The experience of working with a successful experiment from the NSF perspective

BOREXINO Collaboration Meeting at LNGS

December 1, 2021

Brad Keister & Jim Whitmore

Retired NSF Program Directors

Program Director History

- Brad worked at NSF from June 1997 as its permanent program director for Experimental Nuclear Physics until he retired in 2018. He led the NSF activities for Borexino from June 1997 until 2006.

- Jim started at NSF in 2001-04 as an IPA (temporary position) and then from 2006 to 2021 as a permanent program director for Experimental Particle Astrophysics. He led the NSF activities for Borexino from 2006 until June 2021 when he retired.

NSF funding history

- **1986:** Discussion with R. Raghavan for BOREX
- **1991**: Discussion of proposal for Borexino
- **1991-1996:** Counting Test Facility (CTF) construction and operation, a 4-ton facility
- **1994:** Award for containment vessel and scintillator purification system for both CTF and BOREXINO.
- **1995:** Award for design of Borexino detector
- **1998:** Award for Construction of the detector, an international project involving Italy, Germany, and the US
- **1999-2000:** Awards for developing aspects of a calibration and monitoring scheme for the Borexino solar neutrino detector, whose principal purpose is to measure the solar ^{7}Be neutrino flux at an energy of 0.86 MeV. Borexino will attempt to observe direct evidence of neutrino oscillations and confirm the present hypothesis of neutrino mass.
- **2002:** Award: After several years of R&D with a prototype detector, and four years of construction, Borexino is expected to become operational in 2002. The objective of this award in the two-year period 2002-2004 is to complete the commissioning and start-up phase of Borexino and begin taking solar neutrino data.
- **2005:** Award: The detector was built with prior funding from the NSF and with funds from European science agencies. The goal of this award is to bring the detector into full operation within the next two years and to start data acquisition.
- **2007:** data taking started on May 16; on August 22: first result for ^{7}Be flux in *SCIENCE*

- ***Total NSF funding 1993 to 2021 is over $31M;***
- ***This includes both construction and personnel support for the 3 US groups***

Comments from Brad (1)

- I can remember the earlier days of Borexino construction that represented the classic combination of challenges, risks and rewards for physicists and agencies when approaching scientific questions with very high potential impact.

- Borexino was proposed to NSF in the early 1990s. The reviewers – experts in the field – very much liked the idea of Borexino and its discovery potential at very low neutrino energies but were sharply divided in their assessment whether record low levels of pseudocumene radiopurity could ever be achieved.
- So, a compromise (if one can call it that) was reached: NSF would fund a smaller-scale Counting Test Facility (CTF), whose goal was to demonstrate the technical feasibility of purifying liquid scintillator to a level adequate for the full Borexino experiment. The collaboration achieved this goal, and then came back to NSF with the proposal to move ahead with the full design. The Italian and German agencies had already approved their portions of the project. The expert reviews were again split, perhaps not surprisingly, and at NSF, both the Physics and the Astronomy Divisions had to agree to sign on.

Comments from Brad (2)

- My first week in June 1997 was a critical technical make-or-break review of Borexino at NSF HQ: all agreed that the only way to know if Borexino would work was to build it.
- The technical review went well, and eventually both NSF divisions (PHY and AST) signed on.
- Then came the actual construction process. Borexino was not really a ‘standard’ construction project because there were many elements that were simply not known at the outset. So things took longer and some costs had not been anticipated. But the project moved along, and NSF also reaffirmed its willingness to take the financial risks involved.
- I remember almost annual visits to Borexino, watching the pieces of the stainless-steel sphere come together like a jigsaw puzzle, followed by the array of phototubes, along with elaborate purification system. Then there was the ultra-clean lab at Princeton where the nylon vessel was assembled.

