# Study of very low energy neutrinos from the Sun and the Earth with the Borexino detector

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1. Very short recall of the standard solar model ( SSM) and of the neutrino oscillation phenomenon

2- Short description of the Borexino detector.

3- Status of the study of the solar neutrinos

4- Geo-neutrinos

5- What next.

# Why solar neutrinos?

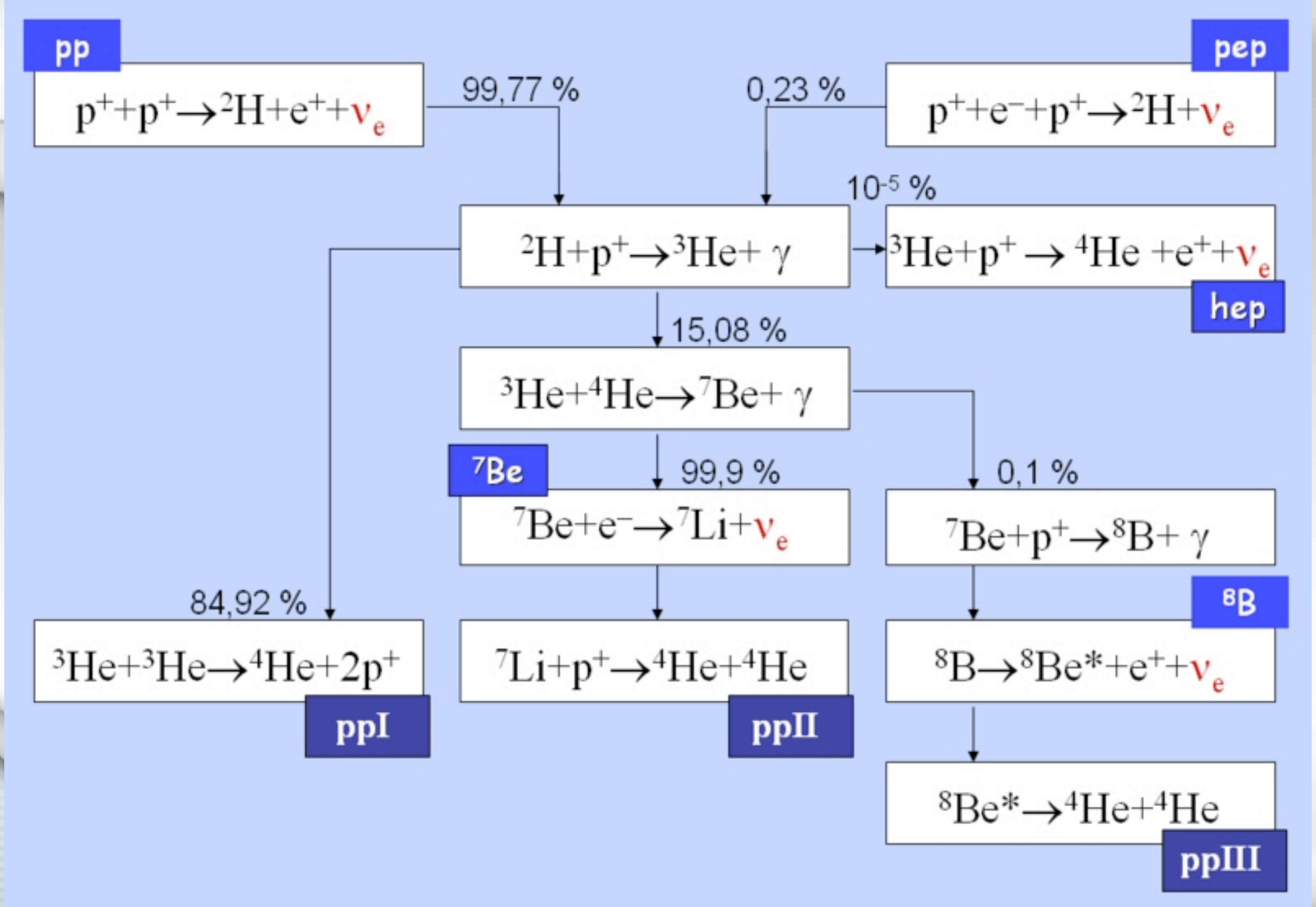
Two main reasons:

- @ The neutrino physics (neutrino oscillation)
- @ The physics of the Sun

The study of the neutrinos from the Sun has triggered the search for the neutrino oscillation.The pioneers have been the radiochemical experiments which studied the $\nu_e$ flux via the following reactions: **$^{71}Ga(\nu_e, e^-)^{71}Ge$, $E_{th}$ = 233 keV**(Gallex, Sage, GNO) and **$^{37}Cl(\nu_e, e^-)^{37}Ar$, $E_{th}$ = 814 keV** (Homestake). They found a deficit with respect to the previsions of the S.S.M., but they were unable to measure separately the various solar neutrino fluxes.

Later this deficit has been confirmed by two Cherenkov real time experiments: SuperK and SNO, with $E_{th}$ at 5 Mev ( more recently decreased by SNO to 3 MeV corresponding to 4.2 $\nu$ energy). The definitive evidence for the oscillation phenomenon has been obtained by SNO via the charged current: $\nu_e + d = p + p + e^-$ and the neutral current: $\nu_x + d = p + n + \nu_x$, measured at the same time; the n.c.,induced by all neutrinos showed a rate compatible with the total solar flux as predicted by the SSM.

# Nuclear reactions in the Sun



**pp**

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

**pep**

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

$10^{-5}$ %

${}^2H + p^+ \rightarrow {}^3He + \gamma$

${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

**hep**

15,08 %

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

**7Be**

99,9 %

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

0,1 %

${}^7Be + p^+ \rightarrow {}^8B + \gamma$

**8B**

84,92 %

${}^3He + {}^3He \rightarrow {}^4He + 2p^+$

**ppI**

${}^7Li + p^+ \rightarrow {}^4He + {}^4He$

**ppII**

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

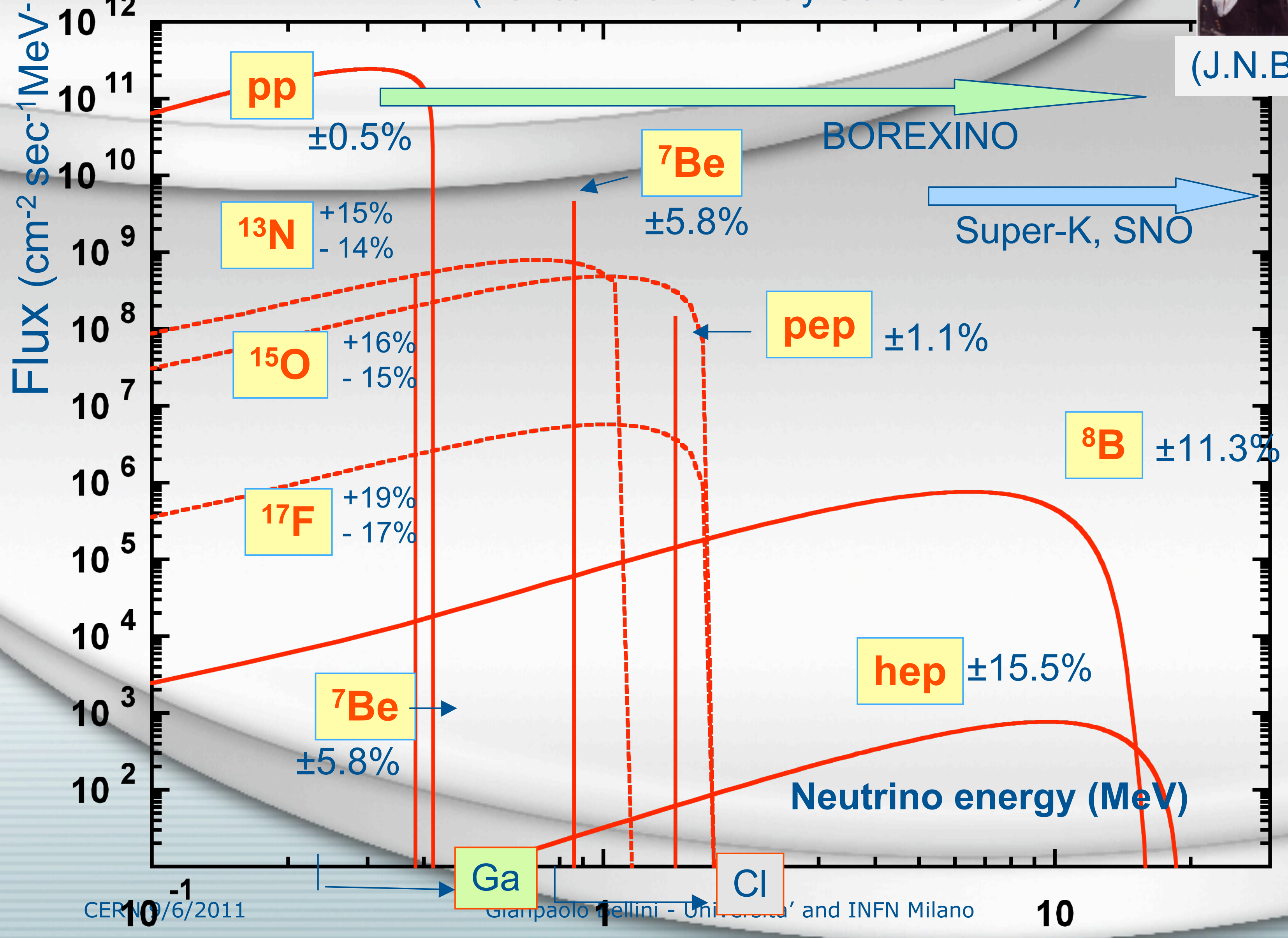
**ppIII**

# Solar neutrino spectrum

predicted by the Standard Solar Model (SSM)

(Bahcall-Pena-Garay-Serenelli 2008)

(J.N.Bahcall)



# Solar Neutrino Fluxes- metallicity problem

| $\nu$ flux | GS98 | AGS09 | $cm^{-2}\ s^{-1}$ |
|---|---|---|---|
| pp | 5.98 (1±0.006) | 6.03 (1±0.006) | x $10^{10}$ |
| pep | 1.44 (1±0.012) | 1.47(1±0.012) | x $10^{8}$ |
| hep | 8.04 (1±0.30) | 8.31 (1±0.30) | x $10^{3}$ |
| $^{7}$Be | 5.00 (1±0.07) | 4.56 (1±0.07) | x $10^{9}$ |
| $^{8}$B | 5.58 (1±0.14) | 4.59 (1±0.14) | x $10^{6}$ |
| $^{13}$N | 2.96 (1±0.14) | 2.17 (1±0.14) | x $10^{8}$ |
| $^{15}$O | 2.23 (1±0.15) | 1.56 (1±0.15) | x $10^{8}$ |
| $^{17}$F | 5.52 (1±0.17) | 3.40 (1±0.16) | x $10^{6}$ |

SHP11:
A.M. Serenelli, W. C.Haxton
and C. Pena-Garay,
arXiv:1104.16.39v1 [astro-ph]

@ GS98 (high metallicity)-solar atmosphere modeling in one dimension starting from the solar surface abundances (via spectroscopy)-excellent agreement with the helioseismology (sound speed)

@ AGS09 ( low metallicity)- 3D modeling- less carbon, nitrogen, oxygen, neon and argon - disagreement with the helioseismology

# Neutrino oscillation

$$|\nu_\alpha\rangle = \sum_i U_{\alpha,i}|\nu_i\rangle$$

$\nu_\alpha$, flavor eigenstates   $\nu_i$, mass eigenstates

$U_{\alpha,i}$, mixing matrix

## 2 ν approach

IN VACUUM

$$\boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 \frac{L}{4E}\right)}$$

$$L_V = \frac{4\pi E}{\Delta m^2}$$

θ → mixing angle; $\Delta m^2 = m_2^2 - m_1^2$ for solar

MSW

$\nu_e$ interacts via charged current and neutral current

$\nu_{\mu,\tau}$ interact only via neutral current

$$\boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\theta_M \cdot \sin^2\left(\Delta m_M^2 \frac{L}{4E}\right)}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - X)^2}$$

$$\Delta m^2_{M,12} = \Delta m^2_{12}\sqrt{\sin^2 2\theta + (\cos 2\theta - X)^2}$$

$$L_M = \frac{4\pi E}{\Delta m_M^2} = \frac{L_V}{\sqrt{\sin^2 2\theta + (\cos 2\theta - X)^2}}$$

$$\boxed{X = \frac{2\sqrt{2}G_F n_e E}{\Delta m^2}}$$

Matter effect is dominating if $\cos 2\theta < X = \frac{2\sqrt{2} G_F n_e E}{\Delta m_{12}^2}$

Vacuum is dominating if $X << \cos 2\theta$

On the basis of $n_e E$, the oscillation is either vacuum driven or matter enhanced

In the Sun $n_e$ can be considered constant, then the regime depends essentially on the neutrino energy.

# Three $\nu$ approach- $\nu_1, \nu_2, \nu_3$

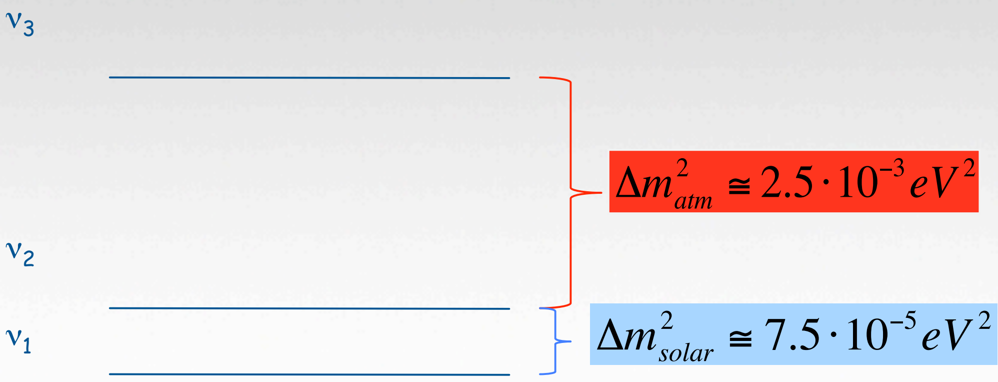
Two mass differences : $\Delta m^2_{atm}, \Delta m^2_{solar}$

Three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$

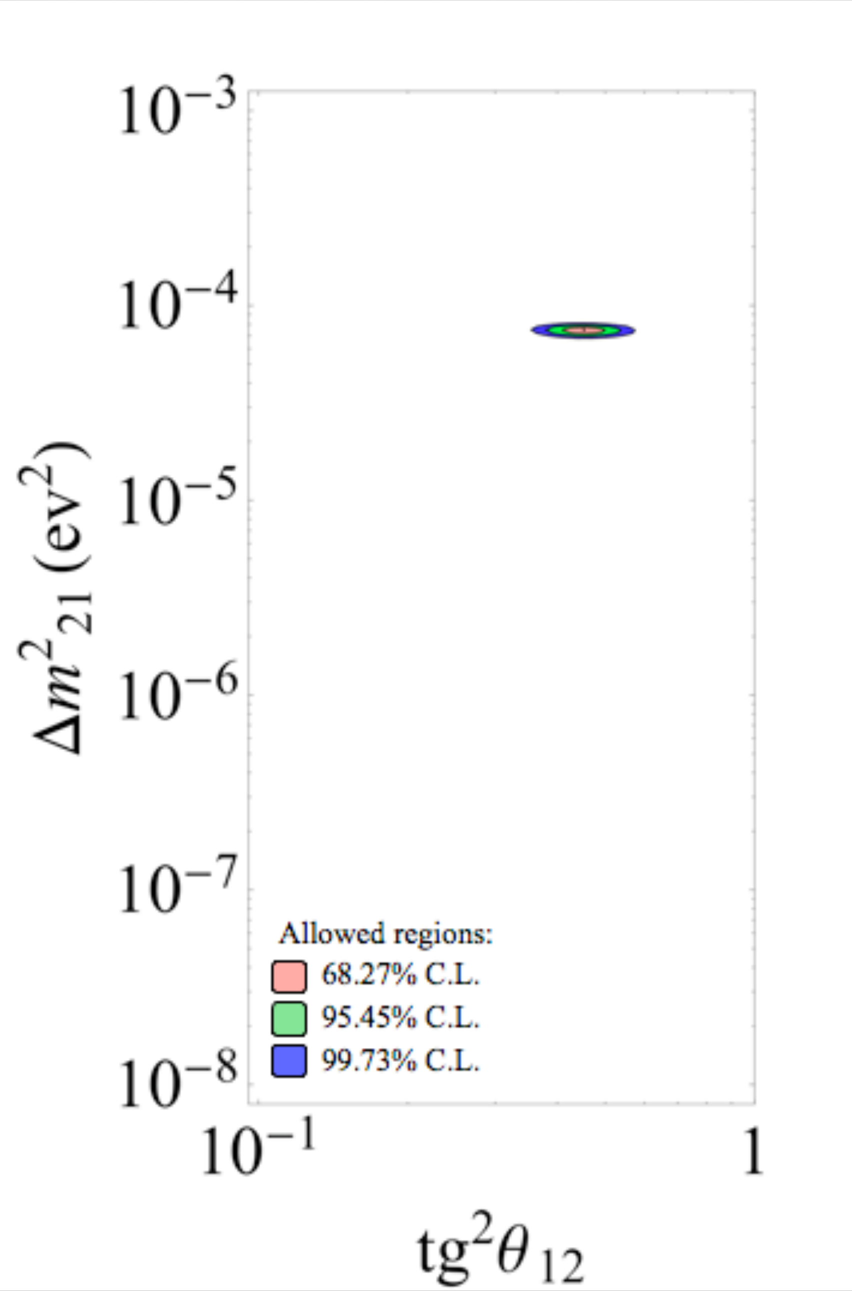
$\theta_{12}$ measured with solar

$\theta_{23}$ measured with atmospheric

$\theta_{13}$ very small or zero-- if $\neq 0$ and complex mixing matrix, then CP is violated in the $\nu$ sector
# experiments just to measure $\theta_{13}$ ( Double-Chooz;T2K, Reno, Daya Bay)



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



## All Solar without Bx+ Kamland

Pep and CNO, fixed at SSM values

Kamland: $\bar{\nu}_e$ from reactors (180 km baseline)-
$\Delta m^2$ region explored: $10^{-5}$-$10^{-4}$ $eV^2$

