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# Update of the results on solar neutrino physics exploiting the most recent Borexino data

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The BOREXINO experiment concluded the data acquisition at the end of 2021. The analysis of the most recent data has produced an improvement of the precision and the significance of CNO neutrino detection ($7\sigma$) with important implication on the Sun's physical modelling. In addition, exploiting the annual modulation of the full data-set of the combined Phase-II and Phase-III, a $5\sigma$ measurement of the Earth's orbit eccentricity, using solar neutrinos only, has been recently achieved. The latter result has been made possible by detector longstanding high-precision solar neutrino detection.

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## 1. Borexino in a nutshell

Borexino, concluded in late 2021, has been the only solar neutrino experiment capable of reconstructing the position and the energy on an event-by-event base, with an energy threshold as low as $E_{th} \approx 150$ keV, thanks to its ultra-high radio-purity. Borexino is located in the Hall C of Laboratori Nazionali Gran Sasso (LNGS-INFN) [1]. The detector consists of concentric shells whose radiopurity increases as moving upwards the detector centre (see e.g. Ref. [2]): the innermost core, contained in a 125 $\mu$m thick ultra-pure nylon vessel (4.25 m radius), is filled with 280 tons of liquid scintillator (1,2,4-Trimethylbenzene with 1.5 g/l of PPO wavelength shifter). The active target is immersed in a stainless steel sphere (SSS) filled up with about 1000 tons of buffer liquid (1,2,4-Trimethylbenzene with DMP quencher). The internal surface of the sphere is instrumented with more than 2000 photomultiplier tubes (PMTs) that detect the scintillation light produced by ionising particle interaction. The SSS is embedded in a 2000 ton water Cherenkov detector, instrumented with 200 PMTs. A long calibration campaign (2010) enabled Borexino to reconstruct the event position with an accuracy of ~ 10 cm (at 1 MeV) and energy resolution $\sigma(E)/E = 5\%/\sqrt{(}E/[MeV])$ [3].

The Borexino data are split in three Phases: Phase-I, (mid-2007, beginning of 2010), ends with the calibration campaign, in which the first measurement of the $^7$Be solar neutrino interaction rate [4–6] has been achieved; Phase-II, (beginning of 2012, mid-2016) begins after the water extraction purification campaign, in which the first evidence of the $pep$ neutrinos [7] and a 10% measurement of the $pp$ neutrinos [8] has been released, and later updated in the comprehensive analysis of solar neutrinos [9–11]; Phase-III, (mid-2016, October 3rd 2021), in which the first detection of the CNO neutrinos [12] has been published. In addition, as allowed by its exceptional radio-purity, Borexino has set strong limits on rare processes (see e.g., [14–18] and released other studies concerning neutrino physics in general, as e.g. geo-neutrino interaction rate measurement (for review, see e.g. [19]). The Borexino event selection for solar neutrino detection is largely reviewed in [20].

## 2. The CNO detection updated

The latest Borexino measurement of the CNO solar neutrinos with an improved uncertainty of (+30%, -12%) on its rate has been recently published in [21]. The new data-set includes a 30% more exposure as compared with the previous release [12]. Also in this paper, the CNO is extracted by exploiting the independent constraint of the $pep$ and the $^{210}$Bi. The latter is realised thought the quantification of the $^{210}$Bi activity from the $^{210}$Po, an alpha emitter related to parent $^{210}$Bi through the secular equilibrium of the $A = 120$ chain starting with $^{210}$Pb. The latest period of Phase-III features high quality data in this sense, enabling a more stringent constraint, with a consequent improvement of the CNO neutrinos detection.

This result strengthens the result anticipated in [12], with a significance of $7\sigma$ CL. Figure 1 reports the CNO $\Delta\chi 2$ profile obtained from the multivariate spectral fit (dashed black line) and after folding in the systematic uncertainties (black solid line). The blue, violet, and grey vertical bands show 68% CI for the low and *high metallicity* prediction respectively, respectively. See [21] and Refs. therein. The updated rate for the CNO neutrino interaction in Borexino is now $6.7^{+2.0}_{-0.8}$ cpd/100t. Moreover, the CNO neutrinos measurement together with the $^8$B neutrino flux constraint

