Overview and accomplishments of the Borexino experiment

Gioacchino Ranucci
INFN - Milano

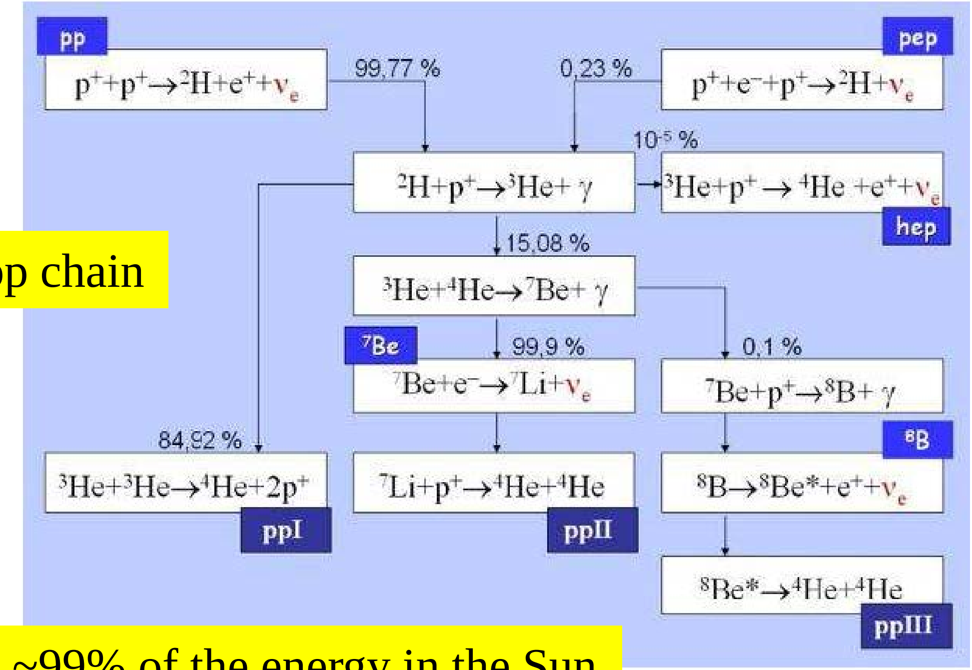
On behalf of the Borexino Collaboration

Moscow – **ICPPA 2015**

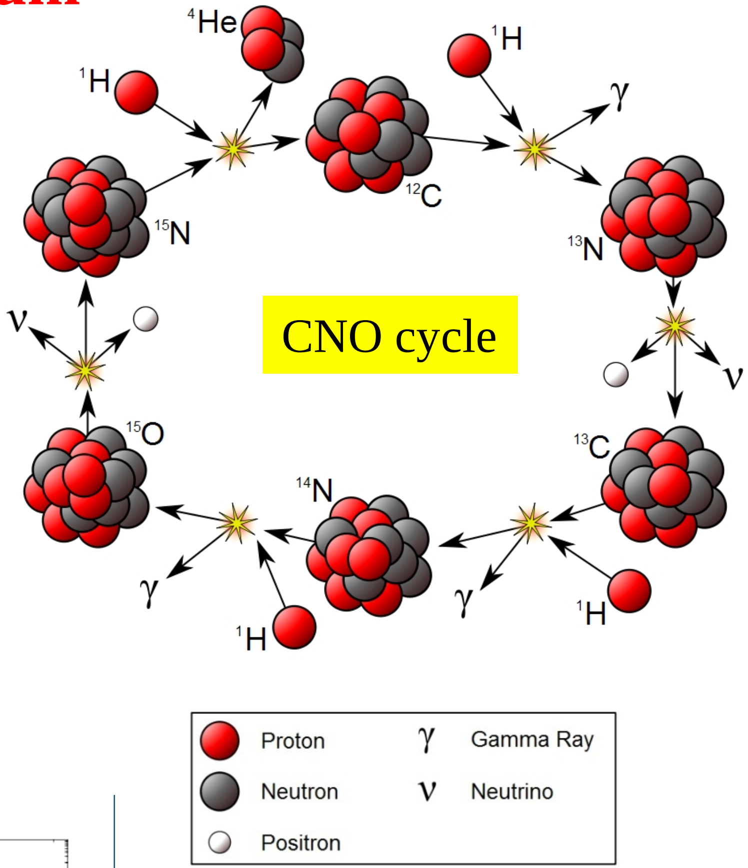
6 October 2015

Solar neutrinos production and spectrum

pp chain

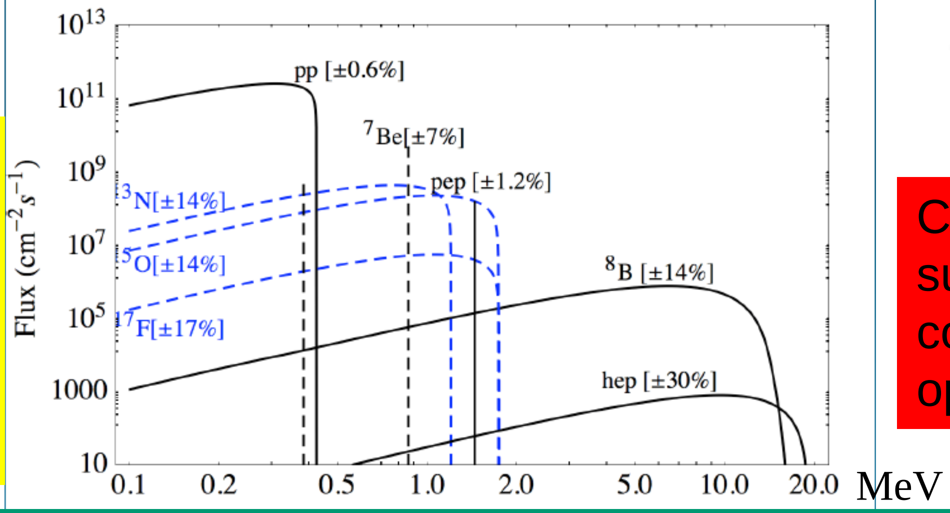


~99% of the energy in the Sun

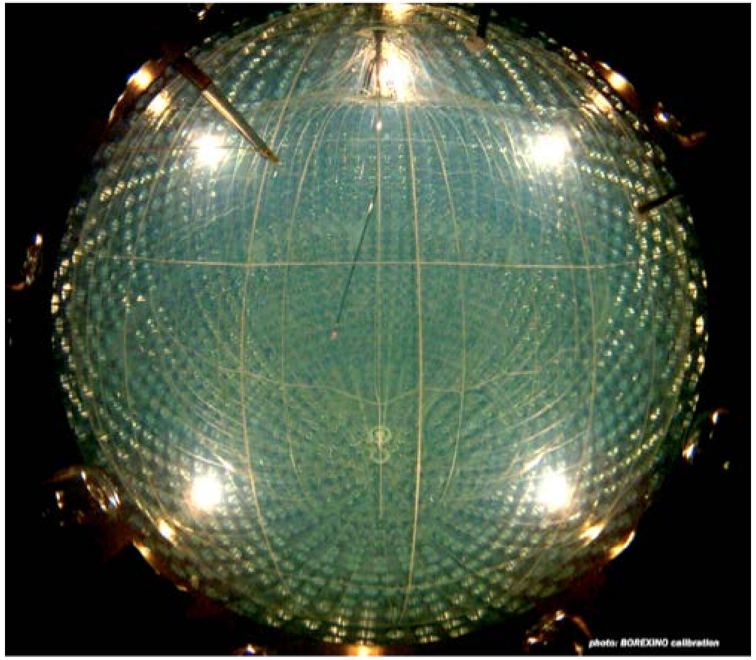


SSM prediction

A. Serenelli et al., Astroph. J. 7432 2011



Controversy about the surface metallicity composition of the Sun still open: High Z vs Low Z



Many accomplishments of Borexino in the solar neutrino arena and beyond…

Milano

München

Heidelberg

Hamburg

Mainz

Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian Kraków

the Borexino Collaboration

JINR Dubna

Virginia Tech

Houston

Paris

Moscow

Princeton

UMass Amherst

Kurchatov Moscow

Los Angeles

St. Petersburg

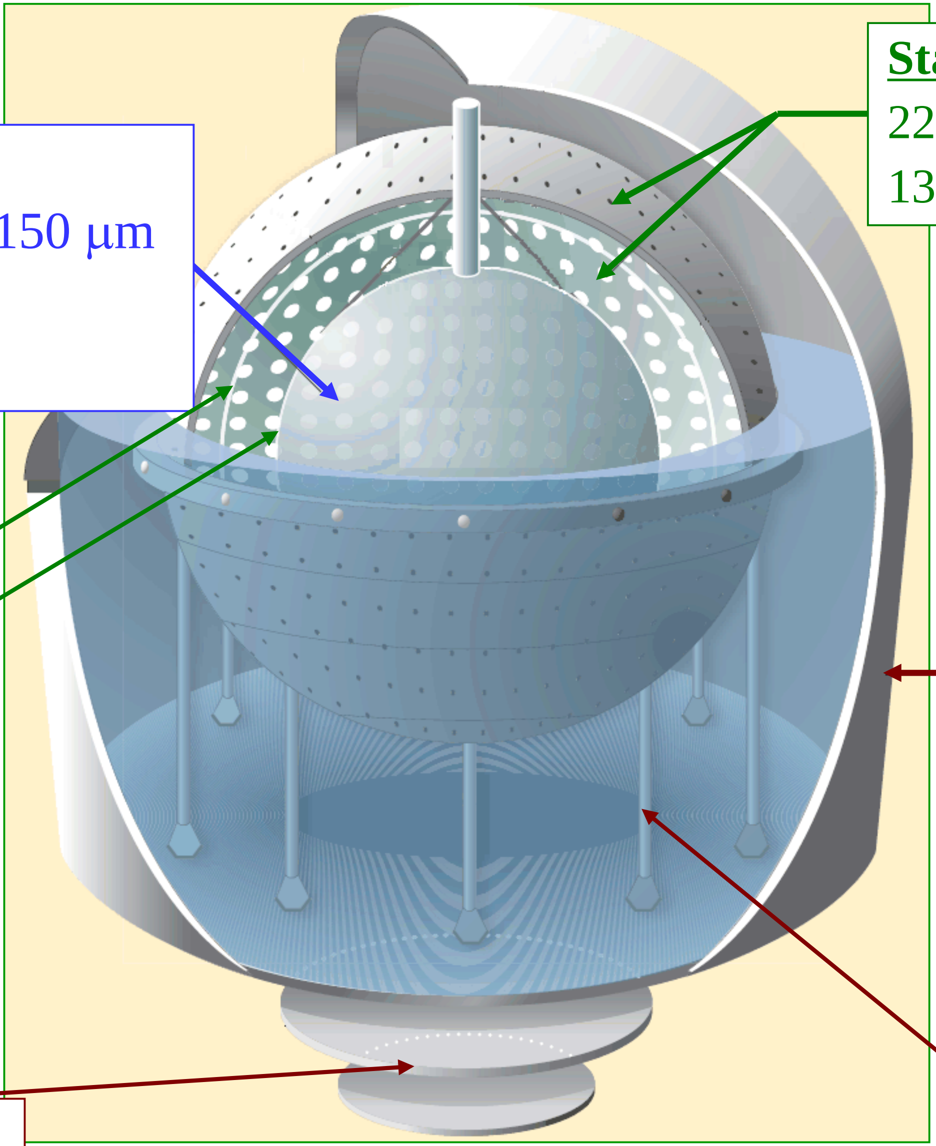
Borexino at Gran Sasso: low energy real time detection

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

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Neutrino electron scattering

