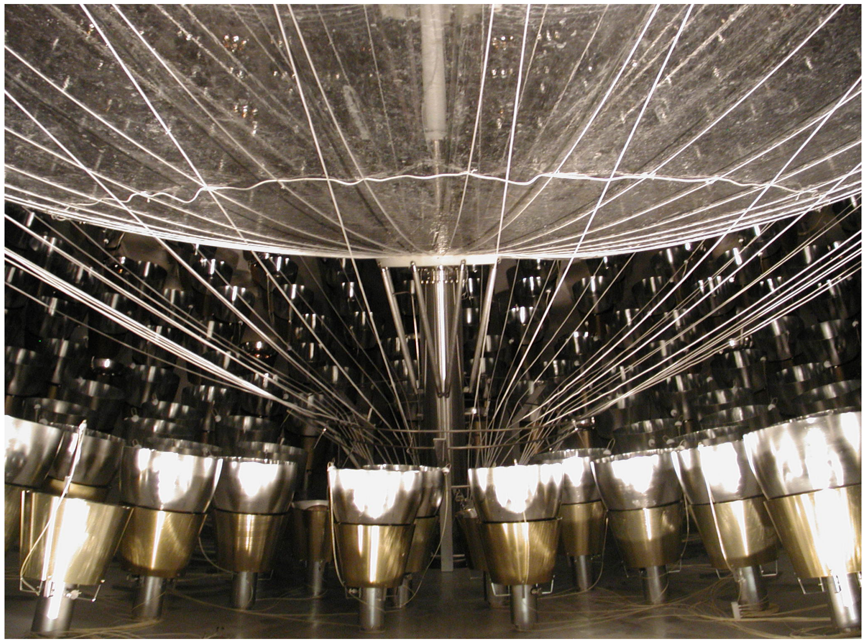
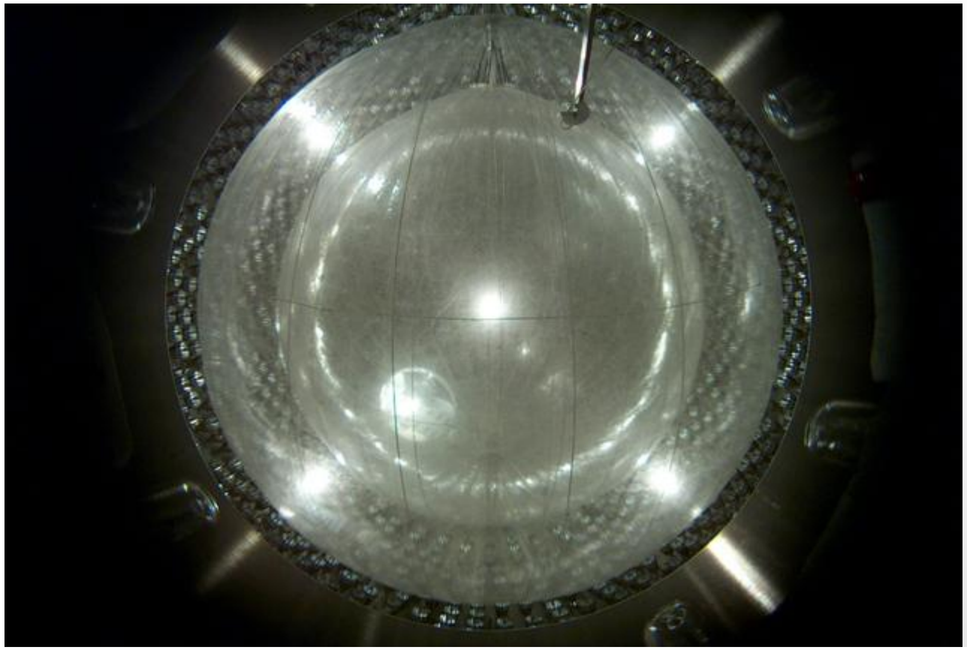
27 years of Borexino
1990-2017

Bruno Pontecorvo International Award 2016

Enrico Fermi award 2017





- **1990**- Start up of the design; main goal: to detect **in real time** the **low energy solar neutrinos** and especially **the neutrino flux from ^{7}Be**. At that time the Cerenkov experiments were exploring the 0.1% of the total solar neutrino flux

  Main problem: the **natural radioactivity** inside the detector (in the scintillator and in the construction materials) and from outside (rocks and environment)

