Hints for decaying dark matter from S_8 measurements

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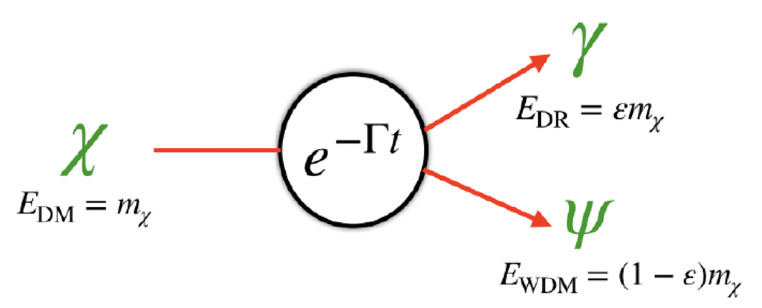
Recent weak lensing surveys have revealed that the direct measurement of the parameter combination $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ – where σ_8 is a measure of the amplitude of matter fluctuations on 8 h^{-1}Mpc scales – is $\sim 3\sigma$ discrepant with the value reconstructed from cosmic microwave background (CMB) data assuming the ΛCDM model. We show that it is possible to resolve the tension if dark matter (DM) decays with a lifetime of $\Gamma^{-1} \simeq 55$ Gyrs into one massless and one massive product, and transfers a fraction $\varepsilon \simeq 0.7$ % of its rest mass energy to the massless component. This has implications for DM model building, galactic small-scale structure problems and the recent Xenon-1T excess.

Basics of the 2-body decay

We consider 2-body decaying cold dark matter (**DCDM**), where the decay products are one massive warm dark matter (**WDM**) particle and one massless dark radiation (**DR**) particle. This framework adds two free parameters with respect to ΛCDM: the DCDM lifetime, Γ^{-1}, and the fraction of DCDM rest mass energy converted into DR,

$$\varepsilon = \frac{1}{2}\left(1 - \frac{m_{\rm wdm}^2}{m_{\rm dcdm}^2}\right),$$

where $0 \leq \varepsilon \leq 1/2$.



$\varepsilon = 0$ corresponds to ΛCDM
$\varepsilon = 1/2$ corresponds to decay solely into DR

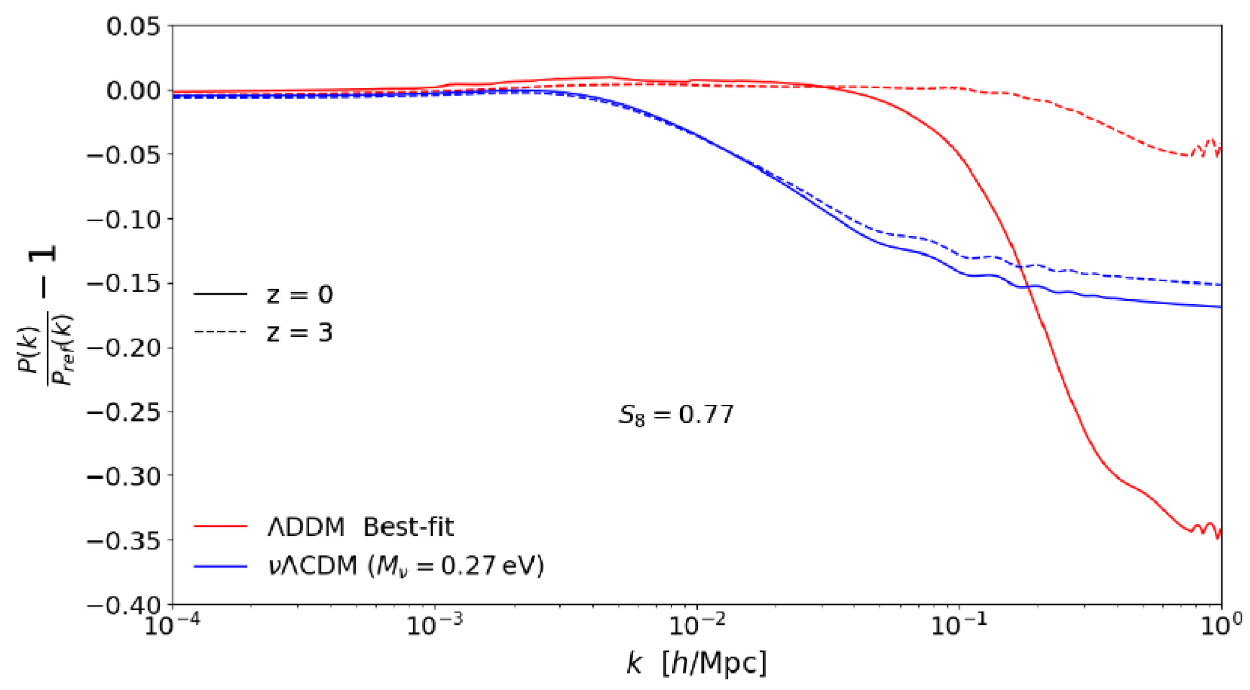
To describe the evolution of the DCDM, WDM and DR at the background and linear perturbation level, we use the Boltzmann formalism of [1]. The treatment of the WDM perturbations is very computationally expensive because one is forced to follow the evolution of the full phase-space distribution (PSD). To speed up the calculations, we use a **novel fluid approximation for the WDM**, which is based on a previous approximation for massive neutrinos [2]. In the synchronous gauge, the corresponding continuity and Euler equations read:

