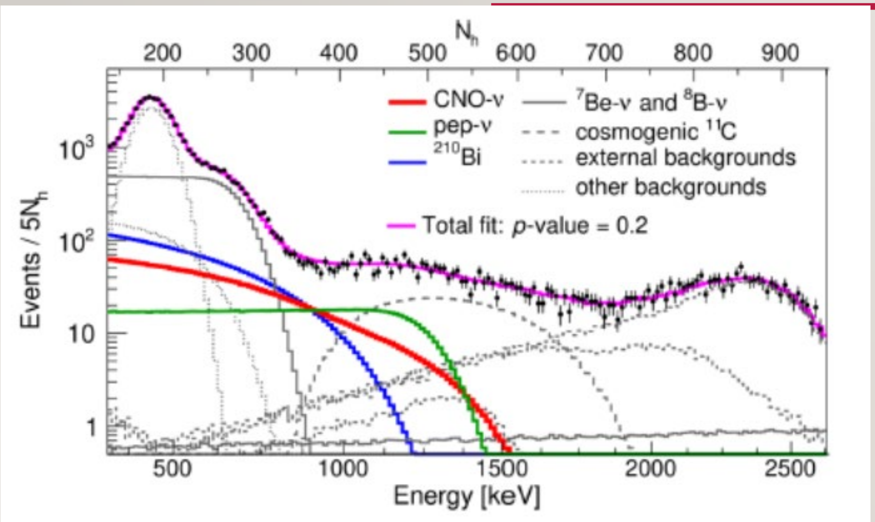
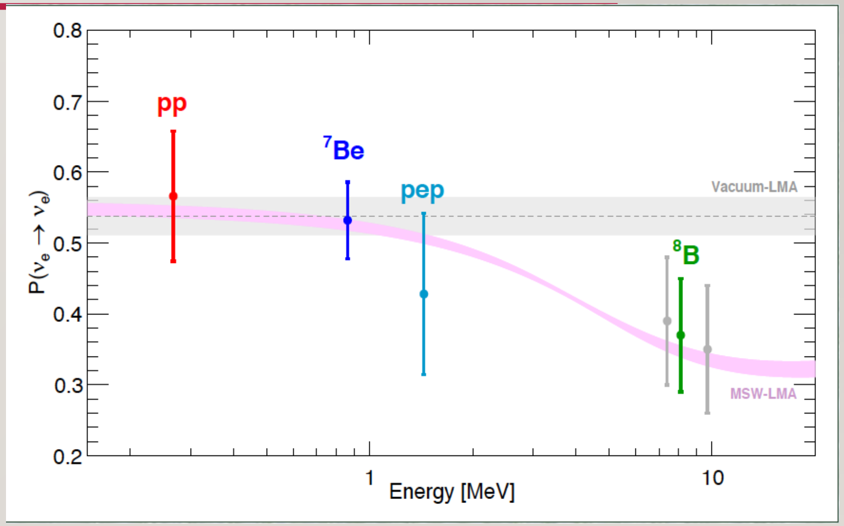
# THE CHALLENGE OF BOREXINO




Gianpaolo Bellini Università and INFN- Milano- Italy

# Why challenge

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**Goal.** Spectral measurement of solar neutrinos including the very low energy part with energy threshold well below 1 MeV

## Situation in the early '90 of the last century

- Solar neutrino problem still open- experiments on solar neutrinos in preparation as radiochemical Gallium based and Cherenkov experiments.
- The Cherenkov exp. had to fix a threshold at 4.5-5. MeV due to natural radioactivity and lack of light; then only a tiny fraction (~0.01%) of the total flux is studied
- Radiochemical expt, cannot separate various solar neutrino fluxes

# Why challenge

- Then only an extreme radiopurity never achieved before could have allowed such an experiment

- Those who had faced such a feat before, had quickly given up

- We were surrounded by the skepticism of a large part of the scientific community and this caused some early collaborators to leave before starting. This skepticism partly continued even during the experiment as we proceeded with progressively more difficult measurements

- Our luck was to find a Director of the Gran Sasso laboratory who gave us the needed underground space and a INFN President who understood the potential of the project and shared the risks with us, deciding to finance it

# Borexino strategic choices

- Compact volume: involve as little material as possible (all materials are radioactive)
- Scintillator: high light yield and low light quenching-organic liquid scintillator easier for radio-purification: a hydrocarbon, Pseudocumene-PC as solvent plus a fluorescent dye-PPO (1.5 g/l) as solute; 500 p.e./MeV with 30% coverage-
- Strong scintillator radiopurification- a gain of 6-10 orders of magnitude – High radiopurity of the detector and ancillary systems: custom and home-made components
- An instrument able to measure the extreme radiopurity as per project demands: Counting Test Facility

# A bit of history

| 1988-1990 | 1990-1995 | 1996-2007 | 2007-2010 | 2011-2016 | 2016-2021 |
|---|---|---|---|---|---|

Discussions started Involving mostly Milano, Princeton, Munich TUM and two other Italian institutions . These discussions continued until 1990.

R&D program to study and implement methods to achieve a radiopurity at least 10 orders of magnitude higher than that present in most solids and liquids.

The Counting Test Facility demonstrates the achievement of radiopurity as per design

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Construction, installation and tuning of the detector- Nothing is standard in Borexino. Detector filling with purified scintillator

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**2007-2010:** First phase of data taking

**2010-2011:** 17 months of a second scintillator purification

**2011-2016:** Second phase of data taking

Measurements of the single fluxes of the pp chain nuclear reactions emitting neutrinos- Test and confirmation of MSW effect

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**2011-2016**
17 months of a second scintillator purification

Second phase of data taking

Measurements of the single fluxes of the pp chain nuclear reactions emitting neutrinos

**2016-2021**
Third phase: detector thermally insulated

Detection and measurement of the CNO cycle

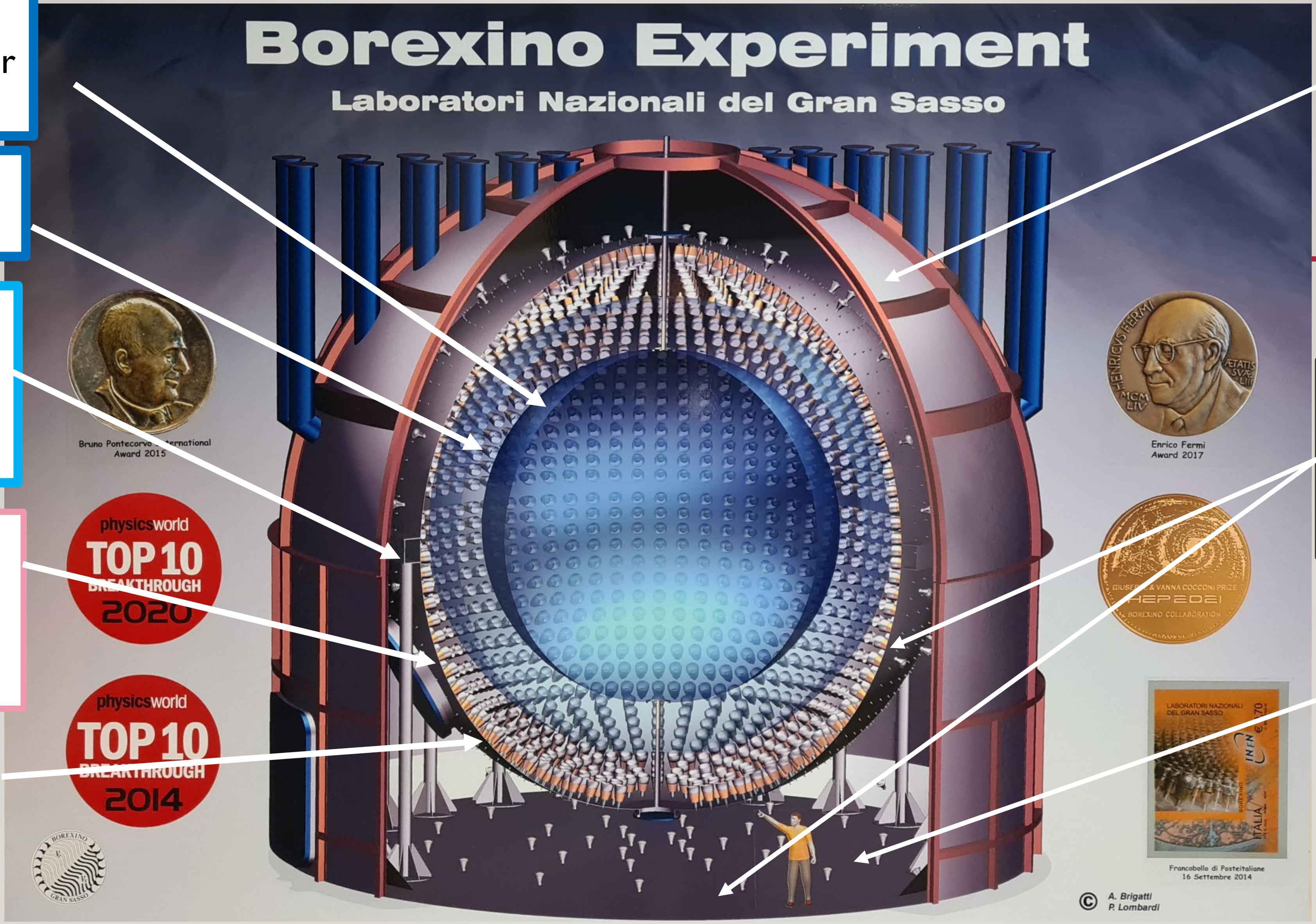
278 tons of
liquid scintillator
PC+PPO

IV-125 μm thick
ultrapure nylon

OV 2nd nylon
Vessel- barrier
against emission
PMT and SSS

SSS (6.85 m
radius),
supports 2212
8" PMTs

Buffer liquid
600 t PC+
DMP (3.5 g/l)




*WT*, 16.9 m high and
9.0 m of radius; 2400 t
ultrapure water.

TYVEK to enhance light
collection on the SSS
outer wall and the WT
inner walls

200 PMTs- muon veto

# Detection principle

$\nu$

$$\nu_x + e \rightarrow \nu_x + e$$

expected counts ~50 cpd/100t

$\bar{\nu}$

**Prompt:**

$$\bar{\nu}_e + p \rightarrow n + e^+$$

$E_{thr}$=1.8 MeV

**Delayed (τ~254 μs):**

$n + p \rightarrow d + \gamma$

*Detected energy: 2.2 MeV*

Threshold: 1.8 MeV

**Fiducial volume**: from total IV to 78 t, depending on the analysis
**Threshold**: down to ~ 150 keV

# The key condition for a success is a radio purity pushed to ultratraces level

$^{238}$**U** and $^{232}$**Th** and their progeny (in LS $\lesssim$ **10$^{-16}$ g/g**); $^{40}$**K** (LS $\lesssim$ **10$^{-18}$ g/g**), $^{222}$**Rn** (< 1 cpd/100 t), submicron dust particles containing **K, Th, and U oxides** (advanced cleaning); Noble gases (**Ar, Kr**): radioactive isotopes that soluble in PC. (Kr:anthropogenic /Ar:cosmogenic )
**All background sources should produce < 1cpd/100ton** in LS

$^{14}$C cannot be purified; so it must pay attention on the procurement

scintillator

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**scintillator**

**Ultrafiltration**
0.05 μm- for particulate, $^{40}$**K,** $^{238}$**U** and $^{232}$**Th** and their progeny

**Distillation**: $^{238}$**U** and $^{232}$**Th** and their progeny and PPO concentrated solution-
Distill. at 80°to avoid contaminants from the distillation column materials
PPO- Solid, contains $^{40}$K at ppm level: high concentration master solution

**water extraction**: to remove water soluble contaminants -PPO solution, scintillator.
**Countercurrent column**

**gas stripping** with ultraclean nitrogen- removal of dissolved Ar, Kr, Rn, and also oxygen which spoils scintillator light yield

**Advanced cleaning**
submicron sized dust particles containing K, Th, and U oxides

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$^{14}$C needs particular attention because it cannot be purified so you have to pay attention on the procurement

Detector filling with scintillator, treated with Ultrafil., distill., stripping In batch

Second purification in continuous with Ultrafil., WE., stripping

**scintillator**

**Ultrafiltration** -0.05 μm- for particulate - $^{238}$**U** and $^{232}$**Th** and their progeny

**Distillation**: $^{238}$**U** and $^{232}$**Th** and their progeny-PPO solution at 80°C to avoid contaminants from the distillation column PPO- Solid, contains ppm $^{40}$K-, master solution 13 wt%

**water extraction**: to remove water soluble contaminants $^{40}$K-PPO solution, scintillator. Countercurrent column

**gas stripping** with ultraclean nitrogen- removal of dissolved Ar, Kr, Xe , $^{222}$Rn oxygen, which spoils scintillator light yield

**Advanced cleaning** submicron sized dust particles containing K, Th, and U oxides

# $^{14}C$ problem: production and procurement

$^{14}C$ $^{14}C$ cannot be purified; 2678 years lifetime, produced inside the oil by cosmic rays, neutrons and in general rocks emissions. Equilibrium level with cosmic radiation: $10^{-12}$ $^{14}C/^{12}C$- <u>needed $10^{-18}$ $^{14}C/^{12}C$</u>


