Measurement of solar neutrino fluxes with Borexino

S. Marcocci[24], *M. Agostini*[24,22], *K. Altenmüller*[22], *S. Appel*[22], *G. Bellini*[13], *J. Benziger*[17], *D. Bick*[4], *G. Bonfini*[12], *D. Bravo*[20], *B. Caccianiga*[13], *F. Calaprice*[16], *A. Caminata*[3], *M. Carlini*[12], *P. Cavalcante*[12], *A. Chepurnov*[23], *D. D'Angelo*[13], *S. Davini*[24], *A. Derbin*[15], *L. Di Noto*[3], *I. Drachnev*[24], *A. Etenko*[10], *K. Fomenko*[2], *A. Formozov*[13], *D. Franco*[1], *F. Gabriele*[12], *C. Galbiati*[16], *C. Ghiano*[3], *M. Giammarchi*[13], *M. Goeger-Neff*[22], *A. Goretti*[16], *M. Gromov*[23], *C. Hagner*[4], *E. Hungerford*[25], *Aldo Ianni*[12], *Andrea Ianni*[16], *K. Jedrzejczak*[6], *D. Jeschke*[22], *M. Kaiser*[4], *V. Kobychev* [7], *D. Korablev* [2], *G. Korga* [12], *D. Kryn* [1], *M. Laubenstein* [12], *B. Lehnert* [26], *E. Litvinovich*[10,11], *F. Lombardi* [12], *P. Lombardi* [13], *L. Ludhova* [13], *G. Lukyanchenko* [10,11], *I. Machulin*[10,11], *S. Manecki*[20], *W. Maneschg*[5], *E. Meroni*[13], *M. Meyer*[4], *L. Miramonti*[13], *M. Misiaszek*[6,12], *M. Montuschi*[21], *P. Mosteiro*[16], *V. Muratova*[15], *B. Neumair*[22], *L. Oberauer*[22], *M. Obolensky*[1], *F. Ortica*[14], *M. Pallavicini*[3], *L. Papp*[22], *L. Perasso*[3], *A. Pocar*[19], *G. Ranucci*[13], *A. Razeto*[12], *A. Re*[13], *A. Romani*[14], *R. Roncin*[12,1], *N. Rossi*[12], *S. Schönert*[22], *D. Semenov*[15], *H. Simgen*[5], *M. Skorokhvatov*[10,11], *O. Smirnov*[2], *A. Sotnikov*[2], *S. Sukhotin*[10], *Y. Suvorov*[27,10], *R. Tartaglia* [12], *G. Testera* [3], *J. Thurn* [26], *M. Toropova* [10], *E. Unzhakov* [15], *A. Vishneva* [2], *R.B. Vogelaar*[20], *F. von Feilitzsch*[22], *H. Wang*[27], *S. Weinz*[28], *J. Winter*[28], *M. Wojcik*[6], *M. Wurm*[28], *Z. Yokley*[20], *O. Zaimidoroga*[2], *S. Zavatarelli*[3], *K. Zuber*[26], and *G. Zuzel*[6]

[1]AstroParticule et Cosmologie, Universitè Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Citè, 75205 Paris Cedex 13, France
[2]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[3]Dipartimento di Fisica, Università degli Studi e INFN, Genova 16146, Italy
[4]Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany
[5]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[6]M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland
[7]Kiev Institute for Nuclear Research, 06380 Kiev, Ukraine
[8]Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia
[9]Kepler Center for Astro and Particle Physics, Universität Tübingen, 72076 Tübingen, Germany.
[10]NRC Kurchatov Institute, 123182 Moscow, Russia
[11] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia.
[12]INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy
[13]Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy
[14]Dipartimento di Chimica, Università e INFN, 06123 Perugia, Italy
[15]St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia
[16]Physics Department, Princeton University, Princeton, NJ 08544, USA
[17]Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
[18]Physics Department, Queen's University, Kingston ON K7L 3N6, Canada
[19]Amherst Center for Fundamental Interactions and Physics Department, University of Mas-

