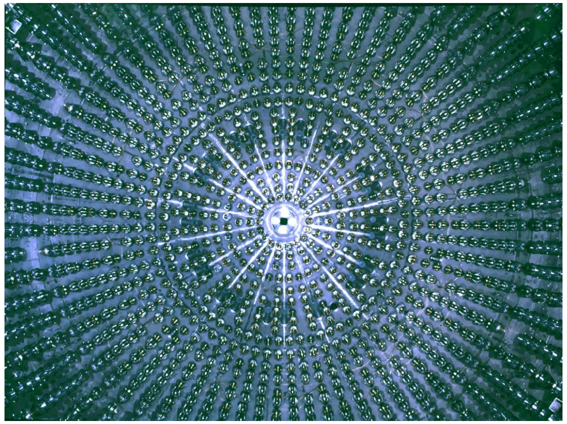
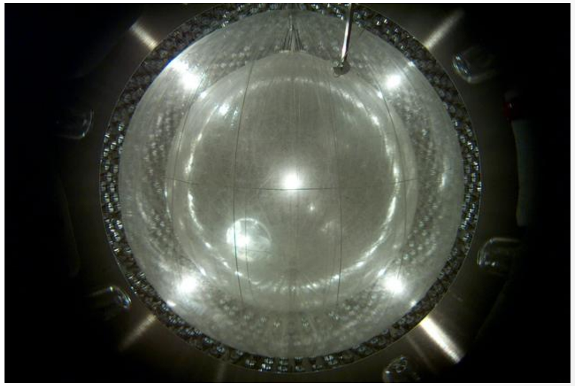
Neutrino Physics and Astrophysics with Borexino





lectio magistralis

Gianpaolo Bellini Milano
Bruno Pontecorvo Award
JINR 23 sept. 2016

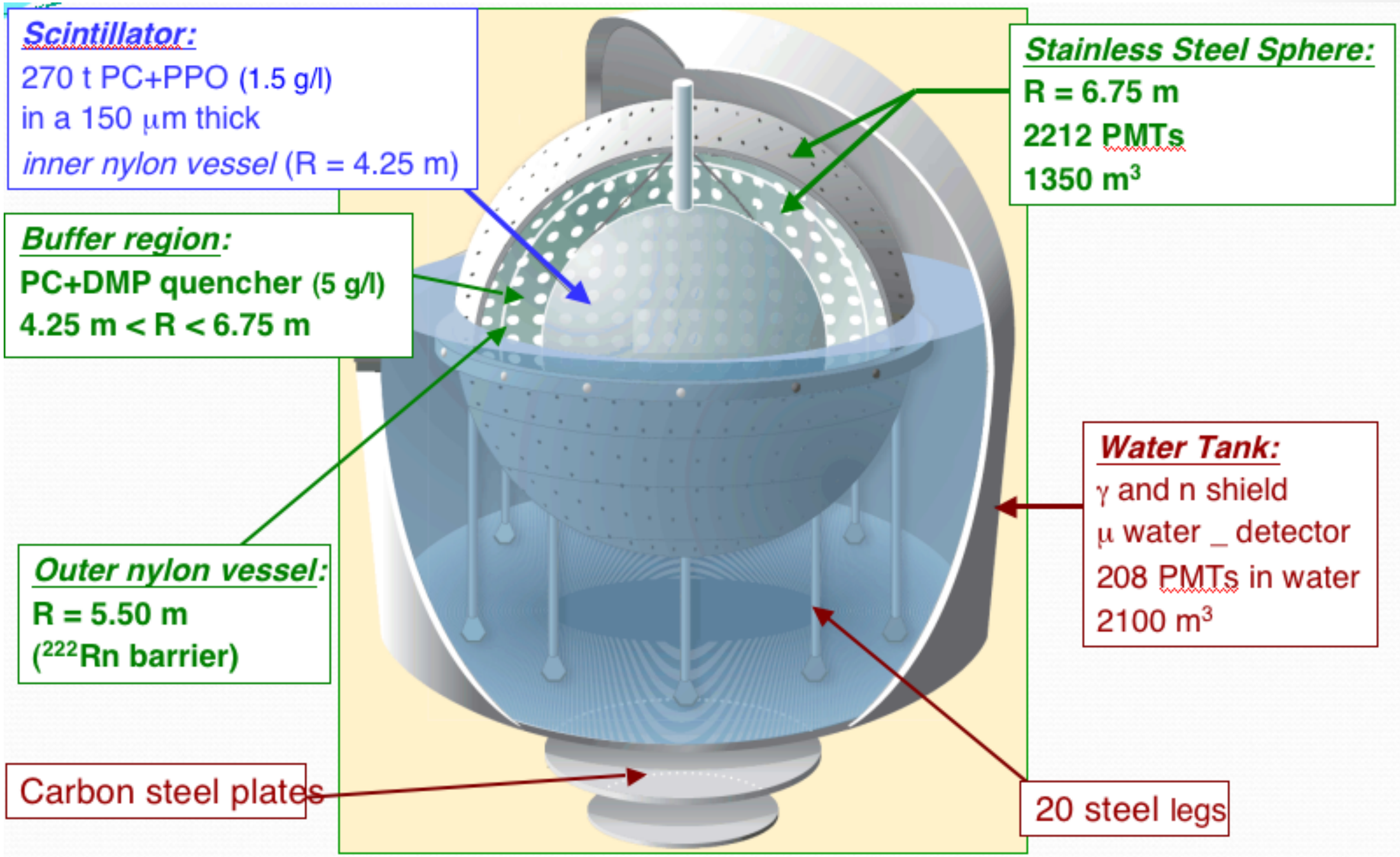
1957-1958 Bruno Pontecorvo proposed the **ν oscillation**
(at that time only ν_e was known)

"there must exist a much weaker interaction which does not conserve the lepton number"

1967 – again B.P. suggests a possible $\nu_\mu \rightarrow \nu_e$ transition
and solar neutrino oscillation:

1978- B.P. and S. Bilenky point out that:

There are no principles requiring that neutrinos are massless
Neutrino oscillation is the best method to measure the very small Δm^2



The choice of the liquid scintillation technique was dictated by the high light-yield of the scintillator (50 times more than in the Cherenkov technique), and then a good energy resolution – in Bx 500 pe/ MeV

