10 years of research with the Borexino experiment

Gioacchino Ranucci

Istituto Nazionale di Fisica Nucleare Milano

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One of the basic mankind's question: why does the Sun shine?

Ancient Greek's "chariot of the Sun" example of first developed "theories"

La *Sala del Tiepolo* in «palazzo Clerici» Milano

Turning point at the passage between 19th and 20th centuries

- In the 19th century hot controversy between Lord Kelvin and Darwin: age of he Earth and the Sun to account for the evolution of the life on our planet, incompatibility with the sources of energy known at that time

- Clue $\rightarrow$ Aston experiment in 1920: m(He)<4 m(H)

- Eddington: argued in his 1920 presidential address to the British Association for the Advancement of Science that Aston's measurement meant that the Sun could shine by converting hydrogen atoms to helium....

Formulation of the nuclear hypothesis

"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 → Identification of potential CNO cycle

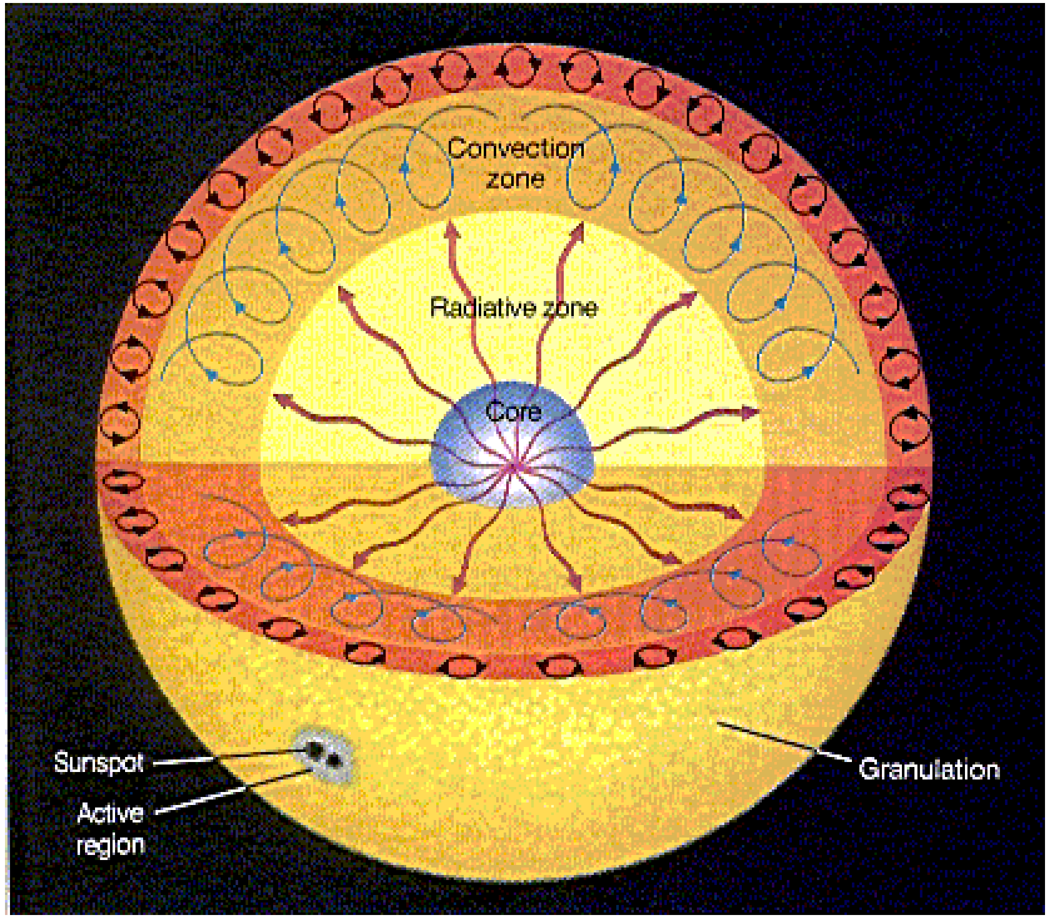
1938 Bethe → Identification of potential *p-p* chain and full definition of the nuclear hypothesis

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?



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: the experimental players taking part to an almost five decades long successful plot

Radiochemical experiments:

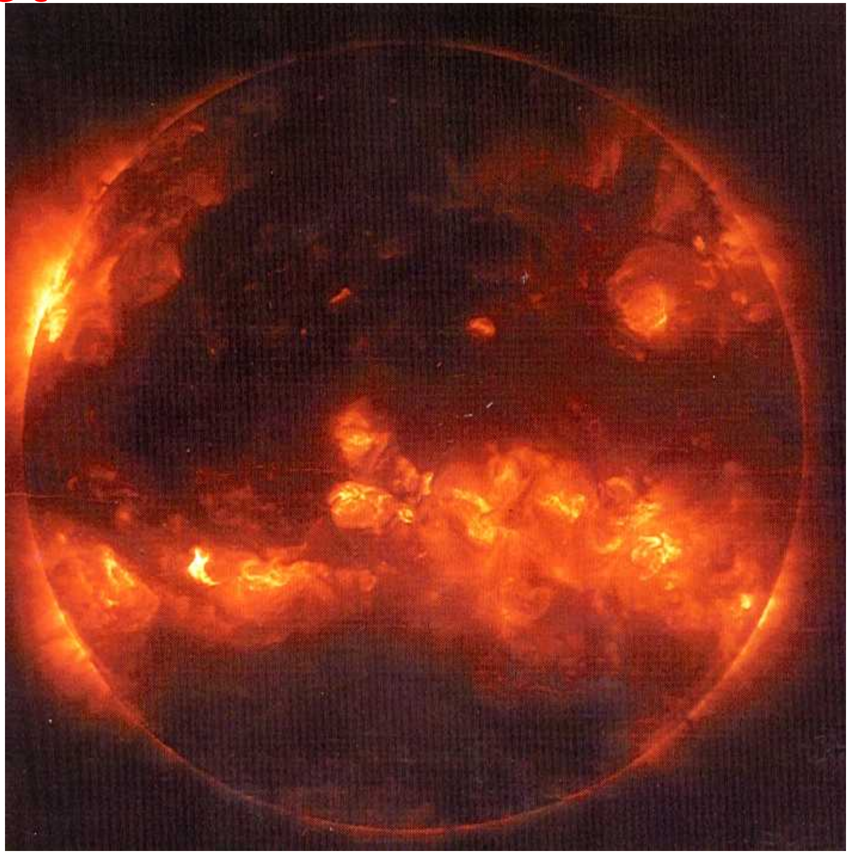
- **Homestake** (Cl)
- **Gallex/GNO** (Ga)
- **Sage** (Ga)

Real time Cherenkov experiments

- **Kamiokande/Super-Kamiokande**
- **SNO** (Heavy water)

Scintillator experiment

- **Borexino**



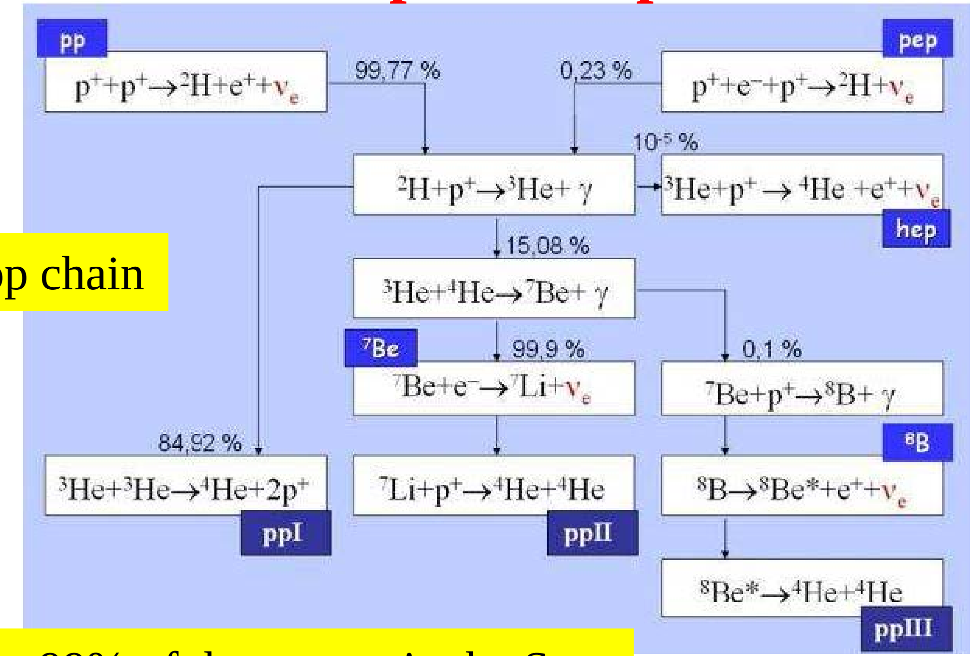
Common ingredient in this challenging rare events search→ ultra-low background

Overall two major accomplishments:
- proof of the Nuclear hypothesis
- Through the identification and solution of the “solar neutrino problem” → contribution to the proof of neutrino oscillations - MSW effect: resonant neutrino flavor conversion in matter

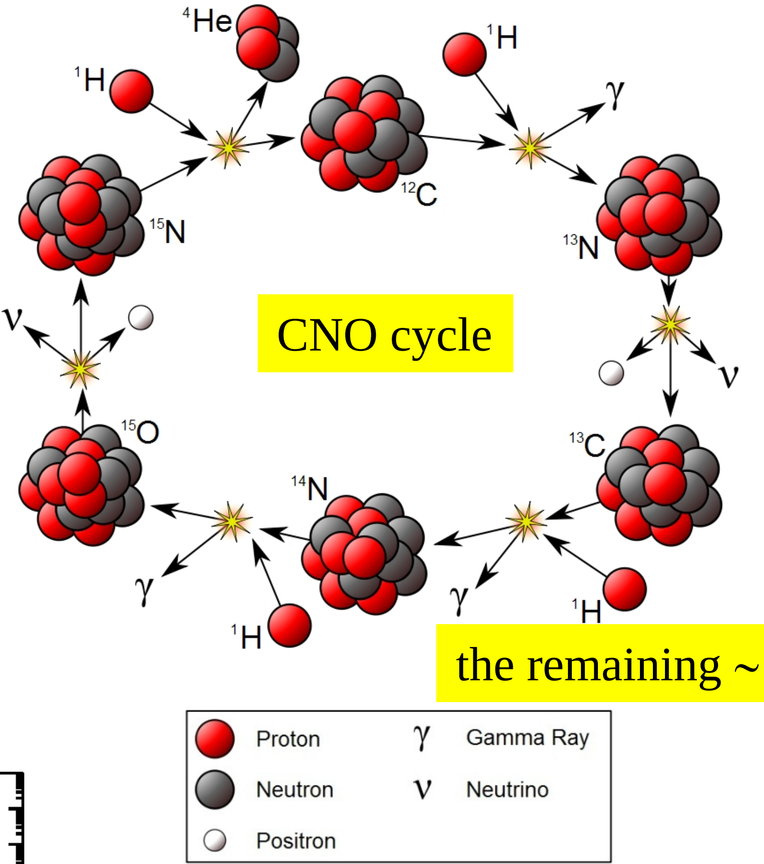
Where we are today theoretically: SSM Solar neutrinos production and spectrum predictions

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



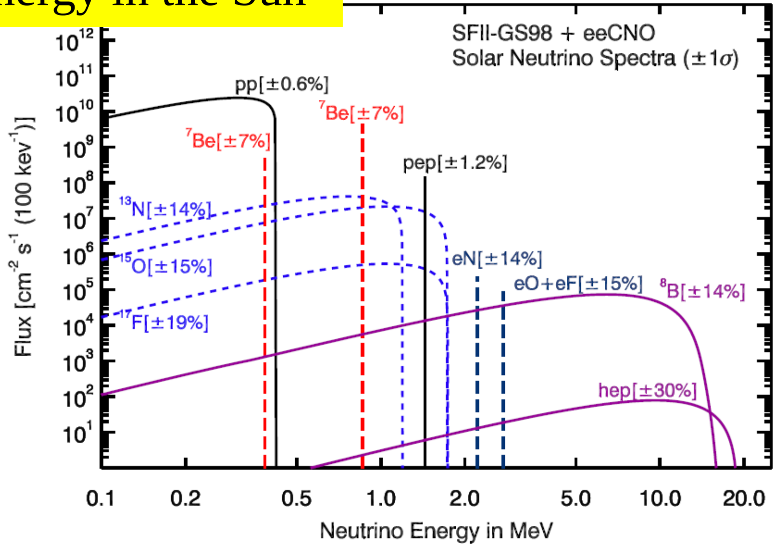
CNO cycle

Dominant in massive stars

the remaining ~1% ?

