A new mechanism for dark energy: the adaptive screening

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We describe how known matter effects within a well-motivated particle physics framework can explain the dark energy of the Universe. By considering a cold gas of particles which interact via a vector mediator, we show that there exists a regime where the gas reproduces the dynamics of dark energy. In this regime the screening mass of the mediator is proportional to the number density of the gas, hence we refer to this phenomenon as "the adaptive screening mechanism". As an example, we argue that such screening mass could result from Anderson localization of the vector mediators. The proposed dark energy mechanism explains the recent Baryon Acoustic Oscillations observations and can be tested by the EUCLID experiment, as well as by studying properties of dark photons and sterile neutrinos.

Introduction. Cosmological observations have progressively established that about 68% of the total energy density of the Universe is in the form of a mysterious agent, the dark energy (DE). This evasive component is usually modelled in the equation of state (EOS) \( p = w \rho \), which relates the components pressure \( p \) to its energy density \( \rho \) through the parameter \( w \). The dedicated experiments currently measure the latter at 95% confidence level in the interval \( w = -1.13^{+0.12}_{-0.14} \) and set the characteristic energy scale at \( \Lambda_{0}^{1/4} \approx 10^{-3} \) eV [1-11]. The same measurements allow for the suggestive interpretation of DE as a small but non-vanishing pure vacuum energy: the famous cosmological constant, for which \( w = -1 \) must hold at all times. However, within the standard model of particle physics, zero-modes of the known fields, the quark-gluon condensate at the QCD phase transition or the Higgs bosons vacuum expectation value should all induce sizeable contributions into the former. As none of these contributions has been observed in Nature, it seems plausible that some unknown mechanism is at work to set a vanishing vacuum energy, enforcing by net the cancellations of the mentioned quantum effects. However ad-hoc such idea might seem, the corresponding point of view has already been adopted in contemporary physics. An example is brought by quintessence theories [12, 13], where a nearly-massless slow-rolling scalar field accounts for the measured DE density on top of a vanishing vacuum contribution. In the present paper we also assume that vacuum has a null energy density, with the purpose of introducing a new, dynamical mechanism to explain the origin of DE.

In this Letter we consider a natural setup for the dark sector, where the particles of a cold and diluted gas are coupled to a light vector field - the dark photon [21]. In this framework we show that whenever the adaptive screening is active, i.e. whenever the mediator mass is dominated by an effective screening mass proportional to the number density of the gas particles, then the gas may enter a regime in which the EOS parameter is \( w \approx -1 \) and therefore act as a DE.

As an example, we choose to put forward the Anderson in the context of the metal-to-insulator transition in the presence of impurities [14]. It was later realized that localization transitions are general wave phenomena that occur in random media with dimensionality of two or larger, roughly speaking due to the destructive interference between the waves scattered from the randomly distributed scattering centers. The latter, in our case, are represented by the gas particles. To date localization effects have been observed in a variety of systems ranging from electromagnetic [15-17] to acoustic waves [18].

In the following, after presenting the basis of the new mechanism, we assume that the gas is composed of a single species of light fermions \( \psi \) and show how the measurements of DE density cast a stringent bound on the mass of the fermions itself, \( \Lambda_{0}^{1/4} \propto m_{\psi} \approx 10^{-3} \) eV. The resulting mass scale is typical to neutrino physics and, interestingly, an extra “sterile” neutrino with a squared mass splitting \( \Delta m_{\psi}^{2} \approx 10^{-5} \) eV\(^2\) has previously been proposed in literature as a solution to the upturn problem of the solar neutrino flux [19, 20]. Our framework also predicts the existence of dark photons which will be investigated in dedicated experiments [21]. Another feature, which discriminates between our mechanism and a pure cosmological constant, is a possible late-time onset of DE. Such phenomenon has been proposed as explanation for the recent Baryon Acoustic Oscillations (BAO) observations [22] and may be confirmed by the upcoming EUCLID experiment [23].

The mechanism. In order to illustrate how the adaptive screening mechanism works, let us consider a dilute gas of non-relativistic particles coupled via a long range repulsive force \( U(r_{ij}) \). The latter is characterised by the potential \( U_{\text{int}}(r_{ij}) \) between each couple of particles labeled by \( i \) and \( j \). By supposing that such system be isolated, given

\( 1 \) A repulsive potential ensures that the energy density of the system is always positive and guarantees the local stability of gas.
the occupied volume $V$ and the internal energy $U$ of the gas, we can calculate the pressure through $p = -\partial U/\partial V$. If the total number of particles is conserved, the EOS parameter can be expressed in terms of the total energy density $\rho := U/V$ and the number density of the gas particles $n$ as in

$$w := \frac{p}{\rho} = \frac{\partial \log \rho}{\partial \log n} - 1. \quad (1)$$

We also require that the vacuum, defined as the state with $n = 0$, has a vanishing energy density $\rho(n = 0) = 0$. Therefore every DE regime, for which $w = -1$, has necessarily to be created dynamically.

