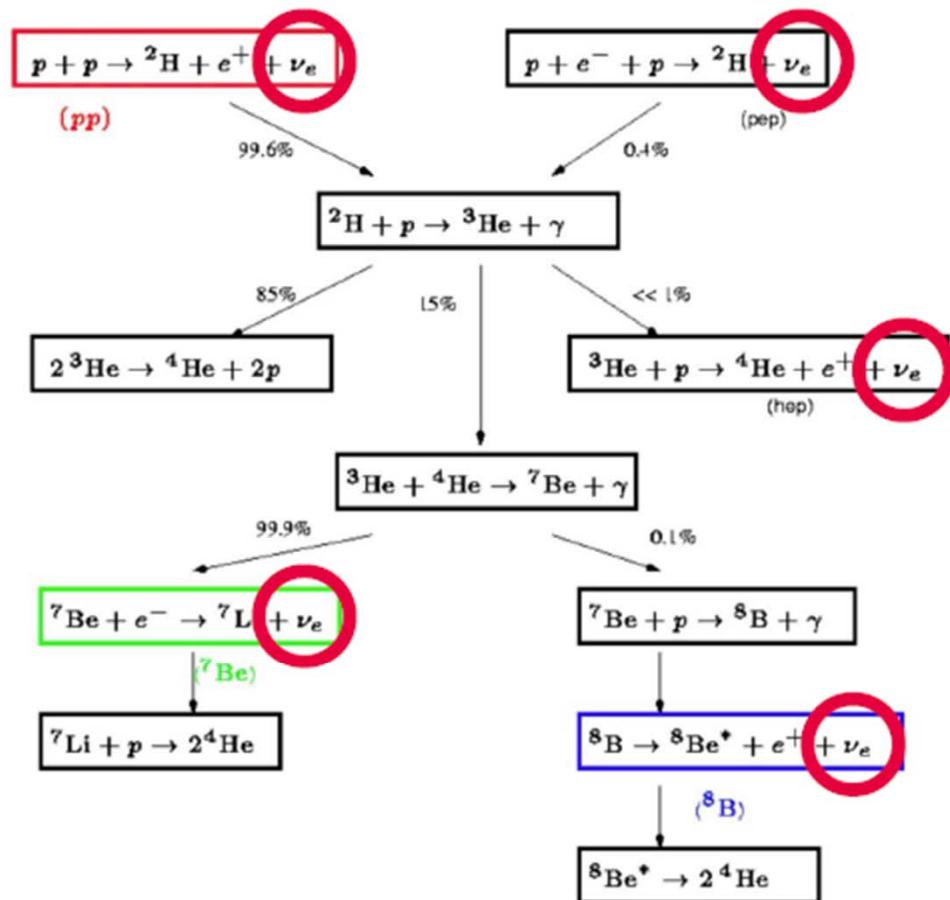


# Recent results and future perspectives of the solar neutrino experiment Borexino

Gioacchino Ranucci  
On Behalf of the Borexino Collaboration  
NPB 2012  
Shenzhen – 24/9/2012

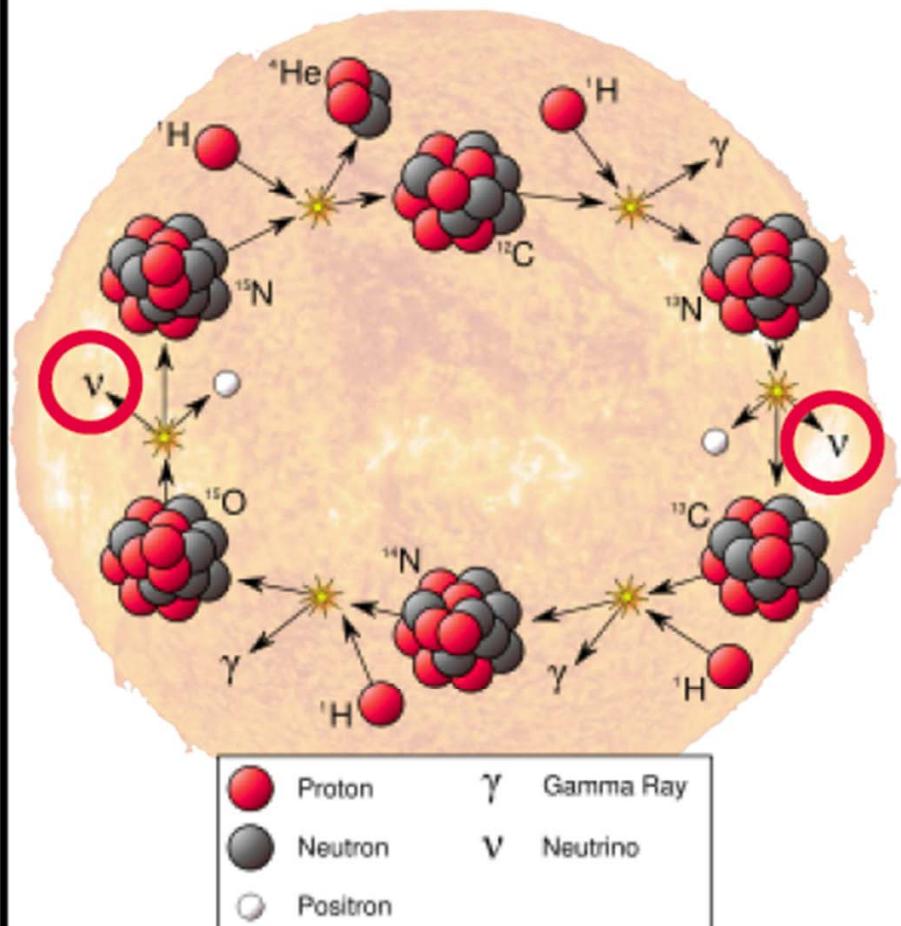
# Solar Neutrinos

## pp Chain



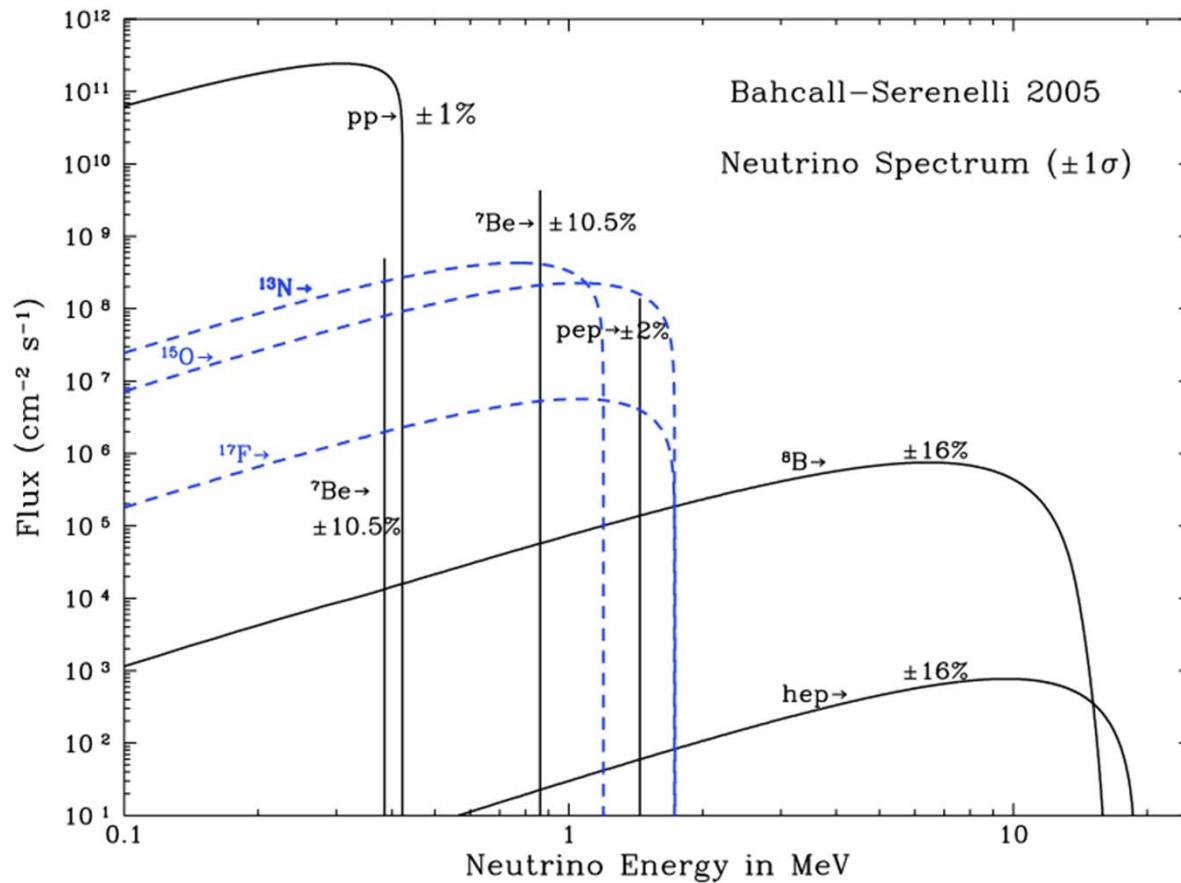
## CNO Cycle

(contributes ~1% of solar energy)



# Neutrino production in the Sun

Neutrino energy spectrum as predicted by the **Solar Standard Model (SSM)**



John Norris Bahcall  
([Dec. 30, 1934](#) – [Aug. 17, 2005](#))

${}^7\text{Be}$ : 384 keV (10%)  
862 keV (90%)  
Pep: 1.44 MeV

Surface metallicity  
composition controversy  
still open: High Z vs Low  
Z

# Solar neutrino experiments: a more than four decades long saga

Radiochemical experiments:

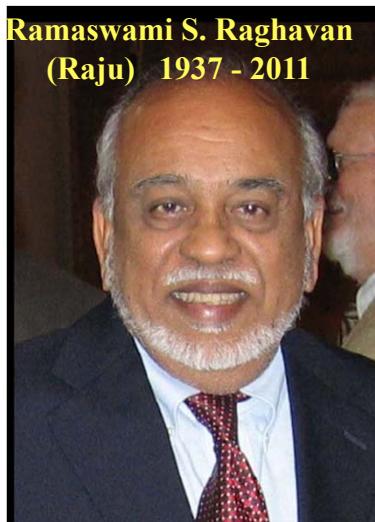
**Homestake (Cl)**

**Gallex/GNO (Ga)**

**Sage (Ga)**

Real time Cherenkov experiments

**Kamiokande/Super-Kamiokande**



**SNO**

Scintillator experiments

**Borexino** A light blue double-headed horizontal arrow pointing between the Borexino text and the Super-Kamiokande text.



