Probing an Interacting Dark Sector Model with Galaxy Cluster Abundance

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1. Motivation

Forecast the constraints on a beyond-CDM model from future galaxy cluster data (CMB-S4) combined with next generation weak lensing data (ngWL) like the ones we will get from Euclid or Rubin surveys. The reason to look into an interacting dark sector is

- to explore the properties of the dark sector,
- to address the S_8 tension.

2. Interacting Dark Sector

An interacting dark sector can be described by a non-abelian $SU(N)$ theory. The mapping between the particle physics properties of the model to cosmological parameters can be done using the **Effective field THeory Of Structure formation** (ETHOS) formalism [1]. Besides the equations describing ΛCDM components, extra equations are included for IDM and DR.

- IDM equations

$$\dot{\delta}_{\rm IDM} + \theta_{\rm IDM} - 3\dot{\phi} = 0\,, \tag{1}$$

$$\dot{\theta}_{\rm IDM} - c^2_{\rm IDM}k^2\delta_{\rm IDM} + \mathcal{H}\theta_{\rm IDM} - k^2\psi = \Gamma_{\rm IDM-DR}\left(\theta_{\rm IDM} - \theta_{\rm DR}\right)\,. \tag{2}$$

- DR equations

$$\dot{\delta}_{\rm DR} + \frac{4}{3}\theta_{\rm DR} - 4\dot{\phi} = 0\,, \tag{3}$$

$$\dot{\theta}_{\rm DR} - \frac{1}{4}k^2\delta_{\rm DR} + k^2\sigma^2_{\rm DR} - k^2\psi = \Gamma_{\rm DR-IDM}\left(\theta_{\rm DR} - \theta_{\rm IDM}\right)\,. \tag{4}$$

