

A Universe dominated by dark energy?

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Abstract. Observations of our Universe have led to a current consensus model which has a number of unexpected and, some would say bizarre characteristics. These include two epochs in time when it exhibits a ‘strange’ behaviour, namely the Big Bang moment of creation itself and the subsequent period of initial inflation. In addition the models now require two unseen and dominant constituents of the Universe to explain its dynamics, which are known as ‘dark matter’ and ‘dark energy’. Having said that, once these four features are included the model is very successful in explaining a vast range of astronomical observations, spanning virtually the whole lifetime of the Universe. This paper focusses on dark energy, starting from an historically much simpler model and then building up to the present day understanding with reference to the key observations which have driven changes in paradigm. Possible suggestions as to the nature of dark energy are considered and finally a section is included concerning how future observations may lead to a better understanding.

1. Introduction

The development in recent decades of modern instrumentation to observe our Universe has revolutionised our perception and understanding of how it behaves and how it has evolved. There is now an enormous volume of precision data which has permitted construction of sophisticated mathematical models of the Universe that can be tensioned against the observations. Although these models have a number of free parameters the agreement with data is extensive and compelling. Moreover the constraints on the various free parameters are sufficiently tight that it appears inescapable that the Universe contains both dark matter (DM) and dark energy (DE). These two components serve different complementary purposes with the DM providing additional gravitational source mass pulling the Universe together, whilst the DE acts to push the Universe apart. Only a brief summary of DM will be given below.

2. Models of the Universe

Before the advent of modern telescopes allowing the true nature of objects seen in the night sky to be understood, the prevailing view was that the Earth was effectively the centre of the Universe. This changed in the 17th century with Isaac Newton’s laws of gravity [1], which provided the basis for understanding how gravity worked as a force. The two basic equations relevant in this context are;

$$F_g = \frac{Gm_1m_2}{r^2}, \quad (1)$$



where F_g is the gravitational force acting between two (gravitational) masses, m_1 and m_2 , and r is the separation between them and G is a constant, and

$$F = ma, \tag{2}$$

where a is acceleration of the (inertial) mass, m , caused by the force F .

Application of these equations to the behaviour of the Solar System subsequently prompted a change to a Sun-centred cosmology for the known Universe at that time. The next critical step forward was the formulation of gravity proposed by Albert Einstein as General Relativity (GR) in 1916 [2] and applied to cosmology in 1917 [3]. GR forms the underlying basis of all modern cosmological models. GR is a geometrical theory in which the very structure of spacetime is modified by the presence of gravitational sources. This is embodied within the (field) equations for GR;

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -\kappa T_{\mu\nu}, \tag{3}$$

where $T_{\mu\nu}$ represents the so-called stress-energy-momentum content of spacetime, $\kappa \left(= \frac{8\pi G}{c^4} \right)$ is a constant and the terms on the left-hand side describe the response of spacetime to its content. Λ is the cosmological constant which Einstein added in 1917 [3] to allow a closed static Universe to exist. Although he later abandoned it, the apparent correspondence with DE has prompted its readoption. Equation 3 is a complex set of coupled equations and allows for various solutions.

2.1. Basic theoretical cosmological models using GR

In the years following the publication of GR and Einstein's static Universe model, there were a number of solutions found relevant to cosmology. The first of these was from Willem de Sitter in 1917 [4] and this considered a hypothetical universe including the Λ term but with zero matter content. The solution showed an open universe undergoing continual accelerating expansion. Alexander Friedmann produced the first general framework for a homogeneous and isotropic universe in 1922 [5]. Georges Lemaître was the first to postulate that the real Universe was expanding and that this should be seen by the recession of nearby galaxies [6]. Shortly after this relevant astronomical observations began to influence the development of specific models and the Einstein-de Sitter model of 1932 [7], prompted by the measurement of galaxy recession velocities, was the first of many. Some example curves showing the expansion scale factor, a/a_0 , of the 'size' of the Universe as a function of time are shown in figure 1. Values of Ω_m are for densities as a fraction of the critical density above which the evolution becomes closed and the Universe will recollapse.

