to the effective redshift range 0 to 3.06.
Table 2. Various experimental configurations considered in this work.

| Configuration | $T_{\text{inst}}$ (K) | Dishes ($N_d \times N_b$) | $D_{\text{dish}}$ (m.) | $S_A$ (sq. deg.) | $z_{\text{min}}$ | $z_{\text{max}}$ |
|---------------|-----------------------|---------------------------|------------------------|-----------------|----------------|----------------|
| BINGO         | 50                    | 50                        | 25                     | 5000            | 0.1            | 0.5            |
| CHIME         | 50                    | 1280                      | 20                     | 25000           | 0.8            | 2.5            |
| FAST          | 20                    | 20                        | 500                    | 2000            | 0.5            | 2.5            |
| TianLai       | 50                    | 2048                      | 15                     | 25000           | 0.5            | 1.55           |
| MeerKAT       | 29                    | 64                        | 13.5                   | 25000           | 0.5            | 1.5            |
| SKA I MID     | 28                    | 190                       | 15                     | 25000           | 0.0            | 3.06           |

Figure 2. Cosmological forecasts for SKA I MID, (i) with the effects of astrophysical uncertainties (‘Without astrophysical prior’), (ii) without the effects of astrophysical uncertainties (‘Fixed astrophysics’), and (iii) with the effects of astrophysical uncertainties but also an astrophysical prior added, coming from current knowledge (‘With astrophysical prior’).
3.1 Effect of astrophysical priors

The marginalized parameter space (MPS) of the astrophysical parameters obtained with the astrophysical parameters fixed to their mean values. This is shown in Fig. 3. The forecasts are shown in Fig. 2, for each of the five cosmological parameters: $\Omega_m, n_s, h, \sigma_8, \beta$, and $v_{c,0}$ from Eq. (11) for each of the bins.

The best astrophysical constraints with the higher $\ell$-range are indicated by the red dashed curves in Fig. 2. The figures show that the constraints improve on the addition of the information in different tomographic bins. The best constraints are in the range of 2% - 50%, depending upon the parameter under consideration.

As a complementary analysis, we also indicate the constraints on the astrophysical parameters, both with the marginalization over the cosmological parameters, as well as with the cosmological parameters fixed to their mean values. This is shown in Fig. 3. The figure also shows the constraints for the case of marginalization over only the second astrophysical parameter (denoted as the ‘Fixed cosmology’ case). It can be seen that the constraints in the case of the ‘Fixed cosmology’ improve with the addition of tomographic bins, and saturate as we combine the information from 6 or 7 redshift bins. The saturated values of the constraints (the ‘asymptotic’ or ‘best’ constraints) are graphically illustrated in the bar charts of Fig. 4.

3.2 Effects of increasing $\ell$-range

We now explore the effects of increasing the $\ell$ range for this experiment, to investigate smaller scales (increasing $\ell$ from 1000 to 2000). The asymptotic constraints on the cosmological parameters are shown in the left panel of Fig. 5. All the cosmological constraints are improved by the extension to a larger $\ell$ range. The strong improvement in the parameter $n_s$ is expected, since this parameter is directly connected to the scale $k$. The best astrophysical constraints with the higher $\ell$-range are shown in the right panel of Fig. 5. Again, the forecasts for both parameters improve on reaching smaller scales.\(^5\)

3.3 Effects of astrophysical parametrization

Thus far, we have used a parametrization of the HI-halo mass (HHM) relation which was fitted to the currently available constraints, in the form of Eq. (1). However, in the light of the data available from future experiments (such as the SKA I), it may be

\(^5\) As can be expected, the parameter $\alpha$ is not constrained by the $C_\ell$, this is because it determines the overall normalization and as such cancels in the power spectrum definitions (Eq. (7) and Eq. (8)). The parameters $c_0$ and $\gamma$ are also found to be poorly constrained by the intensity mapping measurement alone, however, their constraints also are found to show improvement on extending the $\ell$-range to $\ell_{\text{max}} = 2000$. 

\[\Delta \varphi = 0.05\] spanning the whole redshift range covered by the experiment, and compute the $C_\ell$’s using Eq. (10) at the midpoints of each of the redshift bins. Using the values thus obtained, we compute the Fisher forecasts for the parameters $\Omega_m, n_s, h, \sigma_8, \beta$ and $v_{c,0}$ from Eq. (11) for each of the bins.

