# Emulators for Ultra-Light Dark Matter

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## Dark Matter

A diverse set of astrophysical and cosmological observations indicate consistently the presence of dark matter (DM) in the universe. Despite the scientific efforts over decades, the fundamental nature of this component remains unknown.

Very precise measurements in cosmological scales are remarkably well described with a dark matter component that behaves as cold dark matter (CDM).

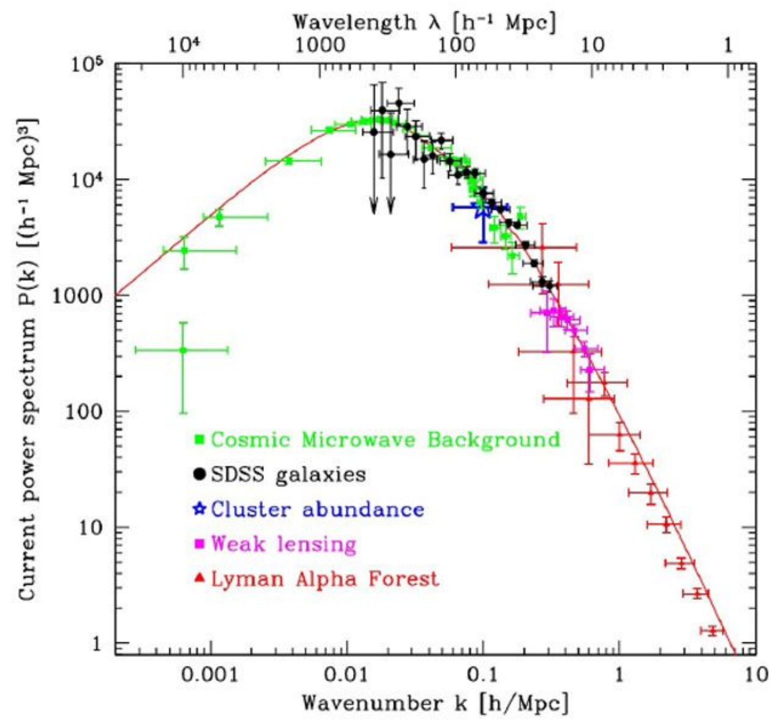


Fig 1. From Tegmark et al., 2003. The ΛCDM fitting to the matter power spectrum.

However, in smaller scales, $\lambda \lesssim 2\pi/10$ Mpc, present measurements are not so precise to bound the DM behavior that strongly. This allows the exploration of different phenomenologies in those scales. One class of candidates that present a rich non-CDM phenomenology on small scales are bosons with masses in the range $10^{-25}$ eV $\lesssim m \lesssim 2$ eV, called ultra-light dark matter (ULDM) [1].

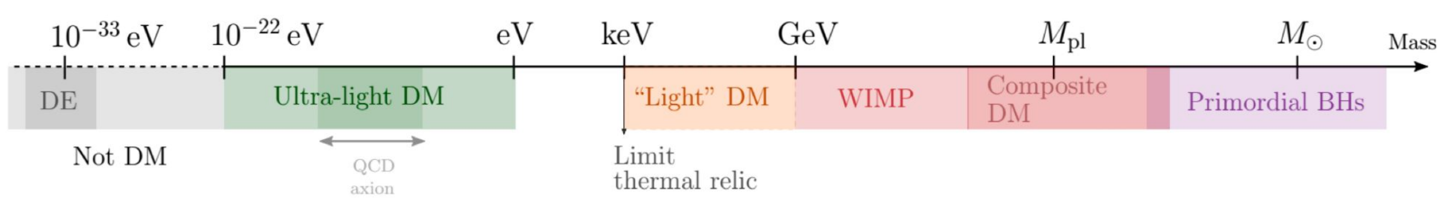


Fig. 2. From [1]. Mass scale for different classes of DM models.

## Ultra-Light Dark Matter

The smallness of the ULDM mass provide it with a de Broglie wavelength, $\lambda_{dB} \approx 1/mv$, of the order of galaxies size. This implies that ULDM manifest a wave behavior inside galaxies and a CDM-like behavior on scales $\lambda \gg \lambda_{dB}$.

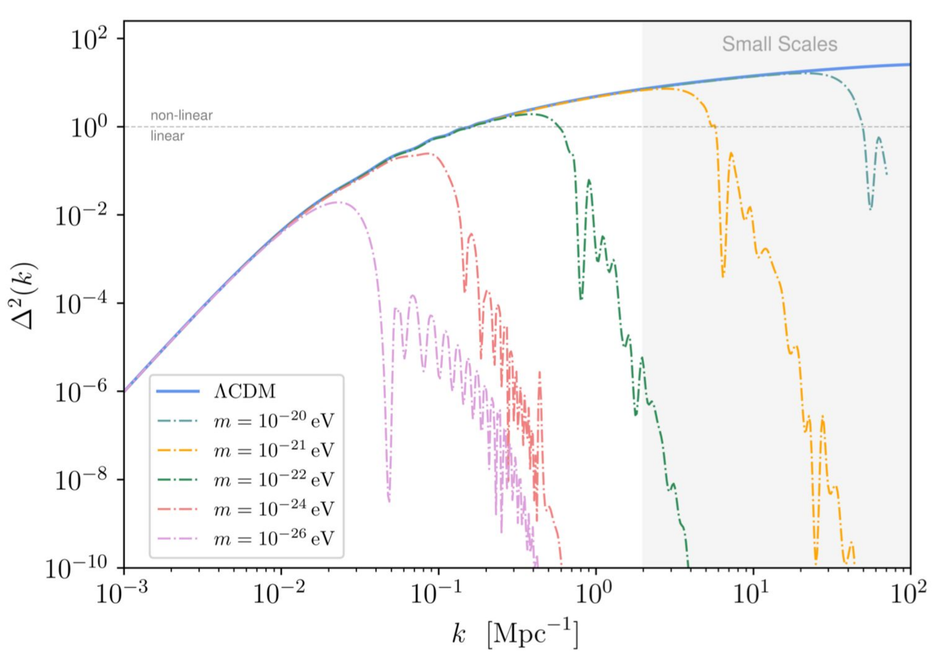


Fig. 3 From [1]. The matter power spectrum suppression for a scalar and non-interacting ULDM model (fuzzy dark matter).

