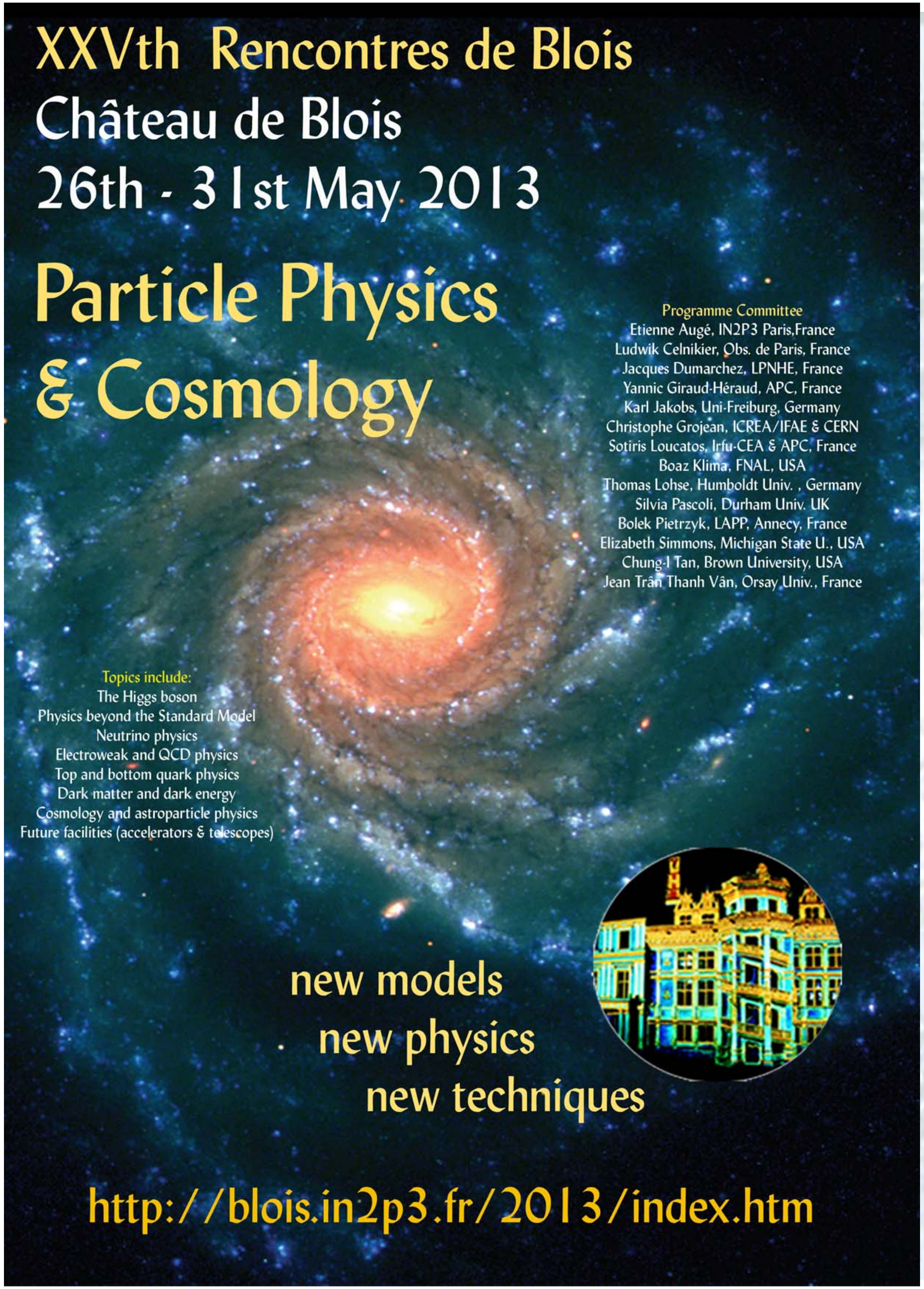


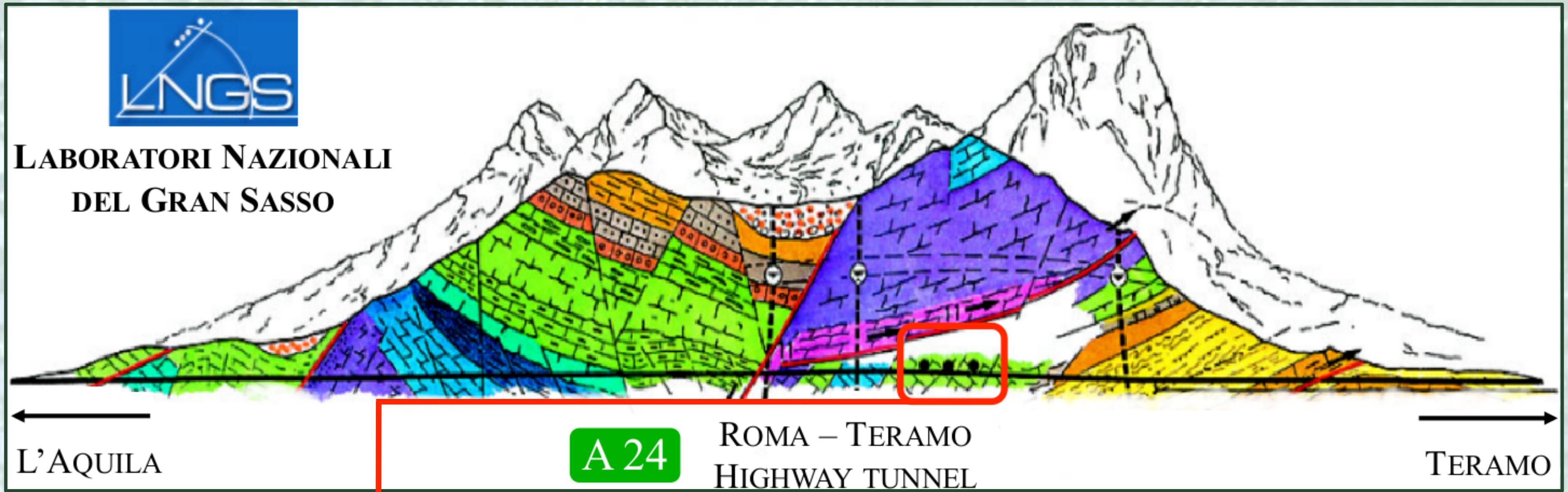
RESULTS AND PERSPECTIVES OF THE BOREXINO EXPERIMENT

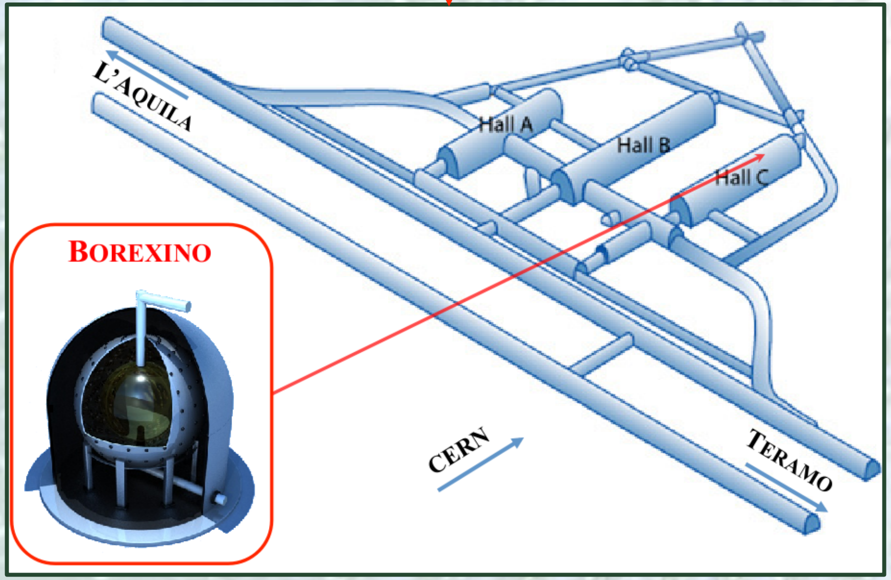
ALESSANDRA CARLOTTA RE

(on behalf of the Borexino Collaboration)

