Roman CCS White Paper

Opportunities for galaxy – 21-cm cross-correlations at high redshifts

Roman Core Community Survey: *High Latitude Wide Area Survey*

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Abstract: Several low-frequency cosmology experiments are currently seeking a detection of 21-cm emission from the Epoch of Reionization. Wide-field galaxy surveys like the Roman High Latitude Survey are extremely complementary to 21-cm experiments, as they directly detect bright galaxies mostly likely to reside in the centers of large ionized bubbles during the EoR, while 21-cm experiments target the patchwork of bubbles themselves. Here, we show that the prospects for cross-correlations between Roman and HERA would be strengthened considerably by going 1-2 magnitudes deeper than the nominal HLS (in each of the four filters) over a contiguous 10-100 deg^2 region in the South near -30 degrees declination, where HERA, as well as the MWA and eventually the SKA, will observe. Additional depth in the spectroscopic survey would be beneficial as well, in order to guarantee Ly-a detections at redshifts $z \gtrsim 7.2$, while coverage in the F087 filter could provide useful photometric constraints on galaxies at $z \sim 6$-7.

Redshifted 21-cm emission from neutral hydrogen during the Epoch of Reionization (EoR) is a powerful probe of the first generations of luminous sources to form after the Big Bang. The basic expectation is that ionizing photons from early galaxies carve out large ionized bubbles in the otherwise neutral intergalactic medium (IGM), which then appear as 'holes' in 21-cm maps. X-rays, generally assumed to be produced mostly by accreting compact objects, are expected to heat the gas on large scales and so modulate the 21-cm signal brightness relative to the microwave background in the (mostly) neutral regions outside bubbles. The size distribution of ionized bubbles and temperature of the neutral IGM can thus be inferred from 21-cm maps, and provide an indirect constraint on the efficiency of ultraviolet (UV) and X-ray photon production and escape. As a result, 21-cm measurements have the potential to transform our understanding of galaxy formation by providing a new window into star formation and accretion onto compact objects at early times.

A critical first step toward 21-cm map-making is to pursue a *statistical* detection of 21-cm fluctuations. The power spectrum of the 21-cm field is one way to characterize such fluctuations, and is currently being targeted by a fleet of experiments like the Hydrogen Epoch of Reionization Array (*HERA*), Murchison Widefield Array (*MWA*), and the Low-Frequency Array (*LOFAR*). Despite strong foregrounds and an array of potential systematic uncertainties, these experiments are closing in on a first detection of 21-cm fluctuations from high redshift, and are already able to constrain models of X-ray production with upper limits alone [5,6]. However, any reported detection of 21-cm fluctuations will understandably be met with skepticism; the measurements are extraordinarily challenging, and the signal of interest – at least over a limited bandwidth – lacks the kind of 'smoking gun' signature that other probes are fortunate enough to exhibit (e.g., waveforms from gravitational wave events).

The most powerful confirmation of high-z 21-cm studies would be the simultaneous detection of an ionized bubble (via 21-cm) *and* the overdensity of galaxies within it (via, e.g., *Roman, JWST*), as has been pointed out in many studies focused largely on future measurements with the Square Kilometer Array (SKA). However, we may not need to wait for the SKA to come online to achieve such confirmation. The expected configuration – where galaxies source ionized bubbles and so occupy dark patches in the 21-cm background – will manifest *statistically* as an *anti*-correlation between the 21-cm background and high-z galaxy populations. Such a measurement would not only validate efforts to detect high-z 21-cm emission, it would open the door to exciting new constraints on the EoR. For example, the length scale (or spatial frequency, *k)* at which 21-cm emission and galaxies 'de-correlate' is a reliable indicator of the typical bubble size [1], while the amplitude of the cross-correlation signal depends on the timeline of reionization and temperature of the IGM, and so encodes much of the same information as the 21-cm power spectrum [7].

Predictions for the strength of the 21-cm – galaxy cross-correlation signal are uncertain for the exact same reason it's such an interesting observable: it depends on the astrophysics of galaxies and the details of cosmic reionization, both of which are poorly understood. However, there is reason to be optimistic: in a recent paper [2], we showed near-future 21-cm data from HERA and Lyman-ɑ emitters (LAEs) detected in the Roman high-latitude survey (HLS) could yield a strong detection over a fairly broad range in parameter space. For our fiducial "best-guess" model, we anticipate that a ≳10 sigma detection may be possible. However, in some not-unfathomable corners of parameter space – e.g., more pessimistic assumptions regarding foreground contamination in HERA data, or an intrinsic dearth of LAEs at high redshift – a detection may be marginal, at least for the nominal HLS, with limiting AB magnitude of 26.7 for the imaging survey and a line flux limit of 10^{-16} erg/s/cm^2 for the spectroscopic survey [3,4].

