Cosmos and History: The Journal of Natural and Social Philosophy, vol. 5, no. 2, 2009

DARK MATTER, DARK ENERGY AND MODERN COSMOLOGY: THE CASE FOR A KUHNIAN PARADIGM SHIFT

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ABSTRACT: Several works in the last few years devoted to measure fundamental probes of contemporary cosmology have suggested the existence of a delocalized dominant component (the "dark energy"), in addition to the several-decade-old evidence for "dark matter" other than ordinary baryons, both assuming the description of gravity to be correct. Either we are faced to accept the ignorance of at least 95 % of the content of the universe or consider a deep change of the conceptual framework to understand the data. Thus, the situation seems to be completely favorable for a Kuhnian *paradigm shift* in either particle physics or cosmology. We attempt to offer here a brief discussion of these issues from this particular perspective, arguing that the situation qualifies as a textbook Kuhnian anomaly, and offer a tentative identification of some of the actual elements typically associated with the paradigm shift process "in the works" in contemporary science.

KEYWORDS: Cosmology, dark matter, dark energy, scientific revolutions, T.S. Kuhn

INTRODUCTION

Thomas S. Kuhn (1922-1996) in the 20th century imprinted a strong pattern under which scientific research is seen today. Even philosophers, historians and epistemologists which disagree with his views about these subjects still find difficult to avoid a discussion for or against Kuhn's own framework (see, for example, S. Fuller 'Is There Philosophical Life after Kuhn?', *Philosophy of Science*, vol. 68, 2001, 565-572).[1]

In his book *The Structure of Scientific Revolutions* the author discussed in a long essay style the basic concepts and operating mechanisms of the scientific enterprise, quite often resorting to a normative viewpoint.[2] Scientific progress is seen mainly as a

[1] Fuller, S., 'Is There Philosophical Life after Kuhn?' *Philosophy of Science*, vol.68, 2001, 565-572.
[2] Kuhn, T.S. (K70).*The Structure of Scientific Revolutions*, Chicago, Univ. Chicago Press, 1970.

succession of paradigm shifts between periods of "normal science", inside which the task of the scientists is rather to confirm and reinforce the existing paradigms. The boundaries of these "normal science" periods have been termed by him *scientific revolutions*, truly extraordinary episodes in the research history, triggered by the repeated failure in solving a (big) problem(s) in the field and/or a new discovery shaking the very field foundations and not easily fitted into the existing paradigm. The latter concept may be in turn defined the sum of the theories and value commitments shared by the scientific group, later rephrased provisionally as "discipline matrix" for this specific meaning. According to this definition, the scientific groups are bound by theories but also other elements (concepts, procedures and even symbolic generalizations usually called "laws" such as Newton's $\vec{f} = m \times \vec{a}$ and a similar entities), constituting the common grounds on which research is conducted. Scientific research is thus seen from a common context (*gestalt*), and it is only when the efforts to fit a problem/phenomenon into the paradigm fail repeatedly that "extraordinary science" sets in, and is accepted (or rather, tolerated) by traditionalists in search of a more satisfactory understanding. A lot of criticism has been published against these ideas, and sometimes bold extrapolations of them constructed for application in other fields, like public policies and pedagogy. In addition, the Kuhnian perspective has been recognized as akin to Darwinian evolution, or rather to the *stasis* theory of Eldredge and Gould[3] postulating punctuated equilibrium of biological evolution instead of a gradual and continuous change of life forms.

Cases which may be considered textbook examples of the paradigm shift are known in several sciences (although never without some dispute). They range from truly big, ground-shaking revolutions such as the well-known Copernican and Newtonian; to smaller and more specialized events like the emergence of gauge principles in field theory. A more recent possible example, to which this work is devoted, is the case of modern cosmology in which one set of new facts is being widely discussed and seeking for a comprehensive global picture, still absent or very blurred. Because of its importance we shall outline the scientific case in some extent (but keeping technical details to a minimum) in the next section, with emphasis to the connections to previous ideas and results.

THE ACCELERATED UNIVERSE

Quite recently the interest in astrophysics and cosmology bloomed boosted by the advance of technological facilities, and allowed a series of studies which reached and captured the imagination of the public opinion. Specifically, cosmology has been highlighted by the reports from 1998 on about the *acceleration* of the universe seen in

[3] Eldredge, N. and Gould, S. J., 'Punctuated equilibria: an alternative to phyletic gradualism', in T.J.M. Schopf (ed.), *Models in Paleobiology*, San Francisco, Freeman, Cooper and Co , 1972.

studies of type Ia supernovae[4,5,6] with an indication of a non-zero value of a delocalized component known as "dark energy" (hereafter dark energy) as a possible (but not unique) solution.

The argument for suck a remarkable claim is as follows. Type Ia supernovae form a class of stellar explosions long associated to the death of an "old" evolved star. This general statements relies on the fact that, in contrast to other explosive events (known as type Ib, or type II) hydrogen is absent in the ejected gas. Therefore, it is concluded that the exploding star had exhausted the hydrogen and hence, it must have evolved from the hydrogen-burning phase well before the event. What is a crucial step, and forms the basis of the cosmological analysis is the contention that type Ia supernovae are quite homogeneous as long as their absolute brightness is considered, and therefore form a set of *standard candles*.