This wave behavior is related with the manifestation of the quantum pressure of these particles, what weakens its gravitational collapse in small scales. **This implies that ULDM models suppress the matter power spectrum in small scales.** Moreover, the ULDM models present other signatures, as the presence of cores and interference patterns in the distribution of DM inside galaxies.

## Barrier for Parameter Inference

The main goal of our project is to use observations to bound fundamental properties of ULDM models, as spin, mass and self-interactions. To do so with cosmological measurements as the matter and the cosmic microwave background (CMB) power spectra it is necessary to make robust statistical analysis.

These analysis require the repeated calculation of the models predictions, scanning the corresponding parameter space. Predictions of the power spectra can be easily obtained with the Boltzmann codes CAMB (Lewis et al., 2011) and CLASS (Blas et al., 2011). However, for ULDM models, the Boltzmann codes take few minutes to compute them just once. **This long time turn unfeasible to use CAMB or CLASS to do parameters inference for ULDM models.**

## Emulation Strategy

Our strategy to overcome this cost barrier is to **replace the Boltzmann codes by an emulator during parameters inference**. This emulator is meant to use previous results to learn the dependence of the theoretical predictions on model parameters. From this, it should be able to provide the theoretical predictions in a much faster way than de Boltzmann codes.

## Neural Networks

Emulators may be based on different types of algorithms. One of the most common are Neural Networks (NNs), which are machine learning algorithms organized in layers and nodes [2]. The nodes, also called as neurons, receive a set of numbers as input and return a function of the linear combination of those numbers.

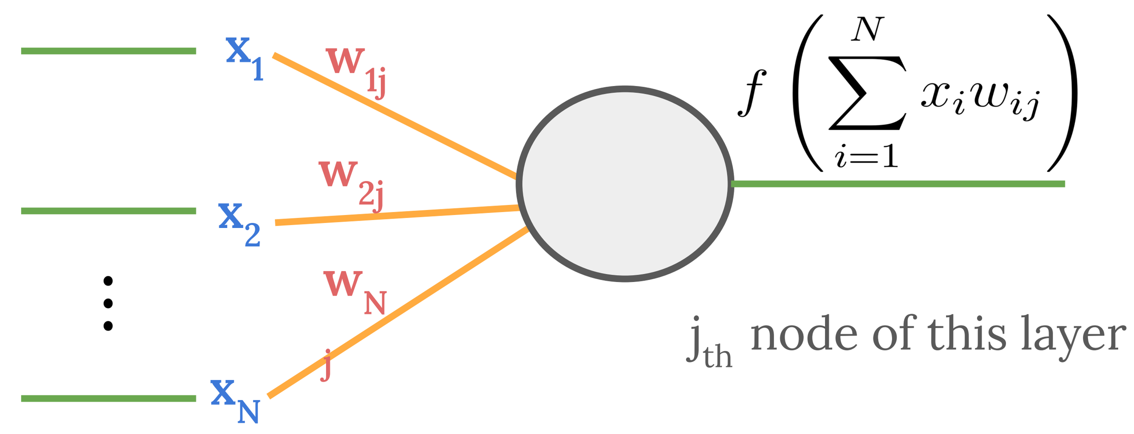


Fig. 3. Node scheme.

Each $x_i$ factor corresponds to the $i_{th}$ initial input given to the network (for the first layer) or to the output of the $i_{th}$ node of the previous layer. The $w_{ij}$ factors are known as **weights**. The function $f$ is called **activation function** and it is chosen depending on the purpose of the network.

Given an input-output example set of the function one wants to emulate, the **training** of the NN corresponds to fit the weights $w_{ij}$ in such a way that the **loss function** is minimized. The loss function quantifies how far from the target function the NN prediction is. One common choice of loss function is the mean squared error [2],

$$MSE = \frac{1}{n}\sum_{i}^{n}[Y(\Theta_i) - \hat{Y}(\Theta_i, w)]^2 ,$$

where $Y(\Theta_i)$ is the value of the target function evaluated for the set of parameters $\Theta_i$ and $\hat{Y}(\Theta_i, w)$ is the NN prediction for the same $\Theta_i$, using the set of weights w. The factor n is the number of samples considered to calculate the MSE.

## Final Considerations

Recently, emulators are becoming common in cosmology. The `CosmoPower` [3] and `CosmicNet` [4] are examples of emulators based on NNs in the context of cosmology. However, as far as we know, there are no emulators for ULDM models available. So that, this project can play an important role in constraining ULDM models.

## References

[1] E. G. M. Ferreira, "Ultra-light dark matter," The Astronomy and Astrophysics Review, vol. 29, Sept. 2021.
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[3] A. Spurio Mancini et al., "Cosmopower: emulating cosmological power spectra for accelerated bayesian inference from next-generation surveys," MNRAS, vol. 511, p. 1771–1788, Jan. 2022.
[4] S. Günther et al., "Cosmicnet II: emulating extended cosmologies with efficient and accurate neural networks," Journal of Cosmology and Astroparticle Physics, vol. 2022, p. 035, Nov. 2022.

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