INFN - Sezione di Milano

LABORATORI NAZIONALI DEL GRAN SASSO





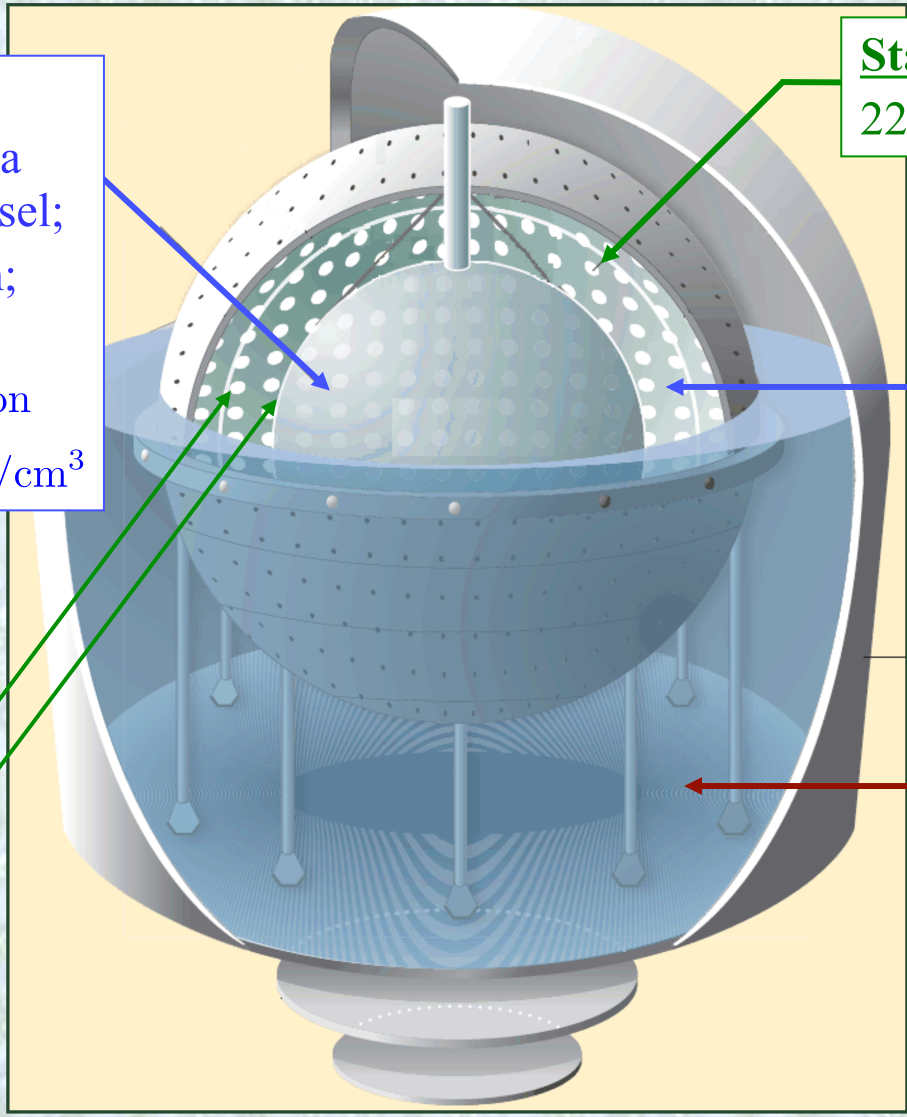
The **LNGS** altitude is 963 m and the average rock cover is about 1,400 m.

The shielding capacity against cosmic rays is about 3,800 meter water equivalent (m.w.e.): the muon flux is reduced of a factor 10^6 respect to the surface.

$$\Phi(\mu) \sim 1\, \mu/\mathrm{m}^2/\mathrm{h}$$

THE BOREXINO DETECTOR

Scintillator:
280 ton of PC+PPO in a 125 μm thick nylon vessel;
Fiducial mass ~ 100 ton;
Electron density: $(3.307 \pm 0.003) \times 10^{29}/\text{ton}$
Mass density: $\simeq 0.879\ \text{g/cm}^3$



Stainless Steel Sphere:
2212 PhotoMultipliers

Non-scintillating buffer:
900 ton of quenched scintillator

Water Tank:
2.8 kton of pure H_2O
γ and n shield
μ water Č detector
208 PMTs in water

Nylon vessels:
Outer: 5.50 m
Inner: 4.25 m

THE BOREXINO DETECTOR (2)

✧ **Main goal**: the detection of low energies solar neutrinos, in particular ^{7}Be neutrinos.

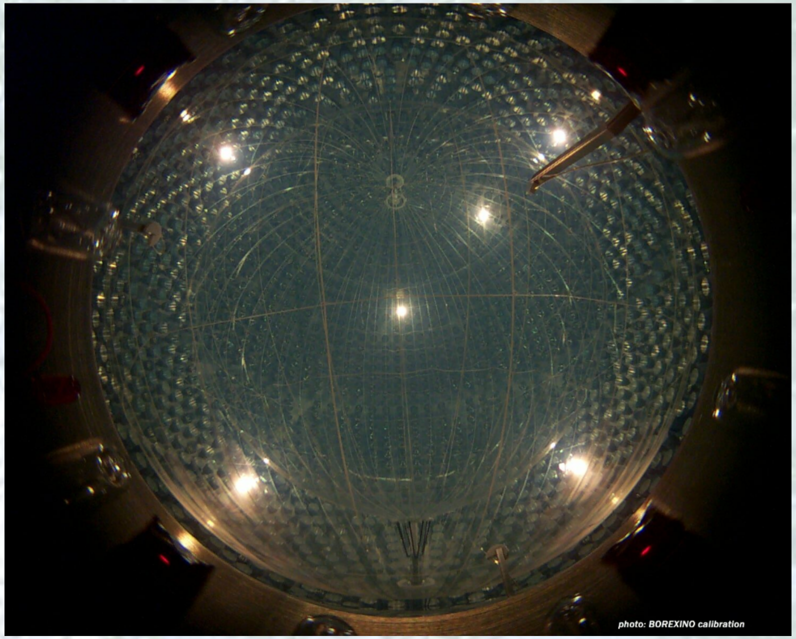
✧ **Detection method**: elastic scattering of neutrinos on electrons.

$$\nu_x + e \rightarrow \nu_x + e \quad x = e, \mu, \tau$$

✧ **Detection medium**: large mass of organic liquid scintillator.

- Advantages: large light-yield;
- Disadvantages: no directional information.

Signal is indistinguishable from background: high radiopurity is a MUST!



The expected rate of ^{7}Be solar neutrinos in 100 ton of BX scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/Kg.

Just for comparison, natural water is about 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K.

