The PAU survey: Lyα intensity mapping forecast

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ABSTRACT
In this work, we explore the application of intensity mapping to detect extended Lyα emission from the IGM via cross-correlation of PAUS images with Lyα forest data from eBOSS and DESI. Seven narrow-band (FWHM=13nm) PAUS filters have been considered, ranging from 455 to 515 nm in steps of 10 nm, which allows the observation of Lyα emission in a range $2.7 < z < 3.3$. The cross-correlation is simulated first in an area of $100 \text{ deg}^2$ (PAUS projected coverage), and second in two hypothetical scenarios: a deeper PAUS (complete up to $i_{AB} < 24$ instead of $i_{AB} < 23$, observation time x6), and an extended PAUS coverage of $225 \text{ deg}^2$ (observation time x2.25), both cross-correlated only with DESI. A hydrodynamic simulation of size 400 Mpc/h has been used to simulate both extended Lyα emission and absorption in the Lyα forest, while the foregrounds in PAUS images have been simulated using a lightcone mock catalogue. The total probability of detection is estimated to be 23% and 33% for PAUS-eBOSS and PAUS-DESI respectively, from a run of 1000 simulated cross-correlations with different realisations of instrumental noise and quasar positions. The hypothetical PAUS scenarios increase this probability to 58% (deeper PAUS) and 60% (extended PAUS), with the extension of angular coverage being far more time-efficient for Lyα intensity mapping than the increase of exposure time. These findings seem to indicate that this methodology could also be applied to broad-band surveys.

Key words: large-scale structure of Universe – cosmology: observations

1 INTRODUCTION
In the last few years, the amount of observational data for the Universe at different wavelengths has steadily increased, which has led to the development of new methods and techniques to analyse these observations. Intensity mapping (IM) is one of these techniques, consisting of the tracing of large-scale structure with one or more emission lines, without resolving any kind of finite source, like galaxies or quasars. The use of a sharp and narrow spectral feature, such as an emission line, allows us to map the structure not only in angular coordinates but also in redshift, which provides 3-D tomography of the tracer (Peterson et al. 2009).

Originally, this technique was proposed to study the power spectrum with the 21-cm emission line at high, pre-reionization redshifts ($z > 5$) (Madau et al. 1997; Loeb & Zaldarriaga 2004), but its application at lower redshifts has also been studied, e.g., as a method to measure Baryonic Acoustic Oscillations (BAO) (Chang et al. 2008). Other emission lines have also been considered, such as the CO rotational line at intermediate (Breysse et al. 2014; Li et al. 2016) or high redshift, (Carilli 2011), CII emission line (Gong et al. 2012; Yue et al. 2015), or the Lyα line (Silva et al. 2013; Pullen et al. 2014). Given the short wavelength of this last line (121.567 nm), Lyα emission can only be observed at

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$z > 2$ with ground-based telescopes, which limits any IM study with this tracer to relatively high redshifts.

Since IM does not resolve individual objects but considers all emission at certain wavelengths, one of the main challenges that IM studies face is contamination by foregrounds. This source of noise can be removed via cross-correlation with other datasets of objects with well-known redshift, an approach that has been successfully applied in detections of the 21-cm line (Chang et al. 2010), CHI emission line (Pullen et al. 2018) and the Lyα line (Croft et al. 2016), coming from HI in the intergalactic medium (IGM).

In the Lyα case, in Croft et al. (2016) all data used for IM was extracted from the Sloan Digital Sky Survey III (SDSS-III, Eisenstein et al. (2011)) Baryon Oscillation Spectroscopic Survey (BOSS, Dawson et al. (2013)). Lyα emission is estimated by selecting spectra of Luminous Red Galaxies (LRGs) at $z < 0.8$ and subtracting a best fit model for each galaxy spectrum, which leaves a significant amount of Lyα surface brightness from higher redshifts. These residual spectra are cross-correlated with quasars from the same catalogue, which gives a detection at mean redshift $z = 2.5$ of large-scale structure at a $8\sigma$ level, and a shape consistent with the ΛCDM model.

This cross correlation, however, only yields a positive signal on scales up to 15 Mpc/h. Given the quasar density of BOSS, this implies that only 3% of the space (15 Mpc/h around quasars) is being mapped, and large scale structure of Lyα emission in general is not being constrained by this measurement. Lyα emission is extended at high enough redshift (approximately $z > 3$), with Lyα blobs (Taniguchi et al. 2001; Matsuda et al. 2004) forming visible structures around quasars up to hundreds of kpc in size, and the integrated faint Lyα emission in turn covers almost 100% of the sky (Wisotzki et al. 2018). Therefore, cross-correlation of the Lyα emission with a more suitable dataset (less rare than quasars) is expected to provide a positive signal on larger scales.

One of these possible datasets to cross-correlate with is the Lyα forest i.e., the set of absorption lines that appears in the spectrum of quasars due to the HI mass distribution between the object and the observer (Rauch 1998). Each Lyα forest spectrum contains information about the HI distribution along a large fraction of the entire line of sight, which should allow cross-correlation over larger, more representative volumes. In Croft et al. (2018) a first attempt at cross-correlation was performed between Lyα forest from BOSS and similar LRG spectra with the best galaxy fit subtracted to those used in Croft et al. (2016), but no signal was found. Nonetheless, BOSS was not designed with Lyα IM as an objective, and it is certain that larger and more suitable datasets are needed to obtain a clear detection (Kovetz et al. 2017). Such a dataset would need data with redshift precision close to that achieved by spectroscopy over large areas, providing a volume large enough to study large scale structure with Lyα IM (Croft et al. 2018). One potential candidate that may fulfill these requirements are narrow-band imaging surveys, such as the Physics of the Accelerating Universe Survey (PAUS, Castander et al. 2012; Eriksen et al. 2019).

The object of this work is to simulate the cross-correlation of PAUS images with Lyα forest data from two different spectroscopic surveys, in order to compute the two-point correlation function (2PCF), as well as to evaluate if meaningful constraints can be obtained. The spectroscopic surveys considered for this purpose are the already available SDSS extended Baryon Oscillation Spectroscopic Survey (eBOSS, Dawson et al. (2015)), and the upcoming Dark Energy Spectroscopic Instrument (DESI) Experiment DESI Collaboration (2016).

For all the calculations in this paper the following flat cosmology has been assumed: $h = 0.702, \Omega_0 = 0.275, \Omega_m = 0.725, \Omega_b = 0.046, n_s = 0.968, \sigma_8 = 0.82$. This is the cosmology of the hydrodynamic simulation we have used to model the Lyα extended emission and the Lyα forest (Ozbek et al. 2016), which has also been used for the entirety of the work for the sake of consistency.

The paper is structured as follows. In Section 2 the two datasets to be cross-correlated (PAUS and eBOSS/DESI) are briefly summarised. Section 3 shows how these datasets are simulated by combining the aforementioned hydrodynamic simulation and a lightcone mock catalogue. In Section 4, the estimator to compute the observed cross-correlation from the two datasets is explained, as well as some caveats to be taken into account for this particular case. Section 5 describes the theoretical calculation of the two-point correlation function from the matter power spectrum. Section 6 shows the results from both the theoretical correlation function and the simulated cross-correlation; the bias of the extended Lyα emission/Lyα forest is derived from its comparison, and the likelihood of a cross-correlation detection is evaluated for different cases. Finally, we conclude with Section 7.

## 2 SURVEYS TO CROSS-CORRELATE

### 2.1 PAUS

PAUS is a photometric imaging survey currently being carried out at the William Herschel Telescope with the PAU Camera (Castander et al. 2012), whose main feature is the use of 40 narrow-band filters with a full width at half maximum (FWHM) of ≈ 13 nm, with mean wavelengths of 455 to 845 nm in steps of 10 nm (Fig. 1). Such a configuration allows one to obtain photometric redshifts (photo-z) with sub-percent precision over large sky areas (Martí et al. 2014). Preliminary results (Eriksen et al. 2019) already achieve better photo-z precision than state-of-the-art photo-z measurements in the COSMOS field (Laigle et al. 2016).

Although the main purpose of the survey is the elaboration of high-density galaxy catalogues with high-precision redshifts for cross-correlations of lensing and redshift distortion probes (Gaztañaga et al. 2012), the narrow-band data from PAUS may also be used for intensity mapping. The background of PAUS images, where no objects are resolved, also contains valuable cosmological information. Given the wavelength range of the NB filters, Lyα luminosity is observed in the range $2.7 < z < 6$, distributed in 40 redshift bins, one per each NB filter. At this redshift range faint Lyα emission surrounds most objects (Wisotzki et al. 2018), but foreground contamination must be removed first in order to study it.

