Borexino/DarkSide

Second phase of Borexino: solar neutrinos, geo-neutrinos, sterile neutrinos, dark matter

(JINR Participation)

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Annotation

The project is continuation of the Borexino/DarkSide program. The Borexno detector is the first detector able to register sub-MeV neutrinos in real time, performing direct observations of ^{7}Be, pep, pp and ^{8}B solar neutrinos.The most important task for Borexino remains the measurement (bounding) of the CNO-neutrino flux. As a result of the thermal insulation of the detector performed in 2015, event rate of ^{210}Po has stabilized, making the task of measuring the CNO neutrino flux feasible. Precision of the pp-neutrino flux measurement can still be improved up to 6-7% by including the Phase-I data in the analysis. Another important task will be an improvement of geo-neutrino flux measurement. We are planning to perform measurements with ^{144}Ce-based anti-neutrino source located beneath the detector (CeSOX program).

The DarkSide prototype detector (DS-50) is taking data since 2013. Design of the full scale 20-ton detector (DS20k) is now at the stage of detailed study, the project and the physical program of the investigations has been published. The expected sensitivity to WIMP-nucleon cross section is at the level of 10^{-47} cm^{2}.

Dubna group, having gained an expertise with the Borexino, is planning to continue the work on the mainstream analysis, including CNO, pp and geo-neutrino studies, as well as the sterile neutrino program within CeSOX program. In the DarkSide, we are planning to participate in data analysis aiming at precise experimental measurement of the ^{39}Ar spectral shape and improvement of the analytical energy scale description. The group will also participate in the Monte Carlo modeling of DS20k components, in particular SiPM modeling,

simulation of radiation neutron capture at different parts of the structure in order to choose the optimal configuration from the point of view of minimizing the backgrounds. We also participate in studies of detector's sensitivity to supernova neutrinos.

1 Introduction

The most important task for the second phase of Borexino remains the measurement of the CNO-neutrino flux. Theoretical predictions for this flux differs by up to 30-40% for two classes of solar models, thus measurement of the CNO flux with moderate precision will help to solve the ambiguity. The key point of the analysis is the achievement of the low count of ^{210}Po in order to obtain a supporting term from the parent ^{210}Bi, which is the major residual background mimicking the CNO spectrum. It was decided to insulate the detector with aim of the suppression of convective movement bringing ^{210}Po from the inner nylon vessel to the fiducial volume. By the end of 2017 the temperature in the detector has stabilized. Temperature control is conducted with a system of temperature sensors mounted in different parts of the inner volume. As a result of temperature stabilization, event rate of ^{210}Po has also stabilized, making the task of measuring the CNO neutrino flux feasible. Precision of the pp-neutrino flux measurement can still be improved by including the Phase-I data in the analysis. Our group has developed an approach without the suppression of alpha-particles contribution which was successfully applied to the Phase-II data analysis. Taking into account better energy resolution at the beginning of the detector operation we expect an improvement in the precision of the pp-neutrino flux measurement of up to 6-7% by including the Phase-I data in the analysis.

Another important task for the second phase of the experiment is an improvement of geo-neutrino flux measurement. It is proposed to reject the spatial event selection (it would practically double the available statistics) and to improve the selection of events correlated with cosmic muons (at the moment a simple muon veto is used leading to about 10% loss of statistics). As a result of the absence of spatial selection, a contribution from the external background appears in the observed anti-neutrino spectrum. Work on the understanding of the source of this background and adding its shape in the spectral analysis is included in the working plan for the near future. Moreover, Borexino data will be used for investigation of non-standard contributions to neutrino interactions by deviation of the recoil electrons spectral shape from the Standard Model prediction.

In Borexino, we are planning to perform measurements with ^{144}Ce-based anti-neutrino source located beneath the detector (CeSOX program). The source of about 100 kCi activity will be produced at the Mayak plant by April 2018. Hardware preparations for the source accommodation in the outer tunnel under the detector and calorimetry measurements are completed. Besides this, biological tungsten shielding is manufactured. The collaboration is ready for the data analysis and processing directly after the start of data taking.

Concerning the dark matter investigations, our group participates in the DarkSide collaboration, the start of the activities was triggered by our involment in the CTF (the prototype of the Borexino used as a host for the DS50) operations. The DarkSide prototype detector (DarkSide-50 or DS-50) is successfully taking data since November 2013. Design of the full scale 20-ton detector (DS20k) is now at the stage of detailed study, the project and the physical program of the investigations (Yellow book) is published. Due to the multi-ton scale of the underground argon target the expected sensitivity to WIMP-nucleon cross section is at the level of 10^{-47} cm^2 for several years of data taking.

Significant progress is achieved in the whole low activity argon (LRAr) production chain, either within Urania (sub-project for underground argon extraction) and Aria (sub-project for isotope separation) activities.

In April 2015 the DS-50 cryostat was filled with 153 kg of underground argon (UAr), the first result was the measurement of abundance of radioactive ^{39}Ar which appeared to be 200 times less than in the atmospheric argon (AAr). In the dark matter search mode the exposure of (2616±43 kg·d) allowed to obtain a limit on the spin-independent WIMP-nucleon interaction cross section of $2.0 \cdot 10^{-44}$ cm^2 for WIMPs of mass 100 GeV. Nowadays the DS-50 detector continues data taking, acquired exposure corresponds to 650 days livelime, data is now being processed for blind analysis.

The group from JINR, having gained an expertise with low-background Borexino detector, is planning to take a part in the data analysis of the second stage of the experiment, especially in geo-neutrino measurements, improvement of the pp-neutrino flux measurement, as well as in new studies with anti-neutrino source in the framework of the SOX project. In DarkSide, we are planning to participate in data analysis aiming at precise experimental measurement of the ^{39}Ar spectral shape and improvement of the analytical energy scale description. The group will also participate in the Monte Carlo modeling of DS20k components, in particular SiPM modeling, simulation of radiation neutron capture at different parts of the structure in order to choose the optimal configuration from the point of view of minimizing the backgrounds. We also participate in studies of detector's sensitivity to supernova neutrinos.

2. Status of studies

Borexino is a unique detector able to perform measurement of solar neutrinos fluxes in the energy region around 1 MeV or below because of its low level of radioactive background. After several years of efforts and tests with the prototype CTF the design goals have been reached and for some of the radioactive isotopes (namely from the daughter isotopes from the decay chains of ^{238}U and ^{232}Th) largely exceeded. The low background is an essential condition to perform the measurement: in fact solar neutrinos induced scintillations cannot be distinguished on an event by event analysis from the ones due to background. The shape of the solar neutrino spectra is the main signature that has to be recognized in the experimental energy spectrum by a suitable fit procedure that includes the expected signal and the background. The basic signature for the mono-energetic 0.862 MeV ^{7}Be neutrinos is the Compton-like edge of the recoil electrons at the maximum energy of 665 keV.

The detector is located deep underground (approximately 3800 m of water equivalent, mwe) in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy), where the muon flux is suppressed by a factor of 10^{6}. The main goal of the experiment was the detection of the monochromatic neutrinos that are emitted in the electron capture of ^{7}Be in the Sun (see original proposal [1]) with 5 % precision. The complete up to date technical description of the Borexino detector has been reported in [2] and [3]. The feasibility of reaching the level of radiopurity required by Borexino was first proven in the tests performed in the counting test facility (CTF) in 1996 [4, 5].

The main physics goals of the second phase of the Borexino presents as follows (end of 2017 status):

- improvement of the results on the Solar pp neutrino by including the phase I data in the analysis;
- providing a final update of the terrestrial neutrino flux measurements, extending the FV to the whole inner vessel;
- measurement of CNO solar neutrino flux;
- search for non-standard interactions of neutrino;
- study of the neutrino oscillation on the short baseline (search for sterile neutrino), SOX program;
- search for dark matter with the modified CTF detector (DarkSide-50).

More details on the physics program are provided in the Appendix.

The sensitivity plots of the SOX experiment are compared with the contour(s) allowed by the reactor anomaly in Fig.1, and also with the mixing angle upper bound [71] that can be inferred from the solar neutrino experiments and from the relatively large value of Θ_{13} measured by Daya Bay , T2K and Double Chooz [72]. We assume to achieve 1% error in the measurement of the source activity, as well as in the knowledge of the fiducial volume with which we select the candidate events. Based on a careful calibration of the detector with standard sources which is already foreseen in context of the solar neutrino program, a determination of the FV at less than 1% uncertainty will be achieved.

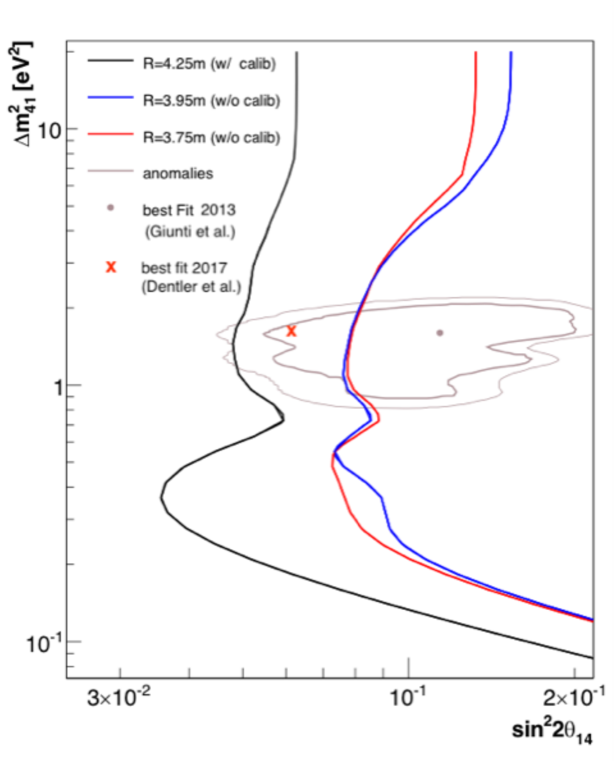

Figure 1 Sensitivity of the ^{144}Ce-^{144}Pr experiment. The closed area are the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. The lines are the sensitivity line for different conditions of the experiment (excluded regions lays to the right of the lines). The red cross marks new best fit point from the analysis of all the available data [68].

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3. Description of the proposed research

The successful purification campaign marked the start of the second stage of the experiment (Phase II), the regular data taking of the Borexino Phase II started on December 14 of 2011. After the success of the pp measurement (year 2014), obtained with the first portion of the data collected in the second stage, the plan was to exploit the new data recorded and the information of the detector performances gathered with the calibration, for a second round of release with improved precision of the fluxes published before, i.e. ^{7}Be, ^{8}B, pep, producing at the same time a tighter upper bound on the CNO. The preliminary analysis of the Phase II data have been released in 2017 [9], the data taking will continue till the start of the another calibration campaign two months before the installation of the antineutrino source for the SOX experiment.

