Recent results from Borexino on solar neutrinos

D. Basilico[1,*], *S.* Appel[2], *Z.* Bagdasarian[3], *G.* Bellini[1], *J.* Benziger[4], *R.* Biondi[5], *B.* Caccianiga[1], *F.* Calaprice[6], *A.* Caminata[7], *A.* Chepurnov[8], *D.* D'Angelo[1], *A.* Derbin[9], *A.* Di Giacinto[5], *V.* Di Marcello[5], *X.F.* Ding[6], *A.* Di Ludovico[6], *L.* Di Noto[7], *I.* Drachnev[9], *D.* Franco[10], *C.* Galbiati[6,11], *C.* Ghiano[5], *M.* Giammarchi[1], *A.* Goretti[6], *A.S.* Göttel[3,12], *M.* Gromov[8,13], *D.* Guffanti[14], *Aldo* Ianni[5], *Andrea* Ianni[6], *A.* Jany[15], *V.* Kobychev[16], *G.* Korga[17,18], *S.* Kumaran[3,12], *M.* Laubenstein[5], *E.* Litvinovich[19,20], *P.* Lombardi[1], *I.* Lomskaya[9], *L.* Ludhova[3,12], *G.* Lukyanchenko[19], *I.* Machulin[19,20], *J.* Martyn[14], *E.* Meroni[1], *L.* Miramonti[1], *M.* Misiaszek[15], *V.* Muratova[9], *R.* Nugmanov[19,20], *L.* Oberauer[2], *V.* Orekhov[14], *F.* Ortica[21], *M.* Pallavicini[7], *L.* Pelicci[3,12], *Ö.* Penek[3], *L.* Pietrofaccia[6], *N.* Pilipenko[9], *A.* Pocar[22], *G.* Raikov[19], *M.T.* Ranalli[5], *G.* Ranucci[1], *A.* Razeto[5], *A.* Re[1], *M.* Redchuk[3,12], *N.* Rossi[5], *S.* Schönert[2], *D.* Semenov[9], *G.* Settanta[3], *M.* Skorokhvatov[19,20], *A.* Singhal[3,12], *O.* Smirnov[13], *A.* Sotnikov[13], *R.* Tartaglia[5], *G.* Testera[7], *E.* Unzhakov[9], *F.* Villante[5,23], *A.* Vishneva[13], *R.B.* Vogelaar[24], *F.* von Feilitzsch[2], *M.* Wojcik[15], *M.* Wurm[14], *S.* Zavatarelli[7], *K.* Zuber[25], and *G.* Zuzel[15]

[1]Dipartimento di Fisica, Università degli Studi and INFN, 20133 Milano, Italy.
[2]Physik-Department, Technische Universität München, 85748 Garching, Germany
[3]Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[4]Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
[5]INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy
[6]Physics Department, Princeton University, Princeton, NJ 08544, USA
[7]Dipartimento di Fisica, Università degli Studi e INFN, 16146 Genova, Italy
[8]Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia
[9]St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia
[10]AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France
[11]Gran Sasso Science Institute, 67100 L'Aquila, Italy
[12]III. Physikalisches Institut B, RWTH Aachen University, 52062 Aachen, Germany
[13]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[14]Institute of Physics and Excellence Cluster PRISMA+, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany
[15]M. Smoluchowski Institute of Physics, Jagiellonian University, 30348 Krakow, Poland
[16]Institute for Nuclear Research of NAS Ukraine, 03028 Kyiv, Ukraine
[17]Department of Physics, Royal Holloway University of London, Egham, Surrey,TW20 0EX, UK
[18]Institute of Nuclear Research (Atomki), Debrecen, Hungary
[19]National Research Centre Kurchatov Institute, 123182 Moscow, Russia
[20]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia
[21]Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi e INFN, 06123 Perugia, Italy
[22]Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA 01003, USA
[23]Dipartimento di Scienze Fisiche e Chimiche, Università dell'Aquila, 67100 L'Aquila, Italy
[24]Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[25]Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany

Abstract. Borexino has been a neutrino detector based on ultrapure liquid scintillator, located at the Laboratori Nazionali del Gran Sasso, Italy. Its main scientific goal was the real-time measurement of solar neutrino fluxes, which play an irreplaceable role for the comprehension of the mechanisms powering our star. Over the past two years, the Borexino collaboration has pursued the improvement of the CNO flux measurement, obtaining further indications about the solar metallicity. In a parallel way, Borexino has demonstrated for the first time the possibility of exploiting the directional Cherenkov information, in a liquid scintillator detector, for the detection of sub-MeV solar neutrinos.

1 Introduction

Solar neutrinos are generated by the thermonuclear reactions taking place in the innermost layers of the Sun. The main contribution to the energy production in the Sun is given by the *pp* chain sequence, which make up the $\approx 99\%$ of solar luminosity. The CNO cycle reactions, which involves employs Carbon, Nitrogen and Oxygen as catalysts nuclei, contribute marginally in the Sun, but they are expected to play a dominant role in more massive and older stars. The measurements of solar neutrino fluxes can be

*e-mail: davide.basilico@mi.infn.it

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

used either to test the MSW-LMA paradigm assuming the Standard Solar Model (SSM) flux predictions [1] or, in a complementary way, to probe our understanding of solar physics assuming the validity of the neutrino oscillation mechanism [2]. Indeed, they represent a unique and helpful tool in settling the solar metallicity problem.

In the following, the most recent results obtained by Borexino on solar neutrinos will be reviewed. Firstly, the improvement of CNO solar neutrino spectroscopy will be described. Then, a novel technique to exploit the scarce Cherenkov light for directional measurements will be introduced.

2 Borexino detector

Borexino [3] has been a large-volume liquid scintillator detector, whose primary scientific goal consisted in the real-time measurement of solar neutrino fluxes. It was located deep underground (3800 m m.w.e.) in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy), where the atmospheric muon flux is suppressed by a factor of 10^{-6} with respect to the Earth surface. The detector design, as shown in Fig. 1, is driven by the principle of graded shielding: the inner scintillating core is located at the center of a set of spherical layers of increasing radiopurity from outside to inside. This configuration suppresses as much as possible the external background due to the surrounding rocks and to the cosmic muons. The detector is instrumented with 2112 PMTs, mounted inwardly on a mechanical support sphere: they measure the intensity and the arrival time of this light, allowing the reconstruction of the energy and position of the events.

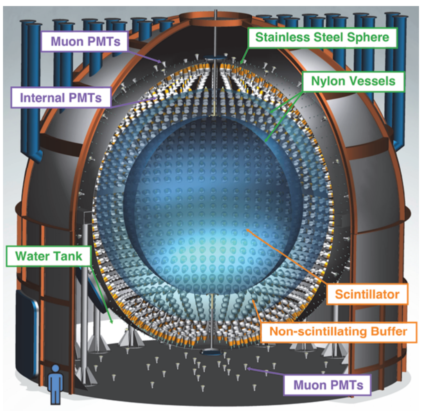

Figure 1. Schematic view of the Borexino detector.

Thanks to its excellent radiopurity levels, Borexino completed the spectroscopy of the solar neutrinos emitted from the primary *pp* chain reactions [4–9]. By analyzing the Phase-III dataset (2016-2020), it also claimed the first detection of the CNO neutrinos flux, paving the way for a solution to the long-standing solar metallicity problem [10].

