

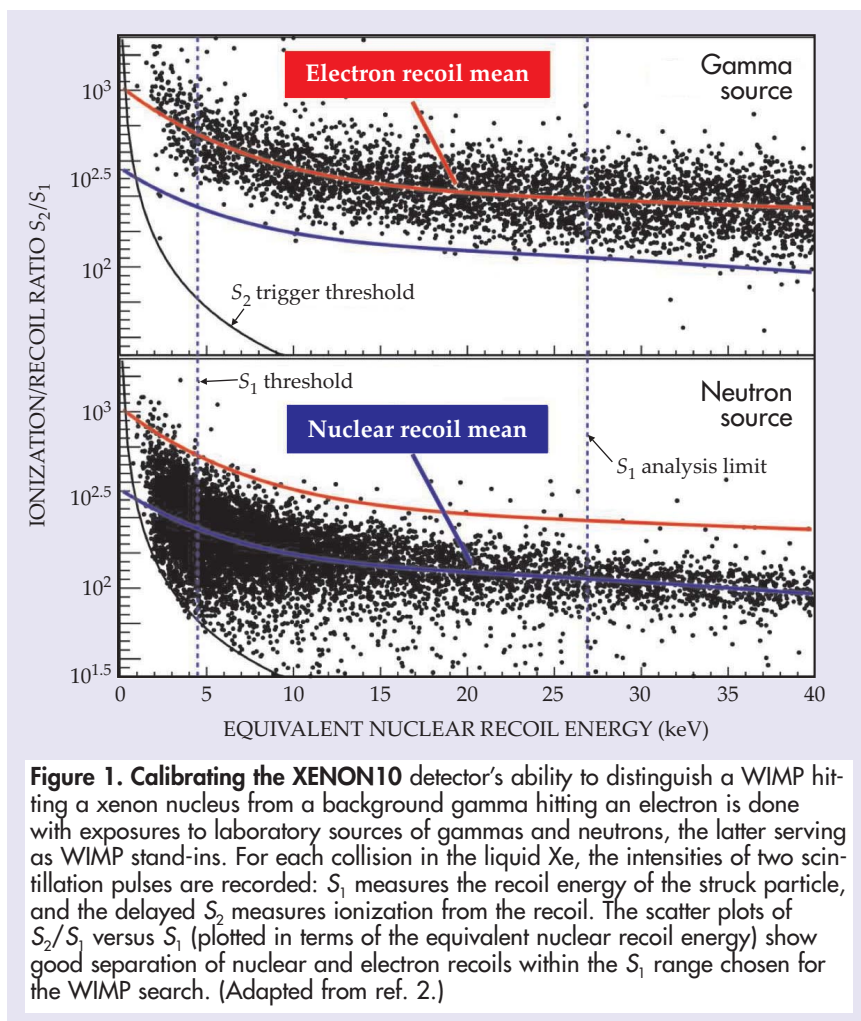
# Liquid xenon detector joins the search for dark matter

The dark matter that dominates the material content of the cosmos is thought to be made up of WIMPs, weakly interacting particles perhaps 100 times heavier than protons.

**The evidence** for nonbaryonic dark matter is compelling. An impressive variety of observational data has convinced cosmologists that protons and neutrons, and indeed all of the particles known from the laboratory, account for less than 20% of the mass of matter in the cosmos. Cosmologists and particle theorists favor the hypothesis that the predominant dark-matter particles are WIMPs (weakly interacting massive particles) with a mass on the order of 100 GeV (a hundred times the proton mass) and a scattering cross section typical of the weak nuclear interactions.

The existence of WIMPs is predicted by supersymmetry theory, theories with extra spacetime dimensions, and other attempts to speculate beyond particle theory's standard model. WIMP searches are proceeding on two fronts: The Large Hadron Collider at CERN will soon be providing 14-TeV proton-proton collisions. If WIMPs are not much heavier than 200 GeV, the hope is that they will be found among the collision products at the LHC. The other approach, less constrained by the putative WIMP's mass, is to look for the very rare elastic collisions one expects between ambient dark-matter particles in our corner of the Milky Way and nuclei in a very sensitive detector.

