Alternative Dark Energy Models: An Overview

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ABSTRACT

A large number of recent observational data strongly suggest that we live in a flat, accelerating Universe composed of $\sim 1/3$ of matter (baryonic + dark) and $\sim 2/3$ of an exotic component with large negative pressure, usually named Dark Energy or Quintessence. The basic set of experiments includes: observations from SN Ia, CMB anisotropies, large scale structure, X-ray data from galaxy clusters, age estimates of globular clusters and old high redshift galaxies (OHRG’s). Such results seem to provide the remaining piece of information connecting the inflationary flatness prediction ($\Omega_T = 1$) with astronomical observations. Theoretically, they have also stimulated the current interest for more general models containing an extra component describing this unknown dark energy, and simultaneously accounting for the present accelerating stage of the Universe. An overlook in the literature shows that at least five dark energy candidates have been proposed in the context of general relativistic models. Since the cosmological constant and rolling scalar field models have already been extensively discussed, in this short review we focus our attention to the three remaining candidates, namely: a decaying vacuum energy density (or $\Lambda(t)$ models), the X-matter, and the so-called Chaplygin-type gas. A summary of their main results is given and some difficulties underlying the emerging dark energy paradigm are also briefly examined.

I. INTRODUCTION

In 1998, some results based on Supernovae (SNe) type Ia observations published independently by two different groups, drastically changed our view about the present state of the universe \cite{1, 2}. In brief, the Hubble-Sandage diagram describing the observed brightness of these objects as a function of the redshift lead to unexpected and landmark conclusion: the expansion of the Universe is speeding up not slowing down as believed during many decades. Implicitly, such SNe type Ia observations suggest that the bulk of the energy density in the Universe is repulsive and appears like a dark energy component; an unknown form of energy with negative pressure [in addition to the ordinary dark matter] which is probably of primordial origin. In a more historical perspective, as the one shown in the chronological scheme above, one may say that contemporary cosmology started with the SNe “experiments”. The current expectation is that im-
Important clues to the emerging dark energy paradigm will be provided by the next generation of SNe projects with advancing technology, as well as by a large set of complementary cosmological observations.

The existence of an extra component filling the Universe has also indirectly been suggested by independent studies based on fluctuations of the 3K relic radiation, large scale structure, age estimates of globular clusters or old high redshift objects, as well as by the X-ray data from galaxy clusters. Actually, the angular power spectrum of fluctuations in the cosmic microwave background (CMB) favors a model with total density parameter $\Omega_T = 1$, a value originally predicted by inflation, whereas the density parameter associated with cold dark matter (CDM) is $\Omega_m \sim 0.3$, a value independently required by the power spectrum of the large scale structure (LSS) and X-ray data from galaxy clusters (see scheme above). The difference $\Omega_{DE} = \Omega_T - \Omega_m \sim 0.7$ is the density parameter of the dark energy component. Such a picture has recently been confirmed with even more precision by the Wilkinson Microwave Anisotropy Probe, and all these ingredients together reinforce what is usually referred to as the standard concordance model of cosmology.

Although considering that dark energy changed the traditional view of the Universe, the absence of natural guidance from particle physics theory about its nature gave origin to an intense debate, as well as to many theoretical speculations. In particular, a cosmological constant ($\Lambda$) – the oldest and by far the most natural candidate – is the simplest from a mathematical viewpoint but not the unique possibility. The $\Lambda$ term was originally introduced by Einstein in 1917 to obtain a static world model. It is a time independent and spatially uniform dark component, which may classically be interpreted as a relativistic perfect simple fluid obeying the equation of state $p = -\rho$. In the framework of quantum field theory the presence of $\Lambda$ is due to the zero-point energy of all particles and fields filling the Universe which manifests itself in several quantum phenomena like the Lamb shift and Casimir effect. However, there is a fundamental problem related to such a theoretically favored candidate which is usually called the cosmological constant problem. Shortly, it is puzzling that the present cosmological upper bound ($\Lambda_o/8\pi G \sim 10^{-47}GeV^4$) differs from natural theoretical expectations ($\sim 10^{71}GeV^4$) by more than 100 orders of magnitude. This puzzle at the interface of astrophysics, cosmology, and quantum field theory has been considered by some authors as the greatest crisis of modern physics, and, as such, it acts like a Damocles sword on the cosmological constant solution for the present accelerating stage of the Universe.