SSM spectral prediction

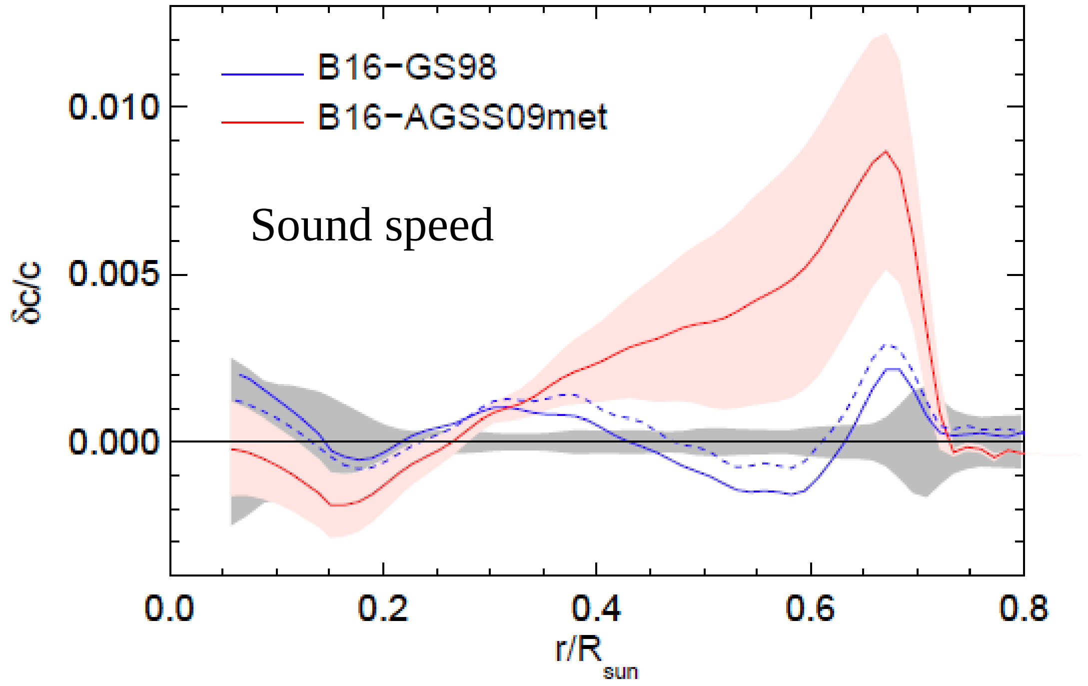
A. Serenelli arXiv:1601.07179



MeV

Not yet the end of the "story": Controversy about the surface metallicity composition of the Sun still open: High Z vs Low Z models

Standard Solar Model vs Helioseismology



GS 98 high metallicity

AGSS09 low metallicity

N. Vinyoles et al.
arXiv:1611.09867v4

Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0^a

Helioseismology --> high-Z

But more sophisticated Sun's surface modeling→low-Z

The prediction of solar ν flux is sensitive to the Sun metallicity

Units:
pp: 10^{10} cm^{-2} s^{-1};
Be: 10^{9} cm^{-2} s^{-1};
pep, N, O: 10^{8} cm^{-2} s^{-1};
B, F: 10^{6} cm^{-2} s^{-1};
hep: 10^{3} cm^{-2} s^{-1}

Flux	B16-GS98 HZ	B16-AGSS09met LZ
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi(^{7}Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\Phi(^{8}B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
CNO $\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
CNO $\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
CNO $\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$

N. Vinyoles et al.
arXiv:1611.09867v4

^{7}Be: 8.7% diff

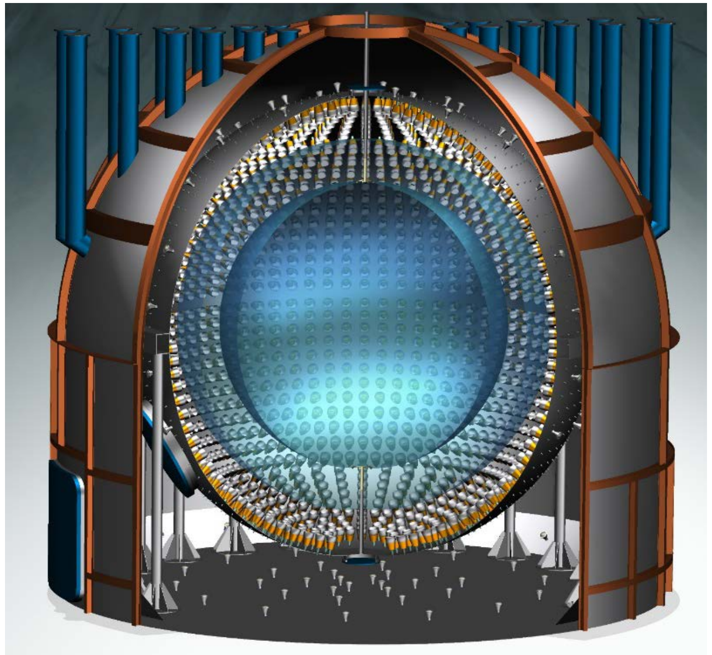
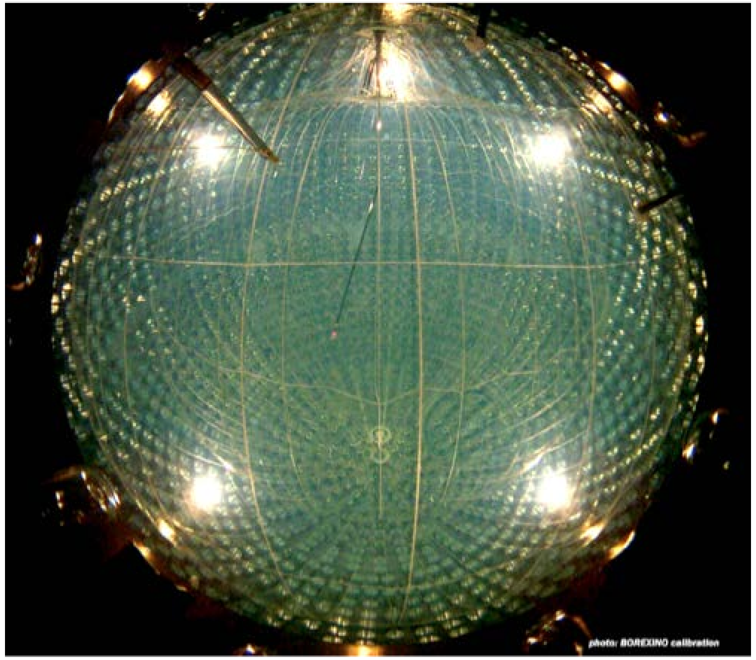
^{8}B: 17.6% diff

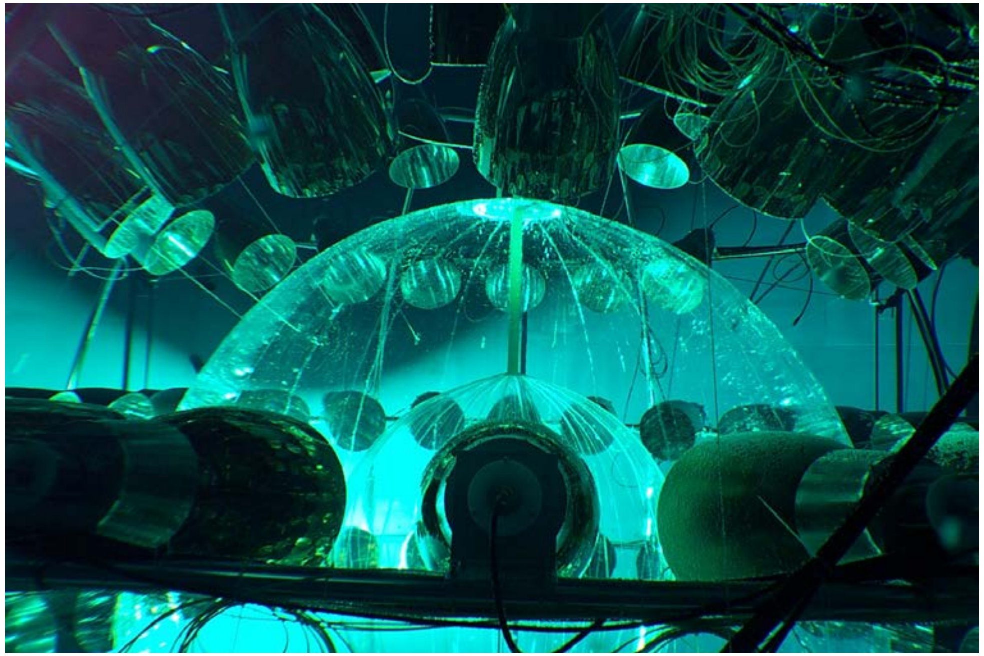
CNO: 40% diff

The experimental measurement of the CNO flux is the clue towards the resolution of the metallicity puzzle

The ultimate frontier of the **solar neutrino saga** to understand the SUN

Other intriguing detected and potential effects make the field very vital and of persistent attraction also for the continued study of neutrino properties



Borexino

- ✓ Approaching the full solar neutrino spectroscopy in a single experiment through the individual real time detection of each spectral component - 4 out of 5 so far

- ✓ Unique Validation in the low energy regime of the LMA-MSW ν oscillation paradigm through the experimental determination of the Pee

Borexino Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

TUM Technische Universität München

University of Houston

JAGIELLONIAN UNIVERSITY IN KRAKÓW

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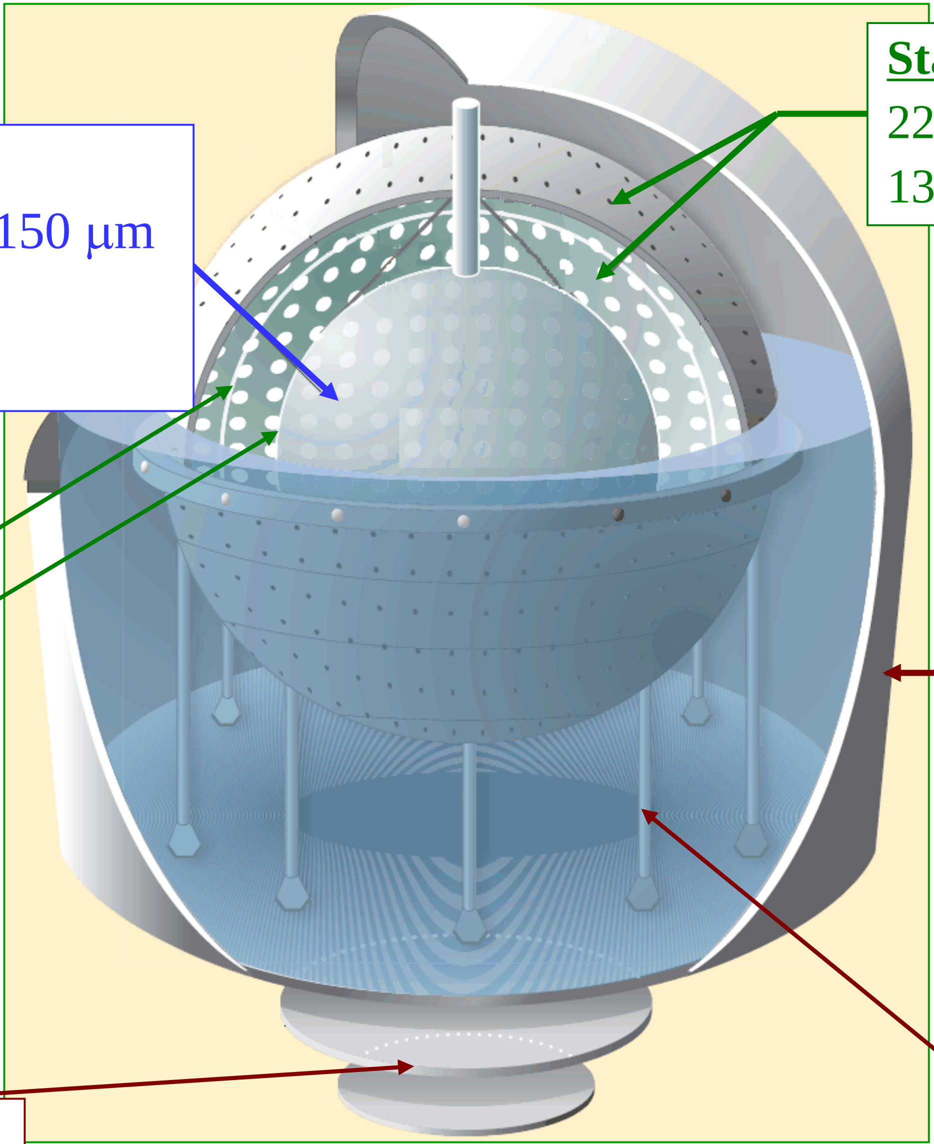
Borexino at Gran Sasso: low energy real time detection



Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel
Nominal FV 100 t

Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Design based on the principle of graded shielding

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

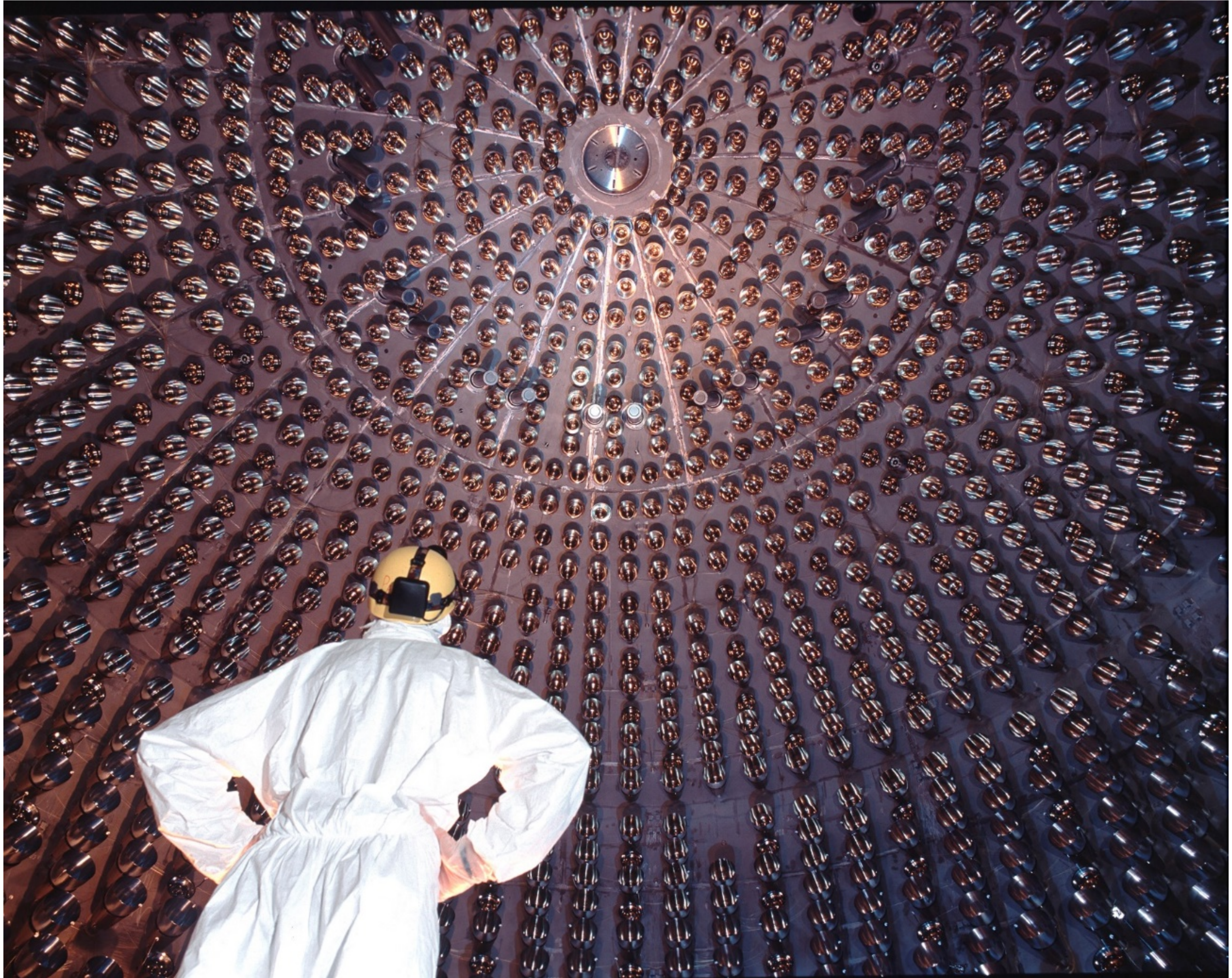
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

