Dark Matter Hunters

Professor Elena Aprile
Professor Kaixuan Ni
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Scientia

DARK MATTER HUNTERS

Professor Elena Aprile and her collaborators, **Drs Kaixuan Ni** and **Luca Grandi**, join together with a worldwide consortium of scientists to design massive detectors for identifying the invisible matter that makes up the majority of our Universe.

For over 100 years, scientists have suspected that the 'empty' space between stars and other visible objects in our Universe is probably not empty. As far back as 1884, the Scots-Irish scientist and mathematician Lord Kelvin noted that the motion of stars in the Milky Way galaxy was inconsistent with the amount of matter observed – the stars and interstellar dust clouds we could see – and that much of the mass in the galaxy might be what he called 'dark bodies'. In 1906, the French scientist Jules Henri Poincaré termed Kelvin's dark bodies as 'matière obscure' – dark matter.

In the ensuing decades, a number of scientists had corroborated the fact that much or even most of the matter in our galaxy and others is dark matter. By the 1980s, this had become quite a problem in astrophysical circles. The majority of the Universe's was invisible to our instruments – so what is it, and how do we measure it?

This is a problem that Professor Elena Aprile of Columbia University has been working on for over 15 years. Theoretically, dark matter exists, but it does not interact with light or normal matter, so we cannot directly measure it. As Professor Aprile says: 'We know it's there, but it continues to escape instruments invented so far.' That leaves it up to her and her colleagues to directly measure it. To do that, they have built detectors containing increasing amounts of the inert element xenon, in the hope that some of the massive 'dark' particles that rain down on earth will collide with xenon atoms.

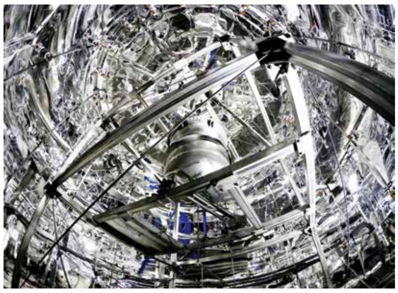
The XENON Project

Early in her physics career, Professor Aprile studied under Professor Carlo Rubbia, who shared the Nobel Prize in Physics in 1984 for discovering several subatomic particles using a particle accelerator at CERN. Inspired by Professor Rubbia, Professor Aprile became interested in detecting subatomic particles using the noble gases – specifically argon and xenon – which have the advantage of being inert, meaning that they rarely react with the electrons of other atoms and molecules.

If a high-energy particle travels through a tank of liquid argon or xenon and collides with its atoms and molecules, it transfers energy. This energy causes electrons of argon or xenon atoms to become dislodged and travel through the liquid to reach the detector. Not only does this process produce detectable electrons, but energised argon and xenon atoms can also release light – alerting scientists of a collision with a high-energy particle.

While Professor Aprile did her graduate work with argon, she then moved on to the heavier noble element xenon, and has since become a pioneer in the use of liquid xenon for particle detection. The design of these exquisitely sensitive xenon detectors is something that came in handy in the hunt for dark matter – especially if it is made up of dark particles called WIMPs.