The forecasts are shown in Fig. 2, for each of the five cosmological parameters, by the blue solid lines. In all cases, we see that the tomographic information significantly tightens the constraints. The saturation occurs after about six or seven redshift bins.

Figure 3. Astrophysical forecasts for SKA I MID, (i) with the effects of cosmological uncertainties (‘Without cosmological prior’), and (ii) without the effects of cosmological uncertainties (‘Fixed cosmology’).
possible to constrain more parameters of this relation. In this section, we investigate whether (and how) a different (and extended) parametrization of the HIHM affects the results on the forecasts obtained.

We use, for this purpose, a HIHM relation of the form:

\[ M_{\text{HI}}(M, z) = \alpha f_{\text{H}, c} M \left( \frac{M}{10^{13} M_\odot} \right)^{\beta(z)} \times \exp \left[ - \left( \frac{v_c(z)}{v_c(M, z)} \right)^2 \right] \]  

(17)

where

\[ \beta(z) = \beta_1 + \beta_2 \frac{z}{z + 1} \]  

(18)

and

\[ v_c(z) = v_{c, 0} + v_{c, 1} \frac{z}{z + 1} \]  

(19)

which is a superset of the fiducial HIHM considered in the previous sections. This function reduces to Eq. (1) when \( \beta_2 = v_{c, 1} = 0 \), with \( \beta_1 \) reducing to the original \( \beta \). Thus, the above form of the HIHM introduces two more free parameters, \( v_{c, 1} \) and \( \beta_2 \) into the formalism.

We proceed as in the previous section for the Fisher matrix analysis. The asymptotic (best) relative constraints on the cosmological parameters with this new parametrization are shown in the left panel of Fig. 6. We also indicate, as before, the cosmological constraints with the astrophysical parameters fixed to their fiducial values (denoted by ‘Fixed astrophysics’). Since the current data do not constrain the values of \( v_{c, 1} \) and \( \beta_2 \) (Padmanabhan et al. 2017), we do not consider the effects of astrophysical priors on these two parameters.

We also address the complementary case, i.e. the best constraints on the four astrophysical parameters, in the right panel of Fig. 6. We also indicate the constraints with the cosmological pa-

---

**Figure 4.** Left panel: Asymptotic (best) constraints on the cosmological parameters, (i) without the astrophysical prior, (ii) with fixed astrophysics, and (iii) with the astrophysical prior coming from the present data, for the case of \( \ell_{\text{max}} = 1000 \). Right panel: Astrophysical forecasts for SKA I MID for the case of \( \ell_{\text{max}} = 1000 \), (i) without cosmological priors, and (ii) with fixed cosmology.

**Figure 5.** Left panel: Asymptotic (best) constraints on the cosmological parameters, (i) without the astrophysical prior, (ii) with fixed astrophysics, and (iii) with the astrophysical prior coming from the present data, for the case of the extended \( \ell \)-range, up to \( \ell_{\text{max}} = 2000 \). Right panel: Astrophysical forecasts for SKA I MID for the case of \( \ell_{\text{max}} = 2000 \), (i) without cosmological priors, and (ii) with fixed cosmology.
parameters fixed to their fiducial values (the ‘Fixed cosmology’ case). Relative constraints are shown in the cases of the two parameters $v_{c,0}$ and $\beta_1$. For the new parameters $v_{c,1}$ and $\beta_2$, whose fiducial values are set to zero, we indicate the absolute values of the standard deviation obtained by the Fisher analysis.

Comparison of the left panel of Fig. 6 to that of Fig. 4 reveals that the cosmological constraints are degraded only very weakly by the addition of the two new astrophysical parameters. The absolute errors on the quantities $v_{c,1}$ and $\beta_2$ asymptote to values of 0.3. This study indicates, therefore, that the cosmological recovery is not sensitive to the choice of the astrophysical parametrization used in the analysis.

4 EXTENSION TO OTHER EXPERIMENTS

We now extend the results for the fiducial configuration to the case of the other experiments - BINGO, CHIME, TianLai, MeerKAT and FAST. In each case, we work with a 21 cm autocorrelation intensity mapping survey with the experimental parameters as given in Table 2 (see also Bull et al. 2015). As in the previous section, we compare the forecasts with and without considering the effects of astrophysical parameters, shown in Fig. 7. The thick lines show the forecasts marginalizing over all the parameters (‘Without astrophysical priors’), and the thin lines show the case when the astrophysics is held fixed. We note the following:

(i) As with the fiducial configuration, the cosmological forecasts are affected by the addition of the astrophysical parameters.

