Snowmass2021 - Letter of Interest

A 21-cm based standard ruler at $z \sim 20$

Thematic Areas: (check all that apply ☐/■)

■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Astro-particle physics cosmology
■ (CompF2) Theoretical Calculations and Simulation

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Abstract: Direct measurements of the expansion rate $H(z)$ of the universe are currently limited to low redshifts $z \lesssim 5$. This creates a big gap between the local universe and the epoch of recombination, at $z \sim 10^3$, where new physics may present in many forms. Data from upcoming 21-cm surveys holds the key to understanding the cosmic-dawn era, covering $z \sim 10 - 30$, between us and the CMB. While many astrophysical uncertainties plague 21-cm measurements, it has been recently discovered that the acoustic physics of recombination becomes imprinted in the 21-cm signal through the relative velocity between dark matter and baryons. This gives rise to velocity-induced acoustic oscillations (VAOs), with the acoustic scale imprinted on them, which can be used as a standard ruler at cosmic dawn. Here we delineate the efforts that ought to be undertaken to fully exploit this observable.

Background

The expansion rate of our universe, parametrized through the Hubble rate $H(z)$ at different redshifts z, is an important cosmic observable. Its value is given by the entire energy content of the cosmos, and thus carries information about not only the visible matter, but also the dark matter and dark energy. It is therefore critical to measure $H(z)$ throughout the entire history of the universe to understand its composition.

Current measurements of $H(z)$ are shown in Fig. 1. This expansion rate can be directly measured at low z through different observables, such as standard candles and strong-lensing time delays[1–3]. Additionally, the distribution of matter in the universe provides a handle on $H(z)$ through the baryon acoustic oscillations (BAOs), which are a standard ruler of a well-known length[4;5]. This allows different cosmic surveys of matter fluctuations to measure $H(z)$[6–9]. Nevertheless, these measurements do not reach beyond $z \sim 5$, as there are no extensive surveys at such high redshifts[10].

A Standard Ruler in 21-cm Data

A promising probe to reach higher redshifts is the 21-cm line of neutral hydrogen, which will provide access to a large cosmic volume unobservable by other data sets. Of particular interest is the cosmic-dawn era, roughly spanning the redshift range $z = 10 - 30$, which saw the formation of the first stars. These

