Beyond the Standard Model of Cosmology

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Abstract. Recent cosmological observations of unprecedented accuracy, by WMAP in particular, have established a ‘Standard Model’ of cosmology, just as LEP established the Standard Model of particle physics. Both Standard Models raise open questions whose answers are likely to be linked. The most fundamental problems in both particle physics and cosmology will be resolved only within a framework for Quantum Gravity, for which the only game in town is string theory. We discuss novel ways to model cosmological inflation and late acceleration in a non-critical string approach, and discuss possible astrophysical tests.

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‘DÉJÀ VU’ ALL OVER AGAIN?

The current situation in cosmology has many striking parallels with the situation that emerged in particle physics a decade or so ago. Indications from many different types of astronomical observations have converged on a ‘Standard Model’ of cosmology that is as successful as the Standard Model of particle physics.

In cosmology, the convergent indicators have included light-element abundances, galactic rotation curves, COBE, HST, large-scale structures, high-redshift supernovae, and many more observations [1]. In particle physics, the many convergent experiments of the 1980’s and before were validated and confirmed much more precisely by measurements at the LEP and other accelerators during the 1990’s and subsequently [2]. The missing link in the Standard Model of particle physics is the Higgs boson, and the current status of our information about it is shown in Fig. 1. Likewise, the ‘Standard Model’ of cosmology has been triumphantly validated and confirmed this decade by the WMAP observations of the cosmic microwave background (CMB) [3], but there are also some missing links, as discussed below.

WMAP is the LEP of cosmology. As seen in Fig. 2, it has measured with greater precision than was possible before the material and energetic content of the Universe. In combination with other CMB measurements and large-scale structure observations, WMAP has provided the most stringent upper limit on the amount of hot dark matter and hence the sum of the neutrino masses, as seen in Fig. 3. WMAP observations of the peaks in the CMB perturbation spectrum have confirmed with higher precision the estimates of the baryon density of the Universe made previously on the basis of light-element abundances [4]. WMAP data confirm that the total energy density of the Universe is very close to the critical density, Ω_{crit} ∼ 1, and the combination of WMAP with other CMB data favours an amount of cold dark matter Ω_{m} ∼ 0.3 that is consistent with the previous indications from large-scale structures and high-redshift supernovae [5]. Combining all the cosmological data, the amount of cold dark matter is determined precisely and the need for substantial dark energy with Ω_{Λ} ∼ 0.7 becomes overwhelming, as seen in Fig. 2.
FIGURE 1. Data from LEP and other particle accelerators confirm predictions of the Standard Model with high accuracy, if there is a Higgs boson with mass is near the bottom of the $\Delta \chi^2$ curve indicated by the blue band \[2\]. Direct searches at LEP have excluded a mass below 114 GeV, as shown by the yellow shading.

FIGURE 2. Data from WMAP, its extensions to include other CMB data, high-redshift supernovae and the HST all converge on a cosmology with $\Omega_m \sim 0.3$, $\Omega_{\Lambda} \sim 0.7$ and $\Omega_{\text{tot}} \sim 1$ \[3\].

THAT IS NOT ALL!

Despite its successes, this emergent ‘Standard Model’ of cosmology is deeply unsatisfactory. Just like the Standard Model of particle physics, it fits (almost) all the data in its respective field, but it is equally incomplete, and the picture of the Universe that it provides is rather bizarre. In particle physics, the ‘standard’ list of problems left unanswered by the Standard Model include the origins of particle masses - which are thought to be due to a Higgs boson - the proliferation of particle types - which are thought to be related to the matter-antimatter asymmetry observed in laboratory experiments - the unification of particle interactions - which seems to require a hierarchy of mass scales whose maintenance needs some stabilizing mechanism, and the formulation of a quantum theory of gravity. These problems find remarkable parallels in issues beyond the ‘Standard Model’ of cosmology.

What is the origin of inflation? We are asked to believe that the great size and age of the Universe are due to an early phase of (near) exponential expansion, during which quantum fluctuations in density laid the seeds for the subsequent formation of structures in the Universe. The front-runner for the inflationary mechanism is some elementary scalar field (inflaton) analogous to the Higgs field of the Standard Model of particle physics discussed above \[6\], but other possibilities may be suggested by string theory, as discussed below.

What is the origin of matter? This is generally thought to be linked to the small asymmetry between matter and antimatter seen in the laboratory, which is in turn thought to be possible only because of the proliferation of particle
FIGURE 3. Data from WMAP, other CMB experiments and large-scale observations set an upper limit on $\Omega_\nu$ corresponding to an upper limit of 0.23 eV on each neutrino mass [3].

... types. Possible microscopic mechanisms include decays of heavy (s)neutrinos or CP-violating Higgs physics.

