The Integrated Sachs-Wolfe Effect in Interacting Dark Matter-Dark Energy Models

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Abstract

Interacting dark matter-dark energy models (IDMDE) can provide solutions to the current challenges that may affect cosmic structures. The main idea of such models is that the mass of dark matter particles can be specified by their interactions with a scalar field whose energy density is characterized by dark energy. In this work, we propose to study the integrated Sachs-Wolfe (ISW) effect in IDMDE models. To this end, we initially study a theoretical framework for IDMDE models. Moreover, we briefly discuss the stability conditions of IDMDE models. In the following, we calculate the ISW auto/cross-power spectrum for the IDMDE model and compare it with the corresponding result obtained from the ΛCDM model.

Keywords: Interacting Dark Sector; Integrated Sachs-Wolfe Effect; Power Spectrum; Cross-Correlation.

Theoretical Framework

In the background, a general coupling can be described by the energy balance equations of cold dark matter (c) and dark energy (x):

$$\rho_{\rm c}' + 3\mathcal{H}\rho_{\rm c} = -a^2 Q^0 = -aQ,$$
$$\rho_{\rm x}' + 3\mathcal{H}(1+\omega_{\rm x})\rho_{\rm x} = a^2 Q^0 = aQ, \tag{1}$$

where prime denotes derivative with respect to the conformal time τ, $a(\tau)$ is the scale factor, $Q \equiv Q^0/a$ is a coupling parameter, $\mathcal{H} = a'/a$ is the conformal Hubble parameter and $\omega_{\rm x} = p_{\rm x}/\rho_{\rm x}$ is the dimensionless parameter of the equation of state related to dark energy.

In this work, we choose a specific functional form of the energy density transfer rate as [1]

$$Q = 3H\xi(1+\omega_{\rm x})\rho_{\rm x}, \tag{2}$$

where ξ is the coupling parameter. The novelty of the selected form for the energy density transfer rate is that the model can alleviate large-scale perturbation instability if and only if the coupling parameter adheres to $\xi \geq 0$ [2].

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The ISW effect

When photons move into a gravitational potential well, they become blueshifted. On the other hand, they will be redshifted as they move out of the gravitational potential. The ISW signal is caused by a stretching effect that results from an imbalance between the structure growth and the cosmic expansion. The rise and fall of large-scale gravitational potentials along the paths of CMB photons in the late-time Universe leaves tiny secondary CMB temperature anisotropies on the primary CMB temperature fluctuations. Therefore, CMB photons can be studied to determine the cosmic acceleration and the structural growth rate.

The ISW-auto spectrum and the ISW-cross spectrum can be calculated respectively as follows [3]:

$$C_{\rm ISW}^{\rm TT}(l) = \int_0^{\chi_{\rm H}} \frac{W_{\rm T}^2(\chi)}{\chi^2}\frac{H_0^4}{k^4} P(k = \frac{l+1/2}{\chi})d\chi,$$
$$C^{\rm Tg}(l) = \int_0^{\chi_{\rm H}} \frac{W_{\rm T}(\chi)W_{\rm g}(\chi)}{\chi^2}\frac{H_0^2}{k^2} P(k = \frac{l+1/2}{\chi})d\chi, \tag{3}$$

where $P(k)$ is the present-time matter power spectrum, $k = (l+1/2)/\chi$ is the wavenumber obtained through the Limber approximation of the small angle, χ is the comoving distance, and $W_{\rm T}$ and $W_{\rm g}$ are the window functions.

The temperature anisotropy due to the ISW effect is specified by taking an integration on the time-varing quantity, $(\phi - \psi)$, along the line-of-sight

$$\Theta_{\rm ISW} = \frac{\Delta T}{T_{\rm CMB}}\bigg|_{\rm ISW} =$$
$$\frac{3}{c^3}\int_0^{\chi_{\rm H}} a^2 H(a)\frac{\partial \mathcal{F}(a)}{\partial a}\frac{\delta_{\rm m}(k, a=1)}{k^2}d\chi, \tag{4}$$