  Goals: 10^{-16} g/g for ^{238}U and ^{232}Th equivalent; 10^{-18} $^{14}C/^{12}C$

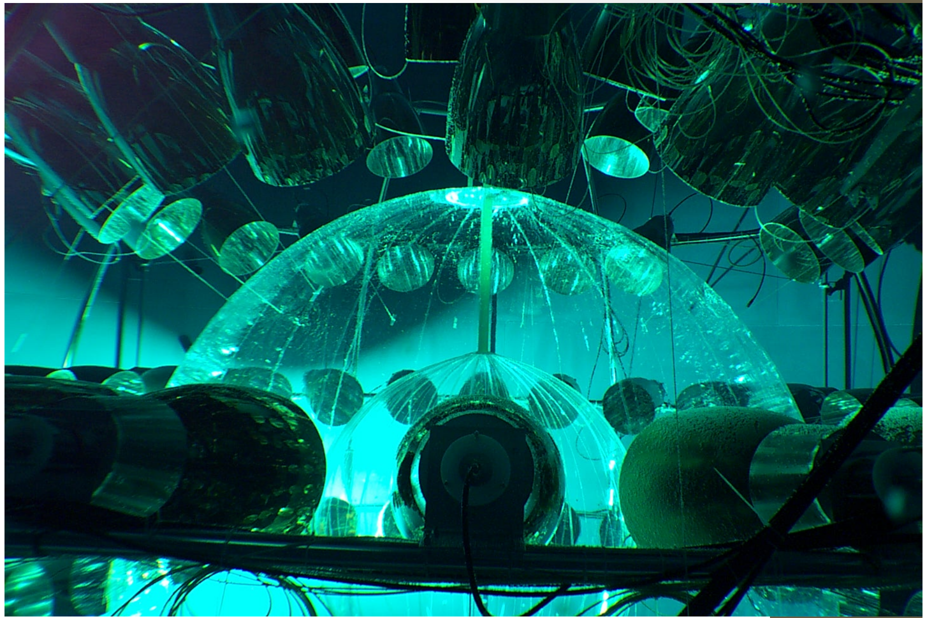
- **1991-1994** R&D for methods able to radio-purify the scintillator up to the goal

But: no commercial instrument reaching the needed sensitivity (plasma mass spectrometer: up to about 5×10^{-14} g/g). Therefore an ad hoc detector has been conceived and installed in the underground lab: the **Counting Test Facility (CTF),** a Borexino bench-mark, a reduced and simplified version of Borexino-5 tons of scintillator surrounded by 1000 tons of highly purified water

1995- ***CTF*** *running*- test on the scintillator purified by our systems in place (water extraction and distillation at low temperature, stripping with ultra-purified nitrogen).

Measured Radioactivity level: 5×10^{-16} g/g , corresponding to the CTF sensitivity

1996-1997 Approval of Borexino by INFN, NSF, German agencies



Nothing is standard in Borexino!!

- Three methods to clean the scintillator
- Ultrapure N_2 stripping (Cryogenic system)
- Ultrapure water: 18.0 MegaOhm cm
- Special selection of all the components of the plants
- All surfaces electro-polished
- Tightness of all systems and plants: $<10^{-8}$ bar cm^3 s^{-1}
- All operations concerning the detector in clean rooms: the detector itself maintained as a class 10000 clean room
- Special care in the PC procurement: old layer crude oil, loading and unloading stations on purpose

- Vessels: selection and extrusion of the materials in controlled area, construction in clean room with Rn control.

May 2007- start up of the data taking once the detector filled with the scintillator already distilled

May 2007-summer 2010 - Phase 1- fluxes of ^{7}Be,pep,^{8}B (with threshold down to 3 MeV), limit on CNO, geo-neutrinos, best limits on rare processes