**very deep layers**

**dedicated pipeline and loading station built** on the production site and treated as the detector components

Isotank $N_2$ blanketing

Isotank filled with flowing nitrogen blanket; **optical absorbance routinely made at the production site.**

Transport from Sardinia (Sarroch) to GS underground in **no more than 22 hours**, ferry included, to avoid cosmogenic production of nuclides as $^{7}Be$ radioactive

To test the reached radiopurity we built a detector having the sensitivity enough to measure the needed radiopurity (mass spectrometer with plasma source ≈ $10^{-10}$ g/g)

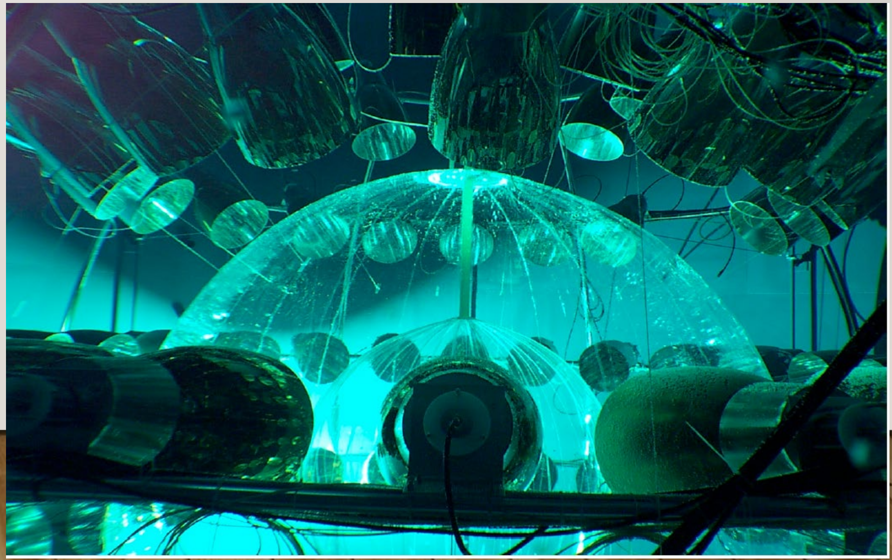
Counting test facility- CTF

5 tons of LS
100 PMTs
1000 tons of highly purified water

Purified LS resulted to be at the limit of CTF sensitivity
$^{238}U, ^{232}Th \rightarrow 5 \times 10^{-16}$ g/g
$^{14}C/^{12}C \rightarrow 2 \times 10^{-18}$

Design radiopurity
$^{238}U, ^{232}Th \rightarrow 10^{-16}$ g/g

**Borexino was doable**


The entire detector must be **built to maintain the radiopurity record achieved for the scintillator** by means of appropriate techniques and methods**- all components have been custom designed, prototyped, built, tested following in most cases unconventional approaches, treated and assembled with methods developed in-house.**

Nylon vessels. IV+OV-- IV. in direct contact with the scintillator: then its bulk and surface need to be as free as possible of radioactivity

Nylon film **125 μm thick** to have ***mass as low as possible*** in contact with the scintillator**, extruded in controlled air; handled in Class 100 cleanroom, equipped with the first-ever built radon scrubbing device and adsorption filter, precision-cleaned via non-contact ultrasonic process,**
**IV nested ad initio into the OV**, which protects the IV; **interspace between IV and OV filled with ultrapure nitrogen also maintained during installation in the SSS; the first IV filling done with synthetic air**


# Photomultipliers.

PMTs developed in collaboration with a company to implement:

- special **low-radioactivity glass** and a particular crucible to avoid possible contaminations-
- low **radioactivity ceramics and dynode cascade**,
- **low jitter time** for better spatial reconstruction
- isolated with resin for water and PC,  coupled with optical concentrators, pickled, passivated. electropolished,  mirrored; advanced cleaned


# Plants components and interconnection pipes.

The **components of all the plants have been carefully studied,** while the plants themselves have been treated with unusual methods. **Even the smallest details must be analyzed.** all material components have been selected with very sensitive detectors for low radioactivity**--** Just some examples

- All surfaces are treated with **pickling, passivation, electropolish**, sometimes **chelation** and **mirror shooting** with **roughness < 0.8 μm**, class <50 cleaning operation


# Plants components and interconnection pipes.

The components of all the plants have been carefullt studied, while the plants themselves have been treated with unusual methods Even the smallest details must be analyzed. all material components have been selected with very sensitive detectors for low radioactivity-Just some examples:.

- All surfaces treated with **pickling, psssivation, electropolish**, sometimes chelation and mirrored with **roughness< 0.8 µm**, class <50 cleaning operation
- The **tightness is $<10^{-8}$ mbar l/s every single joint and $<10^{-6}$ mbar l/s overall** to avoid external air leaks where the most important contaminants are the **$^{222}$Rn** (>100 Bq/m$^3$) and the oxygen, which absorbs light between 300 and 450 nm attenuating the scintillation light.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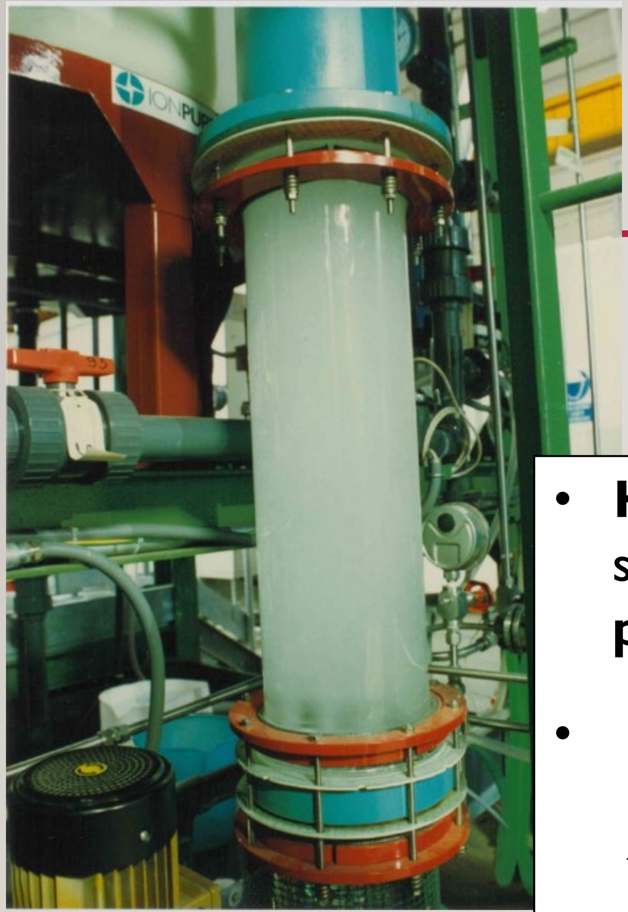
- Pumps and gaskets internal components replaced with **Teflon. All flanges, valves, VCR fitting and pumps equipped with a nitrogen purging port :** in case of failure and leaks, the scintillator would remain in contact only with pure nitrogen

## Extensive use of Nitrogen.



**Purifying agent to remove gaseous impurities** from the scintillator component, **dynamic blanket** on all vessels (liquid handling system) and detector, **plant pressurization**, filling of the gap between IV and OV, advanced cleaning

The ultimate achievable purity of the liquids is limited by the purity of $N_2$ itself

Most challenging N contaminants: $^{222}$Rn and $^{85}$Kr.

- **High Purity Nitrogen- special installed plant for** purification via 2 kg cooled selected high purity activated carbon traps in liquid phase **reaching an exceptional purity : $^{222}$Rn<1 μBq/m$^3$**

- **Low Argon and Krypton Nitrogen-**from a specialized company- **problem of recontamination** during storage- storage tank with electrical evaporators- tests with **neutron activation and a special very Rare Mass Spectrometer with a very high sensitivity:** these very exceptional measurements required long preparation and training

## Strict control of the ubiquitous $^{222}$Rn

Radon emanation measured **on or very close** to materials surface; it **is pumped or flushed** out and **accumulated in a clean carrier gas (He or N).** After two mean-lives, the radon extracted from the carrier gas is transferred **to miniaturized proportional counters with a sensitivity of a few atoms,** , **and then measured**. The **IV nylon surface and bulk emanation purity** has been measured on wet nylon, and found to be below the measurability , as expected taking into account the nylon selection

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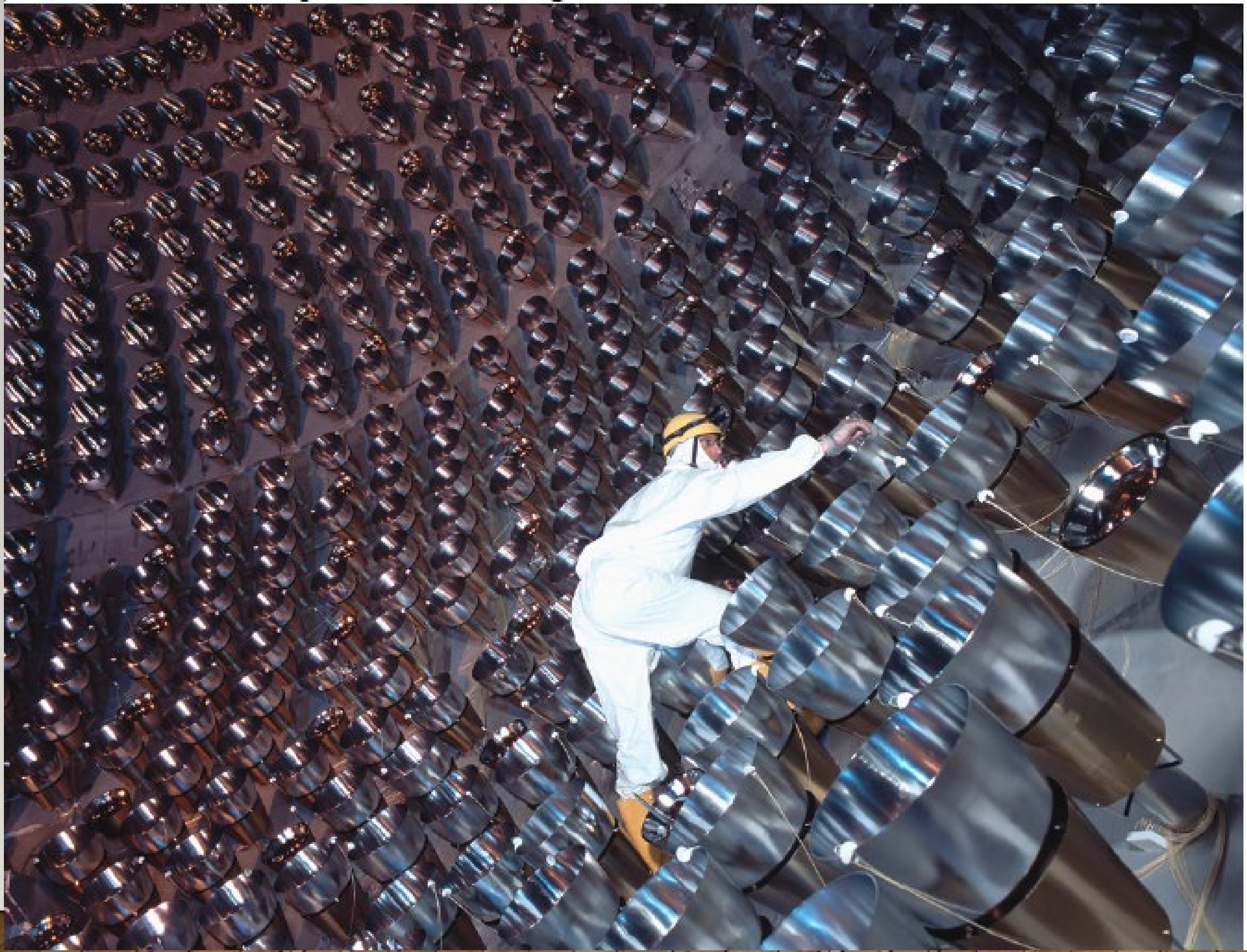
**Advanced cleaning .** Alconox detergent, ultra-pure water at 80°C at 3 MOhm x cm resistivity; < 50 dust class, 0.05 micron filtration etc during hours- special module installed-

These are only some example of the methods used in the construction of Borexino, where each components and actions have been individually particularly cared and checked