where $\mathcal{F}(a)$ is

$$\mathcal{F}(a) \equiv a^2 H^2(a)\Omega_{\rm m}(a)D_+(a). \tag{5}$$

References

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Results

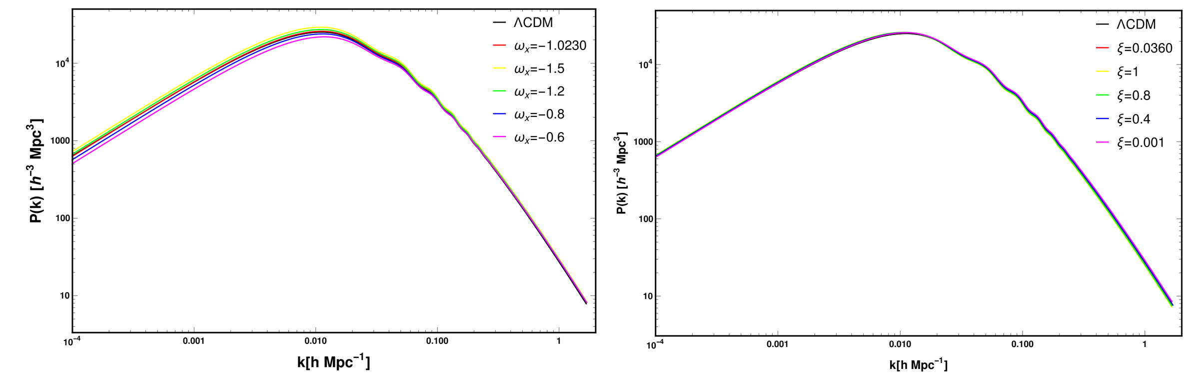

Figure 1: The matter power spectrum as a function of comoving wavenumber k for the IDMDE and ΛCDM models. **Left:** For different values of the dimensionless parameter of dark energy equation of state $\omega_{\rm x}$. **Bottom:** For different values of the coupling parameter ξ.

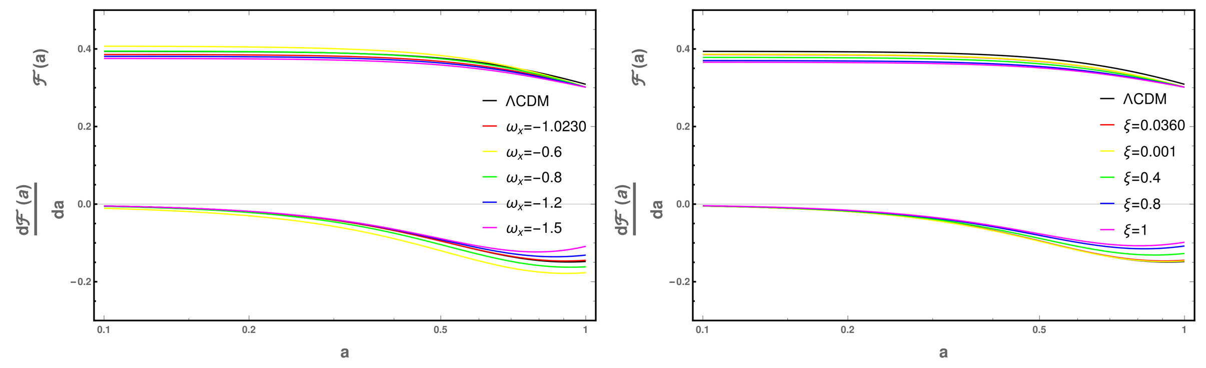

Figure 2: The time evolution $\mathcal{F}(a)$ of the ISW source term and its derivative $d\mathcal{F}(a)/da$ as functions of scale factor a, for the IDMDE and ΛCDM models. **Left:** For different values of the dark energy equation of state $\omega_{\rm x}$. **Right:** For different values of the coupling parameter ξ.

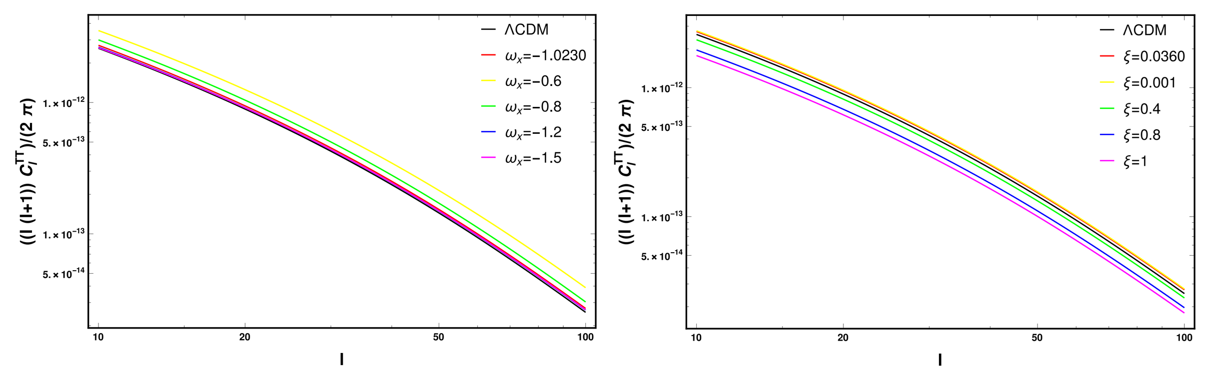

Figure 3: The amplitude of the ISW-auto power spectrum as a function of multipole order l for the IDMDE and ΛCDM models. **Left:** For different values of the dark energy equation of state $\omega_{\rm x}$. **Right:** For different values of the coupling parameter ξ.