Nowadays, there are many other candidates appearing in the literature, among them:

(i) a $\Lambda(t)$-term, or a decaying vacuum energy density.

(ii) a relic scalar field (SF) slowly rolling down its potential.

### Dark Energy: Genealogy

| SNe Ia | CMB | Dark Matter | Globular Clusters |
|--------|-----|-------------|------------------|
| $q_o < 0$ | $\Omega_{total} = 1$ | $\Omega_m \approx 0.3$ | $t_U \approx 14$ Gyr |

**Diagram:**

- SNe Ia
- CMB
- Dark Matter
- Globular Clusters

**Legend:**
- $q_o < 0$
- $\Omega_{total} = 1$
- $\Omega_m \approx 0.3$
- $t_U \approx 14$ Gyr
(iii) “X-matter”, an extra component characterized by an equation of state \( p_x = \omega \rho_x, -1 \leq \omega < 0. \)

(iv) a Chaplygin-type gas whose equation of state is given by \( p = -A/\rho^\alpha \), where \( A \) is a positive constant and \( 0 \leq \alpha \leq 1. \)

The list is by no means as exhaustive as one may think at first sight. Since the basic condition for an accelerating Universe is a dominant component with negative pressure, there are other possibilities which have occasionally been considered in the literature \([12]\). Note also that the model dominated by cosmological constant \((p_v = -\rho_v)\) is a limiting case of the X-matter parametrization \((\omega = -1)\).

The last three candidates above (SF, X-matter, and Chaplygin gas) share an additional physical property, namely, the effective equation of state parameter \( \omega(z) = p/\rho \) may be a function of the redshift. In particular, this means that many different models may explain the same set of data. Therefore, in order to improve our understanding of the nature of dark energy, an important task nowadays in cosmology is to find new methods or to revive old ones that could directly or indirectly quantify the amount of dark energy present in the Universe, as well as determine its effective equation of state parameter. In other words, by learning more about the cosmic acceleration at low and high redshifts, one may expect to discriminate among the existing theories of dark energy by better determining \( \omega \) and its time dependence.

In this short review we present a simplified picture of the main results and discuss briefly some difficulties of the emerging dark energy paradigm. Since the consequences of a cosmological constant and a rolling scalar field (usually considered the best candidates) have already been extensively discussed in recent review papers \([13]\), in the present work we emphasize only the main results related to the remaining dark energy candidates.

II. ALTERNATIVE DARK ENERGY MODELS

In what follows we restrict our attention to the class of spacetimes described by the FRW flat line element \((c = 1)\)

\[
ds^2 = dt^2 - R^2(t) \left[ dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right],
\]

where \( R(t) \) is the scale factor. Such a background is favored by the cosmic concordance model since it is a direct consequence of the recent CMB results \((\Omega_T = 1)\). Now, let us discuss the cosmic dynamics and some observational consequences for alternative dark energy candidates.

A. Time-varying \( \Lambda(t) \)-term

Decaying vacuum cosmologies or \( \Lambda(t) \) models \([14, 15, 16, 17, 18, 19, 20, 21]\) are described in terms of a two-fluid mixture: a decaying vacuum medium \( (\rho_v(t) = \Lambda(t)/8\pi G, p_v = -\rho_v) \) plus a fluid component (“decaying vacuum products”) which are characterized by their energy density \( \rho \) and pressure \( p \). Historically, the idea of a time varying \( \Lambda(t) \)-term was first advanced in the paper of Bronstein \([14]\). Different from Einstein’s cosmological constant, such a possibility somewhat missed in the literature for many decades, and, probably, it was not important to the recent development initiated by Ozer and Taha at the late eighties \([15]\).