**This has been the key to success of BX which allowed its discoveries**.

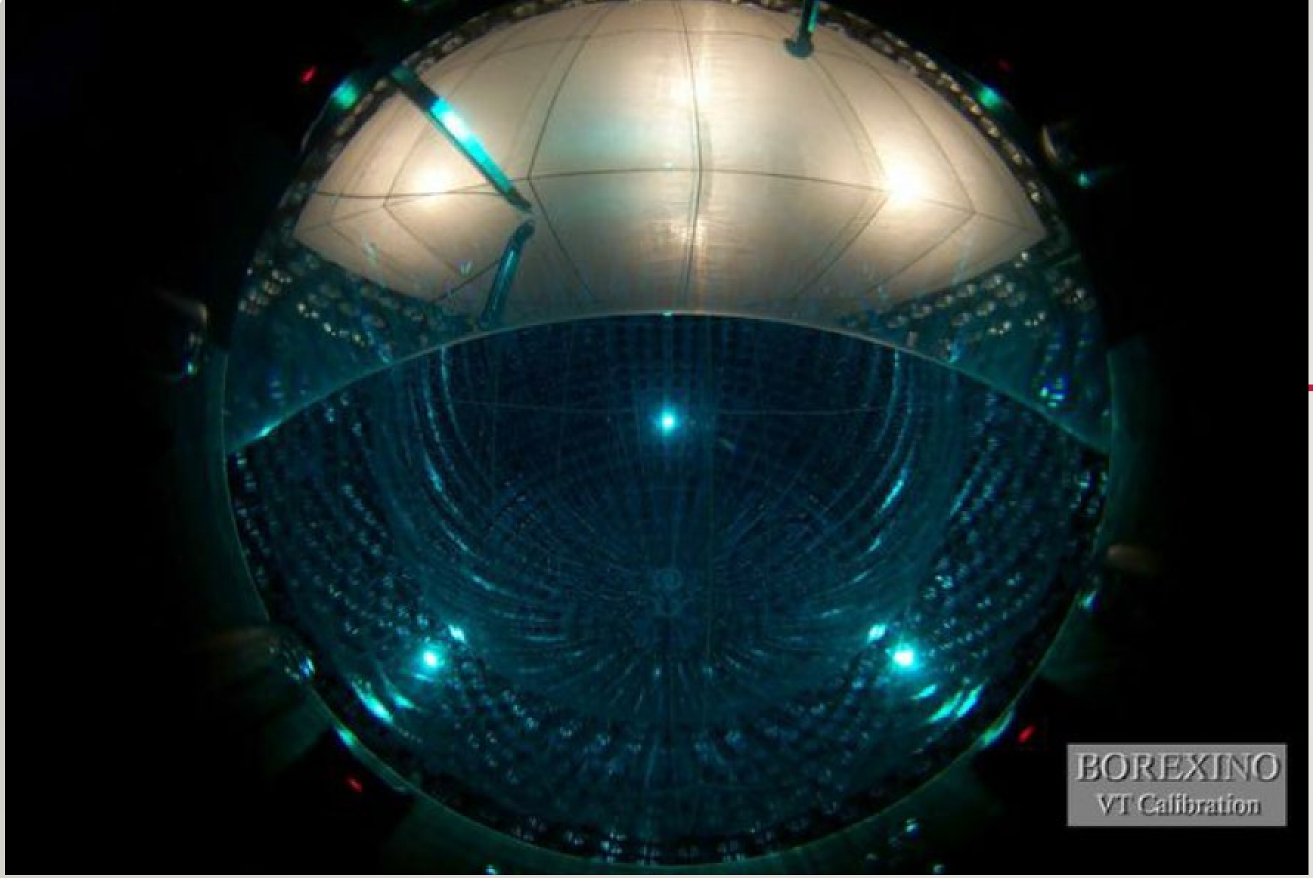
| Radio isotope | Source | Software reduction | Achieved Phase1 | Achieved Phase2 |
|---|---|---|---|---|
| $^{14}C$ | Intrinsic PC | Threshold<br>Fit on the shape | ≈ 2 $10^{-18}$ $^{14}C/^{12}C$ | |
| $^{238}U$<br>$^{232}Th$ | Dust, particulate all materials | α/β tagging<br>fit | (5.3±0. 5) 10 $^{-18}$ g/g<br>(3.8±0. 8) $10^{-18}$ g/g | <9.4 10 $^{-20}$ <5.7 $10^{-19}$ g/g<br>(95%  CL) |
| $^{85}Kr$ | Air, nuclear weapons | | 30±5 cpd/100t | 6.8±0.8 cpd/100t |
| $^{395}Ar$ | Air, cosmogenic | fit | << 1 cpd/100t | |
| $^{210}Po$ | Embedded on surfaces | fit | | 11.5±1. 3 cpd/100t<br>(Achieved in phase 3) |
| $^{222}Rn$ and its progeny | In the underground air and water | α/β tagging,<br>delayed coincidences | < 1 cpd/100t | |



Inside SSS
Equipped as a class 10000 clean room

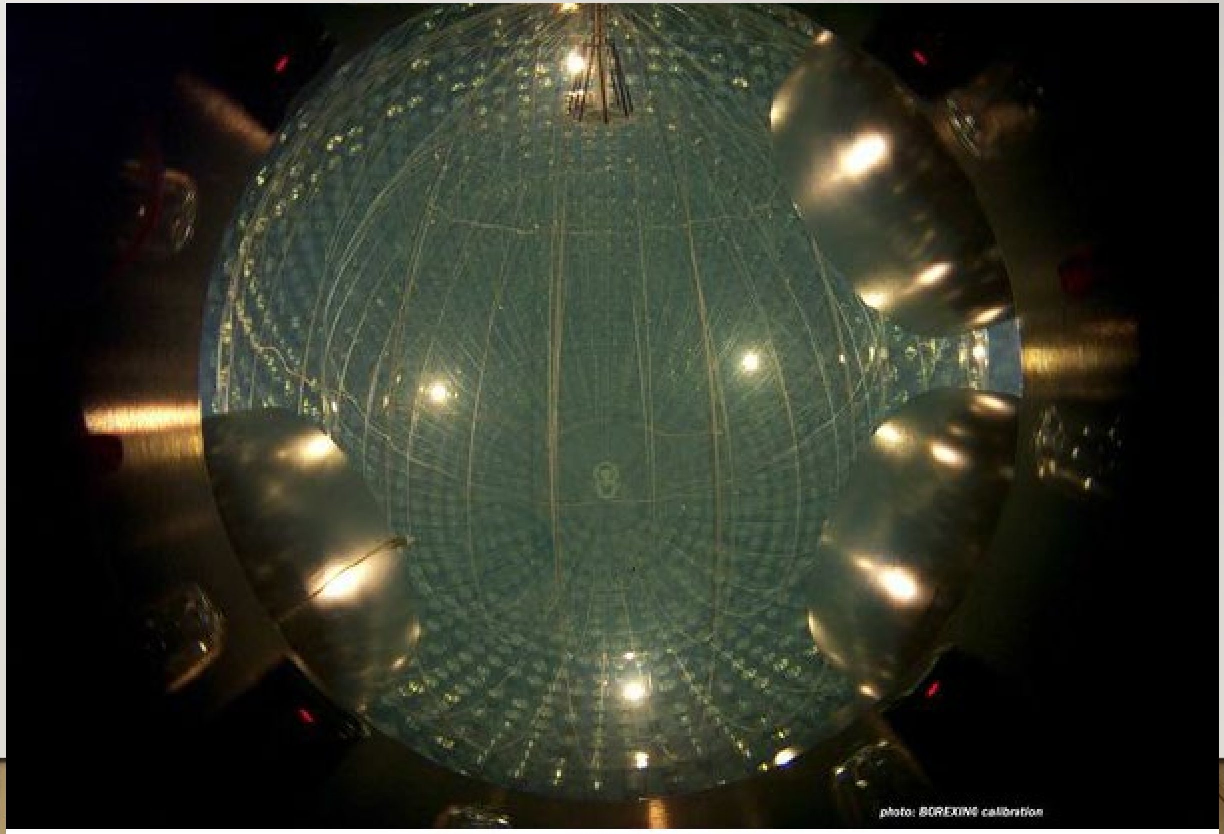
Further 5 clean room installed for Borexino

external SSS walls and WT internal walls covered with Tyvek which reflects the light emitted by the Cherenkov events produced by the muons

