Constraining dark matter decay with cosmic microwave background and weak-lensing shear observations

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Received 28 November 2022 / Accepted 12 February 2023

ABSTRACT

From observations at low and high redshifts, it is well known that the bulk of dark matter (DM) has to be stable or at least very long-lived. However, the possibility that a small fraction of DM is unstable or that all DM decays with a half-life time ($\tau$) significantly longer than the age of the Universe is not ruled out. One-body decaying dark matter (DDM) consists of a minimal extension to the $\Lambda$CDM model. It causes a modification of the cosmic growth history as well as a suppression of the small-scale clustering signal, providing interesting consequences regarding the $S_8$ tension, which is the observed difference in the clustering amplitude between weak-lensing (WL) and cosmic microwave background (CMB) observations. In this paper, we investigate models in which a fraction or all DM decays into radiation, focusing on the long-lived regime, that is, $\tau \gtrsim H_0^{-1}$ ($H_0^{-1}$ being the Hubble time). We used WL data from the Kilo-Degree Survey (KiDS) and CMB data from Planck. First, we confirm that this DDM model cannot alleviate the $S_8$ difference. We then show that the most constraining power for DM decay does not come from the nonlinear WL data, but from CMB via the integrated Sachs-Wolfe effect. From the CMB data alone, we obtain constraints of $\tau \gtrsim 288$ Gyr if all DM is assumed to be unstable, and we show that a maximum fraction of $f = 0.07$ is allowed to decay assuming the half-life time to be comparable to (or shorter than) one Hubble time. The constraints from the KiDS-1000 WL data are significantly weaker, $\tau \gtrsim 60$ Gyr and $f < 0.34$. Combining the CMB and WL data does not yield tighter constraints than the CMB alone, except for short half-life times, for which the maximum allowed fraction becomes $f = 0.03$. All limits are provided at the 95% confidence level.

Key words. dark matter – cosmological parameters – gravitational lensing: weak – large-scale structure of Universe

1. Introduction

There is overwhelming evidence for the existence of dark matter (DM), but we still know very little about its nature and composition. DM most probably consists of one or several new particles, requiring an extension of the standard model (Bertone et al. 2005; Feng 2010). The bulk of these particles has to be rather cold, interacts weakly at most, and is stable over at least one Hubble time. However, small deviations from these assumptions remain possible. Furthermore, a multi-particle DM sector would allow sub-species to evade the requirements mentioned above. They might be hot, interact strongly, or be very unstable, for instance.

In this paper, we focus on the possibility that a fraction or all of the DM fluid decays into radiation via a simple one-body decay channel. The nature of this radiation component is not specified and is not relevant to our analysis. Decay into photons or other standard model particles would lead to constraints from the absence of an observable radiation signal in the sky, however, which would exceed the constraints provided here. We therefore implicitly assume a DM decay into dark radiation.

Recent weak-lensing (WL) surveys such as CFHTLenS (Heymans et al. 2012; Fu et al. 2014), KiDS (Kuijken et al. 2019; Giblin et al. 2021; Hildebrandt et al. 2021; Asgari et al. 2021, A21), HSC (Aihara et al. 2017, 2022; Hamana et al. 2020; Liu et al. 2022), and DES (The Dark Energy Survey Collaboration 2005; Abbott et al. 2022; Amon et al. 2022) have reported a mild but persistent difference of the clustering amplitude $\sigma_8$ of the cosmic microwave background (CMB) as measured by the Planck satellite (Planck Collaboration I 2020; Planck Collaboration VI 2020; Planck Collaboration V 2020). This difference is usually quantified with the combined $S_8$ parameter, which is defined as $S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$, with $\Omega_m$ being the total matter budget of the Universe. If a fraction of the DM were allowed to decay, the clustering signal at low redshift would be modified, which might provide a solution to the $S_8$ difference in principle, as was pointed out by Enqvist et al. (2015, E15), Berezhiani et al. (2015, Chudaykin et al. (2016) and Archidiacono et al. (2019). However, other authors have questioned these conclusions, showing that an agreement of the clustering amplitude between WL and the CMB cannot be easily achieved (Simon et al. 2022, S22; McCarthy & Hill 2022).

Independent of the $S_8$ difference, several works have focused on providing forecasts and constraints for the one-body decaying dark matter (DDM) model using a variety of data from Milky Way satellite counts (Mau et al. 2022), WL shear observations (E15; Enqvist et al. 2020, E20), and CMB data (S22). Most authors have focused on the assumption that all DM is unstable, while models with decaying sub-species as part of
2. Decaying dark matter model

The DDM consists of a minimal extension of the standard ΛCDM model, where DM particles, instead of being stable, decay into massless relativistic particles propagating at the speed of light. A phenomenological description of this model includes two parameters (in addition to those describing the ΛCDM model), namely the decay rate of the DM particles \( \Gamma \) and the fraction \( f \) of decaying to total DM budget. As a result, the matter is transformed into radiation affecting the background evolution of the Universe, that is,

\[
\begin{align*}
\rho_{\text{ddm}} &+ 3H\rho_{\text{ddm}} = -a\Gamma \rho_{\text{ddm}}, \\
\dot{\rho}_{\text{de}} & + 4H\rho_{\text{de}} = a\Gamma \rho_{\text{ddm}},
\end{align*}
\]

(1)

