Coupling between cold dark matter and dark energy from neutrino mass experiments

J.R. Kristiansen[1], G. La Vacca[2,3], L.P.L. Colombo[4], R. Mainini[1,5],
S. A. Bonometto[2,3]

[1]IInstitute of Theoretical Astrophysics, University of Oslo, Box 1029, 0315
Oslo, Norway
[2]Physics Dept. G. Occhialini, Milano–Bicocca University, Piazza della Scienza
3,
20126 Milano, Italy
[3]I.N.F.N., Sez. Milano–Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
[4]Physics Dept., University of Southern California, Los Angeles, CA 90089-0484
[5]I.N.A.F., Roma Observatory, Via Frascati 33, 00040 Monteporzio Catone,
Italy
E-mail: j.r.kristiansen@astro.uio.no, lavacca@mib.infn.it

Abstract

We consider cosmological models with dynamical dark energy (dDE) coupled to
cold dark matter (CDM), while simultaneously allowing neutrinos to be massive.
Using a MCMC approach, we compare these models with a wide range of cos-
mological data sets. We find a strong correlation between this coupling strength
and the neutrino mass. This correlation persists when BAO data are included
in the analysis. We add then priors on ν mass from particle experiments. The
claimed detection of ν mass from the Heidelberg-Moscow neutrinoless double–β
decay experiment would imply a 7–8σ detection of CDM-DE coupling. Simi-
larly, the detection of ν mass from coming KATRIN tritium β decay experiment
will imply a safe detection of a coupling in the dark sector. Previous attempts
to accommodate cosmic phenomenology with such possible ν mass data made
recourse to a $w < -1$ eoS. We compare such an option with the coupling option
and find that the latter allows a drastic improvement.

1. Introduction

Today we have a standard model of cosmology, the so-called ΛCDM model,
providing an excellent fit to all cosmological data. This model tells us that dark
energy (DE) and cold dark matter (CDM) account of $\sim 75\%$ and 20% of the
present cosmic energy budget, respectively [1, 2]. It is then quite embarrassing
that we fail to understand the nature of both DE and CDM. Furthermore, if
DE is a smooth cosmological *fluid* with an equation of state $w = -1$, our model
is troubled by two fundamental questions related to its relative and absolute

density, the *coincidence* and *fine tuning* problems: Why did DE start to dominate just when structures had time to form? Why is its density ~ 120 orders of magnitude smaller than the (naïvely) expected quantum vacuum density?

One way to circumvent the coincidence problem amounts to introducing a coupling between CDM and dynamical DE (dDE) [3, 4]. The energy transfer from CDM then allows DE to comprise a significant fraction of the cosmic energy budget over a large part of the cosmic history. Unfortunately, switching on a coupling apparently worsens the fit of cosmological data.

More recently, however, it has been noted that neutrino masses (m_ν) and a CDM-dDE coupling affect cosmological observables in opposite ways [5, 6]. However, not only our ignorance about m_ν softens the constraints on the coupling, but a much more puzzling effect arises: models with $m_\nu \neq 0$ and coupling appear (slightly) favored in respect to $m_\nu \sim 0$ uncoupled models.

Neutrinos are abundant in the Universe, second only to photons when it comes to number density; ν oscillation experiments tell us that they are massive [7] and measure the mass split between ν–mass eigenstates, so that the largest split (~ 0.05eV from atmospheric ν's) is a lower limit on the heaviest ν mass.

Particle experiments have placed various upper limits on the absolute ν mass scale. The Mainz and Troitsk experiments, measuring the end–point of the electron energy distribution in tritium β decay, gave a 95% C.L. limit $m_\beta < 2.0$eV [8]. A further controversial detection of an absolute ν mass came from the Heidelberg-Moscow (HM) experiment; on the basis of its outputs, a part of the experiment team claims a 3σ lower limit $m_{\beta\beta} = (0.2 - 0.6)$eV [9, 10] (the mass measured by neutrinoless double β decay ($0\nu\beta\beta$) experiments, $m_{\beta\beta}$, is however a different combination of mass eigenvalues than the mass m_β, from tritium β decay).

In 2011, the experiment KATRIN [11], also studying tritium β decay, is expected to start taking data. With a prospected sensitivity of $\sigma_{m_\beta^2} \approx 0.025$eV^2, it should be able to detect m_ν values in the range of the $m_{\beta\beta}$ claim.