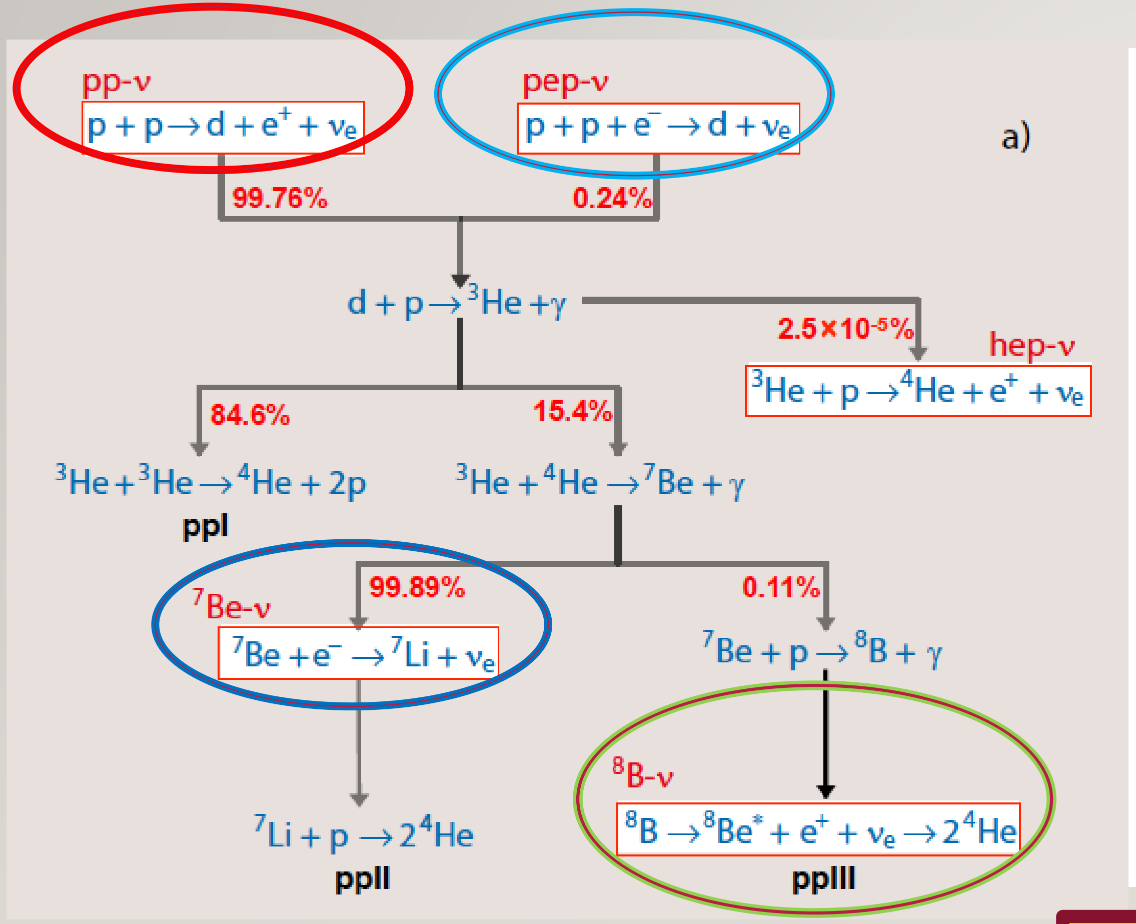


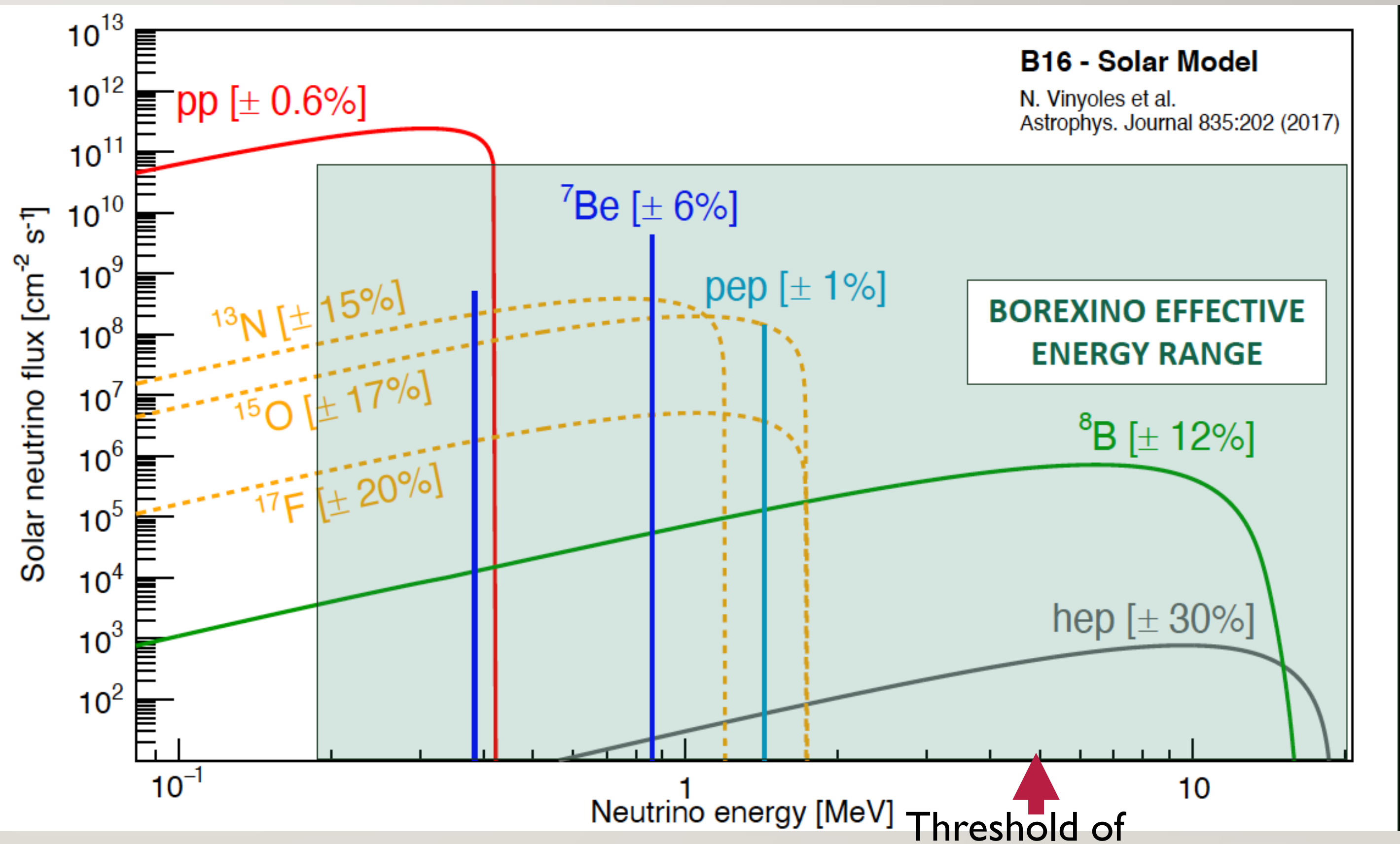

Detector during the filling

Detector filled



# Measurements of the single fluxes from the pp chain nuclear reaction emitting neutrinos

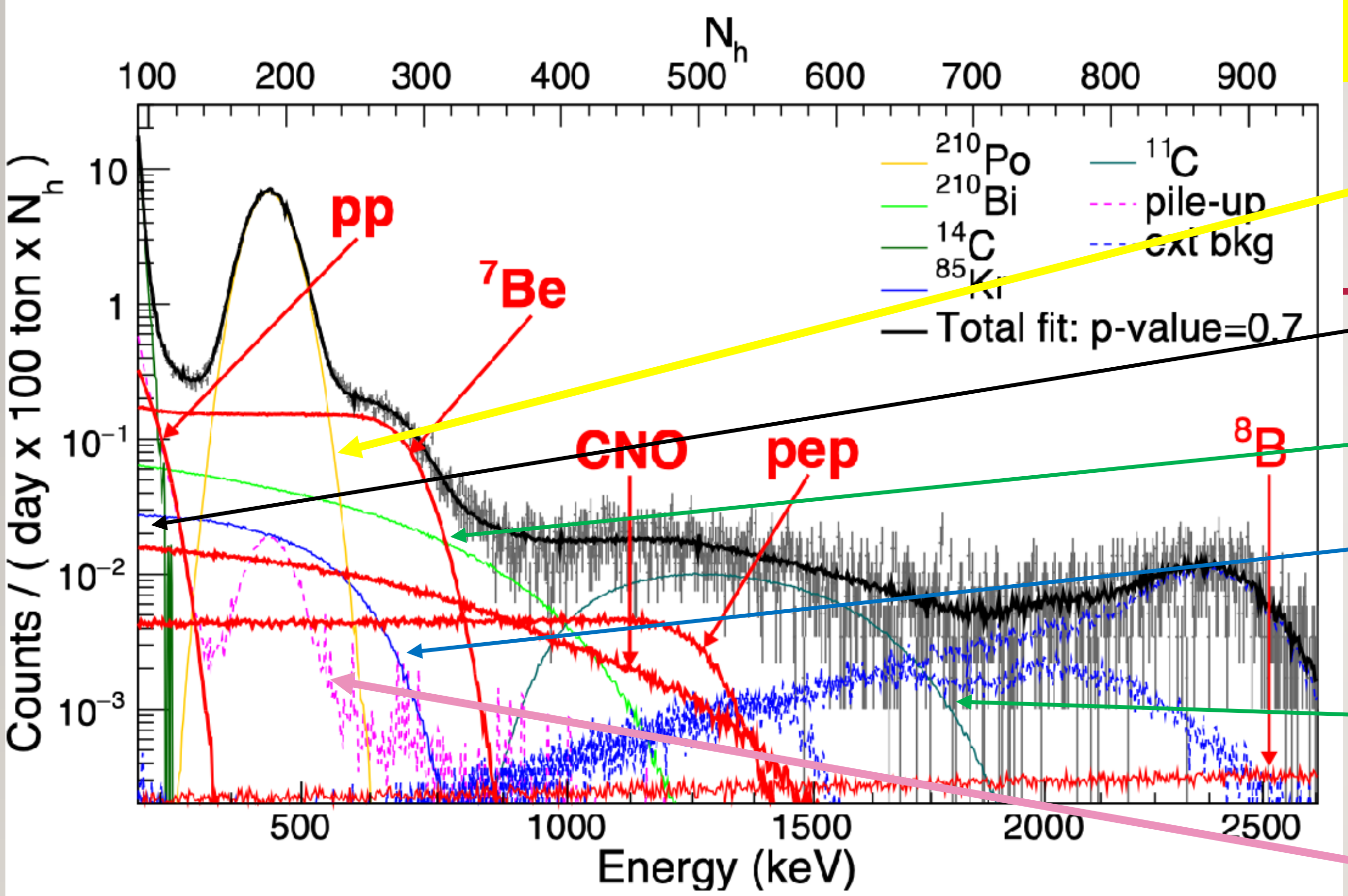



Threshold of Cherenkov expt:

$\nu_x + e^- \rightarrow \nu_x + e^-$

# First spectroscopy of pp,$^{7}$Be and pep




$^{210}$ Po

$^{14}$C

$^{210}$ Bi

$^{85}$Kr

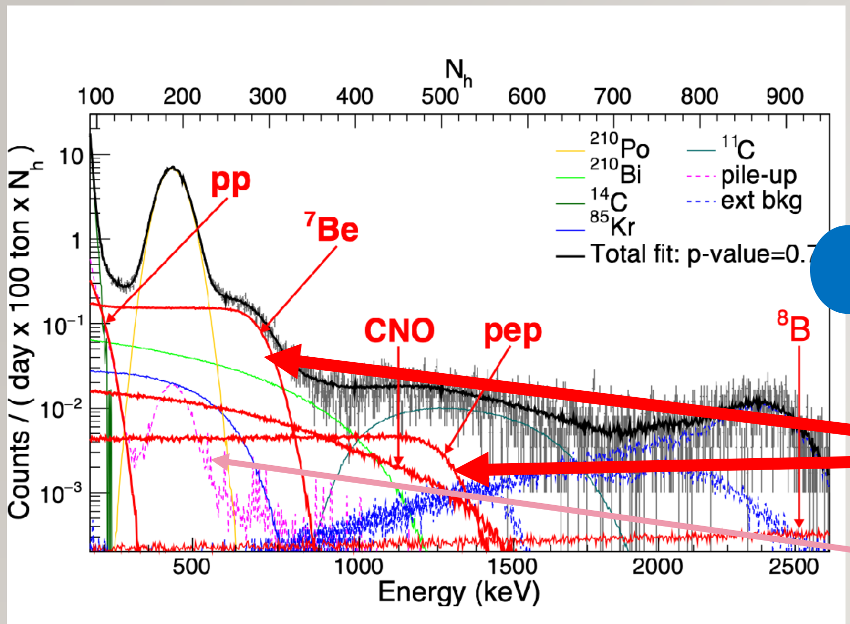
Residue despite the very high radiopurity

Cosmogenic $^{11}$C

Pile-up due to the $^{14}$C rate

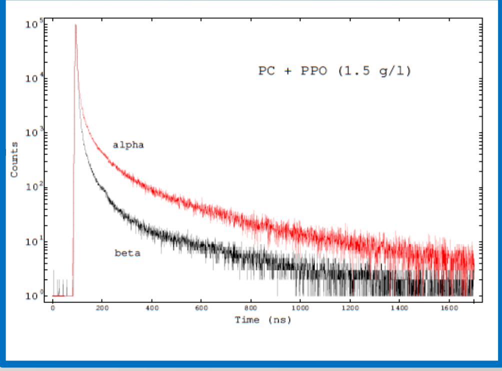
Final fit but previously measured separately, before $^{7}$Be, then $^{8}$B, pep and finally pp

# Tools against radioac. residues




**Extended use ab initio of Montecarlo to simulate the various contaminants residues**

**α/β discrimination based on signal time-** Gatti parameter- later perceptron approach based upon a neural network with 13 α/β discriminating input variables

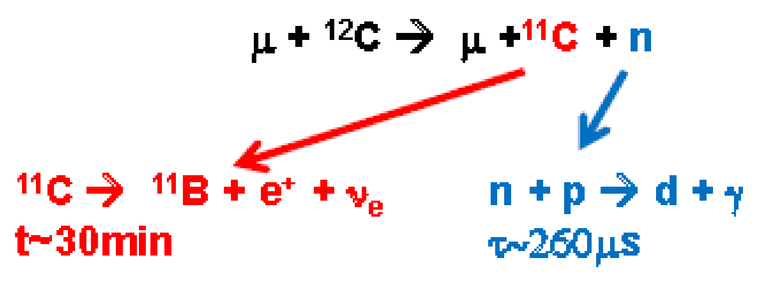



Compton shoulder for $^7$Be and pep

pp pile up for $^{14}$C rate

**$^{11}$C** (β+ decay, τ = 29.4 min) continuously produced by muons (1.2 μ /m$^2$h survived through the GS overburden): spallation on C; due to the e+-annihilation, the spectrum is shifted above 1 MeV and falls in pep ν's energy window .

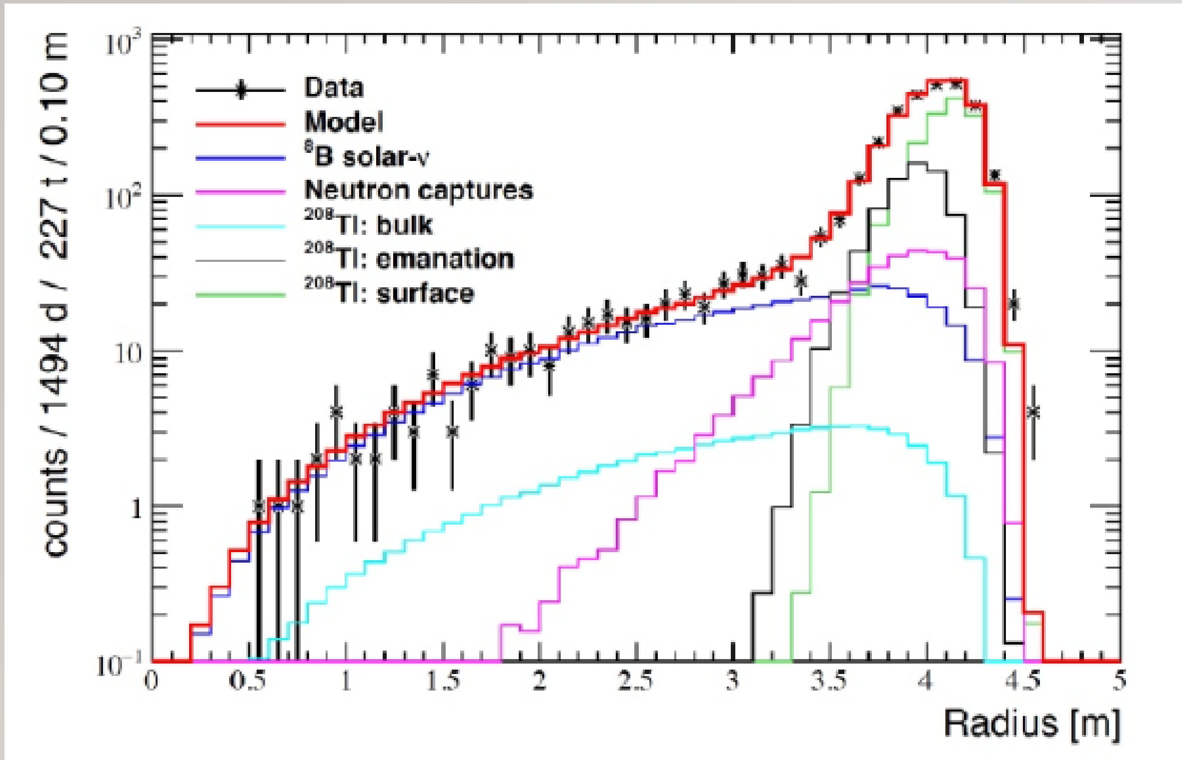
**Three-Fold Coincidence** reduces to $^{11}$C rate to 10%.




**Pulse shape discrimination** reduces $^{11}$C rate to 5% .

-ortho-positronium with 140 ns lifetime, reduced to about 3 ns in the LS

-2 γs produced in the positron annihilation--distributed topology reduces to 5%




$^8$B- studied in 3.2-16 MeV where sensitivity is maximum

- **below 3.2** there are 2.614 MeV γ-rays background **from $^{208}$Tl decays,** originating from $^{232}$Th in the IV nylon, despite very thin and very pure material
- **fit on radial distribution** of events **to separate** the $^8$B neutrino signal (uniformly distributed in the scintillator) from the **external background**.

