Deciphering the solar neutrino flux and properties with Borexino

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Formulation of the nuclear hypothesis on how the Sun and stars shine

"If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race---or for its suicide" A. Eddington

1938 Von Weizsacker and Bethe→ independent formulation of the CNO cycle

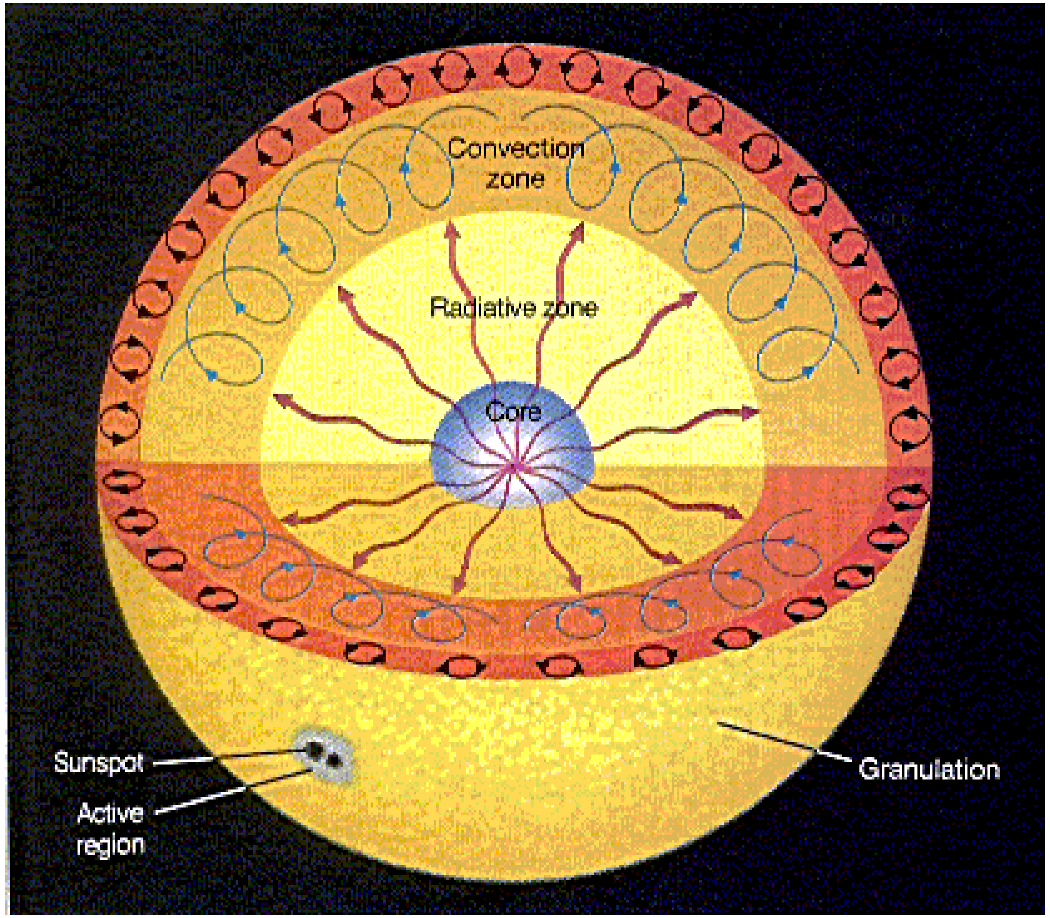
1938 Bethe → Formulation of the *p-p* chain and full definition of the nuclear hypothesis

How to prove it ?

Hypothesis : there are nuclear reactions occurring in the core summarized as

$$4\,^{1}H \rightarrow \,^{4}He + 2e^{+} + 2\nu_e + \text{energy}$$

Can it be proved experimentally?

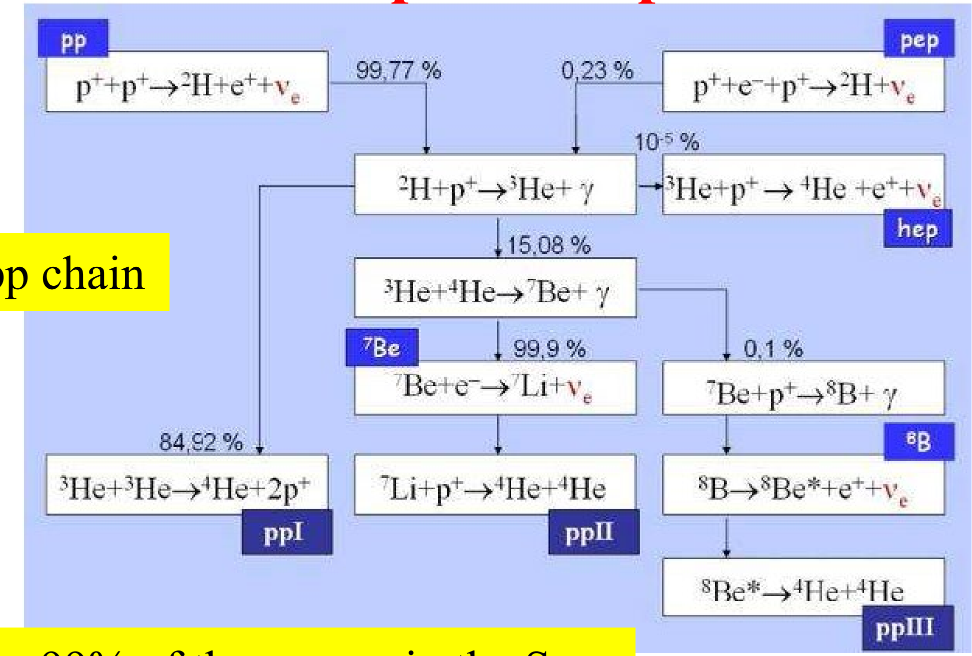


Yes, neutrinos coming from the reactions are the smoking gun! They pass undisturbed through the solar matter and if detected at Earth they would prove unambiguously the nuclear hypothesis; possibility debated in the context of the discussions about neutrino detection just after the world war II (Pontecorvo ‘47) From this trigger the Solar Neutrino Saga - a five decades long successful experimental drama culminated with the Borexino results

Where we are today theoretically: SSM Solar neutrinos production and spectrum predictions

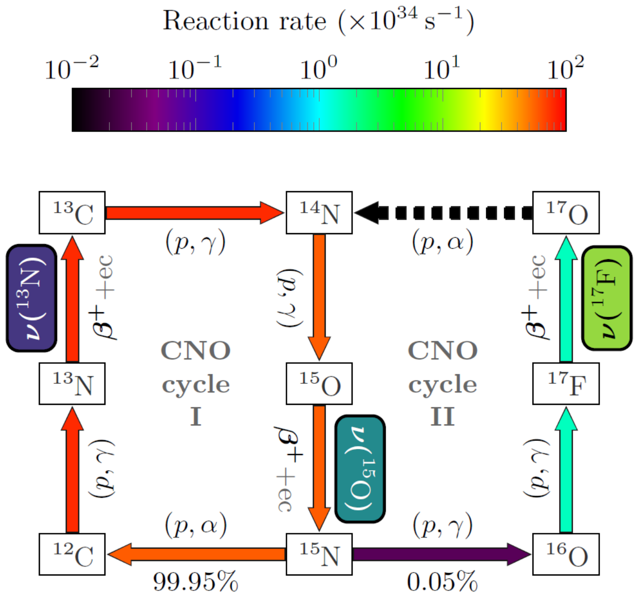
Achieved with persistent dedication and devotion by John Bahcall over more than 40 years of enduring efforts

pp chain



~99% of the energy in the Sun

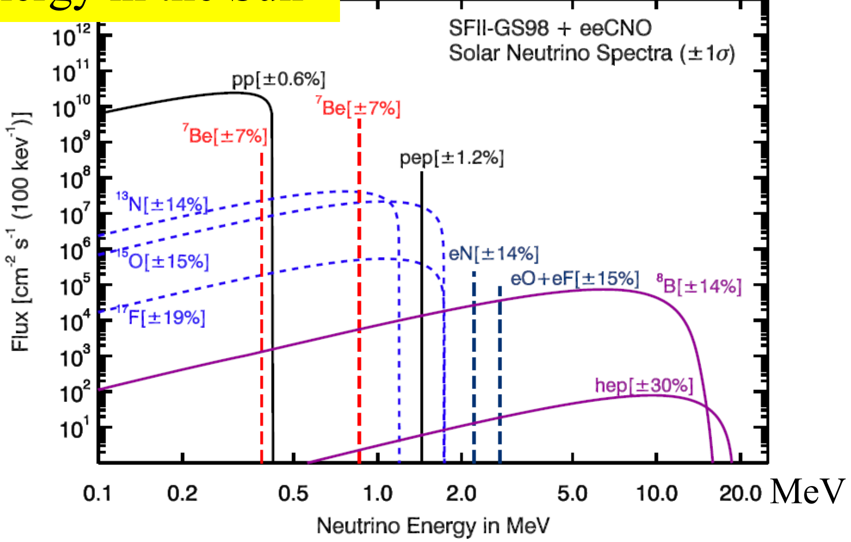
CNO cycle



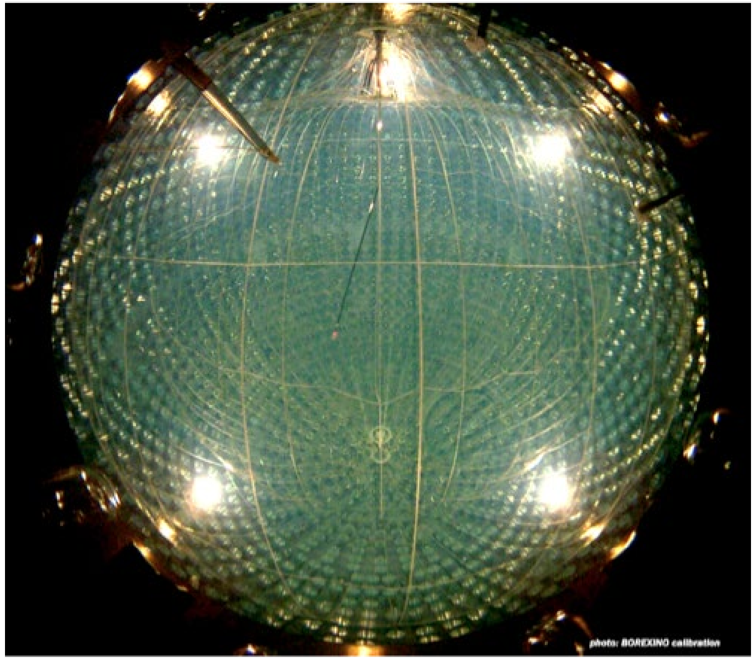
Dominant in massive stars

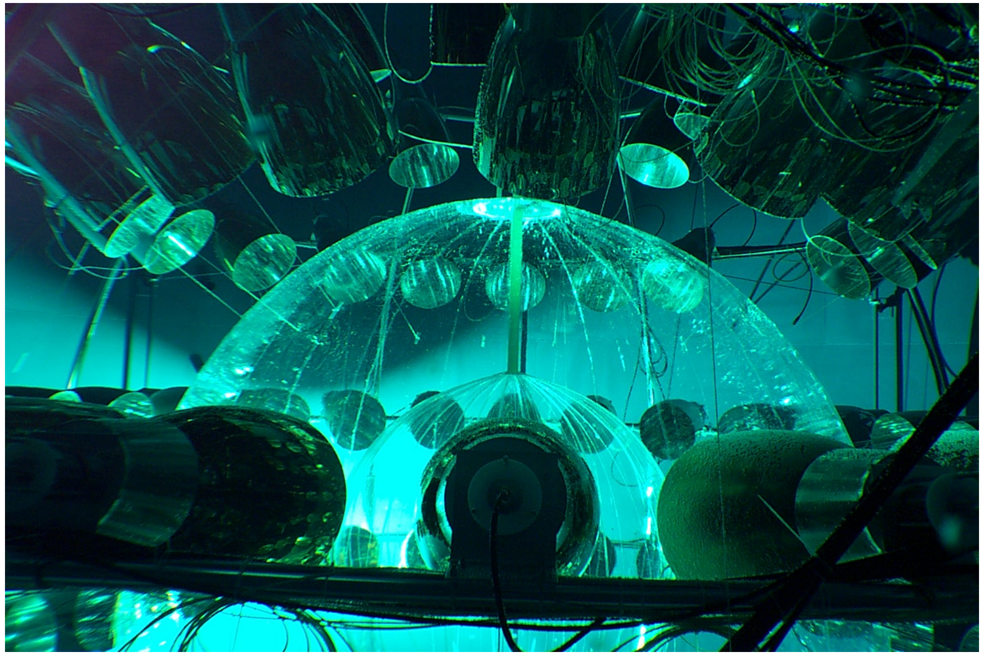
the remaining ~1% ?