Culminated with the proof of neutrino oscillation - MSW effect: resonant<sub>4</sub> conversion in matter



## Borexino Collaboration



Kurchatov  
Institute  
(Russia)



Dubna JINR  
(Russia)



APC Paris



Jagiellonian U.  
Cracow  
(Poland)



Heidelberg  
(Germany)



Munich  
(Germany)



Perugia



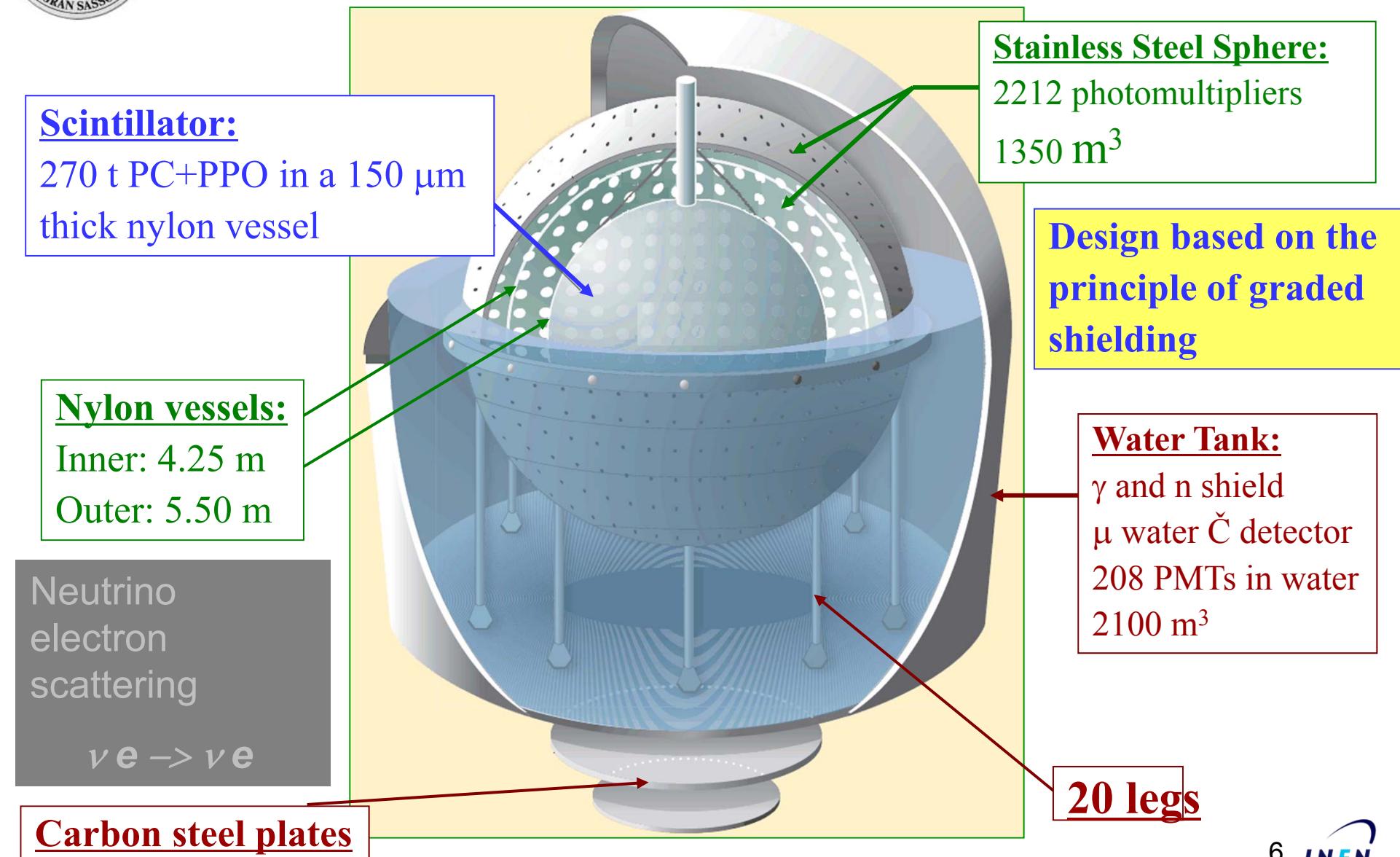
Princeton University

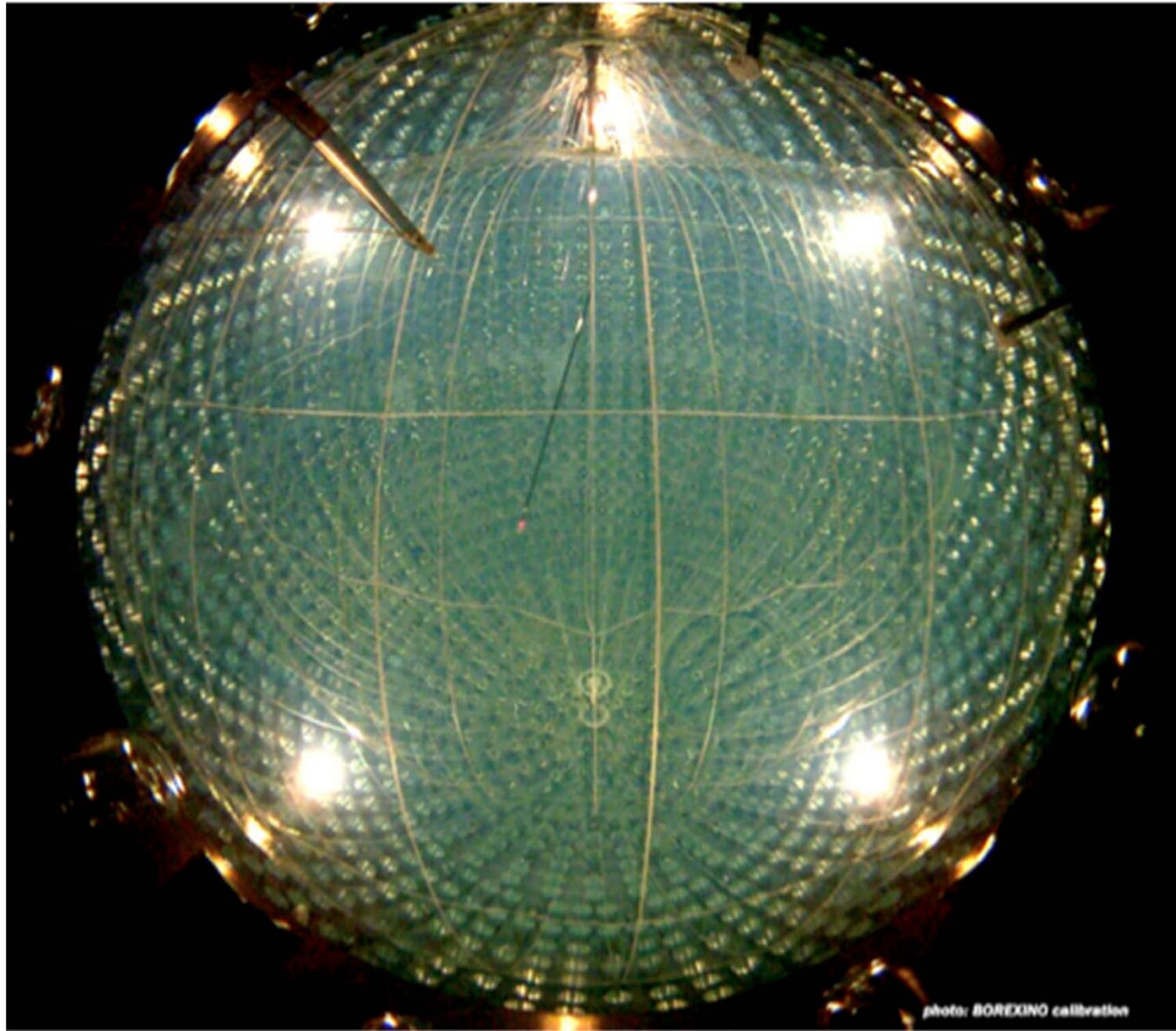


UMass

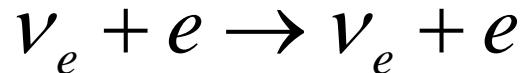


# Borexino at Gran Sasso: low energy real time detection





## Detection principle



Elastic scattering off the electrons of the scintillator  
threshold at  $\sim 60$  keV (electron energy)

Goals:  ${}^7\text{Be}$  flux (862 keV),  ${}^8\text{B}$  with a lower threshold down to  
3.0 MeV, pep (1.44 MeV), possibly pp and CNO in the  
future, Geo-antineutrinos , Supernovae neutrinos  
(in read already accomplished), requiring ultra-low  
**background – the big challenge of the experiment!**

Further proposed measurements with  $\nu$  and  $\bar{\nu}$  artificial  
sources for sterile neutrino search

Long term future : Double Beta decay with Xenon-136

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



# Radiopurity construction requirements

- Detector and plants materials

- Low intrinsic radioactivity
- Low radon emanation
- Chemical compatibility with PC

- Pipes, vessels and pipes

- Electropolished
- Cleaned with filtered detergents (Detergent-8, EDTA)
- Pickled and passivated with acids
- Rinsing with ultrapure water (class 20 – 50 MIL STD 1246 )

- Nylon vessels

- Good chemical and mechanical strength (small buoyancy)
- Low radioactivity (< 1 count/day/100 tons)
- Construction in low  $^{222}\text{Rn}$  clean room
- High purity nitrogen storage

- Thorn-EMI-ETL photomultipliers

- Low radioactivity Shott borosilicate glass (type 8246)
- 1.1 ns time gitter for good spatial resolution
- (Al) light cones for uniform light collection in the fiducial volume
- mu-metal shilding for the earth magnetic field
- 384 PMTs with no cones for muon identification in the buffer region

- Leak tightness

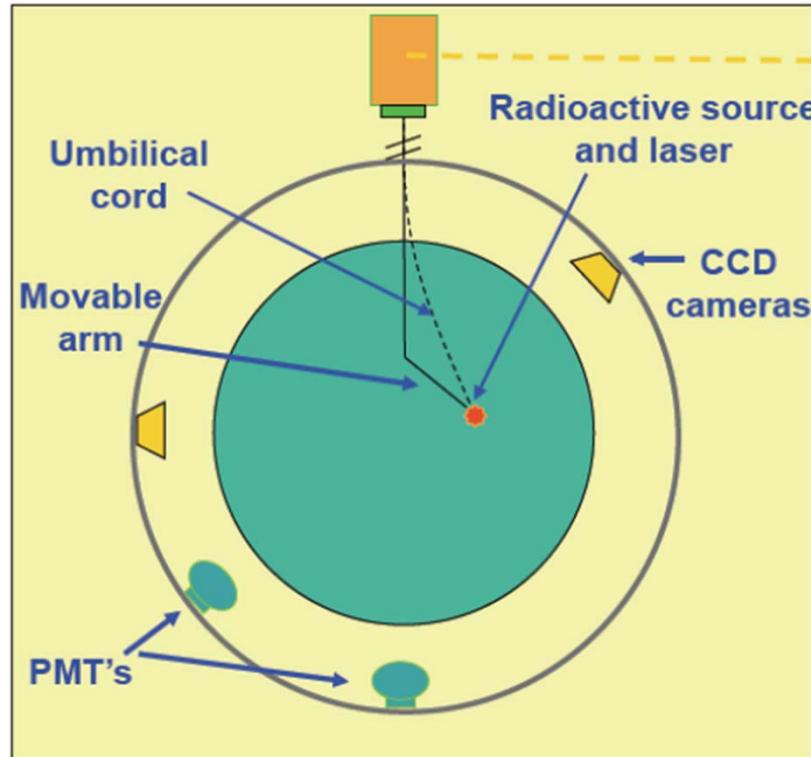
- Leak rate < 10<sup>-8</sup> atm cc /s
- Nitrogen blanketing on critical elements like pumps, valves, big flanges
- Double seal metal gaskets

- Clean rooms

- Mounting room in class 100
- Inner detector in class 1.000
- Outer detector in class 100.000

Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final
Name	Source	Typical	Required	Hardware	Software	Achieved
$\mu$	cosmic	$\sim 200 \text{ s}^{-1} \text{ m}^{-2}$ @ sea level	$< 10^{-10} \text{ s}^{-1} \text{ m}^{-2}$	underground water detector	Cerenkov PS analysis	$< 10^{-10}$ eff. > 0.9992
$\gamma$	rock			water	fid. vol.	negligible
$\gamma$	PMTs, SSS			buffer	fid. vol.	negligible
$^{14}\text{C}$	intrinsic PC	$\sim 10^{-12} \text{ g/g}$	$\sim 10^{-15} \text{ g/g}$	selection	threshold	$\sim 2 \cdot 10^{-18} \text{ g/g}$
$^{238}\text{U}$ $^{232}\text{Th}$	dust, metallic	$10^{-5}\text{-}10^{-6} \text{ g/g}$	$< 10^{-16} \text{ g/g}$	distillation, W.E., filtration, mat. selection, cleanliness	tagging, $\alpha/\beta$	$(1.67 \pm 0.06) 10^{-17} \text{ g/g}$ $(4.6 \pm 0.8) 10^{-18} \text{ g/g}$
$^{7}\text{Be}$	cosmogenic	$\sim 3 \cdot 10^{-2} \text{ Bq/t}$	$< 10^{-6} \text{ Bq/t}$	distillation	--	not seen
$^{40}\text{K}$	dust, PPO	$\sim 2 \cdot 10^{-6} \text{ g/g}$ (dust)	$< 10^{-18} \text{ g/g}$	distillation, W.E.	--	not seen
$^{210}\text{Po}$	surface cont. from $^{222}\text{Rn}$		$< 1 \text{ c/d/t}$	distillation, W.E., filtration, cleanliness	fit	May '07: 70 c/d/t Jan '10: $\sim 1 \text{ c/d/t}$
$^{222}\text{Rn}$	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	$< 10 \text{ cpd } 100 \text{ t}$	$\text{N}_2$ stripping cleanliness	tagging, $\alpha/\beta$	$< 1 \text{ cpd } 100 \text{ t}$
$^{39}\text{Ar}$	air, cosmogenic	$17 \text{ mBq/m}^3$ (air)	$< 1 \text{ cpd } 100 \text{ t}$	$\text{N}_2$ stripping	fit	$<< 85\text{Kr}$
$^{85}\text{Kr}$	air, nuclear weapons	$\sim 1 \text{ Bq/m}^3$ (air)	$< 1 \text{ cpd } 100 \text{ t}$	$\text{N}_2$ stripping	fit	$30 \pm 5 \text{ cpd/100 t}$