Short of actually finding dark-matter WIMPs, the latter approach has had two significant recent successes: Last year a null result by the Cryogenic Dark Matter Search (CDMS) collaboration, headed by Bernard Sadoulet (University of California, Berkeley), set upper limits on the WIMP-nucleon scattering cross section that, for the first time, began to nibble at the region of supersymmetry parameter space favored by particle theorists.<sup>1</sup> And now the XENON collaboration, led by Elena Aprile (Columbia University), reports stronger cross-section limits that take a real bite out of the supersymmetry parameter space.<sup>2</sup>



**Figure 1. Calibrating the XENON10 detector's ability to distinguish a WIMP hitting a xenon nucleus from a background gamma hitting an electron** is done with exposures to laboratory sources of gammas and neutrons, the latter serving as WIMP stand-ins. For each collision in the liquid Xe, the intensities of two scintillation pulses are recorded:  $S_1$  measures the recoil energy of the struck particle, and the delayed  $S_2$  measures ionization from the recoil. The scatter plots of  $S_2/S_1$  versus  $S_1$  (plotted in terms of the equivalent nuclear recoil energy) show good separation of nuclear and electron recoils within the  $S_1$  range chosen for the WIMP search. (Adapted from ref. 2.)

"Upper limits are all very well," says University of Minnesota theorist Keith Olive. "They provide essential constraints to our search for the right supersymmetric model. But even more exciting is a hint that the present CDMS and XENON detectors may be on the verge of actually finding the dark-matter WIMP."<sup>3</sup>

The sensitivity of a dark-matter WIMP detector is proportional to its active mass. CDMS, which had been at the forefront of the search over the past

decade, currently uses a detector (CDMS II) with about 2 kg of nanofabricated germanium and silicon crystals cooled to microkelvin temperatures. Aprile's XENON10 detector, a newcomer in the business, has an active mass of 15 kg of liquid xenon (LXe) at 180 K, just cold enough to keep the Xe from boiling. It's thought that the less demanding Xe detector technology can more easily and cheaply be scaled up to much larger masses. Aprile and company regard XENON10 as a small

prototype for testing the efficacy of the new technique.

## Sampling the halo

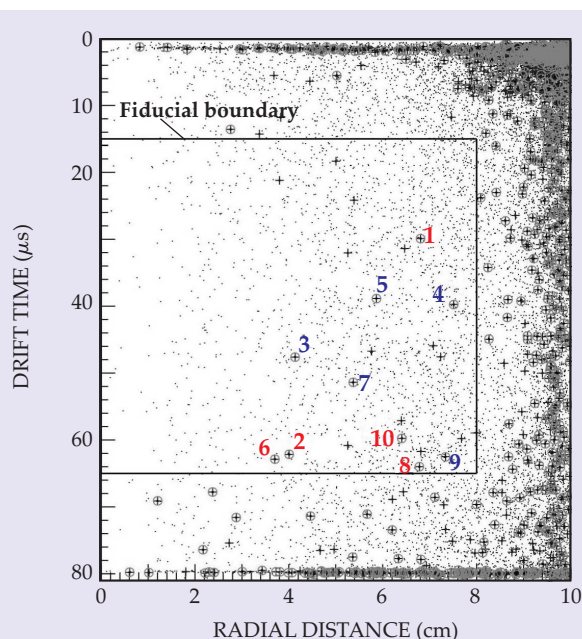
The Milky Way, like all galaxies, is presumed to be embedded in a spherical halo of dark matter that accounts for most of its mass. In the vicinity of the solar system, the dark-matter density is estimated to be about  $0.3 \text{ GeV/cm}^3$ . There's no reason to expect that the halo participates in the general rotation of the galaxy's baryonic matter, which presumably takes the solar system through the accumulation of WIMPs at about 200 km/s. On Earth, that flux would have an annual modulation of roughly 10%.

