Il Colle di Galileo

"New Frontiers in the Search for Dark Matter"

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Abstract. The workshop brought together world experts working on the origin of dark matter, one of the most urgent questions in fundamental physics. For seven weeks, scientists explored new theoretical avenues as well as novel detection strategies. The event benefited from the presence of Simons Fellows, who led discussions on well-motivated theories and the status of current fast-moving experimental searches.

Keywords. Dark Matter, Beyond the Standard Model, New Physics, High energy phenomenology, Cosmology.

Scientific context and motivations

What is in our universe? Such a simple question is at the heart of one of the most urgent open problems in fundamental physics, and it has always been central to the curiosity of human beings. In the last few decades, we have achieved an astonishing unified description: all the matter we observe, from the tiny subnuclear-length scales to the size of our observable universe, is made of the same building blocks. More importantly, we also understand the principles governing the interactions among them. These particles interact through the gravitational force described by the theory of general relativity, and they also interact through strong and electroweak forces. The two combined form the Standard Model of Particle Physics. The discovery of the long-sought Higgs boson on 4 July 2012 marked a milestone: the Standard Model is now a theoretically complete and self-consistent description of strong and electroweak interactions. The symmetry of its equations is stunning, while its capability of passing every collider test is even more impressive.

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Despite its tremendous success, the Standard Model leaves many questions unanswered. One of the most urgent, based on firm observational evidence, is the microscopic nature of dark matter. We have collected evidence for dark matter from several independent observations, such as the rotation curves of galaxies, gravitational lensing, fluctuations in the cosmic microwave background, and formation of structure in the universe. However, all we know about dark matter is inferred from its gravitational effects. What we have learned from these observations and the non-observation of dark matter via other forces is as follows: it makes up 27% of the energy density of the universe, it is mostly cold and massive, it is non-baryonic with suppressed (or vanishing) couplings to the strong and electroweak gauge groups, and it does not interact too strongly with itself. All of these characteristics indicate that explaining the particle identity of dark matter requires new physics beyond the Standard Model.

The motivation for the workshop was to critically assess the status of the hunt for dark matter. This includes both theoretical and experimental approaches, with specific focus on the synergy between these two aspects of a single joint adventure. The workshop brought together world experts in these fields to address these important questions.

Regular workshop activities

With the sole exception of the fifth week, when GGI hosted a conference with a large number of daily talks, the workshop activities consisted of one morning talk each day with plenty of time for questions and discussion. After lunch, participants could interact in an informal setting using GGI's facilities.

Research on dark matter is a very broad field at the interface between high-energy physics and cosmology. To stimulate profitable discussions, each week featured a specific topic, such that participants who were experts on a specific subject could make sure to visit GGI at the right time. New theories for dark matter was the topic of the first week. The second to fourth weeks were dedicated to discussing the three conventional ways to search for dark matter. One can search for dark matter elastic scattering with targets in our deep underground laboratories, such as the case of "Laboratori Nazionali del Gran Sasso" (LNGS). One can also look for the debris of dark matter annihilations in the sky, and this is one of the signatures searched for by the Fermi gamma-ray telescope or the Alpha Magnetic Spectrometer (AMS) located on the international space station. Finally, one could try to directly produce dark matter particles in an accelerator environment, such as the Large Hadron Collider (LHC) at CERN in Geneva.

Week six was devoted to a particular dark matter candidate, the QCD axion, research on which is motivated by the fact that it also explains why strong interactions respect time-invariance to an exquisite accuracy (an issue known as "the strong CP problem"). Finally, primordial black holes dark matter and gravitational waves were the subjects discussed in the last week of the workshop.

Workshops held at Villa il Gioiello

There were three special days on which the scientific activities of the workshop took place at Villa il Gioiello. Distinguished scientists gave presentations on the progress of their recent research, and the day was organized in such a way that after each presentation there was plenty of time for questions. Lunch was provided onsite and workshop participants could spend the afternoon at the Villa to continue scientific discussions.

Tim Tait (University of California, Irvine) gave a talk on a new dark matter candidate within the framework of an emergent solution to the strong CP problem. Yanou Cui (University of California, Riverside) explained how gravitational waves could probe the pre-BBN universe with important consequences on dark matter relic density. Paddy Fox (Fermilab) explained how neutrino experiments could also function as dark matter detectors. Nicholas Rodd (University of California, Berkeley) gave an overview of the future of indirect detection experiments. Stefano Profumo (University of California, Santa Cruz) highlighted the landscape of scenarios for dark matter from primordial black holes. Zurab Berezhiani (University of L'Aquila) brought dark matter candidates from mirror worlds. Roni Harnik proposed new probes for the dark sector based on precision physics experiments. Giovanni Villadoro reported recent progress in the calculation of axion relic density.

Patio discussions

A novel feature of this workshop was the GGI patio discussions. These activities took place during the regular weeks, and not during the conference, as spontaneous blackboard discussions on the outdoor patio. The topics were based on the interest of participants, and the discussions were very interactive with all participants taking part in the debates. Each was moderated by a discussion leader, an expert in the subject under examination. The topics dealt with included the 21 cm line cosmological signal, the galactic center excess, solutions to the cosmological constant problem, and new strategies in the search for axion-like particles.

Conference

During the fifth week, the program turned its attention to the specialist conference. There were morning and afternoon sessions from Monday through Thursday, and one final morning session on Friday. More than 100 scientists from all over the world came to GGI to attend this conference, which featured 46 invited talks. The topics of the nine sessions spanned different aspects of dark matter physics: the landscape of theoretical models, dark matter impact on cosmological structures, dark matter experimental searches, the connection with gravitational wave physics, new atomic physics probes, and dark matter influence on stars.

Simons Fellows

Three eminent scientists in the field spent a significant amount of time at GGI and played a central role in the workshop activities. They helped in organizing the daily seminars, delivered seminars on their research activities, and led discussions. These Simons Fellows for this GGI workshop are:

- Paddy Fox (Fermilab)
- John March-Russell (Oxford University)
- Giovanni Villadoro (ICTP, Trieste)

Summary

It took over two thousand years to learn only 5% of what is in the universe. And it is certainly a blessing for us that we have been able to personally witness the crucial developments which unveiled this 5%, a process which culminated in the Higgs boson discovery. Even more exciting is the extraordinary effort, both theoretical and experimental, to clarify the microscopic identity of dark matter that accounts for 27% of energy density. Even though we have no way to guarantee its discovery in the coming years, such outstanding activity should make all of us very optimistic.

This workshop gathered together the scientific community for seven weeks at GGI, generating several new ideas. Novel theoretical models were conceived within the walls of GGI, which will be tested in the near future. At the same time, new experimental techniques will improve our reach in the next few years and may ultimately lead to new discoveries. It is definitely very exciting for all scientists to be part of this adventure and to have the opportunity to write such an important chapter in the book of Nature.

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Figure 1. A patio discussion at GGI.