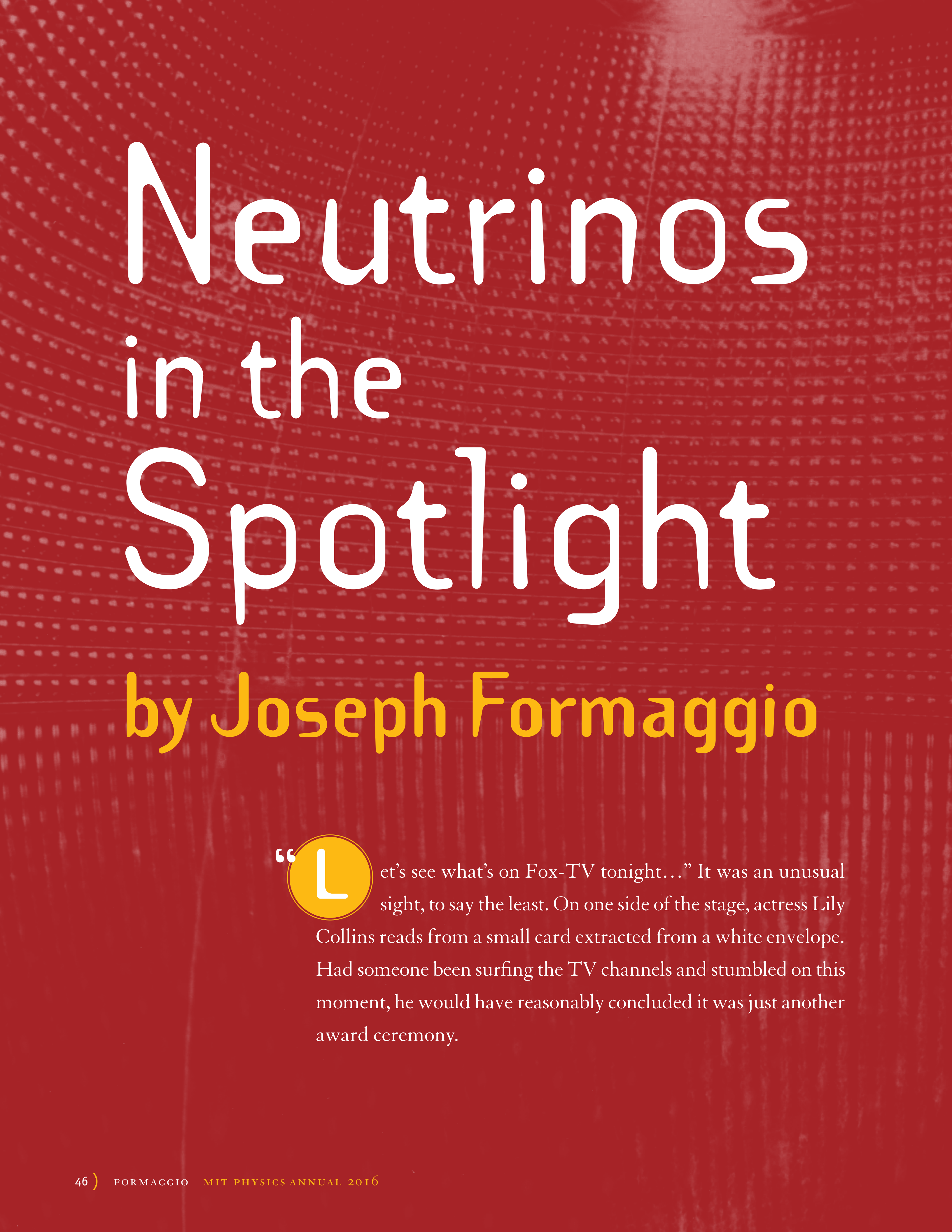

Neutrinos in the Spotlight

by Joseph Formaggio

"Let's see what's on Fox-TV tonight…" It was an unusual sight, to say the least. On one side of the stage, actress Lily Collins reads from a small card extracted from a white envelope. Had someone been surfing the TV channels and stumbled on this moment, he would have reasonably concluded it was just another award ceremony.