In addition the energy **distribution shape is distorted by the oscillations** which depend on energy

**Multivariate fit- Maximization of a binned likelihood -- fitting 3 distributions simultaneously:**

- **Reconstructed energy for TFC-tagged and TFC-subtracted datasets ($^{11}$C identification)**
- **Radial position**

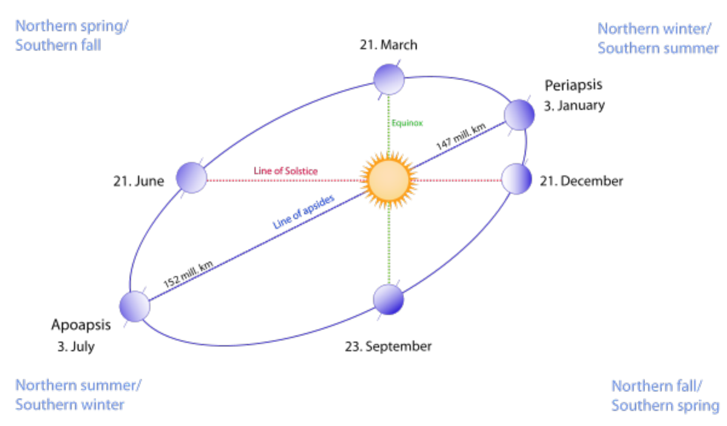
# pp neutrinos rates and fluxes from Borexino-

| | Borexino rates (cpd/100t) | Borexino fluxes ($cm^{-2}s^{-1}$) | SSM HZ Fluxes ($cm^{-2}s^{-1}$) | SSM LZ Fluxes ($cm^{-2}s^{1}$) | (HZ-LZ)/HZ. Dependence on T |
|---|---|---|---|---|---|
| pp | $134 \pm 10^{+6}_{-10}$ | $(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$ | $5.98(1 \pm 0.006) \times 10^{10}$ | $6.03(1 \pm 0.005) \times 10^{10}$ | -0.8% $T^{-0.9}$ |
| $^7$Be | $48.3 \pm 1.1^{+0.4}_{-0.7}$ | $(4.99 \pm 0.11^{+0.06}_{-0.12}) \times 10^{9}$ | $4.93\ (1 \pm 0.06) \times 10^{9}$ | $4.50(1 \pm 0.06) \times 10^{9}$ | 8.9% $T^{11}$ |
| pep | $2.43 \pm 0.36^{+0.15}_{-0.22}$ | $(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$ | $1.44\ (1 \pm 0.009) \times 10^{8}$ | $1.46\ (1 \pm 0.009) \times 10^{8}$ | -1.4% $T^{1.4}$ |
| $^8$B | $0.220^{+0.015}_{-0.016}$ | $5.68^{+0.39+0.03}_{-0.41-0.03} \times 10^{6}$ | $5.46\ (1 \pm 0.12) \times 10^{6}$ | $4.50(1 \pm 0.12) \times 10^{6}$ | **17.6%** $T^{24}$ |
| $^{13}$N + $^{16}$O | $6.7^{+1.2}_{-0.8}$ | $6.7^{+1.2}_{-0.8} \times 10^{8}$ | $4.89(1 \pm 0.0.16) \times 10^{8}$ | $3.51(1 \pm 0.15) \times 10^{8}$ | 27.9% $T^{19}$ |
| | | | | | |

PP Chain

CNO cycle

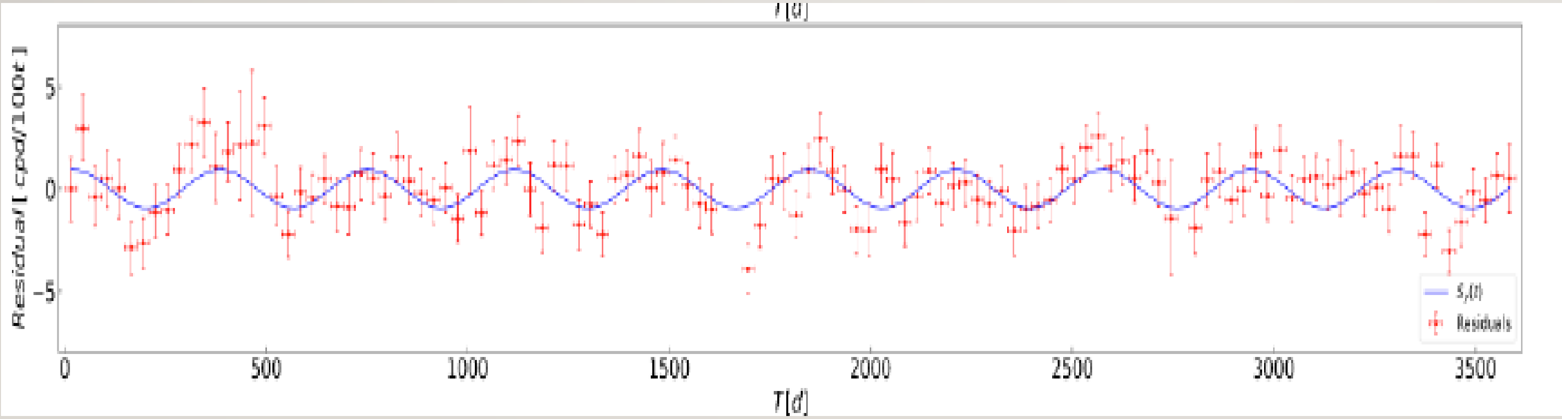
# Determination of the Earth's orbit with solar neutrinos




Annual modulation

10 years-6.7% peak-to-peak amplitude- period of 365 days; energy window of 350-827 keV ($^7$Be)

- the best-fit eccentricity is e=0.0184±0.0032 (stat+syst)
- null hypothesis rejected at > 5σ
- Parameters in **agreement with the astronomical measurements**



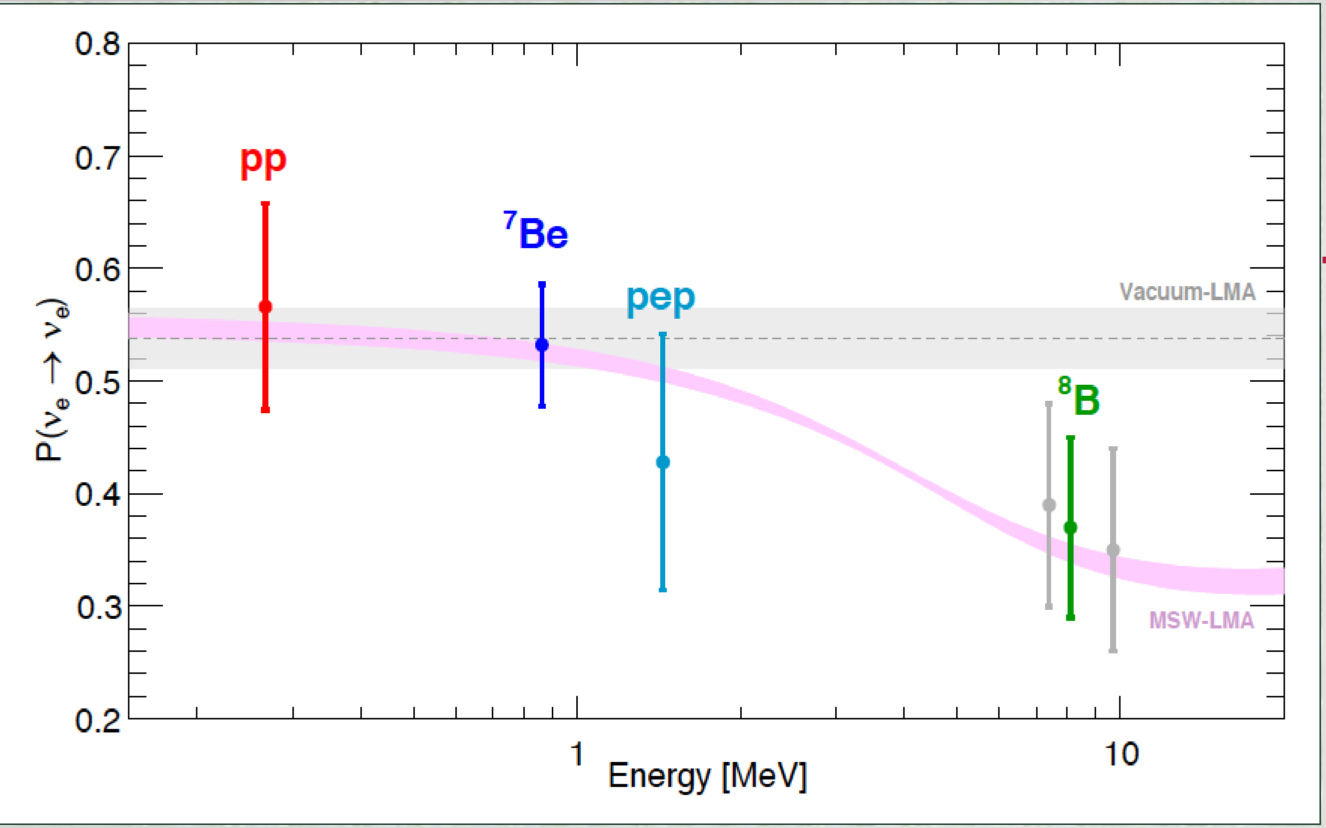

**best measure of the Earth's orbit using solar neutrinos only**

# Solar luminosity

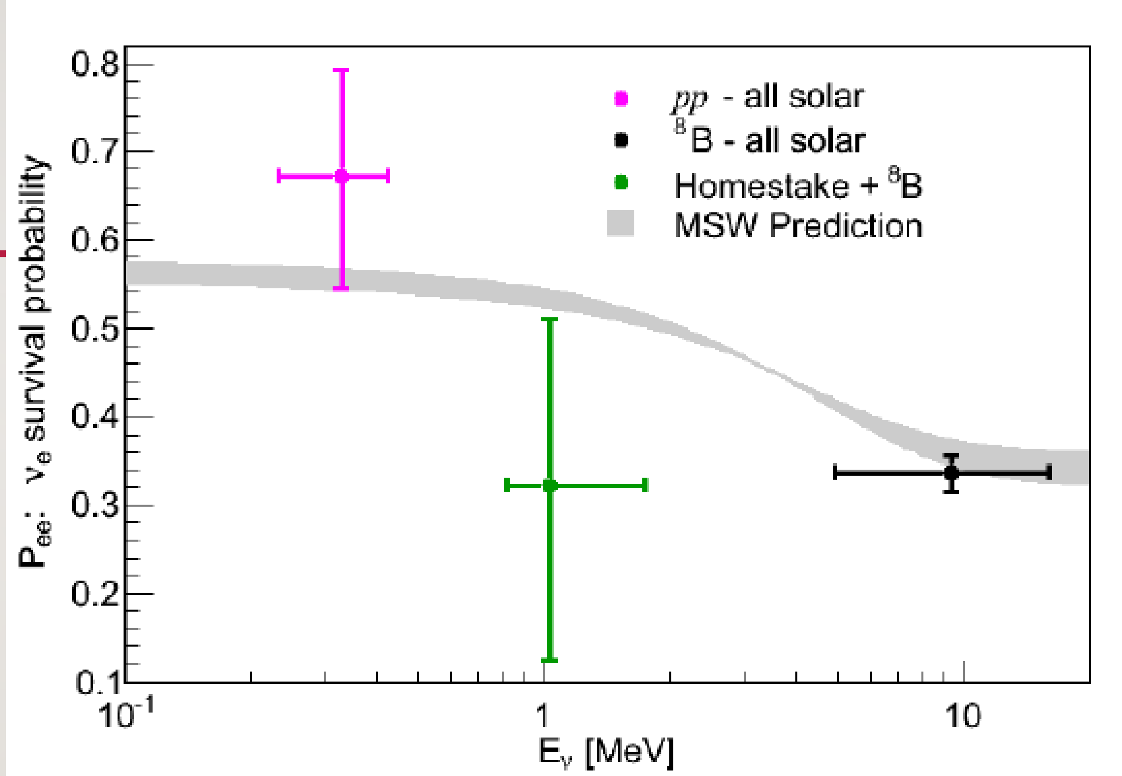
Good agreement between luminosities via photons and via neutrinos

**test of the fundamental assumptions in the SSM paradigm showing that there are no additional energy losses or production mechanisms besides those normally included in Solar Model calculations**

