The changes raised the estimated likelihood of a magnitude-8 or larger quake in California over the next 30 years from 4.7% to 7%. But because a fault system can only release as much energy as is built up by grinding tectonic plates, increasing the frequency of large events means there will be less energy to fuel smaller quakes. For California, this means the expected number of quakes around magnitude-6.7 dropped by about 30%, which more closely approximates the number in the historic record than previous models. "It's a significant step toward being a more realistic representation of the interconnectedness of the faults," Field says. The new model has already been used to update the state's seismic hazard maps, which in turn will inform the engineering of buildings and other important infrastructure.

Scientists are still working on exactly how seemingly unconnected faults separated by 15 kilometers or more ruptured together in the Kaikōura earthquake. Hamling's team concluded that previously unmapped faults near the surface helped bridge the gap, which suggests that hidden faults could be a source of unrecognized risk. But unseen deeper connections could be at work as well. Many of the faults involved in the Kaikōura quake may join up lower in the crust, Hamling says—perhaps at the tectonic boundary deep beneath New Zealand where the Pacific plate is being dragged beneath the Australian plate, which could act as a sort of master structure aiding connectivity.

But faults may not even need a physical connection in order to rupture together, says Jean-Philippe Avouac, a geologist at the California Institute of Technology in Pasadena. It's possible that seismic waves from a rupture on one fault can propagate through the ground with enough energy to cause a distant fault to slip, a process called dynamic triggering. "I'm not sure that we need these links to exist actually," Avouac says.

The New Zealand quake is not only impacting the modeling of future quakes, but is also changing the way scientists think about past ones, says earthquake geologist Kate Clark of GNS Science, a co-author on the *Science* paper. Clark looks for signs in the geologic record of coastal uplift caused by past earthquakes, and usually attributes movement to earthquakes rupturing one fault at a time. "We've probably misinterpreted some past records of coastal uplift and probably oversimplified past scenarios of earthquakes." ■

Betsy Mason is a journalist in the San Francisco Bay Area in California.

PHOTO: JEFFERSON LABORATORY

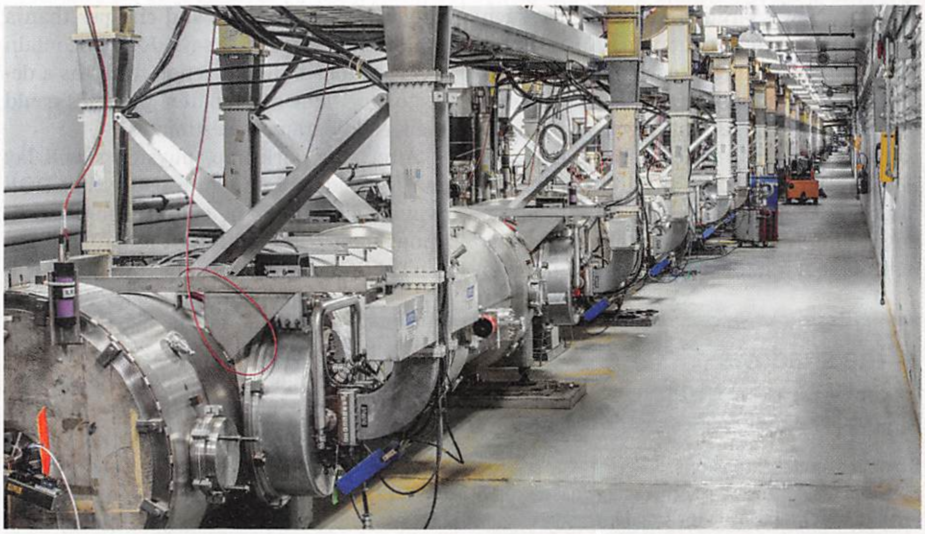
PHYSICS

In search for unseen matter, physicists turn to dark sector

U.S. Energy Department mulls probe of shadow world

By **Adrian Cho**

Scientists hunting unseen dark matter are looking deeper into the shadows. With searches for a favored dark matter candidate—weakly interacting massive particles (WIMPs)—coming up empty, physicists are now turning to the hypothetical "dark sector": an entire shadow realm of hidden particles. The concept "has been percolating for 7 or 8 years, but it's really coming to the fore now," says Jonathan Feng, a theorist at



The electron beam at Jefferson Laboratory creates copious photons in the hopes that a few may be dark.

the University of California, Irvine (UCI).

