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# The Weight of the Vacuum

A Scientific History of Dark Energy

 Springer

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# Preface

Dark energy is a catch-all term for the energy of empty space. It is “dark,” not just in the sense that it does not interact with electromagnetic radiation, but in the deeper sense that its nature and composition are essentially unknown. Dark energy is known to dominate the dynamics of the universe on large scales, and to oppose the natural tendency of the cosmos to collapse under the weight of its own contents. In fact, under the influence of dark energy, the universe has entered a period of “late-term inflation” in which the expansion of space has started to *accelerate*, and will never stop accelerating, world without end.

The idea of an energetic vacuum has many historical antecedents, from the *pneuma* of the Stoic philosophers to the luminiferous ether of the late nineteenth century. It gained particular urgency with the advent of quantum theory, when it was realized that all fields in nature are endowed with irreducible “zero-point energies,” even in their vacuum states. As we now recognize, the sum of these zero-point energies exceeds by some 120 orders of magnitude the actual energy density of the universe, a mismatch so severe that it has rightly been called by Steven Weinberg the “one veritable crisis” left in physics. The full sting of this crisis is not felt within quantum field theories themselves, where such energies can be mathematically absorbed by a procedure known as renormalization. But it becomes unavoidable when such theories are confronted with the one field in nature that has not yet been successfully quantized: gravity. For according to general relativity, *all forms of energy must gravitate*. Thus the crisis is, in essence, a confrontation between the quantum field-theoretic approach to nature that we have inherited from Democritus, and the geometric picture of gravity as curved spacetime that can be traced from Einstein back to Pythagoras. And its resolution is likely to be bound up with the dream of physicists and philosophers through the ages to unify all the laws of nature in one single, all-encompassing “theory of everything.”

We have written this book with two goals in mind. The first is to look back over the theoretical precursors to modern dark energy, and attempt to put the subject in some historical perspective. Such a perspective may have its uses but cannot, of course, lead on its own to the kind of radical new thinking that will be required to solve the underlying issue. The story of the ether is instructive here. Physics at the end of the nineteenth century was gripped by a similar crisis when it was realized that light did not obey the same laws as everything else. Then too, theorists looked

back over history and attempted to extend or modify existing concepts in order to accommodate this new mystery. But a successful resolution—and with it a unified theory of electromagnetism and the rest of nineteenth-century physics—came only when Einstein proved able to jettison a belief so axiomatic that most did not even realize they held it: the independence of space and time. It is likely that dark energy—and with it the unification of gravity and the standard model of particle physics—will similarly be understood by looking, not backward, but *sideways*, at some unstated and apparently unrelated assumption so fundamental that it has previously gone unquestioned.

Our second goal is to record some of the observational hints that preceded the celebrated discovery of dark energy by cosmologists in 1998. It was then that the theoretical crisis assumed its true proportions, for this discovery removed any hope that the standard model was merely incomplete, and that some new underlying symmetry would be found which would ensure an exact cancellation of all the zero-point contributions. In fact, the energy density of the cosmic vacuum is *not* zero, but apparently exists at the preposterously fine-tuned level of about  $10^{-120}$  times that which is expected on the basis of standard (and exceedingly well-tested) quantum field theory. The fact that such a result became widely accepted in considerably less time than the prior proposal of dark matter (not to mention the original discovery of cosmic expansion itself) testifies to the strength of the observational case built by the supernova discovery teams. In such cases it can become possible to see the progress of science as illuminated mainly by the blaze of searchlights. We hope to show how it has also progressed by the aid of candles, sometimes shining in the wrong places altogether, whose light nevertheless grows in fits and starts until it makes the searchlights possible.

In writing this book we have benefitted from the insights of many people. For discussions over the years we thank Ron Adler, Sean Carroll, Arthur Chernin, Fred Cooperstock, Francis Everitt, Hans-Jörg Fahr, Masataka Fukugita, Takao Fukui, Eric Gliner, Leopold Halpern, Joochan Lee, Kei-Ichi Maeda, Bahram Mashhoon, Simon Overduin, Wolf Priester, Bharat Ratra, Varun Sahni, Alex Silbergleit, Bob Wagoner, Paul Wesson, and Richard Woodard among others. The errors that remain are, of course, our own.

March 2014

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