FEATURE

Kavli IPMU Associate Professor Kai Martens
Research Area: Experimental Physics

The Why and How of Catching WIMPs

Introduction

The Kamioka Observatory is located under mount Ikeno between the cities of Toyama and Takayama here in Japan. It is not the kind of observatory that Dark Matter was discovered at, but it may be the kind of observatory that the nature of Dark Matter is revealed at. And XMASS is one of the experiments that try to accomplish this. The why and the how are what we will be discussing over the next few pages. You will have to forgive me though: It is a vast subject and I will take the liberty to cherry pick examples and feature choices that are designed to motivate the path we took with XMASS.

We are the Kavli Institute for the Physics and Mathematics of the Universe. Let us start with that Universe.

Dark Matter and the Universe

One of the great scientific success stories is how particle physics and astronomy were integrated to provide a self-consistent narrative for the history of our Universe. The Lambda Cold Dark Matter paradigm and the Big Bang are at its core, and the Standard Model of elementary particle physics is one of the foundations on which this scientific edifice is erected. Together they make sense of a vast catalogue of astronomical observations. This is the first time in the history of humankind that such a narrative is purely based on science.

Our narrative successfully tracks astronomical observations through this history of the visible Universe. We can watch this history unfold as our telescopes zoom out from ever older objects at ever higher redshifts. Our narrative even reaches beyond the earliest moment of which electromagnetic radiation keeps a record when it explains the relative abundance of the chemical elements as well as the rich structure we see in the distribution of galaxies across the sky.

That is not to say that there are no more problems to be solved. There are misfits: The abundance of ^{7}Li is off by at least a factor three. And while the large scale structure of the matter distribution in the universe is very well reproduced in our models, its small scale structure seems to deviate from expectations. But by and large our narrative meaningfully and successfully relates the relative abundance of chemical elements as it persisted till the first stars were born to the patterns imprinted on the afterglow of the moment when light in the Universe first broke free and the distribution of galaxies today. A stunning success and a towering achievement.

There were a couple of real surprises embedded in the understanding that came with this successful narrative. The biggest one concerns the future more than the past: Since Edwin Hubble we know that the Universe is expanding in some way. That in and of itself is not too surprising: Since the discovery of the cosmic microwave background radiation we have to assume that it was borne in a Big Bang. What we did not expect is that its expansion is accelerating. Our narrative attributes this feature to a component of the Universe that we call Dark Energy - the Lambda in our paradigm. At present Dark Energy contributes about two thirds of all the content of the Universe.

But we shall not concern ourselves with Dark Energy here. XMASS is looking for the second largest contributor to the contents of the Universe: Dark Matter. It weighs in at slightly over a quarter of everything. Only about a mere twentieth of the Universe is like the stuff we know, like the Sun that shines on us, the friend whose hand we shake, or the computer we run our simulations on. That twentieth is the stuff that we see through our telescopes: the tip of the iceberg as far as matter is concerned. This twentieth is also the stuff that we particle physicists think we know quite a bit about: it is the stuff that is described by our Standard Model of particle physics. Despite much energy and treasure spent we have yet to find any significant deviation from the predictions of this Standard Model.

Yet theorists do not consider the Standard Model to be without blemish. To ensure its success it requires a plethora of input parameters and some careful balancing acts that seem too good to just be accidental. Thus theorists are vying to design the next big thing, a theory that encompasses the Standard Model and provides some mechanism to at least reduce the perceived arbitrariness in its internal workings. These theories typically contain new particles that help alleviate one or more of the shortcomings the Standard Model has in the eyes of our theorists.

The Nature of Dark Matter

The assumption that Dark Matter should also be particulate matter seems natural - at least to particle physicists. From astronomical observations and model calculations involving Dark Matter we can extract some constraints on the properties of Dark Matter particles. None of the Standard Model particles fit this bill of requirements. Now that is exciting news: Dark Matter exists in our Universe, and theorists see strong reasons to expect new particles - some of which could fit the bill. In fact there are two main experimental efforts that were spawned by this complicity of cosmological necessity and theoretical aspiration. Axions are a theorist's elegant way of solving what we call the strong CP problem. If axions exist and depending on their specific properties they could be the Dark Matter particle. They are searched for through their possible conversion to real photons. WIMPs are another sort of candidate and generically are just some unknown massive particle that partakes in no interaction stronger than the weak one: Weakly Interacting Massive Particles. Since observations clearly show that Dark Matter does not interact with normal matter through the strong or electromagnetic interaction the familiar weak interaction is indeed the strongest of the known interactions that it could have with either normal matter or itself. If on the other hand a Dark Matter particle had some form of weak interaction, that means that it should reveal its presence through weak interaction with the normal matter around us. Looking for signs of this happening in dedicated experiments is called making a direct detection experiment. XMASS in its current form is designed to be such a direct detection experiment for WIMPs.