If one assumes, in the spirit of the favored supersymmetry models, that the cross section for elastic scattering of WIMPs off nucleons is something like  $10^{-43}$  or  $10^{-44} \text{ cm}^2$ , the galactic flux of dark matter through either a Xe or Ge detector would produce just a few detectable scatters per kilogram per year.

The XENON10 detector is a shielded cylinder containing 15 kg (about five liters) of LXe in equilibrium with a smaller volume of Xe gas on top. It sits under a mountain in the Gran Sasso Laboratory in the Apennines east of Rome. The mountain shields the detector from cosmic-ray muons whose collisions would create an abundance of neutrons that are hard to distinguish from WIMPs.

Arrays of photomultiplier tubes monitor the Xe liquid and gas from below and above for scintillation light. Xenon is a good scintillator. The recoil energy of a Xe nucleus in the liquid hit by a 200-km/s WIMP of comparable mass would be of order 10 keV, enough to produce a discernible scintillation flash. But that initial scintillation signal ( $S_1$ ) alone is inadequate to distinguish a rare recoiling nucleus from an overwhelming background of electrons recoiling from Compton scatters with MeV gammas emitted by uranium and other radioactive contaminants in the surrounding rock.

To make that distinction, the experiment exploits the ionization that accompanies the recoil of both Compton-scattered electrons and nuclei. An electrostatic field imposed on the liquid causes the electrons liberated by ionization to drift upward toward the surface



**Figure 2. Approximate locations of the 10 collisions** (shown numbered) within the fiducial volume of liquid xenon that survived all prespecified cuts designed to excise backgrounds. Radial distance is from the cylindrical detector's vertical axis. Height within the 15 cm of liquid is deduced from the drift time of ionization electrons up to the surface. Each dot marks a collision that registered precisely two scintillation pulses. Those marked + survived the  $S_2/S_1$  ionization cut, and those marked  $\oplus$  survived additional cuts on anomalous phototube hit patterns. The five surviving candidates with blue numbers are statistically consistent with expected background leakage through the  $S_2/S_1$  cut. Each of the other five showed some suspect character. (Adapted from ref. 2.)

at about  $2 \text{ mm}/\mu\text{s}$ . From the surface, those electrons are quickly accelerated up through the gas by a much stronger electrostatic field, thus generating a second, delayed scintillation signal ( $S_2$ ) in their wake. The time delay from  $S_1$  to  $S_2$  measures how far below the liquid surface the initial collision occurred.

More important for distinguishing WIMPs from gammas is the ratio  $S_2/S_1$  of the two scintillation light intensities. It turns out that for a given  $S_1$  (a measure of recoil energy), a recoiling electron is a more prolific liberator of ionization electrons than is a recoiling Xe nucleus. Calibration runs with neutron sources supplying WIMP stand-ins and gamma sources simulating background show that the greater ionization by Compton-scattered electrons produces  $S_2/S_1$  ratios two or three times higher than those of neutron-scattered Xe nuclei.

Scatter plots of  $S_2/S_1$  versus  $S_1$  from the calibration runs, shown in figure 1, reveal good separation between the

gamma and neutron events within the  $S_1$  range chosen for the WIMP search. Based on that separation, Aprile and company imposed an  $S_1$ -dependent upper limit on  $S_2/S_1$  for all candidate WIMP events. That cut, they estimate, succeeds in unmasking better than 99.5% of all gamma-induced impostors.

Near the margins of the detector, the  $S_2/S_1$  ionization cut is not enough to reduce the gamma background to a tolerable level. Because gammas entering the LXe lose energy by repeated collision and are eventually absorbed, the offending flux of energetic gammas is least in the detector's center. Furthermore, near the phototubes and electrode grids at the bottom and top, evidence of multiple collisions or excessive ionization that would otherwise rule out a WIMP is often lost. Therefore the analysis imposes a fiducial-volume cut that accepts WIMP candidates only from the central 5.4 kg of the LXe (see figure 2). In addition to the vertical position measured by the drift-time delay, a collision's horizontal position is deduced from its pattern of phototube hits.

