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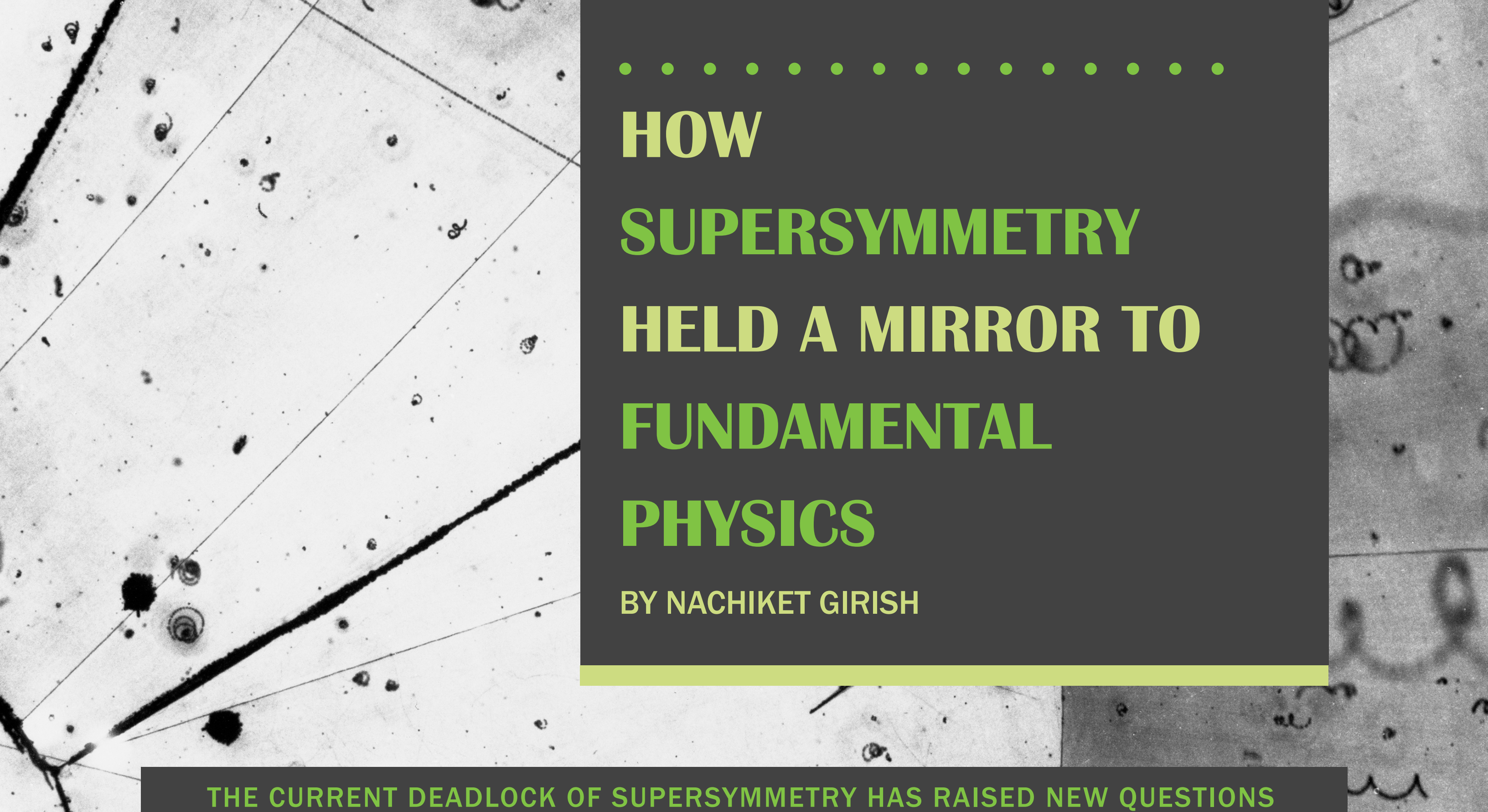