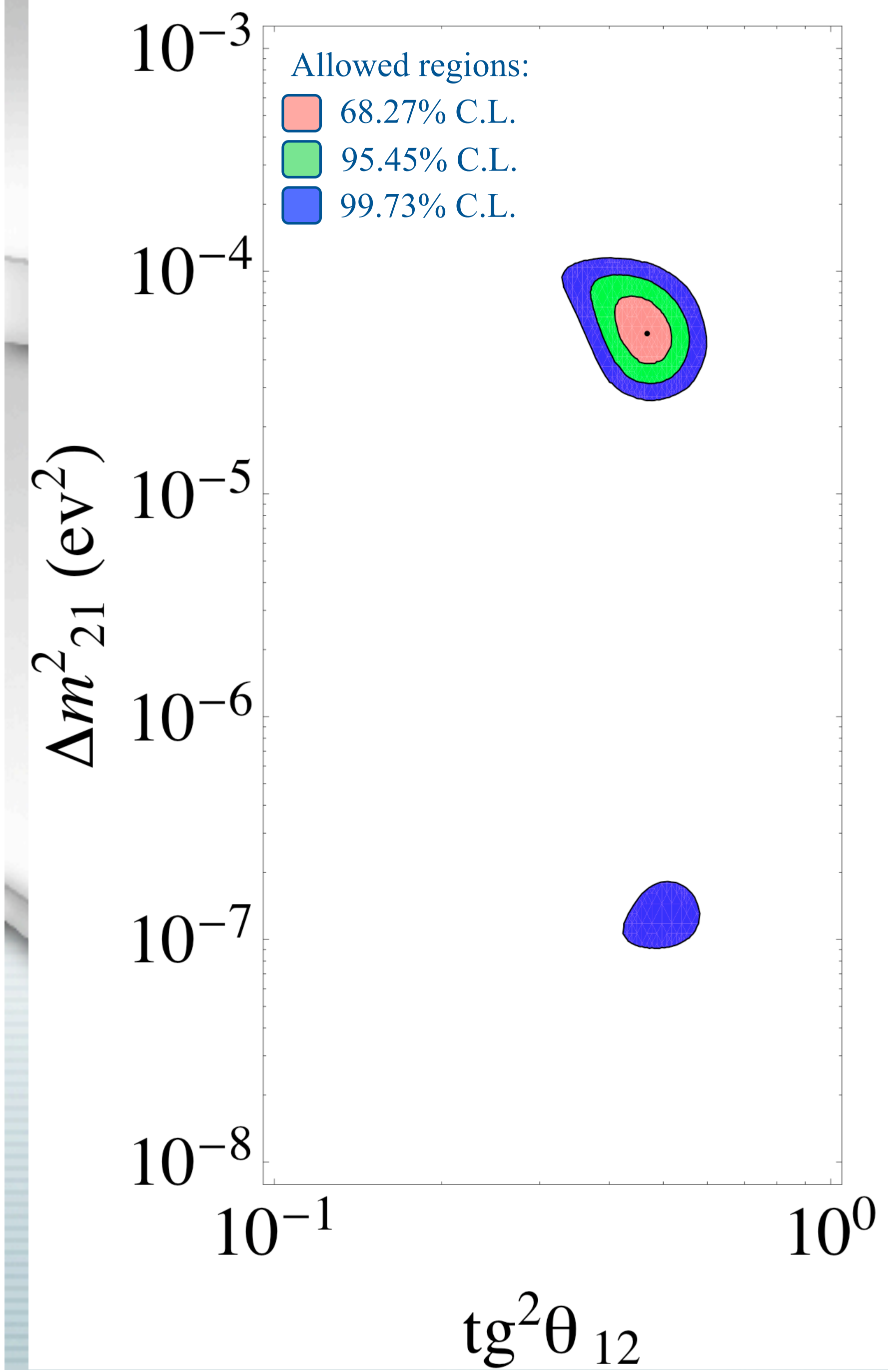
$$Best\ \ fit\ \ values:$$

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

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

SHP11:
A.M. Serenelli, W. C.Haxton
and C. Pena-Garay,
arXiv:1104.16.39v1 [astro-ph

# ALL SOLAR ONLY without BX



*Best fit values:*

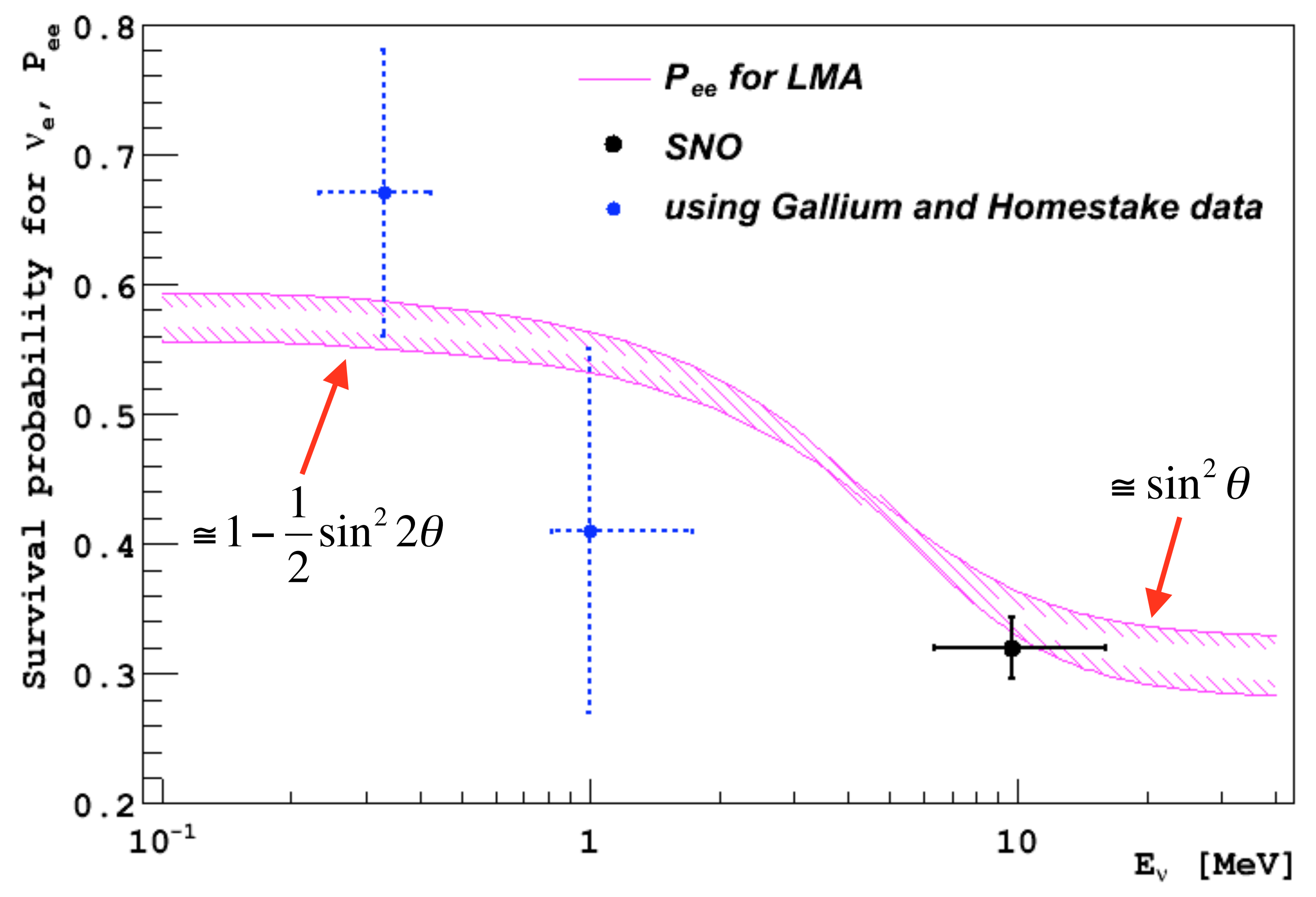
$$\Delta m^2 = 5.37\left\langle {}^{+1.55}_{-0.07} \right. \bullet 10^{-5}\ eV^2$$

$$\tan^2\theta = 0.47\left\langle {}^{0.03}_{0.04} \right.$$

All solar include: SuperK (phases I and III), CNO LETA and phase I, Radiochemical exps.

The tension all solar-Kamland could be explained with $\theta_{13} \neq 0$ or with the existence of an hypothetical sterile ν

# The situation before Borexino



# The Borexino experiment

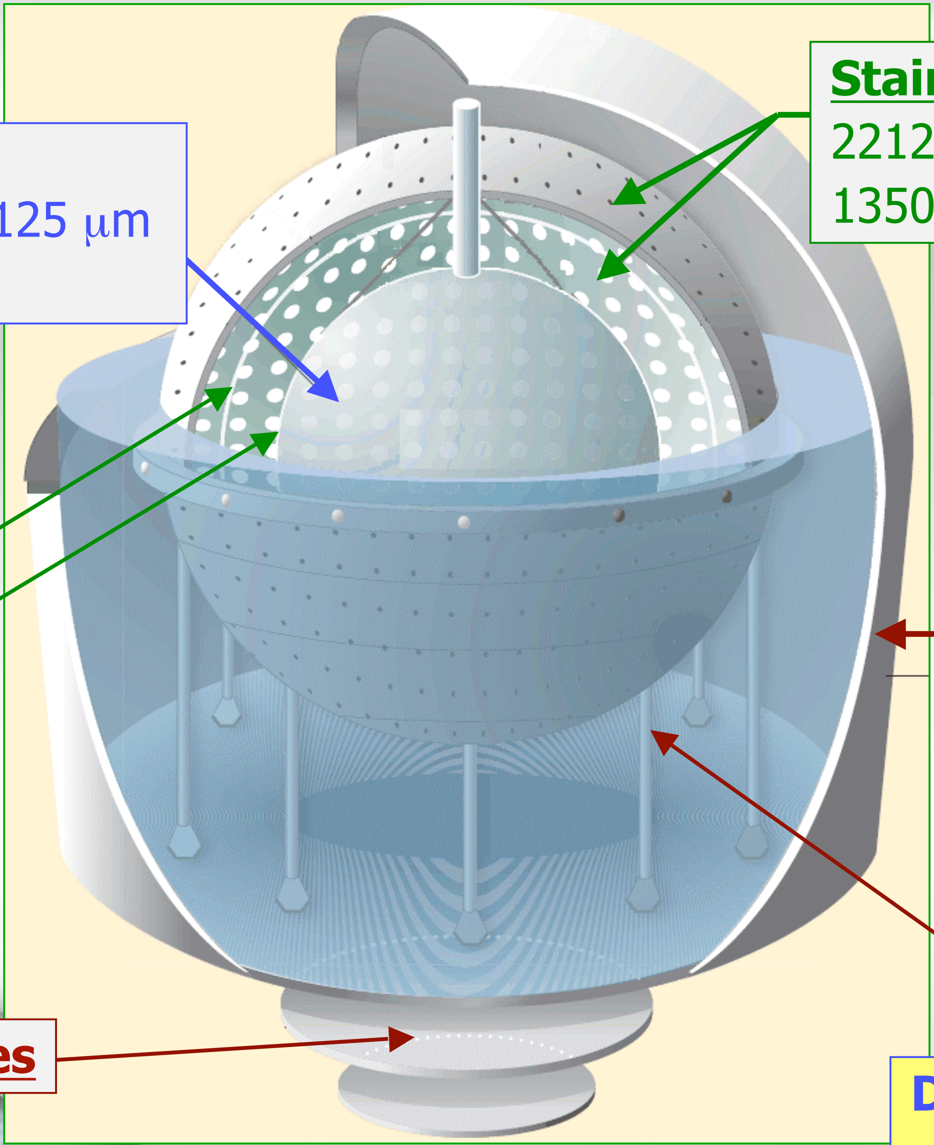
@ Borexino has been designed mainly to study low energy neutrinos from the Sun

→ 300 tons of ultrapure liquid scintillator, carefully shielded against external background
→ world-record radiopurity
→ detect neutrino interactions over 160-200 keV

@ Installed at the Gran Sasso Laboratory with an overburden of 1400 m of rock; 1.2 cosmic muons/$m^2$h

@ Special care in the construction: special technology to radio-clean the scintillator; ultrapure $N_2$ for stripping(Rn, Ar, Kr);special care in the crude oil and in the pseudocumene procurement; extreme caution in the fabrication and assembly of the nylon vessel for the scintillator containment; special development and/or selection of all components; any operation in clean room or in $N_2$ or Ar atmosphere.

# Detector design and layout



**Scintillator:**
270 t PC+PPO in a 125 μm
thick nylon vessel

**Stainless Steel Sphere:**
2212 photomultipliers
1350 $m^3$

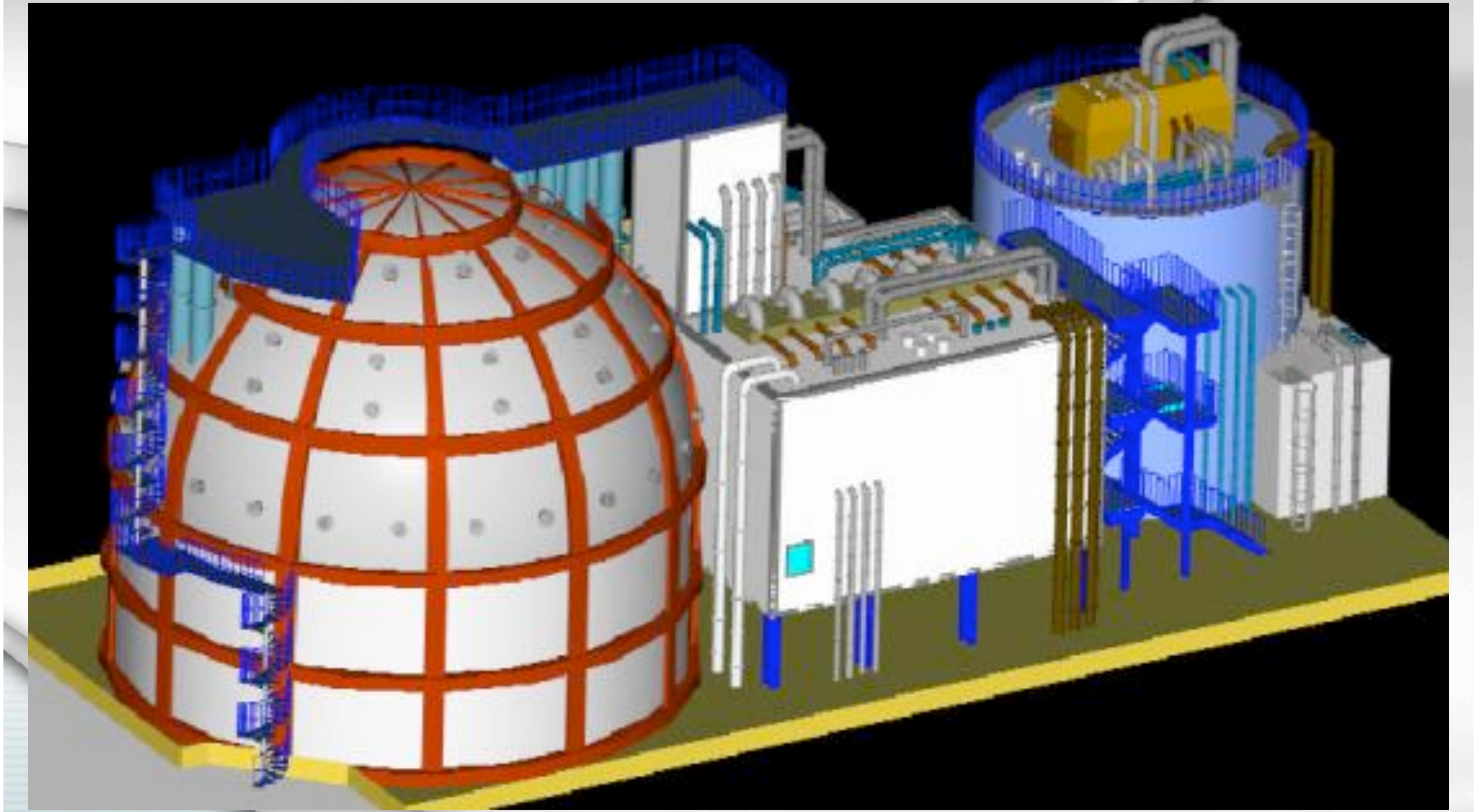
**Nylon vessels:**
Inner: 4.25 m
Outer: 5.50 m

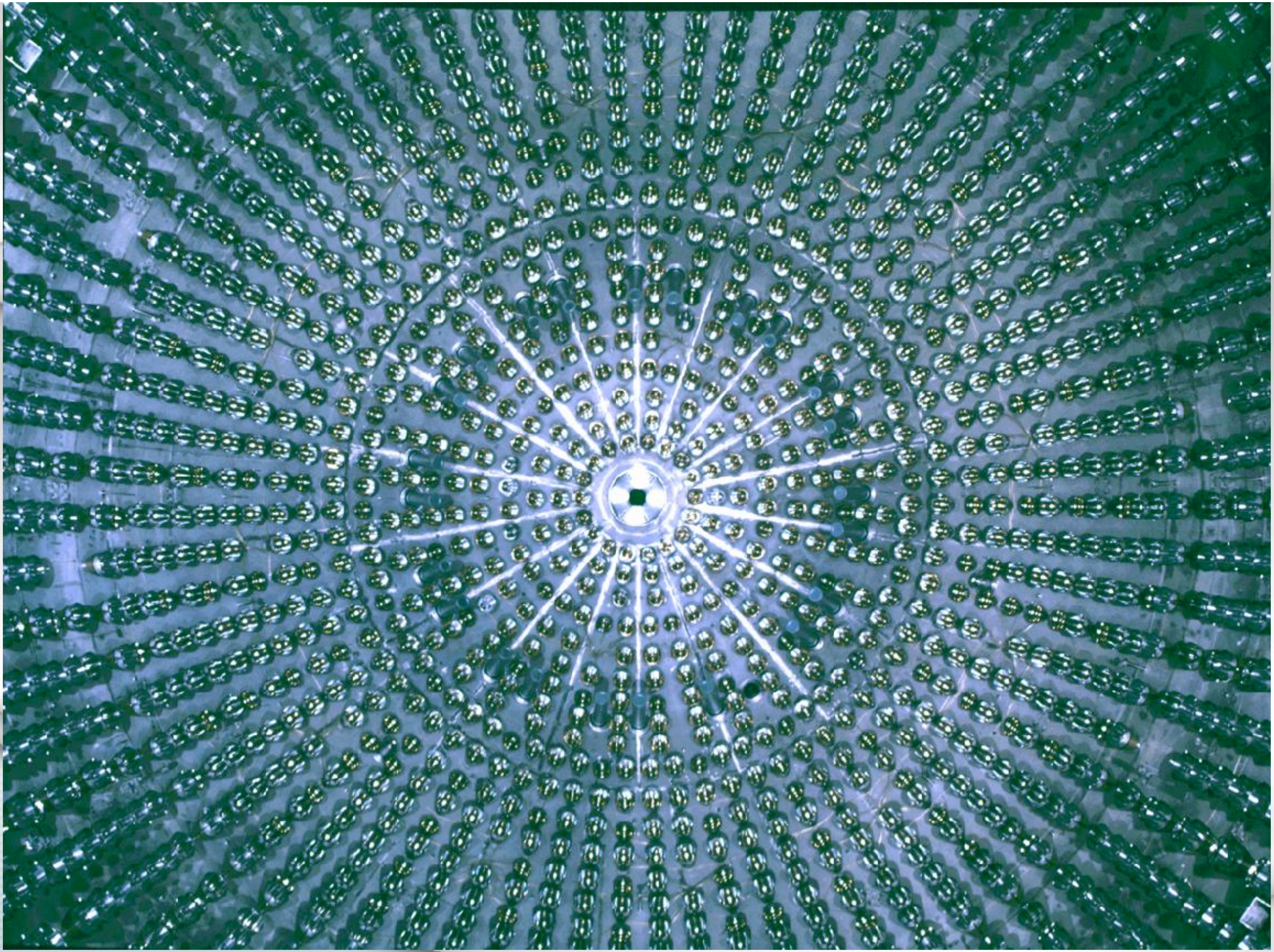
**Water Tank:**
γ and *n* shield
μ water Ch detector
208 PMTs in water
2100 $m^3$