In addition, a remarkable relation between the maximum brightness and a time interval defined properly from the rise of the lightcurve to its decline has been discovered,[7] a feature that allows a further calibration of the astronomical magnitudes (that is, to infer the absolute brightness and to put a distance for each source).

When these explosions are observed in distant galaxies, affected by the expansion of the universe as discovered by Hubble and confirmed in several detailed works, their distances inferred by looking at the lightcurves can be compared to the distance to the same galaxy as inferred by the observations of the position of the atomic element lines (which gives the so-called *redshift*, long attributed to the very expansion of the *substratum* of spacetime). The claims by the dedicated groups can be rephrased as the assertion that distant supernovae are systematically fainter than they "should be" according to the constant Hubble flow. Hence, either supernovae were intrinsically *less* brilliant in the past, or the expansion has *accelerated*, and that is why they look dimmer than expected. Reasons to support the first possibility could be (and have been) advanced, but they were dismissed on observational grounds (for example, some "dust" component absorbing light should do so in the same amounts for each wavelength, something completely at odds with all types of actual cosmic dust observations). The data independently gathered by two different teams do show the same behavior and thus constitutes a cross-checked evidence for the proposed accelerated expansion.

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[4] Riess, A.G. et al., Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. Astron. J., 116, 1009-1038 (1998)

[5] Perlmutter, S. et al., 'Measurements of Omega and Lambda from 42 High-Redshift Supernovae', *Astrophys. J.*, vol. 517, 1999, 565-586.

[6] Tonry, J.L. et al. , 'Cosmological Results from High-z Supernovae'. arXiv astro-ph/0305008, 2003. Available at http://arxiv.org/.

[7] Hamuy, M., Phillips, M. M.; Suntzeff, Nicholas B.; Schommer, Robert A.; Maza, José and Aviles, R. : The Hubble Diagram of the Calan/Tololo Type IA Supernovae and the Value of H_0, *Astron. J.* vol. 112, 1996, 2398-2406 ; Riess, A. G., Press, W. H. and Kirshner, R. P.: A Precise Distance Indicator: Type IA Supernova Multicolor Light-Curve Shapes, *Astrophys. J.*, vol. 473, 1996, 88-98.

Strong as this evidence seems, it is still reinforced by a similar feature independently inferred from the combined data of the WMAP experiment and other initiatives measuring background radiation maps.[8,9] The experiments actually measure tiny temperature fluctuations in the cosmic fluid which decoupled from the rest of matter at the time in which the photons ceased to scatter off charged particles, at the era of hydrogen recombination. Recombination physics is quite well-known and the fraction of ionized hydrogen can be calculated with confidence, and even estimated from first principles. This happens quite early in the primitive expanding universe, at a time around 300 000 yr after the "Big Bang" itself, giving rise to an almost-perfect black body radiation (in fact, by far the best measured in Physics) if not for these tiny irregularities mentioned above. However, these are precisely the inhomogeneities (of the temperature and therefore of the matter density field coupled to it at the very early universe) which are believed to *grow* well after the hydrogen recombination, to eventually form galaxies and the structure of the present universe. It is by measuring the pattern of these fluctuations that the contribution of each component to the total energy density of the universe can be gauged. Generally speaking, cosmologists refer to these components in term of fractions of the closure density, a numerical value that would make the universe to have exactly zero curvature (or, more loosely, an exact balance of all components to produce a simple geometry). The measurements of the cosmic background radiation are strikingly compatible with the sum amounting to this critical value $\Omega_{tot} = 1$ (where $\rho_i / \rho_c \equiv \Omega_i$ is the referred fractional contribution of the i-th component to the closure density, and thus $\Omega_{tot} = \sum \Omega_i$). However, the direct counting of visible components do not amount to much more than $\Omega_{\substack{ordinary \\ matter}} \approx 0.04$, a result also limited from above by the element abundances of primordial nucleosynthesis.[10] Adding the dark matter component (see below), the total matter content of the universe must be $\Omega_{\substack{total \\ matter}} \approx 0.25$. Yet, the difference between the total matter content and the cosmic background radiation inference calls for a dominating component, precisely in the amount needed to explain the supernova data as well (as long as it can do the job of producing the required acceleration, which additionally requires quite a special relationship between its energy density and pressure).

[8] Netterfield, C.B. et al., 'A Measurement by BOOMERANG of Multiple Peaks in the Angular Power Spectrum of the Cosmic Microwave Background', *Astrophys. J.*, vol.571, 2002, 604-614 ; Halverson, N.W. et al. 'Degree Angular Scale Interferometer First Results: A Measurement of the Cosmic Microwave Background Angular Power Spectrum', *Astrophys. J.*, vol. 568, 2002, 38-45.

[9] Bennet, C. et al., 'First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results', arXiv astro-ph/0302207, 2003. Available at http://arxiv.org/

[10] Olive, K.A., Steigman, G. and Walker, T.P., 'Primordial nucleosynthesis: theory and observations', *Phys. Repts.*, vol. 333, 2000, 389-407.