SOLAR ν AND THE STANDARD SOLAR MODEL

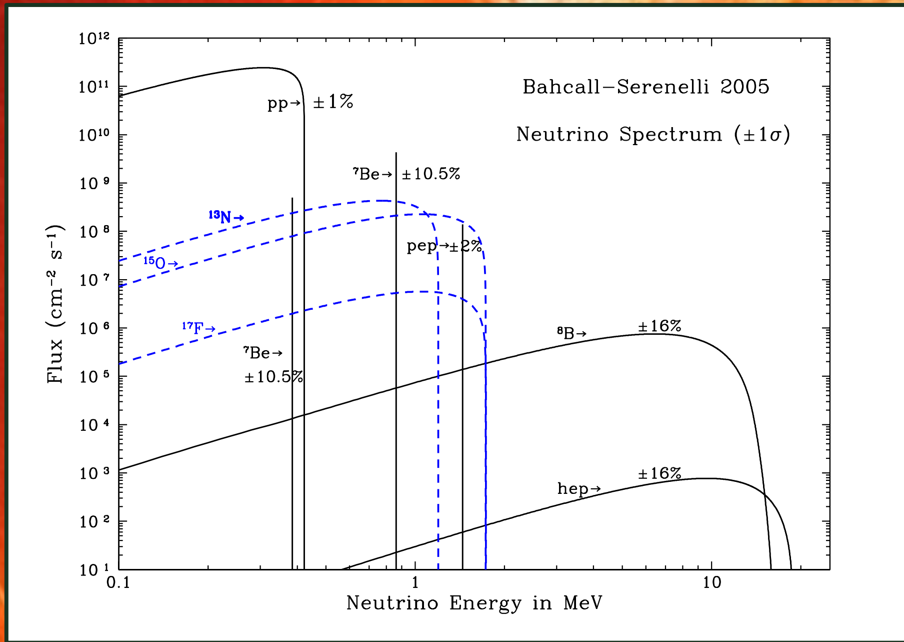
The solar neutrino fluxes and spectra are defined by the Standar Solar Model (SSM).
The SSM main assumptions are:

- Sun in hydrostatic equilibrium;
- Primary energy generation by nuclear reactions;
- Elemental abundances determined by fusion reactions only;

SOLAR NEUTRINO FLUXES - SHP11[1]

ν Flux	High Metallicity [2]	Low Metallicity [3]	Difference %
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	0.8
pep	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	2.1
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	3.4
^{7}**Be**	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	8.8
^{8}**B**	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	17.7
^{13}**N**	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	26.7
^{15}**O**	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	30.0
^{17}**F**	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	38.4

The fluxes are given in units of 10^{10} (pp), 10^{9} (^{7}Be), 10^{8} (pep, ^{13}N, ^{15}O), 10^{6} (^{8}B, ^{17}F) and 10^{3} (hep) $cm^{-2}\,s^{-1}$.



[1] ApJ 743 pp. 24, 2011
[2] Space Sciences Reviews 85-161, 1998
[3] ApJ 705 L123, 2009

SOLAR NEUTRINOS: THE BOREXINO RESULTS

Since the start of data taking, the Borexino collaboration has released many interesting results. In particular…

- The ^{7}Be solar-ν rate measurement[4] with accuracy better than 5%:

$$46.0 \pm 1.5\,(\mathrm{stat})\,^{+1.5}_{-1.6}\,(\mathrm{syst})\ \mathrm{cpd}/100\ \mathrm{ton}$$
$$\Phi(^7\mathrm{Be}) = (2.78 \pm 0.13) \times 10^9\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

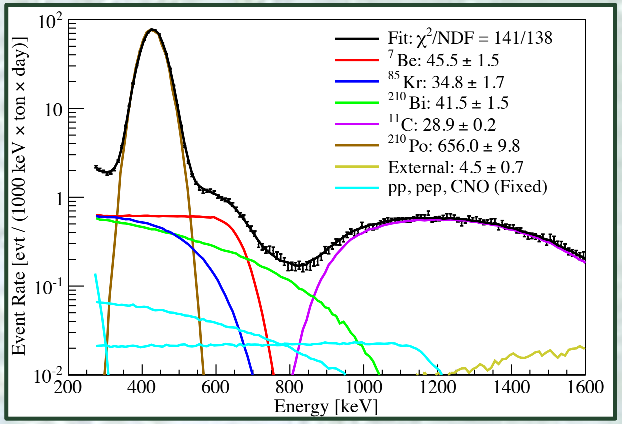
- The evidence of a null day-night asymmetry[5] with accuracy of 1.5 x 10^{-2}:

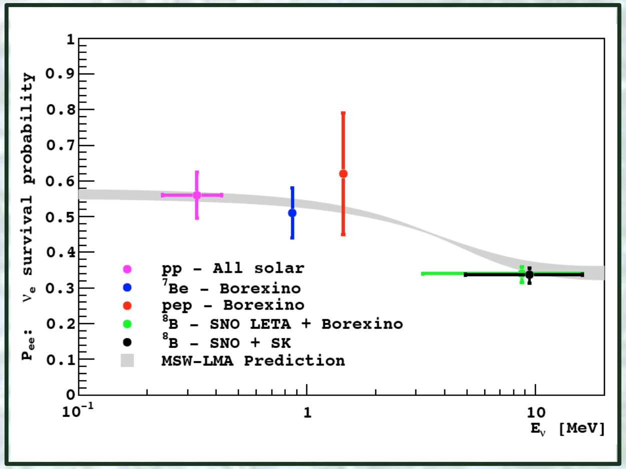
$$\mathrm{A_{DN}} = 0.001 \pm 0.012\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst})$$

- The direct measurement[6] of the pep solar-ν flux:

$$3.1 \pm 0.6\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \mathrm{cpd}/100\ \mathrm{ton}$$
$$\Phi(\mathrm{pep}) = (1.6 \pm 0.3) \times 10^8\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Moreover, the measurement[7] of ^{8}B neutrino flux above 3 MeV, the best (to date) direct limit[6] on the CNO flux and early this year, the ^{7}Be seasonal modulation analysis.





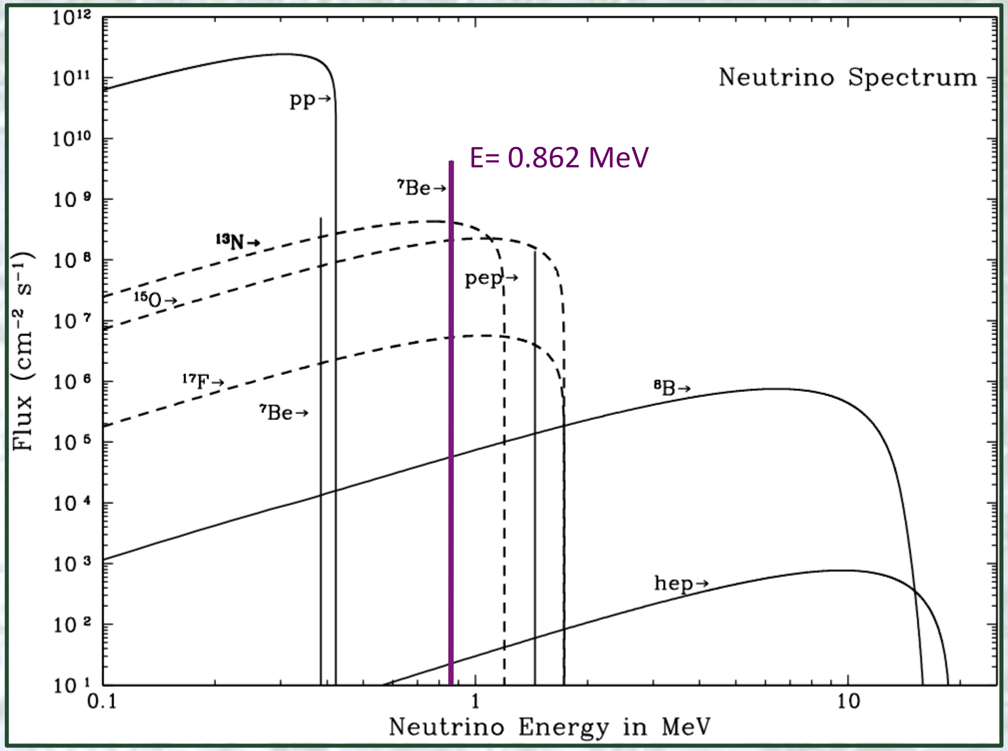
[4] Phys. Rev. Lett., 107, 141302 (2011)
[5] Phys. Lett. B, 707, 22 (2012)
[6] Phys. Rev. Lett., 108, 051302 (2012)
[7] Phys. Rev. D, 82, 033006 (2010)