What is the origin of dark matter? This cannot be composed of conventional baryonic matter, nor of neutrinos, and the favoured option is some sort of massive weakly-interacting particle. A prime candidate is the lightest supersymmetric particle (LSP) [7]; it turns out that the mass scale required for a (formerly) thermal relic dark matter particle coincides with the electroweak range required to stabilize the mass hierarchy with supersymmetry.

What is the origin of the anti-hierarchy? There is a remarkable coincidence between the orders of magnitude of the current densities of baryons, cold dark matter and dark energy. The similarity of the baryon and cold dark matter density might point towards some common origin. However, the underlying physics appears to be very different, and the proximity (within three orders of magnitude) of the hadronic and electroweak scales is not really sufficient to explain this first cosmic coincidence between the visible and dark matter densities. (On the other hand, other particle candidates for cold dark matter, such as axions or Wimpzillas, are less strongly motivated and have less reason to acquire a relic density comparable to conventional matter.) The second coincidence, between the matter and dark energy densities, is even more baffling. This is because the scaling with time of the matter density is completely different from that expected for a cosmological constant, so the present similarity can only be temporary.

What is the origin of dark energy? Naïve models ascribe this to the remnant density of some elementary scalar field, possibly also analogous to the Higgs field. However, its origin should properly be treated in the context of a quantum theory of gravity, which is the only suitable framework for discussing vacuum energy. To make life more difficult, the present value of the dark energy density is not in the ballpark predicted by previous theoretical models, indeed, it is many orders of magnitude smaller than identifiable contributions to the vacuum energy from QCD, the electroweak Higgs field or supersymmetry breaking. This has motivated models in which the vacuum energy is relaxing towards zero, but cosmological data set increasingly stringent limits on its equation of state.

What is the origin of the Big Bang? This is perhaps the ultimate challenge for any reputable quantum theory of gravity. The known laws of physics break down when particle energies approach and exceed $10^{19}$ GeV, which is expected naïvely to have been the case when the Universe was less than about $10^{-43}$ s old. Even our current understanding of string theory seems inadequate under the hot and dense conditions so early in the Universe, and so far one can only speculate about physics at the origin of the Big Bang or before.

THE LHC OF THE SKY?

Many of the outstanding problems in both physics and cosmology, beyond their respective Standard Models, will be addressed by the LHC on the one hand and the Planck Surveyor on the other. The ‘expected’ discoveries in the two fields will impact directly each other’s problems.

Simulations indicate that the LHC experiments ATLAS and CMS will be able to detect or exclude a Standard Model-like Higgs boson, whatever its mass [8]. The discovery of a Higgs boson at the LHC would legitimize elementary scalar fields and so give heart to their advocates as mechanisms for inflation and dark energy. Likewise, as seen in Figs. 4, 5, these LHC experiments will be able to cover most of the space allowed for supersymmetric models by cosmology. The discovery of supersymmetry at the LHC would boost spectacularly the candidacy of the LSP for cold dark matter, whose density might (in favourable cases) be calculable using results from LHC experiments, as seen in Fig. 6.
Measurements of CP-violating matter-antimatter asymmetries at the LHC (following those already being measured at the B factories) might cast light on the cosmological origin of matter. Any evidence of extra dimensions would provide new cohesion to the inchoate morass of string ‘phenomenology’, with the potential to put to experimental test models bearing upon dark energy, inflation and the origin of the Big Bang itself.

FIGURE 4. In many specific benchmark supersymmetric models that yield a relic dark matter density consistent with WMAP, labelled by capital letters, the LHC would observe many types of sparticles, and linear colliders would complement the information obtained from the LHC [9].

FIGURE 5. In a general sampling of supersymmetric models (red squares) the LHC (green crosses) would cover most of the region favoured by WMAP (blue triangles) and more than would be accessible to direct searches for dark matter scattering (yellow points) [10].

What is the ‘LHC of the Universe’, i.e. the astronomical/astrophysical/cosmological instrument that will take us beyond the ‘Standard Model’ of cosmology? The most likely candidate is the Planck Surveyor [11] that is scheduled to be launched in the same year as the startup of the LHC, namely 2007. It may be able to take us into the area of cosmological string phenomenology, for example by observing deviations from the Gaussian, near-scale-invariant adiabatic perturbations that are expected in conventional scalar-field inflation. Or its measurements of polarization in the CMB might provide a tell-tale signature of gravitational waves. Certainly, we can expect it to refine the present determinations of the conventional and dark matter densities, providing a challenge for microphysical measurements at the LHC and elsewhere.
FIGURE 6. In benchmark model B of Fig. 4, LHC measurements of the supersymmetric mass perimeters would enable the dark matter density to be calculated (histogram) with an accuracy comparable to the WMAP range (yellow band) [9].

AN END TO ‘FIELD THEORY AS USUAL’?

It seems unlikely that Quantum Field Theory (QFT) will be challenged by the particle physics beyond the Standard Model that we expect to be discovered at the LHC, though this might be possible in some scenarios for extra dimensions that predict TeV-scale black holes, for example. Moreover, QFT will probably also not be put into question by many of the pressing cosmological problems, such as the origins of conventional and dark matter. However, some cosmological problems may find solutions only beyond the conventional framework of QFT.

