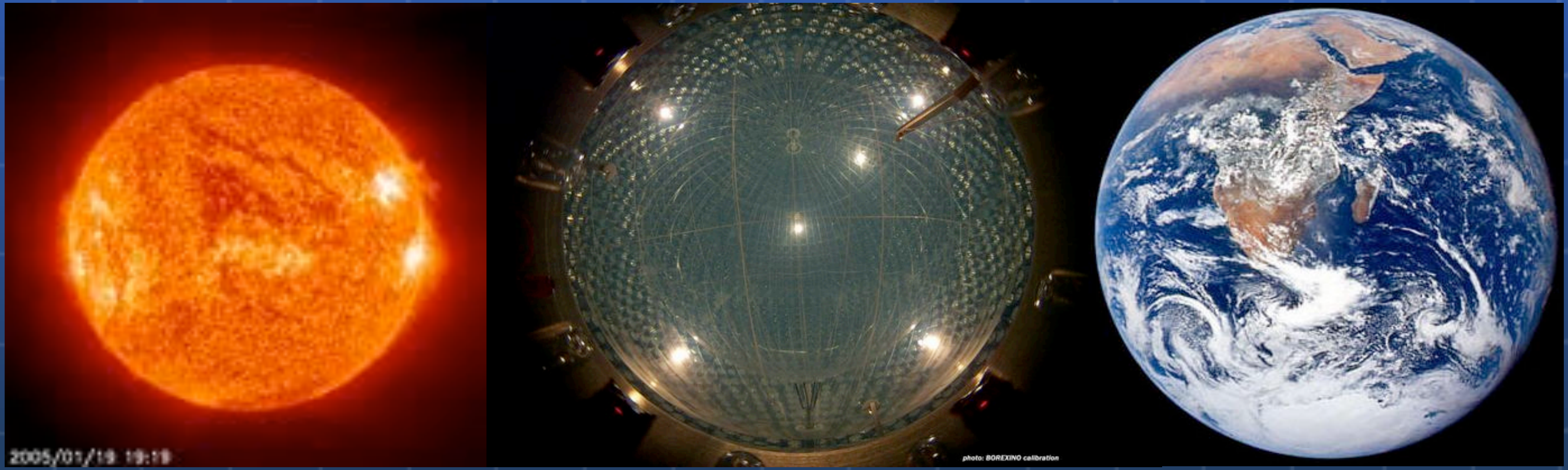
Solar neutrino and terrestrial antineutrino fluxes measured with Borexino at LNGS

Sandra Zavatarelli

INFN Genova (Italy)

(on behalf of the Borexino Collaboration)



Outline:

A large volume ultrapure scintillation detector like Borexino can help to answer to key questions in multiple disciplines!!

- Borexino:
  - *Experimental techniques and the detector*
- Neutrino astronomy results:
  - *What's cool in the solar neutrino physics..*
  - *^{7}Be ν and D/N asymmetry;*
  - *^{8}B ν and the lowest threshold flux measurement (3 MeV);*
  - *ν_e survival probability in the transition region.*
- (Anti)-Neutrino geology:
  - *The first observation of geo-ν in Borexino (at 4.2 σ);*
  - *Limits on geo-reactor power in the Earth core;*
  - *The anti-ν survival probability on a baseline of 1000 km.*
- Particle physics:
  - *New limits on PEP forbidden transitions.*
- Summary and outlook

How do we detect ν /anti-ν in BX ??

Borexino is an ultrapure organic scintillator detector made by 278 tons of PC+PPO

ν_x are detected throught their scattering off electrons:

$\nu_x + e^- \longrightarrow \nu_x + e^-$ $\sigma_{CC}=9.2\ 10^{-45}\ E_\nu(\mathrm{MeV})\ \mathrm{cm}^2$ $\sigma_{CC} \sim 6\ \sigma_{NC}$

anti-ν_e are detected throught the inverse beta decay on protons:

$\nu_e + p \longrightarrow n + e^+$

✓E_{thr} = 1.8 MeV

✓$E_{e+}=E_\nu-0.78$ MeV

✓Delayed coincidence : $\tau_n \sim 256\ \mu s$ in PC

Particle detection via the emitted scintillation light:

✓*Very low energy threshold (40 keV);*

✓*Good energy and spatial resolution (L.Y.~ 500 p.e./MeV)* *..but…*

✓*No directional information*

✓*Background rejection critical: the ν_x induced events can't be distinguished from the other β events due to natural radioctivity*

A ultrapure detector is mandatory….

The BOREXINO detector

- PMT total collected charge -> light yield (p.e) -> event energy
- Photon arrival times on each PMT -> event position

ENERGY RESOLUTION

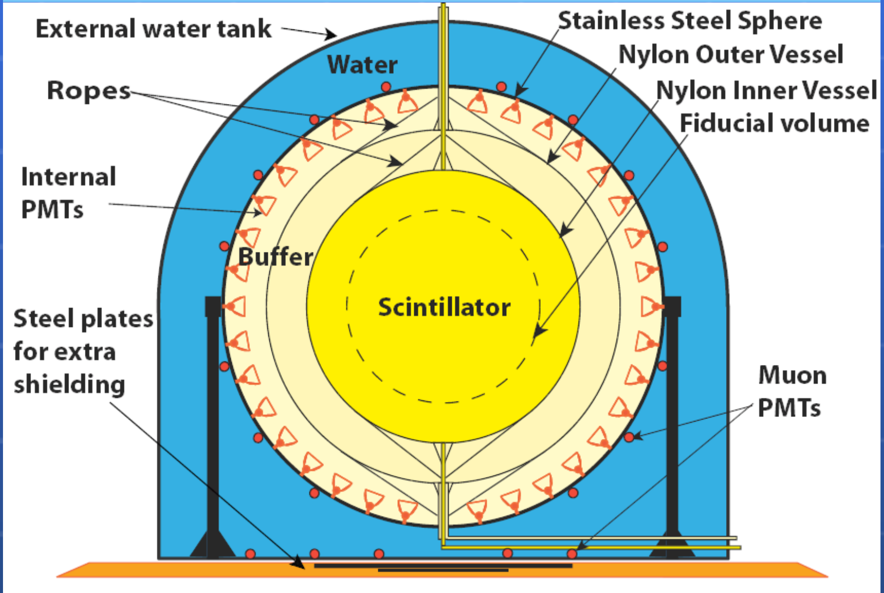
10% @ 200 keV
8% @ 400 keV
5% @ 1 MeV

SPATIAL RESOLUTION

35 cm @ 200 keV
16 cm @ 500 keV

Extreme radiopurity of scintillator = 15 years of work !!!

The dectector is now calibrated!!!

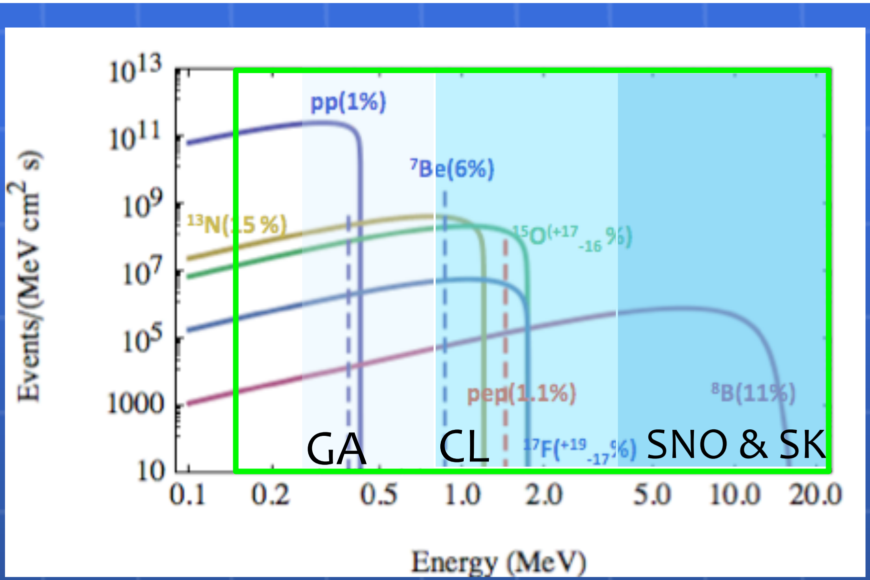


- **External backgrounds:** underground lab., principle of progressive shieldings
- **Internal backgrounds:** accurate material selections and clean manipulations, liquid handling plants in situ (WE, nitrogen stripping, distillation)

Most important backgrounds:

^{238}U~ 2 10^{-17} g/g, ^{232}Th ~ 5 10^{-18} g/g, ^{210}Po~ 10 c/d/t, ^{210}Bi ~ 15 c/d/100t, ^{85}Kr ~ 30 c/d/100t

Neutrino astrophysics: probing our knowledge of the Sun



BOREXINO

Importance of single solar-ν spectrum component precise flux measurements:

✓Solve the high/Low metallicity solar model controversy

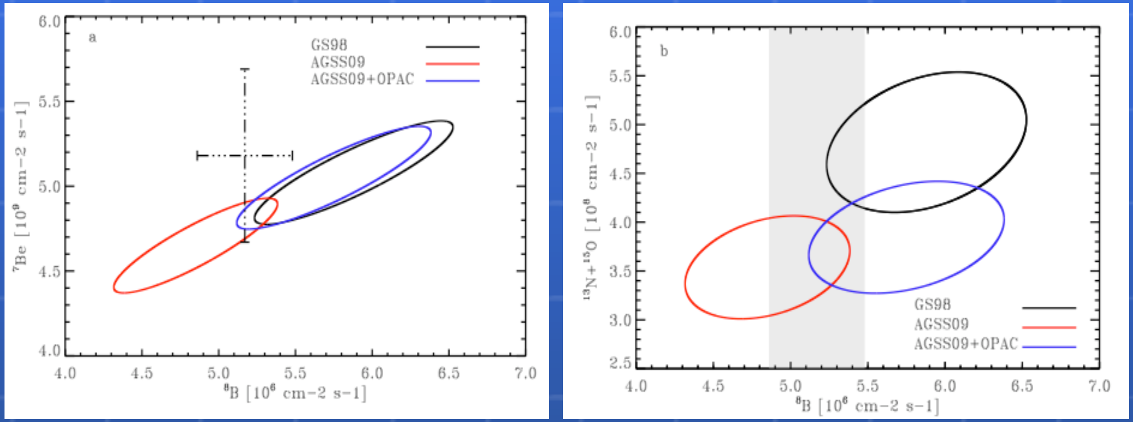
✓Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying ν's

✓Fix the amount of solar energy produced via CNO cycle

Neutrino astrophysics: probing our knowledge of the Sun

		GS98	AGS05
	pp	5.97×10^{10}	6.04×10^{10}
	pep	1.41×10^{8}	1.44×10^{8}
	hep	7.91×10^{3}	8.24×10^{3}
10%	^{7}Be	5.08×10^{9}	4.54×10^{9}
	^{8}B	5.88×10^{6}	4.66×10^{6}
40%	^{13}N	2.82×10^{8}	1.85×10^{8}
	^{15}O	2.09×10^{8}	1.29×10^{8}
	^{17}F	5.65×10^{6}	3.14×10^{6}

Serenelli arXiv:0910.3690



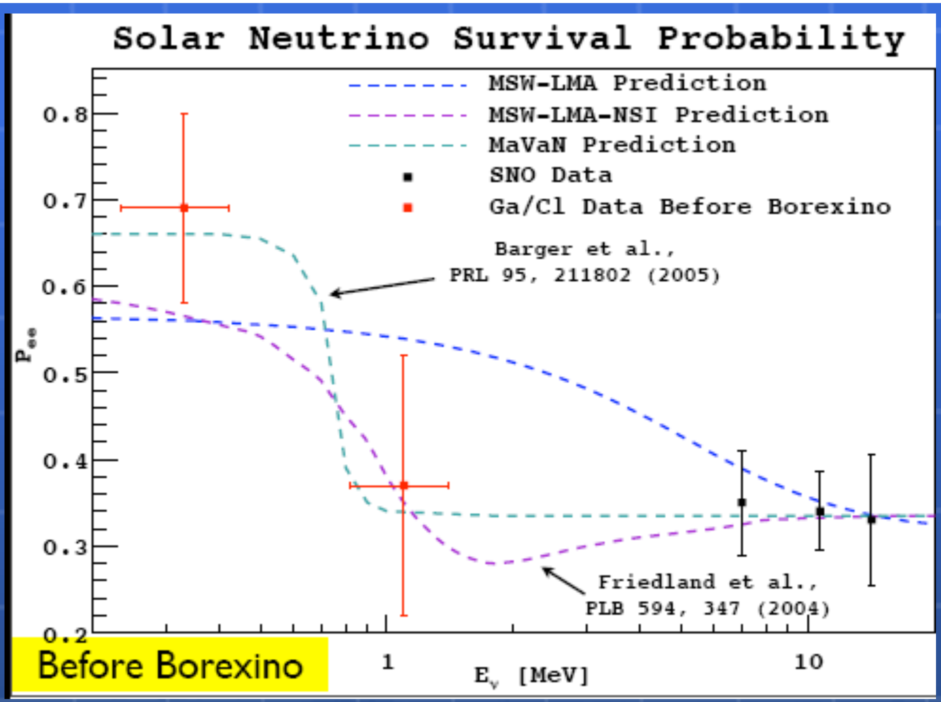
Flux: cm^{-2}s^{-1} (BPS09)