sachusetts, Amherst, MA 01003, USA
[20]Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[21]Dipartimento di Fisica e Scienze della Terra Università degli Studi di Ferrara e INFN, Via Saragat 1-44122, Ferrara, Ital
[22]Physik-Department and Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany.
[23]Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia.
[24]Gran Sasso Science Institute (INFN), 67100 L'Aquila, Italy.
[25]Department of Physics, University of Houston, Houston, TX 77204, USA.
[26]Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany.
[27]Physics and Astronomy Department, University of California Los Angeles (UCLA), Los Angeles, California 90095, USA.
[28]Institute of Physics and Excellence Cluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany.

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Solar neutrinos have been of extraordinary importance for the discovery of neutrino oscillations and allow to study directly the Sun's innermost core. The Borexino experiment, located in the Gran Sasso National Laboratory, is an ultra-pure liquid scintillator detector conceived for the real time spectroscopy of low energy solar neutrinos. We review Borexino's results and we discuss its upcoming future, since the precision era of solar neutrino measurements has just started.

1 Solar neutrinos

The Standard Solar Model (SSM) is a theoretical framework which aims to describe the Sun, and particularly to study the energy production mechanisms, thus predicting the solar neutrino fluxes coming out of them [1]. The SSM has been continuously refined during the years, including results about cross section measurements of relevant nuclear reactions at low energy [2] and Helioseismology measurements [3, 4].

The Sun produces energy via different nuclear reactions. The so called pp chain, which results in the fusion of 4 protons into ^{4}He (see the left part of Fig. 1), is the set of nuclear transitions which gives the most important contribution to the total energy production. The CNO cycle (see the right part of Fig. 1) involves a subdominant set of reactions in the Sun, accounting for $\sim$1% of the Sun's energy release. However, the CNO cycle plays a key role in astrophysics, since it is the dominant source of energy in stars more massive than the Sun and in advanced evolutionary stages of Sun-like stars. A CNO neutrino measurement would constrain the chemical composition of the Sun, leading to improved models for star formation and supernova explosions. A direct measurement of the CNO neutrino component could also solve the long-standing solar metallicity problem [5], for which, basically, two different solutions are possible, namely the *High Metallicity* and *Low Metallicity*.

The theoretical solar neutrino spectra resulting both from the reactions of the pp chain and the CNO cycle are shown on the left panel of Fig. 2.

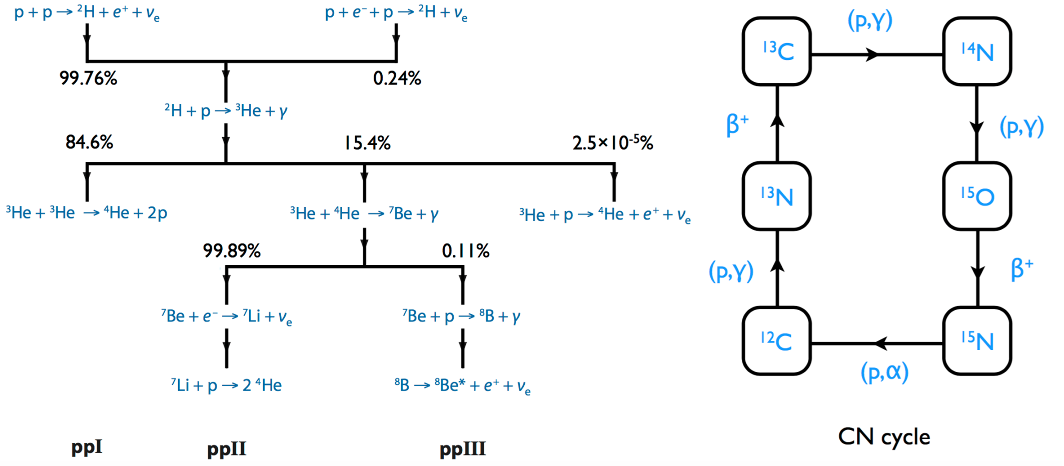

Figure 1: **Left:** Schematic drawing of the pp reactions chain, [6]. **Right:** Sketch of the CNO cycle.