$\nu e \rightarrow \nu e$



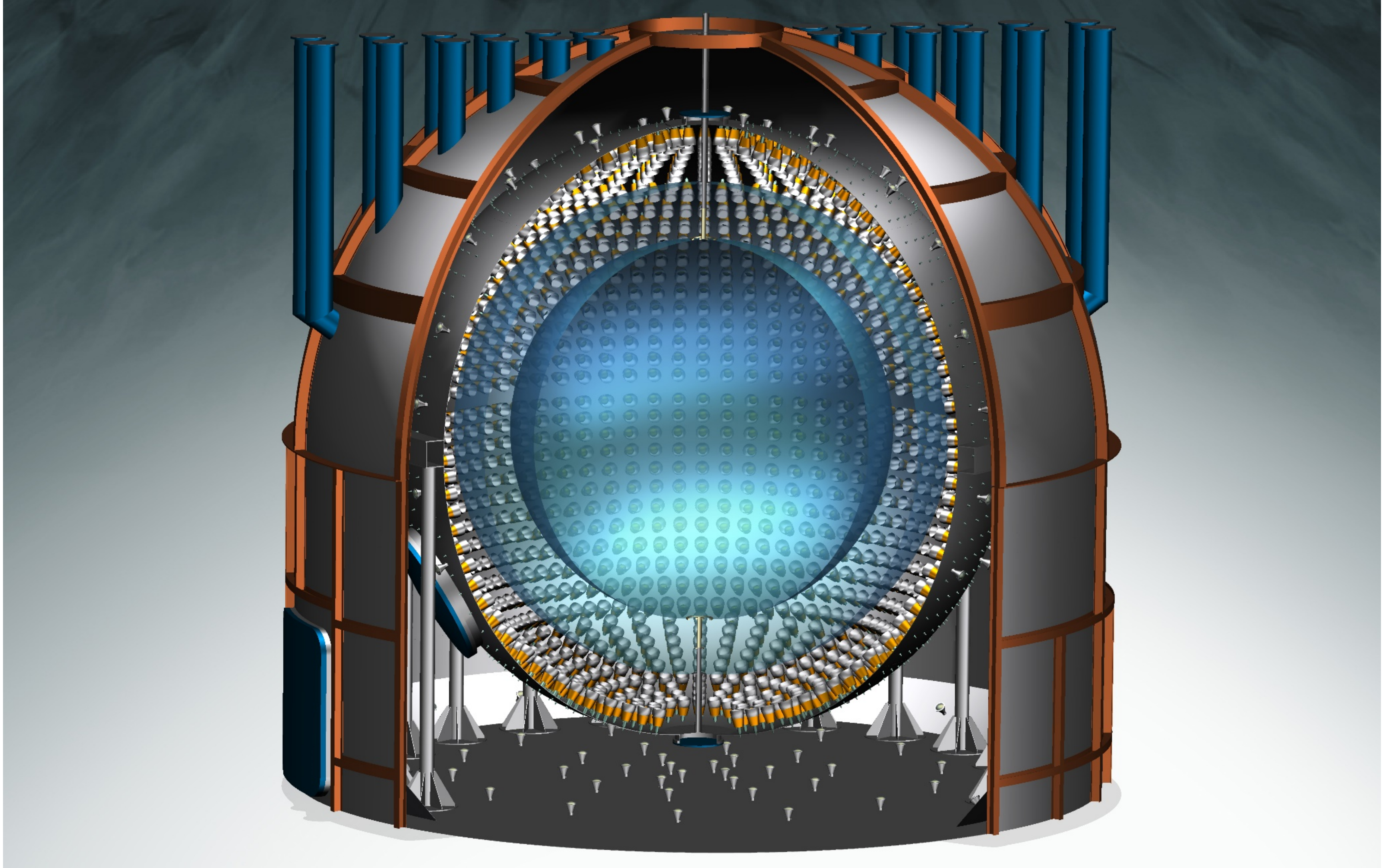
Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

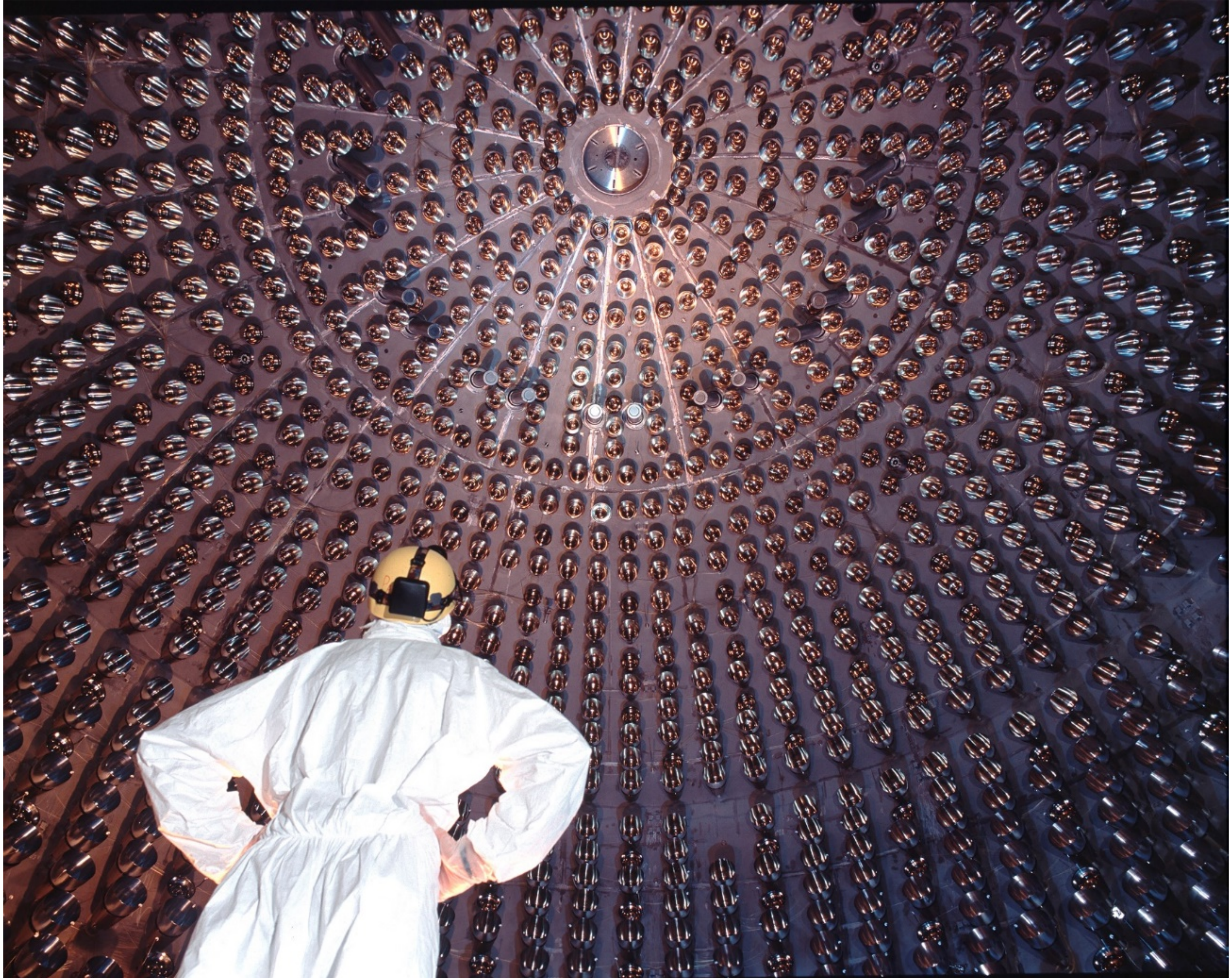
Design based on the principle of graded shielding

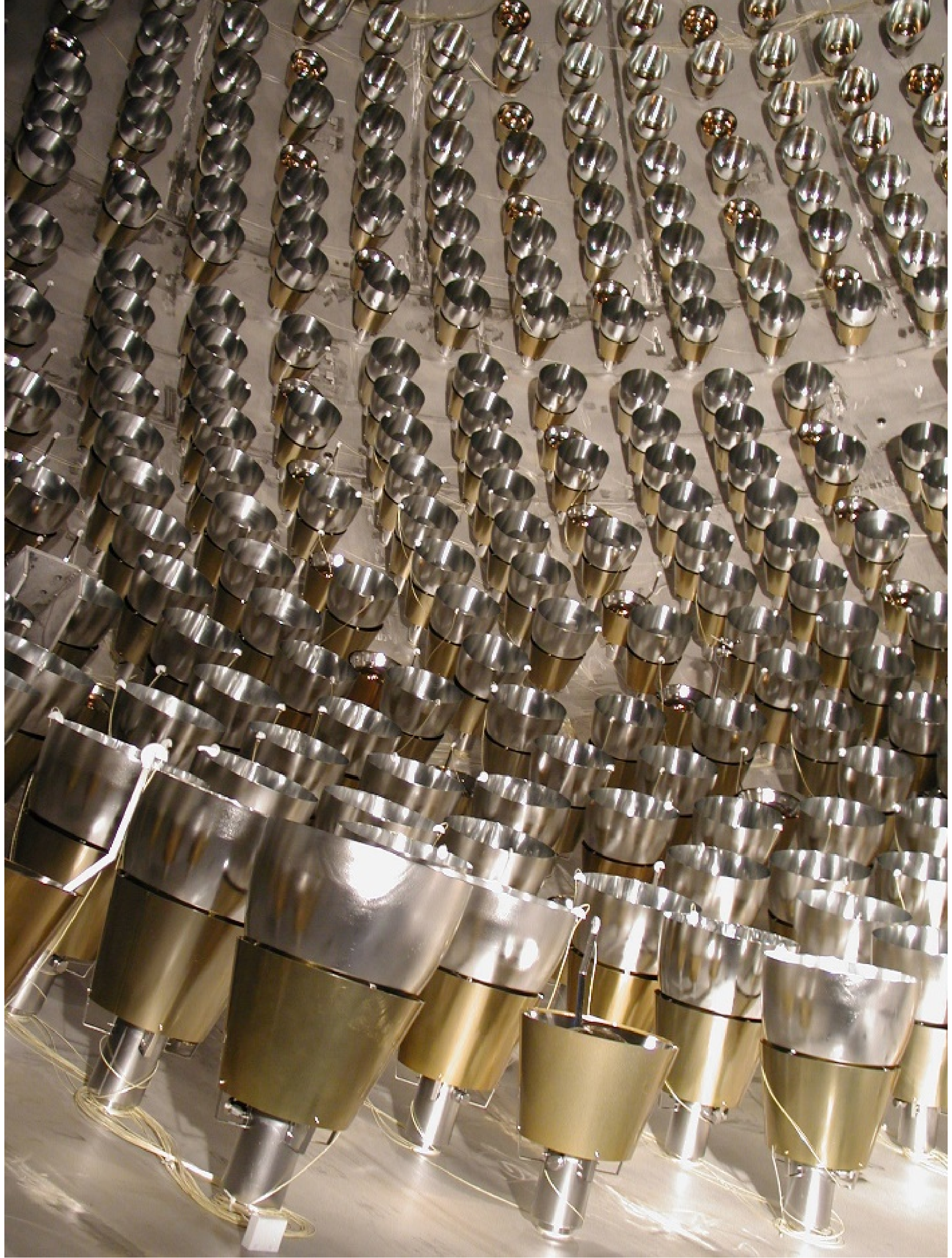
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

