Results and physics implications of the precision measurement of the ^{7}Be solar neutrino flux performed with the Borexino detector

Gioacchino Ranucci on behalf of the
Borexino Collaboration
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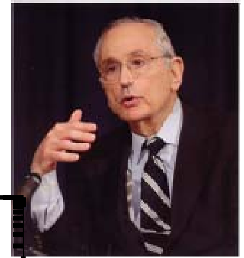
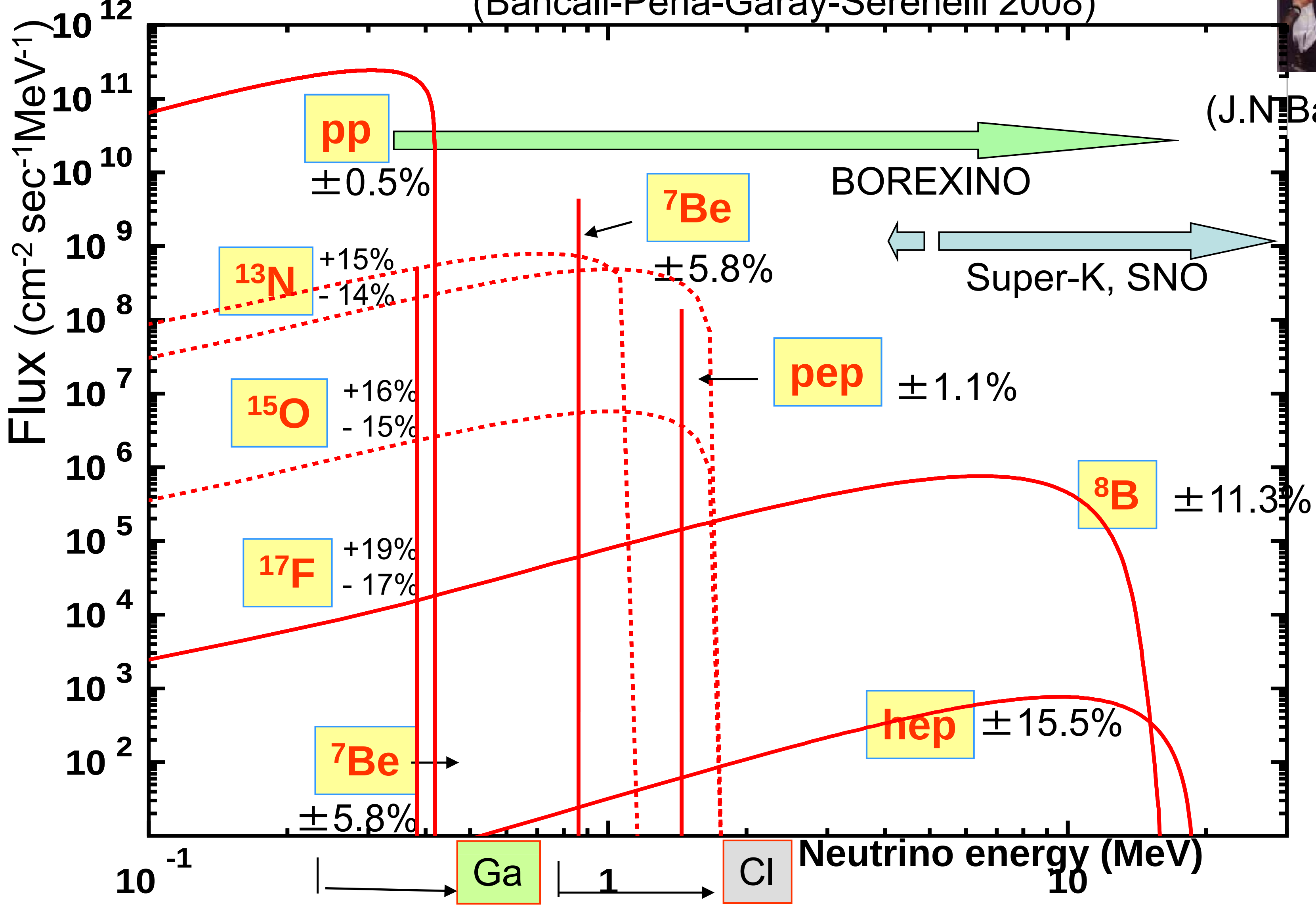
Solar neutrino spectrum

predicted by the Standard Solar Model (SSM)

(Bahcall-Pena-Garay-Serenelli 2008)



(J.N. Bahcall)



Solar neutrino experiments: a more than four decades long saga

Radiochemical experiments:

Homestake (Cl)

Gallex/GNO (Ga)

Sage (Ga)