2 The Borexino experiment

The study of low energy solar neutrinos with a ultra-pure liquid scintillator technique is relevant both for testing the predictions of the Standard Solar Model and for investigating the MSW-LMA neutrino oscillation scenario in an energy range that is not accessible to water Cherenkov detectors [7, 8]. In fact, up to a few years ago, spectroscopic measurements were performed by water Cherenkov detectors above $\sim$ 5 MeV and concerned only ^{8}B neutrinos for less than the 1% of the total flux. The bulk of neutrinos at lower energies were detected only with radiochemical experiments, unable to resolve the individual components. The original main goal of Borexino [9, 10] was the precise measurement of the rate induced by the monochromatic electron neutrinos (862 keV) produced by the electron capture decay of ^{7}Be in the Sun. However, the very high radio purity of the scintillator made it possible for Borexino to largely exceed the expected performance and broaden the original physics program.

Borexino is a liquid scintillator calorimeter [11] designed for the real-time observation of low energy solar neutrinos and anti-neutrinos. Neutrinos are detected through their elastic scattering on electrons and by means of the consequent emission of scintillation light, while anti-neutrinos are detected through inverse beta decay on protons. A sketch of the experiment is shown in Fig. 2. It is located at the Gran Sasso National Laboratories (LNGS) in central Italy, at a depth of 3800 m w.e.. The inner part of the Borexino detector is an unsegmented stainless steel sphere (SSS) that is both the container of the scintillator and the mechanical support of the photomultipliers. Within this sphere, the active mass consists of 278 tons of pseudocumene (PC), doped with 1.5g/l of PPO. The scintillator is contained in a thin (125 μm) nylon Inner Vessel (IV), 8.5 m in diameter. The IV is surrounded by two concentric PC buffers doped with a light quencher. The scintillation light is collected by nominally 2212 photomultipliers

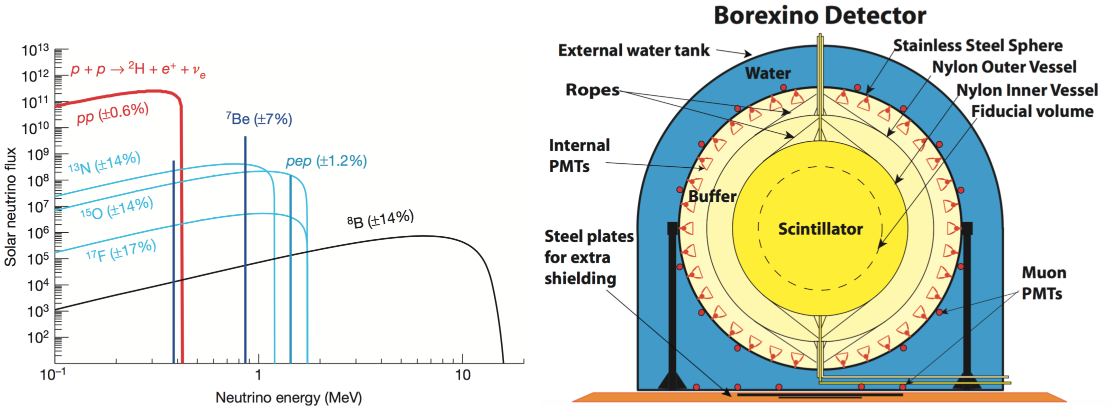

Figure 2: **Left Panel:** Solar neutrino spectral components. **Right Panel:** Sketch of the Borexino detector.

(PMTs) that are uniformly attached to the inner surface of the SSS. All but 384 PMTs are equipped with light concentrators that are designed to reject photons not coming from the active scintillator volume, thus reducing the background due to radioactive decays originating in the buffer liquid or gammas from the PMTs. The 384 PMTs without concentrators are used to study this background, and to help identify muons that cross the buffer, but not the IV.