# Calibration campaign



	$\gamma$							
	$^{57}\text{Co}$	$^{139}\text{Ce}$	$^{203}\text{Hg}$	$^{85}\text{Sr}$	$^{54}\text{Mn}$	$^{65}\text{Zn}$	$^{60}\text{Co}$	$^{40}\text{K}$
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	$n + ^{12}\text{C}$	n+Fe
2.226	4.94	$\sim 7.5$

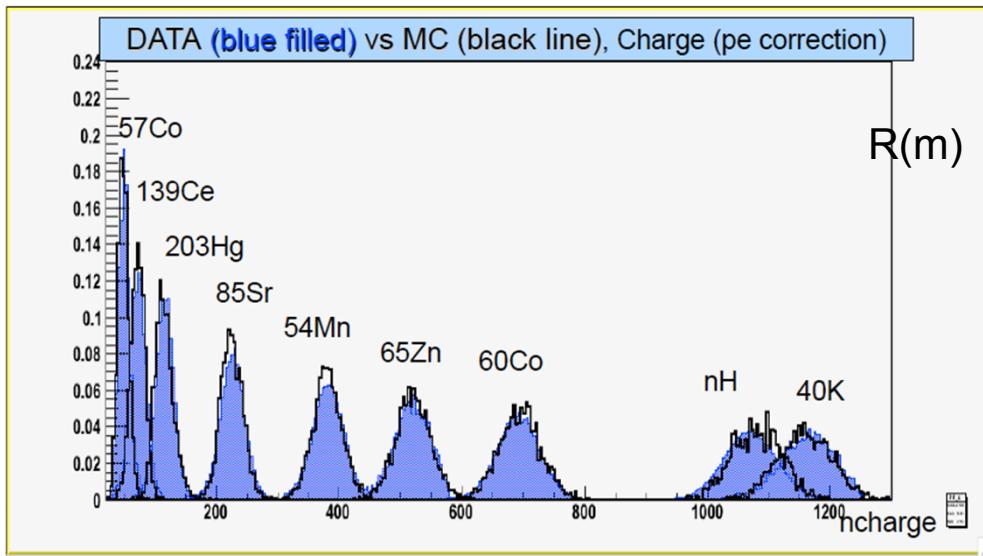
MeV

- $^{222}\text{Rn}$  loaded scintillator
- $^{214}(\text{Bi-Po}) \rightarrow \alpha/\beta$  discrim.
  - Position
  - energy response vs position

## Low energy range (0.14-2 MeV) calibration

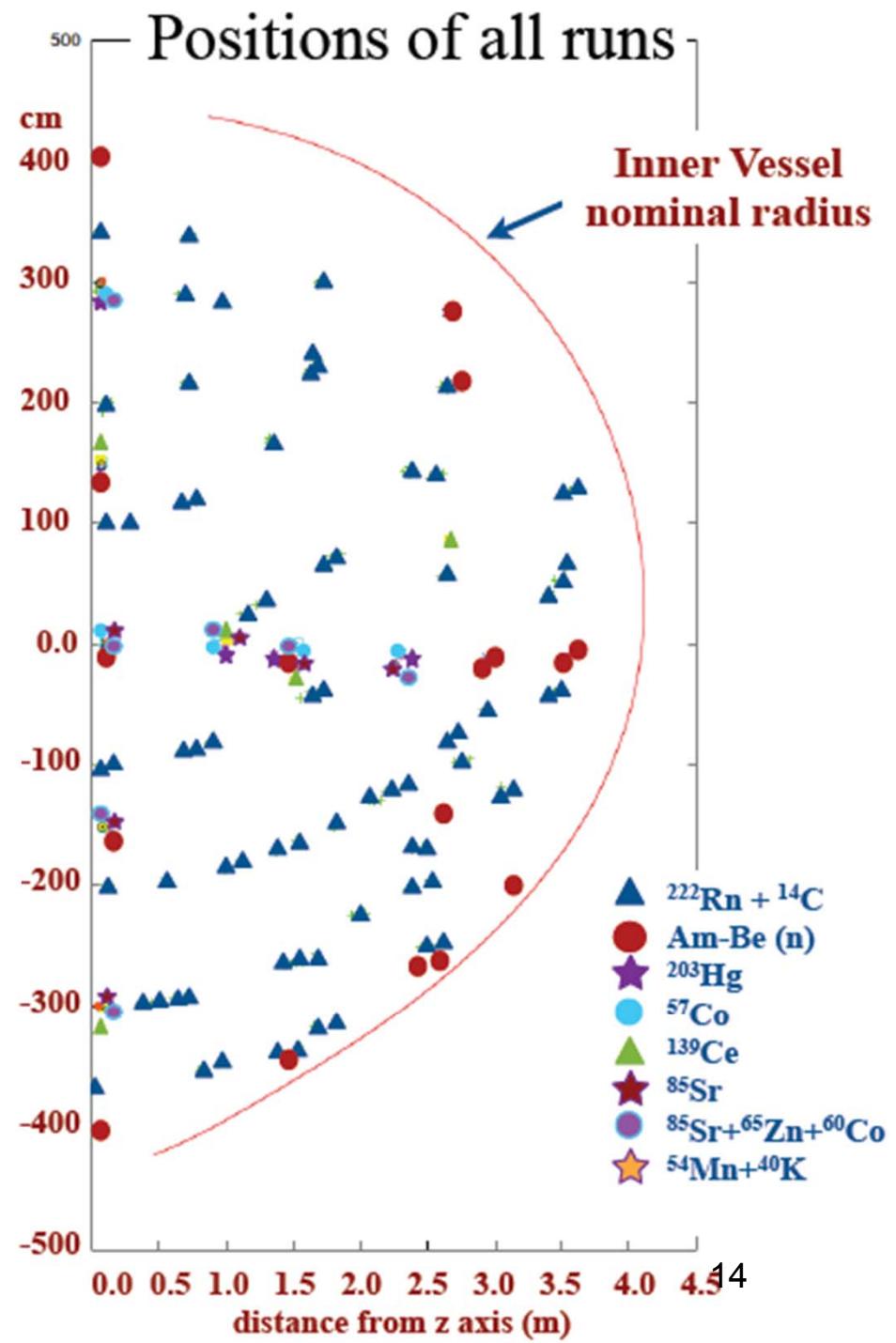
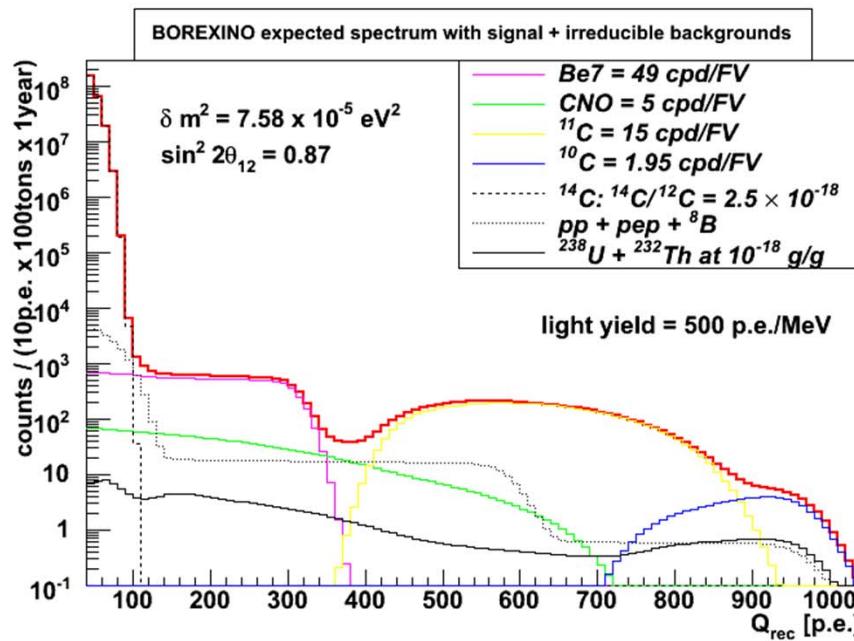
### Energy scale- Resolution

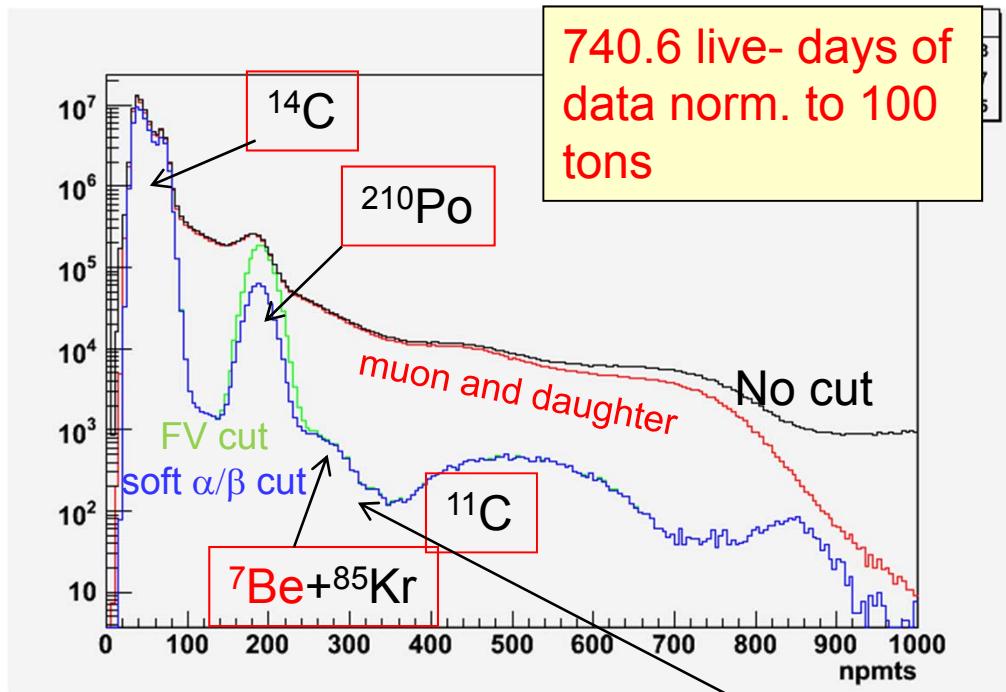
$\frac{5\%}{\sqrt{E}}$  from 200 keV to 2 MeV



- @ MC tuned on  $\gamma$  source results
- @ Determination of Light yield and of the Birks parameter  $k_B$   
 L.Y. → obtained from the  $\gamma$  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  $\sigma$ )**
- @ Fiducial volume uncertainty:  $\boxed{\rangle^{+0.5\%}_{-1.3\%}} (1 \sigma)$