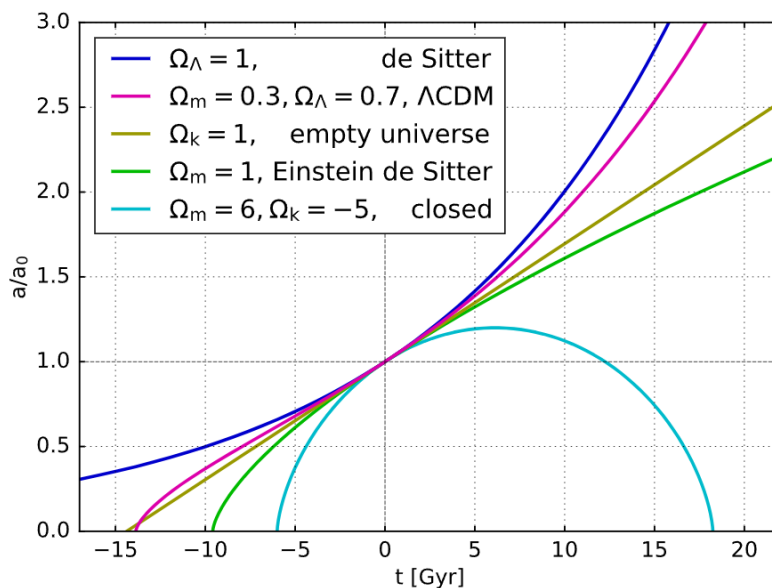


Figure 1. Expansion curves for various universe models, showing behaviours from closed (recollapsing) to open ever expanding geometries. Credit: Geek3 - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=58089339>.

2.2. Astronomical observations which changed cosmology

2.2.1. *Expansion.* Arguably the most significant single measurement which has influenced cosmology is the original clear identification of recession velocities by Hubble in 1929 [8]. This established that the Universe was indeed expanding and that there was a linear relation between distance and velocity. This pointed to the possibility of a moment of origin (creation) which Lemaître suggested could be quantum in nature [9].

2.2.2. *Dark Matter.* At around this same time there were the first observations made which started to question how much non-luminous gravitating material there might be. These included looking at local stellar population densities [10] and galaxy cluster dynamics [11]. The galaxy cluster dynamics in particular did not seem consistent with the virial theorem applied to bound clusters unless there were significant amounts of unseen matter - this was the first serious suggestion of DM. However, further convincing evidence was not forthcoming until measurements of individual galaxy rotation curves became reliable and the turning point for the case for DM was in the late-1970s with the extensive surveys of Rubin et al. [12]. As more general astrophysical information was accrued a number of other questions arose, including why the Universe showed isotropy throughout when there should be no apparent casual connection (horizon problem), why its matter density was close to critical (the flatness problem) and where the seeds for galaxy formation came from. A possible single solution to these questions came from the theory of inflation during a very early phase of the Universe following a Big Bang creation. These theories [13] naturally seemed to suggest $\Omega_m = 1$ which supported the notion of DM as this required densities far in excess of that deduced from the visible matter content alone. The year 1982 saw three papers developing the cold dark matter (CDM) paradigm as a basis for the Universe [14]-[16]. Further evidence for (cold) dark matter was coming from x-ray observations from clusters, gravitational lensing observations and particularly from n-body simulations [17] looking to understand the formation of structures growing out from the seed density fluctuations as seen from cosmic microwave background (CMB) observations of the Universe $\sim 350,000$ years after the Big Bang.