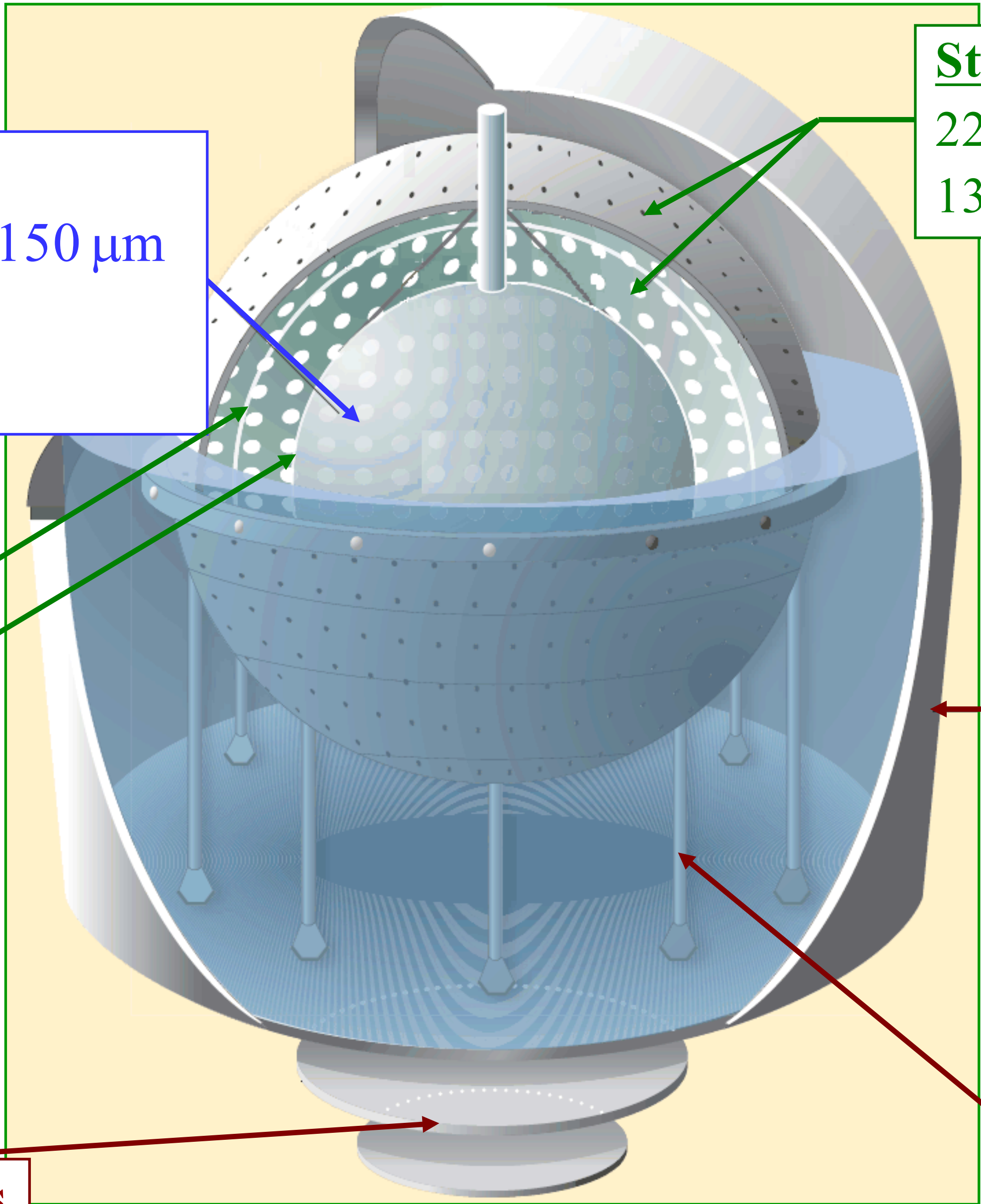
January-June 2010- calibration with 8 artificial γ **sources** (144 keV- 1.4 MeV) inserted in the vessel in axis and off axis, **AmBe** source, **^{222}Rn loaded** scintillator source, laser diffuser.

→ **Light yield :500 pe/Mev; ΔE= 50 keV at 1 MeV and 10 keV at 200 keV; Δs=10 cm at 1 MeV; 15 cm at 500 keV; k_B quenching factor**

Summer 2010-Oct. 2011- further purification of the scintillator (6 cycles of water extraction)

October 2011- end 2017: phase 2- pp, ^{7}Be, pep, ^{8}B, new limit on CNO, geo ν, seasonal modulation
strong effort to measure the CNO flux- very challenging

Next: **2018-2020** –SOX–very short baseline with an artificial source: ^{144}Ce/^{144}Pr



ν detection : $\nu_e + e^- = \nu_e + e^-$

Anti-ν detection: inverse beta decay

$$\bar{\nu} + p \rightarrow e^+ + n$$

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	$17 mBq/m^3$ (air)	<1 cpd/100 t	<< 1 cpd/100 t	
^{85}Kr	air, nuclear weapons	$\sim 1\ Bq/m^3$ (air)	<1 cpd/100 t	30 ± 5 cpd/100 t	6.8 ± 1.8 cpd/100