These recent reports pointed to a problem that should be added to the ancient "dark matter" one, namely, the existence of a clustered component mostly of non-baryonic origin which adds another substantial fraction of the matter-energy content balance. Actually, this proposal dates back to the decade of 1930, when astronomer F. Zwicky compared the matter directly "seen" in the form of stars and gas residing in the galaxy[11] with the matter needed to hold the system together. Since the former fell short by a factor ~ 5-10 to do the job, he concluded that most of the matter was not producing light, and was then "dark" (in fact Zwicky firmly believed that these "dark particles" must be ordinary like protons and nuclei, therefore he rather spoke of "missing light"). Later, similar arguments based on observations were elaborated by many researchers, till the point that the "dark matter" problem became part of the disciplinary matrix of astronomy, rejected by a few and unsolved for several decades. We shall return to this point below to review how astronomers reacted to this situation and its possible relation to the newer "dark energy" fact.

Several possible alternatives for both dark matter and dark energy unexplained components are being considered by the cosmologists/particle physicists communities, the solutions ranging from "conservative" to "wild" approaches. No full solution, and in fact not even a firm hint of it is still available. In this situation we may legitimately wonder whether we are witnessing a scientific revolution "in the works", or if the problems could be rather solved within the existing concepts and theories. We attempt to offer here a brief discussion of these issues, with a tentative identification of some of the actual elements typically associated with the paradigm shift process.

STANDARD COSMOLOGY: FRIEDMANN - ROBERTSON – WALKER MODELS

After a somewhat lengthy development in the first half of the 20th century, the discovery of the cosmic microwave background radiation,[12] primordial nucleosynthesis[13] and large-scale structure[14] studies helped to shape what is called today the "standard" cosmology. The resonant success of General Relativity as a theory of gravitation prompted its application to the largest self-gravitating system of all, the Universe itself. For that purpose, the available data suggested, and a sensible theoretical thinking indicated, the adoption of the so-called Cosmological Principle. This statement is generally expressed as follows: the Universe looks the same in all directions and has no privileged position.

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[11] Wheeler, J.A., quoted for example in the New Scientist site http://www.newscientist.com/channel/fundamentals/mg16121747.700

[12] Penzias, A.A. and Wilson, R.W., ' A Measurement of Excess Antenna Temperature at 4080 Mc/s', *Astrophys.J.*, vol.142, 1965, 419-421.

[13] Olive, K.A., Steigman, G. and Walker, T.P., 'Primordial nucleosynthesis: theory and observations', *Phys. Repts*., vol. 333, 2000, 389-407.

[14] Peebles, P.J.E. *, Principles of Physical Cosmology*, Princeton, Princeton University Press,1993.

In conjunction with the General Relativity framework, the Cosmological Principle serves to select a set of *homogeneous* and *isotropic* solutions (known as Friedmann-Robertson-Walker cosmologies) in which the dynamics is described by the Friedmann equations.[15] The latter equations relate the scale factor of the universe $a(t)$ to the content of matter, radiation and whatever else composes the universe (that is, the above Ω_i`s), given the value of the curvature parameter κ. Einstein equations then relate the matter-energy content (contained in the right-hand side) to the geometric properties of spacetime, with differential operators acting on the fundamental object $g_{\mu\nu}$ (the metric tensor). In Wheeler's powerful words "matter tells spacetime how to curve, and curved spacetime tells matter how to move"[16][14].

The cosmological equations of Friedmann-Robertson-Walker based on General Relativity read

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2} + \frac{\Lambda}{3}} \qquad (1a)$$

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}} \qquad (1b)$$

where the "dot" indicates the derivative with respect to the cosmic time. These equations are supplemented by a "conservation law" which tells how the energy density ρ changes with time as the scale factor $a(t)$ evolves with time, $\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + P)$. The pressure P and energy density ρ of the right-hand sides are actually the sum of whatever components contribute to them. For example, cosmic matter exerts essentially no pressure and therefore is characterized by $P = 0$ in the above equations. Other simple cases include a radiation field for which $P = \frac{1}{3}\rho$, and a few further known "fluids". The important thing to retain is that the features of the components (through ρ and P) determine the behavior of the growing scale factor of the Universe $a(t)$.

[15] See, for instance,Weinberg, S., *Gravitation*, New York , J.Wiley & Sons,1972.
[16] Wheeler, J.A., quoted for example in the *New Scientist* site http://www.newscientist.com/channel/fundamentals/mg16121747.700.

It was at the beginning of the 20th century that Hubble's fundamental discovery of a linear relationship between galaxy distance and recession velocity (later termed "Hubble law") created significant problems for the theoretical description of the Universe based on the triumphant General Theory of Relativity. It is known that initially, a constant × the metric tensor ($\equiv \Lambda g_{\mu\nu}$), among the admissible terms in the gravitational field equations, was introduced by Einstein to produce a static universe. In fact, eqs. 1a and 1b were already written with this contribution explicitly separated, as it can be easily checked.

In this discussion of static vs. expanding cosmologies, it is clear that Einstein himself seemed to dislike a non-zero Λ possibly invoked to produce a static Universe. Eventually such a term was deemed superfluous once the Hubble expansion was amply confirmed, since a non-zero but very small Λ was regarded as a mathematically possible but physically unjustified solution. This is a well-known documented case in the history of science.

As stated above, the recent evidence gathered on Type Ia thermonuclear supernovae and anisotropies of the cosmic microwave background radiation have indicated the *same* content of dark energy dominating the energy balance today. Since this unclustered form of energy should produce an accelerating phase of the universe, the coefficient between the pressure and the energy density must be negative (the right-hand side of eq. 1b must be positive for $\ddot{a} > 0$), something odd for normal fluids, but not much different from a tension in a rubber band.