3 Improved measurement of solar neutrinos flux from the CNO cycle

The key requirements to perform solar neutrino spectroscopy with Borexino consist in the excellent radiopurity levels, the low cosmogenic ^{11}C rate and the application of techniques to reduce it furtherly [11], the precise understanding of the detector backgrounds, and a comprehensive modeling of the detector response. In addition, the spectral shapes of recoiled electrons by CNO neutrinos and of ^{210}Bi background electrons show a strong similarity; for this reason, a constraint of this annoying background, obtained independently from the spectral fit, is required to proceed with the CNO analysis [12]. This is achieved by exploiting the secular equilibrium of ^{210}Bi background with its daughter, the α-decaying ^{210}Po, whose rate can be easily measured thanks to particle identification techniques [13]. This strategy can be adopted only in those scintillator regions which are thermally stable: in such a way the scintillator convective currents, which could move out-of-equilibrium ^{210}Po, are strongly suppressed.

With respect to the previous data release, the CNO analysis has been improved on multiple sides. The exposure of the *final Phase-III* dataset (Jan 2017 - Oct 2021), which is considered for this analysis, is 33.5% larger with respect to the previous analysis one. Most importantly, the final Phase-III dataset is characterized by a better thermal stability: as a consequence, the ^{210}Po convective motions within the fiducial volume are furtherly attenuated. These features led to the extraction of an enhanced ^{210}Bi constraint, directly impacting on the CNO neutrino rate precision. In addition the treatment of the time evolution of the PMTs effective quantum efficiencies, based on the ^{14}C data, has been improved.

The analysis ROI extends from 320 keV to 2640 keV, while the reconstructed events are selected within a software-cut defined 71.3 tonne fiducial volume. The analysis relies on a Monte Carlo based multivariate fit, performed on two energy spectra and the radial distribution of events passing the selection cuts. The Three-Fold Coincidence (TFC), an algorithm for the cosmogenic event reduction, is applied to create the two complementary datasets on which the fit is performed: one depleted (TFC-subtracted) and one enriched (TFC-tagged) in ^{11}C. The spectral fit of the final Phase-III TFC-subtracted dataset is reported in Fig. 2.

By including the Borexino results in the global analysis of solar neutrinos data, along with the KamLAND reactor data, the resulting solar neutrino fluxes are found in good agreement with the high metallicity SSM B16-GS98 [14]. Considering a binary hypothesis test based on the Borexino ^{7}Be, ^{8}B and CNO results, the SSM B16-AGSS09met [15, 16] at 3.1σ C.L. is disfavored at 3.1σ C.L. as an alternative to SSM B16-GS98. Moreover, one can exploit the direct dependence of the CNO cycle flux from the C and N abundances in the solar core, to break the opacity and metallicity degeneracy; therefore, the C and N abundances in the Sun (N_{CN}) can be measured. The results are displayed in Fig. 3 and show a good agreement

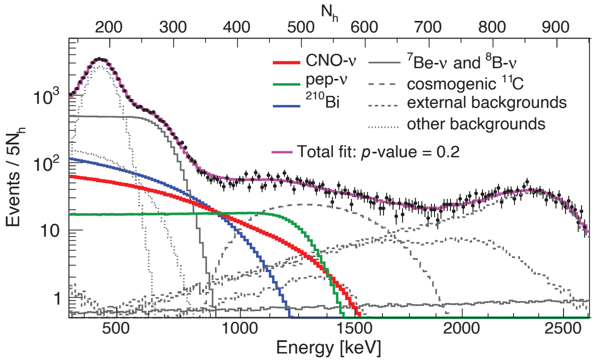

Figure 2. Spectral fit of the final Borexino Phase-III data (black points) after the TFC algorithm application (TFC-subtracted dataset). The sum of the individual components from the fit (magenta) is superimposed on the data (black points). The CNO neutrinos, ^{210}Bi and *pep* neutrinos contributions are reported in solid red, dashed blue and dotted green lines; the other neutrino and background components are shown in grey. The energy estimator N_h, shown in upper scale, is the number of detected photoelectrons normalized to 2,000 live channels.

with the high-metallicity sets (as MB22 [17], GS98), confirming instead a 2σ tension with the low-metallicity ones (AGSS09met, C11 [18], AAG21 [19])