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Liebe Radioaktive Damen und

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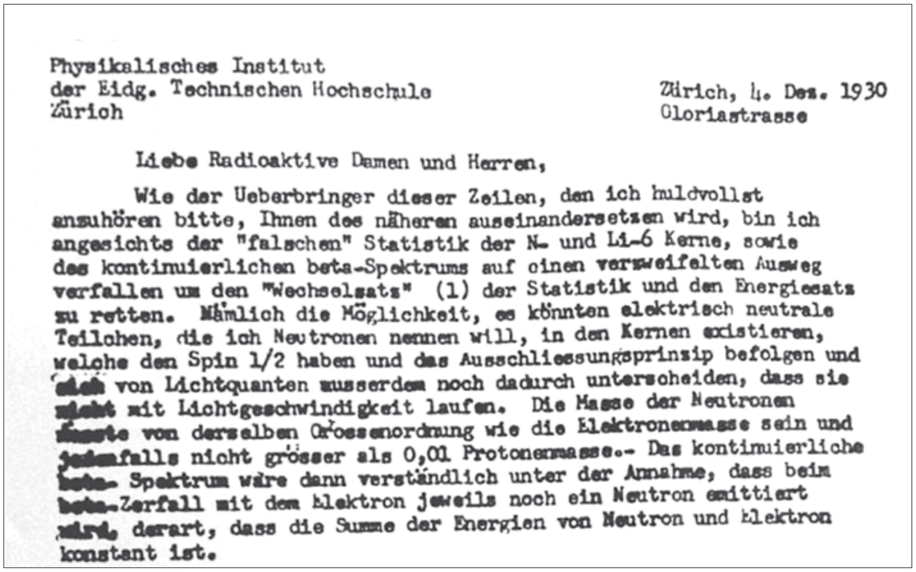

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

FIGURE 1

(Right) ***Telegram sent by Wolfgang Pauli*** *(above) where he outlines his idea for a new, charge-less particle with very little mass to help explain the energy conservation crisis. "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do," he wrote, describing his idea as "a desperate remedy." [Courtesy of the Pauli Archive.]*

But, as Ms. Collins reads from her card, an ensemble of older gentlemen enters stage right. I recognize several of them, not because they are famous actors or artists, but because I have seen them speak at conferences or, as in one particular case, worked closely with him. They were Professors Yifang Wang, Koichiro Nishikawa, Atsuto Suzuki, Kam-Biu Luk, Takaaki Kajita, Yoichiro Suzuki, and Art McDonald. All were being recognized for their work on understanding the properties of neutrinos—on prime-time television.

A mystery thirty years in the making

The event that was being televised that evening was the award ceremony for the 2016 Breakthrough Prize in Fundamental Physics. It recognized the leaders and members of six landmark neutrino experiments: Daya Bay, KamLAND, SNO, Super K, T2K and K2K. The award came at the heels of the Nobel Prize in Physics, which was awarded to Art McDonald and Takaaki Kajita "for the discovery of neutrino oscillations, which shows that neutrinos have mass." It has been a very exciting year for neutrino physics. Of course, the award was perhaps no surprise to those of us in the field; the discovery that the neutrino has mass has vast implications for our understanding of particle physics.

