Neutrino Measurements from the Sun and Earth: Results from Borexino

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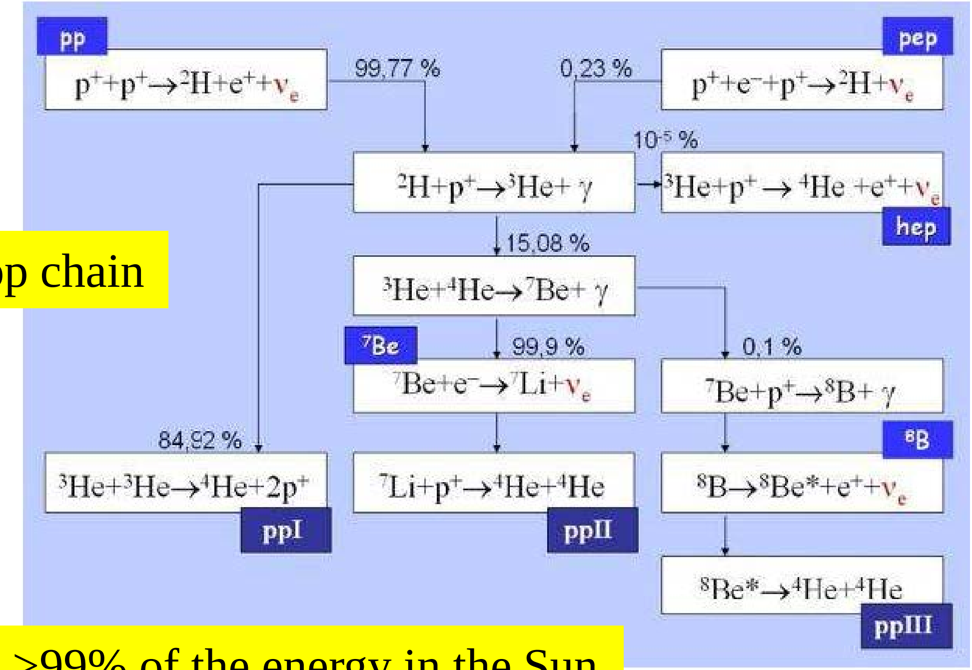
On behalf of the Borexino Collaboration