## MC prediction of signal + intrinsic Background





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

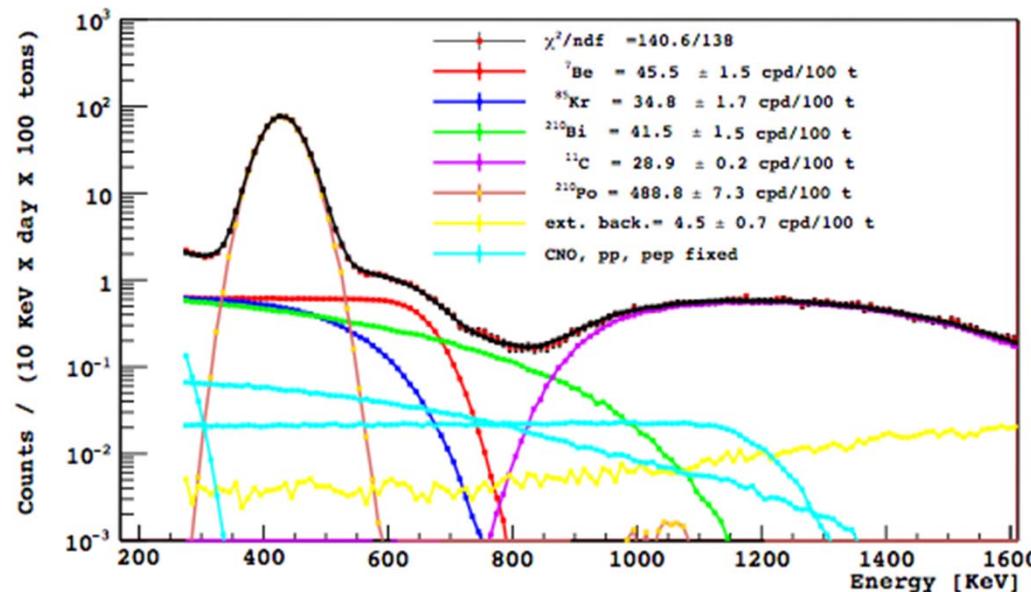
The spectrum after the cuts witnesses the unprecedented ultra-low background achieved in Borexino

**14C**— $\beta$  emitter-156 keV end point

**210Po**— $\alpha$  emitter- likely from the surfaces of the plumbing lines

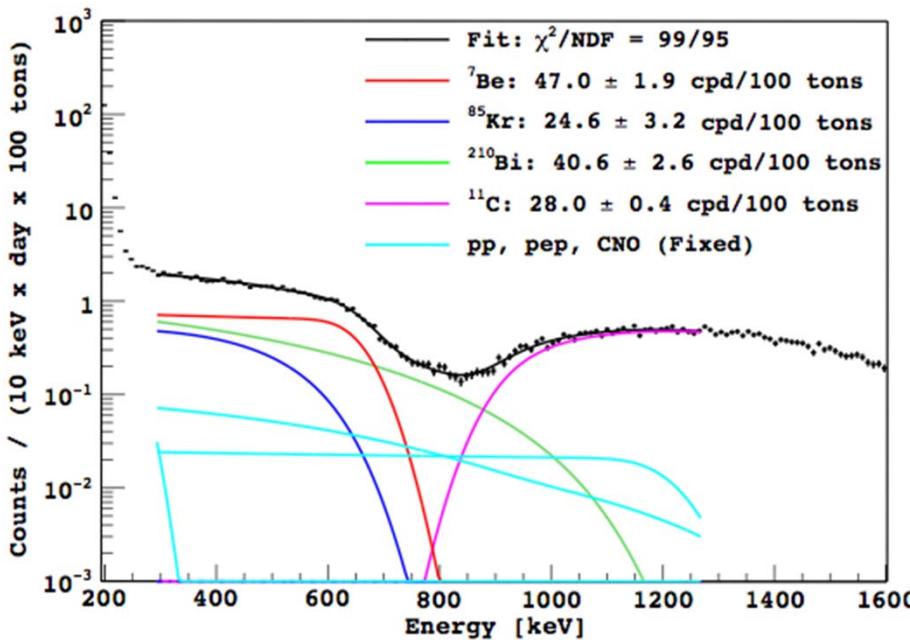
**11C**— $\beta^+$  emitter -cosmogenic-  
1.2  $\mu/\text{m}^2 \text{ h}$

The scattering edge is the unambiguous signature of the  ${}^7\text{Be}$  solar neutrino detection.  ${}^{85}\text{Kr}$  obtained via  $\beta$ - $\gamma$  coincidence analysis  
 $30 \pm 5.3 \pm 1.5 \text{ cpd}/100 \text{ t}_{15}$



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

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



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

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

# Result

${}^7\text{Be}(0.862): 46 \pm 1.5 \text{ (stat.)} \begin{array}{l} +1.5 \\ -1.6 \end{array} \text{(syst)cpd/100 tons}$

Corresponding to an equivalent  $\nu_e$  flux of  $(2.78 \pm 0.13) \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$

By assuming the MSW-LMA solution the absolute  ${}^7\text{Be}$  solar neutrino flux measure is  $(4.84 \pm 0.24) \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$

The ratio of our measurement to the SSM prediction is  $f_{\text{Be}} = 0.97 \pm 0.09$

Other components  
in the fit

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

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

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

# Day/Night asymmetry in ${}^7\text{Be}$ 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)

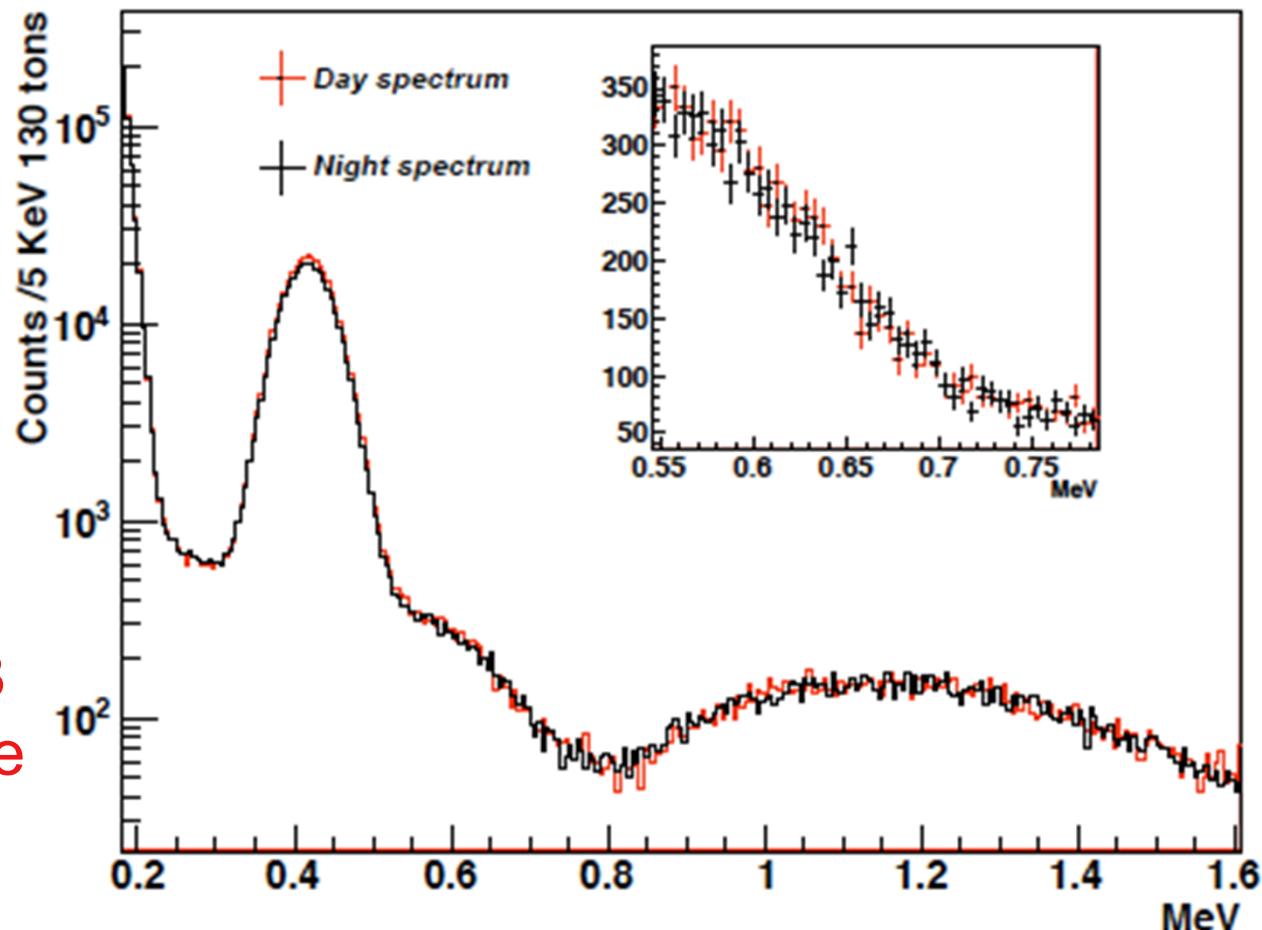
#  $\nu$  energy window:  
550-715 keV

# correction for the  
geometrical  
seasonal variation  
( $\pm 3\%$ ) applied

$$A_{dn} = 0.007 \pm 0.073$$

sys. error negligible

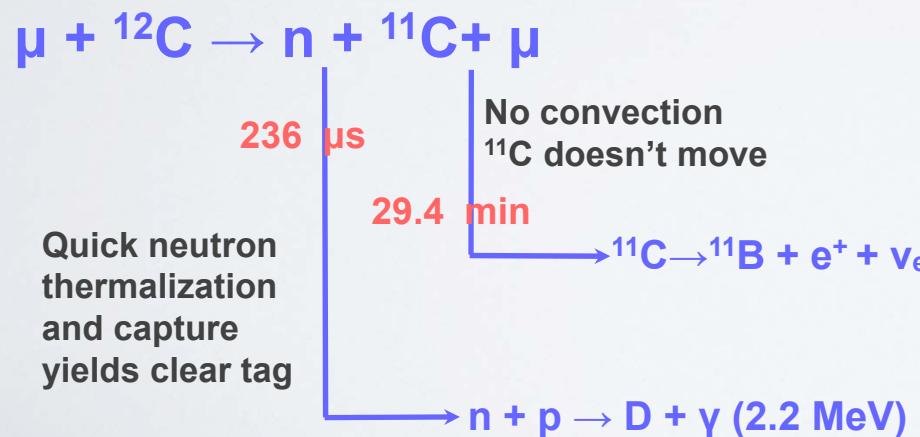
Important for the  
global oscillation  
analysis



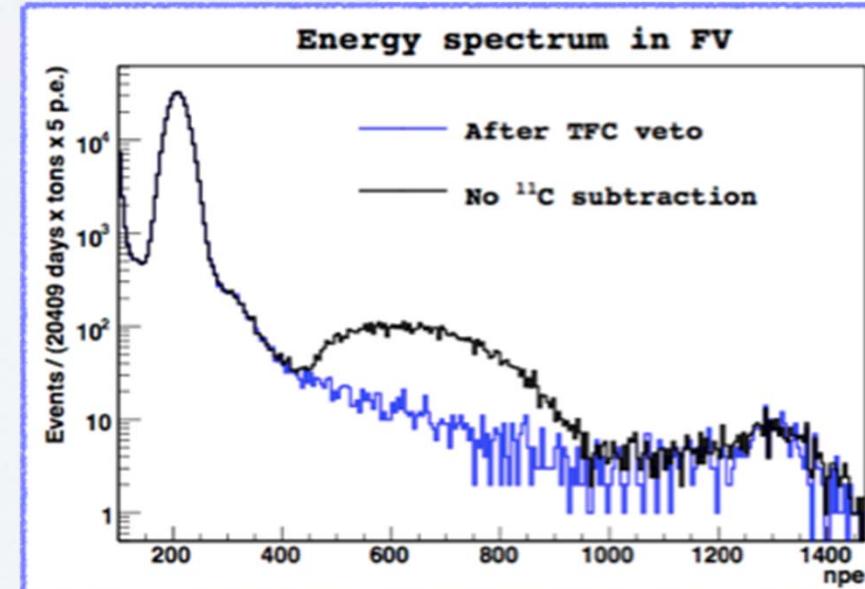
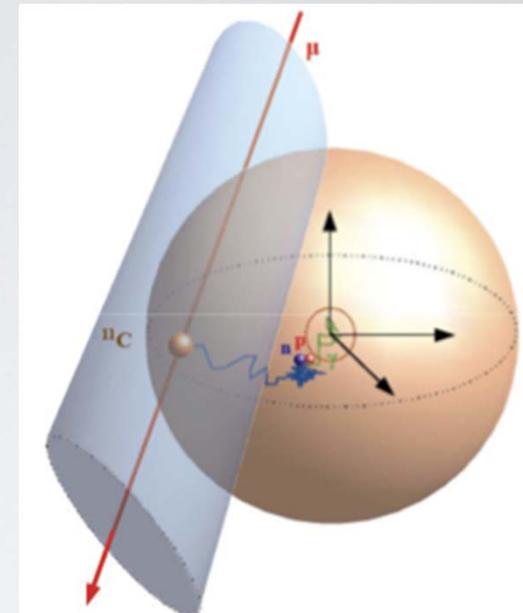
# FIRST DETECTION of PEP neutrinos