Latest SSM spectral prediction
A. Serenelli
EPJA, volume 5, id 78 (2016)
N. Vinyoles et al.
The Astrophysical Journal, 835:202 (16pp), 2017



Controversy about the surface metallicity composition of the Sun: predictions differ up to 28% for the CNO ν flux using lower (LZ) or higher Z (HZ) models





Borexino

- ✓ Timeline from May 2007 up to now – three phases May 07 – August 10 **I** / December 11 – June 16 **II** / July 16 – Feb 20 **III** – still ongoing for a few weeks – **approaching the end of a great story**

Summary of the achievements

- ✓ After the latest CNO result - achieved the full solar neutrino spectroscopy in a single experiment through the individual real time detection of each ν spectral component – definite proof of the nuclear hypothesis
- ✓ Unique Validation in the low energy regime of the LMA-MSW ν oscillation paradigm through the experimental determination of the P_{ee} electron neutrino survival probability of solar neutrinos

The Borexino detector @ Gran Sasso

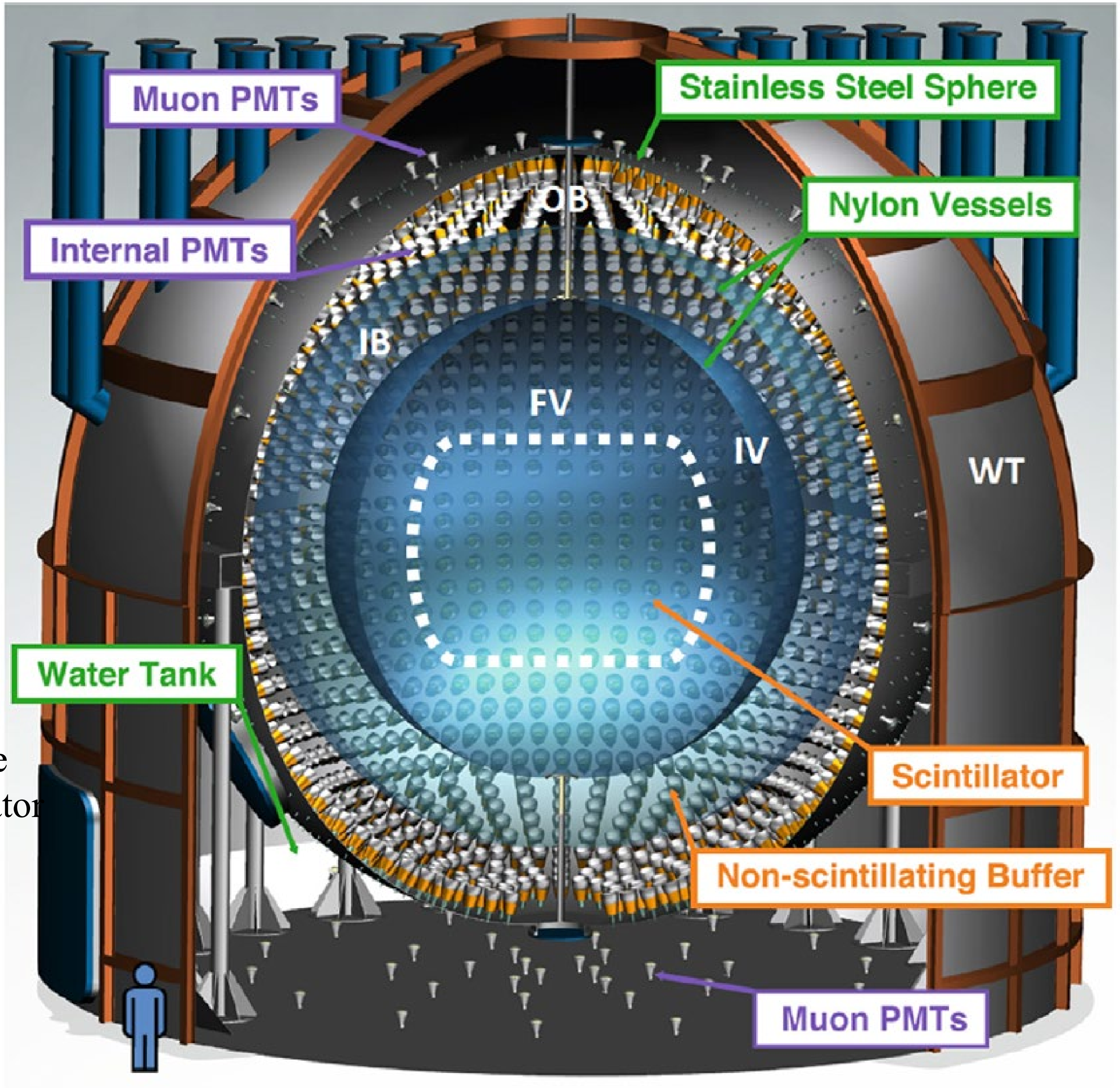
Active volume 280 tons of liquid scintillator