The SSS is supported by 20 steel legs and enclosed within a large tank (WT) that is filled with ultra-pure water. The WT has a cylindrical base with a diameter of 18 m and a hemispherical top with a maximum height of 16.9 m. The WT is a powerful shielding against external backgrounds (γ rays and neutrons from the rock) and is also used as a Cherenkov muon counter and muon tracker. The muon flux, although reduced by a factor of 10^6 by the 3800 m w.e. depth of the Gran Sasso Laboratory, is of the order of 1 m^{-2} h^{-1}, corresponding to about 4000 muons per day crossing the detector. This flux is well above the Borexino requirements and a strong additional reduction factor (about 10^4) is necessary. Therefore the WT is equipped with 208 photomultipliers that collect the Cherenkov light emitted by muons in the water.

The Borexino scintillator has a light yield of $\sim 10^4$ photons/MeV, resulting in ~ 500 detected photoelectrons/MeV. The fast time response of the scintillating mixture allows to reconstruct the events position by means of a time-of-flight technique with a good precision. The signature of ^{7}Be neutrinos is a Compton-like shoulder at 665 keV in the electron recoil spectrum. The energy resolution (1σ) at the ^{7}Be7 energy is as low as 44 keV (roughly $5\% / \sqrt{\text{MeV}}$).

3 Results from Borexino

^{7}Be neutrinos The measurement of the flux of ^7Be neutrinos was the primary goal of Borexino. The first observation was published in the summer of 2007, after only 3 months of data taking. The signal of the ^{7}Be solar neutrinos is extracted from the data through a fit of the energy spectrum of the events collected within the fiducial volume. There is not special signature other then the shape of the spectrum itself (the Compton like shoulder with endpoint at 665 keV) that allows to distinguish the signal from background. The main background is due to the radioactive decay of the isotopes ^{85}Kr, ^{210}Po, ^{210}Bi, and ^{11}C contaminating the scintillator, but their contributions can be disentangled very efficiently through the spectral fit, as shown in Fig. 3.

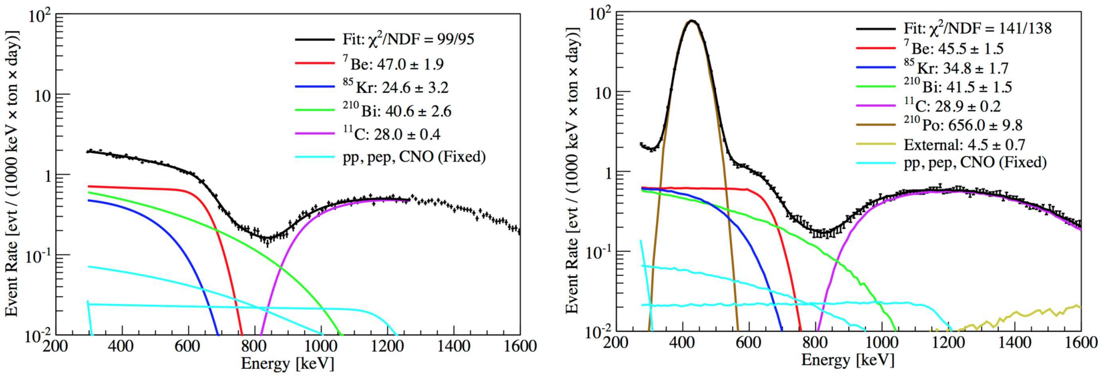

Figure 3: Two example of fitted spectra for the ^{7}Be solar neutrino measurement, [12]. On the left, an analytic fit over the 290-1270 keV energy region to a spectrum obtained with statistical subtraction of the α background is shown. The plot on the right presents a Monte Carlo based fit over the energy region 270-1600 keV to a spectrum where the α component has not been removed. The fit results in the legends have units [counts/(day·100 ton)].