For this work, however, only the seven bluest NBs will be considered, which span from 455 to 515 nm (shaded in
With these seven blue filters, Lyα emission is observed over the range 2.7 < z < 3.3, approximately. At higher filter wavelengths, the observed Lyα emission increases in redshift, thus being farther away and fainter. In addition to this, the fraction of quasars observed at z > 3.3 is extremely small (Fig. 2), which means that the amount of Lyα forest data sampled this space is also very limited. Therefore, adding extra filters only provides a volume for the cross-correlation with lower SNR in PAUS images, and scarcely sampled by the Lyα forest.

The fields targeted by the survey are, in addition to COSMOS, the W1, W2 and W3 fields from the Canada-France-Hawaii Telescope Lensing Survey (CFHTLenS, Heymans et al. (2012)). The sum of the angular area of all these fields is ∼130 deg², but since a full coverage of the CFHTLenS fields is not expected, a total angular area of ∼100 deg² of PAUS images will be considered for this work.

3 Simulation of the survey data

In order to simulate the cross-correlation between different surveys, the first step is to simulate the actual survey datasets. For this work, an already existing hydrodynamic simulation has been used for both Lyα forest data and Lyα emission, while the foregrounds in PAUS images have been computed using a broad-band mock catalogue interpolating the spectral energy distributions (SEDs) of objects by fitting SED templates. On top of the foregrounds, noise from any other sources (electronic, atmospheric, etc.) also needs to be modeled; this is done by assuming that the sum of all noise follows a Gaussian distribution, and measuring the variance of this distribution directly from PAUS reduced images.

This section is divided in two subsections. In Section 3.1, the three elements used for the modelled survey (hydrodynamic simulation, mock catalogue and noise) are described, and in Section 3.2, we explain how these datasets are combined to simulate both PAUS images and eBOSS/DESI Lyα forest data.

3.1 Independent simulations

3.1.1 Hydrodynamic simulation

The hydrodynamic simulation used in this work has been performed with the P-GADGET code (Springel 2005; Di Matteo et al. 2012), with 2·4096² particles in a 400 Mpc/h box using the cosmology specified in §1. Particle masses of 1.19·10³ h⁻¹M⊙ and 5.92·10⁷ h⁻¹M⊙ were used for gas and dark matter respectively, with a gravitational force resolution of 3.25h⁻¹ kpc. In order to speed up the simulation, the density threshold for star formation was lower than usual, so
gas particles became collisionless star particles more quickly. This density threshold was 1000 times the mean gas density. Besides this, black hole formation and stellar feedback were not taken into account. While this results in inaccurate stellar properties of galaxies, it does not significantly affect the IGM, and thus the simulated Lyα forest (Viel et al. 2004).

This simulation was originally computed for Lyα forest studies, and has already been used in several works. In Cisewski et al. (2014) and Ozbek et al. (2016), different methodologies to model the 3D IGM between Lyα forest data were tested with it, while in Croft et al. (2018) it was used to simulate Lyα IM. Fig. 3 shows a voxel plot of the hydrodynamic simulation in both Lyα emission, in luminosity units (erg/s), and absorption, in δ flux contrast, defined as

\[ \delta_i = e^{-\tau_i} - 1. \] (1)

Where \( \tau_i \) is the optical depth of the Lyα forest pixel \( i \), computed along sightlines through the simulation, as in Hernquist et al. (1996). Therefore, with this definition high values of \( \delta \) correspond to regions with low HI density, and vice versa. This δ absorption flux is expected to have a clustering bias with respect to dark matter of \( b_\delta \approx 0.336 \pm 0.012 \) at \( z = 2.25 \) (Slosar et al. 2011), including redshift distortion effects.

While the physics leading to the Lyα forest absorption are reproduced explicitly in the hydrodynamic simulation, we make predictions for the Lyα luminosity using a simple heuristic model, with an amplitude normalised using observational data; not enough is known about all sources of Lyα emission to warrant using a more detailed model.

In this model, the Lyα luminosity is proportional to the square of the baryonic density field at the scale of the spatial binning used for this work (1.56 Mpc/h). This is done with the following expression

\[ L_{\text{Lyα}}(r) = C_L \rho_b(r)^2, \] (2)

where \( \rho_b(r) \) is the baryonic density field, and \( C_L \) is a normalisation constant chosen in order to set the average Lyα luminosity density to 1.1 \( \cdot 10^{40} \, \text{erg/s/(Mpc)}^3 \). This value of Lyα luminosity density is that measured from observed Lyα emitters at redshift \( z = 3.1 \) (Gronwall et al. 2007), which is a conservatively low value to use, as it does not include any sources of Lyα emission which are not readily observed in narrow band Lyα surveys. This includes low surface brightness extended halos around Lyα emitters (e.g., Steidel et al. 2011) (which could host 50% or more extra Lyα luminosity density), or any other low surface brightness emission which could be difficult to detect in surveys aiming to detect objects above a threshold, but which would be included in an intensity map. The Lyα luminosity density we use can be converted to an associated star formation rate density applying a commonly used relation between Lyα luminosity and star formation rate (SFR) of 1.1 \( \cdot 10^{42} \, \text{erg/s/(M}_\odot/\text{yr)} \) at \( z \approx 3 \) (Cassata et al. 2011). This relation yields a SFR density measured from observed Lyα emitters of 0.01 M\(_\odot/\text{yr/Mpc}^3\) (Gronwall et al. 2007).

Once the Lyα luminosity density is determined for a simulation cell in the model, we convolve the Lyα luminosity values with the line of sight velocity field, in order to put the Lyα emission into redshift space. This technique is similar to that used to convert the Lyα forest absorption spectra into redshift space (see e.g., Hernquist et al. 1996).

The baryons are unbiased with respect to dark matter, and thus in the model, the Lyα emission is expected to be biased with respect to dark matter by a factor \( b_\delta \approx 2 \) on linear scales (due to Lyα being related to the square of the baryonic density). This \( b_\delta \) in the model is chosen to be consistent with the measured bias of Lyα emitters at these redshifts (e.g., Gawiser et al. 2007), considering that these are the predominant sources of Lyα emission, and that the contribution of the IGM is subdominant. We note that the assumption of squaring the density will lead to a linear bias of \( b_\delta = 2 \) may not hold at very highest densities, and this may result in artefacts in the form of extremely bright pixels. As it is explained later (§3.2.1), a Lyα flux threshold is set for the simulated PAUS images, partially in order to account for this effect.

3.1.2 Mock catalogue/Foreground simulation

If we consider PAUS images for Lyα IM, most of the detected photons of cosmic origin will not come from Lyα at a certain redshift (depending on the filter used), but from uncorrelated sources at different redshifts than the expected Lyα emission. The main contributors to this contamination of the signal will be foregrounds, i.e., objects with lower redshift between the Lyα emission and the observer. In this work, 96.7% of all the observed flux in the simulation (averaged over all filters) was from foregrounds.

Since the objective of this paper is assessing the potential of cross-correlating PAUS with Lyα forest data, a realistic model of these foregrounds is key for our study. In order to model them, we will need a mock catalogue that spans a range of redshift large enough (at least \( z \approx 2.75 \), but ideally until \( z = 6 \)), where the PAUS redshift range for Lyα ends), with an angular size comparable to the Lyα forest/emission simulation box. Besides, all objects in the catalogue must have their observed SEDs in the PAUS wavelength range (455-855 nm) and with resolution higher than PAUS FWHM (\( \Delta \lambda < 13 \) nm).

The two first requirements (redshift range and angular size) are met by already available mock catalogues, but none of them contain direct SED information (at least, not to the best of the authors knowledge). Such mock catalogues are intended to reproduce large surveys, with the only spectral information available being either broad bands, which do not meet the resolution requirement, or emission lines, which are insufficient to generate the foregrounds.

Our approach to this problem is to take a mock catalogue with broad bands, and interpolate SEDs for all objects by fitting SED templates to the broad bands. The mock catalogue selected is a lightcone originally developed to simulate data from the Euclid satellite, made from a run of the Millennium Simulation using WMAP7 cosmology (Guo et al. 2013). This lightcone is complete up to magnitude 27 in Euclid H band, which makes it ideal for foreground simulations (since most mock catalogues do not reach such depths). The semi-analytical model applied to compute galaxies is GALFORM (Gonzalez-perez et al. 2014), and the lightcone was constructed with the technique described in Merson et al. (2013).
the redshift of the object $z$ is the basis of template bands at the redshift of the linear combination of the templates, and the matrix $X$ must be all non-negative for the SED to make physical sense (since the SED templates are patterns of emitted flux for galaxies, and thus subtracting them has no physical meaning). Therefore, instead of finding the analytical solution, the coefficients are computed using non-negative least squares. This numerical method is approximate, but on average yields relative errors of a few percent when recovering the original bands. Once these coefficients are obtained, the linear combination of SED templates using the coefficients is computed for all objects, thus generating a full mock catalogue with high spectral resolution SEDs.