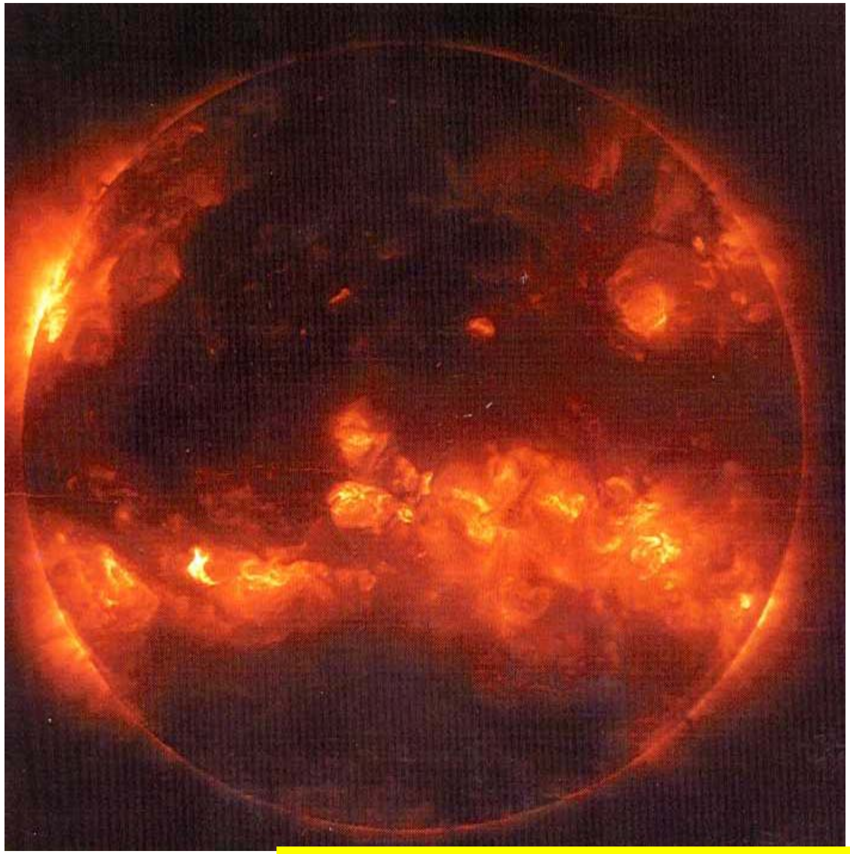
Real time Cherenkov experiments

Kamiokande/Super-Kamiokande

SNO

Scintillator experiments

Borexino

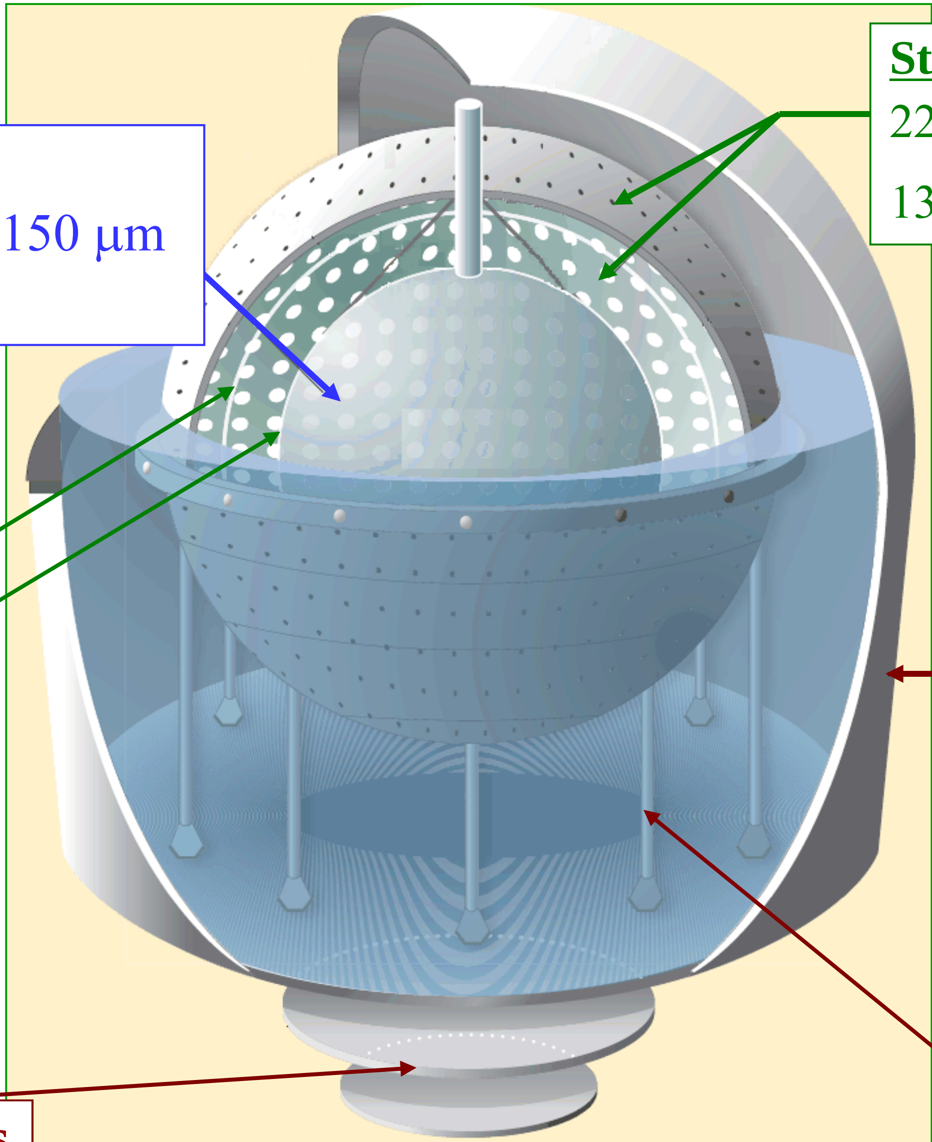


Culminated with the proof of neutrino oscillation - MSW effect

Borexino at Gran Sasso: low energy real time detection

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

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 Collaboration

Milano

Genova

INFN

LNGS Laboratori Nazionali del Gran Sasso

Istituto Nazionale di Fisica Nucleare INFN

Virginia Tech. University

Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

Heidelberg (Germany)

Dubna JINR (Russia)

APC Paris

Munich (Germany)

Perugia

Princeton University

UMass

Detection principle

$$\nu_e + e \rightarrow \nu_e + e$$

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

Goal: ^{7}Be flux (862 keV), ^{8}B with a lower threshold down to 2.2 MeV, pep (1.44 MeV), possibly pp and CNO on the future, Geo-antineutrinos (Phys.Lett.687,2010), Supernovae neutrinos (in read already accomplished), **requiring ultra-low background – the big challenge of the experiment!**

Further proposed measurements with ν and $\bar{\nu}$ artificial sources

Previous releases on ^{7}Be in September 2007 (just a few months after the start up of the data taking) and in June 2008 with 192 life days of data taking, before any source calibration of the detector with -> 10% of total error-stat.+ syst.

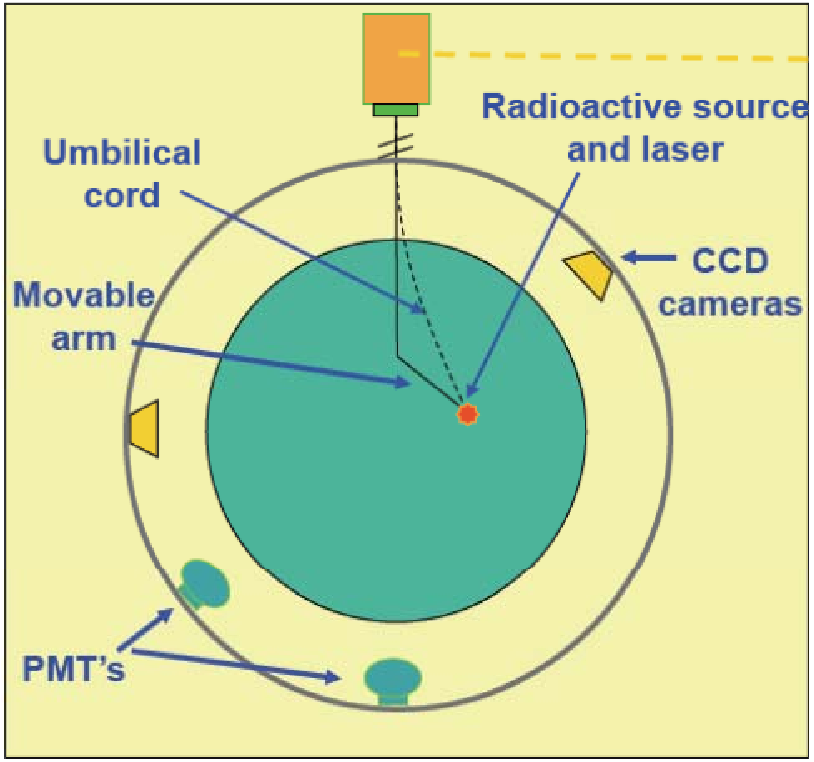
Key ingredients of the latest data releases arXiv:1104.1816 & arXiv:1104.2150 (hep-ex) :