This week, physicists will meet at the University of Maryland, College Park, for a workshop, sponsored by the U.S. Department of Energy (DOE), to mull ideas for a possible $10 million dark matter experiment that could go ahead in the next few years. The effort would complement the agency's current experiments, including the flagship WIMP search, LZ, a $76 million subterranean detector under construction in Lead, South Dakota. And many researchers believe DOE should focus on the dark sector. Jim Siegrist, DOE's associate director for high-energy physics in Washington, D.C., says the goal is to fill in any gap in DOE's searches for dark matter, which makes up 85% of the universe's matter: "Is there anything we're missing?"

WIMPs, dreamed up in the 1980s, once seemed the perfect candidate for dark matter, which shapes the visible universe with its gravity. WIMPs would weigh a few hundred times as much as a proton and interact only through gravity and the weak nuclear force. A simple calculation suggests just enough of them should linger from the big bang to account for dark matter today—a selling point known as the "WIMP miracle." In addition, WIMPs emerge naturally in many versions of supersymmetry, a concept that solves key technical problems in the standard model of the known particles. However, physicists have yet to detect WIMPs bumping into atomic nuclei in underground detectors. And the world's most powerful atom smasher, the Large Hadron Collider (LHC) in Switzerland, has seen no sign of supersymmetry or WIMPs.

The no-shows have led physicists to turn to the dark sector. They speculate that dark matter might consist not of a single massive particle tacked onto the standard model, but of a slew of lighter particles and forces with tenuous connections to known particles (see illustration, p. 1252). For example, in the familiar universe, massless photons convey the electromagnetic force;

in the dark sector, a massive dark photon would convey a dark version of electromagnetism. Theorists generally expect that ordinary and dark photons would subtly intertwine or "mix." Very rarely, then, a particle interaction that would normally produce a high-energy photon would instead produce a dark photon.

Higgs bosons and neutrinos would connect similarly to the dark sector. Thanks to these portals, the infant universe should have produced the right amount of dark matter, much as in the WIMP miracle.

Dark sector particles would be much lighter than WIMPs—less than the mass of a proton—so physicists don't need the energy of the LHC to blast them into existence. A much lower energy but intense electron beam could do the trick. When electrons crash into a solid target they radiate abundant photons—and could occasionally generate a dark photon.

The Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, supports just such fixed target experiments. In 2010, physicists on the A Prime Experiment at CEBAF searched—without success—for dark photons decaying into telltale electron-positron pairs. Last year, physicists on the Heavy Photon Search used CEBAF to try again. In future accelerator experiments, physicists might simply track the scattered electrons instead, looking for a distinctive kink in an electron's trajectory that would result when it emits a dark photon.

Or, as with WIMP detectors, physicists could try to detect dark-sector particles drifting in Earth's vicinity. Because WIMPs are heavy, physicists search for them by looking for the recoil of heavy atomic nuclei such as those in liquid xenon. That technique won't work for much lighter dark-sector particles, which would bounce off a heavy nucleus like ping pong balls off a bowling ball.

Instead, physicists could look for the recoil of wispy electrons, perhaps in a device akin to an existing WIMP detector, says Kathryn Zurek, a theorist at Lawrence Berkeley National Laboratory in California. Or they could create a frigid bath of light nuclei in "superfluid" helium, and look for tiny quantum vibrations triggered by the collisions. Another option would be to look for the breaking of free-flowing pairs of electrons in a superconducting metal. In part because light dark matter particles would be more numerous than WIMPs, a detector for them could be much smaller and cheaper than a WIMP detector, Zurek says. LZ will contain 7 metric tons of liquid xenon, whereas a detector for light dark matter particles could weigh a kilogram, she estimates.