(2)

where derivatives are expressed with respect to conformal time, \( H \) is a conformal Hubble parameter, and \( \rho_{\text{ddm}} \) and \( \rho_{\text{de}} \) are background densities of decaying cold DM and dark radiation, respectively (see e.g. Hubert et al. 2021 for more details about the DM decay process). When only a fraction \( f \) of the total DM is allowed to decay, we define

\[
f = \Omega_{\text{ddm}, \text{ini}}/\Omega_{\text{dm}, \text{ini}}, \quad \Omega_{\text{dm}, \text{ini}} = \Omega_{\text{ddm}, \text{ini}} + \Omega_{\text{cdm}, \text{ini}},
\]

(3)

where \( \Omega_{\text{ddm}, \text{ini}}, \Omega_{\text{cdm}, \text{ini}}, \) and \( \Omega_{\text{dm}, \text{ini}} \) are the decaying, stable, and total DM abundances at a time \( t \ll \tau = 1/\Gamma \), that is, before the start of the decay process.

The background evolution of the Universe was modified as described in Eqs. (1) and (2). In particular, the source terms whose amplitudes are set by the decay rate \( \Gamma \) cause a decrease in the DM and an increase in radiation abundance. In Fig. 1 we show the evolution of the DM abundance between redshift 0 and 5 (solid lines). As expected, the DM abundance decreases towards low redshifts, whereas the amplitude of the effect depends on the decay rate \( \Gamma \). We also indicate the redshift range of the WL data from KiDS as well as the range of late-time integrated Sachs-Wolfe (ISW) effect as measured by Planck (see e.g. Nishizawa 2014). Both observables overlap with the regime in which the effects of DDM are most prominent, making them promising probes to constrain DM decays.

The decay process affects not only the background evolution of the Universe, but also the process of structure formation. Since the scale factor \( a \) evolves at a somewhat slower rate (compared to ΛCDM), the Universe is less evolved, and the clustering process is therefore delayed. We are therefore left with suppression of power at small scales at a given redshift (see Fig. 2, described in the next section). This suppression becomes more pronounced with high \( \Gamma \) and with large \( f \). Scenarios with \( \Gamma \rightarrow 0 \) and \( f \rightarrow 0 \) correspond to the ΛCDM model.

3. Modelling pipeline

In this section, we provide details of our modelling pipeline for both the CMB and the WL observables. We specifically focus on nonlinear clustering, including the effects from DM decay, and we discuss our implementations of baryonic feedback and intrinsic alignment.

3.1. Cosmic microwave background modelling

Although originating from the early Universe, the CMB temperature fluctuations provide strong constraints on reduced models, even for half-life times of the order of (or longer than) a Hubble time. The reason for this behaviour is the late-time ISW effect, which causes a modification of the large-scale CMB modes due to the gravitational redshifting of the CMB photons that pass through evolving potential wells. Following Nishizawa (2014), we can write the ISW spectrum as

\[
C_{l}^{\text{ISW}} = \frac{18}{\pi^2} \Omega_{m,0}^{2} H_{0}^4 \int dkP(k) \left[ \int dr HD(f_{\text{in}} - 1) j_{l}(kr) \right]^2, \quad (4)
\]

where \( D \) is the linear growth factor, and \( f_{\text{in}} = \frac{\Omega_{m,0}^{2}}{\Omega_{\text{dm},\text{ini}}} \) is the velocity growth rate. The cosmological dependence of the ISW effect is governed by the term \( HD(f_{\text{in}} - 1) \) and by the linear power spectrum. As discussed in Nishizawa (2014), the late-time ISW kernel starts to become important at \( z \sim 3-4 \) steadily increasing towards \( z \rightarrow 0 \) when the Universe becomes dominated by dark energy. In Fig. 1 we indicate the redshift range in which
the CMB signal becomes sensitive to the ISW effect with a pink arrow.

To model the CMB including the ISW effect, we relied on the publicly available Boltzmann code \textsc{Class}\footnote{https://github.com/lesgourg/class_public}, which comes with the option to include DM that decays into dark radiation. We modelled high-$\ell$ TT, TE, and EE power spectra of the \textit{Planck} 2018 CMB data using the lightweight version of the \textit{Planck} \textsc{plik} likelihood, called \textsc{plik\_lite} (\textit{Planck Collaboration XX 2016; Planck Collaboration V 2020}), and mimicked SimAll (EE for $2 \leq \ell < 30$) and Commander (TT for $2 \leq \ell < 30$) likelihoods with the prior imposed on the optical depth parameter $\tau_{\text{reio}}$ based on Eq. (4) of \textit{Planck Collaboration VI} (2020, P20b).

Even though this approximation was obtained for the $\Lambda$CDM scenario, the cosmological parameters recovered from CMB after one-body decay is included are very close to $\Lambda$CDM; see Tables B.1 and B.2. This allows for this approximation. Furthermore, Abellan et al. (2021) compared the results of \textsc{plik\_lite} and the full \textsc{Plik} likelihoods for the more general scenario of two-body decays (which makes our model as a limiting case) and reported that the retrieved parameters agreed well. The model parameters along with their prior ranges are listed in Table 1. To evaluate the likelihood, we used all 215 data points for TT (30 $\leq \ell \leq 2508$) and 199 data points for TE and EE (30 $\leq \ell \leq 1996$). We tested our inference pipeline for the $\Lambda$CDM model and obtain an agreement of $\sim 0.1\sigma$ compared to the findings of the \textit{Planck} Collaboration (see Appendix A and Fig. A.2 for more details).