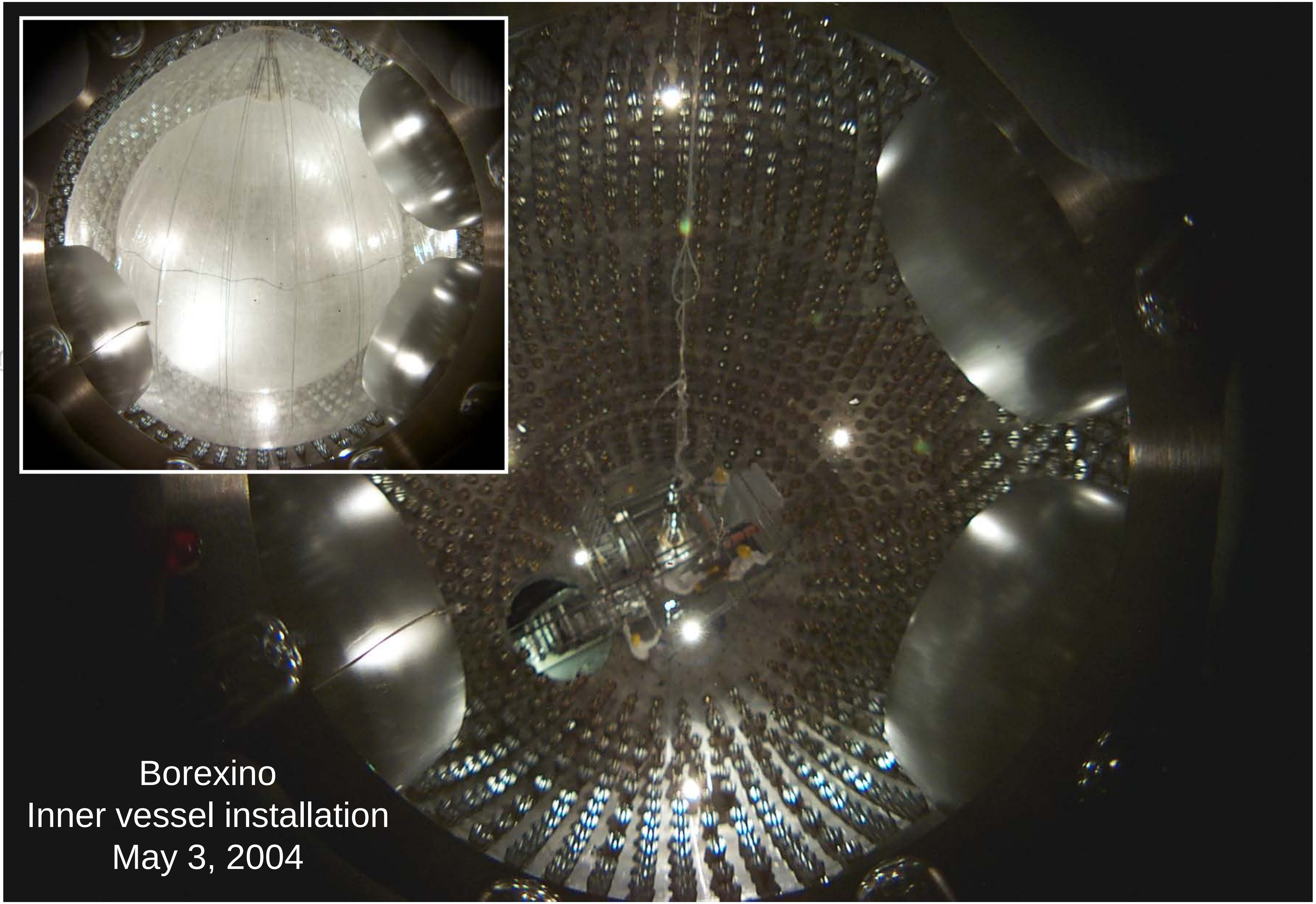
20 legs

Carbon steel plates

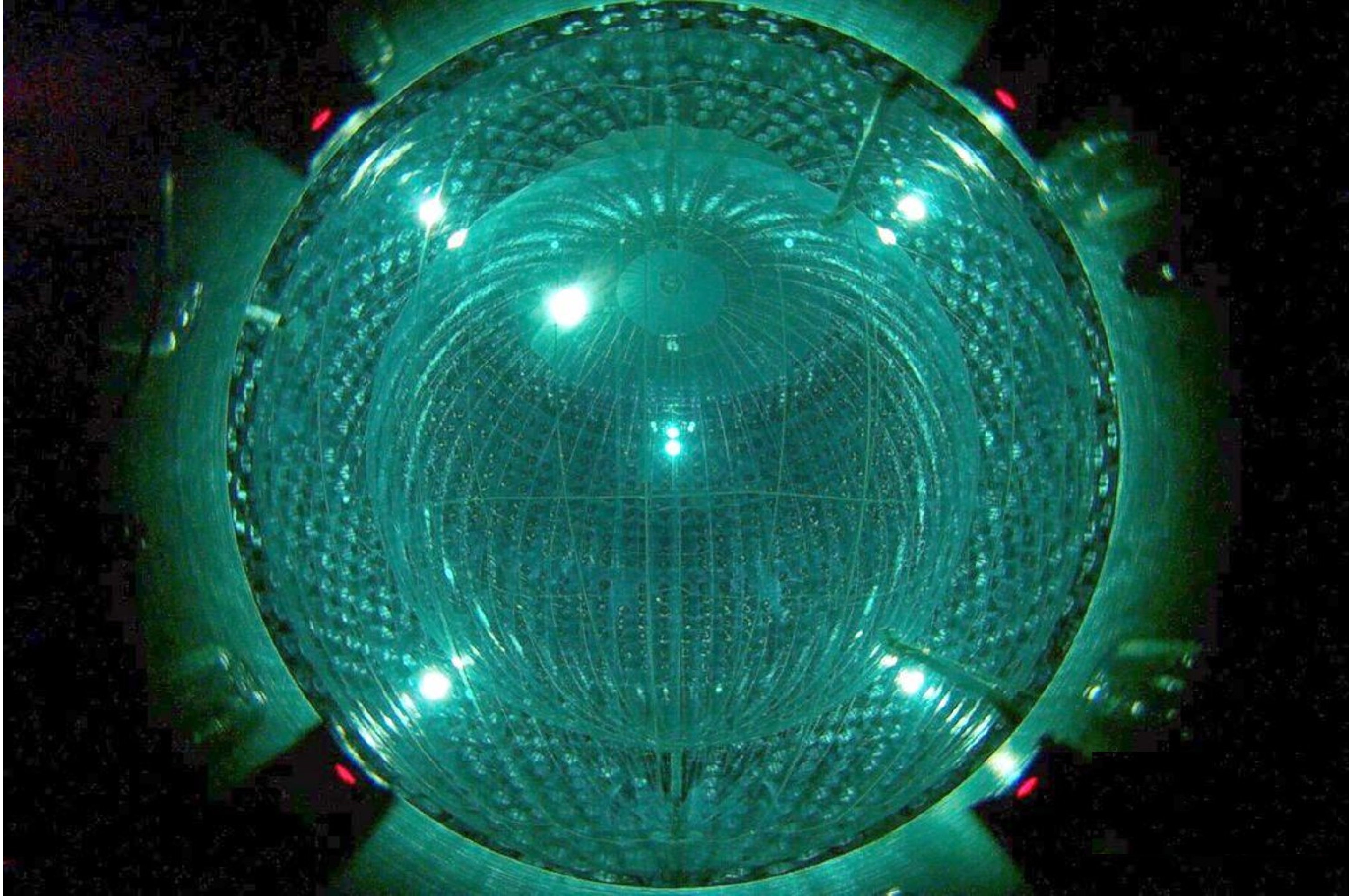








Borexino
Inner vessel installation
May 3, 2004



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
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**

⇨ Extraction of the fluxes through a data-to-model fit
Phase I may 2007 – may 2010
Phase II December 2011 - ……… still in progress
Purification in between

The background saga → the quest for the ultimate purity

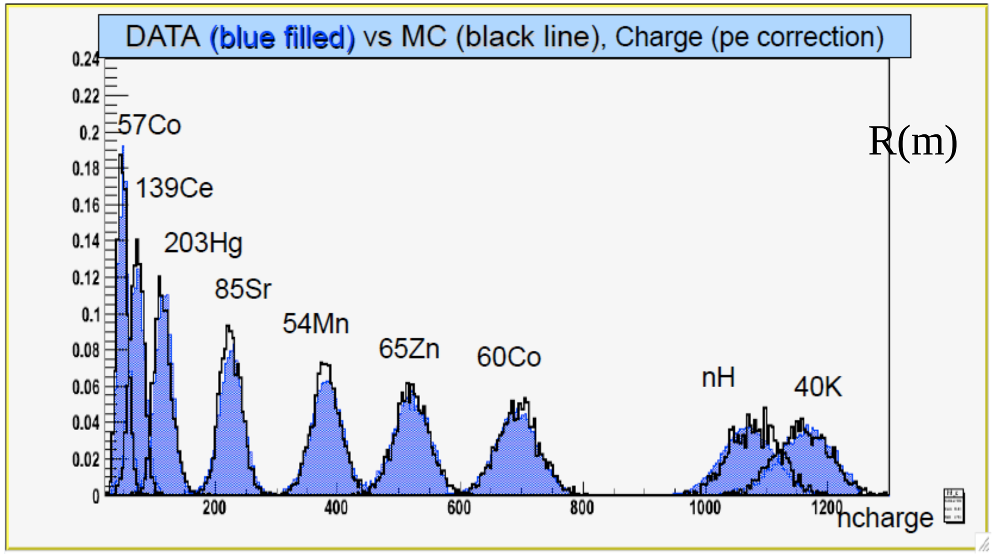
Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final in phase I
Name	Source	Typical	Required	Hardware	Software	
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	$<10^{-10} s^{-1} m^{-2}$	underground water detector	Cerenkov PS analysis	$< 10^{-10}$ eff. > 0.99992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	$\sim 10^{-12}$ g/g	$\sim 10^{-18}$ g/g	selection	threshold	2.7 $\times 10^{-18}$ $^{14}C/^{12}C$
^{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	$5.35 \pm 0.5 \times 10^{-18}$ $3.8 \pm 0.8 \times 10^{-18}$ 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: A little worse due to the less accuracy in the calibration

@ Determination of Light yield and of the Birks parameter k_B

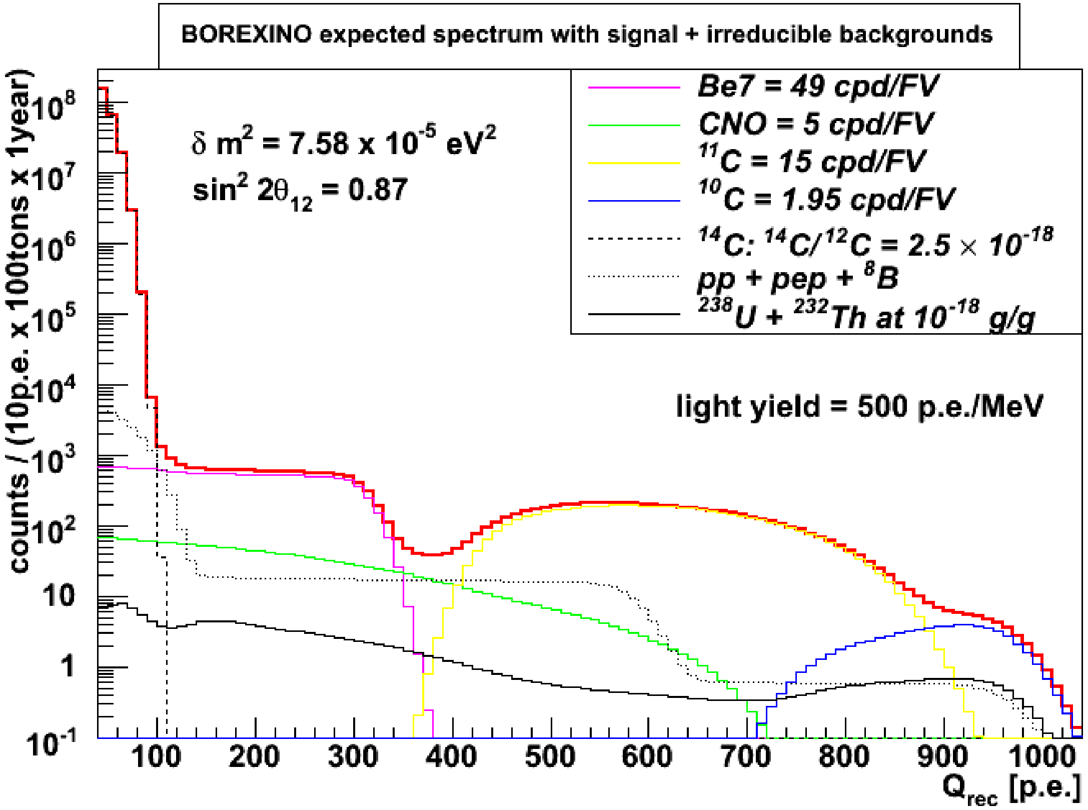
L.Y. $\longrightarrow$ obtained from the γ calibration sources with MC: **~ 500 p.e./MeV**