Steps toward CNO-neutrino flux measurement

The high quality of the accumulated data is such that this plan is fully feasible and is close to be completed, but the exceptional condition of the background and the low level reached ^{210}Po, which has closely approached its intrinsic plateau value in the scintillator, triggered some strategic reconsideration of the next steps to be taken. The major new fact is the low count rate of the ^{210}Po, and the awareness that if its value could be properly stabilized, it would be a very powerful handle to constraint with great efficiency the parent ^{210}Bi in the fit to extract the solar neutrino components. And since the ^{210}Bi the major residual background masking the CNO spectrum, such a strategy can in principle lead to the evaluation of the CNO flux itself, and not only to an upper limit. Thus, the collaboration decided to adopt a radically different approach, devising a plan to decouple thermally the detector from the thermal instabilities of the Hall by covering the external wall of the Water Tank with a suitable insulating material up to the height of 14 m (see Fig.2), the work on insulation finished in august 2015. The purpose is to impede the convective movement triggered by the external temperature variations, letting therefore the non-intrinsic ^{210}Po to redeposit on the surface, leaving the fiducial volume only the stable intrinsic contribution in equilibrium with the parent ^{210}Bi. With an ample period of data taking in this stable conditions if ever reached (6 to 8 months are expected), the plateau value of the ^{210}Po should be measured rather precisely, leading possibly to the sought constraint on the ^{210}Bi and, therefore, in turn to the evaluation of the CNO through the global solar fit in which such a constraint would be exploited. For further precaution, and to allow for an active temperature control (very useful in case of further purification cycles), also the top of the Water Tank was insulated. The detector insulated up to the height of 14 m is shown in Fig.2.

Figure 2 Photo of the detector insulated up to 14 m heights.

The stable thermal condition of the detector reached as a result of the careful stabilization measures implemented by the Collaboration over the years 2016-2017 is most significant technical achievement in view of the possible CNO neutrino flux measurement.

The calibration campaign will be started at the moment when the intrinsic ^{210}Po will be stable and its value determined (or when vice versa the firm conclusion will be reached that the envisaged strategy of the ^{210}Bi constraint through the ^{210}Po is not feasible). In summary all the decisions about the evolution of the activities after the thermal insulation will be fully data driven. Finally, cycles of further purifications targeted specifically to reduce as much as possible the residual ^{210}Bi species, will be also postponed to the conclusion of this attempt centered on the achievement of the highest possible degree of thermal stability of Borexino.

SOX program

In February 2017 the tungsten shield arrived at Gran Sasso; in March 2017 the tunnel underneath Borexino which will host the source has been equipped with a new door and several proximity sensors; in the same month the Genova/TUM calorimeter already located previously in the clean room in front of the Borexino has been tested and calibrated using a mock-up of the source together with the tungsten shield, achieving the remarkable precision of 0.2%; in April 2017 also the CEA calorimeter has been deployed inside the clean room; in May 2017 AREVA has been selected as the transportation Company to bring the source to Gran Sasso, with MIT Ambiente sub-contracting the Italian portion of the overall path; in June 2017 we received the approval from ISPRA (the Italian Nuclear regulation authority) of the procedures for the manipulation of the source upon its arrival in Hall C; throughout the summer the CEA calorimeter has been tested and calibrated, as well, reaching similar accuracy than the Genova/TUM calorimeter.

We are now planning a calibration campaign needed in general to recheck after 8 years the status of the understanding of the detector response, and, of particular relevance for SOX, to verify the effects underwent by the neutrons at the border of the vessel, because of the interface with the buffer. Therefore, this specific border investigation carried out with a neutron source deployed close to the vessel wall will be crucial to understand properly the distribution of the signals induced by the source in the peripheral region of the scintillator.

Dark Side activities

The DarkSide-50 detector is successfully running and taking data since November 2013. The underground argon is shown to contain ^{39}Ar at a level reduced by a factor $(1.4\pm0.2)\times10^{3}$ relative to atmospheric argon. In 2016 a background-free null result was reported from (2616 ± 43) kg·d of data, accumulated over 70.9 live days . When combined with our previous search using an atmospheric argon, the 90% C.L. upper limit on the WIMP-nucleon spin-independent cross section, based on zero events found in the WIMP search regions, is 2.0×10^{-44} cm^2 (8.6×10^{-44} cm^2, 8.0×10^{-43} cm^2) for a WIMP mass of 100 GeV (1 TeV, 10 TeV).

The design of the next phase detector (DS20k) is currently under discussion. The veto sphere presently installed is already designed in order to host a larger cryostat, so the active mass can easily be scaled up to few tons. The expected sensitivity for the WIMP-nucleon cross section will be of the order of 10^{-47}cm^2 in a few years exposure, thanks to a ton-scale active mass of underground Argon. The commissioning of the future detector is foreseen to start after the end of the current phase.

There was significant progress on the entire chain for production of low radioactivity argon (LRAr), including both Urania (the sub-project for underground argon production) and Aria (the subproject for further Ar isotopes separation) fronts. We identified a strong candidate for the low- radioactivity substrates for the DarkSide-20k photodetector modules (PDMs). There was very strong progress towards the construction of the first PDM in its final design. Production of SiPMs at FBK has resumed. The INFN tender for the procurement of large SiPMs batches is expected to be completed by December 2017. The design of the cryogenics for DarkSide-20k is complete and its construction has started in view of the test at CERN agreed upon with the CERN Technology Department. Construction of a few of the DarkSide-Proto elements of the LAr TPC has started to assess manufacturing issues. We are considering re-introduction of the 3M Vikuiti^{TM} specular interference reflector to coat the lateral sides of the LAr TPC as in DarkSide-10 such as to eliminate Cherenkov light radiated in the PTFE reflector and further increase light yield. The final design for the DarkSide-Proto cryostat is complete, and procurement of the stainless steel version is under way.

4 Proposal on the JINR group participation in the Borexino/DarkSide program for 2019-2021

Based on the qualification and experience gained during the first stage of the experiment Dubna physicists plan to participate in the various activities of Borexino(SOX)/DarkSide program.

Participation in the R&D

Dubna scientists are working in the Borexino collaboration starting from the initial stage of the project. The group participated in the construction of a prototype of the Borexino detector, the Counting Test Facility (CTF), and its further exploitation (including the regular shifts during the data taking). The specific responsibility of the group were mainly the on-line software and the data analysis. Another significant contribution provided by Dubna group consisted in building and operating the so called PMT test facility used for testing all PMTs for the both CTF campaigns (200 PMTs in total) and Borexino (2400 PMTs in total). The PMT test facility is still in operation and will be used in a number of important tests for future developments, in particular the mass testing of new PMTs for the veto of the DarkSide 20k detector.

In frame of the Dark Side experiment we are responsible for the development, tests and production of the magnetic shielding of the large volume PMTs for the muon veto system. The production of 220 shields will form the JINR hardware contribution to the DS20k experiment.

The data taking

Borexino will continue to collect data at least till the end of the SOX program (end of 2019), the continuation strategy will depend on the failure rate of the PMTs. We will continue also to take data with DarkSide-50 facility. We will participate in the planned second calibration campaign of the Borexino detector before the SOX campaign.

In accordance to the rules accepted by the collaboration, each participating group covers the number of the data taking shifts proportional to the signatures in the collaboration papers.

Software development

The Dubna group participated in the development of the off-line code for the Borexino experiment. In particular, the position reconstruction code, module for the CNGS muons identification and module for noise events analysis have been developed. The group provided monitoring of the natural radioactive backgrounds and developed software for the detector stability monitoring. Much efforts have been spent on the calibration of the Borexino energy scale and understanding of the detector's performances. The sophisticated physical models developed for the description of scintillation detector energy resolution [52] and the scintillator response function shape [53] have been successfully applied to the Borexino data and are included in the official Borexino data analysis code as standard functions. We developed the events pile-up analysis module for Borexino. We are planning to complete the adaptation of the analysis software for GPU, significantly improving the speed of the analysis.

In frame of the DS experiment we tested the module of the modeling of radiative capture of neutrons on metallic components of the detector (Fe, Ni, Ti) with Geant4.10 package, revealing the discrepancy with experimental data both in cascade production of gammas and in multiple production of gammas withing the cascade. After the finalization of the design of DS20k detector the influence of the discrepancy on the background modeling will be studied.

We are working on estimate of the detection efficiency of the supernova signal from inverse beta-decay signal and elastic (anti)neutrino scattering on electrons. An events generator for detector simulation package g4ds is being developed for the modeling of positron events from IDD events and elastic scattering events following the known initial spectra.

We are participating in the development of the module responsible for the description of the silicon photomultipliers (SiPM) to be used in DS20k experiment. Among the task is inclusion of the dark noise generator, cross talks simulation and afterpulses simulation. Then the module will be adapted for inclusion to the mainframe simulation program of the detector.

We are planning to participate in further Borexino and DarkSide software development and tuning. The priority for the DarkSide project is the work on the tuning of the optimal choice of the detector’s configuration.

Data analysis

The Dubna group is taking an active part in the Borexino data analysis. In the past the group played a leading role in the ^{7}Be neutrino flux analysis (including analysis of the limits on the neutrino effective magnetic moment), analysis of the antineutrino data, analysis of rare processes and pp-neutrino analysis. We are planning to continue the analysis of the pp-neutrino flux and the analysis of the rare processes, including study of nonstandard interactions. We will contribute to the CNO neutrino flux analysis. The group is involved also in the antineutrino analysis which includes geoneutrino analysis, analysis of the diffuse supernova neutrinos and future analysis of the data in the frames of SOX experiment.

We are planning to analyze the DS50 data with a purpose of the extracting the precise shape of $\beta -$ decay of cosmogenic ^{39}Ar with low threshold provided by the set-up. We are estimating the sensitivity of DS20k to the rare processes, studied earlier by us with the Borexino, in particular the sensitivity to the electron decay ($e \rightarrow \nu + \gamma$), search for the violation of the Pauli exclusion principle in argon, search for nucleon (dinucleon) disappearence etc.

4. Human resources

The JINR group involvement in the project is presented in Table 1.

Name	Position	Responsibilities	FTE
Smirnov O.Yu.	Senior Researcher	Administrative tasks, R&D, data analysis (Borexino/DS)	0.7
Gorchakov O.E.	Senior Researcher	MC/Geant4, data analysis (DS)	0.5
Fomenko K.A.	Researcher	MC/Geant4 (Borexino/DS)	0.5
Formozov A.A.	PhD student	R&D, data analysis (Borexino)	0.5
Korablev D.E.	Researcher	PMT tests, electronics (DS)	0.4
Samoylov O.B.	Head of sector	software, data handling (DS)	0.3
Sheshukov A.S.	Researcher	software,data analysis, SN group representative (DS)	0.3
Sotnikov A.P.	Engineer	hardware, electronics, PMT tests (Borexino/DS)	0.4
Vishneva A.V.	Engineer	data analysis (Borexino)	1.0

Table 1 JINR group human resources, FTE is for Full time equivalent. Total FTE=4.6

SWAT analysis

The major risks for the Borexino/DarkSide project:

1. The possibility of the CNO neutrino flux measurement strongly depends upon the success of the the ^{210}Bi measurement.
2. Production of the ^{144}Ce source for the SOX could be an issue for the program
3. Interaction with local authorities is another risk factor for the SOX program.
4. The DS20k program could be influenced too by the existing limitations of the liquid scintillators use in the LNGS.