The Einstein field equations (EFE) and the energy conservation law (ECL) for \( \Lambda(t) \) models are:

\[
8\pi G \rho + \Lambda(t) = 3 \frac{\dot{R}^2}{R^2},
\]

\[
8\pi G p - \Lambda(t) = -2 \frac{\ddot{R}}{R} - \frac{\dot{R}^2}{R^2},
\]

\[
\dot{\rho} + 3H(\rho + p) = -\frac{\dot{\Lambda}(t)}{8\pi G},
\]
where a dot means time derivative. It should be noticed
that the ECL (4) may be rewritten to yield an expression
for the rate of entropy production in this model as
\[
\frac{dS}{dt} = -\frac{\dot{\Lambda} R^3}{8\pi G},
\]
showing that \(\Lambda\) must decrease in the course of time, while
the energy is transferred from the decaying vacuum to the
material component (for more details see [15, 20, 22]).

At this point, we stress the difference between models
with cosmological constant and a decaying vacuum en-
dergy density. In the later case, it is usually argued that
the vacuum energy density is a time-dependent quantity
because of its coupling with the other matter fields of the
Universe. By virtue of the expansion, one may suppose
that the cosmological constant is relaxing to its natu-
ral value (\(\Lambda = 0\)). Broadly speaking, the main goal of
such models is to determine how the energy that drove
inflation at early stages, and accelerates the universe at
present is related to the current small value of \(\Lambda\). Some-
times the decaying vacuum energy density is assumed to
be an explicit time decreasing function. However, in the
majority of the papers, it depends only implicitly on the
cosmological time through the scale factor (\(\Lambda \sim R^{-2}\))
or the Hubble parameter (\(\Lambda \sim H^2\)), or even a combi-
nation of them [16, 18, 19]. An extensive list of phe-
nomenological \(\Lambda\)-decay laws can be seen in the paper by
Overduin and Cooperstock [21]. All these models have
the same Achilles’ heel: there is no Lagrangian description
including the coupling term (nor any physical mecha-
nism) governing the energy change between the decaying
vacuum and other matter fields. The expression defining
\(\Lambda(t)\) is obtained either using dimensional arguments or
in a completely ad hoc way. However, although essen-
tially phenomenological, such an approach may indicate
promising ways to solve the cosmological constant prob-
lem by establishing the effective regime to be provided
by fundamental physics.

Certainly, one of the simplest possibilities for a decay-
ing vacuum energy density is \(\rho_v = \Lambda(t)/8\pi G = \beta \rho_T\),
where \(\rho_v\) is the vacuum energy density, \(\rho_T = \rho_v + \rho\) is
the total energy density, and \(\beta \in [0, 1]\) is a dimensionless
parameter of order unity [16, 18]. By combining such
a condition with the first EFE equation one obtains the
scaling law \(\Lambda(t) \sim H^2\), a natural result from dimensional
arguments. In this scenario, the expansion may be accel-
erated as required by SNe observations, and unlike the
model proposed by Ozer and Taha [17] and Chen & Wu
[18], for which \(\Lambda \sim R^{-2}\), it solves the age problem at
\(z = 0\) [18].

From the observational viewpoint, \(\Lambda(t)\)CDM models
possess an interesting characteristic that may distinguish
them from \(\Lambda\)CDM models. Due to the possibility of an
adiabatic photon production the standard temperature -
redshift relation may be slightly modified. For a large
class of models the temperature is given by [20, 22]
\[
T(z) = T_o \left(1 + z\right)^{1-\beta},
\]
where $T_o$ is the temperature of CMB at $z = 0$. This expression implies that for a given redshift $z$, the temperature of the Universe is lower than in the standard photon-conserved scenario. Although some recent determinations of $T(z)$ (based upon the $J = 0, 1, \text{and} 2$ ground state fine-structure levels of Cl) have obtained values roughly consistent with the standard prediction, it is well known that such measurements must be taken as upper limits once many other excitations mechanisms may have contributed to the observed level populations. In particular, by considering collisional excitations, Molaro et al. [22] found a temperature for the CMB of $T_{\text{CMB}} = 12.1^{+1.7}_{-5.2}$ K at $z = 3.025$. This result implies $\beta \leq 0.22$ at $2\sigma$. More stringent constraints are furnished by big bang nucleosynthesis (BBN). Initially, Birkel and Sarkar [24] obtained $\beta \leq 0.13$, whereas a slightly greater upper bound, $\beta \leq 0.16$, was further derived by Lima et al. [25]. In such analyzes, it was assumed that the $\beta$ parameter has the same value during the vacuum-radiation and vacuum-matter dominated epochs. Probably, if one relaxes this hypothesis it will be much easier to satisfy the nucleosynthesis constraints and solve other cosmological problems. Constraints from SNe observations, angular diameter versus redshift relation, gravitational lensing and other kinematic tests (assuming a constant $\beta$ parameter) have been discussed by many authors [18, 19, 26, 27, 28, 29].