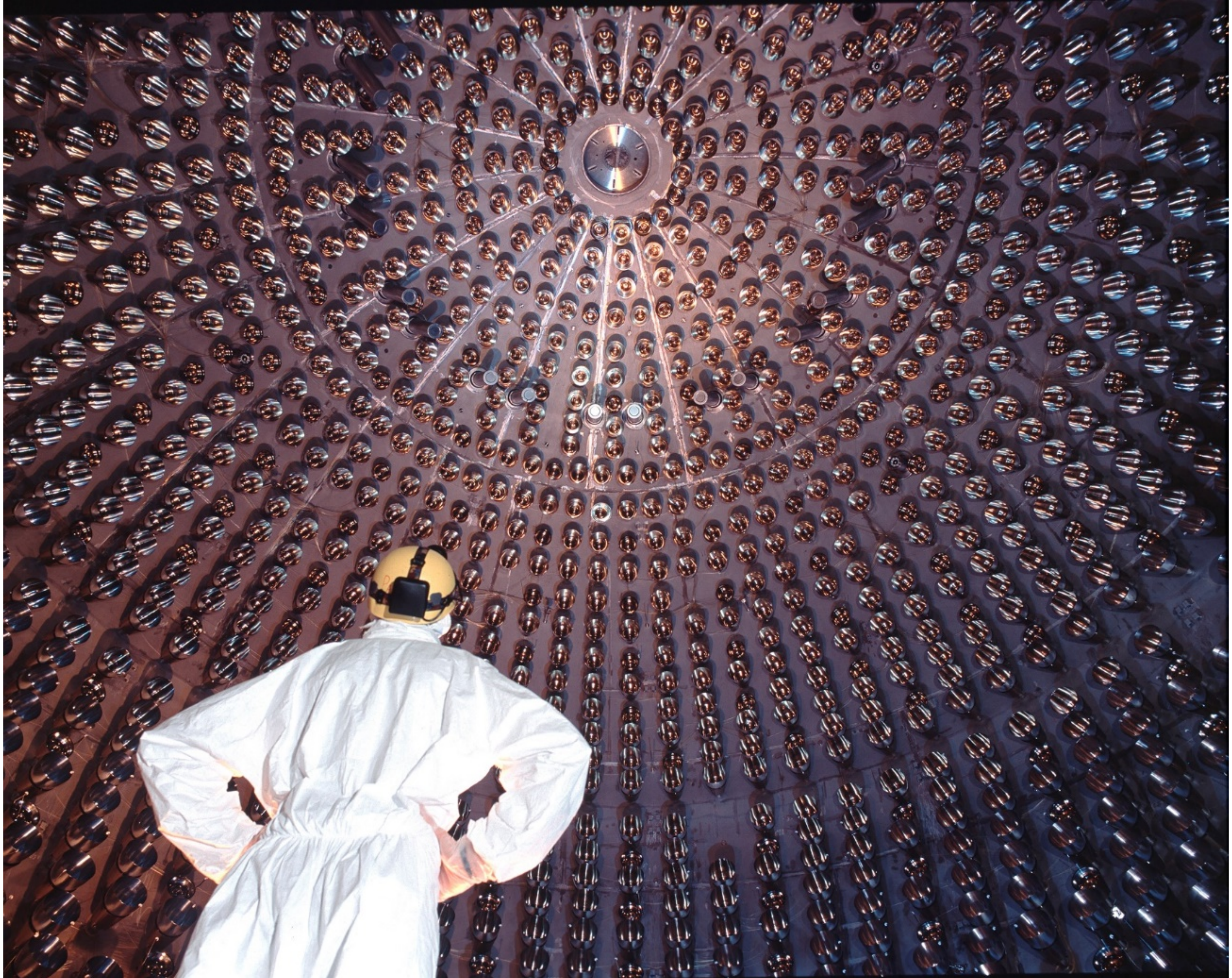
Detection principle

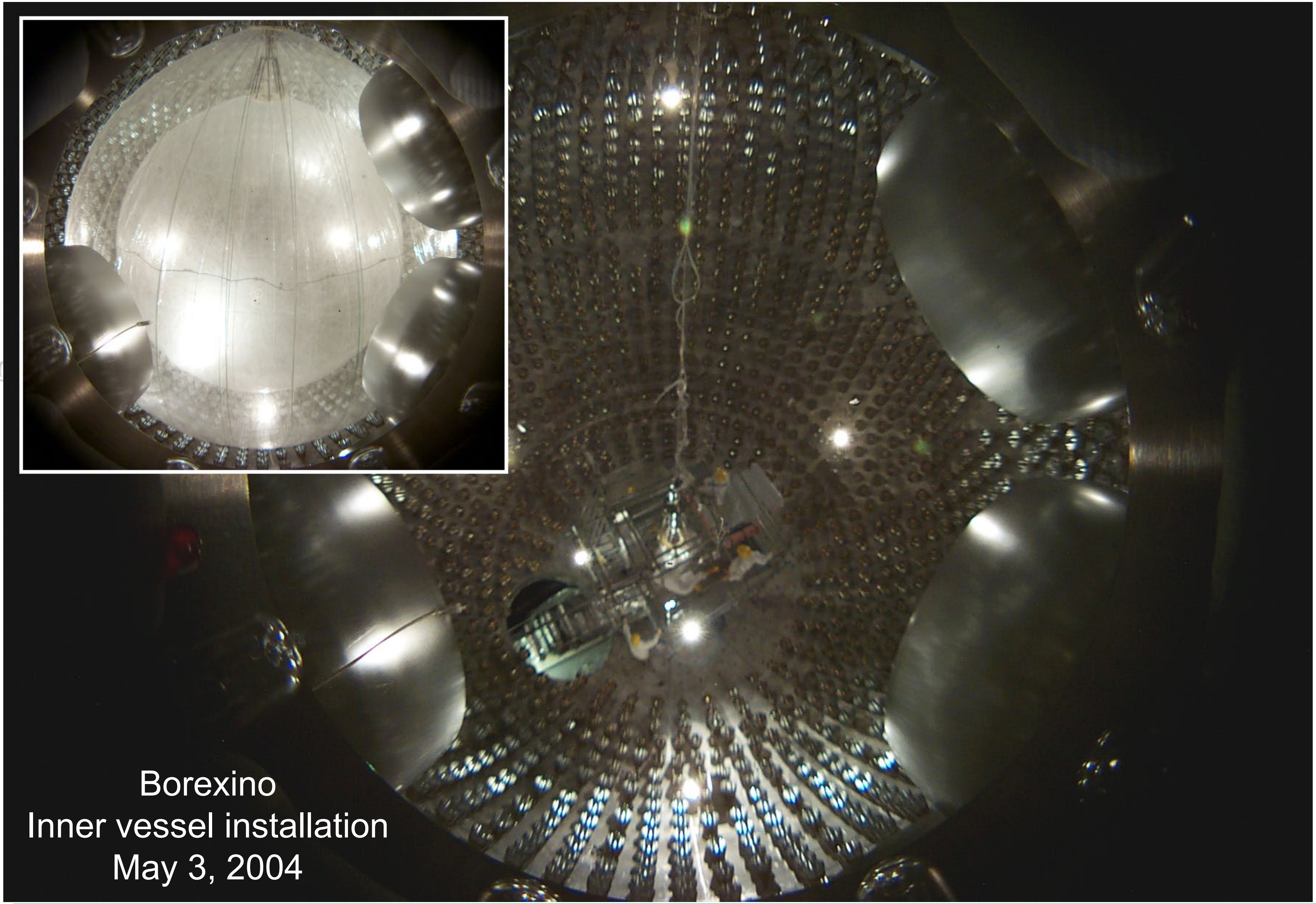
$$\nu_x + e \rightarrow \nu_x + e$$

Elastic scattering off the electrons of the scintillator threshold at ~ 60 keV (electron energy)

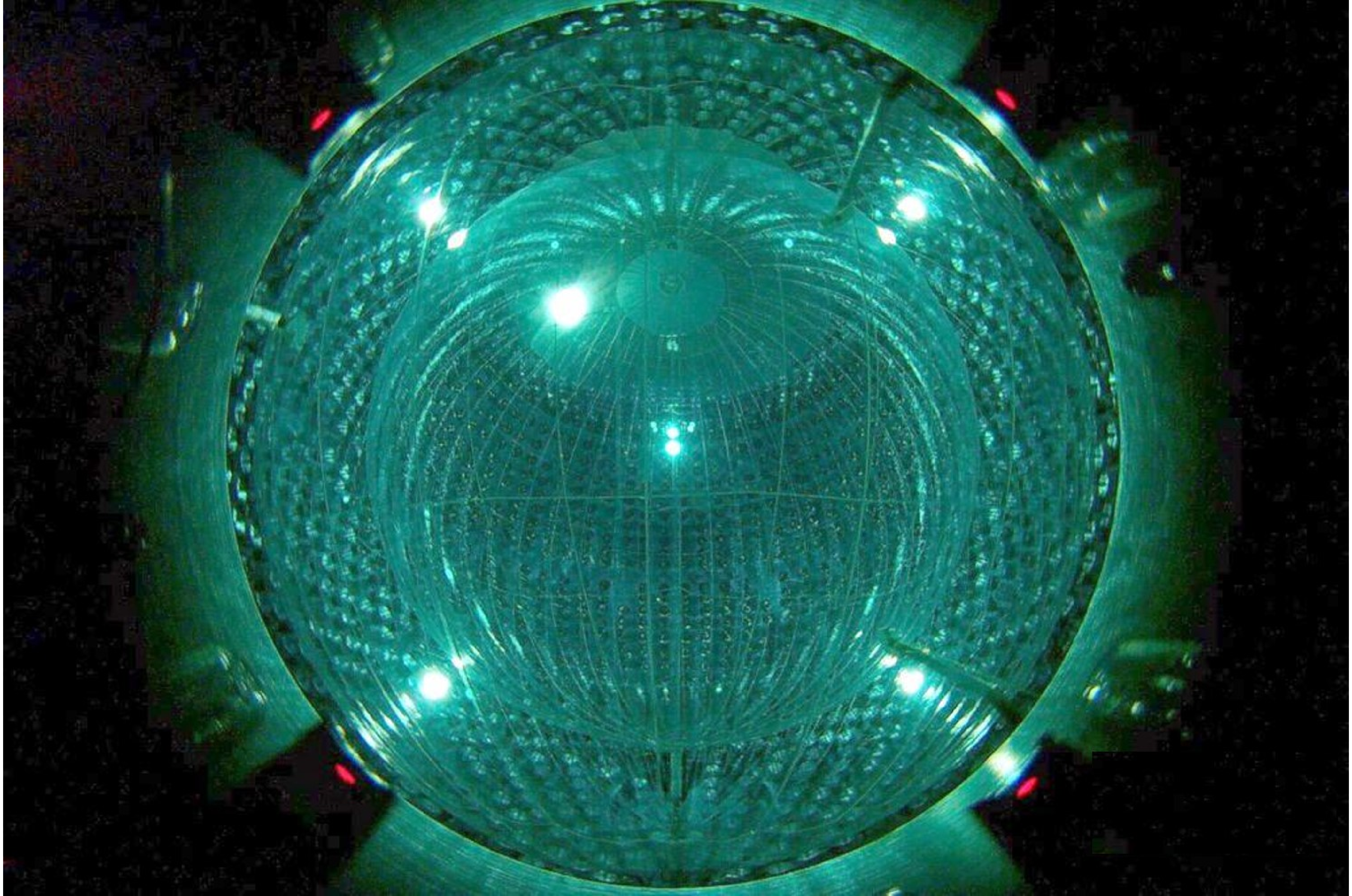
18 m high
20 m diameter







Borexino
Inner vessel installation
May 3, 2004



Detection principle

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

Elastic scattering off the electron of the scintillator
threshold at ~ 60 keV (electron energy)

Capabilities of the experiment : (in read tasks already accomplished)

^{7}Be flux (862 keV),
^{8}B with a lower threshold down to 3 MeV, and hep limit
pep (1.44 MeV) coupled to a tight limit on CNO,
Geo-antineutrinos (beyond the scope of the talk, see talk of S. Zavatarelli in the yesterday neutrino session)
pp neutrinos
Supernovae neutrinos
CNO flux (for details see talk of N. Rossi in the yesterday neutrino session)

full solar ν-spectroscopy in one experiment ! Initial task only ^{7}Be

all requiring ultra-low background especially the solar measurements → the big challenge of the experiment! → turned into an incredible success!!

Results made possible by

a) **Ultra-low background**

b) **Thorough calibration of the detector with internal and external sources**

c) **A detailed MC able to reproduce accurately the calibration results**

d) **High statistics**

e) **Threefold coincidence to remove the in-situ cosmogenic ^{11}C**

f) **Pulse shape discrimination (property of LS) to cope with α background and a series of effective cuts to remove muons and external background**

→ **Extraction of the fluxes through a data-to-model fit**
Phase I May 2007 – May 2010
Phase II December 2011 - July 2016
Purification in between and Phase III from July 2016

The background saga → the quest for the ultimate purity

Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final in phase I
Name	Source	Typical	Required	Hardware	Software	
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	<10^{-10} s^{-1} m^{-2}	underground water detector	Cerenkov PS analysis	< 10^{-10} eff. > 0.99992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	~10^{-12} g/g	~10^{-18} g/g	selection	threshold	2.7 x10^{-18} ^{14}C/^{12}C
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	<10^{-16} g/g	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	5.35 ± 0.5×10^{-18} 3.8 ± 0.8 × 10^{-18} g/g
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	<10^{-6} Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	<10^{-18} g/g	distillation, W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		<1 c/d/t	distillation, W.E., filtration, cleanliness	fit	May '07: 70 c/d/t Jan '10: ~1 c/d/t
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	<10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	<1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	30 ± 5 cpd/100 t

May 2010

20 times better than the design value

Bismuth-210 41.0±1.5±2.3 c/d/100t

With this purity first individual, separate measurements of ^{7}**Be and, pep fluxes,** and first low threshold detection **of** ^{8}**B flux → Outcome of phase I**

Purification between phase I and II

Further achievements based on improved **backgrounds** after the purification

Th< **5.7 10^{-19}** g/g 95% C.L.
U < **9.4 10^{-20}** g/g 95% C.L.
Kr< 7.1 cpd/100 tons 95% C.L.

Purification (water extraction and nitrogen stripping) astonishingly effective in further reducing the already ultralow background
Evaluated through the delayed coincidence tag

Only sizable residual backgrounds:

^{210}Po factor 100 less than at the beginning of data taking

^{210}Bismuth (**the most relevant)** factor 2 less than in phase I

Just after the purification - later ^{210}Po further decreased as effect of decay and of the subsequent thermal stabilization which stopped the recontamination from the vessel surface

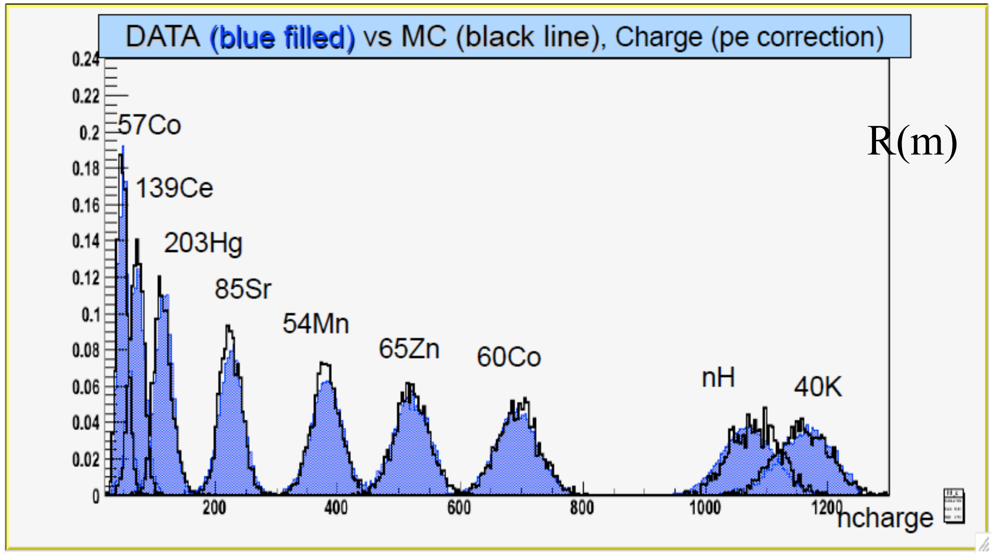
Nature, Volume 512, Issue 7515, pp. 383-386 (2014)

Nature, Volume 562, Issue 7728, pp. 505-510 (2018)

Achievement following these data purity improvement →

The measurement of the fundamental pp flux (Nature 2014) and simultaneous high precision low energy spectroscopy of the pp chain (Nature 2018) **Outcome of phase II**
Furthermore set the stage for the CNO quest (**phase III**)