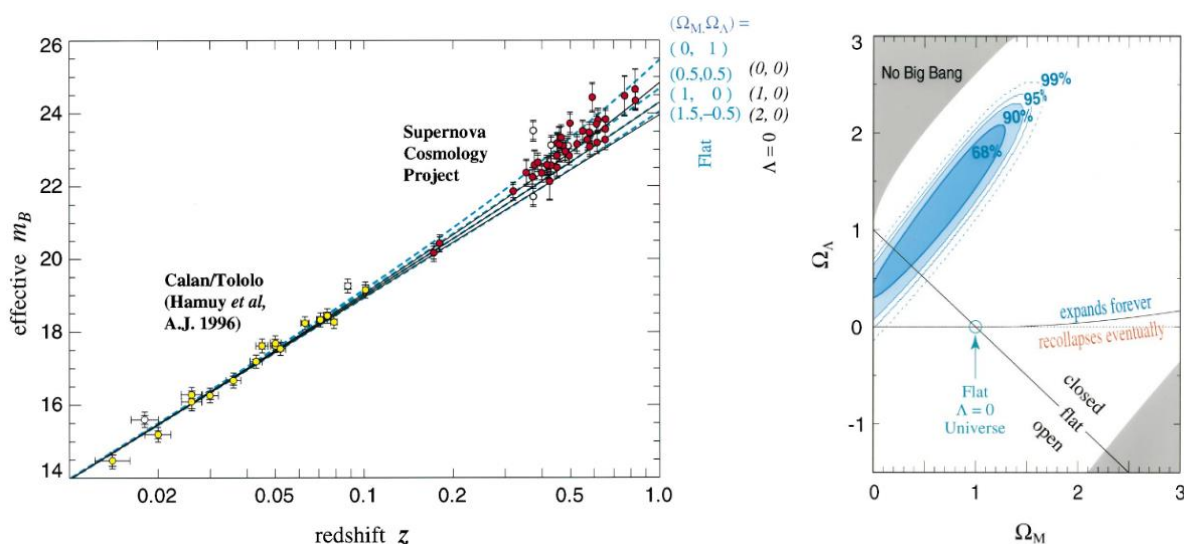


Figure 2. The left-hand plot shows the Hubble diagram for 60 type Ia supernovae. The lower redshift supernovae come from the earlier Calán/Tololo Supernova Survey [18]. The higher redshift sample is from the Supernova Cosmology Project. The solid and dashed curves show the expected relationship for various combinations of Ω_m and Ω_Λ . Note the horizontal scale is logarithmic. The right-hand plot

shows the combined constraints on Ω_m and Ω_Λ as the blue shaded confidence regions. Both plots are taken from [19].

2.2.3. Dark Energy. The first evidence for DE came in 1998 from observing the brightness of Type Ia supernovae used as standard candles to map out the expansion of the Universe [20]. This was closely followed by another group using a different selection of supernovae but producing a similar result [19]. Considering the supernovae as standard candles, the two groups plotted the measured magnitude, albeit with some well-founded corrections, as a function of the measured redshifts. The precise relationship between redshift and distance will depend on the details of how the Universe is expanding and this in turn will depend on the composition of the Universe in terms of its mass content (Ω_m) and its energy content (Ω_Λ). The left-hand plot in figure 2 shows the result from one of the groups. The solid and dashed curves show the expected relationship for various combinations of Ω_m and Ω_Λ and it can be seen that there is a systematic shift away from the pure CDM cosmology ($\Omega_\Lambda = 0$) shown by the high-redshift supernovae. The right-hand plot in figure 2 shows the combined constraints derived for Ω_m and Ω_Λ as blue shaded confidence regions. The constraints showed two things. Firstly Ω_Λ was unlikely to be zero and secondly Ω_m was likely to be larger than that allowed in the baryonic sector by primordial nucleosynthesis models [21]. Hence this was a simultaneous indication of both DE and DM with DE causing an enhanced outward acceleration of the Universe, as evidenced by the lower than expected brightness (higher magnitude) of more distant supernova which appear further away, and DM needed to deepen the gravitational potential opposing the expansion to get the right balance. This was the birth of the Λ CDM model of the Universe.