# **Neutrino oscillation**. Electron neutrinos survival probability




Before BX



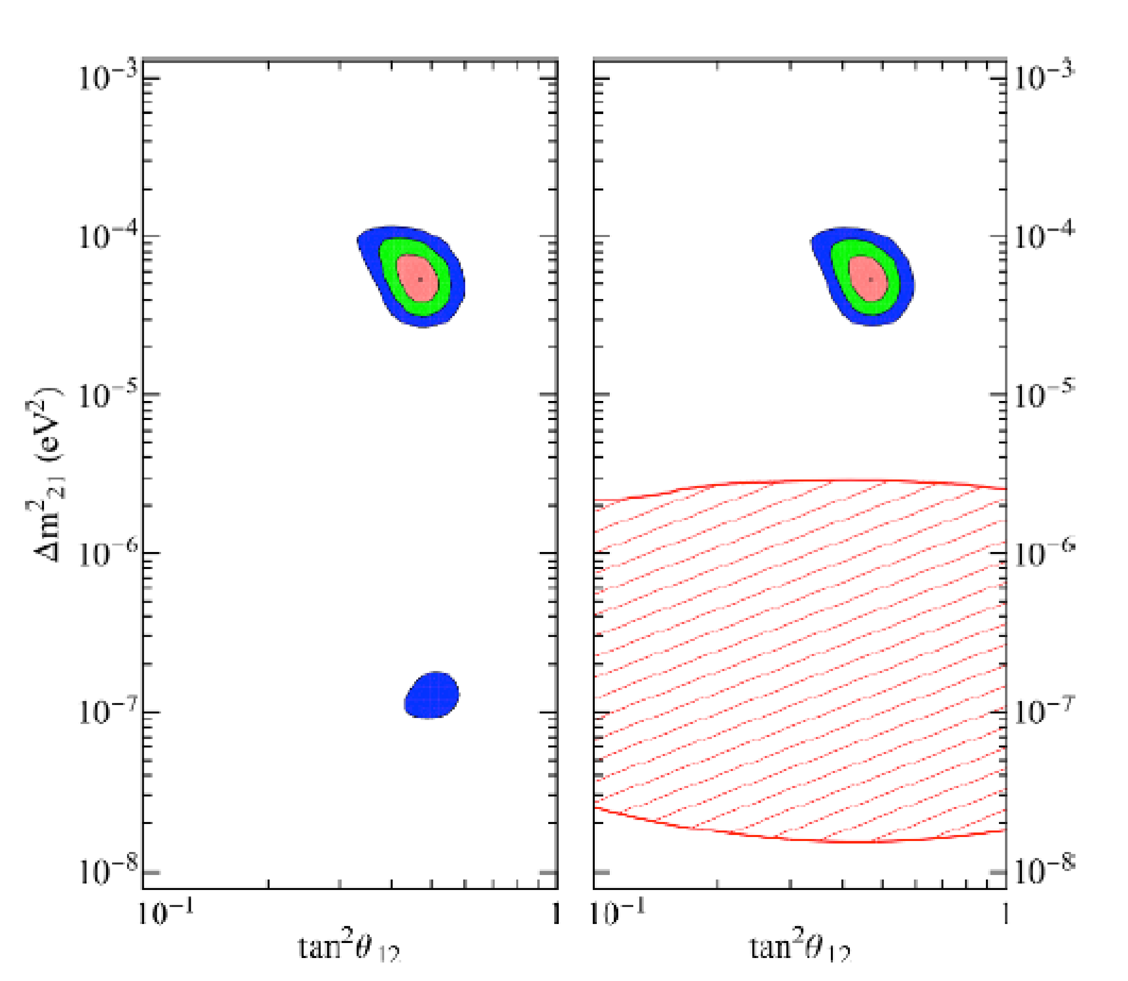

First observation oscillation in vacuum regime $P_{ee}$~0.55 to be compared with matter oscillation $P_{ee}$~0.32. Constant Pee rejected at 98% C.L.- **good test of the paradigmatic MSW effect**

**This is an important BX contribution to the neutrino physics**

day/night effect found null by Borexino in the $^7$Be energy window.

Adn = 2 (RN − RD)/(RN + RD) = Rdiff/ $R_{mean}$ = 0.007∓0.073

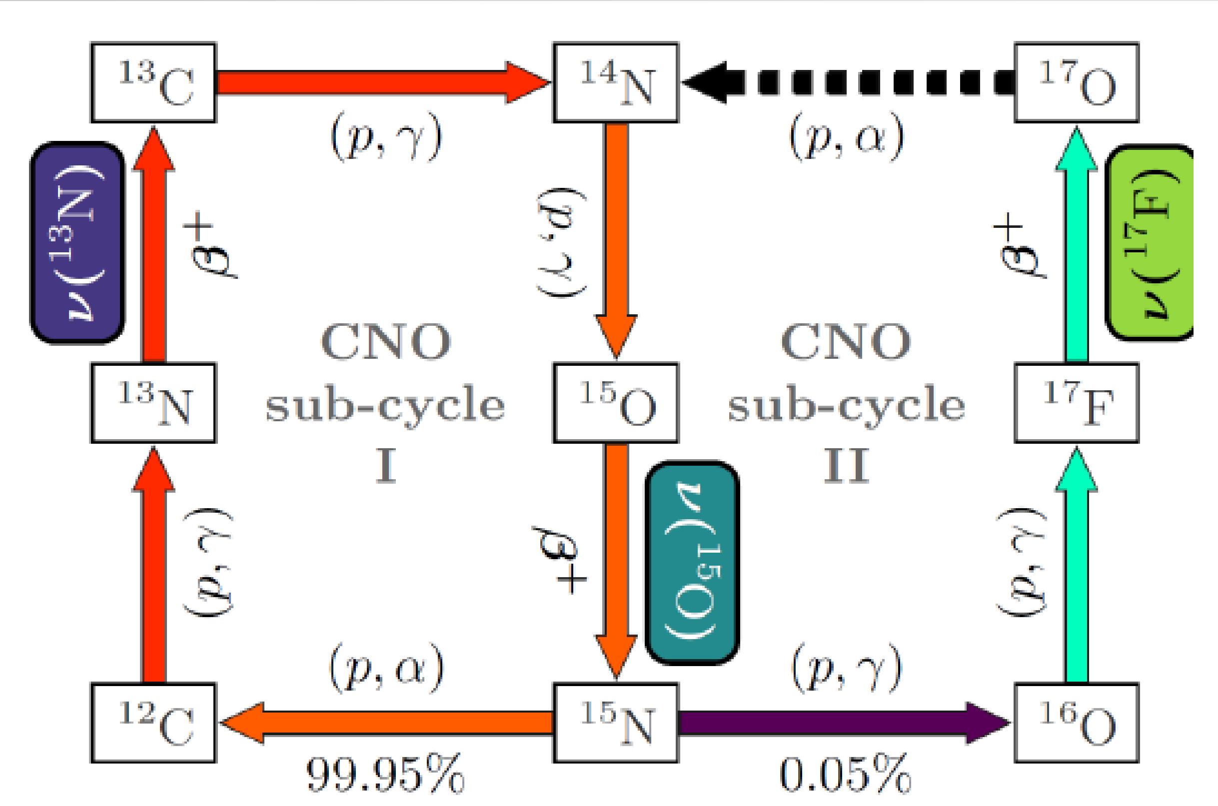
This **excludes at more than 8.5σ the $\Delta m^2_{12}$ energy range <2x10$^{-6}$ eV$^2$**




*

This result singles out LMA solution without KamLAND antineutrinos and then without CPT assumption

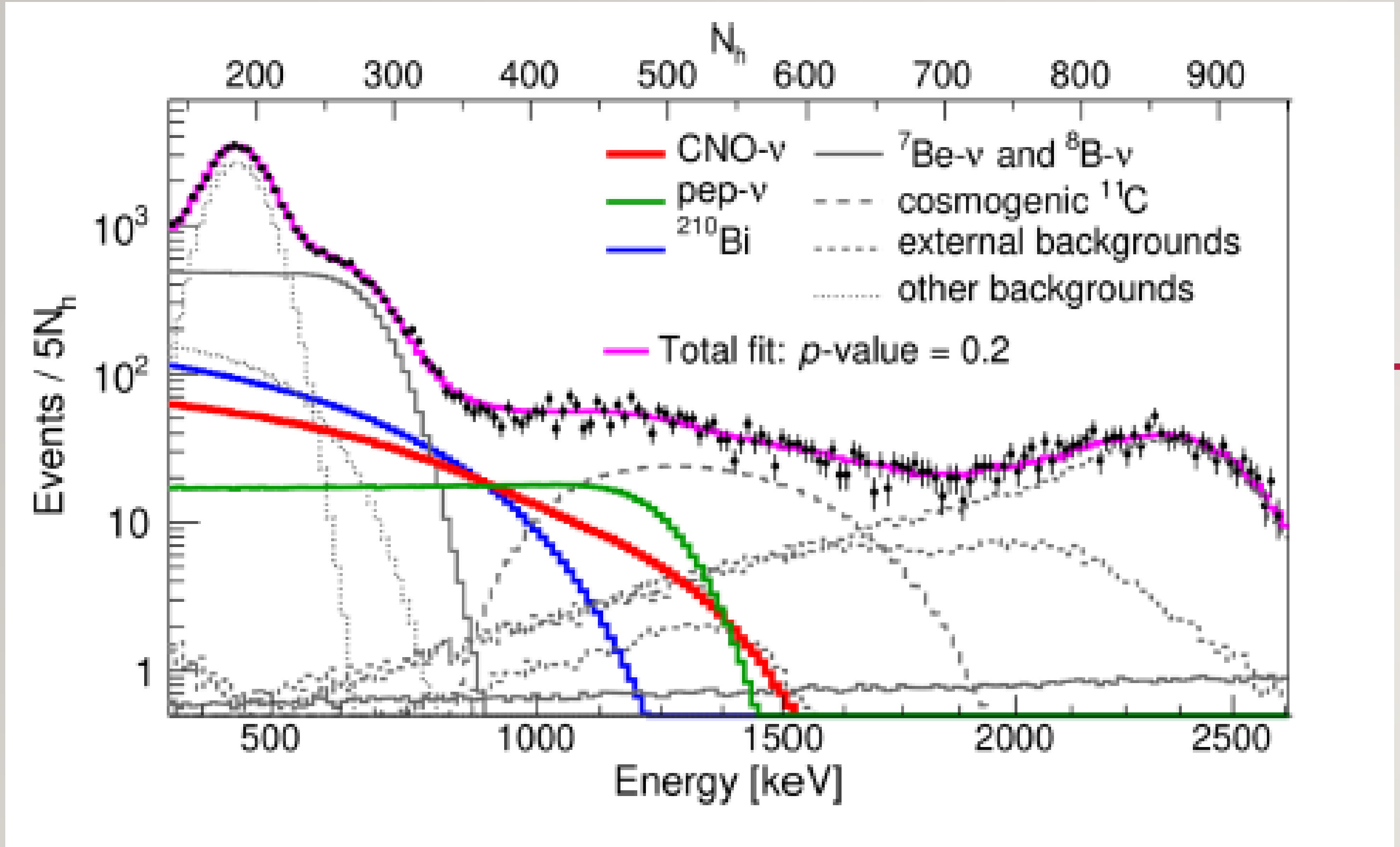
# First direct demonstration that the CNO cycle is real




Hypothesized by Bethe and Von Weizsäcker in 1938

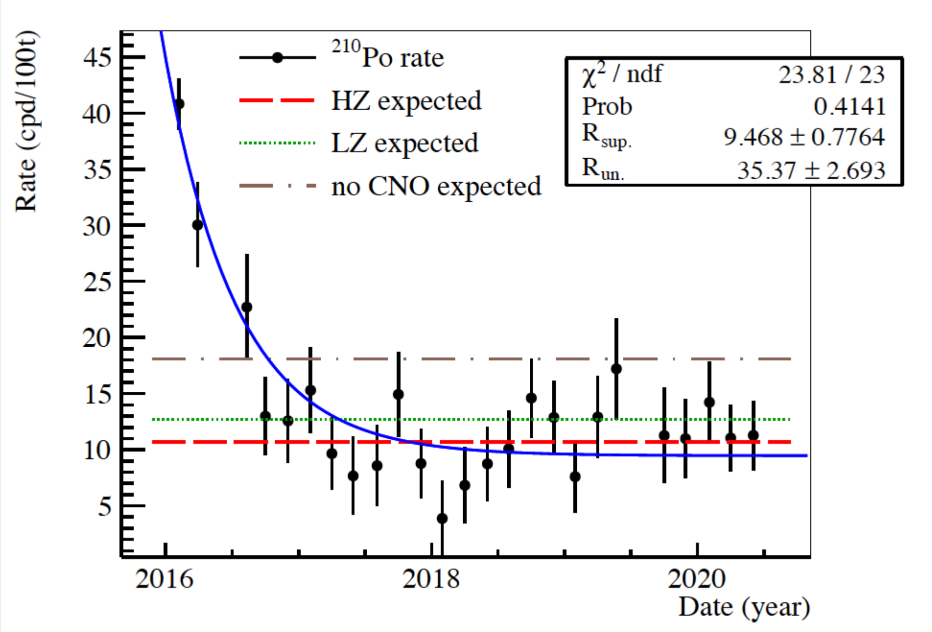
- Hydrogen burning is catalyzed by Carbon, Oxygen and Nitrogen and produces a temperature about one order of magnitude more than pp chain.

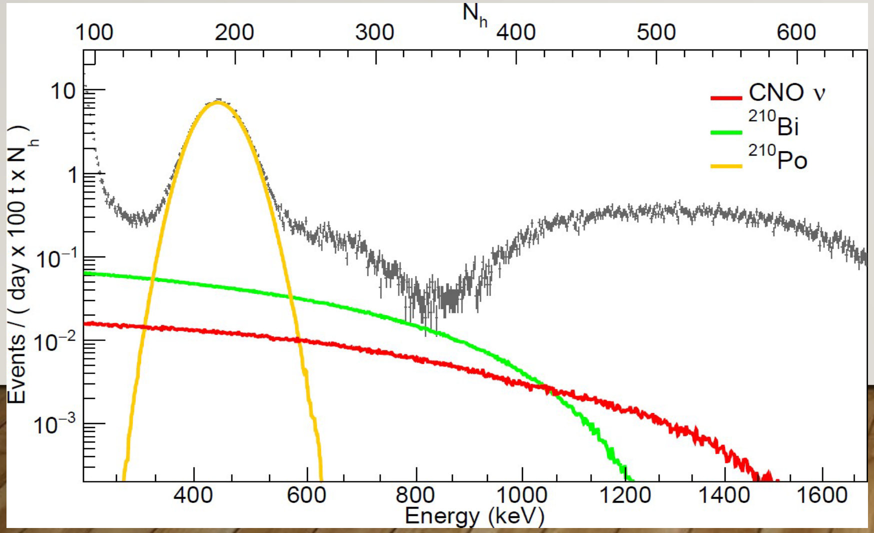
Subsequently astrophysical theories have identified the CNO cycle as dominant in massive stars, i.e. those with a mass greater than the Sun by at least 30%.