### 3.1.3 PAUS Noise

In addition to the foregrounds, PAUS images have noise from a large variety of sources (electronic, optics, atmospheric conditions, etc.). Instead of making a separate physical model for each source, which would be extremely complex, the sum of these noises can be considered to follow a Gaussian distribution, since they are largely uncorrelated. In order to simulate the cross-correlation of PAUS images and the Lyα forest, the only parameter needed to model this Gaussian noise is its standard deviation $\sigma_{\text{noise}}$; its mean value does not affect the SNR of the cross-correlation, as explained in §4. The $\sigma_{\text{noise}}$ used for this Gaussian noise simulation is shown in Table 2; Table 1 shows the $\sigma_{\text{noise}}$ values before converting them to absolute flux density units.

This $\sigma_{\text{noise}}$ has been directly measured from reduced science PAUS images, such as Fig. 5. Since Lyα extended emission is in the background of the images, all resolved sources must be removed for cross-correlation, and the images used to measure $\sigma_{\text{noise}}$ have to be masked accordingly. While this is expected to be done masking all objects in the PAUS reference catalogue (which is complete up to magnitude 25 in broad bands), for this preliminary study this was done by applying sigma-clipping with a clipping limit of $3\sigma$ for 5 iterations, which effectively removes all resolved sources.

For each one of the seven filters considered, 10 reduced science images without defects apparent from simple visual inspection were selected (e.g. noticeable scatter light, cosmic rays, crosstalk between CCDs, etc.), and the specified

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**Figure 3.** Hydrodynamic simulation used for this work. *Left:* Extended Lyα emission, in erg/s and logarithmic colour scale. *Right:* $\delta$ flux contrast, used to model the Lyα forest.

**Figure 4.** The five SED templates used for foreground simulation, normalised to facilitate visual comparison.
sigma-clipping was applied. In each one of the images, the single-pixel \( \sigma \) and mean was computed first, and all the masked pixels were filled by a Gaussian distribution with these measured parameters. This is necessary in order to compute \( \sigma \) for increasing pixel sizes, as pixels with masked regions would have an effectively higher \( \sigma \) (given that they are composed of less original image pixels than their unmasked counterparts). The flux values of these increasing pixel sizes were computed by adding the values of all pixels inside them instead of averaging, since the hydrodynamic simulation considers the total Ly\( \alpha \) luminosity in each 3D pixel, not its spatial average.

The mean \( \sigma \) vs pixel size for the seven filters is shown in Fig. 6. The dashed line is the mean \( \sigma \) for the seven filters extrapolated as if the noise was uncorrelated, with the expression

\[
\sigma_i = \frac{\theta_i}{\theta_0} \sigma_0.
\]

Where \( \sigma_0 \) and \( \theta_0 \) are the standard deviation and angular size for the original pixels of the image, and \( \sigma_i \), \( \theta_i \) its counterparts for the new pixels.

It is clear that the \( \sigma \) measured from the images is correlated for pixel scales larger than 30 arcsec. The vertical bar in Fig. 6 represents the pixel size of the simulated PAUS images, which is limited by the pixel size of the hydrodynamic simulation. At these scales of \( \sim 70 \) arcsec, the measured \( \sigma \) is larger than the uncorrelated \( \sigma \) by a factor of \( \sim 20 \).

However, most of the correlation in the noise is caused by systematics, namely scattered light from the filters and differences between amplifiers in the CCDs that were not corrected by the flats and bias exposures. These should be mitigated as data reduction improves in future releases. Moreover, the actual cross-correlation would not be computed between Ly\( \alpha \) forest and individual exposures; PAUS images would be stacked in RA and dec in order to generate patches of the sky as large as possible for the cross-correlation. This stacking would also necessarily decrease these systematics, given that images are being stacked in sky coordinates, and the largest systematics depend solely on the camera components.

Due to these reasons, the \( \sigma_{\text{noise}} \) used to simulate PAUS noise is the uncorrelated extrapolated value according to Eq. (4), instead of the value measured directly for the corresponding pixel size. For each filter the extrapolated \( \sigma_{\text{noise}} \) is computed from the mean of the 10 images. Besides, this

\[
\sigma_{\text{noise}} = \sigma_{\text{1exp}} = \frac{\theta_{\text{1exp}}}{\theta_0} \sigma_0.
\]

\( \sigma_{\text{1exp}} \) is the expected instrumental noise for a single PAUS science exposure, but for each pointing in PAUS fields several exposures are taken, thus decreasing \( \sigma_{\text{noise}} \) by a factor of \( 1/\sqrt{N_{\text{exp}}} \), where \( N_{\text{exp}} \) is the number of exposures per pointing; for current PAUS science all survey pointings have \( N_{\text{exp}} \geq 3 \).

In Table 1, the mean \( \sigma_{\text{noise}} \) for each filter, extrapolated to the pixel size of the simulation, as well as the scaled noise for three exposures \( \sigma_{\text{3exp}} \), is shown. A hypothetical case for a deeper PAUS (complete up to \( i_{\text{AB}} < 24 \)) is also considered, since it is a possibility currently being explored. This would imply multiplying by six the current exposure time for all survey pointings, hence the \( \sigma_{18\text{exp}} \).

3.2 Simulation of PAUS Ly\( \alpha \) IM

3.2.1 PAUS images: Ly\( \alpha \) IM

In order to simulate the PAUS images for the cross-correlation, the elements explained in the previous subsection (Ly\( \alpha \) emission from the hydrodynamic simulation, foregrounds from the mock catalogue and Gaussian noise) must be converted to units of observed flux density (erg/s/cm\(^2\)/nm) and merged into the seven narrow-band filters.

Since the hydrodynamic simulation gives Ly\( \alpha \) emission in luminosity units (erg/s), the first step is to compute the comoving coordinates of all pixels of the simulation from the point of view of the observer. Assuming the cosmology of the simulation, and knowing that the simulation snapshot is at \( z = 3 \), we consider the comoving distance from the observer to the centre of the box to be the radial comoving distance at redshift 3, \( \chi(z = 3) \). Knowing this, the comoving coordinates
of all cells of the simulation with respect to the observer are also known (as well as their edges), assuming that the three axes of the simulation box are RA, dec and radial directions respectively. The bins of the hydrodynamic simulation are not in spherical coordinates but Cartesian, however, given the small angular size of the sample, the small-angle approximation can be applied.

With the comoving radial distance of all cells known, and the relation \( \chi(z) \) given by the cosmology, the inverse relation \( z(\chi) \) can be computed numerically, and thus a redshift can be assigned to each cell. This allows to compute the luminosity distance simply with its definition for a flat cosmology

\[
D_L(z) = (1 + z) \cdot \chi(z).
\]

Moreover, given that all the emitted flux is Ly\( \alpha \), the rest frame wavelength is also known (\( \lambda_{\text{Ly}\alpha} = 121.567 \text{ nm} \)), which yields the observed wavelength range of all cells in the hydrodynamic simulation, and thus all redshift bins (following the small angle approximation, all cells in the same radial distance bin will have the same redshift, and thus observed wavelength range). With all these elements computed, the observed flux density for all PAUS cells comes from the following expression

\[
f_{\text{obs}} = \frac{L}{4\pi D_L(z_i)^2 \Delta \lambda_{\text{obs}} i}.
\]

Where \( L \) is the cell luminosity given by the hydrodynamic simulation (erg/s), \( D_L \) the luminosity distance in cm, and \( \Delta \lambda_{\text{obs}} \) the observed wavelength range for the redshift bin of the cell, all corresponding to the PAUS cell \( i \).

Having computed the observed flux density for all PAUS cells, the redshift bins of the PAUS simulation need to be merged to simulate the wavelength bins given by PAUS filters. In order to do so, PAUS filters are considered to have top-hat response functions 10 nm wide, ranging from 455 nm (bluest filter) to 845 nm (reddest). Following this criterion, the redshift bins of the simulation completely fill the seven blue filters, which also limits the cross-correlation to seven filters in this work. The last four redshift bins of the simulation fall outside the seventh filter; these bins are discarded for the simulation of PAUS images. For each filter, all redshift bins inside the filter are merged into a single one, with its value being the mean of the merged bins (since observed fluxes are the average flux density over the response function).