The WIMP – the 'weakly interacting massive particle' – is a theoretical



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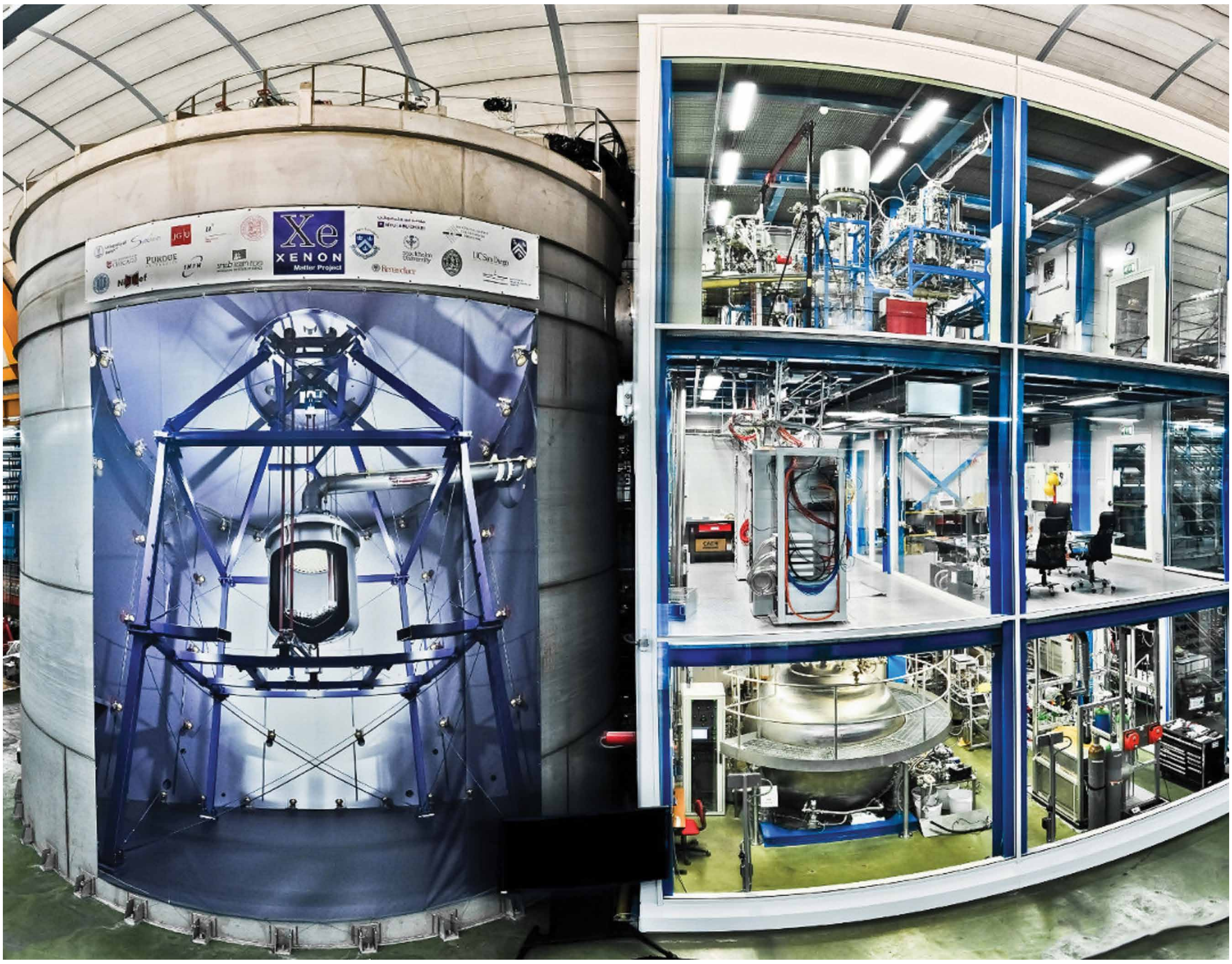
elementary particle of dark matter that does not interact with strong forces, such as electromagnetic forces, but only weakly, through gravity and the weak nuclear force. As well, to fulfil some of the observed effects of dark matter, the particle must have a very large mass compared with other subatomic particles. This is what makes the WIMP a WIMP – big mass, weak interaction. Because it only very weakly interacts, a very sensitive detector must be designed if WIMP interactions are to be picked up as they pass through.
In 2001, Professor Aprile set her mind on using liquid xenon to design an