✓Solve the high/Low metallicity solar model controversy

✓Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying ν's

✓Fix the amount of solar energy produced via CNO cycle

Neutrino astrophysics:
probing our knowledge of the Sun

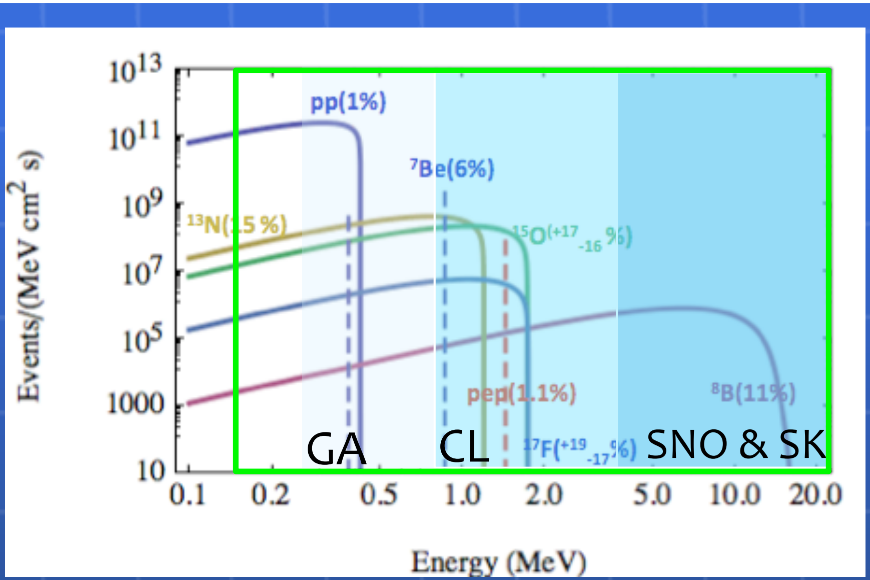


✓Solve the high/Low metallicity solar model controversy

✓Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying ν's

✓Fix the amount of solar energy produced via CNO cycle

Neutrino astrophysics: probing our knowledge of the Sun



BOREXINO

Importance of single solar-ν spectrum component precise flux measurements:

✓Solve the high/Low metallicity solar model controversy

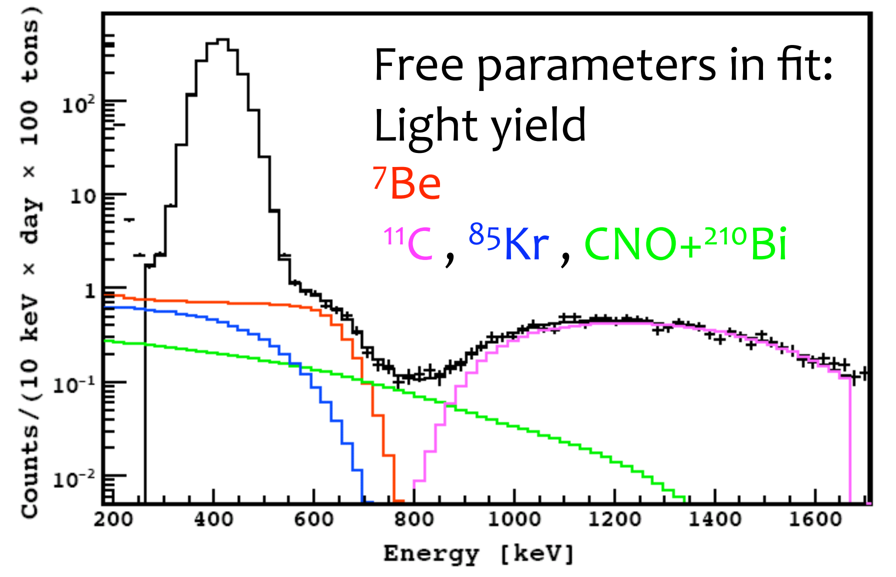
✓Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying ν's

✓Fix the amount of solar energy produced via CNO cycle

Neutrino astrophysics: the measure of the ^{7}Be solar neutrino flux

1st result (30 % precision) - Phys.Lett.B (2007): ^{7}Be Rate = $47 \pm 7_{stat} \pm 12_{syst}$ cpd/100t (47.4 days)

2nd result (10% precision)- PRL 101 (2008): **^{7}Be Rate = $49 \pm 3_{stat} \pm 4_{sys}$ cpd/100 tons (192 days)**



Expected rate cpy/100 t		
No oscilations	BPS07 (GS98)	BPS07 (AGS05)
75 ± 4	48 ±4	44 ± 4

3rd result: now a 5% precision measurement and the seasonal variation study are possible!!!

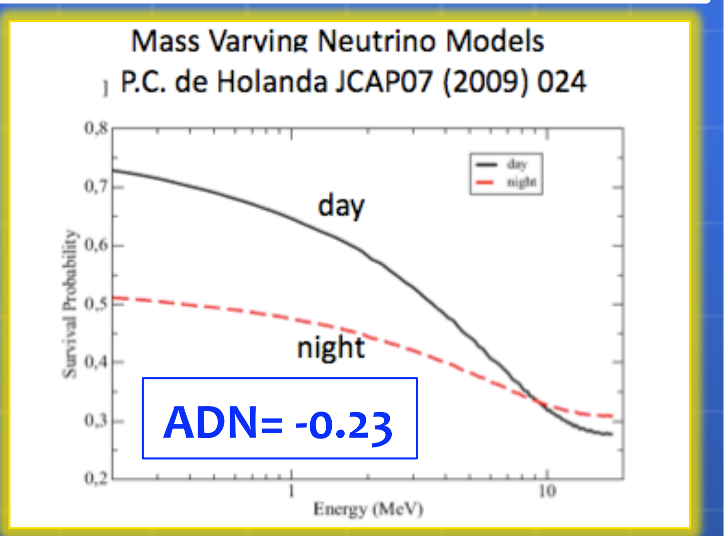
- **Detector calibrated**
- **Monte Carlo fitting procedure implemented**
- **^{85}Kr content known at 16% level (delayed coincidence)**
- **3 years of statistics!!!**

Neutrino astrophysics:
^{7}Be solar neutrino flux day/night asymmetry

- LMA solution to SNP -> no asymmetry
- MaVaN models -> possible asymmetry

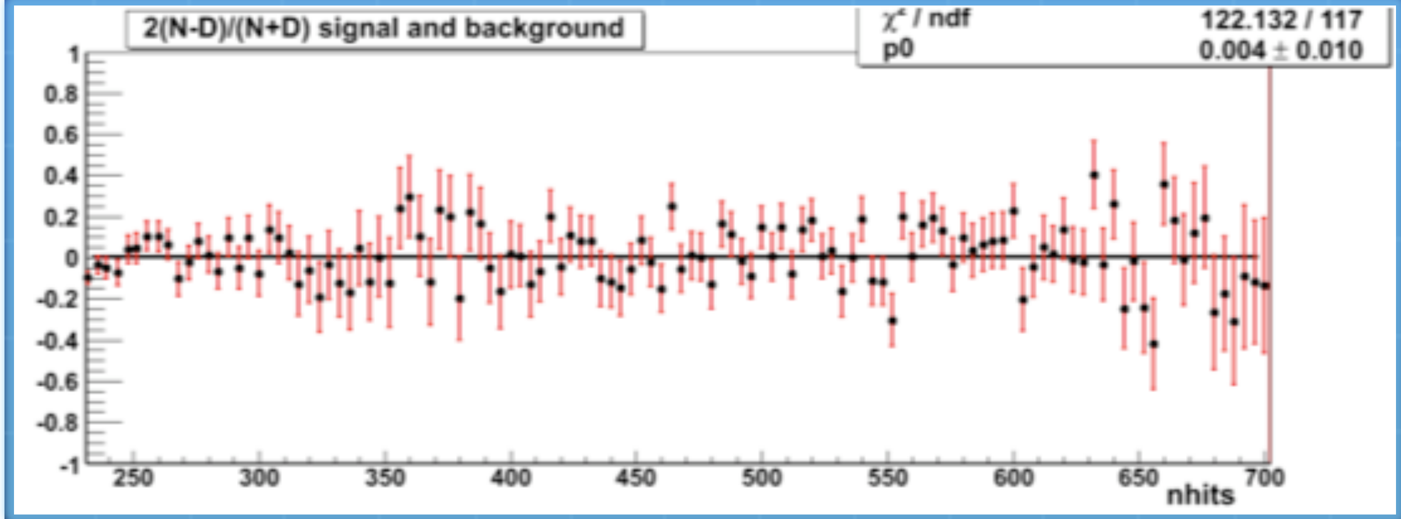
$$ADN = \frac{N - D}{(N + D) / 2}$$

Borexino result: *ADN*= 0.007 ± 0.073 (*stat*)



Mass Varying Neutrino Models
P.C. de Holanda JCAP07 (2009) 024

ADN= -0.23



Day spectrum 387.5 d
Night spectrum 401.57 d
Stat. Error: 2.3 cpd/100t

MaVaN model rejected at more than 3σ

Neutrino astrophysics: the measure of the ^{8}B solar neutrino flux

arXiv:0808.2868v3 [astro-ph] accepted by Rev. Phys. D

BX: Φ^{ES} (3.0-16.3 MeV) = (2.4 ± 0.4 ± 0.1) 10^{6} $cm^{-2}s^{-1}$ E_{thr}=3 MeV

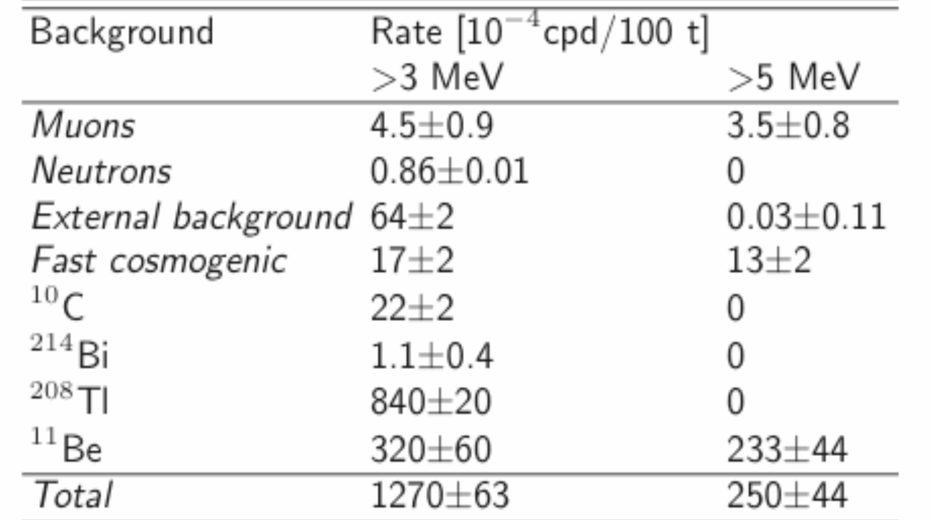
First measurement of ^{8}B-ν:

- with liquid scintillator
- with the lowest energy threshold for a spectral measurement (3 MeV)

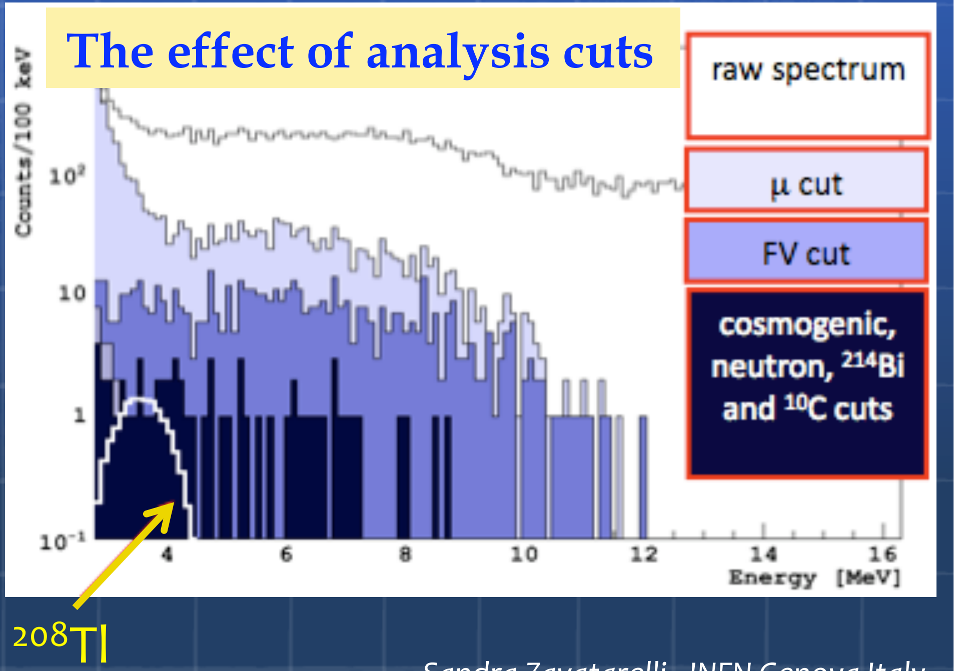
Two analysis threshold : 3 MeV and 5 MeV

Expected signal rate ~ 0.25 cpd/100t

S/B ratio ~ 1/6000

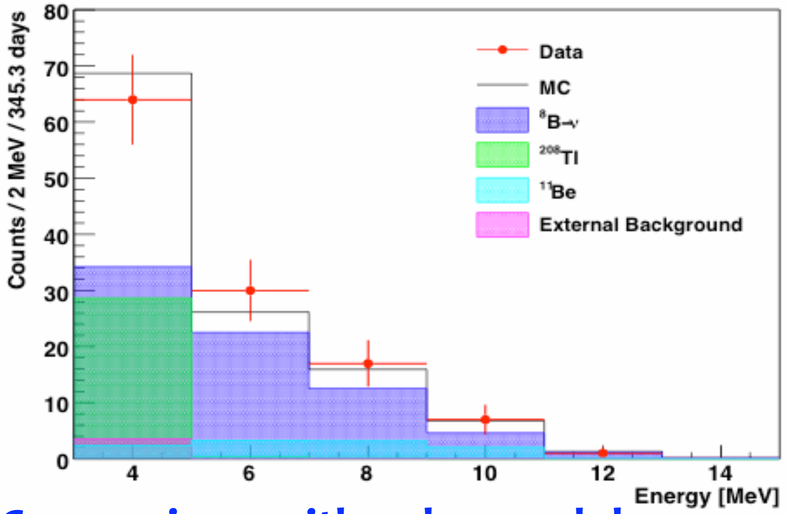


Background	Rate [10^{-4}cpd/100 t] >3 MeV	>5 MeV
Muons	4.5±0.9	3.5±0.8
Neutrons	0.86±0.01	0
External background	64±2	0.03±0.11
Fast cosmogenic	17±2	13±2
^{10}C	22±2	0
^{214}Bi	1.1±0.4	0
^{208}Tl	840±20	0
^{11}Be	320±60	233±44
Total	1270±63	250±44