$$\dot{\delta}_{\rm wdm} = -3\mathcal{H}(c_s^2 - w)\delta_{\rm wdm} - (1+w)\left(\theta_{\rm wdm} + \frac{\dot{h}}{2}\right) + (1-\varepsilon)a\Gamma\frac{\bar{\rho}_{\rm dcdm}}{\bar{\rho}_{\rm wdm}}(\delta_{\rm dcdm} - \delta_{\rm wdm}),$$

$$\dot{\theta}_{\rm wdm} = -\mathcal{H}(1-3c_g^2)\theta_{\rm wdm} + \frac{c_s^2}{1+w}k^2\delta_{\rm wdm} - k^2\sigma_{\rm wdm} - (1-\varepsilon)a\Gamma\frac{1+c_g^2}{1+w}\frac{\bar{\rho}_{\rm dcdm}}{\bar{\rho}_{\rm wdm}}\theta_{\rm wdm}.$$

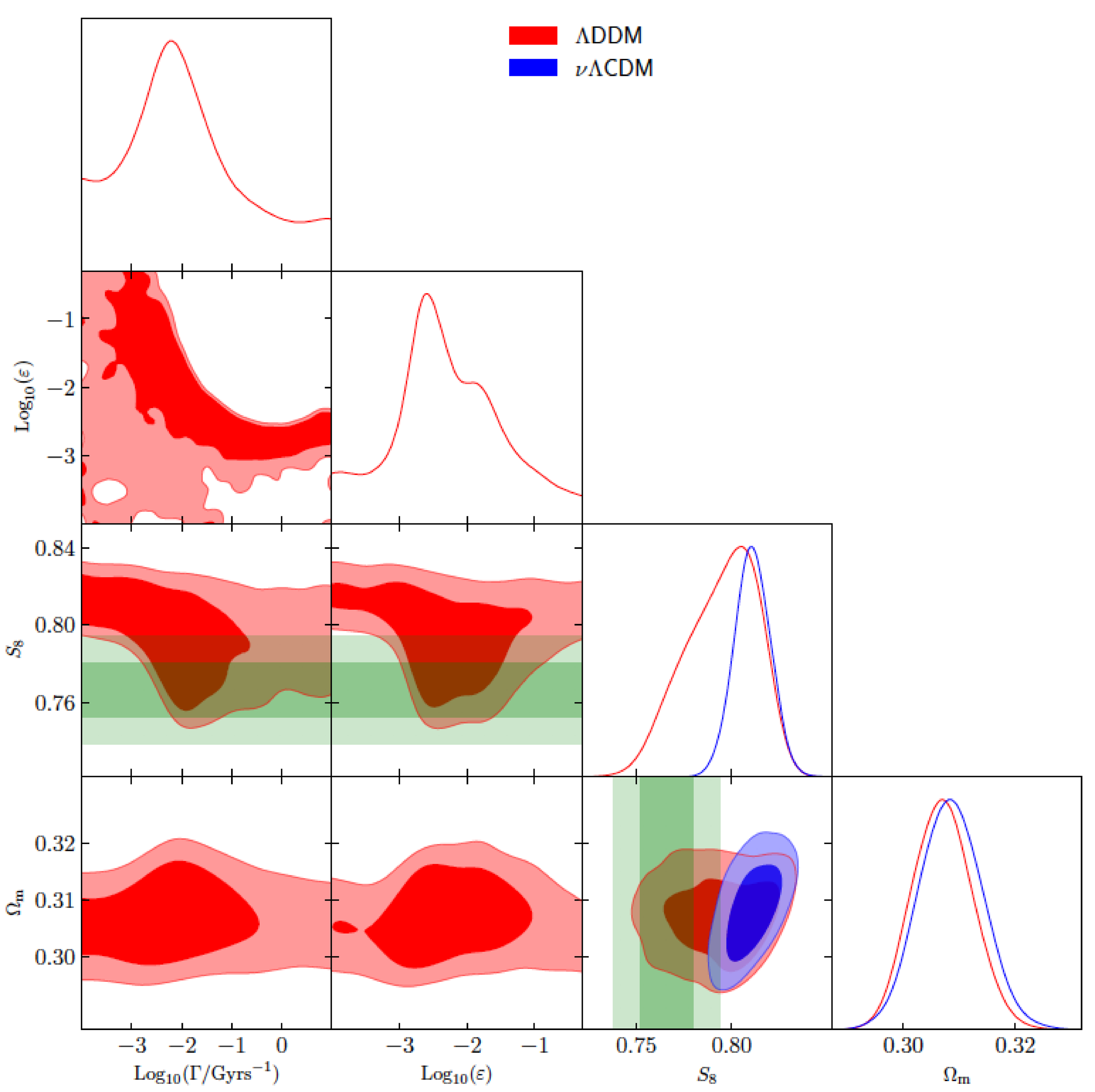
Impact on the matter power spectrum

In this decaying scenario (dubbed ΛDDM), the velocity kick received by the WDM leads to a **suppression** of gravitational clustering **below its free-streaming length**, thereby reducing the σ_8 value as compared to that inferred from the ΛCDM model, in a similar fashion to massive neutrinos and standard WDM.



Contrarily to the latter scenarios, the suppression of the matter power spectrum is much less significant at high z (since the abundance of WDM was smaller in the past), allowing the ΛDDM model to avoid many observational constraints.

Results of the Monte Carlo analysis



The ΛDDM model is fully characterized by 8 free parameters:

$$\{\Omega_b h^2, \ln\left(10^{10}A_s\right), n_s, \tau_{\rm reio}, \Omega_{\rm dcdm}^{\rm ini}, H_0, \log_{10}(\Gamma), \log_{10}(\varepsilon)\}.$$

We have implemented the DDM equations in our modified version of the Boltzmann solver `CLASS` [2]. We make use of the code `MONTEPYTHON-v3` [3] to perform the Monte Carlo Markov Chain analysis, testing the ΛDDM model against:

- The high-ℓ CMB TT, TE, EE + low-ℓ TT, EE+lensing data from **Planck** 2018
- The Baryon Acoustic Oscillations (**BAO**) measurements from 6dF, SDSS DR7, BOSS DR12 and eBOSS DR14 Ly-α
- The Pantheon supernova Ia (**SNIa**) catalogue