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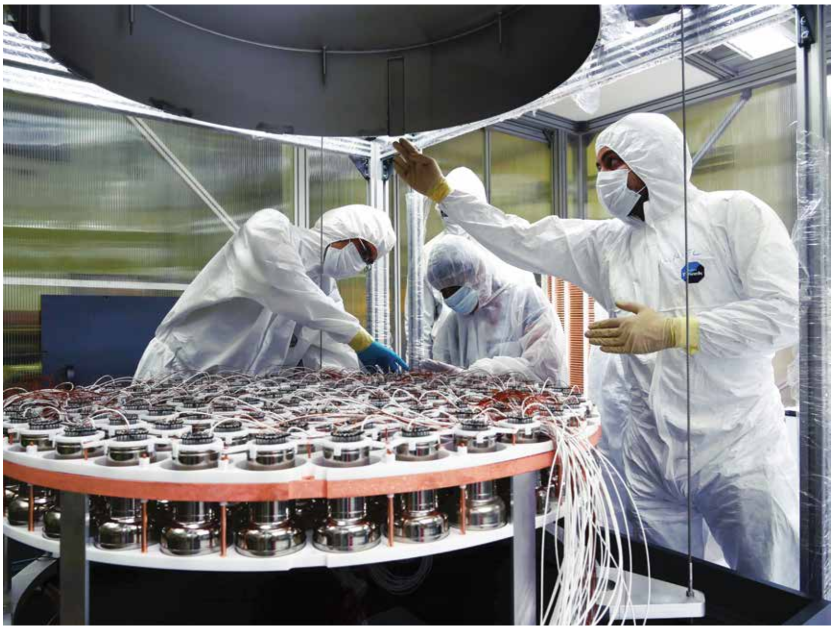
experiment that would be very sensitive in the search for dark matter. With her experience gained from working with liquid xenon gamma ray detectors for NASA, Professor Aprile started a crusade that has almost circled the globe – the XENON project – a consortium of about 165 scientists in multiple centres around the world focused on finding the elusive WIMP. The idea is to detect these WIMPs as they collide with liquid xenon atoms in detectors that are operated deep underground to minimise noise from cosmic radiation. The combination of xenon's exquisite response to radiation and a deeply-buried location reduces background noise from other particles and will hopefully allow the weakly-interacting WIMP to be detected. While embarking on this great project, Professor Aprile, like Professor Rubbia before her, inspired others to follow her lead. Her very first graduate student on the XENON project was Kaixuan Ni.

Ni came from Beijing to study at Columbia University and joined Professor Aprile's group at the beginning of the XENON project. The first stage of the project, XENON10, was a liquid xenon detector operated in record time underground at the Gran Sasso National Laboratory in Italy – the *Laboratori Nazionali del Gran Sasso*, or LNGS. About 120 km from Rome, the LNGS is billed as the largest underground research facility in the world, and is an ideal place for carrying out projects such as XENON. XENON10 consisted of a 25-kilogram liquid xenon detector and searched for WIMPs by simultaneously measuring the light emitted and ionisation produced by radiation in pure liquid xenon.

Dr Ni was apparently enthused with the concept of XENON and dark matter detection, and after he graduated from Columbia, he continued to work on data analysis for XENON10 as a postdoctoral fellow at Yale University. The first results of the project, published in 2008 in the journal *Physical Review Letters*, didn't actually detect any WIMPs, but it allowed the scientists to put a limit on how big they could be and how sensitive the detector could be designed. In Dr Ni's words, the results from XENON10, reported in one of the most cited papers in the field of dark matter, 'surpassed the results from the previously leading technology using cryogenic detectors and placed the liquid xenon detector technology on everyone's radar'.

After spending two years at Yale, Dr Ni returned to Professor Aprile's group at Columbia as a research scientist, to work on the next iteration of the XENON project, called XENON100. This time, the detector contained 62 kilograms of liquid xenon as the WIMP target, surrounded by 99 kilograms of more xenon as active shielding, all inside a



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low-radioactivity stainless-steel vacuum insulated vessel, itself embedded in a passive radiation shield. The experiment was set up underground at the LNGS in Italy, where XENON10 had been housed. The results of XENON100, published in 2012 in *Physical Review Letters*, improved the limits of detection by more than a factor of 20 compared to XENON10, making the experiment the most sensitive in the world for several years.

But Dr Ni didn't stop there. Six years at Shanghai Jiao Tong University in Shanghai, China, was all it took for him, together with colleagues there, to put together a Chinese version of XENON, called PandaX, which was built at the JinPing underground laboratory located in the mountains in southwest China. Published in 2016 in Physical Review Letters, the first three months of operation of the PandaX-II with a 500-kilogram liquid xenon detection chamber witnessed no dark matter interactions. However, the target was getting larger and detector was getting better. From China, Dr Ni then took a faculty position at the University of California, San Diego, where he started yet another branch of the XENON project – XENON1T.

Darkside and XENON1T

Life sometimes takes interesting turns. For Dr Luca Grandi, his first conference on Dark Matter was a turning point. When he was still an undergraduate, he met Professor Aprile at a conference. 'We ended up sitting one next to the other,' he says. 'From some candy I had she figured out I was Italian like she was, and we discovered that we had both been students of Carlo Rubbia.' He kept in touch with Professor Aprile and the connection came in handy.