HOW SUPERSYMMETRY HELD A MIRROR TO FUNDAMENTAL PHYSICS

BY NACHIKET GIRISH

THE CURRENT DEADLOCK OF SUPERSYMMETRY HAS RAISED NEW QUESTIONS ABOUT WHAT MAKES A SOUND PHYSICAL THEORY

If you have seen physics in the news lately, you likely get the impression that now is an exciting time to be a physicist. Just this month, the Nobel Prize for physics was awarded to a woman, Donna Strickland, for the first time in 55 years. The observation of gravitational waves three years ago heralded a whole new era of observational astrophysics. Three years before that was the massive triumph of particle physics with the discovery of the Higgs Boson.

What you might not remember, however, is what these discoveries represent. The observation of gravitational waves was the verification of a prediction Einstein made a hundred years ago, while the Higgs Boson was experimental confirmation of a fifty-year-old hypothesis. This symbiotic relationship between theory and experiment is the defining principle of science.[1] Theorists are the pioneers who plow through unexplored routes in search of new destinations, while experimentalists check every step to evaluate whether the theorists are heading in the right direction.

But even as we celebrate these monumental achievements of science, physics itself is going through a period of uncertainty, with one of the hottest theories of particle physics—supersymmetry—increasingly finding no support from experimental data. The debate over how to explain the lack of support for supersymmetry has shaken the very foundations of scientific philosophy.

THE STANDARD MODEL AND BEYOND

Our story begins in the 1970s, with the development of the Standard Model, the broadest and most successful quantum theory physics has ever seen.[2] This theory explains almost every single phenomenon we can observe and has justifiably been called "the pinnacle of human achievement."[2]

Despite the Standard Model's great success, however, it is not bereft of problems. One of its most significant difficulties is known as the "hierarchy problem." Theoretical calculations of the mass of the Higgs Boson and other related particles have revealed a troubling difficulty—quantum corrections should have caused the masses to be far, far greater than what had actually been observed.[3] Quantum corrections are terms which theorists must add to their equations when solving problems using a method known as perturbation theory. In this method, a complicated problem is solved by first writing the solution for the simplest case of the problem, and then adding further terms—the quantum corrections—to take into account the more complex features of the problem which the original solution had ignored.[4]

One possible but highly controversial explanation was that these corrections fortuitously canceled each other out. Alternatively, it was possible that there was a hidden mechanism which balanced them out. Attempts to solve this problem led to the development of one of the most exciting new tools of theoretical physics—supersymmetry.

Developed in the 1970s by several physicists, supersymmetry postulates that every matter particle or *fermion* has a corresponding partner which is a force particle or *boson*. A photon of light, for instance, is a boson, while an electron is a fermion. These partner particles are thought to cancel the quantum corrections caused by the regular particles.[5] Not only does supersymmetry thus neatly resolve the hierarchy problem, it has the added benefit of proposing an explanation for dark matter—the mysterious class of matter we know exists but have yet to observe—by offering the supersymmetric partners of our regular particles as possible dark matter candidates.[6] It almost seems too good to *not*