From the beginning, the neutrino has been a rather peculiar member of the particle zoo family. Wolfgang Pauli predicted their existence in 1930 *(Figure 1)*. For a long time, physicists had convinced themselves—based on the predictions of the Standard Model, which describes particles and their interactions—that neutrinos should be massless particles. However, a number of oddities about neutrinos had started to become apparent in various experiments that were studying sources of neutrinos. In one case, the number of neutrinos produced in the upper atmosphere by cosmic rays did not agree with predictions. In another, there was an outstanding "solar neutrino puzzle" whereby almost two-thirds of neutrinos produced in the core of the sun were "missing." Many models and theories were proposed to explain these discrepancies, among them the possibility that neutrinos might be changing from one type to another[1]. As early experiments were sensitive only to one specific type of neutrino, the theory was that we were miscounting the total number of neutrinos. The phenomenon, known as neutrino oscillations, provided an elegant solution to the results seen by these early experiments. However, the proposition came at a high cost: for the theory to be correct, the neutrinos must have differences in their inherent masses. But, if the neutrinos displayed mass differences, then they must also have a mass that is non-zero[2].

That was a big no-no for the Standard Model.

What was revolutionary about the work of Kajita (of the Super-Kamiokande experiment in Japan) and McDonald (of the Sudbury Neutrino Observatory (SNO) in Canada) was that they were able to provide definitive proof of the phenomena of neutrino oscillations. Super-Kamiokande measured the characteristic signature of oscillations by studying neutrinos produced in the upper atmosphere of the Earth. On the other side of the Earth, SNO made its measurements of neutrinos coming from the solar core. By cleverly using deuterated water (D_2O instead of H_2O), SNO was able to count *all* types of neutrinos, regardless of which kind they started out as. Their measurement, like their Japanese colleagues, clearly demonstrated the signature of oscillations *(Figure 2)*.

Thus, the observations made by Super-K, SNO, and many others since, solidified the evidence for neutrino oscillations. In the process, Kajita and McDonald helped resolve two major puzzles in the field of physics. And we now have inherited a world where neutrinos have mass.

FIGURE 2

Images of the Sudbury Neutrino Observatory *(left)* ***and the Super-Kamiokande Experiment*** *(right). [Courtesy of the Sudbury Neutrino Observatory and the Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo.]*