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

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

c) **4 x statistics**

Calibration campaign



	γ							
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4

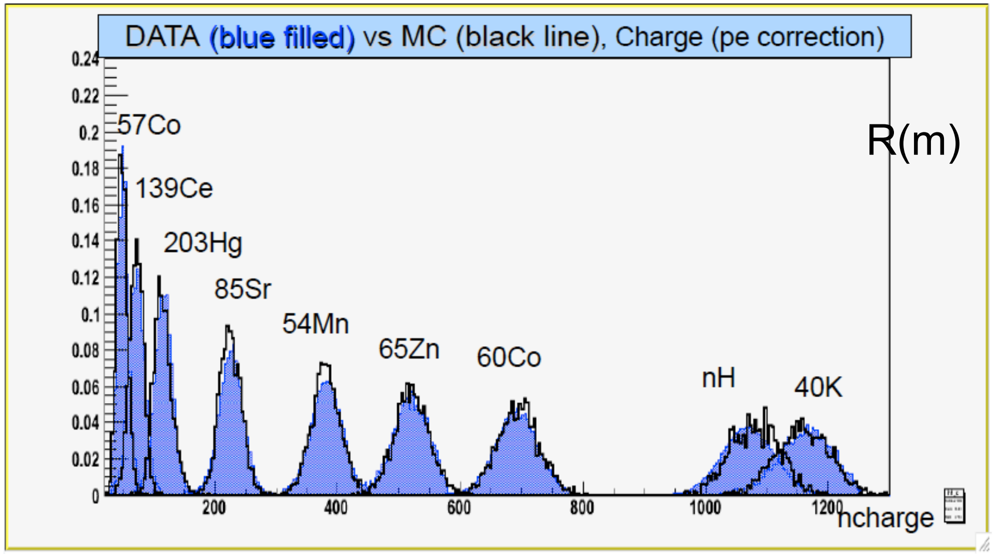
Am-Be source

n			
n-p	n +^{12}C	n+Fe	
2.226	4.94	~7.5	MeV

^{222}Rn loaded scintillator

- ^{214}(Bi-Po) ⟶ α/β discrim.
- Position
- energy response vs position

Low energy (0.14-2 MeV)



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

@ MC tuned on γ source results

@ Determination of Light yield and of the Birks parameter k_B

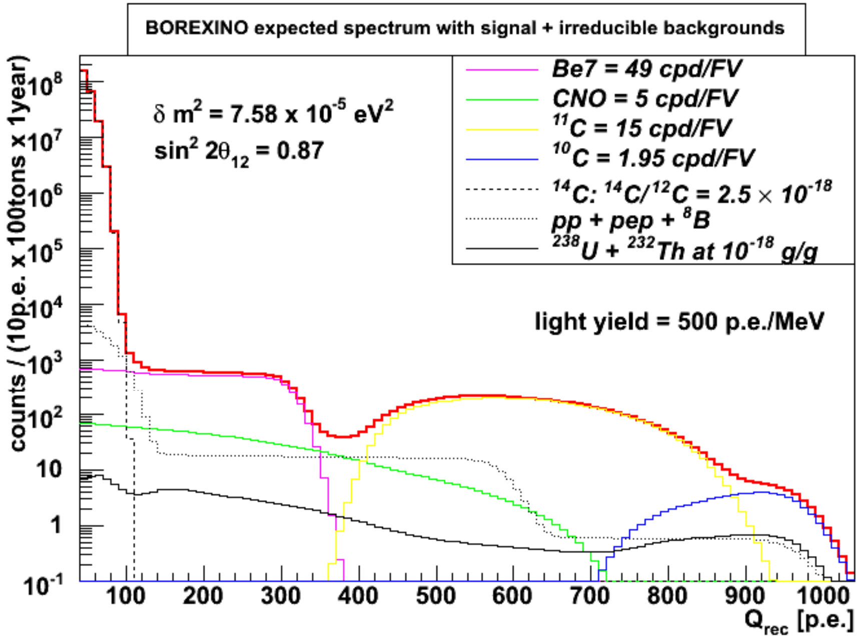
L.Y. → obtained from the γ calibration sources with MC: **511 p.e./MeV**

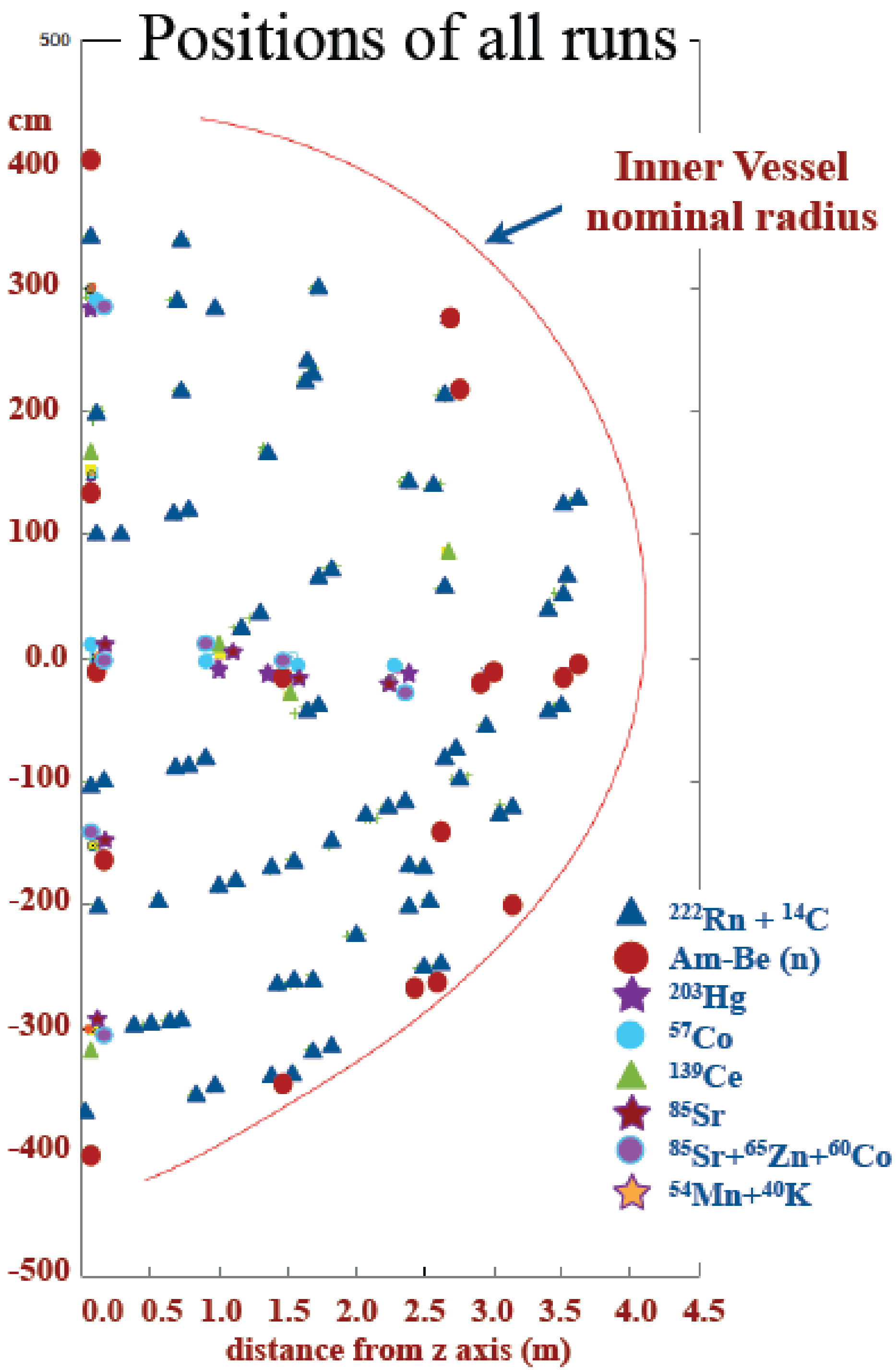
→ left as free parameter in the total fit in the analytical approach