Borexino data taking history in four lines: start up-may 2007

phase 1-2007-2010

further purification 2010-2011

since dec. 2011- phase 2

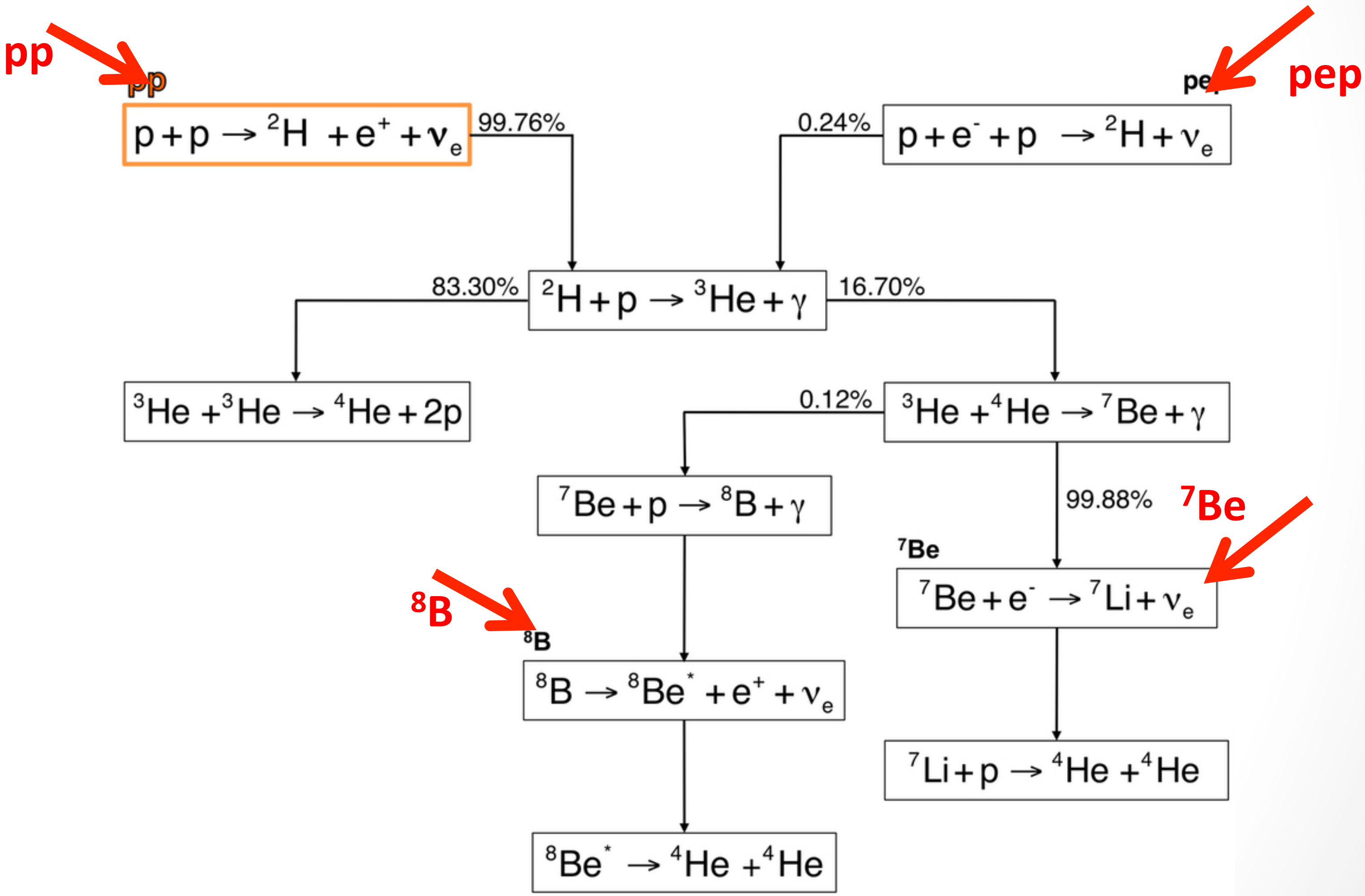
Radio-Isotope		Concentration or Flux		Achieved	Achieved
Name	Source	Typical	Required	phase 1	Phase 2
^{14}C	intrinsic scintillator	$\sim 10^{-12}$ $^{14}C/^{12}C$	$\sim 10^{-18}$ $^{14}C/^{12}C$	$\sim 2x10^{-18}$ $^{14}C/^{12}C$	
^{238}U ^{232}Th equiv.	dust, particulate, all materials	$10^{-5} - 10^{-6}$ g/g	$<10^{-16}$ g/g	$(5.0\pm0.9)10^{-18}$ g/g $(3.0\pm1.0)10^{-18}$ g/g	$< 9.5\ 10^{-20}$ g/g $< 7.2\ 10^{-19}$ g/g
^{7}Be	cosmogenic	$\sim 3x10^{-2}$ Bq/t	$<10^{-6}$ Bq/t	not observed	
^{40}K	dust, PPO	$\sim 2x10^{-6}$ g/g (dust)	$<10^{-18}$ g/g	not observed	
^{210}Po	surface contamination.	Decaying with a half time of ~ 138 days	<700 cpd/100t	500.-20.cpd/100t	~20 cpd/100t
^{222}Rn	emanation from materials, rock	10Bq/l air, water 100-1000 Bq/kg rock	<10 cpd/100t	<1 cpd /100 t	
^{39}Ar	air, cosmogenic	$17mBq/m^3$ (air)	<1 cpd/100 t	<< 1 cpd/100 t	
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	<1 cpd/100 t	30±5 cpd/100 t	<6.4 cpd/100 t fit consistent with 0

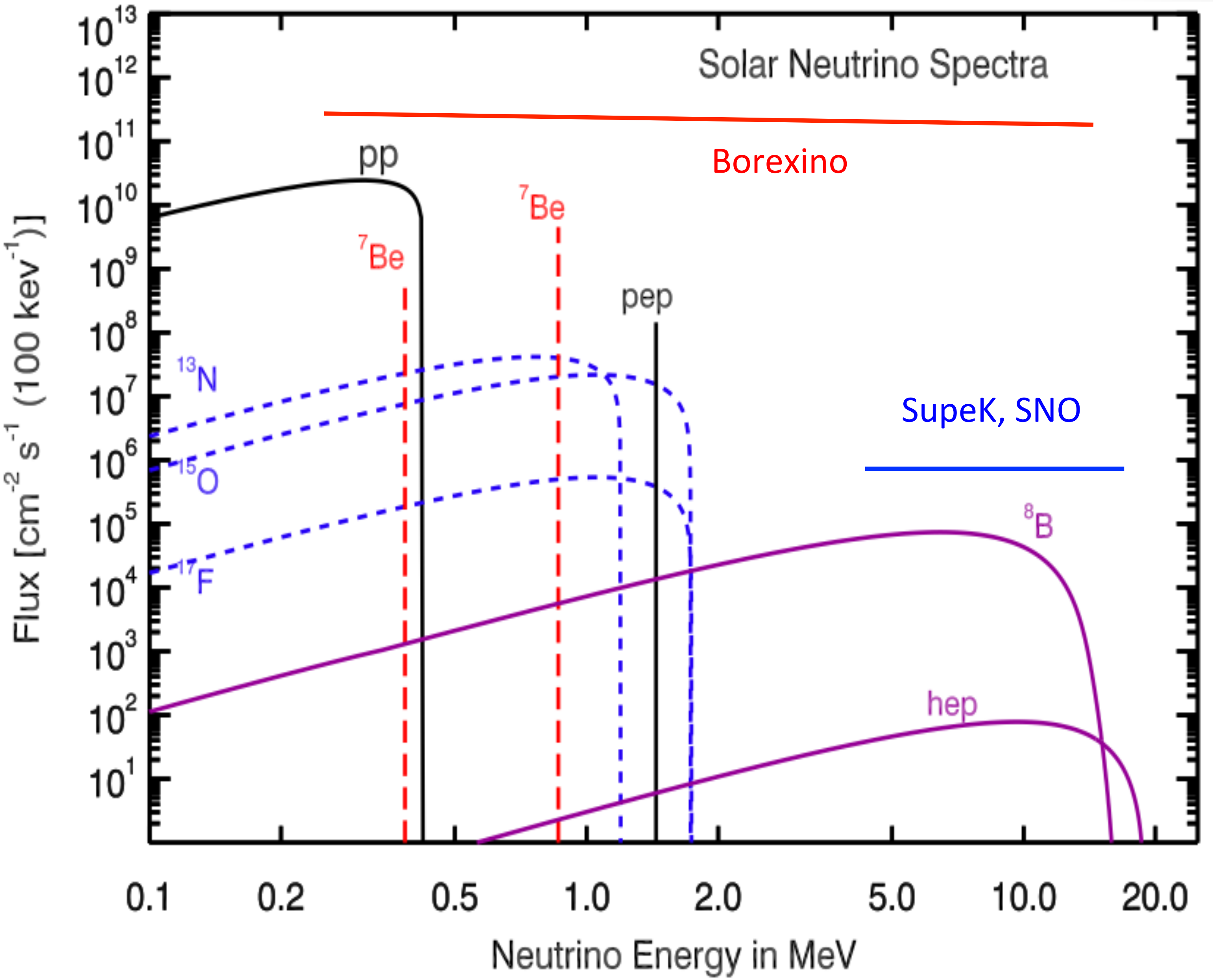
unprecedented radio-purity, never reached by any other experiment until now