SOLAR NEUTRINOS: THE BOREXINO RESULTS (2)

^{7}Be solar neutrino:

- the ^{7}Be solar neutrino flux: accuracy below 5%.

$$46.0 \pm 1.5\,(\text{stat})\,^{+1.5}_{-1.6}\,(\text{syst})\ \text{cpd}/100\ \text{ton}$$
$$\Phi(^7\text{Be}) = (2.78 \pm 0.13) \times 10^9\ \text{cm}^{-2}\,\text{s}^{-1}$$



- the day-night asymmetry (A_{DN}) measurement (E=862 keV).

$$A_{DN} = 0.001 \pm 0.012\,(\text{stat}) \pm 0.007\,(\text{syst})$$

- the seasonal modulation signal:

Due to Earth eccentricity (ε = 0.0167, maximum on January 3), over one solar year period, we should observe a Perihelion-Aphelion difference of ±7% in neutrino flux that is a ^{7}Be neutrino rate variation between 47.5 and 44.5 cpd/100 ton.

SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
pep	$1.44 \times 10^8\ \text{cm}^{-2}\,\text{s}^{-1}$	12%
^{7}**Be**	$5.00 \times 10^9\ \text{cm}^{-2}\,\text{s}^{-1}$	7 %
^{8}**B**	$5.58 \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$	14%

SOLAR NEUTRINOS: THE BOREXINO RESULTS (3)

^{7}Be solar neutrino:

- the seasonal modulation signal:

Expected: T = 1 y

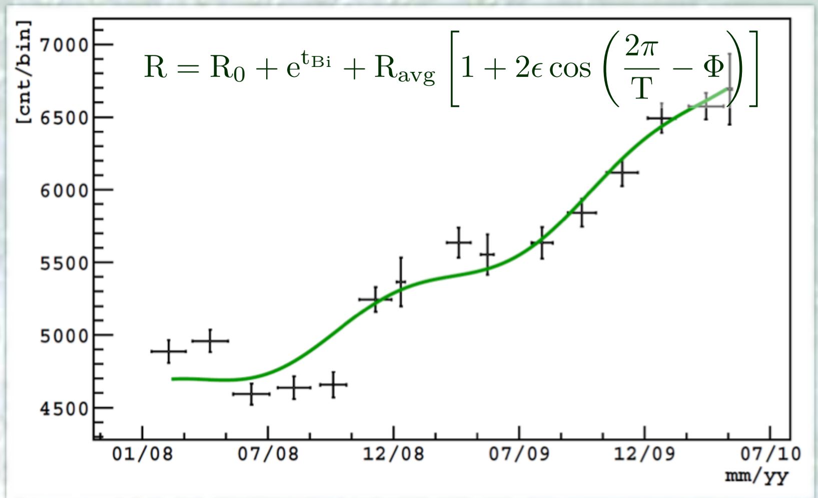
ε = 0.0167

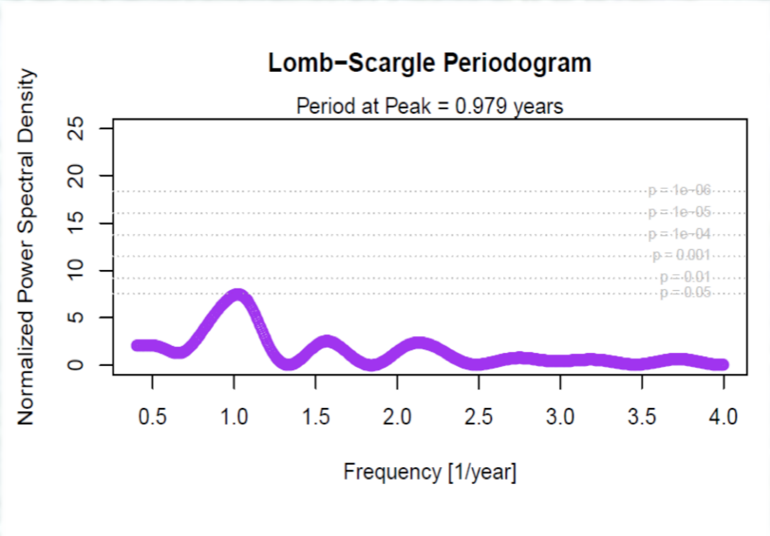
Two different methods give consistent results:

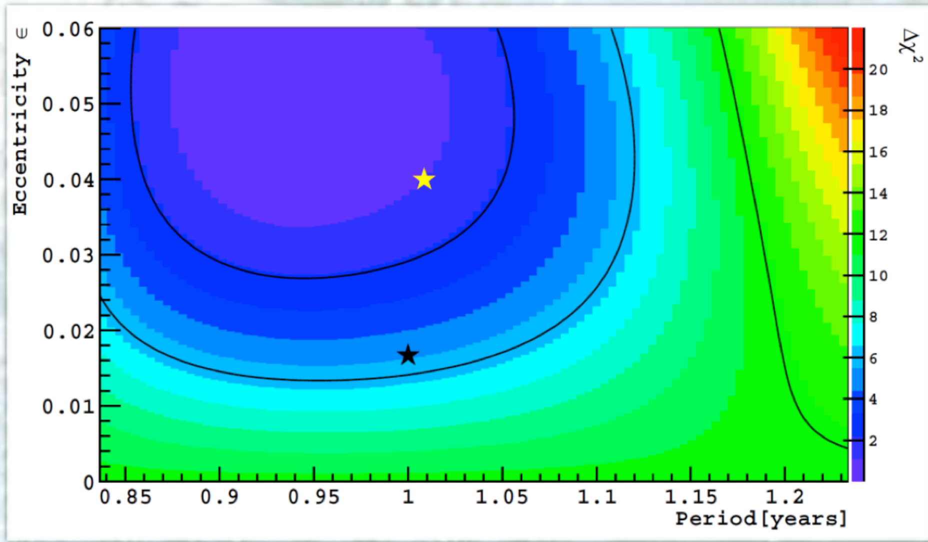
LombScargle analysis T=0.979 y

Fit: ε = 0.0398 ± 0.0102 (within 2σ)

T = 1.01 ± 0.07 y







SOLAR NEUTRINOS: THE BOREXINO RESULTS (4)

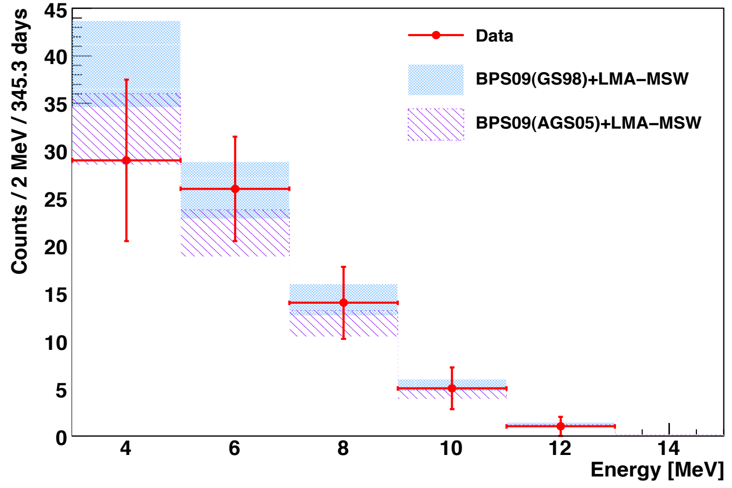
^{8}B solar neutrino:

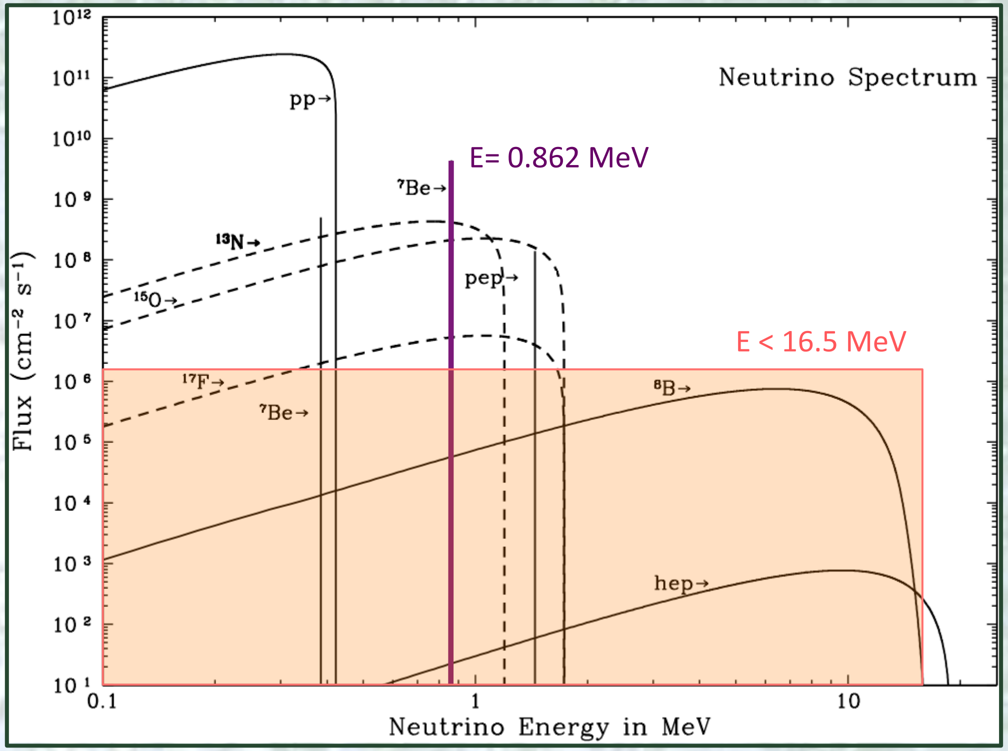
- the ^{8}B neutrino total rate (E_{th}= 3 MeV);

$$0.217 \pm 0.038(\mathrm{stat}) \pm 0.008(\mathrm{syst})\ \mathrm{cpd}/100\ \mathrm{ton},$$
$$\Phi(^{8}\mathrm{B}) = (2.40 \pm 0.41) \times 10^{6}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,.$$

accuracy about 18%

- the ^{8}B neutrino spectral shape.





SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
pep	$1.44 \times 10^{8}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	12%
^{7}**Be**	$5.00 \times 10^{9}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	7 %
^{8}**B**	$5.58 \times 10^{6}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	14%

SOLAR NEUTRINOS: THE BOREXINO RESULTS (5)

pep solar neutrino:

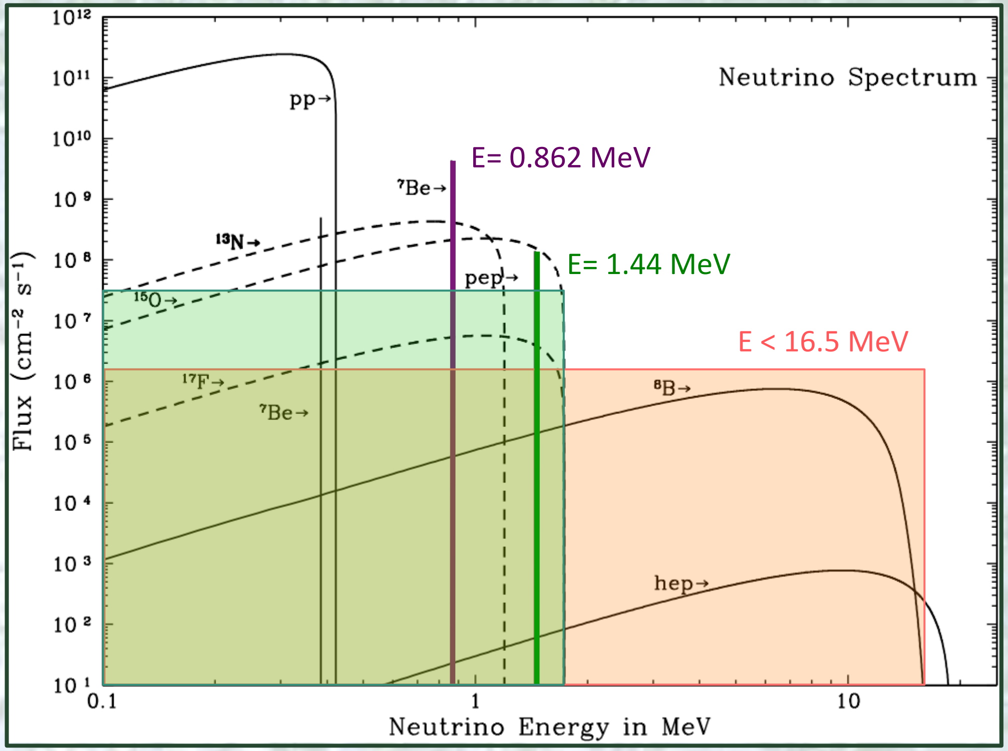
-the pep total ν-rate:

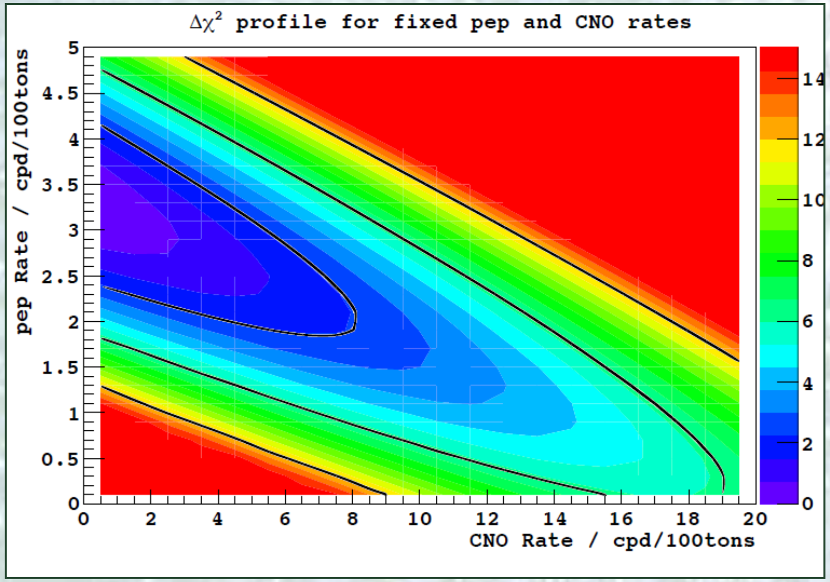
$$3.1 \pm 0.6\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{cpd}/100\ \text{ton}$$
$$\Phi(\text{pep}) = (1.6 \pm 0.3) \times 10^{8}\ \text{cm}^{-2}\,\text{s}^{-1}$$

accuracy about 20%

- the (best to date) limit on CNO:

$$< 7.9\ \text{cpd}/100\ \text{ton}\quad (95\%\ \text{C.L.})$$





SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Error
pep	$1.44 \times 10^{8}\ \text{cm}^{-2}\,\text{s}^{-1}$	12%
^{7}**Be**	$5.00 \times 10^{9}\ \text{cm}^{-2}\,\text{s}^{-1}$	7 %
^{8}**B**	$5.58 \times 10^{6}\ \text{cm}^{-2}\,\text{s}^{-1}$	14%

GEO-NEUTRINOS: WHY TO STUDY THEM?

