The longstanding adventure of Borexino, from ideas to stars

1988-2021

Gianpaolo Bellini

The beginning

1988- Raju Raghavan and myself start discussing about an experiment on solar neutrinos. RR proposes **a big experiment (10000 tons) using a boron loaded scintillator,** TMB-trimethylborate, to study the neutrinos **from the .^{8}B nuclear fusion in the Sun** with a **threshold at ~ 5 MeV** over the natural radioactivity max. energy. This experiment was called **BOREX** – But no much interest: 2 Cherenkov expt. were doing the same research, even if with the scintillator the performances are better

1988-1989 Discussions on a new experiment able to measure the neutrinos **from ^{7}Be with a threshold below 1 MeV;** constraints: **high radiopurity in the entire detecto**r, minimize the construction materials and then **use only one vessel for the scintillator.**

- invited Franz Von Feilitzsch and Frank Calaprice and others
- when we decided to proceed with this experiment the **physicists community was very skeptical and this attitude has accompanied us always throughout the experiment construction and in some part of the analysis.**

  Because this experiment is conceived as definitely smaller than Borex, it has been called **BOREXINO, a**lthough if this name no longer corresponds to the new project .

1990-1995 The real work begins with a period **of R&D for the development of tools and methods for the radio purification of the scintillator,** whose composition consists of **pseudocumene** ((PC, 1,2,4-trimethylbenzene) as solvent and **PPO** (2,5-diphenyloxazole,a fluorescent dye) at a concentration of 1.5 g/l as solute. The **1.5 g/l concentration was chosen as a compromise between the need of a high scintillation light and the potential contribution to internal background (mainly Potassium and Polonium present in the PPO**).

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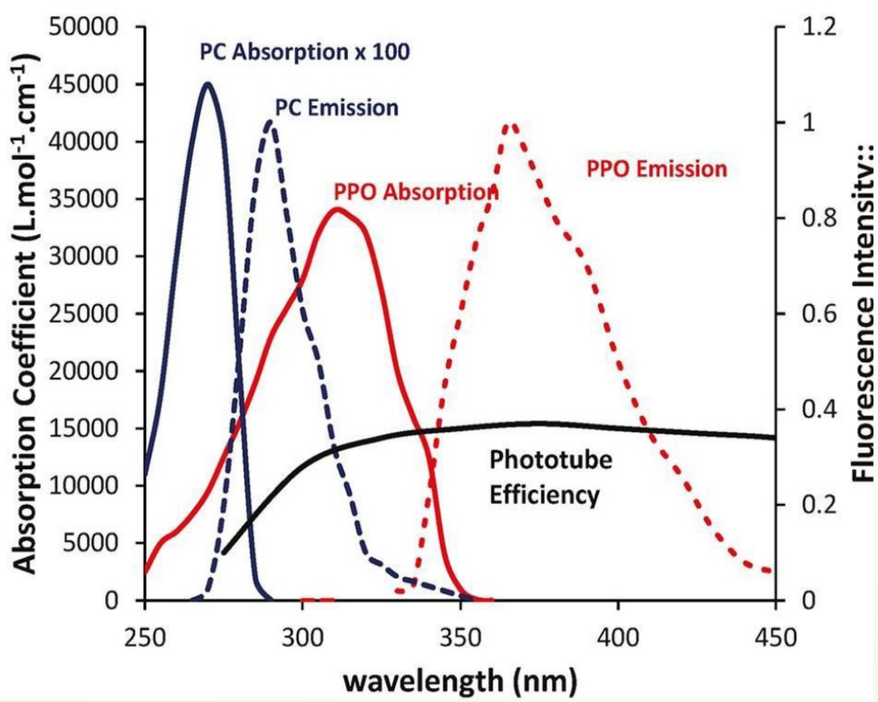
Why Pseudocumene and PPO?

- At the end of the 80’s the **PC** was the preferred choice with respect to the first generation solvents, like toluene, benzene and others, **because *less harmful***; in ***PC fast fluorescence component is followed by a slow component as delayed fluorescence and phosphorescence***, featuring timing much longer than that of the fluorescence alone- useful to ***distinguish between different particles***- in addition*:* ***high light yield***
- **PPO**- very **good match between the wavelength of the PPO light and the spectral response of the phototubes; i**n addition**:** ***translation of the light wl toward a lower absorbance region of the scintillator***

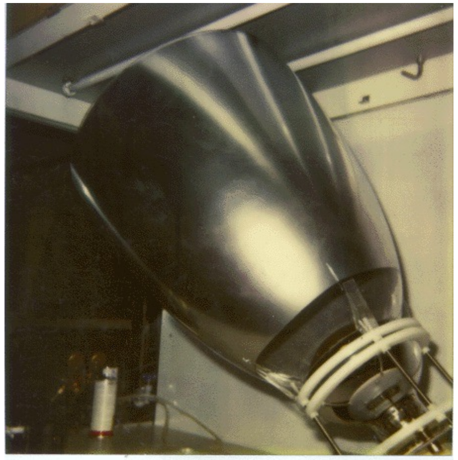


- A problem arose: how to measure the radio purity to ascertain if **we were able to reach the design requirements: 10^{-16} g / g.** The most sensitive instrument existing at that time **was the mass spectrometer with plasma source**, whose max. sensitivity however reached a maximum of **10^{-10} g / g**. We therefore decided to build a **benchmark for Borexino, *the Counting Test Facility* - *CTF*** conceived as a scaled and simplified version of Borexino: **4 t of scintillator surrounded by 1000 t of highly purified water with 100 photomultipliers.**

- ➔ ***purification plant*** *for the water* (Milano- Marco Giammarchi)

  ➔ PMTs: **8" ETL** 9351; because **we the glass is very radioactive for our purposes, we established a collaboration with *ETL for a glass with low radioact.*(Gioacchino).** Light concentrators **larger than the Wiston cones** (Lothar and Istvan) .Construction of the *CTF began in 1992*; tank by TUM, PMTs mounted by Augusto Brigatti and Giovanni Bacchiocchi-

➔ **Bruce spent Christmas and New Year *1994- 1995* at G.S. with his father-in-law and his uncle to fill the CTF** with the purified water- also Manuzio took part in it



Electronics done in Milano: Gioacchino, Pierino Inzani – **and in Genova-** Gemma (PMT monitoring); **DAQ**: Emanuela, Golubchikov