- Borexino obtained first evidence of **pep neutrinos**
  - Thanks to the very low background and analysis tools developed for  $^{11}\text{C}$  rejection
    - Three fold coincidence tagging of  $^{11}\text{C}$  events
    - $\beta^+ - \beta^-$  separation exploiting **positronium** induced pulse shape distortion
    - Multivariate maximum likelihood test using all available information

## • Three-fold coincidence



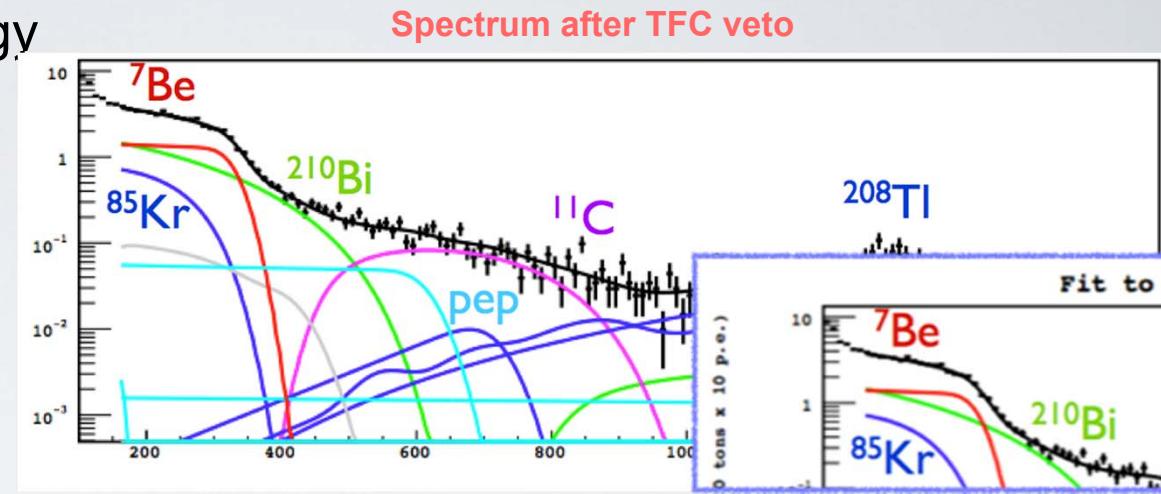
PHYSICAL REVIEW C 74, 045805 (2006)



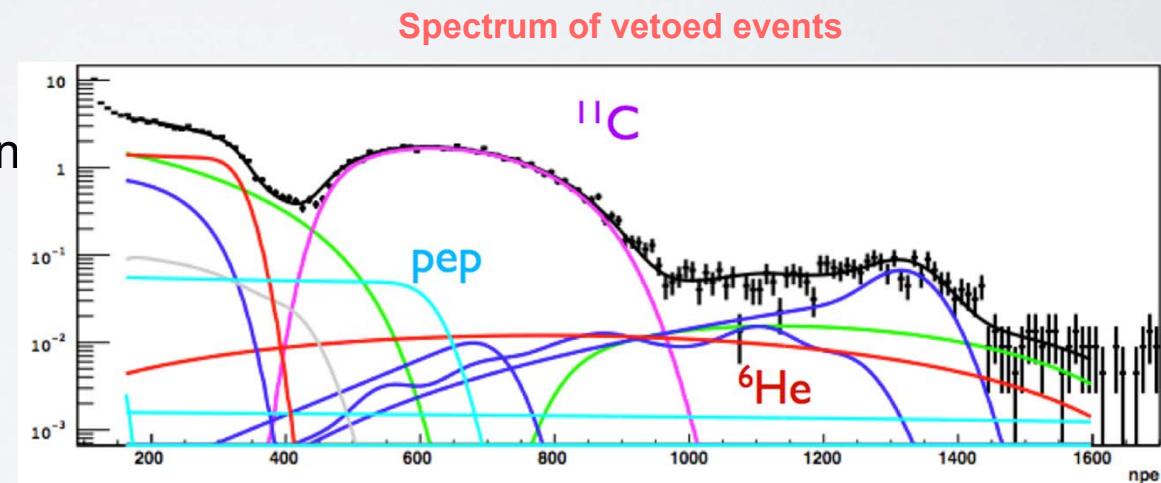
# FIRST DETECTION of PEP neutrinos

- Multidimensional fit strategy

- Binned likelihood which includes
  - **energy spectrum**
  - **BDT parameter**
  - **radial shape**



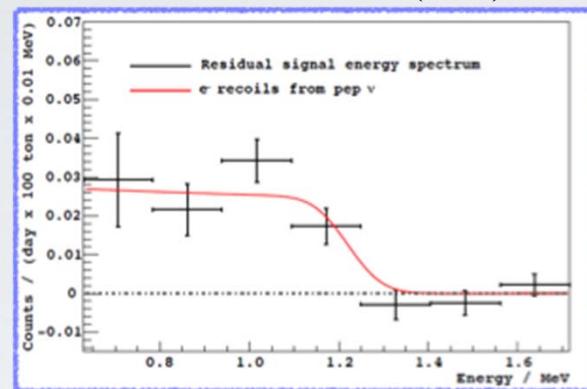
- Simultaneous fit to events surviving TFC veto and to rejected events, constrainin non-cosmogenic species to be the same
- Hundreds of MC experiments done to check the strategy



# FIRST DETECTION of PEP neutrinos

- Rate:  $3.1 \pm 0.6_{\text{(stat)}} \pm 0.3_{\text{(sys)}}$  cpd/100 t

PRL 108, 051302 (2012)



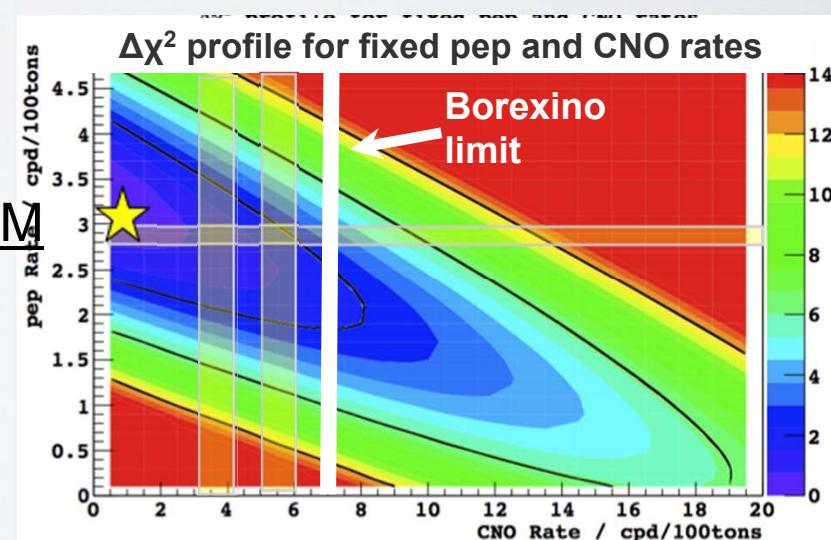
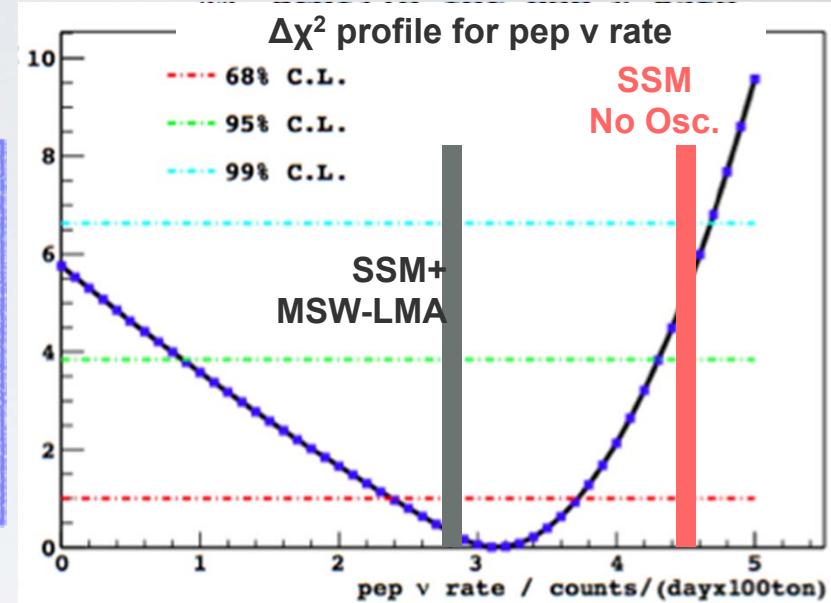
- No oscillations excluded at 97% c.l.
- Absence of pep solar ν excluded at 98% c.l.

- Assuming MSW-LMA:

- $\Phi_{\text{pep}} = 1.6 \pm 0.3 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$

- CNO limit obtained assuming pep @ SSM

- CNO rate < 7.1 cpd/100 t (95% c.l.)  
(1.5 times the SSM prediction)



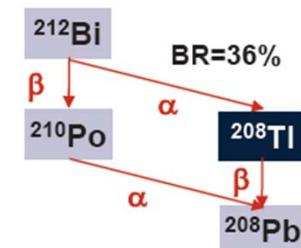
## $^8\text{B}$ with lower threshold at 3 MeV (488 live days)

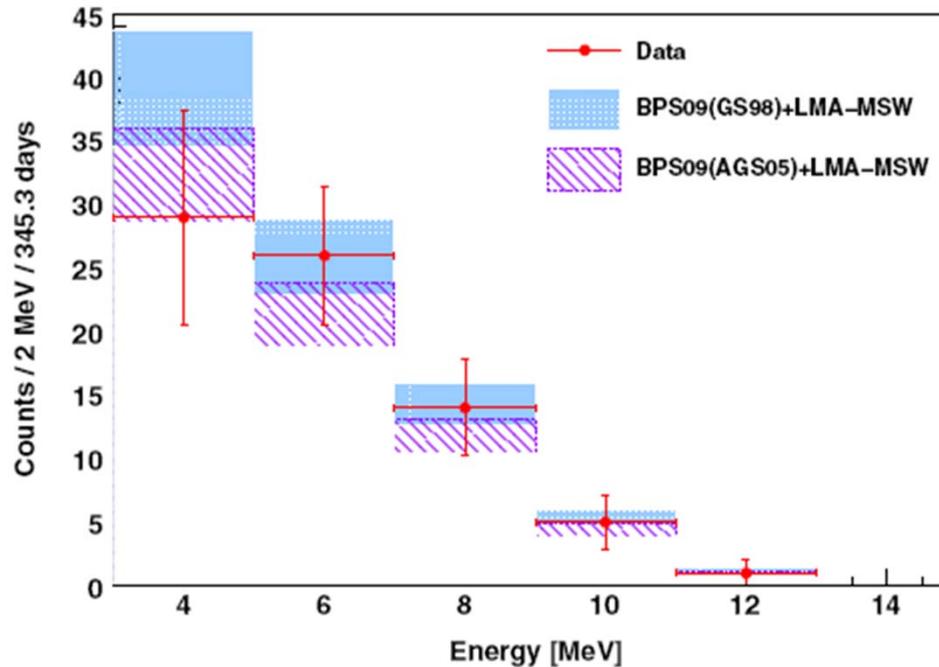
- Background in the 3.0-16.5 MeV energy range