With redshift bins already merged to simulate PAUS filters, the average Ly\( \alpha \) redshift for each filter can be used to convert from observed flux densities (erg/s/cm\(^2\)/nm) to absolute flux densities (erg/s/nm), with the following expression

\[
F_{\text{obs}} = \frac{4\pi D_L(z_{\text{obs}})^2}{\Delta \lambda_{\text{obs}} i}.
\]

Where \( z_{\text{obs}} \) is the redshift of Ly\( \alpha \) in the respective narrow band. This is done in order to cancel out the dimming of observed Ly\( \alpha \) flux with redshift (due simply to the increasing distance between said emission and the observer), which would introduce an artificial gradient in the emission field to be cross-correlated. However, the previous conversion to observed fluxes was necessary, since we can only convert to absolute fluxes with observational data using the observed redshift, i.e., PAUS redshift bins, not the much finer redshift bins of the original simulation.

On top of this conversion to absolute fluxes, a realistic threshold can be imposed to Ly\( \alpha \) fluxes, both to remove possible artefacts that may be derived from the assumption that Ly\( \alpha \) luminosity is proportional to baryon density squared, and also to account for the fact that resolved objects will be removed from PAUS images before cross correlating (which may remove some bright Ly\( \alpha \) emitters at high redshift).

The chosen Ly\( \alpha \) absolute flux threshold is 10 times the brightest pixel of the simulated foregrounds, whose computation will be explained in §3.2.2. This value is chosen assuming that the foreground simulation gives a realistic estimate of how much unresolved flux can be expected, and taking into account that resolved objects are masked based on their g band luminosity. This broad band has FWHM=138.7 nm (Fig. 1), which is one order of magnitude wider than PAUS narrow bands. Therefore, Ly\( \alpha \) emission observed in a PAUS filter will be reduced by a factor of 10 when observed in the g filter. A maximum value of 1.53 \cdot 10^{-3} \text{ erg/s/nm} was set as a threshold, which affected only 0.0024 \% of all pixels. To visualise the extent of this threshold, Fig. 7 shows histograms of absolute fluxes for the Ly\( \alpha \) emission, foregrounds and instrumental noise, divided by the mean Ly\( \alpha \) flux and together with the Ly\( \alpha \) threshold, represented as a vertical line.

After all these steps, the result is a simulation of Ly\( \alpha \) extended emission in PAUS filters. However, given the redshift and the size of the simulation, this simulation only covers ~ 25 deg\(^2\), with an angular pixel size of 1.38 arcmin\(^2\); since the expected area to cross-correlate is 100 deg\(^2\), the simulation is replicated four times in mosaic pattern, which effectively covers the expected area. The result can be seen in Fig. 8, top panel.
3.2.2 PAUS images: foregrounds

Given that resolved objects will be removed from PAUS images before cross-correlating, only the objects too faint to be resolved must be included in the foreground simulation. The PAUS reference catalogue is complete up to magnitude 25 in the $g$ band; consequently, only the objects in the mock lightcone dimmer than this value are selected. Besides this, since the lightcone is elliptical in angular coordinates, it is cropped to the largest inscribed rectangle. This rectangle is smaller than the 25 deg$^2$ at z$\sim$3 of the hydrodynamic simulation, so it is repeated in a mosaic pattern and cropped to cover the same angular area as the original Ly$\alpha$ simulation.

All the foreground objects have their SEDs computed by template fitting, as explained in the previous subsection, and they are binned in RA and dec using the same angular bins as the Ly$\alpha$ flux simulation. Since the templates are fitted to apparent magnitudes, by using the definition of AB magnitude the interpolated SEDs are already in observed flux units of erg/s/cm$^2$/nm.

For each one of these RA x dec pixels, the net observed SED is computed as the sum of the SEDs inside the bin. These stacked SEDs are then integrated and averaged over the response functions of the seven blue filters according to the expression below, which gives the observed foreground flux,

$$f_{nb} = \int_0^{\infty} d\lambda f_{\text{SED}}(\lambda) R_{nb}(\lambda)\int_0^{\infty} d\lambda R_{nb}(\lambda).$$

(8)

Here $f_{\text{SED}}$ is the flux density of the interpolated SED, $R_{nb}$ the response function of a certain narrow band, and $f_{nb}$ the observed flux density in that narrow band. With this expression the observed foreground flux in the PAUS filters is obtained; in order to convert to absolute fluxes Eq. (7) is used.

The result is a three-dimensional array covering ~25 deg$^2$ that can be directly added to the Ly$\alpha$ observed flux simulation. As in the Ly$\alpha$ flux case, this array needs to be replicated four times in a mosaic pattern for an effective coverage of 100 deg$^2$. This time, however, for each replication the array is rotated clockwise (keeping the redshift direction the same), in order to ensure that each 25 deg$^2$ subset is a different realisation of Ly$\alpha$ emission+foregrounds (if the rotation was not performed, replicating the arrays for a 100 deg$^2$ would be analogous to sampling the same 25 deg$^2$ area four times). The result of these simulated foregrounds can be seen in Fig. 8, middle panel.

This rotation introduces discontinuities in the foreground structure, since the periodic boundary conditions of the mock catalogue are broken. Nevertheless, the cross-correlation is computed by selecting cubes of PAUS cells around forest cells, so only forest cells close enough to the discontinuities will be affected by them.

As shown in Fig. 10, the cross-correlation is only computed in perpendicular (angular) direction up to 20 Mpc/h. Given that the whole angular size of the simulation is 800 Mpc/h, and that the discontinuities are two straight lines dividing the simulation in RA and dec, this leaves <10% of the forest cells potentially affected by the discontinuities. Also, the dominant noise contribution is instrumental noise, not the foregrounds, so even in the small fraction of forest cells affected by discontinuities, the effects of these on the cross-correlation should be fairly small.

3.2.3 PAUS images: Combination and noise

Considering that both have the same units and the same binning, the Ly$\alpha$ and foregrounds absolute flux simulations can be directly added into a total absolute flux array. The only step left to properly simulate PAUS observations is...
to add the instrumental noise. For this simulation, these noise values follow a Gaussian distribution of mean zero and $\sigma$ dependent on the filter. This $\sigma$ is the instrumental noise directly measured from images and scaled for the number of exposures, as specified in Table 1, converted to absolute flux units according to Eq. (7). These absolute flux noise values, $\sigma_{\text{noise abs}}$, as well as the scaled value that is used, $\sigma_{\text{exp abs}}$, and the hypothetical deep PAUS, $\sigma_{\text{18exp abs}}$, are displayed in Table 2. The final result of Ly$\alpha$ flux+foregrounds+instrumental noise is shown in Fig. 8, bottom panel.

With this simulation, despite repeating both the Ly$\alpha$ emission and the foregrounds in a mosaic pattern, we ensure that the cross-correlation always samples a different combination of signal+noise, since instrumental noise is generated for the full simulation and foregrounds are rotated.

While it may be argued that the clustering signal from Ly$\alpha$ emission is repeated, the only caveat of this is that cosmic variance may be underestimated. Given that the original diameter of the hydrodynamic simulation is 400 Mpc/h, far above the homogeneity scale (e.g., Gonçalves et al. 2018), and that the predominant sources of noise are by far foregrounds and instrumental noise (as seen in §6.2), any effect cosmic variance may have on the result is negligible.

3.3 eBOSS/DESI: Ly$\alpha$ forest

To simulate the Ly$\alpha$ forest data of eBOSS/DESI surveys, the hydrodynamic absorption simulation show in Fig. 3 is replicated four times in a mosaic pattern, as if it was shown in the PAUS simulation.

After this operation, random cells in the simulation array are selected with the quasar density redshift distribution shown in Fig. 2 (depending on the survey to be simulated), with the redshift of each cell computed as for the Ly$\alpha$ emission simulation. The RA and dec coordinates of the quasar cells are selected randomly from a uniform distribution. The total number of quasar cells (i.e., the number of quasars in the sample) is also computed from the redshift distribution, considering that the simulation has an angular area of 100 deg$^2$ and that only quasars with $z > 2.7$ are to be included (since quasars at lower redshift will have all Ly$\alpha$ forests outside the redshift range of the simulation).

The cells between the quasar cells and the observer (the cells in the same angular bins and negative redshift direction) are considered Ly$\alpha$ forest cells, including the quasar cells themselves. Only these forest cells are taken into account for cross-correlation; everything else in the hydrodynamic simulation is masked.

In addition to this, if a quasar is at redshift high enough so that Ly$\beta$ forest appears at $z > 2.7$, its forest cells that would be covered by the Ly$\beta$ region are also masked, given that these regions of the quasar spectrum contains both Ly$\alpha$ and Ly$\beta$ absorption lines superimposed from different redshifts. While these Ly$\beta$ forest regions can be used for cross-correlation studies (e.g., Blomqvist et al. (2019)), here we adopt the conservative approach and remove them from the cross-correlation. These masked Ly$\beta$ cells account for 12% of the total forest cells.