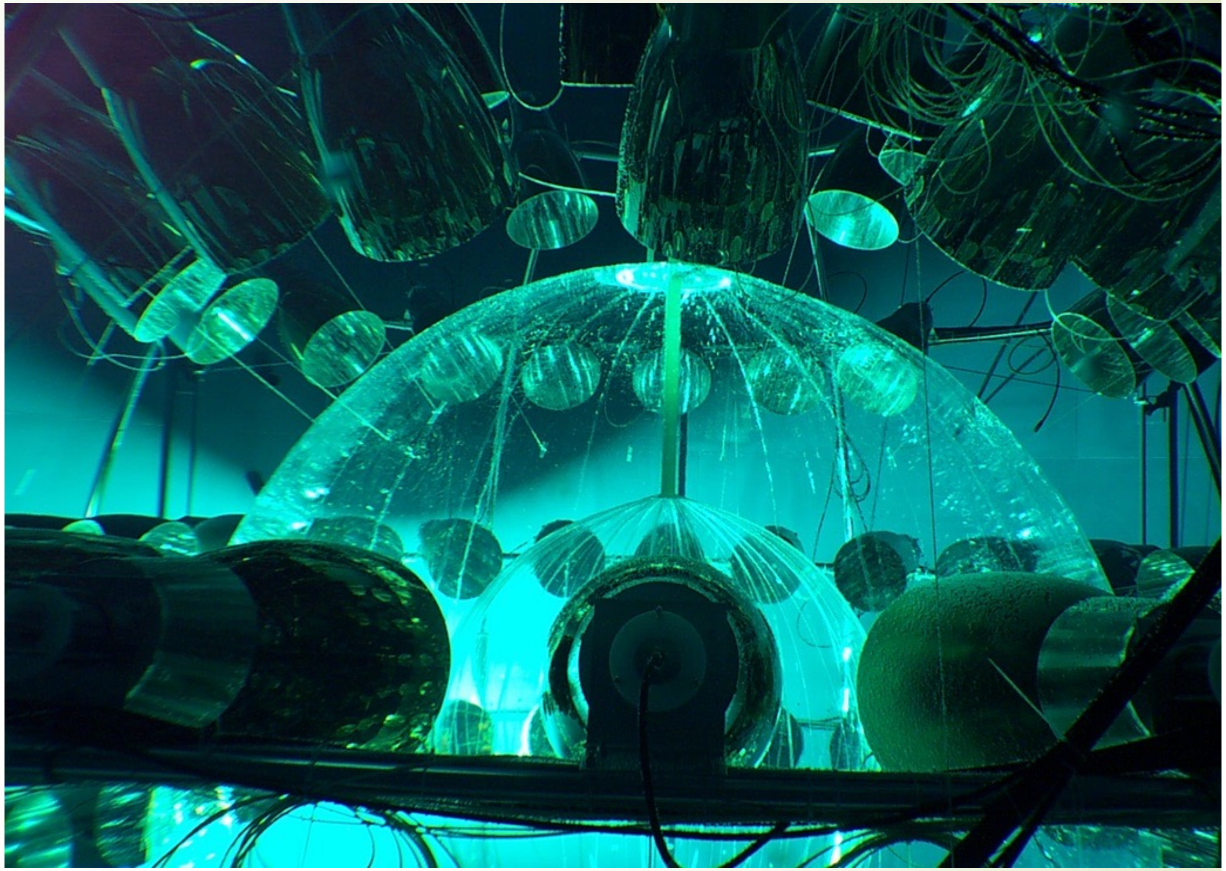
The **vessel containing the scintillator was made in Princeton with thin nylon** and as in Borexino another nylon balloon was installed around the Vessel as a barrier for the Radon emitted by the PMTs.

In the same years, **methods for the purification of PC** was first **tested at the Bell Lab** by Raju and Antonio de Bari, a chemist from Pavia. But most of the tests done at **Princeton** by Jay and Frank The realization of the purification systems was carried out at GS (I refer only to the CTF): **under-vacuum distillation, water extraction, ultrafiltration, nitrogen sparging**. The pseudocumene for the CTF was radio-purified with **water extraction., ultrafiltration and Nitrogen sparging.**

At the beginning of **1995 we measured the radio-impurities due to ^{238}U and ^{232}Th and their progeny**. The measurement gave ***5x 10^{-16} g / g***, the CTF maximum sensitivity. The results were released in a seminar I given at the GS Lab. in March 2005 at presence of the INFN President and Executive Committee.

The President at that time, Luciano Maiani, who later became Cern DG, ***approved in principle Borexino,***

We had the opportunity to proceed with Borexino, thanks to two persons: **Enrico (Puccio) Bellotti, GS lab. director until 1993,** who allowed us to install the CTF in the middle of hall C, leaving beyond enough room for Borexino, and **Luciano Maiani**. **Both took the risk that the experiment did not achieve its goals, thus resulting in a failure**, surrounded as we were by the skepticism of many scientists who considered this experiment impossible.



Cover of the journal SCIENCE 1995

However, the problem was not yet over, because, it is true that we had reached the design radiopurity for the Th and U, but **we were observing other radiations in the scintillator with significant rates** . We were not able to understand what it was and we spent a few months discussing, calculating and investigating, but the opinions were different.

At the end, one afternoon in **early December 1995**, Gioacchino and I, with Scardaoni, **we decided to do a test by increasing the amount of Radon in the water**. As the water loop continued to run to purify the water, we decided **to reduce the nitrogen flow into the counter-current tower to decrease nitrogen sparging into the water.** We continued to increase the radon and take data, until the percentage of Rn in the water had increased 10 times.

From the analysis of the data we finally realized that *the counts we observed were due to radiations emitted by materials*, essentially water, PMTs and other sources, external to the CTF Inner Vessel.

Then, we finally understood that we were able to reach the radio purity necessary to proceed with the experiment.

During this period the collaboration consisted of 5 Italian groups: Genova, LNGS, Milano, Pavia, Perugia; one from: US, Princeton; from Russia, JINR Dubna; from Germany, TUM Garching.

CTF has been not only a benchmark for Borexino, but produced also **results on the rare events and many of these results have been and are still now the best limits**

- Search for electron decay mode $e \to \gamma + \nu$ with prototype of Borexino detector. Phys. Lett. B525 (2002) 29
- New limits on nucleon decays into invisible channels with the Borexino Counting Test Facility. Phys. Lett. B563 (2003) 23.
- Study of the neutrino electromagnetic properties with the Prototype of the Borexino Detector. Phys. Lett. B563 (2003) 37.
- New experimental limits on heavy neutrino mixing in ^{8}B decay obtained with the Prototype of the Borexino Detector. JETP Lett. 78 (2003(261.
- **New experimental limits on violations of the Pauli exclusion principle** obtained with the Borexino Counting Test Facility. Europ. Phys. Journ. C37 (2004) 421.
- Lifetime measurements of ^{214}Po and ^{212}Po with the CTF liquid scintillator detector at LNGS. Eur. Phys. J. A49 (2013) 92.

The analysis code was done essentially by Istvan Manno, with a late contribution of Gemma, Silvia Bonetti and others.