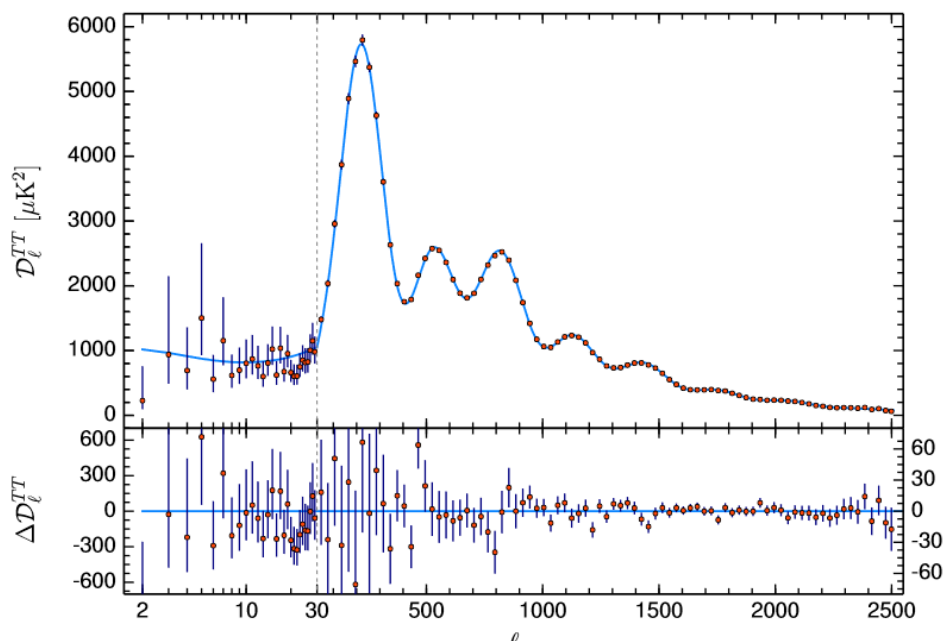


Figure 3. The Planck temperature angular power spectrum. The top plot shows the data together with the best fit curve using a 6-parameter flat Λ CDM model of the Universe. The lower plot shows the residuals between the fit and the data. Note the horizontal axis changes from logarithmic to linear at $l = 30$. The image is taken from [22].

Since 1999 the model has been consolidated by bringing together more and more astrophysical observations to look for parameter values within the model which best fit all data simultaneously. The most recent new data is from the Planck satellite measuring the anisotropies in the cosmic microwave background [22]. Figure 3 shows the angular power spectrum from the temperature data of the CMB

map taken by the Planck satellite. The solid blue line shows the best fit to the data using a model of the Universe with six free parameters based on a Λ CDM cosmology. The data shows some non-trivial complex features and yet the model fit reproduces them very closely. An extensive suite of other data has been used to constrain the fit, including: other high-precision CMB measurements, baryon acoustic oscillation measurements from galaxy redshift surveys, Type Ia supernovae, redshift-space distortions in galaxy redshift surveys, measurements of the Hubble constant, weak gravitational lensing of galaxies by large-scale structures, galaxy clustering and cross-correlation within large-scale structure, and counts of clusters of galaxies. The stated conclusion is that the authors find ‘... *good consistency with the standard spatially-flat 6-parameter Λ CDM cosmology ...*’ with a constraint of $\Omega_{\Lambda} = 0.6847 \pm 0.0073$. Hence the presence of a DE component is not only confirmed, it is the dominant component. The corresponding matter density constraint is $\Omega_m = 0.315 \pm 0.007$ split 84:16 between cold dark matter and baryonic matter (otherwise referred to as ‘normal matter’). Hence we appear to live in a bizarre Universe where everything we can see around us and out in space is only 4.9% of what is actually there, at least when expressed as an energy density. The burning questions are then what is the true nature of DM and what is the true nature of DE?