After the workshop, physicists will lay out their ideas in a white paper that DOE will consider over the coming months—although Siegrist cautions the $10 million isn't guaranteed. Some hope the agency will quickly mount a "shovel ready" experiment, in particular an accelerator-based effort that looks for the dark photon by the kinked-trajectory method. "For $10 million you could build a really nice detector and set it down next to an existing accelerator," says Timothy Tait, a UCI theorist. Others would prefer to develop techniques to directly detect light dark matter, even if it takes longer to mount an experiment. "I really hope this R&D can be part of the program," Zurek says.

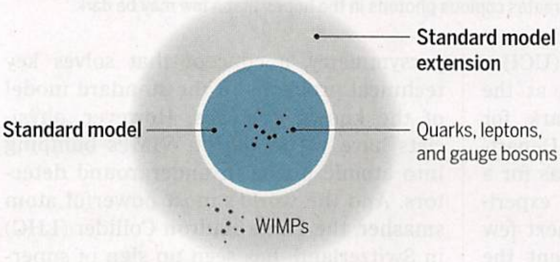
JoAnne Hewett, a theorist at SLAC National Accelerator Laboratory in Menlo Park, California, says she hopes DOE will seize the opportunity to launch not just a single experiment, but a more comprehensive 10- to 15-year program to probe the dark sector. Such experiments "cover a very important range and they're cheap," she says. "It really makes them must-do experiments." ■

In the shadows

Dark matter particles predicted by extensions of the standard model have not turned up, so a realm called the dark sector may be probed.

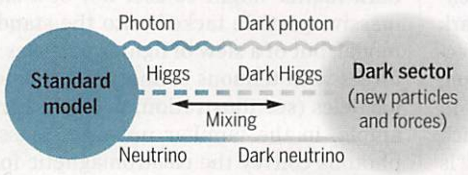
Standard model extensions

Dark matter could be weakly interacting massive particles (WIMPs) existing in an extension to the standard model of known particles.



Dark sector

Dark matter could also be particles from a shadowy dark sector that interact with standard particles through subtle mixing.



NUCLEAR WEAPONS

Tweak makes U.S. nukes more precise—and deadlier

Improved targeting could upset strategic balance with Russia and spur arms race

By **Eliot Marshall**

U.S. weapon designers may deserve a pat on the back for the sheer cleverness of an improved targeting system that is turning aging nuclear warheads into surgically precise weapons. But a new analysis warns of risky consequences. The fix, which has been developed quietly over 2 decades and is now being deployed on U.S. submarine-launched ballistic missiles, makes a small adjustment to the height at which a warhead explodes. The result is a dramatic improvement in the odds that the blast will destroy its target.

To Russia, whose defensive radars provide very short warning of a ballistic missile attack, the fix could raise fears that the United States is capable of launching a first strike that would knock out Russia's silo-based nuclear missiles before they can be launched. That undermines nuclear deterrence and creates "a deeply destabilizing and dangerous strategic nuclear situation," according to the report in the 1 March issue of the *Bulletin of the Atomic Scientists* (*BAS*).

The tweak to a nuclear weapon's fuze, or detonation control, could add to tensions that are rising on several fronts. Earlier this month, U.S. officials confirmed that Russia has deployed a new missile in violation of the Intermediate-Range Nuclear Forces (INF) Treaty, a 1987 pact affecting Europe. At the same time, Russia has been leaking information about its plans for a new seagoing robotic bomb designed to hit U.S. ports. And in December 2016 the Pentagon's Defense Science Board recommended resurrecting small, low-yield nuclear weapons of the sort that were eliminated from the U.S. arsenal

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