1996-2007 Construction, installation and tuning of the detector-

Extension of the collaboration: I contacted the Heidelberg group (Till Kirsteen) and Collége de France (Hervè de Kerret)- Furthermore, the pre-existing groups have grown with other components

11 years it is a very long period, but justified by two circumstances: for **more than 2 years we were stopped by the court of Teramo because about 30 liters of PC** were spilled into a **creek that passes through Isola del Gran Sasso** (error due to a misunderstanding between two operators); and more **important *nothing is standard in the Borexino detector, neither for what concerns the components nor the methods.***

1 **All construction materials of the detector and of the Storage** area, have been selected ***for a very low radioactivity-*** measurements have been done with Ge detector in the Laubenstein lab. also with Arpesella (LNGS)

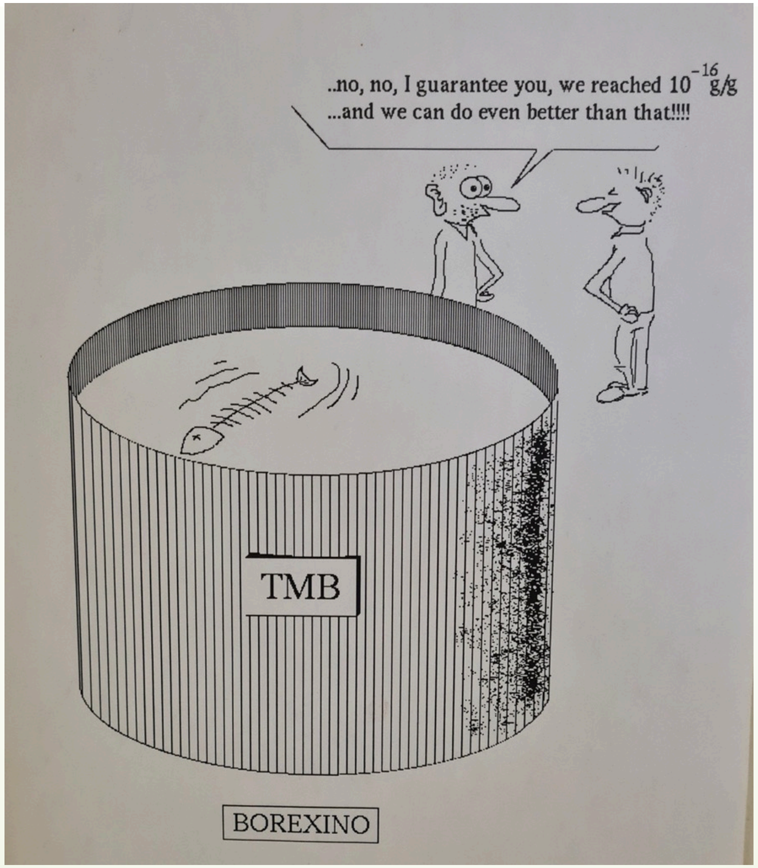
2 All the internal surfaces of the **SSS, of the storage vessels, of all the lines are *pickled and passivated*** in order to **extract contaminants embedded in the surfaces** and made **easiest to clean** them from particulate and dust, which contain radioactive elements (Danilo Giugni).

3 The PMTs were built in collaboration with the company to use ***glass with particularly low radioactivity*** (Gioacchino)

Gianpaolo Bellini

4. All the parts of the ***pumps*** in contact with the PC ***are in Teflon*** (Corrado Salvo, Roberto and others)

5. The **PMTs to be installed within the SSS were sealed with a steel capsule with mineral oil and epoxy resin** (Milano and LNGS). They were **tested into the « two liquids tank», in PC surrounded by water, and left there until 2010** (Hall di montaggio); they were monitored by a system carried out by Oleg. The **muon veto PMTs, to be installed in the WT water, were encapsulated in steel with mineral oil inside** (TUM)



6. The **nylon film has been prepared in a controlled area** and the vessel **has been manufactured *in clean room of class 100 Rn free*** (Princeton- Cristiano and others)).

7. A ***cryogenic plant*** (Heidelberg- Gerd, Simgen) **purifies the nitrogen for the sparging and the blanket above the scintillator in the detector.** The analysis **of the content *of ^{39}Ar and ^{85}Kr was analyzed*** in a ad **hoc plant** in Heidelberg (Zuzel, Simgen)

8 **Five clean rooms** have been set up, **one in the hall di Montaggio**, the others around the detectors. **CR 1, class 1000, was at the entrance of the** Water Tank so that **whatever entered the detector was cleaned**;

on the top of the detector a **clean room of class 10-100 with a glove box, was used for the calibrations.**
Finally the **SSS itself is equipped as a class 10,000** c. r.

9 The detector ***was sealed at the level of*** 10^{-8} ***mb l/s,*** the same as the swagelok valves (metal gaskets) , **to prevent the entry of Rn from underground air,** where it is present **at the rate of > 100 Bq / m^3** (Milano, Genova, LNGS)

10 The welds were mainly ***orbital welds,*** and some of them **TIG, in nitrogen atmosphere**

11\. The percentage of solute and the *properties of the scintillator*, in particular its **absorpion and transparency**, have been studied in Perugia (Masetti, Mazzuccato, ecc.) and also in Genoa (Gemma e coworkers), already for CTF . A laboratory test was also developed which was **then used continuously during the *procurement of the PC* in** *Sarroch* (Ortica), during its production. The same groups also studied the percentage of the quencher DMP to be added to the PC used as buffer liquid, percentage decreased after the IV small hole to reduce the difference of pressure.

12 The ***water purification system*** **is the same as for the CTF**, also because in that case the water had to be very purified being in direct contact with the IV; an **analysis system has been added and the water *showed a presence of*** ***10^{-14} g / g for Th and U, with lower sensitivity for K.*** The system was built and installed by Heidelberg For use in water extraction, **water passed trough a futher distillation plant** (Princeton) .

13 The **electronics has been carried out in Genova**: Sandro Vitale, Gemma , Marco Pallavicini, Vittorio Lagomarsino. Process electronics (LABEN) has been installed already in 1999. **Later the fast ADC by Paris7** (and Moscow Univ.)