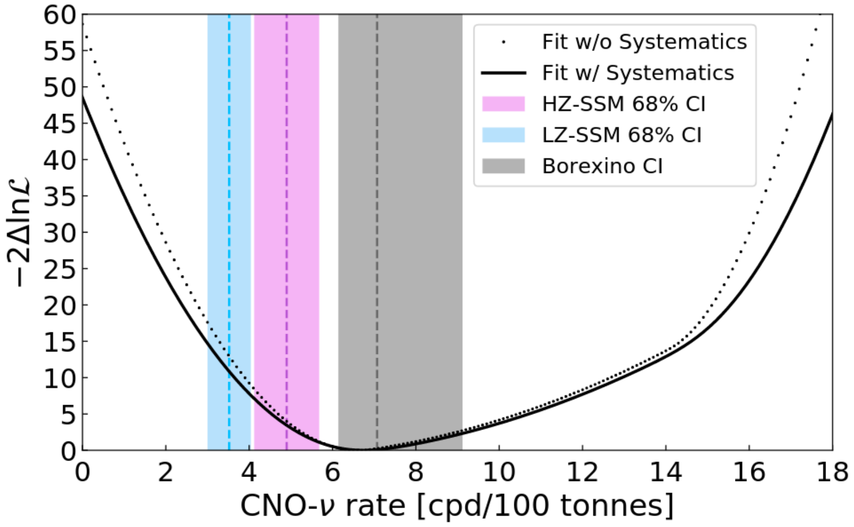

**Figure 1:** CNO $\Delta\chi 2$ profile obtained from the multivariate spectral fit (dashed black line) and after folding in the systematic uncertainties (black solid line). The blue, violet, and grey vertical bands show 68% CI for the low and *high metallicity* prediction respectively, respectively. See [21] and Refs. therein.

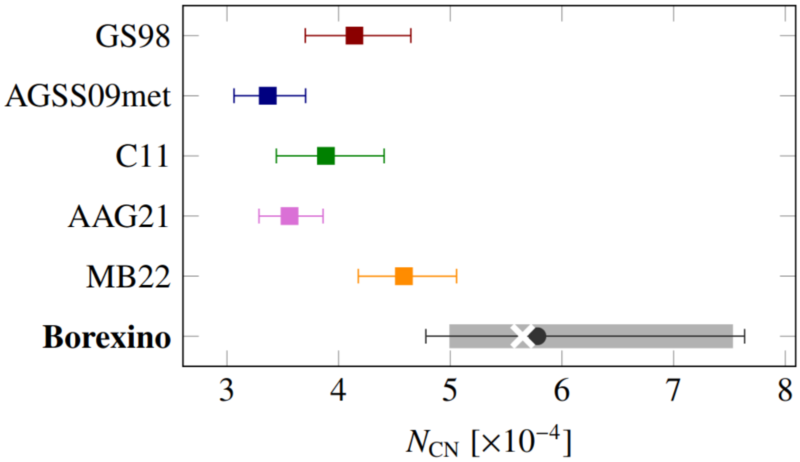

**Figure 2:** Comparison of abundance of CN over H in the solar photo-sphere, from spectroscopy (squares) and from the Borexino measurement (circle).

from the global analysis (i.e. including other solar neutrino experiments) has been exploited to determine the CN abundance in the Sun, avoiding the *opacity-metallicity* degeneracy, see again [21] and Refs. therein.

The CN abundance determined with this method, agrees very well with the *high metallicity* models, while exhibiting a mild tension ($\sim 2\sigma$) with *low metallicity* models (see Fig. 2). In particular, the Borexino result on CNO, combined with $^7$Be and $^8$B solar neutrino fluxes measured also by Borexino, disfavour the traditional *low metallicity* model AGSS09 at $3\sigma$ CL. This results pave the way for future experiments that can potentially provide important clues to definitively solve the longstanding *metallicity* puzzle of the standard solar model.

## 3. Earth's orbit eccentricity with solar neutrinos

The annual modulation of the solar neutrino flux, related to the Sun-Earth distance variation as a function of time during each year, is studied in Borexino over a period of 10 years including Phase-II and Phase-III, until the end of the data-taking. This modulation is expected to be of 3.4%, as determined by the Earth's orbit eccentricity equal to $\epsilon = 0.0167$ [22]. The present improved result was anticipated, with less significance, in Phase-I [20] and in early Phase-II [23].

The time series over 10 years, is produced by selecting events in a fixed energy window chosen to maximise the signal-to-background ratio. The search for solar neutrino signal modulations in the frequency domain, between one cycle/year and one cycle/day, was performed using the generalised Lomb-Scargle method, see [22] and Refs. therein.