Comments from Brad (3)

- Then came the multipoint failure that led to the chemical spill in 2002. There was now an existential question whether Borexino would be shut down, let alone whether it would achieve the desired radiopurity.
- But after several years – at that time, at least – Borexino got a reprieve, and then progress became rapid. The spill-related shutdown had enabled all of the subsystem groups to complete construction and testing.
- With the experiment back on, it was then a short sequence of steps (in light of the timeline since the mid 1990s) to fill Borexino first with water, then with pseudocumene, and then take data.

Comments from Brad (4)

- In the meantime, Jim Whitmore had taken over the program that included Borexino, so I was then watching from the sidelines.
- In the end, the naysayers were proven wrong, and **Borexino obtained very nice quantitative data for ^{7}Be solar neutrinos – the basis for the proposed project.**
- But the group has now gone far beyond that with the detection of neutrinos at even lower energies in order to test more elements of the model for energy production in the sun.
- I'm not in the best position to comment on the endgame for Borexino, but I can remember the earlier days of Borexino construction that represented the classic combination of challenges, risks and rewards for physicists and agencies when approaching scientific questions with very high potential impact. **I'm happy to have taken part!**

What makes an experiment successful?

- **Significant science results over a period of time:**

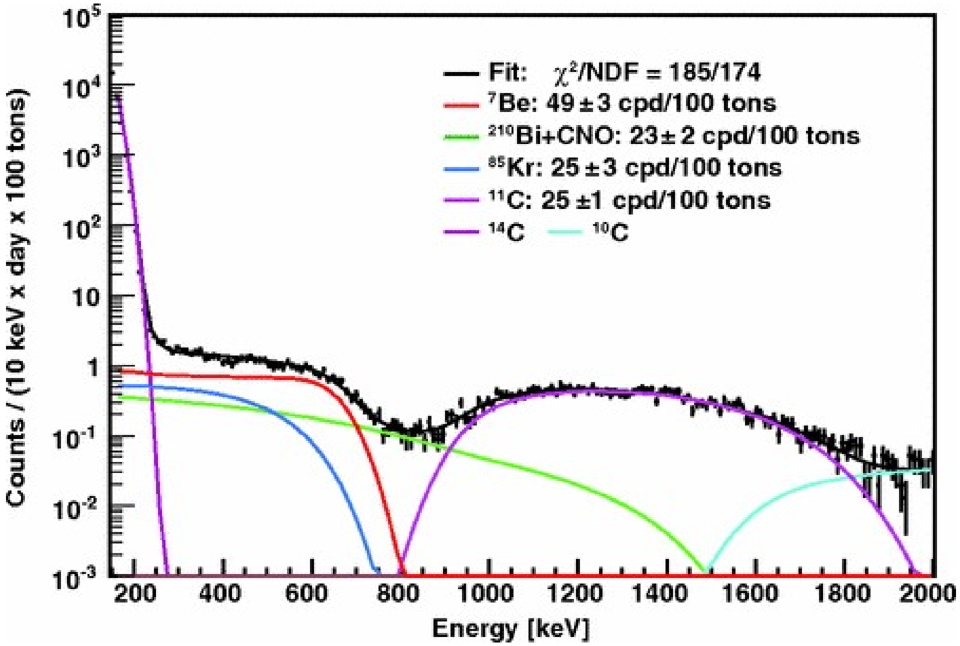
- I will pick four such results from your experiment:

- 1) ^{7}Be solar neutrinos (PRL, August 2008)
- 2) pp solar neutrinos (Nature, August 2014)
- 3) Geoneutrinos (PRD, January 2020)
- 4) CNO solar neutrinos (Nature, November 2020)

1) ^{7}Be solar neutrinos - *PRL* August 2008

Phys Rev Lett 101, 091302 (2008)