Other than the removal of the Ly$\beta$ forest, no other systematics nor errors are considered for the Ly$\alpha$ forest simulation of this preliminary study. Although Ly$\alpha$ forest data is also affected by many sources of error (e.g., contamination by other absorption lines, continuum subtraction, instrumental error of the spectrograph), the absorption lines of HI in quasar spectra are a signal easily detectable by itself, without any need of cross-correlation with other datasets. For example, in Chabanier et al. (2019), which uses Ly$\alpha$ forest data from the first eBOSS release with redshift binning similar to this work, the mean SNR at $z = 3.2$ is 6.0, which is a clear detection. For comparison, the average SNR in the PAUS Ly$\alpha$ simulation is 0.017, considering that the Ly$\alpha$ flux is the signal and the noise is the sum of foregrounds flux and the $\sigma$ of instrumental noise; hence any contribution to the cross-correlation noise made by the Ly$\alpha$ forest error is going to be subdominant at most.

A voxel representation of this Ly$\alpha$ forest simulation, displaying only forest cells used for cross-correlation, is shown in Fig. 9, both for eBOSS and DESI expected quasar densities.

4 SIMULATED CROSS-CORRELATION ESTIMATOR

4.1 Estimator definition

In order to compute the cross-correlation from the PAUS and eBOSS/DESI simulated datasets explained in the previous section, an estimator of the 2PCF is needed. The estimator used for this work is

$$\xi(r) = \frac{\sum_i \left( \delta_i \sum_{\ell \in \text{Bin}(i)} g_{ij} \right)}{\sum_i \left( \sum_{\ell \in \text{Bin}(i)} g_{ij} \right)}.$$  \hspace{1cm} (9)

This estimator is defined for distance bins $r_n$. Since the cells to be cross-correlated have finite volumes, distances are assumed from the coordinates of their centres. Regarding the other terms in the equation, $\delta$ is the $\delta$ flux of the forest cell $i$, as defined in Eq. (1), and $g_{ij}$ is the absolute flux contrast for the pixel $j$ in simulated PAUS images, defined as

$$g_{ij} \equiv \frac{F_{ij}}{F_{ij}} - 1.$$  \hspace{1cm} (10)

In other words, this estimator is the average value of the products of all cell pairs in a certain distance bin. This distance $r$ in Eq. (9) is defined as the total distance between cells (monopole cross-correlation), but it could also be defined as the distance projected onto the line of sight (parallel cross-correlation, $\xi(\parallel)$), or perpendicular to it (perpendicular cross-correlation, $\xi(\perp)$). Consequently, the parallel and perpendicular estimators $\xi(\parallel)$ and $\xi(\perp)$ can be defined

| $\lambda$ (nm) | 455 | 465 | 475 | 485 | 495 | 505 | 515 |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| $\sigma_{\text{noise abs}}$ | 3.92 | 3.75 | 3.69 | 3.54 | 3.80 | 4.05 | 4.29 |
| $\sigma_{\text{exp abs}}$ | 2.26 | 2.16 | 2.13 | 2.04 | 2.20 | 2.34 | 2.48 |
| $\sigma_{\text{18exp abs}}$ | 0.92 | 0.88 | 0.87 | 0.83 | 0.90 | 0.95 | 1.01 |
simply by switching the definition of distance, $|i - j|$, by $|i - j| \cdot \vec{n}_{\text{los}}$ and $|i - j| \times \vec{n}_{\text{los}}$ respectively (where $\vec{n}_{\text{los}}$ is the unit vector parallel to the line of sight).

Normally, the average computed by this estimator is weighted by a function of the pipeline error, as well as additional errors terms derived from data reduction (e.g. Font-Ribera et al. (2012)). However, for this preliminary work the error in simulated PAUS images is approximately constant,

$$|\alpha| \langle \text{Ly} \rangle$$

is not sampled uniformly in redshift in this cross-correlation with only slight variations between filters (see Table 2), and the Lyα forest error has been considered negligible, so no weighting has been applied.

The error on the estimator is computed using jackknife resampling. The simulation has been divided in 25 subsamples by imposing uniform cuts in RA and dec. Since space is not sampled uniformly in redshift in this cross-correlation (because Lyα forest available data depends on the quasar redshift distributions), no cuts have been performed in redshift, so all jackknife subsamples cover the whole redshift range of the simulation.

### 4.2 Noise bias

The cross-correlation estimator introduced in Eq. (9) is biased if at least one of the signals being cross-correlated contains noise of mean different than zero, which is of particular importance for this study. In order to demonstrate this, let us assume that the estimator is used to cross-correlate two arbitrary observable scalar fields, $f(r)$ and $g(r)$. For both fields, a finite number of samples at different points are observed, $f_i$ and $g_i$, and from these points the respective means $\langle f \rangle$ and $\langle g \rangle$ are computed. In order to apply the estimator, the contrasts of both fields need to be determined, which, as in Eq. (1) and Eq. (10), would be done with the following expressions

$$f_{\text{contrast}} = \frac{f_i - \langle f \rangle}{\langle f \rangle}; \quad g_{\text{contrast}} = \frac{g_i - \langle g \rangle}{\langle g \rangle}. \quad (11)$$

If $f_i$ and $g_i$ are replaced in Eq. (9) by $f_{\text{contrast}}$ and $g_{\text{contrast}}$, and these are substituted by its definition in Eq. (11), the following expression can be obtained

$$\xi(r) = \frac{\sum_i \left( f_i - \langle f \rangle \right) \sum_j \left( g_j - \langle g \rangle \right)}{\langle f \rangle \langle g \rangle \sum_i \left( 1 \Sigma_j^1 \right)} = \frac{\sum_i \left( f_i - \langle f \rangle \right) \sum_j \left( g_j - \langle g \rangle \right)}{\langle f \rangle \langle g \rangle \sum_i \left( 1 \Sigma_j^1 \right)}.$$  \quad (12)

Here the second summation in the right side of Eq. (9) has been rewritten as $\sum_i^j$ for simplicity. Now, let us consider that the field $g(r)$ is the sum of two independent fields, the signal $S(r)$ and the noise $N(r)$, so

$$g(r) = S(r) + N(r). \quad (13)$$

By our definition, the noise $N(r)$ is uncorrelated with $f(r)$, so for a sample large enough a hypothetical estimated cross-correlation between $f(r)$ and $N(r)$ would tend to zero. Following Eq. (12), this can be expressed as

$$\sum_i \left( f_i - \langle f \rangle \right) \sum_j \left( N_j - \langle N \rangle \right) \to 0. \quad (14)$$

Conversely, the hypothetical cross-correlation $\xi_S(r)$ between $S(r)$ and $S(r)$ would be

$$\xi_S(r) = \frac{\sum_i \left( f_i - \langle f \rangle \right) \sum_j \left( S_j - \langle S \rangle \right)}{\langle f \rangle \langle S \rangle} \sum_i \left( 1 \Sigma_j^1 \right) \to 0. \quad (15)$$

Nevertheless, only the field $g(r)$ can be observed, and thus the only cross-correlation that can be computed is that of the $f(r)$ with $S(r)$ plus $N(r)$:

$$\xi_{S+N}(r) = \frac{\sum_i \left( f_i - \langle f \rangle \right) \left[ \sum_j \left( S_j - \langle S \rangle \right) + \sum_j \left( N_j - \langle N \rangle \right) \right]}{\langle f \rangle \langle S + N \rangle} \sum_i \left( 1 \Sigma_j^1 \right). \quad (16)$$

If a sample large enough is assumed, Eq. (14) holds true, and since the noise component of the cross-correlation tends to zero, the denominator in Eq. (15) and Eq. (16) is identical. Therefore, the following relation can be derived between the

Figure 9. 3D simulations of the Lyα forest sampled pixels. Left: eBOSS. Right: DESI.
hypothetical cross-correlation of the signal, $\xi_S(r)$, and the actual cross-correlation of the signal with noise, $\xi_{S+N}(r)$, is

$$\xi_{S+N}(r) = \frac{\langle S \rangle}{\langle S + N \rangle} \xi_S(r).$$

(17)

If the noise of the observable $g(r)$ had mean zero, we would have $\xi_{S+N}(r) = \xi_S(r)$, and thus the estimator would be unbiased. However if we consider PAUS images to be the observable $g(r)$, the noise $N(r)$ would be the foreground plus instrumental noise. The first component necessarily has a mean larger than zero, since it is a sum of observed fluxes, while the second also should in principle, given that it includes effects such as scattered light and airglow, which are strictly positive.

Nevertheless, this noise bias does not affect the SNR, and thus the probability of detection. Considering that the error is computed via jackknife resampling (i.e., the $c$ of the cross-correlation computed for different subsamples), this noise bias will multiply the cross-correlation value and its error equally, and therefore will cancel out when computing the SNR.

