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Dark Matter Search with XENON1T

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Chapter S

Dark matter search with XENON1T (summary)

Physics aims to understand the universe at its most fundamental level, as precisely as possible. Recent decades saw great progress towards this goal, including the spectacular discoveries of the Higgs boson and gravitational waves. Surprisingly, however, we still do not understand what the majority of the universe is made of. For every kg of ordinary matter, our universe contains 5.4 kg of *dark matter* [1] – unknown particles that interact very weakly with atoms and light. Discovering the nature of dark matter is among the primary unsolved problems of particle physics.

Figure 1 summarizes our current understanding of dark matter and ordinary matter in the universe. The early universe was so hot that (radiation) pressure resisted gravitational collapse of overdensities of matter. In today's cooler universe, matter can collapse to stars by radiating away the energy gained during collapse. Dark matter does not interact with radiation, and therefore collapsed already in the early universe, dragging matter along with it to form the seeds of galaxies, clusters, and the cosmic web of superclusters. However, since dark matter cannot lose energy by radiation, it does not collapse all the way to stars. Instead, it settles in dynamical (virial) equilibrium structures such as spherical haloes around galaxies.

Evidence for dark matter comes from several independent observations. Dark matter haloes around galaxies and clusters (bottom right in figure 1) are visible through their gravitational effects on matter (the motion of stars and galaxies) and light (gravitational lensing). The tug-of-war between gravity and pressure in the early universe (top left in figure 1) left its signatures in the cosmic microwave background (CMB), a faint leftover radiation liberated when the early universe cooled enough to become transparent, and carries unmistakable imprints of dark matter's gravitational effects. More strikingly, the CMB shows that the early universe was so homogeneous that galaxies could not have formed without the seeds of structure laid down by dark matter

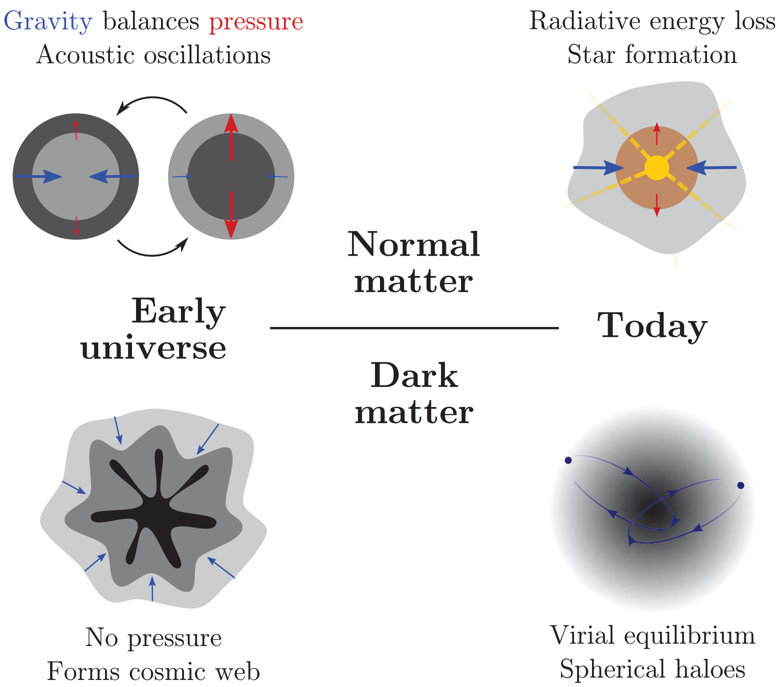

Figure 1: Simplified history of matter and dark matter in the universe.

(bottom left in figure 1). Without dark matter, the night sky would be dark, and there would be no one to see it.

This astrophysical and cosmological evidence shows dark matter interacts gravitationally with matter. However, gravity is too weak to measure individual particles (other than black holes), so experiments try to detect dark matter particles in one of three other ways:

- produce dark matter by smashing together ordinary matter at *colliders*,
- observe visible decay products of *annihilation* of dark matter and anti-dark matter in the universe, and
- search for tiny motions of normal atoms that result from elastic *scattering* ('bouncing') of passing dark matter particles.

Each method has limitations: colliders cannot make dark matter if that requires making a heavy intermediate particle first; annihilation searches must assume dark antiparticles exist and rule out ordinary astrophysical origins of any signal they see; while scattering searches cannot see dark matter light enough to bounce off atoms without transferring detectable amounts of energy.

