# Cosmological structure's growth rate in interacting dark sector models [1]

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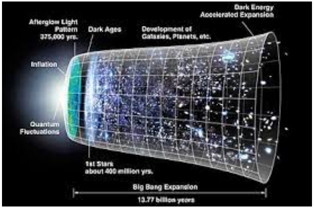
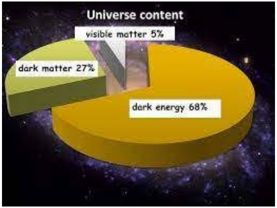
[1] in prep.

# Introduction




The simplest model to describe dark energy is associate it with a constant vacuum energy density $\rho_V$ characterized by equation of state parameter $w = -1$, equivalent to a cosmological constant in Einstein gravity [1]. The cosmological model that incorporates a constant vacuum energy plus cold dark matter in a homogeneous and isotropic universe is known as $\Lambda CDM$.

# Introduction

In this work we studied the effects of dark energy perturbations on the evolution of the dark matter growth rate $f$ in a decomposed Chaplygin gas model with interacting dark matter and dark energy. We consider two different cases:

(i) geodesic dark matter with homogeneous vacuum, and

(ii) a covariant ansatz for vacuum density perturbations.

Here we neglect the contributions of baryon and radiation components.

# Growth Function and Density Contrast

The growth rate of large scale structure can test if dark matter clusters or deviates from itself due to self interactions. The parametrization of the growth rate of matter perturbations is [2]

$$f = \frac{\dot{\delta}_m}{H\delta_m}. \quad (1)$$

And it depends of the density contrast

$$\delta_m \equiv \frac{\delta\rho_m}{\rho_m} = \frac{\rho_m(\vec{x},t) - \bar{\rho}_m(t)}{\bar{\rho}_m(t)} \quad (2)$$

where $\bar{\rho}_m(t)$ is the background energy density.

## Decomposed Chaplygin Gas

Using the continuity equation ($\dot{\rho} + 3H(\rho + p) = 0$) and the generalized Chaplygin gas (gCg) equation ($p = -\frac{A}{\rho^{\alpha}}$) [3] we have

$$\rho(t) = \left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{1}{(1+\alpha)}}, \tag{3}$$

where A is a constant, B is an integration constant and $\alpha$ is a free parameter.

- $(a \ll 1) \rightarrow \rho \propto a^{-3}$ (early times)
- $(a \gg 1) \rightarrow \rho \propto A^{1/(1+\alpha)}$ (late times).

So the gCg model can be thought as a mix of both dark energy and dark matter.

# The source term

Spliting the unified fluid into two components ($p_m = 0$ and $p_V = -\rho_V$) it is possible to write the continuity equation in the form

$$\dot{\rho}_m + 3H\rho_m = Q, \tag{4}$$

$$\dot{\rho}_V = -Q, \tag{5}$$

where the energy-momentum transfer $Q$ between the components is given by

$$Q = 6\alpha H_0(1 - \Omega_{m0})\left(\frac{H}{H_0}\right)^{-(2\alpha+1)}\dot{H}. \tag{6}$$

The sign of $Q$ depends of the sign of the gCg $\alpha$ parameter. Since $\dot{H} < 0$ we have two scenarios

- If $\alpha < 0 \to Q > 0$: vacuum energy decays into cold dark matter (particle creation),
- If $\alpha > 0 \to Q < 0$: cold dark matter decays into vacuum energy (particle annihilation).

# The source term

In the case where we have $\alpha = -0.5$ the vacuum energy density decays linearly with $H$, while dark matter is created at a constant rate. On the other hand, for $\alpha = 0$ we re-obtain the standard model with a cosmological constant and conserved matter.

# Geodesic perturbative model

We assume that the energy transfer between dark components follows the dark matter velocity, $Q^{\mu} = Qu^{\mu}$, and the momentum transfer $\bar{Q}^{\mu}$ is zero at background and perturbative levels, which implies $\delta\rho^{c}_{V} = 0$. The consequences is that the dark matter particles follows geodesics in a comoving frame. The main equation of the geodesic perturbative model is

$$\ddot{\delta}^{c}_{m} + \left[\frac{Q}{\rho_m} + 2H\right]\dot{\delta}^{c}_{m} + \left[\frac{d}{dt}\left(\frac{Q}{\rho_m}\right) + 2H\frac{Q}{\rho_m} - \frac{1}{2}\rho_m\right]\delta^{c}_{m} = 0 \qquad (7)$$

where the function $Q/\rho_m$ into the brackets is the creation/annihilation rate of dark matter.