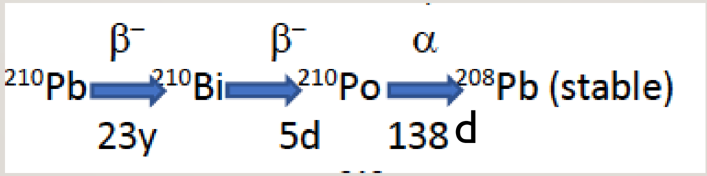



pep constrained by the solar luminosity and by the pp rate, $\Phi_{pep}/\Phi_{pp}$ connected with the Sun temperature and fixed by the phase space
Then pep accuracy ~1 cpd/100 tons

CNO and $^{210}$Bi correlated- fit returns their sum



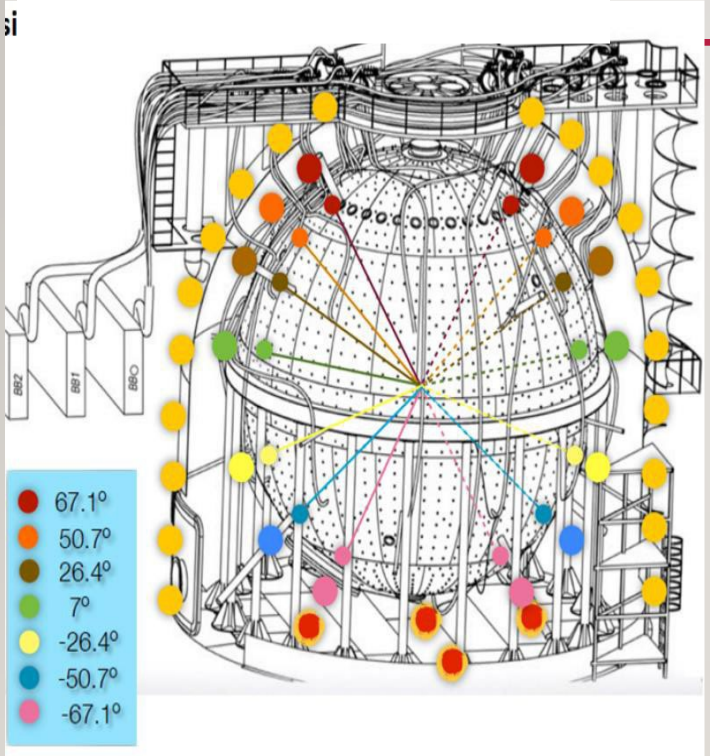

**But convective movements moving $^{210}$Po from the IV inner surface**

**Then we have to avoid the convective motions**

**a stabilization of the temperature is needed**

**Detector thermal insulation + copper coils on top- Top-bottom gradient**
under insulation- water in serpentines controls the top temperature
at about 15.5 K -the bottom temperature (rock ) is ~ 7. K

**temperature probes-**




**$^{210}$Bi spatial uniformity systematics**

**Excellent temperature stability achieved within the probes resolution 0.07 °C**

$^{210}$Po rate from the Low Polonium Field : $R_{min} = 11.5 \pm 1.3 \frac{cpd}{100t}$

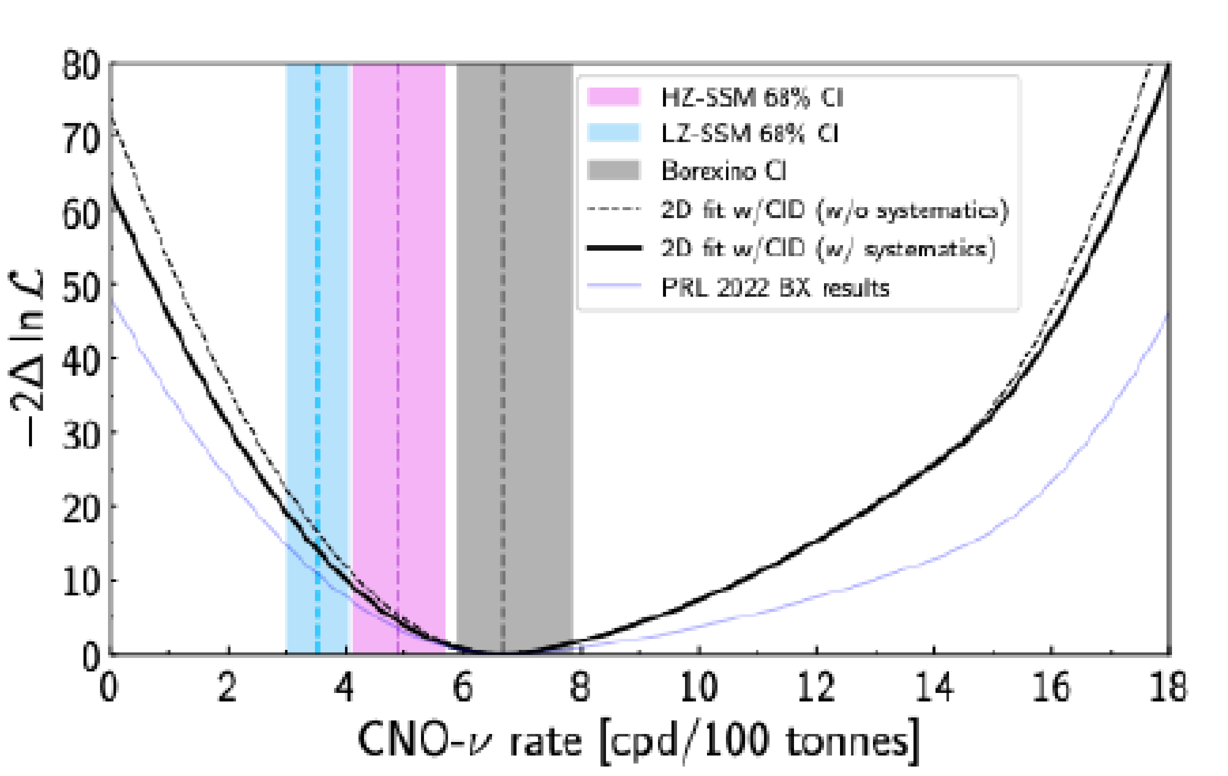
$R(^{210}Bi) \leq 11.5 \pm 1.3$ cpd/100t

we cannot exclude in principle that residual $^{210}$Po from the vessel surface would be present

Fit with pep and $^{210}$Bi constrained

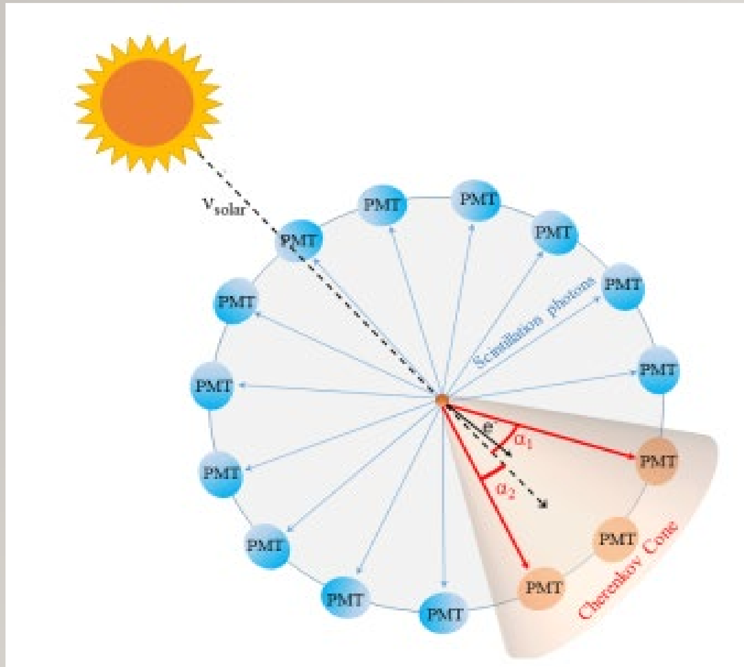
CNO rate: $6.7^{+2.0}_{-0.8}$ cpd/100t (stat+sys),

Flux: $6.7^{+2.0}_{-0.9}$ x $10^8$ cm$^{-2}$ s$^{-1}$
No CNO-excluded at 7σ C.L.

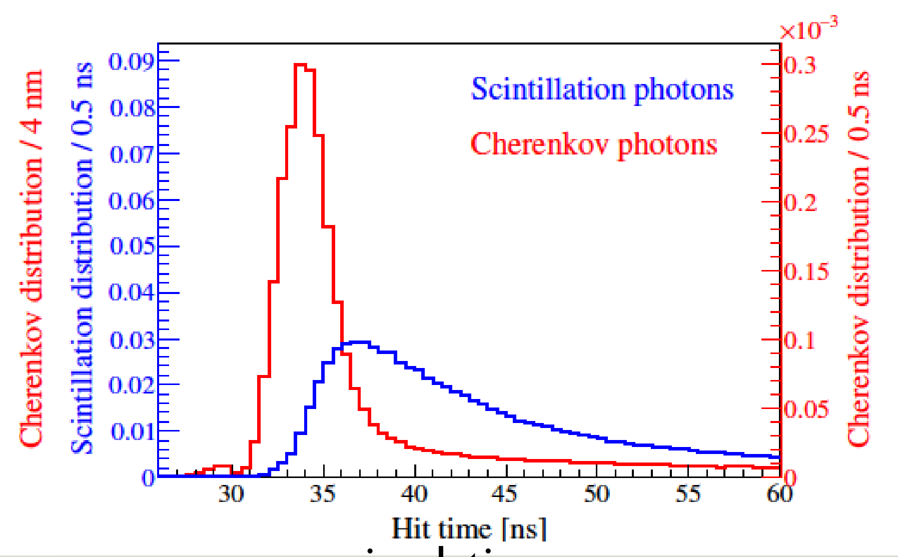


# Directionality

**Correlated and Integrated Directionality (CID):** a novel technique developed within the BX collaboration




**The recoil electron scattered roughly in the direction of the solar neutrino**
**Scintillation hits uncorrelated with the Sun direction**
Cherenkov **background** events **uncorrelated**
Cherenkov **neutrino signals correlated**
Then usefull for disentangle neutrinos signals from background events



simulation

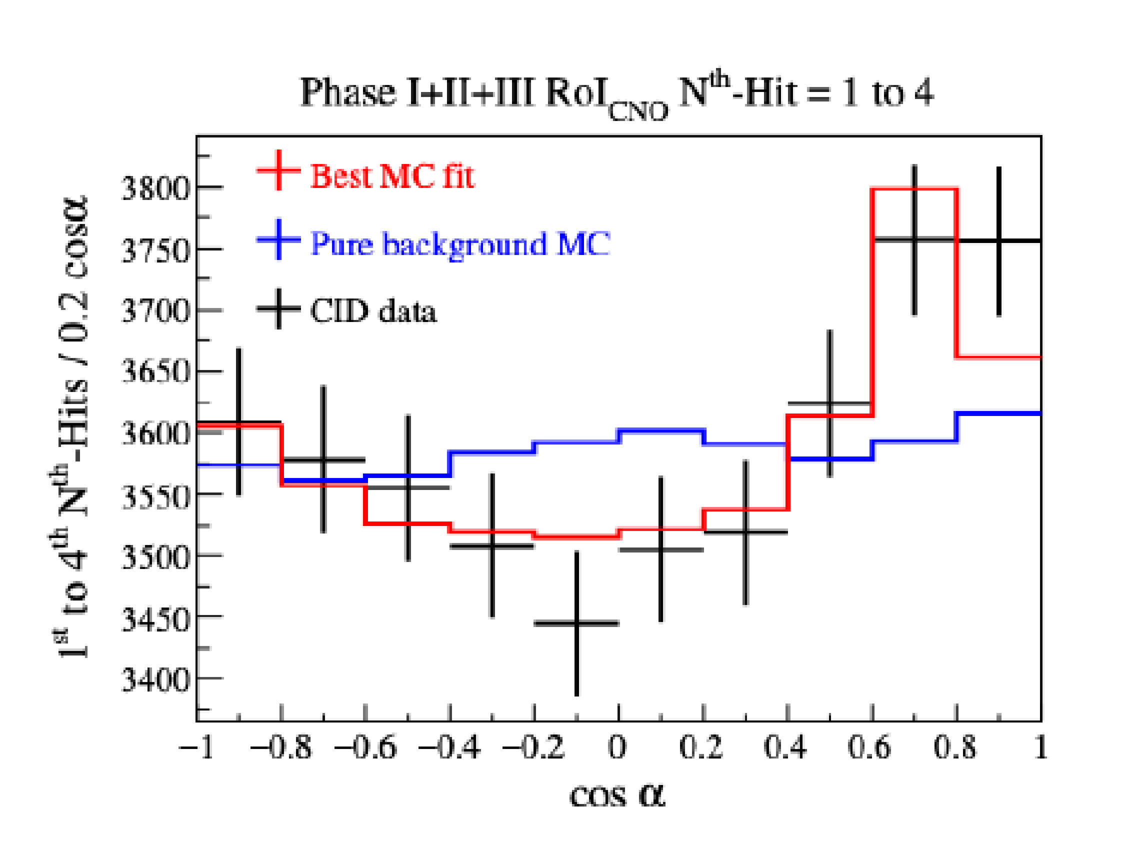
**Cherenkov light emitted instantly**; the scintillation light emission follows a Multi-exponential decay time where the **fastest component has 1.6 ns**
**For each event, the earliest hits (1,2) have more probability to be due to Cherenkov events**