Boston – Neutrino 2014

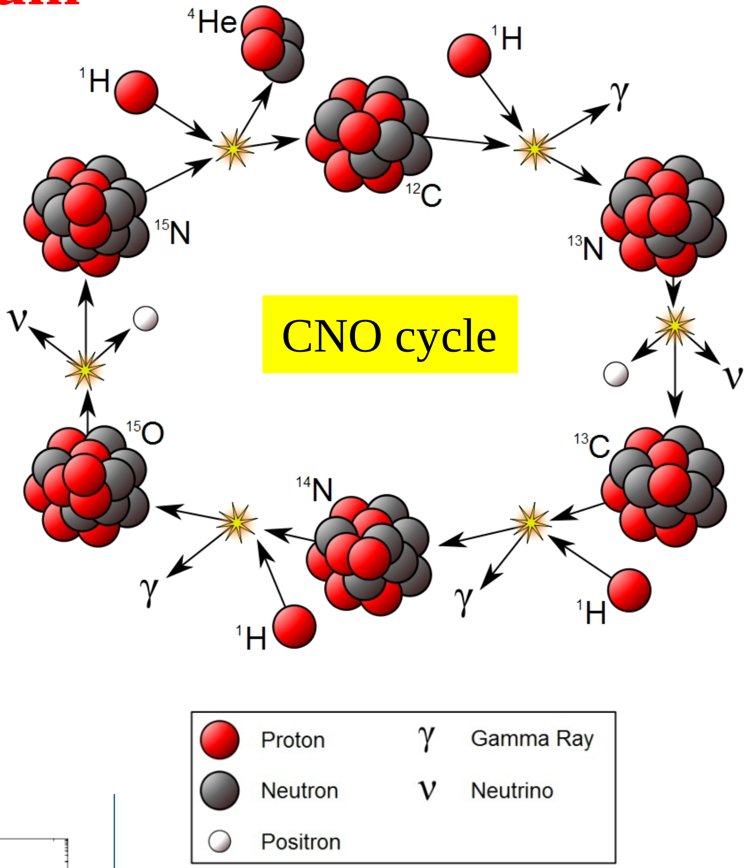
3 June 2014

Solar neutrinos production and spectrum

pp chain

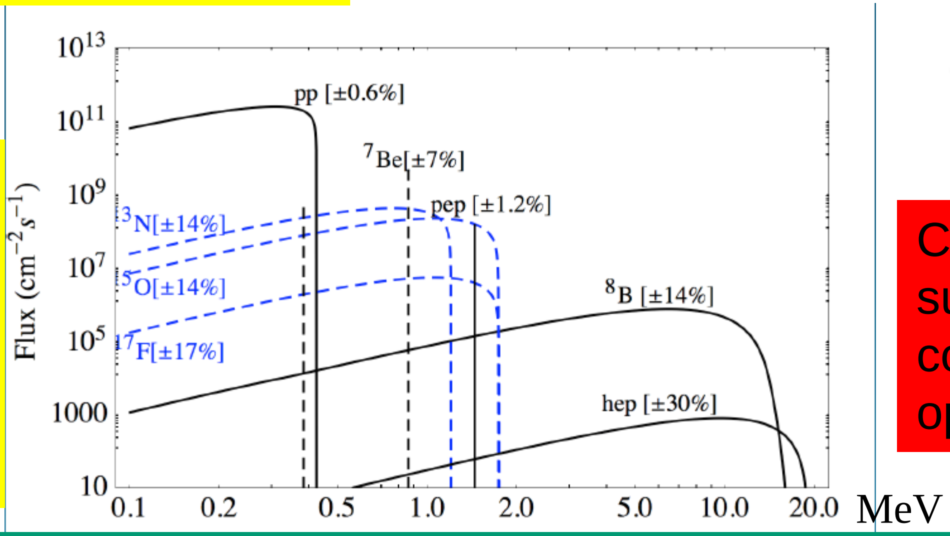


>99% of the energy in the Sun

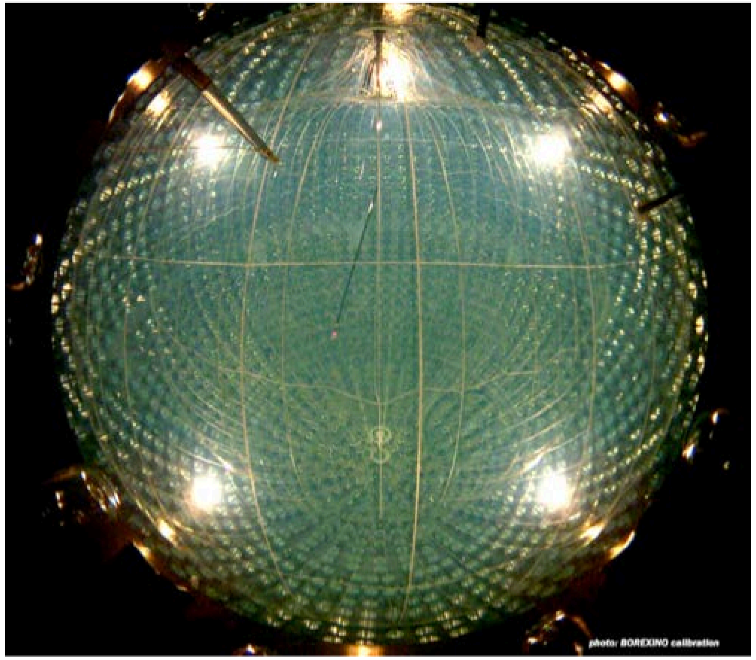


SSM prediction

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…

INFN

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

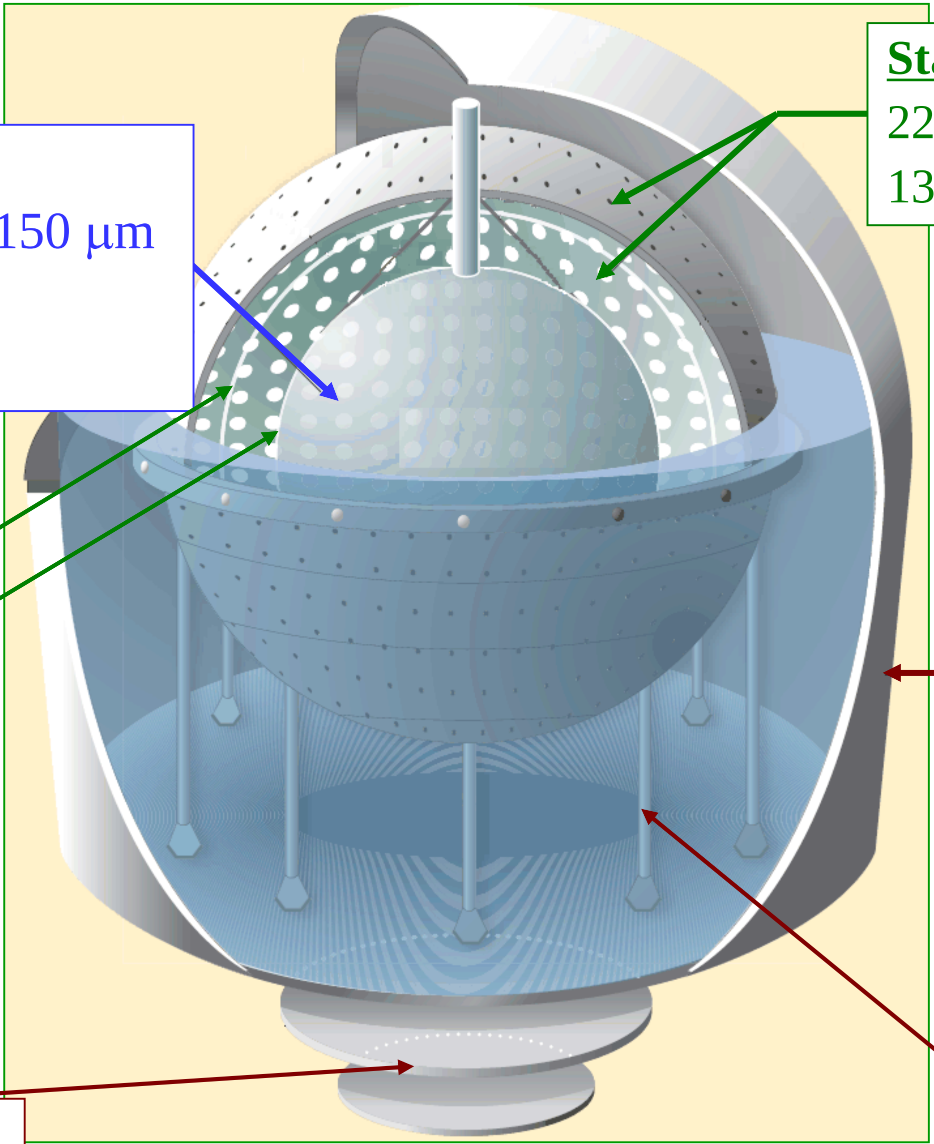
Los Angeles

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

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

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

→ Extraction of the fluxes through a data-to-model fit
Phase I may 2007 – may 2010
Phase II December 2011 - ………end of 2014
Purification in between

The background saga → the quest for the ultimate purity

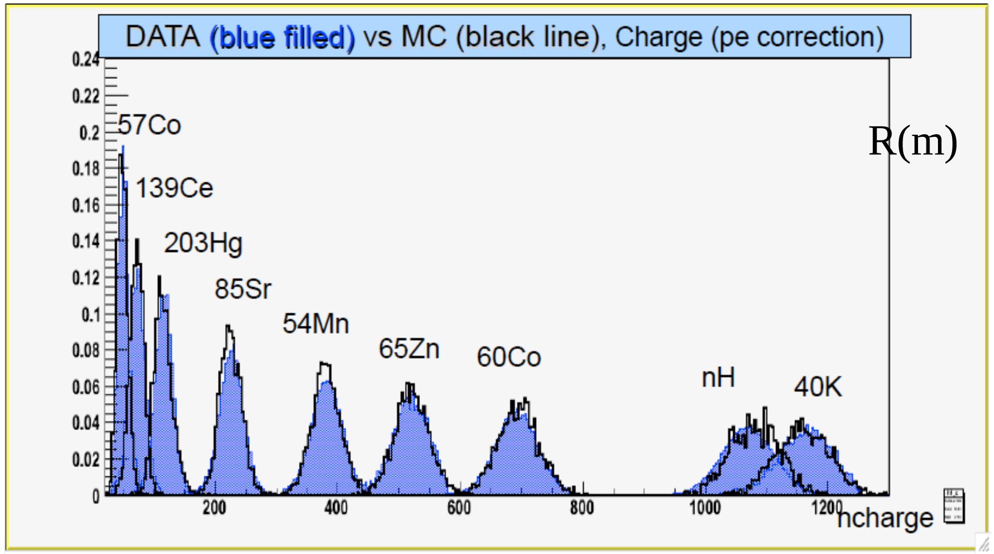
Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final in phase I
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	$<10^{-10} s^{-1} m^{-2}$	underground water detector	Cerenkov PS analysis	$< 10^{-10}$ eff. > 0.99992
γ	rock			water	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. → obtained from the γ calibration sources with MC: **~ 500 p.e./MeV**