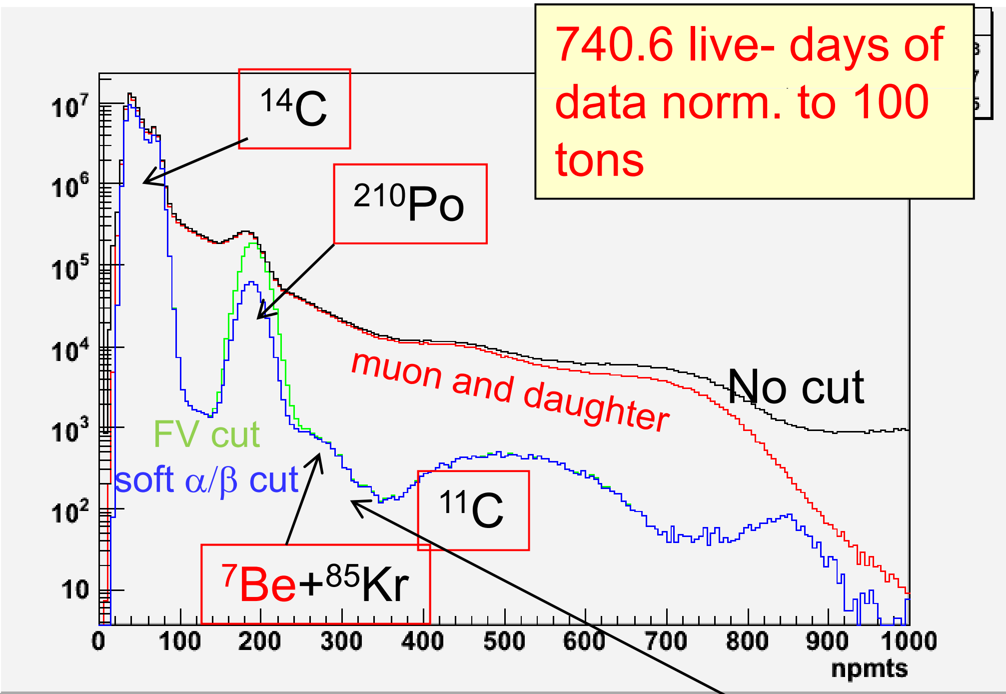
@ Precision of the energy scale global determination: **1.5%** (1 σ)

@ Fiducial volume uncertainty: $\left.\right\rangle^{+0.5}_{-1.3}\%$ (1 σ)

MC prediction of signal + intrinsic Background







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

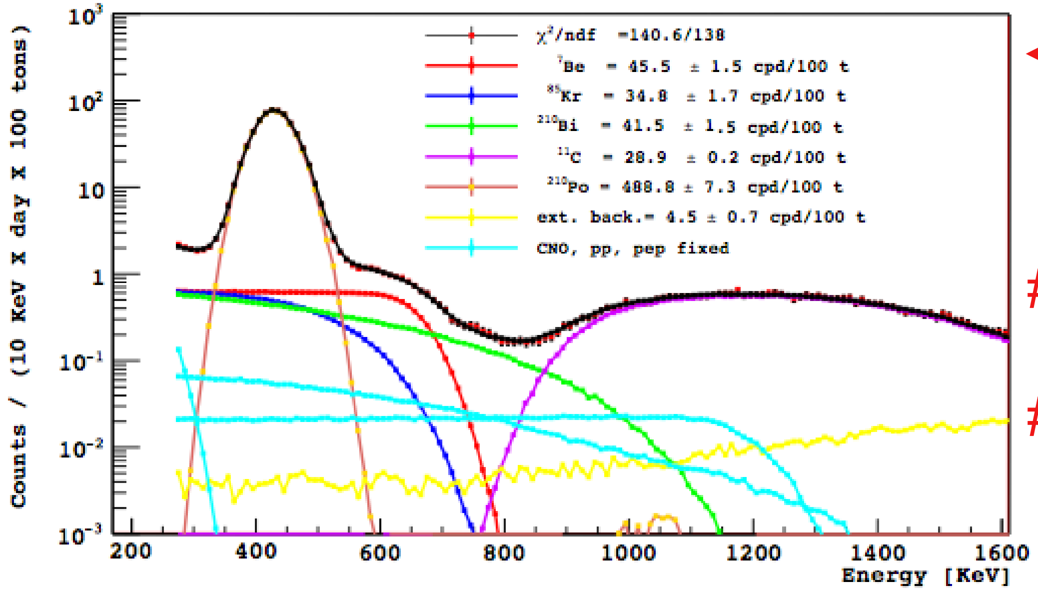
Effect of the application of the selection cuts on the raw spectrum

-Muon removal

- Restriction to the Fiducial volume
- PSD alpha-beta discrimination
  - simple cut
  - statistical subtraction