At present, the best upper limits on the ν mass scale come from cosmology, yielding $\Sigma m_\nu \equiv M_\nu \lesssim 0.2$eV [12, 13] and $M_\nu \lesssim 1.5$eV (at 95% C.L.), depending on data sets and cosmological models [12, 13, 14, 15, 16, 1, 2, 17].

All this is true if the possibility of a dDE–CDM coupling is neglected.

In this paper, similarly to what is done in [6], we will allow for such a coupling, reporting for the first time results when baryonic acoustic oscillation (BAO) data are taken into account. Then we consider the ν mass limits set by a part of the HM collaboration (KKDC claim, herafter), and impose this as a prior on M_ν. Finally we shall investigate how a m_β detection from KATRIN would affect limits on coupling.

The possibility that forthcoming neutrino experiments yield mass values in apparent conflict with cosmic data had been considered by various authors. The most promising option, perhaps, had been discussed by [18, 19], who found that allowing w, the state parameter of DE, to take values < -1 eased such constrast. Here we compare this option with the coupling option and find that the latter one leads to a drastically better agreement between terrestrial and cosmological

measures.

In the following section we discuss our cosmological model and outline the observable effects of the CDM-dDE coupling and massive ν's. In Section 3 we discuss the experimental bounds on the absolute ν mass scale. The data and methods used are presented in Section 4, while Section 5 is devoted to reporting and discussing our results. In Section 6 we summarize our findings and conclude.

2. Cosmological model

Our models differ from the standard ΛCDM in three different aspects: (i) DE is a self–interacting scalar field ϕ rather than a cosmological constant Λ. (ii) A linear dDE–CDM coupling is allowed. (iii) We allow ν's to be massive.

We shall consider the Ratra-Peebles (RP) potential [20] and a SUGRA self–interaction potentials [21], reading

$$V(\phi) = \Lambda^{\alpha+4}/\phi^\alpha \ , \quad V(\phi) = (\Lambda^{\alpha+4}/\phi^\alpha)\exp(4\pi\phi^2/m_p^2) \ , \tag{1}$$

respectively; they allow tracker solutions for any $\alpha > 0$. For both potentials, once α and Λ are assigned, the DE density parameter $\Omega_{o,DE}$ is uniquely defined. In our fitting procedure, however, we use $\Omega_{o,DE}$ and $\lambda = \log(\Lambda/\text{GeV})$ as free parameters.

Limits on these models *without* coupling between DE and CDM have been studied in [22]. For most cosmological parameters, WMAP5 results lead to a slight narrowing of error bars, in respect to WMAP3. In the case of λ, however, [22] find a significant shift downward of the 2–σ upper limit on the energy scale Λ. In the SUGRA case, in particular, only $\lambda \lesssim -3.5$ is allowed. Such small values are well below the range motivated by particle physics. Therefore the physical appeal of the SUGRA potential is spoiled.

Following the procedure in refs. [5, 6] we assume a linear coupling between the DE and CDM energy components, which leads to the coupled equations

$$\ddot{\phi} + 2\frac{\dot{a}}{a}\dot{\phi} + a^2 V'(\phi) = Ca^2\rho_c \tag{2}$$

$$\dot{\rho}_c + 3\frac{\dot{a}}{a}\rho_c = -C\dot{\phi}\rho_c \ ; \tag{3}$$

here a is the scale factor, ρ_c is CDM density, C denotes the coupling strength. We then define the dimensionless coupling parameter

$$\beta \equiv \sqrt{3/16\pi}\ m_p C, \tag{4}$$

used as a free parameter for our cosmological models. For a more thorough discussion of the effects of coupling on dDE and CDM evolutions, see, *e.g.*, [5].

Let us however outline that, when the β degree of freedom is opened, Λ values as large as $30\,\text{GeV}$ become allowed, at the 1–σ level, while, at the 2–σ level, no significant constraint on the energy scale Λ remains. Even for the RP

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potential, for which a limit $\lambda \lesssim -8.5$ held, in the absence of coupling, values $\lambda \sim -2$ become allowed.