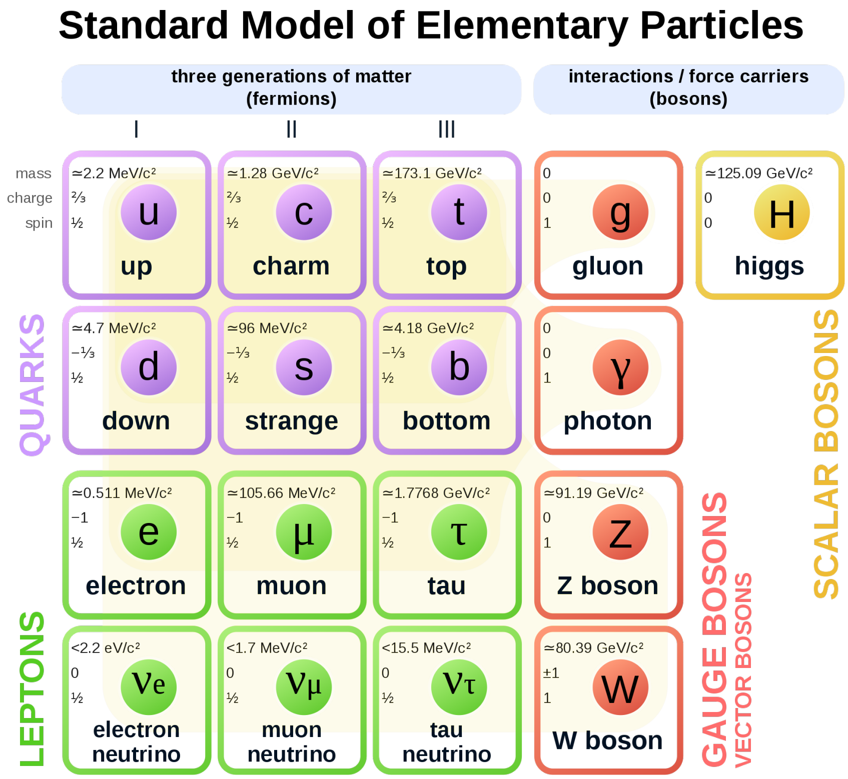

Figure 1: *The standard model, the theory of almost everything.*

be true.

The problem was that verifying the predictions of supersymmetry would require particle accelerators capable of reaching energies no accelerator of that time could reach. To remedy this, physicists built the Large Hadron Collider (LHC) in 2008. It was, and remains, the largest machine ever built, designed to generate sufficiently high energies to explore the new physics beyond the standard model.[7]

OPTIMISM TURNS TO DESPAIR

It is here that the mood of this narrative becomes less upbeat. In the ten years that the LHC has been operational, it has not detected a single supersymmetric or dark matter particle. Nor has it given any clues whatsoever for the existence of supersymmetry. The discovery of the Higgs, though a phenomenal success, was but an additional confirmation of the Standard Model.

The current state of affairs, affectionately dubbed the "nightmare scenario," leaves physicists in a unique quandary. Supersymmetry has not been disproved—in fact, that outcome would have been much more helpful, as it would have at least provided theorists with some direction. On the contrary, the experimental data neither supports nor disproves any of the predictions of supersymmetry. Though the LHC has been able to confirm and reaffirm the Standard Model, it has failed to fulfill its founding purpose.[8] The upshot is that a large number of physicists are left with a theory they spent several decades developing to such a degree that even its critics acknowledge its mathematical potential—without any idea of its validity.

Supporters of supersymmetry suggest that physicists simply underestimated the masses of the supersymmetric particles; perhaps, the superparticles are actually heavier than what even the LHC can currently detect.[9] Not only might some consider this a suspiciously ad hoc claim, but increasing the predicted masses of the superparticles also raises questions regarding the principle of naturalness.

NATURALNESS IN PHYSICAL THEORIES

Naturalness is a principle in scientific philosophy which demands that the physical parameters of a scientific theory should arise as "naturally" from fundamental principles as possible; that is, there should be an underlying principle which explains all the predictions of the theory. According to this concept, such a theory is preferable to one in which theorists can artificially fine-tune the values of their predicted constants so that the constants conveniently combine to give the expected result.[8]

In the case of supersymmetry, in order to correctly cancel the quantum corrections to the Higgs mass, theorists required the superparticles to be more or less equal in mass to their partners. But as the LHC kept reaching progressively higher energy and mass scales without finding any superparticles, hopeful supersymmetry proponents claimed even higher masses for the partner particles. In order to salvage the situation, supporters of supersymmetry had to fine-tune the values of a variety of other constants, so that when combined, they still yielded the correct Higgs mass.[3] Paradoxically, at some point this explanation amounts to the same reasoning inherent in the non-supersymmetric Standard Model—that the serendipitous cancellation of the quantum corrections, or in this case, the superparticles attaining the required fine-tuned values, is just a coincidence.

