# Snowmass2021 - Letter of Interest

# *Cosmic dawn: A probe of dark matter at small scales*

**Thematic Areas:** (check all that apply □/■)

■ (CF3) Dark Matter: Cosmic Probes
■ (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:** The distribution of matter fluctuations in our universe—parametrized through its two point function, the power spectrum—is key for understanding the nature of dark matter and the physics of the early cosmos. Importantly, the formation of the first stars near cosmic dawn depends sensitively on the properties of these small-scale fluctuations. The 21-cm hydrogen line is a promising tracer of this early stellar formation, which took place in small haloes (with masses $M \sim 10^6 - 10^8 M_\odot$), formed out of matter overdensities with comoving wavenumbers as large as $k \approx 100$ Mpc$^{-1}$. Observations of both the 21-cm global signal and its spatial fluctuations at cosmic dawn thus offer a unique way to probe the small-scale matter power spectrum in the denser high-redshift environment of the earlier Universe. We enumerate the theoretical and observational improvements that ought to be undertaken to obtain a measurement of the high-$k$ power spectrum.

## Background

The nature of dark matter (DM) remains elusive. Cosmology is one of the few tools to understand the behavior of DM even if it does not couple to the visible sector. While at large cosmological scales DM appears to be cold and collisionless, little is know about its small-scale behavior. It is precisely at these small scales where the DM microphysics would readily manifest, as generic deviations from the pure cold DM (CDM) paradigm (e.g., DM that is warm, fuzzy, or self-interacting) produce a suppression or enhancement of small-scale fluctuations. It is, thus, imperative to find novel cosmic observables that can target the DM distribution at small scales.

Significant observational and theoretical efforts have been devoted to studying the behavior of DM with different cosmic targets. These efforts have reached impressive precision. The benchmark observable is the matter power spectrum—the two point function of matter fluctuations—which is set by the DM behavior early on. A recent compilation of measurements of the matter power spectrum can be found in Chabanier et al. (2019)[1] up to wavenumbers $k = 3\,\mathrm{Mpc}^{-1}$ (all distances are comoving unless otherwise stated), all in agreement with the expected CDM behavior.

Fluctuations with larger wavenumbers contribute to the formation of DM haloes with smaller mass, which host increasingly fainter galaxies as halo mass shrinks[2]. This makes detecting and characterizing these small DM haloes through their stellar content very challenging even in the local Universe, let alone at cosmological distances. While strong gravitational lensing[3] will allow us to probe some of these dark haloes down to $M_h \sim 10^7\,M_\odot$ at $z \lesssim 3$, extending our sensitivity to even smaller halo masses and higher redshifts require a radically different set of observations. One such probe is the 21-cm signal from cosmic dawn, which is sensitive to DM haloes in the range $M_h \sim 10^{6-8} M_\odot$ at high redshifts, hence providing a powerful cosmic tool to learn about the small scales of our universe and, thus, the nature of dark matter.

## 21-cm as a Probe of Dark Matter

The cosmic-dawn era begins when the first stars formed, at $z \sim 10 - 30$, between the epoch of recombination and the local universe[4;5]. The radiation emitted by the first stars excited hydrogen, allowing CMB photons to be resonantly absorbed by the gas[6–8] and producing a negative 21-cm brightness temperature. Later on, hydrogen is heated by the X-rays emitted by the first galaxies, producing observable 21-cm emission. The combination of these two processes gives rise to a characteristic 21-cm signature trough during cosmic dawn, plotted in Fig. 1, and allows us to indirectly trace high-$z$ galaxies through their effect on neutral hydrogen.

By studying the timing of the 21-cm signal we can, therefore, reconstruct the evolution of early stellar formation. While many uncertainties remain about the properties of the first galaxies, we expect them to have (total) masses $M_{\rm mol} \sim 10^6\,M_\odot$, large enough for gas to cool through molecular-hydrogen lines[10]. Lyman-Werner feedback will slowly increase this galaxy-formation threshold to $M_{\rm atom} \sim 10^8\,M_\odot$, at which point the gas can cool down through atomic-hydrogen transitions[11–16]. All haloes below $M_{\rm atom}$ were formed out of extremely small-scale matter fluctuations, with comoving wavenumbers $k \gtrsim k_{\rm atom} = 40\,\mathrm{Mpc}^{-1}$. Suppressing said matter fluctuations delays the formation of structure (including the first stars), and thus all the 21-cm cosmic milestones. Increasing them, on the other hand, will produce stellar formation at earlier times.