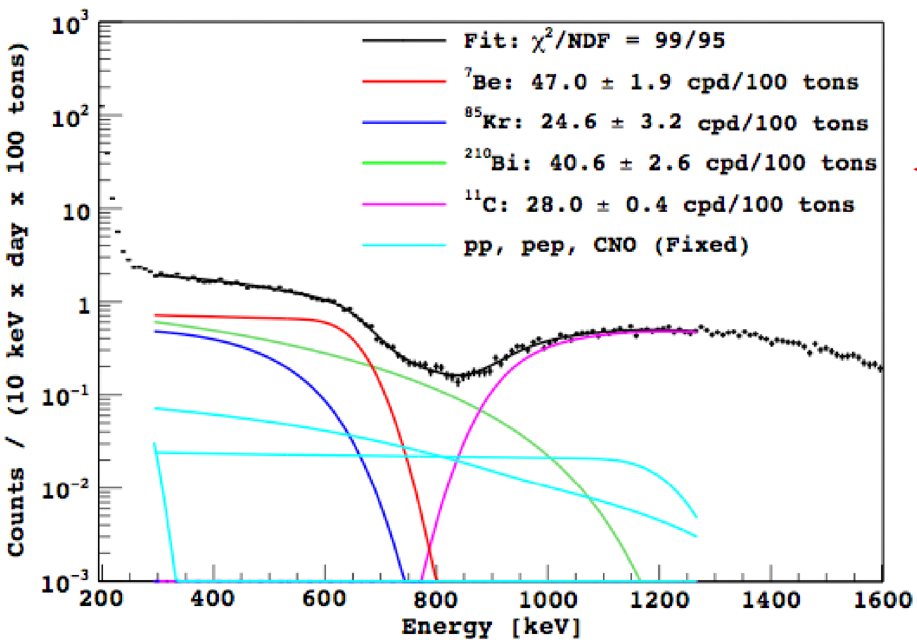
The scattering edge is the unambiguous signature of the ^{7}Be solar neutrino detection. ^{85}Kr obtained via β-γ coincidence analysis

30±5.3±1.5 cpd/100 t



MC- fit range: 250-1600 keV
Soft α subtraction

- \# pp, pep, CNO fixed, according MSW-LMA high metallicity
- \# free parameters: ^{7}Be, ^{85}Kr, ^{210}Bi (β emitter) , ^{11}C, ^{210}Po (α emitter), ^{14}C, ^{214}Pb (β emitter)



Analytical- fit range 300- 1250 keV
statistical α subtraction

The ^{7}Be flux is extracted via a multi-component fit

NFN- Milano

Result

^{7}Be(0.862): 46±1.5 (stat.) $\left.\right\rangle^{+1.5}_{-1.6}$ **(syst)cpd/100 tons**

Corresponding to an un-oscillated ν_e flux of (2.78±0.13)x10^{9} cm^{-2}s^{-1}
By assuming the MSW-LMA solution the absolute ^{7}Be solar neutrino flux measure is $(4.84 \pm 0.24) \times 10^{9}$ cm^{-2}s^{-1}
The ratio of our measurement to the SSM prediction is fBe=0.97±0.09

Other components in the fit

$$^{85}\mathrm{Kr} \quad 28.0 \pm 2.1_{\mathrm{stat}} \pm 4.7_{\mathrm{syst}}$$
$$^{210}\mathrm{Bi} \quad 40.3 \pm 1.5_{\mathrm{stat}} \pm 2.3_{\mathrm{syst}}$$
$$^{11}\mathrm{C} \quad 28.5 \pm 0.2_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}$$

^{85}Kr in very good agreement with the correlated coincidence determination

Unprecedented better than 5% precision in low energy solar neutrino measurements

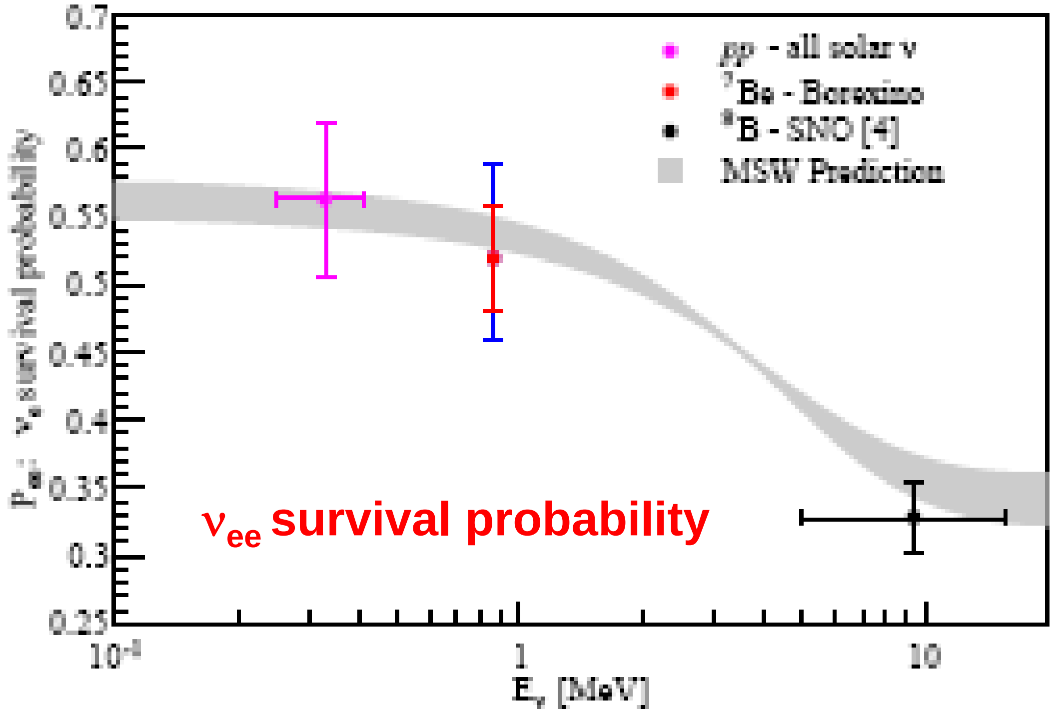
Implications of the result

Survival Probability : Pee= 0.51 ± 0.07

Error dominated by theoretical uncertainties

No oscillation hypothesis excluded at 5 σ

(expected from SSM 74±5.2 counts)



Tight constraints on pp $f_{pp} = 1.013^{+0.003}_{-0.010}$ and CNO (<1.7% 95% C.L. of solar luminosity) fluxes

Accurate low energy validation of the MSW-LMA oscillation paradigm

Day/Night asymmetry in ^{7}Be rate

757 live days
Day (positive Sun altitude)   385.5 days
Night (negative Sun altitude) 363.6.57 days

