Gerald Gabrielse in his low-energy-physics lab at Northwestern University in Evanston, Illinois, with postdoc Wayne Huang.

standard model. If such hints emerge, they could point the way to explaining the mysteries of dark matter and dark energy, which collectively constitute some 95% of the Universe. "This is sort of a tectonic shift in the way we think of doing physics," says Savas Dimopoulos, a theorist at Stanford University in California.

SQUASHED SPHERE

In some ways, these small-scale experiments are a return to how particle physics was once done. Gabrielse drew particular inspiration from a 1956 experiment by physicist Chien-Shiung Wu. In a laboratory at what is now the US National Institute of Standards and Technology in Gaithersburg, Maryland, Wu found an asymmetrical spatial pattern in how radioactive cobalt-60 atoms emit electrons. The finding, along with theoretical work, confirmed that two particles discovered almost a decade before were actually one and the same. It also helped to solidify faith in the burgeoning theoretical framework for the Universe's fundamental particles and most of its fundamental forces, which would soon evolve into the standard model.

But physics was already moving towards bigger and more-expensive experimental machinery. Buoyed by a flush of post-Second World War cash and prestige, and by predictions that new particles would emerge in high-energy collisions, physicists proposed increasingly powerful and expensive particle accelerators. And they got them: facilities sprung up at Stanford; at Fermilab near Batavia, Illinois; at CERN near Geneva; and elsewhere. Quarks, muons, neutrinos and, finally, the Higgs boson were discovered. The standard model was complete.

And yet, as a description of the Universe, it is incomplete. The standard model doesn't explain, for example, why antimatter and matter were not created in equal parts at the start of the Universe. If they had been, they would have annihilated each other, leaving behind a featureless void. The standard model also says nothing about dark matter, which seems to bind galaxies together, or about the dark energy that is pushing the Universe apart at an accelerating rate. "I like to call the standard model the great triumph and the great frustration of modern physics," says Gabrielse. On the one hand, he says, it lets physicists predict some quantities "to ridiculous accuracy. On the other hand, we have a hole we can drive the Universe through."

Gabrielse's work trapping and probing particles at very low energies has taken him to a smaller facility at CERN, home of the LHC, to hunt for differences between matter and antimatter (see *Nature* **548,** 20–23; 2017). He and his colleagues have produced the most precise measurement yet of a physical quantity — the size of the electron's internal magnet, or spin[1].

But one of his biggest focuses in the past decade has been pinning down the shape of the electron. Although it is usually seen as a simple point with negative charge, the electron could have hidden complexity. If certain symmetries of nature — rules that say the Universe behaves the same under various reversals — are violated, the electron's charge won't have a perfectly spherical distribution. Instead, virtual particles that constantly wink in and out of existence will skew the overall distribution of charge, squashing it slightly out of shape and giving it what physicists call an electric dipole moment, or EDM (see 'Searching the particle sea').

The standard model predicts a tiny squashing — so small, Gabrielse says, that "there's essentially no hope to measure it in my lifetime". But some theories posit as-yet-undetected particles that could make the electron's EDM roughly one billion times larger. Many of those theories fall into a class called supersymmetry, an extension of the standard model that could explain why the Higgs boson's mass is smaller than expected, and that could unify the electromagnetic, weak and strong forces in the early Universe. It might also reveal the nature of dark matter.

> "THIS IS SORT OF A TECTONIC SHIFT IN THE WAY WE THINK OF DOING PHYSICS."

Attempts to measure the electron's EDM go back more than four decades. Physicists have taken advantage of the fact that an electron with an EDM can rotate, or precess, around an electric field, tracing out a loop. The stronger the electric field, the faster — and more easily detectable — the precession.

But complications abound. Experimentalists can't work with solitary electrons, because a strong electric field would cause them to skitter away. Luckily, atoms and molecules effectively lock electrons in place — and can produce internal electric fields stronger than the strongest laboratory-made field. Because atoms and molecules absorb light at specific frequencies, researchers can use lasers to trap and cool them — and nudge their internal electrons into different configurations.

By the mid 2000s, several generations of experiments building on these techniques had ratcheted down the upper limit on the size of the electron's EDM, but not quite to the level that would reveal the influence of particles predicted by supersymmetry or other extensions of the standard model. One of those experiments was conducted at Yale University in New Haven, Connecticut, by physicist David DeMille and his colleagues, using thallium ions[2]. But DeMille was running out of ideas for teasing more accuracy from his experiment, which was demanding an increasingly byzantine arrangement of highly calibrated lasers, vacuum chambers and cryogenics.

A breakthrough came in 2008, when two theorists at JILA, a research institute in Boulder, Colorado, reported[3] that the molecule thorium oxide had an internal electric field roughly 1,000 times the strength of thallium's, which would make a precession effect in its electrons much easier to see. Around the same time, Gabrielse — who was then at Harvard University in Cambridge, Massachusetts — had wrapped up a long-running study and decided that he wanted to get into the electric-dipole game. He talked to John Doyle, also a physicist at Harvard, who had invented a new way to make focused beams of cold, slow-moving molecules. DeMille also contacted Doyle, and the three decided to join forces. In 2009, the trio's experiment, called Advanced Cold Molecule Electron EDM, or ACME, received a 5-year, $6.2-million grant from the US National Science Foundation.

PRECESSION PROCESSION

The group set up shop at Harvard. Gabrielse worked on making the team's lasers — eight in total — more stable and accurate. Doyle focused on producing high-quality beams of thousands of thorium oxide molecules. And DeMille designed a system to align the molecules and shield them from outside interference.

In the experiment, a lab-made electric field orients the thorium oxide molecules. A pair of lasers then sets the spin direction of an electron inside each molecule to be perpendicular to the molecule's internal electric field, and a magnetic field is used to make the particle's spin precess. If the electron has an EDM, it will slightly add to or subtract from that rotation. After about one millisecond, polarized laser light bouncing off the molecules reveals how far their electrons have precessed. The experiment is then repeated with the molecules' orientations reversed, which should reverse the direction of precession due to an EDM. The larger the difference in precession angle, the larger the EDM.

In early 2014, the researchers reported[4] that they had not seen evidence for an EDM in their set-up, which was sensitive to an angular difference of about 100-millionths of a degree. That drove the upper limit of the electron EDM down by more than a factor of 10, to 8.7×10^{-29} in units of centimetres multiplied by electron charge. If an electron were the size of Earth — and Earth a perfect sphere — the limit would correspond to moving a patch of material roughly 20 nanometres thick from one pole to the other.

The ACME team argued that the result has big implications for theories beyond the standard model, nixing many hypothetical supersymmetric particles that would exist in an