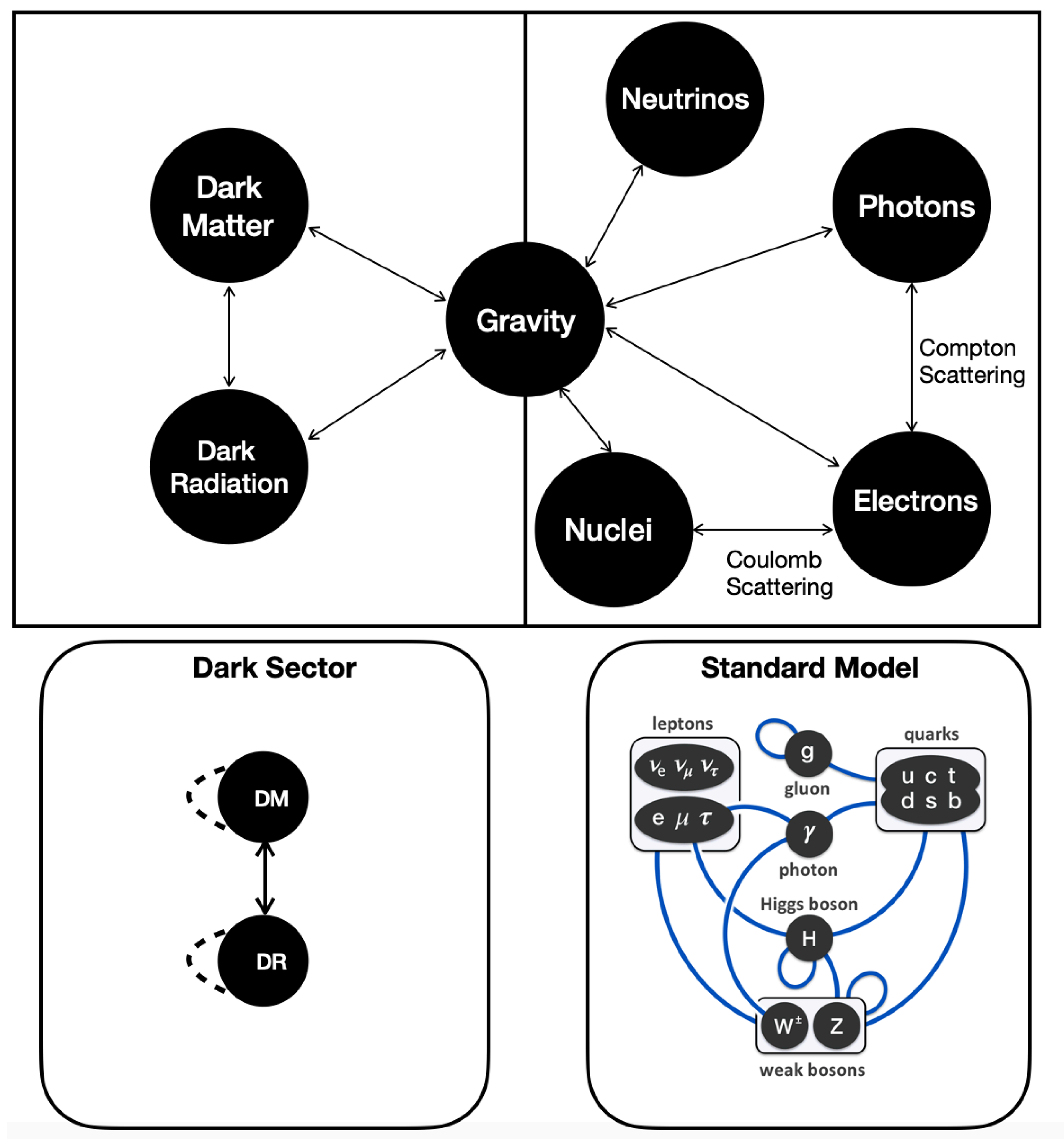

Figure 1: Schematic description of the Universe with an interacting dark sector before recombination.

The main parameters describing this model are

- $\xi_{\rm DR} \equiv \frac{T_{\rm DR}}{T_{\rm CMB}}\Big|_{z=0}$: temperature ratio, can be mapped to the density of DR,
- $f_{\rm IDM} \equiv \frac{\Omega_{\rm IDM}}{\Omega_{\rm IDM}+\Omega_{\rm CDM}}$: fraction of interacting dark matter,
- $a_{\rm dark}$: intensity of the interaction ($\Gamma_{\rm DR-IDM} \propto a_{\rm dark}$).

Due to the interaction with relativistic species (DR), IDM acquires momentum
→ can escape from over densities
→ suppresses the structure formation.

3. Generating Mockdata

To generate the mock catalog for each survey, we compute the matter power spectrum for a given model (ΛCDM or IDM–DR) with the Boltzmann solver CLASS [2]. The matter power spectrum is then used to calculate the HMF. We use the Tinker [3] simulation-based HMF in the mass range $M \in [10^{13}, 10^{16}]\,h^{-1}{\rm M}_\odot$. We generate mock data for two different benchmark cosmologies. The first ($Mock_{\rm IDM-DR}$) is based on the IDM–DR model with parameters chosen such that it is compatible with Planck 2018 data, and in addition yields a lower value of S_8 due to the interaction of DM with DR, close to those reported by weak-lensing shear measurements. We choose here to compare to the recent joint analysis of DES-Y3 and KiDS-1000 [4]. The second ($Mock_{\Lambda\rm CDM}$) is based on a ΛCDM model with input values chosen as the mean parameter posteriors from Planck 2018 temperature and polarization anisotropy without CMB lensing [5]. We take the overlapping region between CMB-S4 and the ngWL survey Euclid, which is roughly $\Omega_s = 10, 100\,{\rm deg}^2$ and even larger for Rubin. We find approximately 24,000 clusters for $Mock_{\rm IDM-DR}$ and 32,000 clusters for $Mock_{\Lambda\rm CDM}$.

4. Constraints

We show the constraints from CMB-S4×ngWL mockdata for the two benchmark points. All parameters are recovered within 1σ, and will allow us to reduce the uncertainty on S_8 by about a factor of two compared to CMB data from Planck (with a relative error of 1% for clusters and 2.4% for Planck). For the case of *Mock*$_{\rm IDM-DR}$, CMB-S4×ngWL will be able to recover the value of $\xi_{\rm DR}$ with a relative error of $\sim 13\%$ (Fig. 2). For $Mock_{\Lambda\rm CDM}$, the degeneracy between $\xi_{\rm DR}$ and S_8 is lefted, and we get an upper bound on the temperature ratio $\xi_{\rm DR}$ (Fig. 3).