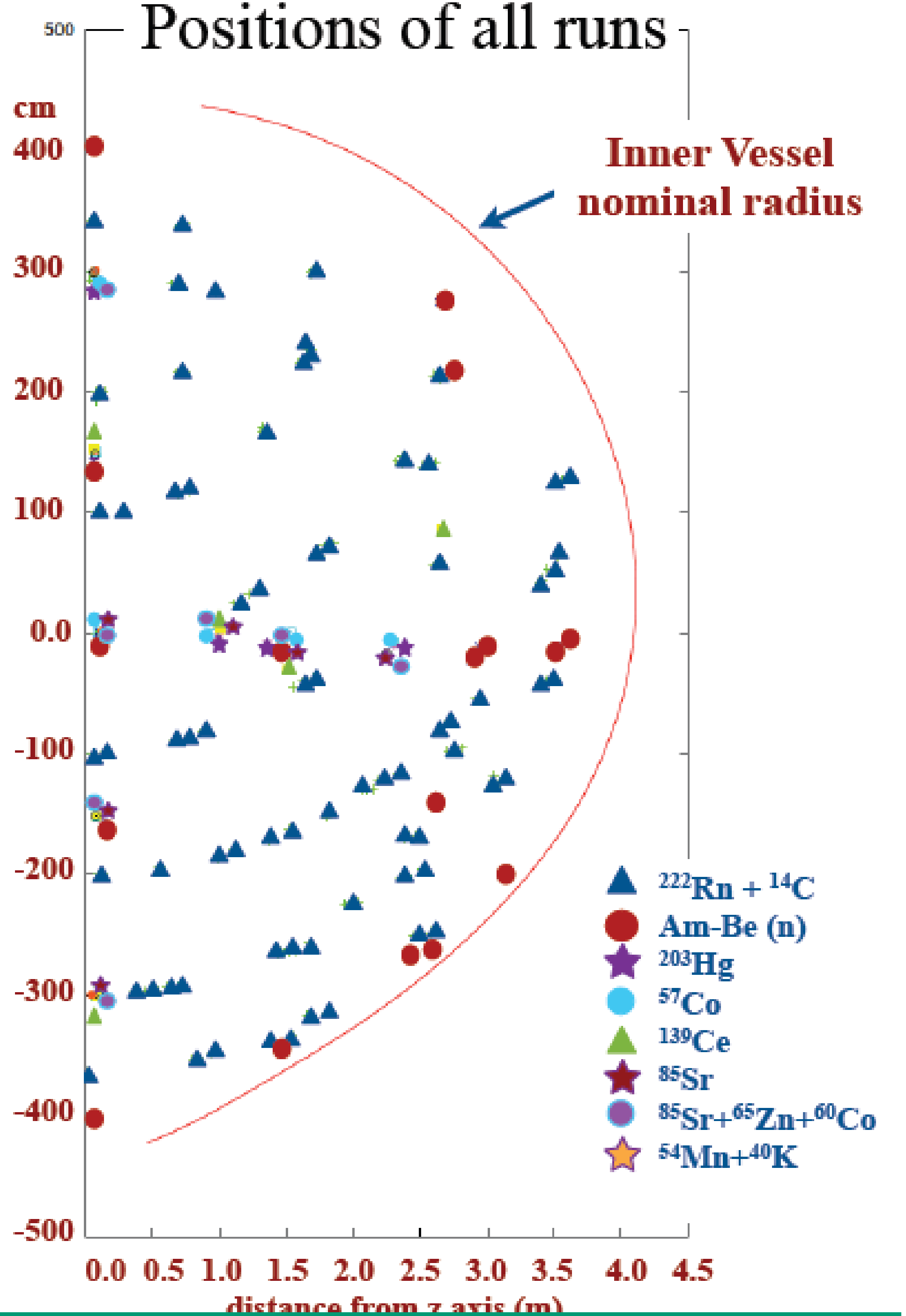
$\searrow$ left as free parameter in the total fit in the analytical approach

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

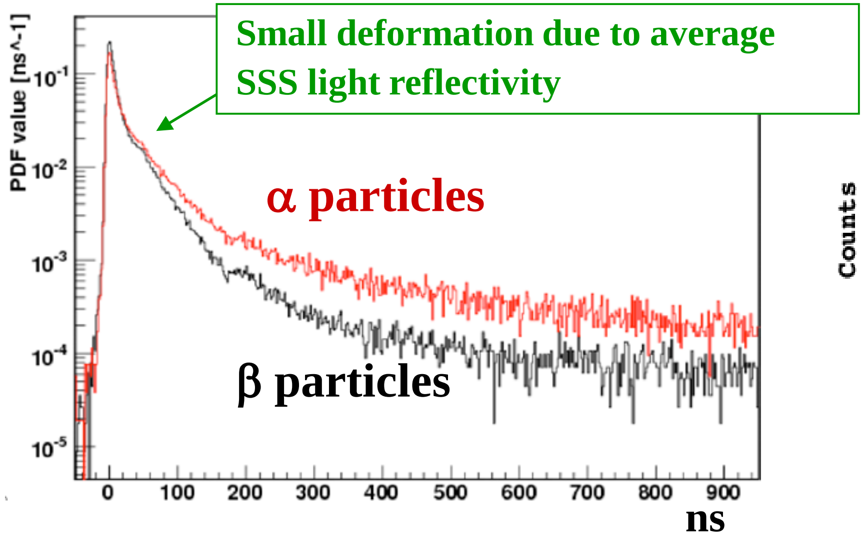
@ Fiducial volume uncertainty: $\boxed{\,{}^{+0.5}_{-1.3}\,\%}$ (1 σ) (radon sources)