The effects of massive neutrinos in cosmology have been studied thoroughly for many years, and we refer to [14] for an extensive review of the topic. Cosmological observations are mostly sensitive to the sum of ν–masses, M_ν, related to the ν density parameter by the relation $\Omega_\nu h^2 = M_\nu/93.14\mathrm{eV}$.

If $M_\nu \lesssim 4.5\,\mathrm{eV}$, most ν's were still relativistic at matter-radiation equality and act then as radiation, so postponing the equality compared to a model where all the DM is cold. When keeping the total DM density constant, increasing Ω_ν shifts the peaks of the anisotropy spectrum C_ℓ to lower ℓ and boosts their heights.

When it comes to the matter power spectrum $P(k)$, the main effect is ν free-streaming from small scale fluctuations, damping $P(k)$ for large wavenumbers k.

The combined effects on C_ℓ and $P(k)$ spectra, when compared with observations, lead then to the limits outlined above [12, 13, 14, 15, 16, 1, 2]. These effects, however, as outlined in [5, 6], are almost opposite to those of dDE–CDM coupling, for both C_ℓ and $P(k)$. A Fisher–matrix analysis then shows a strong degeneracy between the β and M_ν parameters. Pinning down one of the parameters by some other means clearly results in improved limits on the other parameter.

3. Neutrino mass bounds from earth based experiments

Two different ways are being followed to measure the absolute scale of ν masses: $0\nu\beta\beta$ and tritium β decay experiments.

The $0\nu\beta\beta$ process can only occur if ν's are massive Majorana spinors, *i.e.* they coincide with their own antiparticles. From the measurement of $T_{1/2}^{0\nu}$ ($0\nu\beta\beta$ half life) one can then deduce an effective mass $m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i$, being

$$m_{\beta\beta}^2 = \frac{m_e^2}{C_{mm} T_{1/2}^{0\nu}}. \tag{5}$$

Here U_{ei} is the PMNS ν mixing matrix, m_i are mass eigenvalues, m_e is the electron mass. C_{mm}, the nuclear matrix element relevant for the nuclide considered, is the main problem with $0\nu\beta\beta$, because of its large theoretical uncertainty.

The most sensitive limits, up to now, were derived from detectors enriched in ^{76}Ge. Using such nuclide, the Heidelberg–Moscow (HM) [23] and the IGEX [24] gave the limits $T_{1/2}^{0\nu} > 1.9 \times 10^{25}y$ and $T_{1/2}^{0\nu} > 1.6 \times 10^{25}y$, respectively. However, a part of the HM collaboration published results claiming a more than 5σ detection of a signal, giving an effective neutrino mass of $m_{\beta\beta} = (0.2-0.6)\mathrm{eV}$ (3σ limits) [9, 10] (which we refer to as the KKDC claim).

In view of nuclear matrix uncertainties, this claim is not in contradiction with another $0\nu\beta\beta$ experiment, CUORICINO [25], based on ^{130}Te, placing an upper limit of $m_{\beta\beta} < \{0.19 - 0.68\}\mathrm{eV}$.

Both ^{130}Te and ^{76}Ge double–β decays are however still being investigated through the CUORE and the GERDA experiments, respectively. The CUORE

experiment [26] is running in the Laboratori Nazionali del Gran Sasso (LNGS), where the GERDA experiment [27] is also being placed.

Tritium β decay is a different road to the absolute neutrino mass scale, where one accurately measures the energy distribution of the outgoing electron, and uses this to infer an effective electron neutrino mass, $m_\beta^2 = \sum_i |U_{ei}| m_i^2$.

Currently, the best limits on m_β from tritium β decay come from the Mainz and Troitsk experiments, yielding an upper limit of $m_\beta < 2.0\,\text{eV}$ (95% C. L.). The much more sensitive KATRIN experiment [11] is scheduled to start taking data this year. When completed, KATRIN is expected to reach a sensitivity of $\sigma_{m_\beta^2} \approx 0.025\,\text{eV}^2$, and thus be able to confirm the KKDC claim.