ASTROPHYSICS

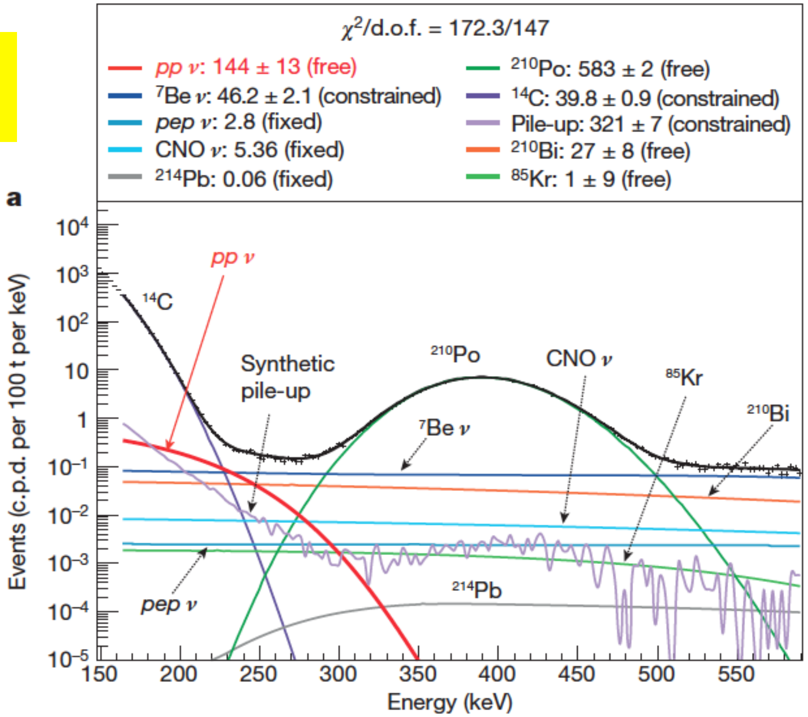
astr.

The Sun functioning is based on the pp chain:




Solar Neutrino Spectra
Borexino
SupeK, SNO
pp
7Be
7Be
pep
13N
15O
17F
8B
hep
Flux [cm-2 s-1 (100 kev-1)]
10^13 10^12 10^11 10^10 10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1
0.1 0.2 0.5 1.0 2.0 5.0 10.0 20.0
Neutrino Energy in MeV

pp



Physics World:
Top 10 Physics Breakthrough of 2014

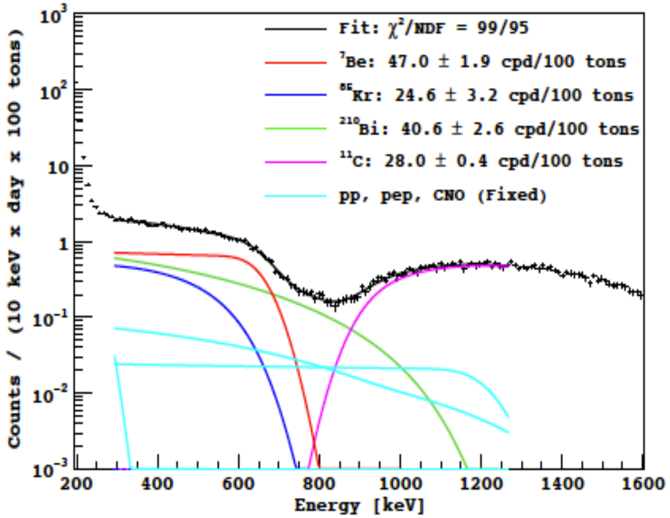
Main problem ^{14}C (end point: 156keV)
pp- end point: 264 keV

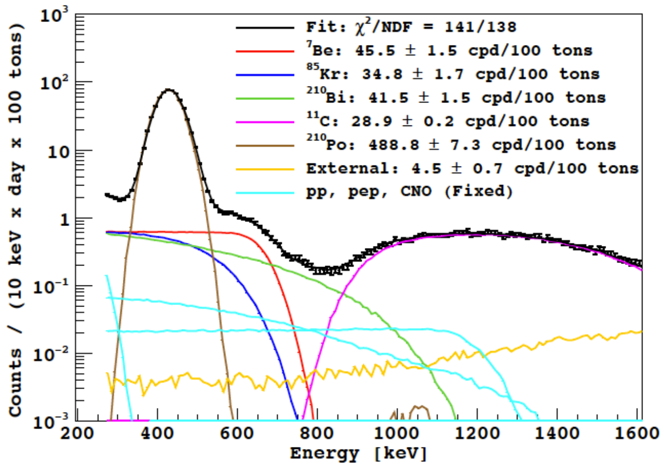
pile up: ^{14}C-^{14}C and ^{14}C-pp (data driven method)

fit range: 165-590 keV

Φ_{pp}=(6.6±0.7) 10^{10} cm^{-2} s^{-1}

^{7}Be





Compton-like shoulder at 660 keV
fit range: 200-1270 keV

Φ_{7Be}=(4.43±0.22) 10^{9} cm^{-2} s^{-1}

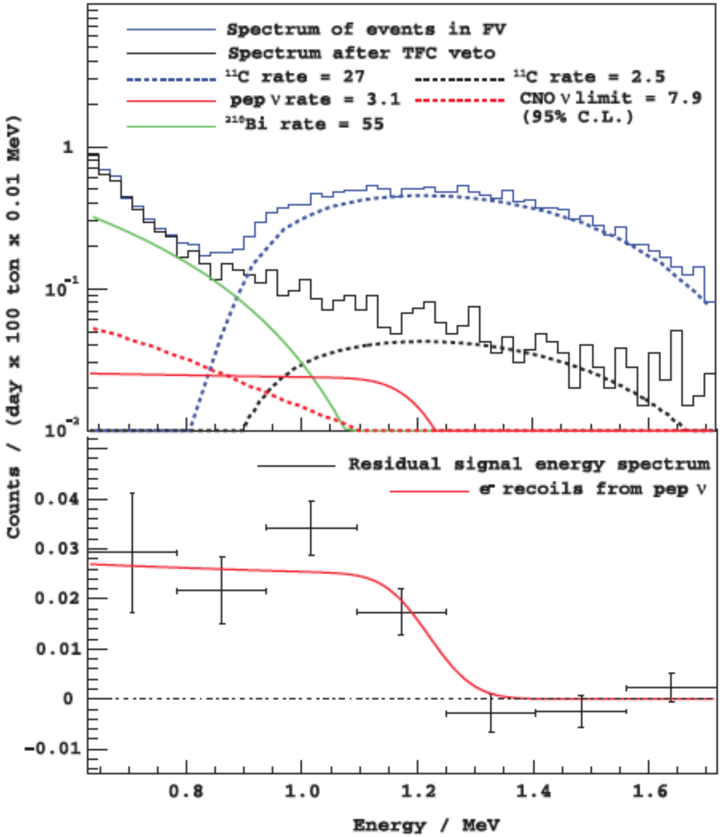
pep/ CNO

pep signal is ten time lower than ^{7}Be

- About 3cpd/100t
- CNO: rate similar to pep

Most important background

- cosmogenic ^{11}C :
- ^{210}Bi :
- External background (γ from PMT):



TFC: incident muon
e^{+} annihilation from ^{11}C decay (prompt signal)
p capture of the thermalized neutron (delayed signal-~240 μs)

Pulse shape discrimination: in 50% of the cases the formation of ortho-positronium the e^{+} annihilation is delayed

Fit simultaneously

1) Energy spectra after ^{11}C subtraction
2) Energy spectra of the subtracted events
3) Radial distribution of the events

CNO energy distribution shows a shape very similar to the ^{210}Bi spectrum (~ 15-20 cpd/100 t).