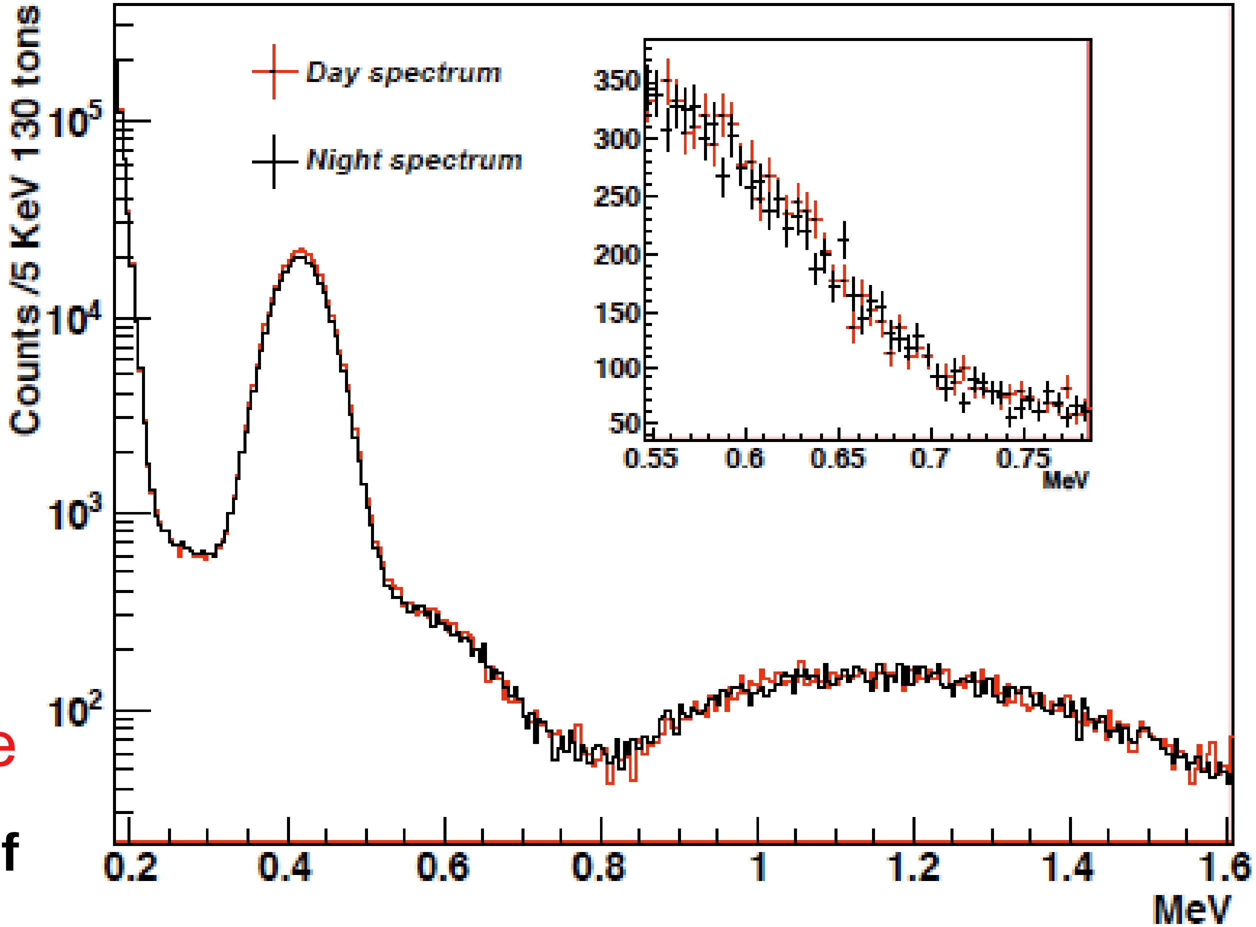
F.V. R < 3.0 or <3.3 m (130 t)