Motivation for thinking of Dark Matter particles as WIMPs comes from a calculation that shows that a particle annihilating with its own antiparticle at a rate determined by the weak interaction scale would naturally result in the Dark Matter density that we

The XMASS hall with its water shield tank

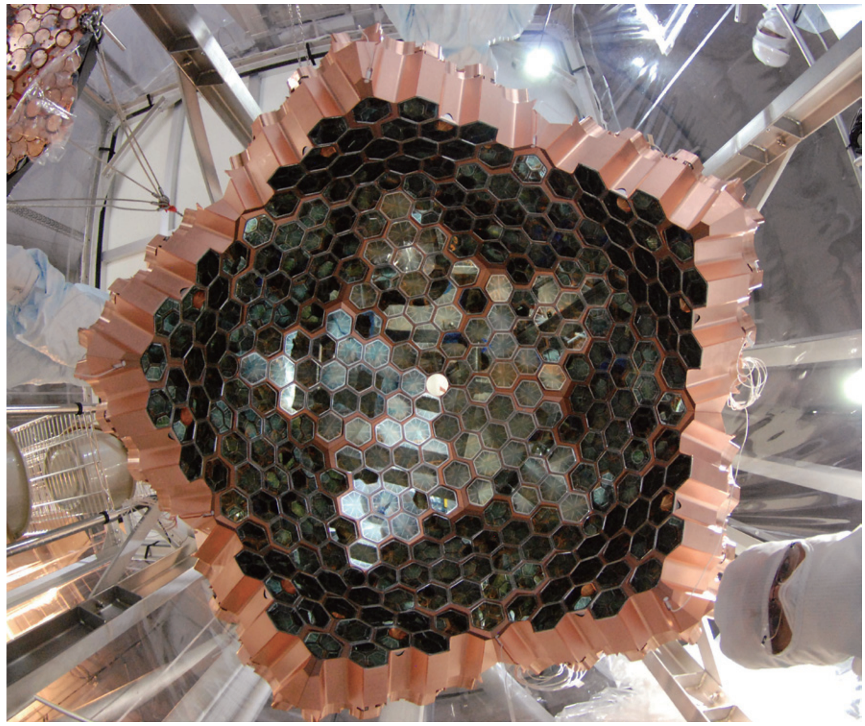
observe in today's Universe. Intriguing indeed. This quantitative coincidence is known as the "WIMP miracle".

For completeness I should mention that there are of course attempts to explain the Universe we see without Dark Matter. None of them has come anywhere near the success the cold Dark Matter paradigm has in explaining the many different aspects of our observations. Typically such attempts are addressing on particular problem (like galaxy rotation), but unlike cold Dark Matter fail to simultaneously solve the other problems they were not specifically designed to solve.

Before I delve into the specifics of what we are doing here in Kamioka let me also comment on the fact that there are now a few experimental signatures that have been attributed to WIMP interactions in direct detection experiments. As most experimentalists warily argue about the closeness to experimental thresholds (where backgrounds take over) of these alledged Dark Matter signatures, some theorists are already vying to provide a scenario that accommodates all those supposed observations (plus the reported non-observations). It will take time and strenuous effort to discover the truth about Dark Matter. Ultimately we will not believe any WIMP signal until we get consistent results on a variety of different target materials. The weak interaction acting on matter is after all well understood, and theorists can calculate the expected interaction rate on a different target material once a cross section is inferred from even a single positive measurement.