5 THEORETICAL CORRELATION FUNCTION

To validate the result of the simulated cross-correlation, as well as to derive the clustering, comparison against a theoretical 2PCF is needed. The first step is to compute the unbiased matter-matter 2PCF from the theoretical matter power spectrum. For this work, this 2PCF has been initially computed as a field depending on two variables, the dis-}

\[ \xi(r_\parallel, r_\perp) = \frac{1}{2\pi^2} \int_0^\infty dk k P_m(k) \sin \left( k \sqrt{r_\parallel^2 + r_\perp^2} \right) \exp(-k r_{\text{cut}}). \]

(18)

Where $P_m(k)$ is the non-linear matter power spectrum computed with CAMB (Lewis et al. 2000), and the non-linear modelling of HALOFIT (Peacock et al. 2014). This power spectrum has been computed at the redshift of the hydrodynamic simulation snapshot ($z = 3$), using its cosmology. Regarding other terms, $r_{\text{cut}}$ is the radius of the exponential cutoff set in order to avoid large oscillations in the theoretical 2PCF due to small-scale effects that are not represented in its counterpart measured in the simulation. For this study, the chosen value for this cutoff is $r_{\text{cut}} = 3$ Mpc/h.

Given that no redshift space distortion nor any other effects are taken into account in Eq. (18), there is no anisotropy by definition in this expression, which may make the computation of the 2PCF in two directions seem redundant. Nevertheless, the effects of the binning of the simulated data need to be taken into account, which introduce clear anisotropies in the final result. This effect arises from the fact that correlation is being performed between spatial cells with finite volumes, whose value of the field to cross-correlate is the average over the volume of the cell.

If the length of these cells to cross-correlate is equal or smaller than the binning of the correlation estimator (Eq. (9)), this effect will be negligible, given that by binning the estimator already averages over a similar length. This is the case for the Lyα forest cells in all directions or the PAUS cells in RA and decl directions, where their length (1.56 Mpc/h, given by the hydrodynamic simulation bins) is smaller than the binning of the estimated cross-correlation (see Fig. 12).

On the other hand, this effect is not negligible for the redshift direction in PAUS cells, where the mean cell size is 56.25 Mpc/h (since redshift bins have been merged to simulate PAUS filters). Averaging the Lyα flux in PAUS images over such distances will certainly have an effect on the estimated cross-correlation, which also has to be simulated in the theoretical 2PCF. Considering that the redshift direction in the simulation has a direct correspondence with $r_\parallel$ in Eq. (18), this smoothing can be emulated by averaging each point in the computed $\xi(r_\parallel, r_\perp)$ field over a length in $r_\parallel$ equal to the average PAUS cell size

$$\tilde{\xi}(r_\parallel, r_\perp) = \frac{1}{l_\parallel} \int_{l_\parallel - l_\parallel/2}^{l_\parallel + l_\parallel/2} \frac{dr_\parallel'}{\int_0^{r_\parallel + l_\parallel/2} dr_\parallel' \xi(r_\parallel', r_\perp)}. \quad (19)$$

Where $l_\parallel = 56.25$ Mpc/h. By definition of the 2PCF, $r > 0$, so for $r_\parallel < l_\parallel/2$ this expression changes to

$$\tilde{\xi}(r_\parallel, r_\perp) = \frac{1}{l_\parallel} \int_0^{l_\parallel + l_\parallel/2} dr_\parallel' \xi(r_\parallel', r_\perp) + \frac{1}{l_\parallel/2 - r_\parallel} \int_0^{l_\parallel/2 - r_\parallel} dr_\parallel' \xi(r_\parallel', r_\perp). \quad (20)$$

If the 2PCF is interpreted as an average product of cell pairs at a certain distance, such as in the estimator, this last expression represents the case where the small Lyα forest cell lies inside the redshift range of the PAUS cell it is being cross-correlated with. The smoothing integral needs to cover the whole $l_\parallel$, but since the distance between cells necessarily has to be non-negative, the integral is truncated in two terms: one for the portion of the PAUS cell at higher redshift than the Lyα forest cell, and another for the portion at lower redshift. Fig. 10 shows the effect of this 2PCF smoothing (dashed lines) compared to the non-smoothed 2PCF (solid lines) for the three correlation types considered in this work.

In addition to this smoothing effect, bias from the tracers also needs to be taken into account. So far, the unbiased matter-matter 2PCF has been considered (called $\tilde{\xi}_{\text{mm}}(r_\parallel, r_\perp)$ henceforth), but the cross-correlation in this work uses Lyα emission and Lyα forest absorption. The 2PCF of different tracers can be obtained from the unbiased 2PCF with the following expression

$$\tilde{\xi}_{\text{HI2}}(r_\parallel, r_\perp) = b_1(r_\parallel, r_\perp) b_2(r_\parallel, r_\perp) \tilde{\xi}_{\text{mm}}(r_\parallel, r_\perp). \quad (21)$$

Where $b_1$ and $b_2$ are the biases of the respective tracers (Lyα emission and Lyα forest in this case). These biases have been considered dependent on distance for this work, and have been left as free parameters to be adjusted.

Finally, this two-dimensional 2PCF has been converted to a 2PCF depending solely on a single distance parameter, either the total distance between cell pairs $r = \sqrt{r_\parallel^2 + r_\perp^2}$, or the parallel/perpendicular distances, in order to be compared to the estimator defined in Eq. (9). The estimator
could also be defined as a function of both $r_\parallel$ and $r_\perp$, however, this would greatly reduce the number of cell pairs available per bin, and thus the SNR of the measured cross-correlation.

For the monopole 2PCF, this has been performed by computing $\tilde{\xi}_{\text{mm}}(r_\parallel, r_\perp)$ in a very fine uniform grid of $r_\parallel, r_\perp$ values, and then averaging these values in bins of total distance $r = \sqrt{r_\parallel^2 + r_\perp^2}$. Regarding the parallel and perpendicular 2PCFs, they have been obtained from the theoretical two-dimensional 2PCF simply by numerical integration, according to the following expressions:

$$
\tilde{\xi}_{\text{mm}}(r_\parallel) = \frac{1}{R_\perp} \int_0^{R_\perp} \mathrm{d}r_\perp \tilde{\xi}_{\text{mm}}(r_\parallel, r_\perp)
$$

$$
\tilde{\xi}_{\text{mm}}(r_\perp) = \frac{1}{R_\parallel} \int_0^{R_\parallel} \mathrm{d}r_\parallel \tilde{\xi}_{\text{mm}}(r_\parallel, r_\perp),
$$

where $R_\parallel$ and $R_\perp$ are the maximum binning distances used by the estimator in Eq. (9) for the parallel and perpendicular directions. These 2PCFs, unlike the monopole, depend on the total range over which the correlation is computed, which makes them less suitable for comparison of the results against the theory. Consequently, only the monopole 2PCF will be used to compare the results of the simulation against the theory in §6.

6 RESULTS

The results presented in this paper are divided between three subsections. In Section 6.1, the real bias of the tracers of the simulation (Lyγ emission and absorption) is measured by comparing the absorption and emission auto-correlations against the theoretical 2PCFs. These measured biases are then applied to the theoretical 2PCF, and compared against the estimated cross-correlation in simulations without either foregrounds or PAUS noise (Lyγ emission in the simulated images). In Section 6.2, the probability of a detection (SNR>3) when adding instrumental noise to the simulation is explored at different scales, and in Section 6.3, this analysis is repeated for two hypothetical cases (deeper PAUS and PAUS with extended coverage).

6.1 Cross-correlation without instrumental noise. Comparison against theory

In order to compare the cross-correlation results against the theoretical prediction (and thus validate that the cross-correlation results are sound), the actual biases of the tracers of the hydrodynamic simulation need to be measured. Although bias values have been provided in §3.1.1, these are only approximate. For the emission bias, $b_e \sim 2$ is an approximation that only holds for small perturbation values. Regarding the absorption bias, the value $b_a = 0.336 \pm 0.012$ is a measurement extracted from eBOSS data at lower redshift, and does not necessarily have to match the simulation used in this work.