Φ_{pep}= (1.63±0.35)10^{8} cm^{-2} s^{-1}

Φ_{CNO}< 7.7 x 10^{8} cm^{-2} s^{-1}.

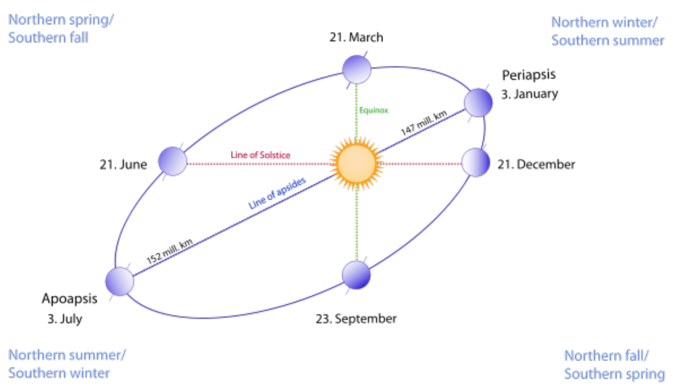
^{8}B not monochromatic, then no fit on the energy spectrum, but on the radial distribution- main background ^{208}Tl, subtracted via ^{210}Bi-^{210}Po coincidence
-threshold down to 3.2 MeV ν energy

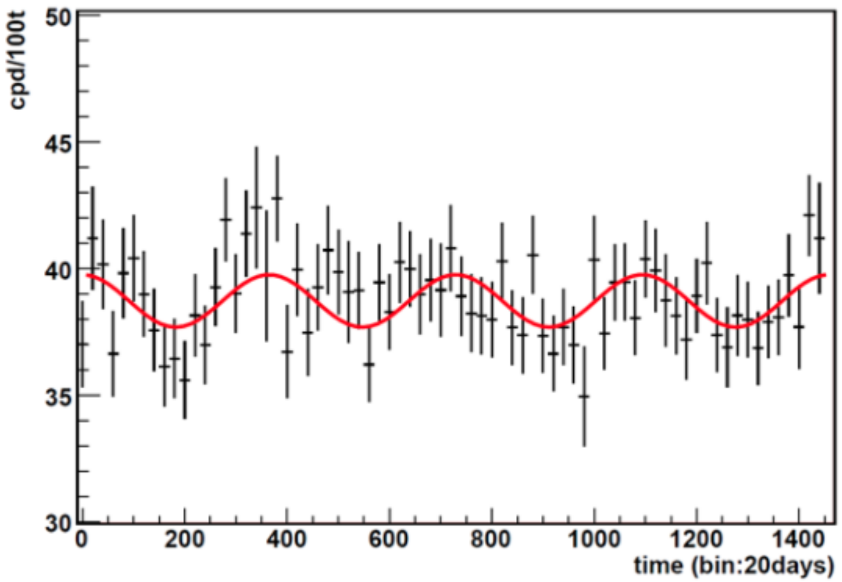
$\Phi_{8B}=(2.4\pm0.4\pm0.1)\ 10^{6}\ cm^{-2}\ s^{-1}$

good agreement with SNO and SK

seasonal modulation

eccentricity of the Earth orbit- ± 3.5%





max flux: Jan. 3rd

total agreement with a Lomb-Scargle periodogram

phase II- bins 20 days since dec.2011
energy range of ^{7}Be spectrum

Solar neutrino flux	GS98 ($cm^{-2} s^{-1}$) High metallicity Z/X=0.0229***	AGS09 ($cm^{-2} s^{-1}$) Low metallicity Z/X=0.0178***	Experimental results (Borexino)	Global fit including solar, reactor, accel. data ($cm^{-2} s^{-1}$)**
pp	5.99 (1±0.006) x 10^{10}	6.04 (1±0.005) x 10^{10}	6.6 (1±0.106) x 10^{10}	$5.97^{+0.037}_{-0.033}$ x 10^{10}
^{7}Be	4.80 (1±0.06) [4.93]^* x 10^{9}	4.38 (1±0.06) [4.50]^* x 10^{9}	4.94±0.22 x 10^{9} *	$4.80^{+0.24}_{-0.22}$ x 10^{9}
pep	1.44 (1±0.01) x10^{8}	1.47 (1±0.009) x10^{8}	1.63±0.35 x 10^{8}	1.448±0.013 x 10^{8}
^{13}N ^{15}O ^{17}F	2.78 (1±0.15) x10^{8} 2.05 (1±0.17) x10^{8} 5.30 (1±0.20) x10^{8}	2.05 (1±0.14) x10^{8} 1.44 (1±0.16) x10^{8} 3.26 (1±0.18) x10^{8}	<7.7 x 10^{8} total CNO	≤ 13.7 x10^{8} ≤ 2.8 x 10^{8} ≤8.5 x 10^{7}
^{8}B	5.32 (1±0.12) [5.46] ^* x10^{6}	4.37 (1±0.12) [4.50]^* x10^{6}	5.2± 0.3 x 10^{6}	$5.16^{+0.13}_{-0.09}$ $^{+0.30}_{-0.26}$ x10^{6}

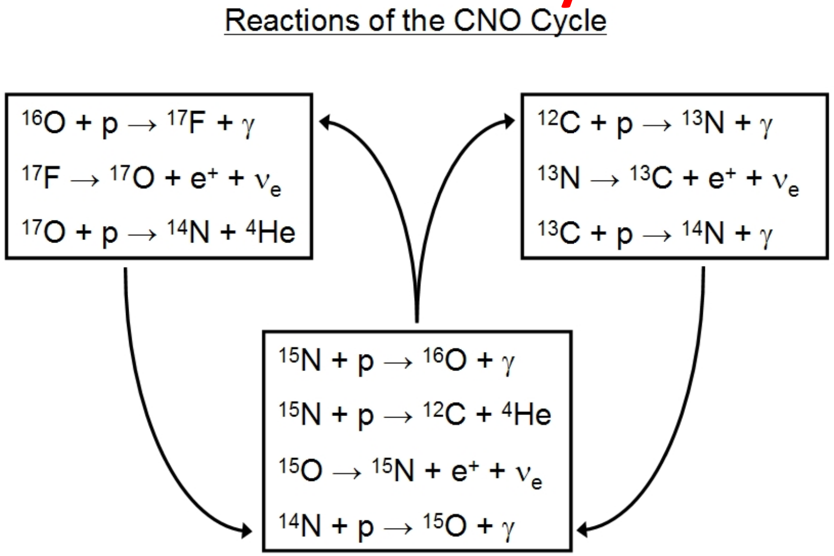
- This is the ^{7}Be flux for both the ^{7}Be lines, extrapolated from the higher energy line flux measured by Borexino (96% of the total) in phase 1; the preliminary results of the phase 2 are in agreement with this quoted value and with a total error reduced to 3-3.5%