The total energy density of the non-relativistic gas comprises two contributions, given respectively by the rest mass $M$ of particles and by their interaction energy

$$\rho(n) = M n + \rho_{\text{int}}(n), \quad \rho_{\text{int}}(n) := U_{\text{int}}/V. \quad (2)$$

Plugging the above equation into Eq. (1) gives

$$w = \frac{M n}{M n + \rho_{\text{int}}} \left( 1 + \frac{1}{M} \frac{\partial \rho_{\text{int}}}{\partial n} \right) - 1. \quad (3)$$

In a regime where $M n \ll \rho_{\text{int}}$ and the dependence of $\rho_{\text{int}}$ on $n$ is negligible, the gas is characterised by $w \approx -1$ and reproduces the desired DE behaviour. This observation is the basis of the adaptive screening mechanism.

Assuming a repulsive potential and an approximately uniform number density distribution, the total potential energy density in Eq. (2) is given by [24]

$$\rho_{\text{int}} \approx \frac{g^2 n^2}{2m^2}, \quad (4)$$

where $g$ is the coupling between the gas constituents and the interaction mediators having a mass $m$. In the diluted cold gas approximation, once the Anderson localization is active, the former comprises two contributions,

$$m(n) = m_0 + \sigma n. \quad (5)$$

Here $m_0$ is the invariant mass of the mediator while the term $\sigma n$ represents the effect of the non-perturbative screening. The presence of the second contribution implements the adaptive screening mechanism. On dimensional grounds we expect the effective elastic scattering cross-section of the mediator on a gas particle to be $\sigma \approx \pi \sigma_M / n^2$, where typically $\mathcal{O}(10^{-1}) \lesssim \sigma \lesssim \mathcal{O}(10^{-2})$.

With the above results we can now study the behaviour of $\rho(n)$ and $w$ in different regimes. Plugging Eq. (1) and (5) into Eq. (2) and (3) yields

$$\rho = M n + \Lambda \left( \frac{n}{n + n_2} \right)^2, \quad (6)$$

$$w = \frac{n_2 - n}{n_2 + n} \left( 1 + n/n_1 \left( 1 + n_2/n \right)^2 \right)^{-1}, \quad (7)$$

where we defined the characteristic densities

$$\Lambda := \frac{g^2}{2\sigma^2} = \frac{M^4}{2\kappa^2 g^6}, \quad (8)$$

$$n_1 = \frac{\Lambda}{M}, \quad n_2 = \frac{m_0}{\sigma}, \quad n_3 = \frac{n_2^3}{n_1}. \quad (9)$$

As made clear by Fig. 1 and Tab. I, the above definitions identify four regimes distinguished by different values of the EOS parameter of the gas. In the first regime $n \gg n_1$, the rest mass of the gas constituents dominates the energy density of the system, which therefore behaves like dust: $w = 0$. As the number density drops (due to the expansion of the Universe) to $n_2 \ll n \ll n_1$, the localization effects prevail and the adaptive screening mechanism ensures an approximately constant energy density. In this regime we recover the DE behaviour, $w \approx -1$, while the energy density itself converges to $\Lambda$. Such dynamics is maintained until $n_3 \ll n \ll n_2$, where the rest mass of the vector mediator is setting the screening length of the potential. In this stage the interaction energy of the system is quickly depleted owing to $w \approx 1$. Below the threshold $n = n_3$ the rest mass contribution of the gas constituents tops the interaction one and $w = 0$ is established once again. The last two regimes are also predicted in studies of self-interacting dark matter [24], confirming our results in the absence of the adaptive screening effect.

In the above derivation we assumed $n_2 \lesssim 10^{-4} n_1$, which translates in the following bound on the mediator mass $m_0$,

$$m_0 \lesssim 10^{-4} \frac{M}{2g^2}. \quad (10)$$

When the background of an expanding Universe is considered, the requirement that the interaction mediators...
as $\rho$ enters a stiff fluid regime and its energy density is diluted by the expansion of the Universe. By setting the DE density to have been diluted by the expansion of the Universe, the dark matter energy density that is compensated by the gas of non relativistic fermions. By setting the DE component is negligible, our mechanism is cosmologically indistinguishable from the $\Lambda$CDM model. Conversely, our mechanism predicts the onset of DE at later times. Such transition explains the recent BAO observations and may be confirmed in future by the Euclid experiment. The expected signature is a downturn in the dark matter energy density that is compensated by the raise of DE component. A further characteristic of our framework is that the current DE regime will be abandoned in the future. When $n \lesssim n_2$, the component enters a stiff fluid regime and its energy density is diluted as $\rho \propto a^{-6}$ with the Universe expansion.

In addition, our mechanism can be tested in particle physics experiments. To provide an example, consider a gas of non relativistic fermions. By setting the DE density to the present value $\Lambda = \Lambda_0 \simeq (10^{-3} \text{ eV})^4$ and assuming $g = O(1)$ we have $M \approx 10^{-3} \text{ eV}$, and the upper bound $m_0 \lesssim 10^{-7} \text{ eV}$. We will later discuss the possible implications of our scenario for neutrino physics.