## Surviving candidates

The XENON collaboration's paper<sup>2</sup> reports the result of 1400 hours of detector runs in search of WIMP collisions with nuclear recoil energies ranging from a detection threshold of 4.5 keV up to 27 keV. After all cuts winnowed the many thousand collision events in the LXe that triggered precisely two scintillation pulses, only the 10 WIMP candidates numbered in figure 2 remained. In accordance with the current fashion of "blind" data analysis, the experimenters had chosen all the cuts by examining earlier calibration and shakeout runs before letting themselves see their effects on the actual search.

To set conservative limits on the WIMP-nucleon scattering cross section (see figure 3), the collaboration treated all 10 surviving candidates as possibly genuine without subtracting any estimate of remaining background. "But based on our statistical analyses," says Richard Gaitskill, leader of the collaboration's Brown University contingent, "we don't think that any of those 10 is likely to be a WIMP. We expected that

about seven electron-recoil events would leak through the  $S_2/S_1$  ionization cut. And five of the 10 surviving events are consistent with such leakage." The other five all turn out to have questionable characteristics detailed in the paper.

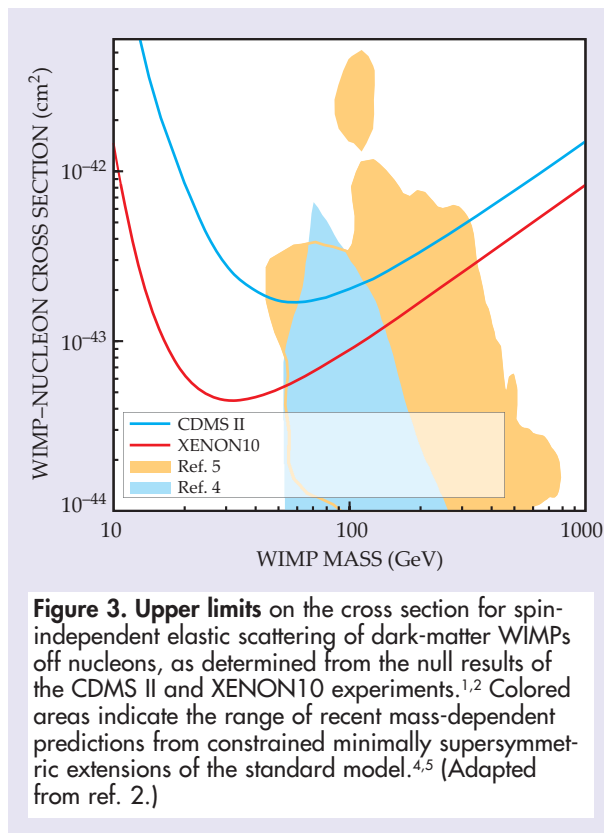
Last year CDMS reported only a single remaining background event in its 1800-hour run.<sup>1</sup> Sadoulet and company identify collisions in their ultracold semiconductor crystals by the nonthermal phonons they generate. Compton-scattered impostors are unmasked, as in XENON10, by their excessive ionization. But CDMS II's superior separation capability misses a significantly smaller fraction of impostors. In a few months, CDMS will be reporting on a longer run with bigger masses of Ge and Si.

The Xe experiment's 10 surviving events highlight a problem. Search sensitivity grows with exposure only to the extent that the background doesn't. Little is gained if doubling the experiment's run time doubles the number of surviving background events. Therefore Gaitskell and some other collaboration members are planning a new experiment called LUX, which would be a 300-kg scale-up of XENON10. The idea is "self shielding" by LXe outside the detector's fiducial volume. The mean free path of an MeV gamma in LXe is about 6 cm. So the attrition of those intruders grows exponentially with increasing linear scale.

LUX is intended for the former Homestake gold mine in South Dakota, which was selected by NSF in July as the site for its deep-underground science and engineering laboratory (see the news story on page 34). Aprile and the remnant of the XENON collaboration are opting for quicker, more incremental upscaling steps at Gran Sasso. Early next year they hope to be running with a 60-kg LXe detector.

