Centrality of Understanding Vacuum Energy Density

The density of "empty" space, as measured by gravity, is many orders of magnitude smaller than our current understanding of fundamental physics seems to suggest. For the idea that space is permeated with various symmetry-breaking fields and condensates, as well as quantum fluctuations (virtual particles), is central to our best, vastly successful world-model, the so-called Standard Model. Gravity, which according to Einstein responds universally to all forms of energy-momentum, ought to care about all this structure. But apparently it does not.

In the absence of data, natural guesses for the vacuum energy density, or cosmological constant, might have been 10^{108} ev^4, from the quantum-gravity (Planck) scale, 10^{96} ev^4, from unified gauge symmetry breaking, or perhaps as small as 10^{44} ev^4 if low-energy supersymmetry enforces large cancellations. In reality, it is no larger than 10^{-12} ev^4! In my opinion, this disparity is the biggest and most profound gap in our current understanding of the physical world.

Recent observations appear to indicate that the vacuum energy density, although "unnaturally" small, may be non-zero, and indeed large enough to dominate the energy density of the Universe on cosmological scales. These observations raise the stakes further, by providing a very concrete challenge for fundamental physics: to calculate its value. It is not completely fanciful to imagine that this problem will play, in twenty-first century physics, a role analogous to that played by the problem of black-body radiation in twentieth century physics. It might require inventing entirely new ideas, and abandoning old ones we thought to be well-established.

Besides its interest for fundamental physics, the possible vacuum density has far-reaching implications for cosmology. It determines the rate at which the Universe will expand in the future.

Since vacuum energy density is central to both fundamental physics and cosmology, and yet extremely poorly understood, experimental research into its nature must be regarded as a top priority for physical science.

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