Low energy range (0.14-2 MeV) calibration



@ MC tuned on γ source results

Energy scale-Resolution

$$\frac{5\%}{\sqrt{E}}$$ from 200 keV to 2 MeV

Beyond 2 MeV: γ from n capture on C and H

@ Determination of Light yield and of the Birks parameter k_B

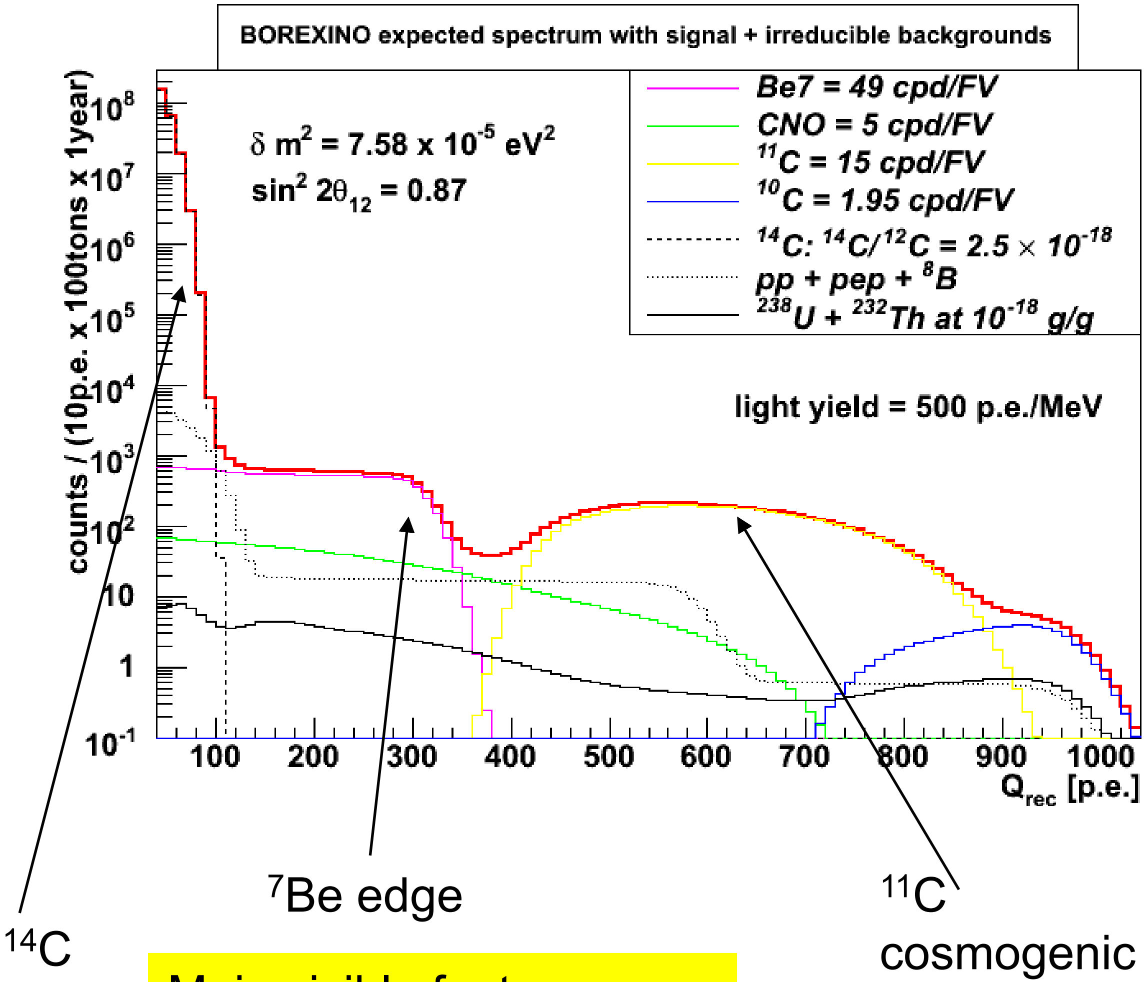
L.Y. → obtained from the γ calibration sources with MC: **~ 500 p.e./MeV**

→ left as free parameter in the total fit in the analytical approach

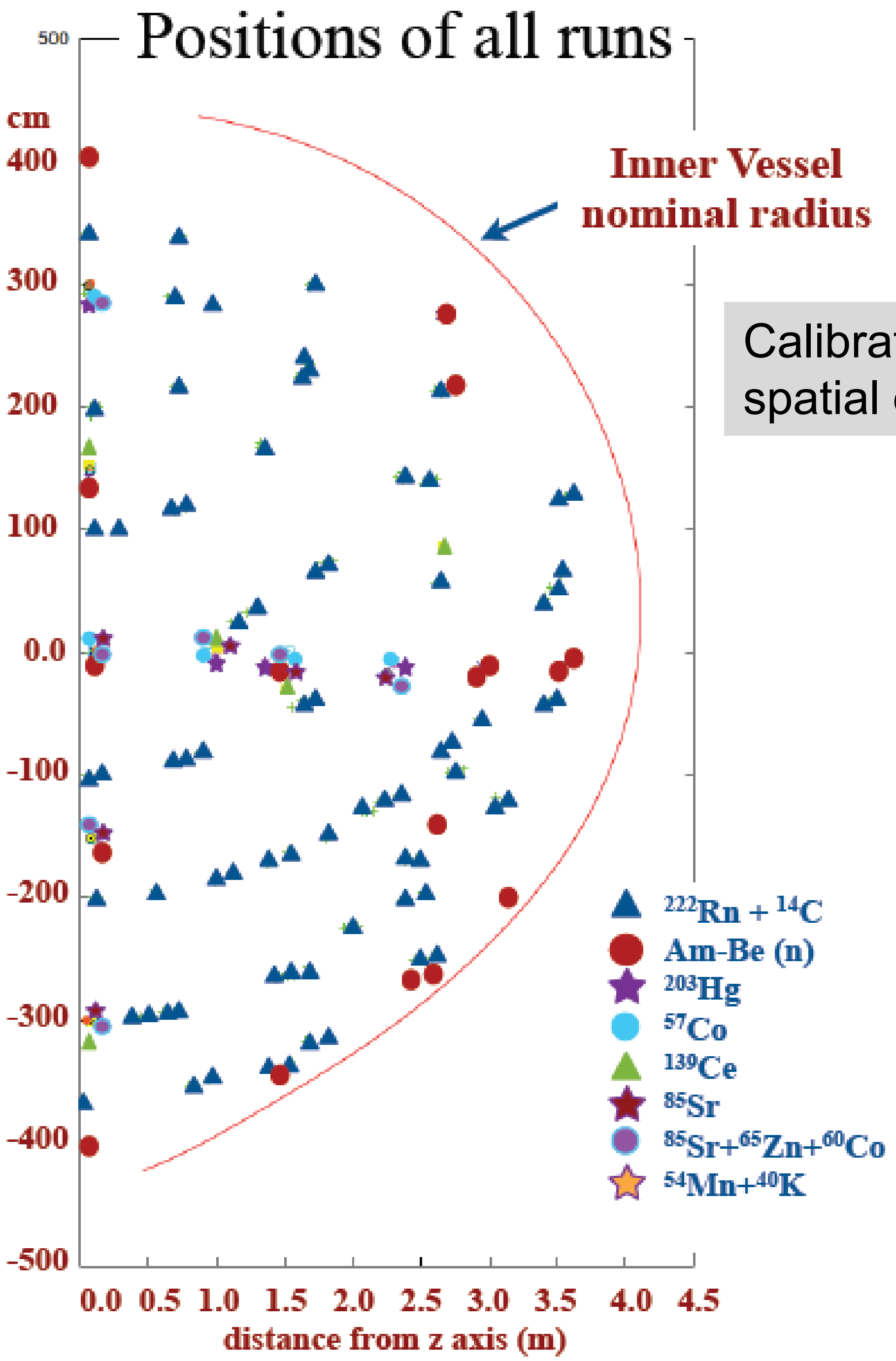
@ Precision of the energy scale global determination: max deviation **1.5%**

@ Fiducial volume uncertainty: $\left.\begin{matrix}+0.5\\-1.3\end{matrix}\right.\%$ (1 σ) (radon sources)