These biases have been computed correlating the emission/absorption arrays of the hydrodynamic simulation (Fig. 3) with themselves, using the same binning as in the PAUS-eBOSS/DESI simulation (wide redshift bins for PAUS, only Lyγ forest cells for eBOSS/DESI). No foregrounds or noise were added for this correlation, since they do not have the same physical units, and the purpose of this calculation is just to determine the real bias while testing that the binning of the simulation and the smoothing effect are properly taken into account. Considering Eq. (21), and also that we are correlating a certain tracer with itself, the bias of the tracer can be estimated from the smoothed theoretical prediction $\tilde{\xi}_{\text{mm}}$ and the estimated correlation of the tracer $\hat{\xi}_t$ with

$$
b_t(r) = \frac{\sqrt{\hat{\xi}_t(r)}}{\tilde{\xi}_{\text{mm}}(r)}. \tag{23}
$$

Where $t$ is any tracer, and the expression has been considered only for the monopole 2PCF. The results of this bias determination can be seen in Fig. 11. The error of the bias at all distance bins is simply the propagated error of the cross-correlation; any error that could be included in the theoretical 2PCF (e.g., cosmic variance) has been considered negligible.

As can be seen in Fig. 11, the actual measured $b_a$, around 0.4, is larger by ~20% than the bias expected at $z = 2.25$ from the literature, however, the actual bias may increase with redshift, and this simulation is not expected to yield a perfect match of $b_a$ with measurements. Regarding $b_e$, the measured bias is actually much closer to the approximate value $b_e \sim 2$; this is to be expected, since this approximate value is derived directly from the expression used to simulate the Lyγ emission field (Eq. 2).

With these measured biases, the simulated cross-correlation can be compared to the theoretical 2PCF with the following expression

$$
\hat{\xi}_{\text{ea}}(r) \sim -b_e(r) b_a(r) \tilde{\xi}_{\text{mm}}(r). \tag{24}
$$

Where the theoretical 2PCF $\tilde{\xi}_{\text{mm}}(r)$ is binned with the same binning used in the estimator $\hat{\xi}_{\text{ea}}(r)$, and the minus sign comes from the fact that the cross-correlation is between an emission and an absorption field. A comparison of

Figure 10. Theoretical unbiased 2PCFs times squared distance, before and after applying smoothing. The distance range of each one of the 2PCFs is the same as all the results shown in §6.
the simulated cross-correlation, without either foregrounds or instrumental noise, to the theoretical 2PCF with the measured biases is displayed in Fig. 12. Only the monopole 2PCF is displayed, since the parallel and perpendicular 2PCFs depend on the range in which the 2PCF is computed, as shown in Eq. 22. No foregrounds or instrumental noise have been added both to ensure a good SNR to validate our model, and because the noise bias described in Eq. 17 would also need to be corrected to compare the simulation against theory.

With no foregrounds or instrumental noise, there is a clear detection of cross-correlation at $r > 30$ Mpc/h with DESI, and several bins show a clear detection up to $r \sim 30$ Mpc/h with eBOSS. For all the bins with a detection, the errorbars of the theoretical prediction and the actual cross-correlation overlap; this validates the simulated cross-correlation. Besides, this also proves that, for an ideal case without any other sources of noise, this cross-correlation could be used to constrain either the bias of the tracers or the 2PCF on scales up to $\sim 30$ Mpc/h.

Nevertheless, when the foregrounds and the instrumental noise from PAUS are added to the simulation, the general SNR of the cross-correlation drops considerably. Therefore, instead of simulating the cross-correlation and comparing to the theory (assuming that a detection is almost certain), a different approach has been taken to evaluate the probability of a detection.

### 6.2 Cross-correlation PAUS-eBOSS/DESI.

#### Probability of detection

As explained in §3, a simulation of the cross-correlation contains two stochastic elements: the instrumental Gaussian noise in PAUS images, and the quasar cells in eBOSS/DESI that determine the Ly$\alpha$ forest cells to be sampled (following the redshift distributions in Fig. 2).

Without the instrumental noise, different realisations of the Ly$\alpha$ forest do not modify significantly the cross-correlation results. Nevertheless, when the instrumental noise is added to the PAUS simulation, the SNR of the cross-correlation heavily decreases, up to the point of a detection (SNR $> 3$) depending on the realisation of the noise and the Ly$\alpha$ forest (i.e., the SNR is not consistent between different runs of the simulation pipeline). Fixing one of these stochastic elements (either the Ly$\alpha$ forest position or the instrumental noise) does not give consistent results either.

Therefore, the approach we have taken is to simulate the cross-correlation 1000 times, with different realisations of the instrumental noise and the Ly$\alpha$ forest each time, and compute the probability of detection (SNR $> 3$) for different distance binnings. For each one of the realisations, the monopole, parallel and perpendicular 2PCF have been computed using all possible uniform distance binnings: from one single bin for the whole distance range, to 12 uniform distance bins. This upper bound for the number of the distance bins comes from the discrete nature of the spatial binning in the simulation; finer distance bins would result in empty bins (without any cell pairs) for some cases.

The probability of detection versus distance has been computed considering that a detection covers the full span of the bins where SNR $> 3$ (so detections with wider binning cover larger spans), and counting overlapping detections as a single one (i.e., if in the same realisation and the same 2PCF a detection happens with two different binnings, and these detections have an overlap in distance, this only counts as a single detection in the overlap). Results are shown in Fig. 13.

As it would be expected, cross-correlation with DESI noticeably increases the detection probability for all three 2PCFs; however, the probability of any detection is still far from certain. Moreover, the monopole/parallel 2PCF and the perpendicular 2PCF seem to sample better different scales: the parallel 2PCF has a very low probability of detection at small scales, and shows a sharp increase in detection probability around 10 Mpc/h, while the perpendicular 2PCF has exactly the opposite behaviour. The cause of these contrasting trends in the detection probability for different 2PCFs is the smoothing effect that PAUS filters have in the parallel (redshift) direction, displayed in Fig. 10.

In the parallel cross-correlation, and to a lesser extent, the monopole 2PCF, smoothing decreases the absolute value of the 2PCF at scales of 10 Mpc/h and 15 Mpc/h respectively, while at larger scales the 2PCFs are increased (at least, as far as the size of the hydrodynamic simulation...
allows to compute the 2PCF, 30-35 Mpc/h). This trend matches almost perfectly the detection probabilities in Fig. 13, with sharp increases in the monopole and parallel 2PCF at the same scales.

On the other hand, the perpendicular 2PCF in Fig. 10 shows a smaller decrease, even when going to larger scales than the ones depicted in Fig. 10; this small effect of the smoothing results in higher detection probabilities at smaller scales, where the 2PCF has higher absolute values. This result shows that the parallel and perpendicular 2PCFs are highly complementary, and both should be taken into account for any future observational studies of Lyα IM with PAUS (or similar surveys) in order to maximise the probability of a detection at all scales.

Furthermore, the total probability of any detection (regardless of the kind of 2PCF and the binning) has also been computed, considering that a realisation with two or more detections in two different 2PCFs) still count as a single one. These results are summarised in Table 3.

When considering these results, it is important to take into account that in this preliminary study no weightings to improve SNR of the estimator in Eq. 9 have been considered, and only uniform binnings have been applied for the 2PCF's computation. Further tuning of these parameters could result in a higher SNR, and thus a higher chance of detection. Consequently, it is safe to assume that these detection probabilities are a pessimistic estimate, albeit close to what can be expected from cross-correlating observational data.

### Table 3. Probability of any detection for simulated cross-correlations PAUS-eBOSS and PAUS-DESI.

| Surveys       | Probability |
|---------------|-------------|
| PAUS-eBOSS    | 22.7%       |
| PAUS-DESI     | 32.8%       |

### 6.3 Hypothetical cases: PAUS deep, PAUS extended

In addition to the PAUS-eBOSS and PAUS-DESI simulations, two hypothetical cases have also been considered: PAUS deep, a survey with the same field coverage, but complete up to a magnitude deeper (i<sub>AB</sub> < 24), and PAUS extended, with the same exposure time as current PAUS, but a larger angular area of 225 deg<sup>2</sup>. These hypothetical PAUS cases have only been cross-correlated with the DESI simulation, since eBOSS would be rendered obsolete by DESI before such hypothetical surveys could be finished.

PAUS deep has been simulated analogously to PAUS, with the sole difference being the instrumental noise, now reduced by a factor of √6, as displayed in Table 2 (σ<sub>eBOSS,abs</sub>). Regardino PAUS extended, the Lyα emission array has been repeated in a mosaic of 3x3, instead of 2x2, thus yielding an angular coverage of 225 deg<sup>2</sup>. To cover this mosaic of Lyα emission, the foregrounds array has been repeated and rotated for the first 4 iterations; after that, it has been mirrored in RA direction and repeated until the 3x3 mosaic has been filled. This gives 8 possible combinations of Lyα emission-foregrounds: the 4 rotations of the foreground array plus the 4 mirrored rotations, which sets a limit on the maximum area we can simulate in this study. In fact, the 3x3 mosaic already has one redundant combination of Lyα emission-foregrounds (since it is composed of 9 realisations). Simulating even larger areas would result in largely redundant foregrounds, which would provide too optimistic results given that the same combination of Lyα emission-foregrounds would be sampled several times.