### 3.2. Weak-lensing modelling

To model WL cosmic shear observables, we followed the approach of Schneider et al. (2022, Sch22), with some changes as specified below. Most notably, we used the Pycosmo package (Refregier et al. 2018; Tarsitano et al. 2020) combined with \textsc{Class} to calculate the WL shear power spectra. For the non-linear power spectrum, we relied on the revised halo model of Takahashi et al. (2012). We included massive neutrinos with a fixed mass of 0.06 eV following the recipe from P20b. For the intrinsic alignment component, we used the non-linear alignment model (NLA) introduced by Bridle & King (2007) and described in Hildebrandt et al. (2016).

In the following, we describe some other aspects of the modelling pipeline. We specifically focus on the implementation of DM decay, the handling of baryonic effects, and the connection to the band power data from KiDS.

#### 3.2.1. Decaying dark matter

To include the effects of one-body decay on the non-linear matter power spectrum, we used the fitting function of Hubert et al. (2021), which corresponds to a modified version of the fit from E15. The function is defined by the ratio $P_{\text{DDM}}(k,z)/P_{\Lambda\text{CDM}}(k,z) = 1 - \epsilon_{\text{nonlin}}(k,z)$, where

\begin{equation}
\frac{\epsilon_{\text{nonlin}}(k,z)}{\epsilon_{\text{lin}}(k,z)} = \frac{1 + a(k/\text{Mpc})^{-\beta}}{1 + b(k/\text{Mpc})^{-\gamma}} f, \tag{5}
\end{equation}

with the factors $a$, $b$, $p$, and $q$ given by

\begin{align*}
a(r,z) &= 0.7208 + 2.027 \left(\frac{\text{Gyr}}{\tau}\right) + 3.031 \left(\frac{1}{1 + 1.1z}\right) - 0.18, \\
b(r,z) &= 0.0120 + 2.786 \left(\frac{\text{Gyr}}{\tau}\right) + 0.6699 \left(\frac{1}{1 + 1.1z}\right) - 0.09,
\end{align*}

where $\tau$ is in Gyr.

### Table 1. Parameters and choices of priors employed in our MCMC analysis.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Acronym</th>
<th>Prior</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Initial) cold DM abundance</td>
<td>$\omega_c$</td>
<td>Flat</td>
<td>$[0.051, 0.255]$</td>
</tr>
<tr>
<td>Baryon abundance</td>
<td>$\omega_b$</td>
<td>Flat</td>
<td>$[0.019, 0.026]$</td>
</tr>
<tr>
<td>Scalar amplitude</td>
<td>$\ln(10^{10}A_s)$</td>
<td>Flat</td>
<td>$[1.0, 5.0]$</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>$h_0$</td>
<td>Flat</td>
<td>$[0.6, 0.8]$</td>
</tr>
<tr>
<td>Spectral index</td>
<td>$n_s$</td>
<td>Flat</td>
<td>$[0.9, 1.03]$</td>
</tr>
<tr>
<td>Optical depth</td>
<td>$\tau_{\text{reio}}$</td>
<td>Normal</td>
<td>$[0.0, 0.0056, 0.0086]$</td>
</tr>
<tr>
<td>Intrinsic alignment amplitude</td>
<td>$A_{\text{IA}}$</td>
<td>Flat</td>
<td>$[0.0, 2.0]$</td>
</tr>
<tr>
<td>Planck calibration parameter</td>
<td>$A_{\text{Planck}}$</td>
<td>Normal</td>
<td>$[0.0, 0.0025]$</td>
</tr>
<tr>
<td>First gas parameter (BECnu)</td>
<td>$\log_{10}(M_\gamma)$</td>
<td>Flat</td>
<td>$[11.0, 13.0]$</td>
</tr>
<tr>
<td>Second gas parameter (BECnu)</td>
<td>$\tau_\gamma$</td>
<td>Flat</td>
<td>$[2.0, 8.0]$</td>
</tr>
<tr>
<td>Stellar parameter (BECnu)</td>
<td>$\tau_\delta$</td>
<td>Flat</td>
<td>$[0.05, 0.40]$</td>
</tr>
<tr>
<td>Decay rate</td>
<td>$\log_{10}(\tau)$</td>
<td>Flat</td>
<td>$[-4.0, 1.13]$</td>
</tr>
<tr>
<td>Fraction of DDM</td>
<td>$f$</td>
<td>Flat</td>
<td>$[0.0, 1.0]$</td>
</tr>
</tbody>
</table>

**Notes:** Flat denotes a uniform prior within boundaries specified in the last columns. For the Gaussian prior (normal), we state the mean and standard deviation.

\begin{align*}
p(\tau, z) &= 1.045 + 1.225 \left(\frac{\text{Gyr}}{\tau}\right) + 0.2207 \left(\frac{1}{1 + 1.1z}\right) - 0.099, \\
q(\tau, z) &= 0.992 + 1.735 \left(\frac{\text{Gyr}}{\tau}\right) + 0.2154 \left(\frac{1}{1 + 1.1z}\right) - 0.056.
\end{align*}