This thesis describes a dark matter search with XENON1T, the world's most sensitive dark matter scattering detector. Figure 2 shows how XENON1T works. First, dark matter recoils off a xenon atom in the detector (specifically,

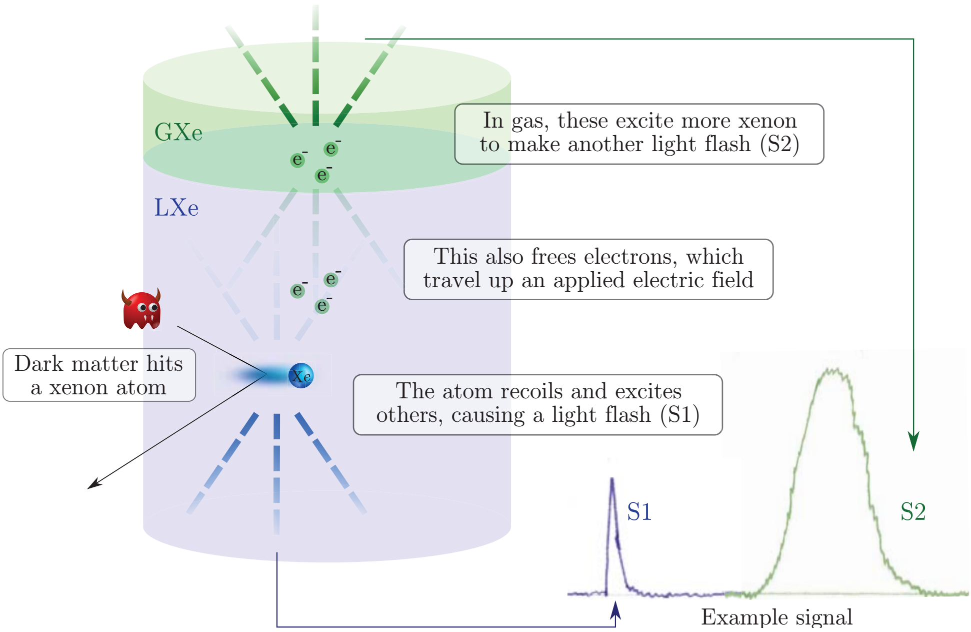

Figure 2: Operating principle of a dual-phase liquid-xenon (LXe) gaseous-xenon (GXe) time projection chamber (TPC) such as XENON1T.

its nucleus). The xenon atom, set in motion, excites some of its neighbours and ionizes others. Excited xenon atoms (after forming short-lived Xe_2 molecules) emit photons which are detected by sensitive light sensors called photomultipliers (PMTs) at the top and bottom of the detector. Electrons freed during ionization are pulled by an electric field towards a region with gaseous xenon (GXe). Here, a stronger electric field accelerates them enough to excite more xenon, causing a second, larger light flash (S2). The light distribution over the PMTs and the time between the S1 and S2 signals together indicate the 3D-position of the original dark matter interaction.

Unfortunately, many other processes cause light flashes in xenon, which XENON1T must protects itself against. To shield from cosmic rays, XENON1T operates deep underground in the *Laboratori Nazionali del Gran Sasso* under the Italian Appenines. To shield from natural background radioactivity, XENON1T is made from specially screened materials and submerged in a 10 m high instrumented water tank. Moreover, the dark matter search uses only events from the inner tonne of the three tonnes of liquid xenon used for XENON1T, so the other two tonnes act as additional shielding. The dominant remaining background is radioactive contaminants (in particular radon) released into the xenon from detector materials. Background from neutrino scattering will be dominant in future dark matter detectors. Most of these backgrounds cause recoils of *electrons* rather than whole xenon atoms, and can be separated (imperfectly) from dark-matter induced nuclear recoils