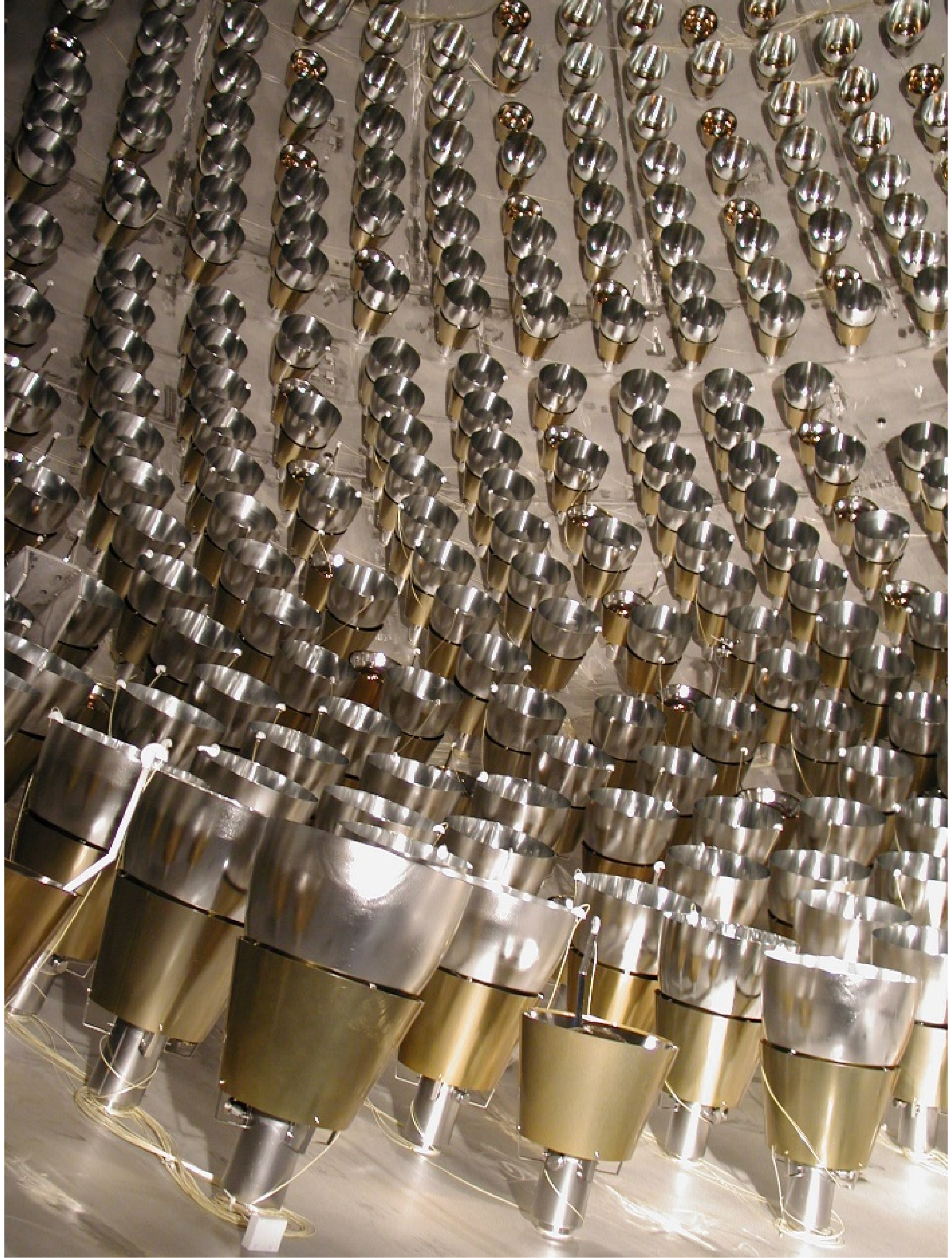
Neutrino electron scattering

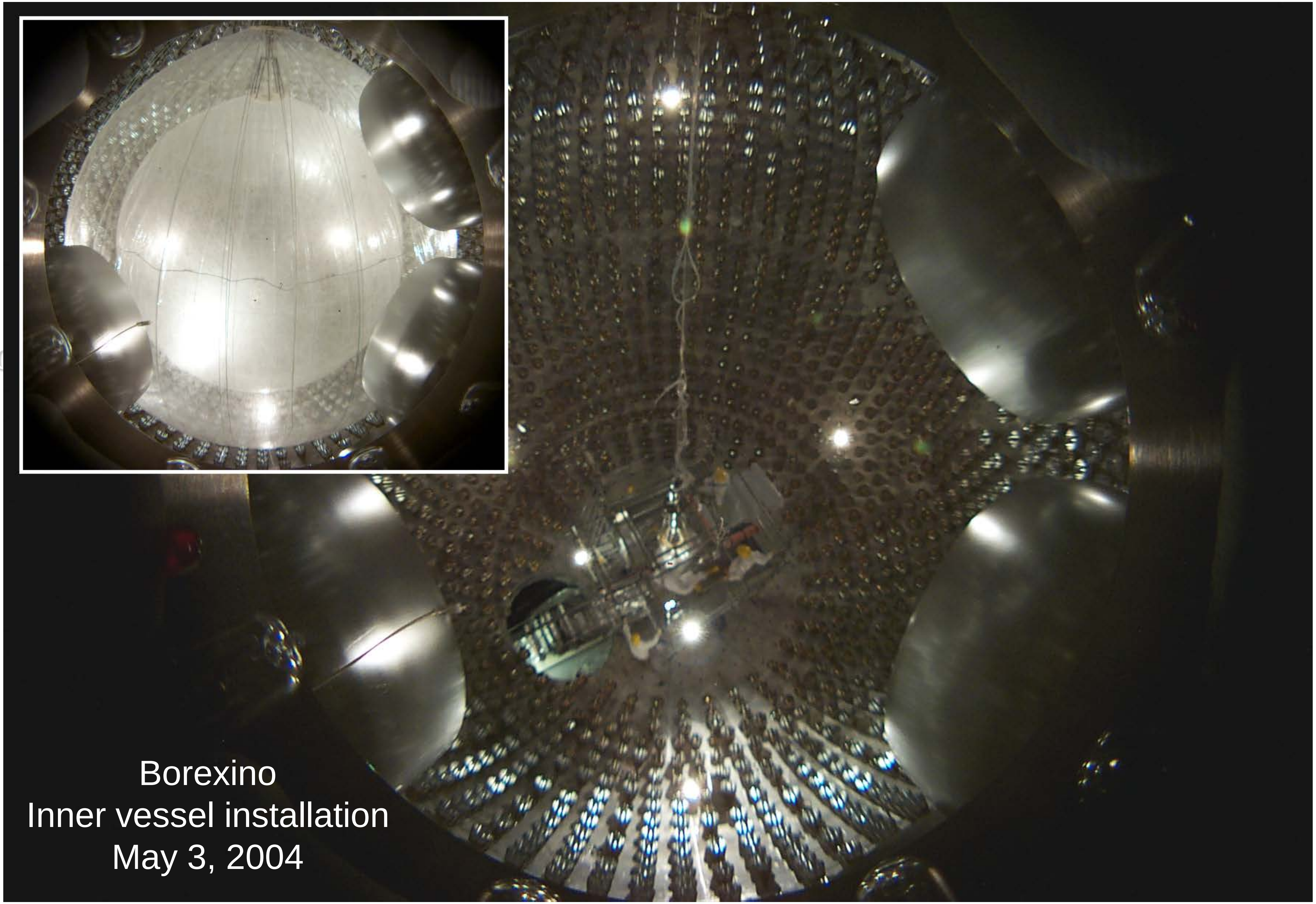
$\nu e \rightarrow \nu e$

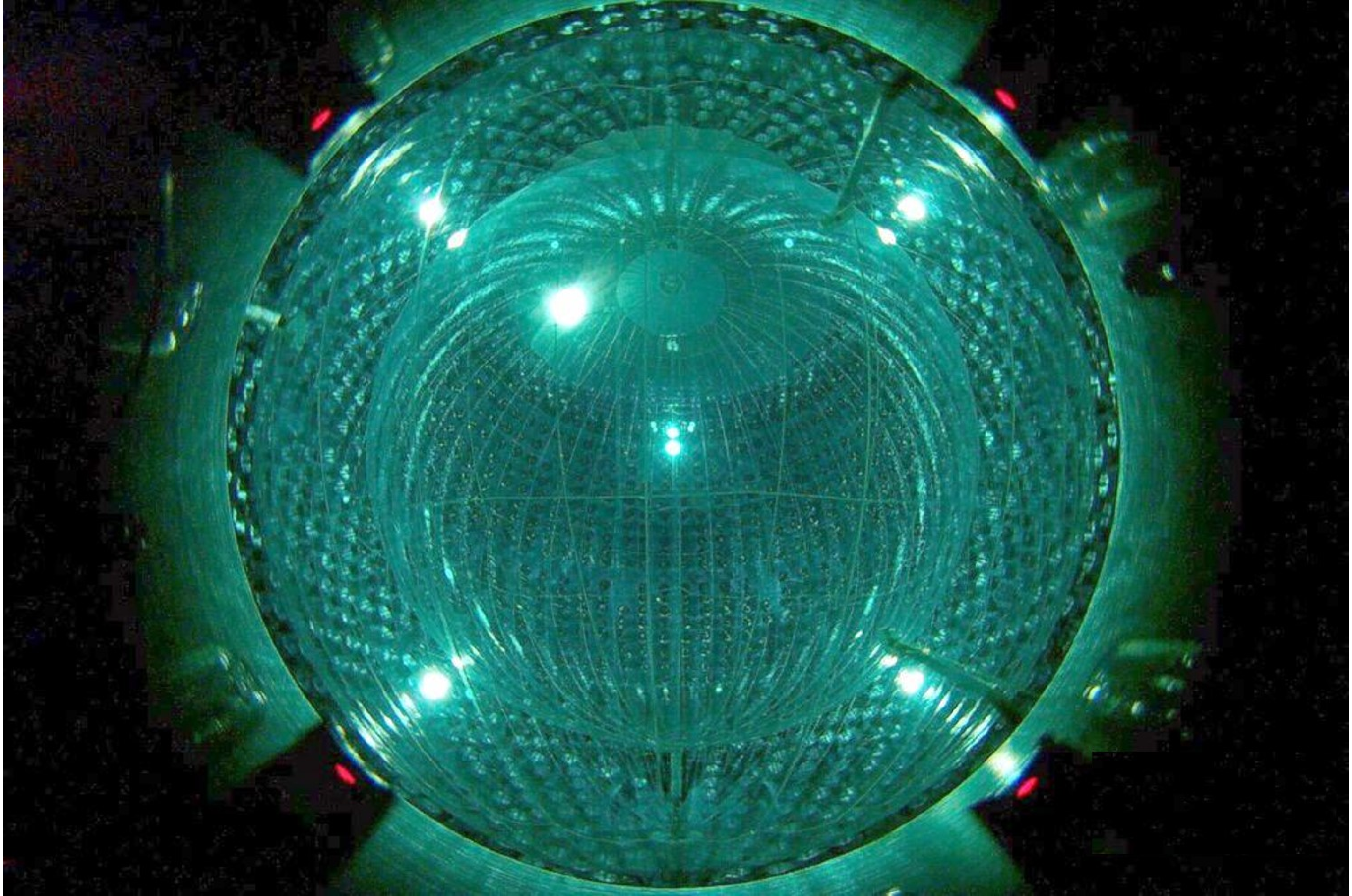
20 legs

Carbon steel plates






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,
pep (1.44 MeV) coupled to a tight limit on CNO,
Geo-antineutrinos (Phys.Lett.687,2010),
pp neutrinos
Supernovae neutrinos
and possibly actual CNO measure in the future

In principle full solar ν-spectroscopy in one experiment !

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) **Pulse shape discrimination to cope with α background**

→ Extraction of the fluxes through a data-to-model fit
Phase I may 2007 – may 2010
Phase II December 2011 - ………end of 2016 (still ongoing)
Purification in between

The background saga → the quest for the ultimate purity

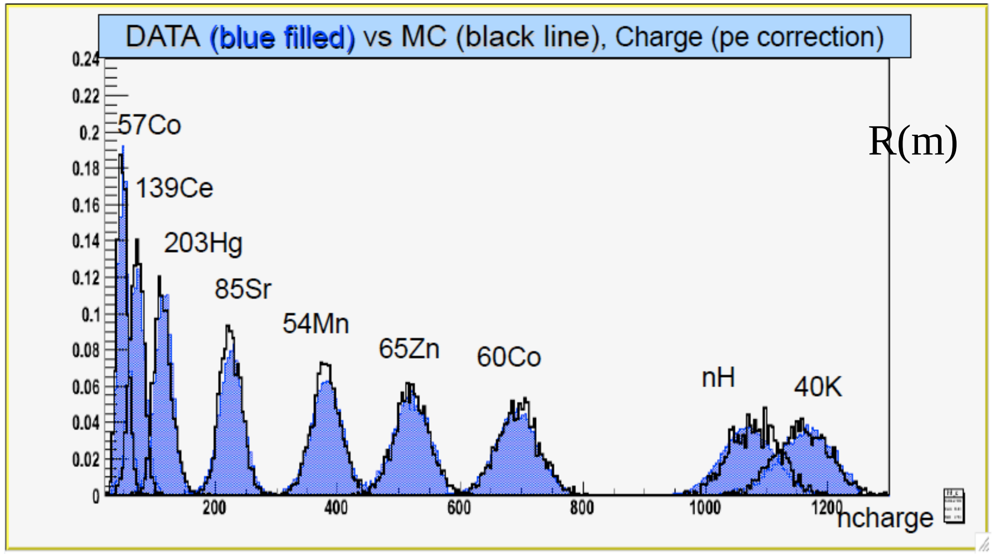
Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final in phase I
Name	Source	Typical	Required	Hardware	Software	
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	$<10^{-10} s^{-1} m^{-2}$	underground water detector	Cerenkov PS analysis	$< 10^{-10}$ eff. > 0.99992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	$\sim10^{-12}$ g/g	$\sim10^{-18}$ g/g	selection	threshold	2.7 $\times10^{-18}$ $^{14}C/^{12}C$
^{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