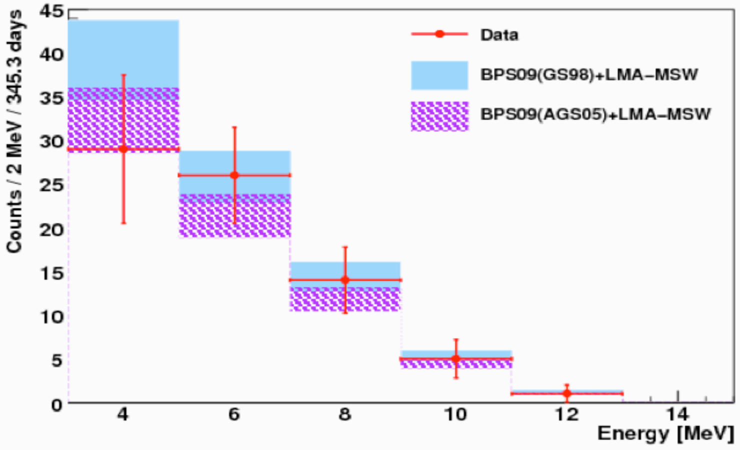


Neutrino astrophysics: the ^{8}B-ν final spectrum compared with models and other results

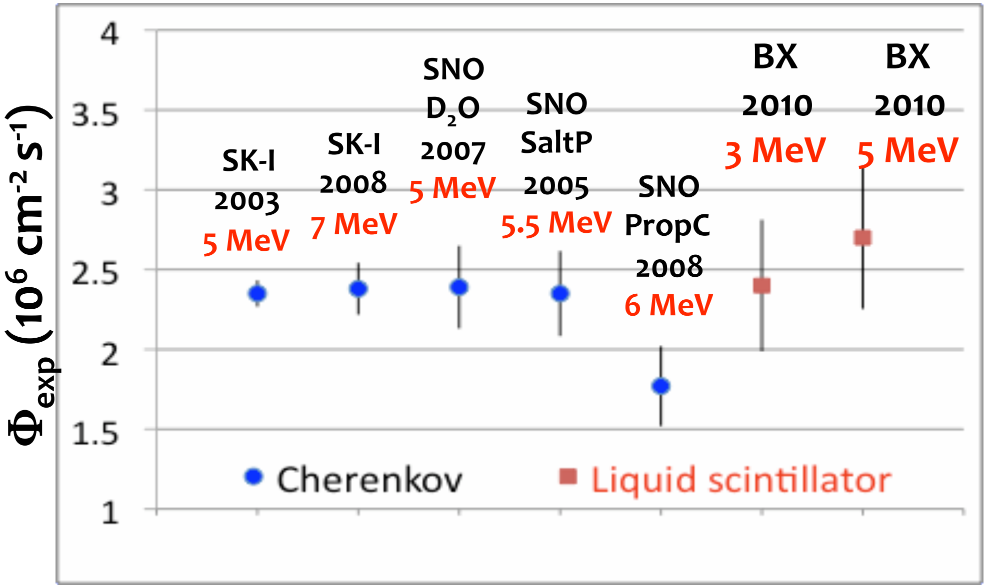
Final spectrum (exp.: 97 tons y)



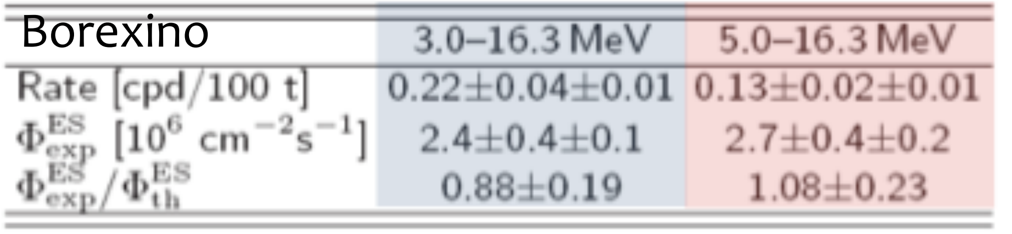
Comparison with solar models



^{8}B solar ν flux measurements via elastic scattering



Threshold is defined @ 100% trigger efficiency

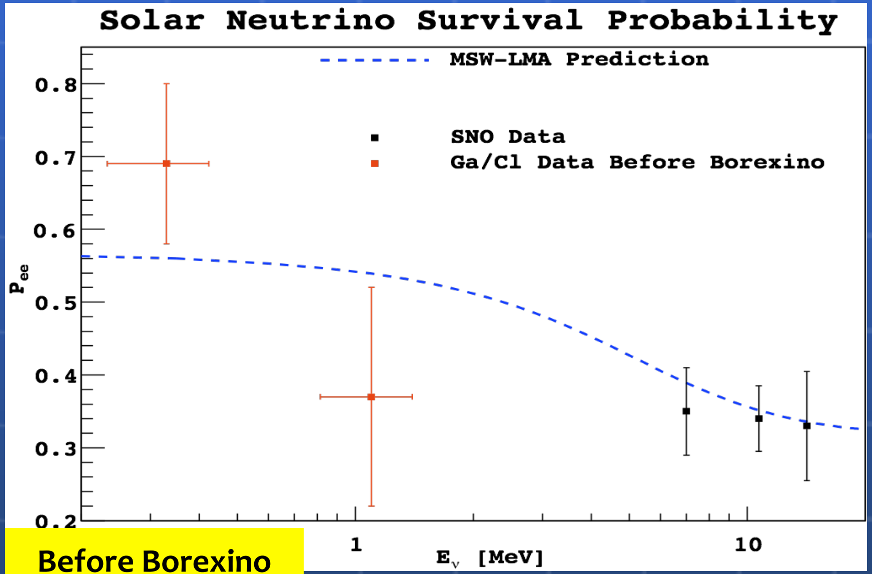


Borexino	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	0.22±0.04±0.01	0.13±0.02±0.01
Φ^{ES}_{exp} [10^6 cm^{-2}s^{-1}]	2.4±0.4±0.1	2.7±0.4±0.2
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88±0.19	1.08±0.23

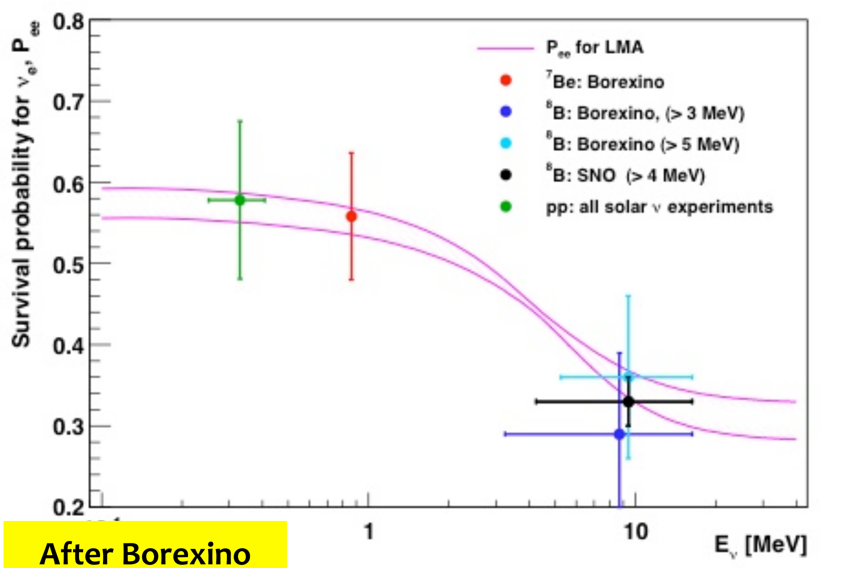
Neutrino astrophysics: testing the LMA solution to the solar neutrino problem

✓ **Borexino is the first experiment able to investigate simultaneously, in real time, the vacuum and matter regimes of oscillation**

Solar ν_e survival probability in vacuum-matter transition



Before Borexino



After Borexino

^{7}Be ν: P_{ee}=(0.56 ± 0.10) ^{8}B ν: $\overline{P}_{ee}$=(0.29 ± 0.10) Distance = 1.9 σ

✓CNO, pep and pp ν-flux measurement: possible in case of positive result of running purifications

Anti-Neutrino geology: Geo-ν a unique direct probe of the Earth interior

The Earth shines in anti-ν ($\Phi_\nu \sim 10^6$ cm^{-2} s^{-1})

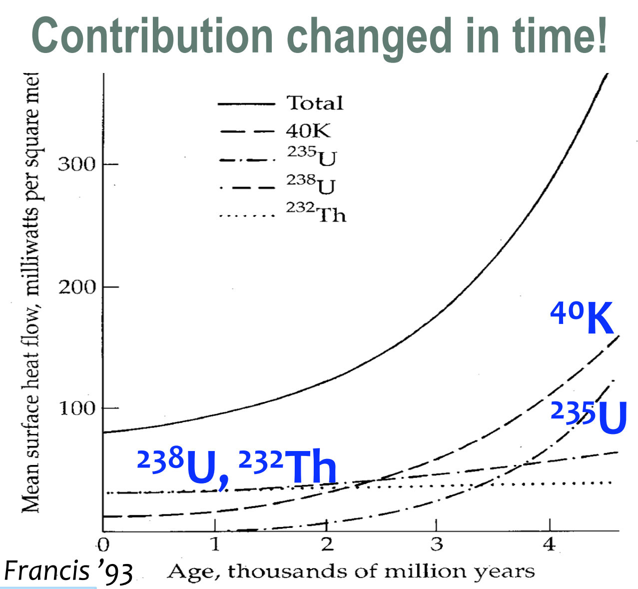
$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- + 6\,\bar{\nu}_e + 51.7$ MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- + 4\,\bar{\nu}_e + 42.8$ MeV

$^{40}K \rightarrow {}^{40}Ca + e^- + 1\,\bar{\nu}_e + 1.32$ MeV

✓Now the existing large mass scintillation detectors (Borexino, Kamland) made their detection feasible!!!

✓**Released heat and anti-neutrinos flux in a well fixed ratio!**

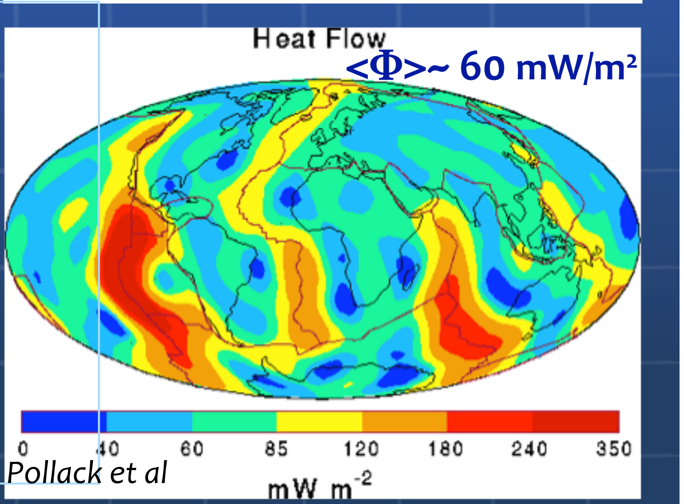


Contribution changed in time!

Francis '93

Open questions:

- *What is radiogenic contribution to the Earth energy budget?*
- *What is the distribution of the radiogenic elements?*
  - *How much in the crust and how much in the mantle?*
  - *Core composition: energy source driving the geo- dynamo? ^{40}K ? Geo-reactor (Herndon 2001)?*
- *Are the standard geochemical models (BSE) correct?*

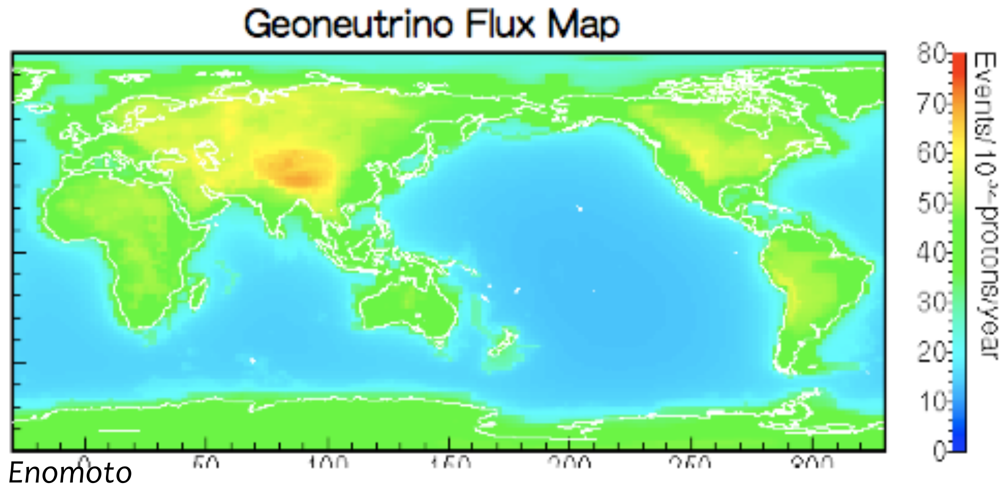


Pollack et al

Geo-ν: expected fluxes

Models based on:

- Data on crustal thickness and composition
- Bulk Silicate Earth composition hypothesis (BSE)
- Chemical behavior of elements (U/Th/K= refractory-lithofile)



Enomoto

Flux not homogeneous!! Strong contribution from local geology…..

Need of multi-site measurements!!

-Continental sites (Borexino,Kamland, SNO+…)

- Oceanic site (Hanohano???)

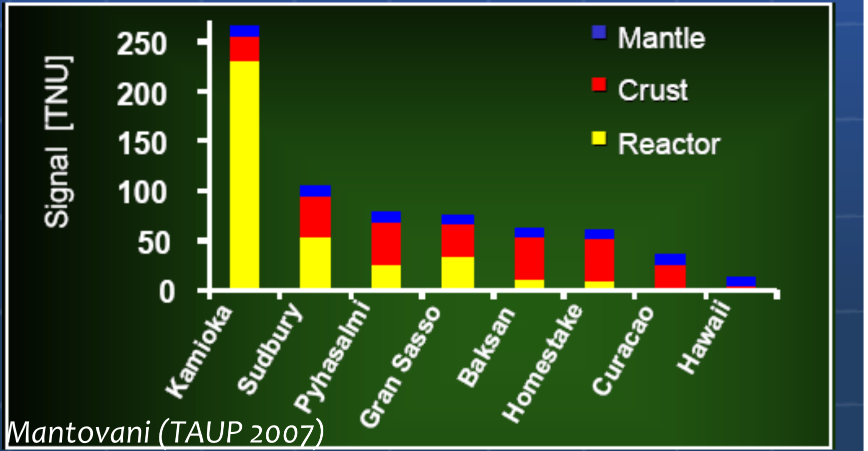
Borexino:

✓ Low intrinsic radioactivity;

✓ Far from reactor power plants;

✓ Underground site: Φ_μ reduced by ~ 10^6.