4. Data and methods

We use a modified version of the public program CAMB [28] to calculate CMB and matter power spectra. A modified version of the public MCMC engine CosmoMC [29] is used to generate confidence limits on the parameters: $\{\omega_b,$ $\omega_c,\ \theta,\ \tau,\ n_s,\ \ln 10^{10} A_s,\ \log_{10} \Lambda,\ \beta,\ M_\nu\}$. Here ω_b, ω_c are the reduced density parameters of baryons, CDM; θ is the ratio of the sound horizon to the angular diameter distance, τ is the optical depth, n_s and A_s are the primordial scalar spectral index and amplitude (at $k = 0.05\text{Mpc}^{-1}$). We marginalize over SZ amplitude. The parameters above are given flat priors, unless otherwise is explicitly stated.

We mostly use two different combinations of cosmological data sets; WMAP5 data only, and WMAP5 plus other cosmological data (referred to as WMAP5++). For the sake of comparison, in a specific case, we also consider the option of omitting BAO constraints, as specified below.

We then apply priors on ν mass according to the KKDC claim and the prospected KATRIN results. Data sets and priors used are described in the following. The MCMC chains are run on the Titan cluster at Oslo University.

4.1. Cosmological data

Firstly, we tested our models using only the five year data from the WMAP measurements of the CMB radiation (WMAP5) [30, 2, 1]. The WMAP5 data are analyzed with the Fortran 90 likelihood code provided with the data release.

In WMAP5++ we then included the galaxy power spectrum from the 2dF survey [31], SNIa data from the SNLS survey [32], and added gaussian priors on the Hubble parameter of $h = 0.72 \pm 0.08$ from the HST key project [33], the physical baryon density, $\omega_b = 0.022 \pm 0.002$ [34, 35, 36] inferred from the ^{4}He abundance after Big Bang nucleosynthesis, and BAO data from [37].

The BAO analysis in [37] includes both the SDSS DR7 data and data from 2dF. Angular distance measurements are compared at $z = 0.2$ and $z = 0.35$, by using the distance measure $d(z) \equiv r_s(z_d)/D_V(z)$. Here $r_s(z_d)$ is the comoving sound horizon at the baryon drag epoch (see [37, 38]) and $D_V(z) \equiv \left[(1+z)^2 D_A^2 z/H(z)\right]^{1/3}$, where D_A is the angular diameter distance. This provides information on the late expansion of the Universe, which is important to

constrain DE nature. Following [39, 37], from the BAO analysis, the inferred likelihood $\mathcal{L}$ of a model can be estimated by $-2 \ln \mathcal{L} \propto \mathbf{X}^{-1} \mathbf{C}^{-1} \mathbf{X}$, where

$$\mathbf{X} = \begin{vmatrix} d(0.2) - 0.1905 \\ d(0.35) - 0.1097 \end{vmatrix} , \quad \mathbf{C}^{-1} = \begin{vmatrix} 30124 & -17227 \\ -17227 & 86977 \end{vmatrix} \tag{6}$$

4.2. KKDC and KATRIN priors

In order to include KKDC priors on ν mass, we use the procedure in refs. [40, 41]. To account for the dispersion in nuclear matrix (C_{mm}) estimates, we follow [41], where upper and lower extremes from a compilation of *reliable* theoretical estimates are used, defining a 3σ uncertainty width of C_{mm}. Combined with the uncertainty in $T_{1/2}^{0\nu}$, this results in a KKDC prior of $\log_{10}(m_{\beta\beta}/\mathrm{eV}) = -0.23 \pm 0.07$ (at 1σ). In this mass range the ν mass eigenvalues are almost degenerate, so that we can use that $M_\nu = 3m_{\beta\beta}$ without any loss of accuracy.

As far as KATRIN is concerned, we use their expected uncertainty $\sigma_{m_\beta^2} = 0.025 \, \mathrm{eV}^2$ for a Gaussian distribution around a best-fit value m_β^2, as in refs. [42, 19, 43]. We then assume a fiducial value $m_\beta = 0.3 \, \mathrm{eV}$ ($M_\nu = 0.9 \, \mathrm{eV}$), as a compromise between cosmological upper limits and KKDC lower limit.

KKDC and KATRIN priors are imposed in the post processing of MCMC chains, using a modified version of the GetDist program provided with the CosmoMC package.

5. Results and discussion

A first point we want to remark is that including the BAO prior in the likelihood analysis causes just minor shifts on the limits, as shown in Table 1, and does absolutely not conflict with previous findings.