Dr Grandi went on to graduate and earn his PhD under Dr Rubbia, for his research with argon detectors. After working as a postdoctoral researcher in Italy on liquid argon detectors, Dr Grandi moved to the US and did postdoctoral work at Princeton, where he was one of the founders of the Darkside project. Darkside aimed to detect WIMPs using argon-based detectors, based on Dr Rubbia's work back in Italy. In fact, the successive Darkside projects, Darkside10 and Darkside50, were built at LNGS in Italy.

Dr Grandi then landed a faculty position at the University of Chicago and the famed Enrico Fermi Institute. Within a few months he started reconsidering his plans and soon realised that the xenon technology did indeed have a higher chance of detecting dark matter, due to its mature status, so he touched base with Professor Aprile at Columbia. Together with their worldwide collaborators, including Dr Ni in San Diego, they developed the latest iteration of the XENON project – XENON1T. Funded by the US National Science Foundation, like its predecessors, XENON1T is currently the largest and most sensitive liquid xenon detector, taking dark matter search data at the LNGS in Italy, and using 3.3 tonnes of liquid xenon. As the first tonne-scale xenon detector in the world, XENON1T is pushing detection limits to their lowest levels yet.

Bigger is Hopefully Better

XENON1T is, so far, the epitome of noble liquid WIMP detector technology. Already online since November of 2016, XENON1T has been putting out data that shows it to have the best sensitivity of any dark matter detector. The chamber contains a whopping 3,300 kilograms of xenon cooled to −95°C housed in a 1 m tall and 1 m wide cylindrical container. But even with that much xenon, detections may be few and far between. It is estimated that only one WIMP interaction should occur per year for every tonne of xenon. So, the plan is to wait and watch.

The detection sensitivity has been worked down to the minimum that is possibly attainable so far. When and if a WIMP shows its hand, Professor Aprile and her XENON team will be there to record it. If not, then it will be back to the drawing board for the astrophysicists. Professor Aprile admits that 'XENON1T won't see anything if the WIMP hypothesis is incorrect'. But there is all that dark matter out there that needs to be explained. And besides, at one potential interaction per tonne per year, we have only begun to wait for results. In the meantime, we have time to enjoy the stars and admire the constellations, and let XENON1T look at the dark spaces in between.

Meet the researchers

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Professor Elena Aprile received her Laurea in Physics from the University of Naples, Italy, in 1978. She then continued her studies at the University of Geneva, Switzerland, where she received a PhD in Physics in 1982. From 1982 to 1985 Dr Aprile was a postdoctoral fellow at Harvard University. Thereafter, she joined the faculty of Columbia University, where she is now Professor of Physics. Professor Aprile's research is currently focused on understanding Dark Matter through a direct detection experiment using noble liquids, currently liquid xenon. She is internationally recognised for her work with noble liquid detectors and her contributions to particle astrophysics in the search for Dark Matter.

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Professor Kaixuan Ni received his Bachelors in Physics from Peking University, Beijing, China, in 2000. Thereafter, he pursued doctoral studies with Professor Elena Aprile at Columbia University in New York, where he received his PhD in 2006 with the first doctoral thesis in the XENON dark matter search program, 'Development of a Liquid Xenon Time Projection Chamber for the XENON Dark Matter Search'. After postdoctoral research at Yale University, Dr Ni worked at Columbia University as an associate research scientist and Shanghai Jiao Tong University as a distinguished fellow and associate professor. In 2015, he joined the faculty at the University of California - San Diego where he is currently Associate Professor in the Department of Physics. Dr Ni's research interests include the physics of Dark Matter and neutrinos. He is heavily involved in development of particle detectors based on liquid xenon for the investigation of Dark Matter.

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Professor Luca Grandi received his Laurea in Physics in 2001 and his PhD in 2005 from University of Pavia in Italy. He then did postdoctoral work at National Institute of Nuclear Physics in Pavia, the National Laboratory of Gran Sasso in Assergi, and at the University of L'Aquila. Dr Grandi then worked for three years as an Associate Research Scholar at the Princeton University before he joined the Department of Physics at the University of Chicago, where he is now Assistant Professor in the department. He is also a member of the Enrico Fermi Institute and of the Kavli Institute for Cosmological Physics at the University. Dr Grandi's research is currently focused on the development of two-phase noble liquids Time Projection Chamber technology for the direct detection of Dark Matter.

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