Reactor flux- irreducible background!!



Mantovani (TAUP 2007)

Geo-ν: the signature in Borexino

Prompt:

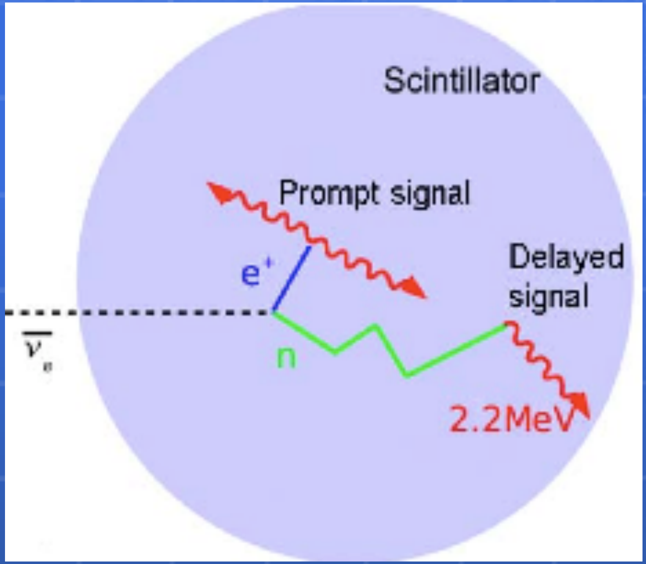
ν + p -> n + e^+

E_{thr}=1.8 MeV

Minimum det. energy: 2x 511 keV

Expected rate:

2.5 cpy/100 t



Delayed (τ~256 μs):

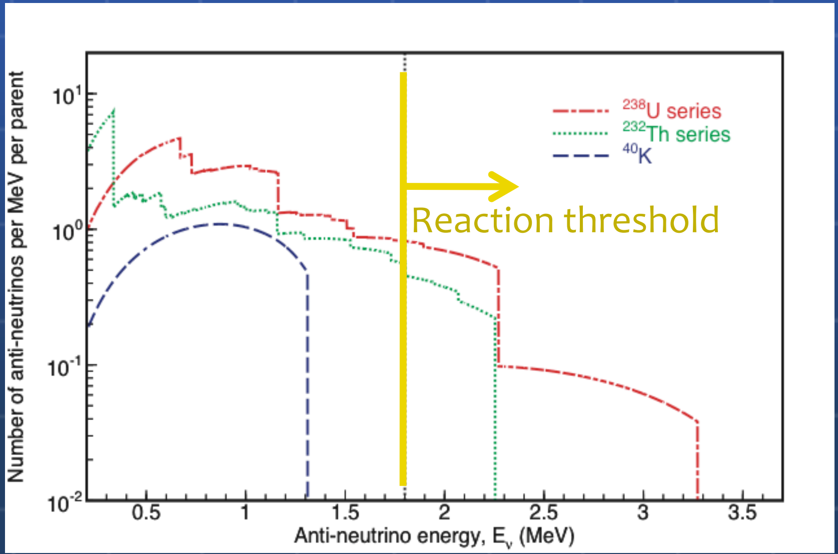
n + p -> d + γ

Detected energy: 2.2 MeV

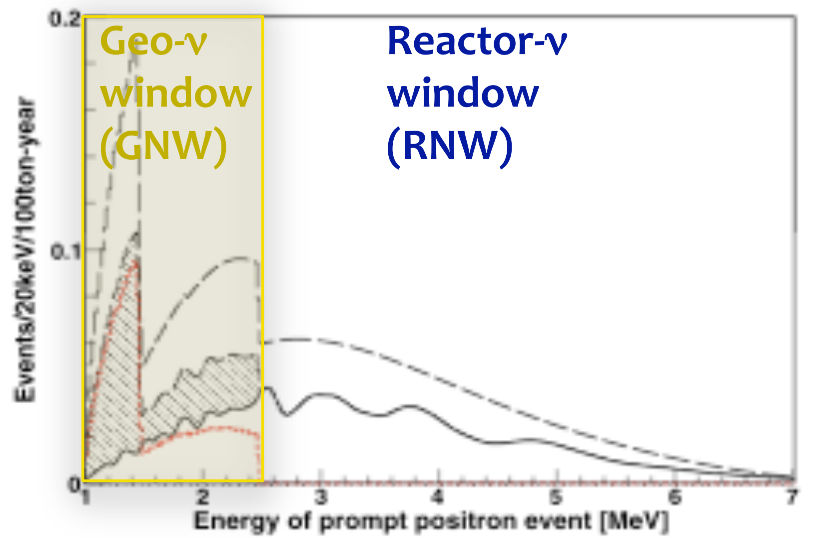
Energy window of observation:

NW: 1-2.6 MeV

Geo-ν energy spectrum



Expected positron energy spectrum in BX



Geo-ν: the background in BX

Geo-ν expected signal (BSE) = 2.5 cpy/100 t

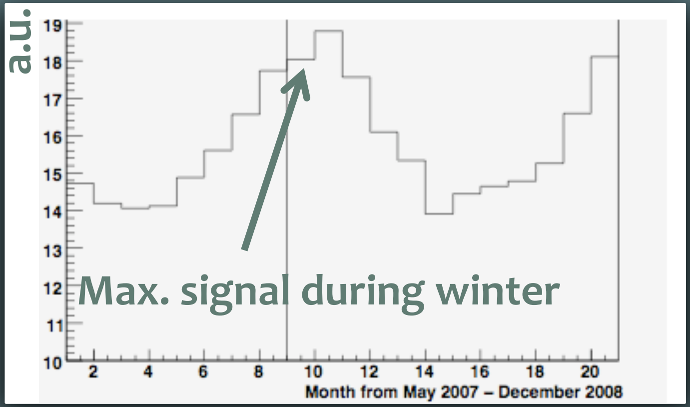
Reactor antineutrinos

- ✓ Overall rate: 5.0 ± 0.3 cpy/100 t
- ✓ Rate in the GNW: 2.0 ±0.1 cpy/100 t

We are in contact with IAEA and EDF:

-Thermal powers for each European reactors are known on a monthly base;

-Expected signal @ LNGS evaluated with a dedicated code (sys. uncertainty: 5.4%)



Max. signal during winter

Signal (BSE)/(Reactor background) ~ 1.25 In the GNW

Cosmogenic/enviromental background

- ✓ Overall rate: 0.14 ± 0.02 cpy/100 t
- ✓ Rate in the GNW: 0.12 ±0.01 cpy/100 t

Muon correlated events

Cosmogenic ^{9}Li and ^{8}He decay via β-n

- τ~ 150 ms
- 2 s detector veto after scintillator muons
- Residual background: 0.03±0.02 cpy/100 t

Radiogenic $^{13}C(\alpha,n)^{16}O$

- ^{210}Po a emitter: 12 cpd/100 t
- ^{13}C low abundance: $^{13}C/^{12}C$~1.1 %
- Background: 0.014±0.001 cpy/100 t

Random coincidences

Searching for events in a window of 2 ms-2 s: 0.080 ±0.001 cpy/100t

Signal(BSE)/(non anti-ν Background) ~ 21

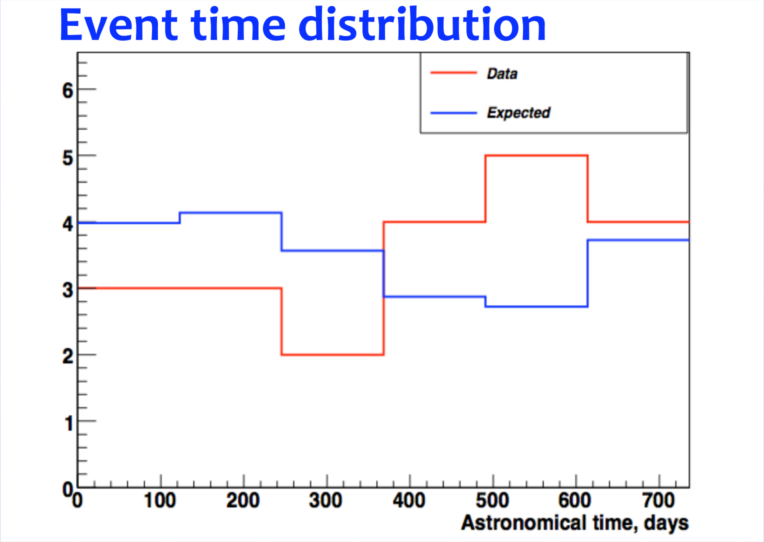
Geo-ν: the selected events

Data set : Dec. 2007- Dec.2009

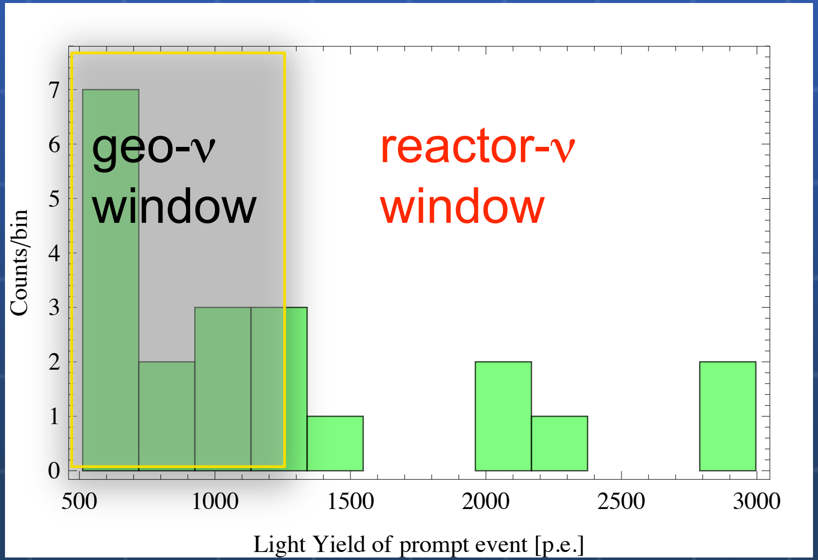
21 selected antinu candidates in 252.6 tons y

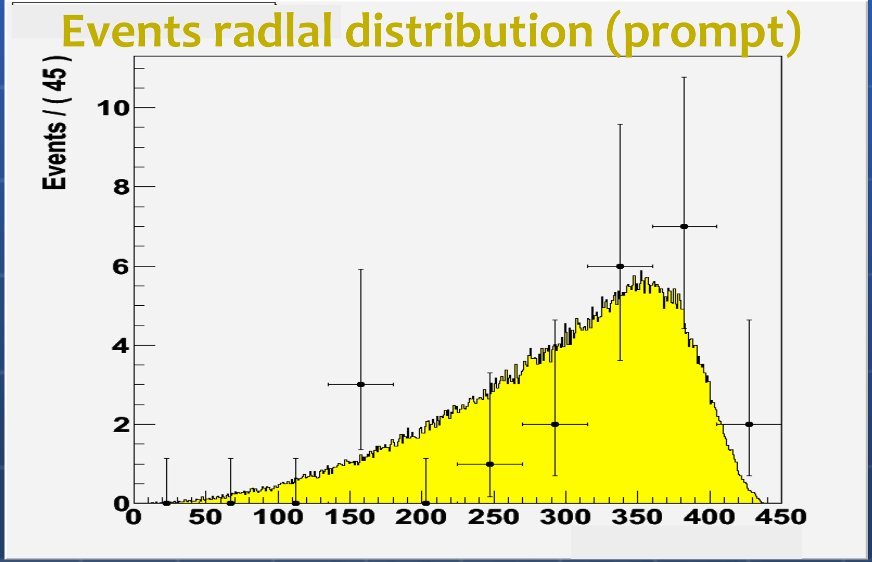
Selection cuts – ε (with MC): 0.85 ± 0.01

- Light yield prompt event> 410 p.e.
- 700 p.e .< light yield delayed event< 1250 p.e.
- ΔR< 1m
- 20 μs < Δt < 1280 μs
- R_{IV}-R_{prompt} >0.25 m



Event time distribution

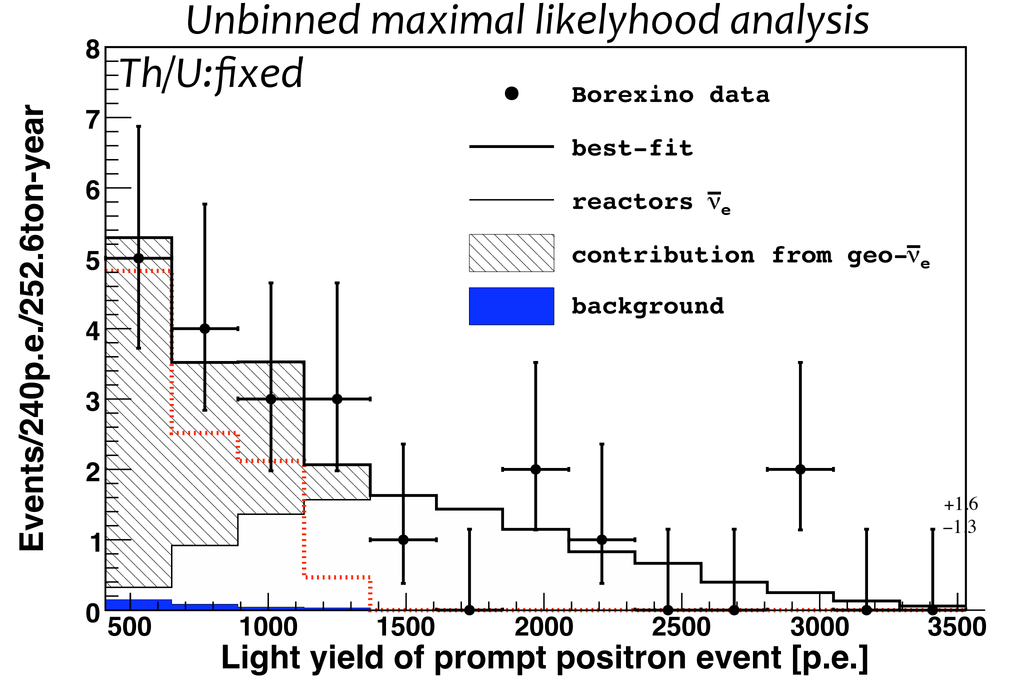




Events radlal distribution (prompt)