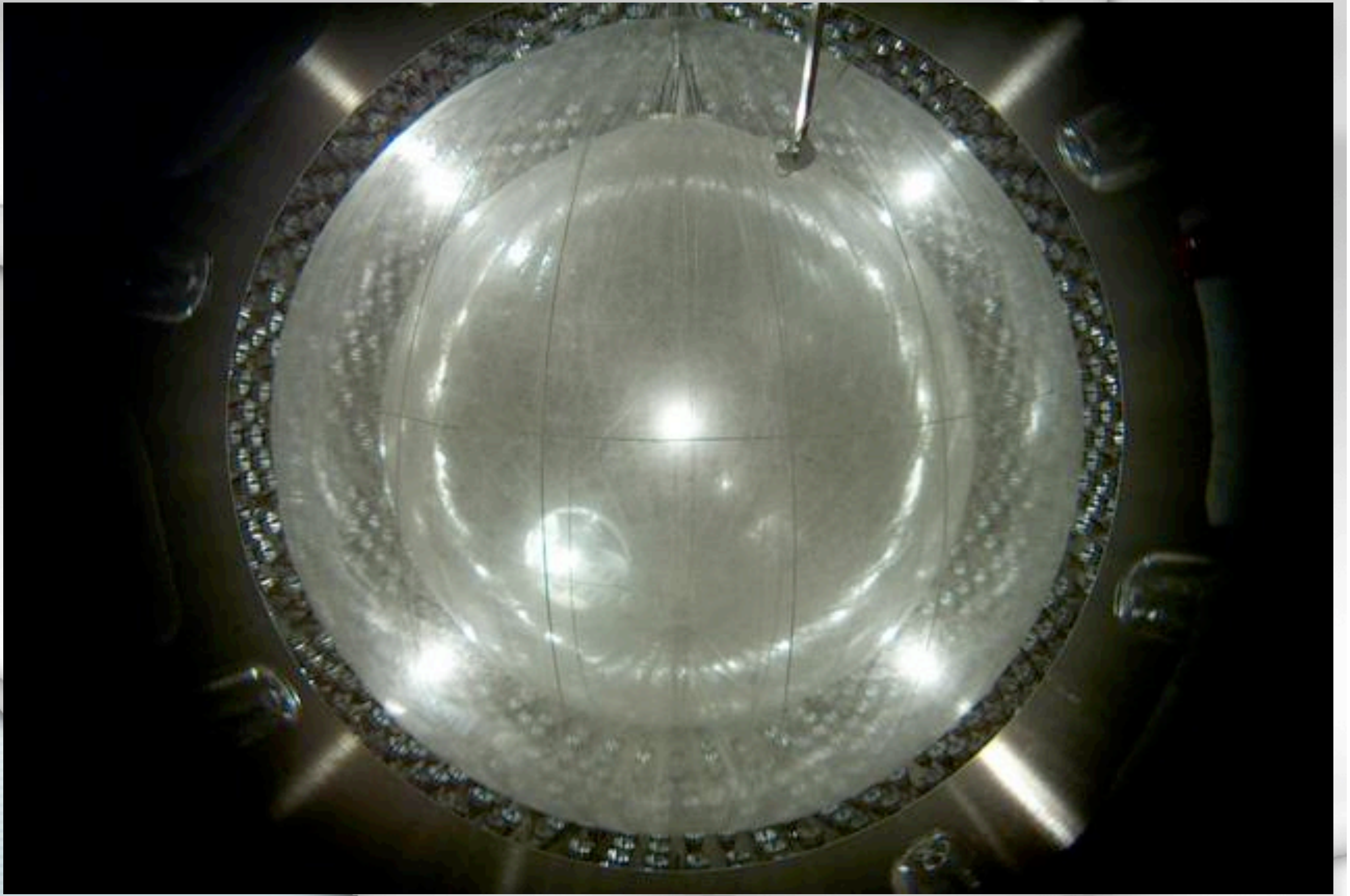
**20 legs**

**Carbon steel plates**

**Design based on the principle of graded shielding**



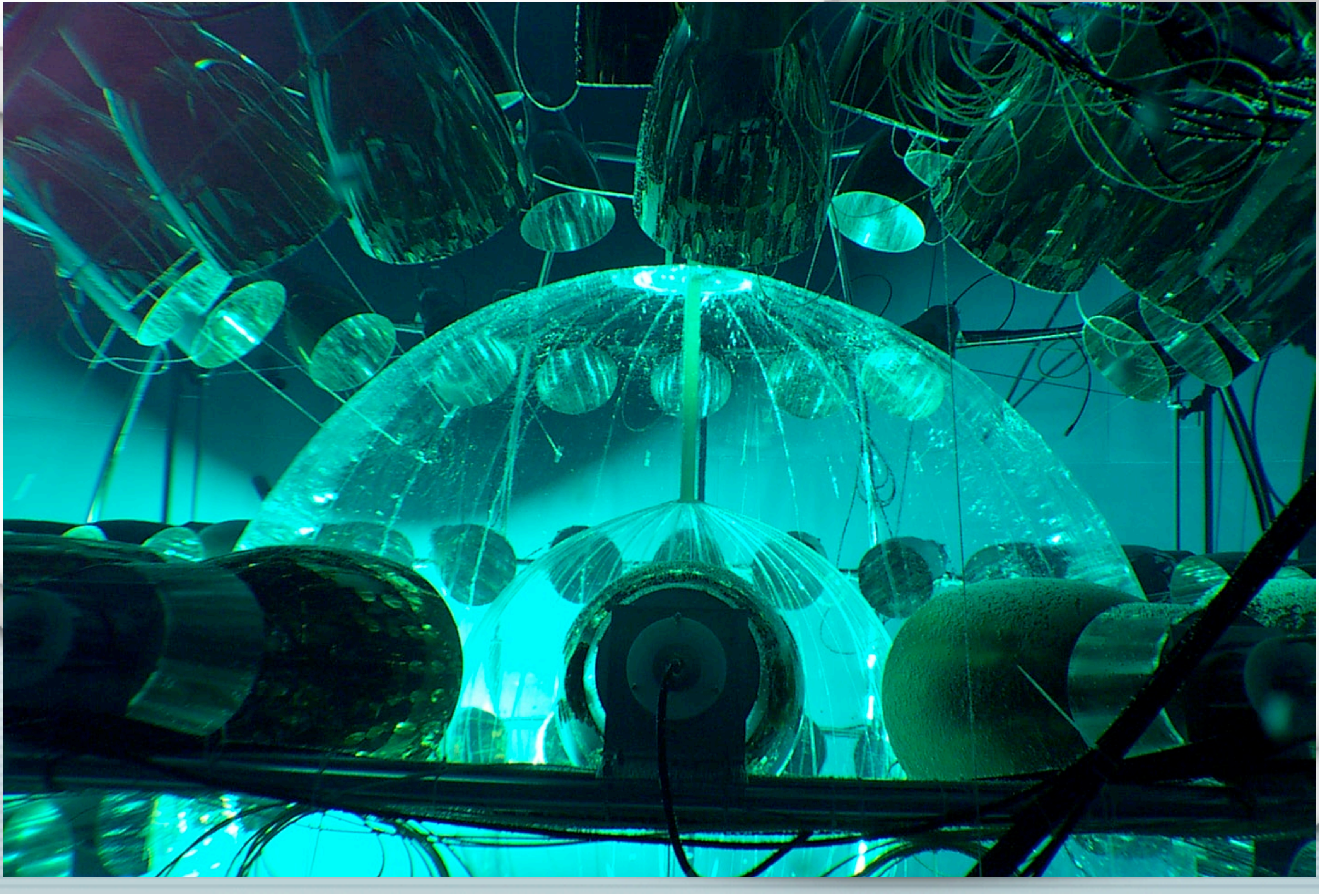




|  | Material | Typical conc. of the unpurified materials | Final radiopurity levels |
|---|---|---|---|
| $^{14}C$ | scintillator | $^{14}C/^{12}C<10^{-12}$ | $\boxed{^{14}C/^{12}C \cong 2\cdot 10^{-18}}$ |
| $^{238}U$,$^{232}Th$ equiv. | - Hall C dust<br>- stainless. steel<br>- nylon | $\}$ $10^{-5}$-$10^{-6}$ g/g | $\boxed{10^{-17} - 10^{-18}\ g/g}$ |
| $K_{nat}$ | Hall C dust | ~ $10^{-6}$ g/g | $\boxed{< 3\cdot 10^{-14}\ g/g}$ |
| $^{222}Rn$ | - external air.<br>- air underground | ~20 Bq/m$^3$<br>~40-100 Bq/m$^3$ | $\boxed{<1\ \ \mu Bq/m^3}$ |
| $^{85}Kr$<br>$^{39}Ar$ | in $N_2$ for stripping | ~ 40 ppt<br>~10 ppm | $\boxed{\begin{array}{l}\sim 0.16\ \ mBq/m^3 \\ \sim 0.5\ \ mBq/m^3\end{array}}$ |
| - $^{222}Rn$<br>-$^{238}U$,$^{232}Th$ equiv.<br>-$^{226}Ra$ | LNGS - Hall C water | Few kBq/m$^3$<br>~$10^{-10}$ g/g<br>2 Bq/m$^3$ | $\boxed{\begin{array}{l}\sim 30\ \ \mu Bq/m^3 \\ \sim 10^{-14}\ \ \ g/g\end{array}}$ |

To check ultra-low radioactive levels a very high sensitivity detector has has been installed -- sensitivity: down to 5 $10^{-16}$g/g U,Th equivalent; ≈ $10^{-18}$ $^{14}C/^{12}C$

# The counting test facility--C.T.F.



# Borexino is measuring the solar $\nu_e$ e.s.

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

with a threshold at ~60 keV (hardware), ~160-200 keV (software) electron energy

Measurements: Total energy released in the interactions, the position (via the PMT timing), $\alpha/\beta$ discrimination

Goal: $^7$Be flux (862 keV)[ Phys. Lett.B 658(2008)101; PRL 101(2008) 091302,last paper arXiv 1104.2150 (hep-ex) and 1104.1816 (hep-ex)]; $^8$B with a lower threshold down to 2.2 MeV [Phys.Rev.D,82,033006, 2010]; pep (1.44 MeV), possibly pp and CNO on the future;Geo-antineutrinos [Phys. Lett. B687,2010], Supernovae neutrinos. Best limits for rare events: Best limit on the Paullian transition [Phys. Rev. D82,3 (2010),033006]; limits on antineutrinos in the Sun flux [Phys. Lett.B, 687(2010) 687], etc.

Further proposed measurement with a $\nu$ and $\bar{\nu}$ artificial sources

# Calibration campaigns

Am-Be source

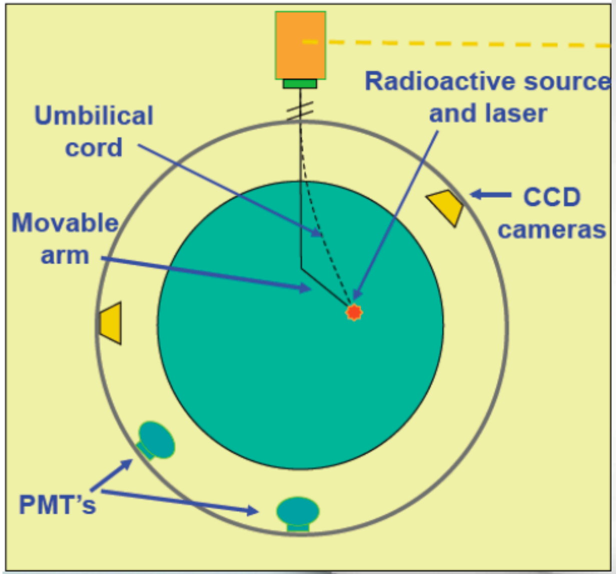
| | γ | | | | | | | | n | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $^{57}$Co | $^{139}$Ce | $^{203}$Hg | $^{85}$Sr | $^{54}$Mn | $^{65}$Zn | $^{60}$Co | $^{40}$K | n-p | n $+^{12}$C | n+Fe |
| **energy (MeV)** | 0.122 | 0.165 | 0.279 | 0.514 | 0.834 | 1.1 | 1.1,<br>1.3 | 1.4 | 2.226 | 4.94 | ~7.5 |

$^{222}$Rn loaded scintillator

- $^{214}$(Bi-Po)

α/β discrimination

→ Mc tuned with the calibration results



Energy scale resolution: $\frac{5\%}{\sqrt{E(MeV)}}$ from 200 keV to 2 MeV

Over 2 MeV: A little worse due to the less accuracy in the calibration.

Light yield obtained by the γ sources with MC: 511 p.e./MeV
uncertainty: 1.5%

Fiducial volume: Reconstruction program and MC tuned on the calibration results: R<3m -1.67<z<1.67 cm

$$\Delta(x,y,z) = 10 - 12 \ \ cm$$

75.7 tons; 88 m$^3$ Uncertainty: $\boxed{\left\langle {}^{+1.3}_{-0.5}\% \right.}$ (1 σ)

# $\alpha/\beta$ discrimination- Gatti parameter

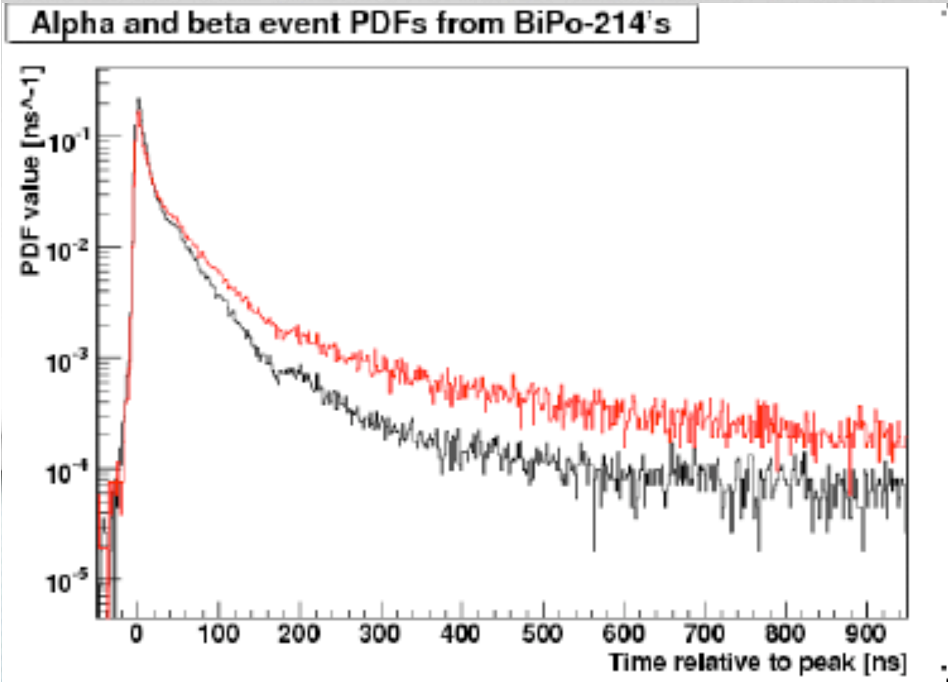
$G_\alpha = \sum_i P_i \beta_i$

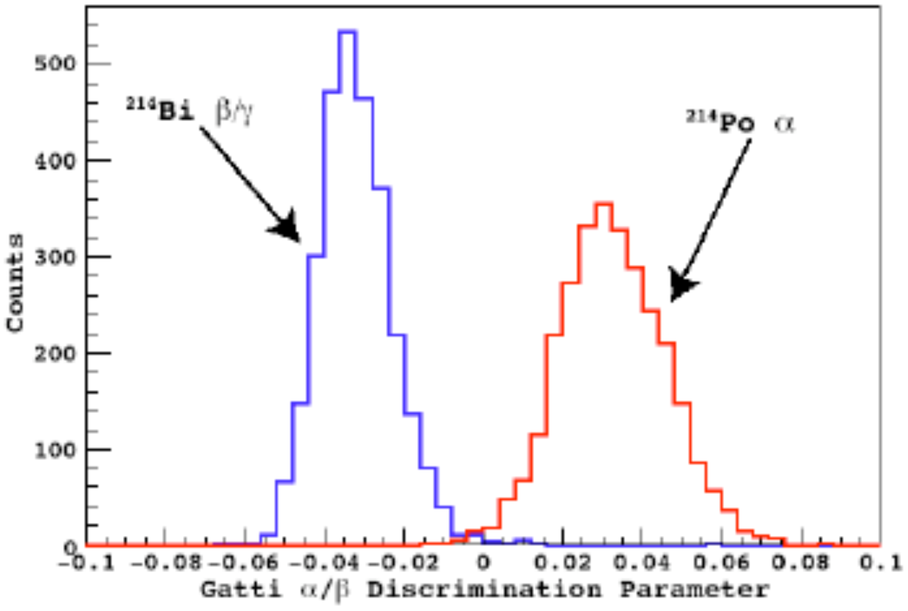
$\alpha_\iota, \beta_\iota$ –>n. p.e. for the indiv. shape within a given $\Delta$t (2 ns)

$G_\beta = \sum_i P_i \alpha_i$

$\overline{\alpha}_i, \overline{\beta}_i$ –>av. shape of current pulses (pdf)

$$P_i = \frac{\left(\overline{\alpha}_i - \overline{\beta}_i\right)}{\left(\overline{\alpha}_i + \overline{\beta}_i\right)}$$

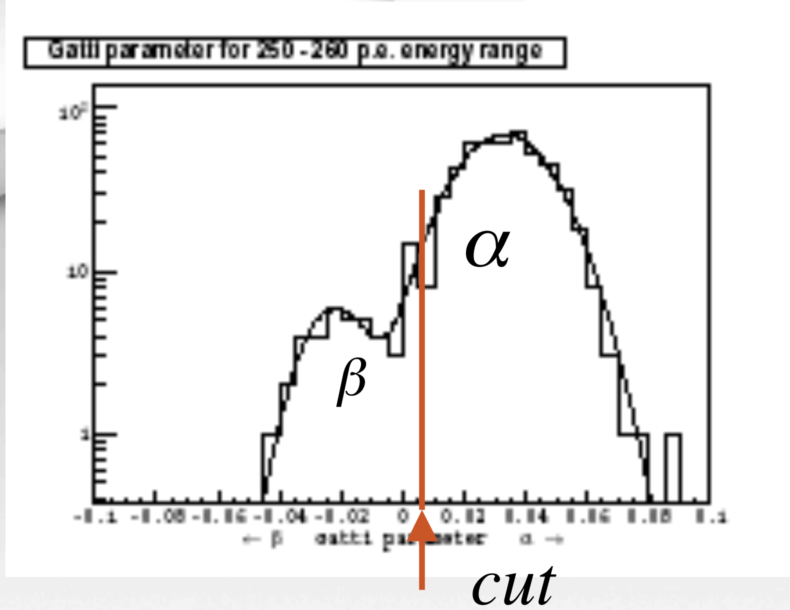




The analysis for the reference curves has been done $^{222}$Rn

MC builds itself the references curves from the scintillator PDFs

# α/β discrimination-- two different approaches



1 So called "soft cut"

The cut is chosen to not reject
β particles- done bin per bin
Reduction to 60%
It removes also noise events