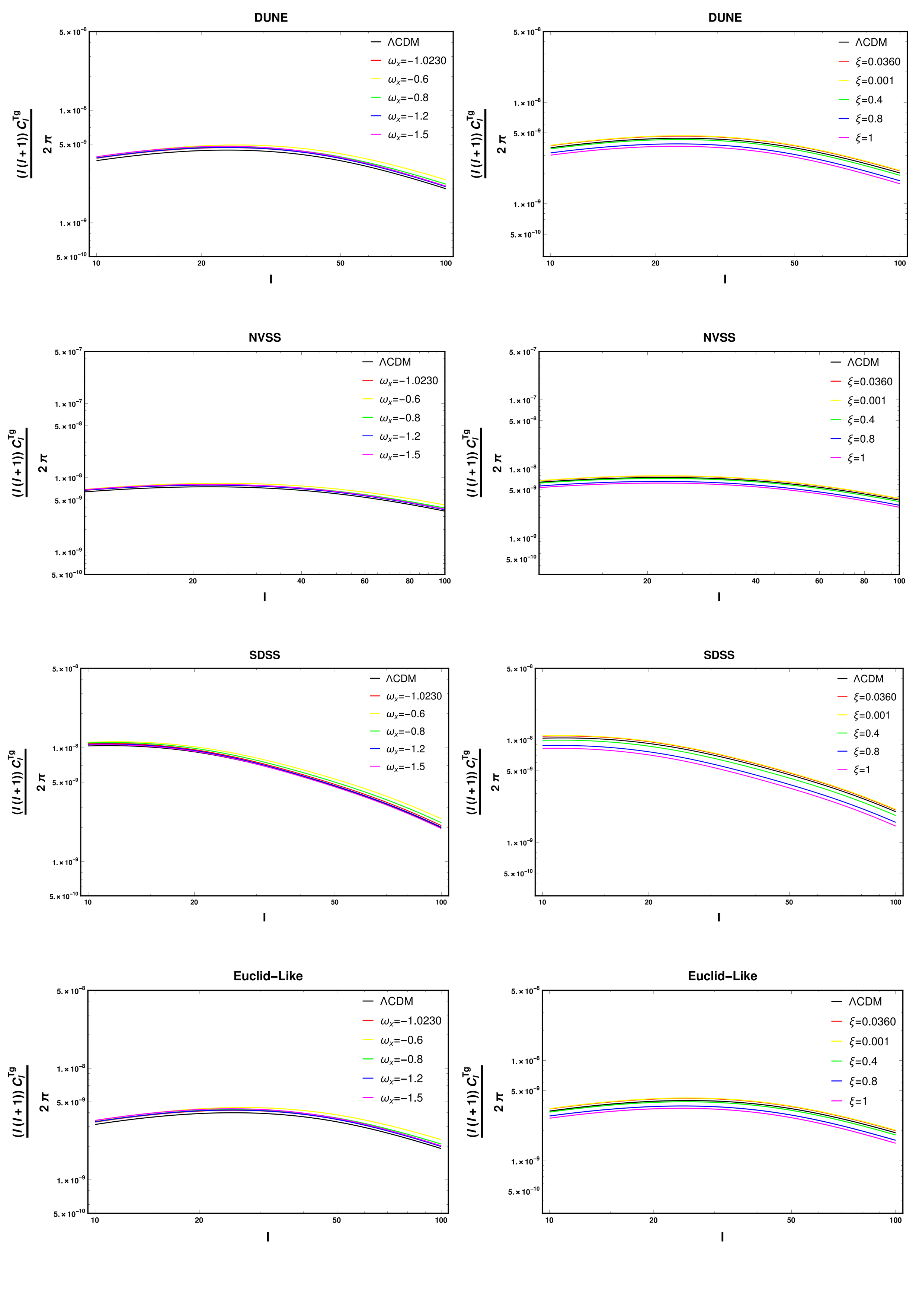

Figure 4: The amplitude of the ISW cross power spectrum as a function of multipole order l for the IDMDE and ΛCDM models for DUNE, NVSS, SDSS, and Euclid-like surveys. **Left:** For different values of the dark energy equation of state $\omega_{\rm x}$. **Right:** For different values of the coupling parameter ξ.

Conclusion

Because the gravitational potential is static during the matter-dominated era, the ISW signals would be negligible. Thus, as illustrated in Fig. 2, the ISW effect can only be explained by the transition to a dark energy-dominated era in the late-time Universe.

The results indicate that the amplitude of the ISW auto-power spectrum in the IDMDE model for different phantom dark energy equations of state behaves similar to the one for the ΛCDM model, whereas, for the quintessence, dark energy equations of state, the amplitude of the ISW-auto power spectrum for the IDMDE model should be higher than the one for the ΛCDM model. Also, it turns out that the corresponding results by different coupling parameter values demonstrate that ξ is inversely proportional to the amplitude of the ISW-auto power spectrum in the IDMDE model.

Finally, by employing four different surveys, we calculate the amplitude of the ISW-cross power spectrum as a function of multipole order l for the IDMDE model. The results exhibit that the amplitude of the ISW-cross power spectrum for the IDMDE model for all values of $\omega_{\rm x}$ is higher than the one obtained for the ΛCDM model, while deviations are still less than 0.1 order of magnitude. Also, it turns out that the amplitude of the ISW-cross power spectrum in the IDMDE model changes inversely with the value of coupling parameter ξ.