The schedule of the project can be significantly affected by the manufacturer (MAYAK) ability to produce the ^{144}Ce in time. In the case of the delay the CNO neutrino program will be pushed forward, as there are strong evidences for the temperature stabilization on therefore the ^{210}Po count stabilization that is needed for the ^{210}Bi measurement. In such a way the delay of the SOX program will give more time for the CNO program, reducing the risks of the point 1. The interaction with local authorities is a substantial part of the program, and again in the case of the delay the collaboration will have more time to solve the issue.

The LS issue for the muon veto system could be resolved by applying another technical solution, as an example using plastic scintillator or the cryogenic module. The choice is being discussed by the collaboration.

There are no other substantial risks. The Borexino is unique detector, it do not have competitors for its mainstream program (CNO and pp neutrino). The analysis of the pp-neutrino and update of the geo-neutrino analysis will be based on the data already accumulated, therefore there is no risk for this and related parts of the program.

The SOX program is considered an important experiment for the search of sterile neutrino. The main competitors are reactor experiments, but the method used is different. The possible delay doesn’t influence the impact of the program.

The DS20k will be unique experiment of the second generation using LAr, in such a way there is no direct competition for the program. The Xe experiments could reach the region of the Ar sensitivity, the issue of the competition with Xe experiments is being taken into consideration in the program, but this are “priority” issues irrelevant for the physics case. The measuerement with Xe and Ar could be considered complementary, as irreducible “(coherent) neutrino floor” background is different

Appendix

A Main results of the experiment (status at the end of 2017) and Dubna group contribution

Analysis of the first Borexino data showed that the main goals concerning the natural radioactivity have been achieved. The contamination of the liquid scintillator with respect to the U/Th is at the level of 10^{-17} g/g; the contamination with ^{40}K is at the level of 10^{-14} g/g; the ^{14}C content is $2.7 \pm 0.7 \times 10^{-18}$ g/g with respect to the ^{12}C. Among the other contamination sources only ^{85}Kr, ^{210}Bi and ^{210}Po have been identified. The ^{85}Kr counts ~ 0.3 ev/day/tonne, it is β- emitter with 687 keV end-point. The ^{210}Po is the most intense contamination (with initial count of ~60 counts/day/tonne), it decays emitting monoenergetic α with 5.41 MeV energy, the half-life time of the isotope is 134 days. The residual contaminations do not obscure the expected neutrino signal, the presence of the 862 keV monoenergetic ^{7}Be solar neutrino is clearly seen in the experimental spectrum. In such a way, the collaboration succeeded to purify the liquid scintillator from residual natural radioactive isotopes down to the levels much lower than was initially envisaged for the ^{7}Be neutrino measurement, which resulted in broadening of the initial scientific scope of the experiment.

The main goal of the experiment was the detection of the monochromatic neutrinos that are emitted in the electron capture of ^{7}Be in the Sun with 5% precision. This goal has been achieved during the first stage of the experiment [6, 7, 8], the precision of the measurement was recently improved to 3% with the Phase II data [9]. The Borexino reported the first measurement of neutrino ^{8}B neutrinos with liquid scintillator detector with a 3 MeV threshold on electrons recoil [10], later improving the result with more statistics [11]. The stability of the detector allowed also to study the day-night effect of the ^{7}Be solar neutrino signal, thereby allowing to completely exclude the LOW solution of the neutrino oscillation based on solar data alone [12]. Finally, the low background of the detector, the refined analysis on threefold coincidences [13] and the positronium discrimination method based on the positronium formation study made it possible to explore the 1-2 MeV region with unprecedented sensitivity. This led to the first observation of solar neutrinos from the basic pep reaction [14]. In addition, the best limit for the CNO production in a star has been established.

The results of the first phase of the experiment has been summarized in [15].

In 2014 the Borexino collaboration reported the first observation of solar neutrinos from the primary pp reaction [16] by exploring the Solar neutrino energy region that was never studied before in real-time mode. This was a first result obtained in the second phase of the experiment.

The last update of the solar neutrino result has been released in 2017 [9],[11]. For the first time analysis of pp, ^{7}Be, and pep solar neutrino fluxes was performed simultaneously as a result of precision calibration of the energy scale in wide energy region, from 200 to 2000 keV.

In this way, Borexino has completed direct detection of ^{7}Be, pep, pp and ^{8}B solar neutrino spectrum components thereby providing complete evidence of the transition from MSW and vacuum oscillation of the LMA solution of the Solar Neutrino Problem.

The unprecedented characteristics of its apparatus make Borexino very competitive in the detection of anti-neutrinos, particularly those of geophysical origin, the first measurement of the geoneutrino flux was reported in [17]. An update of the results was published in [18] and [19].

A series of physics results beyond the original physical program were obtained. The stringent limits on solar and other antineutrino sources have been obtained [20], this work took advantage from the methodology developed for the geoneutrino analysis.

The Borexino data has been used to set limits on the hypothetical 5.5 MeV solar axions that can be produced in $p+d \rightarrow {}^{3}He + A$ reaction in the Sun. The Compton conversion of axion to a photon $A+e \rightarrow e+\gamma$, axioelectric effect $A+e+Z \rightarrow e+Z$, decay of axion in two photons $A \rightarrow 2\gamma$ and Primakoff conversion on nuclei $A+Z \rightarrow \gamma+Z$ were considered. Model-independent limits on axion-electron (g_{Ae}), axion-photon ($g_{A\gamma}$), and isovector axion-nucleon (g_{3AN}) couplings are obtained: $|q_{Ae} \times g_{3AN}| \leq 5.5 \cdot 10^{-13}$ and $|q_{A\gamma} \times g_{3AN}| \leq 4.6 \cdot 10^{-11}$ GeV^{-1} at m$_{A}$<1 MeV (90% confidence level). These limits are 2–4 orders of magnitude stronger than those obtained in previous laboratory-based experiments using nuclear reactors and accelerators [21].

The Pauli exclusion principle (PEP) has been tested for nucleons in ^{12}C [22]. The approach consists of a search for γ , n, p, and $\beta^{\pm}$ emitted in a non-Paulian transition of 1$P_{3/2}$-shell nucleons to the filled 1$S_{1/2}$ shell in nuclei. The following most stringent up-to-date experimental bounds on PEP violating transitions of nucleons have been established: $\tau(^{12}\text{C} \rightarrow {}^{12}\text{C} + \gamma) < 5.0 \cdot 10^{31}$ yr, $\tau(^{12}\text{C} \rightarrow {}^{11}\text{B} + \text{p}) < 8.9 \cdot 10^{29}$ yr, $\tau(^{12}\text{C} \rightarrow {}^{11}\text{C} + \text{n}) < 3.4 \cdot 10^{30}$ yr, $\tau(^{12}\text{C} \rightarrow {}^{12}\text{N} + e^- + \nu_e) < 3.1 \cdot 10^{30}$ yr, and $\tau(^{12}\text{C} \rightarrow {}^{12}\text{B} + e^+ + \nu_e) < 2.1 \cdot 10^{30}$ yr, all at 90% C.L. The corresponding upper limits on the relative strengths for the searched non-Paulian electromagnetic, strong and weak transitions have been estimated as $\delta_\gamma^2 < 2.2 \cdot 10^{-57}$, $\delta_N^2 < 4.1 \cdot 10^{-60}$, and $\delta_\beta^2 < 2.1 \cdot 10^{-35}$.

The muon flux at the underground Gran Sasso National Laboratory (3800 m.w.e.) has been measured using four years of Borexino data [23, 24], the flux is $(3.41 \pm 0.01) \cdot 10^{-4}$ $m^{-2}s^{-1}$. A modulation of this signal is observed with a period of (366±3) days and a relative amplitude of (1.29±0.07)%. The measured phase is (179±6) days, corresponding to a maximum on the 28th of June. Using the most complete atmospheric data models available, muon rate fluctuations are shown to be positively correlated with atmospheric temperature, with an effective coefficient $\alpha_T = 0.93 \pm 0.04$. This result represents the most precise study of the muon flux modulation for LNGS site and is in good agreement with expectations.

Another task not envisaged in the original Borexino program was the CNGS muon neutrino speed measurement, that was performed in a short time in view of the great interest to the problem after the superluminal neutrino observation claim by OPERA experiment. The final result for the difference in time-of-flight between an E = 17 GeV muon neutrino and a particle moving at the speed of light in vacuum is δt = 0.8 ± 0.7 (stat) ±2.9 (sys) ns, well consistent with zero [25].

In 2015-2017 Borexino collaboration established stringent limits on electron lifetime with respect to the decay mode $e \rightarrow \nu + \gamma$ [26], set new limit on the effective magnetic moment of Solar neutrino of $\mu_\nu^{eff} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.) improving earlier result of $\mu_\nu < 5.4 \cdot 10^{-11} \mu_B$ at 90% CL [27], performed a search for low-energy neutrinos in coincidence with Gamma Ray Bursts (GRB) [28] and with gravitational wave events [29]. We completed also the analysis of the seasonal variations of the ^{7}Be neutrino signal, demonstrating the Solar origin of the signal [30].

Dubna scientists have a long record of working in the Borexino experiment. The group participated in the construction of a prototype of the Borexino detector, the Counting Test Facility (CTF), and its further exploitation (including the regular shifts during the data taking). The specific responsibility of the group were mainly the on-line software and the data analysis.

Another significant contribution provided by Dubna group consisted in building and operating the so called PMT test facility used for testing all PMTs for the both CTF campaigns (200 PMTs in total) and Borexino (2400 PMTs in total). The very first version of the test facility has been used for the PMT selection for the Borexino, on the base of the test the ETL 9351 8" PMTs has been selected [31]. Later the test facility has been upgraded to operate with maximum of 128 electronics channels providing a possibility of the fast PMTs testing [32]. The PMT test facility has been used for the PMTs characterization, the amplitude [33] and time response of ETL9351 [34] has been studied in detail. On the base of the tests, fast HV tuning algorithm has been developed [35] and applied for the automated PMT gain control system for the Borexino PMTs test facility and for the CTF.