- The weak lensing measurements by **KiDS-1000+BOSS+2dFLens**, that we model as a split-normal likelihood on $S_8 = 0.766^{+0.02}_{-0.014}$

In order to gauge the importance of the late-time decay in the success of the resolution, we compare the ΛDDM model with another scenario that features a small-scale power supression, namely massive neutrinos ($\nu\Lambda$CDM), for which we vary the total neutrino mass M_ν on top of the six ΛCDM parameters.

In the ΛDDM scenario, we find that the best-fit has $\mathbf{\Gamma^{-1} \simeq 55(\varepsilon/0.007)^{1.4}}$ **Gyrs**, yielding $S_8 \simeq 0.77$ and $\Omega_m \simeq 0.31$, in excellent agreement with the KiDS-1000+BOSS+2dFLens measurement. On the contrary, the $\nu\Lambda$CDM model can only achieve $S_8 \simeq 0.81$, with $M_\nu < 0.161$ (95% C.L.).

The improvement in the fit can be confirmed by looking at the $\chi^2_{\rm min}$ difference :

$$\Delta\chi^2_{\rm min} = \chi^2_{\rm min}(\Lambda\mathrm{DDM}) - \chi^2_{\rm min}(\nu\Lambda\mathrm{CDM}) = -5.4$$

Sone promising implications

1. **Model building**: This kind of decays naturally arises in several Supergravity scenarios [4].
2. **Small-scale crisis of ΛCDM**: It has been shown that this class of decaying models leads to a reduction in the abundance of subhalos as well as their concentrations [5].
3. **Xenon-1T excess**: It has been recently pointed out that the Xenon-1T anomaly can be explained by a fast DM component, such as the WDM product of the 2-body decay [6].

Upcoming surveys, such as Euclid or LSST, measuring the growth rate $f\sigma_8$ at redshifts $0 \leq z \leq 1$ will be able to disentangle the 2-body DM decay from ΛCDM.

The next step will be to model non-linear effects.

References

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