**B. X-Matter**

In the Cosmological scenarios driven by X-matter plus cold dark matter (sometimes called XCDM parametrization) both fluid components are separately conserved [30]. The equation of state of the dark energy component is $p_x = w(z)p_x$. Unlike to what happens with scalar field motivated models where $w(z)$ is derived from the field description [31], the expression of $w(z)$ for XCDM scenarios must be assumed a priori. Usually, it varies with some power of the redshift, say, $w(z) = w_o(1 + z)^n$. Models with constant $w$ are the simplest ones and their free parameters can easily be constrained from the main cosmological tests.

More recently, in order to detect the possibility of bias in the parameter determination due to the imposition $\omega \geq -1$, some authors have studied models with constant $w$ by considering two different cases: the standard XCDM ($-1 \leq \omega < 0$) and the extended XCDM (also named “phantom” energy [32]) in which the $\omega$ parameter violates the null energy condition and may assume values $< -1$. In the case of X-ray data from galaxy clusters, for instance, a good agreement between theory and observations for $w > -1$ is possible if $0.29 \leq \Omega_m \leq 0.33$ (68.3% c.l.) and $\omega \leq -0.55$ [33]. These results are in line with recent analyses from distant SNe Ia [34], SNe + CMB [35], SNe + LSS [36], gravitational lensing statistics [37] and the existence of old high redshift objects (OHRO’s) [38]. In particular, Garnavich et al. [34] used the SNe Ia data from the High-Z Supernova Search Team to find $\omega < -0.55$ (95% c.l.) for flat models whatever the value of $\Omega_m$ whereas for arbitrary geometries they obtained $\omega < -0.6$ (95% c.l.). Such results agree with the constraints obtained from a wide variety of different phenomena, using the “concordance cosmic” method [39]. In this case, the combined maximum likelihood analysis suggests $\omega \leq -0.6$, which ruled out dark components like topological defects (domain walls and string) for which $\omega = -n/3$, being $n$ the dimension of the defect. More recently, Lima and Alcaniz [40] investigated the angular size - redshift diagram ($\theta(z)$) models by using the Gurvits’ et al. published data set [41]. Their analysis suggests $-1 \leq \omega \leq -0.5$ whereas Corasaniti and Copeland [42] found, by using SNe Ia data and measurements of the position of the acoustic peaks...
TABLE I: Limits to \( \Omega_m \) and \( \omega \)