The rate of the neutrino-electron elastic scattering interactions from 862 keV ^7Be solar neutrinos in Borexino resulted of 46.0 ± 1.5(stat) ± 1.5(syst) counts/(day·100 ton), [12]. This corresponds to a ν_e-equivalent ^7Be solar neutrino flux of $(3.10 \pm 0.15)\times 10^9$ cm^{-2}s^{-1} and, under the assumption of ν_e transition to other active neutrino flavors, yields an electron neutrino survival probability of 0.51±0.07 at 862 keV. The no flavor change hypothesis is ruled out at 5.0σ. Borexino also investigated the eventual day-night asymmetry in the ^7Be solar neutrino interaction rate. The measured asymmetry is 0.001 ± 0.012 (stat) ± 0.007 (syst) [13], in agreement with the prediction of MSW-LMA solution for neutrino oscillations. This result disfavors MSW oscillations with mixing parameters in the LOW region at more than 8.5σ. This region is, for the first time, strongly disfavored without the use of reactor anti-neutrino data and therefore the assumption of CPT symmetry.

pep and CNO neutrinos Thanks to the development of novel data analysis techniques for the rejection of the cosmogenic ^{11}C and of external gammas (the main backgrounds in the 1-1.5 MeV region), a first evidence of pep solar neutrinos could be obtained. Particularly, a “three-fold coincidence” vetoing method was developed [14]. It consists in eliminating the parts of the fiducial volume through which the muon tracks passed, possibly creating the ^{11}C isotope. For a further reduction of the background of positrons produced by the ^{11}C decays, a pulse shape discrimination variable for $\beta/\beta+$ events has been developed (see *e.g.* the left side of Fig. 4). It exploits the different time distribution of the scintillation photons, due to the possible ortho-positronium formation [15]. The fit is then performed with a multivariate approach, fitting simultaneously the energy spectrum, the pulse shape discrimination variable for $\beta/\beta+$ and the radial distribution of the events, in order to decouple the uniformly distributed neutrino-like events from the external gammas. All the details can be found in Ref. [16].

The interaction rate of pep neutrinos in Borexino is 3.1 ± 0.6(stat) ± 0.3(syst) counts/(day·100 ton) [16]. The absence of the solar neutrino signal is disfavored at 99.97% C.L., while the absence of the pep signal is disfavored at 98% C.L. . The strongest constraint on the CNO solar neutrino interaction rate (<7.9 counts/(day·100 ton), at 95% C.L.[16]), could be obtained through the likelihood ratio test shown in the right part of Fig. 4.

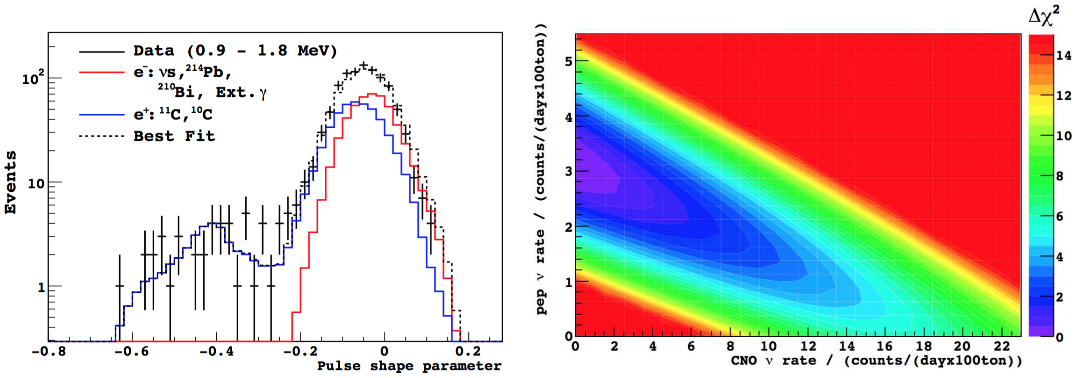

Figure 4: **Left Panel:** Experimental distribution (black) of the pulse shape parameter for $\beta/\beta+$ discrimination. The best-fit distribution (black dashed) and the corresponding β (red) and $\beta+$ (blue) contributions are also shown. **Left Panel:** $\Delta\chi^2$ profile obtained from likelihood ratio tests between fit results where the pep and CNO neutrino interaction rates are fixed to particular values (all other species are left free) and the best-fit result.