The probability of detection for 1000 realisations of these simulations is shown for the monopole, parallel and perpendicular 2PCFs in Fig. 14, together with original PAUS-DESI simulation, while Table 4 displays the probability of any detection.

Both cases show a greatly increased probability of detection, close to 60%, which almost doubles the original PAUS-DESI simulation. The same complementary trend is observed in Fig. 14, with the perpendicular 2PCF sampling better at scales below 10 Mpc/h, while the monopole and...
**Figure 13.** Probability of a detection as a function of distance in the simulated cross-correlation PAUS-eBOSS and PAUS-DESI, for 1000 different realisations of instrumental noise+Ly\(\alpha\) forest.  
Top panel: Monopole 2PCF.  
Middle panel: Parallel 2PCF.  
Bottom panel: Perpendicular 2PCF.

**Table 4.** Probability of any detection for simulated cross-correlations between hypothetical PAUS extensions and DESI.

| Surveys            | Probability |
|--------------------|-------------|
| PAUS deep-DESI     | 58.3%       |
| PAUS extended-DESI | 60.3%       |

parallel 2PCF have a much higher chance of detection at larger scales.

For these last two 2PCFs, PAUS extended seems to provide a much higher increase of probability of detection (an increase by a factor of 2-3) at distances larger than 10 Mpc/h, while the improvement of PAUS deep compared to original PAUS is negligible. The perpendicular 2PCF at
small scales, however, shows similar improvement with either PAUS deep or PAUS extended.

PAUS deep would need 6 times the observation time from current PAUS to observe the same area (going from 3 exposures for each pointing to 18), while PAUS extended only would need 2.25 times the observation time to be carried out (since 225 deg² are being observed instead of 100 deg², with the same exposure time per pointing). Consequently, in order to do Lyα IM with PAUS or similar narrow-band photometric surveys, covering larger areas of the sky seems a far more suitable approach than focusing on relatively small fields at deeper magnitudes.

7 CONCLUSIONS

In this work the possibility of performing Lyα IM by cross-correlation of spectroscopic Lyα forest data with the background of narrow-band images from PAUS has been simulated and evaluated. Lyα forest emission and absorption has been simulated from a hydrodynamic simulation of size 400 Mpc/h designed for the study of the IGM (Cisewski et al. 2014; Ozbek et al. 2016; Croft et al. 2018). The foregrounds in PAUS images have been simulated from a lightcone mock catalogue made from the Millennium Simulation with the WMAP7 cosmology (Guo et al. 2013), and using the GALFORM (Gonzalez-perez et al. 2014) semi-analytical model. SED templates (Blanton & Roweis 2006) have been fitted using non-negative least squares to the broad-band data of this mock catalogue in order to achieve PAUS spectral resolution for these foregrounds. Instrumental noise has only been added to the simulated PAUS images (measured directly from reduced PAUS science images); errors in spectroscopic Lyα forest data have been considered negligible.

Furthermore, the theoretical 2PCFs (monopole, parallel and perpendicular correlations) have been computed with the derivation shown in Gaztaña et al. (2009) from the matter power spectrum, obtained using CAMB (Lewis et al. 2000). The smoothing of these theoretical 2PCFs due to the large redshift bins for Lyα emission in PAUS narrow-band images has been simulated, and the biases of both Lyα emission and absorption have been measured by comparing the theoretical monopole 2PCF to the correlation of the Lyα absorption and emission arrays, using the same spatial binning as the PAUS-DESI cross-correlation.

The simulated cross-correlations without foregrounds or instrumental noise show that, despite the redshift smoothing of Lyα emission in PAUS images, and the limited fraction of space sampled by Lyα forest data, the theoretical monopole 2PCF can be recovered, and the bias of both Lyα emission and absorption can be measured. This shows the validity of this technique in an ideal case to both place constraints on the 2PCF and the bias of the extended Lyα emission or the Lyα forest.

Nevertheless, a bias has been identified in the cross-correlation estimator when cross-correlating fields with noise with mean larger than zero (such as the foregrounds and the instrumental noise for this case). This noise bias, while not affecting the SNR, should be taken into account if constraints such as the Lyα emission bias or the Lyα mean luminosity are to be derived from cross-correlation. A constrained model of the foregrounds and other noise sources average values would be needed; conversely, assuming a known bias and expected Lyα luminosity this same cross-correlation could be used to place constraints on foregrounds emission.

When the cross-correlation is run with the instrumental noise and foregrounds in PAUS images, SNR greatly decreases, up to the point where not all realisations yield a detection. A realisation of this cross-correlation contains two stochastic elements: the instrumental noise, derived from a random Gaussian distribution, and the positions of the quasars, drawn from the quasar redshift distribution of eBOSS/DESI. Fixing one of these stochastic elements does not provide consistent SNR either, so the probability of a detection (i.e., the cross-correlation reaching a certain SNR threshold) has been evaluated using a purely frequentist approach.

In order to evaluate the probability of a detection, 1000 realisations of the simulated cross-correlations have been carried out with different realisations of both instrumental noise and quasar positions, and for each one the monopole, parallel and perpendicular 2PCFs have been computed for different uniform binnings (from 1 to 12 uniform distance bins).

Considering a detection threshold of SNR > 3, Lyα emission has been detected in 22.7% of PAUS-eBOSS simulations and 32.8% of PAUS-DESI simulations. Moreover, the perpendicular and parallel 2PCF show complementary behaviours: the former has relatively high detection probabilities (around 25% for PAUS-DESI per distance bin) at scales up to 10 Mpc/h, while the latter displays a non-negligible probability of detection (close to 10% for PAUS-DESI) at scales larger than 10 Mpc/h. These different trends are due to the smoothing of the 2PCF in redshift direction, which affects far more the parallel 2PCF than its perpendicular counterpart.

These results show that, while not being a certainty, Lyα IM has a non-negligible probability of detecting extended Lyα emission even just with PAUS-eBOSS, although with DESI the odds increase notably. Besides this, there is a probability of detection at scales up to 35 Mpc/h, which would be far more extended than the current detection of Lyα emission at 15 Mpc/h in Croft et al. (2016). Given that this 35 Mpc/h scale is approximately the limit at which the 2PCF can be properly estimated given the size of the hydrodynamic simulation used in this study, it is entirely possible that detections of Lyα emission via cross-correlation appear at larger scales with enough observational data.

It is also worth nothing that for this work only uniform binning of the 2PCF has been considered, and no weighting in the cross-correlation estimator nor other approaches to increase SNR have been explored (mainly because of the large computational cost of estimating the probability of detection). Therefore, the probability of detection when processing observational data may be slightly higher than the results of this work.

Moreover, two hypothetical cases have also been evaluated for cross-correlation with DESI: a deeper PAUS with six times the current minimum exposure time per pointing, and an extended PAUS covering 225 deg² instead of 100 deg². The probability of a detection is increased to 58.3% and 60.3% respectively, and while at r < 10 Mpc/h both hypothetical surveys yield similar results, at larger scales increasing the angular area yields a much higher detection...
probability (more than a factor of 3 compared to current PAUS-DESI) with less observation time. Therefore, larger angular coverages in narrow-band photometric surveys are a better approach than increased exposure times, at least if the survey is deep enough to be complete up to $\Delta I_B < 23$, such as PAUS.

Given that increasing angular coverage seems the optimal strategy to maximize SNR, and that it has been shown that cross-correlation smoothing due to the narrow-band filters can be properly modelled and accounted for, we can assume that this methodology could be also applied to broadband surveys. The smoothing scale would be much larger for such observations, which would clearly decrease the expected cross-correlation signal, but the greater angular coverage (one or even two orders of magnitude larger), could make up for this effect and even result in higher SNR.

In conclusion, this work shows that IM via cross-correlation of the background of PAUS images with eBOSS/DESI Ly$\alpha$ forest may yield a detection of extended Ly$\alpha$ emission at scales up to 35 $\text{Mpc}/h$ (and possibly larger), albeit this is not certain, since it depends on the stochastic elements of the cross-correlation. Even if such a detection is not a certainty, it would open a new window for the study of the IGM and HI structure at different scales; a medium that contains most of the baryonic matter in the Universe, yet it is both poorly understood and extremely difficult to constrain.

Furthermore, our simulations show that extending PAUS coverage up to 225 deg$^2$ increases the detection probability from 30% to at least 60% when cross-correlating with DESI. In addition to this, this study also proves that in an ideal case without any noise sources, this methodology allows one to properly recover both the theoretical 2PCF and the bias of the tracers, and thus it is a theoretically sound tool for cosmological studies.

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