3. The nature of the dark sector

The answer to both of the questions posed at the end of the last section is similar but unhelpful in many ways. As yet there are no definitive direct positive measurements to guide us in either case, although there are some useful null results from the direct DM searches.

3.1. Dark matter

There are two generic types of solution offered for DM. One is to introduce a new species of particle produced in the early Universe, which predominantly only interacts gravitationally. Examples of popular types receiving an early focus are hypothetical particles such as weakly interacting massive particles (WIMPs) and axions, both already proposed to exist for other reasons. However, despite direct searches for these there are no clear detections to date despite significant improvements in experiment sensitivities. In addition there has been no convincing sign of any signatures of relevant effects beyond the Standard Model in collider experiments, such as the LHC or from indirect searches (in gamma-rays and/or neutrinos) for annihilation products. This has led to a recent vast expansion in the theoretical landscape of possible new particle species introduced specifically to solve the DM problem [23]. The second approach is to try to modify either the behaviour of gravity or the inertial response to gravity in the low acceleration regime. The most popular and persistent approach is that of MOND (MODified Newtonian Dynamics) [24]. MOND was first proposed to address the flat galaxy rotation curve dilemma. As such it was a non-relativistic formulation and could not easily be adapted to work in situations where GR was required, i.e. for gravitational lensing or on the scale of the Universe. However, there have been extensive works to try to find extensions to GR which provide a MONDian type behaviour at low-accelerations and efforts continue [25] despite much inherent opposition.

3.2. Dark energy

It is beyond the scope of this paper to fully review all the works on DE as these are very numerous and diverse (and very theoretical). The summary talk in 2015 stated there were “... *more than 10,000 papers on different explanations/models...*” [26]. Hence a recent summary paper will be used to distil the current situation. For this it is useful to turn again to the Planck results which have been used to address the implications for both DE and modified gravity [27]. To set the scene, in the introduction of this 2015 work there is the following; “...*there appears to be a vast array of possibilities in the literature and no agreement yet in the scientific community on a comprehensive framework for discussing the landscape of models [DE]*”.

3.2.1. A vacuum energy density. The simplest but not particularly illuminating model for DE is to just accept that Λ is a basic cosmological constant within the theory as originally introduced by Einstein [3]. Mathematically this works at the moment, as evidenced by the excellent model fits to the data. It is a single parameter, whose value according to the Planck measurements is $\Lambda = (4.24 \pm 0.11) \times 10^{-66} \text{eV}^2$ [22]. It is tempting to consider Λ as arising from a vacuum energy density [28]. However, estimates of its value are many orders of magnitude larger than the derived value. This in itself is a separate conundrum.

3.2.2. A background fluid medium. In this case the DE is considered to act like a background fluid exerting an outward pressure and with an equation of state of the form

$$w = p/\rho, \tag{4}$$

where p is the pressure and ρ is the energy density. If DE is due to the cosmological constant the expectation is that $w = -1$. However, in principle this type of approach can be extended to fluids with a time-dependent equation of state. To first order in a Taylor expansion this can be represented as $\{w_o, w_a\}$ and written in terms of the scale factor, a , of the Universe, which gives

$$w(a) = w_o + (1 - a)w_a. \tag{5}$$

3.2.3. Field theory approach. Here the effect of DE arises from generalised classes of interaction. Effective field theory [29], [30] constructs Lagrangians representing all plausible symmetry operations, whilst specific less well motivated theories can be constructed by direct parameterisations of potentials. Specific examples of effective field theories include [30]: quintessence, $f(R)$, k -essence, Galileon (Kinetic Braiding), DGP, Ghost Condensate, Horndeski (Generalised Galileon), and Horava-Lifshitz.