** from J. Bergstroem et al., arXiv: 1601.00972v1 [hep-ph] 5 jan 2016

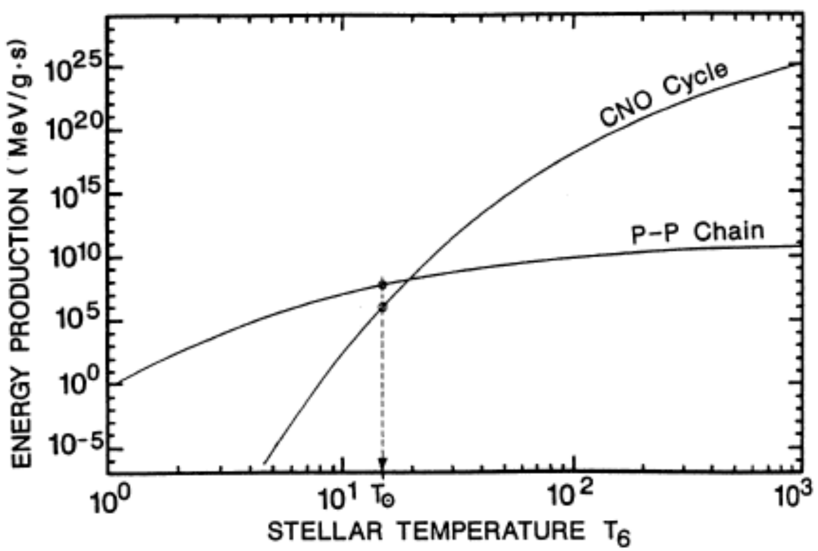
*** from A. Serenelli , F. Villante et al. –paper in preparation- They review the uncertainties of the opacities and up to date the cross section factors: S_{11} (pp), S_{34} (^{3}He+^{4}He), S_{17} (^{7}Be+p), S_{114} (^{14}N+p)-in these calculations S_{34} is assumed by de Boer et al. 2014

^* These different numbers are obtained assuming for S_{34} what Iliadis et al. (very recent) and Adelberger et al. 2011 have quoted (F. Villante-private communication)---- heliosysmology

CNO cycle
in the Sun only 1%



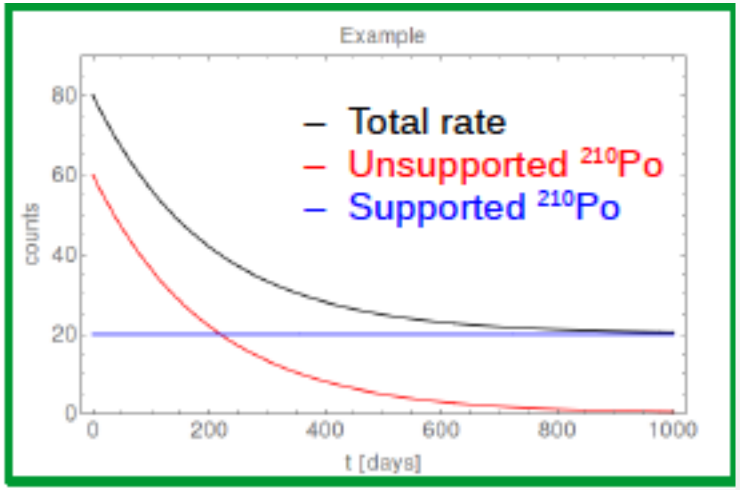
hypothesized as the primary cycle in the massive stars and then for hydrogen burning in the Universe



strategy: need of an independent constraint on ^{210}Bi rate (remove degeneracy with CNO spectrum)

from ^{210}Po: two components:

- embedded on the lines (138.376 days half time)
- ^{210}Pb → ^{210}Bi (β) → ^{210} Po (α)
- easily identified via pulse shape discrimination



Borexino reached fundamental achievements in the Sun Physics

Borexino has demonstrated experimentally that the Sun shines via the proton-proton nuclear reaction chain in the solar interior: **pp**, pep, ^{7}Be, ^{8}B***

* already measured also by SNO and superK
** the radiochemical exp. measured the whole integrated solar flux over 233 keV

The agreement between the solar luminosity in neutrinos, as measure by Borexino, and in photons demonstrates the Sun stability on ~10^{5} years time scale

Borexino has the chance to give a contribution to the solution of the metallicity puzzle in the SSM-

NEUTRINO PHYSICS

Neutrino oscillation

In two neutrino scenario

IN VACUUM

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

IN MATTER

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

If X=cos2θ -maximum mixing

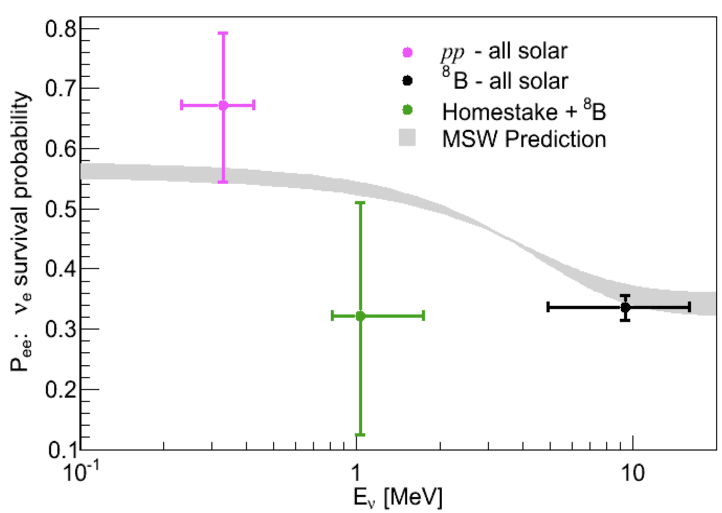
$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - X)^2}$$

$4\pi E/\Delta m^2$

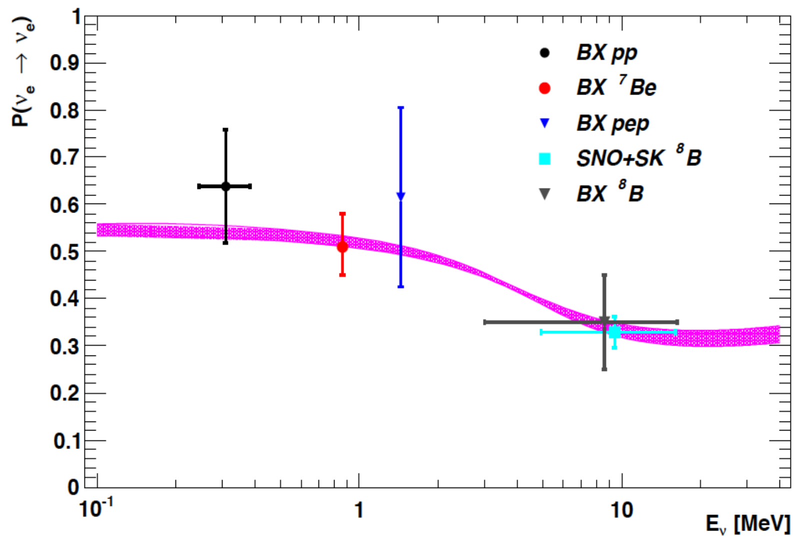
$$L_M = \frac{4\pi E}{\Delta m_M^2} = \frac{L_V}{\sqrt{\sin^2 2\theta + (\cos 2\theta - X)^2}}$$