| Method                  | Reference | \( \Omega_m \) | \( \omega \) |
|-------------------------|-----------|----------------|-------------|
| CMB + SNe Ia............ | [30]      | \( \sim 0.3 \) | \( \sim -0.6 \) |
|                         | [35]      | \( \sim < -0.6 \) |
| SNe Ia + LSS............ | [36]      | \( \sim < -0.6 \) |
| GL................................| [37]      | \( \sim -0.55 \) |
| X-ray GC.................. | [33]      | \( \sim 0.32 \) | \(-1 \) |
| X-ray GC \(^a\)........... | [33]      | \( \sim 0.31 \) | \(-1.32 \) |
| SNe Ia.................... | [34]      | \( \sim < -0.55 \) |
| SNe + X-ray GC \(^a\).... | [45]      | \( \sim 0.29 \) | \(-0.95^{+0.30}_{-0.35} \) |
| SNe Ia + GL............... | [46]      | 0.24           | \(< -0.7 \) |
| OHRO’s.................... | [38]      | 0.3            | \(< -0.27 \) |
| Various................... | [39]      | 0.2 - 0.5      | \(< -0.6 \) |
| \( \theta(z) \).......... | [40]      | 0.2            | \(< -1.0 \) |
|                         | [42]      | \( \sim < -0.96 \) |
| \( \Delta \theta \)...... | [43]      | 0.2 - 0.4      | \(< -0.5 \) |
| CMB....................... | [47]      | 0.3            | \(< -0.5 \) |
| CMB + SNe + LSS........ | [44]      | 0.3            | \(< -0.85 \) |
| CMB + SNe + LSS........ | [51]      | \( \sim < -0.71 \) |
| CMB + SNe + LSS\(^a\)   | [51]      | \( \sim > -2.68 \) |

\(^a\)extended XCDM

The case for extended XCDM is an interesting one. First, it was observed that a dark component with \( \omega < -1 \) may provide a better fit to SNe Ia observations than do \( \Lambda \)CDM scenarios \( [32] \). Although having some unusual properties, this “phantom” behavior is predicted by different approaches as, for example, kinetically driven models \( [48] \) and some versions of brane world cosmologies \( [49] \) (see also \( [50] \) and references therein). In actual fact, the best-fit model is considerably modified when the “phantom” behavior is allowed. In particular, for the X-ray data from galaxy cluster quoted above, it occurs for \( \Omega_m = 0.31, \omega = -1.32 \) and \( \chi^2_{\text{min}} = 1.78 \) \( [33] \). Such limits are more restrictive than the ones obtained by Hannestad & M"ortsell \( [51] \) by combining CMB + Large Scale Structure (LSS) + SNe Ia data. At 95.4% c.l. they found \(-2.68 < \omega < -0.78 \).

A summary of recent constraints on the dark energy parameter \( \omega \) is presented in Table I. As one may see there, the estimates of \( \Omega_m \) and \( \omega \) are compatible with the results obtained from many independent methods. In general, joint analyses involving X-ray data, gravitational lensing, OHRO’s, SNe type Ia, CMB, and other different methods are very welcome. First, in virtue of the gain in precision as compared to studies using only a specific set of data. The second reason, and, perhaps more important, is that most of cosmological tests are highly degenerate, thereby constraining only certain combinations of cosmological parameters but not each parameter individually.

C. Chaplygin-type gas

It is widely known that the main distinction between the pressureless CDM and dark energy is that the former agglomerates at small scales whereas the dark energy is a smooth component. Such properties seems to be directly linked to the equation of state of both components. Recently, the idea of a unified description for
CDM and dark energy scenarios has received much attention. For example, Wetterich [52] suggested that dark matter might consist of quintessence lumps while Kasuya [53] showed that spintessence type scenarios are generally unstable to formation of $Q$ balls which behave as pressureless matter. More recently, Padmanabhan and Choudhury [54] investigated such a possibility through a string theory motivated tachyonic field. Another interesting attempt at unification was suggested by Kamenshchik et al. [55] and further developed by Bilić et al. [56] and Bento et al. [57]. It refers to an exotic fluid, the so-called Chaplygin type gas ($C_g$), whose equation of state is

$$ p_{C_g} = -A/\rho^\alpha, $$

(7)

where $A$ and $\alpha = 1$ are positive constants. The above equation for $\alpha \neq 1$ constitutes a generalization of the original Chaplygin gas equation of state proposed in Ref. [57], whereas for $\alpha = 0$, the model behaves as $\Lambda$CDM. The idea of a Unified Dark-Matter-Energy (UDME) scenario inspired by an equation of state like (7) comes from the fact that the Chaplygin type gas can naturally interpolate between non-relativistic matter and negative-pressure dark energy regimes [56, 57]. Since in this approach there is only one dark component beside baryons, photons and neutrinos, some authors have termed this UDME scenario as a Quartessence cosmology [58].