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

### Cuts

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





## Exp. ${}^8\text{B}$ spectrum vs models

	Threshold [MeV]	$\Phi_{{}^8\text{B}}^{\text{ES}}$ $[10^6 \text{ cm}^{-2} \text{ s}^{-1}]$
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 <sub>2</sub> O [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	$2.7 \pm 0.4 \pm 0.2$

Systematic errors →

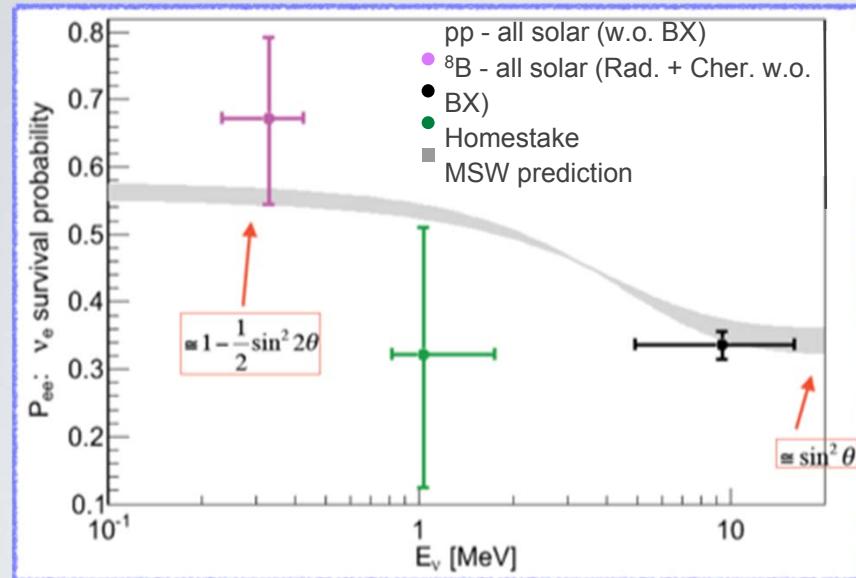
Source	$E > 3 \text{ MeV}$		$E > 5 \text{ MeV}$	
	$\sigma_+$	$\sigma_-$	$\sigma_+$	$\sigma_-$
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

SSM; H.M.( $2.7 \pm 0.3$ )  $\times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$   
L.M.( $2.2 \pm 0.2$ )  $\times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

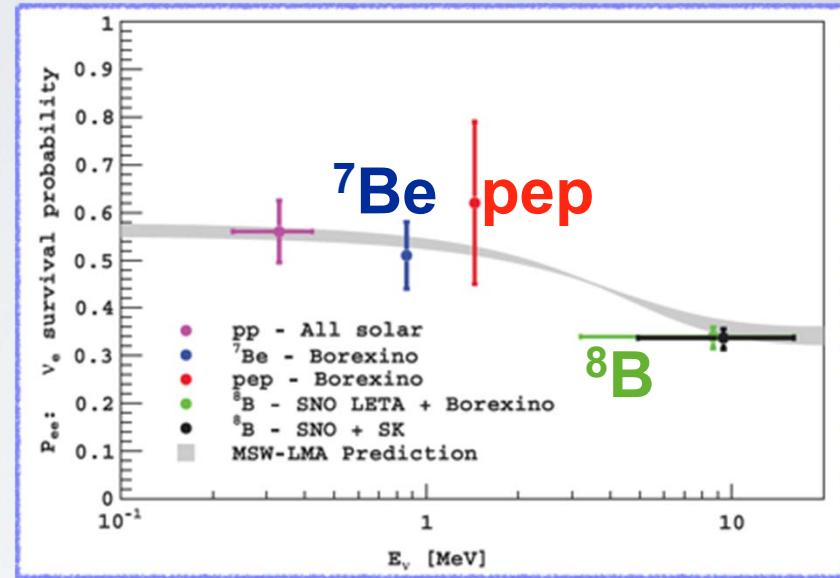
Phys. Rev. D, 82 (2010) 033006

# BOREXINO IMPACT ON NEUTRINO OSCILLATION PHYSICS

Before Borexino

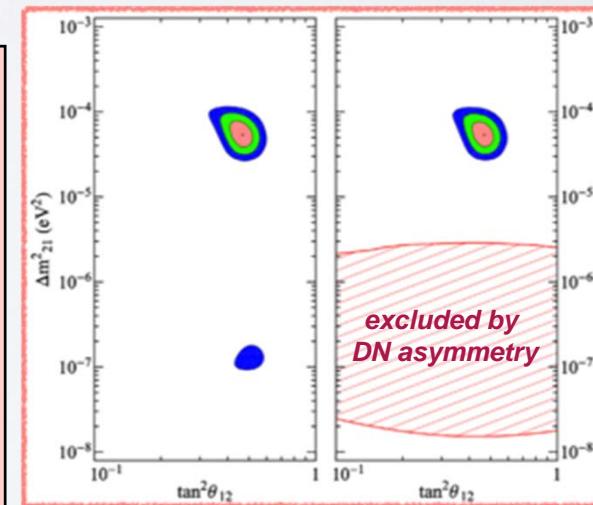


Borexino 2012



In the near future (Phase 2: 2012-2015)

- Improve  $^7\text{Be}$ ,  $^8\text{B}$  → more test of MSW
- Confirm pep with a stronger significance and reduced error
- Improve upper limit on CNO → probe metallicity (perhaps)
- Attempt direct pp measurement



# Geo-neutrinos: anti-neutrinos from the Earth

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

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

- Earth emits (mainly) antineutrinos  $\Phi_{\bar{\nu}} \sim 10^6 \text{ cm}^{-2}\text{s}^{-1}$  whereas Sun shines in neutrinos.
- A fraction of geo-neutrinos from U and Th (not from  $^{40}\text{K}$ ) are above threshold for inverse  $\beta$  on protons:  $\bar{\nu} + p \rightarrow e^+ + n - 1.8 \text{ MeV}$
- Different components can be distinguished due to different energy spectra: e. g. anti- $\nu$  with highest energy are from Uranium.
- Signal unit: **1 TNU** = one event per  $10^{32}$  free protons per year

## **Select events via the inverse beta decay against**

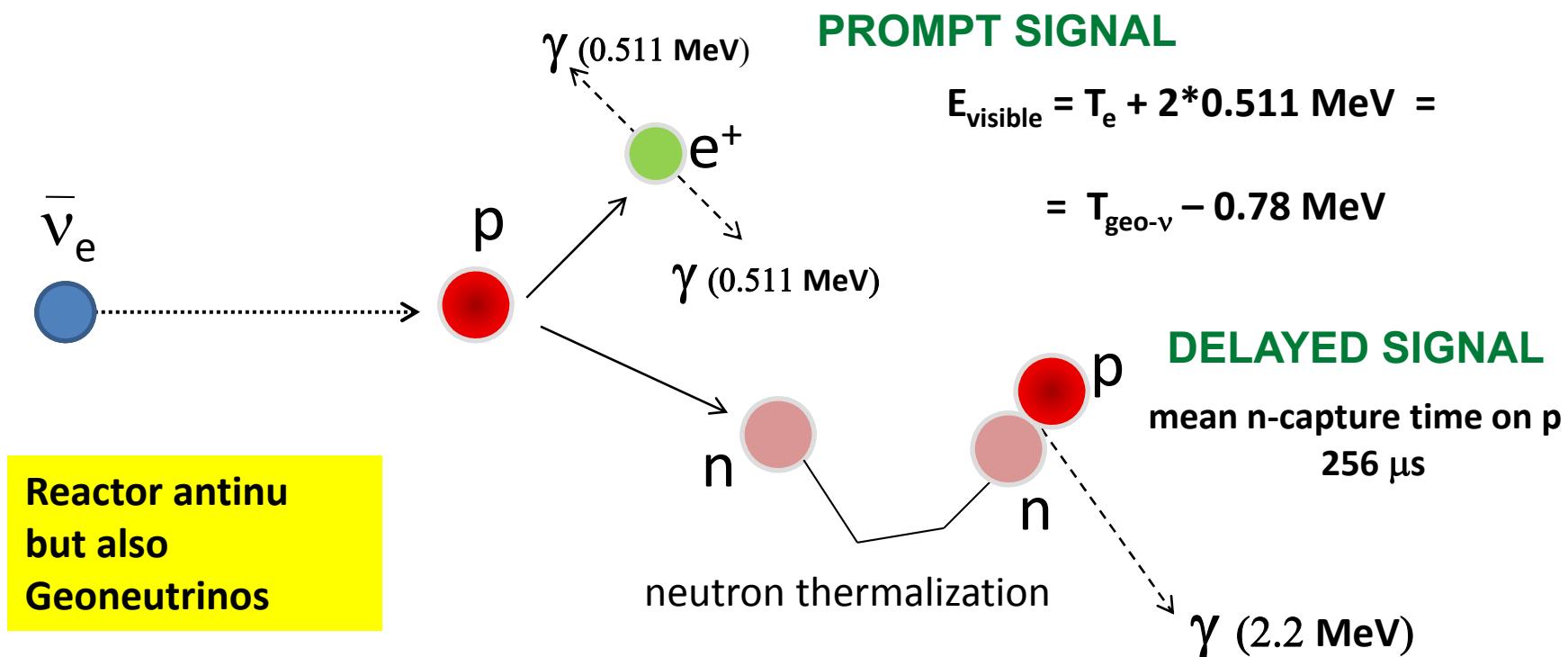
Generic Background mimicking delayed coincidences

Specific background represented by the reactor neutrino signal

With the help of a MC to disentangle the geo- and reactor- contributions

# Detecting anti- $\nu$ : inverse $\beta$ -decay

Energy threshold of  $T_{\text{geo-}\bar{\nu}} = 1.8 \text{ MeV}$  i.e.  $E_{\text{visible}} \sim 1 \text{ MeV}$

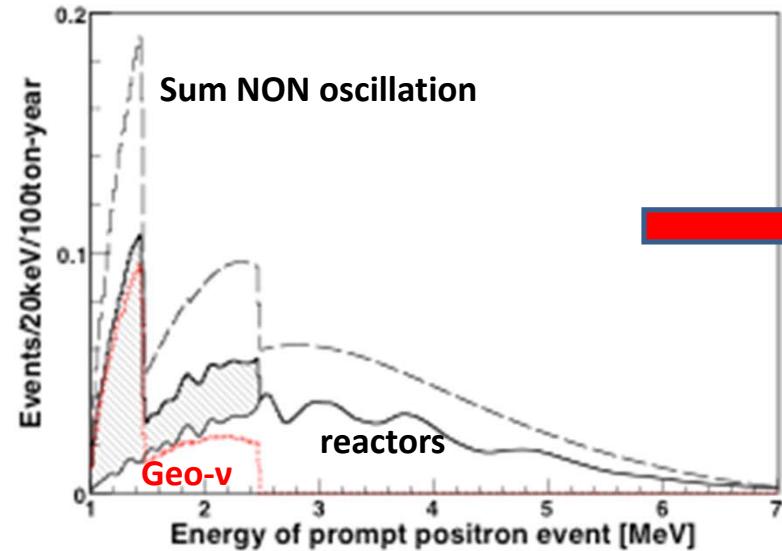


The coincidence technique makes the background requirements much less challenging !