(ii) The degradation is offset by the increased sensitivity due to the tomographic addition of several redshift bins, saturating, in many cases, with four or five redshift bins.

(iii) We note the same trend of improvement of the constraints by adding the information from the current knowledge of the astrophysical data (or equivalently, with fixed values of the astrophysical parameters).

Fig. 8 shows the astrophysical constraints on each of the experimental configurations. Again, the tomographic addition of information from different redshift bins improves the forecasts, just as in the fiducial case considered in the previous sections.

5 SUMMARY AND OUTLOOK

In this paper, we have used the present understanding of the mean and uncertainties in the astrophysical parameters related to neutral hydrogen in the post-reionization universe, to develop forecasts for cosmological and astrophysical parameters with current and future intensity mapping surveys.

We first considered a particular (‘fiducial’) experiment, the SKA I MID, and studied the effect of the astrophysical ‘systematic’ (which needs to be considered in addition to the other systematics caused by instrumental effects and foregrounds). For this experiment and considering scales up to $\ell_{\text{max}} = 1000$, we found that marginalizing over the astrophysical parameters (without priors) broadens the forecasted cosmological constraints. This broadening is by a factor of $2.4 - 2.6$ for the parameters $h$, $n_s$, and $\sigma_8$, and $1.1 - 1.3$ for the parameters $\Omega_b$ and $\Omega_m$. However, it is, for the large part, alleviated by the addition of prior information coming from our knowledge of astrophysics today. We studied the robustness of these results to changes in the choice of the astrophysical parametrization considered, and found that an extended HIHM relation did not lead to significant differences in the recovery of the cosmological parameters. Probing smaller scales by increasing $\ell_{\text{max}}$ from 1000 to 2000 resulted in a factor of $\sim 1.5 - 1.8$ improvement in the constraints, enabling levels of $4 - 8\%$ to be reached for the astrophysical parameters $v_{c,0}$ and $\beta$. We also studied how the constraints improved by increasing the number of tomographic redshift bins, and found saturation, in most cases, with $4 - 5$ redshift bins.

We then compared these results to intensity mapping with other current and future generation facilities, with similar findings. Specifically, for these experiments, the astrophysical uncertainties also cause a broadening in the cosmological constraints, which is, in large part, alleviated by the addition of the prior coming from the current knowledge of the astrophysics.

We note that the astrophysical uncertainties used for the cur-
Cosmological forecasts for the other experiments – BINGO (red), TianLai (green), FAST (blue), CHIME (maroon) and MeerKAT (orange) compared to the fiducial case of SKA I MID (violet). In all cases, the forecasts obtained on marginalizing over all parameters (‘Without astro prior’) are shown by the thick solid lines. The forecasts with the astrophysical parameters fixed to their mean values (‘Fixed astrophysics’) are shown by the thin lines for comparison.

This will also help to reduce the systematics from the instrumental effects. Some examples of these have been explored in, e.g., Villaescusa-Navarro et al. (2015); Obuljen et al. (2017); Pourtsidou et al. (2017). We leave the extensions of the present formalism to cross-correlation studies in future work.

Recent data prior are assumed to be dominated by statistical errors (see also Padmanabhan et al. (2017)). The effects of systematic errors, the foreground contamination or instrumental effects are not considered in the above forecasts, the primary aim being to explore the inherent broadening in the parameters due to the present state of knowledge of the astrophysics which goes into the HI halo model. The cosmological and astrophysical constraints can be improved by the combination of these estimates with the priors from, e.g. CMB experiments, and cross-correlations with other probes.
Relative error in $\beta_c$,

\[ \sigma_{\beta_c} \]

APPENDIX A: FISHER AND MCMC COMPARISON

In this appendix, we provide a few examples that illustrate the robustness of the Fisher matrix formalism for forecasting the cosmological parameters in cases where the matrix is well-conditioned (with conditions numbers $\lesssim 100$). Typically, this happens when the low-redshifts ($z < 0.1$) are included in the forecasting, since the constraints are seen to get increasingly stronger at lower redshifts. Here, we focus on the lowest redshift bin, $z \sim 0.082$, and indicate this comparison for two cases: (i) Joint forecasts on the $\sigma_8 - \Omega_m$ plane, and (ii) Joint forecasts on the $\sigma_8 - \Omega_m - \beta$ plane, i.e., exploring the effect of astrophysical degradation, both using the fiducial SKA 1 MID (B1 + B2) configuration. We obtain the constraints on the parameters using both the Fisher formalism as described in the main text as well as a Bayesian Markov Chain Monte Carlo (MCMC) likelihood analysis, and compare the results.