MC prediction of signal + intrinsic Background

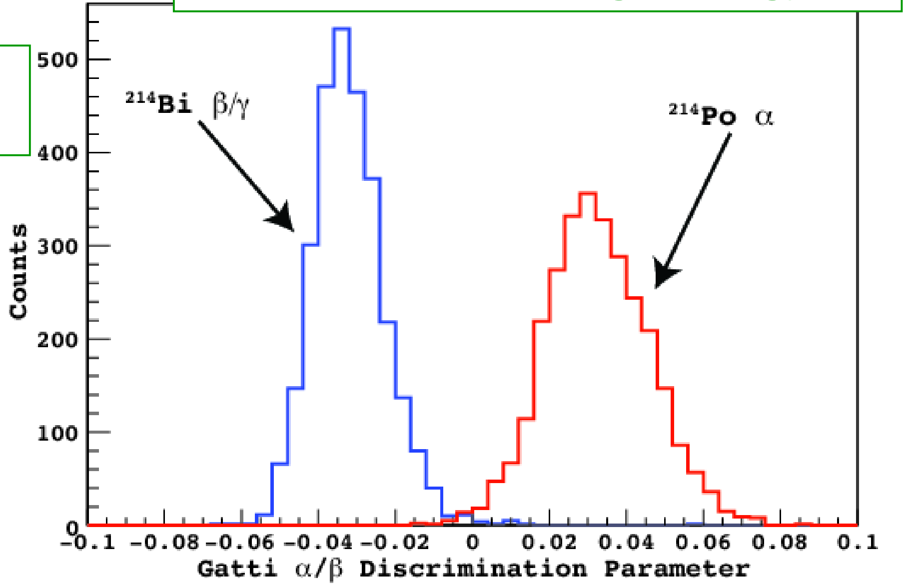




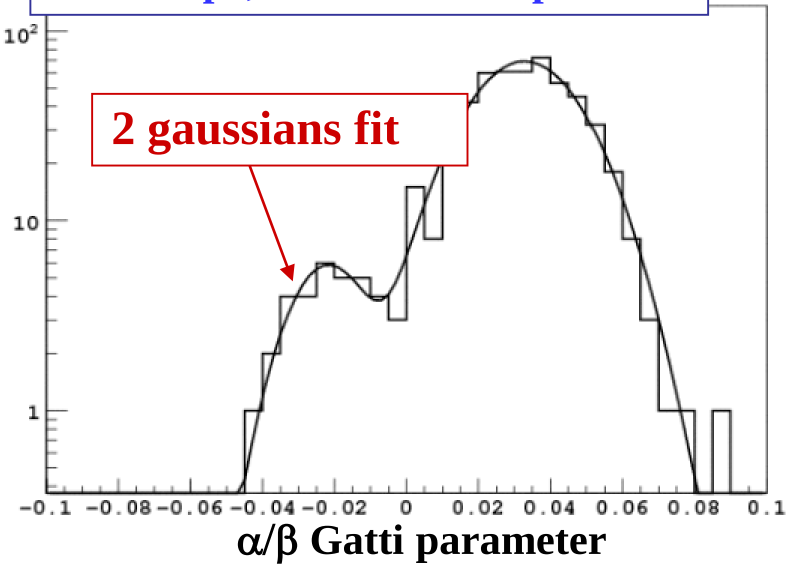
α/β discrimination



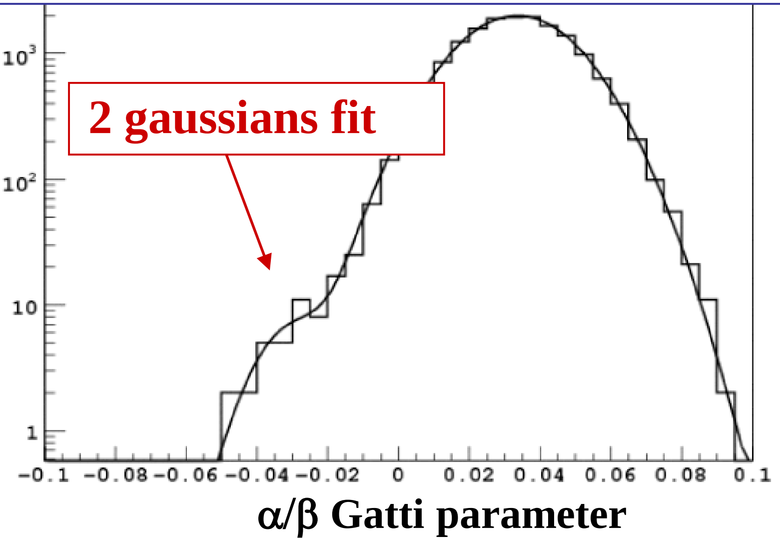
Full separation at high energy



250-260 pe; near the ^{210}Po peak

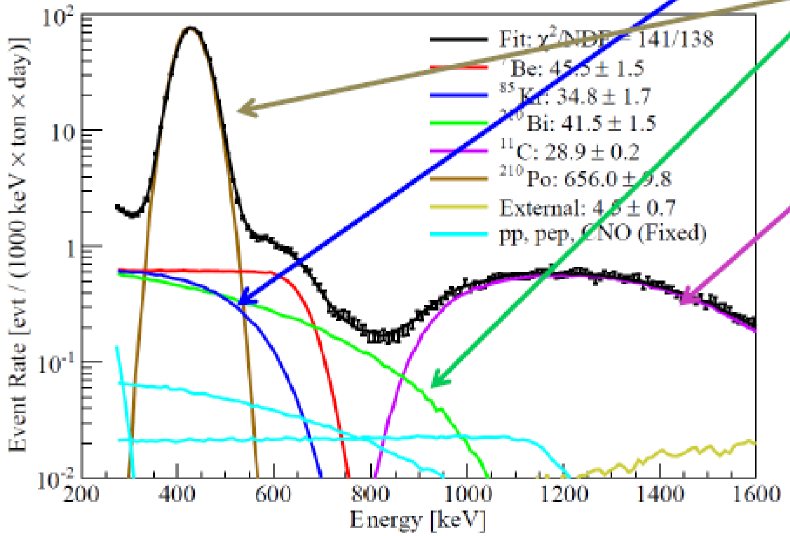


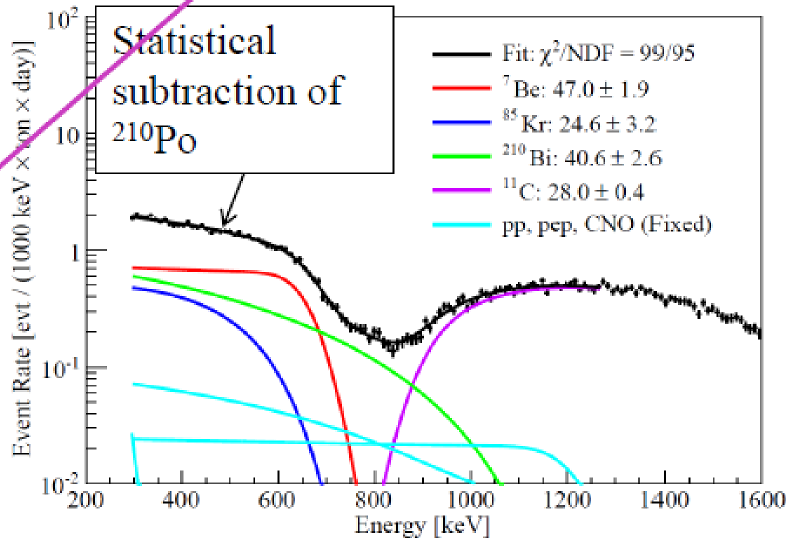
200-210 pe; low energy side of the ^{210}Po peak



^{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

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

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

- Unprecedented 5% precision in low energy regime
- Estimate of the total flux $(4.43\pm0.22)\times10^9\ cm^{-2}s^{-1}$
- ν_e survival probability 0.51 +- 0.07 @0.862MeV

HZ model $4.47(1\pm0.07)\times10^9$ $cm^{-2}s^{-1}$

- 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)

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

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

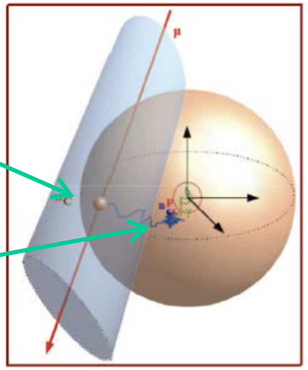
G. Bellini et al., Borexino Collaboration, Phys. Lett. B707 (2012) 22.

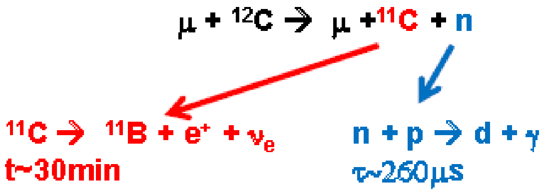
G. Bellini et al., Borexino Collaboration, arXiv:1308.0443 (2013).

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

Interaction point and ^{11}C production point

Position of the γ



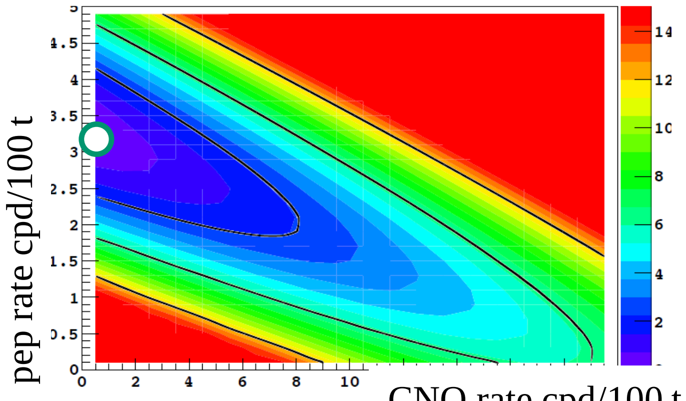


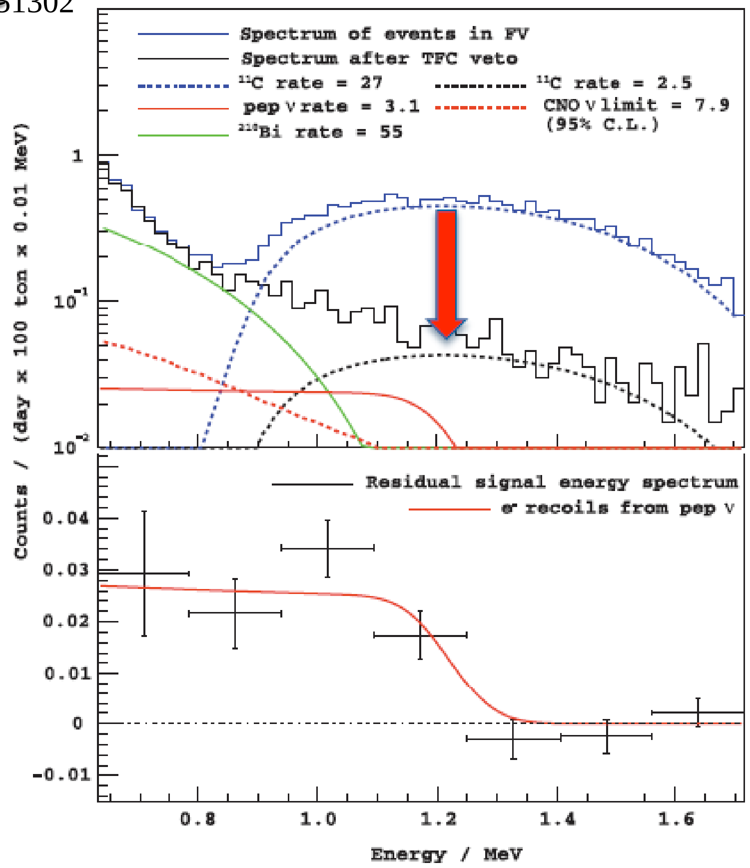
Threefold coincidence for ^{11}C rejection

- 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

Δchi^2 profile for fixed pep and CNO rates





Details in the talk

S. Davini "CNO and pep solar neutrino measurements and perspectives in Borexino"

this afternoon parallel session

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)

•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

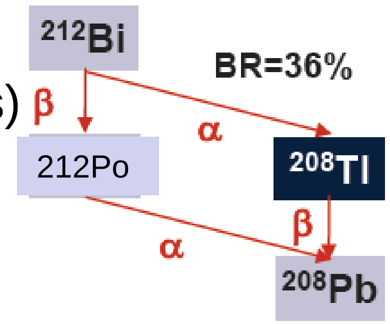
•@**Muon cut + 2 mms** dead time to reject induced **neutrons** (240 μs)

•@**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

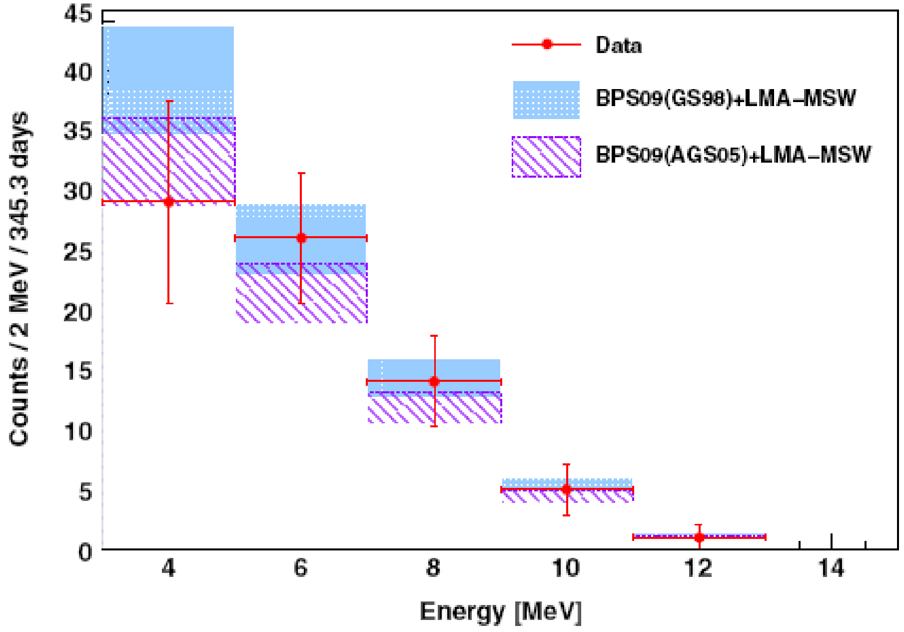
•@^{214}Bi-^{214}Po coincidences rejected (τ=237 μs- ^{222}Rn daughter)

•@^{208}Tl from ^{212}Bi-^{212}Po (B.R.64%-τ=431ns) we evaluate the ^{208}Tl production via →



^{8}B with lower threshold at 3 MeV

Exp. ^{8}B spectrum vs models



Data compatible with both high metallicity and low metallicity models

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [7]	5.0	$2.35\pm0.02\pm0.08$
SuperKamiokaNDE II [2]	7.0	$2.38\pm0.05^{+0.16}_{-0.15}$
SNO D_2O [3]	5.0	$2.39^{+0.24}_{-0.23}\,^{+0.12}_{-0.12}$
SNO Salt Phase [26]	5.5	$2.35\pm0.22\pm0.15$
SNO Prop. Counter [27]	6.0	$1.77^{+0.24}_{-0.21}\,^{+0.09}_{-0.10}$
Borexino	3.0	$2.4\pm0.4\pm0.1$
Borexino	5.0	$2.7\pm0.4\pm0.2$

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

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%

Phys. Rev. D, 82 (2010) 033006

Nature, August 28, 2014

ARTICLE

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called *pp* neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the nuclear origin of the Sun's energy and contributing to the discovery of neutrino oscillations, those from proton–proton fusion have hitherto eluded direct detection. Here we report spectral observations of *pp* neutrinos, demonstrating that about 99 per cent of the power of the Sun, 3.84 × 10^{33} ergs per second, is generated by the proton–proton fusion process.

Detection of the pp fundamental flux (we observe the engine of the Sun at work!) possible thanks to the very stable and clean data accumulated in the first 2 years of the Borexino Phase-II data taking

Irreducible background to cope with : ^{14}C and its pile-up→ detector response understood down to ~ 150 keV

Milestone result in experimental solar neutrino physics: first spectroscopic and real time observation of the neutrinos from the key fusion reaction which powers the Sun

What makes the Sun shine

Neutrinos produced in the nuclear reaction that triggers solar-energy generation have been detected. This milestone in the search for solar neutrinos required a deep underground detector of exceptional sensitivity. SEE ARTICLE P.383

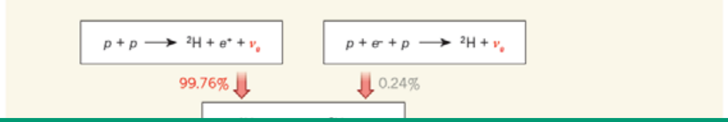
WICK HAXTON

A remarkable detector of solar neutrinos called Borexino has operated for the past seven years in Italy's Gran Sasso Laboratory, shielded by more than a kilometre of rock from the cosmic rays that bombard Earth's surface. A prolonged effort has reduced background signals from radioactive elements present in the detector that would otherwise obscure the neutrino signal.