Given this situation, a late (contemporary) acceleration shares some of the features postulated much earlier for a primordial *inflationary* phase, and the attention has been turned to it as well. What is inflation? Inflation is a brief, early phase of the Universe in which the expansion rate has been much higher than any solution based on a "reasonable" fluid dominance, in fact in many theories the expansion of the scale factor was exponential ($a(t) = a_{initial} \times \exp(Ht)$), something that needed unusual properties of the component dominating the Universe dynamics, not unlike a negative relation between P and ρ but at a much higher energy scale (that is, closer to the Big Bang itself). *Inflation* gradually become a key ingredient in modern cosmology, not only because it helps to solve important problems of the observed universe (horizon, formation of structure, etc.), but also because density perturbations generated inside it are later greatly amplified, with a characteristic flat spectrum, and are observed as "frozen" at the radiation-matter decoupling. In fact the cosmic microwave background radiation data gathered today is of high quality and permits a scrutiny of the fluctuations generated at an early epoch in the universe. The consistency of these analyses with inflationary predictions is very significant. Therefore, and before turning to the issue of dark matter/dark energy itself, we may ask first whether the evidence is strong enough to state the Inflation itself happened.

INFLATIONARY THEORIES: IS INFLATION REALLY PART OF THE PARADIGM?

It is perhaps significant that the very specific word "paradigm" is now being widely used in the specialized literature to design the latest status of the Inflation. As stated, a general definition of the latter states that it is a (brief) period of the universe in which the expansion is extremely fast, possibly exponential, caused by a peculiar behavior of the equation of state $P(\rho)$. It is certainly an elegant and neat form of solving some serious problems related to the Big Bang cosmology, and furthermore predicts some nice features amenable of direct observation, such as the power spectrum of the primordial fluctuations. Some cross-checks of these inflationary ideas, including the power spectrum, continue to indicate the need of a dark matter, a clustered non-baryonic component of galaxies and galaxy clusters which has been discussed for several decades. In fact, inflationary ideas date back to the early '80s, and are therefore much newer than the referred Zwicky's paper[17] pointing out the existence of dark matter in galaxies.

However, as a generic mechanism, Inflation does *not* offer a direct answer to the question of the dark matter and dark energy, but rather predicts just the total Ω_{tot} and form and shape of $\delta\rho/\rho$, which in turn forces the existence of some yet unknown components as a consequence of it (as mentioned above, baryons alone are much too scarce to fill the budget). It is very remarkable that adding up the "observed" dark matter and the dark energy we "naturally" arrive at the inflationary prediction value $\Omega_{\text{tot}} = 1$.

As a feature to model and understand the data, it may be stated that Inflation is still challenged by the community, but it has gained an ample credit lately. For many, it is now a part of the discipline matrix. But what is important to remark is that Inflation did not disturb the dynamics of the rest of Friedmann-Robertson-Walker cosmology because, from a Kuhnian point of view, it was not intended to destroy or substitute it, but rather came to justify its initial conditions (or more precisely, the unimportance of them) (see the related discussion in M.S. Turner, 'Dark Matter and Dark Energy: The Critical Questions', 2002, arXiv astro-ph/0207297).[18] Even accepting that picture, the *type* of Inflation that happened and specially *what* caused that Inflation (scalar fields?) are not yet answered (see the remarks by H. Zinkernagel, 'Cosmology, particles and the unity of science, *Studies in History and Philosophy of Modern Physics*, 33, 2002, 493-516).[19] Therefore, while the *existence* of Inflation is

[17] Zwicky, F., 'Die Rotverschiebung von extragalaktischen Nebeln', *Helv. Phys. Acta*, vol.6, 1933, 110-127.
[18] Turner, M.S., 'Dark Matter and Dark Energy: The Critical Questions', arXiv astro-ph/0207297, 2002. Available at http://arxiv.org/.
[19] Zinkernagel, H., 'Cosmology, particles and the unity of science', *Studies in History and Philosophy of Modern Physics*, vol.33, 2002, 493-516.

considered by many as part of the paradigm, its *realization* rather qualifies as an unsolved problem, perhaps to be "explained away" in the same act as the very existence of the dark matter+dark energy if both features emerge from a still more fundamental theory, such as braneworlds or M-Theory (see, for example, S. Nojiri and S.D. Odintsov, 'Where new gravitational physics comes from: M-theory?', 2003, arXiv hep-th/0307071)[20] invoking extra dimensions of the Universe. It is fair to conclude here that the standard Friedmann-Robertson-Walker cosmology is a much better understood framework than Inflation itself, and despite its success the latter has been incorporated (but not yet merged) to the former.

It is also important to remark again that Inflation is expected to act at extremely early times only, when the universe was likely governed by physics at the highest energies. This is a very extreme regime, not yet probed in accelerators or laboratories, and therefore physicists naturally entertain various ideas to produce Inflation without actually worrying too much about the "low-energy" Universe. In contrast, dark matter and dark energy comprise the overwhelming majority of our everyday, steady, cold universe, and become in this sense a matter of concern, because we certainly should introduce them explicitly in almost every cosmological consideration dealing with theory/data.