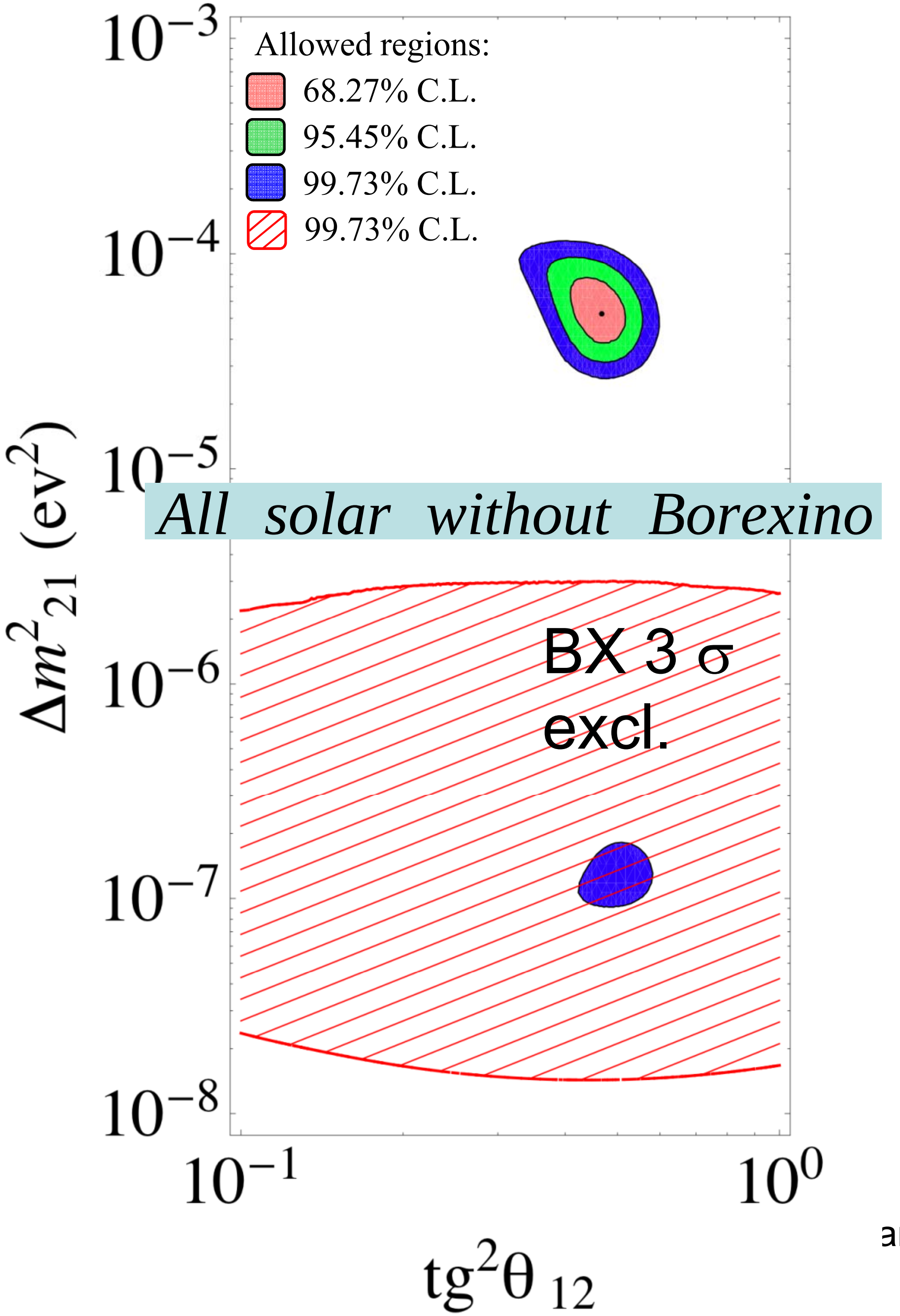
ν *energy window*: 550-715 keV

correction for the geometrical seasonal variation (± 3%) applied

A_{dn}= 0.007±0.073
sys. error negligible

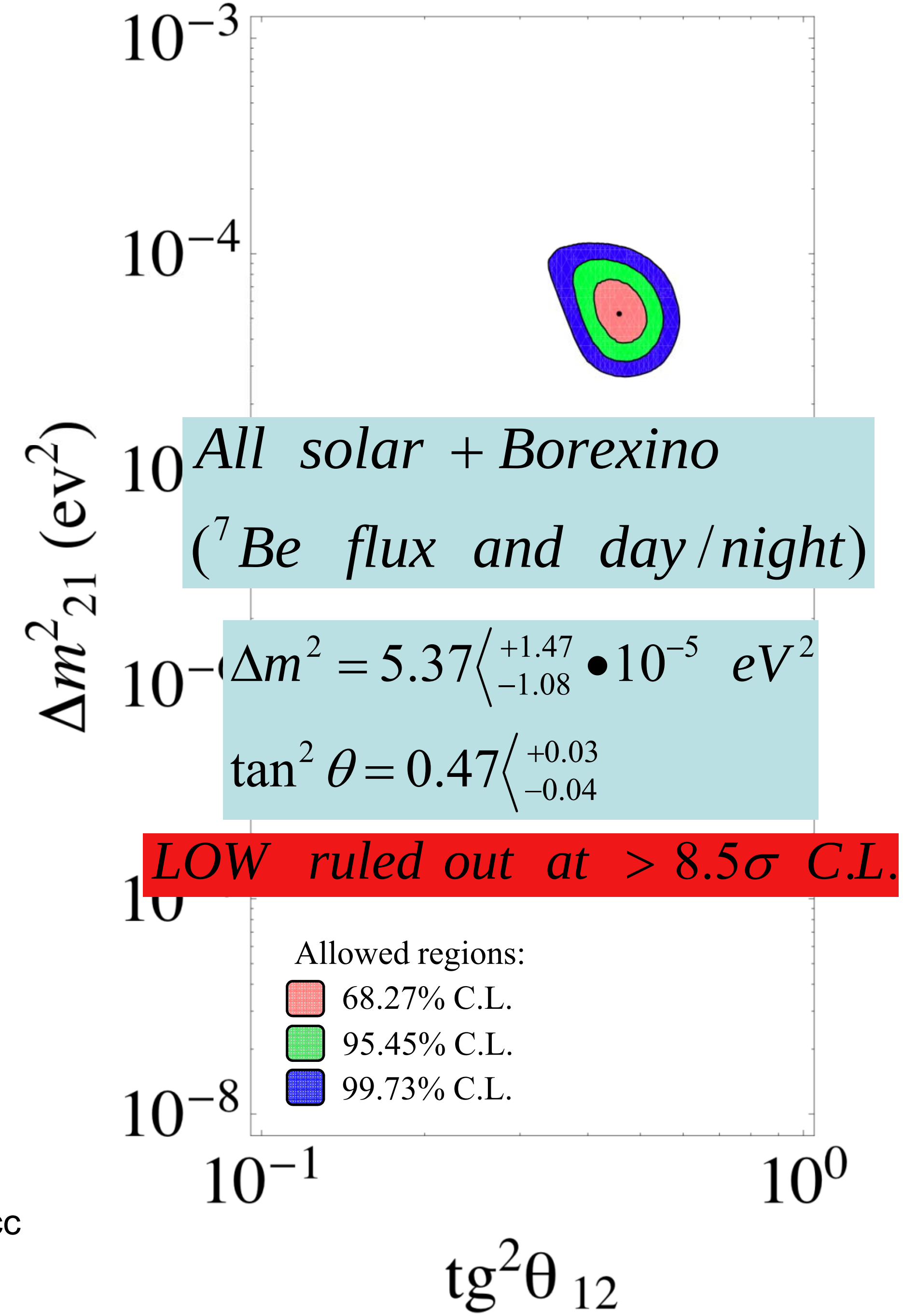
further confirmation of LMA solution





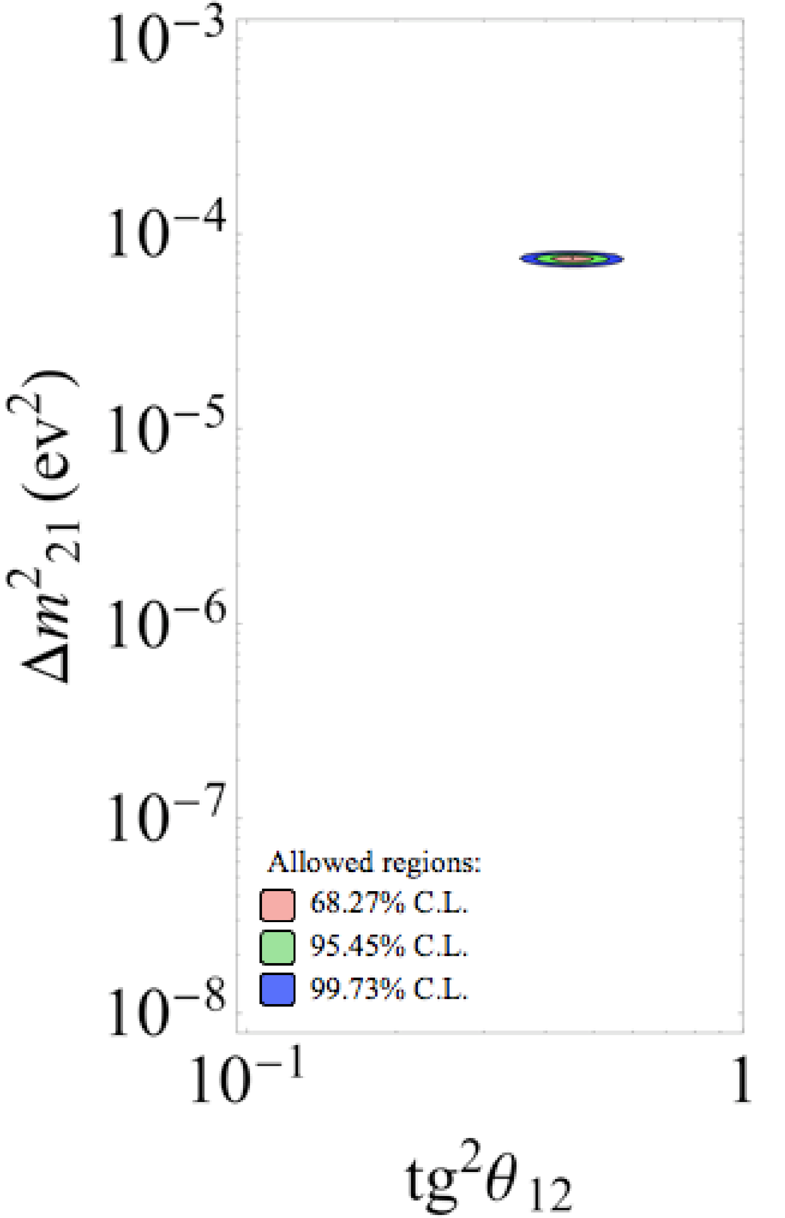
Allowed regions:
68.27% C.L.
95.45% C.L.
99.73% C.L.
99.73% C.L.
All solar without Borexino
BX 3 σ excl.
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
10^{0}
Δm^2_{21} (ev^2)
$tg^2\theta_{12}$