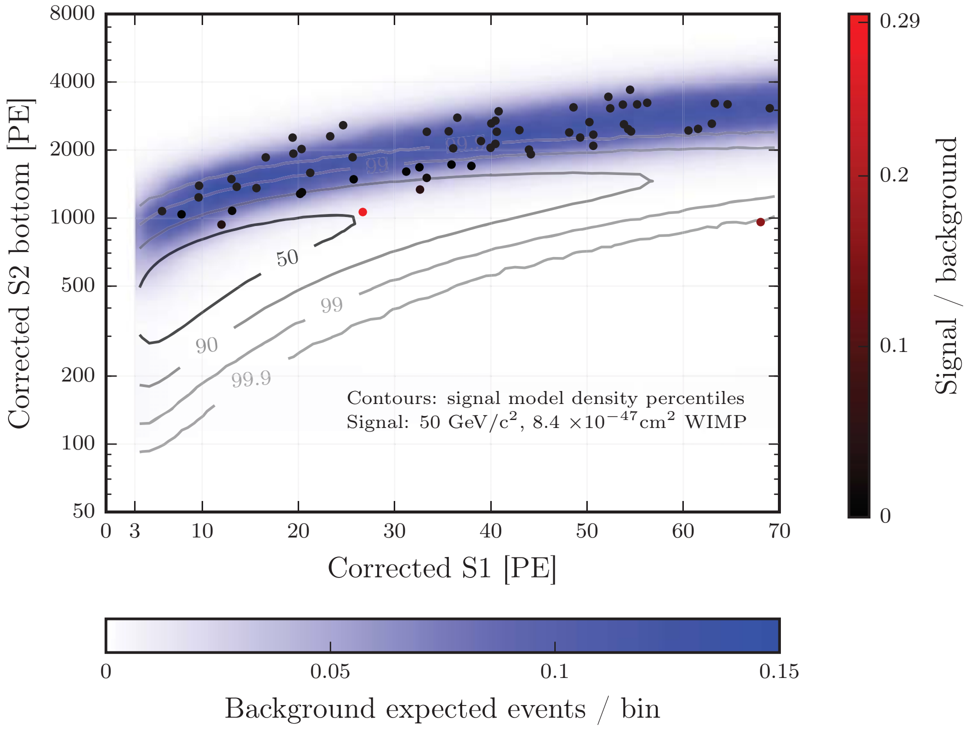

Figure 3: Dots: events found in XENON1T's first dark matter search, as a function of S1 and S2 signal size measured in photoelectrons (PE). Blue shading shows where we would expect background events, contours where we would expect dark matter events (for a particular dark matter model indicated on the figure). The contours are density percentiles, so half the dark matter events would fall in the contour labeled '50'. The red shading of the dots indicates the ratio of signal/background likelihoods for each event: a value of 1 would mean an event came equally likely from background or dark matter (if the indicated dark matter model is true).

by their different ratio of S1 and S2 light.

Figure 3 shows the events XENON1T observed during its first dark matter search run of 34.2 days (described in detail in chapter 5). Most events are consistent with background models derived from calibration data, in which radioactive sources were placed near the detector on purpose. Even the most dark-matter like event (red dot in the center of figure 3) is consistent with background from (primarily) electronic recoils. One event at high S1 and low S2 (just above the center right in figure 3) defies simple explanation, but is also not in a region where dark matter signals are expected. Most likely this comes from a very rare background, such as accidental coincidence of unrelated S1 and S2 signals.

These first results show XENON1T's background, in the region relevant for

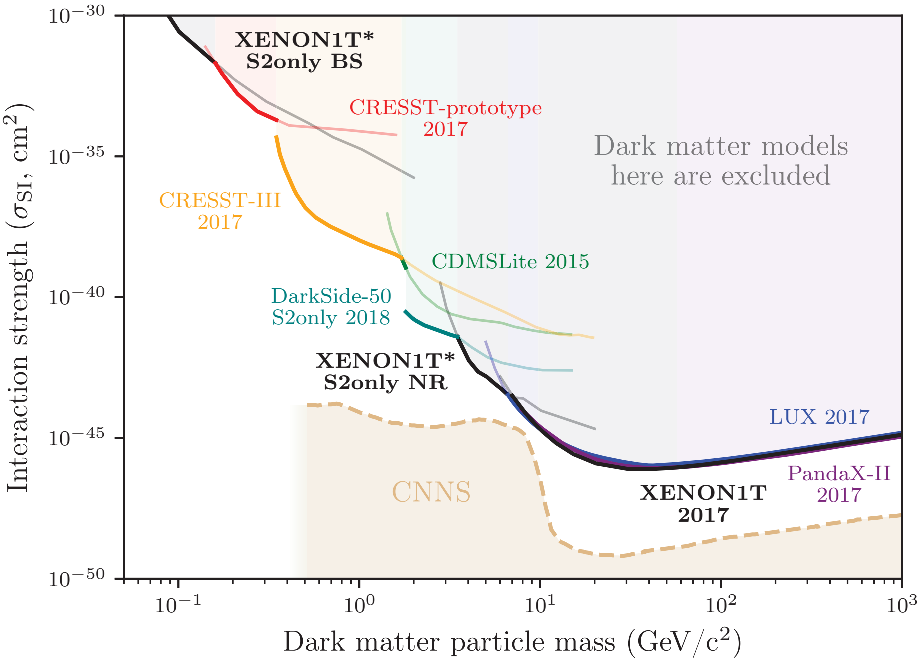

Figure 4: Constraints on the strength with which dark matter and normal matter interact for different possible dark matter masses. World-leading constraints are drawn as thick lines (with coloured shading above), others as thin lines. The black constraints (from XENON1T) are derived in this work, including the unpublished proof-of-concept results indicated by asterisks. The region labeled CNNS indicates models which are difficult to detect due to backgrounds from nuclear recoils of (primarily solar) neutrinos [4] (for the lowest WIMP masses, this is far beyond reach of current technology and was not computed).

dark matter searches, is lower than any experiment ever achieved. As we see no evidence for dark matter, we also set new limits on the strength with which dark matter and ordinary matter interact, shown in figure 4. Constraints from the LUX and PandaX-II experiments are similar, but these smaller experiments are nearing or past their end-of-life, as their larger backgrounds make longer searches futile. In contrast, XENON1T will soon release results of a year-long search, expected to set up to an order of magnitude stronger constraints – or discover dark matter.

In the coming years, XENON1T will be upgraded to XENONnT, containing ∼3 times as much xenon [2]. The next generation of experiments will include detectors with more than 10 t of xenon such as DARWIN [3]. The coming decade will show a dark matter discovery, or falsify most currently established dark matter models. Let dark matter beware – XENON1T is coming for you!