Datasets	M_ν (eV)	β
WMAP5	1.70 (1.52)	0.136 ± 0.085 (0.098 ± 0.069)
WMAP5++ (without BAO)	1.17 (1.13)	0.104 ± 0.047 (0.100 ± 0.043)
WMAP5++	1.19 (1.19)	0.094 ± 0.041 (0.092 ± 0.042)

Table 1: We report 95% marginalized upper limits on M_ν (first column) as well as mean value and 1σ uncertainties on β for the SUGRA (RP) coupled models and different combinations of data sets (second column).

Let us then consider the effects of adding mass priors.

In Figure 1 we show marginalized 68% and 95% confidence contours in the $M_\nu - \beta$ plane with and without a KKDC prior on M_ν. The left (right) panel concerns the SUGRA (RP) potential. Before including KKDC priors, results are similar to those in our previous paper [6]. In the WMAP5++ case, however, where we now include BAO data, the curves shift slightly farther from the 0-0 case, bringing the 0–0 point well outside 1σ contours for both RP and SUGRA cases. However, without additional priors on M_ν, the 0-0 model is not excluded by cosmological data alone.

Figure 1: 68% and 95% confidence intervals in the $M_\nu - \beta$ plane. The left panel shows resulting limits when using a SUGRA potential, while the right panel shows the limits when using a RP potential. Black, thin lines indicate the results when using WMAP5 as the only cosmological data set, and red, thick lines show the results when using WMAP5++. Dotted lines are the cosmology only limits. The resulting limits when also including the KKDC limit on M_ν are shown with solid lines. We notice that the intersection between β and M_ν allowed areas, when KKDC controversial results are allowed or omitted, does not vanish but is rather small.

When we add the KKDC prior on M_ν, we have a significant offset from the 0-0 model: $\beta = 0$ is excluded with 7.3 σ (8.0σ)in the SUGRA (RP) case. This conclusion relies on the use of WMAP5++; CMB spectra are not sufficiently affected by M_ν, to allow for a statistical detection of β alone, even when the KKDC prior is imposed. This is not unexpected, as CMB data primarily probes the Universe at high z, before DE became important.

Figure 2 shows 1D likelihood distributions for both SUGRA and RP models, when using WMAP5++ and the KKDC prior. Here we also plotted the mean likelihood for each bin, in addition to the marginalized likelihood. In ref. [6] a problem that was discussed was the discrepancy between these two distributions for the β parameter, which was caused by a very non-gaussian correlation between the $\log_{10}\Lambda$ and β parameters, especially for small values of β. From Figure 2 we see that this problem is not very pronounced here. When β is forced to high values by the KKDC prior, the two probability measures correspond quite well to each other, even though we still see some minor shifts.

In Figure 3 the 2D marginalized likelihood contours are shown when the KKDC prior is replaced by the prospected prior from KATRIN with a fiducial neutrino mass of $M_\nu = 0.9$eV. Although the best-fit M_ν here is smaller than in the KKDC case, we still get a significant preference for a non-zero β when using WMAP5++. For the SUGRA potential, $\beta = 0$ gets excluded with 3.9σ significance, while the corresponding number is 3.6σ for the RP potential.

The controversial results of the HM experiment, as well as the possibility that KATRIN detects a ν mass value, had already triggered a discussion on the way to soften cosmological constraints. The best option put forward, up to now, was perhaps the possibility of allowing the state parameter of DE, w, to delve into the *phantom* regime.

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Figure 2: 1D likelihood distributions for β, using WMAP5++ sets and the KKDC prior on M_ν. Thick, red lines corresponds to the SUGRA model, while thin black lines refers to the the RP model. Solid lines denote marginalized likelihood. Dotted lines indicate average likelihood of the samples in each bin.

Figure 3: The same as Figure 1, but using a KATRIN prior with a fiducial neutrino mass of $m_\beta = 0.3$eV ($M_\nu = 0.9$eV) instead of the KKDC prior. Let us also point out that, at variance from the KKDC case, the KATRIN prior is fully consistent with cosmological constraints, essentially leading to a restriction of the allowed area in the M_ν–β plane.