The remaining function $\epsilon_{\text{lin}}(r,z)$ describes the redshift evolution of the suppression and is given by

\begin{equation}
\epsilon_{\text{lin}}(r,z) = \alpha \left(\frac{\text{Gyr}}{\tau}\right) \left(\frac{1}{(0.105z) + 1}\right)^\gamma, \tag{6}
\end{equation}

where $\alpha$, $\beta$, $\gamma$ are functions of $\omega_b$, $h$, and $\omega_m = \omega_b + \omega_{dm}$, that is,

\begin{align*}
\alpha &= (5.323 - 1.4644u - 1.391v) + (-2.055 + 1.329u) + 0.8672(u + 0.2682 - 0.359u)w^2, \\
\beta &= 0.9260 + (0.05753 - 0.02690)w + (-0.01373 + 0.006713)v, \\
\gamma &= (9.553 - 0.7806u) + (0.4884 + 0.1754)v + (-0.2512 + 0.07558)w^2.
\end{align*}

We defined $u = \omega_b/0.02216$, $v = h/0.6776$ and $w = \omega_m/0.14116$. The fitting function is able to reproduce results from N-body simulations with an error smaller than 1% up to $k = 13\hMpc^{-1}$ (Hubert et al. 2021). In order to calculate the DDM matter power spectrum at nonlinear scales, we multiplied the term $1 - \epsilon_{\text{nonlin}}$ with the $\Lambda$CDM power spectrum from the revised halo model of Takahashi et al. (2012).

In Fig. 2 we illustrate the effect of DDM on the linear (solid lines) and nonlinear (dashed lines) matter power spectrum. Different colours correspond to different decay rates ($\Gamma$) for a fixed $f = 1$ (left panel) and different fractions ($f$) for a half-life time $1/\Gamma = 13.5$ Gyr (right panel). In general, DM decay leads to a suppression of power towards small scales. This effect is amplified by nonlinear clustering. The power suppression can be understood by the fact that the clustering in the DDM model is delayed compared to $\Lambda$CDM, causing galaxy groups and clusters (which dominate the power spectrum signal) to form later.

#### 3.2.2. Baryonic feedback

Baryonic feedback effects play an important role in the WL signal (e.g. Chisari et al. 2018; van Daalen et al. 2020;...
Aricó et al. (2021). They lead to suppression of the matter power spectrum, which may be of similar shape to the suppression due to DDM (Hubert et al. 2021; Amon & Efstathiou 2022). In order to account for potential degeneracies between the DM and the baryonic sector, it is therefore particularly important to model baryonic effects in the DDM cases.

We used the emulator BCemu (Giri & Schneider 2021), which includes the effects of baryonic feedback on the matter power spectrum. BCemu is based on the baryonisation model described in Schneider & Teyssier (2015) and Schneider et al. (2019). It has seven free model parameters describing the specifics of the gas and stellar distributions around haloes, as well as one cosmological parameter that is the baryon ($f_b = \Omega_b/\Omega_m$). We fixed four of the seven parameters and only varied the gas parameters $\log_{10} M_g$ and $\eta_i$, as well as the stellar parameter $r_b$. Furthermore, the baryon fraction $f_b$ was varied in accordance with the cosmological parameters. This three-parameter model has been shown in Giri & Schneider (2021) to match the DDM cases.

From the angular shear power shown in Eq. (7), we calculated the band power spectrum following Joachimi et al. (2021). The angular shear power was shown in Eq. (7), where $A \in \{G, I\}$, $\chi$ is the comoving radial distance, and $f_k(\chi)$ is the comoving angular diameter distance. The window functions of the gravitational and intrinsic alignment components are given by

$$W_G^{(i)}(\chi) = \frac{3H_0^2\Omega_m}{2c^2} \frac{f_k(\chi)}{a(\chi)} \int_0^{\chi} d\chi' n_s^{(i)}(\chi') \frac{f_k(\chi' - \chi)}{f_k(\chi')},$$

$$W_I^{(i)}(\chi) = -A \frac{1}{1 + \chi^{(i)}(\chi)} \frac{H_0^2\Omega_m}{D(a(\chi))} n_s^{(i)}(\chi),$$

where $D(a)$ is the linear growth factor, and the $n_s^{(i)}$ terms correspond to the redshift distribution of source galaxies for each tomographic bin (i). The term $C_{\nu}^{\alpha \beta}$ was fixed to 0.0139, and $z_{\text{pivot}}$ was set to 0.3 (see Joachimi et al. 2011).

From the angular shear power shown in Eq. (7), we calculated the band power spectrum following Joachimi et al. (2021). We refer to Sch22 for more details about this procedure. The prescription for cosmic shear modelling above does not strictly rely on $\Lambda$CDM. In our case, all relevant changes to the modelling enter via modifications of the nonlinear matter power spectrum.

4. Model inference

We used the emcee package (Foreman-Mackey et al. 2013) with the stretch move ensemble method in our MCMC analyses. For the WL and the CMB setup, we assumed multivariate Gaussian likelihoods. The convergence of the chains was checked with the Gelman-Rubin criterion assuming $R_c < 1.1$ (Gelman & Rubin 1992). In the case of the CMB analysis, we used the covariance matrix provided alongside the Plk_lite likelihood. For the WL analysis, we relied on the band power covariance matrix published by the KiDS collaboration (Joachimi et al. 2021).