14 **Precision cleaning of all lines done with a *cleaning module* with proper acids and detergents** (Corrado, Aldo)

15 PC procurement (Marco Giammarchi, Scardaoni). **difficult agreement with Polimeri Europa** (Enichem) in Sarroch-Sardinia. **Special production** sessions: **oil from very old and deep layers** (Libia) **to have low ^{14}C content; in the distillation tower** the **production of the PC was reduced to have a better distillation;** permission to install in the company site **a special unloading station and connection lines** between production towers and the station with **clean materials and clean procedure;** request for a space to install a laboratory **to analyse the produced PC to check the transparency** (Marco, Ortica); **production only during the day until 1 isotank would be filled. We oeganized the** logistics so that the isotanks, **once filled, reached the underground laboratory in about 18 hours in order to minimize the production of radioactive nuclides** (such as ^{7}Be) **by cosmic rays. At GS** we had to move **the loading station** out of Hall C, forced by Opera, in a recess of **the TIR Gallery** underground, setting up **a safety area** (Tartaglia with Barone) in agreement with the firemen. **PC checked on the CTF to measure the ^{14}C.**

16. Storage area- **The four PC tanks** made by Walter Tosto, were treated like all the detector vessels, **pickled and passivated d**irectly at the production site (Laura Perasso). A **retaining wall has been built around defining a volume corresponding the whole content of the 4 vessels;** an **automatic cooling system** starts operating when the containers were increasing their temperature; **a fire extinguishing system starts** also operating automatically when needed, while various **oxygen sensors** give signals in case of danger (Tartaglia with the engineering department of the laboratory.)
The 4 storage **tanks are equipped with rupture discs;** in order to avoid that, in the event of overpressure, any breakage of the discs **could lead to the emission of gases and vapors noxious / toxic at high temperatures in Hall C , all the rupture discs have been connected to a blow-down system that collects these gases and leads them to a tank full of water and metal material:** in this way it is possible to reduce both the temperature and the pressure of the vapor / gas flow. This system has never needed to operate (Sergio Parmeggiano, Roberto)).

17. Purification plants- The **low pressure distillation column** was built in Princeton, mounted inside a **skid, with ultrafiltration; the skid was sent directly to the underground laboratory**. The **water extraction system** was set up in Hall C in a vessel built with all the necessary cares to preserve radiopurity.

18 The PC was **distilled and filtered during the filling** of the detector; a 30 g per PC liter **of PPO solution (master solution) was prepared, water extracted and independently filtered**. The filling took place simultaneously with the buffer PC and the PC in the Inner vessel which was gradually mixed with the master solution.
The whole operation was very delicate because it was necessary to proceed with a simultaneous filling of all the parts of the detector maintaining the same levels in order to avoid pressure variations that would have broken the IV. **In 2010, we proceeded with a further purification using water extraction in batch, because the scintillator was already in the IV, reaching something x** 10^{-19} **/** 10^{-20} **g/g .**

19. Exhaust system. All the tanks and lines containing the scintillator are in a nitrogen atmosphere and the **free surface of all the tanks has a nitrogen blanket with a very light flow.** All flows are collected and directed to the **Exhaust system,** present in the TIR gallery, which consists of two large tanks containing **activated carbon filters** (n. 2 charcoal filters), and fans for recirculation. The filters work alternately. when a filter goes into saturation, a switch starts the other. The "spent" activated carbon is regenerated by an external company. **After the activated carbon**, the **gas passes through a VOC (VOC = Volatile Organic Carbon)**, which measures the concentration of PC (it has never found signals higher than its sensitivity) . After the VOC test the nitrogen **is released in the TIR Gallery**.

20 When **Alessandro Bettini** started the direction of the laboratory in **1997-1998,** he realized that what the Abruzzi region required for building in **seismic areas** was completely inadequate and he was right. So he asked us **to review our projects and our facilities**. This worries me a lot because both the SSS and the WT were in an advanced stage of construction. First of all it was necessary to have an idea of what the real seismic problem was and then to adapt the structures of Borexino. I looked for two very expert persons at the Politecnico di Milano and I found them in prof. **Faccioli, an earthquake expert** and also a member of the European commission for a seismic map of the EU entire territory, and in prof. **Castellani, Director of the Institute for the constructions in seismic area.** The first **produced a detailed document with the profile of the possible earthquake with the PGA (= Peak ground acceleration) which varied between 0.12 and 0.13 and a magnitude between 5.7 and 6.5.** The laboratory, after consulting other professionals as well, adopted Faccioli's work as a reference. Consequently Castellani re-made calculations taking into account Faccioli's predictions and he did **not find much to change with regard to the SSS, while for the WT he prescribed the external reinforcements with steel profiles around the structure**. Also the construction project which contains, among other things, the electronics, the counting room, etc. was heavily reinforced. Unfortunately Faccioli was completely right because the **Aquila earthquake that occurred a few years later followed the profile and magnitude he predicted.**

21. Water disposal. Water resulting from operations that have potentiallycontaminated it, is sent from the hall C to 3 **tanks of $10m^3$ in the TIR gallery** and then disposed via road tankers, as "authorized waste". The water produced by the **plant purification, but not used, must be disposed** through the two tanks of the flip flop which, **after analysis with the TOC (=Total Organic Carbon) instrument,** it is discharged directly into the wastewater network.

22 It is also important to remember the work done by our **German colleagues on an alternative scintillator**, the 1,2 -dimethyl-4- (1-phenylethyl) -benzene (phenyl-o-xylylethane, **PXE**) as solvent and 1,4-diphenylbenzene (para Terphenyl, p-Tp) as primary and 1,4-bis (2-methylstyryl) benzene (bis-MSB) as secondary solute. The text was done at the beginning of 2000 in the CTF. Its most important properties concern: density, approximately equal to 1 to be compared with the 0.85 of the PC; the Flashpoint at 145 ° C compared to the 45 ° C of the PC; the presence of ^{14}C at 9.1 10^{-18} ^{14}C /^{12}C to be compared with the 2. 10^{-18} of PC. As far as purification is concerned, the test is not complete; the operation was done with a Silica gel column. **I don't have a complete recollection of why we preferred the PC: I think it was connected with the test successfully done in the CTF and the doubts we had about Silica gel; besides we had already dedicated time and work to PC .** There where also some doubts on the PXE ability in the α/β discrimination and in the light yield, both worse than in PC. This work was done mainly by Stefan Schoenert with Harding and with the help of Frank Hartmann. The related article was published only in 2008. NIM A, 585, 1–2, 21, 48

