S_8 Tension in the Context of Dark Matter-Baryon Scattering

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Abstract

We explore an interacting dark matter (IDM) model that allows for a fraction of dark matter (DM) to undergo velocity-independent scattering off of baryons. In this scenario, structure on small scales is suppressed relative to the cold DM scenario. Using the effective field theory of large-scale structure, we perform the first systematic analysis of BOSS full-shape galaxy clustering data for the interacting scenario, and we find that this model alleviates the S_8 tension between large-scale structure (LSS) data and *Planck* CMB data. Adding the S_8 prior from DES in our analysis further leads to a mild ~3σ preference for non-vanishing DM-baryon scattering, assuming ~10% of DM is interacting and has a particle mass of 1 MeV. This scenario is consistent with other small-scale structure observations, and produces a modest ~20% suppression of the linear power at k ≲ 1 h/Mpc. Our results can be interpreted as a pointer to the early-time power suppression on small scales as a desirable and generic feature that may have the potential to resolve S_8 tension between cosmological data sets. The validity of the specific interacting DM model explored here will be critically tested with incoming survey data.

Introduction

- Under the ΛCDM model, observations that probe different points in cosmic history currently disagree on the inferred values of H_0 and the amplitude of density fluctuations at late times, quantified by S_8 (Abdalla et. al. 2022).
- These cosmological tensions could be a consequence of unknown systematic errors, or an indication that new physics beyond ΛCDM is needed to correctly model the early and the late universe simultaneously.
- We consider a simple extension of ΛCDM that includes elastic scattering between DM and baryons, present in a number of compelling DM models (Sigurdson et. al. 2004, Dvorkin et. al. 2014, Gluscevic et. al. 2018, Boddy et. al. 2018). In IDM cosmology, DM particles exchange heat and momentum with Standard Model particles. The resulting drag and collisional damping of matter perturbations lead to a scale-dependent suppression of structure, illustrated in Fig. 1.
- We derive the first bounds on the DM-baryon elastic scattering cross section from LSS data, using galaxy clustering measurements from BOSS and an S_8 prior from DES. Taking both Lyman-α forest measurements and MW satellite measurements into account, the suppression of power from 0.2 < k < 2 h/Mpc is only allowed up to 25%. We thus focus on IDM scenarios where only a fraction of DM particles feature interactions with baryons and the corresponding fraction of DM density fluid undergoes collisional damping, while the rest of DM is collisionless.

Methodology

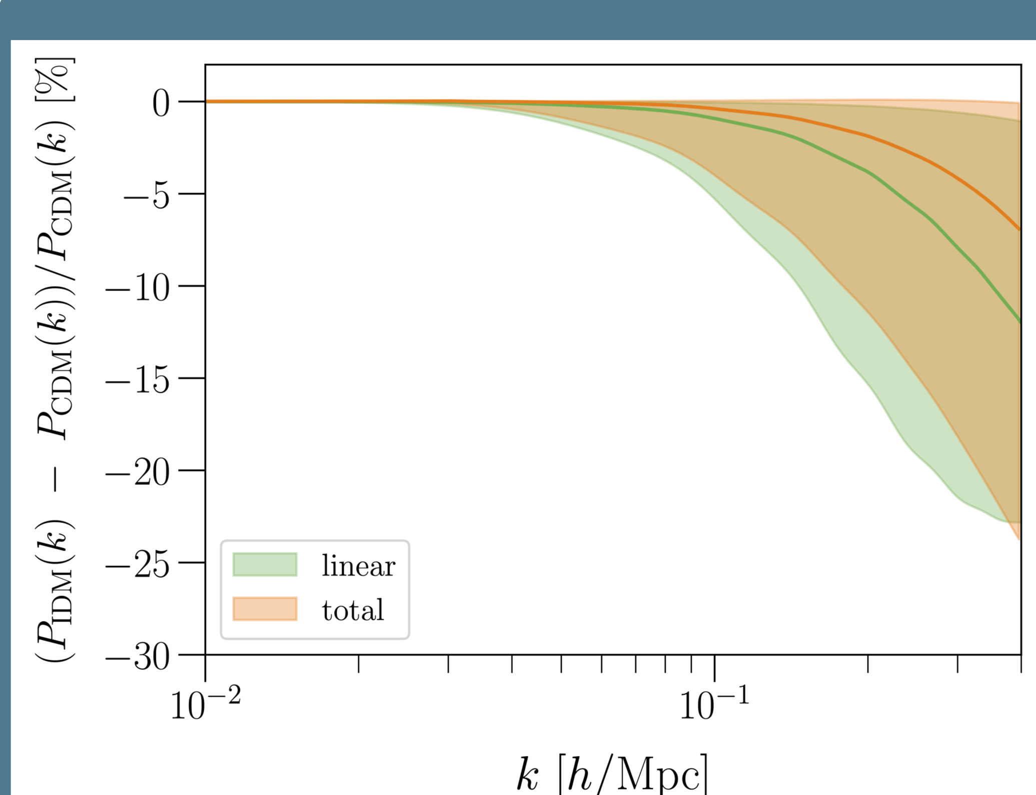

FIGURE 1. Percent difference between the matter power spectrum for an IDM cosmology with DM-baryon scattering and collisionless CDM cosmology. The linear power spectrum is shown in green, and the total power spectrum is shown in orange.