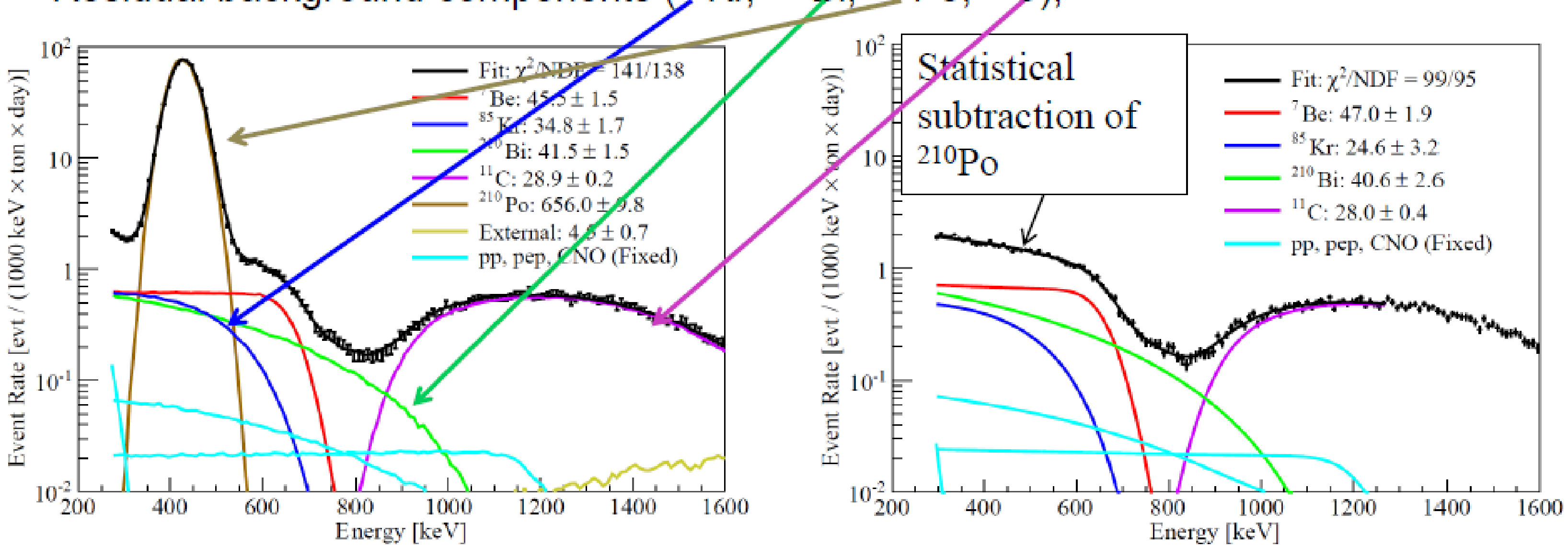
→ left as free parameter in the total fit in the analytical approach

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

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

^{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)

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

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

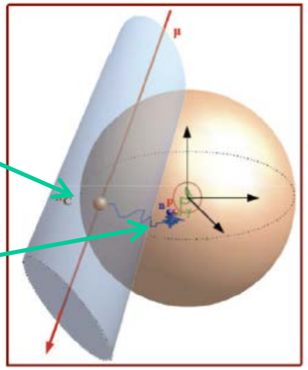
G. Bellini et al., Borexino Collaboration, Phys. Lett. B707 (2012) 22.

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



$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

${}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$ t~30min

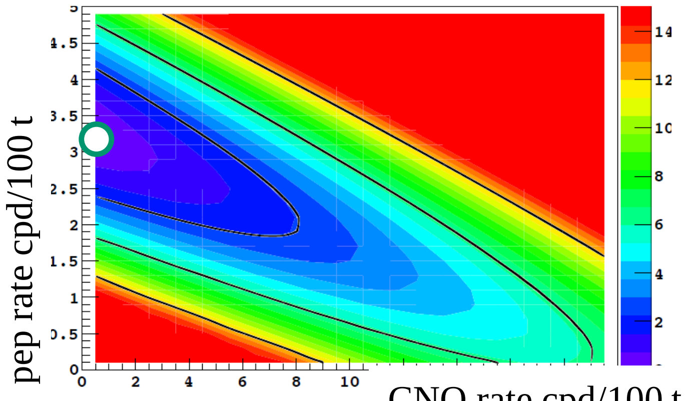
$n + p \rightarrow d + \gamma$ τ~260μs

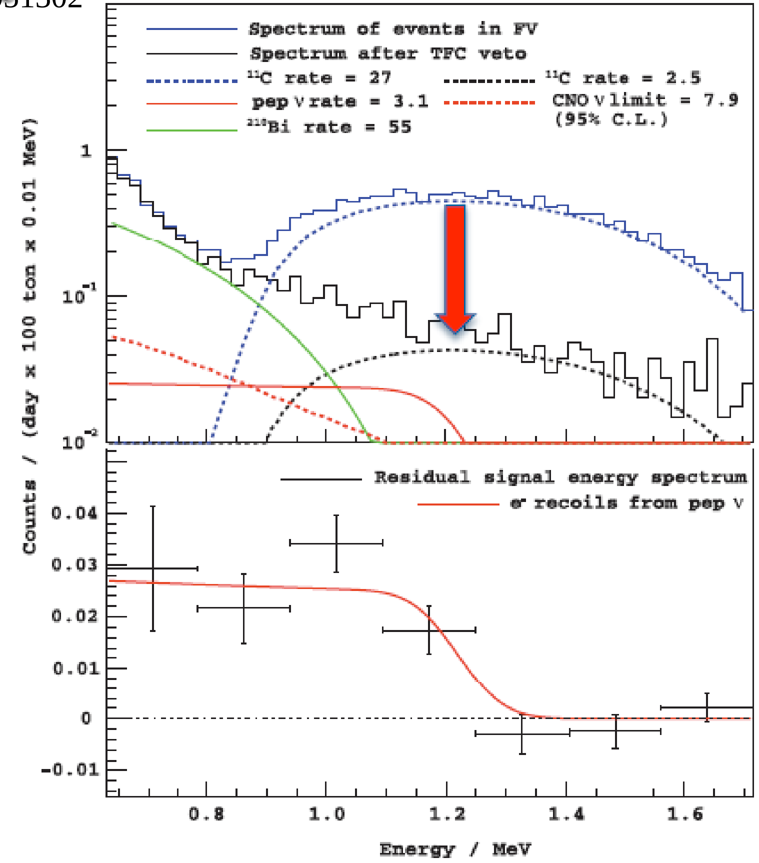
Threefold coincidence for ^{11}C rejection

- 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





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….