Motivated by these possibilities, there has been growing interest in exploring the theoretical and observational consequences of the Chaplygin gas, not only as a possibility for unification of the dark sector (dark matter/dark energy) but also as a new candidate for dark energy only. The viability of such cosmological scenarios has been confronted by many observational results and their two free parameters have been constrained by many authors. For example, Fabris et al. [59] analyzed some consequences of such scenarios using type Ia supernovae data (SNe Ia). Their results indicate that a cosmology completely dominated by the Chaplygin gas is favored in comparison to $\Lambda$CDM models. Recently, Avelino et al. [60] used a larger sample of SNe Ia and the shape of the matter power spectrum to show that such data restrict the model to a behaviour that closely matches that of a $\Lambda$CDM models while Bento et al. [61, 62] showed that the location of the CMB peaks imposes tight constraints on the free parameters of the model. More recently, Dev, Alcaniz & Jain [63] and Alcaniz, Jain & Dev [64] investigated the constraints on the C-gas equation of state from strong lensing statistics and high-z age estimates, respectively, while Silva & Bertolami [65] studied the use of future SNAP data together with the result of searches for strong gravitational lenses in future large quasar surveys to constrain C-gas models. The trajectories of statefinder parameters [66] in this class of scenarios were studied in Ref. [67] while constraints involving Cosmic Microwave Background (CMB) data, Fanaroff-Ryley type IIb radio galaxies and X-ray data from galaxy clusters, have also been extensively discussed by many authors either as a dark energy or in the UDME picture [58, 62, 65, 68, 69].

### III. CONCLUSION

The search for cosmologies driven by dark energy is presently in vogue. The leitmotiv is the observational support for an accelerated Universe provided by the type Ia supernovae (SNe) experiments at intermediate and high redshifts.

This short review focused on some alternative candidates to dark energy. This ubiquitous component plus the dark matter are responsible for nearly 95% of the matter-energy content filling the Universe. However, different from dark matter, the extra dark (energy) component is intrinsically relativistic and its negative pressure...
FIG. 2: The Chaplygin gas solution for SNe observations. The plot shows the deceleration parameter in the original Chaplygin gas ($\alpha = 1$) as a function of redshift for some selected values of $\Omega_m$ and $A_s = A \rho_0^{-2}$. The horizontal line ($q_o = 0$) divides models with a decelerating or accelerating expansion at a given redshift. Note that all models are accelerating at redshifts $z \lesssim 1$ (from Dev, Jain and Alcaniz [63]).

is required by the present accelerating stage of the Universe. Its tiny density and weak interaction presumably preclude the possibility of identification in the terrestrial laboratory. Unfortunately, even considering that we are in the golden age of empirical cosmology, the existing data are still unable to discriminate among the different dark energy candidates, thereby signaling that we need better observations in order to test the basic predictions. This means that the determination of cosmological parameters will continue to be a central goal in the near future. The fundamental aim is to shed some light on the nature of the dark energy, but it is not clear if it can be revealed using background tests with basis only in a different equation of state. Another possibility is to add some hypothesis concerning the nature itself (is it formed by massive or massless particles?), and to follow examining its consequences. It is also worth notice that the energy of this relativistic dark component grows in the course of an adiabatic expansion. Macroscopically, the energy increases on account of the thermodynamic work done on the system (negative pressure). This intriguing behavior is in marked contrast to what happens to any component with positive or null pressure. Naturally, a possible microscopic explanation for such a fact is of great interest because it depends on the intrinsic nature of the dark energy, and may also have important consequences to the ultimate fate of the Universe.

On the other hand, since the current models are more complicated than the Einstein-de Sitter Universe, such a situation is somewhat uncomfortable either from theoretical or observational viewpoints. It has also to be admitted that none dark energy model has been successful enough to deserve the status of a “standard model”. However, the present time for many cosmologists is very exciting because although preserving some aspects of the basic physical picture, the new invisible actor (dark energy) which has not been predicted by the standard model of Particle Physics, and is responsible for repulsive gravity, may alter profoundly the traditional view of space-time and matter.

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