Before concluding this Section it is then worth comparing our results with those obtainable if we just allow for $w < -1$, an option already deepened by [19]. Figure 4 shows the likelihood distributions on the M_ν–w plane with or without the KKDC constraint. This figure confirms the findings of [19], also when the more limited data set considered by them (including, i.e., just WMAP3 outputs) is replaced by the whole system of data considered in the rest of this work.

As is known, SUGRA (or RP) uncoupled cosmologies yield no significant likelihood improvement (or worsening) in respect to ΛCDM. They are therefore analogous benchmarks for model likelihood confrontation. It is then clear that, if we just allow w to run in the *phantom* range, we hardly gain a ~ 2–σ likelihood improvement. On the contrary, if we open the coupling option, already with $M_\nu = 0.9$ eV, we approach ~ 4–σ's; passing from 2 to 4–σ means achieving statistical significance.

However, even letting apart statistical evaluations, direct inspection shows

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Figure 4: Likelihood distribution with or without the KKDC prior (solid or dotted lines, respectively, indicating 1 and 2 σ's), when a DE state parameter $w < -1$ is allowed and considering all cosmological data. Notice that the high likelihood areas, with or without the KKDC prior, have just a minor intersection at the 2–σ level. Let us recall that, with the coupling option, there is a (small) intersection even at 1–σ.

that spectral distortions due to increasing M_ν, both in C_l and $P(k)$, are just opposite to those due to β. On the contrary, $w < -1$ spectral changes exhibit a different scale dependence; in fact, their capacity to allow higher ν masses is substantially related to their favoring greater Ω_m values.

6. Summary and conclusions

We have studied the effects of coupling between a dynamical DE component and CDM. The observational effects of such a coupling are almost opposite to those caused by massive neutrinos, which results in a strong degeneracy between the coupling parameter β and the neutrino mass M_ν.

This suggests the possibility that interactions within the dark sector have been hidden to observations, up to now, by the existence of a significant ν mass value. The ν mass, possibly responsible for this *chamaleontic* effect, lays just below the range already inspected in H^3 β–decay experiments. Such a range will be however soon explored by the KATRIN experiment, while the ν mass detection claimed by a part of the HM team is just above the suitable range.

In this work, such a possibility was also tested including, for the first time, BAO measurements.

Previous analysis had already shown that a cosmology with ν mass and coupling is statistically preferred to ΛCDM. The inclusion of BAO data slightly increases such preference which, however, still keeps $\mathcal{O}(2\sigma)$.

Such $\beta - M_\nu$ "degeneracy" can be broken by an external prior on M_ν from earth based experiments. If we assume the KKDC claim on neutrino mass to be

correct, this then results in a 7–8 σ detection of a non-zero β. If the upcoming KATRIN experiments confirm a neutrino mass in the range allowed by the KKDC experiment, this will on its own standing give a statistically significant detection of a non-zero β.

Other options considered before, to try to reconcile cosmic data with ν mass in such range, are far less effective.

In particular, even if the option $w < -1$ is added to ΛCDM models, a prior $M_\nu \sim 1$ eV badly modifies the likelihood distribution, so indicating an apparent conflict with cosmological measurements. On the contrary, when such a prior is added to cosmological data, within the context of $\beta \neq 0$ models, already (slightly) favored by data in respect to ΛCDM, it just leads to a further restriction of the allowed parameter area. In a sense, it appears a "welcome" new limit, just narrowing parameter error bars.

A detection of a non-zero $m_\beta \gtrsim 0.3$eV by KATRIN would radically renew the cosmic scenario: the concordance cosmology, ΛCDM, would be statistically falsified; a CDM–DE coupling would become a concrete option.

One should also keep in mind that in the coming years, with data from the Planck satellite, the CMB measurements will improve vastly, further narrowing the uncertainties in the $\beta - M_\nu$ plane, as was shown in [5].

It may be then worth pointing out that admitting a linear interaction between CDM and DE, as done here, is just the next approximation to assuming them fully decoupled. The idea underlying this analysis is that modeling the Dark Cosmic Sector with two independent components is just a first step towards understanding its complex nature. After a hypothetical confirmation of the coupling option by laboratory data, further cosmic data might allow to go even beyond the assumption of linear interaction, possibly providing a more detailed insight into one of basic question of modern physics, the nature of the cosmic dark components.

Acknowledgments

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