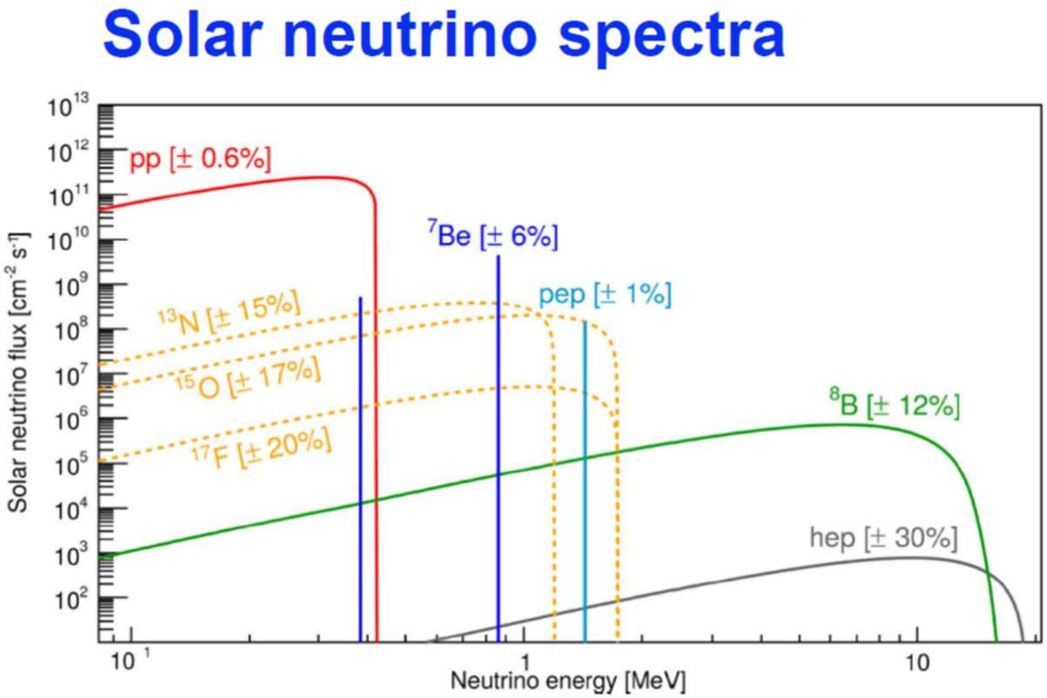
"We report the direct measurement of the low energy (0.862 MeV) ^{7}Be solar neutrino signal rate performed with the Borexino detector. The hypothesis of no oscillation for ^{7}Be solar neutrinos is inconsistent with our measurement at the 4σ C.L. Our result is the first direct measurement of the survival probability for solar ν_e in the transition region between matter-enhanced and vacuum-driven oscillations." (Data collected from May 2007 to April 2008.)



2) pp solar neutrinos - *Nature* August 2014

Borexino has made several breakthroughs in the measurements of solar neutrinos since it started 30 years ago, including this first complete measurement of the pp-neutrinos that produce 99% of the proton-proton fusion process that produce the Sun’s energy. (CNO are the remaining 1%.) Data from Phase 2: Jan 2012-May 2013.

The energy generated by stars comes from the fusion of light nuclei into heavier ones. In the Sun, hydrogen is transformed into helium predominantly via the *pp* cycle, a chain of reactions releasing 26.73 MeV and electron neutrinos. The cycle begins with the fusion of two protons into a deuteron, which occurs 99.76% of the time:


Solar neutrino spectra

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$; the neutrinos produced in this step are referred to as *pp* neutrinos, see figure.

The solar neutrino spectrum predicted by the SSM of Bahcall and collaborators.

The flux (vertical scale) is given in $cm^{-2}\ s^{-1}\ MeV^{-1}$ *for continuum sources and* $cm^{-2}\ s^{-1}$ *for mono-energetic ones.*