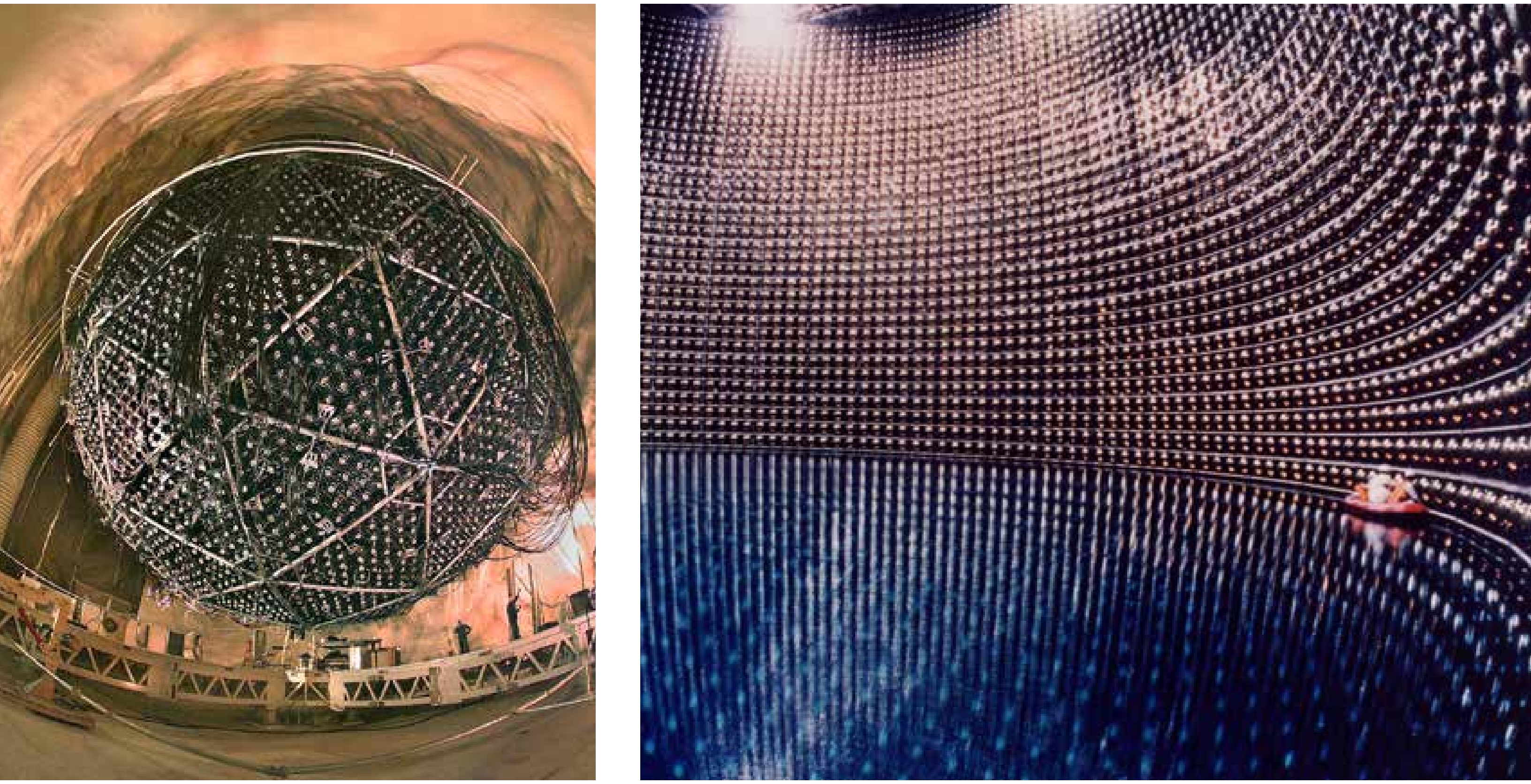

FIGURE 3

Passage of the KATRIN neutrino mass experiment *through the center of town on its way toward installation. [Courtesy Karlsruhe Tritium Neutrino (KATRIN) collaboration.]*

Unknown unknowns

Despite it being almost 86 years since the idea of the neutrino was first conjured, it still stands today as one of the least understood particles that we know exists. Now, someone keeping up with the latest discoveries in the scientific literature may object to such a proposition. Surely the Higgs boson, whose discovery is not even five years old, should hold that title. However, very quickly after its discovery its properties were very readily measured. The Higgs's mass was known very accurately once it was seen, as was how it communicates with other particles. Indeed, the properties of the Higgs fit very well within the framework upon which it was predicted. Neutrinos, in contrast, do not share this level of understanding. The mass scale of these particles is still unknown. The essential nature of neutrino mass—which is tied to whether the neutrino is its own anti-particle—remains a mystery. Indeed, even the reason as to why neutrinos has any mass at all is still a subject of debate within the physics community.

But where there are questions, there is room for discovery.

Let us briefly consider just three of the major questions we hope to uncover from neutrinos in the hopefully-not-so-distant future.

How much does a neutrino weigh?

This is somewhat of a deceptive question. After all, didn't we just celebrate the fact that neutrinos have mass? Alas, although we know that neutrinos have a finite mass, the overall scale of neutrino masses remains hidden. This is because oscillation experiments, by their very nature, can only be sensitive to mass differences. The analogy I enjoy using is where you are told how much you can save if you buy a car, but are never told the actual price of the vehicle. For measuring the mass scale, a different technique is required. A number of experiments are now underway to uncover this fundamental property [3]. Once measured, we hope to gain a greater understanding of the nature of mass itself *(Figure 3)*.

Is the neutrino its own nemesis?