The test facility has been used for the tests of the PMT sealing, this was a long term tests in the conditions very close to those of the Borexino, the PMTs has been completely immersed in the pseudocumene with the base left in the ultrapure water. Specially designed stainless steal tank containing water and PC has been installed at the laboratory (the two liquids test tank, TLTT). The tests lasted for 3 years and proved the reliability of the chosen design of the sealing. Later on a multiplexed optical-fiber system for the PMT calibration of the Borexino experiment has been tested using TLTT and the PMT test facility [36]. Using test facility 2000 PMTs with the best performances were selected for the installation in the Borexino detector. The high efficiency of the equipment permitted to complete PMT testing within 4 months. The analysis software was developed on the base of the CERN ROOT libraries under a Linux system. The program automatically analyzes the charge spectrum, the transit time spectrum, and the spectrum of the ionic afterpulses and then plots all the data in the test sheet. All numerical data were inserted in a database immediately. The results of the acceptance test were reported in [37].

Our group participated in operation of the prototype detector (CTF) that was taking data till 2011. The CTF at that moment was the world's largest ultralow-background scintillator detector with lowest energy threshold [4, 5, 38, 39]. We analyzed the data collected with a second version of the CTF in order to search for a number of possible manifestations of the non-standard physics. A number of new fundamental limits were established: neutrino magnetic moment [40] and Solar antineutrino flux were constrained at the low neutrino energies [41], electric (from the constraints on the $e \to \nu + \gamma$ decay [42]) and barion (from the absence of nucleon and dinucleon disappearence [43]) charge conservation was checked at new levels, new limits on Pauli exclusion principle violation in ^{12}C and ^{16}O nuclei were established [44], and the search of the new mass eigenstates of heavy neutrino was performed using the CTF data looking for the neutrino decay with a mass bigger than $2m_e$ [45]. The CTF data has been also used to set limits on the solar axions emitted in the M1-transition of $^{7}Li^*$ [46]. The main physics results obtained with the CTF detector were reviewed in [47].

Later with the data of the CTF we measured the life-time of the ^{214}Po [48] and provided a measurement of the ^{214}Bi beta-spectrum shape relevant for the geoneutrinos studies [49].

Our group significantly contributed to the mainstream physics analysis, especially in the ^{7}Be neutrino flux analysis, antineutrino flux analysis (including geo-neutrino analysis, awarded the DLNP first prize for experimental work in 2013) and analysis of rare processes. We provided the major contribution to the pp-neutrino measurement (the possibility of pp-neutrino detection with LS detectors has been demonstrated in [50, 51]), the result was awarded the JINR first prize for the best scientific work of 2014 and was selected by EPS experts to be one of the top 10 breakthroughs in physics in 2014. We provided also the major contribution to the work on the electric charge conservation and limit on the effective magnetic moment of neutrino. The so-called “analytical approach” in the Borexino solar neutrino analysis was developed by our group, in particular on the CTF experience reported in [52, 53].

Status of backgrounds

The data acquisition is performing rather well, maintaining the average duty cycle of ~ 90%, which has characterized the latest years of run. The only data instability of Borexino is that externally induced by the temperature variations of the Hall C. It is worth to stress that they impact only the ^{210}Po, so that the originally planned goals of the Phase II program, which do not depend on the level of ^{210}Po, are not influenced at all. The great overall stability of the scintillating core of the detector (with except of ^{210}Po) is signaled by the extremely low background maintained after four years of unperturbed data taking. The last updates released for the Neutrino 2014 conference are: ^{238}U and ^{232}Th, respectively, $<9.5\cdot10^{-20}$ g/g and $<7.2\cdot10^{-19}$ g/g at 95% C.L., ^{85}Kr 6.8±1.8 cpd/100 tons at 95% C.L.; ^{210}Bi, the only sizable remaining beta species, 25.5 ±1.8 counts/day/100tons.

Stability of the detector’s hardware

Concerning the hardware status, the two sources of instabilities of the equipment are continuously monitored: PMT’s and Inner Vessel shape. The situation with the PMTs can be characterized by a number of failed devices for each year since the beginning of the data-taking: 2007 - 22, 2008 - 15, 2009 - 22, 2010 - 46, 2011 - 63, 2012 - 91, 2013 – 76, 2014- 76, 2015- 62, 2016 - 67, 2017 - 38 (11 months).

The current rate of failures is thus stabilized to approximately 6 PMTs/month (last year even less), adequate to ensure the proper functioning of the detector for the few additional years required to complete the solar program and the SOX project. The former doesn’t depend critically on the energy resolution.

The small leak in the inner vessel, which is reduced to a negligible level, is monitored by checking the amount of mass contained in the nylon balloon through the precise determination of its shape (and hence volume). Specifically, the geometry of the balloon is obtained by studying the deposit in the scintillator of the external gammas from the PMTs: the reconstructed spatial distribution of these background events is used to determine the profile of the vessel on a weekly basis. Despite the gradual variation of the shape, due to the very small residual density difference between the scintillator and the buffer, the mass of the scintillator contained in the balloon features only a very limited variation over the past four years of phase II.

The collaboration have not carried out special hardware refurbishments, with the exclusion of the preparation activity in the clean room in front of the detector for SOX. The latest plant which underwent a thorough refurbishment was the High Purity Nitrogen system.

Astrophysics

The future contribution of Borexino to studying the workings of stars is directly connected to the possibility of measuring the CNO flux. The detection of solar neutrinos has not only confirmed the basic theory of how the Sun shines, via the proton-proton nuclear reaction chain in the solar interior, but has revolutionized particle physics by the discovery that neutrinos oscillate and, thus, have mass. But the complete theory of how stars shine and what generates the enormous amount of energy emitted by billions of them throughout the Universe has yet to be fully tested. The theory of energy generation in stars posits that two processes power stars during their main sequence lifetime: the proton-proton (p-p) chain which builds helium from hydrogen and is the dominant energy source in stars like the Sun and lower mass stars, and the CNO cycle, which is theorized to be the primary channel for hydrogen burning in stars more massive than the Sun, and is in fact the primary channel for hydrogen burning in the Universe. The CNO cycle is considered to produce a small but detectable fraction of the Sun's energy. Larger stars however, with central temperatures higher than the Sun's, should generate their energy mostly via the CNO cycle. The model of energy generation in more massive stars has never been tested and demands observational confirmation. While neutrinos from the center of distant massive stars cannot easily be detected, we can detect CNO neutrinos from the center of our Sun. This, by appropriate scaling, would experimentally test the theory of energy generation in other stars. Similar to the pioneering work of John Bahcall and Ray Davis the observation of CNO neutrinos will test how massive stars shine by providing the experimental evidence of the existence of these neutrinos from the Sun, confirming our current understanding of energy generation in the core of the stars. Such an investigation might also reveal the unexpected, as was the case with Solar Neutrinos.

Solar neutrino program

One of the goals of the Borexino experiment is the measurement of all the solar neutrino fluxes, with the exception of the hep flux, too faint for detection in Borexino. The pp, ^{7}Be, pep and ^{8}B (this last with the lowest threshold to date) results have been recently updated [9], the precision of the pp-neutrino flux measurement can be still improved if all the available data used. In addition Borexino challenges the measurement of the CNO neutrino flux.

ν flux	GS98	AGS09	$cm^{-2}s^{-1}$	Experimental result
pep	1.44(1±0.01)	1.46(1±0.009)	$\times 10^{8}$	$1.39 \pm 0.19_{-0.13}^{+0.08}$ (with LZ for CNO) Borexino
				$1.27 \pm 0.19_{-0.12}^{+0.08}$ (with HZ for CNO) Borexino
pp	5.98(1±0.006)	6.03(1±0.005)	$\times 10^{10}$	$6.1 \pm 0.5_{-0.5}^{+0.3}$ Borexino
^{7}Be	4.93(1±0.06)	4.50(1±0.06)	$\times 10^{9}$	$4.99 \pm 0.13_{-0.10}^{+0.07}$ Borexino
^{8}B	5.46(1±0.12)	4.50(1±0.12)	$\times 10^{6}$	5.6±0.4 Borexino
				$5.25 \pm 0.16_{-0.013}^{+0.011}$SNO-LETA
^{13}N	2.78(1±0.15)	2.04(1±0.14)	$\times 10^{8}$	
^{15}O	2.05(1±0.17)	1.44(1±0.16)	$\times 10^{8}$	<7.9 Borexino (total CNO)
^{17}F	5.29(1±0.20)	3.26(1±0.18)	$\times 10^{8}$	

Table 2 SSM predictions and current experimental results

In table 2 the solar fluxes measured by Borexino so far are compared with the SSM prediction, for low and high metallicity. The experimental results agree, within the errors, with the SSM predictions, but cannot distinguish between the two metallicities, due to the uncertainties of the model and the experimental errors. It would be useful, at this moment, to recall what the metallicity puzzle is. The solar surface heavy element abundance has been calculated about ten years ago with a 1D model, which uses data from spectroscopic observations of the elements present in the photosphere (GS98 [55]). This model agrees with the helioseismology observations, namely the measurement of the speed of the mechanical waves in the Sun. More recently a 3D hydro-dynamical model (AGSS09 [56]) of the near-surface solar convection, with improved energy transfer, has changed the Z/X ratio with respect to the previous 1D treatment: 0.0178 (low metallicity) to be compared with the previous 0.0229 (high metallicity). The 3D model results perfectly reproduce the observed solar atmospheric line (atomic and molecular) profiles and asymmetries, but are in clear disagreement with the helioseismology data. At present there is no satisfactory solution to this controversy [57]. The 1D and the 3D models predict different neutrino fluxes from the various nuclear reactions, as shown in Table 2, where they are compared with the experimental results obtained until now.

As stated above, it is not possible, at present, to decide which one between the two solutions is the best due to model uncertainties and experimental errors. A measurement of the CNO flux, with reasonable errors, could distinguish between the two models which predict substantially different fluxes.

The pp solar neutrino flux before Borexino never has been measured directly. Gallex and Sage have measured the integrated solar flux from 233 keV, which, together with the Borexino ^{7}Be neutrino flux measurement and the experimental data on the ^{8}B neutrino flux, can be used to infer the pp neutrino flux with a relatively small uncertainty, once the luminosity constraint is applied. Nevertheless a direct experimental observation, which can be compared with the solar luminosity and the SSM prediction, would be an important achievement.

The actual results are obtained by analyzing the data of the second phase of the experiment, which are roughly the two thirds of the total data. Despite the fact that the Phase II data dominates in the exposition, the data of the first stage are more sensitive with respect to the pp-neutrino due to the fact that there were more PMTs in operation, i.e. the energy resolution was better. The improvement of pp flux measurement is still a part of the Borexino phase 2 program.

Supernova neutrino detection.