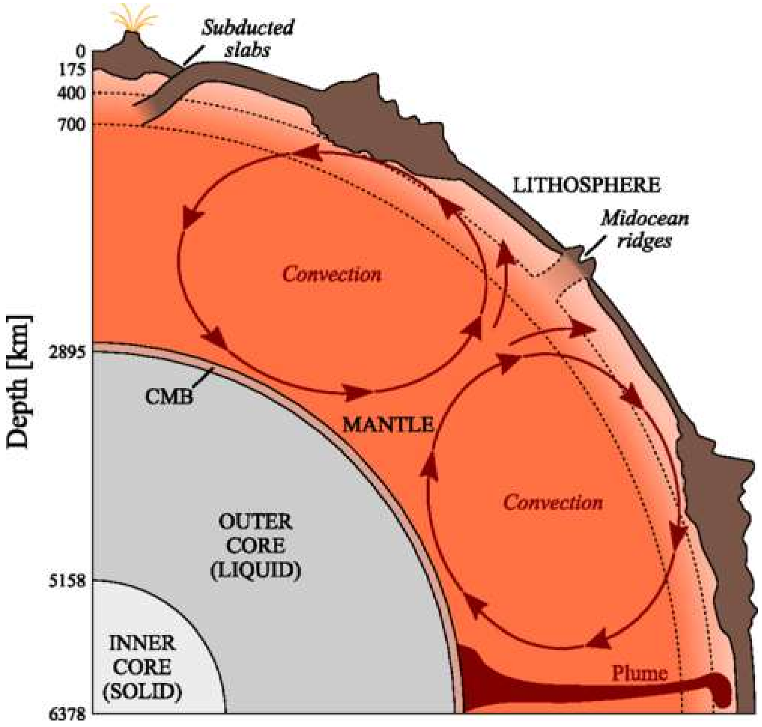
3) Geoneutrinos - *PRD* January 2020

Phys. Rev. D101, 012009 (2020)

- Geoneutrinos are electron antineutrinos produced by decays of long-lived isotopes which are naturally present in the interior of the Earth, such as the ^{238}U and ^{232}Th chains.

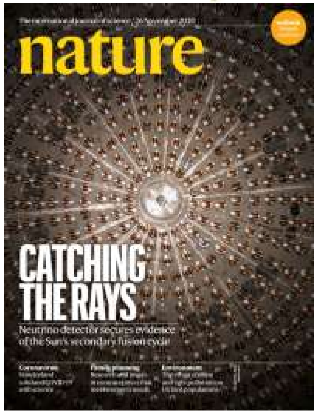
- From 3263 days (December 2007 to April 2019), the experiment observed 53 geoneutrinos from ^{238}U and ^{232}Th, from an exposure of 1.29×10^{32} protons x year.
- They found the radiogenic heat from U and Th in the mantle to be 24.6 (+11.1-10.4) TW.
- The total radiogenic heat of the Earth is found to be 38.2 (+13.6-12.7) TW.

- An upper limit on the number of events from a hypothetical georeactor at the center of the Earth, concludes that its existence with a power greater than 2.4 TW has been excluded at 95% C.L.



4) CNO solar neutrinos - *Nature* Nov 2020 (1)