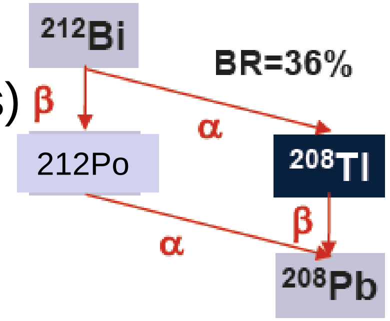
^{8}B with lower threshold at 3 MeV (488 live days)

•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

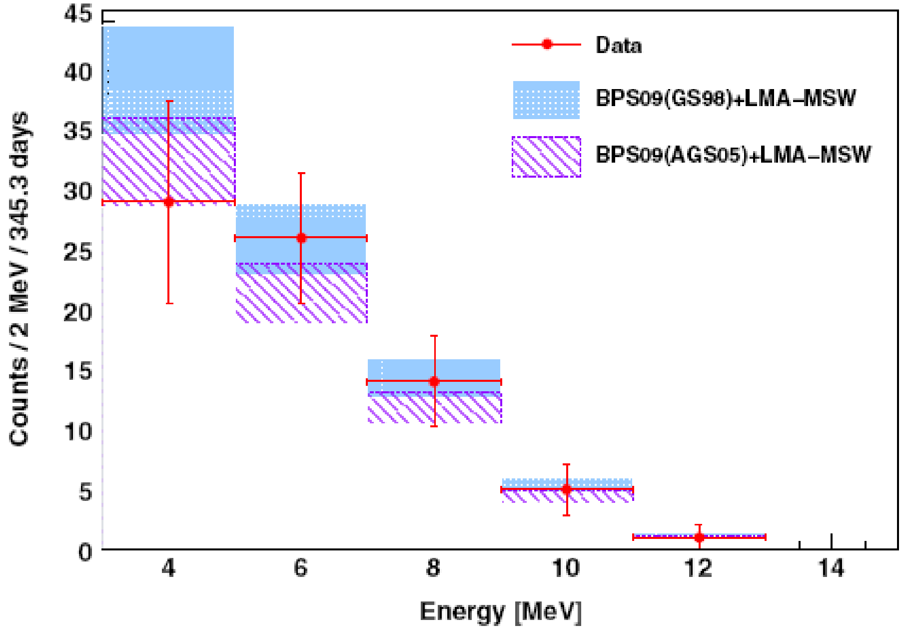
Cuts

- @**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 →



^8B with lower threshold at 3 MeV

Exp. ^8B 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	$2.7\pm0.4\pm0.2$

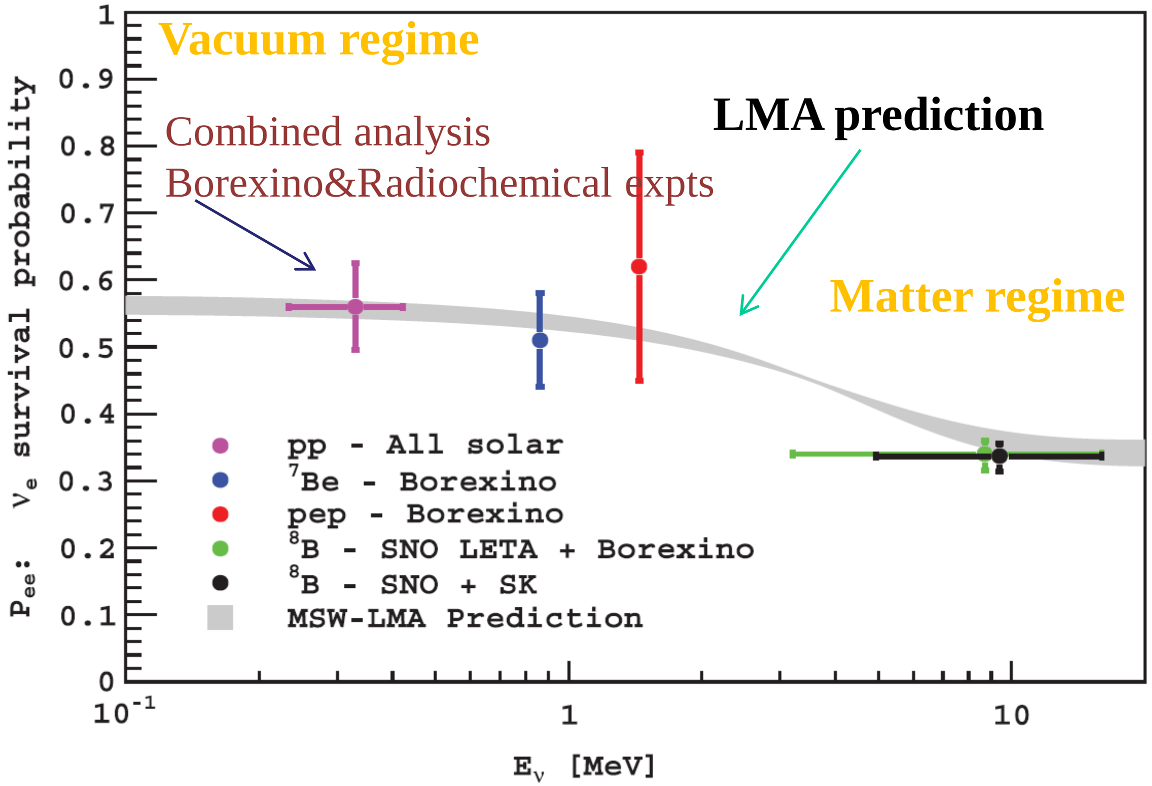
SSM; H.M.(2.7 ± 0.3) x10^6cm^{-2}s^{-1}
L.M.(2.2 ± 0.2) x10^6cm^{-2}s^{-1}

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

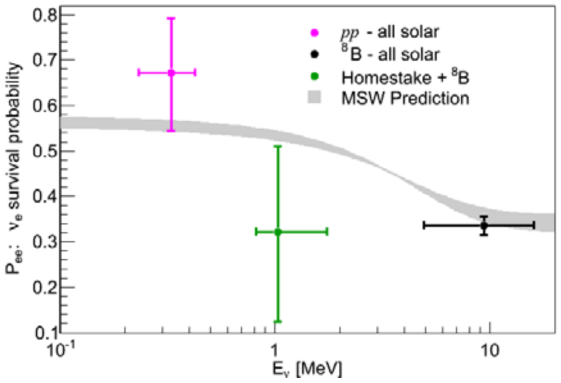
The global oscillation picture: survival probability of the electron neutrinos