# Inhomogeneous vacuum model

An alternative model is to consider inhomogeneities of the vacuum energy density ($\delta\rho_V^c \neq 0$). We have to assume the covariant version for the vacuum energy density, so the perturbation of this quantity up to second order is

$$\ddot{\delta}_m^c + \left[\frac{2Q}{3\rho_m} + 2H + \left(A - \frac{\dot{K}}{K}\right)\right]\dot{\delta}_m^c + \left[\frac{d}{dt}\left(\frac{2Q}{3\rho_m}\right) + 2H\left(\frac{2Q}{3\rho_m}\right) - \frac{1}{2}\rho_m K + \frac{2Q}{3\rho_m}\left(A - \frac{\dot{K}}{K}\right)\right]\delta_m^c = 0. \tag{8}$$

This equation allowed us to compute the evolution of dark matter perturbation. The factor 2/3 of the creation/annihilation rate of matter is due to the assumption of the vacuum energy perturbations.

# Inhomogeneous vacuum model

In the deeper matter dominated epoch ($z \gg 1$) the factor $H \gg Q/\rho_m$ is satisfied at high redshift and we have $\delta_m \propto a$, resulting in the standard growth rate $f = 1$.
At late time ($z \ll 1$) we have $\delta\rho_V^c \propto a$.
On scales inside the Hubble horizon the observational data of linear power spectrum lies in the comoving wave number range $0.01 Mpc^{-1} < k < 0.1 Mpc^{-1}$. So, we selected the range values for the gCg parameter $-0.5 \leq \alpha \leq 0.5$ to compare the difference between our models.

# Results and Conclusions

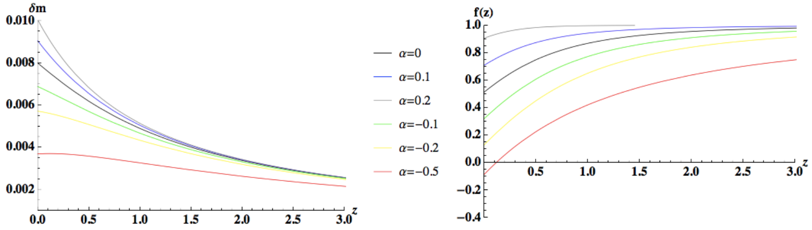



Figure: Dark matter density contrast and growth rate for $\Lambda CDM$ model (black curve) and for interacting models as indicated in the legend.

When compared with $\Lambda CDM$ model, both $\delta_m^c$ and $f$ are suppressed for the models with $\alpha < 0$ due to homogeneous creation of dark matter and are enhanced for the models with $\alpha > 0$ due to decays of dark matter.

# Results and Conclusions

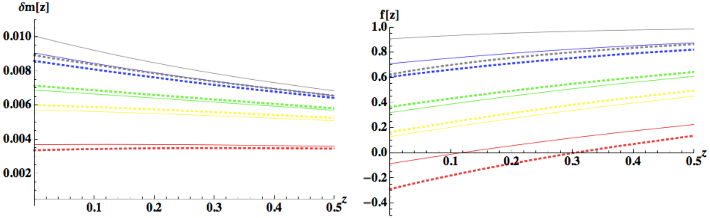



Figure: Dark matter density contrast in the left and growth rate in the right for the following models: $\alpha = -0.5$ (red), $\alpha = -0.2$ (yellow), $\alpha = -0.1$ (green), $\alpha = 0.1$ (blue) and $\alpha = 0.2$ (gray). Solid curves are for geodesic model and dotted curves for inhomogeneous vacuum energy.

For the case of $\alpha = -0.5$, corresponding to dark matter creation at constant rate, a large suppression appear in the dark matter growth rate.

# Results and Conclusions

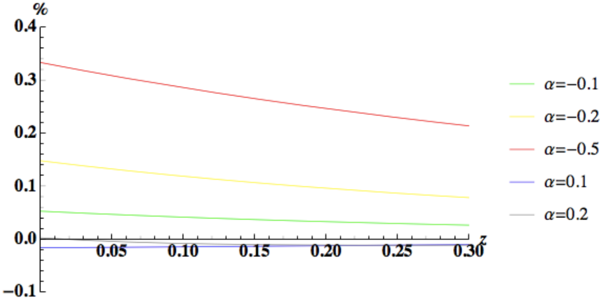



Figure: Plot of the relative percentage difference between the dark matter density contrast using the scale $k$=0.1 and $k$=0.01 to the inhomogeneous model.

In spite of depending of the value of the Chaplygin gas parameter $\alpha$, vacuum perturbations suppress or enhance the dark matter growth rate as compared to the geodesic model.

# Bibliography I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Thanks! :)