"INVENTION" VS. "DISCOVERY" OF Λ AND A COMPARISON WITH THE HISTORY OF DARK MATTER

As previously stated, so far a careful analysis of the observational evidences[21] from supernovae and cosmic microwave background radiation suggests that the "ancient" einstenian idea of just a constant term in the field equations is *not* ruled out and may be useful as a realistic model. However, when we take a closer look, the einstenian concept of Λ is actually quite different from the present one. While Einstein entertained the idea of a term $\Lambda \times g_{\mu\nu}$ as a simple possibility allowed by symmetry criteria (and was therefore "invented" in this sense, on theoretical grounds), we may argue that effects of Λ have been "discovered" in contemporary data. It was Einstein contention to allow a term of this type on the left-hand side (thus, attached to the geometrical content), instead of devising some kind of fluid contributing with the same term to the right-hand side (that is, a component of the Universe enforcing the geometry).

The words "invention" and "discovery" are precisely the same ones employed by Kuhn (K70) in his definition of both concepts, exemplified by the controversy

[20] Nojiri, S. and Odintsov, S.D., 'Where new gravitational physics comes from: M-theory?', arXiv hep-th/0307071, 2003. Available at http://arxiv.org/.

[21] Riess, A.G. et al., 'Type Ia Supernova Discoveries at z > 1 from the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution', *Astrophys.J.*, vol.607, 2004, 665-687.

between Steele, Priestley and Lavoisier for the priority in the discovery/understanding of oxygen. This observation leads to question which is the actual status of more complex models going beyond the simplest cosmological constant, such as quintessence fields.[22] Quintessence fields are nothing but a phenomenological attempt to introduce some dynamical component which can act as an accelerator agent producing effectively a negative relation $P(\rho)$ as a result of its action. The chosen name is, of course, directly related to the aristotelic concept of the composition of the world revived in this unexpected turn.

It is clear that we have "invented" those models, and their obvious *ad hoc* character reinforces the use of this term. However, it would not be totally out of question to speak of a "discovery", and certainly if a particular model becomes accepted to explain the data (say, a scalar field with some potential term), we may hear about the "discovery" of quintessence, even if never detected in the conventional sense. Such a hypothetical model might prove later to be a mock manifestation of some different physical entity (i.e. extra terms in Friedmann's equation induced by high-energy physics). It is well-known that the recognition of a fact needs not only data, but also its proper understanding, which in this case is not yet achieved, and possibly lasting a finite and unpredictable amount of time. But since the dark energy is unlikely to be detected directly, a quite large acceptance time may be required irrespectively of the actual outcome.

It is fair to state that, in many senses, we "see" Λ quite differently than Einstein did. We believe now that Λ is related to the zero-point energy of quantum fields, and it is quite strange to the community that its value is orders of magnitude smaller than the "natural" number 10^{121} inferred from a simple calculation imposing the usual fluctuation behavior of the known elementary fields. A point we would like to stress is that the measurement of a tiny Λ signals a breakdown of a more restricted paradigm ("nature manages to drive Λ to zero"), which reigned for several decades championed by the defenders of the Occam's razor cosmologies. In fact, many reasons to *justify* $\Lambda = 0$ were put forward prior to 1998. The small, but non-zero value of Λ may prove even more difficult to justify than an exactly null figure. We do not have any reason for such a huge mismatch between theory and observations, just as Kepler did not have a reason for elliptic planetary orbits, later found by Newton using his own mechanics. Perhaps a completely new approach changes our way of looking at Λ,or there are anthropic reasons to produce a tiny Λ, but they have to be studied and clarified.[23] All this suggests again that a new viewpoint may be

[22] Bludman, S., 'What We Already Know About Quintessence', arXiv astro-ph/0312450, 2003. Available at http://arxiv.org/.
[23] Vilenkin, A., 'Anthropic predictions: the case of the cosmological constant', arXiv astro-ph/0407586, 2004. Available at http://arxiv.org/.

needed, even if we choose to keep "standard" gravity and succeed to identify the dark energy component.

In contrast to the case of dark energy, it is interesting to note that the dark matter problem is almost coeval with the development of Friedmann-Robertson-Walker cosmologies. It is *not* an anomaly appearing after that paradigmatic theory was established, but rather a background fact, constantly reinforced and extended over the years. However, the community eventually choose to *dismiss* dark matter as a cosmological "problem" and pushed it to the realm of Particle Physics/Astrophysics (committed to find a suitable exotic particle/compact remnant candidate(s)). In contrast, all issues related to dark energy have been always seen as part of the cosmological problem. Imagine that the small but non-zero Λ had arisen before. Would it have anticipated the present crisis in the standard cosmology? or it would have rather followed the path dark matter did, namely to be considered not really a problem, but rather an *ingredient* to be addressed and found by some other related discipline?. We strongly suspect that the second alternative would have been the one chosen, simply because it reflects the behavior of the community when faced with an analogous earlier situation. We believe that a small non-zero dark energy (in its simplest "cosmological constant" incarnation) has now closed the room for sweeping such problems (dark matter+dark energy) under the rug.