MC prediction of signal + intrinsic Background

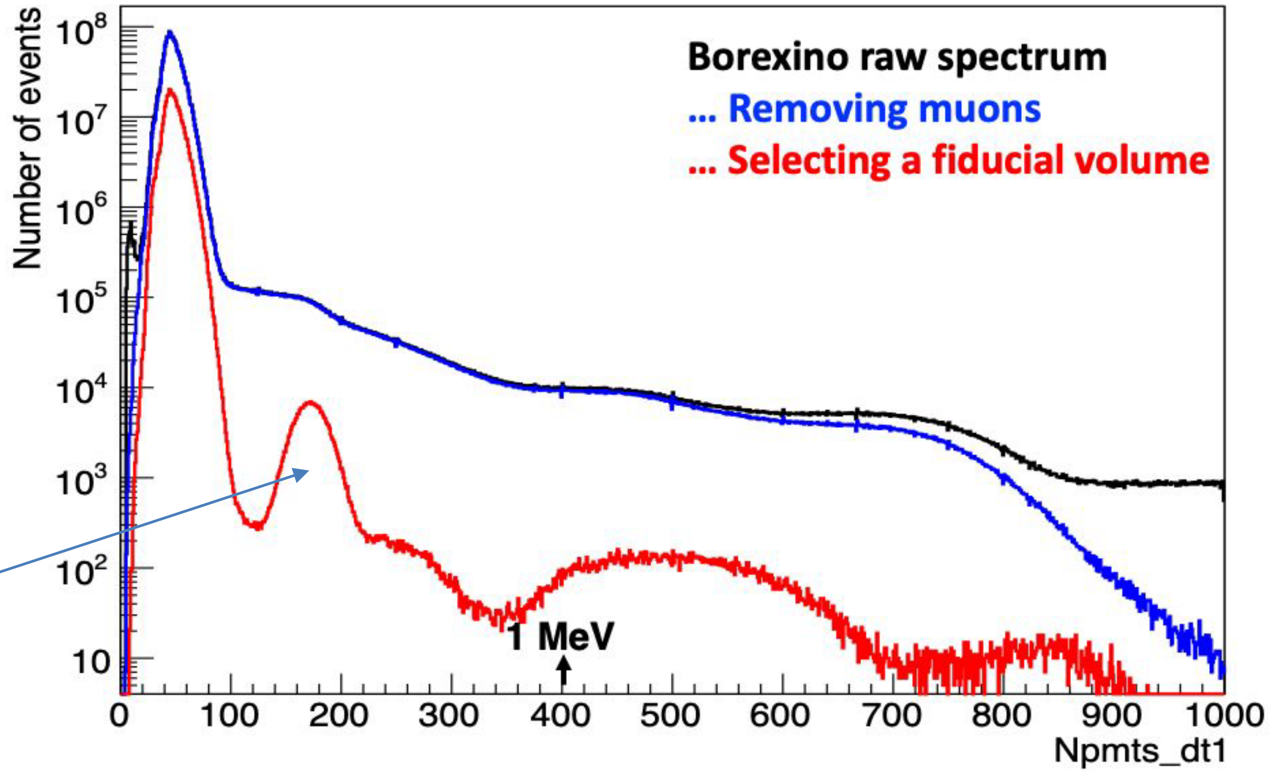


Main visible features



Calibration runs spatial distribution

Actual data histogram



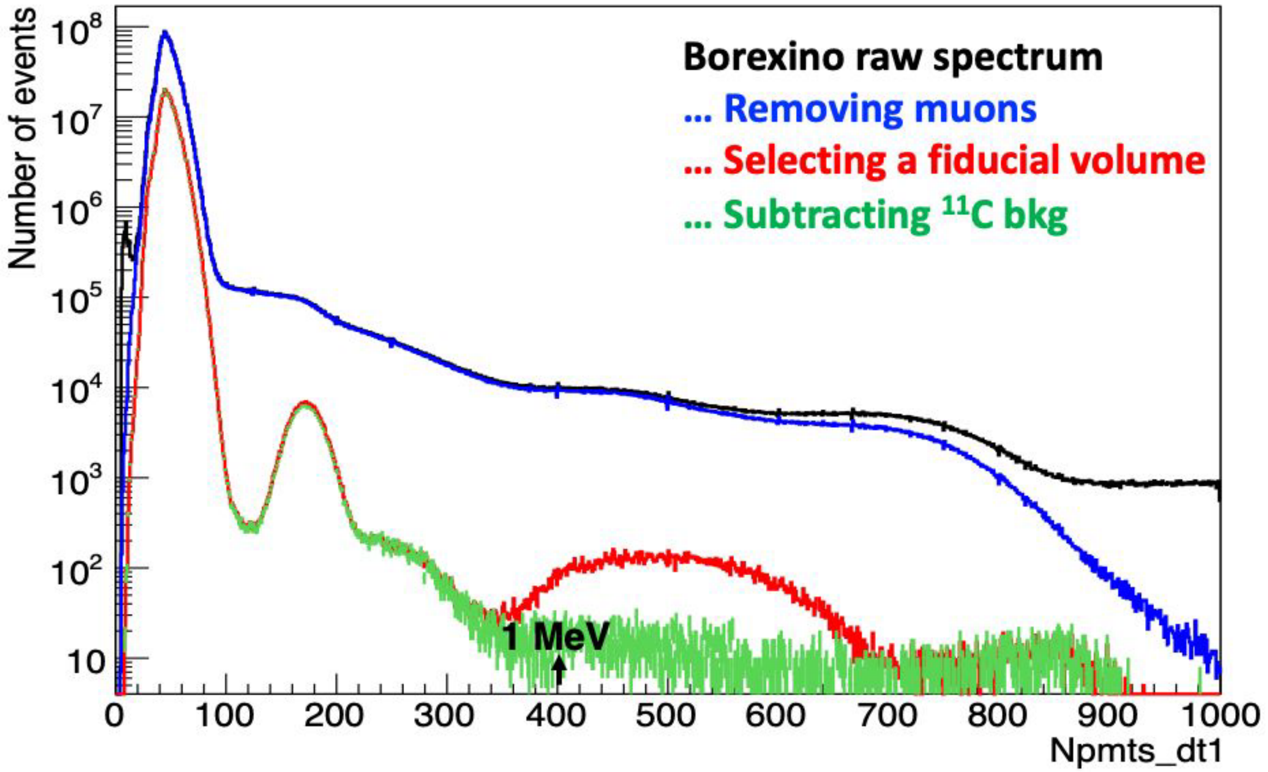
^{210}Po

The same features noted in the MC spectrum plus the ^{210}Po out of equilibrium peak

an ubiquitous isotope in all low background experiments always accompanied by the precursor ^{210}Bi

Even at the Borexino very high radiopurity conditions, we still have background events contaminating our solar neutrino signal and we need to apply software cuts to data, in order to remove as much background as possible. Furthermore, we need a powerful tool to separate the signal from the residual background components.

Reduction of the ^{11}C via the threefold coincidence

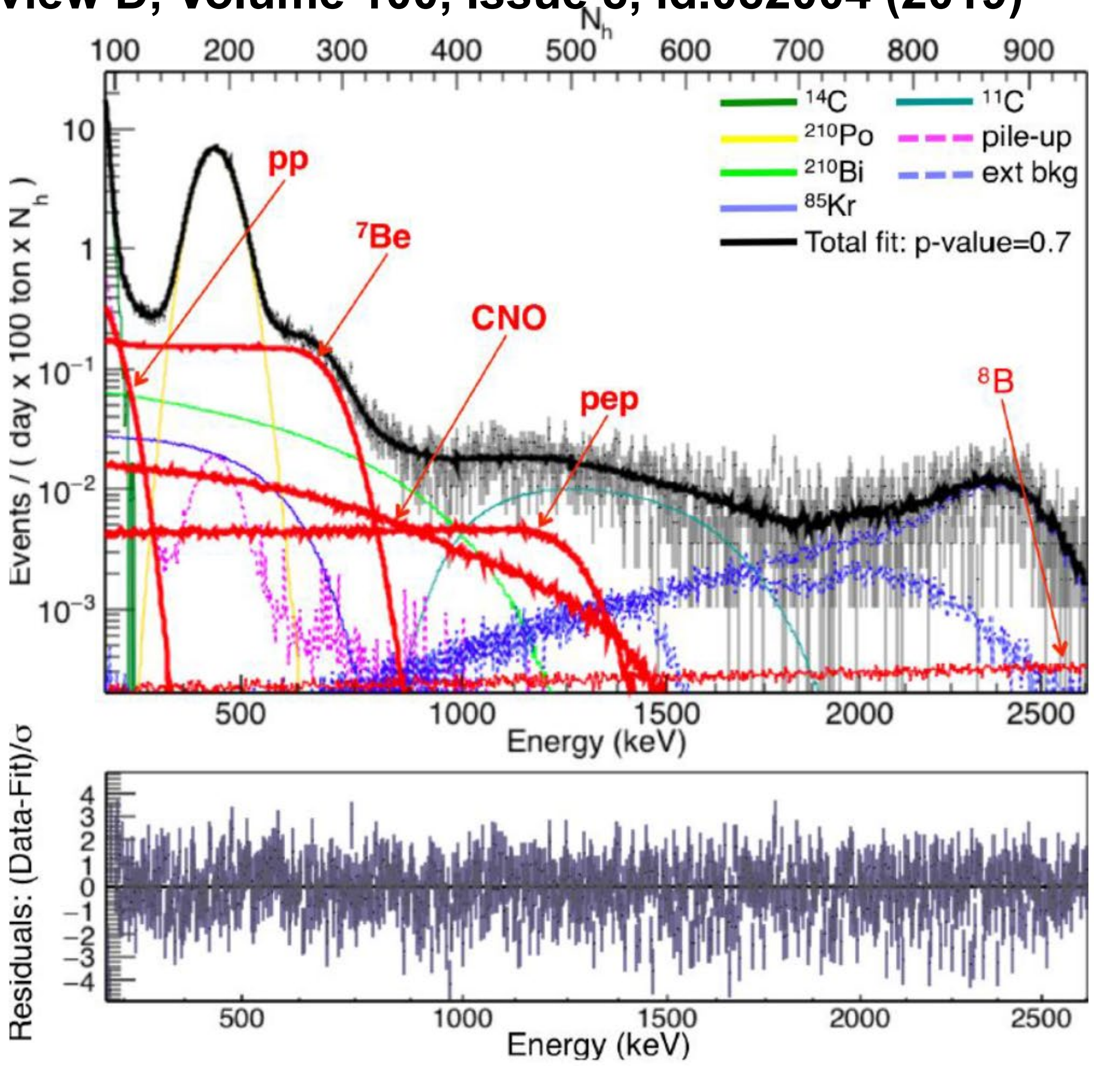


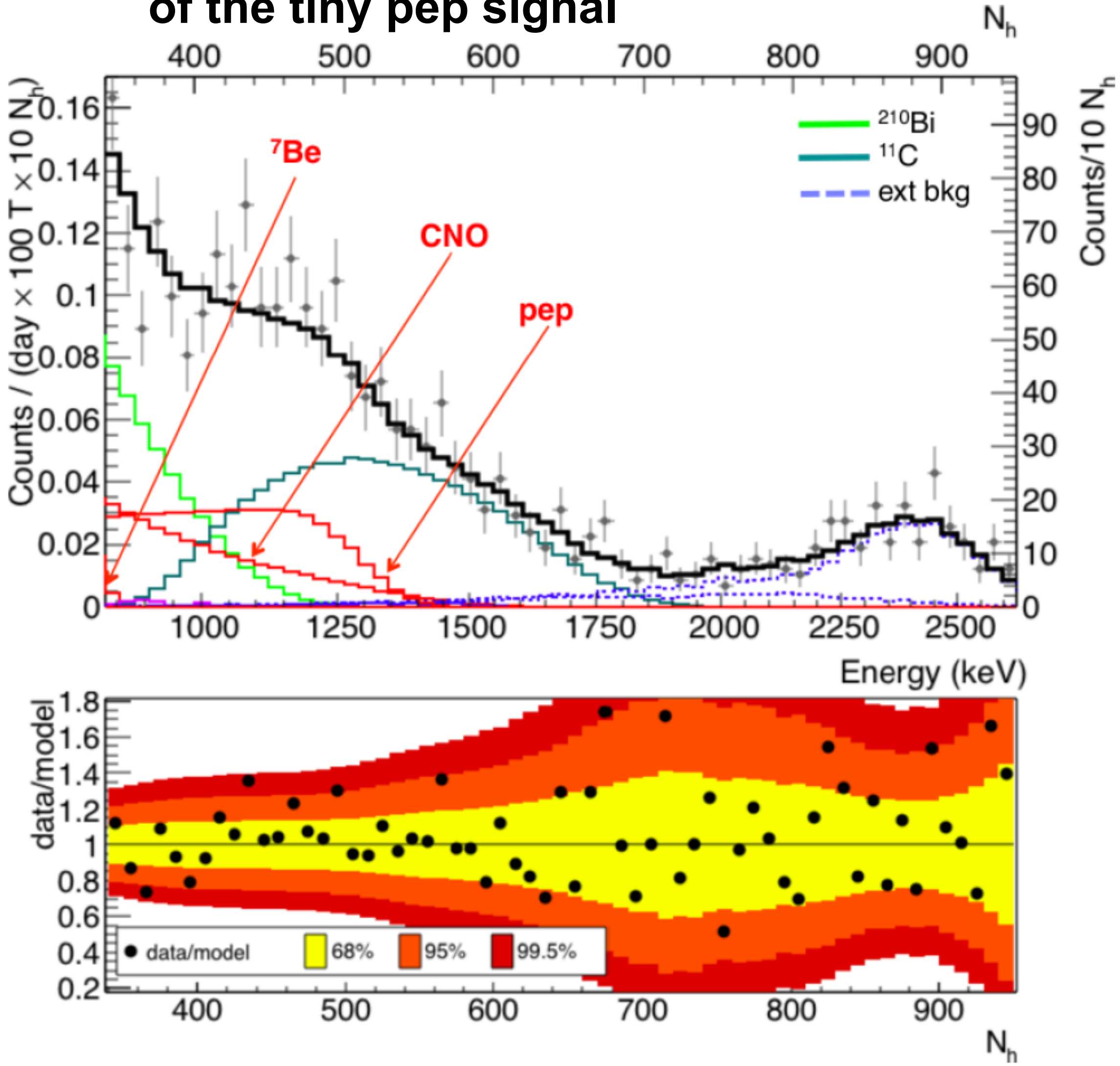
^{11}C can be tagged and removed exploiting the space and time correlation between the parent muon the spallation neutron(s) and the ^{11}C β^+ decay

Phase II data simultaneous low energy spectroscopy data-to-model fit

Nature, Volume 562, pp. 505-510 (2018) and Physical Review D, Volume 100, Issue 8, id.082004 (2019)

In particular, more than 5σ evidence of the tiny pep signal





Nature, Volume 562, pp. 505-510 (2018)
and Physical Review D, Volume 100, Issue 8, id.082004 (2019)

Summary of the low energy pp chain flux results from the previous fit

	Borexino results cpd/100t	expected HZ cpd/100t	expected LZ cpd/100t
pp	$134 \pm 10^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.4
^{7}Be(862+384 KeV)	$48.3 \pm 1.1^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05