Within an IDM cosmology that features elastic scattering between DM and baryons, the linear Boltzmann equations contain interaction terms that capture momentum transfer between the two cosmological fluids:

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2}, \qquad \dot{\delta}_{\rm b} = -\theta_{\rm b} - \frac{\dot{h}}{2},$$
$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_{\rm b} - \theta_\chi),$$
$$\dot{\theta}_{\rm b} = -\frac{\dot{a}}{a}\theta_{\rm b} + c_{\rm b}^2 k^2 \delta_{\rm b} + \frac{\rho_\chi}{\rho_{\rm b}} R_\chi(\theta_\chi - \theta_{\rm b}) + R_\gamma(\theta_\gamma - \theta_{\rm b}),$$

where subscripts χ and b denote DM and baryons, respectively; *δ* denotes density perturbations, *θ* rep resents velocity divergence; *h* is the trace of the scalar metric perturbation; *c* represents the sound sp eeds in respective fluids; R_γ is the momentum transfer rate between baryons and photons from Compton scattering; and R_χ is the momentum transfer rate between DM and baryons from their non-gravitational interaction:

$$R_\chi = \frac{a c_n \rho_{\rm b} \sigma_0}{m_\chi + m_{\rm b}} \left(\frac{T_\chi}{m_\chi} + \frac{T_{\rm b}}{m_{\rm b}} + \frac{V_{\rm RMS}^2}{3} \right)^{-\frac{n+1}{2}},$$

where m_χ is the DM particle mass, m_b is the mean baryon mass among protons, electrons, and Helium, *T* denotes fluid temperatures, and V_{RMS} is the root-mean-square bulk relative velocity between DM and baryons.

To solve the Boltzmann equations of presence of IDM, we use a modified version of the Boltzmann solver CLASS, which allows for DM-baryon scattering parameterized by a momentum transfer cross section as $\sigma = \sigma_0 v^n$, where *n* = 0 in the case of velocity-independent scattering.

Methodology (cont.)

In order to make a prediction for late-time evolution of the matter power spectrum on scales corresponding to galaxy clustering, weak lensing, and related LSS observables, we merge the modified IDM CLASS code with a CLASS-PT module, previously developed as a tool for the computation of LSS power spectra in the mildly non-linear regime (Ivanov et. al. 2022). CLASS-PT is a non-linear perturbation theory extension of CLASS that calculates non-linear 1-loop corrections to the linear matter power spectrum, and outputs the redshift-space galaxy power spectrum (Chudaykin et. al. 2020).

Data sets analyzed:
- *Planck* 2018
  - Full TT, TE, EE, and lensing power spectra
- BOSS DR12
  - Anisotropic galaxy clustering data at z = 0.38 and 0.61
  - Galaxy power spectrum multipoles analyzed up to k_{max} = 0.2 h/Mpc
  - Real-space power spectrum proxy analyzed from 0.2 < k < 0.4 h/Mpc
  - Bispectrum monopole analyzed up to k_{max} = 0.08 h/Mpc
  - We also add the post-reconstructed BOSS DR12 BAO data to this dataset following Philcox et. al. 2020.
  - **We stress that our EFT-based full-shape analysis is quite conservative as we consistently marginalize over all necessary nuisance parameters that capture galaxy bias, baryonic feedback, non-linear redshift space-distortions, etc. Thus, our analysis is agnostic about the details of galaxy formation.
  - **Note that we fit the BOSS galaxy clustering data within the IDM scenario in a fully consistent and rigorous manner, without any hidden ΛCDM assumptions.
- DES-Y3
  - In the form of a prior on S_8: S_8 = 0.776 ± 0.017

We perform MCMC parameter estimation using our merged CLASS code. We use the MCMC sampler MontePython and interface it with our version of CLASS (Brinckmann et. al. 2018, Audren et. al. 2012). We choose the Metropolis-Hastings algorithm and assume flat priors on:

$$\{\Omega_b, \Omega_{DM}, 100\Theta_s, \tau_{reio}, \ln(10^{10}A_s), n_s\} + \sigma_0$$

We also run our analysis with a log prior on σ_0. Following Gluscevic et. al. 2018, we fix the IDM particle mass m_χ in each MCMC fit and consider the following benchmark particle masses: 100 keV, 1 MeV, 20 MeV, and 100 MeV. We choose this mass range because of the strict constraints on IDM from direct detection above 1 GeV, and constraints on N_{eff} that rule out masses lower than ~1 MeV (Lewin et. al. 1995, An et. al. 2022). We set the fraction of DM that interacts with baryons f_χ to be 10%, while the rest of the DM behaves as CDM. We model free-streaming neutrinos as two massless species and one massive species for which m_ν = 0.06 eV, in line with the *Planck* convention. A chain is deemed converged if the Gelman-Rubin convergence criterium |R-1| is less than 0.01.