**Adaptive screening from localization.** We focus now on the behavior of the gas in a cold and diluted limit. With the gas particles acting as stationary scattering centers, the virtual mediators are localized consequently to the effect of the randomness in the environment. This provides a way to implement the adaptive screening mechanism in our system. Despite Anderson localization having been proposed more than fifty years ago and having being observed in a large variety of systems, to date the localization transition has still been proven in three spatial dimensions only by using numerical methods. Therefore, we present the necessary conditions for localisation to happen and, based on the analogy with systems in which this phenomenon indeed occurs, we argue that localization is a characteristic feature of our setup too.

In three spatial dimensions, the Ioffe-Regel condition $\ell \lesssim \lambda$ provides an approximate criterion for distinguishing between the non-localized and localized regimes. Here $\ell = (\sigma n)^{-1}$ is the mean free path of a wave and $\lambda$ is its wavelength. If the Ioffe-Regel condition is satisfied, the propagator over a distance $x$ is then suppressed as $\exp(-\xi x)$ because of localization. Estimates of the localization length $\xi$ are given in literature, yielding $\xi \approx \ell^{1/2}$. In the localized regime, on top of the proper mass contribution in Eq. (5), the vector mediator consequently receives an effective screening mass $\xi^{-1} \approx \sigma n$. The range of the interactions mediated by the vector particle is then constantly adapting to the changes in the density of the fermion gas, in a way that the interaction energy density of the gas is held approximately constant. The adaptive screening mechanism is therefore active and, for Eq. (3), the system reproduces the desired DE dynamics.

**A link to neutrino physics.** The mass scale $M \approx 10^{-3} \text{ eV}$, obtained by imposing the current DE measurements, suggests the existence of a new sterile neutrino species. It is suggestive that a particle with compatible properties is currently being investigated in relation to the solar neutrino upturn problem. The solar neutrino events expected at energies of few MeV. A possible solution calls for a very light sterile neutrino species $\psi$ characterized by the mass square difference $\Delta m^2_{\psi} = m_{\psi}^2 - m_\nu^2 (0.7 - 2) \times 10^{-5} \text{ eV}^2$ with respect to the lightest active neutrino mass $m_\nu$. Once a small mixing with the corresponding neutrino is provided, $\sin^2(2\theta_{1\nu}) \sim 10^{-3}$, the sterile neutrino reduces the survival probability of the electron component that otherwise causes the expected upturn. Interestingly, if $m_\psi \gg m_1$, then the above solution points to the same mass scale $m_\psi \approx 10^{-3} \text{ eV}$ that DE measurements indicate in our model, giving rise to a new interplay between neutrino physics and cosmology.

Our scenario can then be tested within the latter, for instance through the bounds on the absolute (active) neutrino mass scale which effectively constrain $m_1$. Alternatively, big bang nucleosynthesis and analyses of the cosmic microwave background radiation might constrain our mechanism, being sensitive to the number of thermalised relativistic degrees of freedom at the corresponding epochs. Whether our neutrinos yield a negligi-
mable contribution to the latter [19, 30], the massive dark photon which mediates their interactions can effectively constrain the scenario [21]. On the particle physics side, the “3+1” neutrino scheme proposed to solve the upturn problem is consistent with the latest global analysis of the sector. [20, 31] and is currently subject to a dedicated investigation through reactor experiments [32, 33].

Notice that a sterile neutrino as light as $m_{\nu} \lesssim 10^{-3}$ eV can only constitute a sub-dominant fraction of dark matter due to phase space constraints and the Pauli blocking argument [34]. We, however, remark that a self-interacting dark matter is motivated by the missing satellite, core-vs-cusp and too-big-to-fail problems [35].

Conclusions. In this Letter we have shown that known matter effects can give rise to the dark energy of the Universe. Our setup consists of a cold gas of particles interacting via a vector mediator, the dark photon, characterised by an environmentally induced mass that is proportional to the number density of the gas constituents. This implements “the adaptive screening mechanism” and allows our system to mimic the dynamics of dark energy – an approximately constant energy density ensures $w \approx -1$. As an example, we show that the Anderson localization could be one possible realization of the adaptive screening mechanism. The proposed framework explains the late time onset of the dark energy implied by recent Baryon Acoustic Oscillations observations [22] and testable in the upcoming EUCLID experiment [23]. A characteristic feature of our scenario is the presence of massive dark photons, currently subject of an intense experimental search. Once a fermion gas is considered, the proposed framework predicts a relation between the mass of the gas particles and the scale of dark energy, $\Lambda_{\text{QCD}}^{1/4} \approx M g^{-3/2}$ (Eq. (8)). It is suggestive that current measurements of $\Lambda_{\text{QCD}}$ recover the mass scale $M \approx 10^{-3}$ eV already proposed within neutrino physics in connection to the upturn problem of the solar neutrino flux.

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