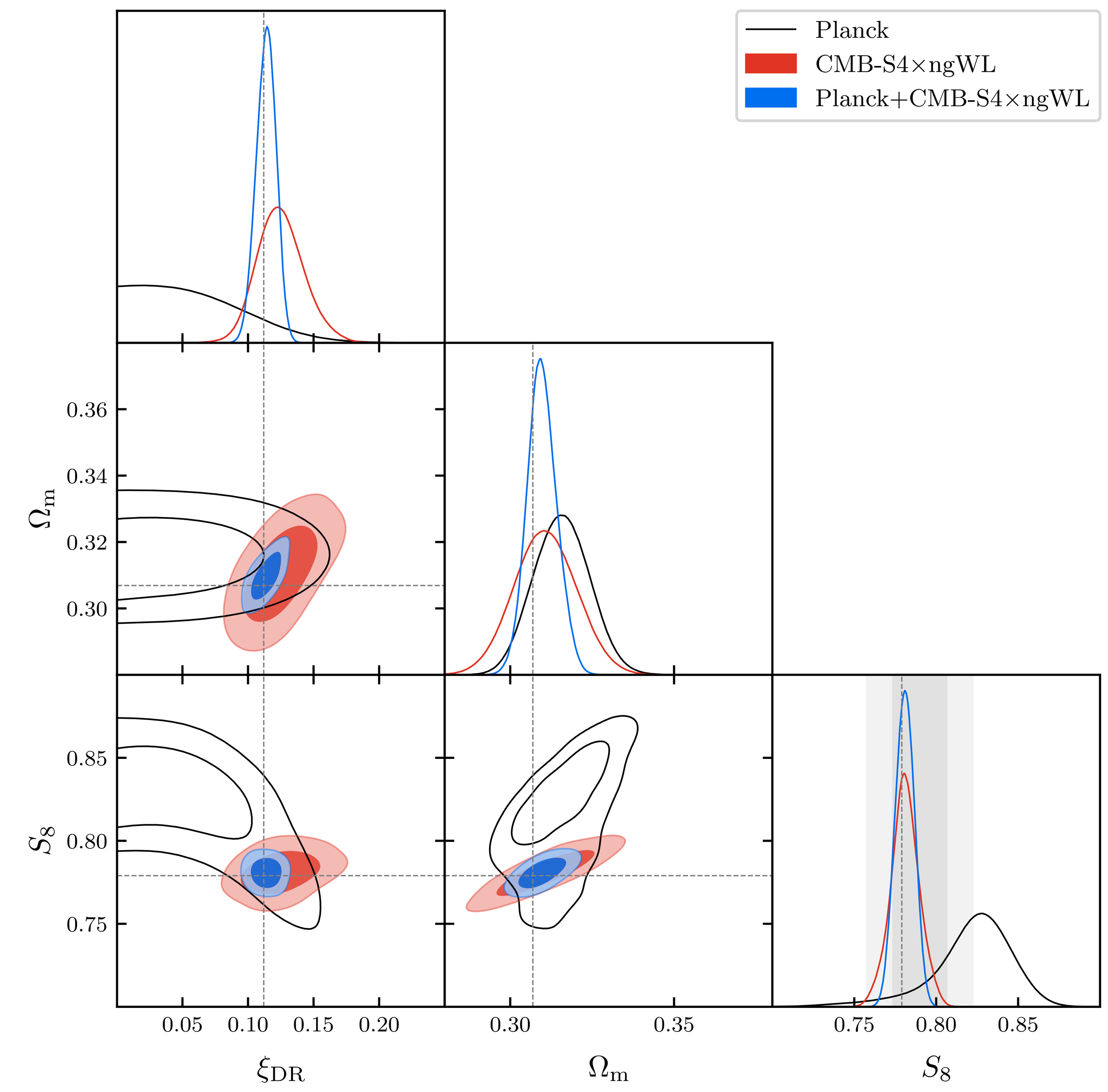

Figure 2: Posteriors within the IDM–DR model when assuming the *Mock*$_{\rm IDM-DR}$ benchmark model. The gray shaded area refers to the results from the joint analysis of DES-Y3 and KiDS-1000 [4], and the dotted lines refer to the input values of the benchmark model used to generate the mockdata.

