Constraining mixed dark matter models with the Lyman-α forest

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Small-scale structure problems in the standard ΛCDM model could potentially be solved in a hybrid dark matter model that allows for a fraction of dark matter to be warm with a mass in the keV range: **Cold+Warm Dark Matter (CWDM)**. This model could further reconcile the measurements giving rise to the S_8 tension. This project builds upon the work presented in [1].

In the CWDM paradigm, structure growth is affected by the free-streaming of dark matter at the small non-linear scales probed by the Lyman-α (Ly-α) forest, the main observable of the IGM. To investigate this feature, it is important to first characterize the thermal state of the IGM and its effect on the Ly-α forest.

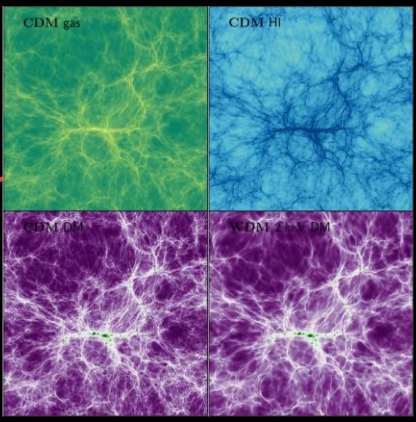


Figure 1. Credit: Vid Iršič.

The IGM contains most of the neutral hydrogen that gives rise to the Ly-α forest, which, from Fig.1, mainly dominates the cosmic gas (baryon) distribution and clusters around dark matter, resulting in high-density regions, filaments and voids. Fig.1 shows a slice through a cosmological box of size 20 h^{-1} Mpc with $2{\times}1024^3$ dark matter and gas particles at z = 4.2 using the Sherwood-Relics simulations with the `P-Gadget3` code [2]. Top: Hydrogen distribution with bright (left) and neutral hydrogen with darker (right) high density regions. Bottom: Dark matter distribution in the standard CDM model (left) compared to a 2 keV WDM model (right).

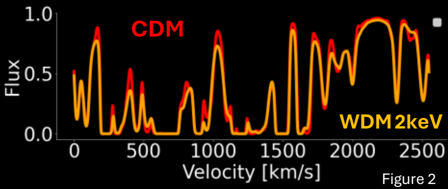
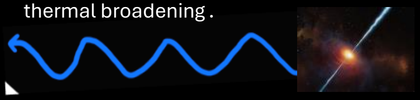


Figure 2

After reionization, the IGM approaches asymptotically the relation: $T = T_0\Delta^{\gamma-1}$, with T_0 the gas temperature at mean density (Δ= 1), and $\gamma - 1$ a power-law index [3]. T affects the Ly-α forest through thermal broadening.



The Ly-α forest is further sensitive to pressure smoothing, parameterized via the cumulative energy deposited into gas per proton, u_0, which depends on the prior IGM thermal history [4].

Marginalizing over the effects of T_0, γ and u_0 on the Ly-α forest is fundamental to constrain dark matter models.

Fig. 2 shows the transmitted flux F along a random LOS at z = 4.2 for standard CDM and for a 2 keV WDM model, related to the deficit of photons τ travelling through e.g. the box in Fig. 1 by $F = e^{-\tau}$.

Effect of DM free-streaming

Flux power spectrum

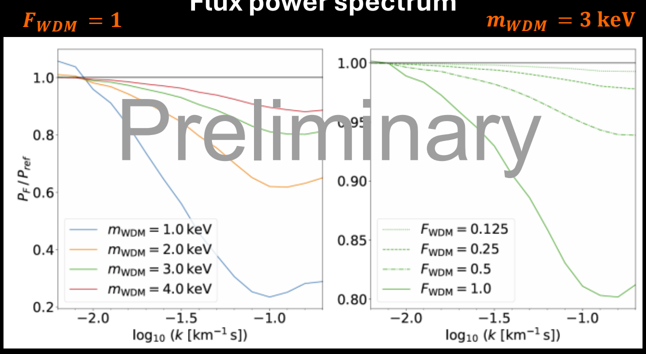


Figure 3: Flux power spectrum ratio of simulated CWDM models to the reference CDM model showing the small-scale power suppression due to dark matter free-streaming. Large-scale power enhancement is also visible due to effective optical depth τ_{eff} rescaling used to calibrate simulations against measurements.