anucc



All solar + Borexino
(^7Be flux and day/night)
$\Delta m^2 = 5.37\left\langle^{+1.47}_{-1.08}\right. \bullet 10^{-5}\ eV^2$
$\tan^2\theta = 0.47\left\langle^{+0.03}_{-0.04}\right.$
LOW ruled out at $> 8.5\sigma$ C.L.
Allowed regions:
68.27% C.L.
95.45% C.L.
99.73% C.L.
10^{-3}
10^{-4}
10^{-8}
10^{-1}
10^{0}
Δm^2_{21} (ev^2)
$tg^2\theta_{12}$

Global Analysis- two ν oscillation- $\theta_{13}=0$



All Solar without Bx+ Kamland

Pep and CNO, fixed at SSM values

Best fit values:

$$\Delta m^2 = 7.50\left\langle {}^{+0.17}_{-0.23} \right. \bullet 10^{-5} eV^2$$

$$\tan^2\theta = 0.46\left\langle {}^{+0.04}_{-0.03} \right.$$

What next

Measurement of the pep flux

Measurement of the ^{8}B flux with a low threshold down to 2.2 MeV

Measurement of geoneutrinos with 2 times statistics

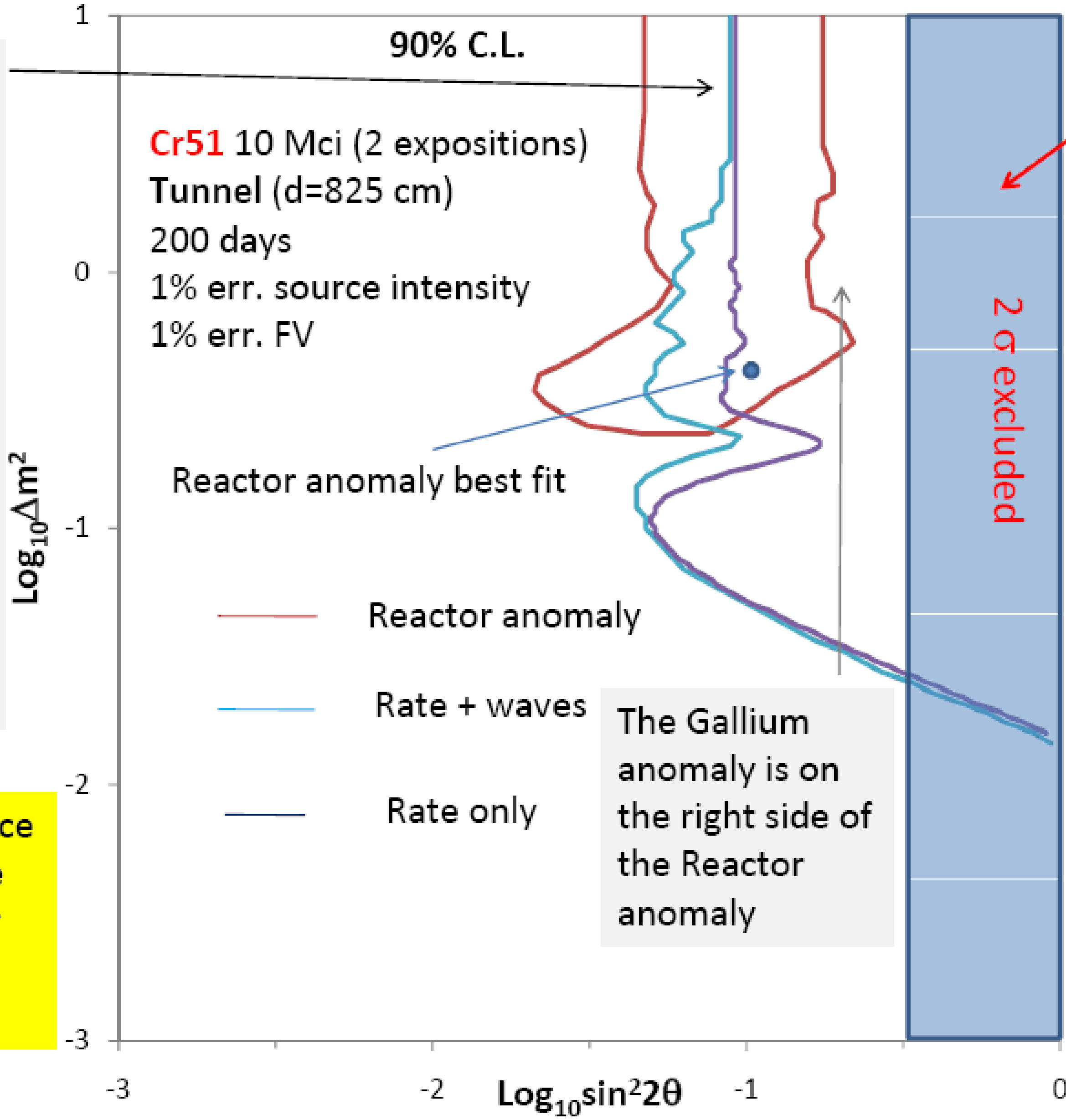
Perhaps the pp flux

Goals for phase II (after the re-purification): CNO flux, upgrading of the pep flux measurement

Expression of interest for a SBL experiment with neutrino and antineutrino sources (sterile neutrinos?)

At high Δm^2 the fast oscillations are smeared by the detector spatial resolution $\Rightarrow$ effectively rate-only analysis

The Cr51 source material is the same used for the Gallex calibration



Solar+KamLAND constraints for θ_{13} =0 From arXiv:1105.1705 - A. Palazzo

The excluded region would further extend toward the left for $\theta_{13} \neq 0$ T2K result

Other sources and positions are currently being investigated

Conclusions

Borexino has measured the ^{7}Be solar neutrino flux with a total error less than 5 %

In this way Borexino studied ν oscillations in the untested low energy vacuum-like regime, validating the currently favored MSW-LMA oscillation paradigm

This result is further strengthened by the measurement of the absence of day-night asymmetry in the ^{7}Be flux

The ultra-low background of the experiment will allow a further broad physics program, including sterile neutrino oscillation search via deployment of neutrino sources