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

The best way to understand the Borexino contribution to the study of the neutrino oscillation is to compare **the electron-neutrino survival probability** before and after Borexino.



before



after

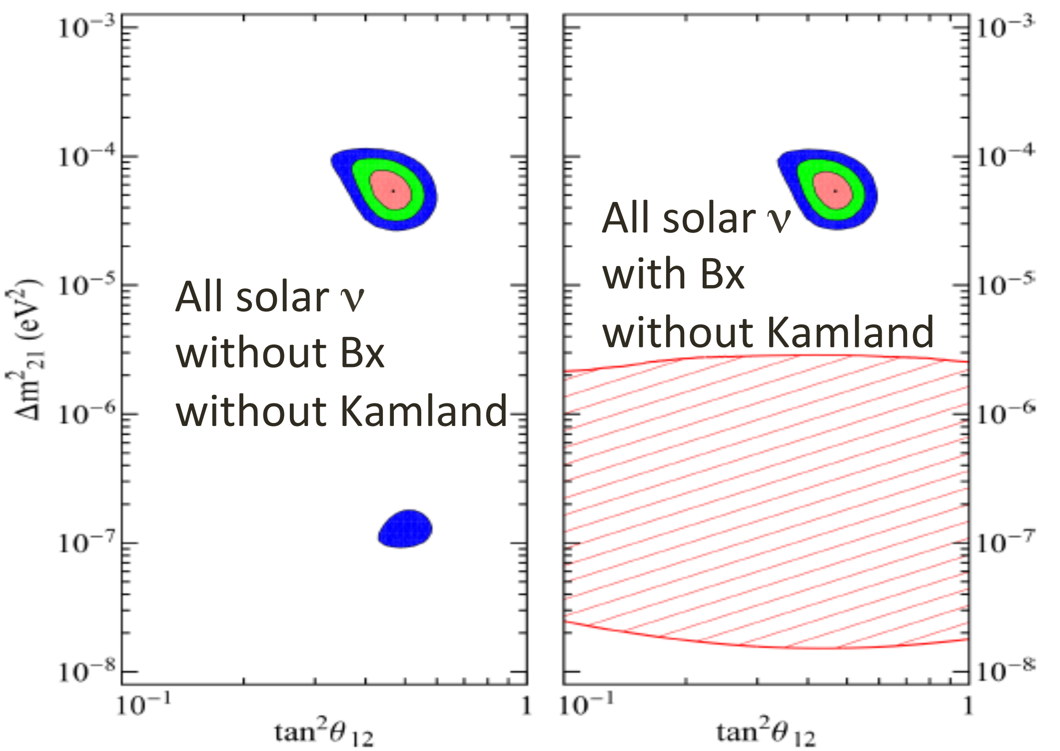
Borexino succeeded to observe for the first time the oscillation in vacuum measuring the pp neutrino survival probability (0.64±0.12) and to determine the ratio between the survival probabilities in vacuum and in matter, using pp and ^{8}B, this last measured by Borexino above 3 MeV. This ratio turns out to be =2.2±0.86.

Study of the day/night asymmetry

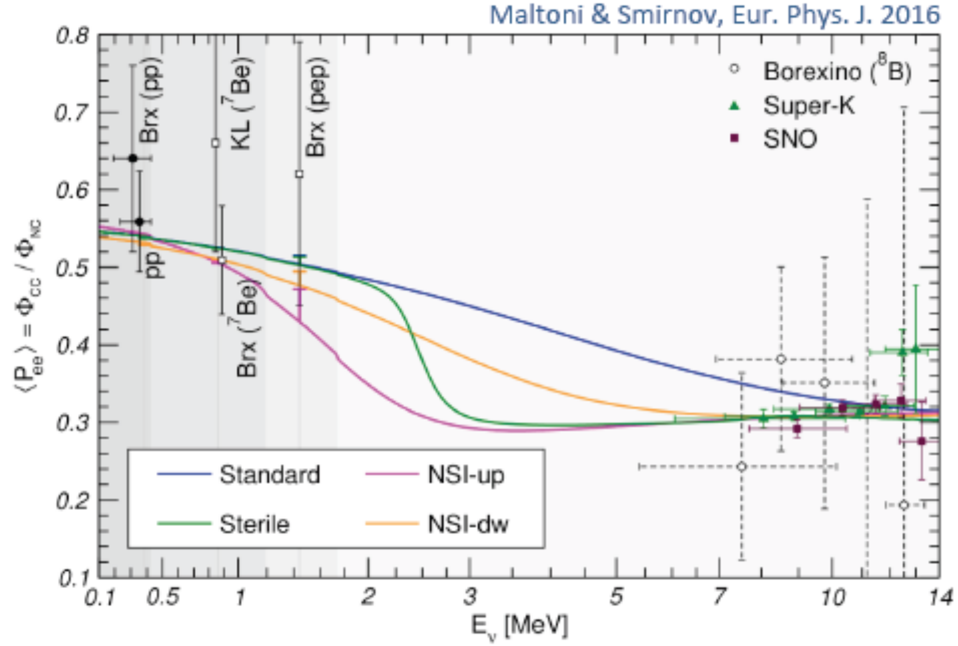
- regeneration of the elecron neutrinos crossing the Earth
- D/N effect is a consequence of MSW
- not expected for ^{7}Be in the LMA-MSW model
- large effect expected in the "LOW" solution (excluded by solar exp + Kamland)
- no contradiction with the recent SK results

$$A_{DN} = \frac{N-D}{(N+D)/2} = 0.001 \pm 0.012\,(stat) \pm 0.007(sys)$$

Solar data alone select the LMA-MSW if one includes the Borexino D/N result-8.5 σ C.L. (no use of CPT)



Transition region between the vacuum and matter regime



Recent SuperK paper (June 2016) does not change substantially the situation—measurements down to ~4 MeV

Subleading effects (beyond the S.M.):

1-very light sterile mixes very weakly with active neutrinos, which have the smallest mass splitting (solar) (Smirnov & De Hollande, Phys. Rev. 2011).

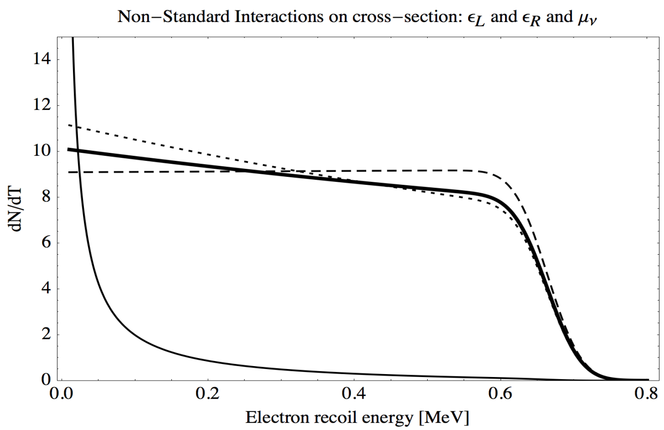
The green curve is calculated for

$$\Delta m^2_{21} = 7.5 \bullet 10^{-5} eV^2 \quad \Delta m^2_{01} = 1.2 \bullet 10^{-5} eV^2 \quad \sin^2\alpha = 0.005 \quad \sin^2\theta_{12} = 0.31$$