## Superpartners

The upper limits from the CDMS II and XENON10 null results shown in figure 3 are given in terms of the cross section for the spin-independent elastic scattering of a WIMP off a single free nucleon. The WIMP is presumed to be a fermion whose elastic scattering amplitude has both spin-dependent and spin-independent terms. Because the



**Figure 3. Upper limits on the cross section for spin-independent elastic scattering of dark-matter WIMPs off nucleons, as determined from the null results of the CDMS II and XENON10 experiments.<sup>1,2</sup> Colored areas indicate the range of recent mass-dependent predictions from constrained minimally supersymmetric extensions of the standard model.<sup>4,5</sup> (Adapted from ref. 2.)**

spin-independent amplitudes of all the nucleons in the nucleus add coherently, it's safe to assume that spin-independent scattering dominates in detectors with heavy nuclei like Xe and Ge. The spin-independent cross section for a WIMP scattering off a nucleus of mass number  $A$  is  $A^2$  times the cross section in hydrogen.

The figure also shows the range of predictions by so-called constrained minimally supersymmetric standard models.<sup>4,5</sup> Supersymmetry theory has been evolving since the early 1970s. Adding to the known spacetime symmetries a new, badly broken symmetry under the exchange of integral and half-integral intrinsic spins, the theory predicts that every known fundamental fermion species will have a heavier bosonic "superpartner," and vice versa. Despite the fact that no superpartner has yet been found, the theory is widely regarded as the first best hope for getting beyond the standard model.

Looking among the putative superpartners for a plausible dark-matter candidate, particle theorists and cosmologists have converged on the "neutralino," a predicted superposition of the fermionic superpartners of the photon and the Higgs and  $Z^0$  bosons. It's expected to be the lightest of all superpartners, and therefore stable. Given free reign, minimally supersymmetric

extensions of the standard model have just over 100 free parameters. "With so much freedom, you can't do much," says Olive. So to make useful predictions, theorists constrain the models to exhibit the expected unification of electroweak and strong nuclear forces at  $10^{16}$  GeV, the "grand-unification" energy scale. That constraint reduces the number of free parameters to a manageable five. Varying those five parameters over values not yet foreclosed by accelerator data yields the range of predicted cross sections shown in figure 3 as a function of WIMP mass.

## The hint

Olive and coworkers call attention<sup>3</sup> to a statistically marginal departure from standard-model expectations recently found by the CDF collaboration at Fermilab's Tevatron.<sup>6</sup> If taken seriously, they argue, the CDF result narrows the supersymmetry prediction of the cross section enough that XENON10 should already have seen WIMPs.

Assuming that the Tevatron result survives and that the 10 XENON events are indeed background, Olive and company suggest two ways out: The estimate of local dark-matter density, on which the quoted experimental limits depend, is quite uncertain; it could easily be too high by a factor of two. Alternatively the fault could lie with the assumed quark structure functions of the nucleon. That's a nuclear-physics issue outside the immediate purview of supersymmetry. But it's essential for translating the WIMP-quark interactions predicted by any supersymmetric model into WIMP-nucleon scattering cross sections.

**Bertram Schwarzschild**

## References

1. D. S. Akerib et al., *Phys. Rev. Lett.* **96**, 011302 (2006).
2. J. Angle et al., <http://arxiv.org/abs/0706.0039>.
3. J. Ellis, S. Heinemeyer, K. A. Olive, G. Weiglein, <http://arxiv.org/abs/0706.0977>.
4. J. Ellis, K. A. Olive, Y. Santoso, V. C. Spanos, *Phys. Rev. D* **71**, 095007 (2005).
5. L. Roszkowski, R. Ruiz de Austri, R. Trotta, <http://arxiv.org/abs/0705.2012>.
6. CDF collaboration, [http://www-cdf.fnal.gov/~aa/mssm\\_htt\\_1fb/note/cdf8676.pdf](http://www-cdf.fnal.gov/~aa/mssm_htt_1fb/note/cdf8676.pdf).