While in principle there is nothing wrong with this kind of theory—we might simply be lucky to live in a universe where fundamental constants are custom-made for our existence—it flies in the face of the principle of naturalness, which demands an explanation for this coincidence. In following this approach, moreover, proponents of supersymmetry can keep raising the target particle-mass level for experimentalists to

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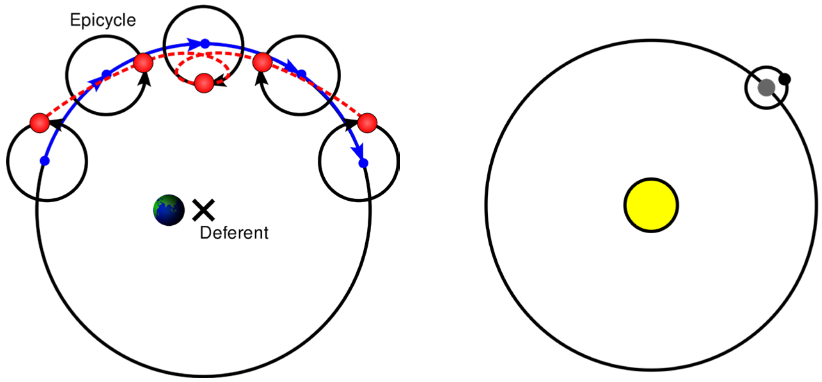

Figure 2: *Ptolemy vs. Copernicus. Since a large number of epicycles of very convenient sizes and orientations need to be added to get the required accuracy in Ptolemy's model, we consider his geocentric theory to be fine-tuned and "unnatural." We thus prefer the much simpler heliocentric theory proposed by Copernicus.*

reach by simply fiddling with their constants—and thus keep justifying their research (and their funding). These modifications make the theory more fine-tuned and thus less natural and elegant.

The trouble is that the concept of naturalness is purely human, and does not necessarily have anything to do with the universe we live in. Indeed, when there is no experimental evidence clearly falsifying one theory or another, the choice of which one to use often becomes a matter of taste. For instance, in discussing a possible modification to supersymmetry in his paper "The State of Supersymmetry after Run I of the LHC," author Nathaniel Craig, a physicist at the Institute for Advanced Study at Princeton University, evaluates the modified theory by noting that "there is no reason it can't be there, but it's fairly unsatisfying as a theory of nature."[8] There is, however, no quantitative reason to reject a theory simply for being "unsatisfying."

On the other hand, historically, similar cases have demonstrated that the simpler theory is usually correct. For example, Ptolemy clung to the geocentric idea of the solar system by proposing that heavenly bodies moved around the earth in multiple nested circles called epicycles. By arbitrarily adjusting the number and size of epicycles in his model, he could make his theory as accurate as desired.[10] In contrast, Copernicus proposed a much simpler heliocentric model of the solar system, with Newton later providing the underlying physical explanation for this model. Despite the matching accuracy of both theories, Copernicus' more elegant heliocentric model of the solar system is what ultimately proved to be the more correct one. Be it theories of the solar system or those of the expanding universe, scientists have had to develop new theories whenever the reigning ones have required overly contrived modifications.[11]

This dilemma leaves physics at an interesting crossroad, one in which the debate over the validity of a theory is, to a certain extent, philosophical rather than scientific in nature. Young researchers entering the field now have a difficult choice to make: continue efforts at justifying the absence of experimental evidence by fine-tuning—hoping that some evidence shows up sooner rather than later—or break away and explore radically different ideas. Which way should future research go? This debate, regardless of how it is resolved, will have an immense impact on the future of theoretical physics. It is indeed an exciting time to be a physicist.

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