The mechanism by which neutrinos acquire mass is likely fundamentally different than that of the other particles we know—again because according to the Standard Model the mass of the neutrino should really be zero. One mechanism by which this mystery can be resolved is if the neutrino possesses a peculiar property; that

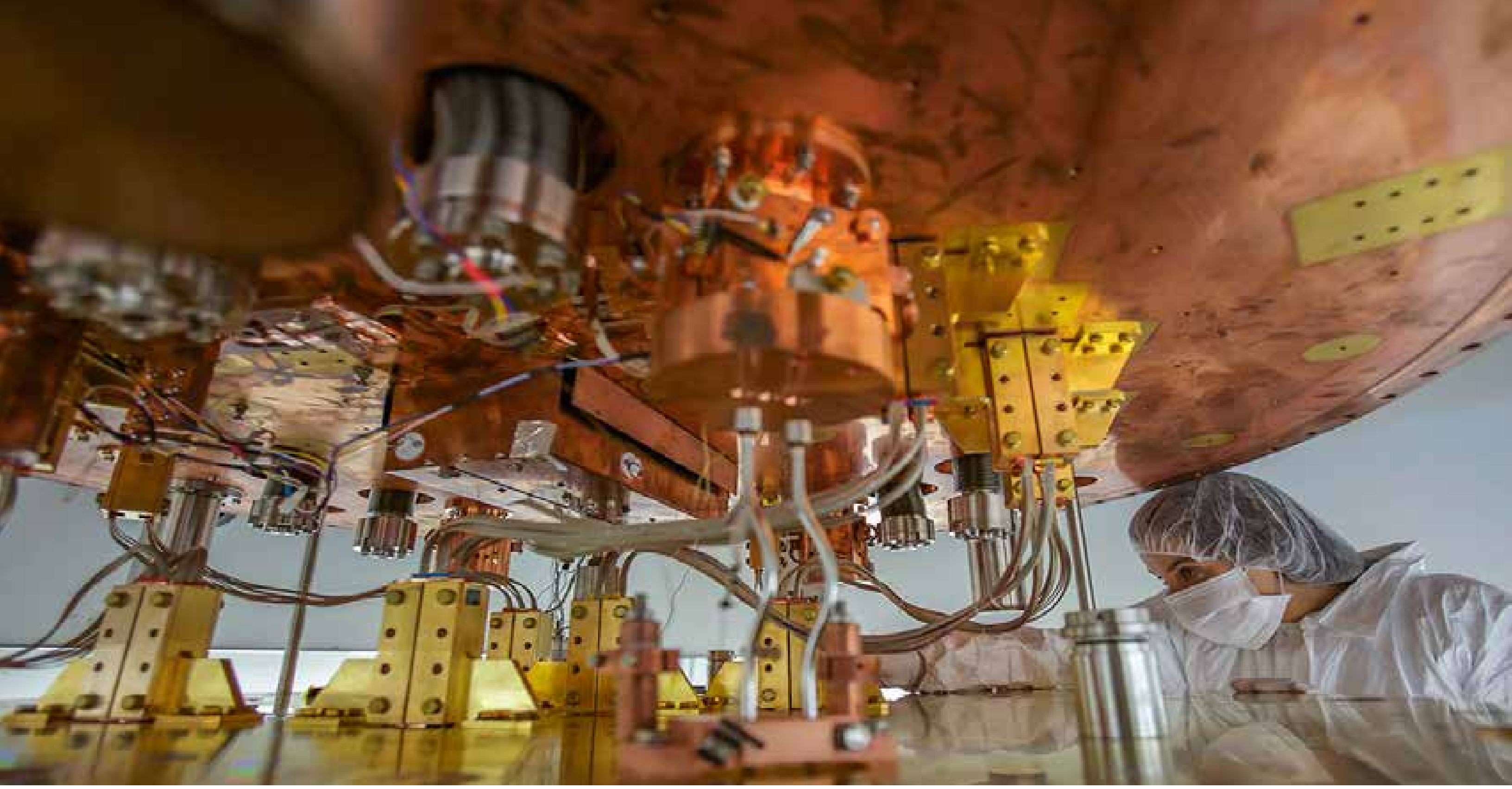

FIGURE 4

Work preparation for the CUORE *neutrinoless double beta decay experiment in Gran Sasso, Italy. [Courtesy: CUORE collaboration.]*