2 So called "statistical subtraction"

Bin per bin the area below the α curve is evaluated and then the equivalent number of events is subtracted

# CUTS for the $^7$Be search

1 Muons: # detection in the ID and veto of 300 *ms* (cosmogenic *n capture after 255* μs); detection in the OD (Cherenkov) and veto of 2 ms livetime missed: 1.6%

2 Fiducial volume

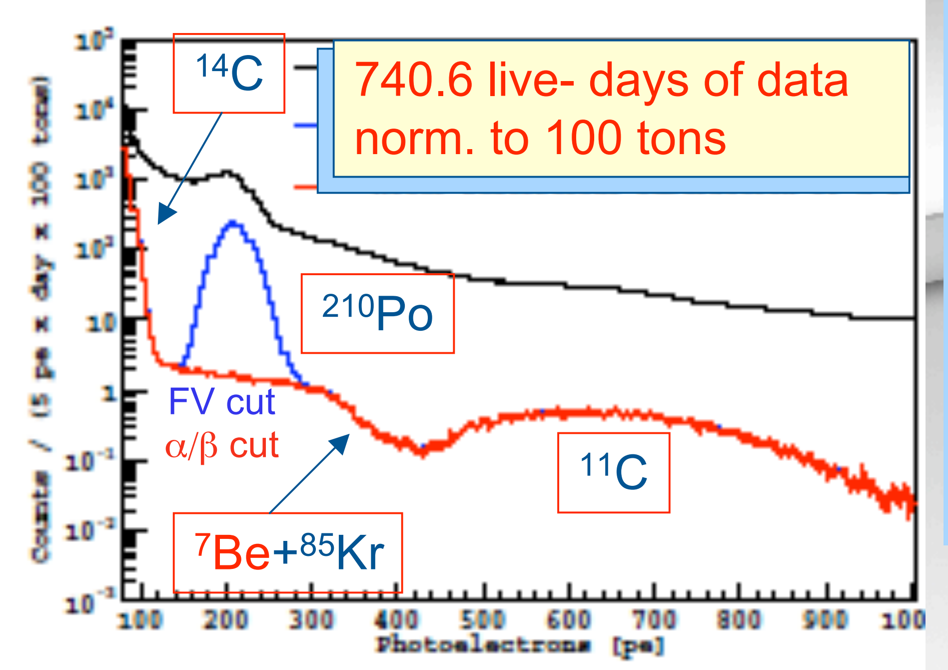
3 Coincidences within 2 ms and events within 1.5 m of dist. are rejected - correlated events and $^{214}$Bi-$^{214}$Po (λ:238.1 μs)- no ν events contribute

4 Check the charge - $0.6 < \frac{C}{q_{\exp}} < 1.6$ ($q_{exp}$ is the expected mean charge for single hit-average among the involved PMTs)

5 Isotropic emission of the scintillation light around the interaction point -reject additional noise events

6 Rejected: pile-up of multiple events in the same DAQ gate :random $^{14}$C and fast coincidences, as $^{212}$Bi-$^{212}$Po [λ:433.3 ns]-service triggers (laser, pulser, etc)- negligible prob. two ν events fall in the same gate.

Only 0.6% of live-time is missed due to the cuts 2-6



740.6 live- days of data
norm. to 100 tons

$^{14}$**C**-β emitter-156 keV end point

threshold 160 keV

$^{210}$**Po**– α emitter- embedded in the inner walls of the lines- t =200 days

$^{11}$**C**- $\beta^+$ emitter -cosmogenic- 1.2 μ/ m$^2$ h- τ=29.4 minutes

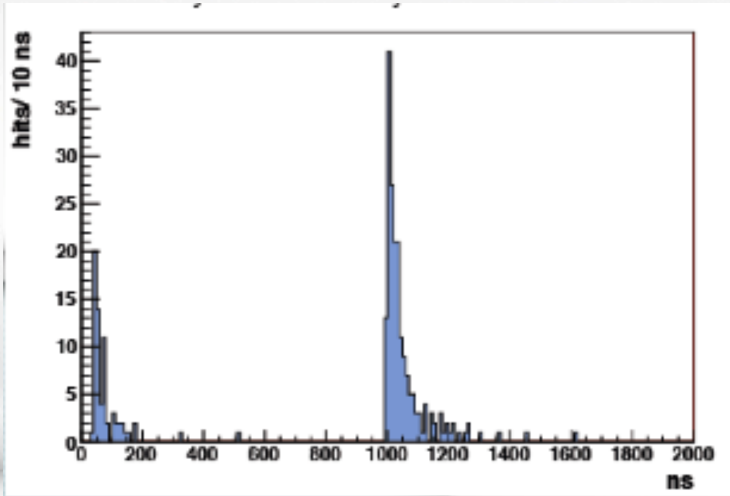
**$^{85}$Kr**

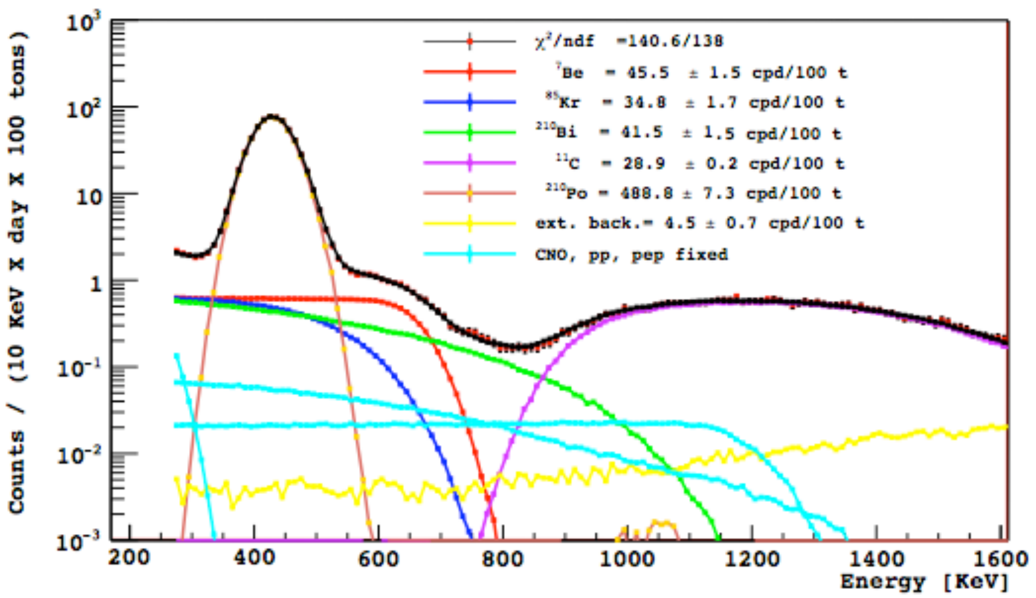
$$^{85}\mathrm{Kr} \xrightarrow{\beta\ 173\ \mathrm{keV}} {}^{85}\mathrm{Rb}^* \xrightarrow{\gamma\ 514\ \mathrm{keV}} {}^{85}\mathrm{Rb}$$

$$\tau = 1.464\ \mu\mathrm{s}$$

B.R. 0.46% ~ 750 l. days
33 candidates

30.4±5.3±1.5 cpd/100 t

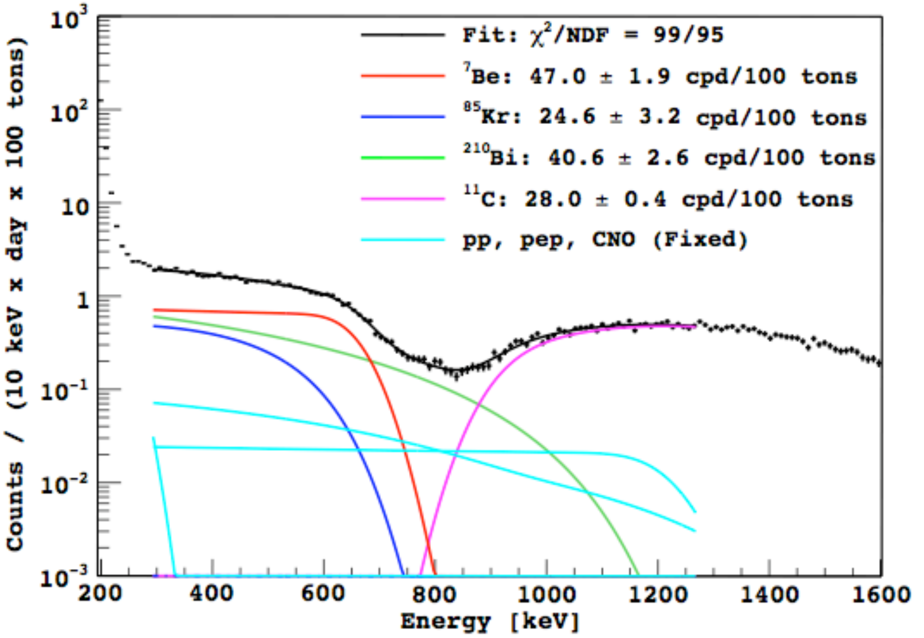




MC- fit range: 250-1600 keV
Soft $\alpha$ subtraction

\# pp, pep, CNO fixed, according MSW-LMA high metallicity

\# free parameters: $^{7}$Be,$^{85}$Kr, $^{210}$Bi ( $\beta$ emitter) ,$^{11}$C, $^{210}$Po ($\alpha$ emitter), $^{214}$ Pb ($\beta$ emitter)

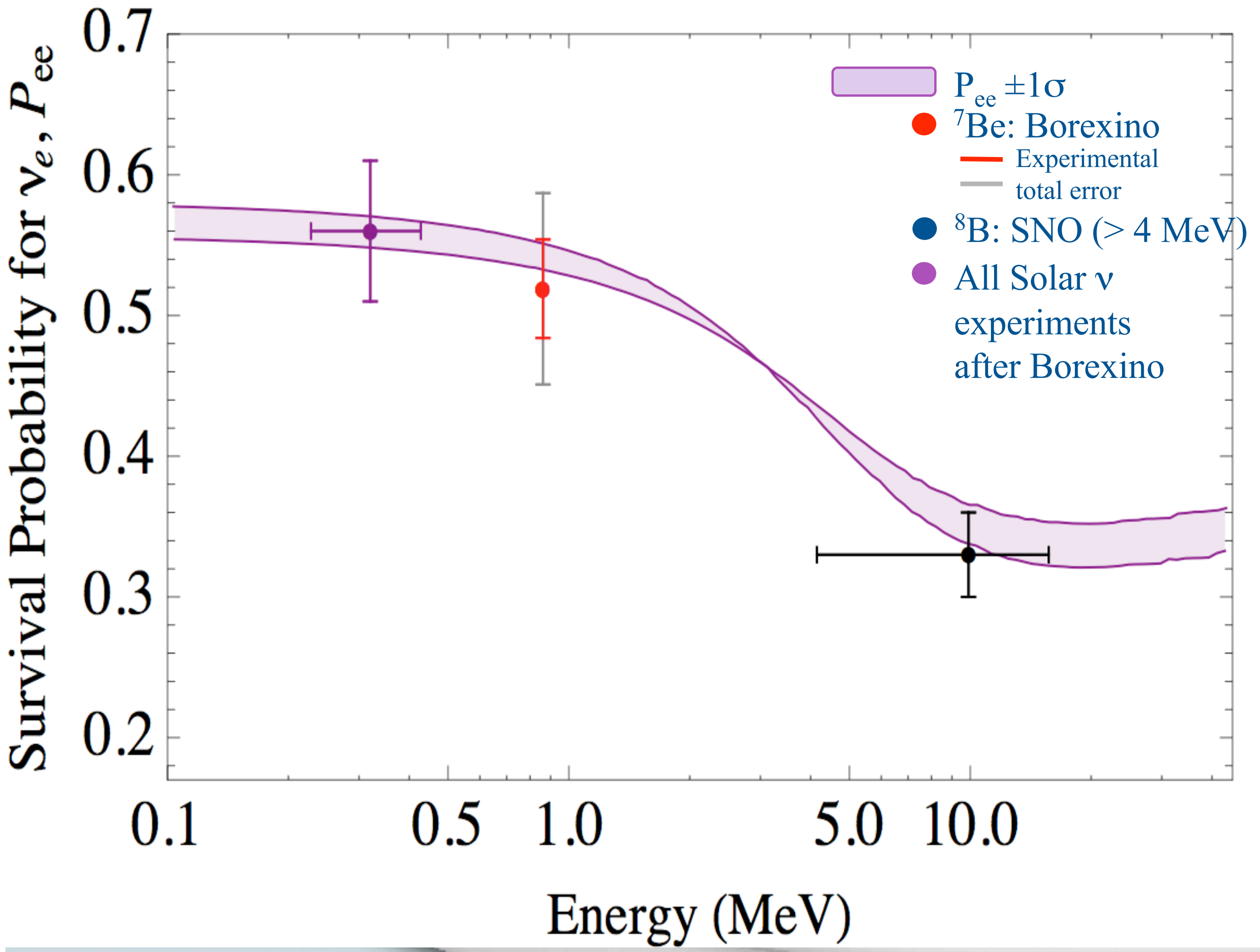


Analytical- fit range 300-1250 keV
statistical $\alpha$ subtraction

# SYSTEMATICS

| **source** | **%** |
|---|---|
| Trigger eff. and stability | <0.1 |
| Livetime | 0.04 |
| Scintillator density | 0.05 |
| Sacrifice of cuts | 0.1 |
| Position reconstruction | $\left\langle \begin{matrix} +1.3 \\ -0.5 \end{matrix} \right.$ |
| Energy scale | 2.7 |
| Fit assumptions | 1.7 |
| Fit methods | 1.0 |
| **Total syst errors** | $\left\langle \begin{matrix} +3.6 \\ -3.4 \end{matrix} \right.$ |

# 46±1.5 (stat.)± $\left\langle\begin{matrix}+1.6\\-1.5\end{matrix}\right.$ (syst)cpd/100 tons



$\Phi(^7\mathrm{Be})=(4.87\pm0.24)$
$\times10^9\ \mathrm{cm^{-2}s^{-1}}$
$f_{Be}=0.97\pm0.05\pm0.07$

$\Phi(pp) = 6.06^{+0.02}_{-0.06} \cdot 10^{10}\,cm^{-2}s^{-1}$
$f_{pp} = 1.013^{+0.003}_{-0.010}$
*assuming the luminosity constraint*

$\Phi(CNO) < 1.3\cdot10^9\ cm^{-2}s^{-1}$ (95% C.L.)
$f(CNO) < 1.7$

Borexino data validate the MSW-LMA model in Vacuum

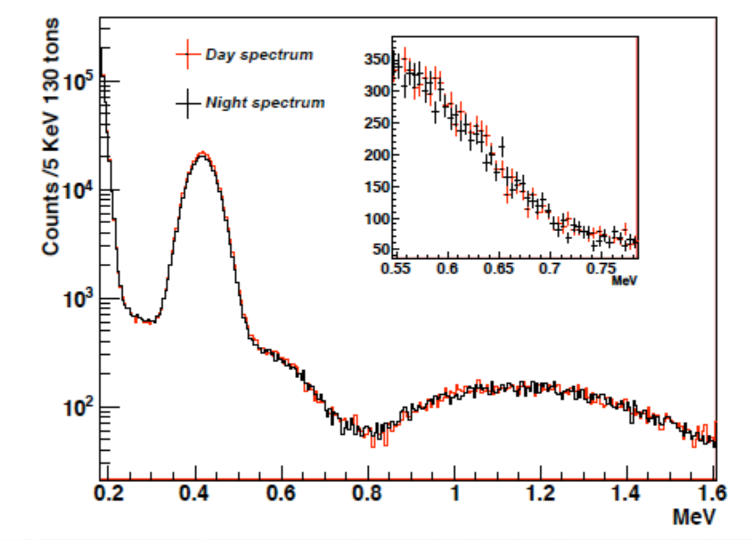
# Day/Night asymmetry in the $^7$Be region

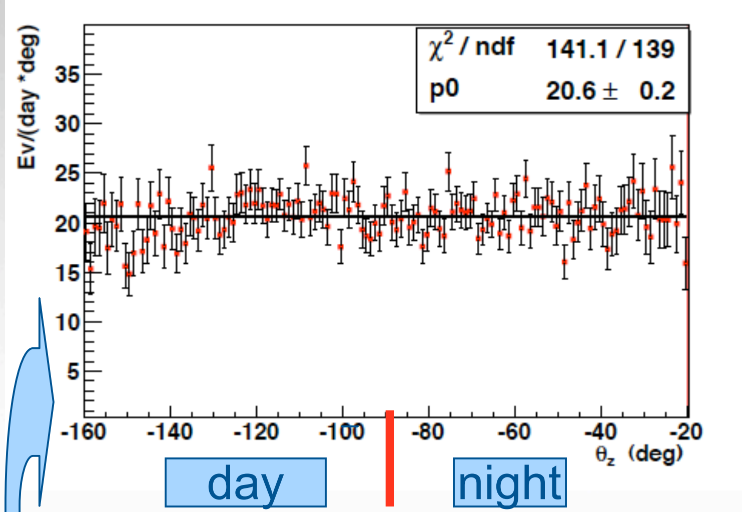
Day (positive Sun altitude) 385.5 days
Night (negative Sun altitude) 363.6 days

# F.V. R < 3.0 or <3.3 m (130 t) and -1,67<Z<1.67

# ν *energy window*: 550-715 keV

# Exp. Function corrected bin to bin for the geometrical seasonal variation (± 3%)





Nadir angle distrib. in the ν window, normalized to the exp. exposure function

Day/night asymmetry parameter →

$$A_{dn} = 2\frac{R_n^{^7Be} - R_d^{^7Be}}{R_n^{^7Be} + R_d^{^7Be}} = \frac{R_{diff}}{R}$$

**First approach**: fit in the standard F.V. the D and N spectra separately to obtain $R_D$ and $R_N$.

$A_{dn}$= 0.007±0.073 (systematic error negligible with respect to the stat.)

**Second approach:** 1) subtract *D* and *N* spectra, normalized to the day live time.

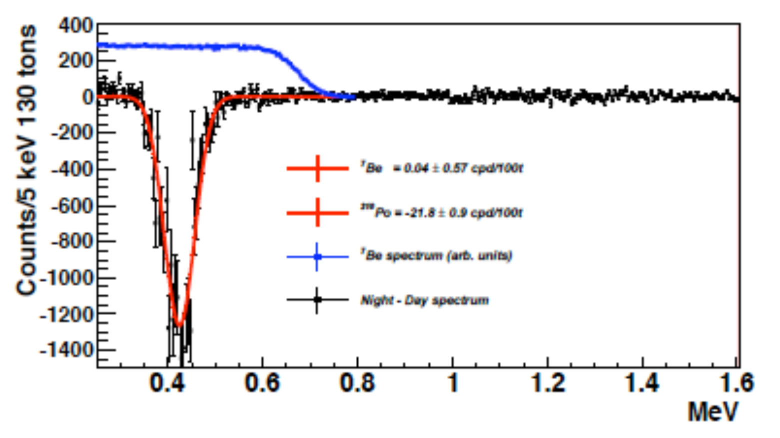
2) search for a residual component having the shape of the electron recoil spectrum due to the $^7$Be ν.

