Snowmass2021 - Letter of Interest

Small-scale structure at high redshift: Lyman-alpha forest

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (TF9) Astro-particle physics & Cosmology
■ (CompF2) Theoretical Calculations and Simulation

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Abstract: The low-density and high-redshift intergalactic medium displays a filamentary structure at small and medium scales which is traced by Lyman α forest absorption features, and is sensitive to the small-scale properties set by the dark matter. Since the thermal broadening of Lyman α forest lines is approximately constant with redshift, the presence of a cutoff in the matter power spectrum due to the free-streaming of dark matter becomes more prominent in velocity space at high redshift. Advances in the observational techniques will allow for mapping an unprecedented volume of the high redshift $z > 4$ Universe. This will increase the statistical power of the small-scale clustering that holds key information about the primordial nature of the dark matter. Recent development in the numerical techniques of the intergalactic medium, together with emerging theoretical modelling, will allow for an order of magnitude improvement over the current published constraints. In addition to the nature of dark matter, these measurements, combined with the CMB, also hold the potential to greatly improve our constraints on the production mechanism of sterile neutrinos, the amount of curvature in the Universe, and the inflationary slow roll parameters.

The fundamental nature of dark matter is one of the foremost open questions in science. Resolving this problem will require collaboration between particle physics, cosmology and astronomy. Particular questions which remain to be addressed are the fundamental particle nature of dark matter, it's formation mechanism, and interactions. As limits on the number density of several well-motivated candidates preclude them being all the dark matter, mixed models will become increasingly interesting.

The intergalactic medium (IGM) is the rarefied gas that fills the vast volumes between the galaxies in the universe. Physical effects, ranging from the nature of dark matter to the radiation from star-forming galaxies and quasars, set the observable properties of the IGM, making the IGM a powerful probe of both fundamental physics and astrophysics. Baryons in the IGM trace dark matter fluctuations on Mpc scales, while on smaller ($\lesssim$100 kpc scales) the $T \sim 10^4$K gas is pressure supported against gravitational collapse. Analogous to the classic Jeans argument, baryonic fluctuations are suppressed relative to the pressureless dark matter (which can collapse) and the gas is pressure-smoothed or "filtered" on small scales. At any given redshift, the pressure smoothing scale depends not only on the prevailing pressure/temperature at that epoch, but also on the temperature of the IGM in the past. Therefore, while the IGM is very sensitive to the timing and heat injection of the Epoch of Reionization[2,17,18], complex and poorly understood physical processes related to galaxy formation only play a minor role in determining its structure[3,11].

The free-streaming horizon of dark matter particles lead to a 3D smoothing at high redshift that keeps decreasing as non-linearities increase. Therefore, the small-scale suppression in non-CDM dark matter models moves from very large scales to smaller scales at progressively lower redshifts. These characteristics of the Lyman-α flux power spectrum have allowed for some of the tightest constraints on nature of dark matter clustering[1,6,7,19,20,24]. The current analysis have been shown to be sensitive to the scale of either suppression[14,15] or enhancement[8,16] of the small scale power. Constraints from the Lyα forest that vary both the abundance of the dark matter and the particle mass, can be linked to bounds on inflationary physics[10]. The degeneracies between the dark matter and the baryonic physics can be broken by: (a) extending the redshift range[6,19], as the different smoothing processes show very different redshift evolution; or (b) exploring the physically motivated parameter space by imposing informative priors[4,20].

Forward modeling the structure of the IGM for a given cosmological and DM scenario is a theoretically well-posed problem, albeit requiring expensive cosmological hydro-dynamical simulations. Despite this apparent simplicity, accurate simulations of the IGM are computationally challenging because of the multi-scale nature of the problem[12]. A spatial resolution of $\approx 20\ \mathrm{kpc}$ is required to resolve the density structure of the IGM, while a relatively large box size is required to capture the large-scale power, to obtain a fair sample of the universe, and to model the topology of reionization. In addition, HI and HeII reionization processes add additional source of fluctuations that is almost completely decoupled from the density field. While the HeII reionization ($z \sim 3$) has been well studied, and shown to have minimal effect on the 1D flux power spectrum, this is not the case for the HI reionization ($z > 5$). Various semi-analytical and approximate methods[9,23] have shown that the effect of HI reionization in the 1D flux power spectrum is of the order of $\sim$ few percent, at the level below the current measurement errors. To answer the question definitively, the future theoretical and computational challenge lies in solving coupled hydro-dynamical and radiative transfer simulation in a cosmological set-up.