Nature Vol 587, Nov 26, 2020, p. 577



nature

CATCHING THE RAYS

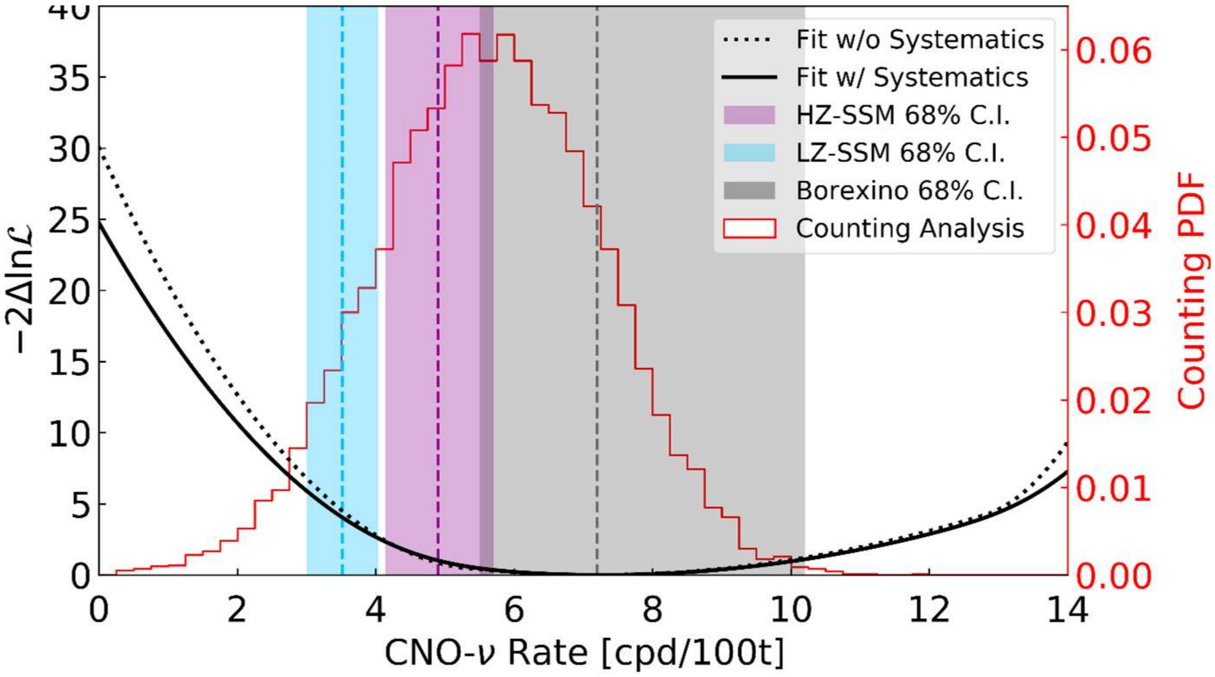
Neutrino detector secures evidence of the Sun's secondary fusion cycle

- The measurement of the CNO cycle is an important discovery for the hypothesis that this cycle is **the dominant process that lights up massive stars** (ie with a mass > 1.3 times the solar mass).
- The **metallicity of the Sun (Z)** refers to the fraction of solar mass residing in elements heavier than Helium and is a fundamental diagnostic of the Sun’s evolution.

- “We report here the direct detection of neutrinos from the solar CNO cycle, providing direct evidence of the catalysed hydrogen fusion that was proposed independently by Bethe and Weizsäcker in the 1930s.
- This result quantifies the rate of the CNO cycle in the Sun and paves the way for a solution to the long-standing ‘**solar metallicity problem**’—the discrepancy between the physical properties (for example, the solar sound speed profile and the depth and composition of the external convective envelope) predicted by solar models using updated (low) metal abundances from spectroscopy (low-metallicity standard solar model, **SSM-LZ**), and those inferred from helioseismology, which favours a higher metal content (high-metallicity standard solar model, **SSM-HZ**). Despite detailed studies, this discrepancy remains an open problem in solar physics.
- Our experimental observation of CNO neutrinos confirms the overall solar picture and shows that, with future experimental improvements, a direct measurement of the metallicity of the Sun’s core could be within reach.”

4) CNO solar neutrinos (2)

- “Folding the systematic uncertainty over the log-likelihood profile we determine the final CNO interaction rate to be 7.2 cpd per100 t (−1.7+3.0).
- A hypothesis test based on a profile likelihood test statistics excludes the no-CNO signal scenario with a significance greater than 5.0σ at a 99.0% confidence level.
- The observed CNO rate is compatible with both SSM-HZ and SSM-LZ predictions, and as such we cannot distinguish between the two different models: the statistical compatibility for HZ is 0.5σ and for LZ is 1.3σ (see Fig.). When combined with other solar neutrino fluxes measured by the Borexino experiment, the LZ hypothesis is disfavoured at a level of 2.1σ.”