Geo-neutrinos are the anti-neutrinos produced in the decays of the progenies of Uranium, of Thorium and Potassium. Geo-neutrinos bring to the surface information from the interior of the planet: they are a unique direct probe of our Earth's interior!

We could find answers to the questions:

- What is the radiogenic contribution to the terrestrial heat?
- What is the distribution of the radiogenic elements within the Earth?

BOREXINO features

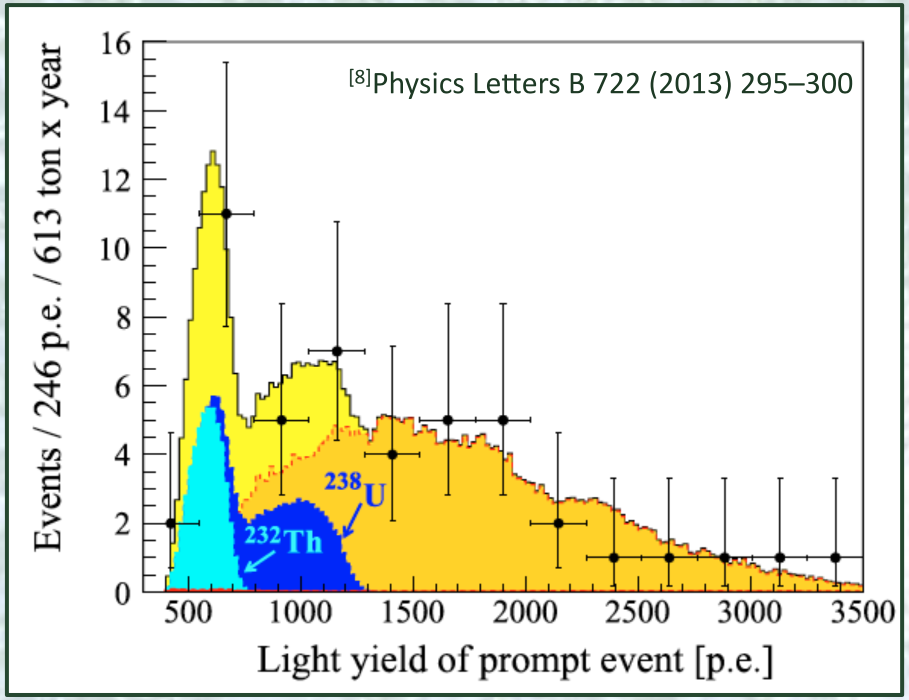
→ - The unprecedented low intrinsic radioactivity;

→ - Far from reactor plants → Very favourable Geo-ν / reactor anti-ν ratio;

→ - Due to the underground location, $\Phi(\mu)$ reduced by ~ 10^6.

➡ Borexino offers a unique opportunity for a sensitive search for anti-neutrinos in the MeV range.

MEASUREMENT OF GEO-NEUTRINOS:



Q_{prompt} light yield spectrum of the prompt 46 candidates and the best-fit with U(blue) and Th(cyan) contributions.

The Borexino collaboration updated the 2010 result with 2.4 times more exposure and in April 2013 released[8] the measurement of geo-neutrinos from 1353 days of data-taking (i.e. 613±26 ton*y, after cuts): 46 golden candidates were found!

$$\mathrm{N_{GEO}} = 14.3 \pm 4.4 \text{ events} \quad (38.8 \pm 12.0 \text{ TNU})$$

$$\mathrm{N_{REAC}} = 31.2^{+7.0}_{-6.1} \text{ events} \quad (84.5^{+19.3}_{-16.9} \text{ TNU})$$

$$\text{TNU}: \text{ Terrestial Neutrino Unit} = 1 \text{ ev/yr}/10^{32} \text{ protons}$$

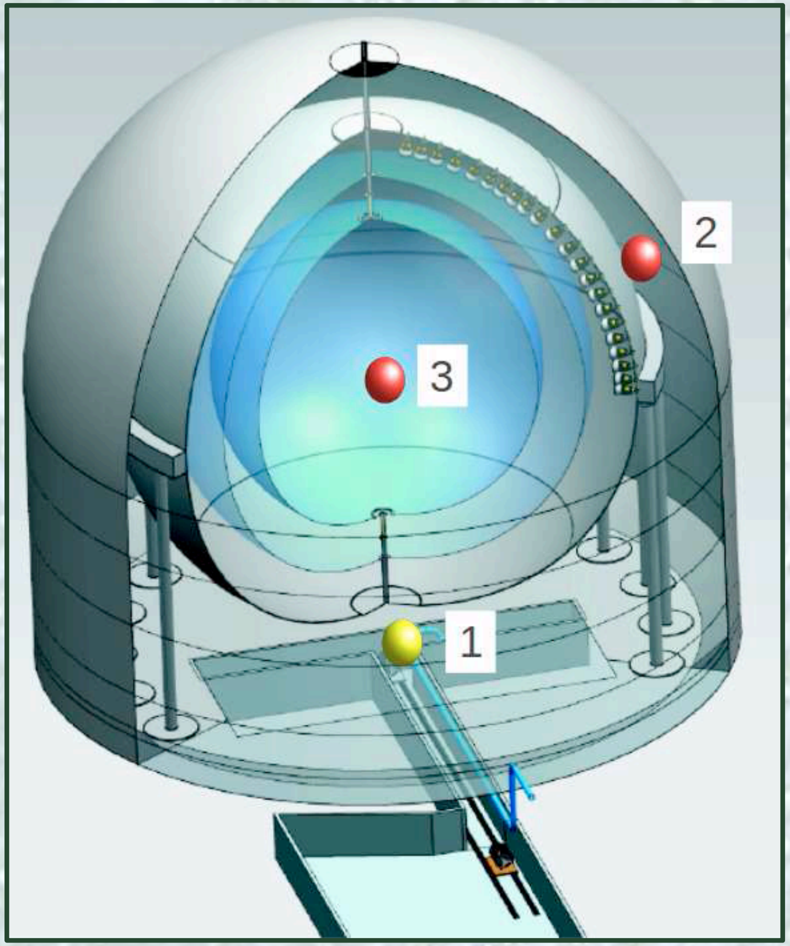
The null-hypothesis of geo-neutrinos is rejected at 4.5σ

An active geo-reactor of 4.5 TW is rejected at 95% C.L.

Subtract relatively well known (based on rock samples) crustal contribution from measured geo-neutrinos signal to obtain mantle geo-ν signal: (15.4 ± 12.3) TNU

For the first time U and Th contribution can be fitted separately (26.6 TNU vs. 10.6 TNU).

FEW WORDS ON SOX: SHORT-DISTANCE OSCILLATION IN BOREXINO



Main motivation: Search for sterile neutrinos or other short distance effects on P_{ee}.

test the existence of low L/E neutrino and/or antineutrino anomalies by placing well known artificial sources close to or inside Borexino.