F.V.< 3.3 m

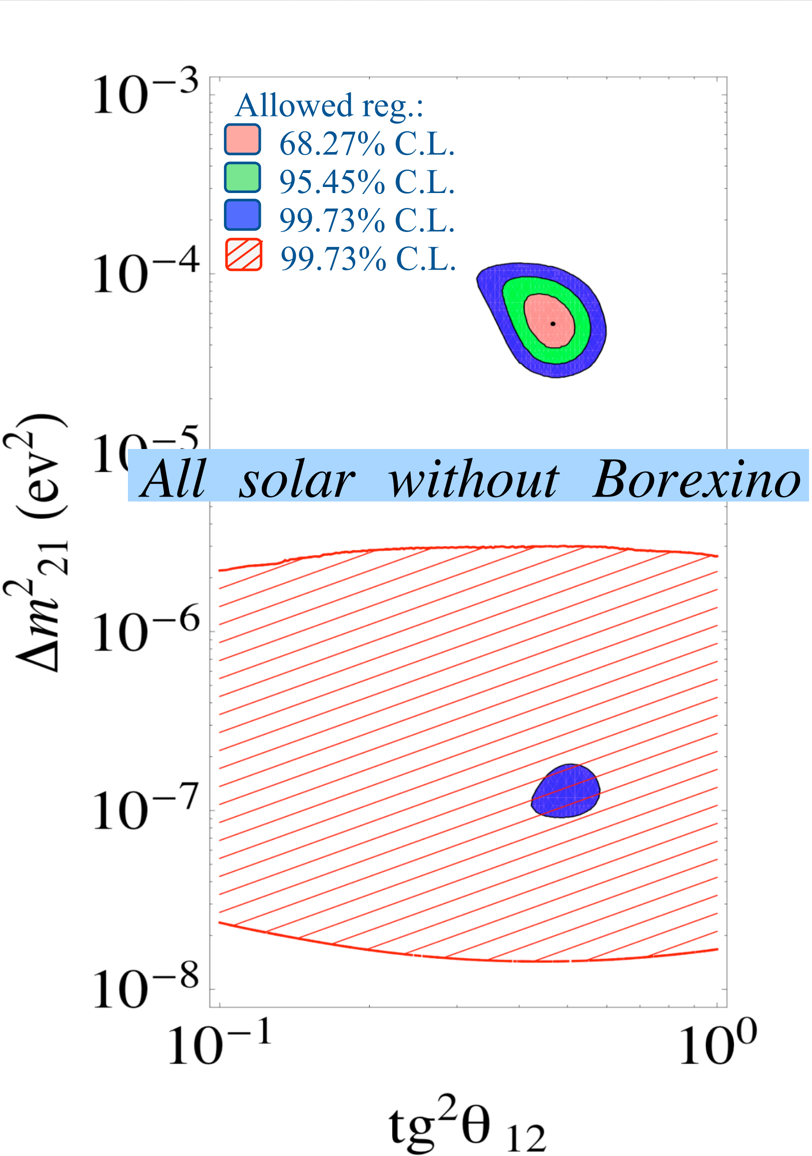
$^{210}$Po ($\tau_{1/2}$=138.38 days) not contributing in the same time to day and night

Same procedure with D and N spectrum with α statistical subtraction- the difference between the two procedures quoted as systematic error.

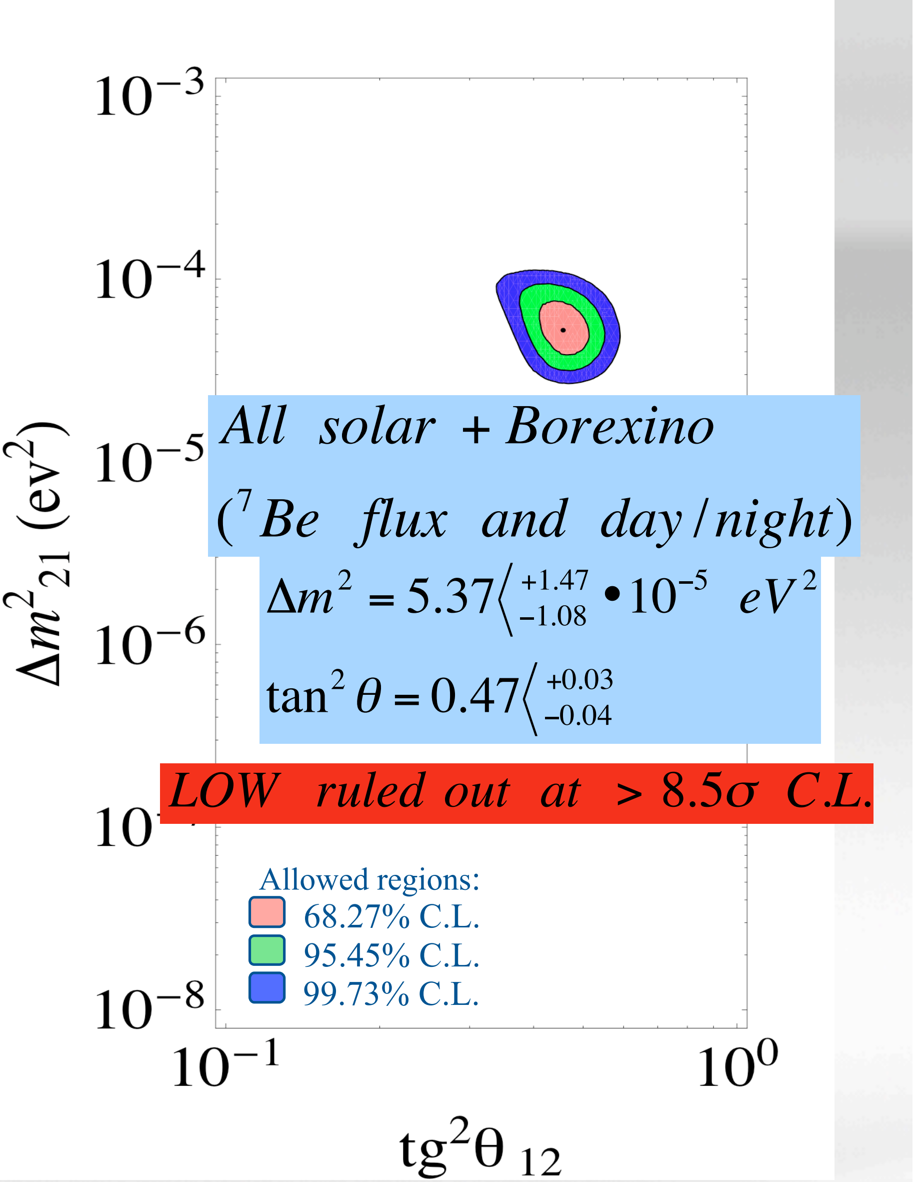
**$A_{ND}$= -0.001±0.012(stat.)±0.007(syst)**



| Source | error on |
|---|---|
| Live time | 5 $10^{-4}$ |
| Cut efficiency | 0.001 |
| $^{210}$Bi variation with time | ±0.005 |
| $^{210}$Po stat.subt. | ±0.005 |



*All solar without Borexino*



*All solar + Borexino*

*($^7Be$ flux and day/night)*

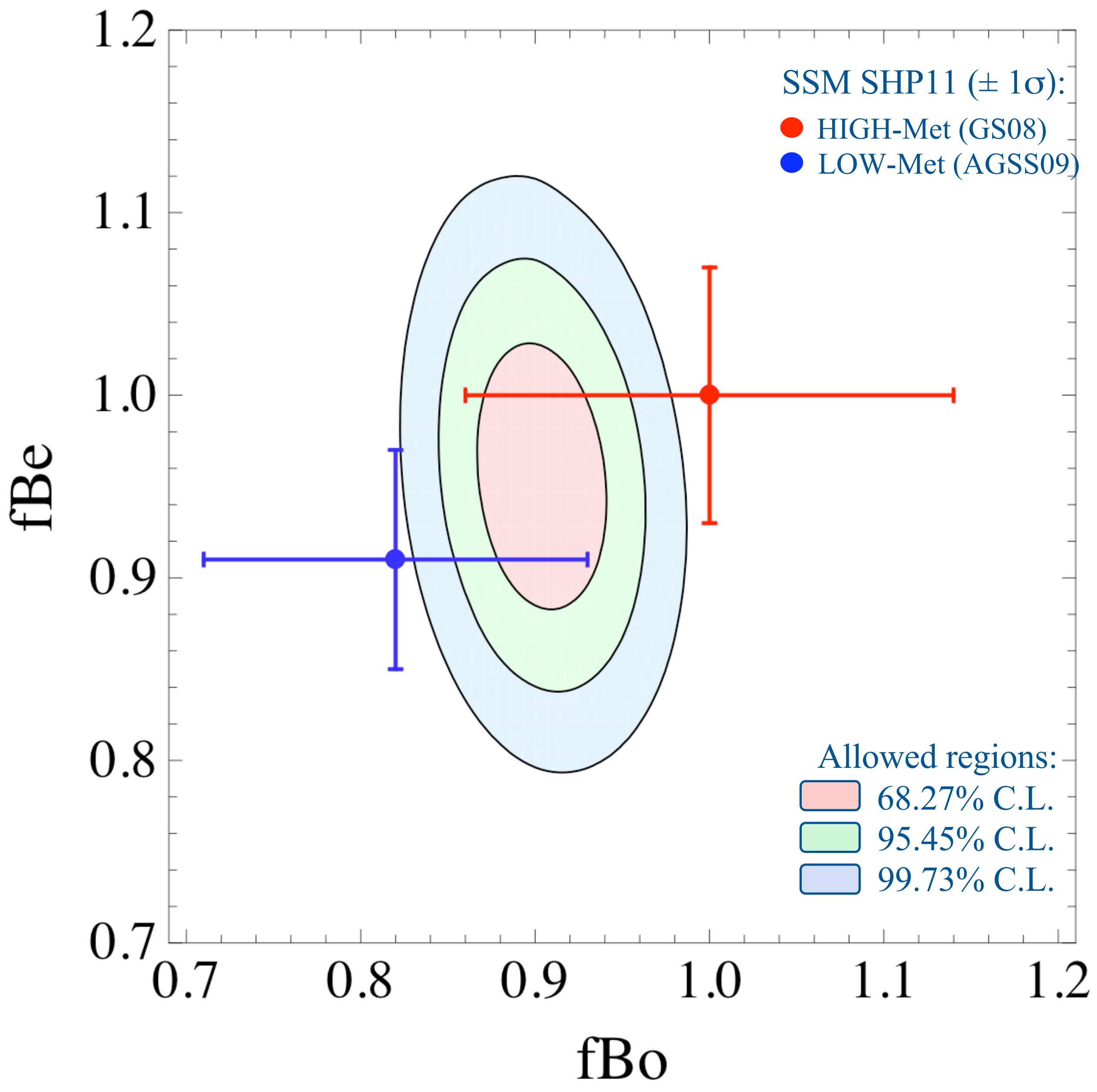
$$\Delta m^2 = 5.37\left\langle{}^{+1.47}_{-1.08}\right. \bullet 10^{-5}\ eV^2$$

$$\tan^2\theta = 0.47\left\langle{}^{+0.03}_{-0.04}\right.$$

*LOW ruled out at $> 8.5\sigma$ C.L.*

Then solar neutrino results with the addition of Borexino can isolate the LMA region without the Kamland antineutrino data

# Comparison with SSM- metallicity puzzle



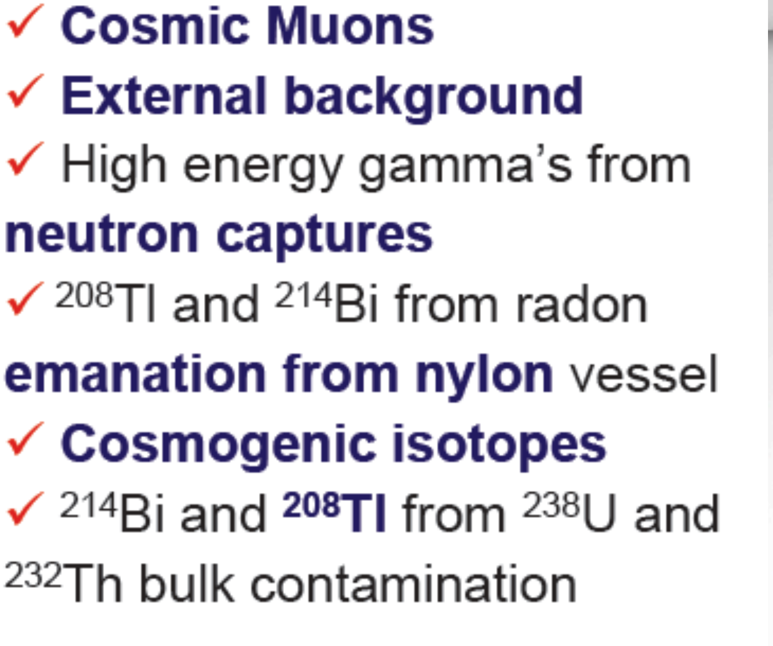
SHP11:
A.M. Serenelli, W. C.Haxton
and C. Pena-Garay,
arXiv:1104.1639v1 [astro-ph]

GS98:
N. Grevesse and A. J. Sauval,
Space Sciences Reviews 85,
161 (1998)

AGSS09:
Aldo M. Serenelli *et al 2009*
*ApJ* ***705 L123***

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

## Background in the 3.0-16.5 MeV

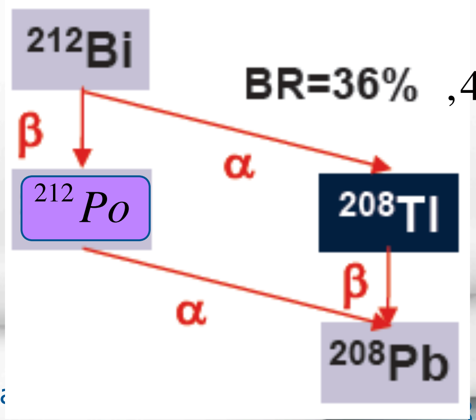


- ✓ **Cosmic Muons**
- ✓ **External background**
- ✓ High energy gamma's from **neutron captures**
- ✓ $^{208}$Tl and $^{214}$Bi from radon **emanation from nylon** vessel
- ✓ **Cosmogenic isotopes**
- ✓ $^{214}$Bi and **$^{208}$Tl** from $^{238}$U and $^{232}$Th bulk contamination

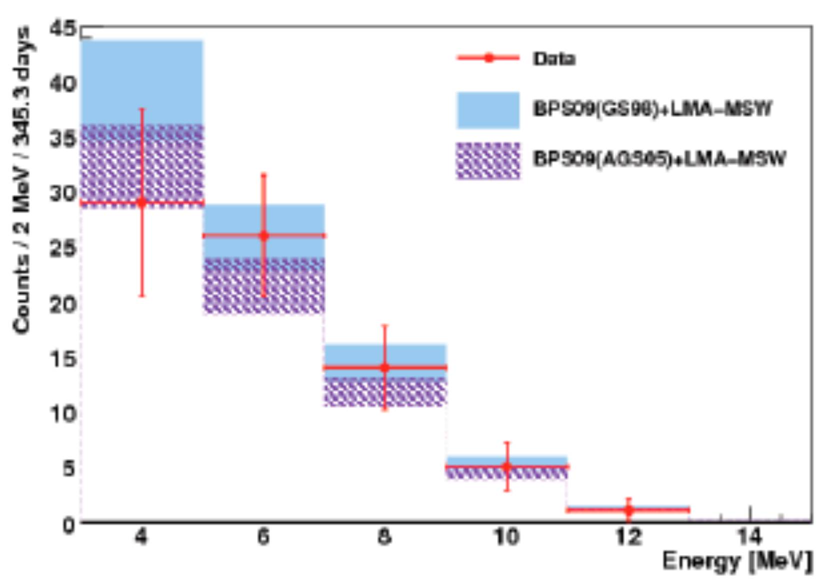
## Cuts

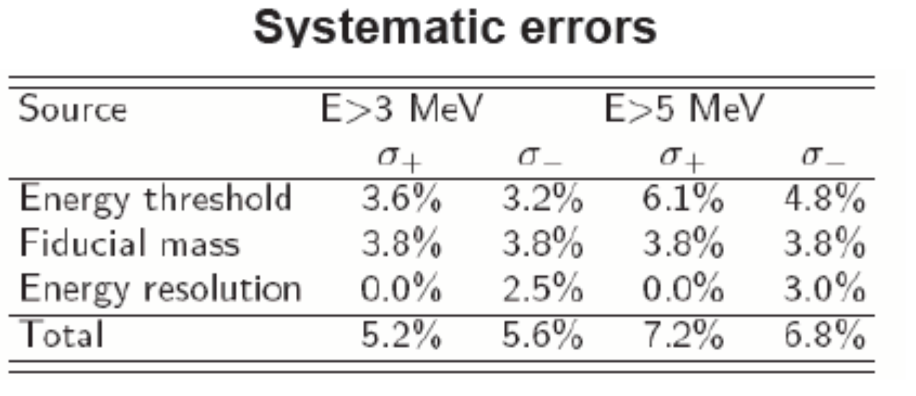
- @**Muon cut + 2 mms** dead time to reject induced **neutrons** (240 $\mu$s)
- @**Fiducial volume**
- @**Muon** induced radioactive **nuclides:**6.5 s veto after each crossing muon (~30% dead time)-$^{10}$C ($\tau$=27.8 s) tagged with the **Three-fold coincidence** with the $\mu$ parent and the neutron capture)-$^{11}$Be ($\tau$=19.9 s) statistically subtracted
- @$^{214}$Bi-$^{214}$Po coincidences rejected ($\tau$=237 $\mu$s-$^{222}$Rn daughter)
- @$^{208}$Tl (only one contributing to bkg above 3 MeV) from $^{212}$Bi-$^{212}$Po we evaluate the $^{208}$Tl production