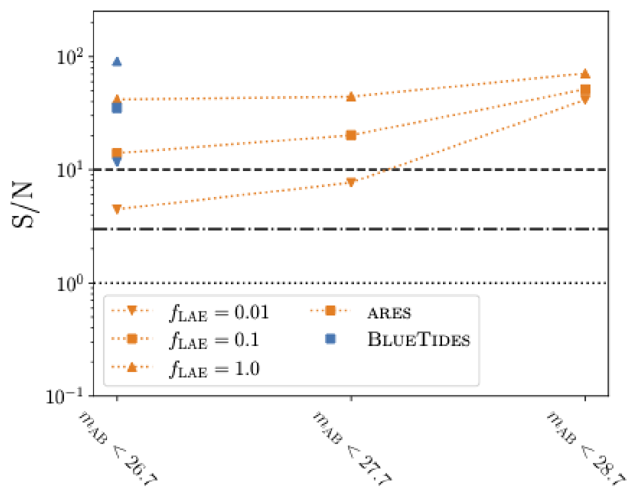

Figure 1: Total detection significance expected for HERA 21-cm x Roman LAEs, including all available k modes and all z≳7.2, as a function of limiting magnitude (x-axis) and intrinsic fraction of galaxies with detectable Ly-a emission (f_{LAE}). We also show predictions based on two different galaxy formation models, a semi-analytic model (ARES; orange) and the BlueTides hydrodynamical simulation (blue), to further illustrate the range of possibilities. From [2].

While still a crucial step forward for the field, a marginal cross-correlation detection would not permit much in the way of astrophysical inference, given that the bulk of the constraining power comes from studying the redshift- and *k*-dependence of the cross-correlation signal. A whopping detection, on the other hand, would enable this more granular z- and k-dependent analysis, and so permit meaningful astrophysical inference. We found that the main factor limiting the detection significance is shot noise due to the low expected surface density of high-z galaxies. The solution is simple in principle: we need to go deeper to achieve a higher surface density of galaxies. We found in that going 1-2 magnitudes deeper in a 100 deg^2 patch of the HLS in the HERA stripe (declination -30 ± 5 degrees) would guarantee a strong (≳10 sigma) cross-correlation detection in every scenario we explored (see Fig. 1).