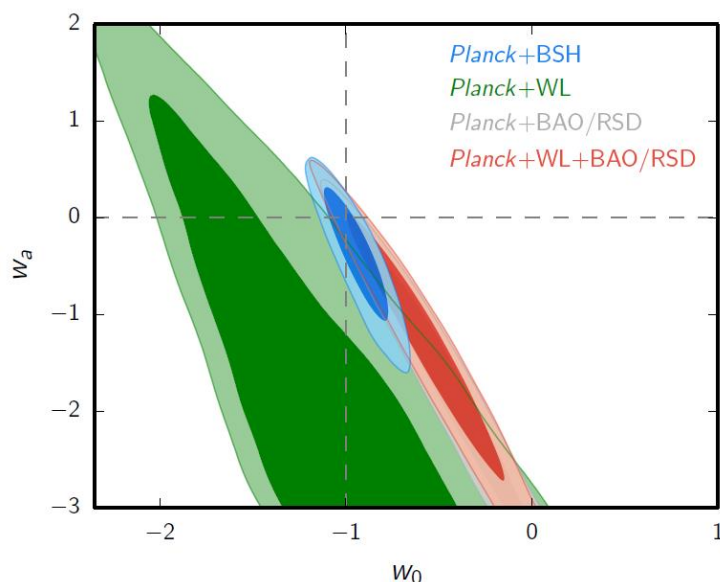


Figure 4. Combined constraints between w_o and w_a derived from the Planck data. The tightest constraints come from the use of Planck data combined with those from baryon acoustic oscillations, supernovae and measurements of the Hubble constant (the blue contours labelled BSH in the image). The image is taken from [27].

3.2.4. Tests of dark energy models. Analysis of the Planck data has resulted in constraints on a number of parameters within the various classes of DE theory [27]. Constraints are not yet particularly useful and it is not appropriate to enumerate all the results here. Instead the interested reader is referred to table 1 in [27] and the subsections and references contained therein. However, it is useful to discuss one result here which illustrates the potential of future measurements. This is a test looking for any first order variation of w in the context of a fluid-based model, and the combined constraints in w_o and w_a are shown in figure 4. The tightest constraints come from the blue shaded confidence regions

(see caption for a description of these) and the true solution should lie within those contours. Indeed it can be seen that the combination $\{w_o, w_a\} = \{-1, 0\}$ is consistent with the analysis and this shows that the Planck data are adequately fitted by a constant $w = -1$ solution as expected within a straightforward Λ CDM cosmology.