Our Kamioka Experiment

XMASS stands for an experimental program that



XMASS 800kg detector inner surface: photocathodes and copper

is built around a unique detector concept as well as a unique target material. The program was first laid out in 2000 by Kavli-IPMU's deputy director Yoichiro Suzuki presenting at the LowNu workshop in Sudbury, Canada. As an acronym XMASS can be read as Xenon detector for weakly interacting MASSive particles, Xenon MASSive neutrino detector, or Xenon neutrino MASS detector. This variety points to the versatility of the experimental program: In its current incarnation with a total mass of 835kg of xenon in its active detector volume it was designed to be a discovery machine for WIMPs in the sense of the first reading of the acronym. In its final version XMASS will have a fiducial mass of ten tons, ten times the target mass of the next generation of detectors that the community is currently preparing for. At that point the detector's physics reach will cover the search for neutrinoless double beta decay in ^{136}Xe, as referred to in the neutrino mass detector reading. At the same time such a massive detector will detect solar pp and ^{7}Be neutrinos from the sun, acting as a massive neutrino detector. In that final version of XMASS the solar neutrino signal will actually become the limiting background for the detector's WIMP detection capabilities.

Background is the main concern in all rare event searches—not only the WIMP part of the program. To avoid cosmogenic activation of our detector materials (from penetrating high energy muons created in the atmosphere) we have to go underground; as deep as possible. The Kamioka laboratory allows easy 24/7 access to its experiments for researchers, and provides substantial overburden to shield against those muons. XMASS is the first Dark Matter detector to use an active water shield to flag and veto cosmic ray muons. Passively this

XMASS collaborators and their sphere

water shield also absorbs external gamma radiation and thermalizes fast neutrons emerging from the surrounding rocks. The experiment thus has a deeply layered defense against external sources of background. Its experimental hall is lined with a radon retardant and flushed with outside air to suppress radon, a common scourge in underground environments. As in Super-Kamiokande the air volume at the top of XMASS' sealed water tank is supplied with specially prepared radon free air.

Inside the active volume of our detector the high density of liquid xenon itself provides the innermost layer of defense against external background. If in our data analysis we use data only from a reduced innermost volume near the center of all the xenon contained inside the detector, the "unused" outer shell of liquid xenon absorbs external gamma rays and further reduces the background in that innermost volume, which we call the fiducial volume. In that sense the active volume of our detector is self-shielding, an important aspect of our detector design.

The central idea of our XMASS detector concept is to maximally exploit the scintillation signal from recoiling charges in a radiochemically very clean environment. Liquid xenon with its high scintillation light yield and high mass number is the active target material of choice. Unlike argon and krypton it has no long lived isotopes that would contribute intrinsic backgrounds in the active volume. Yet even trace amounts of krypton mixed into our xenon would be detrimental to the experiment. XMASS developed a highly efficient distillation system that reduced the remaining krypton in our xenon to the parts per trillion level. Contaminants that are not chemically inert noble gases can easily be removed with commercially available “getter” units. We found that we could maintain optimal detector conditions even without continually passing the xenon through those getters. We have succeeded in building a detector that can operate very stably with optimal performance yet without the need for any active circulation. Once it is operating and initial cleaning procedures are completed, all our detector needs is some refrigeration to balance the various sources of heat entering the liquid xenon. This is a remarkable achievement and an important endorsement of our strategy.

The largest sources of background found in the commissioning phase of our current XMASS 800 kg detector were beta-emitting radioactive isotopes on or near the inner surface of our detector. The specific sources were identified and are being addressed in a refurbishment effort which is now coming to its conclusion. Yet despite this background we have published limits on low mass WIMP interactions and axions from the Sun during our commissioning phase for the detector. We are looking forward to much improved background conditions in the refurbished detector.

Our focus on scintillation light is reflected in the symmetry of our detector geometry and the highly optimized lining of its inner surface with the photocathodes of 642 high quantum efficiency photomultiplier tubes (PMTs): their photocathodes constitute 60% of this inner surface. Indeed our current detector’s hallmark is its superior signal yield for scintillation light. Electrons with a kinetic energy of 122 keV on average produce 14.7 photoelectons per keV of electron energy in our PMTs. This is the best performance among xenon based Dark Matter experiments.

XMASS relies solely on the scintillation signal generated by recoiling charges in its inner volume. The pentakisdodecahedral geometry of our detector reflects the spherical symmetry of scintillation light emission. Scalability of this straightforward geometry is a big advantage resulting from our choices. As our competitors are moving towards ton scale detectors we too expect to take the next step in the XMASS experimental program with another Dark Matter detector at the one ton scale: we call it XMASS 1.5. A total liquid xenon mass of 5 tons will be filling that detector, and we want to start building it next year. Our experimental hall in the Kamioka Observatory and our water shield inside that hall are already big enough even for the final step in our experimental program, the experiment with a ten ton fiducial mass. To get there, work is to be done and physics is to be extracted along the way - let’s get to it.