Interaction	Prompt energy release	Delayed energy release	Delay	Events
	MeV	MeV	ms	E>200 keV
$\nu_e + e \rightarrow \nu_e + e$	0-30	-	-	5

$\nu_e + p \rightarrow n + e^+$	0.9-50	1.9	0.26	78
$^{12}C(\nu_e, e^-)^{12}N$	0-40	0.9-17	11	9
$^{12}C(\nu_e, e^+)^{12}B$	0.9-50	0-13	20	3
$^{12}C(\nu, \nu')^{12}C^*$	-	13	-	15
$\nu + p \rightarrow \nu + p$	0-2	-	-	52

Table 3 The supernova induced neutrino interactions that are observable in Borexino. The energy of the prompt signal from the primary interaction products is presented in the second column, while the the delayed signal from secondary decays and de-excitations (not shown in the table) are presented in the third column. The average time difference between prompt and delayed signal is shown in the fourth column. The expected number of interactions from a “typical" supernova for each interaction is shown in the last column.

Calculations suggest that in the case of a “typical" galactic supernova (at 10 kpc and 3×10^{53} ergs of binding energy release) about 150 events above 200 keV will occur in the inner vessel of the Borexino detector within tens of seconds. The reaction rates and the energy of the signal are summarized in Table 3. The event rates for supernova neutrino interactions are expected to be 1 to 3 orders of magnitude larger than the uniform background and, therefore, the Borexino detector is well suited for the early detection of a galactic supernova.

The Borexino joined the Super Nova Early Warning System (SNEWS). The SNEWS has been running in automated mode since 2005. Currently, besides the Borexino other six neutrino experiments are involved: Super-K (Japan), LVD (Italy), Ice Cube (South Pole), KamLAND (Japan), Daya Bay (China), and HALO (Canada). The SNEWS takes advantage of time correlation between possible supernova neutrino signals among the different detectors to offer the astronomical community with a reliable alert in the case that a galactic supernova is imminent. No nearby core collapses have occurred since SNEWS started running, but we are ready for the next one.

Geo-neutrino flux measurement

Geoneutrino is an electron antineutrino accompanying β-decay of nuclear isotopes present in the Earth. Interest in geoneutrino has risen very recently, in parallel with development of large volume detectors, able to detect their tiny fluxes. The main scientific outcomes expected from these measurements are the abundances and distributions of radioactive elements inside the Earth, beyond the reach of direct measurements by sampling. The natural radioactivity of the Earth is a powerful source of heat, influencing the thermal history of the Earth. The knowledge of the radioactive content of the Earth's depths is essential for many problems in geoscience.

Geo-neutrinos are produced in the β-decays of ^{40}K and of several nuclides in the chains of the long-lived radioactive isotopes ^{238}U and ^{232}Th, which are naturally present in the Earth. The Earth emits geo-neutrinos with a flux of about 10^6 $cm^{-2}s^{-1}$. It is important to note that the released radiogenic heat and the geo-neutrino flux is in a well fixed and known ratio. Therefore, it is possible in principle to determine the amount of the radiogenic heat contributing to the total terrestrial surface heat flux (Urey ratio) by measuring the geo-neutrino flux. The knowledge of the geo-neutrino flux at different locations through the globe, in different geological settings and/or by identifying the incoming direction of detected geo-neutrinos, may made possible to:

- study the distribution of radioactive elements within the Earth, to determine their abundances in the crust and in the mantle;
- determine if there are radioactive elements in the Earth's core;
- understand if the mantle composition is homogeneous or not;
- test, validate, and discriminate among different geological models;
- exclude or confirm the presence of a geo-reactor in the core;
- determine the so-called Urey ratio by measuring the radiogenic heat flux, an important parameter for both geochemistry and geophysics;
- study the bulk U and Th ratio in the silicate Earth, an important parameter for geochemistry, which could shed light on the process of the Earth's formation.

We can see that geo-neutrinos can be used as a unique direct probe of the Earth interior, not accessible by any other means. All these information could provide important data used as inputs for geological, geophysical, and geochemical models describing such complex processes as the mantle convection, movement of tectonic plates, geo-dynamo (the process of the generation of the Earth's magnetic field), Earth formation etc. Until now Borexino and KamLAND demonstrated strong evidence for the geoneutrino presence in the detected spectra. But the data are not yet sensitive enough to discriminate among the various Earth models and to fix some of the open problems mentioned before. Borexino, with its unprecedented radio-purity and the advantage of a low reactor v rate at the Gran Sasso site, is able to produce further important insights in this physics.

With Borexino combined data from phase 1+2 we will be able to measure geo-neutrino rate with a relative precision of about 15%. Borexino anti-neutrino measurement was almost background free already in phase 1, so the error reduction is mostly statistical. The potential of geological predictions of a rate measurement with 15% relative error will depend of course on its central value with respect to the predictions of different geological models. It is not expected that such a measurement would discriminate with high significance among these models, but it can give hints of discrimination for some models and for the evidence of the presence of radioactive elements in the Earth mantle. Even the existing data from KamLAND and Borexino, in a combined analysis, give hints of the exclusion of a fully radiogenic model and of the detection of mantle geoneutrinos. Such analysis indicate also that it is of a great importance to gather geo-neutrino measurements at different locations around the globe. In the near future it is possible that also KamLAND will release new geo-neutrino measurement probably with increased precision, since many Japanese reactors were switched off. In that case a common Borexino+KamLAND data analysis could produce a further tool able to discriminate among different geological approaches.

The Non Standard neutrino Interactions.

The hypothesis of Non Standard Interactions (NSI) of the neutrinos with other fermions can be considered presently a hot problem in the neutrino physics. This hypothesis has been predicted by several models as an extension of the Standard Model (SM), as for instance the left-right symmetric models and supersymmetric models with R-parity violation.

The NSI can be described at low energy by effective four fermion interactions:

(1) $\mathcal{L} = -2\sqrt{2}G_F \epsilon_f^{\alpha\beta C} (v_\alpha \gamma^\mu P_L v_\beta)(f \gamma_\mu P_C f)$

where G_F is a Fermi constant and $\epsilon_f^{\alpha\beta C}$ is the constant that characterizes the strength of interaction, indexes $\alpha\beta$ are neutrino flavors and C is left L or right R chirality of the operator.

Borexino can contribute to the search of NSI study by further studying neutrino oscillations; in particular, the transition region between vacuum and matter oscillations and by a careful studying the elastic scattering $v - e$.

B Short Baseline Neutrino Oscillation Experiment with Borexino (SOX program)

The solar neutrino detector Borexino is perfectly suited to host a short baseline neutrino oscillation experiment able to shed light on the many intriguing experimental hints, accumulated so far, pointing to the possible existence of a sterile neutrino at the few eV mass scale. The extreme radiopurity achieved in the liquid scintillator acting as detection medium, witnessed by the extremely successful detection of low energy solar neutrinos, and the thorough understanding of the detector performances gained throughout almost five years of data taking (and several calibration campaigns), make the Borexino the ideal choice for the sterile neutrino experimental investigation. The studies indicate, in particular, that Borexino could be a well suited location both for an external neutrino source experiment and for an internal anti-neutrino source test [62]. The sensitivity evaluations already performed show that both would provide conclusive results regarding the hypothetical oscillation process involving sterile neutrinos.

It is proposed to realize, in the context of the Borexino program, an experiment sensitive to a large fraction of the parameter space for short distance neutrino flavor oscillations into sterile components. It will aim at the complete confirmation or at a clear disproof of the so called neutrino anomalies, a set of evidences of neutrino oscillations outside the standard 3-active flavor scenario observed at LSND [63], MiniBoone [64] with nuclear reactors [65], and with solar neutrino Gallium detectors [66]. If successful, this experiment would demonstrate the existence of sterile neutrino components and would open a brand new era in fundamental particle physics and cosmology. A solid signal would mean the discovery of the first particles beyond the Standard Electroweak Model and would have profound implications in our understanding of the Universe and of fundamental particle physics. In case of a negative result, it would be able to close a long standing debate about the reality of the neutrino anomalies; in both case it would guarantee additional, important physics outputs by probing the existence of new physics in low energy neutrino interactions, by providing a measurement of the neutrino magnetic moment, and by yielding a superb energy calibration for Borexino, which would be very beneficial for future high-precision solar neutrino measurements. The experiment would be done by exploiting the exceptional features of the Borexino detector, and by preparing state-of-the-art neutrino and anti-neutrino sources. The experiment will be carried out by deploying a ^{144}Ce-^{144}Pr anti-neutrino source with 2-4 PBq activity.

In the quest of understanding the fundamental laws of Nature and the origin and evolution of our Universe, neutrinos play a very unique role. The observation of neutrino flavor mixing implies a finite neutrino mass, representing the most compelling experimental hint that the Standard Model of Electroweak interactions is incomplete. Additional evidence in this sense comes also by several theoretical arguments (unitarity at TeV scale and naturalness among others) leading to the widespread belief that, in one way or another, a new fundamental theory is required. Since the mass scale of this new theory might be very large, it is not unlikely that the direct production of the associated new particles will not be possible even at the LHC energy. It is, therefore, of the utmost importance to identify alternative ways of probing the hypothesis of a still undetected particles beyond the SM.

A possible way to do so is by proving the existence of neutrino oscillation into additional sterile components, possibly right handed Dirac neutrinos, or additional Majorana neutrinos. Indeed, if new generations of particles do exist, it is very likely that new neutrino species exist as well, that can mix with the known active neutrinos [67]. The possible existence of sterile neutrinos is supported by a set of non-conclusive, but anyhow intriguing pieces of experimental evidence coming both from particle physics and from cosmology. On one side, several experiments probing neutrino and anti-neutrino oscillations at relatively small values of L/E have observed either a lack of events in their detectors or the appearance of active neutrinos that might be explained by 2nd order processes requiring the existence of sterile neutrinos. The LSND experiment has observed an excess of electron anti-neutrino events in a muon anti-neutrino beam produced by the LANSCE facility at the Los

Alamos National Laboratory in the United States. This excess, if interpreted in terms of neutrino oscillations, indicates the existence of a neutrino flavor of mass in the range 1-10 eV. This finding is not compatible with the well-established neutrino flavor oscillation process identified by means of solar, atmospheric and reactor experiments, thus leaving oscillations into sterile neutrinos as a viable explanation. The MiniBoone experiment was built at Fermilab with the primary goal of testing the LSND result. Contrary with LSND, MiniBoone has taken data with both muon neutrinos and anti-neutrinos. The MiniBoone result has rejected the LSND result in the neutrino mode, while it has observed an event excess in anti-neutrino mode. This has made the scenario more complex and more intriguing. The results can be interpreted in terms of sterile neutrinos with at least 2 components with CP violation, or invoking neutrino non-standard interactions. Both LSND and MiniBoone do not appear, by themselves, very convincing. Though, no clear error has been identified, yet, in both experiments. More solid and convincing evidence comes from a reevaluation of the anti- neutrino flux from nuclear reactors and from a subsequent reanalysis of a large set of experimental results obtained with detectors located at short distance from the nuclear core. The new calculation, claimed to be more accurate, shows that all experiments, but one, have seen an anti-neutrino flux significantly lower than that expected, hence pointing to a disappearance effect that might be explained with sterile neutrinos. Other indications for short distance oscillations come from the gallium solar neutrino experiments Gallex and SAGE, which have performed measurements with radioactive neutrino sources made with ^{51}Cr and ^{37}Ar.