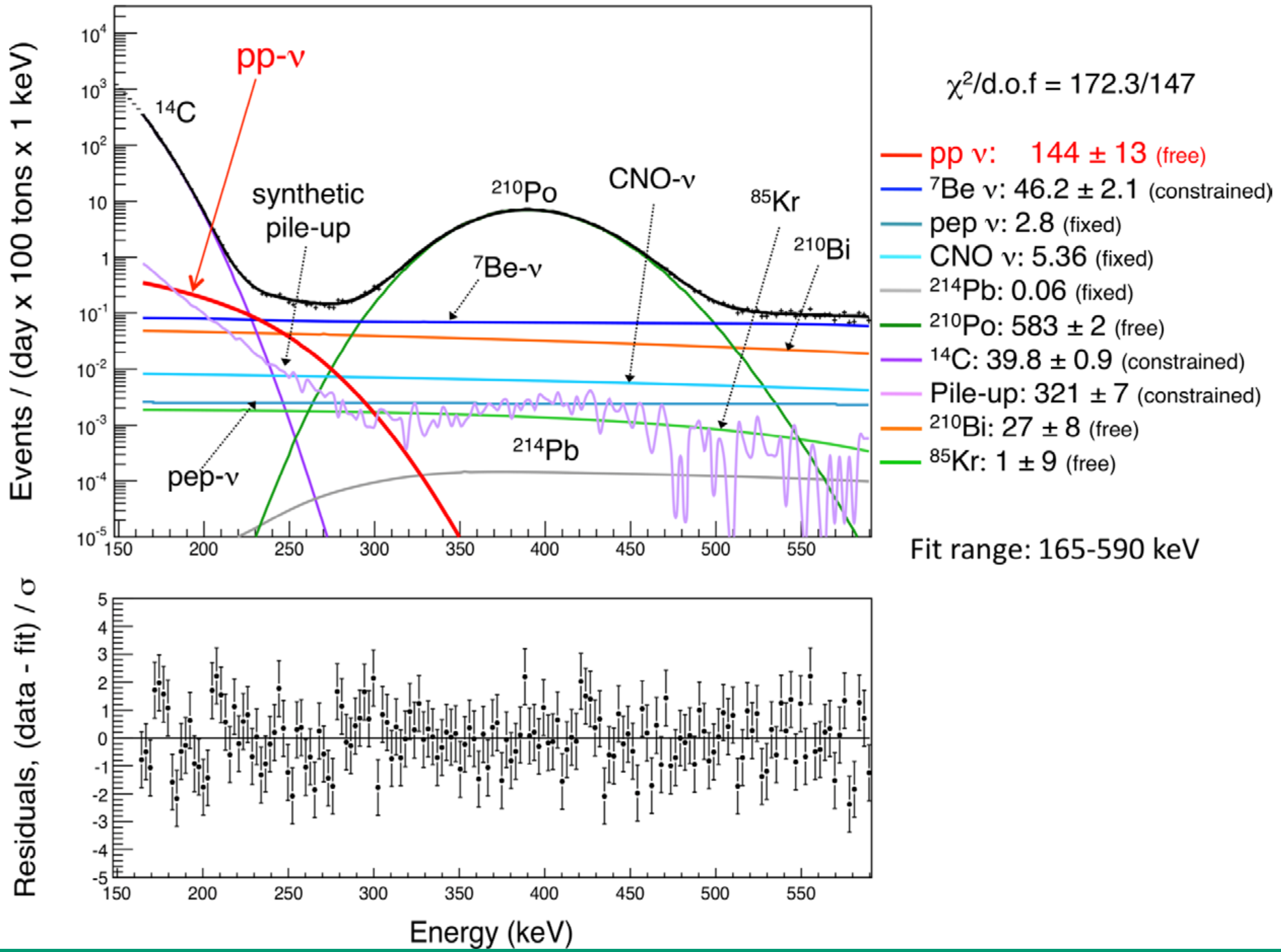
Aston's measurements in 1920 of the mass difference between four protons and a helium-4 (^{4}He) nucleus, Arthur Eddington proposed that the source of solar energy is the fusion of

criticism that the Sun is not sufficiently hot to sustain nuclear fusion, Eddington invited his critic to "go and find a hotter place".

This dispute was resolved by George Gamow, who showed that quantum tunnelling would allow two solar protons to approach one another within the range required for nuclear fusion to occur. The detailed reactions leading to the synthesis of ^{4}He were then deduced[3]: the proton–proton (*pp*) chain (Fig. 1) in the case of small, slowly evolving stars such as the Sun, and the carbon–nitrogen (CN) cycle in more-massive, rapidly evolving stars. Steady nuclear-energy release in the solar core keeps the temperatures high, ionizing hydrogen (H) and ^{4}He and producing a plasma in which the electrons act as a gas. The Sun burns in a



The results of the standard spectral fit



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

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

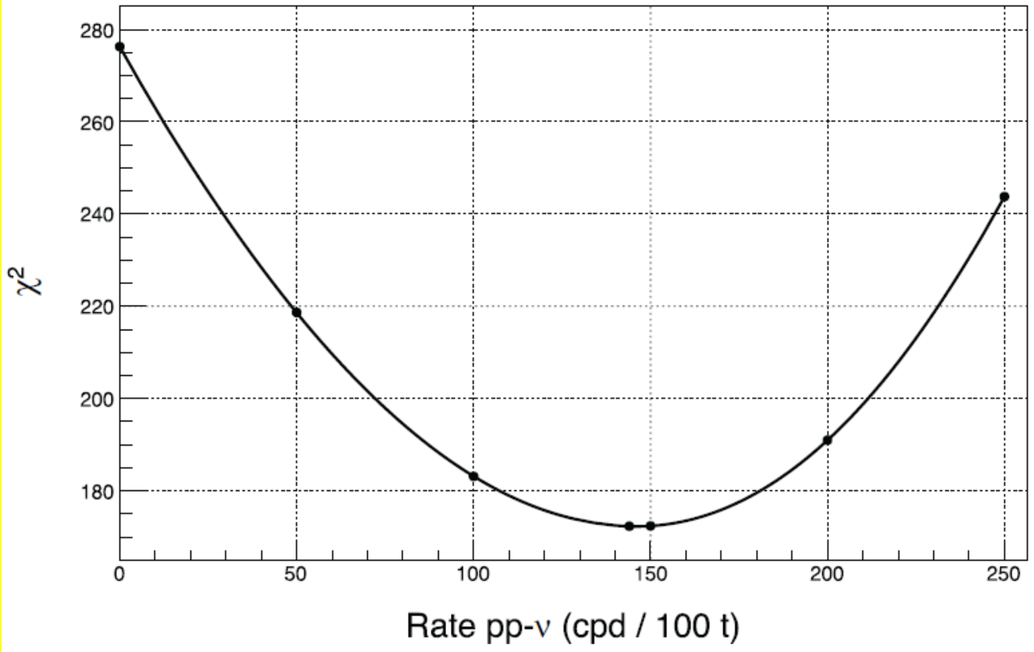
compared to expected (MSW/LMA,HM)

131±2 cpd/100 t

Details in the talk

O. Smirnov (JINR) "Measurement of Solar pp-neutrino flux with Borexino: results and implications"

this afternoon parallel session



pp neutrino flux:

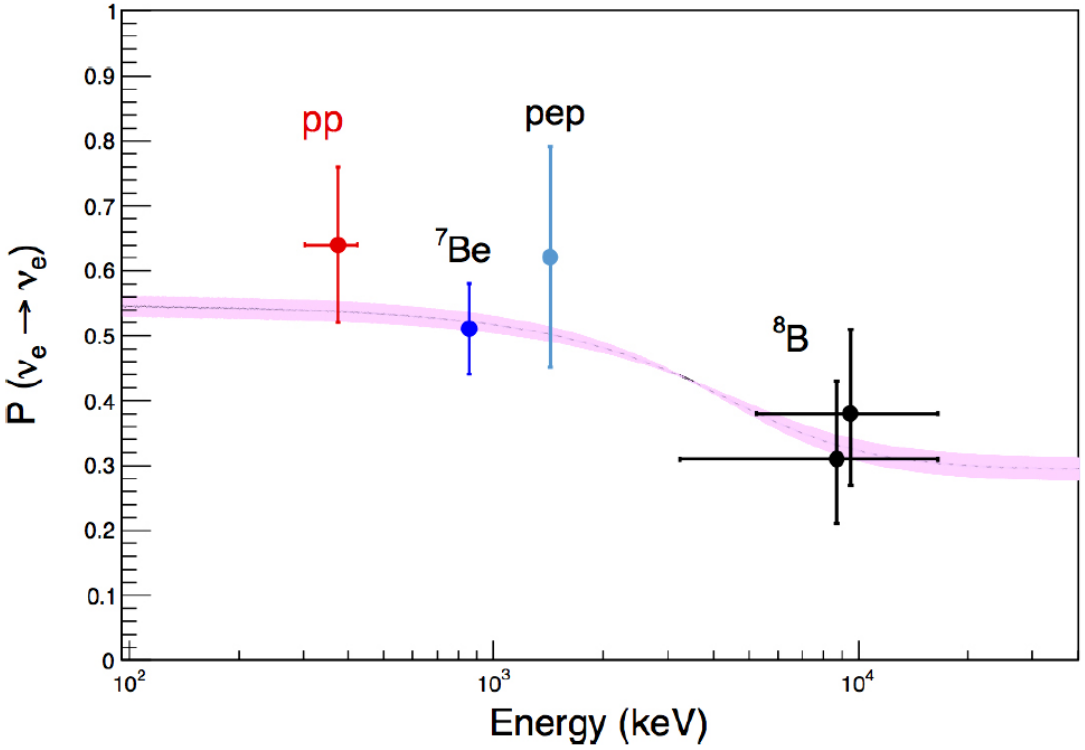
$(6.6\pm0.7)\cdot10^{10}$ cm^{-2}s^{-1}

vs

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

Zero pp count is excluded at 10σ level

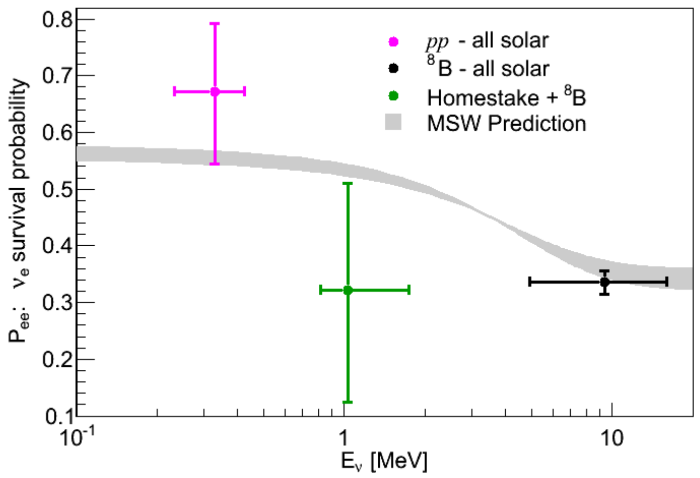
The global oscillation picture: survival probability of the electron neutrinos



FROM BOREXINO ALONE VALIDATION AT LOW ENERGY OF THE LMA-MSW OSCILLATION PARADIGM

Open issues : ^{8}B upturn at low energy
Subleading effects?