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

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

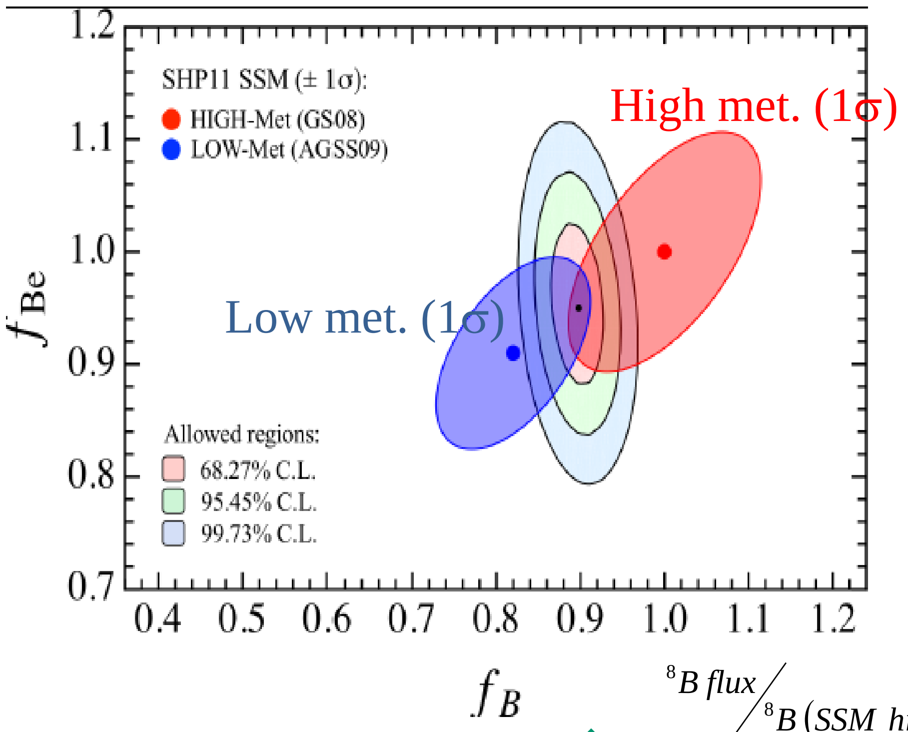
Before the Borexino results



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

Can the current data discriminate between high and low metallicity ?

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



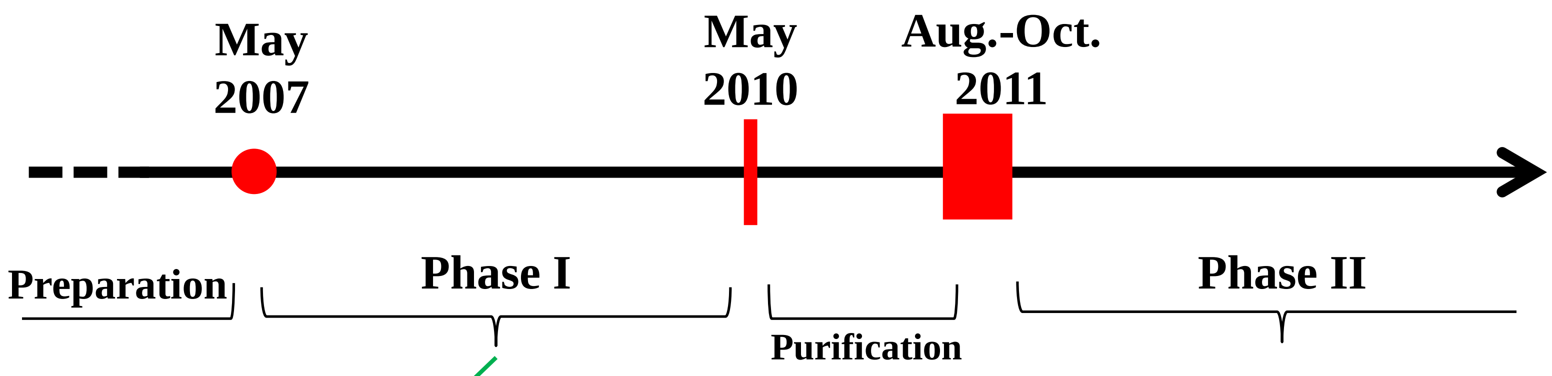
$$ {}^{8}B\ flux \Big/ {}^{8}B\,(SSM\ \ high\,met.) $$

The Borexino data cannot disentangle between the two models

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

Borexino timeline



Planned end of phase II December 2014
Followed by a new calibration campaign

Measurement of the pp flux currently in progress with Phase-II data. Stay tuned!

- **(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
- Short-baseline ν oscillation: SOX
- With 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?

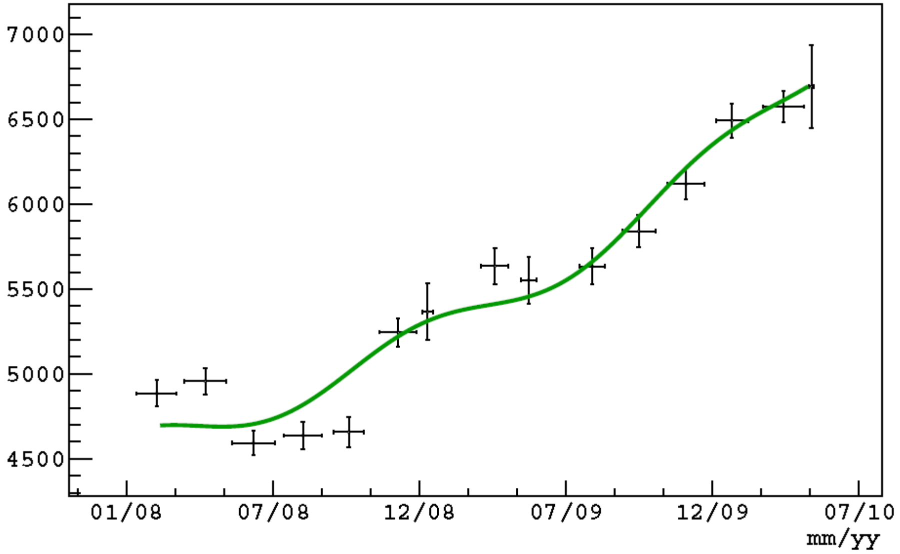
Improved ^{7}Be → some hint about metallicity?

CNO is the ideal metallicity discriminator → **more purification !** beyond the present phase II **^{210}Bi is the challenge**

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

Phase 1 data

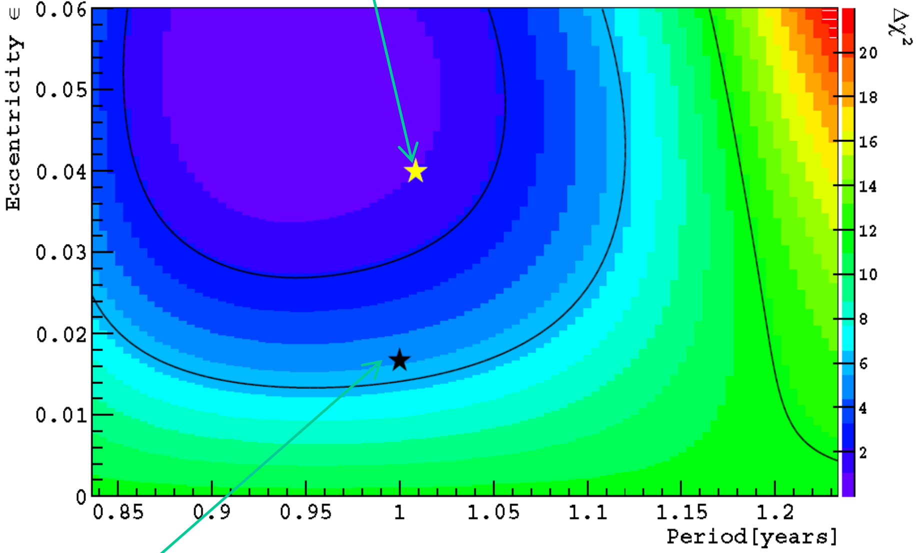
Counts in 60 days (progressive increase of background)