The up-to-date analysis of the experimental situation in search for the sterile neutrinos can be found in a recent paper [68]. The first “negative” results from NEOS and DANSS feature sensitivity "fingers" reaching into the anomaly region. Correspondingly, the best fit point of the anomalies has predictably shifted to lower oscillation amplitudes and is now residing at around $\sin^2 2\theta_{14} = 0.06$ and $\Delta m^2 = 1.5$ eV^2. The new best fit point is marked with a red cross in the SOX sensitivity plot Fig.3.

Neutrino generator for SOX experiment

The neutrino generator is made of 2.5 kg ultra-pure ^{144}Ce, extracted from fresh spent nuclear fuel at Mayak, Russia. At the beginning of the data taking, the source activity will exceed 3.7 PBq. ^{144}Ce has a half life of 285 days and beta-decays into ^{144}Pr, that again decays with a half life of 17 minutes into stable ^{144}Nd. The beta decay of ^{144}Pr has a Q-value of 3 MeV, hence it generates a sufficient amount of with an energy above the inverse beta-decay threshold. The source activity and the shape of the β-spectrum have to be known with unprecedented accuracy to ensure a satisfactory sensitivity for measuring the sterile neutrino mixing parameters [69].

The source activity will be determined by measuring its heat output. Two thermal calorimeters are constructed for redundancy, one by CEA Saclay, the other one by the TUM and Genova University groups. The maximum tolerance for the activity estimation is 1%. A cooling liquid is passing through a copper heat exchanger, which is mounted around the ν-generator shield, the temperature change and the mass flow are precisely measured. Thermal insulation is achieved by suspending the source and the heat exchanger with insulating Kevlar ropes inside a vacuum. Radiative heat transfer is minimized by thermalizing the outer shell of the vacuum tank to match the surface temperature of the heat exchanger, which again is surrounded by several layers of superinsulator foils. The error of the power measurement will be below 0.4% (note that in 1995, the Gallex experiment obtained better than 2% precision, based on the current state-of-the-art we expect even higher accuracy).

The precision measurements of the ^{144}Ce– ^{144}Pr spectral shape are necessary for the success of the experiment, as spectral shapes reconstructed following previous measurements can differ up to 20%, resulting in a 10% variation of the expected antineutrino interaction rate in Borexino. The measurements are in preparation.

Sterile neutrinos using total counts and waves

Borexino can study short distance neutrino oscillations in two ways. The first way is the standard disappearance technique used by many experiments at reactors, accelerators and with solar neutrinos: if oscillations occur, the total count rate measured at a given distance from the source is lower than the one expected without oscillations. The second way, is a very strong feature of this proposal [70]: due to the facts that the expected Δm^2 is of the order of 1 eV^2 and that the energy of radioactive induced neutrinos is of the order of 1 MeV, the typical oscillations length is of the order of a few meters and the oscillations waves can be directly observed in a large detector like Borexino, whose active diameter exceeds 6 m. Based on spatial reconstruction, the observed event rate will decline and reappear inside the detection volume as a function of the distance from the source.

The sensitivity plots are compared with the contour(s) allowed by the reactor anomaly in Fig.3, and also with the mixing angle upper bound [71] that can be inferred from the solar neutrino experiments and from the relatively large value of Θ_{13} measured by Daya Bay , T2K and Double Chooz [72]. We assume to achieve 1% error in the measurement of the source activity, as well as in the knowledge of the fiducial volume with which we select the candidate events. Based on a careful calibration of the detector with standard sources which is already foreseen in context of the solar neutrino program, a determination of the FV at less than 1% uncertainty will be achieved.

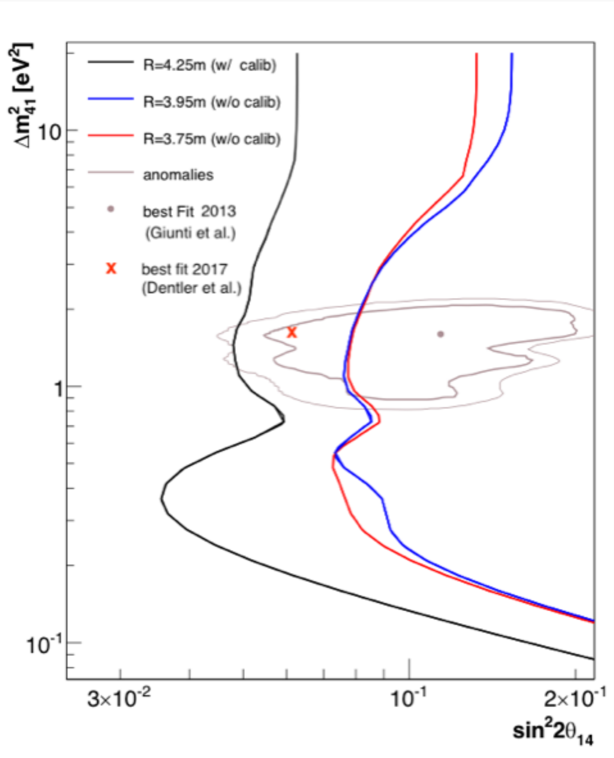

Figure 3 Sensitivity of the ^{144}Ce-^{144}Pr experiment. The closed area are the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. The lines are the sensitivity line for different conditions of the experiment (excluded

regions lays to the right of the lines). The red cross marks new best fit point from the analysis of all the available data [68].

C Direct search for dark matter : Dark Side experiment.

Our knowledge of the energy balance of the Universe is derived only by indirect observations. We know that the baryonic matter (the so called luminous matter) only accounts for roughly the 5% of the energy content, while Dark Energy and Dark Matter are estimated to provide the larger contributions, which account for the 68% and the 27% respectively (according to the recent results of the Planck experiment). The first hypotheses on the existence of Dark Matter date back to the beginning of the 20th century and they are presently well supported by several indirect observations. In spite of this, the knowledge of the nature of these particles, not predicted by the Standard Model, is extremely poor. One of the most favored candidate is known as WIMP, an acronym for Weakly Interactive Massive Particle. These particles are supposed to have masses in the GeV-TeV range, to not interact strongly nor electromagnetically, but only through gravitational and weak forces. The current upper limit on the WIMP-nucleon cross section, extremely low, is $7.6 \times 10^{-46} cm^2$ for 33 GeV WIMP mass at 90% CL [73]. The indirect search for WIMPs can be performed by looking for ordinary decay products of WIMP-WIMP annihilation in the Universe or by producing WIMPs in collider experiments; the direct detection channel can be exploited by searching for nuclear recoils induced by elastic scattering of WIMPs on ordinary nuclei.

Noble liquids are suitable for direct detection of Dark Matter: they are dense, inexpensive and easy to be purified (a detector can be scaled up to large volumes) and they have high ionization and scintillation yields (roughly one electrons every 20 eV and 40k photons/MeV respectively). When a charged particle interacts within noble liquids, it looses energy by both ionization and excitation, according to the stopping power of the interacting particle. The excited atoms de-excite producing a prompt light signal in the UV range (scintillation light, called S1 in the following). Electrons and ions produced by ionization can be separated by means of an electric filed. A fraction of free electrons, however, undergo to the recombination process with ions produced along the particle track. The recombined atom is in an excited state and the de-excitation increases the S1 signal. The recombination effect is larger at higher ionization densities, and hence stronger for nuclear recoils with respect to electronic recoils. As a result, nuclear and electronic recoils can be discriminated with a rejection factor of the order of 10^2-10^3 [74, 75].

Liquid noble gases experiments, thanks to the double phase TPC technique, are suitable for measuring both the scintillation and the ionization components: the ionization electrons are drifted up to a gaseous layer, lying on the top of the liquid noble volume, and extracted by means of an applied electric field. During the extraction, a second light emission occurs (called S2), thanks to the electro-luminescence effect, proportional to the number of ionization electrons. The main two noble liquid targets used in currently running experiments are Argon and Xenon. The predicted interaction cross section is slightly different, being larger at low WIMP masses for Xenon. Xenon is denser and highly radio-purer with respect to Argon. Further, the Xenon technology is more advanced and already provided the most stringent limits on the WIMP-nucleon cross section.

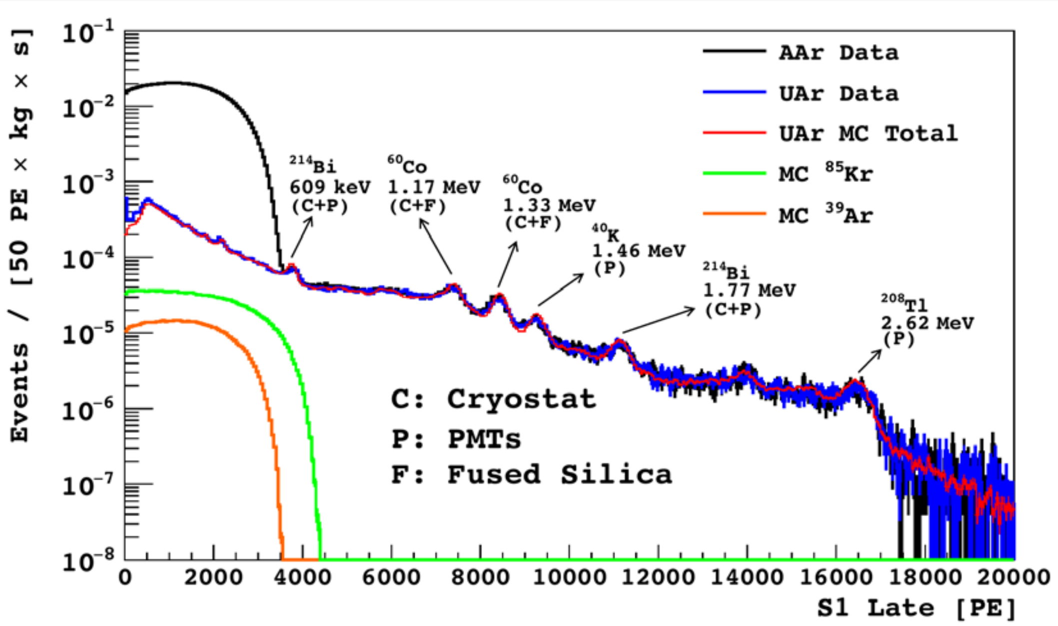

Figure 4 Comparison between the data taken with atmospheric Argon (black) and the underground Argon (blue). The depletion factor results to be ~1500.