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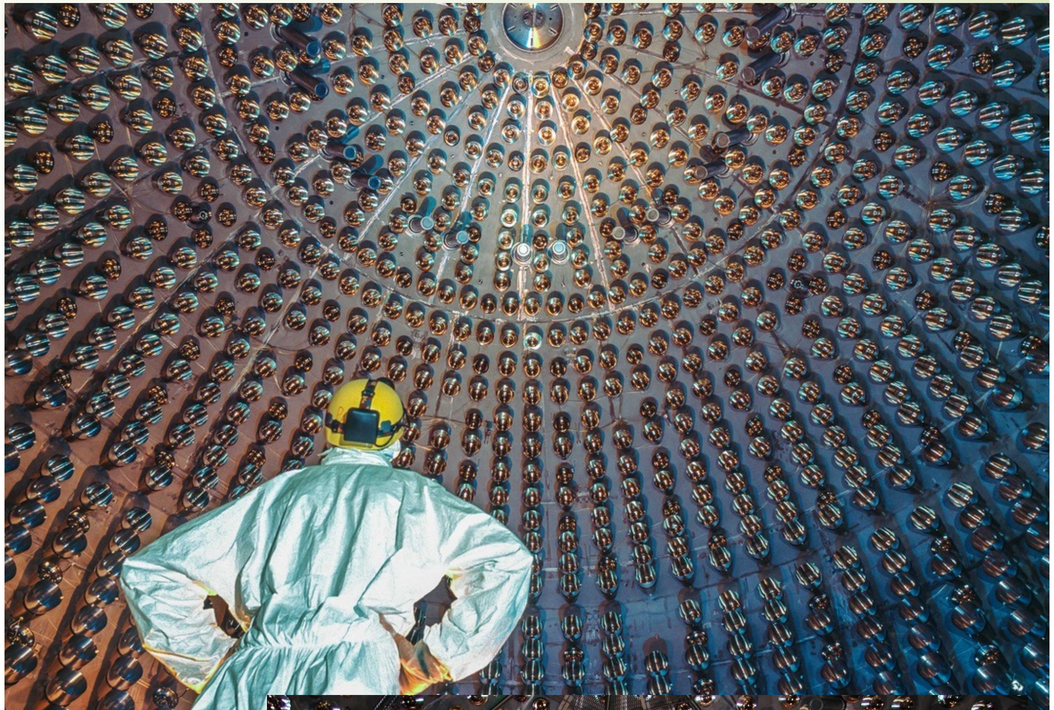
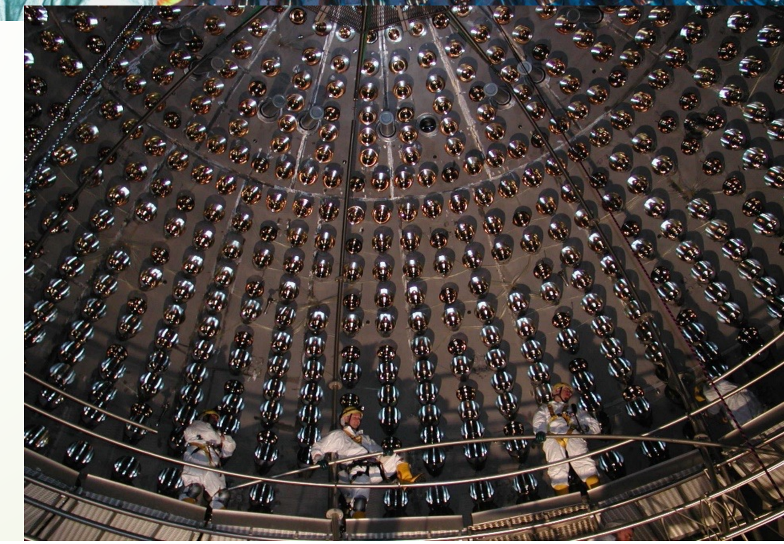
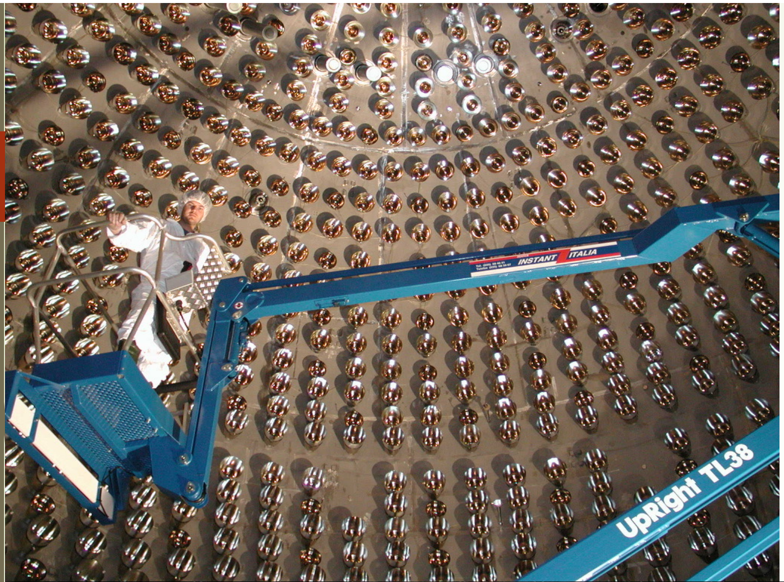
Installation of the **optical fibers-** Lino (Barbara)

Paolo is contemplating the work done with Augusto and the Cooperativa guys.