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

T=1.01 +- 0.07 y
ε=0.0398 +-0.0102

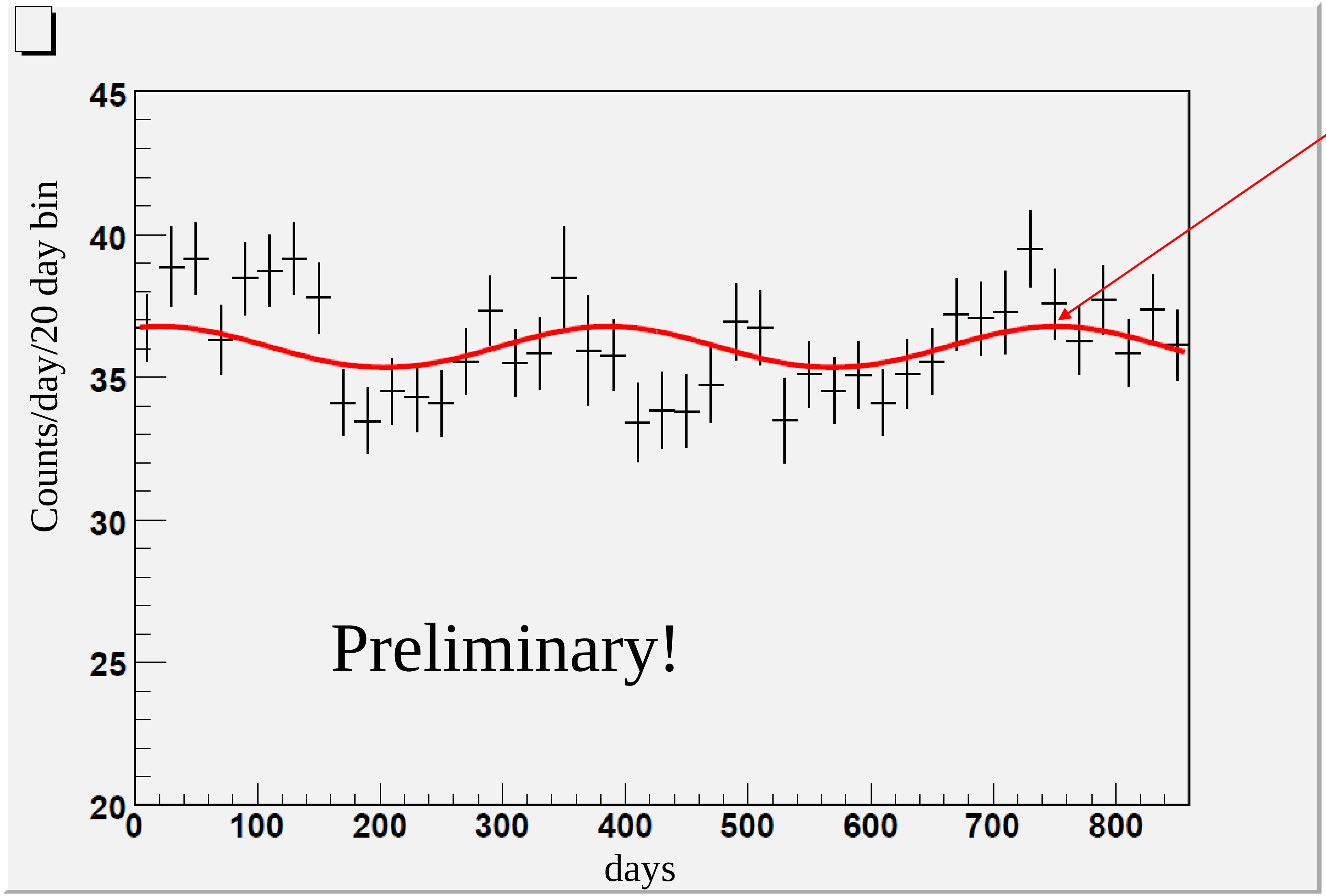
Inferred period and eccentricity



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

Earth emits antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,cm^{-2}s^{-1}$ 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:

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

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.

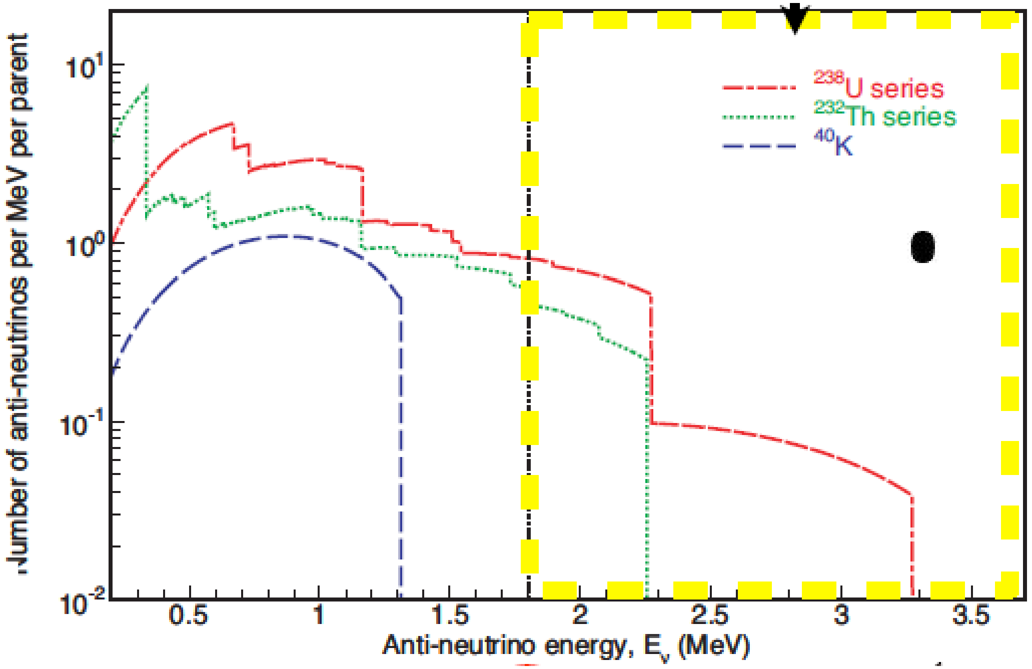
Two releases so far from Borexino

- 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



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

•"prompt signal"

e^{+}: energy loss + annihilation

(2 γ 511 KeV each)