In Table 1 we provide a summary of all model parameters, including information about their priors. For the CMB analysis and the WL analysis, we sampled over 9 and 12 parameters, respectively. The combined chains contain 13 free parameters. We used flat priors for all cosmological parameters except for...
the optical depth \( \tau_{\text{esc}} \), for which we assumed a Gaussian prior with a mean \( \tau_{\text{esc}} = 0.0506 \) and standard deviation \( \sigma_{\tau} = 0.0086 \), as explained in Sect. 3.1. For cold DM abundance \( \omega_c \) and primordial power spectrum amplitude \( A_s \), we used a prior wide enough to be uninformative. In the DDM scenario, \( \omega_c \) stands for the initial cold DM abundance. In terms of CLASS input variables, we set \( \omega_{\text{cdm}} = (1 - f)\omega_c \) and \( \omega_{\text{ini, dcdm}} = f\omega_c \). In the case of the DDM scenario, \( \omega_c \) is not sensitive enough (\( \omega_c, \theta_s, n_s, \log_{10} M_\ast, \theta_2, \) and \( \eta_8 \)), we defined wide prior ranges following the analyses in A21 and Sch22. Regarding the baryonic parameters, the prior ranges are limited by the range of the emulator. They comfortably include all results from hydrodynamical simulations, however (Schneider et al. 2020a,b; Giri & Schneider 2021). For the Planck absolute calibration \( A_{\text{Planck}} \) we followed the suggestion of the Planck Collaboration\(^6\) and choose Gaussian prior \( N(1.0, 0.0025) \). The adopted intrinsic alignment model (NLA) assumes two free parameters \( A_{\text{IA}} \) and \( \eta_{\text{IA}} \) entering via Eq. (9) of Sect. 3.2.3. Following A21, for example, we set \( \eta_{\text{IA}} = 0 \), and kept only \( A_{\text{IA}} \) as a free parameter.

We ran six chains in total, three assuming a ΛCDM cosmology, and three including the possibility of DM decay. The three runs refer to the CMB alone, the WL alone, and the combined setup. The main results from these chains in terms of DM constraints and cosmology are shown in the next section. Further details are provided in Appendix B, where we list the best-fit values and errors for all the parameters involved in the MCMC analysis.

5. Results

The main goal of this paper is to constrain DM decays with Planck and KiDS-1000 data. However, before showing the obtained limits on the decay rate and the fraction of decaying to total DM, we discuss the effect of the DDM scenario on the \( S_8 \) difference.

In the left panel of Fig. 3, we show the posterior contours of the \( \sigma_8 - \Omega_m \) plane for our different data and modelling choices. For the case of ΛCDM, the results from KiDS and Planck are shown in black and blue, respectively. The best-fit values and 68% errors of the combined \( S_8 \) parameter are given by

\[
S_8 = 0.735^{+0.031}_{-0.024} \quad (\text{WL, ΛCDM}),
\]

\[
S_8 = 0.841 \pm 0.017 \quad (\text{CMB, ΛCDM}),
\]

corresponding to a difference of 3.0σ, which we obtained using the same conventional method as was used in A21 (see their Eq. (16)). These findings agree well with the original results from the KiDS (A21) and Planck (P20b) collaborations, as shown in the right panel of Fig. 3 and Appendix A.

The posterior contours of the DDM case are shown in yellow and green for Planck and KiDS, respectively. They do not show any visible shift with respect to the ΛCDM case, except that the KiDS contours become broader, especially towards lower values of \( \sigma_8 \) and \( \Omega_m \). We assume this to be the result of degeneracies between the baryonic and DDM parameters. Regarding the combined \( S_8 \) parameter, the best-fitting values and 68% errors are given by

\[
S_8 = 0.723^{+0.041}_{-0.027} \quad (\text{WL, DDM}),
\]

\[
S_8 = 0.841 \pm 0.017 \quad (\text{CMB, DDM}),
\]

yielding an \( S_8 \) difference of 2.7σ. This small decrease in the difference is not due to a better concordance of the \( S_8 \) values, but rather to a general increase in the error budget in the DDM case of the constraints derived from the WL data.

The above point can be further quantified by investigating the decrease in the minimum chi-squared (\( \chi^2_{\text{min}} \)) from the standard

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6 \url{https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/CMB_spectrum_%26_Likelihood_Code}
Table 2. Minimum $\chi^2$ values from inference with KiDS and Planck data separately as well as from the combined run.

<table>
<thead>
<tr>
<th></th>
<th>KiDS $\chi^2_{\text{min}}$ (ACDM)</th>
<th>Planck 2018 $\chi^2_{\text{min}}$ (DDM)</th>
<th>Combined $\chi^2_{\text{min}}$ (ACDM)</th>
<th>$\sqrt{Q_{\text{MAP}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2_{\text{min}}$</td>
<td>158.7</td>
<td>580.2</td>
<td>750.5</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{min}}$</td>
<td>0.0</td>
<td>$-0.1$</td>
<td>$-0.3$</td>
<td></td>
</tr>
<tr>
<td>$\Delta$ AIC</td>
<td>4.0</td>
<td>3.9</td>
<td>3.7</td>
<td></td>
</tr>
</tbody>
</table>

**Notes.** In the last column, the difference between the two datasets as viewed by difference in maximum a posteriori criterion. The last two rows show the difference of the minimum $\chi^2$ between the CDM and DDM models, subtracting the first from the second, and the balance of the goodness-of-fit improvement and the increase in the number of parameters using the Akaike information criterion.