Results

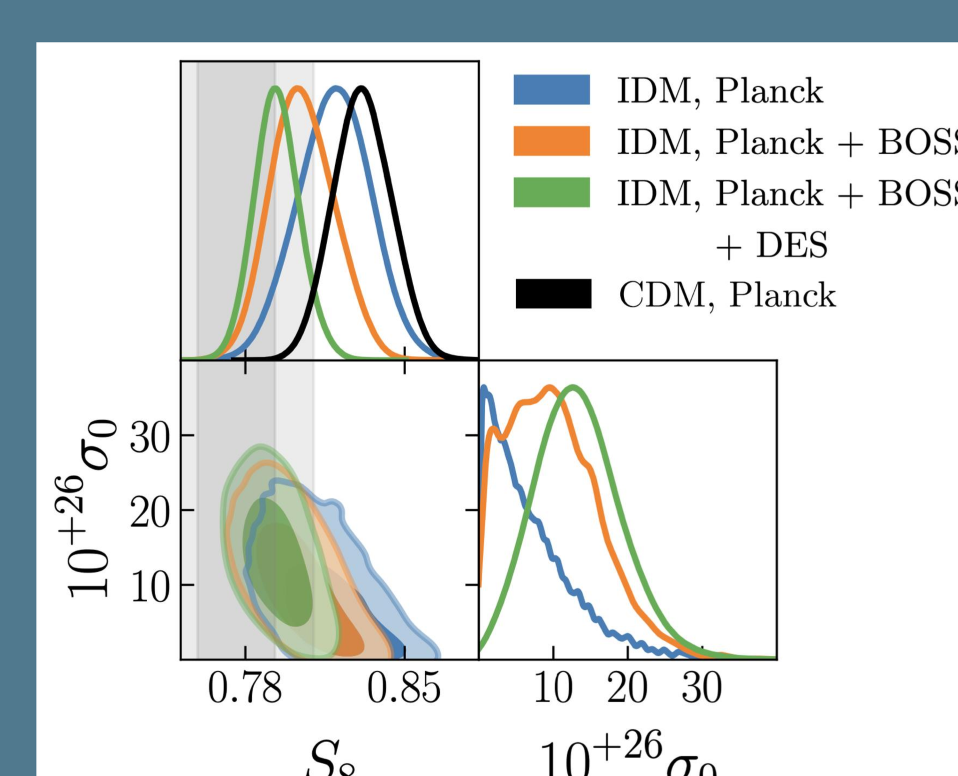

FIGURE 2. 1D and 2D marginalized posterior distributions for relevant parameters in our analysis of the m_χ = 1 MeV, f_χ = 10% IDM model, compared to standard results under ΛCDM.

We find that for all masses tested in the range [0.1, 100] MeV, our model alleviates the standard S_8 tension between *Planck* and DES by 30%, decreasing it from 2.6σ to 1.8σ, while leaving the H_0 tension unchanged. When *Planck* is combined with BOSS, our model reduces the S_8 tension with DES from 2.6σ to 1.3σ.

Model	ΛCDM, *Planck* + BOSS + DES	IDM, *Planck* + BOSS + DES
σ_0 [10^{-26} cm^2]	–	$13.23\ (5.163)^{+5.2}_{-6.5}$
S_8	$0.813\ (0.813) \pm 0.009$	$0.794\ (0.804)^{+0.009}_{-0.01}$
$\Delta\chi^2_{\rm min}$	–	−6.7

TABLE 1. Mean and best-fit values of relevant parameters from a *Planck* + BOSS + DES analysis of the f_χ = 10%, m_χ = 1 MeV model, as well as the χ2 statistics.

The f_χ = 10%, m_χ = 1 MeV IDM model:
- Presents a similar χ^2 value as LCDM when analyzed under *Planck* only
- However, $\Delta\chi^2$ = -3.48 under *Planck* + *BOSS* and $\Delta\chi^2$ = -6.7 under *Planck* + BOSS + DES, corresponding to a 2.6σ preference for non-zero interactions
- $\Delta\chi^2$ = -3.02 under BOSS only

We also find that our fractional IDM model shows a consistent preference over CDM, regardless of DM interacting fraction.

Discussion

Beyond the context of IDM, our results more generally point to the specific modification of the linear matter power spectrum (a power cutoff and a suppressed plateau at high k) which might be preferred by a combination of data and alleviate the S_8 tension. The difference in the overall power on small vs. large scales leads to a scale-dependent difference in the amount of structure, as compared to CDM; this is the key feature that allows this model to fit both LSS and CMB well, without incurring a discrepancy in other standard cosmological parameters.