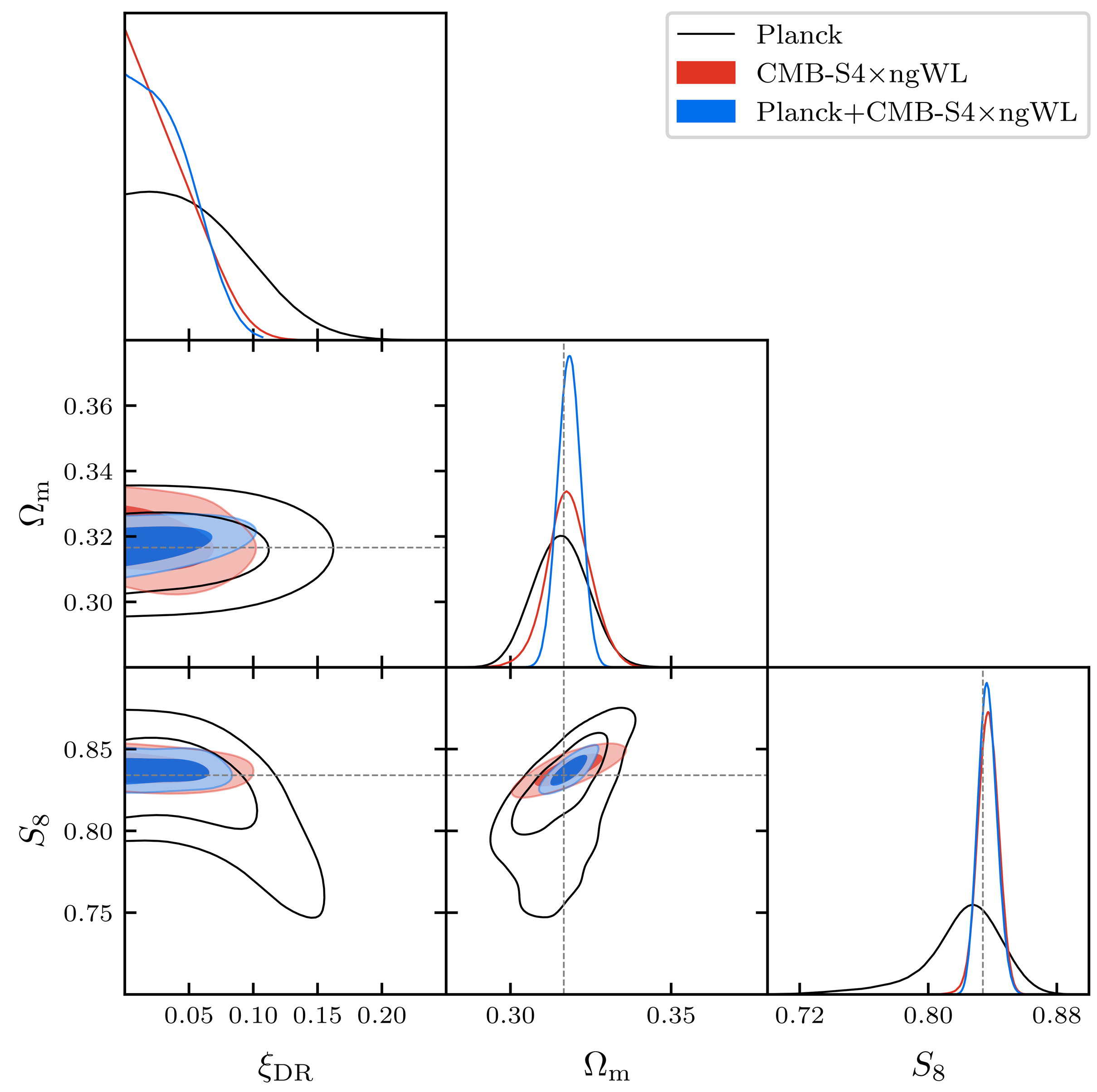

Figure 3: Posteriors within the IDM–DR model when assuming the $Mock_{\Lambda\rm CDM}$ benchmark model.

5. Conclusion

We forecasted the constraints on an interacting dark sector from future galaxy cluster data combined with next generation weak lensing data for mass calibration (CMB-S4×ngWL). We found that cluster abundance will be able to distinguish between the two models (IDM–DR and ΛCDM), and measure S_8 at a percent level, which means it will offer a definitive answer about the tension.

References

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