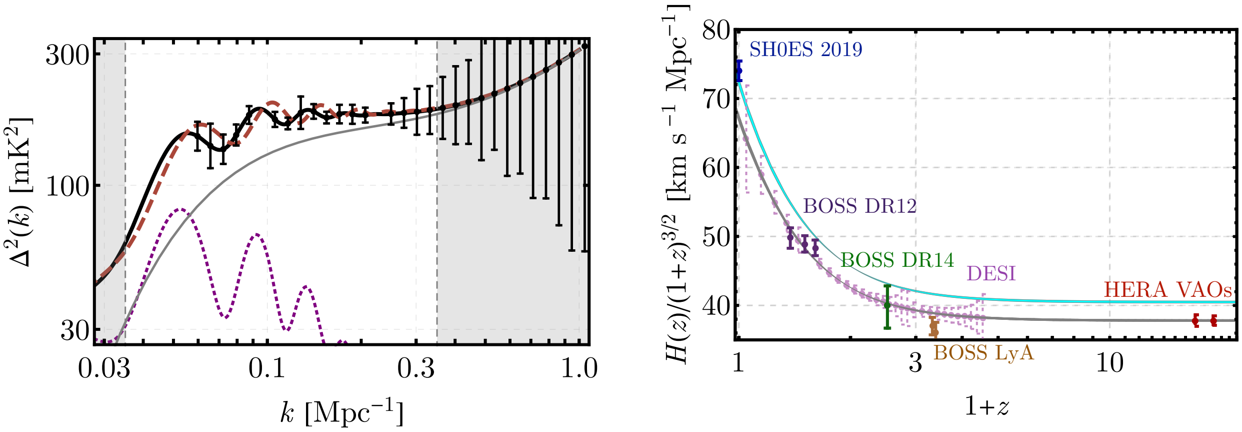

Figure 1: **Left:** Power spectrum of 21-cm fluctuations at $z = 16$, from Muñoz 2019[11]. The gray line shows the case without velocities, whereas the purple-dotted line is the VAO-only contribution, which has marked acoustic oscillations. The black line shows the total power spectrum, which inherits said oscillations. The VAOs act as a standard ruler, as they would be shifted if the size of the universe was different. As an example, the red-dashed line has a value of $H(z = 16)$ that is 10% smaller, which shifts the VAOs to larger k. Errors in this plot correspond to three years of HERA data. **Right:** Summary of $H(z)$ measurements from Muñoz 2019[11]. In dark-purple, green, and brown we show the current constraints from BAO analyses of galaxies, quasars, and the Lyman-α forest, from the Baryon Oscillation Spectroscopic Survey (BOSS)[6–9]. The red points show the projections using 21-cm observations of the velocity-induced acoustic oscillations (VAOs) with HERA. The gray band represents the uncertainty from current CMB observations, assuming standard cosmology, which is in clear tension with the distance-ladder measurement from the Supernova H_0 Equation of State (SH0ES) collaboration[1], shown in blue. Finally, the dotted-violet points correspond to forecasted BAO constraints from DESI[10], which cannot reach the redshifts probed by VAOs. In both figures the sound horizon is inferred from Planck CMB data[12], except for the cyan line in the right panel, which has a value of the sound horizon 7% smaller, as argued to resolve the H_0 tension[13;14], and can be easily detected by HERA.

stars filled the Universe with ultraviolet (UV) photons, exciting the hyperfine transition in neutral hydrogen and allowing it to efficiently absorb 21-cm photons from the cosmic microwave background (CMB)[15–17]. In addition, hydrogen was later reheated by the abundant X-rays produced by stellar formation, eventually sourcing 21-cm emission against the CMB[18–20]. These two effects allow us to indirectly map the distribution of the first star-forming galaxies during cosmic dawn through the 21-cm hydrogen line.

The first galaxies formed out of matter overdensities at small scales[21–23], where baryons and dark matter (DM) do not behave identically[24;25]. Only the baryons interact with photons, and thus suffer BAOs. This generates relative velocities between the two fluids[26], which fluctuate on acoustic scales, and strongly suppress the formation of the first stars due to their supersonic nature[26–38]. These velocities become imprinted into the 21-cm power spectrum[39–43], as shown in Fig. 1. This gives rise to a new type of "wiggles": velocity-induced acoustic oscillations (VAOs)[43], with the same acoustic origin as the BAOs, albeit a different shape. These VAOs provide a new standard ruler during cosmic dawn[11].

The HERA interferometer, currently finishing construction, will be able to measure the expansion rate using these VAOs for $z = 15 - 20$, as shown in Fig. 1. Not only would this bridge the gap between the local measurements at $z \lesssim 5$ and the CMB at $z \sim 10^3$, but it can also help understand the origin of the tension in measurements of the expansion rate today, dubbed H_0. Local observations yield a value of H_0 that is in strong disagreement with that inferred from the CMB[12]. Different possible solutions to this tension involve new physics, such as early dark energy [13;14;44;45], or decaying DM[46;47]. VAOs can provide a new standard ruler to test these models, showing their potential for the study of new physics.

Observational Challenges

Measuring the 21-cm power spectrum accurately and precisely is difficult because of three separate—but related—challenges. The first is sensitivity. The signals are faint, and therefore large telescopes are necessary. The second is the issue of foreground contamination. Unlike for the CMB, foregrounds are overwhelmingly bright at the relevant frequencies regardless of whether one looks within the Galactic plane or towards the Galactic pole. Finally, an exquisite control of systematics (including but not limited to issues such as unknown beam responses or mutual coupling problems between antennas) is required.

Each of the aforementioned problems is formidable in their own right, but the overall observational challenge lies in the pernicious combination of effects. For instance, the foregrounds are often considered to be spectrally smooth, and are therefore in principle distinguishable from the cosmological signal, which is expected to fluctuate rapidly with frequency. However, low-level instrumental effects such as cable reflections can corrupt this delicate separation, causing the observed foreground signals to pick up extra structure and thus to masquerade as cosmological signal. This problem is compounded by the fact that the foregrounds are not yet well-understood at the required levels of precision at these low frequencies, plus the fact that to meet sensitivity requirements, 21-cm interferometers tend to be closely packed arrays. This regime of dense, large-N arrays is unusual in traditional radio interferometry, and it is currently a open question as to how to avoid instrument systematics in this limit. We emphasize, however, that the forecasts presented above use only data outside the foreground "wedge", and are expected to be clean of foregrounds.

Multiple investments are therefore needed for progress. For example, further empirical observations of foregrounds are needed in order to construct better models for mitigation efforts. Test arrays explicitly designed to study coupling effects (and other systematics) in a realistic *in situ* setting are required. Techniques in precision polarization calibration should be tested on real data from large arrays. All of these efforts (and others) should be coupled with a robust end-to-end simulation effort. This will require development on the theory frontier (for example, with explorations of the robustness of VAO signatures in the context of new feedback prescriptions). However, a robust understanding will also require the inclusion of carefully modeled systematics that are accounted for in any mock constraints.

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