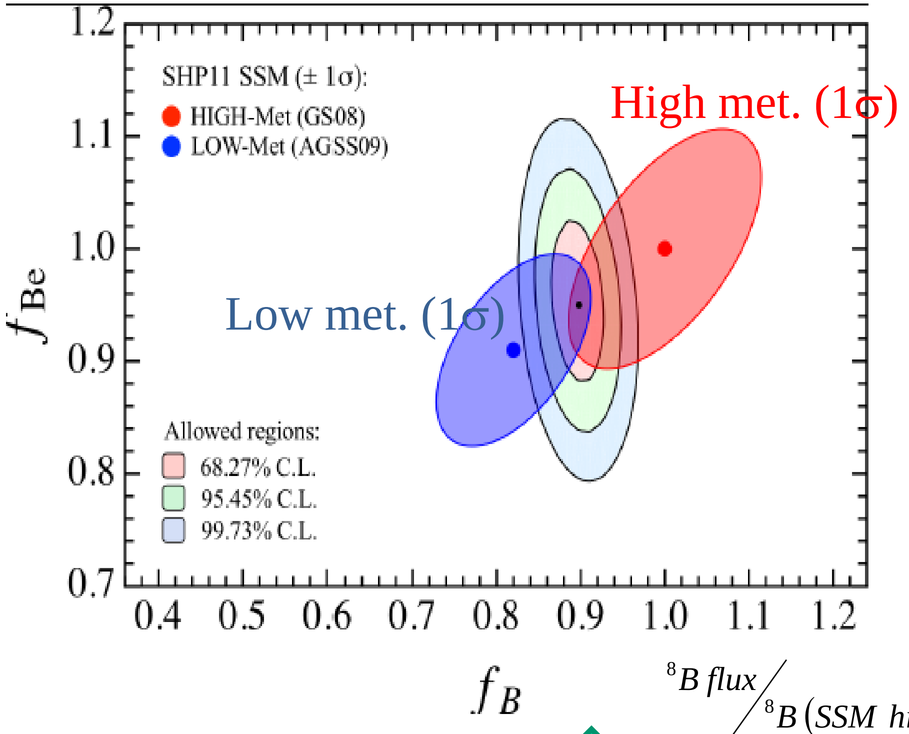
Before the Borexino results



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

Can the current data discriminate between high and low metallicity ?

$$f_{Be} = {}^{7}Be\ flux \big/ {}^{7}Be\,(SSM\ \ high\,met.)$$



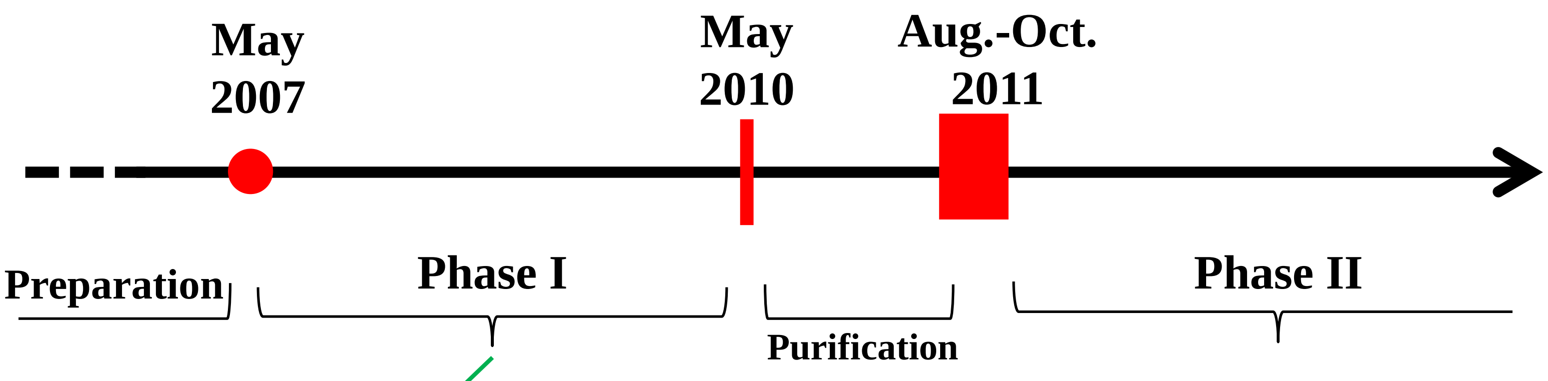
$$f_B = {}^{8}B\ flux \big/ {}^{8}B\,(SSM\ \ high\,met.)$$

ν	Diff. %
pp	0.8
pep	2.1
^{7}Be	8.8
^{8}B	17.7
^{13}N	26.7
^{15}O	30.0
^{17}F	38.4

The major predicted difference is in the CNO flux

The Borexino data cannot disentangle between the two models

Borexino timeline



The end of phase II will coincide with the start-up of SOX around fall 2016 – *See talks in this afternoon parallel session*

Planned also a new calibration campaign

Measurement of the pp fundamental flux achieved with Phase-II data already accumulated

- **(First) 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 > 4σ (initial phase II data included)**

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

- Measurement of pp-ν flux new milestone towards the full solar-ν spectroscopy
- New round of the previous measurements with improved precision - in progress
- Geo-ν observation at almost 6σ (almost all phase II data included)
- Short-baseline ν oscillation: SOX from fall 2016
- With PO210 tagging and /or possible further purification : Measurement of CNO-ν flux (beyond phase II)

Perspectives for phase II

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

Po210 factor 100 less than at the beginning of data taking

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

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?

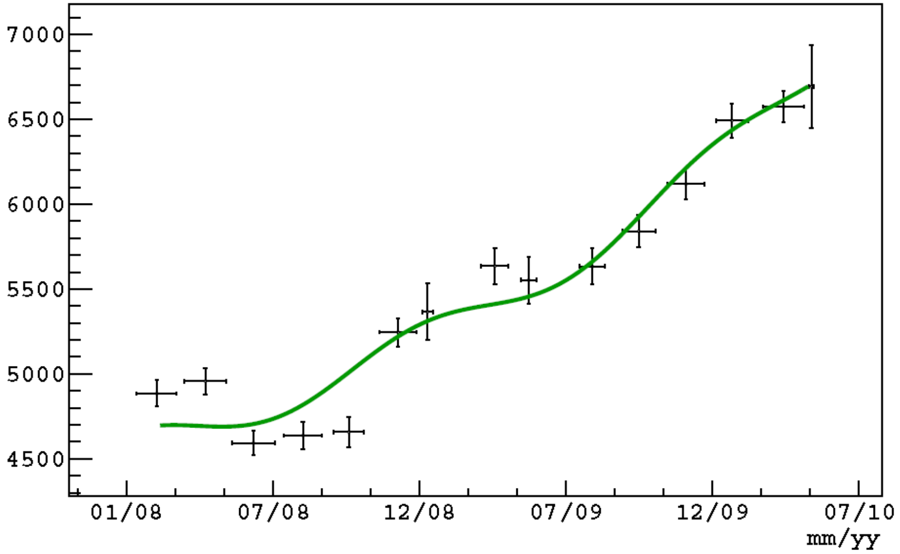
Improved ^{7}Be → some hint about metallicity?

CNO is the ideal metallicity discriminator → **^{210}Bi is the challenge** → ^{210}Po tagging (temperature stability) and/or possible further purification (beyond the present phase II)

Consistency check : seasonal variation due to the Earth's orbit eccentricity

Phase 1 data

Counts in 60 days (progressive increase of background)

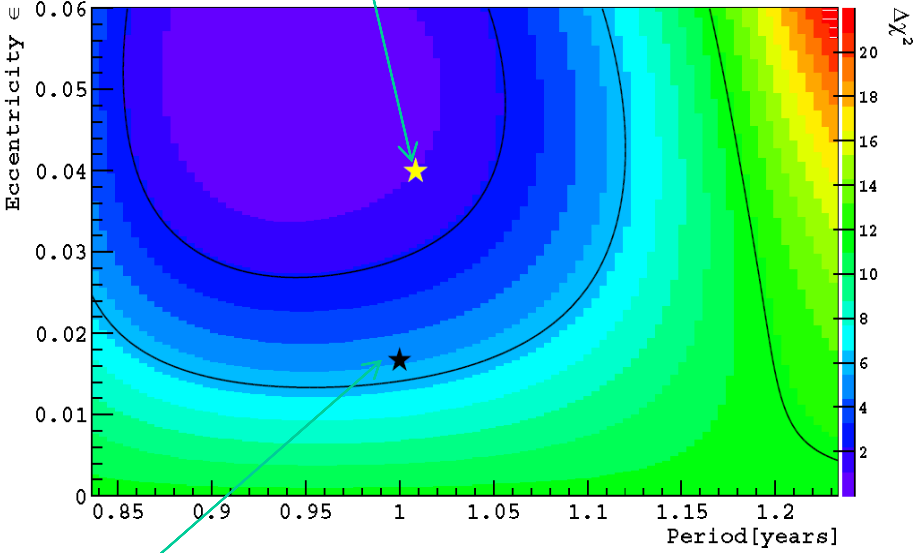


$$R = R_0 + e^{\Lambda_{Bi} t} + \overline{R}\left[1 + 2\varepsilon\cos\left(\frac{2\pi}{T} - \varphi\right)\right]$$

T=1.01 +- 0.07 y

ε=0.0398 +-0.0102

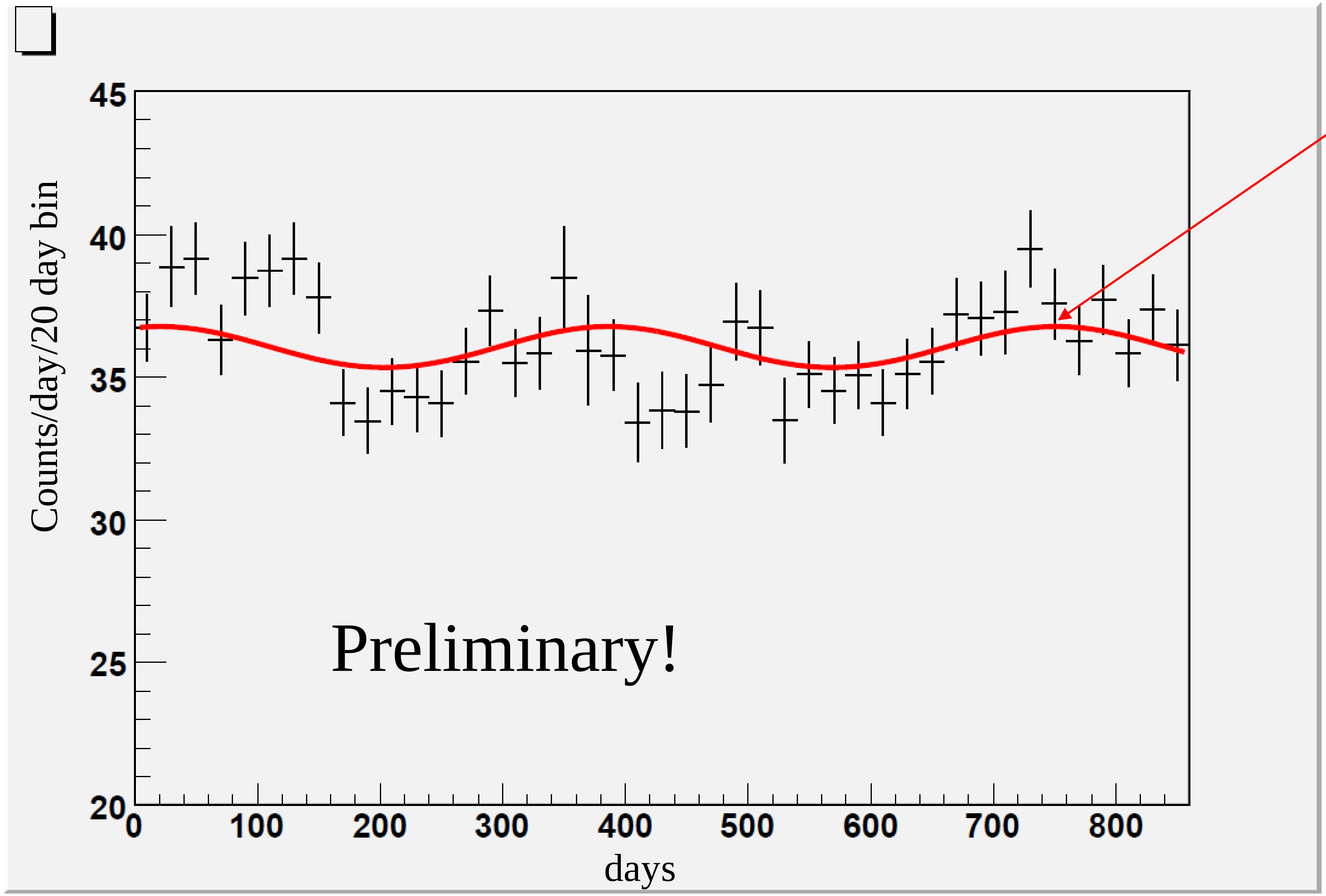
Inferred period and eccentricity



ΔChi^2 profile

expected values
are within the 2 σ contour

Annual modulation perspective in phase II



Expected modulation signal

The reduced and more stable background of phase II suited to produce a better agreement with the expected modulation parameters T and ε

Geo-neutrinos: anti-neutrinos from the Earth a new probe of Earth's interior

U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well fixed ratio:

Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]	ε_H [W/kg]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

Earth emits antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ whereas Sun shines in neutrinos.