$B.R.\ 64\%, 431\ ns$



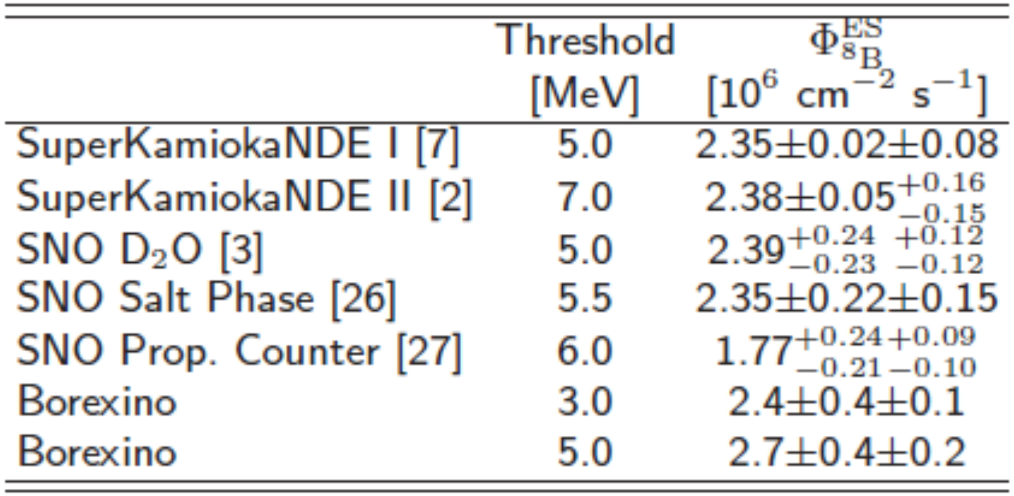
$,4.47\,\mathrm{min}$





## Systematic errors

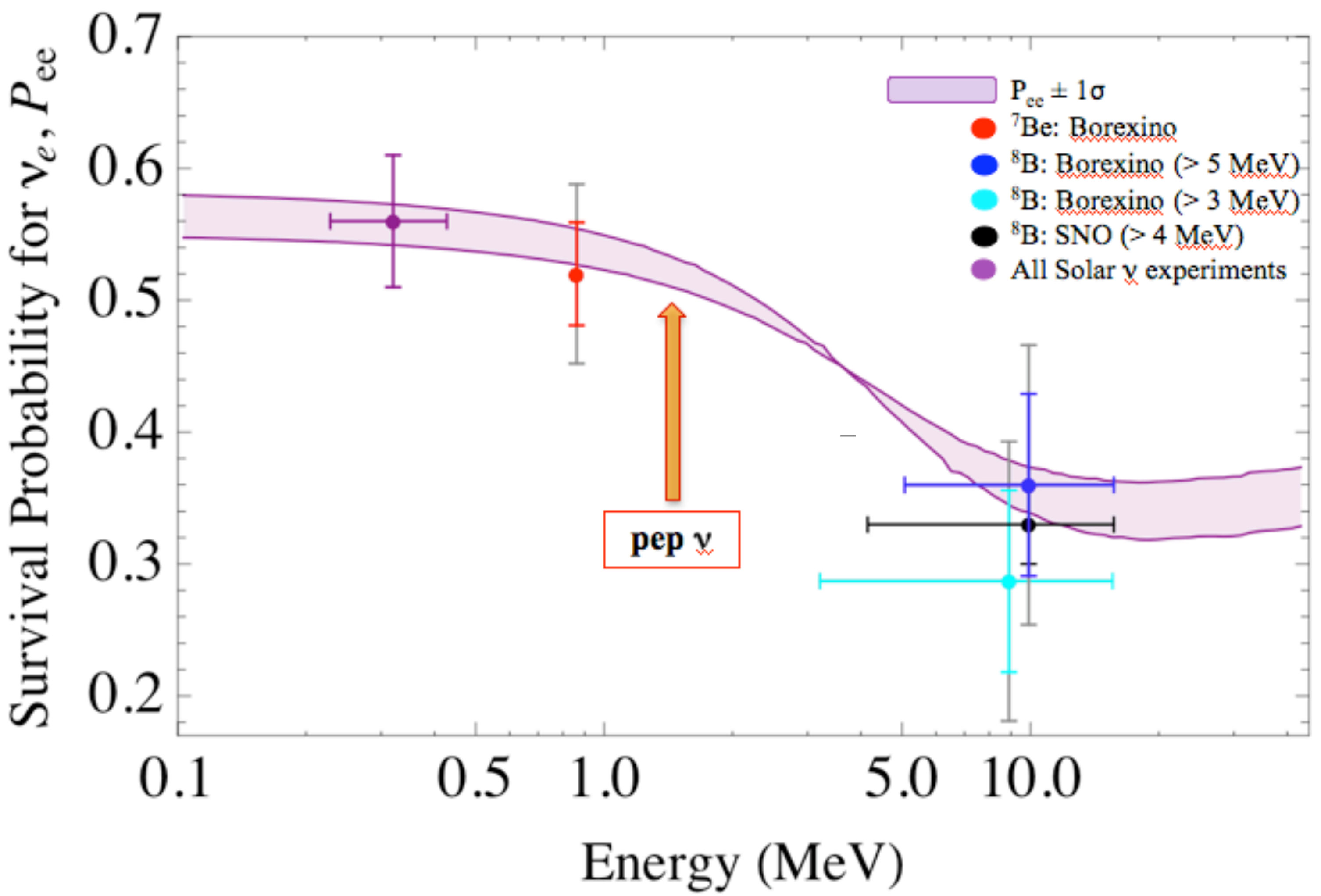
| Source | E>3 MeV |  | E>5 MeV |  |
|---|---|---|---|---|
|  | $\sigma_+$ | $\sigma_-$ | $\sigma_+$ | $\sigma_-$ |
| Energy threshold | 3.6% | 3.2% | 6.1% | 4.8% |
| Fiducial mass | 3.8% | 3.8% | 3.8% | 3.8% |
| Energy resolution | 0.0% | 2.5% | 0.0% | 3.0% |
| Total | 5.2% | 5.6% | 7.2% | 6.8% |



|  | 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 | $2.7 \pm 0.4 \pm 0.2$ |

|  |  |
|---|---|
| SSM H.M. | 4.59±0.14 $10^6$ $cm^{-2}$ $s^{-1}$ |
| SSM L.M. | 5.59±0.14 " " " |
| Exp. No oscill. | 5.0±0.9 " " " |

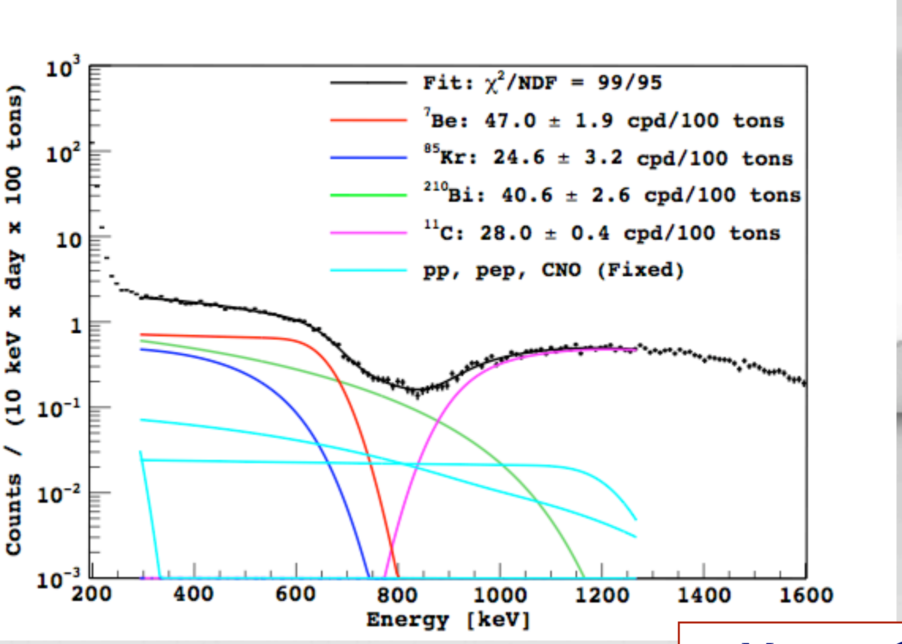
# The survival probability after 3 years of Borexino data taking



Pee ($^7$Be)=
$0.52^{+0.07}_{-0.;06}$

Pee($^8$B)=
$0.29 \pm 0.1$

$P_{ee}^{vac} - P_{ee}^{matter} =$
$0.23 \pm 0.073$



# Measurement of the solar neutrino flux from pep(1.445 MeV)

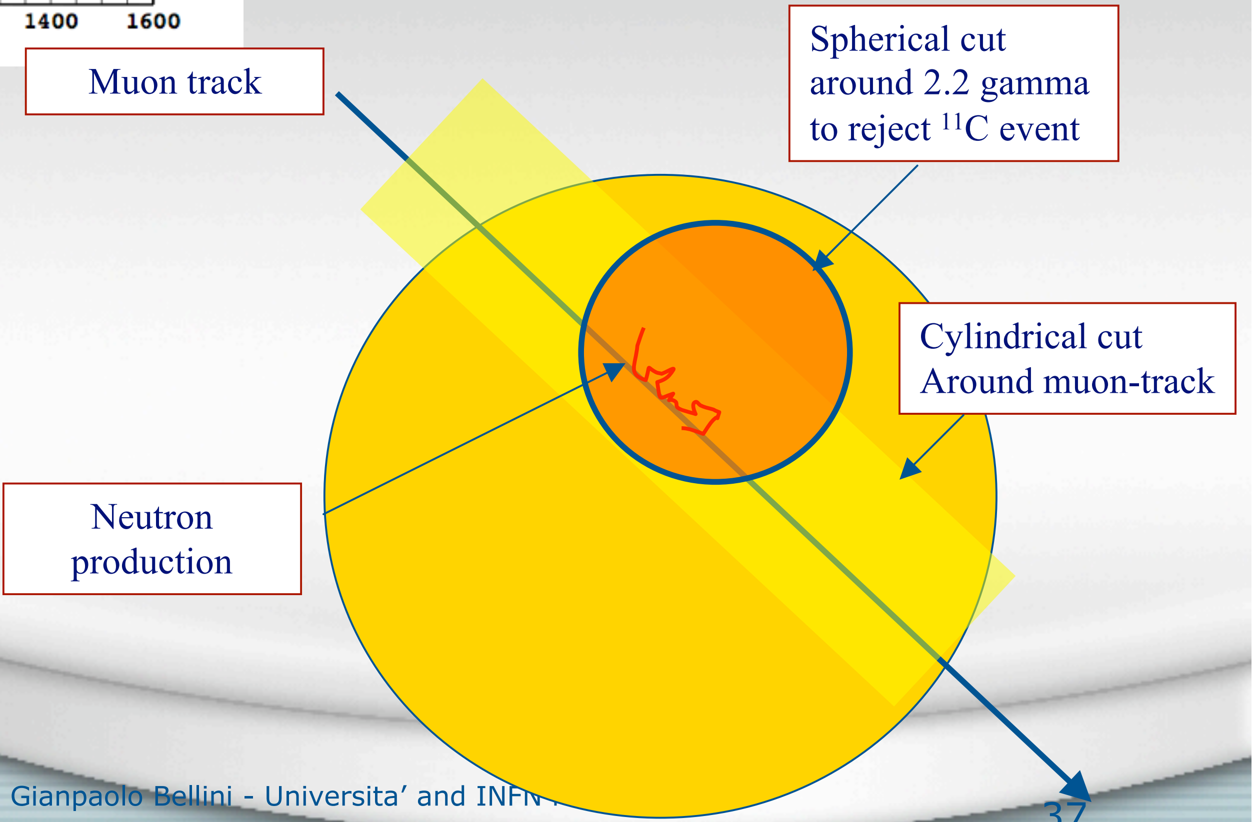
## Main problem: $^{11}$C

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

${}^{11}B + e^+ + \nu_e$

n capture

$\gamma$ (2.2 MeV)

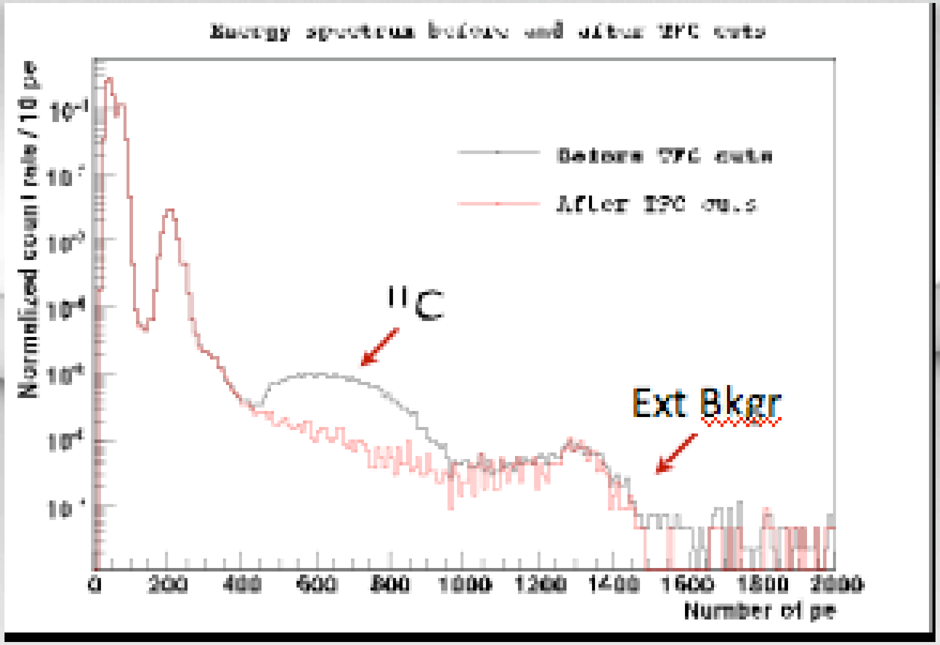


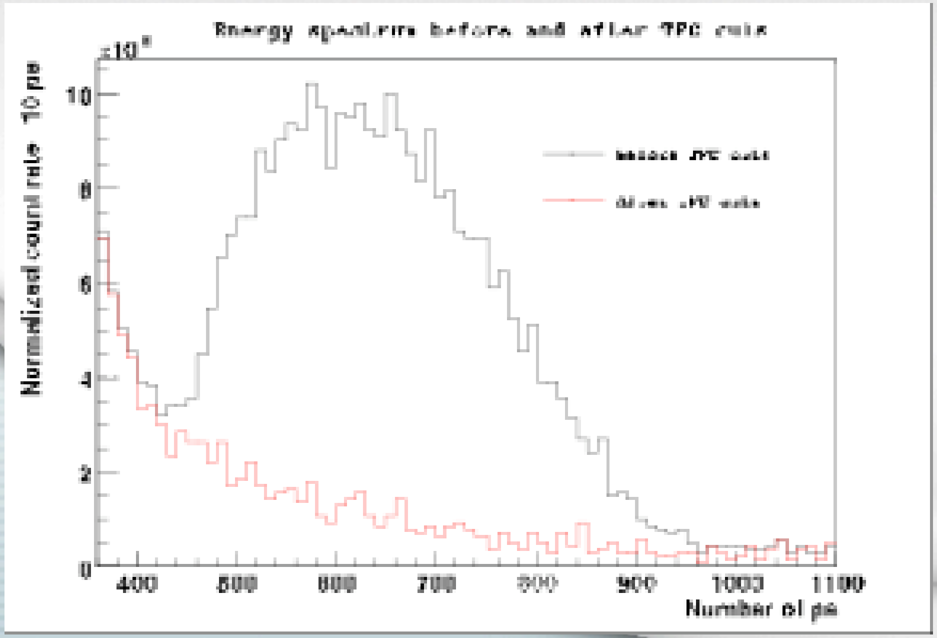
Muon track

Spherical cut around 2.2 gamma to reject $^{11}$C event

Cylindrical cut Around muon-track

Neutron production





$^{11}$C reduction 90%

Exposure loss 50%

Release of the result by July 2011.

# GEONEUTRINOS

- The radioactive decays are an important source of the terrestrial heat;

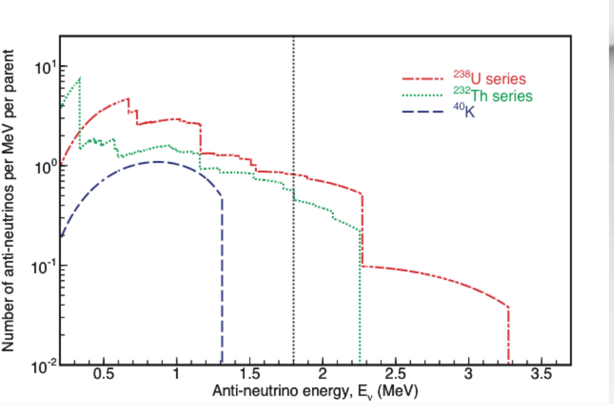
- The geo. estimations of the total terrestrial heat ranges from ≈31 to 44 TW. Geophysics models (Bulk Silicate Earth is the more accepted) predictions of the contribution of the radioactive decays to the Earth heat range from 100% ( max. radiogenic), to about 50% (B.S.E.) to a smaller % limited to what observed in the crust (minimum radiogenic)

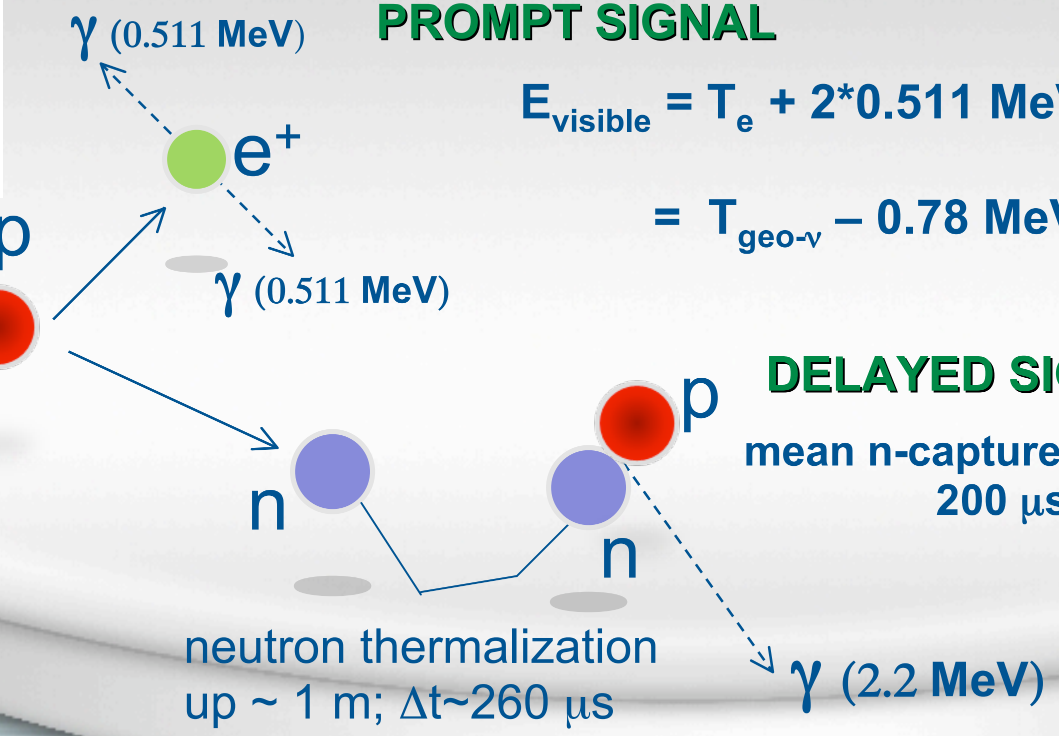
- Some geological measurements are obviously limited to the crust, where the investigations are based upon bore-holes.

- Radioactive decays are supposed to be present in the crust, in the mantle, but not in the core (chemical affinity).