is, that the neutrino is its own anti-particle. The consequences of such a discovery would be a complete game changer for our understanding of particle physics. The signature of this property is searching for an extremely rare process known as NEUTRINOLESS DOUBLE BETA DECAY. Rare is an understatement here since the process has a lifetime far, far longer than the age of the universe. Despite the daunting task, there are a number of experiments beginning to take data worldwide that hope to discover this process and shed light into the nature of neutrino mass [4] *(Figure 4)*.

Did neutrinos save the universe?

In particle physics, the universe is divided into the realm of particles and anti-particles. Using the rules of the Standard Model alone dictates that the universe should have no preference of one versus the other. As such, our matter-dominated world should have never come into existence. The question of why we have a matter-dominated universe versus nothing is one which our language cannot explain currently. The process, known as CHARGE-PARITY (CP) VIOLATION, is therefore invoked as a "must" to explain why we observe more matter than antimatter in the universe. Observation of this property is again within our experimental reach, and the race is on [5].

A brave new(er) world...

In the 1970s, the particle physics community came to a consensus that the Standard Model of particle physics was the proper framework to describe the interactions of particles and forces. The convincing evidence for accepting this model was due, in part, to measurements made with neutrinos. Neutrinos were key in the formulation of the Standard Model. Now, almost forty years later, we see that neutrinos—specifically the discovery of neutrino mass—might indeed be the Standard Model's undoing.

A massive neutrino world is inherently different than a massless one, at least for particle physicists. The discovery has now helped spur a new generation of experiments probing more deeply toward answering some of the fundamental questions raised by this new knowledge. And the hope is that neutrinos will be celebrated once again for showing us a richer and better understood world.

REFERENCES

[1] Neutrinos come in three different flavors: the electron neutrino, the muon neutrino, and the tau neutrino.

[2] Or, at least two of them have to be non-zero. The lightest neutrino could, in principle, still have zero mass.

[3] The MIT Physics Department has a strong involvement in two major efforts toward this goal: the KATRIN experiment in Germany and the Project 8 experiment in the U.S.

[4] MIT has a strong footprint in this line of research as well. Professor Lindley Winslow is engaged in both the CUORE and KamLAND-Zen experiments searching for this rare process.

[5] Yet another strong MIT presence in this experimental program. Professor Janet Conrad leads two experimental efforts, IsoDAR and DAEδALUS, for both of which the eventual goal is to probe the matter/anti-matter asymmetry of neutrinos.

PROFESSOR JOSEPH FORMAGGIO*'s research explores the nature of neutrinos and their deep connection between particle physics and cosmology. This exploration is conducted via three areas of experimental research: the Sudbury Neutrino Observatory (SNO), studying neutrinos produced in the solar core; KATRIN, a next-generation tritium beta decay experiment geared at directly measuring the neutrino mass down to fractions of an electron volt; and Project 8 / CosmoNeut, which explores a novel technique by which to measure neutrino masses and, eventually, push toward the possible detection of relic neutrinos. Formaggio received his BS degree from Yale University in physics in 1996. Thereafter, he received his PhD in physics from Columbia University, where he did his dissertation on neutrino physics by analyzing data taken at the NuTeV experiment located at the Fermi National Laboratory. His research focused on searches for exotic particles predicted by certain theoretical extensions of the Standard Model of particle physics. In 2001, he joined the SNO as a postdoctoral fellow at the University of Washington, where he was later appointed as a research assistant professor. He joined MIT in 2005 as an assistant professor of physics and was appointed Division Head, Experimental Nuclear and Particle Physics, as of July 2015.*