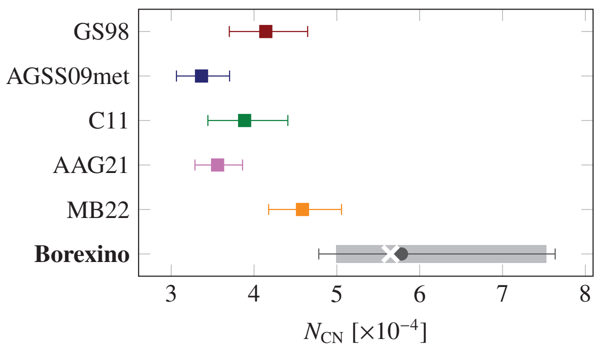

Figure 3. Abundance of Carbon and Nitrogen in the solar photosphere ($N_{\rm CN}$) obtained from spectroscopy (squares) and from Borexino analysis (circle). The uncertainty due to the precision of CNO flux measurement is shown as the grey area. The white cross refers to the same study repeated after considering the B16-AGSS09met as reference SSM instead of B16-GS98.

4 First directional measurement of sub-MeV solar neutrinos with Borexino

In liquid scintillator detectors as Borexino, the emitted photons following an electron recoil are mainly due to scintillation processes. The Cherenkov photons play a sub-dominant role, accounting for few percent of the total emitted light: this scarcity prevents the possibility to perform an event-by-event direction reconstruction.

Nevertheless, Borexino has been able to perform a measurement of sub-MeV solar neutrinos, by exploiting this feeble Cherenkov light [20, 21]. We employed a novel analysis technique named *Correlated and Integrated Directionality* (CID): the detected PMT-hit pattern of an event is correlated to the position of the Sun, which is well-known for each event. This process is repeated for a large number of events, leading to an angular distribution between the hit PMTs and the solar direction. The directional angle α is defined for each PMT hit as the angle between the known solar direction and the photon direction, given by the reconstructed event vertex of the recoil electron and the hit PMT position. An example of the angular correlation of photon hits is shown in Fig. 4. The dominant scintillation light is emitted isotropically and is uncorrelated with the Sun position. For this reason, the analysis is restricted to the first and second hits as they are characterized by the highest Cherenkov over scintillation ratio. In this analysis, as shown in Fig. 5, the $\cos\alpha$ first hit distribution of solar neutrinos is expected to have a signature Cherenkov peak at ~ 0.7, while the one for radioactive background should be almost flat.

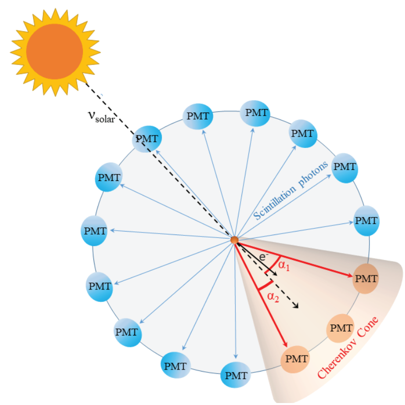

Figure 4. Angular correlation of photon hits expressed in terms of the directional angle α, given by the reconstructed vertex of the solar neutrino event and the position of the Sun. In this case, the first two event hits, with directional angles α_1 and α_2, are both induced by Cherenkov photons.

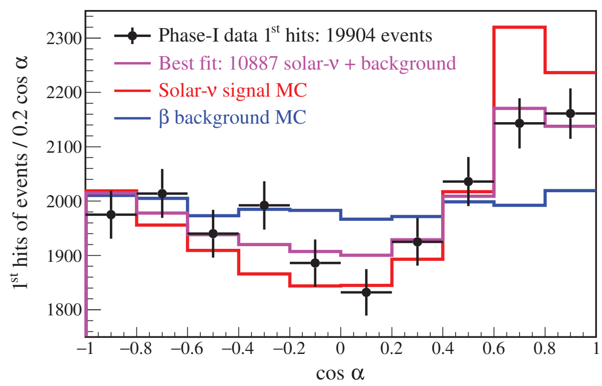

Figure 5. The $\cos\alpha$ distributions of the 1st hits of all the selected events (black points) compared with the best fit curve (magenta) of the resulting number of solar neutrinos plus background. The Monte Carlo based probability distributions of neutrino signal and β background used in the fit are reported in red and blue respectively.