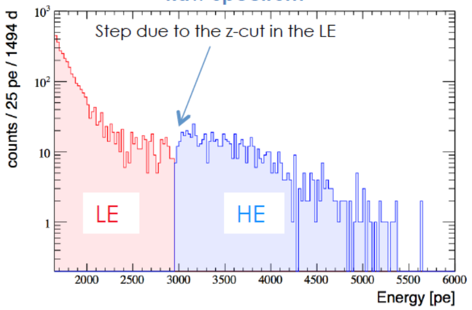
	Borexino results Flux ($cm^{-2}s^{-1}$)	expected HZ Flux ($cm^{-2}s^{-1}$)	expected LZ Flux ($cm^{-2}s^{-1}$)
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5})\ 10^{10}$	$5.98\ (1\pm 0.006)\ 10^{10}$	$6.03\ (1\pm 0.005)\ 10^{10}$
^{7}Be(862+384 KeV)	$(4.99 \pm 0.13^{+0.07}_{-0.10})\ 10^{9}$	$4.93\ (1\pm 0.06)\ 10^{9}$	$4.50\ (1\pm 0.06)\ 10^{9}$
pep (HZ)	$(1.27 \pm 0.19^{+0.08}_{-0.12})\ 10^{8}$	$1.44\ (1\pm 0.009)\ 10^{8}$	$1.46\ (1\pm 0.009)\ 10^{8}$
pep (LZ)	$(1.39 \pm 0.19^{+0.08}_{-0.13})\ 10^{8}$	$1.44\ (1\pm 0.009)\ 10^{8}$	$1.46\ (1\pm 0.009)\ 10^{8}$

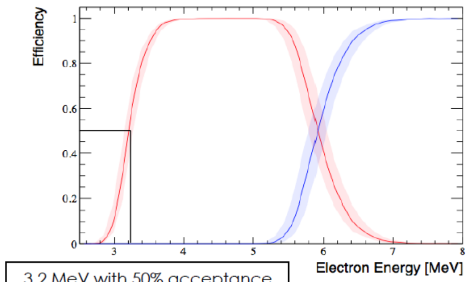
Beginning of the precision era in the study of low energy solar neutrinos
^{7}Be precision 2.7%

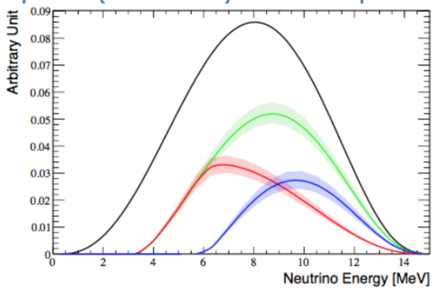
LE and HE Ranges

pp study completed with the ^8B determination with phase II data
Background subtraction and spectral analysis in two energy ranges
PHYSICAL REVIEW D 101, 062001 (2020)

Splitting the sample at 2950 npe (> 5 MeV): no natural radioactivity expected above this threshold







Mean neutrino energies:

LE: 7.9 MeV
HE: 9.9 MeV
LE+HE: 8.7 MeV

3 MeV electron threshold
5 MeV electron en. boundary between LE and HE

Moreover limit on the hep flux < 1.8×10^5 cm^{-2} s^{-1}

Completion of the investigation of the pp chain

Systematic Errors and Results

Source	LE σ	HE σ	LE+HE σ
Active mass	2.0	2.0	2.0
Energy scale	0.5	4.9	1.7
z-cut	0.7	0.0	0.4
Live time	0.05	0.05	0.05
Scintillator density	0.5	0.5	0.5
Total [%]	2.2	5.3	2.7

In addition we have tested:
- pdf **radial distortion**: ±3%
- Emanation **vessel shift**: ±1%
- **Response functions** for the emanation component generated at 6 cm from the vessel (instead of 1 cm)
- **Binning** dependence

None of these potential systematic sources affected the measured 8B rate outside 1 statistical sigma

$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \text{cpd}/100\,\text{t},$$
$$R_{HE} = 0.087^{+0.08}_{-0.010}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \text{cpd}/100\,\text{t},$$
$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \text{cpd}/100\,\text{t}.$$

Expected rate in the LE+HE range:
0.211± 0.025 cpd/100 t
Assuming B16(G98) SSM and MSW+LMA

Equivalent unoscillated flux

SuperKamiokande	2.345 ±0.014 ±0.036 x 10^6 cm^{-2} s^{-1}
BX 2010	2.4 ±0.4 x10^6 cm^{-2} s^{-1}
This measurement	**2.55 ±0.18 ±0.07 x 10^6 cm^{-2} s^{-1}**

Phase I
Phase II

Error halved

Closing on the pp chain burning mechanism experimental investigation

The complete spectroscopy from **pp to ^{8}B** represents the first and unique full determination of the pp cycle → **final crowing of the experimental quest for the burning mechanism fueling the Sun!**

Quantitative probe of the pp solar fusion long advocated by John Bahcall

$$R = \frac{Rate(^3He+^3He)}{Rate(^3He+^4He)} \qquad R = \frac{2\,\Phi(^7Be)}{\Phi(pp)-\Phi(^7Be)}$$

Expected values: (C. Pena Garay, private comm,)

$$R = 0.180 \pm 0.011 \quad HZ$$
$$R = 0.161 \pm 0.010 \quad LZ$$

Measured value:

Nature, Volume 562, pp. 505-510 (2018)

$$R = 0.18 \pm 0.02$$

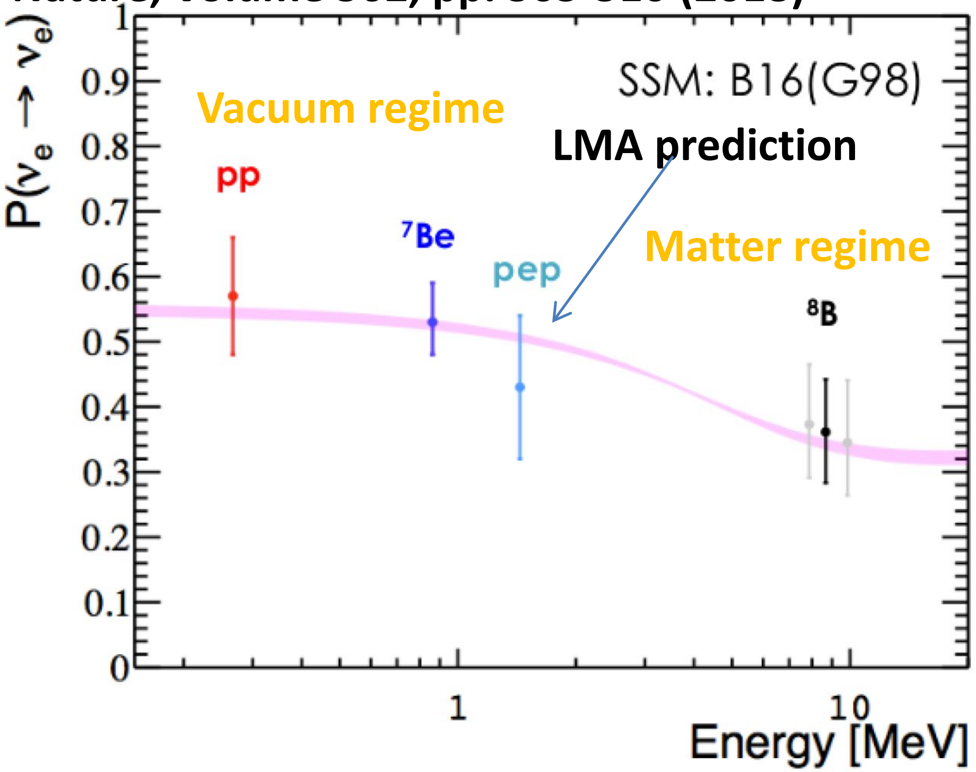
Borexino completes and closes the experimental quest of the pp mechanism powering the Sun

Moreover, using Borexino results we can calculate the neutrino solar luminosity which is found to be well in agreement with the measured photon luminosity

Further confirmation of the nuclear origin of the solar power. It proves that the Sun has been in thermodynamic equilibrium over the last 10^5 years, the time required for radiation to flow from the center to the surface of the Sun

The global oscillation picture: survival probability of the electron neutrinos contrasted with the improved Borexino results of phase II

Nature, Volume 562, pp. 505-510 (2018)

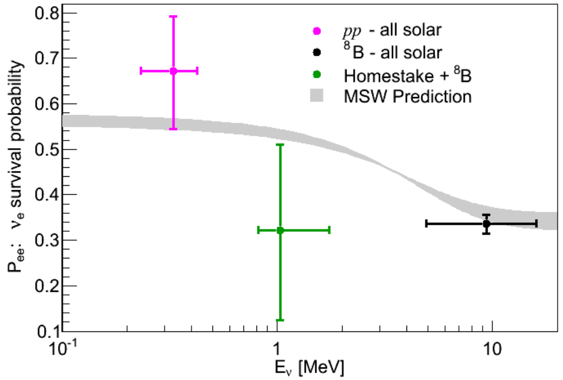


FROM BOREXINO ALONE VALIDATION OF THE **LMA-MSW** OSCILLATION SOLUTION OVER THE FULL SOLAR NEUTRINO SPECTRUM

Reinforced by the improved precision of the phase II data

^{7}Be 2.7%

Simultaneous low energy spectroscopy



Before the Borexino results

"Although historically by measuring Δm^2_{21} KamLAND has uniquely selected the LMA solution, now the solar neutrino experiments alone can do this due to new measurements by Borexino, which validated the solution at low energies, and due to higher accuracy of other results."
M. Maltoni and A.Yu. Smirnov EPJA 52 , 87 2016

P_{ee} curve (magenta band) as expected from ν oscillation+Matter effect (LMA-MSW)

$$A^{^7Be}_{DN} = \frac{D-N}{(N+D)/2} = (-0.1 \pm 1.2 \pm 0.7)\%$$

Borexino Coll., Phys. Lett. B707 (2012) 22

Day-Night asymmetry of ^{7}Be neutrinos consistent with 0 in agreement with the LMA-MSW expectation

The next and last step of the Borexino journey throughout the nuclear reactions powering the SUN : detection of solar neutrinos from the CNO cycle

Phase III data

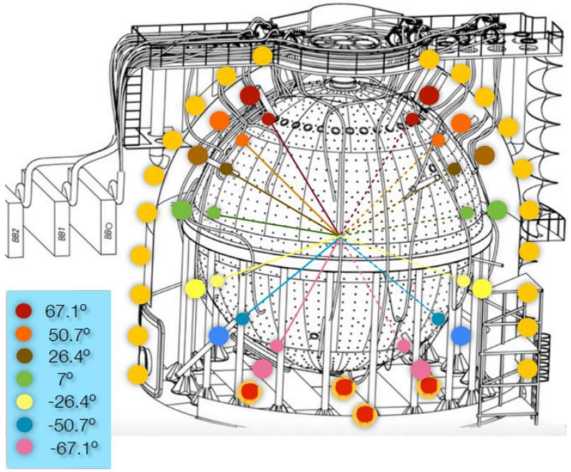
July '16 – Feb '20

Main issue: ^{210}Bi background indistinguishable from the CNO spectrum **^{210}Bi/CNO degeneracy**
Handle: ^{210}Bi determination via intrinsic (in the LS) ^{210}Po successor
Requirement: stop of the extra ^{210}Po from the surface of the vessel due to convective motions of the scintillator
Action on the detector: thermal stabilization to maintain the liquid as still as possible - **very challenging task**