The delay of the Argon technology with respect to the Xenon based one is due to the non-negligible content of ^{39}Ar in atmospheric Argon. ^{39}Ar is a β emitter, with a Q-value of 565 keV and half life of about 269 years. The typical activity of atmospheric Argon, due to cosmic rays activation, is of the order of 1 Bq/kg and this always prevented the built of a large detector for rare events experiments. The problem can be solved thanks to the recent development of the underground Argon (UAr) extraction technique. This Argon is depleted in ^{39}Ar and a depletion fraction larger than 1000 has been achieved, as shown in Figure 4.

The DS50 Geant Monte-Carlo (G4DS) was validated by its ability to reproduce the background spectra in the latest analysis of the DarkSide-50 UAr data, as well as other specific distributions measured in the the DarkSide-50 LAr TPC. As an example, Fig. 4 shows the occupancy of each PMT for both S1 and S2 signals as measured in DarkSide-50, and compares the distributions to the predictions of G4DS [83].

A mass production of underground Argon seems also to be possible at affordable price for future large scale detectors. While a nuclear recoil mostly excites the fast state, a typical electronic recoil mostly excites the slow one. Thus, simply looking at the fraction of S1 light that occurs in the first tens of nanoseconds of the signal itself, it is possible to discriminate between nuclear and electronic recoils up to a factor 10^8[77] . In Liquid Xenon the two time constants are similar ($\tau_1 \sim 22$ ns and $\tau_2 \sim 45$ ns) and the implementation of this technique is prevented [78].

The DarkSide prototype detector (DS50).

The DarkSide goal is a background free experiment with a multi-ton scale double phase liquid Argon TPC. In order to accomplish such an ambitious result, the DarkSide collaboration is proceeding through a staged approach. The first prototype (Darkside-10 [79]), built in Princeton and running until 2013, proved the stability of the detector and a light yield of about 9 photoelectrons/keV was measured. In the current prototype (Darkside-50) the active mass of the detector has been increased from 10 kg to 50 kg. The DarkSide-50 experiment is running in Hall C at LNGS since September 2013.

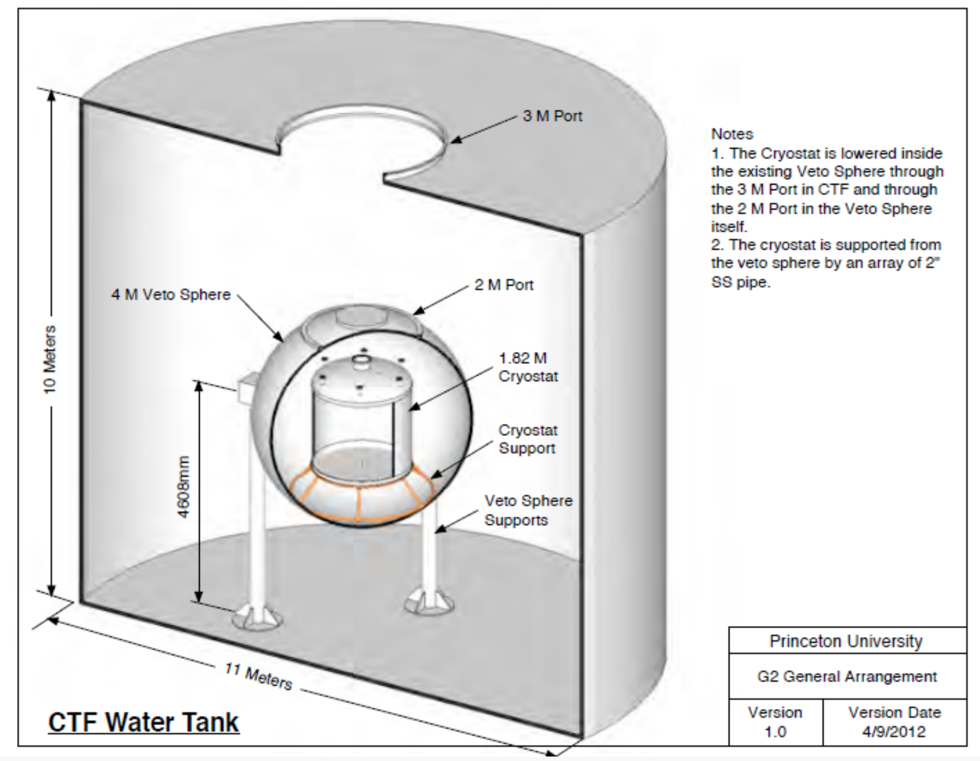

Figure 5 Schematic drawing of the DarkSide detector

DarkSide-50 is deployed, enclosed in it's liquid scintillator neutron veto, in the Borexino Counting Test Facility at the Gran Sasso Underground Laboratory (LNGS). The experiment is composed of three nested detectors: innermost is the LAr TPC, acting as dark matter detector containing (46.4±0.7) kg of active LAr; this is surrounded by the organic liquid scintillator veto (LSV), serving as shielding and as anti-coincidence for radiogenic and cosmogenic neutrons, γ-rays and cosmic muons; this is in turn surrounded by the water Cherenkov veto (WCV), acting as a shield and as anti-coincidence for cosmic muons.

Two arrays of 19 photo-multipliers are pointing to the center of the volume from the top and from the bottom surfaces (two quartz windows). On the top of the liquid, a 1 cm height gas region is created by heating the LAr. A uniform electric field (200 V/cm) is maintained along the vertical axis of the cylinder and a stronger electric field is present is the gas region (2800 V/cm) for the extraction of ionization electrons. All the internal surfaces of the TPC are reflective and coated with TPB (ThetraPhenylButadiene), a wavelength-shifter required in order to convert the 128 nm LAr scintillation light in visible one, to match the photocathode sensitivity. The cryostat is placed inside a 4 m diameter sphere, filled with an organic Liquid Scintillator and equipped with 110 PMTs (8 inches), acting as a neutron veto. The solution is made by 50% Pseudocumene (PC) and TriMetylButadiene (TMB), the latter being a molecule, loaded with Boron, with a very high neutron capture cross section. Also PPO in 5 g/l concentration is added to reduce the light quenching. The mean lifetime of neutrons inside this solution is of the order of 2 μs and the veto efficiency has been estimated to be higher than 99.9%. The main goal of the neutron veto is the rejection of WIMP-like interactions (nuclear recoils) produced inside the TPC by radiogenic and cosmogenic neutrons; moreover is designed to work actively, not only shielding the TPC from the environment, but also measuring the real neutron background. The Neutron Veto sphere is then placed inside a 10 kton water tank, with 80 PMTs (8 inches) installed on the side and on the bottom, acting as a Cherenkov detector for the surviving cosmic muons at the depth of the Laboratories. A sketch of the three nested detectors is shown in Figure 6.

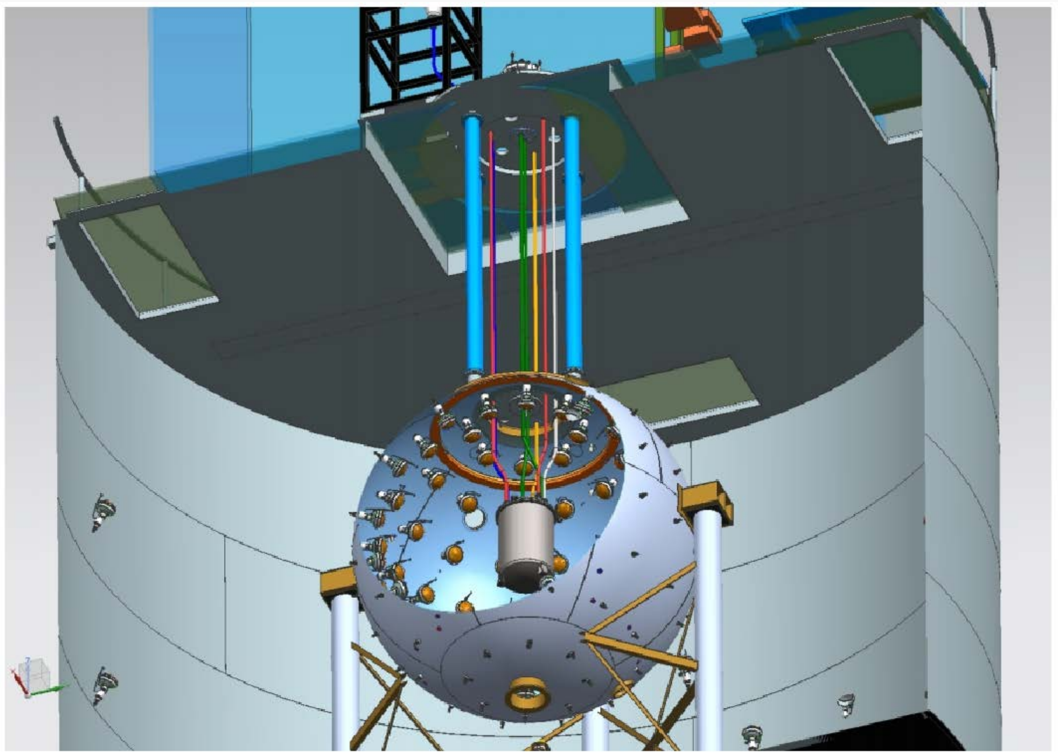

Figure 6 The nested detector system of DarkSide-50. The outermost gray cylinder is the Water Cherenkov Detector, the sphere is the Liquid Scintillator Veto, and the gray cylinder at the center of the sphere is the LAr TPC cryostat.

The calibration of the detector has been realized with the insertion of ^{83}Kr inside the Argon circulation loop. This radio-nuclide emits two low energy gammas (for a total deposit of 41.5 keV) and has a mean life of 1.8 hours. The position of the 41.5 keV peak over the 39Ar β-spectrum allows to measure the light yield of the detector: 7.9±0.4 photo-electrons/keV without the electric field and ~ 7.0 photo-electrons/keV at 200 V/cm. The stability of the detector response can also be evaluated selecting the events populating the 41.5 keV peak. While the maximum electron drift time, for the 200 V/cm electric filed, is set to 375 μs ($v_{drift} \sim 0.93$ mm/μs), the measured electron lifetime is larger than 5 ms. The internal non-uniformity both in terms of light and electrons collection have been evaluated as well.

For the neutron expectation band, it is safe to adopt the results of the SCENE experiment [80], a calibration experiment designed to study the nuclear recoils in LAr with a neutron beam and a small TPC. The reduced dimensions of the TPC are convenient in order to obtain a clean sample of single scattering events and nuclear recoils have been studied for different neutron energies and electric fields. A calibration campaign with neutron (AmBe) and gamma (^{57}Co, ^{133}Ba and ^{137}Cs) sources at different energies was also performed.