The considered dataset is Phase-I one (2007-2010) with a 0.54-0.74 MeV ROI, which includes ^{7}Be, *pep*, and CNO neutrinos. The best fit for the number of solar neutrino events returns $N_{\text{solar}-\nu} = 10887^{+2386}_{-2103}$ (stat.) $\pm$ 947 (syst.) (68% C.I.) out of the 19904 selected events. By fixing the *pep* and CNO rates to the SSM prediction, the resulting ^{7}Be rate is found in agreement with the Borexino spectroscopy results. The no-neutrino hypothesis is excluded with a $> 5\sigma$ confidence level, resulting in the first observation of sub-MeV solar neutrinos using the CID method.

In conclusion, this analysis provides experimental proof that the directional information of Cherenkov light is accessible even for sub-MeV neutrinos in a liquid scintillator detector.

References

[1] N. Vinyoles, A.M. Serenelli, F.L. Villante, S. Basu, J. Bergström, M. Gonzalez-Garcia, M. Maltoni, C. Peña-Garay, N. Song, Astrophys. J. **835**, 202 (2017), 1611.09867

[2] A.M. Serenelli, W.C. Haxton, C. Pena-Garay, Astrophys. J. **743**, 24 (2011), 1104.1639

[3] G. Alimonti et al. (Borexino), Nucl. Instrum. Meth. A **600**, 568 (2009)

[4] G. Bellini et al. (Borexino), Phys. Rev. D **89**, 112007 (2014), 1308.0443

[5] M. Agostini et al. (Borexino), Nature **562**, 505 (2018)

[6] M. Agostini et al. (Borexino Collaboration), Phys. Rev. D **100**, 082004 (2019)

[7] G. Bellini et al. (Borexino), Nature **512**, 384 (2014)

[8] M. Agostini et al. (Borexino), Phys. Rev. D **101**, 062001 (2020), 1709.00756

[9] M. Agostini et al. (BOREXINO), Astropart. Phys. **92**, 21 (2017), 1701.07970

[10] M. Agostini et al. (Borexino), Nature **587**, 577 (2020), 2006.15115

[11] M. Agostini et al. (Borexino), Eur. Phys. J. C **81**, 1075 (2021), 2106.10973

[12] M. Agostini et al. (BOREXINO), Eur. Phys. J. C **80**, 1091 (2020), 2005.12829

[13] F. Villante et al., Phys. Lett. B **701**, 336 (2011)

[14] N. Grevesse, A.J. Sauval, Space Sci. Rev. **85**, 161 (1998)

[15] P. Scott, N. Grevesse, M. Asplund, A.J. Sauval, K. Lind, Y. Takeda, R. Collet, R. Trampedach, W. Hayek, Astron. Astrophys. **573** (2015)

[16] P. Scott, M. Asplund, N. Grevesse, M. Bergemann, A.J. Sauval, Astron. Astrophys. **573** (2015)

[17] E. Magg, M. Bergemann, A. Serenelli, M. Bautista, B. Plez, U. Heiter, J. Gerber, H.G. Ludwig, S. Basu, J. Ferguson et al., A&A **661**, A140 (2022), 2203.02255

[18] E. Caffau et al., Sol. Phys. **268**, 255 (2011)

[19] M. Asplund, A.M. Amarsi, N. Grevesse, A&A **653**, A141 (2021), 2105.01661

[20] M. Agostini et al. (Borexino), Phys. Rev. Lett. **128**, 091803 (2022)

[21] M. Agostini et al. (Borexino), Phys. Rev. D **105**, 052002 (2022)