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

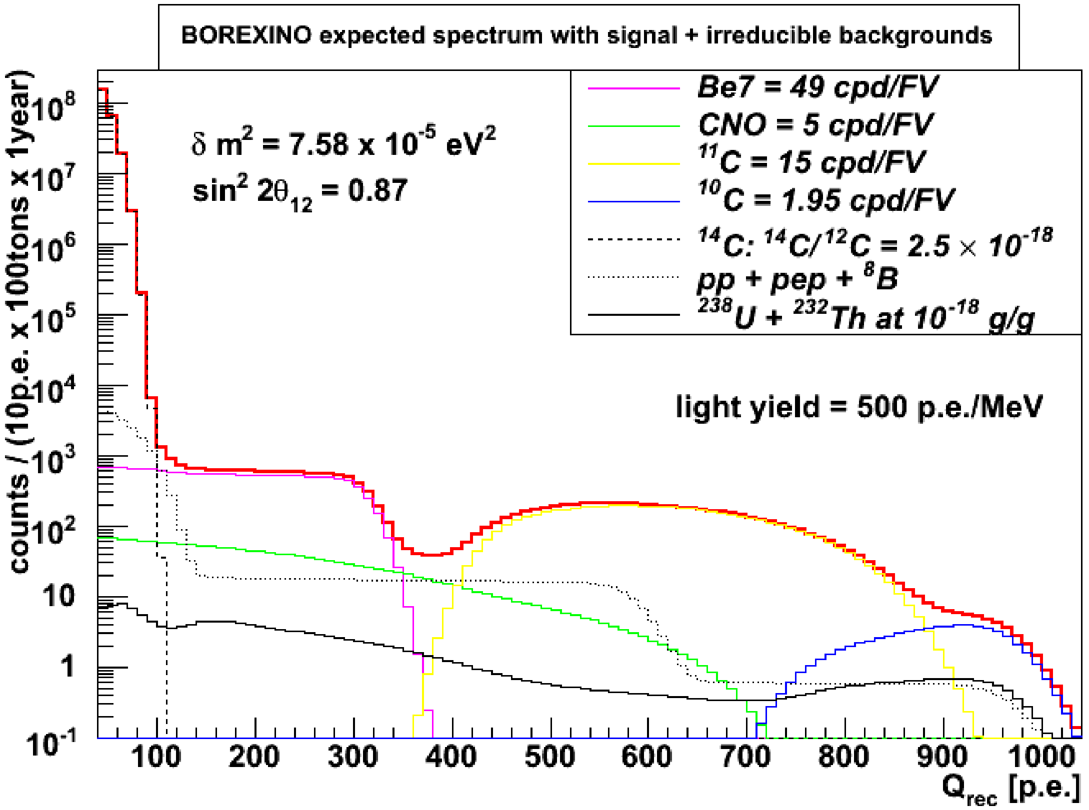
L.Y. → obtained from the γ calibration sources with MC: **~ 500 p.e./MeV**

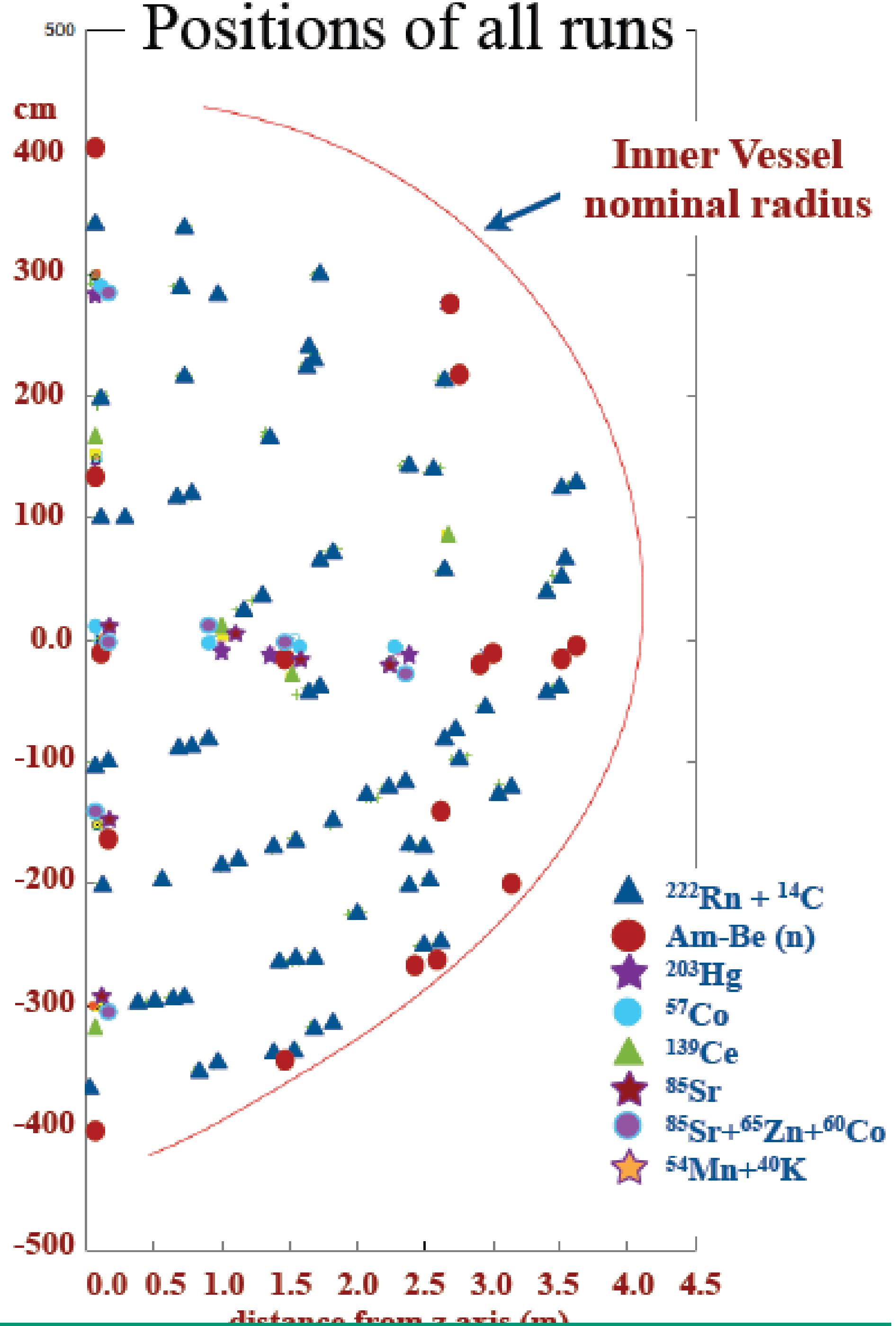
→ left as free parameter in the total fit in the analytical approach

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

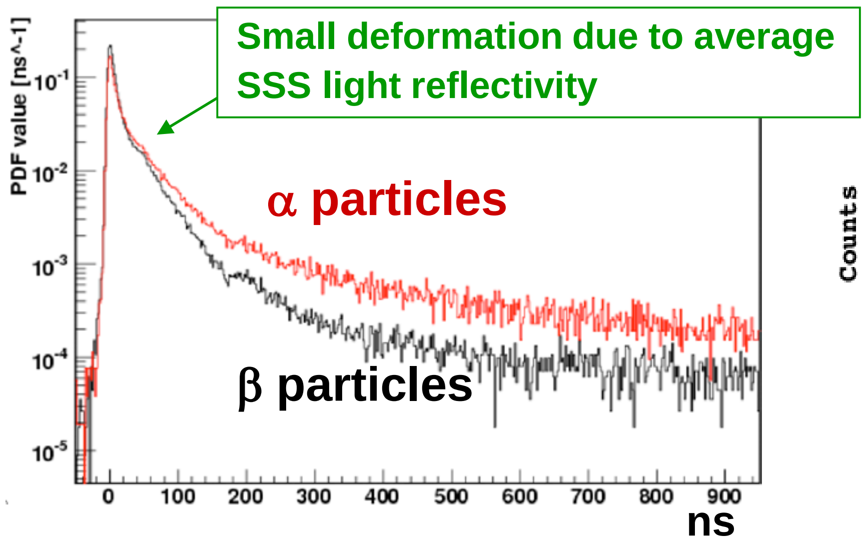
@ Fiducial volume uncertainty: $^{+0.5}_{-1.3}\%$ (1 σ) (radon sources)

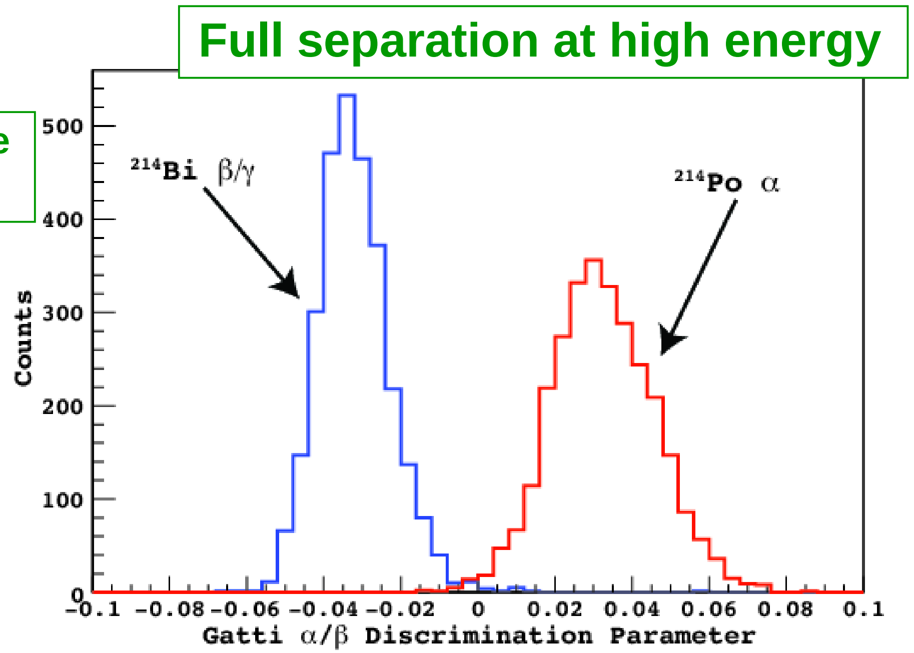
MC prediction of signal + intrinsic Background

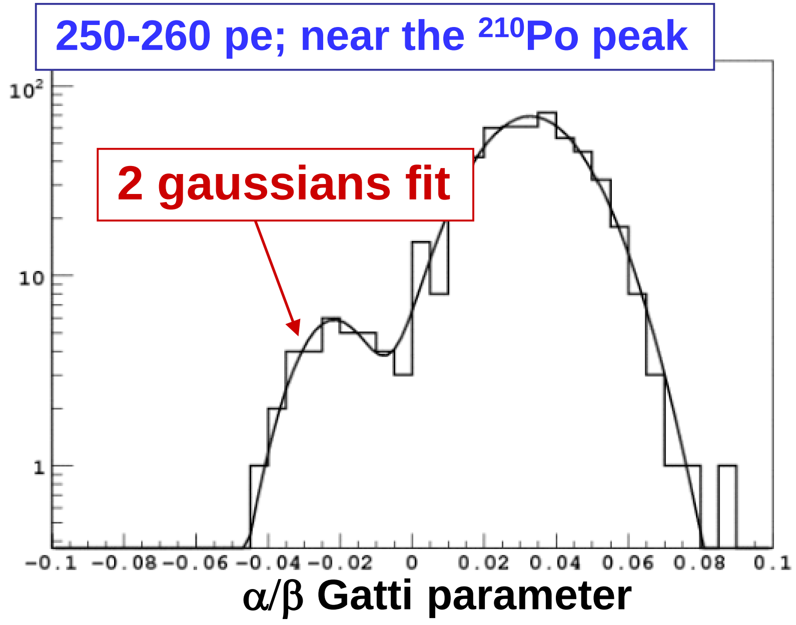


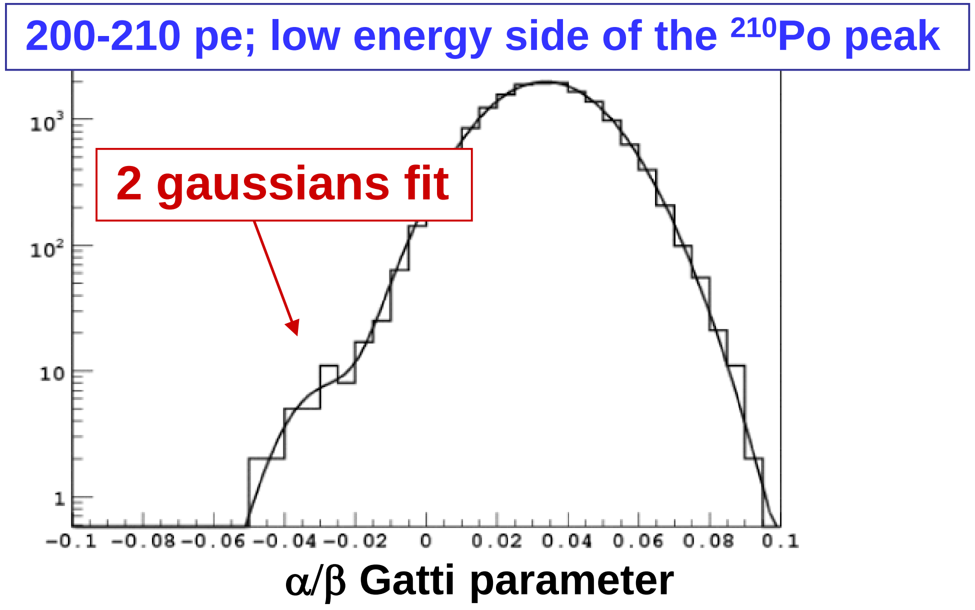


α/β discrimination

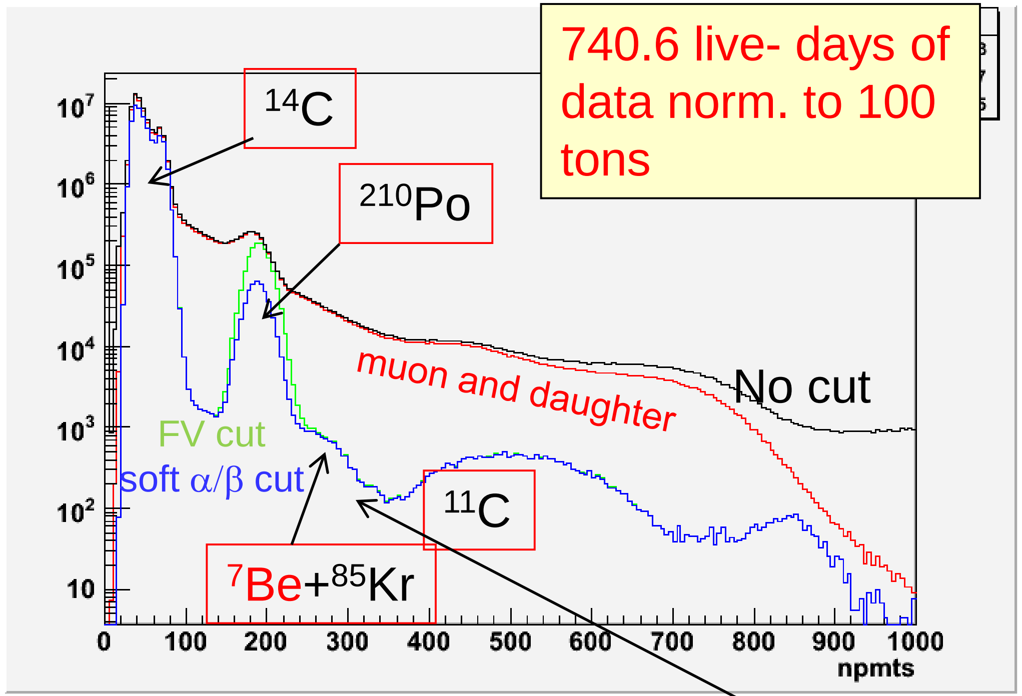








Phase I results ^{7}Be



The spectrum after the cuts witnesses the unprecedented ultra-low background achieved in Borexino