ACDM to the DDM model. The change in the Akaike information criterion $\Delta \text{AIC} = \Delta \chi^2_{\text{min}} + 2(N_{\text{DDM}} - N_{\text{ACDM}})$, which compensates for the increase in the goodness of fit due to the increased parameter space, gives

\[
\Delta \text{AIC} = 4.0 \quad \text{(WL),} \tag{14}
\]

\[
\Delta \text{AIC} = 3.9 \quad \text{(CMB)} \tag{15}
\]

for the WL and the CMB case. In the definition of $\Delta \text{AIC}$, $\Delta \chi^2_{\text{min}}$ stands for the difference of $\chi^2_{\text{min}}$ between DDM and ACMD and $N_{\text{DDM}}$ ($N_{\text{ACDM}}$) denotes the number of free parameters in the DDM (ACDM) model. Although two more parameters, the decrease in $\Delta \chi^2_{\text{min}}$ is not sufficient in the DDM case compared to ACMD (models for which the increased number of free parameters is compensated for by the better goodness-of-fit result in $\Delta \text{AIC} < 0$).

We now turn our attention towards the constraints on one-body decay obtained by the CMB, WL, and combined datasets used in this paper. The two-dimensional constraints for the DDM parameters $\Gamma$ and $f$ are illustrated in Fig. 4. All limits are provided at the 95% confidence levels. The contours exhibit the expected hyperbolic shape, excluding the regime in the top right corner of high decay rates and larger fractions of decaying to total DM. The results from Planck (yellow contours) show much stronger constraining power than those from the KiDS data. This means that the ISW effect is currently more sensitive to DM decay than WL. However, this is likely to change in the near future due to new WL observations from Euclid (Hubert et al. 2021).

The combined CMB + WL constraints, shown as purple contours in Fig. 4, are comparable in strength to the CMB-only limits. The small differences between $f = 0.2–0.9$ are most likely caused by the inherent differences between the KiDS and Planck datasets. A similar behaviour has been reported by E15.

In Fig. 4 we compare our results to several recent studies from the literature. Because these studies only provide constraints using current data. For the limiting case of $f = 1$, we add other results from recent studies by Enqvist et al. (2015, E15; grey arrow), Enqvist et al. (2020, E20; red arrow), and Simon et al. (2022, S22; blue arrow). All results are provided at the 95% confidence level.
obtain limits of \( f < 0.34 \), \( f < 0.07 \), and \( f < 0.03 \) for the KiDS, Planck, and the combined analysis at the 95\% confidence level.

6. Conclusions

We have investigated the one-body DDM scenario and its effects on structure formation in the light of CMB TTTEEE data from Planck 2018 and the cosmic shear angular power spectra from the KiDS-1000 data release. The free parameters of the DDM model are the decay rate (\( \Gamma \)) and the decaying to total DM fraction (\( f \)).

We obtained new constraints on \( \Gamma \) and \( f \) from the CMB, from WL, and from the combined CMB + WL analysis. In agreement with previous results, we find that the CMB constraints are stronger than those from WL alone. This apparently surprising result is due to the ISW effect, which provides strong constraints on the late-time background evolution of the Universe.

For the limiting case of \( f = 1 \), we obtain \( \Gamma^{-1} \geq 288 \) Gyr, which is stronger than previous constraints from E15 and E20 and similar to the findings of S22. For high decay rates (\( \Gamma \sim H_0 \)), on the other hand, we find a limit on the decay to total DM fraction of \( f < 0.03 \), which is based on the combination of CMB and WL data. The CMB alone provides weaker constraints of \( f < 0.07 \).

Along with the derivation of new constraints on the one-body DDM scenario, we also investigated the effect of decay on the \( S_N \) difference reported for example by the KiDS collaboration (Heymans et al. 2012). At face value, we find a slight reduction of the difference from 3.0\( \sigma \) to 2.7\( \sigma \) from an ACDM to a DDM model. We showed, however, that this reduction is entirely caused by the increase in free parameters. Our maximum a posteriori probability analysis (MAP) yields no improvement from a ACDM to a DDM scenario.

We conclude that there is currently no evidence for a DM sector featuring one-body decay from matter to radiation. For most of the parameter space, current WL observations are not constraining enough to compete with the stringent limits obtained from the CMB radiation via the integrated Sachs-Wolfe effect. In the near future, however, results from stage-IV lensing surveys such as Euclid are expected to probe currently untested DDM scenarios.

Acknowledgements: This work is supported by the Swiss National Science Foundation under the grant number PCEFP2_181157. Nordita is supported in part by NordForsk.

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Schneider, A., Refregier, A., Grandis, S., et al. 2020a, JCAP, 04, 020
Simon, T., Abellán, G. F., Du, P., Poulin, V., & Tsai, Y. 2022, Constraining Decaying dark Matter with BOSS Data and the Effective Field Theory of Large-scale Structures
Appendix A: $\Lambda$CDM benchmark

We compared the results of our pipeline in the case of $\Lambda$CDM to the original results of KiDS collaboration A21 and to Sch22 using a similar approach of band power modelling. For brevity, we only present the $\Omega_m - \sigma_8$ contours shown in Fig. A.1. The difference in 1- and 2$\sigma$ contours is marginal compared to the original KiDS-1000 results. The most significant differences (to our best knowledge) arise from the choice of baryonic prescription; the KiDS-1000 pipeline uses the one-parametric HMCODE baryonic feedback model (Mead et al. 2015), while this work adopted a four-parametric (three baryonic parameters plus the baryon-to-matter ratio) version of BCemu (Giri & Schneider 2021). Compared with Sch22, the 68% and 95% confidence intervals are slightly more extended. The modelling pipelines, which otherwise are very similar, employ a different number of baryonic parameters, specifically, eight (seven baryonic parameters plus the baryon-to-matter ratio) in the case of Sch22 and four in this work. This results in broader posterior contours in the case of Sch22. Quantitatively, our results agree better with those of A21 at 0.2$\sigma$ for $\sigma_8$ and at the level of 0.1$\sigma$ for $\Omega_m$.