Geo-ν: the observation of the geo-ν signal

Phys.Lett.B 687 (2010) 299-304



Our best estimates are:

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

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

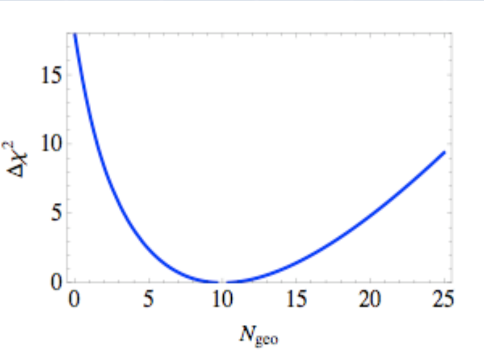
@ 99.73% C.L

@ 68.3% C.L

Background in the geo-ν energy window: **0.31 ± 0.05**

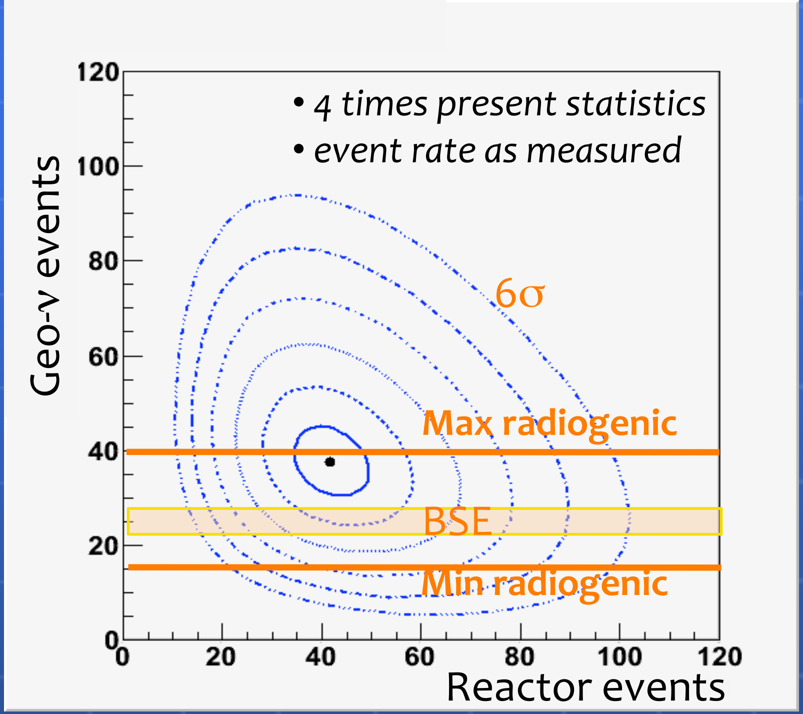
- *By studing the profile of the likelyhood respect to N_{geo}:*

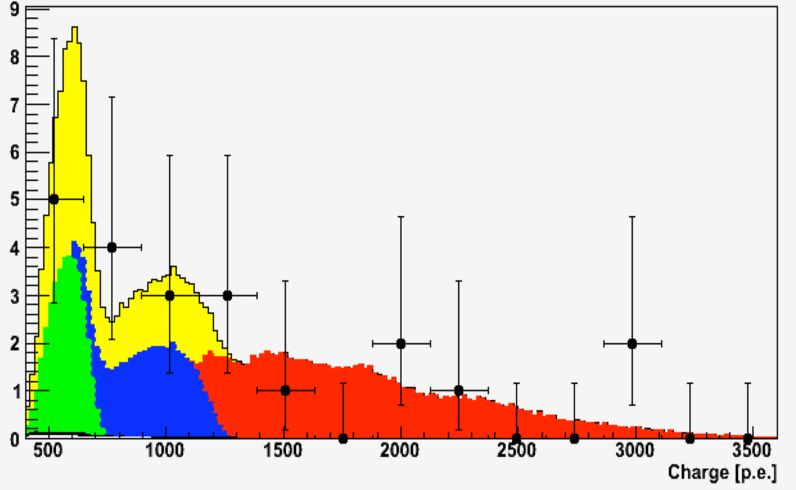
Null geo-ν hypothesis rejected at 4.2 σ



Geo-ν (U+Th) flux [10^6 cm^{-2} s^{-1}]	
Borexino	$7.2^{+2.9}_{-2.4}$
BSE (Mant.2004)	$4.6^{+0.5}_{-0.9}$
Max. rad. Earth	7.2
Min. rad. Earth	2.9

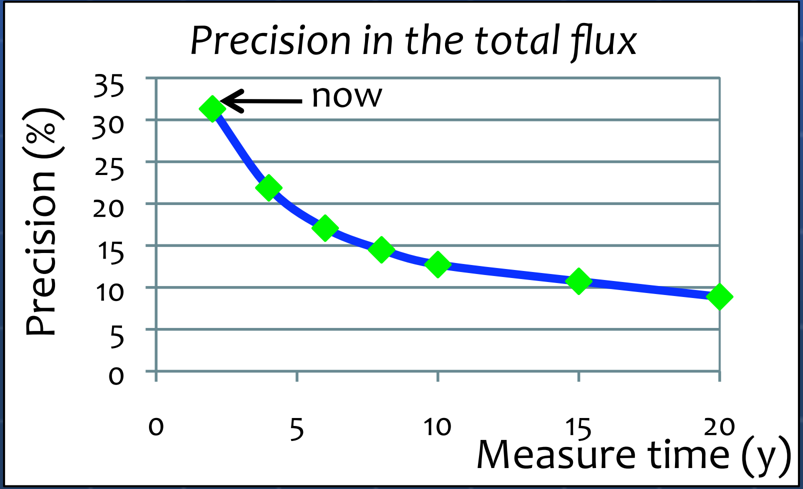
Geo-ν: future BX results!

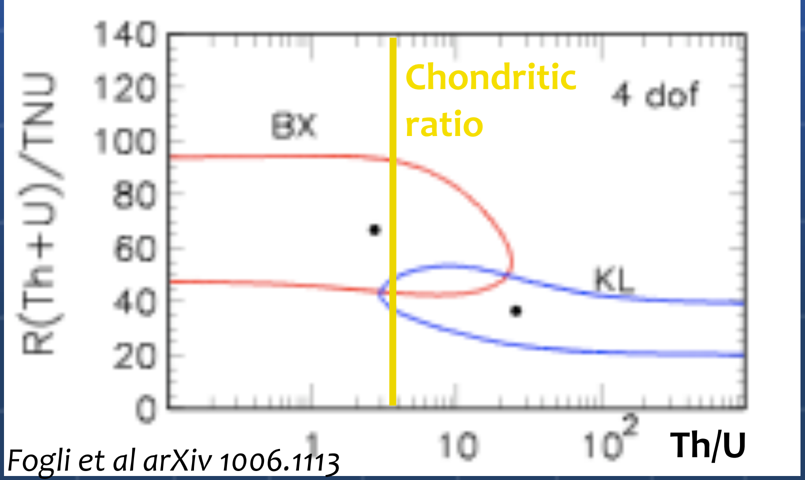




U/Th ratio free:

- *Difficult to constrain with enough precision by a single exp. (if detector size ≤ kton)*
- *Better results through combined analysis:*

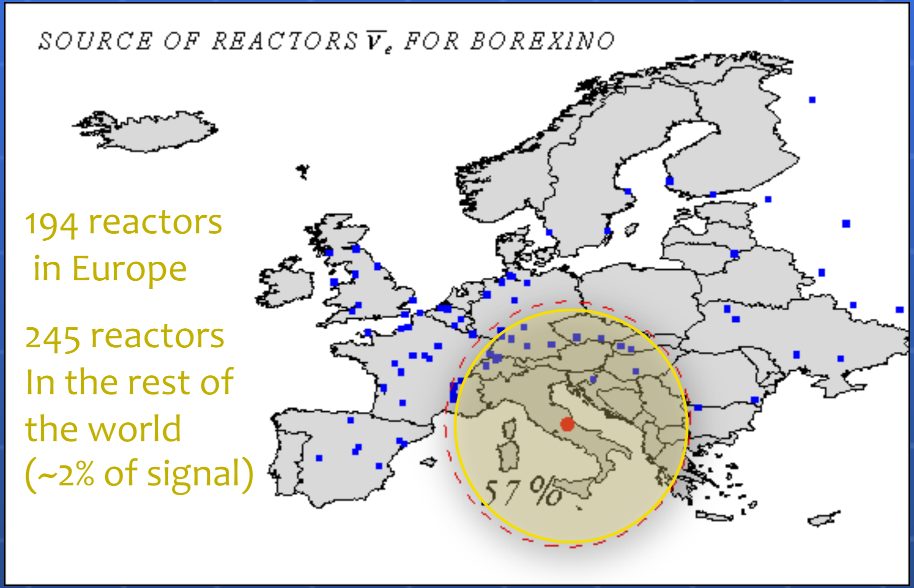




Fogli et al arXiv 1006.1113

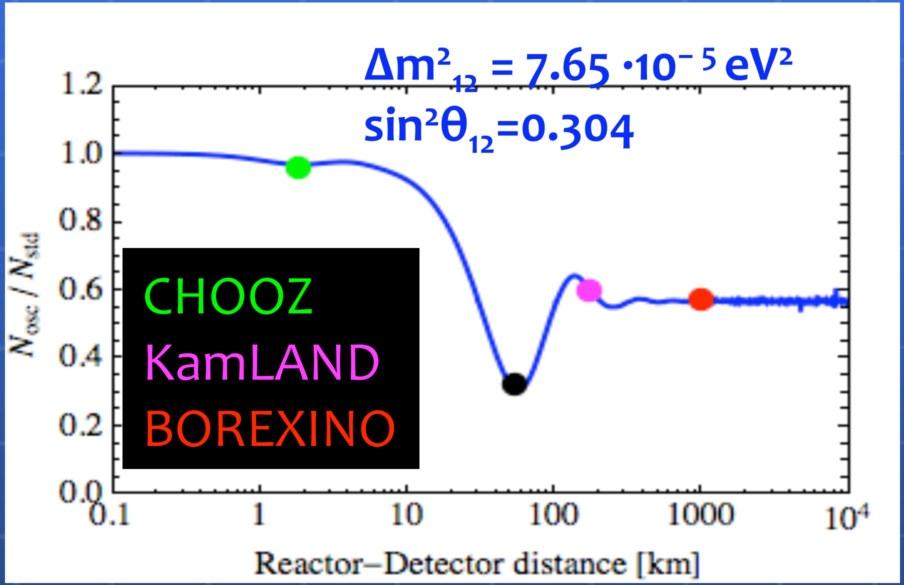
The detection of the European reactor anti-ν

$$P_{ee}\left(E_{\bar{\nu}},L\right) \cong 1-\sin^2(2\vartheta_{12})\sin^2\left(\frac{1.27\Delta m_{12}^2\left[eV^2\right]L[m]}{E_{\bar{\nu}}}\right)$$



194 reactors
in Europe

245 reactors
In the rest of
the world
(~2% of signal)



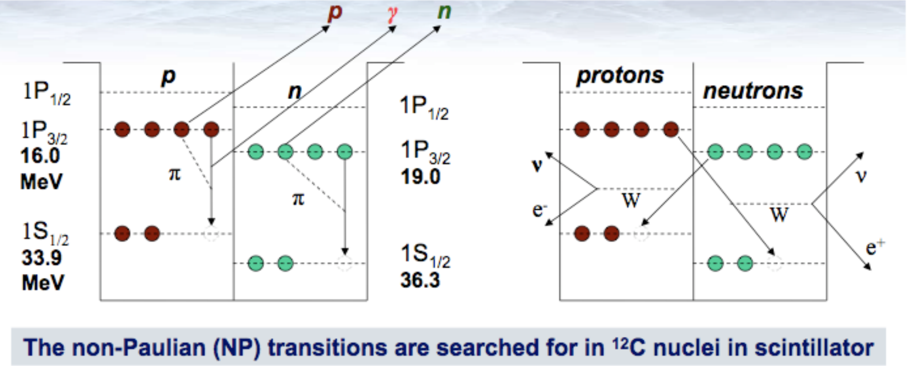
Mean baseline ~ 1000 km

- 6 events observed in the RNW
- 16.3 ± 1.1 events expected (no osc.)

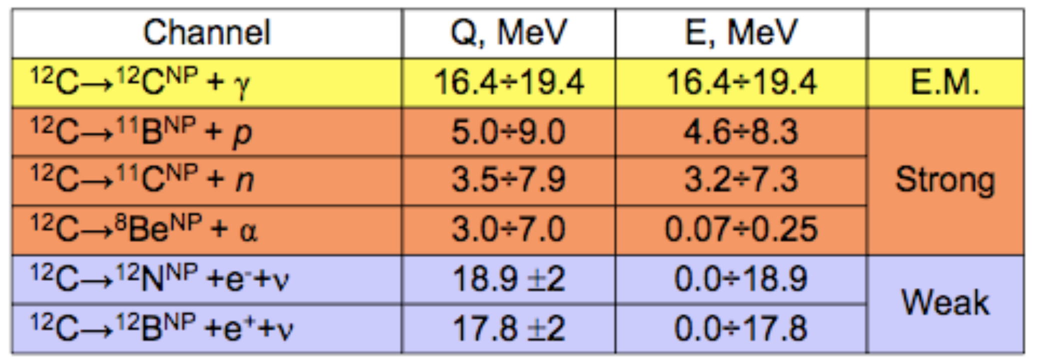
- The non oscillation hypothesis is excluded at 99.60 C.L.
- Geo-reactor power in the Earth core < 3TW @ 95% C.L.