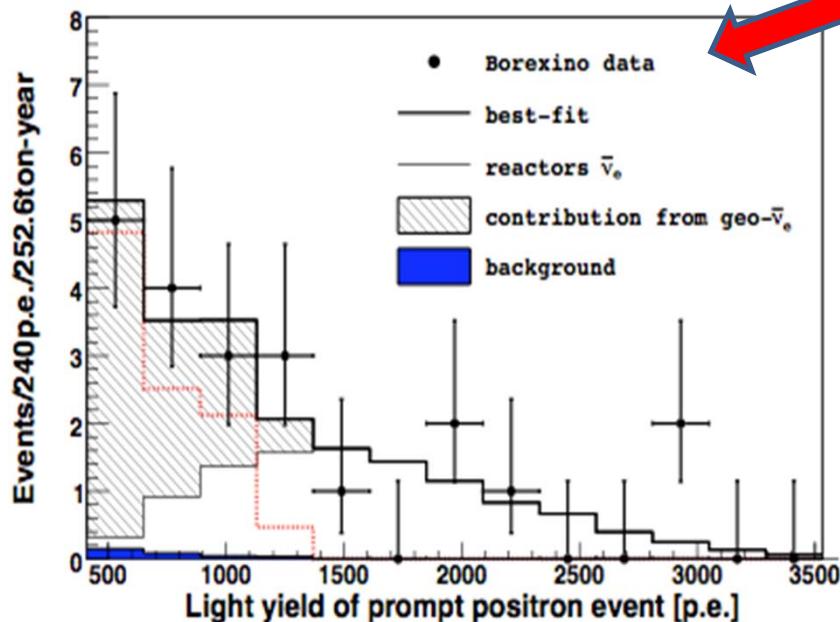
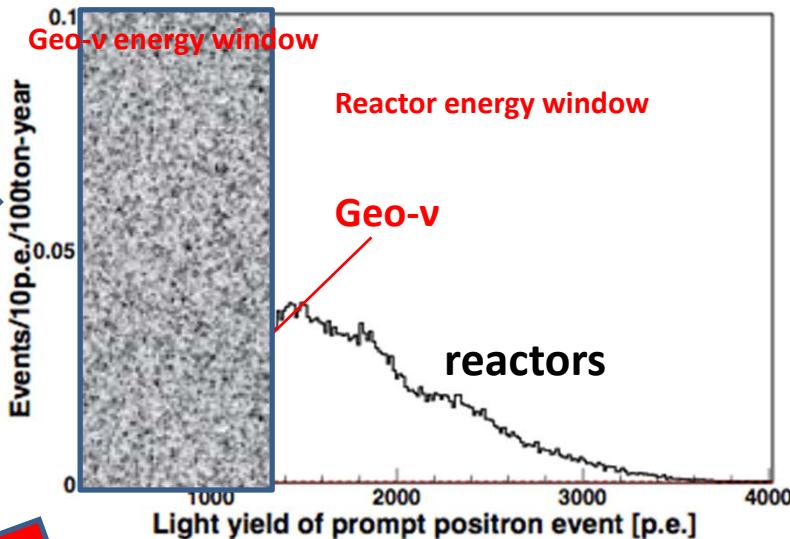
Background source	events/(100 ton-year)
Cosmogenic $^9\text{Li}$ and $^8\text{He}$	$\times$ $0.03 \pm 0.02$
Fast neutrons from $\mu$ in Water Tank (measured)	$< 0.01$
Fast neutrons from $\mu$ in rock (MC)	$< 0.04$
Non-identified muons	$0.011 \pm 0.001$
Accidental coincidences	$\times$ $0.080 \pm 0.001$
Time correlated background	$< 0.026$
$(\gamma, n)$ reactions	$< 0.003$
Spontaneous fission in PMTs	$0.003 \pm 0.0003$
$(\alpha, n)$ reactions in the scintillator [ $^{210}\text{Po}$ ]	$\times$ $0.014 \pm 0.001$
$(\alpha, n)$ reactions in the buffer [ $^{210}\text{Po}$ ]	$< 0.061$
<b>TOTAL</b>	<b><math>0.14 \pm 0.02</math></b>

To be compared: 2.5 geo- $\nu$ /100 ton-year assuming BSE)

## Theoretical spectra: input to MC



## MC output: includes detector response function



USED IN THE UNBINNED MAXIMUM LIKELIHOOD  
FIT OF THE DATA

$$N_{geo} = 9.9^{+4.1 +14.6}_{-3.4 -8.2}$$

68.3 % 99.7%

$$N_{react} = 10.7^{+4.3 +15.8}_{-3.4 -8.0}$$

68.3 % 99.7%

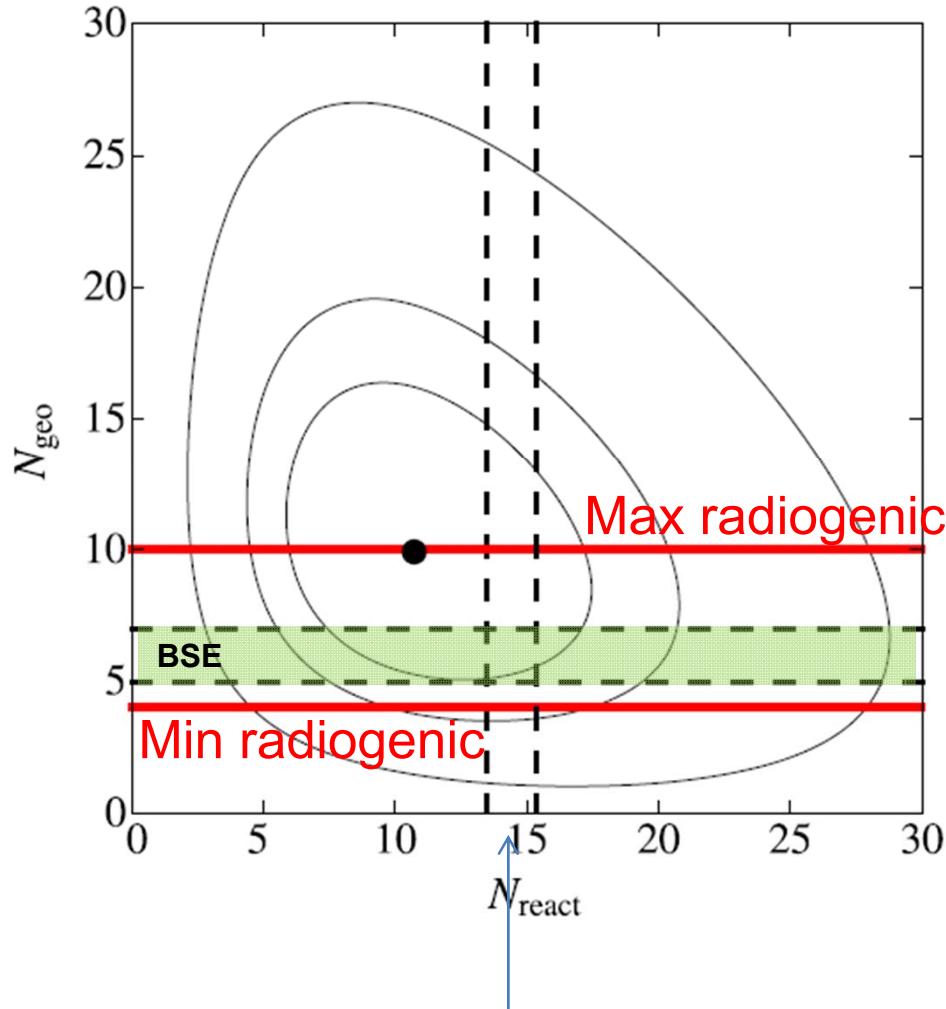
99.997% C.L.  
statistical significance

## Interpretation of the results: data vs BSE model

Minimal Radiogenic Earth scenario: U and Th from only those Earth layers whose composition can be studied on direct rock-samples

Maximal Radiogenic Earth scenario assumes that all terrestrial heat is produced exclusively by radiogenic elements

Allowed regions 68%, 90%, 99.73%



Expectation for the reactors

## The medium and long term future of Borexino

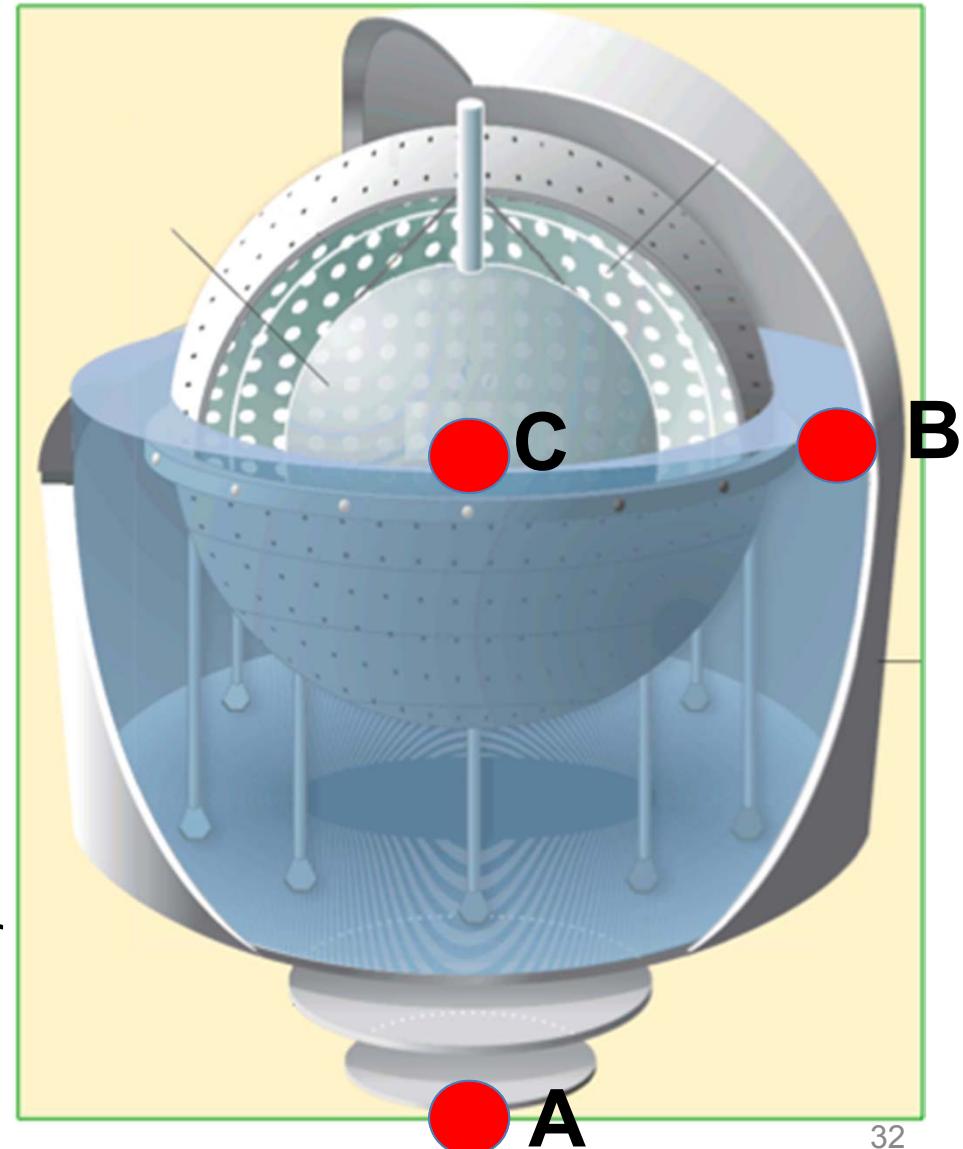
Source experiment to test the sterile neutrino hypothesis

- Neutrino Source Cr-51 – **within phase 2**
- Anti-neutrino source Ce-144 – **beyond 2015**

Xe-136 dissolved in the scintillator for a neutrinoless double beta decay experiment - **long term possibility**

# Source test for sterile neutrinos

- A: underneath WT
  - D=825 cm
  - No change to present configuration
- B: inside WT
  - D = 700 cm
  - Need to remove shielding water
- C: center
  - Major change
  - Remove inner vessels
  - To be done at the end of solar Neutrino physics