pp neutrinos The pp reaction in the core of the Sun is the keystone process for the energy production and is the source of the largest component of the neutrino flux. Its measurement is a major experimental milestone in solar neutrino physics, and paves the way to a deeper understanding of the Sun dynamics. This measurement was made possible by the very low radioactive background, particularly in ^{85}Kr, achieved after an extensive purification campaign performed in 2010-2011 and thanks to the extremely good performance of the detector as a whole. Most of the remaining, unavoidable, background is due to ^{14}C β-decays, whose endpoint is 156 keV, very close to the pp region of interest. To estimate its rate independently from the main analysis, a sample of data in which the event causing the trigger is followed by a second event within the same trigger window (16 μs long, while physical events last 100-500 ns) has been analyzed. These second events are not subject to the trigger threshold, so they register down to much lower energies. By fitting this spectrum against the known ^{14}C spectral shape, the ^{14}C rate in Borexino results of 40 ± 1 Bq per 100 tons.

Because of its high rate, ^{14}C naturally generates a considerable amount of pile-up: two physical events can occur so close to each other in time that the detector fails to resolve them. With the above measurement of the ^{14}C rate, the expected rate of ^{14}C-^{14}C pile-up is 100 per day per 100 tons, comparable to the expected pp neutrino interaction rate. The pile-up component can be determined using an independent, data-driven method: real triggered events with no cuts are artificially overlapped with random data obtained from the ends of real trigger windows, uncorrelated with the triggering event. The synthetic events are then reconstructed using the same software used for real events, and selected with the same criteria. Using this method, it is possible to obtain the true rate and spectral shape of pile-up in the detector.

The solar pp neutrino interaction rate measured by Borexino is 144 ± 13(stat.) ± 10(syst.) counts/(day·100 ton) [17]. The spectral fit result is summarized in Fig. 5. The absence of pp solar neutrinos is excluded with a statistical significance of 10σ. Once statistical and systematic errors and the latest values of the neutrino oscillation parameters are taken into account, the measured solar pp neutrino flux is (6.6 ± 0.7) 10^{10} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, in accordance with the Standard Solar Model.

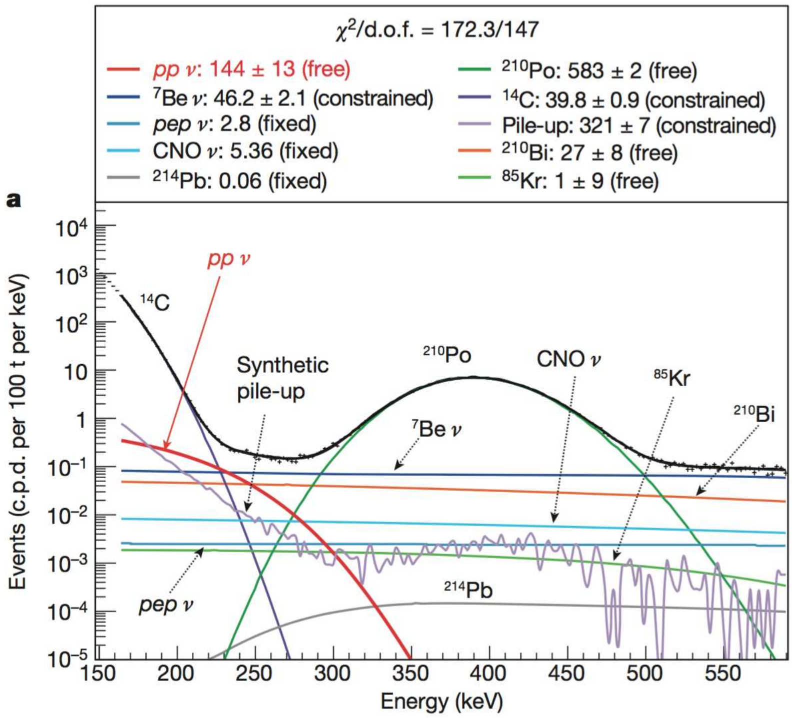

Figure 5: The best fit of Borexino's spectrum in the pp energy window is shown. The best-fit pp neutrino component is shown in red, the ^{14}C background in dark purple and the synthetic pile-up in light purple. The large green peak is ^{210}Po α-decays. The values of the parameters (in counts per day per 100 t) are in the inset above the figure.