There will be three SOX phases.

✧ **SOX A**: ^{51}Cr source (10 Mci) in the pit beneath the detector (i.e. 8.25 m from the center).
Scheduled: 2015/2016

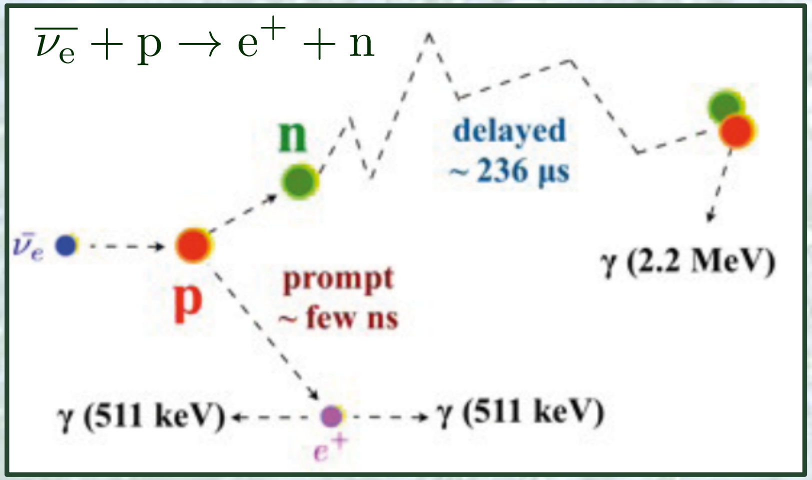
✧ **SOX B**: ^{144}Ce-^{144}Pr source (75 kCi) in the water tank (i.e. 7.15 m from center). PPO everywhere to enhance sensitivity.
Scheduled: 2015/2016 ??

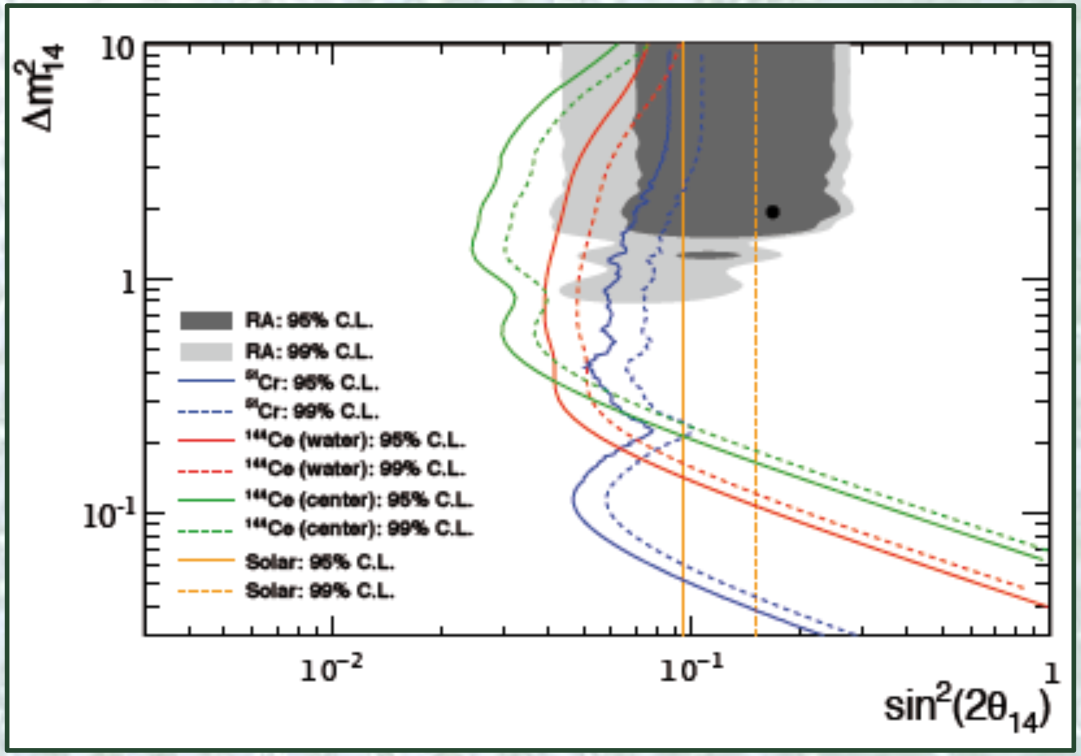
✧ **SOX C**: ^{144}Ce-^{144}Pr source (~50 kCi) in the center of the detector.
Only after the end of solar program (>2016)

FEW WORDS ON SOX: SHORT-DISTANCE OSCILLATION IN BOREXINO(2)

Source	Production	T[d]	Decay mode	Energy [MeV]	Mass [kg/Mci]	Heat [W/kCi]
^{51}Cr	Neutron irradiation of ^{50}Cr in reactor	40	EC	0.746	0.011	0.19
^{144}Ce - ^{144}Pr	Chemical extraction from spent nuclear fuel	411	β-	< 2.9975	0.314	7.6

In Borexino, electron anti-neutrinos are detected via the inverse beta decay reaction (E_{th} = 1.8 MeV)





CONCLUSION AND PERSPECTIVES

Since 2007, the Borexino experiment has had a very rich physics program:
- SOLAR NEUTRINOS: ^{7}Be, ^{7}Be DayNight Asymmetry, ^{7}Be seasonal modulations, ^{8}B (above 2.8 MeV), pep, CNO;
- GEONEUTRINOS;
- SUPERNOVÆ (anti)NEUTRINOS;
- EXOTIC PARTICLES SEARCH;
- RARE PROCESSES;
- NEUTRINO PROPERTIES;

In the so-called Borexino-phase II, we have many goals! Among them….
- SOLAR NEUTRINOS: * Improve the limit on CNO and the significance of the pep signal (target: 3σ or more but ^{210}Bi suppression is required); * Search for pp neutrinos (^{85}Kr suppression helps);
- STERILE NEUTRINO(s) SEARCH.

THE BOREXINO COLLABORATION

Univ. & INFN Genoa, ITA
TUM Munich, GER
Jagiellonian U. Cracow, POL
Inst.f.Nucl.Res. Kiev, UKR
Univ.d.St. & INFN Perugia, ITA
MPI-K Heidelberg, GER
APC, Paris, FRA
JINR Dubna, RUS
Univ.d.St. & INFN Milan, ITA
Princeton Univ. Princeton, USA
INFN Lab.Naz. Gran Sasso, ITA
Univ. Hamburg, GER
Kurchatov Inst., Moscow, RUS
NPI, St.Petersbourg, RUS
Massachusetts U. Amherst, USA
Virginia Tech Blacksburg, USA