Fig. A.1. Comparison of $\Lambda$CDM posterior contours in the $\Omega_m - \sigma_8$-plane obtained in this work with two recent studies that modelled the cosmic shear band power signal.

In Fig. A.2 we show a comparison of our $\Lambda$CDM results with CMB Planck 2018 data and compare them to the result published in P20b (see Tab. 2, setup TT,TE,EE+lowE). We also included lowT at the top of this setup). We display all six inferred cosmological parameters centred on Planck values and normalized by Planck 1$\sigma$ confidence intervals, thus displaying $(x - \bar{x}_{\text{planck}})/\sigma_{x_{\text{planck}}}$ for a parameter $x$. Most of the parameters agree to $\sim$ 0.1$\sigma$. The largest discrepancy is observed for $n_s$ at the level of 0.6$\sigma$.

Fig. A.2. Values and 1$\sigma$ confidence intervals of cosmological parameters resulting from our $\Lambda$CDM analysis related to the values obtained by Planck Collaboration VI (2020, P20b), (TT,TE,EE+lowE). We also guide the eye by depicting the 1, 2, and 3$\sigma$ intervals as grey bands.

Appendix B: MCMC results

We present the detailed results of our MCMC analyses in Tab. B.1 ($\Lambda$CDM) and B.2 (DDM). In the top part of the tables, we show cosmological, baryonic, and DDM parameters directly sampled during the MCMC. The middle part displays the derived $\Omega_m$, $\sigma_8$ and $S_8$ values, and the bottom part is dedicated to the details about the MCMC statistics (priors, likelihoods, and $\chi^2$ values). A long dash indicates that a specific parameter is not relevant for a specific setup, and $\text{unconst}$ indicates unconstrained parameters.
Table B.1. The $\Lambda$CDM results of our MCMC analysis. We separately report individual results based on WL (KiDS-1000) and CMB (Planck 2018) data alone, as well as values inferred from the combined MCMC chain. We show the mean (best-fit) values of the sampled (top) and derived (middle) parameters and the obtained prior, likelihood, and $\chi^2$ values (bottom).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KiDS ACMD 68% limits</th>
<th>Planck ACMD 68% limits</th>
<th>KiDS + Planck ACMD 68% limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_c$</td>
<td>0.146($0.081^{+0.034}_{-0.056}$)</td>
<td>0.1208($0.12000$) ± $0.0014$</td>
<td>0.1182($0.11880$) ± $0.0012$</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>unconst($0.02455$)</td>
<td>0.02231($0.02236$) ± $0.00015$</td>
<td>0.02248($0.02253$) ± $0.00013$</td>
</tr>
<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>2.56($3.50^{+0.61}_{-0.80}$)</td>
<td>3.050($3.110$) ± $0.017$</td>
<td>3.039($3.069$) ± $0.017$</td>
</tr>
<tr>
<td>$h_0$</td>
<td>unconst($0.6041$)</td>
<td>0.6700($0.6734$) ± $0.0061$</td>
<td>0.6815($0.6799$) ± $0.0057$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>unconst($0.9377$)</td>
<td>0.9622($0.9640$) ± $0.0043$</td>
<td>0.9678($0.9668$) ± $0.0041$</td>
</tr>
<tr>
<td>$\tau_{reio}$</td>
<td>unconst</td>
<td>0.0566($0.0841$) ± $0.0083$</td>
<td>0.0540($0.0677$) ± $0.0077$</td>
</tr>
<tr>
<td>$A_{TA}$</td>
<td>0.75($0.89^{+0.33}_{-0.38}$)</td>
<td>-</td>
<td>0.63($0.44^{+0.25}_{-0.31}$)</td>
</tr>
<tr>
<td>$A_{\text{planck}}$</td>
<td>-</td>
<td>1.0005($1.0031$) ± $0.0025$</td>
<td>1.0003($1.0005$) ± $0.0025$</td>
</tr>
<tr>
<td>$\log_{10} M_c$</td>
<td>&lt; 13.1(12.6)</td>
<td>-</td>
<td>&gt; 13.8(15.0)</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>&lt; 5.45(2.23)</td>
<td>-</td>
<td>&gt; 5.88(7.74)</td>
</tr>
<tr>
<td>$\eta_s$</td>
<td>unconst($0.21$)</td>
<td>-</td>
<td>unconst($0.13$)</td>
</tr>
<tr>
<td>$\log_{10}(\Gamma \times \text{Gyr})$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$f$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.347($9.066^{+0.066}_{-0.11}$)</td>
<td>0.3189 ± $0.0087$</td>
<td>0.3043 ± $0.0070$</td>
</tr>
<tr>
<td>$S_8$</td>
<td>0.70($0.11^{+0.01}_{-0.13}$)</td>
<td>0.8154 ± $0.0080$</td>
<td>0.8029 ± $0.0073$</td>
</tr>
<tr>
<td>$\ln(\text{prior})$</td>
<td>5.99</td>
<td>7.88($0.76^{+12}_{-4.1}$)</td>
<td>13.9($12.9^{+10}_{-3.1}$)</td>
</tr>
<tr>
<td>$\ln(\text{ln}(\text{lik}_{\text{WL}}))$</td>
<td>$-81.3(-79.3)^{+1.2}_{-0.54}$</td>
<td>-</td>
<td>$-83.5(-83.3)^{+1.2}_{-1.0}$</td>
</tr>
<tr>
<td>$\ln(\text{ln}(\text{lik}_{\text{CMB}}))$</td>
<td>$-294.4(-290.1)^{+2.0}_{-1.1}$</td>
<td>$-295.7(-291.9)^{+2.8}_{-1.6}$</td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{\text{min}}$</td>
<td>158.7</td>
<td>580.2</td>
<td>750.5</td>
</tr>
</tbody>
</table>