As an example, we study the simple case of warm DM (WDM), where DM has thermal motions related to its mass $m_\chi$ which produce suppressed matter fluctuations at small scales (large $k$). We show the 21-cm global signal expected for both CDM and WDM in the left panel of Fig. 1 (including all known astrophysical feedback effects[17]), where WDM has a 5-keV mass, at the edge of current constraints from the Lyman-$\alpha$ forest[18]. Clearly these two models present different 21-cm behavior, as WDM takes longer to form the first

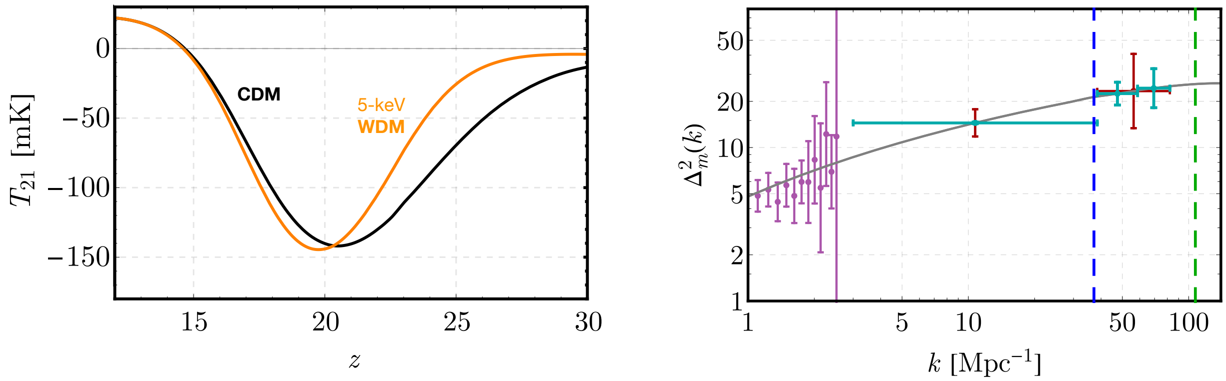


Figure 1: **Left** Two 21-cm global signals, assuming CDM in black and WDM (with a 5-keV mass) in yellow, with otherwise identical parameters. Clearly WDM forms fewer stars in the early universe, where small minihaloes (of $M_h \sim 10^6\, M_\odot$) dominate stellar formation. This delays the 21-cm signal significantly at high $z$. At lower $z$ stars are mostly formed in bigger haloes, where both CDM and WDM agree. **Right** Matter power spectrum at $z = 0$ from Muñoz et al. (2020)[9]. The prediction of CDM is shown as a gray line, and current measurements from the Lyman-$\alpha$ forest[1] are in purple. The forecasted errors for the 21-cm global signal (for an EDGES-*like* experiment) are shown as red crosses, and for the fluctuations (for a HERA-*like* experiment) as cyan crosses. The vertical lines delineate the range of wavenumbers of haloes that form stars during cosmic dawn (corresponding to $M_h \sim 10^6 - 10^8 M_\odot$).

stars at $z \gtrsim 15$. The global signal corresponds to the average absorption or emission across the entire sky, and will be measured by experiments like EDGES, LEDA, PRIzM, and SARAS (with a first detection in Bowman et al. (2018)[19] awaiting confirmation). The situation is even more promising when considering the 21-cm fluctuations, which will be measured by interferometers like HERA, as well as the LWA, MWA, LOFAR, or SKA-Low, given the additional angular information contained in those[9].

There are two avenues to exploit the small-scale information contained in 21-cm observations. The first is to directly compare different alternatives to CDM, as done in several works[20–36]. The second is to obtain model-agnostic constraints to the matter power spectrum at very small scales ($k \sim 50\,\mathrm{Mpc}^{-1}$, corresponding to $M_h \sim 10^7 M_\odot$)[9]. Measuring such large wavenumbers would open a window to the behavior of DM at smaller scales than currently available. This is illustrated in the right panel of Fig. 1, where we show the matter power spectrum linearly extrapolated to $z = 0$, along with current measurements from the Lyman-$\alpha$ forest[1]. We show forecasts from Muñoz et al. (2020)[9] for both the 21-cm global signal and its fluctuations. Clearly, high-redshift 21-cm observations have the potential to map small-scale DM fluctuations at an epoch at which few other probes are available.

## Opportunities and Challenges

The 21-cm line during cosmic dawn will allow us to map matter fluctuations at at scales hitherto unexplored. To fully exploit the information, however, we ought to improve our modeling and observations of the 21-cm signal during cosmic dawn. Improving the modeling would involve more theoretical work focusing on the formation of the first galaxies. Moreover, current numerical simulations of the cosmic-dawn era cannot simultaneously resolve the long distances that UV photons travel before being absorbed (as much as $\sim 100$ Mpc comoving) and the small galaxies that hosted the first stars (with a typical radius below $\sim 100$ kpc comoving). Both these obstacles demand larger computing power and simulation resources. On the observational side, extracting an unambiguous DM signal will require exquisite sensitivity, detailed modelling of foregrounds, and control of systematics beyond what is currently done.

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