Matter power spectrum

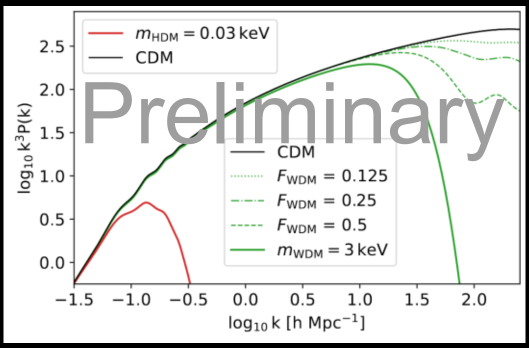


Figure 4: Linear matter power spectrum at z = 0 in CDM, CWDM, WDM and HDM models using CLASS [5].

Effect of thermal parameters and preliminary analysis

We extract the flux power spectra from the simulated Ly-α forest using Sherwood-Relics simulations spanning different cosmologies and thermal histories to constrain CWDM models. We first set up the Bayesian inference analysis framework to constrain a subset of the model parameters (T_0, γ, u_0, τ_{eff}) using the high signal-to-noise ratio and high redshift spectra samples observed by the UVES and HIRES spectrographs [6]. We speed up the parameter recovery by incorporating a neural network emulator into the MCMC code.

The neural network emulator is trained on 90% of the total dataset, and its performance is validated on the remaining 10%. We then test the precision of the model using k-cross fold validation following [6]. Fig. 5 shows the predicted power spectra by our emulator, varying one parameter a time while keeping the remaining three fixed to fiducial values in the CDM simulation.

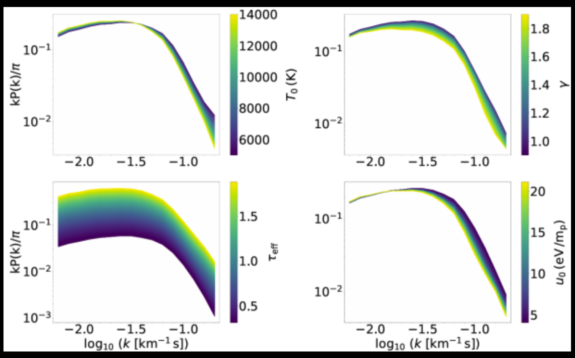


Figure 5.

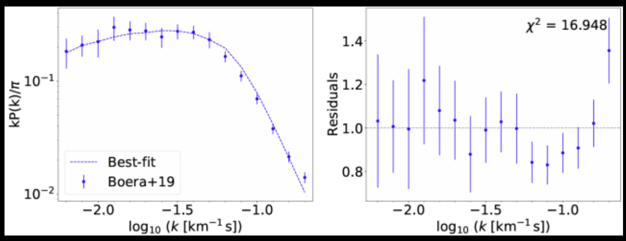


Figure 6.

We run the MCMC with the neural network emulator and obtain best-fit values for T_0, γ, u_0 and τ_{eff}. Fig. 6 shows the best-fit model predicted by the neural network to the data (left) and corresponding residuals and χ^2 (d.o.f = 15) value (right). The model represents the data well across all scales and resembles the best-fit from [1]. Discrepancies at large k values, especially in the last bin, highlight potential limitations of the model: the neural network's performance and not including instrumental and mass resolution correction to the mock spectra. The fit will fundamentally improve by incorporating thermal priors on T_0 and u_0, and by expanding the current parameter subset to include CWDM model parameters.

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