Table B.2. The DDM results of our MCMC analysis. We separately report individual results based on WL (KiDS-1000) and CMB (Planck 2018) data alone, as well as values inferred from the combined MCMC chain. We show the mean (best fit) values of the sampled (top) and derived (middle) parameters and the obtained prior, likelihood, and $\chi^2$ values (bottom).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KiDS 1bDDM 68% limits</th>
<th>Planck 1bDDM 68% limits</th>
<th>KiDS + Planck 1bDDM 68% limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_c$</td>
<td>0.137($0.099^{+0.033}_{-0.063}$)</td>
<td>0.1209($0.12050$) ± $0.0014$</td>
<td>0.1184($0.11760$) ± $0.0011$</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>unconst($0.02205$)</td>
<td>0.02230($0.02236$) ± $0.00015$</td>
<td>0.02246($0.02258$) ± $0.00014$</td>
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<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>2.74($3.08^{+0.70}_{-0.91}$)</td>
<td>3.052($3.100$) ± $0.017$</td>
<td>3.039($3.089$) ± $0.017$</td>
</tr>
<tr>
<td>$h_0$</td>
<td>unconst($0.6074$)</td>
<td>0.6705($0.6719$) ± $0.0062$</td>
<td>0.6812($0.6849$) ± $0.0052$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>unconst($0.9480$)</td>
<td>0.9618($0.9628$) ± $0.0045$</td>
<td>0.9671($0.9685$) ± $0.0041$</td>
</tr>
<tr>
<td>$\tau_{reio}$</td>
<td>unconst</td>
<td>0.0572($0.0818$) ± $0.0084$</td>
<td>0.0536($0.0803$) ± $0.0082$</td>
</tr>
<tr>
<td>$A_{TA}$</td>
<td>0.73($0.82$)</td>
<td>0.841 ± $0.017$</td>
<td>0.64($0.51$) ± $0.27$</td>
</tr>
<tr>
<td>$A_{\text{planck}}$</td>
<td>-</td>
<td>1.0005($1.0001$) ± $0.0025$</td>
<td>1.0004($0.9994$) ± $0.0025$</td>
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<td>$\log_{10} M_c$</td>
<td>&lt; 13.0(12.8)</td>
<td>-</td>
<td>&gt; 13.9(14.76)</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>&lt; 5.64(2.60)</td>
<td>-</td>
<td>&gt; 5.85(7.67)</td>
</tr>
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<td>$\eta_s$</td>
<td>unconst($0.28$)</td>
<td>-</td>
<td>unconst($0.24$)</td>
</tr>
<tr>
<td>$\log_{10}(\Gamma \times \text{Gyr})$</td>
<td>&lt; $-2.24(-2.67)$</td>
<td>&lt; $-2.76(-2.67)$</td>
<td>&lt; $-2.68(-2.89)$</td>
</tr>
<tr>
<td>$f$</td>
<td>unconst($0.841$)</td>
<td>&lt; 0.603($0.116$)</td>
<td>&lt; 0.602($0.361$)</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.323($0.073^{+0.13}_{-0.15}$)</td>
<td>0.3189 ± $0.0087$</td>
<td>0.3023($0.0083^{+0.003}_{-0.007}$)</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.73($0.12^{+0.04}_{-0.027}$)</td>
<td>0.8154 ± $0.0080$</td>
<td>0.8020 ± $0.0072$</td>
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<td>$S_8$</td>
<td>0.723($0.041$)</td>
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<td>0.805 ± $0.015$</td>
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<td>4.94</td>
<td>15.4($10.1)^{+1.3}_{-0.42}$</td>
<td>12.8($7.8)^{+1.0}_{-0.40}$</td>
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<td>$\ln(\text{ln}(\text{lik}_{\text{WL}}))$</td>
<td>$-81.3(-79.4)^{+1.2}_{-0.59}$</td>
<td>-</td>
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</tr>
<tr>
<td>$\ln(\text{ln}(\text{lik}_{\text{CMB}}))$</td>
<td>$-294.5(-290.1)^{+2.1}_{-1.2}$</td>
<td>$-296.5(-292.2)^{+2.6}_{-1.7}$</td>
<td></td>
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<td>580.1</td>
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</tr>
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</table>