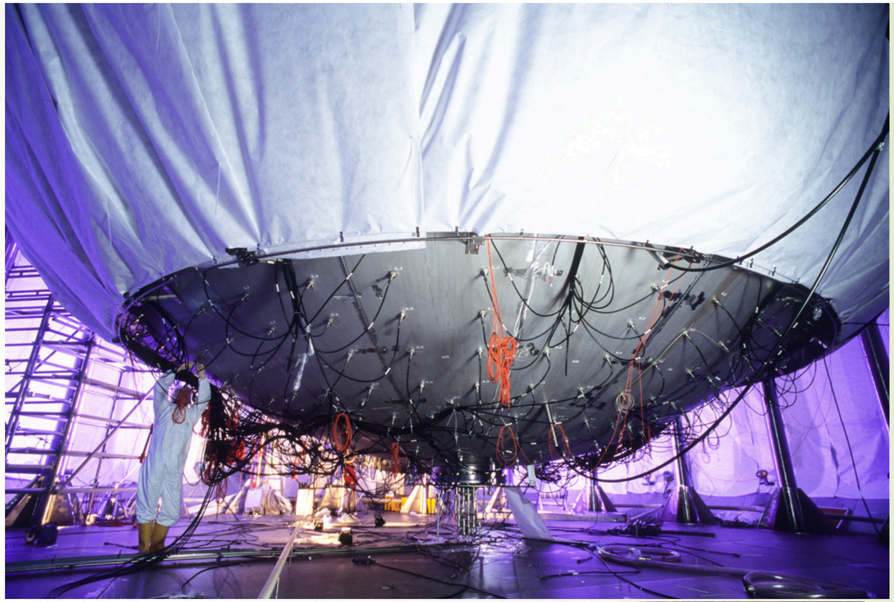


dismantling of the scaffolding

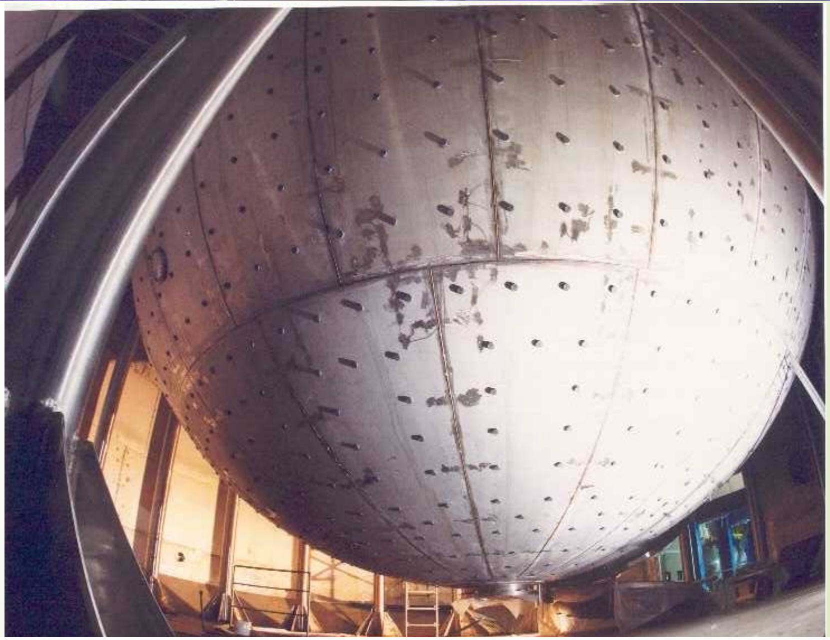




bottom of the IV, once installed



SSS




Gianpaolo Bellini

Aless., Gemma , Barbara

Gemma, Paolo

Gianpaolo Bellini

Elena

Laszlo

Augusto

Installation of the Taivek inside the Borexino wate tank.;the ladder is part of the scaffolding on the SSS outer surface

In the CL4 – class 10-100

Management before 2007 , Black years

Phase 1

Since the work began in 1990, I served as a spokesperson, a role which I have played, in agreement with the collaborators , as a coordinator of all activities. This proceeded well until the start of the work for the Borexino detector in **1996, when the coordination became more difficult** because the groups had grown and **the group leaders tended to direct the activity of the group members regardless of my decisions and those of a body I had created, called Executive Committee.**

So I took the initiative to establish three things: the presence of **a site manager in hall C**, position held by Roberto Tartaglia; a **project manager** for whom Paul Lamarche was appointed in 1999, replaced in 2000 by Lothar and in 2001 by Gioacchino; a **weekly meeting, on Tuesday,** with all the members of the collaboration present at Gran Sasso, technicians included. Normally I was present at 90% of these meetings which were very useful for the coordination.

We proceeded in this way, with an organization not fully satisfactory, **until 2002 when in August**, in a period in which the laboratory had asked not to carry out important operations because **part of the staff was absent, and we had decided to not do operations because many responsible were absent** and I could not be present also due to family reasons, **those present at the meeting decided to go ahead anyway and the operator**, misinterpreting the behavior of a valve and believing that it was closed when it was open and vice versa, **caused a spill of PC, what we estimated in about 30 liters, in a creek** that from the Gran Sasso goes towards the Teramano crossing Isola del Gran Sasso.

The black period

Since the beginning, the laboratory had always been attacked by environmentalists from the Teramo side, probably because those who had advantages, in terms of working positions and orders to the companies, were mainly from L'Aquila area.. So it was like **throwing a lit match in a gasoline-littered area**. The **reaction was very violent and also involved the court of Teramo** which decided **to suspend our activities first by locking the hall C;cafter a few months the Hall has been open but we were forbidden us to use any liquid.**

A commissioner was appointed who decided two things: to make **Hall C completely waterproof** and **to review all the Gran Sasso aquifer** that was used as city water by the taramans. **The first operation was done fairly quickly also with our help and the hall C was waterproofed as a submarine.** The question of the aquifer, on the other hand, never has been faced.

It was a really difficult period because, not knowing what the prospects were (many even thought that we would never start again), **a consistent part of the collaboration left, especially the majority of the US young people**, because, having only temporary contracts, they needed to have assigned new contracts and for that they needed results. But we didn't have a real area in which to try to prove that it wasn't plants problem but human error. **Among other things, I, Gioacchino, the operator who had made the mistake , two persons of the lab. staff, the director Bettini and the INFN president at the time, Iarocci , have been denounced by the judge** for the preliminary investigations and we underwent judicial interrogations and more.

We had many meetings, almost weekly, with the inspector's people fully useless, we were accused of various things, but when we tried to answer , they wouldn't let us explain. **It was all very frustrating**.

Finally in **mid-2004 the judge decided that we could resume our work**. I and two others did not go to trial but we had to pay a kind of fine of some thousand euros. We were also denounced by the Corte dei Conti which argued that the region had to incur expenses, but at the end we have been all acquitted.

Phase 2

After the reopening we changed the management. **The winning decision was the appointment of an operational group including members of the collaboration, but independent from the groups of origin and directed by Augusto Goretti**; I had some discussions with the leaders of the groups but eventually they accepted this decision. We converted the Executive Committee into a **Steering Committee** , **including engineers and physicists expert in the operations, directed by Marco Pallavicini.** It was very important that Augusto and Marco proceeded **without taking into account some, but rare, interferences of the group leaders.** Andrea Ianni was appointed as site manager while Stefano Gazzana always maintained his role of GLIMOS. It seems fair to remind that Augusto Goretti has assumed this role without problems.

The work was resumed and proceeded without major troubles. In the meantime, I made contact with an electrochemical plant in Sardinia and **I succeeded to find a group leader who had worked for many years in the petrochemical sector and who was retired: Rossati. He found two operators with a lot of experience in the petrochemical sector and also retired: Cubaiu and Sorricelli.** We given a contract to all three, who then began to **review all the systems in contact with the PC and did a training to the operations group extended to other people as well**. After a couple of years, however, we did not renew the contract with Rossati because it was too expensive. **At the end of 2006, beginning of 2007 we first started the procurement of the PC which was stored in the storage area and proceeded to fill the detector, after having distilled the PC and purify the master solution. In this way in April 2007 we started the data taking.**

2007 party with the Borexino T-shirt procured by Stefano Gazzana.

- **In April 2007 we started taking data and already in July 2007 we presented the first measurement on ^{7}Be neutrino flux at TAUP 2007 in Sendai and Kunio Inoue**, chairperson of the conference, posted on the conference website **our results as the most important great news of TAUP 2007**

- At the beginning there were two analysis code: **Echidna**, prepared by the analysis group chaired by Gemma, and **Mach 4** prepared in Princeton. After few years we used only one code: Echidna with a few modifications from Mach 4
- Gemma has been **appointed Analysis Coordinator.**

The first publication on solar neutrino appeared in **2007** on the Taup 2007 proceedings and in 2008 on Physics. Letters (B658)- In **2009 upgraded results on ^{7}Be** are published in Phys. Rev. Lett. (101) , and in **2011** on Phys. Rev. Lett. 107, 141362 where the **flux determination is quoted with 5% of uncertainty** , **reduced to 2.5% in** the most recent publication in **2019**, Phys. Rev. D 100, 082004, obtained from the simultaneous fit on ^{7}Be, pp and pep fluxes.