The parameter estimation using MCMC is performed using the likelihood function $\mathcal{L}$ defined through:

\[ -2 \ln \mathcal{L} = -\ln \sum_{\ell} \frac{(C_{\ell,\text{obs}} - C_{\ell,\text{calc}})^2}{\sigma_{C_{\ell}}} \] (A1)

In the above expression, the $C_{\ell,\text{obs}}$ is computed using the best-fitting values of the cosmological and astrophysical parameters. The $\sigma_{C_{\ell}}$ indicates the variance of the angular power spectrum, computed using Eq. (12). The $C_{\ell,\text{calc}}$ is the calculated value of the angular power spectrum with the free parameters (i) $\sigma_8$ and $\Omega_m$ and (ii) $\sigma_8$, $\beta$ and $\Omega_m$. The likelihood in Eq. (A1) is computed using the COSMOHAMMER package (Akeret et al. 2013), and the results are shown in Fig. A1. The dark and light blue shaded regions indicate the 68% and 95% levels respectively obtained with COSMOHAMMER. The blue and red solid curves indicate the corresponding constraints obtained with the Fisher analysis. The MCMC and the Fisher forecasts are remarkably similar, thus validating the use of the Fisher formalism in the text for well-conditioned cases.

REFERENCES

Akeret J., Seehars S., Amara A., Refregier A., Csillaghy A., 2013, Astronomy and Computing, 2, 27

Battye R. A., et al., 2012, arXiv:1209.1041,

Bharadwaj S., Nath B. B., Sethi S. K., 2001, Journal of Astrophysics and Astronomy, 22, 21

Bull P., Ferreira P. G., Patel P., Santos M. G., 2015, ApJ, 803, 21

Chang T.-C., Pen U.-L., Bandura K., Peterson J. B., 2010, Nature, 466, 463

Chen X., 2012, International Journal of Modern Physics Conference Series, 12, 256

Hall A., Bonvin C., Challinor A., 2013, Phys. Rev. D, 87, 064026

Jonas J. L., 2009, IEEE Proceedings, 97, 1522

Limber D. N., 1953, ApJ, 117, 134

Loeb A., Wylezich K. S. B., 2008, Phys. Rev. Lett., 100, 161301

Madau P., Meiksin A., Rees M. J., 1997, ApJ, 475, 429

Masiu K. W., et al., 2013, ApJ, 763, 210

Obuljen A., Castorina E., Villaescusa-Navarro F., Viel M., 2017, preprint, (arXiv:1709.07893)

Oliver L. C., Dickinson C., Battye R. A., Ma Y.-Z., Costa A. A., Remazeilles M., Harper S., 2018, MNRAS, 473, 4242

Padmanabhan H., Choudhury T. R., Refregier A., 2015, MNRAS, 447, 3745

Padmanabhan H., Refregier A., Amara A., 2017, MNRAS, 469, 2323

Pourtsidou A., Bacon D., Crittenden R., 2017, MNRAS, 470, 4251

Scoccimarro R., Sheth R. K., Hui L., Jain B., 2001, ApJ, 546, 20

Seehars S., Paranjape A., Witzemann A., Refregier A., Amara A., Akeret J., 2016, J. Cosmology Astropart. Phys., 3, 001

Sheth R. K., Tormen G., 2002, MNRAS, 329, 61

Smoot G. F., Debono I., 2017, A&A, 597, A136

Switzer E. R., et al., 2013, MNRAS, 434, L46

Villaescusa-Navarro F., Bull P., Viel M., 2015, ApJ, 814, 146

Xu Y., Hamann J., Chen X., 2016, Phys. Rev. D, 94, 123518
Figure A1. Comparison of the constraints obtained with the Fisher and MCMC methods for two illustrative cases at redshift $\sim 0.1$. The top panel shows the constraints on the $\sigma_8 - \Omega_m$ plane, and lower panel shows the case for the $\sigma_8 - \Omega_m - \beta$ parameter space. The dark and light blue shaded regions indicate the 68% and 95% levels respectively obtained with the MCMC. The blue and red solid curves indicate the corresponding levels obtained with the Fisher analysis described in the main text.