Discovery implementation (1)

- The main source of background for this challenging measurement is ^{210}Bi, the daughter of ^{210}Pb in the scintillator.
- To measure the ^{210}Bi background, the Borexino collaboration started an effort in 2015 to make an independent measurement of ^{210}Bi. The method is based on achieving secular equilibrium in the decay chain:
  ^{210}Pb ($T_{1/2}$ = 22y) $\rightarrow$ ^{210}Bi (5d) $\rightarrow$ ^{210}Po (138d) $\rightarrow$ ^{206}Pb (stable).
- Secular equilibrium implies that the decay rate of all members of the chain have the same decay rate, which can then be determined from the alpha decay of ^{210}Po, which is straight forward using pulse discrimination.
- The decays that are observed are in the central fiducial volume of Borexino, namely within a radius of <3 m. However, the ^{210}Po moves from the Inner Vessel surface into the scintillator and by diffusion and temperature-induced convection into the fiducial volume.
- This measurement therefore required a stable detector temperature to reduce the scintillator convective currents to a very low level to assure that any ^{210}Po decays occurring in the fiducial volume came ***only*** from ^{210}Bi decays in that same region.

Discovery implementation (2)

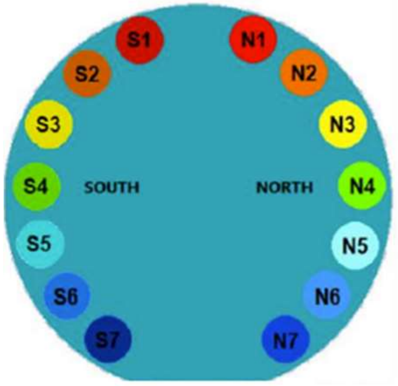
These data were collected during Phase 3, July 2016 to February 2020.

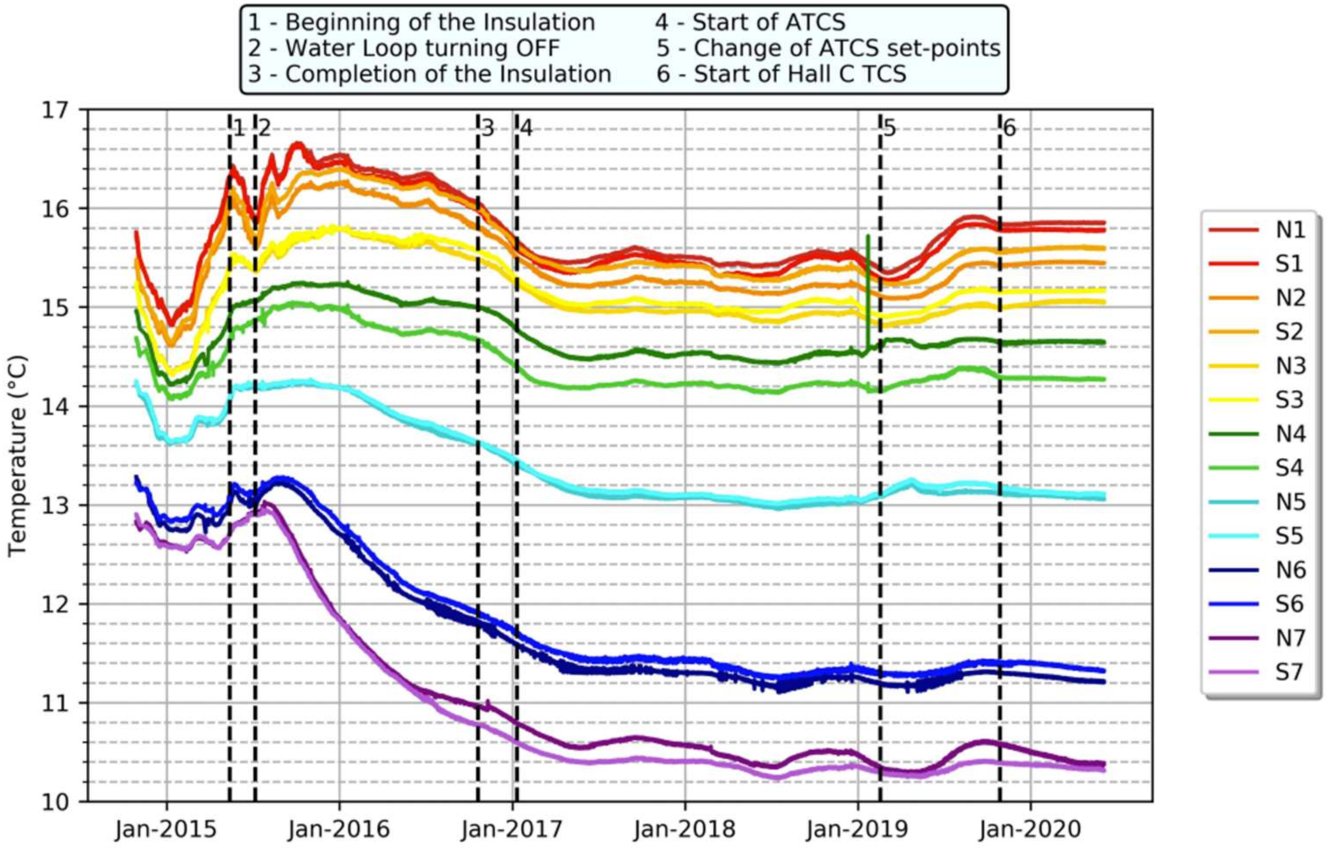
To achieve this, the following actions were taken:

- A comprehensive thermal mapping of the internal detector was initiated in 2014 by re-tasking existing calibration ports to predict their ability to ultimately understand and control mixing. The results were very informative, and justified optimism that thermal insulation would be successful.
- Installation of a thermal insulation system on the outside of the Water Tank. This was completed between May and December 2015.
- 66 temperature probes were installed to monitor the detector within the three heating zones to control the water tank temperature. This was completed in early 2016.
- An active system to control seasonal changes of the air temperature entering the experimental Hall C and surrounding Borexino was installed in 2019, enabling a constant temperature to ± 0.05 C.
- Installation of an active temperature control system to reduce scintillator convective currents. This was completed in several stages, the final one was in January 2020. It maintains a temperature gradient within the inner vessel, resulting in a far more stable fluid configuration.

Discovery implementation (3)

Temperature measured by 14 probes inside the detector. The location of temperature probes are depicted on the left. The dates of operations are marked as vertical lines. ***After commissioning of active temperature control system of Hall C air in November 2019, an extremely stable condition is reached.***





Other success indicators: Recent honors:

- The Borexino experiment was listed in the 2020 Top Ten of Physics World:

  “The Borexino collaboration is chosen for observing neutrinos from the carbon-nitrogen-oxygen (CNO) cycle in the Sun.”

- **The European Physical Society awarded Borexino the 2021 Cocconi Prize**

- “The 2021 Giuseppe and Vanna Cocconi Prize for an outstanding contribution to Particle Astrophysics and Cosmology is awarded to the Borexino collaboration for the groundbreaking observation of solar neutrinos from the pp and CNO chains that provided unique and comprehensive tests of the Sun as a nuclear fusion engine.”

NSF's involvement:

- Overall NSF has contributed more than $31M in construction and scientist support over the more than two past decades.
- The CNO measurement has only become possible with the understanding of the convection currents inside the detector which has required measuring and stabilizing the temperature both in the detector and in the surrounding environment of Hall C.
- The NSF-supported scientists have been instrumental in this activity to achieve a stable temperature in the detector itself (which was started in 2015) as well as the temperature in Hall C (which was started in 2019).
- These scientists have also been working closely with LNGS staff to complete the processes and have been centrally involved in the analysis of the CNO neutrinos.

Summary

- With its discovery of neutrinos from the CNO cycle in the sun and its previous measurements of the pp-cycle neutrinos, **Borexino has "completely unraveled the two processes powering the Sun."**
- Those of us at the NSF who have been involved with the Borexino Collaboration wish to express our admiration for succeeding in a very complex and challenging experiment!
- We congratulate your collaboration on achieving these very important astrophysics results.
- We feel honored to have helped you in your success!
- We look forward to your final analyses when all your newer data have been included.

- THANK YOU and WELL DONE!