It is clear that, in spite of the above facts, we are *not* actually claiming that there were no attempts to solve the dark matter problem prior to the emergence of the dark energy evidence. As a concrete example of an attempt to change the dark matter paradigm we may cite the MOdified Newtonian Dynamics (MOND) of Milgrom et al.[24] In this theory there is a new regime beyond a certain acceleration scale and deviations of Newtonian dynamics happen, for example, on galactic scales (a relativistic version that is derivable from a Lagrangian, another key feature in the present particle physics paradigm, has been recently presented). But now it is clear that this kind of idea could be a solution for part of the whole problem only, since we have to explain the existence of the unclustered dark energy as well, and therefore they seem to be overall less attractive than, say, a decade ago. Of course, there is no deep crisis, just an *impasse* for the supporters of normal science Inflation+Friedmann-Robertson-Walker cosmology, since for them the dark matter+dark energy team should come as a "plug-in" solution from the *outside* of their own discipline.

SOLVING THE IMBROGLIO?

Given the state of the art, and as a working hypothesis, we must seriously consider the possibility the origin of the dark matter and dark energy, and their

[24] Milgrom, M., 'A modification of the Newtonian dynamics - Implications for galaxies', *Astrophys.J.*, vol.270, 1983, 371-389; Milgrom, M., 'MOND-theoretical aspects', *New Astronomy Reviews*, vol.46, 2002, 741-753.

relative contributions to Ω_{tot} may only be solved with a paradigm shift, either by patching of new dark matter+dark energy components or, even more strikingly, by a deep modification in the description of gravity fields. Which of these possibilities to choose is difficult to precise further, because revolutions are complex phenomena and it is unknown, by definition, which will be the emerging state-of-the-art.

As a consequence, and with the aim of substantiating this assertion, we also argue that there is already plenty of evidence to consider that the 1998 anomaly $\Lambda \neq 0$, taken together with the "old" dark matter problem has been enough to trigger an extraordinary science episode as described by Kuhn (K70). Seventy years of the dark matter problem by itself have not been uncomfortable enough to do so, and in fact a considerable fraction of scientists hoped that the dark matter could go away either because of the identification of some conventional candidate copiously produced (black holes, brown dwarfs, etc., recently excluded almost completely using the full set of data of the EROS experiment)[25] or the detection of a particle candidate that would have brought dark matter to the realm of everyday physics (a supersymmetric neutralino, the lightest of the supersymmetry multiplet, as a prime candidate, see B. Sadoulet, `Deciphering the nature of dark matter´. *Rev. Mod. Phys*., vol. 71, 2000, S197-S204).[26]

The parallel with the state-of-the-art of physics at the turn of the 19th century can not be overstated. The astonishing properties of the ether necessary for a comprehensive understanding of the classical world did not preclude Lord Kelvin to claim an essentially complete physical picture in a well-known address to the *British Association for the Advancement of Science*.[27] However, a few years later its complete conceptual elimination and the paradigm shift to Relativistic and Quantum physics were all remarkable. Nonetheless, the ether *was* indeed recognized as a serious problem by the community and it was attacked fiercely by several distinguished members (such as Maxwell and Michelson), thus qualifying as a prototype of the Kuhnian anomaly. If this parallel is correct, the pair dark matter+dark energy may be truly considered as the neo-ether of contemporary physics.

Even though not much has been written about how a paradigm shift actually happens (and there may be several variants), we may advance here some of the simplest hierarchical possibilities, namely a *top-down* or *bottom-up* path. Typically the "top-down" path would be the emergence of dark energy, and possibly of dark matter as well, from a single theory changing quite radically a number of present sacred concepts. A prototype for the former is brane theory, which is still "in the works" and which by construction may harbor new elements contributing to the

[25] Afonso, C. et al., 'Limits on Galactic dark matter with 5 years of EROS SMC data', *Astron. Astrophys*., vol.400, 2004, 951-956.
[26] Sadoulet, B., 'Deciphering the nature of dark matter', *Rev. Mod. Phys*., vol.71, 1999, S197-S204.
[27] Thompson, W., 'Address given at the British Association for the Advancement of Science', 1900.

solution of these problems.[28] Braneworld models typically embed the 3+1 spacetime in a higher-dimension structure, and as such the remaining space-like dimensions constitute the "bulk" in which none of the known elementary forces but gravitation can propagate. Specific claims about the behavior of braneworld solutions for the dark matter/dark energy problems have already been made,[29] the latter fully belonging to the class of extraordinary science attempts. Conversely, a "bottom-up" path could be taken, starting for example with phenomenological models (like the Chaplygin gas, which behaves as dark matter or dark energy in the high and low density limits)[30] later to be incorporated into a larger theory but *not* being merely additive contributions to Friedmann-Robertson-Walker cosmology. This would postpone for the future a physical realization of the phenomenological description with the identification the elements leading to conceptual breaks. There is a definite and largely unavoidable possibility that both approaches, currently being undertaken, can converge in the long term. Hence, we would recognize after the completion of the process a new paradigm and its relation to the present one.

To be sure, it was clear how to incorporate $\Lambda \neq 0$ and dark matter into Friedmann-Robertson-Walker cosmology for years. But the very existence of dark energy (and dark matter as well) is what strikes most. The contentious assertions made above apply if and only if these problems can not be kicked away or brought as "plug-in" solutions, but rather require an involved reworking of cosmology.

FEATURES OF A PARADIGM SHIFT: ARE THEY BEING SEEN?