^{14}C-β emitter-156 keV end point

^{210}Po– α emitter- likely from the surfaces of the plumbing lines

^{11}C- β^{+} emitter -cosmogenic- 1.2 μ/ m^2 h

Effect of the application of the selection cuts on the raw spectrum

-Muon removal

- Restriction to the Fiducial volume

- PSD alpha-beta discrimination

  simple cut

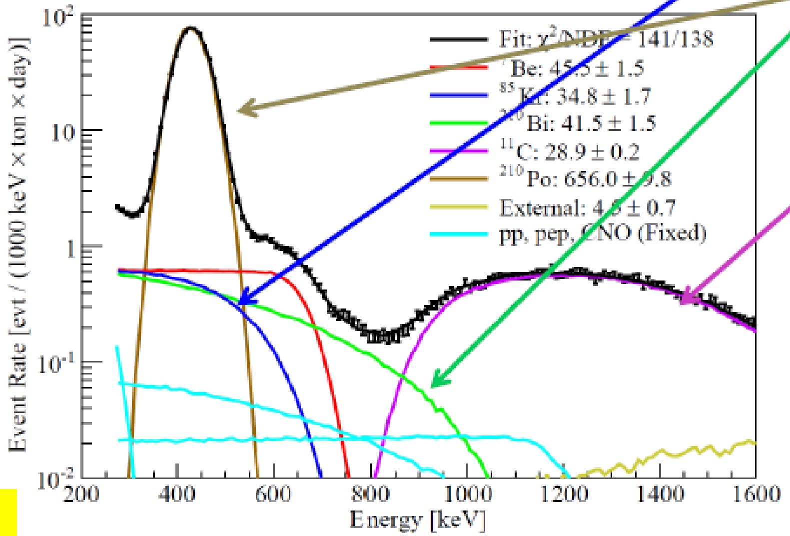
  statistical subtraction

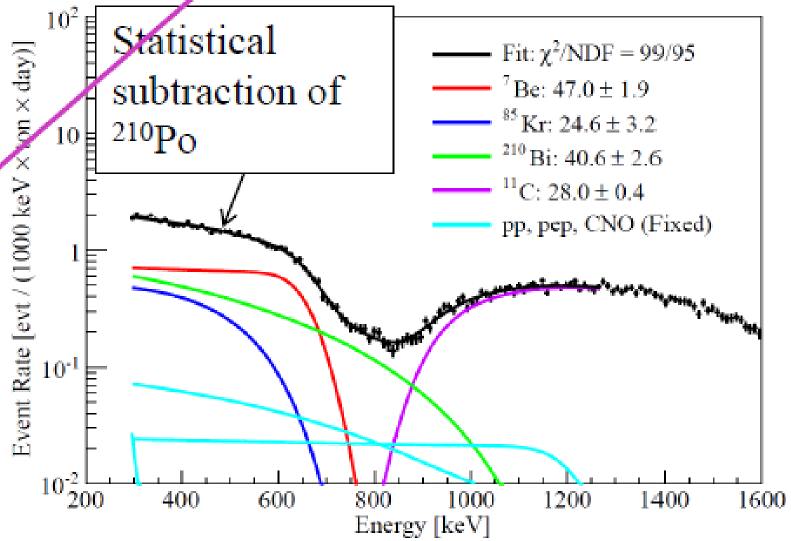
The scattering edge is the unambiguous signature of the ^{7}Be solar neutrino detection. ^{85}Kr obtained via β-γ coincidence analysis

$30 \pm 5.3 \pm 1.5$ cpd/100 t

^{7}Be (0.862 MeV) solar flux from Borexino

- Residual background components (^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C);





After cuts mainly muon and fiducial volume cuts

Experimental spectrum fit to the model to extract the ^{7}Be flux

Phase I results ^{7}Be

$$R_{^7Be} = 46 \pm 1.5\,(stat)^{+1.5}_{-1.6}\,(syst)\ \ cpd/100t$$

$$R_{no\ oscillation} = 74 \pm 5.2\ \ cpd/100t$$

- Unprecedented 5% precision in low energy regime
- Estimate of the total flux (4.43±0.22)×10^9 cm^{-2}s^{-1}
- ν_e survival probability 0.51 +- 0.07 @0.862MeV

HZ model 4.47(1±0.07)×10^9 cm^{-2}s^{-1}

- Search for a day night effect:
- not expected for ^{7}Be in the LMA-MSW model
- Large effect expected in the “LOW” solution (excluded by solar exp+Kamland)

$$A_{DN} = \frac{N-D}{(N+D)/2} = 0.001 \pm 0.012\,(stat) \pm 0.007(sys)$$

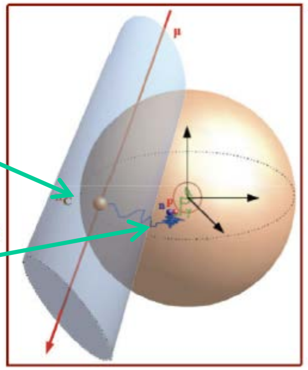
G. Bellini et al., Borexino Collaboration, Phys. Rev. Lett. 107 (2011) 141362.

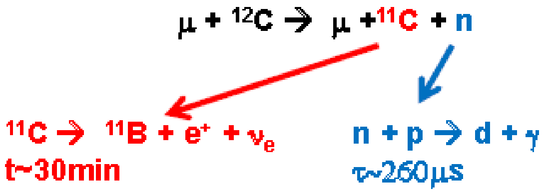
G. Bellini et al., Borexino Collaboration, Phys. Lett. B707 (2012) 22.

G. Bellini et al., Borexino Collaboration, arXiv:1308.0443 (2013).

pep (1.44 MeV) flux measurement and CNO limit in Borexino

Phase I results pep



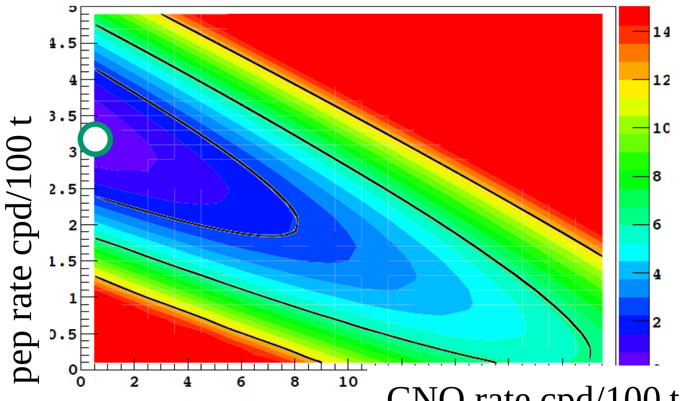


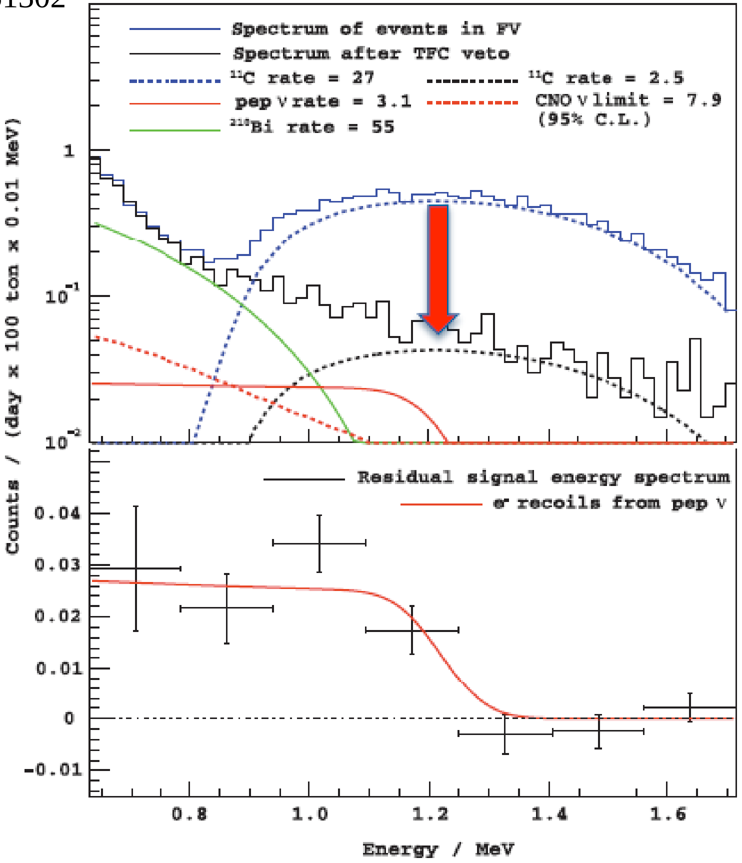
Threefold coincidence for ^{11}C rejection

- n capture on H: γ 2.2 MeV τ=260 μs
- Space and time Veto
- Residual exposure 48.5%

G. Bellini et al., Borexino Coll., Phys. Rev. Lett. 108 (2012) 051302

$\Delta\chi^2$ profile for fixed pep and CNO rates





ν	Interaction Rate (cpd/100t)	DATA/SSM (high metallicity)
	Counts/(days 100 t)	ratio
pep	3.1±0.6 (stat) ± 0.3(sys)	1.1±0.2
CNO	<7.9	<1.5 (95% C.L.)

Best limit on CNO so far….

^{8}B with lower threshold at 3 MeV (488 live days)

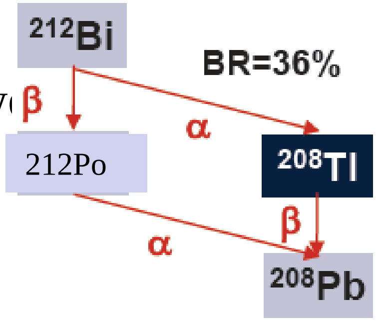
Phase I results ^{8}B

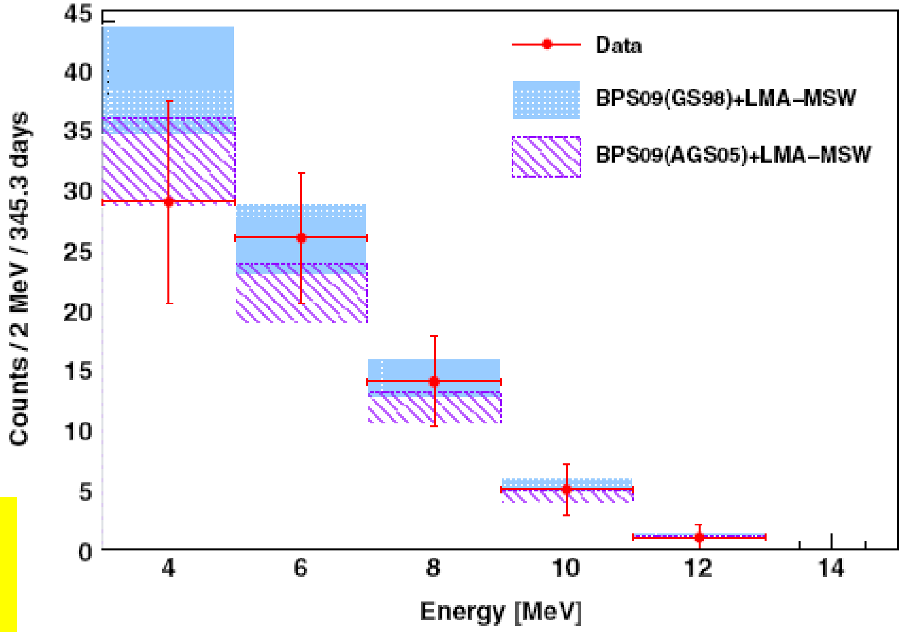
•Background in the 3.0-16.5 MeV energy range

- ✓ **Cosmic Muons**
- ✓ **External background**
- ✓ High energy gamma's from **neutron captures**
- ✓ ^{208}Tl and ^{214}Bi from radon **emanation from nylon** vessel
- ✓ **Cosmogenic isotopes**
- ✓ ^{214}Bi and **^{208}Tl** from ^{238}U and ^{232}Th bulk contamination

Cuts

- •@**Muon cut + 2 mms** dead time to reject induced **neutrons** (240 μs)
- •@**Fiducial volume**
- •@**Muon** induced radioactive **nuclides:**6.5 s veto after each crossing muon (~30% dead time)-^{10}C (τ=27.8 s) tagged with the **Three-fold coincidence** with the μ parent and the neutron capture)-^{11}Be (τ=19.9 s) statistically subtracted
- •@^{214}Bi-^{214}Po coincidences rejected (τ=237 μs-^{222}Rn daughter)
- •@^{208}Tl from ^{212}Bi-^{212}Po (B.R.64%-τ=431ns) w evaluate the ^{208}Tl production via →