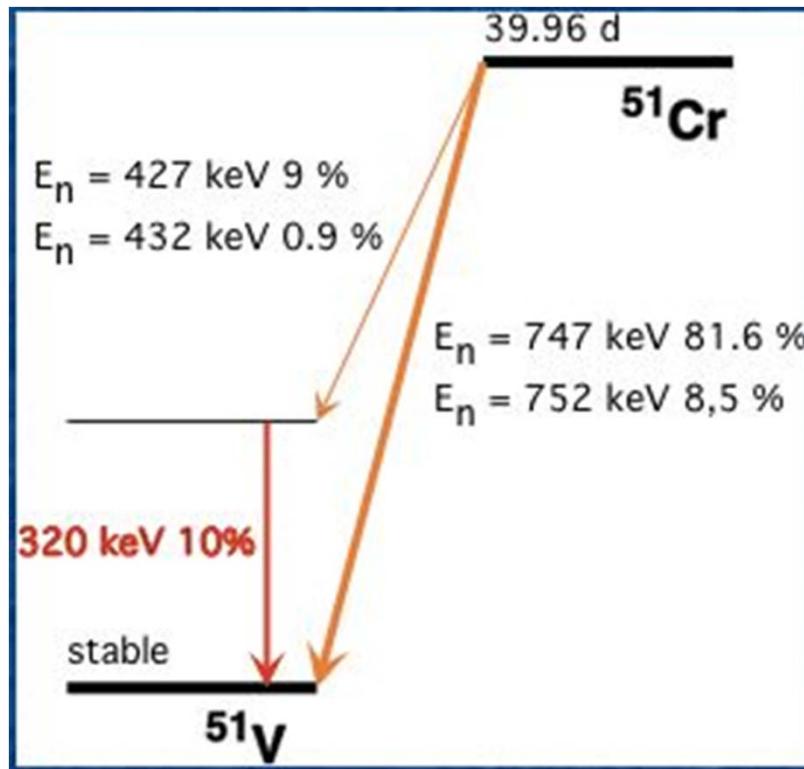




Source  
position A

# **51Cr**

Originally proposed by  
Raju Raghavan



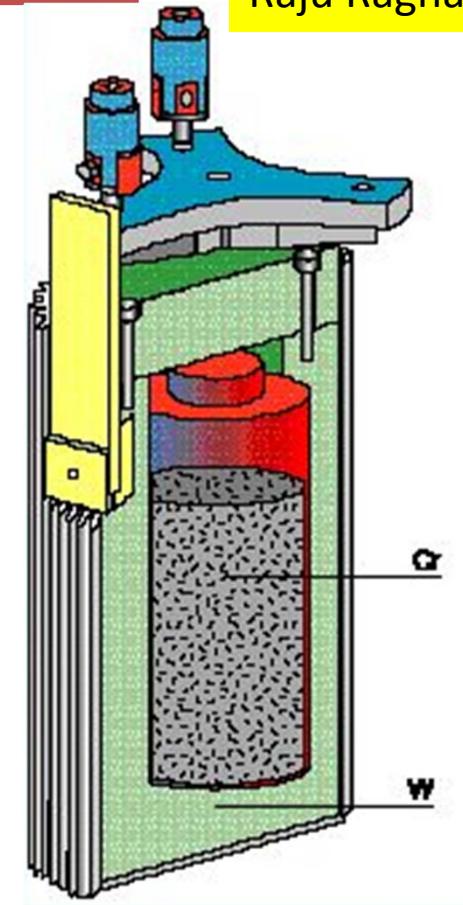
~36 kg of Cr 38% enriched in  $^{50}\text{Cr}$

190 W/MCi from 320 keV  $\gamma$ 's

$7\mu\text{Sv}/\text{h}$  (must be < 200)

SAGE coll., PRC 59 (1999) 2246

Gallex coll., PL B 420 (1998)

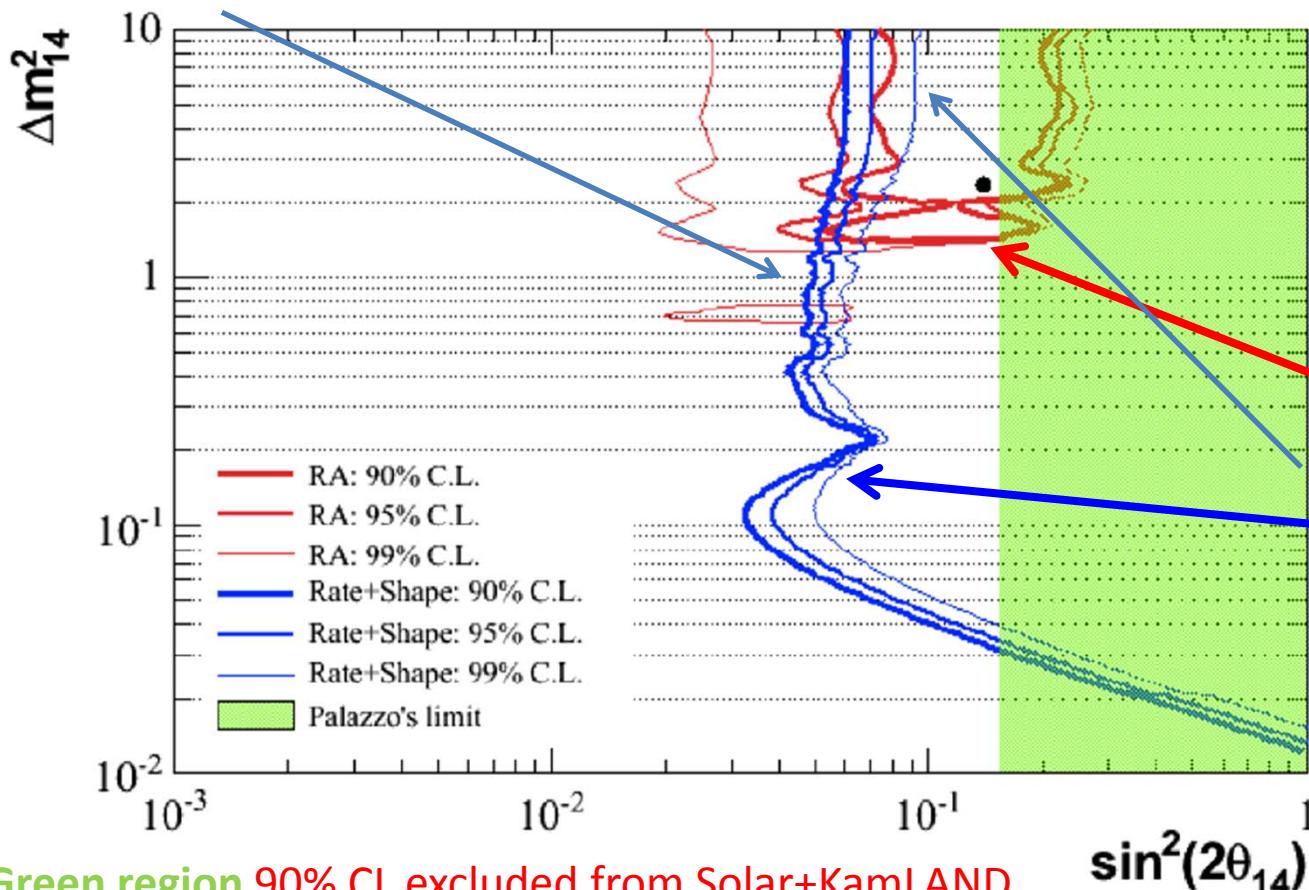


Done two times for Gallex at 35 MW reactor  
with effective thermal neutrons flux of  $\sim 5.4 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1}$   
**~1.8 MCi**

# Reach of the sterile neutrino search with the $^{51}\text{Cr}$ source

## $\chi^2$ analysis of the $^{51}\text{Cr}$ source outside BX

Sensitivity to the rate + waveshape



Green region 90% CL excluded from Solar+KamLAND  
constraints accounting for the  $\theta_{13} \neq 0$  value

A. Palazzo - Phys. Rev. D 85, 077301 (2012)

Rate + shape + additional handle:  
time decay of the source event  
rate to better discriminate  
against the background

- activity=10MCi;
- Error on activity=1%;
- Error on FV=1%;

Reactor anomaly

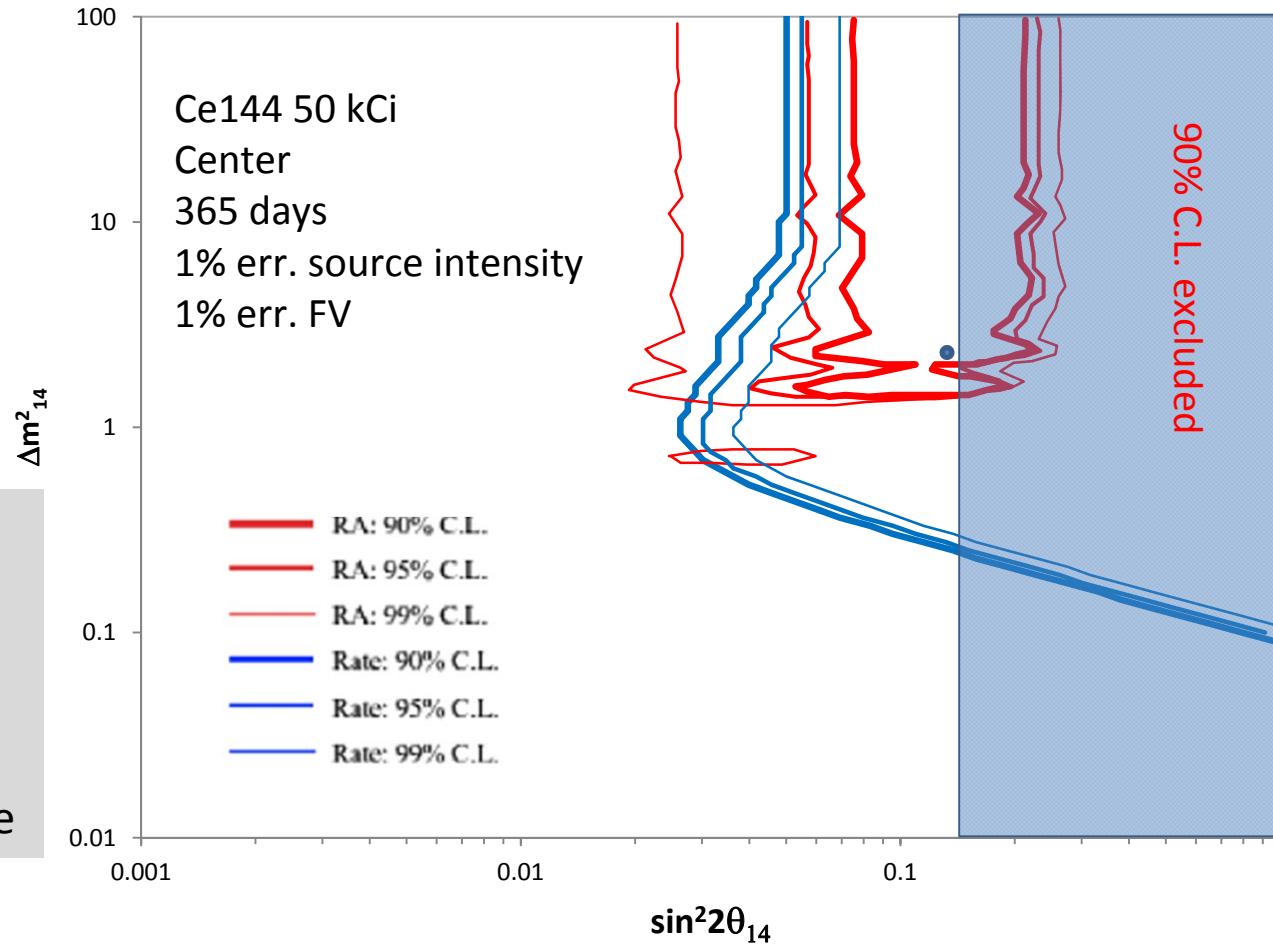
Sensitivity to the rate only  
Exclusion contours

FV error better than 1% already achieved in BX (calibration)

Error of 1% on the source intensity is aggressive – important effort to achieve it<sup>35</sup>

# Reach of the sterile neutrino search with the $^{144}\text{Ce}$ source

Adequate coverage of the region of interest of the oscillation parameter plane



Error of 1% on the source intensity is aggressive – but the FV error could be omitted – included as safety margin

## Conclusions

Borexino has measured the  ${}^7\text{Be}$  solar neutrino flux with a total error less than 5%, identified and measured the **pep** component and studied the  ${}^8\text{B}$  spectrum with a threshold as low as 3 MeV

The  ${}^7\text{Be}$  and **pep** measures allowed Borexino to investigate  $\nu$  oscillations in the previously untested low energy vacuum-like regime, providing additional convincing evidence of the validity of the **MSW-LMA** solution

Absence of day-night asymmetry in the  ${}^7\text{Be}$  flux and detection of **geoneutrinos** are further important accomplishments of the experiment

Solar studies will continue in particular for **pep**, **CNO** and **pp** fluxes

The ultra-low background of the experiment will allow a further broad physics program, including **sterile neutrino oscillation search** via deployment of neutrino sources and possibly **DBD with Xe-136**