Sticking strictly to Kuhn's formulation (K70) of the anomaly issue, three possible outcomes are foreseen. According to him, the anomaly is either i) solved by normal science, ii) declared impossible to solve (because it resisted all radical approaches) and put aside for a future generation; or iii) triggers the emergence of a new paradigm and becomes solved within it, becoming the "normal science" for the next generation.

It is obvious that the combined dark matter+dark energy problem has not been solved by normal science (this is impressive, even when considering the very different timescales as recognized anomalies). It is not clear whether the second alternative can be *actually observed* in a finite timescale, in fact, the dark matter case resisted a few generations of scientists without being "put aside" at all, at least explicitly. We believe that there are good reasons for the third alternative to be considered and closely scrutinized by epistemologists, philosophers of science and cosmologists/particle physicists alike.

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[28] Maartens, R., 'Brane-World Gravity', *Living Reviews Relativity*, vol.7, 2004. Available at http://www.livingreviews.org/lrr-2004-7.

[29] Mak, M.K. and Harko, T., 'Can the galactic rotation curves be explained in brane world models?', arXiv gr-qc/0404104, 2004. Available at http://arxiv.org/.

[30] Gorini, V., Kamenshchik, A., Moschella, U. and Pasquier, V., 'The Chaplygin gas as a model for dark energy', arXiv gr-qc/0403062,2004. Available at http://arxiv.org/.

We may also legitimately ask whether the features suggested by Kuhn as tracers of the state previous to a paradigm shift are also present in contemporary physics.

- First, *isolation* and *characterization* of dark matter by close scrutiny have been achieved, resulting in a pretty good consensual opinion about the scales in which the latter is present (galaxies, clusters, etc.); and excluded/allowed regions in the fiducial mass-cross section plane[31] and exclusion regions for astronomical bodies. The efforts to do the same with the much "newer" dark energy have already resulted in observational limits intended to pinpoint its exact equation of state and its possible temporal evolution.[32] The latter also constitute evident examples of the isolation/characterization processes "in action" (see Fig. 1), attracting a lot of attention and work. The excluded/allowed regions and the "equation of state" are clearly well-defined and acceptable approaches within the idea of dark matter+dark energy being new components only, as expected from the existing framework to analyze the data. The features of Fig. 1 serve here to support our view quite directly.
- A second feature thought to be indicative of a state previous to a paradigm shift is the *flourishing of philosophical/methodological analysis*. A glimpse at the specialized literature amply confirms the occurrence of this feature (to which our very work contributes). This stands in striking contrast with most disciplines and, more importantly, with the pre-1998 status, reinforcing our previous statements.
- A third signal is thought to be the *proliferation of alternatives*, a fact which is also very evident in the literature. We should also add that the *acceleration* of this proliferation is also notorious, although very difficult to track properly. Turner and Huterer ('Cosmic Acceleration, Dark Energy and Fundamental Physics', 2007, arXiv:0706.2186)[33] have analyzed some of the leading solutions today, and it is important to note that all them have been worked out *after* 1998, in attempts to clarify the situation. Moreover, few people stand for each of these solutions, as expected for explanations that have yet to prove their consistency and predictive power.

The remaining two features explicitly discussed by Kuhn as a prelude to a paradigm shift are of pure psychological nature and reflect the attitude of the community toward the facts. They are *despair* and *explicit discomfort*. Both are difficult to quantify, and often expressed only privately (conversations at specialized meetings, for example). Nevertheless, some explicit examples are not too difficult to

[31] Sadoulet, B., 'Deciphering the nature of dark matter', *Rev. Mod. Phys*., vol.71, 1999, S197-S204.
[32] Turner, M.S., 'Dark Matter and Dark Energy: The Critical Questions', arXiv astro-ph/0207297, 2002. Available at http://arxiv.org/.
[33] Turner, M.S. and Huterer, D., 'Cosmic Acceleration, Dark Energy and Fundamental Physics', arXiv:0706.2186, 2007. Available at http://arxiv.org/.

find in the written literature For instance, the situation has been qualified as "embarrassing" by Rees[34] and termed "the Kingdom of total ignorance" by de Lima,[35] among other equally meaningful definitions by leading cosmologists. These shortcomings are actually in part mitigated by the visible advance of the knowledge of fundamental parameters ($\Omega_{\mathrm{tot}} \cong 1$, the value of the Hubble constant, etc., see the relative contributions of the components of the universe in Fig. 2, which assumes a "standard" Friedmann-Robertson-Walker cosmology), and also by the seizing of a big opportunity to make a relevant contribution to the field (this being in itself a psychological factor), but are nonetheless very significant. Overall, we have no reason to doubt that all the features proposed by Kuhn as indicating a fertile ground for a paradigm shift are amply fulfilled nowadays.

CONCLUSIONS

It is not presently known whether the dark matter and dark energy "problems" are just one or many.[36] The possibility of solving them by plugging in some alien component into the Friedmann-Robertson-Walker cosmology + Standard Model of particle physics is still open, although this solution by itself would require a modification of the way we think and understand the content and evolution of the Universe, which would be in itself a "minor" revolution for cosmology at least, but a *major* event for particle physics. There is no firm hint from measured physics about "dark matter" or "dark energy" particles as yet, and their existence would open up a whole new physics deeply affecting the existing view of the microphysical world. The fact that, according to this possibility, we may be ignoring the composition of $> 95\%$ of our universe, and the implication that we are not made of the same material that most of the universe cannot be overstated.