2. NSI- The NSI can be described at low energy by effective four fermion interactions $\ell_{NSI} = -2\sqrt{2} G_F \varepsilon^{e,u,d}_{\alpha,\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{f} \gamma_\mu P_C f'\right)$ where G_F is the Fermi constant, α and β are the neutrino flavors, f and f′ the electron or the light quarks, L and R indicate the projection of the operator P (two chiralities), and finally ε parameterizes the strength of the NS interaction. The curves are calculated for $\varepsilon^u_D = -0.22, \varepsilon^u_N = -0.30; \ \varepsilon^d_D = -0.12, \varepsilon^d_N = -0.16$ (ε_D and ε_N are linear combination of ε)

A test of these subleading effects can be successful if a measurement is carried out in the range 2.-5. MeV. **Borexino phase 2 is measuring an experimental point for ^{8}B between 3.-5. MeV.**

The study of a possible NSI can be done more easily analyzing the energy spectrum of the recoiled electron from the ν-e scattering, in particular for the ^{7}Be neutrinos, which is monoenergetic and then does not need of convolution with the incident neutrino spectrum, as for instance is the case of ^{8}B.



$$\frac{d\bar{\sigma}(T)}{dT}=\frac{2G_F^2 m_e}{\pi}\left[\bar{g}_{eL}^2+\bar{g}_{eR}^2\left(1-\frac{T}{E_{\nu_e}}\right)-\bar{g}_{eL}\bar{g}_{eR}\frac{m_e T}{E_{\nu_e}}\right]$$

T_{max}=0.665 MeV for ^{7}Be

----- ε_{eL}; ε_{eR} = 0.01, 0.2; = -0.02,0.05

Analysis of the phase 1 data-the contaminants ^{85}Kr and ^{210}Bi influence the analysis as far as the uncertainty in the ^{7}Be flux

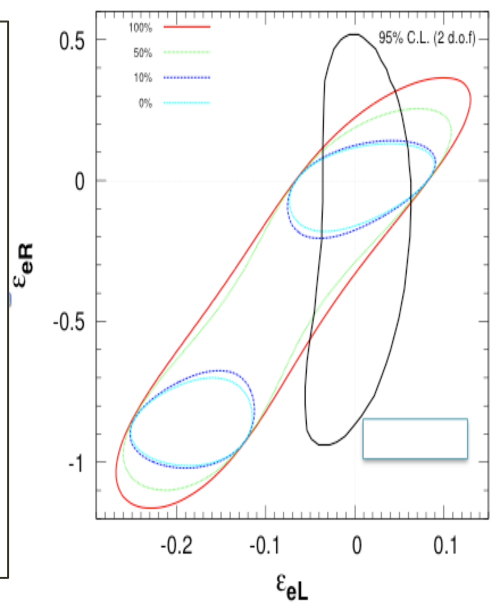
Phase 2:

Kr from 10±3 to ~0. cpd/100 t

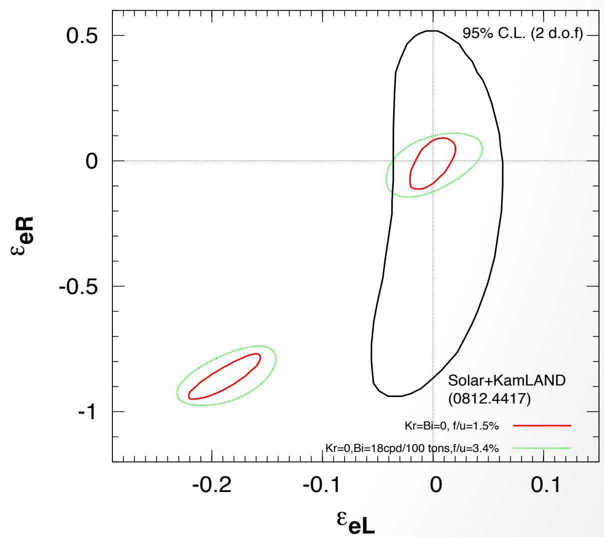
Bi from ~40 to ~15 cpd/100t

^{7}Be flux uncert. from 5% to <3.5%

Bx phase 1



Bx phase 2 (foreseen)



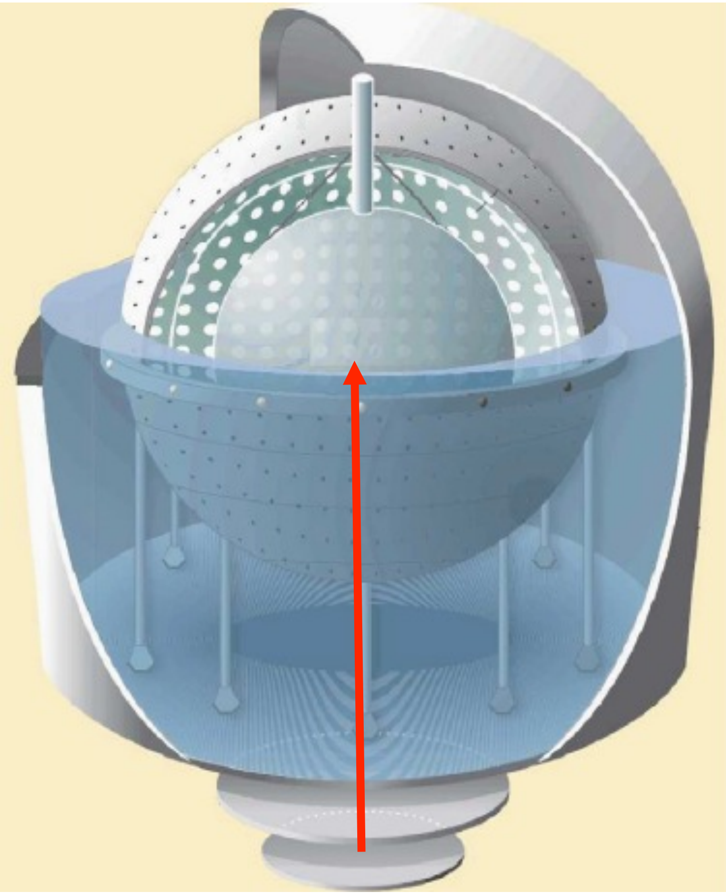
ν

Gianpaolo Bellini Milano
Bruno Pontecorvo Award
JINR 23 sept. 2016

Search for sterile ν in Borexino: SOX

SOX: Short distance neutrino Oscillations with BoreXino

Artificial external neutrino source is allocated in a tunnel present under the Borexino detector, at 8.25 m from the detector center. The source will be a ^{144}Ce-^{144}Pr activated at ~ 5 PBq; it emits antineutrinos with a continuous energy distribution up to 3 MeV. Borexino can study the very short distance neutrino oscillations in the standard *disappearance* technique, but it is possible to observe directly the oscillation waves in the hypothesis of very short baseline oscillations . E/L allows to explore the region around $\Delta m^2 \sim 1 eV^2$ and the typical oscillation length of a few m (detector diameter ~6 m.)



WHY:

LNSD and MiniBooNE :both observe excess of $\bar{\nu}_e$ from $\bar{\nu}_\mu$ beam and MiniBooNE also of ν_e from ν_μ beam
$\Delta m^2 \sim 1 eV^2$ --3.8σ: a fourth ν needed.
E/L agrees with SOX

claimed reactor problem : ~3% deficit--2.5σ
Gallex and Sage source anomaly -Deficit of the detected ν_e- R= 0.76+-0.09- 2.8σ

Very recent: 18 october

NEOS collaboration (South Korea)

24 m from a reactor core-
parameter space $\Delta m^2 \leq 4eV_{41}^2$ excluded
at 95% C.L.