Particle physics: test of the Pauli Exclusion Principle

- Search for γ,n,p,β emitted in non-Paulian transitions on ^{12}C from $^{1}P_{3/2}$ –shell nucleons to the already filled $^{1}S_{1/2}$ shell

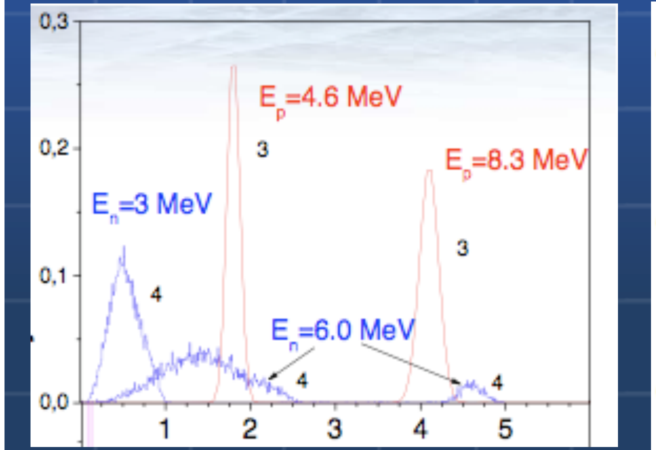


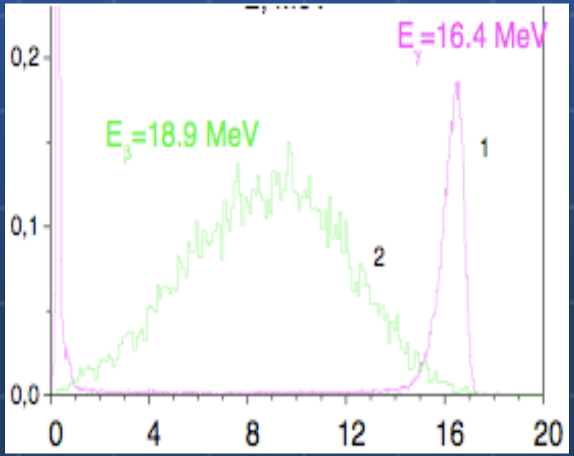
The non-Paulian (NP) transitions are searched for in ^{12}C nuclei in scintillator

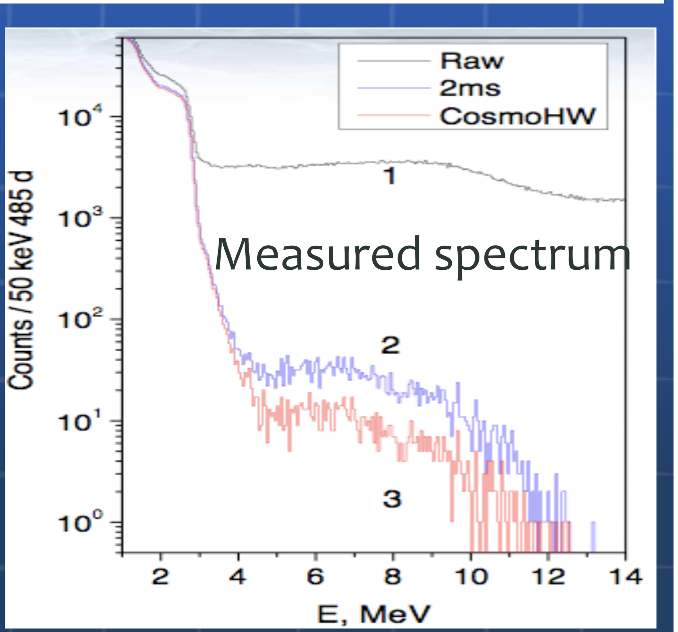


Channel	Q, MeV	E, MeV	
$^{12}C \rightarrow ^{12}C^{NP} + \gamma$	16.4÷19.4	16.4÷19.4	E.M.
$^{12}C \rightarrow ^{11}B^{NP} + p$	5.0÷9.0	4.6÷8.3	Strong
$^{12}C \rightarrow ^{11}C^{NP} + n$	3.5÷7.9	3.2÷7.3	
$^{12}C \rightarrow ^{8}Be^{NP} + \alpha$	3.0÷7.0	0.07÷0.25	
$^{12}C \rightarrow ^{12}N^{NP} + e^- + \nu$	18.9 ±2	0.0÷18.9	Weak
$^{12}C \rightarrow ^{12}B^{NP} + e^+ + \nu$	17.8 ±2	0.0÷17.8	

Examples of expected signals:



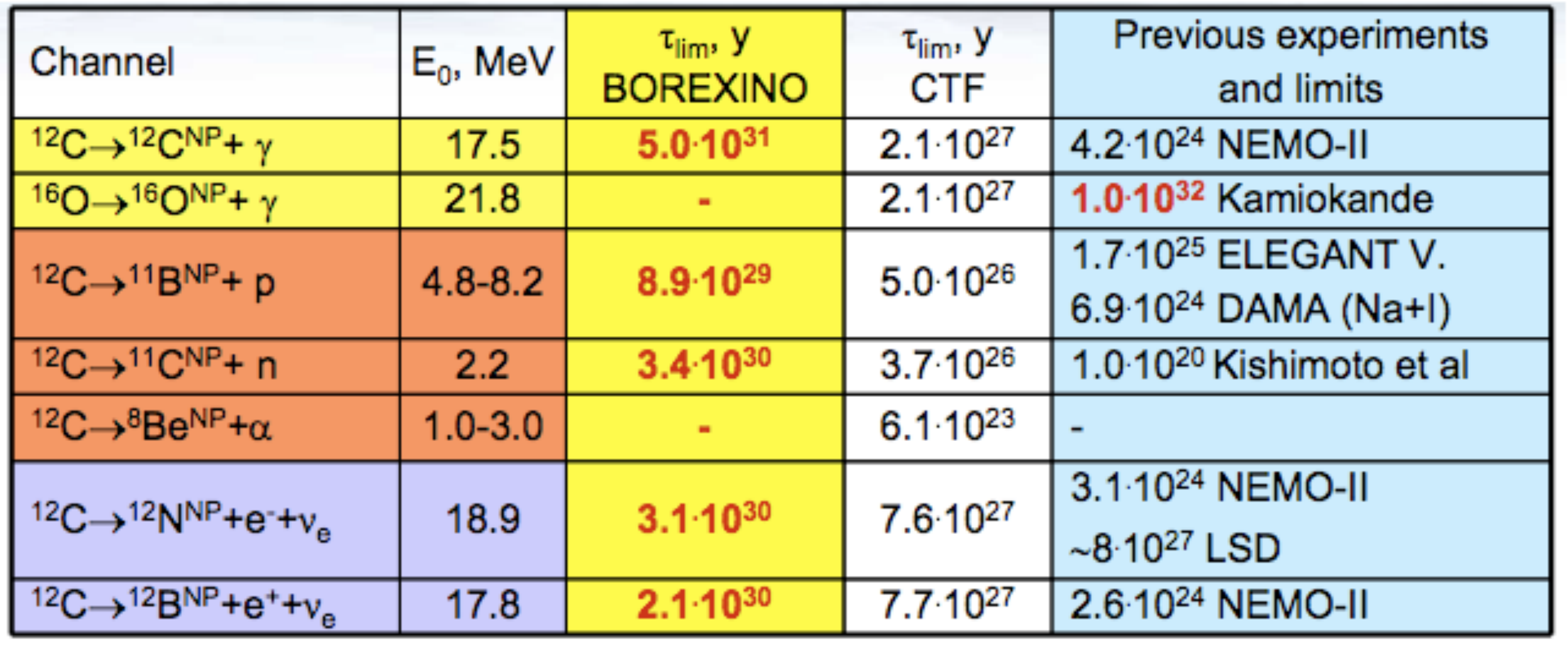




Measured spectrum

Particle physics: limits on PEP principle violating transitions

Phys. Rev. C 81 (2010) 034317 (meas. time : 485 days)



Channel	E_0, MeV	τ_{lim}, y BOREXINO	τ_{lim}, y CTF	Previous experiments and limits
$^{12}C \to {}^{12}C^{NP} + \gamma$	17.5	$5.0\cdot10^{31}$	$2.1\cdot10^{27}$	$4.2\cdot10^{24}$ NEMO-II
$^{16}O \to {}^{16}O^{NP} + \gamma$	21.8	-	$2.1\cdot10^{27}$	$1.0\cdot10^{32}$ Kamiokande
$^{12}C \to {}^{11}B^{NP} + p$	4.8-8.2	$8.9\cdot10^{29}$	$5.0\cdot10^{26}$	$1.7\cdot10^{25}$ ELEGANT V. $6.9\cdot10^{24}$ DAMA (Na+I)
$^{12}C \to {}^{11}C^{NP} + n$	2.2	$3.4\cdot10^{30}$	$3.7\cdot10^{26}$	$1.0\cdot10^{20}$ Kishimoto et al
$^{12}C \to {}^{8}Be^{NP} + \alpha$	1.0-3.0	-	$6.1\cdot10^{23}$	-
$^{12}C \to {}^{12}N^{NP} + e^{-} + \nu_e$	18.9	$3.1\cdot10^{30}$	$7.6\cdot10^{27}$	$3.1\cdot10^{24}$ NEMO-II $\sim 8\cdot10^{27}$ LSD
$^{12}C \to {}^{12}B^{NP} + e^{+} + \nu_e$	17.8	$2.1\cdot10^{30}$	$7.7\cdot10^{27}$	$2.6\cdot10^{24}$ NEMO-II

✓The Borexino results are 3-4 orders of magnitude stronger than CTF ones

✓Limits for NP transitions in ^{12}C with p-, n-, β^- emissions are the best to date

What’s next?

✓ Neutrino astrophysics

- Precise measurement of ^{7}Be ν flux and its seasonal variation
  - 3 years of statistics;
  - Fiducial volume and energy response fixed by calibrations;
  - MC fitting procedure implemented;
  - ^{85}Kr constrained by delayed coincidence measurement;

  Scintillator purification : ^{85}Kr effectively removed by nitrogen stripping.
- More precise measurement of the oscillation probability in the transition region:
  - Fiducial volume and energy response fixed by calibrations;
  - More statistics (measure time + increase of FV mass);
  - ^{7}Be at 5% + 4 y of statistics --> distance between ^{7}Be and ^{8}B P_{ee} at more than 3σ.
- CNO and pep-neutrino flux measurements:
  - Cosmogenic ^{11}C tagging already improved;
  - ^{210}Bi content could be reduced through PC purification.

✓ Anti-Neutrino geology

- Error on fluxes decreased down to 15% in 6 y;
- Test of various existing Earth models, evidence of contribution for the mantle;
- Constrains to U/Th ratio (combined analysis).

✓ Neutrino properties and particle physics

- Coming very soon limits on solar anti-ν fluxes, $\nu \to \bar{\nu}$ conversion in the Sun, μ_ν, $\mu_{\bar{\nu}}$.

THANK YOU!!!

Milano

Genova

Perugia

Dubna JINR
(Russia)

Kurchatov
Institute
(Russia)

APC Paris

Princeton University

Virginia Tech. University

Munich
(Germany)

Heidelberg
(Germany)

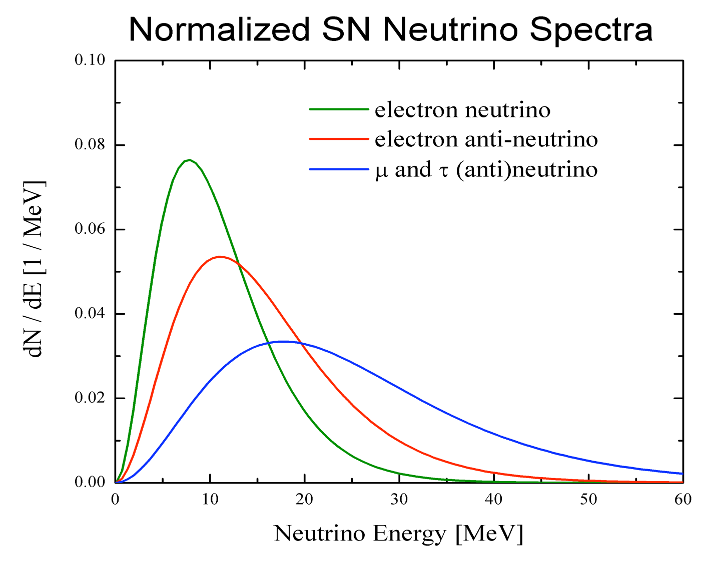
Jagiellonian U.
Cracow
(Poland)