The second measured flux of solar neutrinos was that of **^{8}B, with a threshold at 3 MeV** (SNO and SuperK. ~ 5 MeV) . **The reduction of the threshold is important for the upturn of the Pee in the transition region going from the matter to the vacuum regime.**
The **first paper is from 2010**, Phys. Rev. D82 033006 and **the second one in 2020** in Phys. Rev. D 101, 062001. This second one is definitively improved with respect to the first one: **uncertainty ~ 8%.**

In **2010** we published the first work on **geoneutrinos.** Before us, the Kamland experiment had already observed antineutrinos from the Earth interior, **with evidence of about 2.5 σ. In 2010 we achieved > 3 σ evidence**. For this study a small group from Ferrara joined our collaboration. In our group there was also Livia Ludhova, who joined in 2006-2007; she had obtained two PhDs, one in physics and one in geology, so she had a very useful know-how for this study. The study of geoneutrinos then continued with three other articles: in **2013**, Physics Letters B, 722, 295; in 2015 Phys. Rev. D 92, 031101 (R), where **we reached evidence > 5 σ**; and finally in **2020**, Phys RevD.101.012009, which all data collected by Borexino from December 2007 to April 2019, corresponding to **3267.74 days of data taking**.

In 2012, Phys. Lett. B, 707, 1, 22, we published a paper concerning the day–night asymmetry in the ^{7}Be solar neutrino rate, which we found to be null. As a consequence **the LOW region at about Δm^2_{12}= 10^{-7} eV^2 in the space $\Delta m^2_{12} vs\ tang\ \theta_{12}$, is excluded at more than 8.5 σ using only the Solar neutrinos experiments results, without need of Kamland antineutrinos an therefore without using CPT-**

Between 2009 and 2010 we proceeded to calibrate the detector using 11 artificial sources plus a vial with ^{222}Rn loaded scintillator. This calibration allowed to study the uniformity on space of the detector energy response and the position reconstruction.. The source positioning system is made up of a series of interconnecting hollow rods, put together in one arm which can be bent up to 90° inside the scintillator. On top of the detector the CL4, class 10-100 is installed, which houses all the related operations with a glove-box. The whole system, from gas pressures to flow rates in the glove-box and to the interconnected instruments are monitored automatically. This work has been specially coordinated by Barbara and Bruce with the participation of other persons. The vial and the movable arm have been prepared in VT. JINST 038P (2012) 0712.

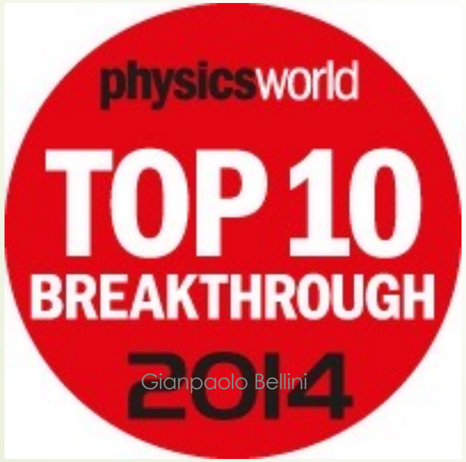
Two pictures concerning the calibrations

Livia and Sandra working on data analysis

Seasonal modulation of the solar neutrino flux, Astroparticle Physics, 92 (**2017**) 21-phase 2 (previously Phys. Rev. D 89 (**2014**) 112007- phase 1) . It is due to the change of the Earth-Sun distance, caused by the eccentricity of the Earth's orbit. The variation follows a sinusoidal shape with a period of one year and a maximum flux difference of about 7%. **Analysis done using 4 years of data. Results in very good agreement with the expectations (systematic 10%). This measurement demonstrates directly the solar origin of the neutrinos, even if it was implicitly demonstrated by the neutrinos energy spectral shape in agreement with the expectation from the nuclear reactions producing them.**

In 2**012** (Phys. Rev. Lett. 108, 051302) we published the measurement of the neutrino flux from the **pep reaction** (and also in Phys. Rev. D 89:11 (**2014**), 112007) . An upgraded analysis is published in ***Nature*** **562 (2018**) 505 with **an uncertainty of about 17%.**

In **2014** we measured the neutrino flux from **the pp reaction. progenitor of the whole pp chain** (Nature 512, 383-386) **This measurement is the most difficult due to the low neutrino energy, whose flux ends at 420 keV with a maximum of 264 kev. The greatest interference is due to ^{14}C**, which has a Q-value of 156 keV. The determination of the flow **was obtained with a total uncertainty of about 11%.**



The **results on pp, ^{7}Be, pep, measured by a comprehensive fit** in "Nature, 562, (2018) 505" under the title: "**Comprehensive measurement of pp-chain solar neutrinos**», giving also the ratio between the two branches pp-II / pp-I of the pp chain. Since this chain produces 99% of all solar energy, we were able to compare **solar luminosity via neutrinos and via photons by demonstrating the thermodynamic stability of the Sun in a 10^5 years scale.**

CNO .Immediately after the publication of the pp progenitor solar neutrino measurement , we began to think on the CNO measurement. **Since time the residual ^{210}Po, present in the scintillator, was monitored (**Nicola Rossi) and we have observed that **in December 2013 the normal decay of ^{210}Po out of the secular equilibrium was interrupted by a spike**. Therefore it seemed clear that we had to **stabilize better the detector temperature**, and, in **December meeting, we decided to proceed with the thermal insulation**. We succeeded to **complete it only in 2016 by adding also an active temperature control** with the installation of copper coils below the insulation. We soon realized that **for a real stabilization of the temperature it was necessary much more time, but in the meantime SOX loomed** and in any case the skepticism of many collaborators began who thought that we never will succeed to measure the CNO.
When the SOX program stopped due to the unsuccessful preparation of the source by the Russians, it was the end of 2017. **We then restarted with a very collegial effort on CNO. Everyone then knows the sequel that resulted in the 2020 publication in Nature, 587, 577**


European Physical Society
PRIZE

The 2021 Giuseppe and Vanna Cocconi Prize
for an outstanding contribution to Particle Astrophysics and Cosmology

is awarded to the

Borexino Collaboration

for their ground-breaking observation of solar neutrinos from the pp chain and CNO cycle that provided unique and comprehensive tests of the Sun as a nuclear fusion engine.

Luc Bergé
President
European Physical Society

Thomas Gehrmann
Chair
EPS High Energy and Particle Physics Division

Mulhouse, France, 26 July 2021

Larger collaboration and adjustments in the management.