^{8}B with lower threshold at 3 MeV

Exp. ^{8}B spectrum vs models

Phase I results ^{8}B

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [7]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [3]	5.0	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase [26]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [27]	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$

Data compatible with both high metallicity and low metallicity models

SSM; H.M.(2.7±0.3) x10^6cm^{-2}s^{-1}
L.M.(2.2 ±0.2) x10^6cm^{-2}s^{-1}

Phys. Rev. D, 82 (2010) 033006

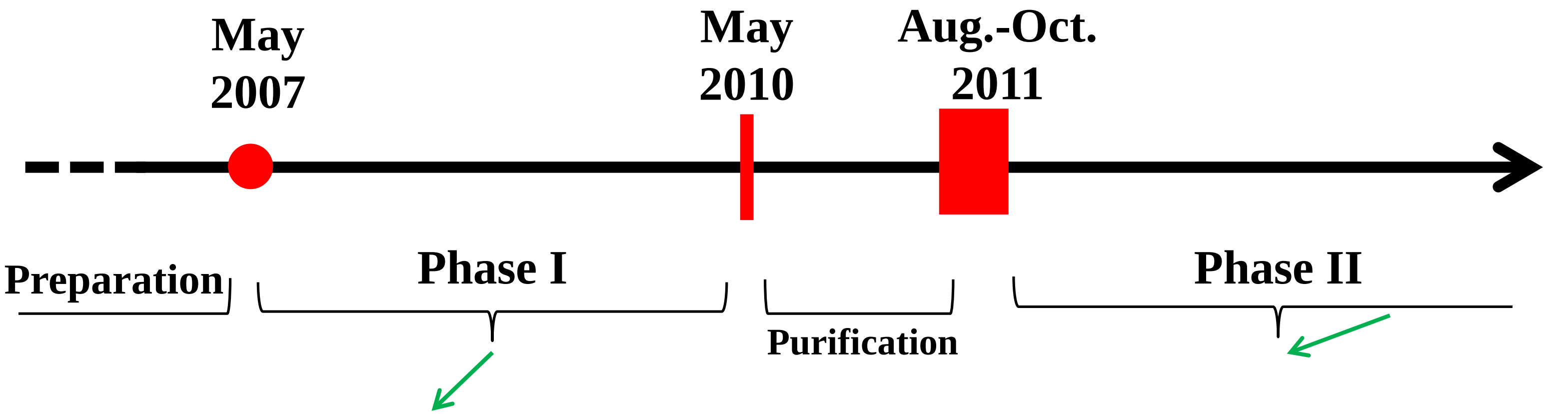
Systematic errors

Source	E>3 MeV σ_+	E>3 MeV σ_-	E>5 MeV σ_+	E>5 MeV σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

Borexino program at a glance

Totally unprecedented accomplishment in the solar neutrino arena: almost complete **precision** solar ν spectroscopy by a single experiment: Borexino alone validates the LMA MSW oscillation paradigm

"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



- **First specific solar ^{7}Be-ν measurement**
- **^{7}Be-ν day-night asymmetry**
- **Low-threshold ^{8}B-ν**
- **First pep-ν detection**
- **Best upper limit on CNO-ν**
- **^{7}Be-ν seasonal modulation**

- **Geo-ν observation at ~ 4.5 σ (initial phase II data included)**

- **Muon seasonal variation**
- **Limits on rare processes**
- **Neutrons and other cosmogenics**

Perspectives for phase II at its beginning

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

Th< 9 10^{-19} g/g 95% C.L.
U < 8 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

^{210}Bi=25.5 +- 1.8 cpd/100t

^{210}Po = 97 +- 3 cpd/100 t

Only 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

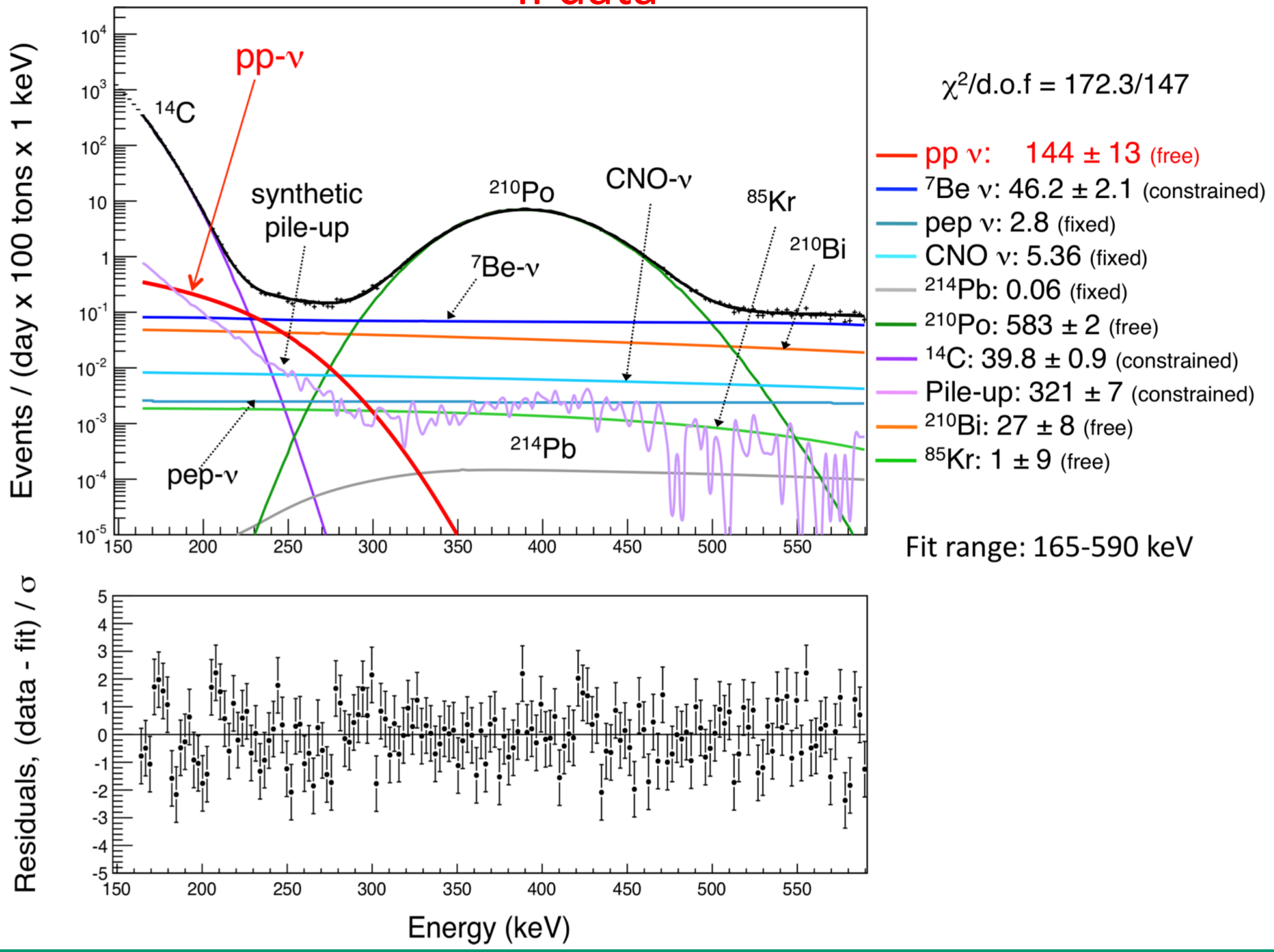
With these data the pp measurement Nature, Volume 512, Issue 7515, pp. 383-386 (2014)

Improved ^{7}Be, ^{8}B, and pep →More stringent test of the profile of the Pee survival probability →sub-leading effect in addition to MSW, new physics, NSI?

Improved ^{7}Be and ^{8}B → some hint about metallicity?

CNO is the ideal metallicity discriminator → **^{210}Bi is the challenge - more purification ?**

Results of the standard spectral fit for pp with initial phase II data

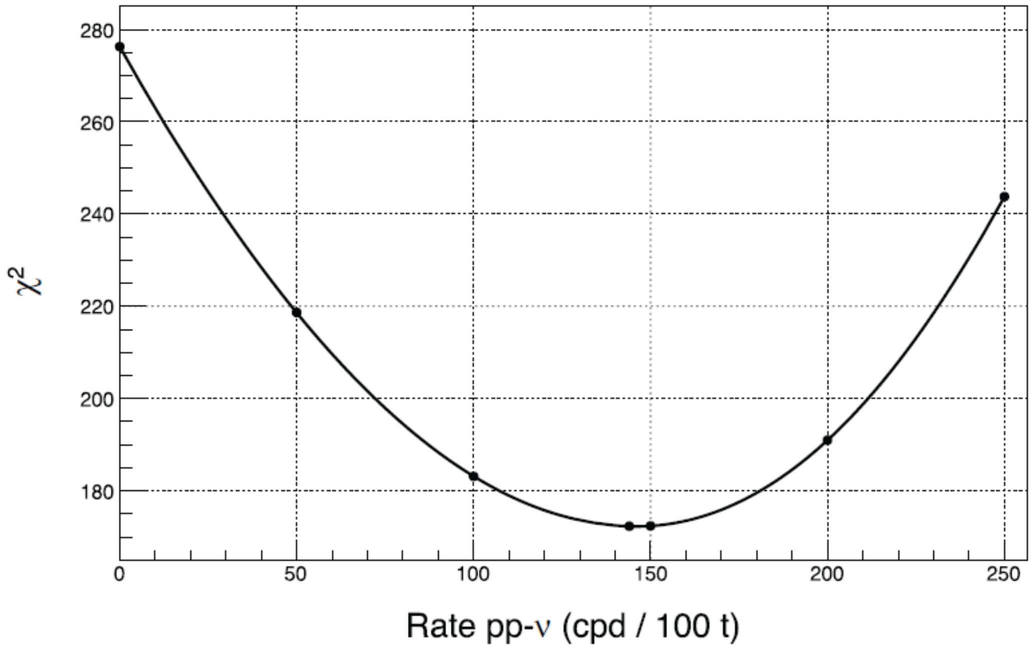


First real-time measurement of pp-neutrino flux (~11% precision)

pp = 144 ± 13 (stat) ± 10 (syst) cpd/100 t

compared to expected (MSW/LMA,HM)

131±2 cpd/100 t



pp neutrino flux:

$(6.6\pm0.7)\cdot10^{10}\ cm^{-2}s^{-1}$

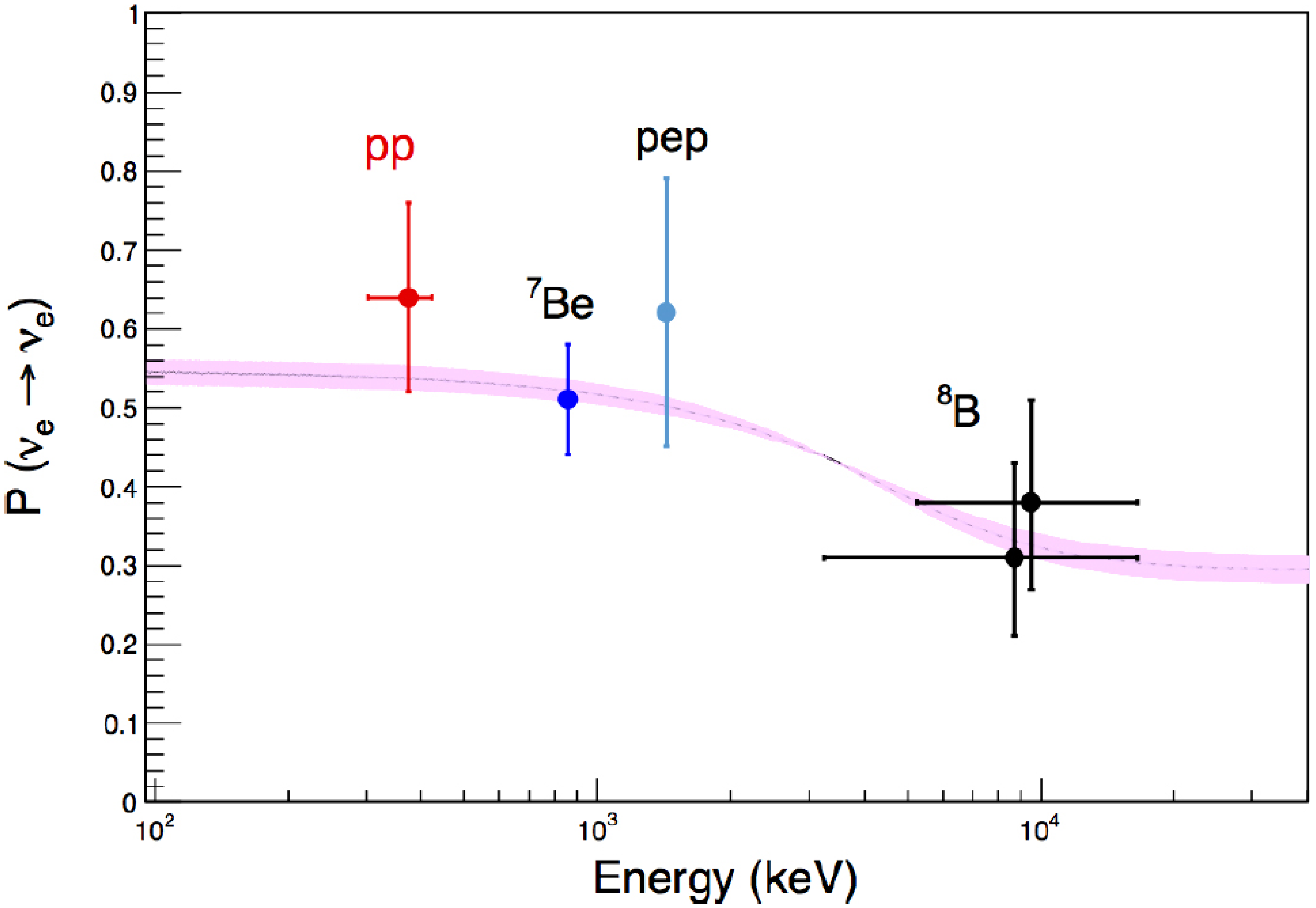
vs

$(5.98\pm0.04)\cdot10^{10}\ cm^{-2}s^{-1}$

Zero pp count is excluded at 10σ level !