A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons:

$$\bar{\nu} + p \rightarrow e^+ + n - 1.8\ \mathrm{MeV}$$

Classical inverse beta decay (IBD) antineutrino detection in liquid scintillation detectors

Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.

Three releases so far from Borexino

- G. Bellini et al., (Borexino Coll.) Phys. Lett. B 687 (2010) 299

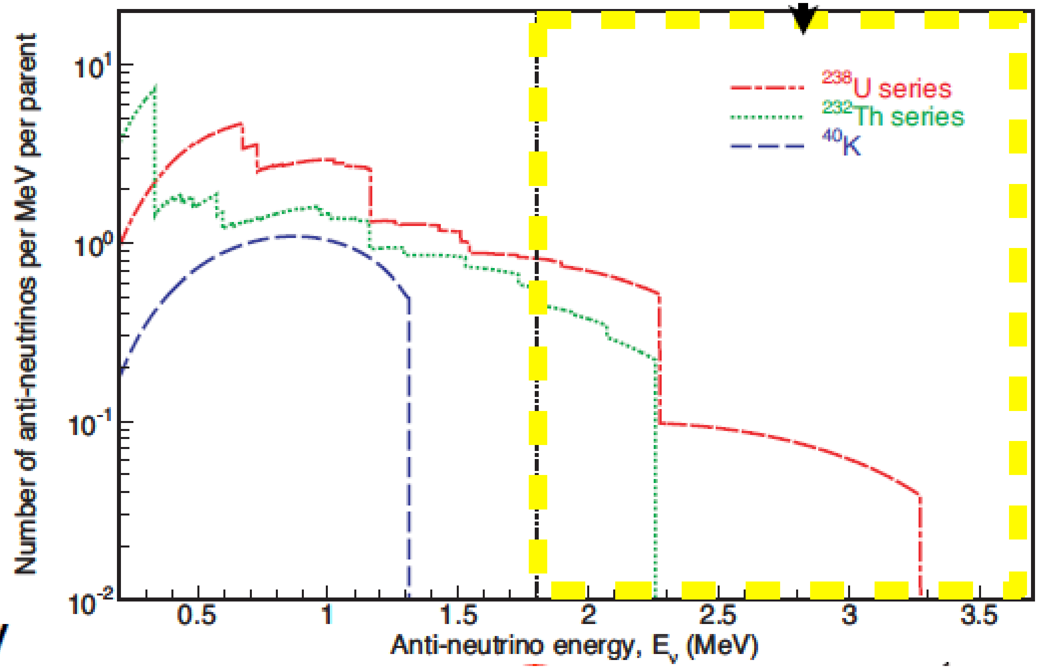
Only phase I data

- G. Bellini et al., (Borexino Coll.) Phys Lett B 722 4 (2013) 295

Phase I plus part of phase II

- M. Agostini et al., (Borexino Coll.) Phys Rev D 92 (2015) 031101 (R)

Phase I plus a longer chunk of phase II



Predicted geo-antiνs energy spectra

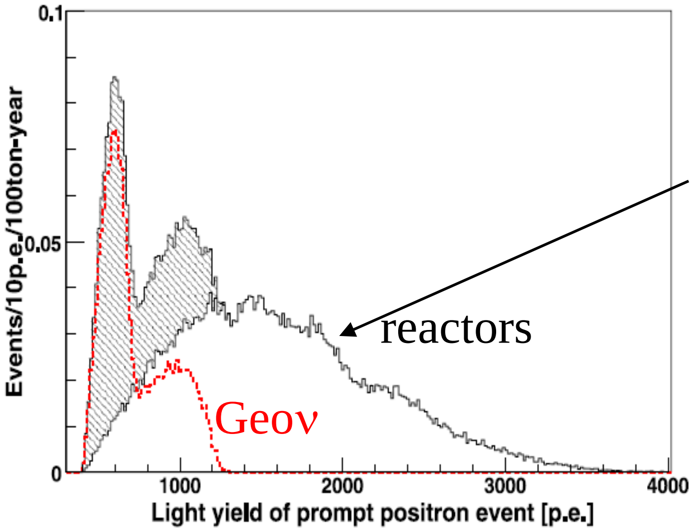
$$\bar{\nu} + p \rightarrow n + e^+ \qquad E_\nu > 1.8 \text{ MeV}$$

•"prompt signal"
e^+: energy loss + annihilation
(2 γ 511 KeV each)
•"delayed signal"
n capture after thermalization 2.2 MeV γ

- Flux in line with the Earth's model expectation
- Low flux: 3 order of magnitude less than ^{7}Be solar ν!
- Geo-ν probe the U,Th content of the Earth (not K)
- Multidisciplinary research: particle physics&geophysics

Spectrum prediction and background in Borexino

Prediction for Borexino



1MeV≈ 500 p.e.

446 reactors
Data from IAEA

^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221 ± 0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α,n) in scintillator	0.165 ± 0.010
(α,n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	<0.43
untagged muons	0.12 ± 0.01
Fission in PMTs	0.032 ± 0.003
^{214}Bi-^{214}Po	0.009 ± 0.013
Total	$0.78^{+0.13}_{-0.10}$

Backgrounds that can mimic the delayed coincidence of the IBD reaction
Only 0.70 +0.13-0.10 events in the whole exposure

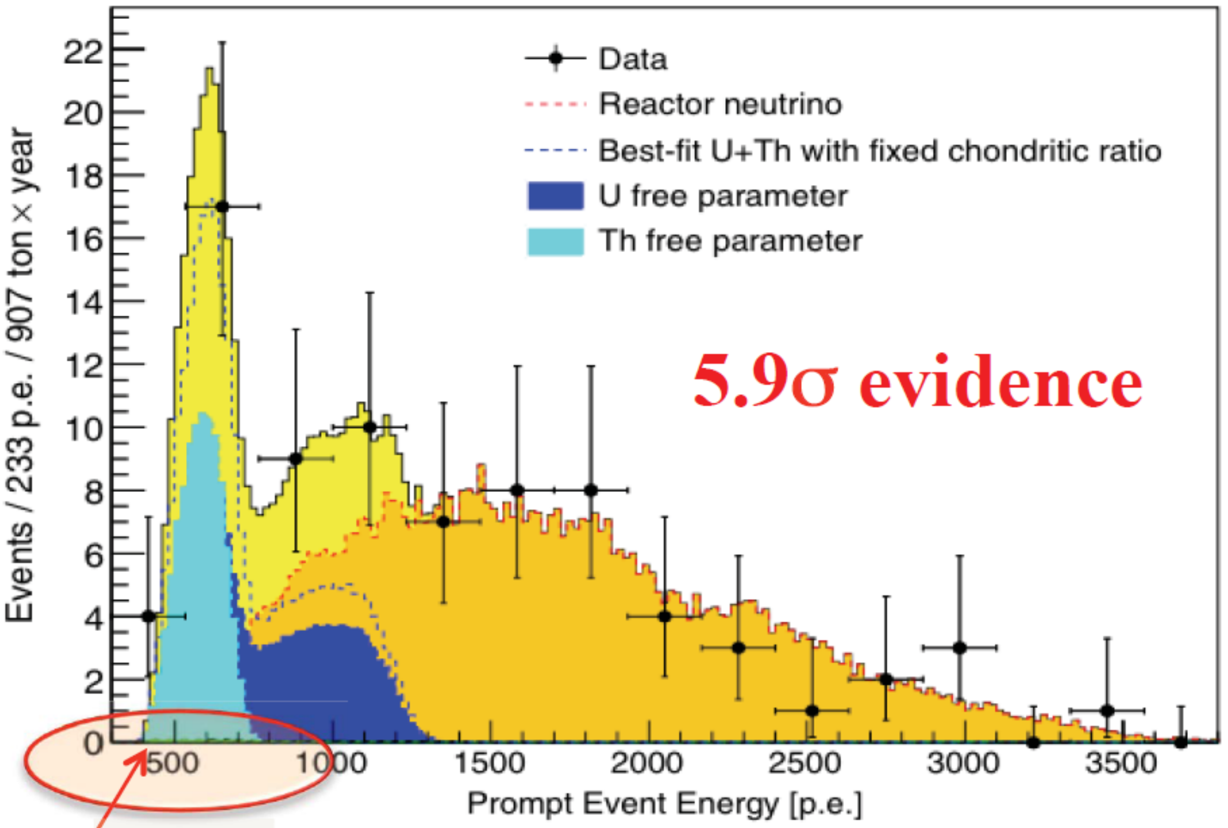
- Reactors anti-νs are the major source of background
- At Gran Sasso intrinsic low background measure (there are not near reactors)
- Borexino ultralow contamination very beneficial (accidental, (α,n), ^{13}C (^{210}Po α, n)^{16}O)

Latest Borexino geoneutrino results

Details in the talk

R. Roncin "Geo-neutrino results with Borexino"

this afternoon parallel session



~1 MeV

~7 MeV

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

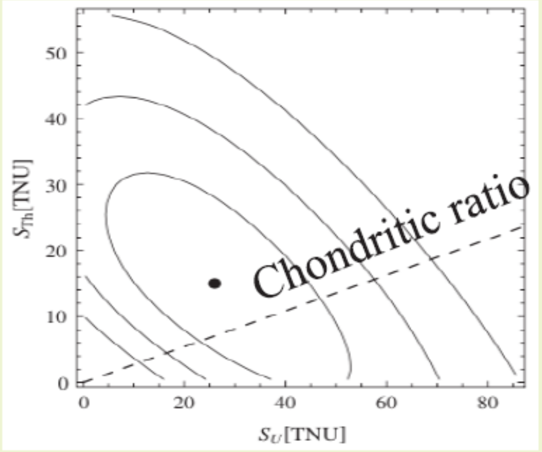
Two types of fits:

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

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

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

2) U and Th free fit paramters



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

Other measurements

With such an exquisite instrument many additional interesting measurements are possible

Some will also be illustrated in the afternoon talks

- A. Vishneva (JINR) "Test of the electric charge conservation law with Borexino detector"

- V.Atroshchenko (NRCKI) and E.Litvinovich (MEPhI) "Estimation of atmospheric neutrinos background in Borexino"

- M. Toropova (MEPhI) "Low energy neutrinos from gamma-ray bursts: experimental search status"

Conclusions

- ✓ Unprecedented purity - even better in phase II
- ✓ Full solar neutrino spectroscopy in only one experiment – pp flux crowned the achievements obtained so far
- ✓ Validation at low energy of the MSW-LMA oscillation solution
- ✓ Neat and clean geo-ν signal
- ✓ The hunt for CNO flux will continue…. This would be the ultimate solar measure!
- ✓ For a detailed description of many of the measures of Borexino and of the SOX program please refer to the talks in the afternoon parallel session