SUMMARY OF ANTI-ν BACKGROUNDS

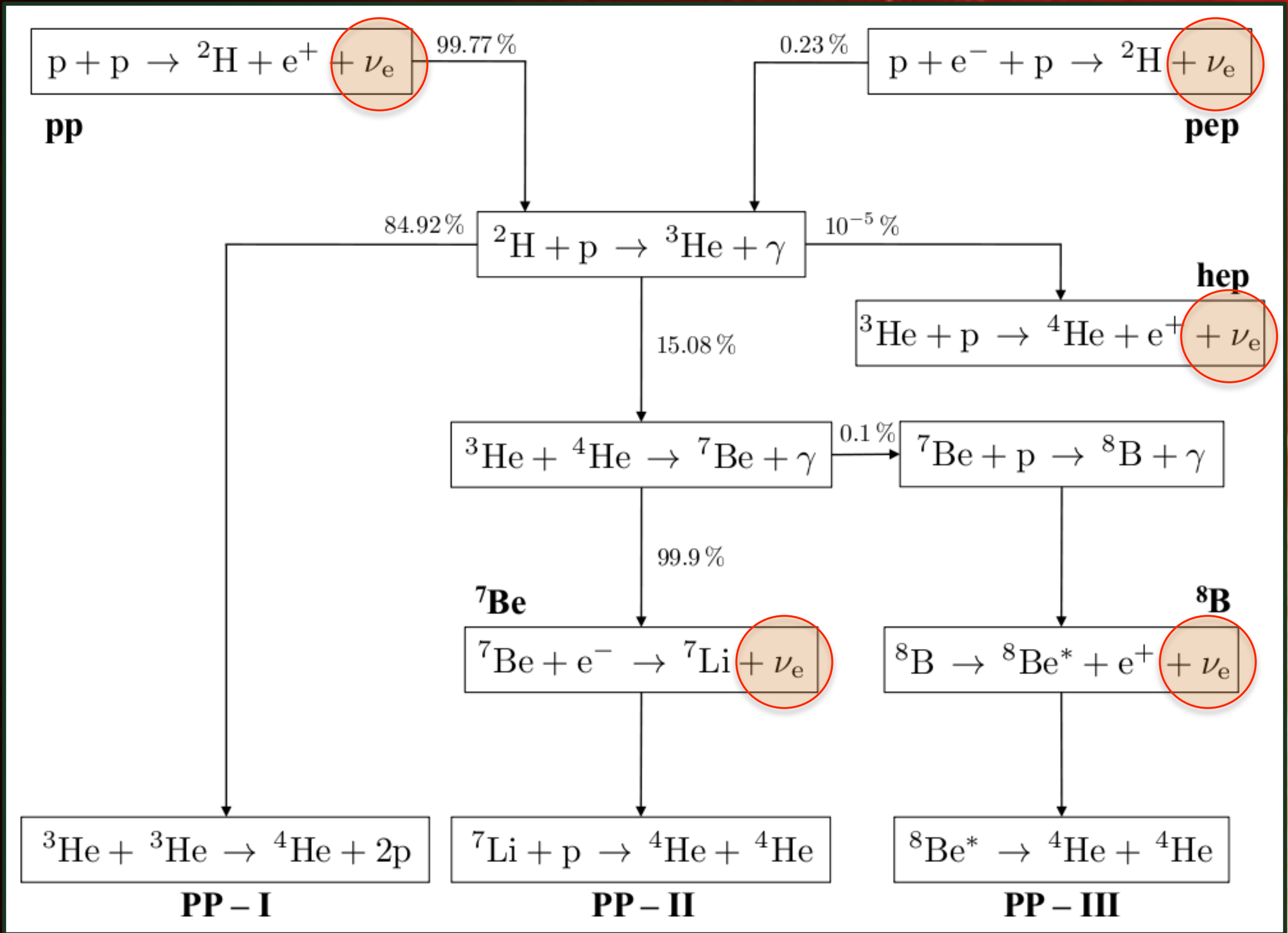
Table 2

Physics Letters B 722 (2013) 295–300

Summary of the background faking anti-neutrino interactions and expressed in number of events expected among the 46 golden anti-neutrino candidates. The upper limits are given for 90% C.L.

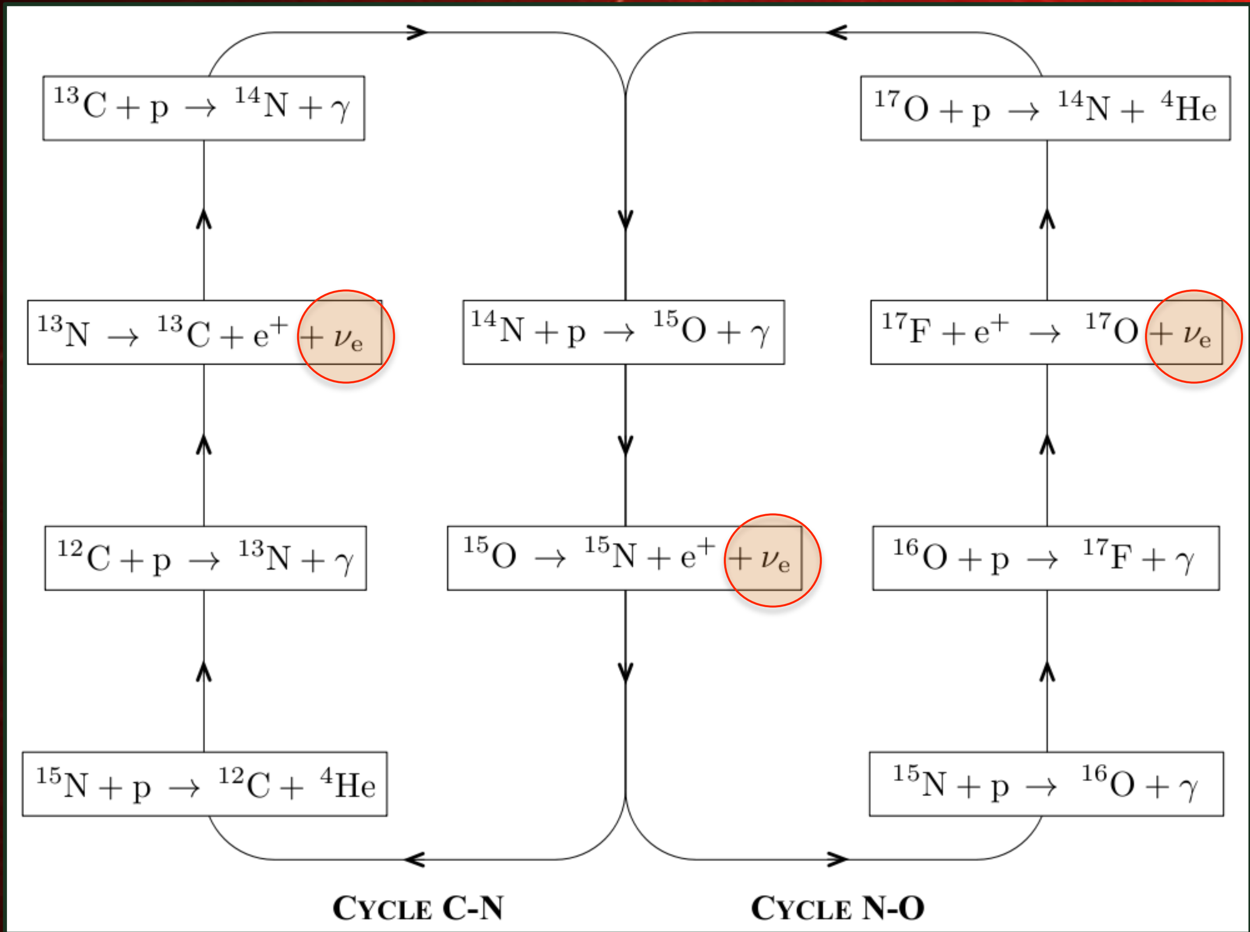
Background source	Events
$^9Li-^8He$	0.25 ± 0.18
Fast n's (μ's in WT)	<0.07
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080 ± 0.007
Accidental coincidences	0.206 ± 0.004
Time corr. background	0.005 ± 0.012
(γ, n)	<0.04
Spontaneous fission in PMTs	0.022 ± 0.002
(α, n) in scintillator	0.13 ± 0.01
(α, n) in the buffer	<0.43
Total	0.70 ± 0.18

SOLAR NEUTRINOS: THE PP CHAIN



John N. Bahcall
1934 - 2005

SOLAR NEUTRINOS: THE CNO CHAIN



Alessandra Carlotta Re – INFN Milano, Italie