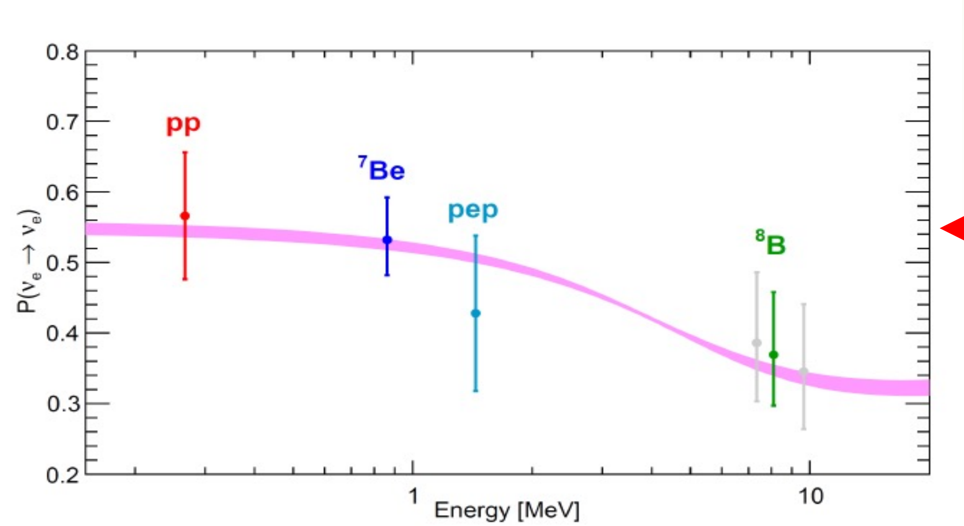
During the construction, data collection and analysis of Borexino, the collaboration expanded with new groups created mostly for parthenogenesis and for the increase of the groups members to which also young people joined in recent years. **Currently the collaboration groups are the following:**
APC, Politecnico di Milano, Forschungszentrum Jülich, Ferrara, Genoa, LNGS, Milano I Univ., J.I.N.R. Dubna, Mainz, Kurchatov, Lomonosov Univ, Jagellonian Univ., Princeton, Petersburg Nuclear Physics Inst., Dresden, T.U.M., Perugia, Amburg, Amherst, Houston, VT

In 2011-2012 I declined as spokesperson in favor of three younger persons: Galbiati, Pallavicini, Ranucci; in **2014 Marco resigned judging that conflicts of interest** could have been created with his new position as president of the INFN II committee**; in 2016 Cristiano resigned and shortly after Marco became Co-spokesperson with Gioacchino**

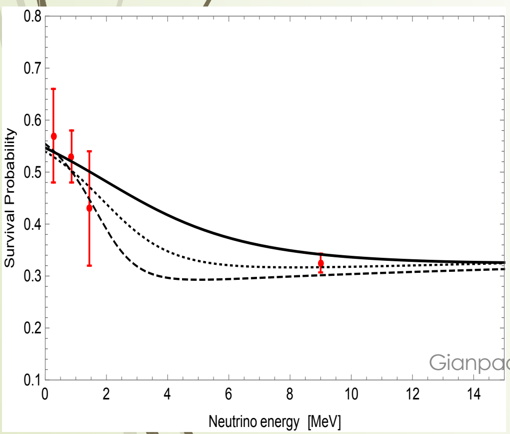
In **2018 Gemma declined as analysis coordinator in favor of Barbara and L**ivia

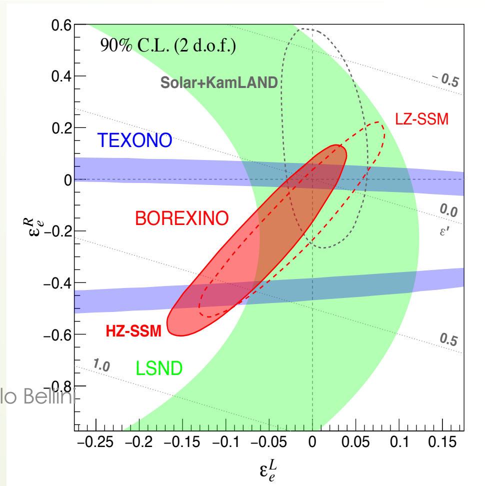

Gianpaolo Bellini

Our results on Sun and stars are very interesting for astrophysicists and astro-particle physicists. But there is a result that is of great interest to physicists and neutrino physics that **concerns the survival probability of the neutrino- electron** in connection with the oscillation phenomenon.



The results obtained in this plot by Borexino are very important because **the oscillation in the vacuum regime was observed for the first time a**nd with only one experiment **all energies from the vacuum to the matter regime were explored.**
What is still missed is the shape of the transition region, not clarified yet. The results of Borexino give some usefull indications but the uncertainty is still large. In the ^{8}B region the results of Superkamiokande have minor uncertainties and could indicate the real existence of the upturn.





However, **this is not enough to exclude, for example, the existence of non-standard neutrino interaction which inflences the shape of the transition region which should be different from what expected by the MSW-LMA model.**
We have studied the possible existence of flavor-diagonal NSI (JHEP 02 (2020) 038) by greatly contributing to restrict the area still allowed to the **strength parameters** ε , but this does not mean that we have already ruled out the existence of the NSI.

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2. Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data, Phys. Rev. D 96, 091103(R)
3. A Search for Low-energy Neutrinos Correlated with Gravitational Wave Events GW 150914, GW 151226, and GW 170104 with the Borexino Detector, The Astrophysical Journal, 850-21, Nov. 2017
4. Borexino's search for low-energy neutrino and antineutrino signals correlated with gamma-ray bursts Astroparticle Physics, Volume 86, January 2017, Pages 11-17,
5. A test of electric charge conservation with Borexino Phys. Rev. Lett. 115, 231802 – Published 3 December 2015
6. New limits on heavy sterile neutrino mixing in ^{8}B decay obtained with the Borexino detector, Phys. Rev. D 88, 072010 – Published 29 October 2013
7. Cosmogenic Backgrounds in Borexino at 3800 m water-equivalent depth , Journal of Cosmology and Astroparticle Physics, Volume 2013, August 2013
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Measurement of CNGS muon neutrino speed with Borexino Physics Letters B, Volume 716, 3–5, 2 , 2012, 401-405

Finally........

A unique experiment, Borexino, has now answered to the millennial question of mankind on how Sun and stars are able to shine.

and now........

I have to thank all members of the collaboration who during three decades come and gone; among them all, about 15 started their work in the early '90s and are still working on the experiment now. Frank, even if sometimes we didn't always agree, has been a great fellow in this enterprise.
But I must remember the 14 collaborators who passed away and I want to recall their names:
Cristina Arpesella, Gianni Bacchiocchi, Alain de Bellefon, Martin Deutsch, Burkhard Freudiger, Hervé de Kerret, Istvan Manno, Andrey Martemianov, Ugo Mazzuccato, Simone Marcocci, Raju Raghavan, Corrado Salvo, Sandro Vitale, and Oleg Zaimidoroga.
But fortunately, during this time, **many more children were born to young Borexino collaborators**

I want to close this summary of Borexino's activity **by saying that this project leaves a legacy to young researchers not to be afraid to engage themselves in very challenging experiments because the important discoveries mainly come from endeavors**, and, in this regard, I would like to mention a sentence of John N. Bahcall, father of the Standard Solar Model and a Borexino's great friend and supporter:
The most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects we have not yet imagined" (J.N. Bahcall in "How the Sun Shines", 2000, Nobel e-Museum (astroph / 0009259)

Thank you for your attention!