•"delayed signal"

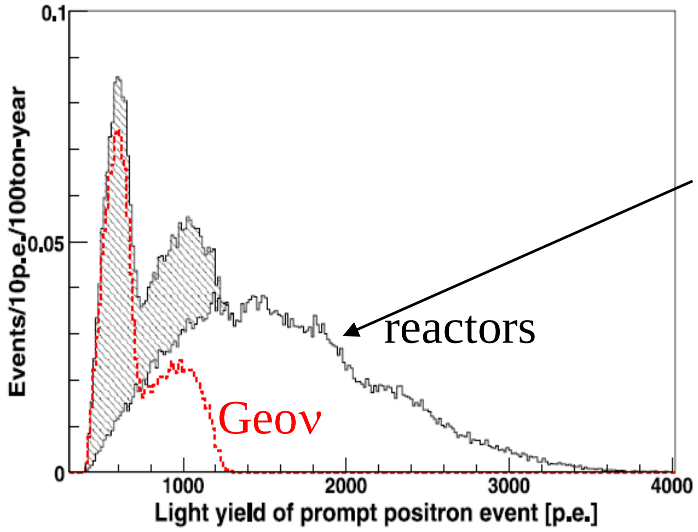
n capture after thermalization 2.2 γ

← Predicted geo-antiνs energy spectra

- 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

Background source	Events
^{9}Li–^{8}He	0.25±0.18
Fast n's (μ's in WT)	<0.007
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080±0.007
Accidental coincidences	0.206±0.004
Time corr. background	0.005±0.012
(γ,n)	<0.04
Spontaneous fission in PMTs	0.022±0.002
(α,n) in scintillator	0.13±0.01
(α,n) in the buffer	<0.43
Total	0.70 ± 0.18

Backgrounds that can mimic the delayed coincidence of the IBD reaction
Only 0.70 ±0.18 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)

Selection of candidates

Event selection

- Q_{prompt} >480 pe
- $Q_{delayed}$ (860,1300) pe
- ΔR (promt-delayed) 1m
- Δt (promt-delayed) (20 ms,1280ms)
- Pulse shape discrimination (Gatti filter) <0.015 :delayed events must be "beta like"
- Total cut efficiency determined by Monte Carlo: 0.84±0.01
- Large Fiducial Volume: distance from the vessel <25 cm

Dynamical vessel shape to follow its variation in time

- Exposure 613±26 ton year (vessel shape 1.6%; posit. rec. 3.8%; cut eff 1%)

In total 46 candidates over the entire exposure → how they distribute between geo and reactor components?

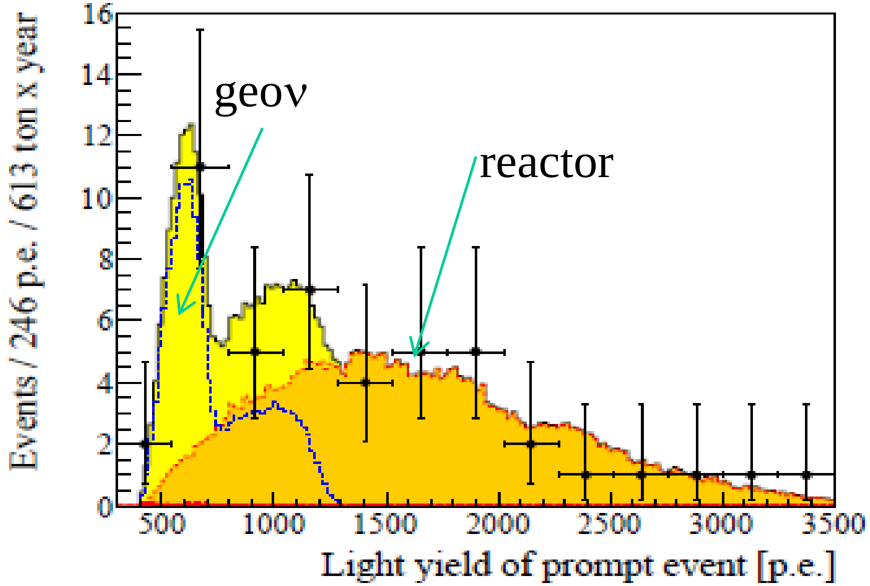
Borexino geo-ν results

Exposure: 613 ton year (3.69 10^{31} proton year)

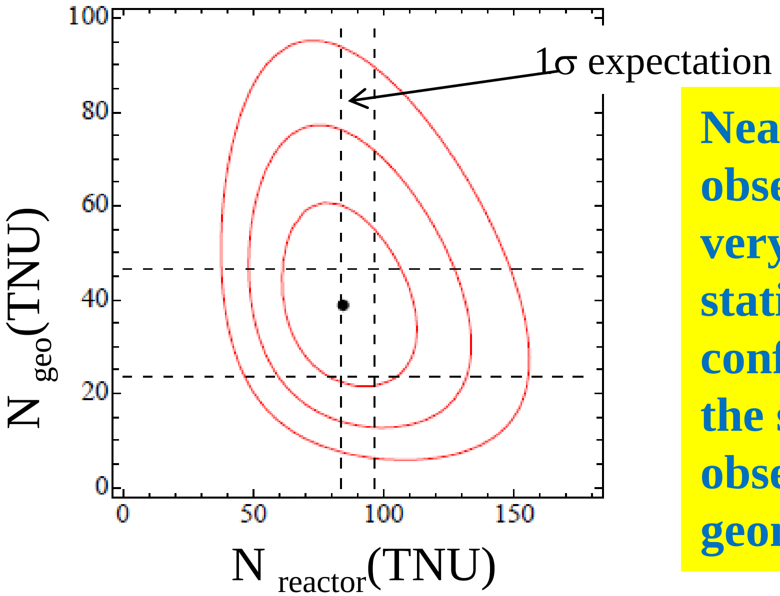
TNU=1ev/ (y 10^{32} protons)

$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	Events	events	events	events	TNU	TNU
33.3±2.4	60.4±2.4	0.70±0.18	14.3±4.4	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$