Backup slides

Other physics goals

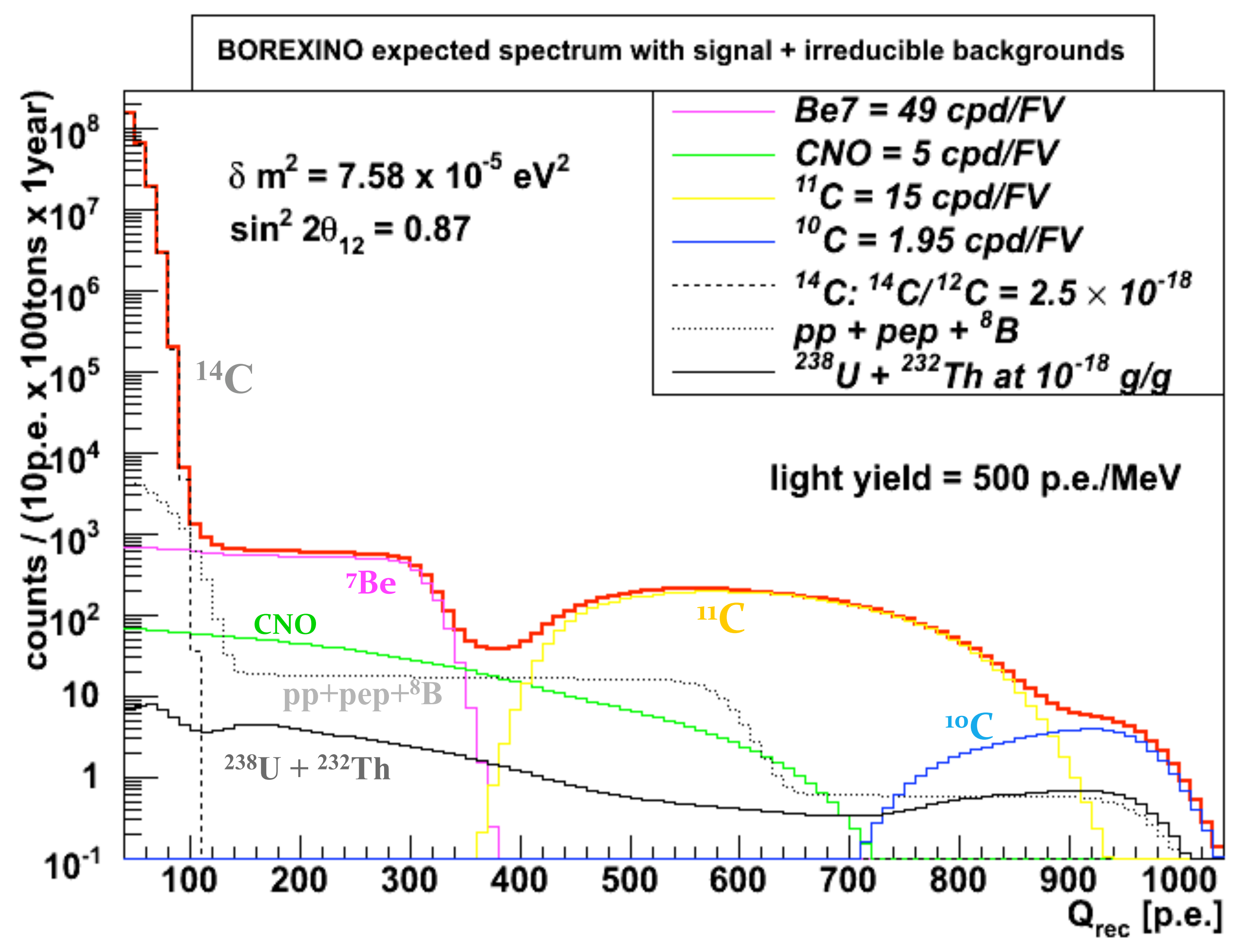
Borexino has joined the SNEW community

Neutrino Spectrum from a Standard SN @ 10kpc



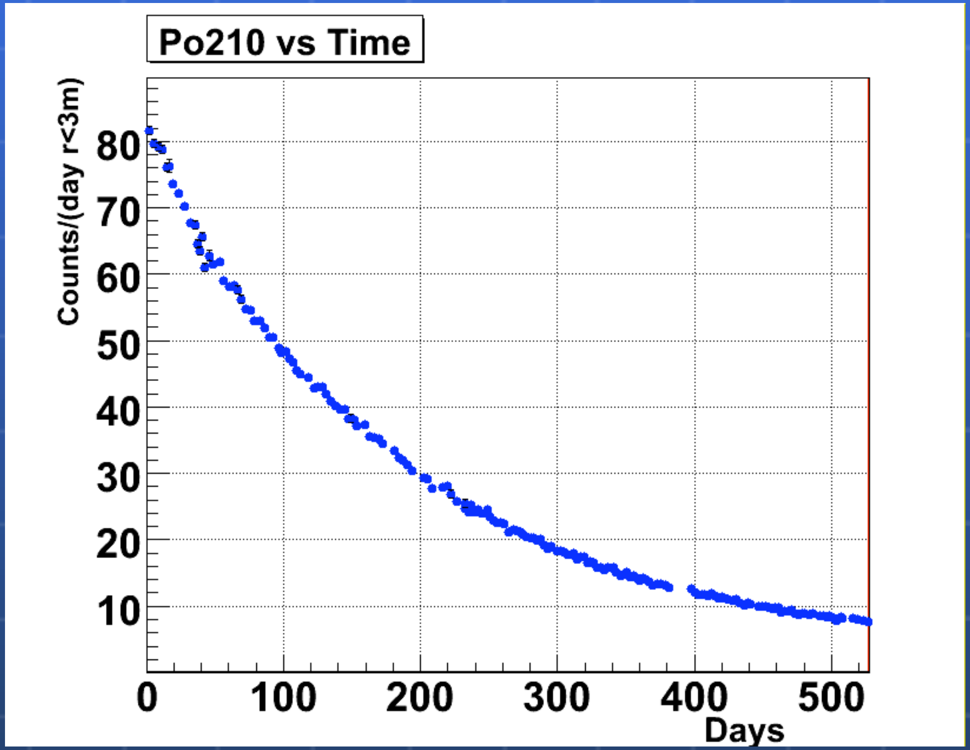
Detection channel	N events
ES (E_ν > 0.25 MeV)	5
Electron anti-neutrinos (E_ν > 1.8 MeV)	78
ν-p ES (E_ν > 0.25 MeV)	52
$^{12}C(\nu,\nu)^{12}C^*$ (Eγ = 15.1 MeV)	18
$^{12}C(\text{anti-}\nu,e^{+)12}B$ ($E_{\text{anti-}\nu}$ > 14.3 MeV)	3
$^{12}C(\nu,e-)^{12}N$ (E_ν > 17.3 MeV)	9

The expected signal +irreducible backgrounds



^{210}Po background

May 13th, 2007- End October 2008



- ^{210}Po not in equilibrium
- Decay time: about 200 days
- α decay : visible energy in the scintillator 0.4 MeV electron equivalent
- Very useful to study the energy resolution and the light yield stability

Constraints on pp & CNO after the ^{7}Be flux

- Combining the results obtained by Borexino on ^{7}Be flux with those obtained by other experiments we can constrain the fluxes of pp and CNO ν_e;
- The measured rate by Clorine and Gallium experiments R_k:

$$R_k = \sum_{i,k} f_i R_{i,k} P_{ee}^{i,k}$$

$$f_i = \frac{\phi_i(\text{measured})}{\phi_i(\text{predicted})}$$

$R_{i,k}$ = expected rate of source "i" in experiment "k" (no oscill.)

$P_{ee}^{e,k}$ = average survival probability for source "i" in experiment "k"

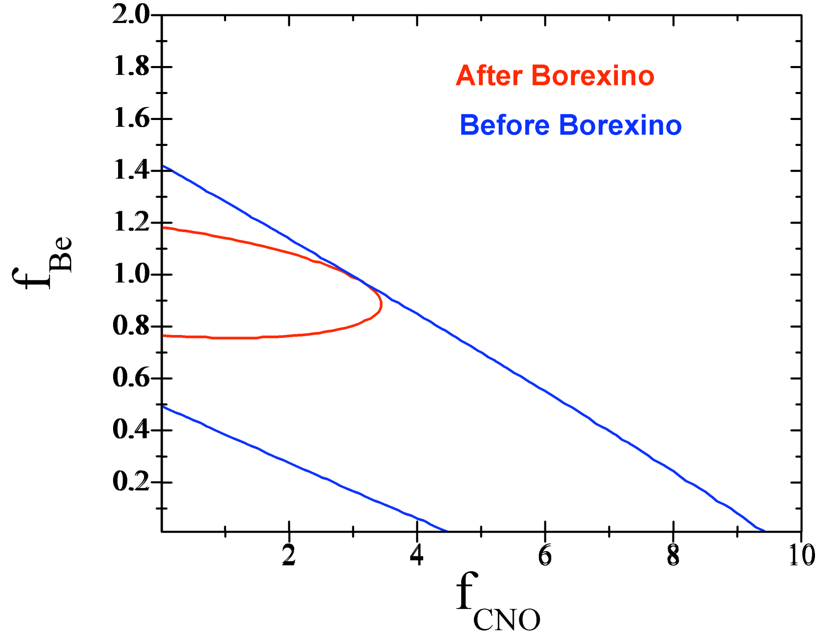
- $R_{i,k}$ and $P_{ee}^{i,k}$ are calculated in the hypothesis of **high-Z SSM and MSW LMA**, ;

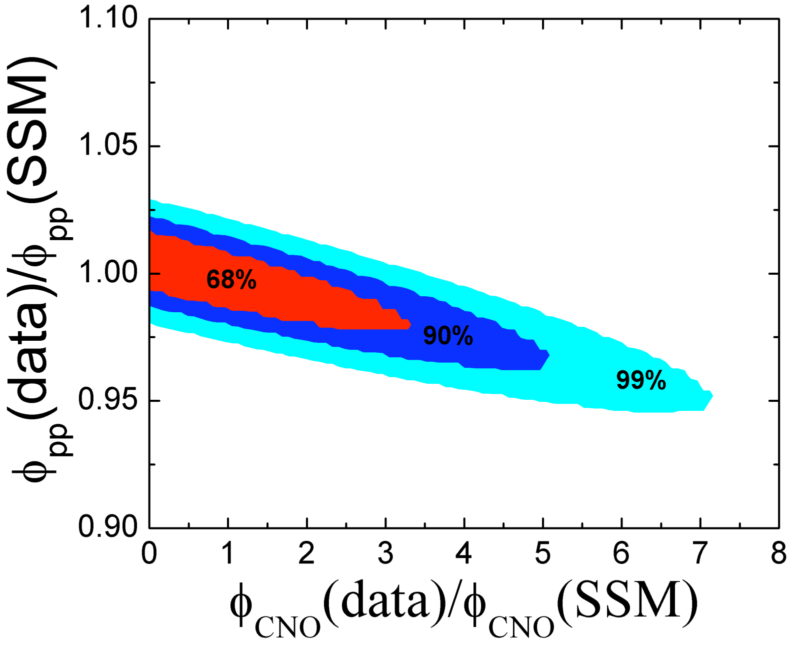
f_{8B} = **0.87 ± 0.07**, measured by **SNO** and **SuperK;**

- **f_{7Be} = 1.02 ±0.10** is given by **Borexino results**;

χ^2 based analysis with the additional luminosity constraint;

Constraints on pp & CNO after the ^{7}Be flux





$$f_{pp} = 1.005^{+0.008}_{-0.020} \ (1\sigma)$$

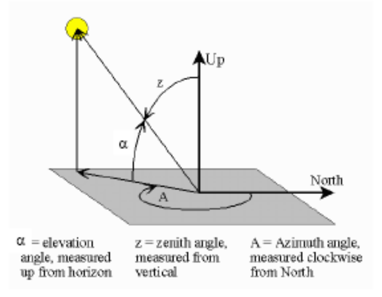
$$f_{CNO} < 3.80 \ (90\% \ C.L.)$$

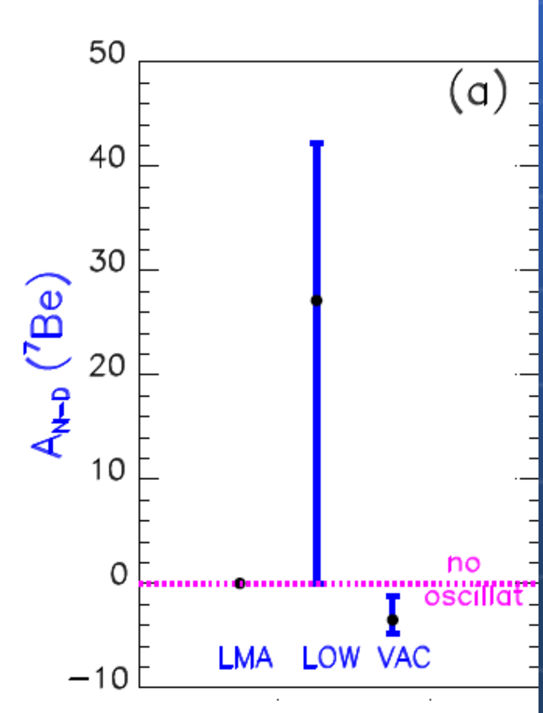
This is the best determination of pp flux (with luminosity constraint)

The D/N asymmetry in the ^{7}Be flux

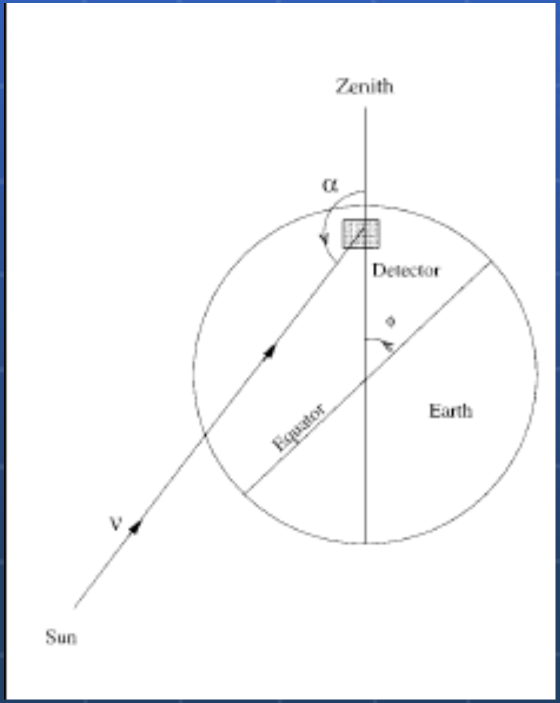
- MSW mechanism: ν interaction in the Earth could lead to a ν_e regeneration effect
- Solar ν flux higher in the night than in the day
- The amount of the effect depends
  - detector latitude
  - energy of the neutrinos

$$\theta \ \Delta m^2$$





The absence of a day night effect for the ^{7}Be is a further confirmation of the LMA solution of the solar neutrino problem



Geo-ν signal at LNGS

Allowed region – consistent with geophysical & geochemical data

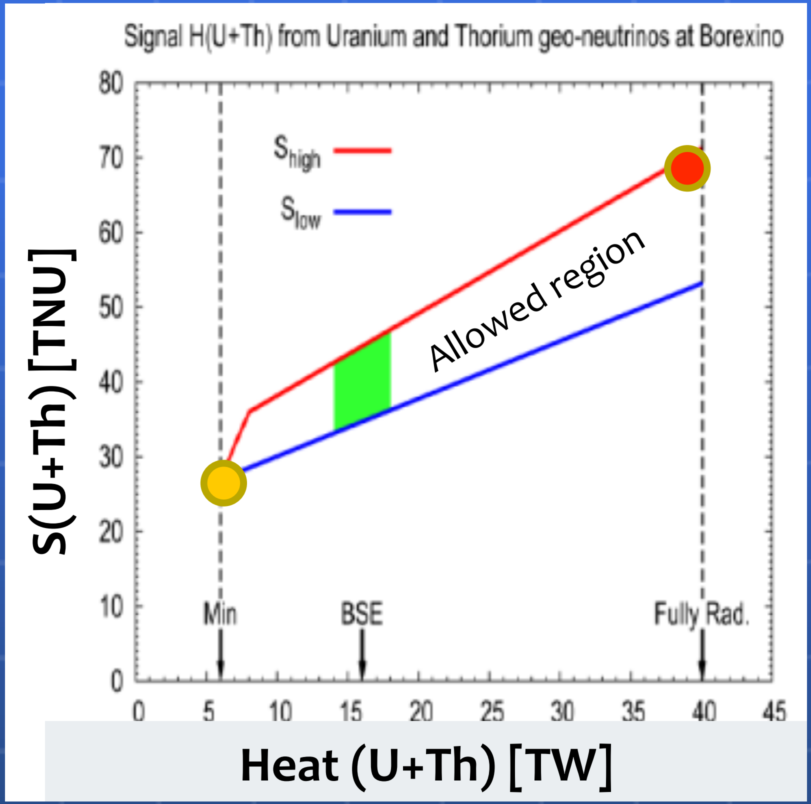
Slope – fixed by the reactions energetics