- $^{238}U$, $^{232}Th$, $^{40}K$ chains ($T_{1/2}$ = (4.47, 14.0, 1.28) x $10^9$ years, resp.):

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV
$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV
$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV





**PROMPT SIGNAL**

$E_{visible} = T_e + 2*0.511\text{ MeV} =$

$= T_{geo\text{-}\nu} - 0.78\text{ MeV}$

**DELAYED SIGNAL**

**mean n-capture time on p 200 μs**

neutron thermalization up ~ 1 m; Δt~260 μs

**Energy threshold of**

$T_{geo\text{-}\nu}$ = **1.8 MeV**

# Background sources: reactor antineutrinos and internal radioactivity

For **reactors** we have considered 194(Europe) + 245(World) power stations

$$\Phi\left(E_{\bar{\nu}_e}\right)=\sum_{r=1}^{N_{react}}\sum_{m=1}^{N_{month}}\frac{T_m}{4\pi L_r^2}P_{rm}\sum_{i=1}^{4}\frac{f_{ri}}{E_i}\Phi_i\left(E_{\bar{\nu}_e}\right)P_{ee}\left(E_{\bar{\nu}_e};\vartheta_{12},\Delta m_{21}^2,L_r\right)$$

Loop over reactors, *r*

Loop over months, *m*

Loop over isotopes, *i*

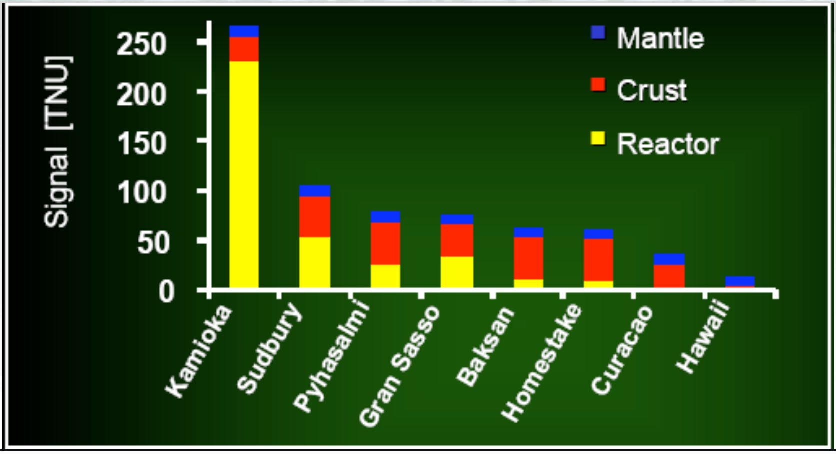
$P_{rm}$: Thermal Power (IAEA, EDF);

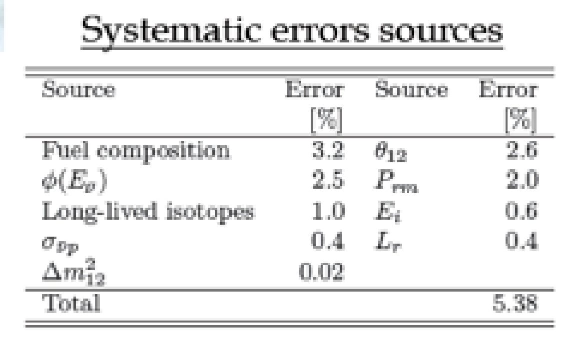
$f_{ri}$: Power fraction of isotope $i$ – $^{235}U$, $^{238}U$, $^{239}Pu$, $^{241}Pu$;

$L_r$: Distance reactor-detector;

$T_m$: Borexino livetime in months;

$P_{ee}$: anti-ν survival probability.





Systematic errors sources

| Source | Error [%] | Source | Error [%] |
|---|---|---|---|
| Fuel composition | 3.2 | $\theta_{12}$ | 2.6 |
| $\phi(E_{\bar{\nu}})$ | 2.5 | $P_{rm}$ | 2.0 |
| Long-lived isotopes | 1.0 | $E_i$ | 0.6 |
| $\sigma_{\bar{\nu}p}$ | 0.4 | $L_r$ | 0.4 |
| $\Delta m_{12}^2$ | 0.02 | | |
| Total | | | 5.38 |

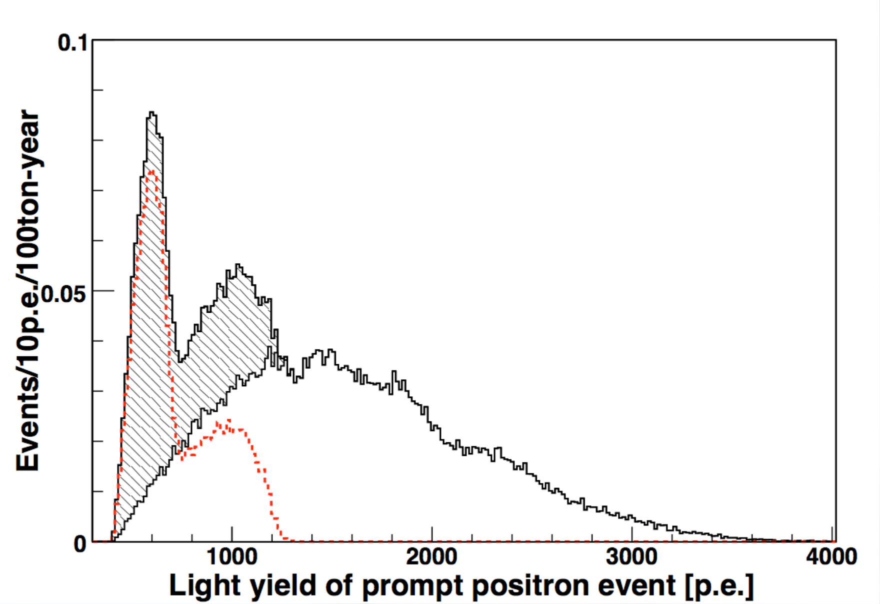
Background due to the **internal radioactivity**:

- $^{13}C(\alpha,n)^{16}O$ -very small due to the high level of radiopurity in Bx -$^{210}$Po
- muon induced cosmogenic activity:$^{9}$Li ($T_{1/2}$=178.3ms, β-n,Q= 5.3,7.4 MeV) $^{8}$He ( $T_{1/2}$=119ms, β-n ,Q= 1.8, 5.7, 8.6, 10.8, 11.2 MeV)- **rejected** with a veto of 2s after detected muons remove

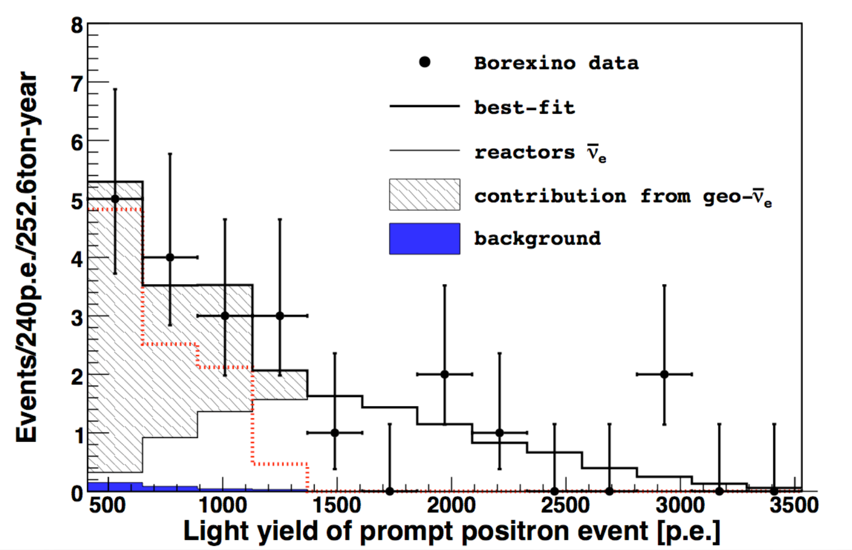
Total background **i. r.**: 0.14±0.02 events/100tons • year

- Data set: from Dec 2007 to Dec 2009
- Total live time: **537.2 live days**
- Fiducial exposure after muon cuts and including detection efficiency: **252.6 ton-year**
- **21 anti-ν candidates selected**

MC spectra for likelihood function

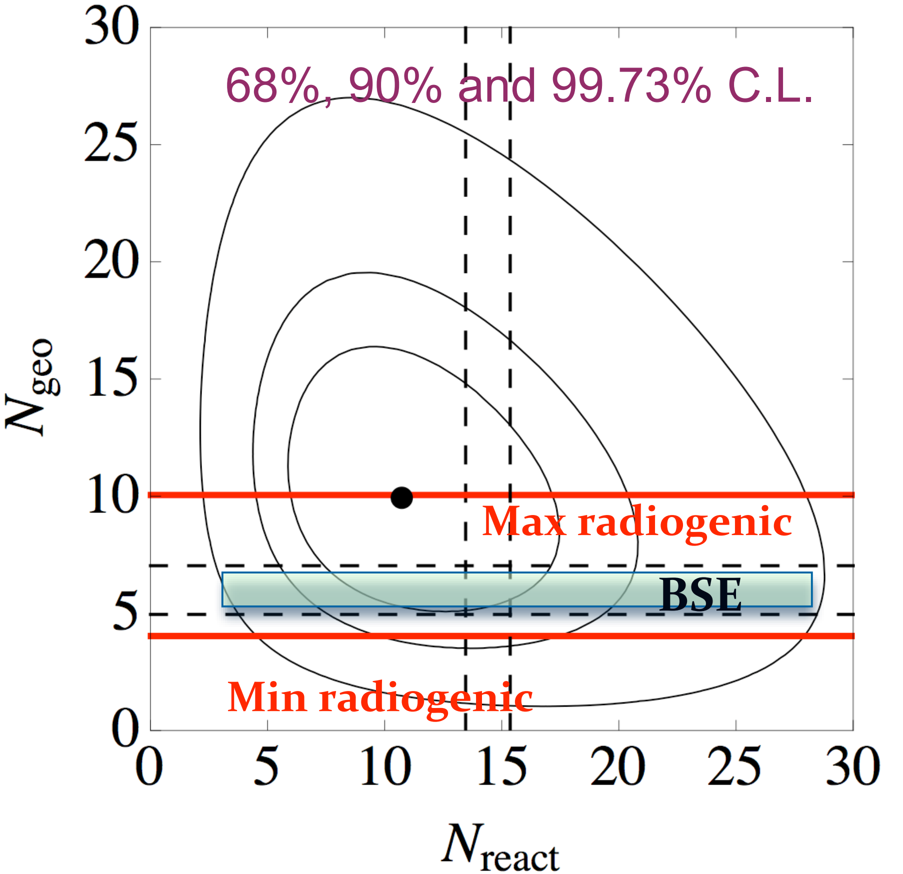


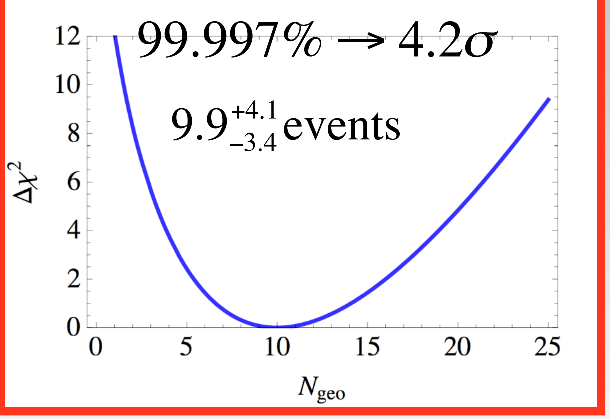
Unbinned ML best fit



# Best-fit parameters from the likelihood analysis

S/N~5/1



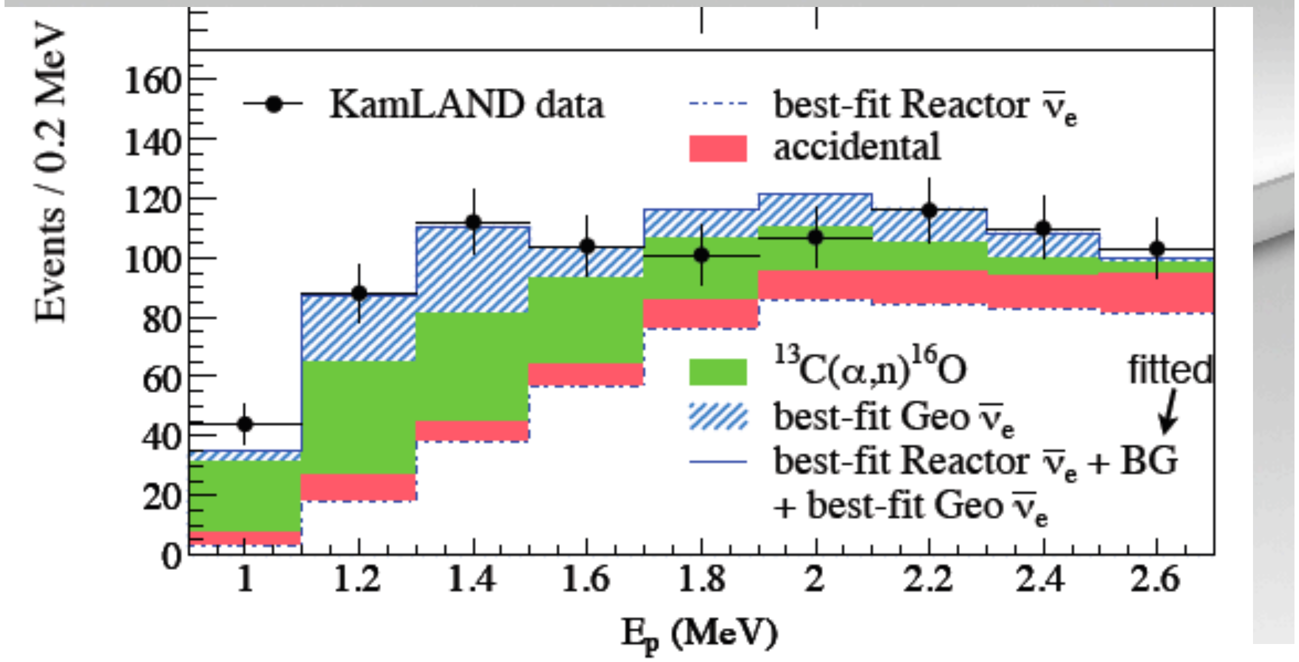


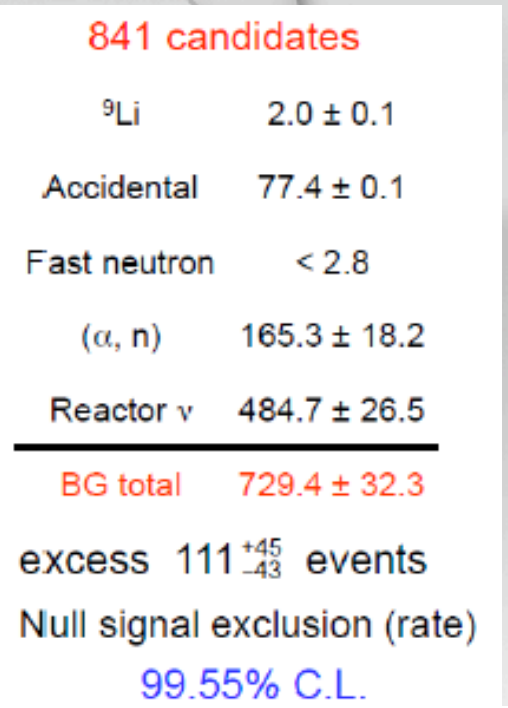
$N_{react} = 10.7^{+4.3}_{-3.4}$

No oscillation rejected at 2.9σ

The effective distance from Borexino is ~1000 km; $\phi_\nu \sim 10^5$ cm$^{-2}$ s$^{-1}$

Phys. Letters B 687(2010)299





841 candidates

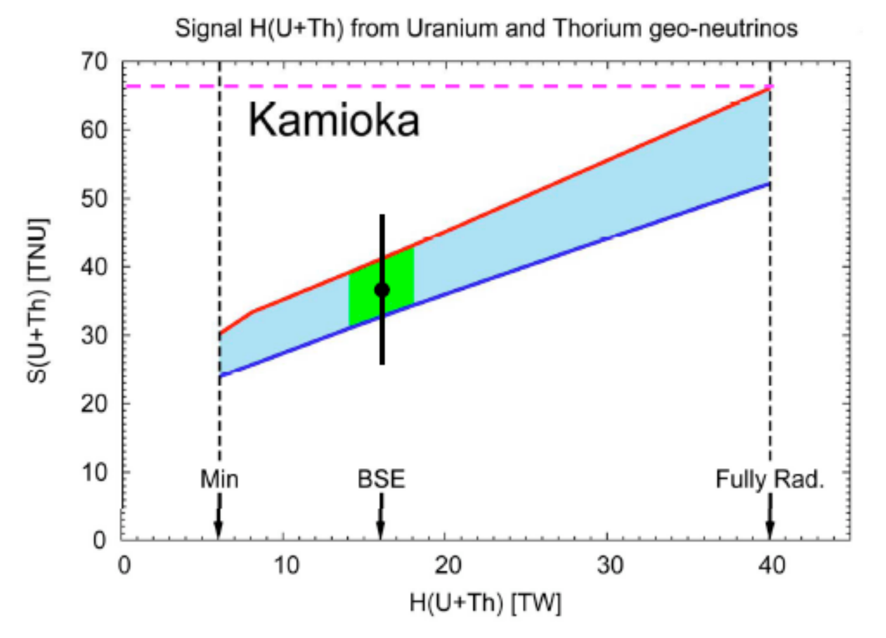
| | |
|---|---|
| $^9$Li | 2.0 ± 0.1 |
| Accidental | 77.4 ± 0.1 |
| Fast neutron | < 2.8 |
| (α, n) | 165.3 ± 18.2 |
| Reactor ν | 484.7 ± 26.5 |
| BG total | 729.4 ± 32.3 |

excess $111^{+45}_{-43}$ events

Null signal exclusion (rate)

99.55% C.L.

S/B ≈1:7 in Kamland



# Conclusions

@ In 3 years of data taking, Borexino has measured the solar $\nu$ from $^7$Be (<5%), from $^8$B with a lower threshold at 3 MeV and from pep (to be released soon).

@ The day/night in the $^7$Be region has been measured at 1%

@ These measurements provided the validation of the MSW-LMA model in the vacuum-driven oscillations and allowed the isolation of the LMA region in the $\Delta m^2$ vs $tg^2\theta$ plane with a global fit using only the solar $\nu$ data.

@ Experimental evidence of geo-neutrinos has been reached at 4.2 $\sigma$ C.L..

@ Best limits for non-paullian transitions and $\bar{\nu}$ in the Sun flux have been achieved

# What next

- # A re-purification campaign is in progress; $^{85}$Kr has been already reduced to negligible level, while $^{210}$Bi is halved. The campaign will be completed by the end 2011.

- # With a re-purified scintillator we plane to measure the pep flux with reduced error and the neutrinos from CNO (both in the transition region-possible check on the non standard interactions).