Instead, we may be well inside a true major scientific revolution in cosmology itself, and thus our vision of the problem still blurred because precisely of that. This would be the case if full revision of the way we look at gravitational physics may be needed (hopefully making dark matter + dark energy go away), as advocated by some. Particle physics would be pretty much unchanged, but this outcome would be comparable to the Newtonian → relativistic shift at the turn of the 20$^{\mathrm{th}}$ century.

In both cases an important paradigm shift will be required, and in fact we have argued here that all the characteristic features of them, as prescribed by Kuhn, are clearly being seen (wild proposals, young researchers outside cosmology seizing the opportunity to contribute, a discomfort inside the cosmologists community, etc.). We

[34] Rees, M., 'Dark Matter: Introduction', *Phil.Trans.Roy.Soc.Lond.*, vol. 361, 2003, 2427-2434.
[35] de Lima, J.A.S. Talk given at the First International Workshop on Astronomy & Relativistic Astrophysics.- Olinda, Brazil, October 2003.
[36] Lue, A., Starkman, G.D. and Vachaspati, T., 'A post-WMAP perspective on inflation', arXiv astro-ph/0303268, 2003. Available at http://arxiv.org/.

also believe that this "orthodox" behavior (in the sense of Kuhn) is quite striking, since true scientific revolutions are complex phenomena for which the original work of Kuhn description may not be completely adequate. By keeping track of these and other signals we may be able to witness and appreciate one of the biggest and rarest events thought to be the very engine of western science in action.

ACKNOWLEDGEMENTS

The author wish to thank the São Paulo State Agency FAPESP for financial support through grants and fellowships and the partial supported by CNPq (Brazil). Conversations with G. Lugones, J.A.S. de Lima, M. Soares-Santos and J.A. de Freitas Pacheco helped to clarify and refine the views here expressed.

FIGURES AND CAPTIONS

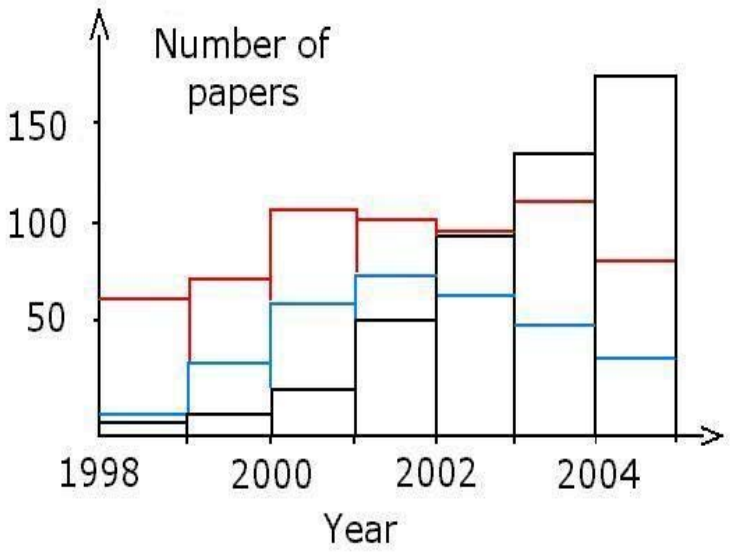

Fig. 1.

Fig. 1. A graphical representation of the rising interest of the community in the dark energy problem. This histogram shows the number of publication having "cosmological constant" (red), "quintessence" (blue) and "dark energy" (black) in their titles, collected from the SPIRES/SLAC databases (http://www.slac.stanford.edu/spires/hep/). While the first two specific terms remained constant or even declined since 1998, the more general term "dark energy" grew exponentially, reflecting the attitude of the community towards the isolation and characterization of the anomaly. Note that the names of "quintessence" and "dark energy" did not even exist prior to 1998.

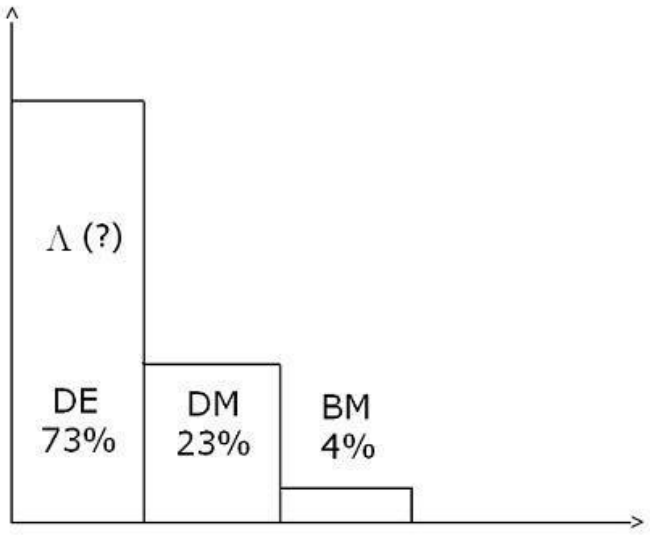

Fig. 2.

Fig. 2. The most likely content of the Universe according to the latest observations. The fractions of dark energy, dark matter and baryonic matter are the best fits to the whole body of data, and suggests that more of 95 % of the content of the universe is unknown.