Intercept + width –
site dependent, U+Th distribution

🟩 Region allowed by the BSE geochemical model

🟡 Minimum from known U+Th concentrations in the crust

🔴 Maximum given by the total Earth heat flow



for LNGS Mantovani et al., TAUP 2007

1 TNU (Terrestrial Neutrino Unit) = 1 event/ 10^{32} protons/year

<u>Important local geology: cca. half of the signal comes from within 200 km range!!</u>

Geo-ν signal: non anti-ν backgrounds

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

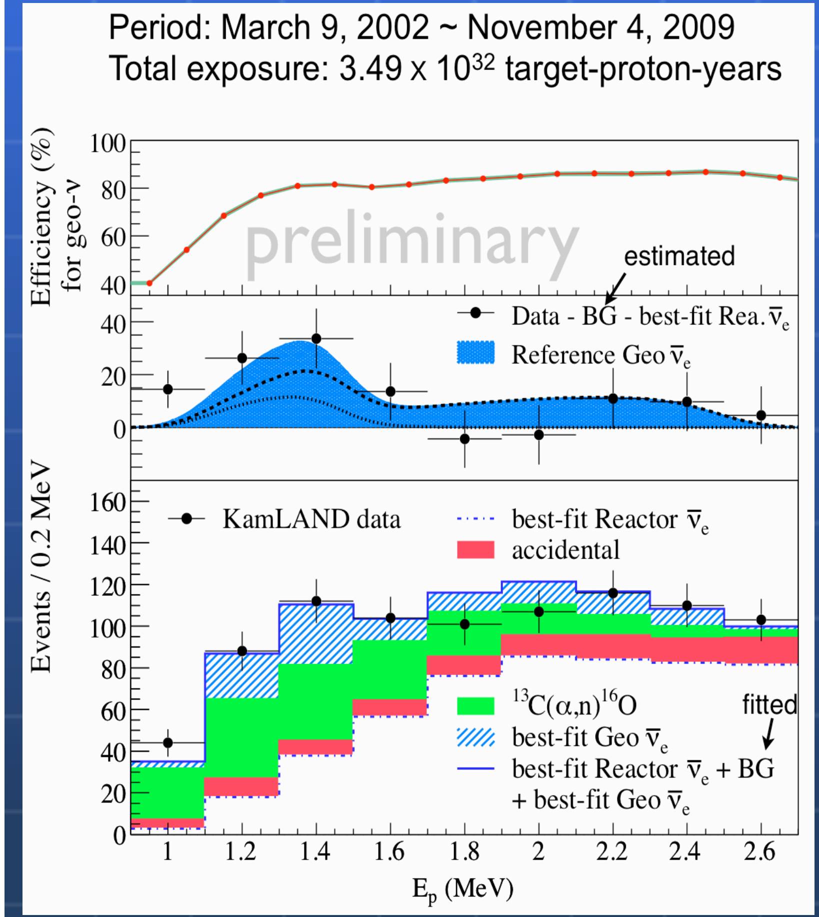
Expected : 2.5 geo-ν/(100ton-year) (assuming BSE)

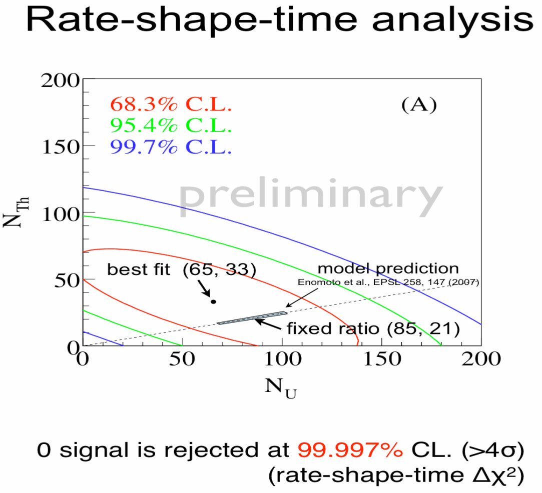
Anti-ν signal in BX: rate analysis

	Predicted from reactors	Background	Observed	Probability to get $N \geq N_{obs}$	Probability to get $N \leq N_{obs}$
Geo-ν window	**5.0±0.3**	**0.31±0.05**	**15**	**5×10^{-4} (3.5σ)**	
Reactor-ν window without oscillations	**16.3±1.1**	**0.09±0.06**	**6**		**5×10^{-3} (2.9σ)**

Geo-ν: new KamLand result

K. Inoue Neutrino 2010


Period: March 9, 2002 ~ November 4, 2009
Total exposure: 3.49 x 10^{32} target-proton-years

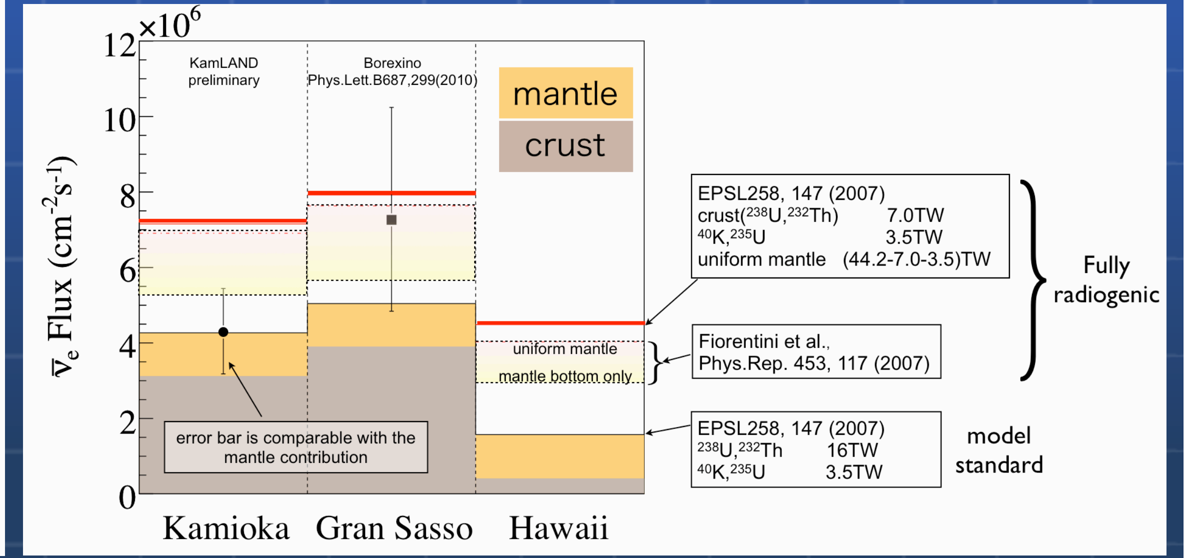

Rate-shape-time analysis

0 signal is rejected at 99.997% CL. (>4σ)
(rate-shape-time Δχ²)

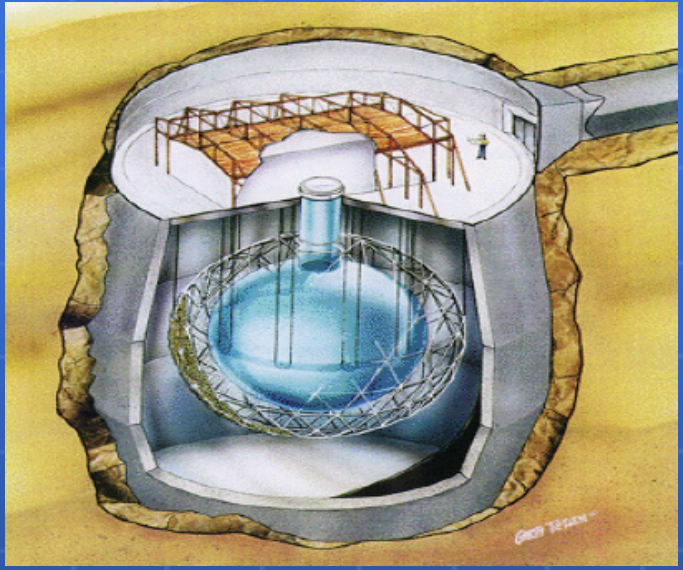
<u>**Complementarity!!**</u>

KamLand: oceanic crust

Borexino: continental crust



SNO+ at Subdury (Canada)

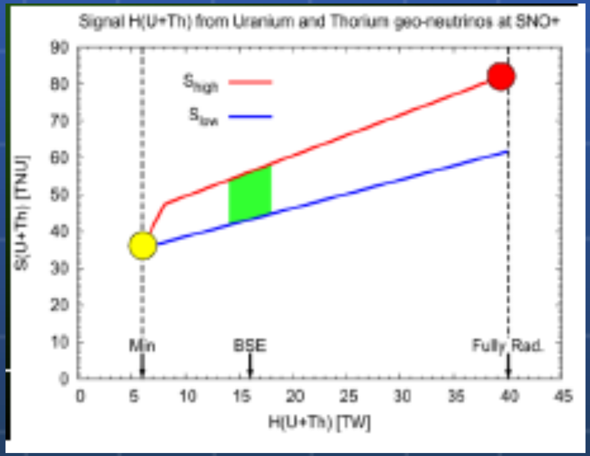


After SNO: D_2O replaced by 1000 tons of liquid scintillator

M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

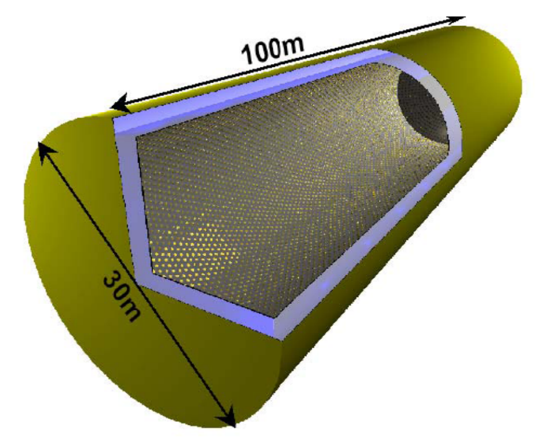
Placed on an old continental crust:
80% of the signal from the crust
(Fiorentini et al., 2005)

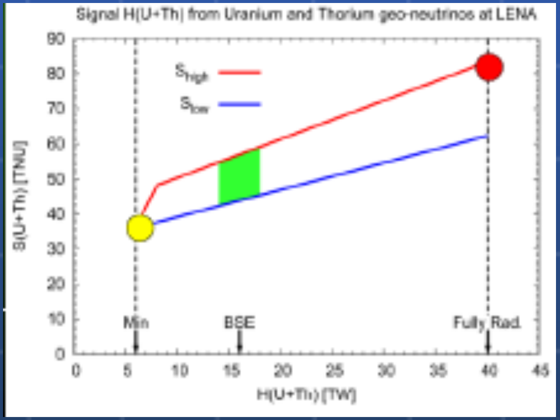
BSE: 28-38 events/per year



Mantovani et al., TAUP 2007

LENA at Pyhasalmi (Finland)





Project for a 50 kton underground liquid scintillator detector

K.A. Hochmuth et al. – Astropart. Phys. 27, 2007.

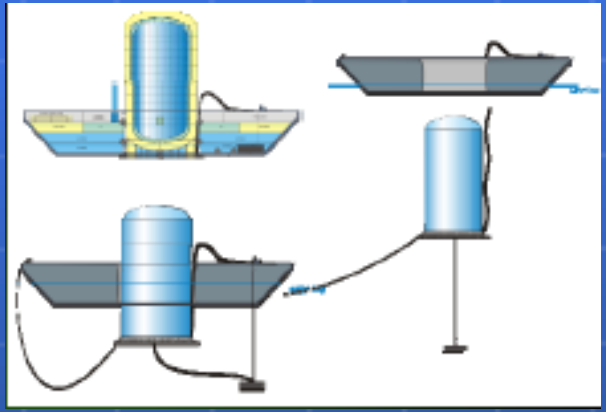
80% of the signal from the continental crust (Fiorentini et al.)

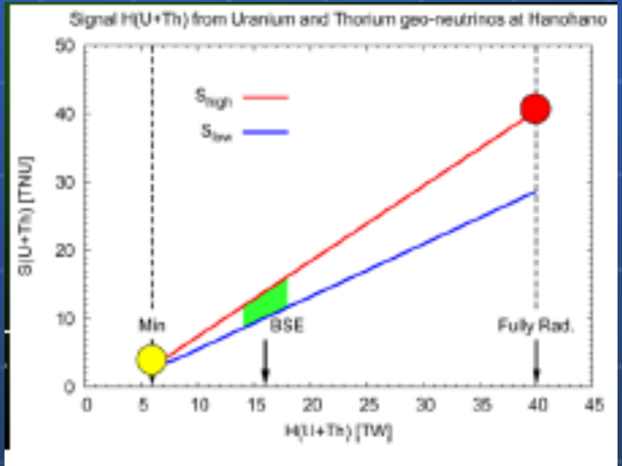
BSE: 800-1200 events/per year

Scintillator loaded with 0.1% Gd:

- better neutron detection
- moderate **directionality** information

Hanohano at Hawaii





Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

Since Hawai placed on the U-Th depleted oceanic crust
70% of the signal from the mantle!
Would lead to very interesting results!
(Fiorentini et al.)

BSE: 60-100 events/per year