Geoneutrinos

geo

Detection method

$\bar{\nu} + p \rightarrow n + e^{+}$ E_{ν}>1.8 MeV

•"prompt signal"
e+: energy loss + annihilation
(2 γ, 511 KeV each)
•"delayed signal"
n capture after thermalization, 2.2 γ
• Space and time coincidence

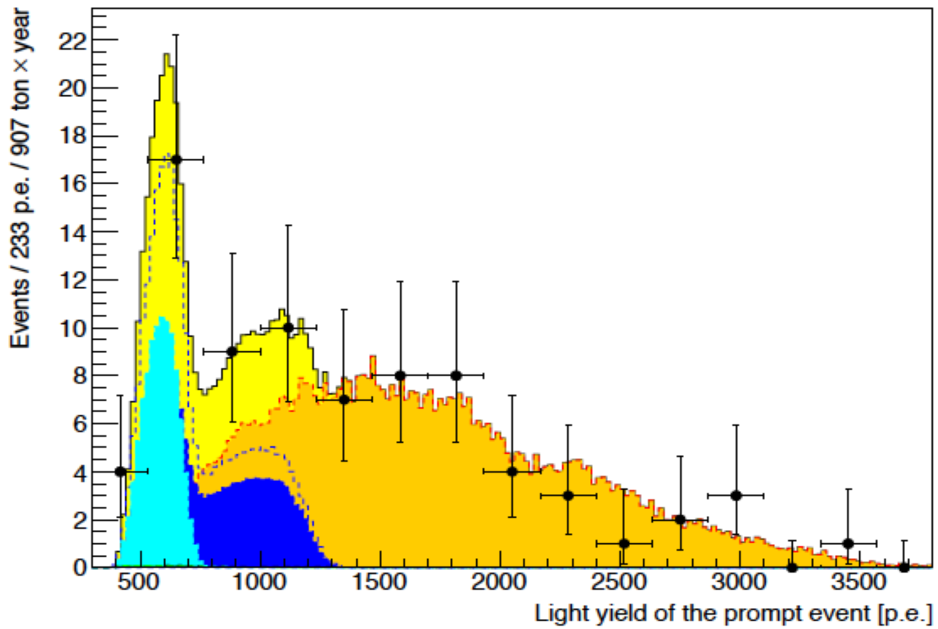
$$^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\,\mathrm{MeV}$$
$$^{235}_{92}\mathrm{U} \longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\,\mathrm{MeV}$$
$$^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\,\mathrm{MeV}$$
$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\,\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV}$$
$$^{40}_{19}\mathrm{K} + e^- \xrightarrow{10.7\,\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\,\mathrm{MeV}$$

Fit on the selected antineutrino spectrum:
black points = data
-------------- = best fit U+Th with fixed mass chondritic ratio (Th/U=3.9):

$$N^{events}_{geo} = 23.7^{+6.5}_{-5.7}(stat.)^{+0.9}_{-0.6}(syst.)$$

$$N^{events}_{reactor} = 52.7^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(syst)$$

blue area=U free parameter
light blue area= U+Th free parameters
---------------- = Reactor neutrinos



$$S_{geo} = 43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(syst)\ TNU$$

TNU= Terrestrial neutrino Unit= 1 event/year/10^{32} protons, 100% efficiency

Borexino reached an evidence at 5.9 σ C.L. and a null hypothesis with a probability of ~ $3.6\ 10^{-9}$

Also Kamland: evidence >4σ and null hypothesis at ~ 2 10^{-6}: more statistics but higher radio-contaminants and reactor $\bar{\nu}_e$ background.

Some hints already reached (also with the Kamland data):

1. The evaluation of the geo-neutrino signal from the mantle is obtained by subtracting the crust contribution from the measured signal. At the Gran Sasso site the crust signal has been evaluated to be S_{crust}= 23.4±2.8 *TNU* and then S_{mantle}=20.9+15.1-10.3 TNU

2. The radiogenic heat represents an important part of the total Earth's energy budget. From the Borexino data, If the chondritic mass ratio and the ratio m(K)/m(U) =10^4 are assumed, the radiogenic heat is =33^{+28}_{-20} TW. The large range is due to the various assumptions on the radioactive nuclide distribution in the mantle: either homogenously diffused or accumulated close the border mantle-core..
   The radiogenic contribution has to be compared with the evaluated total Earth's heat, which ranges from 31 to 47 TW.

3. For the first time it is possible to observe two well separated peaks in the geo-neutrinos energy range, produced by ^{232}Th+^{238}U and by ^{238}U.

In the mean time Borexino reached the following limits:

neutrino effective magnetic moment. Study of the shape of the electron recoil, especially at low energy where it is enhance at ~1/E_e

$$\mu_{eff} \leq 5.4 \bullet 10^{-10} B_{\mu} \ (90\% \ C.\ L.)$$

Test of Pauli exclusion principle. New limits on non paullian transitions of nucleons from $1P_{3/2}$ shell to $1S_{1/2}$ shell in ^{12}C with the emission of γ, n, p and $\beta^{\pm}$ particles: $\tau(^{12}C \rightarrow {}^{12}C^{NP}+\gamma) \geq 5.0.10^{31}$y, $\tau(^{12}C \rightarrow {}^{11}B^{NP}+p) \geq 8.9.10^{29}$y, $\tau(^{12}C \rightarrow {}^{11}C^{NP}+n) \geq 3.4.10^{30}$ y, $\tau(^{12}C \rightarrow {}^{12}N^{NP}+e+\nu) \geq 3.1.10^{30}$y, $\tau(^{12}C \rightarrow {}^{12}B^{NP}+e^{+}+\nu) \geq 2.1.10^{30}$y,

BEST LIMITS

relative strenghts: $\delta_{\gamma}^2 \leq 2.2 \bullet 10^{-57}$ $\delta_{N}^2 \leq 9.6 \bullet 10^{-60}$ $\delta_{\beta}^2 \leq 2.1 \bullet 10^{-35}$

Stability of the electron: $e^{-} \rightarrow \gamma + \nu$ - search for 256 keV γ peak – consistent with zero-

$$\tau \geq 6.4 \bullet 10^{28} \ years \ (90\% \ C.L.)$$

BEST LIMIT

Search for heavy sterile neutrino- The Borexino constrains the mixing of a heavy neutrino with mass 1.5 MeV< **m** <14 MeV appearing in ^{8}B-decay to be

$$|U_{eH}|^2 \leq \left(10^{-3} - 4 \bullet 10^{-6}\right)$$

-- respectively--10 to 1000-fold stronger than those obtained searching for decay $\nu_H \rightarrow \nu_L + e + e^{-}$ at nuclear reactors and 1.5-4 times stronger than those inferred from $\pi \rightarrow e + \nu$

Conclusions:

1. Borexino is still a unique detector to study the low energy neutrinos
2. Its results found experimental evidence that the nuclear reactions supporting the Sun shining belong to the pp cycle
3. For the first time the oscillation in vacuum has been observed experimentally and the related ν_e survival probability has been measured
4. The Borexino data reached the highest (5.9 σ) evidence of the geo-neutrinos
5. As byproduct several best limits have been obtained
6. Borexino will take data until 2020 doing an effort to measure the CNO flux (very challenging) and to check the possible existence of VSB oscillation and of a sterile neutrino

Borexino collaboration (during the construction)

Genova

Milano

Perugia

APC Paris

Princeton University

Virginia Tech. University

Munich (Germany)

Dubna JINR (Russia)

Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

Heidelberg (Germany)

Borexino Collaboration

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TUM Technische Universität München

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

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TECHNISCHE UNIVERSITÄT DRESDEN

APC

Thank you for your attention

Thanks to the Borexino collaboration members who contributed to this challenging project and made it possible!!