- # An analysis of the geo-neutrinos with higher statistics would allow a discrimination among the various geophysics models .

- # Campaigns with two artificial sources to check the hypothesis of short baseline oscillations and the existence of a sterile neutrino.

- An impressive flow of papers have been triggered by a few recent experimental hints and re-analysis of old results
  - @ MiniBoone indication for a 3th $\Delta m^2$ value in the $\nu$ oscillation phenomenon;
  - @ Very short base-line (VSBL) anomaly (reactors; gallium source anomaly);
  - @ W map (effective number of $\nu$ species: 4.34±0.87)

    **sterile neutrino?**
  - @ Minos (neutrino and antineutrino oscillation differ in $\Delta m^2$ ??)

    **non standard $\nu$ interactions? CPT violation?**

arXiv. hep-ex 0179257
hep-ph,1105.1705v1 and others

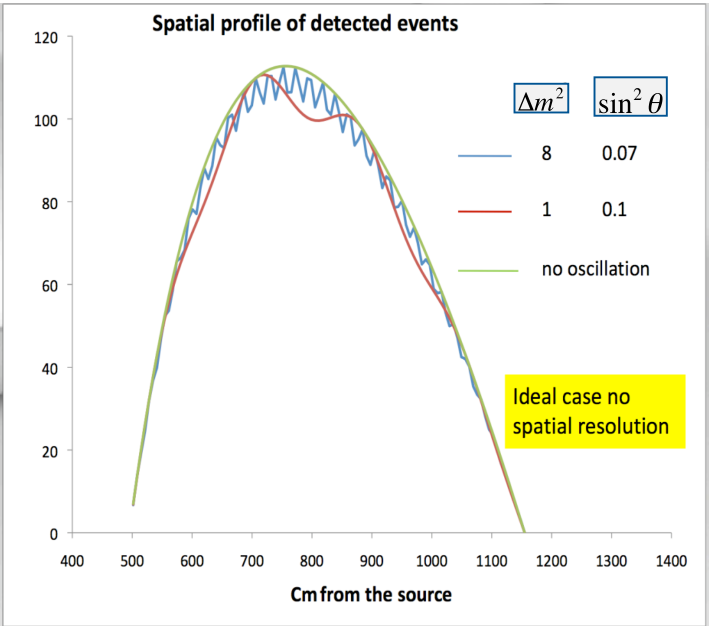
- Proposed measurement in Borexino with artificial sources:
  - $^{51}$Cr;0.747 MeV $\nu$ K capture–$\tau$=39.96d-5 Mci
  - $^{90}$Sr-$^{90}$Y; $\bar{\nu}$$\beta$ decay-1.8 MeV threshold-2 MeV av. energy $\tau$=1.52 $10^4$d-1 MCi

- Tunnel below Borexino →

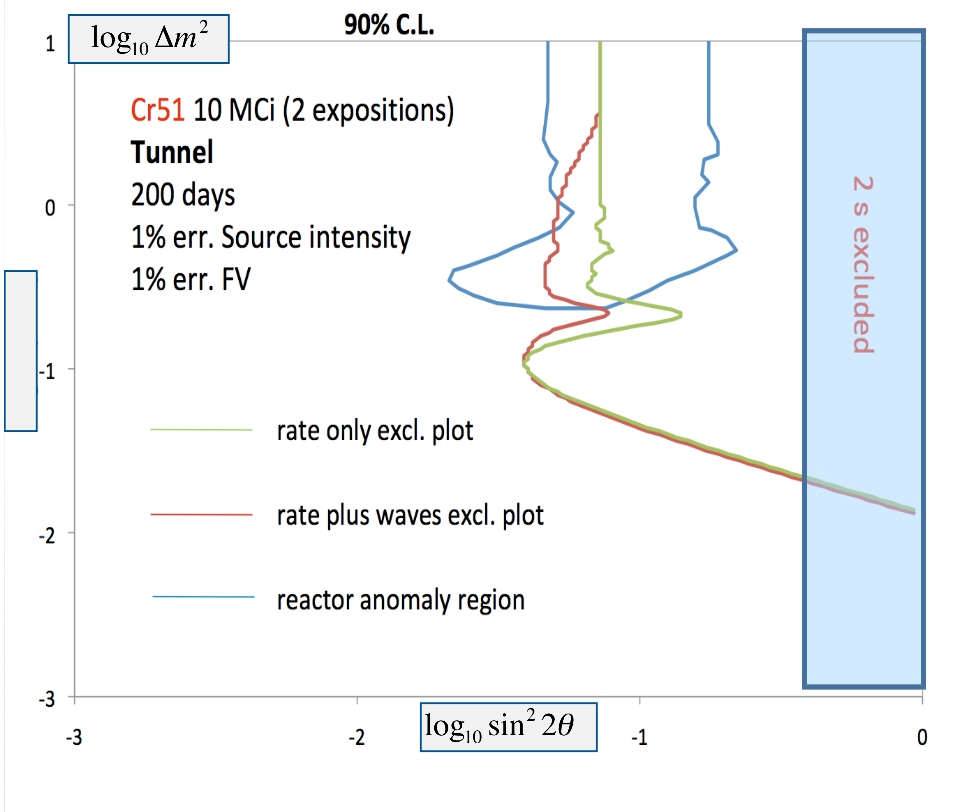
  4m from the inner vessel wall

  8.25 m from the detector centre

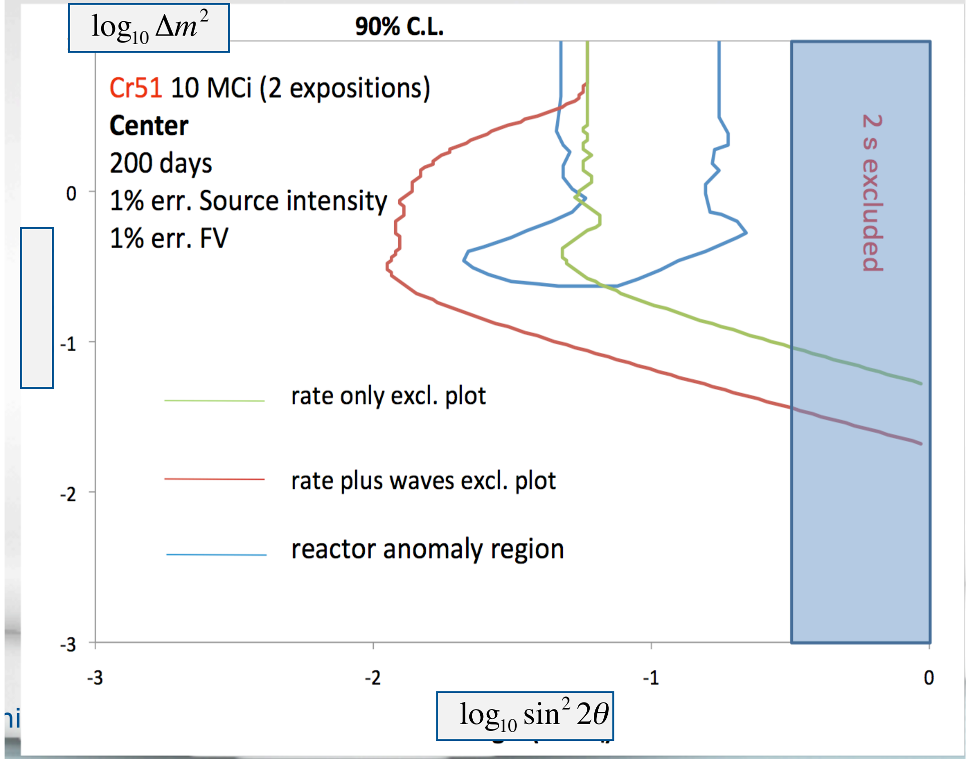
# Possibility to observe the oscillation pattern- Spatial resolution: 10-12 cm from 200 keV-10MeV



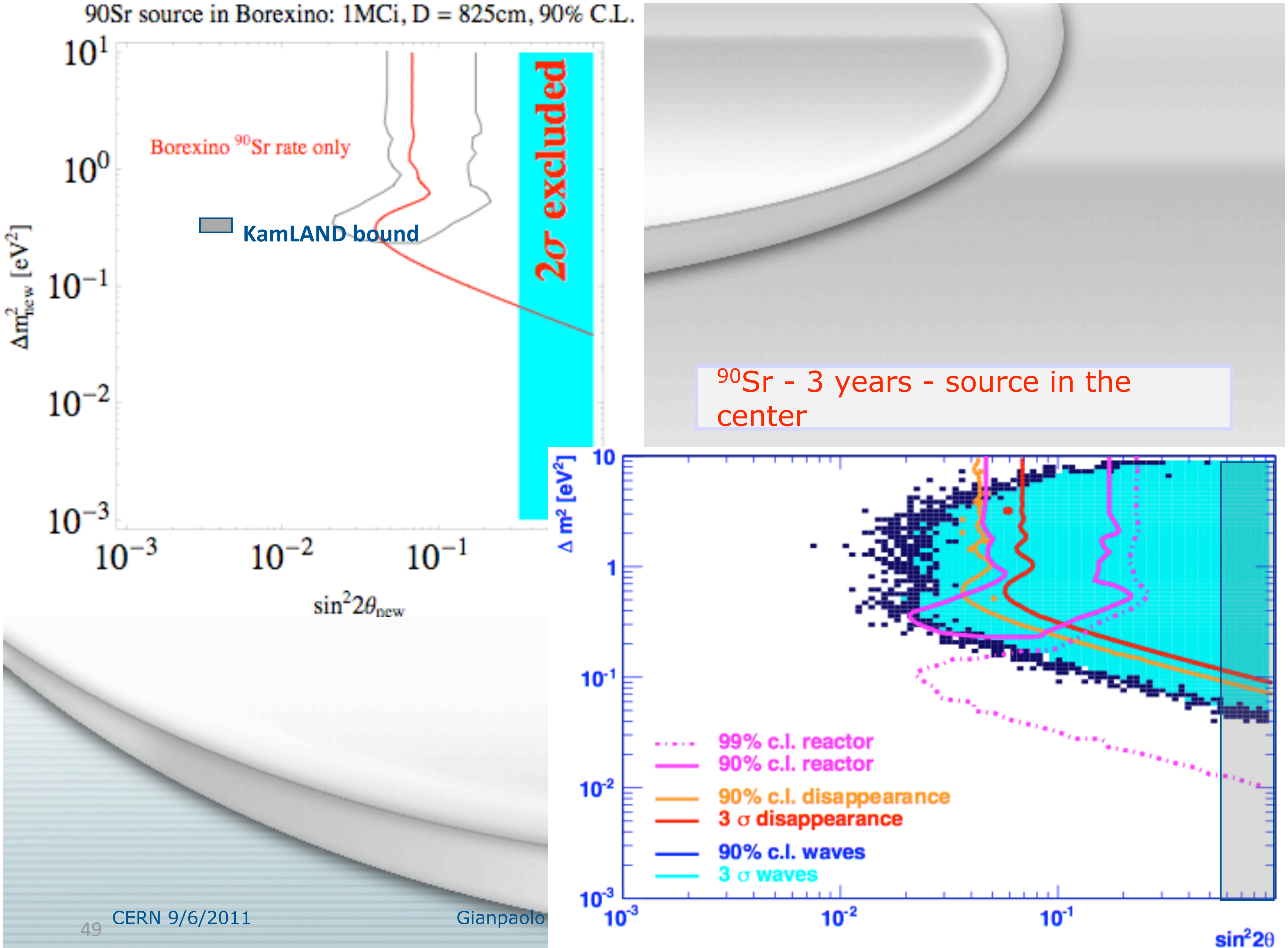
Ideal case no spatial resolution



Cr51 10 MCi (2 expositions)
**Tunnel**
200 days
1% err. Source intensity
1% err. FV



Cr51 10 MCi (2 expositions)
**Center**
200 days
1% err. Source intensity
1% err. FV



$^{90}$Sr - 3 years - source in the center

INFN

LNGS

Gran Sasso

Perugia

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Heidelberg

Hamburg

KFKI RMKI

Budapest

Milano

Genova

München

Kraków

Kurchatov Moscow

## *the Borexino Collaboration*

JINR Dubna

Princeton

Virginia Tech

UMass Amherst

Paris

St. Petersburg

2

# New limits obtained with the Borexino

| Channel | $E_0$, MeV | $\tau_{lim}$, y BOREXINO | $\tau_{lim}$, y CTF | Previous experiments and limits |
|---|---|---|---|---|
| $^{12}C \rightarrow ^{12}C^{NP} + \gamma$ | 17.5 | $5.0 \cdot 10^{31}$ | $2.1 \cdot 10^{27}$ | $4.2 \cdot 10^{24}$ NEMO-II |
| $^{16}O \rightarrow ^{16}O^{NP} + \gamma$ | 21.8 | - | $2.1 \cdot 10^{27}$ | $1.0 \cdot 10^{32}$ Kamiokande |
| $^{12}C \rightarrow ^{11}B^{NP} + p$ | 4.8-8.2 | $8.9 \cdot 10^{29}$ | $5.0 \cdot 10^{26}$ | $1.7 \cdot 10^{25}$ ELEGANT V.<br>$6.9 \cdot 10^{24}$ DAMA (Na+I) |
| $^{12}C \rightarrow ^{11}C^{NP} + n$ | 2.2 | $3.4 \cdot 10^{30}$ | $3.7 \cdot 10^{26}$ | $1.0 \cdot 10^{20}$ Kishimoto et al |
| $^{12}C \rightarrow ^{8}Be^{NP} + \alpha$ | 1.0-3.0 | - | $6.1 \cdot 10^{23}$ | - |
| $^{12}C \rightarrow ^{12}N^{NP} + e^- + \nu_e$ | 18.9 | $3.1 \cdot 10^{30}$ | $7.6 \cdot 10^{27}$ | $3.1 \cdot 10^{24}$ NEMO-II<br>$\sim 8 \cdot 10^{27}$ LSD |
| $^{12}C \rightarrow ^{12}B^{NP} + e^+ + \nu_e$ | 17.8 | $2.1 \cdot 10^{30}$ | $7.7 \cdot 10^{27}$ | $2.6 \cdot 10^{24}$ NEMO-II |

The Borexino results are 3-4 orders of magnitude stronger then CTF ones
The limits for NP transitions in $^{12}C$ with p-,n- and $\beta^{\pm}$- emissions are the best to date
The limit on the NP transition in $^{12}C$ with $\gamma$-emission is comparable to the same result for $^{16}O$ obtained using Kamiokande data for $\gamma$ BR=1
Borexino has unique parameters to study NP transitions with low Q

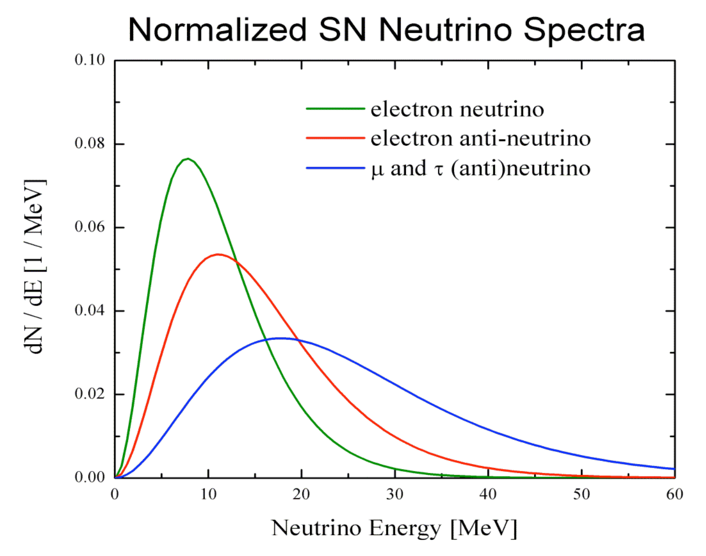
# The relative strength of the NP transitions to the Normal Transitions

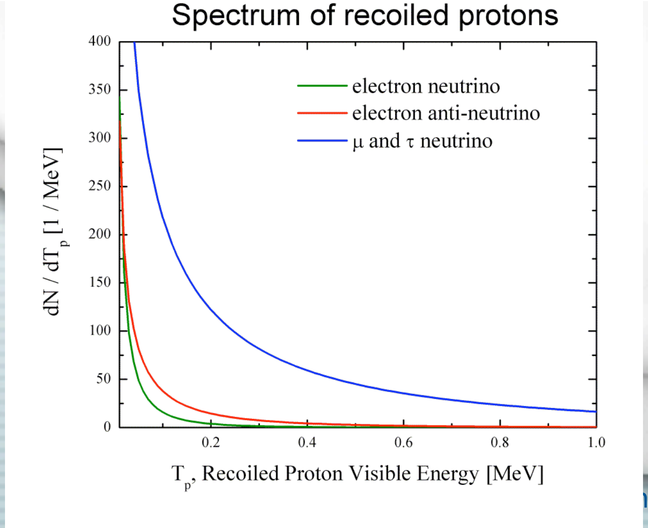
| Channel | $\lambda^{NP}$, $s^{-1}(^{12}C)$ | $\Gamma^{NT} = \hbar\lambda^{NT}$ | $\lambda^{NT}$, $s^{-1}(^{12}C)$ | $\lambda^{NP}/\lambda^{NT}$ | Previous |
|---|---|---|---|---|---|
| **$^{12}C \to {}^{12}C^{NP} + \gamma$** | $5.0 \cdot 10^{-39}$ | 0.0015 MeV | $2.3 \cdot 10^{18}$ | **$\leq 2.2 \cdot 10^{-57}$** | $\leq 2.3 \cdot 10^{-57}$ |
| **$^{12}C \to {}^{11}B(C)^{NP} + p(n)$** | $7.4 \cdot 10^{-38}$ | 12 MeV | $1.8 \cdot 10^{22}$ | **$\leq 4.1 \cdot 10^{-60}$** | $\leq 3.5 \cdot 10^{-55}$ |
| **$^{12}C \to {}^{12}N(B)^{NP} + e^{\pm} + \nu$** | $4.1 \cdot 10^{-38}$ | $1.4 \cdot 10^{-18}$ eV | $2.0 \cdot 10^{-3}$ | **$\leq 2.1 \cdot 10^{-35}$** | $\leq 6.5 \cdot 10^{-34}$ |

**Phys. Rev. C81:034317,2010**

# Signal from a Galactic Supernova

**Standard SN @ 10kpc**





**Borexino [$E_{tresh}$ = 250 keV]**
**(target mass 0.3kt)**

| Detection channel | Normal hierarchy | Inverted hierarchy |
|---|---|---|
| ES<br>($E_\nu > 0.25$ MeV) | 5 | 5 |
| Electron anti-neutrinos<br>($E_\nu > 1.8$ MeV) | 79 | 100 |
| ν-p ES<br>($E_\nu > 0.25$ MeV) | 55 | 55 |
| $^{12}C(\nu,\nu)^{12}C^*$<br>($E\gamma = 15.1$ MeV) | 17 | 17 |
| $^{12}C(\text{anti-}\nu,e+)^{12}B$<br>($E_{anti-\nu} > 14.3$ MeV) | 3 | 6 |
| $^{12}C(\nu,e-)^{12}N$<br>($E_\nu > 17.3$ MeV) | 9 | 6 |