A WIMP interacting inside the sensitive volume is expected to hit a nucleus and to produce a nuclear recoil. As already mentioned, the main tool for rejecting electron recoils that trigger the TPC is the the Pulse Shape Discrimination (up to a factor 10^8). Exploiting the S2/S1 ratio will increase the rejection power by an additional factor $10^2 \div 10^3$.

The most dangerous source of WIMP-like background is represented by cosmogenic and radiogenic neutrons. Some of these events, those with multiple interaction inside the TPC, can be rejected since they produce a multiple ionization signal. The neutrons interacting only once in the TPC are likely to be captured inside the 4π liquid scintillator surrounding veto. A capture on ^{10}B results in the production of ^{7}Li and α particle. The α energy is 1.47 MeV, quenched to ~ 50 keV. With a branching ratio of 94%, a 480 keV γ is also emitted. The measured light yield in the veto scintillator (~ 0.52 pe/keV) is large enough to detect the α also when no α is emitted.

The number of cosmogenic neutrons that penetrate the veto undetected is negligible in a multi-year DarkSide-50 exposure (from calculation). Concerning the internal radioactivity, the major source of neutrons are the PMTs (to be replaced in a future detector by cleaner ones) and the total expected yield is about 100 n/y. From Geant4 based simulation, only 5×10^{-4} of them are expected to interact once in the TPC and to escape the veto without leaving any detectable signal (< 30 pe). This fraction can vary by 20%, because of the large uncertainty on the quenching factor of the α's.

Finally, a fiducialization is applied to the active volume, in order to prevent contamination from α surface emissions (from raw materials qualification), removing events that are originated within 2 cm from the walls.

First results of the DS50

In a first run lasting until March 2015 the DarkSide-50 detector was filled with atmospheric argon (AAr), providing a large amount of data used for LAr pulse shape discrimination (PSD) tests and a first WIMP search using 447.1 live-days of data [81].

The main science run started in April 2015, after the cryostat was emptied and refilled with 153 (±1) kg of underground argon (UAr). The first result of this run was a measurement of a depletion factor of 200 of ^{39}Ar relative to AAr.

In WIMP-search mode, we accumulated 70.9 live-days (2616±43 kg·day) of exposure and published an upper limit on the spin-independent WIMP-nucleon cross section of 2.0×10^{44} cm^2 for a 100 GeV WIMP mass [82]. The DarkSide-50 detector is still running smoothly, and a total of 650 live-days of UAr exposure have been acquired, the live-time fraction is close to 90% with loss because of the calibration campaigns (with internal dispersed source in the UAr flow such as ^{83m}Kr, or neutron sources, i.e., AmBe and AmC deployed outside the cryostat in the LSV), periodic LAr TPC PMTs shutdowns, laser calibration runs, and some maintenance. Calibrations with an internal ^{85m}Kr source are performed periodically to measure the LAr TPC light yield. The most recent results were (8.036±0.001)p.e./keV at null field and (7.308±0.001) p.e./keV at the operating drift field of 200 V/cm, in agreement with previous calibration campaigns. The LAr TPC system continues to show very good stability in terms of cryogenics, PMTs, and electric (drift and extraction) fields. Since the end of the initial 70.9 live-days UAr campaign, the WIMP-search data has been blinded, with the WIMP region of interest (in the pulse-shape parameter f90 vs. primary scintillation S1) hidden from analyzers. Prior to “opening the box," our task is to make reliable predictions of all backgrounds and to design analysis cuts that reduce the total predicted background to <0.1 events in the full exposure. We are currently finalizing this analysis and have started to open test regions (still outside the WIMP region) to check the accuracy of our predictions.

Generation 2 DarkSide detector

A project named DS20k (20k stays for 20000 kg of LAr) represents a second generation of LAr detector using developed techniques. Building on the successful experience in operating the DarkSide-50 detector, the DarkSide Collaboration is going to construct DarkSide-20k, a direct WIMP search detector using a two-phase Liquid Argon Time Projection Chamber (LAr TPC) with an active (fiducial) mass of 23 t (20 t). The DarkSide-20k LAr TPC will be deployed within a shield/veto with a spherical Liquid Scintillator Veto (LSV) inside a cylindrical Water Cherenkov Veto (WCV) (see Fig.7). Operation of DarkSide-50 demonstrated a major reduction in the dominant ^{39}Ar background when using argon extracted from an underground source, before applying pulse shape analysis. Data from DarkSide-50, in combination with MC simulation and analytic modeling, shows that a rejection factor for discrimination between electron and nuclear recoils of $>3 \times 10^{9}$ is achievable. This, along with the use of the veto system, is the key to unlocking the path to large LAr TPC detector masses, while maintaining an “instrumental background-free" experiment, an experiment in which less than <0.1 events (other than *v*-induced nuclear recoils) is expected to occur within the WIMP search region during the planned exposure. DarkSide-20k will have ultra-low backgrounds than can be measured in situ. This will give sensitivity to WIMP-nucleon cross sections of 1.2×10^{-47} cm^2 (1.1×10^{-46} cm^2) for WIMPs of 1 TeV (10 TeV) mass, to be achieved during a 5 yr run producing an exposure of 100 t yr free from any instrumental background. DarkSide-20k could then extend its operation to a decade, increasing the exposure to 200 t yr, reaching a sensitivity of 7.4×10^{-48} cm^2 (6.9×10^{-47} cm^2) for WIMPs of 1 TeV (10 TeV) mass.

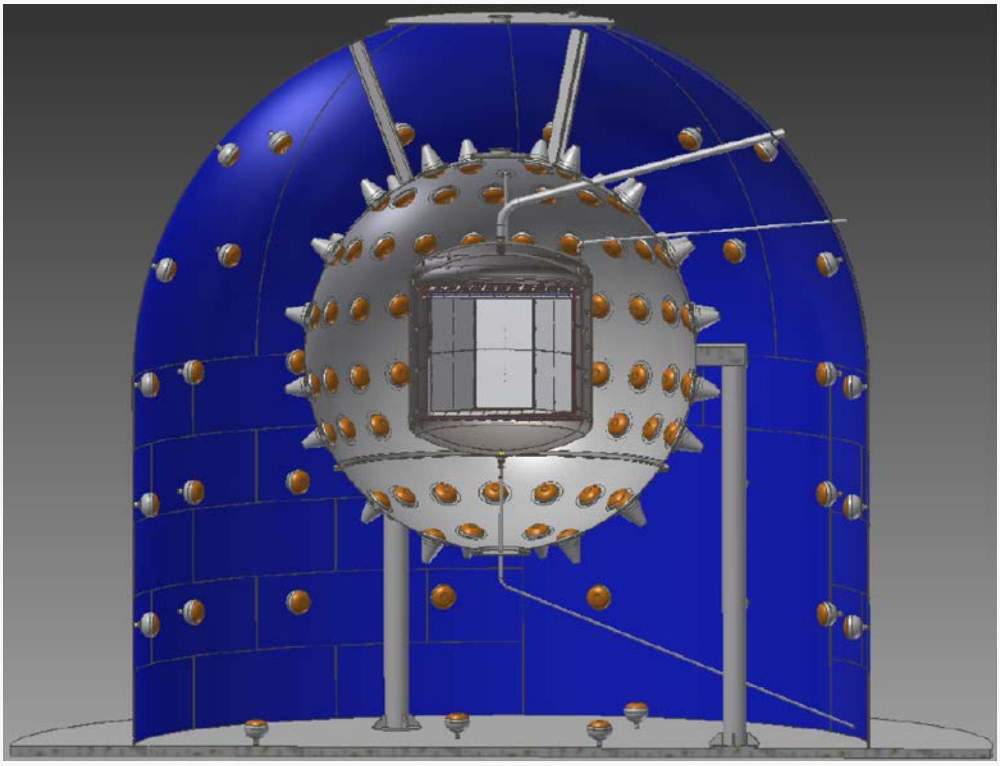

Figure 7 A conceptual design of the DS20k detector (cross section view) showing the water tank, the muon water Cherenkov veto detector, the stainless steel sphere, the LS muon veto, the cryostat and the LAr TPC.

The physical justification and technical details of the project was recently presented in the DS20k collaboration “Yellow Book” [83] (see additional materials), the optimization of the design of the next phase detector is currently under discussion. The sensitivity plot for DS20k (plot includes results and prospects for the DS50 too) is shown in Fig.8.

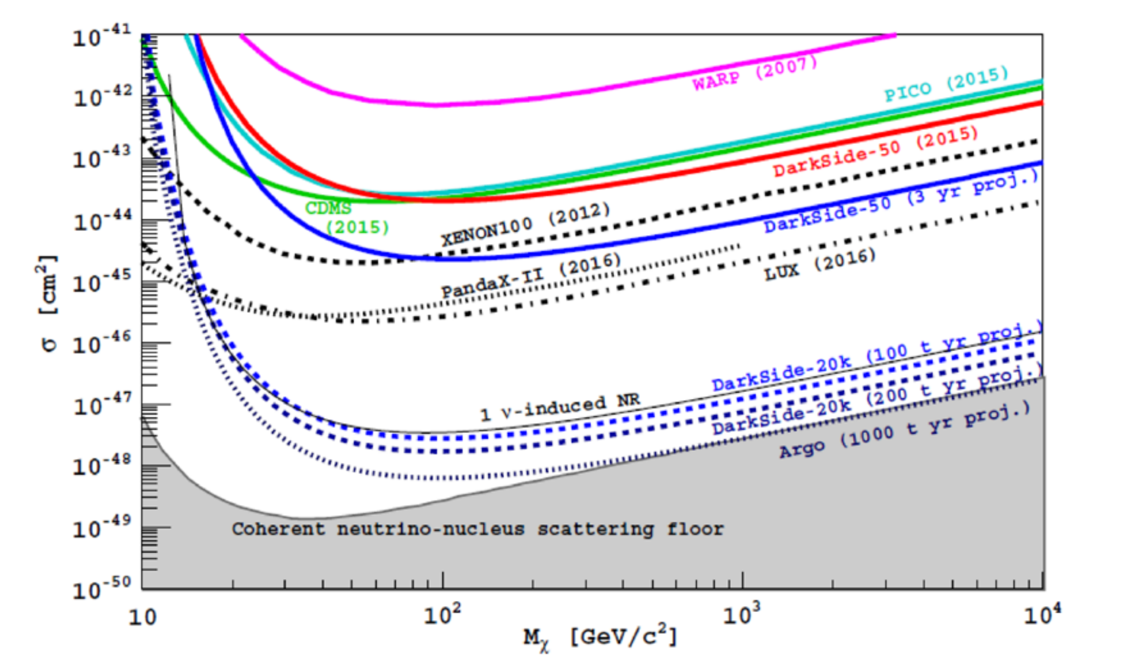

Figure 8 Current results on the direct DM search and sensitivity of the LAr projects.

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