Current measurements of the Lyα flux power spectrum can be split into two distinct categories: low-quality quasar spectra and large volumes; and high-quality spectra for a limited number and spatially distant quasar observations. In the case of the former, past (BOSS; eBOSS) and current (DESI) surveys, the measurements will be dominated by the systematics at $k < 1\ \mathrm{h/Mpc}$ and low redshift $z < 4$. On the other hand, high-quality observations of a handful ($\sim$ 100) of high redshift ($z > 4$) quasar spectra measure scales to wavenumbers of $k \sim 20\ \mathrm{h/Mpc}$[2,22]. These measurements are the ones that strongly constrain the nature of dark matter. They differ from the large volume surveys by using high resolution instruments ($R \sim 80,000$)

and high signal-to-noise observations ($S/N \sim 100$), but are limited by the number of observed quasars. Unlike large volume surveys they are currently dominated by statistical errors.

Analysis of the current data make clear that dark matter constraints benefit from access to higher redshifts ($z > 4$). By improving both the theoretical predictions in this regime, as well as increased statistical power, we could push the lower bounds on the dark matter free-streaming scale by several orders of magnitude. Quantifying the amount of information that can be gained at higher redshifts on the nature of dark matter would be one of the key goals of this white paper. Current bounds on the particle mass of various dark matter models include only a few spectra ($\sim 10 - 15$) at the highest redshifts ($z > 4.5$) (e.g.[5,20,21]). Assuming the measured quasar luminosity function[13], current or upcoming surveys will push this number to ~ 25 (DESI), ~ 50 (SkyMapper) and ~ 100 (LSST) at a fixed magnitude limit of $m_g < 18.5$. The magnitude limit is chosen such that a $S/N \sim 100$ observation is achieved with ~ 8h exposure time at current 8m telescopes (e.g. Keck/HIRES, VLT/UVES) and high resolution ($R \sim 80,000$). Fainter quasars could be observed by increasing the exposure time or the size of the telescope (e.g. ELTs). Achieving high signal to noise for each object requires 1 (good) night per quasar, so for 1000 quasars we require a survey length of 3.5 years. For a ~ 10yr survey doing spectroscopic follow-up on Vera Rubin Observatory-detected objects, high-redshift quasars would require $\sim 1/3$ of the nights per year.

Current lower mass bounds for the WDM model are $m_{\rm WDM} > 2.1$ keV using only high-redshift data and the most simplistic and uninformative priors on the thermal history evolution[6]. Including lower redshift data pushes this bound to > 3.5 keV, and further including informative thermal history priors leads to > 5.1 keV. Using a Fisher forecast analysis and only the high-redshift data, Fig. 1 shows how the lower bounds on the WDM particle mass would improve when using 25, 50, 100 or 1000 high-redshift quasar spectra. At 1000 spectra, the bound is > 14.4 keV; almost an order of magnitude improvement over the current constraints coming from the equivalent high redshift data set analysis. This constraint maps to a lower bound on the ultra-light axion-like particle mass on the order of $\sim 10^{-21} - 10^{-20}$ eV. Combined with higher mass constraints from super-massive black hole super-radiance, this could exclude all ultra-light axions of mass $< 10^{-14}$ eV as the dominant source of dark matter.

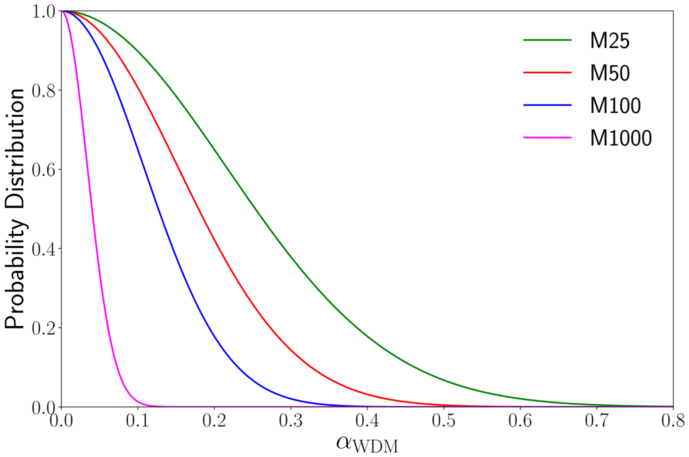

Figure 1: A forecast for the 1D marginalized posterior distribution of the $\alpha_{\rm WDM} = 1$ keV$/m_{\rm WDM}$ parameter for future surveys containing 25, 50, 100 and 1000 quasars at $z > 4.2$. The constraint for 1000 quasars at high redshifts excludes WDM particles masses below 14.4 keV at 2σ.

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