One glaring example is inflation. The CMB data from COBE to WMAP indicate that it probably occurred at an energy scale far beyond the electroweak scale, and potentially close enough to the Planck scale for trans-Planckian and/or stringy effects to be detectable. During the inflationary epoch, the Universe is described by an (approximately) de Sitter space, which has a horizon that provides it with an effective ‘temperature’ related to the Hubble expansion rate. The Universe is described as a mixed quantum state in which information is continually being ‘lost’ across the horizon, and must be summed over. The procedure for doing this is well understood in conventional QFT. However, as discussed above, inflation may be a quantum-gravitational or stringy phenomenon, and horizons pose conundra to string theorists.

String theory is formulated as a theory of the $S$ matrix. However, this cannot be defined when mixed states enter the game. Instead, scattering is formulated in terms of a $\beta$ matrix [12, 13]. This allows transitions between pure and mixed states, or between different mixed states, that cannot be treated within conventional $S$-matrix theory.

The enormity of this problem recently became apparent to string theorists in the context of dark energy [14]. The fact that the expansion of the Universe is currently accelerating suggests that there is an analogous horizon today and, unless the dark energy disappears in a rather abrupt way, the asymptotic future state of the Universe will continue to possess a horizon ad infinitum. This would condemn string theorists to learn to accommodate mixed states, generalize the $S$ matrix and embrace the $\beta$ matrix.

Other considerations also motivate generalizing the $S$ matrix, notably the horizons surrounding black holes, which would seem to require a mixed-state description. String theorists have noted triumphantly that the information ‘lost’ inside the horizon of a stringy black hole may in principle be related to the properties of its internal quantum microstates [15], raising the possibility of recovering the information in the final stage of black-hole evaporation. Also in principle, one could retain the $S$-matrix description by keeping track of the quantum states of such a stringy black hole. In practice, however, these are difficult to observe, and one might necessarily be reduced to summing over these string states and embracing the $\beta$ matrix again [16].
DO NOT BE SO CRITICAL

A plausible framework for addressing these issues is non-critical string theory, in which one allows a deviation from the critical value of the central charge normally imposed in string theory. In the present context, the use of non-critical strings for cosmology was first proposed as a natural way to describe time-dependent space-time backgrounds [17]. Subsequently, this framework was also advocated for black-hole physics, the non-criticality reflecting the summation over unmeasured quantum states [16]. This approach provides a natural scenario for cosmological inflation [18], in which the central-charge deficit is related directly to the Hubble ‘constant’ during inflation, and reflects a summation over quantum states passing through the de Sitter horizon. A specific realization of this inflationary scenario has recently been proposed [19], in which moving D-branes generate the departure from criticality and hence inflation, as illustrated in Fig. 7. An analogous departure from criticality might also underlie the present apparent acceleration of the Universe [20].

![Figure 7](image_url)

**FIGURE 7.** A specific non-critical string scenario for cosmological inflation, in which quantum effects in the presence of a pair of moving D-branes generates vacuum energy that may lead to near-exponential expansion [19].

Scattering in non-critical string theory does not admit an S-matrix description, but instead requires use of the $\mathcal{S}$ matrix. This may not suit critical string theorists, but may be forced upon us by cosmology, as discussed above. There has been a heated debate whether the $\mathcal{S}$ matrix is essential also at the microphysical level, for example because information may be continually lost across the mini-horizons of Planck-scale black-hole fluctuations in space-time foam. This fantastic possibility could be probed, for example, in laboratory experiments on K and B mesons [13, 21]. Other possible observable effects of space-time foam have been proposed, such as an energy-dependent modification of the velocity of photon propagation, which could perhaps be tested by comparing the arrival times of photons from pulsed astrophysical sources [22]. As shown in Fig. 8 present data already tell us that any such effect can only be suppressed by some large energy scale close to the Planck mass or beyond [23].

![Figure 8](image_url)

**FIGURE 8.** Upper limits on time-lags between photons of different energies coming from distant gamma-ray bursters set a lower limit $\sim 10^{16}$ GeV on the scale of energy-dependent deviations from a universal velocity of light [23].

Quantum-gravity phenomenology is a very speculative subject, and the above ideas may turn out to be incorrect and/or untestable. However, if one is to find a convincing signature of quantum gravity, it is surely better not to just wait around for a burst of Hawking radiation from some astrophysical black hole, but rather to search for some characteristic phenomenon that goes beyond conventional QFT.
WATCH THIS SPACE

This brief survey has highlighted some of the key aspects of both particle physics and cosmology, emphasizing the important open questions in each field, the prospects for resolving these problems, and the symbiosis between the two fields. Cosmology and particle physics are inextricably entangled, and solving their deepest problems may require a novel approach to quantum gravity.

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