Borexino measured electron neutrino survival probability for 4 different nuclear reactions after the pp measurement

For the first time a single experiment provided alone the validation of the MSW – LMA neutrino oscillation paradigm over the entire solar neutrino spectrum

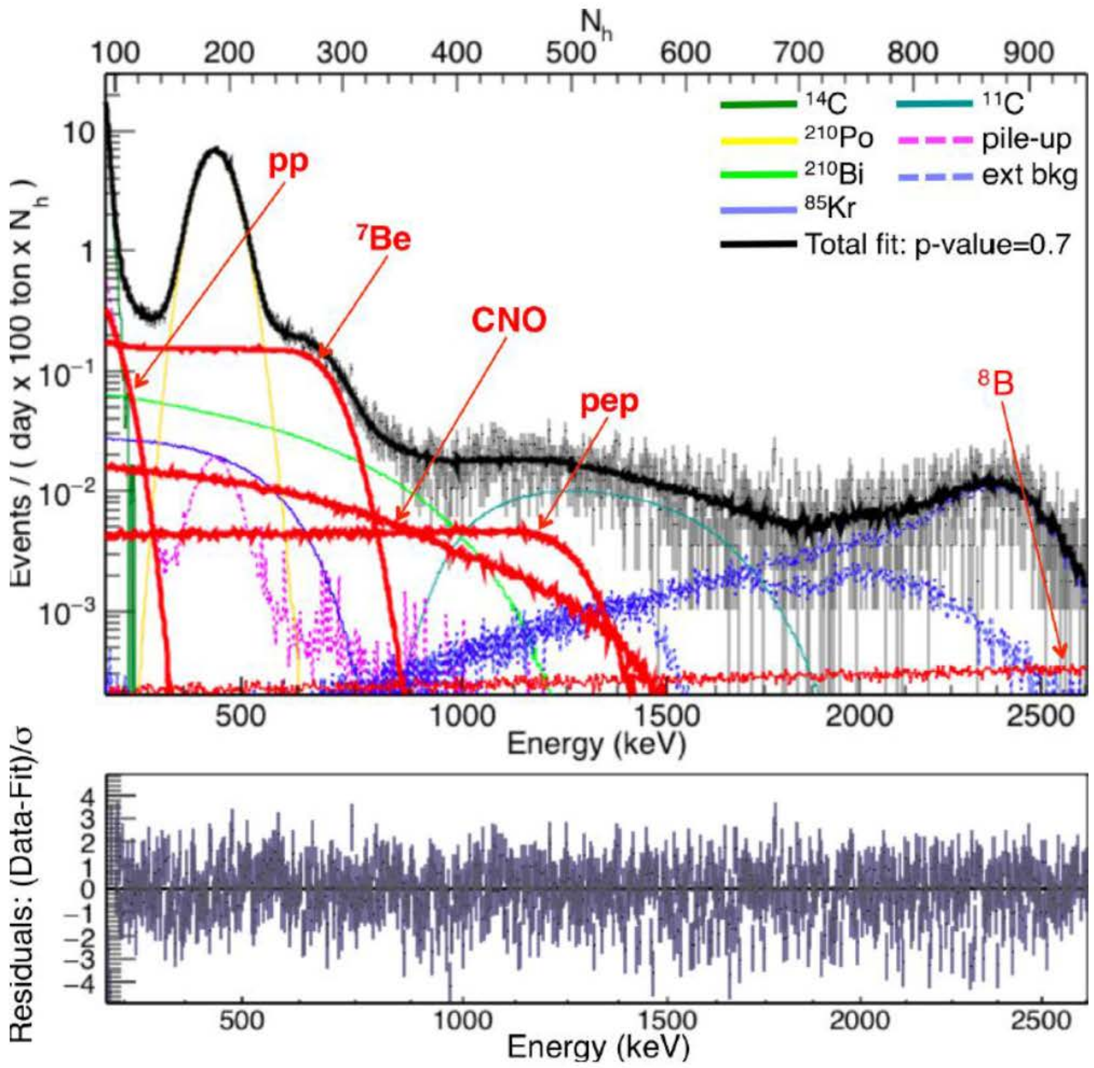


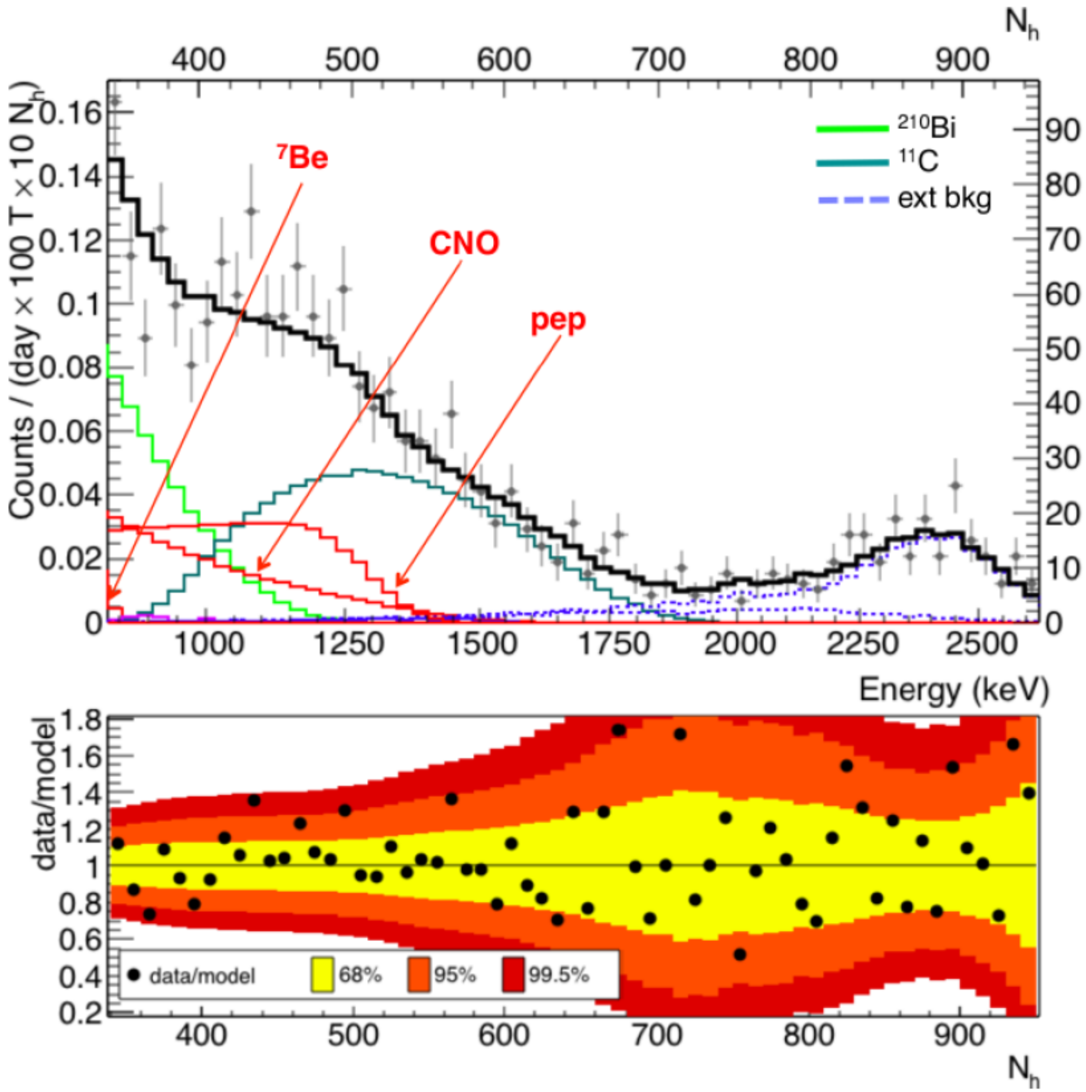
Status at the end of 2014

Phase II data simultaneous low energy spectroscopy and evidence of the pep scattering edge

Released at TAUP@SNOLAB **arXiv:1707.09279**

More than 5σ evidence for the pep signal





Comparison between Phase I and Phase II results

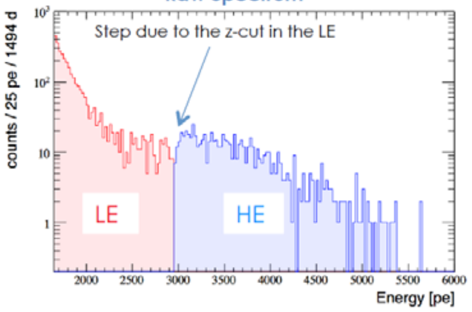
	Phase I	Phase II	Uncertainty reduction $\frac{Phase\ II}{Phase\ I}$
pp	$144 \pm 13 \pm 10$	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be(862KeV)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	0.57
pep	$3.1 \pm 0.6 \pm 0.3$	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61

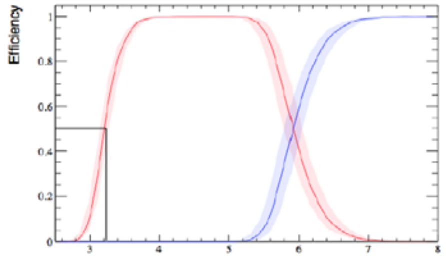
Beginning of the precision era in the study of low energy solar neutrinos
^{7}Be precision 2.7%

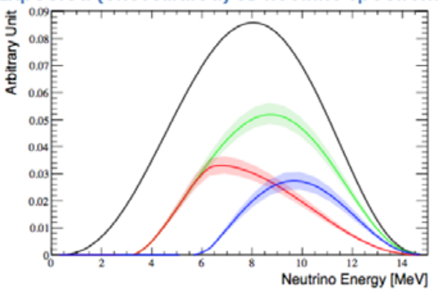
LE and HE Ranges

New ^{8}B released at 10 years of Borexino: Workshop RECENT DEVELOPMENTS IN NEUTRINO PHYSICS AND ASTROPHYSICS

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

D. Franco - APC

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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

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

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

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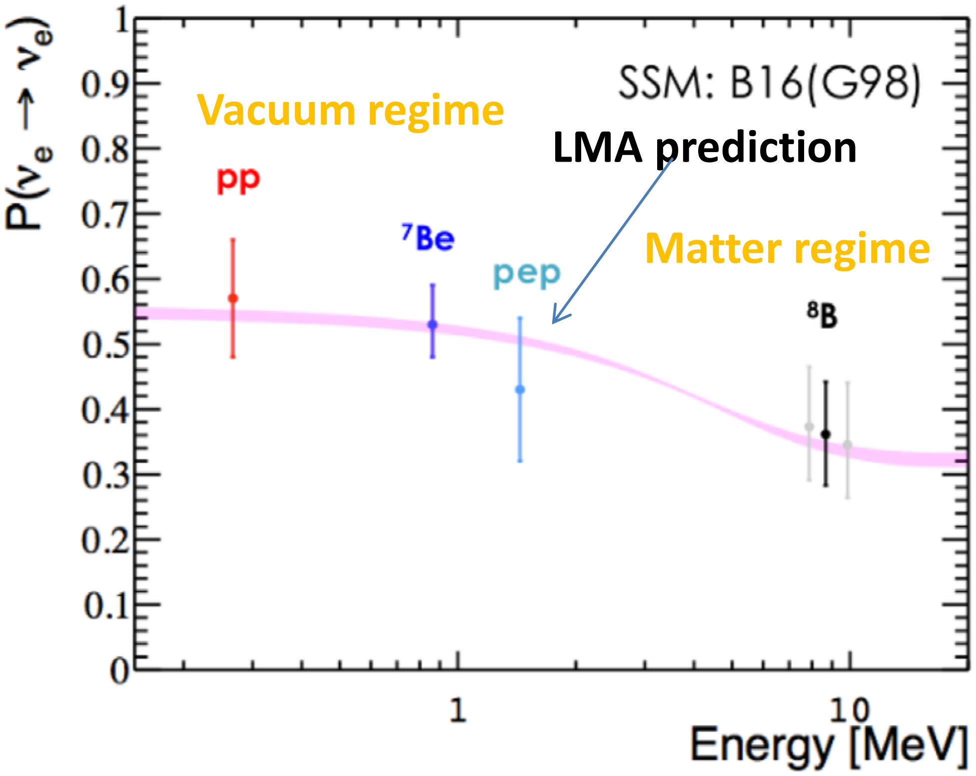
Equivalent unoscillated flux

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}**

The global oscillation picture: survival probability of the electron neutrinos contrasted with the Borexino data points as of today

arXiv:1709.00756

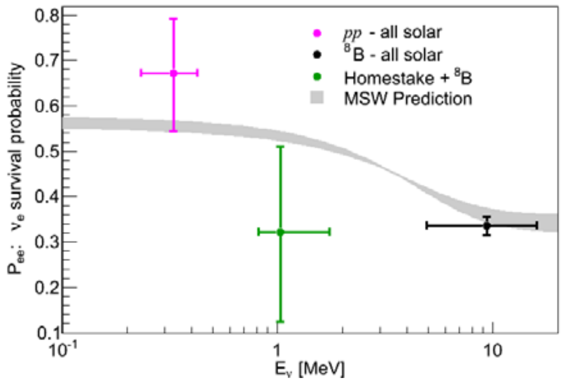


FROM BOREXINO ALONE VALIDATION OF THE LMA-MSW OSCILLATION SOLUTION OVER THE FULL SOLAR NEUTRINO SPECTRUM

Reinforced by the improved precision of the phase II data

^{7}Be 2.7%

Simultaneous low energy spectroscopy



Before the Borexino results

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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

Closing on the pp chain burning mechanism experimental investigation

The complete spectroscopy from **pp to ^{8}B** represents the first and unique determination of the pp cycle $\rightarrow$ **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,)