^{8}B neutrinos Borexino could measure for the first time ^{8}B solar neutrinos with an energy threshold of only 3 MeV. The rate of ^{8}B solar neutrino-induced electron scattering events above this energy in Borexino is 0.217 ± 0.038(stat) ± 0.008(syst) counts/(day·100 ton [18], which corresponds to a flux of (2.4±0.4) × 10^6 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, in good agreement with the measurements from SNO and SuperKamiokaNDE.

4 Other Borexino measurements

Borexino is a "big" ultra-pure calorimeter and, apart from solar neutrinos, could investigate many other rare processes. Other results include the study of solar and other unknown anti-neutrino fluxes [19], a 5.9σ observation of geo-neutrinos with a 98% C.L. evidence of a signal from the mantle [20, 21], a measurement of neutrino velocity [22], searches for solar axions [23], experimental limits on heavy neutrinos [24], and a test of the electric charge conservation and electron decay [25].

5 Outlook

The high impact of Borexino on neutrino physics is very well summarized by Fig. 6, where the survival probability of solar neutrinos is plotted as a function of the neutrino energy. For all the solar neutrino components that Borexino measured, the trend is in good agreement with the MSW-LMA prediction.

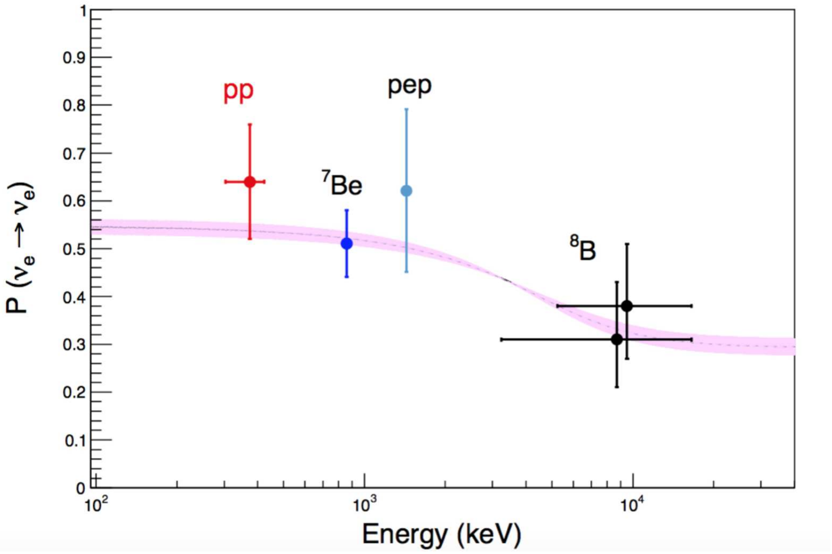

Figure 6: Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the experimental numbers are from Borexino's measurements. The violet band corresponds to the $\pm 1\sigma$ prediction of the MSW-LMA solution.

Apart from the result on the pp solar neutrinos flux, which has been obtained after the purification campaign, all the other solar neutrino components were measured with data sets coming from the so called Borexino Phase-I [26]. The Phase-II, which started right after the purification campaign at the end of Phase-I, is now close to its end, and this will hopefully lead to a general improvement of all the measurements of the solar neutrino fluxes. Particularly, the efforts of the Collaboration are pushing to achieve the best possible result (either an eventual measurement or an improvement of the limit) regarding the CNO flux determination. This would be of extreme importance, since the CNO flux has not been observed yet, and could solve the Solar Metallicity puzzle [5].

The Borexino detector will also be used to search for sterile neutrinos by means of and artificial anti-neutrino source in the framework of the SOX project [27].

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