The detected photons (hits) are indistinguishable on an event-by-event basis
Statistical results

# CNO with the directionality

MC simulations and calibration using the $^{7}Be$ data
Data of the 3 phases from 2007 until 2021
Entire IV detector volume as FV

**CNO rate $7.2^{+2.5+1.2}_{-2.5-0.9}$ $(stat.+syst)$ cpd/100t**
fully compatible with the CNO result of the analysis with $^{210}Bi$ constrained- no CNO rejected at 5 σ




Flat background and signal

**This result demonstrates how robust is the CNO cycle Borexino measurement, with anyway an evidence more than 5σ from two completely independent analyses**

**multivariate fit** with the $^{210}$Bi constraint **plus directionality**

Only phase III data- 2017-2021

- fit upgraded :two-dimensional taking into accounts simultaneously energy and radial distributions,
- binning choice with a toy Montecarlo

**result:** $6.7^{+1.2}_{-0.7}$ **cpd/100 tons with no-CNO rejected at 8σ C.L.,**

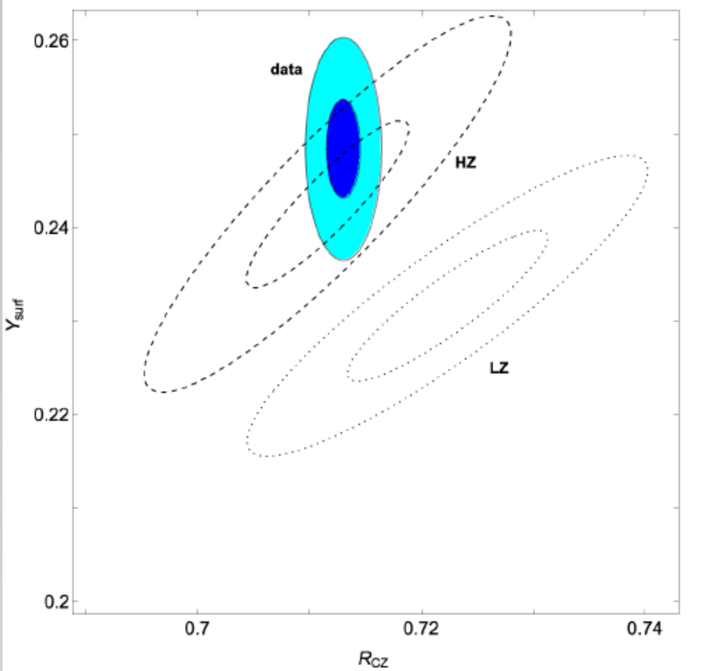
. $\Phi(CNO) = 6.7^{+1.2}_{-0.8} \times 10^{8}\ cm^{-2}\ s^{-1}$

**In this way CNO hypothesized more than 80 years ago and considered by the astrophysical theories as dominants in the massive stars has been finally validated by BX.**

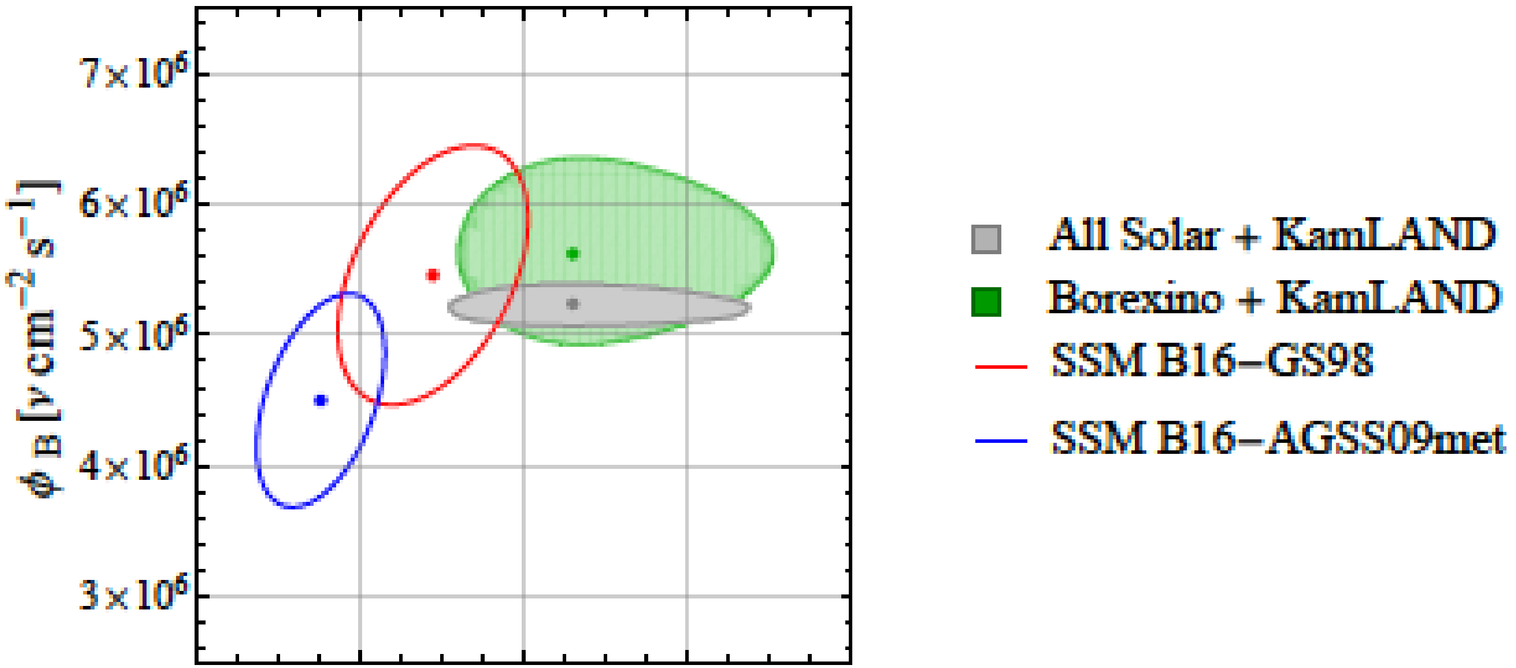
**Then Borexino demonstrated how the stars of any sizes shine: pp chain for sizes close to Sun, and CNO cycle for the massive stars.**

# Long standing puzzle HZ vs LZ

Helioseismology




Neutrino fluxes




$\phi_{CNO}\ [\nu\ cm^{-2}\ s^{-1}]$

LZ disfavored at > 7σ for SSM

LZ disfavored at > 3.1 σ

Ysurf=surface helium
Rcz = depth of the convective zone

BX shows a strong hint in favour of inner HZ

## Further approach

All these results provide a hint in favor of high metallicity.
Nevertheless their interpretation is not univocal due to the **degeneracy between metallicity, opacity, and other SSM inputs**.

The direct dependence of the CNO cycle from the C and N abundances in the core of the Sun can offer a different model

-**independent approach**: solar neutrino fluxes (produced in the pp chain and in CNO-cycle) depend on the so-called environmental parameters (abundances of heavy elements, solar age, luminosity, opacity, diffusion) only indirectly, though the core temperature $T_c$, which is an implicit function of them; the $^8B$ flux is the most sensitive depending on $T_c^{24}$, and CNO on $T_c^{19}$.
In addition, **CNO reactions' rate features a direct dependence on the abundance of C and N in the solar core**. It is so possible to formulate a weighted ratio **CNO/pp-neutrino fluxes that is directly proportional to the C+N abundance in the core of the Sun and essentially independent on the solar central temperature**. By calculating this ratio with the latest CNO Borexino data and comparing it with expectations obtained by using different surface abundance determinations, one. obtains a ~2σ tension with LZ mixtures

This second approach is extremely powerful because it provides a direct determination of C+N core abundance that does not depend on the SSM environmental parameters.

# geoneutrinos

Antineutrinos produced in the Earth interior by $^{40}K$, $^{232}Th$, $^{238}U$ decays; in Borexino well tagged interaction channel: the inverse beta decay, with a kinematic energy threshold of 1.806 MeV, then excluding the $^{40}K$ decays whose energy is below this threshold.
High BX radiopurity (even not needed at the level of solar ν) avoids internal backround

**Bx ( continental crust) and KamLAND ( oceanic crust)**

BX:. From December 2007 to April 2019 data, 154 golden candidates
**$47.0^{+8.4+2.4}_{-7.7-1.9}$ (stat + sys) TNU.**

Background: reactor antineutrinos and scintillator radio-contaminants.

For the Earth mantle radiogenic contribution, the crust one, predicted by local models, has to be subtracted from the total rate---- Bx: ($S_{mantle}$ (U+Th) = $21.2^{+9.5+11.0}_{-9.0-0.9}$(stat+sys) TNU). Taking into account also $^{40}K$ ( 18% from chondritic meteorites)
Earth's radiogenic heat is = $38.2^{+13.6}_{-12.7}$ TW ; ( the total heat estimated at 44-47 TW)

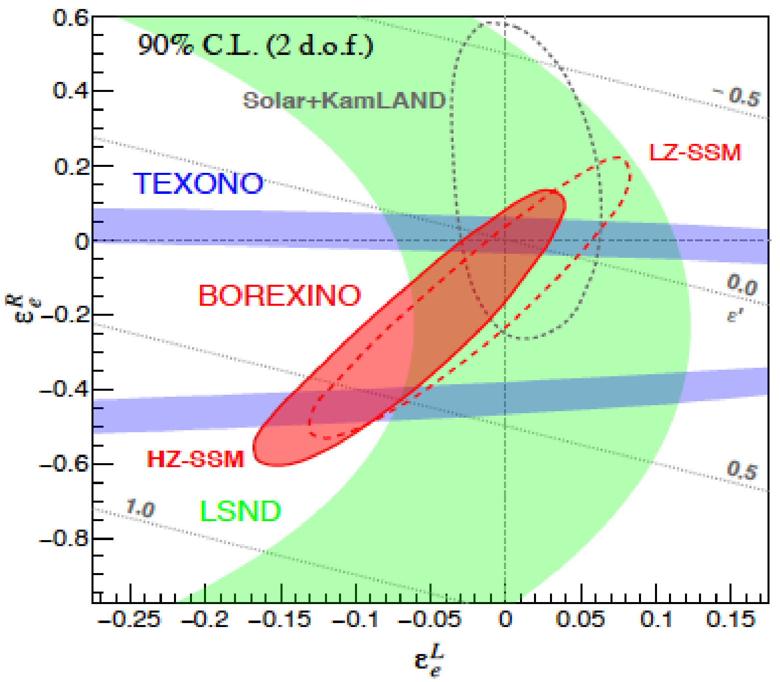
Bx + KamLand :$H^{KL+BX}(U + Th + K) = \mathbf{20.8^{+7.3}_{-7.9}}\ \boldsymbol{TW}$

TNU= 1 event/ $10^{32}$ protons / year with 100% efficiency

# Not Standard neutrino Interaction (NSI)

$$-L_{NC\text{-}NSI}=\sum_{\alpha,\beta} 2\sqrt{2}G_F\, \varepsilon_{\alpha\beta}^{ff'C}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_C f')$$

where $\varepsilon_{\alpha\beta}^{ff'C}$ parametrizes the NSI strength normalized to $G_F$; f and f' are leptons or quarks, a,b=e,$\mu$,$\tau$ and C is the chirality of f,f' current (L or R).




**allowed region for $\varepsilon_e^{R,L}$ with $\varepsilon_\tau^{R,L}$ fixed at zero**

$\epsilon_{\alpha\beta}^{ff'C}$ parametrizes the strength of NSI

A new analysis is currently underway with three important upgrading: the almost doubled statistics, the inclusion of non-diagonal terms and finally a lower $^{85}Kr$ rate which significantly interferes with the analysis. The $^{85}Kr$ rate was reduced by the second purification but until now only an upper limit was considered because of the poor statistics of B. R. direct observation (0.43%) ($^{85}Kr$ decay via $^{87}Rb$). Now the statistic of direct osservation in enough for a quotation

Many best limits studied by Borexino

13 best limits on rare or forbidden events published . At the time of publications, the Borexino limits were the most stringent

Few examples

- **best limits for ν and anti-ν from astrophysical sources**
- diffuse **Supernovae** neutrino background– anti-ν at en. < 8 MeV,
- **fast radio bursts-**the strongest upper limits on FRB and associated neutrino fluences of all flavors in the 0.5 − 50 MeV energy range.
- search for neutrino events in correlation with **gravitational wave (GW) events** for three observing runs (O1, O2 and O3) from GWTC 3 catalog - < 5MeV

It was worth spending 32 years on the Borexino experiment and achieving these major breakthroughs:

- The unprecedented radiopurity of the scintillator and detector.
- Measurement of the individual fluxes of neutrino-emitting pp chain fusion reactions
- First observation of neutrino oscillation in vacuum and check on MSW–LMA model
- First experimental evidence of the existence of the CNO cycle
- Solving the HZ vs LZ long standing puzzle with a strong hint in favor of high metallicity
- Study of geoneutrinos in the continental crust

# the Borexino Collaboration

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