Multiple approaches to monitor, understand, and suppress the temperature variations

Thermal insulation & Active Gradient Stabilization System

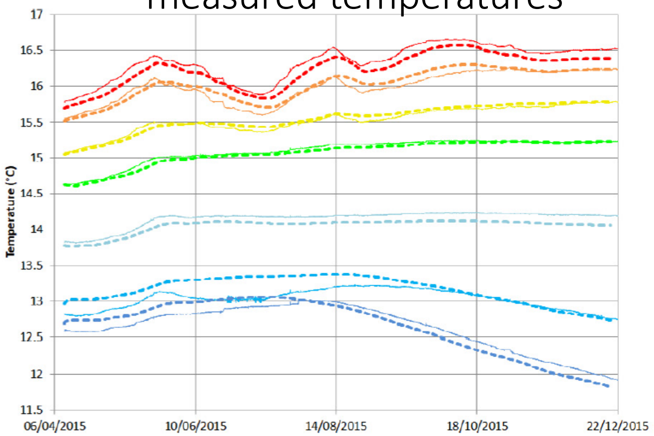
Temperature monitoring probes



54 temperature probes

Fluid dynamical simulation

Very good agreement with measured temperatures



time

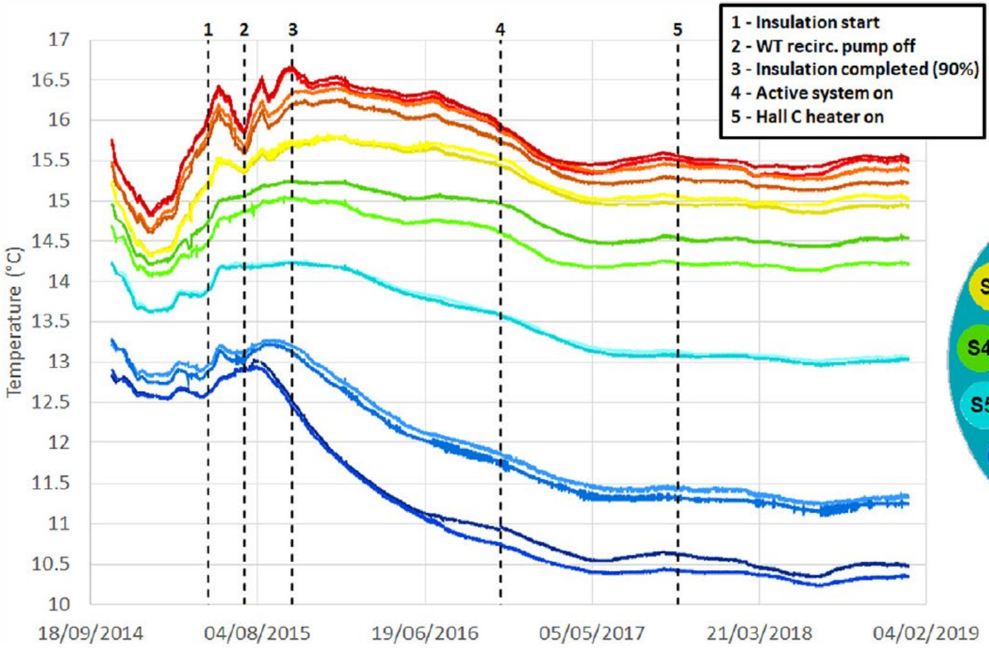
6/04 2015 | 10/06 2015 | 14/08 2015 | 18/10 2015 | 22/12 2015

- Double layer of mineral wool (thermal conductivity down to 0.03 W/m/K) & Active Gradient Stabilization System (2014-2016)
- Temperature Probes (2014-2015)
- Fluid dynamical simulations
- Hall C Temperature Stabilization (2019)

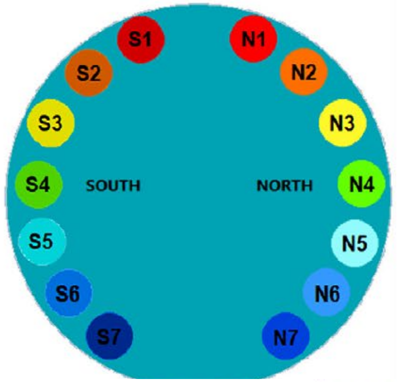
V. di Marcello et al., NIM A 964, id. 163801

Enduring effort over the past **seven years**

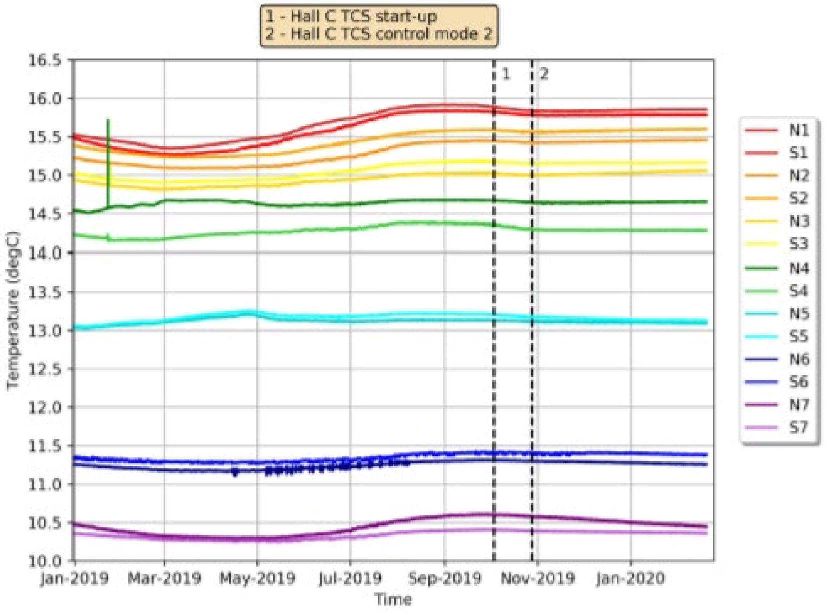
Temperature evolution from the probes



Global view of stabilization from 2015



Probes sensing the outer buffer

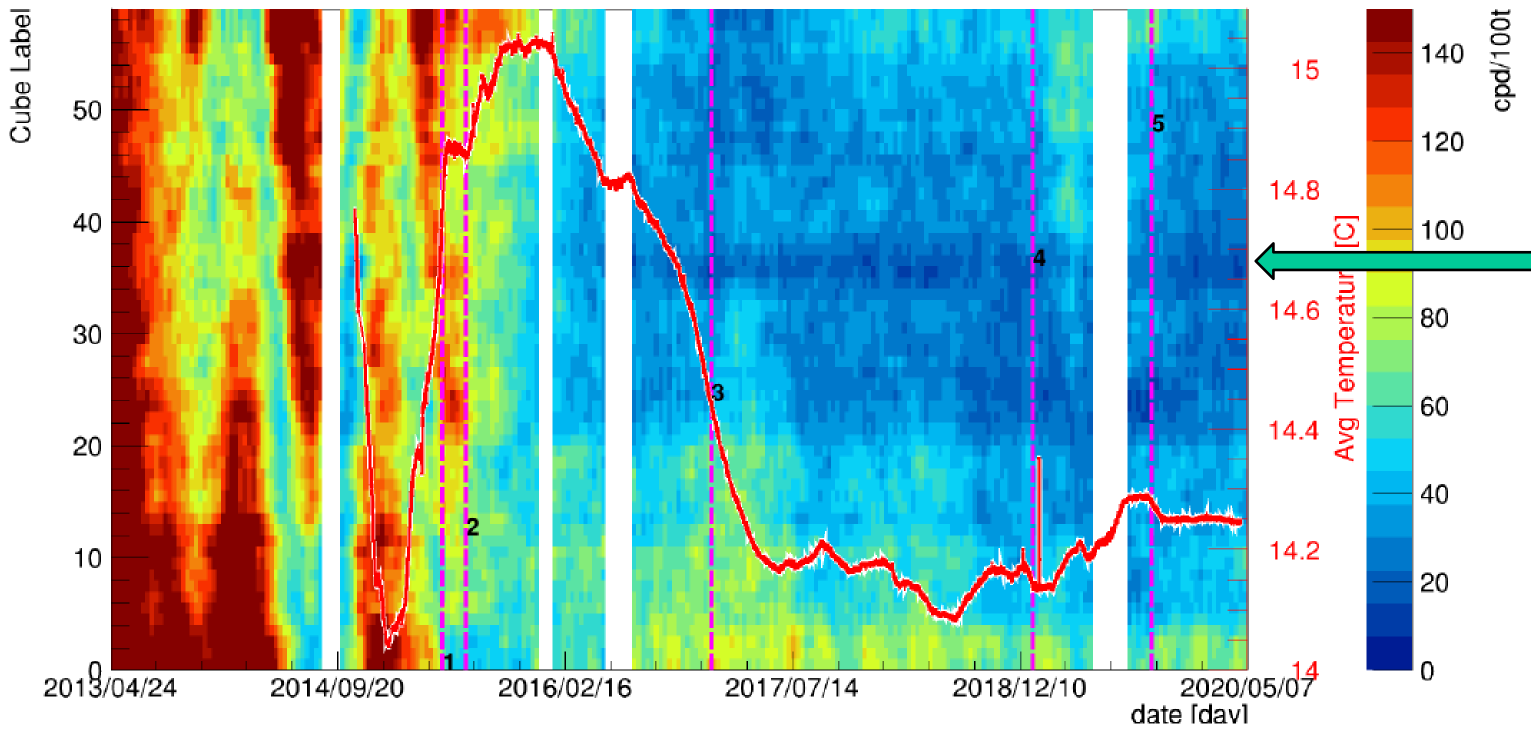


Snapshot of the last year

Achieved excellent temperature stability with the establishment of a clear temperature gradient

Probes resolution 0.07 °C

A 2D detailed view - Polonium data spatial mapping vs. time



Crucial observation: "Low Polonium Field" 20 tons size from which we can infer the intrinsic ^{210}Po and hence the ^{210}Bi - **agreement with simulations**

Convective condition before insulation

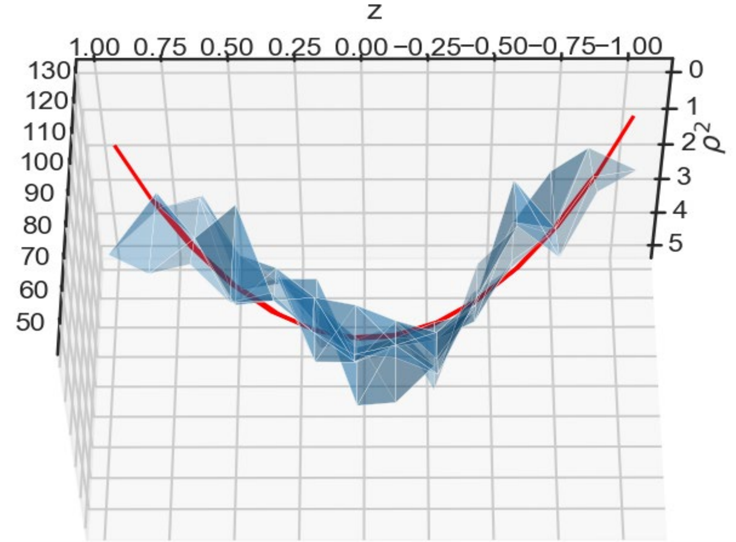
Quiet situation after insulation

Stabilization measures were very effective at reducing the ^{210}Po motion

1. Beginning of the Insulation Program
2. Turning off the water recirculation system in the Water Tank
3. Start of the active temperature control system operations
4. Change of the active control set points
5. Installation and commissioning of the Hall C temperature control system.