No significant periodic signals other than the expected annual modulation are detected. Figure 4 reports time series in the fixed window (*Top*) and the residuals after the detrend procedure described always in [22] (green curve). The latter, see again Fig. 4 *(Bottom)*, is fitted to a sinusoidal function with all free parameters: the amplitude (related to the orbit eccentricity), phase (perihelion position), and frequency (Earth's revolution) are found comparable withing one $\sigma$ with the astronomical measurements. In particular, the best-fit eccentricity is $\epsilon = 0.0184 \pm 0.0032$ (stat+sys), providing the most precise measurement of the Earth's orbit eccentricity obtained using solar neutrinos only, and whose significance exceeds $5\sigma$. Figure 3 shows the comparison of the new Borexino result with other solar neutrino experiments.

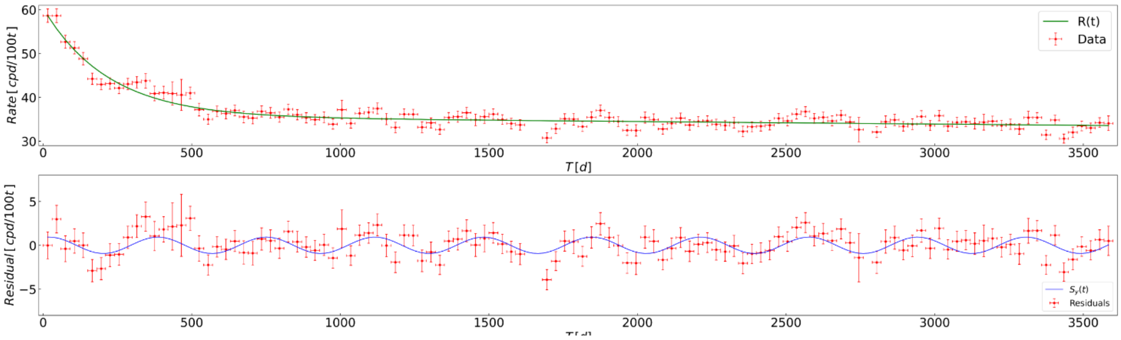

**Figure 3:** *Top:* Full Borexino rate time series (Phase-II and Phase-III) in the fixed window with detrend function (green). The rate in cpd/100t is binned in time intervals of 30 days. The time axis is reported in days since 12:00 AM of December 11th 2011, in UTC time. *Bottom:* Residuals of the time series after detrend, fitted to a sinusoidal function.

The same data-set was split in shorted time bins of 8h, to scan frequencies up to 1 cycle/day. Using the look-elsewhere effect, no other significant frequencies in the full periodogram range where found, including frequencies of interest, as the day-night asymmetry or the Sun's rotation day (about 27 days).

The high-significant measurement of the Earth's orbit eccentricity, made with solar neutrino only by Borexino, confirm the high stability of the detector response and energy resolution, as well

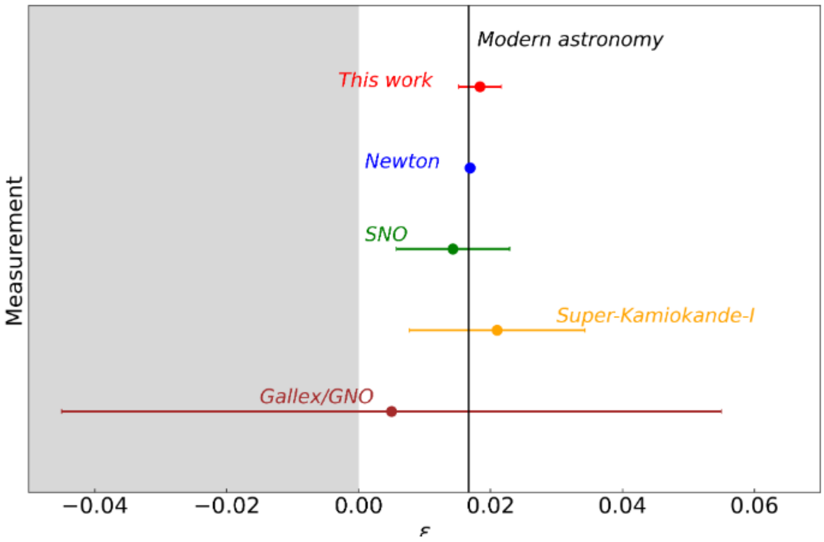

**Figure 4:** Comparison between the Borexino measurement of the Earth's orbital eccentricity (red) with other solar neutrino experiments: SNO (green), Super-Kamiokande (yellow), and Gallex/GNO (brown). The blue point is the eccentricity that one reads in Newton's Principia and the vertical black line is the present astronomical measurement. See [22] and Refs. therein.

as detailed understanding detector background, reinforcing the longstanding success of Borexino in low energy solar neutrino detection.

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