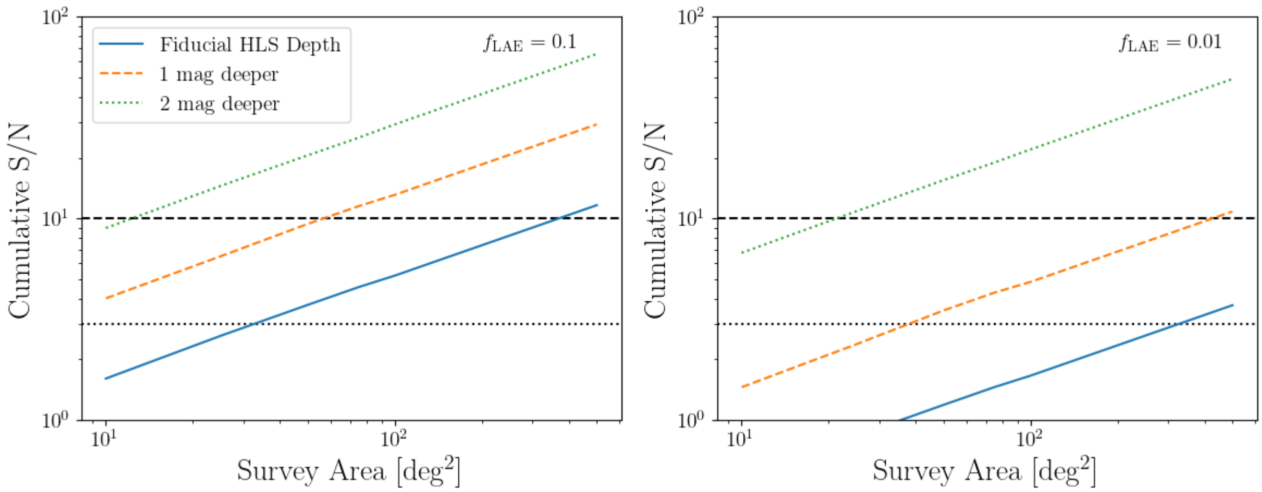

Figure 2. Cumulative signal-to-noise as a function of overlapping survey area between Roman and HERA. Solid lines indicate nominal AB limiting magnitude of 26.7, while dotted and dashed lines indicate depths increased by 1 and 2 magnitudes, respectively. Left: fiducial model with f_{LAE}=10%. Right: more pessimistic scenario with f_{LAE}=1%. Horizontal lines indicate 3 and 10 sigma detection thresholds.

We did not, however, perform a detailed trade study, and so left open the question of whether additional depth over 100 deg^2 is necessary, or if smaller areas would suffice. In Fig. 2, we show the results of such a study, including our fiducial astrophysical model (left) and a more pessimistic scenario in which only 1% of galaxies are LAEs (right). Note that current observations indicate f_{LAE}~10% at z~6-7, but we expect this number to decline at higher redshifts as the IGM becomes more neutral, so the right panel is not implausible. First, in the left panel of Fig. 2, we see that high significance detections are possible in even 10 deg^2 fields of view, provided that the HLS is 2 magnitudes deeper than the nominal survey (dotted line), while an additional depth of 1 magnitude yields ≳10 sigma detections only for fields of view greater than ~60 deg^2 (dashed). We recover the 10 sigma detection quoted in [2] for the nominal depth (solid) and 500 deg^2 of overlap between Roman and HERA. For the more pessimistic scenario (right), 20 deg^2 of overlap is needed if depths are 2 magnitudes deeper than planned (dotted), while the full 500 deg^2 is needed to secure a 10 sigma detection if only 1 additional magnitude of depth is achieved.

Though we focus here on the tradeoffs between survey area and depth, we note that additional filter coverage could be advantageous as well. With the nominal four-filter coverage, the Lyman-break technique can be used to identify galaxy candidates at redshifts above z~7, which can then be used as inputs for the extraction of spectra with the Roman grism. In general, a spectroscopic detection is critical to our approach, since the galaxy – 21-cm cross-correlation is a 3-D measurement (without precise redshifts, the positions of galaxies along the line of sight are too uncertain to yield a strong cross-correlation signal). Given the wavelength coverage of the Roman grism, we can only expect Ly-a detections in $z \gtrsim 7.2$ galaxies. As a result, the addition of (for example) coverage with the F087 filter is not immediately useful, as it would enable the identification of Lyman break galaxies at $z \sim 6\text{-}7$ with no hope of an accompanying Ly-a detection in the spectroscopic survey. Despite this, it may be possible to leverage $z \lesssim 7$ photometrically-detected galaxies *statistically,* using well-crafted 3-point functions. We caution that the use of 3-pt functions in this context is very much an active area of research, but if other programs benefit from F087 coverage enough for it to be added to the HLS, then we would of course prioritize a study of how we could make use of this information for cross-correlation analyses.

Finally, we note that the expected 21-cm – galaxy detection significance depends not only on the particular galaxy formation model and intrinsic LAE fraction of high-z galaxies, as shown in Fig. 1, but also on the precise timeline of reionization and reheating, and details of 21-cm foreground mitigation [2]. As a result, one can never rule out the possibility of a non-detection *a-priori*, whether it be because of unexpected astrophysics or lingering observational systematics. We expect that in the next few years, observations with JWST will help tighten constraints on the properties of reionization-era galaxies, and in doing so help us reassess the cross-correlation prospects for Roman and HERA. In any case, additional depth in the HLS in the South will no doubt be beneficial to other groups as well. For example, one of the MWA's EoR fields targets the area of overlap between the HERA stripe and nominal HLS footprint, so any improvements to the HLS in that region of the sky will immediately affect their ability to do cross-correlations as well. In the future, the SKA-low will be able to observe the same field, given that it is to be built at the same site as the MWA. As a result, additional depth in the South would benefit multiple current and near-future 21-cm experiments, and improve the prospects for a cross-correlation detection tremendously.

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