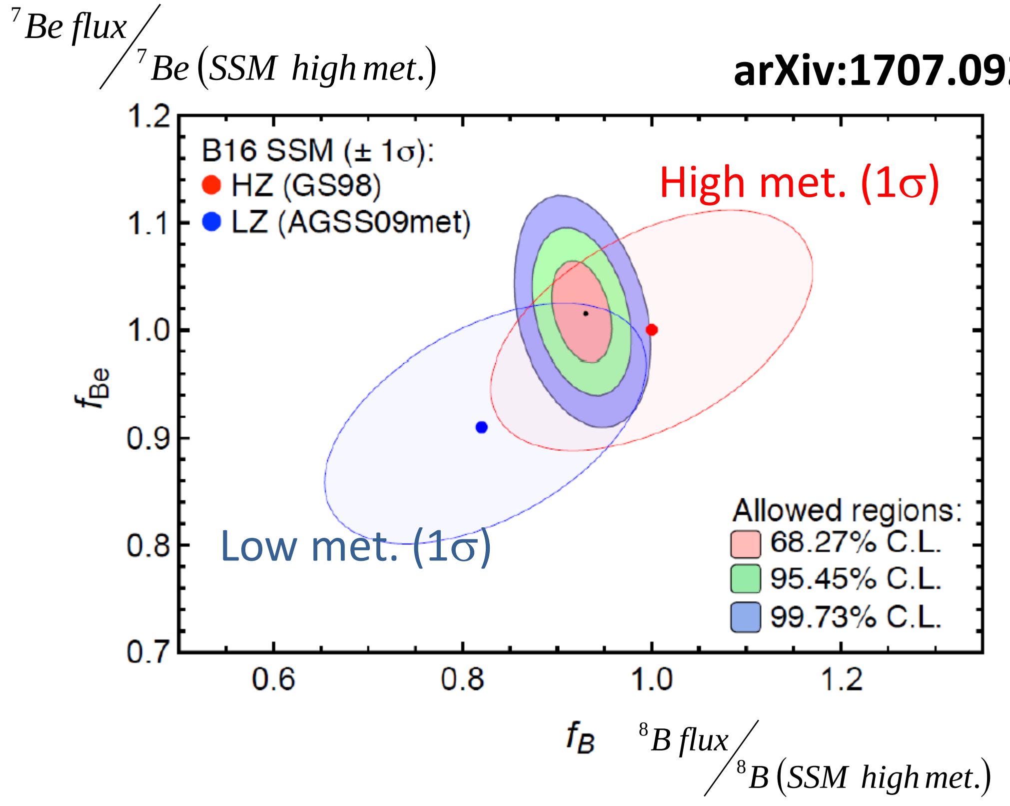
$$R = 0.180 \pm 0.011 \quad HZ$$
$$R = 0.161 \pm 0.010 \quad LZ$$

Measured value:

arXiv:1707.09279 $\quad R = 0.18 \pm 0.02$

Borexino closes and completes a more than one century long scientific adventure

Can the current data discriminate between high and low metallicity ?



arXiv:1707.09279

New pp, ^{7}Be, pep results of the analysis of Phase II data

	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)	**$(1.39 \pm 0.19^{+0.08}_{-0.13})\ 10^{8}$**	**$1.44\ (1 \pm 0.009)\ 10^{8}$**	**$1.46\ (1 \pm 0.009)\ 10^{8}$**

The latest Borexino data though cannot disentangle between the two models point (^{7}Be, ^{8}B) to a slight preference for the HZ

p-value for HZ-SSM 0.998
p-value for the LZ-SSM 0.362

arXiv:1709.00756

Further recent accomplishments

Limit of ν magnetic moment from ^{7}Be scattering spectrum

$$\mu^2_{eff} = P^{3\nu}\,\mu^2_e + (1 - P^{3\nu})\,(\cos^2\theta_{23}\,\mu^2_\mu + \sin^2\theta_{23}\,\mu^2_\tau)$$

$$P_{ee} = P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13} P^{2\nu}$$

$$P^{2\nu} = \sin^2\theta_{12}\,\sin^2(\Delta m^2_{12}\,L/4E)$$

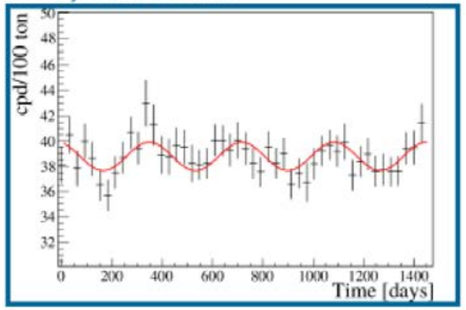
Assuming
LMA-MSW
$P^{2\nu}$ for pp- and ^{7}Be-ν is the same

arXiv:1707.09355

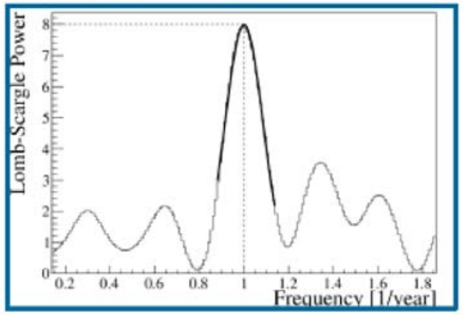
(Dec 2011- May 2016)
1291 days
90% C.L.
from $\mu_{eff} < 2.8 \times 10^{-11}\mu_B$:
$\mu_e < 4.8 \times 10^{-11}\mu_B$
$\mu_\mu < 6.4 \times 10^{-11}\mu_B$
$\mu_\tau < 6.8 \times 10^{-11}\mu_B$

Modulation due to the Earth's orbit eccentricity

I) Sinusoidal fit



2) Lomb-Scargle



The **period**, **amplitude**, and **phase** of the observed time evolution of the signal are **consistent with its solar origin**, and **the absence of an annual modulation is rejected at 99.99% C.L.**

	Simulated Data	Data
T [year]	0.95 ± 0.02	0.96 ± 0.05
ε	0.0155 ± 0.0025	0.0168 ± 0.0031
ϕ [day]	-12 ± 11	14 ± 22

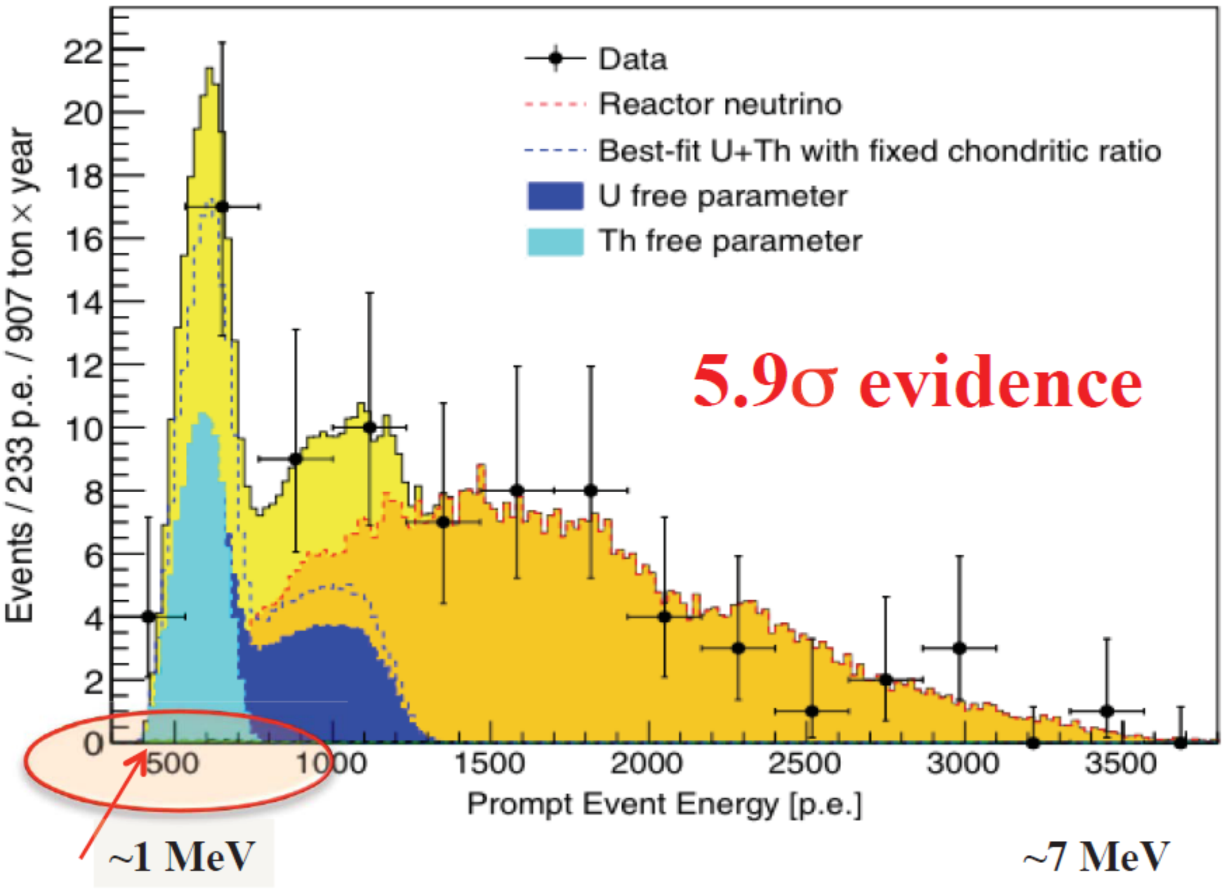
Successful consistency check of the solar origin of the signal and of the stability of the detector

[Astropart.Phys. 92 (2017) 21-29]

	Borexino result	Expected HZ	Expected LZ
CNO ν	< 8.1 95%C.L cpd/100t	4.91 +-0.56 cpd/100t	3.62 +- 0.37 cpd/100t

Previous limit (set by Borexino Phase I):
7.9 cpd/100t
arXiv:1707.09279

Latest Borexino geoneutrino results



Non antineutrino background is almost invisible!

Unbinned maximal likelihood fit:

- Geoneutrinos free
- Reactor antineutrinos free
- Other backgrounds ($0.78^{+0.78}_{-0.10}$ events total) constrained

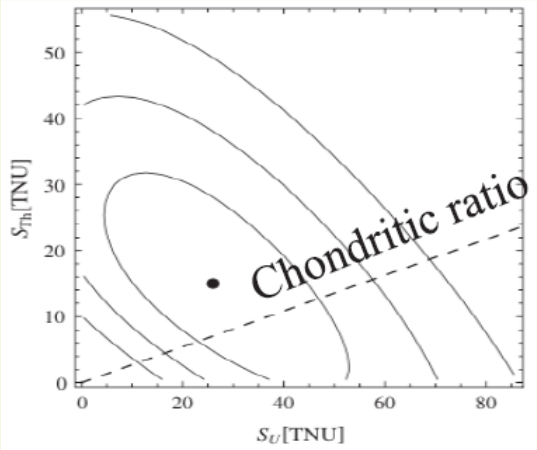
Two types of fits:

1) Th/U mass ratio fixed to chondritic value of 3.9

$N_{geo} = 23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$ events

$S_{geo} = 43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU[1]

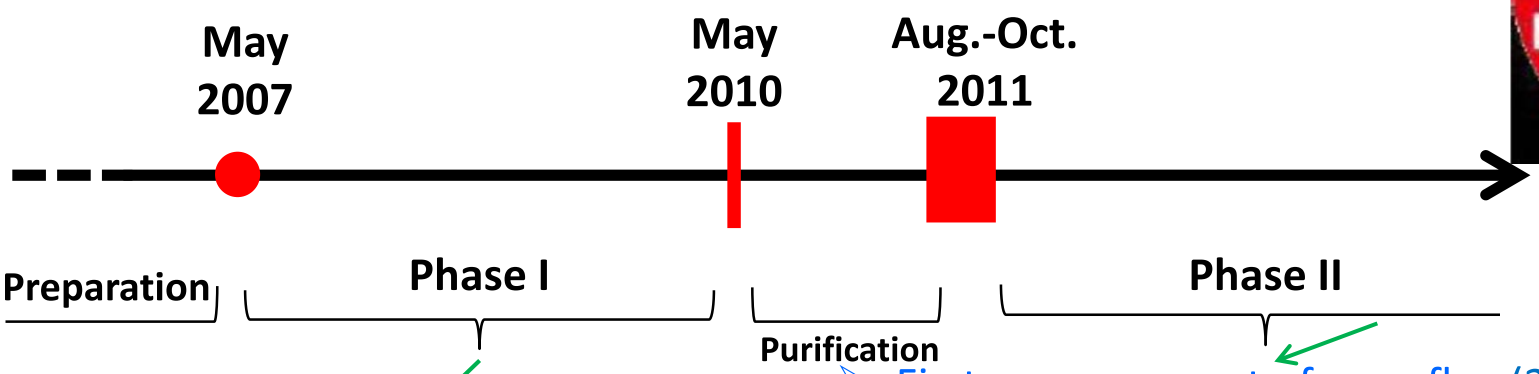
2) U and Th free fit paramters



[1]1 Terrestrial Neutrino Unit (TNU) = 1 event / year / 10^{32} protons, 100% efficiency

Borexino program at a glance

Totally unprecedented accomplishment in the solar neutrino arena: almost complete **precision** solar ν spectroscopy by a single experiment: Borexino alone validates the LMA MSW oscillation paradigm



- **First specific solar ^{7}Be-ν measurement**
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- **First pep-ν detection**
- **Best upper limit on CNO-ν**
- **^{7}Be-ν seasonal modulation**

- **Geo-ν observation at ~ 4.5 σ (initial phase II data included)**

- **Muon seasonal variation**
- **Limits on rare processes**
- **Neutrons and other cosmogenics**

Phase II:

- First measurement of pp-ν flux (2014) **milestone towards the full solar-ν spectroscopy**
- Improved signif. of Geo-ν detection 5.9 σ (2015)
- Improved limit on electron decay (2015)
- Null association with gamma ray bursts (2017)
- Annual modulation (2017)
- Null association with GW (2017)
- New round of the previous solar measurements with improved precision pp ^{7}Be (2.7%) pep (5σ) (2017)
- Neutrino magnetic moment limit (2017)
- New ^{8}B flux with low threshold (2017)

physicsworld TOP 10 BREAKTHROUGH 2014

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M. Maltoni and A.Yu. Smirnov
EPJA 52 , 87 2016

Main tasks for the rest of phase II and possibly beyond

- **Short-baseline ν oscillation: SOX**
- **Quest for the CNO-ν flux – <u>only possible in BX</u>**

Conclusions

- ✓ Unprecedented purity - even better in phase II
- ✓ Full solar neutrino spectroscopy in only one experiment – fueling mechanism of the Sun through the pp chain completely investigated by Borexino
- ✓ Validation at of the MSW-LMA ν oscillation solution by Borexino alone over the entire solar neutrino spectrum
- ✓ Neat and clean geo-ν signal (not covered here)
- ✓ The extremely challenging quest of for the CNO cycle → ultimate solar neutrino frontier for Borexino
- ✓ The sterile search through artificial anti-neutrino source SOX will be the other branch of the future Borexino program