Unbinned likelihood fit

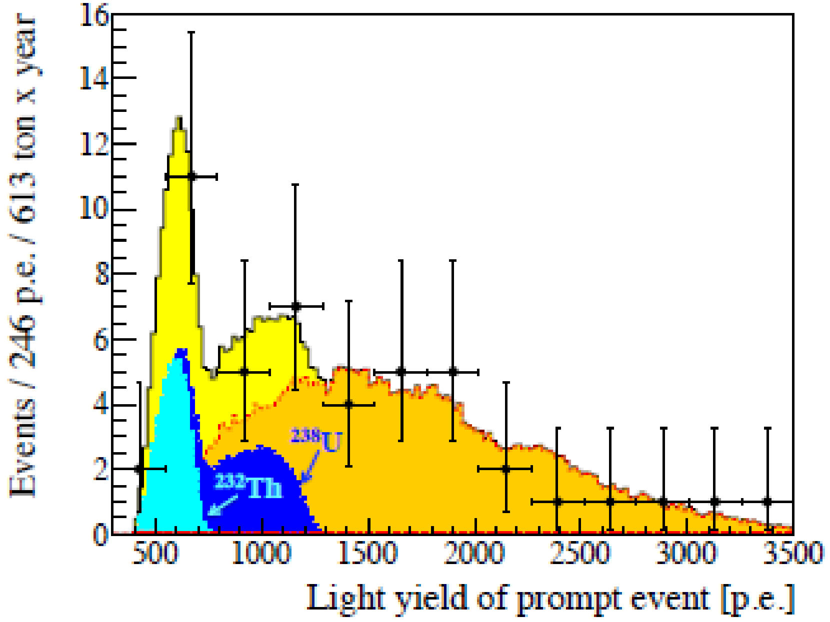


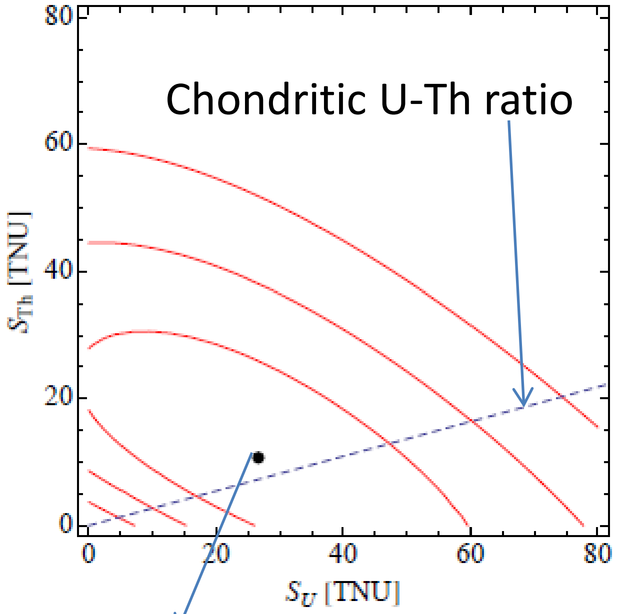
No geoν signal: rejected at 4.5 σ C.L.



Neat and clean observation with very high statistical confidence level of the signal! We do observe geoneutrinos!

Hint about U and Th contributions



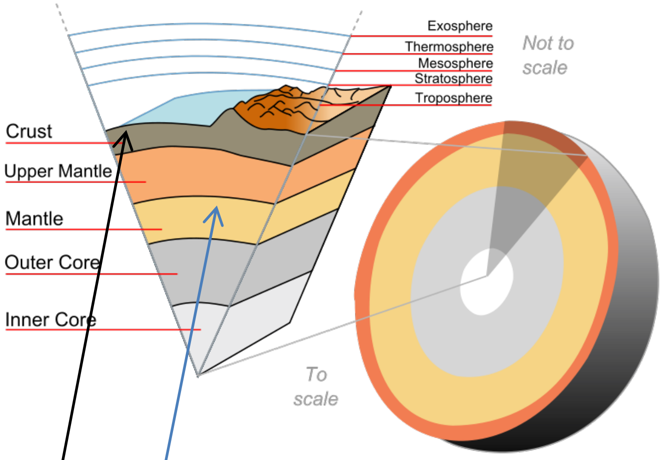


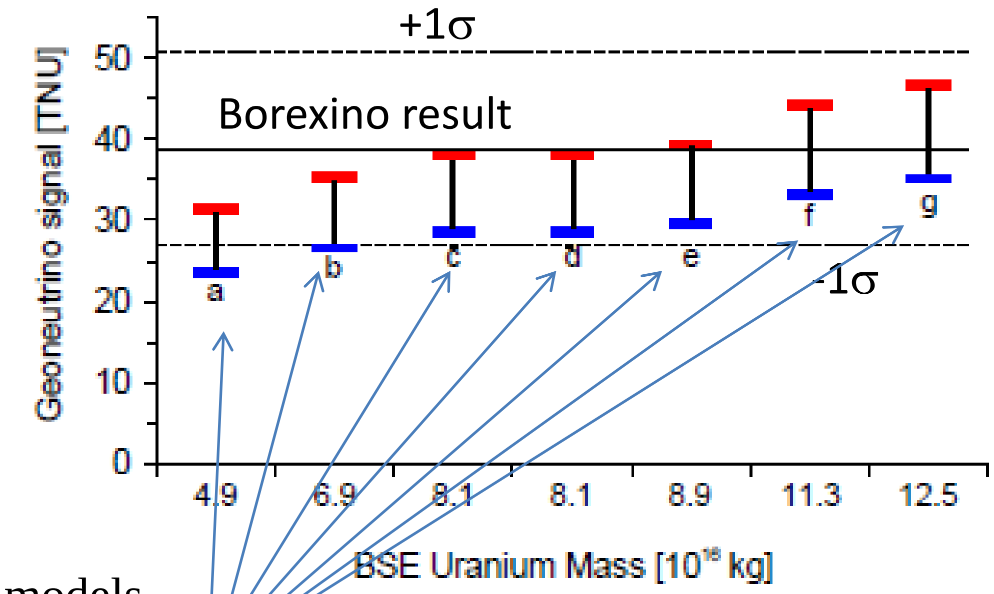
Fit with weight of ^{238}U and ^{232}Th spectra free

Best fit
S(^{238} U)= 26.5 ± 19.5 TNU
S(^{232} T) = 10.6 ± 12.7 TNU

Obviously large uncertainty but close to the expected chondritic ratio

Model comparison





Crust contribution: from local geolog.

Mantle contribution: BSE Earth models

Poster :
ID 12 MIRAMONTI, Lino
Measurement of geo-neutrinos detected in The Borexino Experiment at the Laboratory Nazionali Del Gran Sasso

- Borexino result compared with various variants of the BSE model (see our paper for details)
- Result broadly consistent with expectation
- But we cannot yet discriminate between different models
- **In conclusion a successful demonstration that geo-neutrinos can be a powerful probe of the interior of our planet**

Conclusions

- ✓ Unprecedented purity - even better in phase II
- ✓ Full solar neutrino spectroscopy in only one experiment – pp flux next milestone
- ✓ Validation at low energy of the MSW-LMA oscillation solution
- ✓ Neat and clean geo-ν signal
- ✓ The hunt for CNO flux will continue….
- ✓ For the long term possible “fate” of the detector see the poster ID 59 “R&D For neutrinoless Double beta Decay with Borexino” CAMINATA Alessio and MARCOCCI Simone