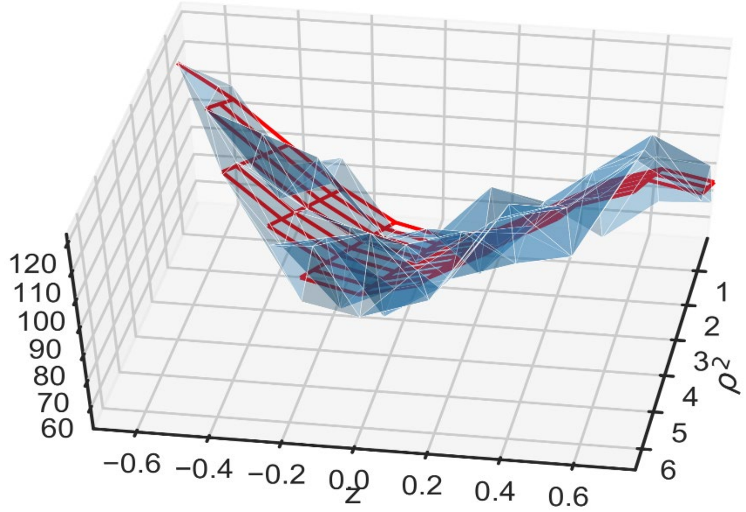
Determination of the ^{210}Po minimum by fitting its spatial distribution

Paraboloid



$$R_{Po} = R_{min}\epsilon \cdot \left(1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}\right) + R_\beta$$

Spline fit:



Account for complexity along the z axis with a cubic spline model using a Bayesian nested sampling algorithm

Both methods agree within systematics:

$R_{min}(cpd/100t)$	σ_{fit}	σ_{mass}	$\sigma_{binning}$	$\sigma_{^{210}Bi\ homog.}$	$\sigma_{\beta\ leak}$	σ_{Total}
11.5	0.88	0.36	0.31	See next slides	0.30	See next slides

^{210}Po and ^{210}Bi final numerical assessment

$$^{210}\mathrm{Pb} \xrightarrow[(23\mathrm{y})]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[(5\mathrm{d})]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[(138\mathrm{d})]{\alpha} {}^{206}\mathrm{Pb}\,(\mathrm{stable})$$

Basis of the approach

^{210}Po rate inferred from the Low Polonium Field with all errors

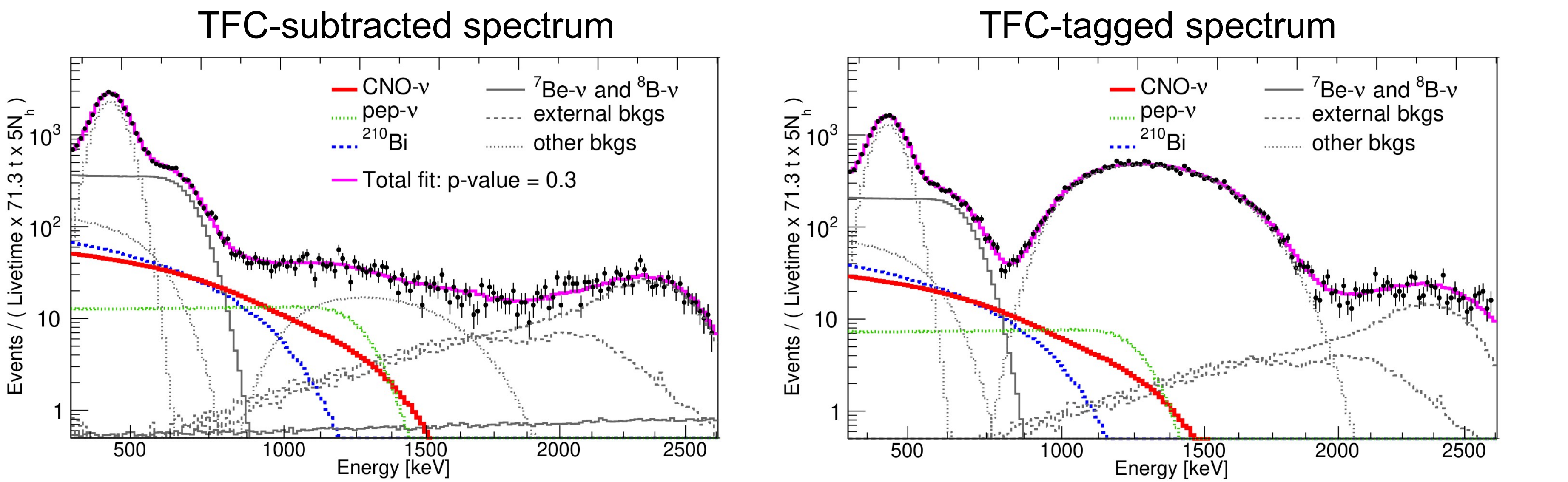
$R_{min}(cpd/100t)$	σ_{fit}	σ_{mass}	$\sigma_{binning}$	$\sigma_{^{210}Bi\ homog.}$	$\sigma_{\beta\ leak}$	σ_{Total}
11.5	0.88	0.36	0.31	0.78	0.30	1.3

The ^{210}Po evaluated rate still possibly contaminated with residual ^{210}Po from the vessel surface $\rightarrow$ upper limit to the rate of ^{210}Bi

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

Sought constraint essential to break the ^{210}Bi/CNO degeneracy $\rightarrow$
Outcome of the relentless years-long effort to stabilize the detector and understand the ^{210}Po behavior in the Inner Vessel

CNO-ν analysis: Phase-III MV fit



Multivariate fit (0.32-2.64 MeV)
July '16 – February '20

Maximization of a binned likelihood **3 distributions simultaneously**:

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

pep-ν rate constrained → solar luminosity constraint
^{210}Bi rate constrained → **^{210}Bi-^{210}Po tagging**
CNO rate → free to vary
Other ν and bkg rates → free to vary

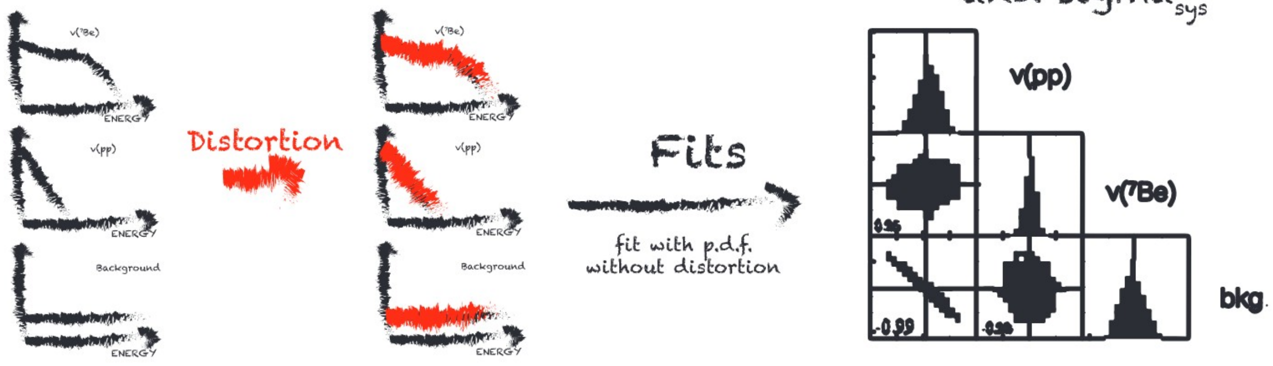
Result

CNO best fit 7.2 cpd/100t
asymmetric confidence interval -1.7 +2.9 cpd/100t
(stat only) asymmetry ↔ ^{210}Bi upper limit

Systematic sources and final CNO-ν result

Monte Carlo → simulate distorted datasets, fit with un-distorted PDFs

Look at the width → Get $\text{sigma}^{\text{expected}}_{\text{stat}}$ and $\text{sigma}_{\text{sys}}$



1) Fit conditions → negligible

2) ^{11}C spectrum deformation by noise cuts

3) Energy response function: energy scale (~0.23%), non-uniformity (~0.28%), non-linearity (~0.4%) from detector calibration

4) ^{210}Bi spectral shape (diff.~18%)

Final syst: **-0.5 +0.6 cpd/100t**

⇨ Final CNO result 7.2 (-1.7 +3.0) cpd/100t stat + sys

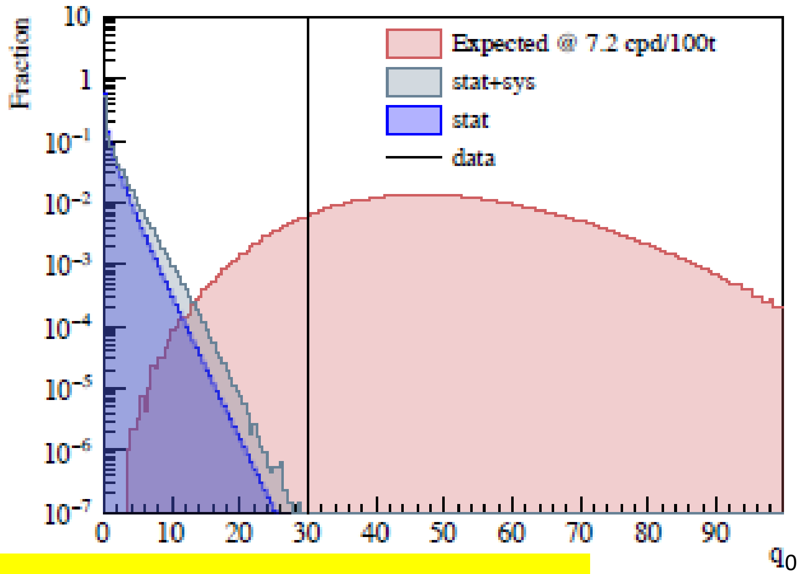
corresponding to a flux of neutrinos on Earth of $7.0\ (-1.9\ \ +2.9)\times 10^{8}\ \text{cm}^{-2}\ \text{s}^{-1}$

Significance of CNO-ν detection

Likelihood ratio test

Determination of the q_0 discovery test statistic from the likelihood with and without the CNO signal

G. Cowan et al., Eur. Phys. J. C, 71:1554,20



13.8 millions pseudo-datasets with deformed PDFs and no CNO to determine the q_0 reference distribution

q_0(data) from the real dataset

From the MC distributions **p-value** of q_0 (grey curve) with respect to q_0 (data) (black line) → correspondingly **significance** greater than **5 σ** at 99% CL

Consistent with **5.1σ** through the log-likelihood from the fit folded with uncertainties

Remember:
CNO provides a handle for the **Sun metallicity**

Compatible with HZ and LZ but comparing pp, ^{7}Be, CNO, ^{8}B fluxes measured by Borexino with SSM-LZ → rejected @ 2.1 σ

No CNO hypothesis disfavored at 5 σ

With these results Borexino marked the first detection ever of CNO solar neutrinos

Nature, Volume 587, Issue 7835, p.577-582 (2020)

Conclusions

The long journey of Borexino to decipher the mysteries of the neutrinos from the Sun has produced the following enduring scientific legacies

- ✓ **Full solar neutrino spectroscopy in only one experiment** which has enabled
  - Complete investigation the main pp fueling mechanism of the Sun
  - first detection ever of the CNO neutrinos with 5 σ significance which confirms the existence of this energy generating cycle dominant in the more massive stars

- ✓ **Validation at of the MSW-LMA ν oscillation solution by Borexino alone** over the entire solar neutrino spectrum

With these outcomes Borexino has accomplished its mission by completely unraveling the two processes powering the Sun and the stars

the pp Chain and the CNO Cycle