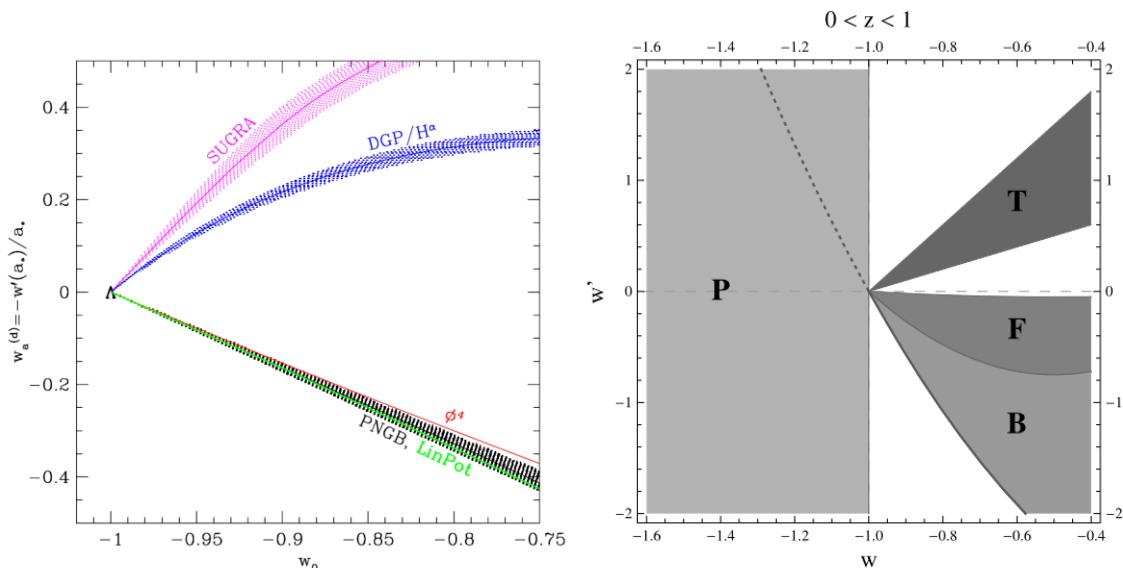


Figure 5. The two plots show regions where solutions for w_o and w_a lie in various types of DE model that can be represented by an equation of state similar to equation 5. The left-hand image is taken from [31] and the right-hand image is from [32].

It is now interesting to ask how tight the combined $w_o - w_a$ constraints need to get before something useful can be said about discriminating between different DE options? Figure 5 shows some example plots of how $\{w_o, w_a\}$ varies as parameters within the models are changed whilst keeping the various cosmological energy densities compliant with observations¹. The first point to note is that $\{w_o, w_a\} = \{-1, 0\}$ is allowed in all models. If this were the actual combination which nature has selected, then it cannot be distinguished from a cosmological constant with this method. The second point is that the potential maximum departure from $\{-1, 0\}$ is comparable to the size of the blue shaded region in figure 4. Hence to show that the equation of state is not only different from $\{-1, 0\}$ but also to differentiate between the various models requires an improvement of an order of magnitude in the measurement uncertainties. The next major advances in astrophysical measurements focussing on the DE will be from the Euclid satellite of the European Space Agency [33]², the Large Synoptic Telescope (LSST) [34] and the WFIRST-AFTA satellite of NASA [35]. Results from these projects are likely to start to come in the mid-2020s. A very interesting prospect in the longer timeframe is offered by the space gravitational wave project, LISA which will be launched in the mid-2030 timeframe [36]. This offers a very different and possibly competitive measurement approach.

4. Discussion

4.1. The state of the Universe

¹ Note that both of these images are from articles which are pre-Planck and assumed cosmological energy densities differ somewhat.

² Euclid was successfully launched on 1st July 2023.

The observational data which leads to the conclusion that the Universe appears to be dominated by both DE and DM is wide ranging across all scales in the Universe and the case is compelling. The Λ CDM model is very successful at explaining a multiple of disparate types of observation in a consistent way. Many ideas exist about the possible nature of both components, but direct experimental verification is lacking despite many decades of effort.

In the case of DM the likely options are relic particles of one sort or another and/or modified gravity. Relic particles can possibly be detected directly through scattering/conversion laboratory experiments or indirectly through the observation of annihilation/decay products. New particles might be produced in collider experiments. There is some hope here as new experiments are coming on line. Detection of modified gravity effects should appear in low acceleration regimes and observation will rely on precision measurements of motions, either in the Solar System (difficult) or through stellar motions such as wide binaries seen in the GAIA data [37]. It is even possible that dedicated weak field experiments (with the equivalence principle such as MICROSCOPE [38] for example) could provide some clues. Finally there have even been some ideas about exploring satellite missions to visit the gravitational saddle point between the Sun and the Earth.

In the case of DE the likely options are new fields of one sort or another and/or modified gravity. Direct experimental detection of relevant new fields seems impossible and further progress relies on more precision astrophysical observations. Detection of modified gravity [39] effects relevant to DE might again come from dedicated weak field experiments.

4.2. *The fate of the Universe*

Within standard Λ CDM with the DE given by a cosmological constant the expansion future of the Universe should follow the trajectory shown in figure 1, i.e. it will expand forever, cooling as it goes [40]. However, other theoretical options for DE where it does not behave like a constant could offer different futures ranging from a more aggressive expansion rate to a closed universe, which ultimately might recollapse. If recollapse does occur, there are even ideas involving recurrent bounce cycles. Differentiating between these is made very difficult however as the current era in which we find ourselves is at the point where all options converge (figure 1) and the immediate future paths look similar, requiring more precision observations to identify or limit the number of options.

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