Second purification campaign of the scintillator

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

Borexino collaboration (during the construction)

Genova

Milano

Perugia

APC Paris

Princeton University

Virginia Tech. University

Munich (Germany)

Dubna JINR (Russia)

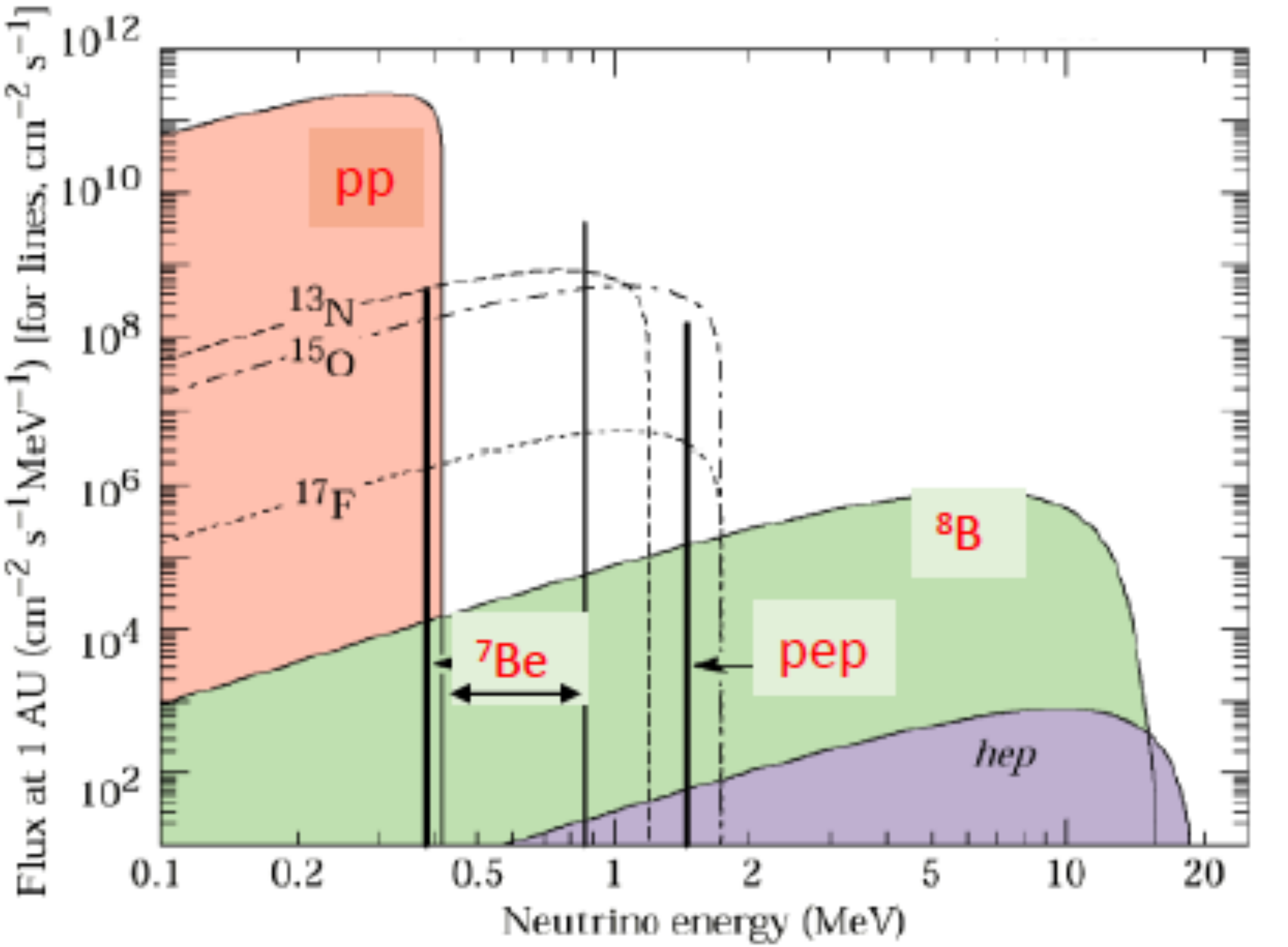
Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

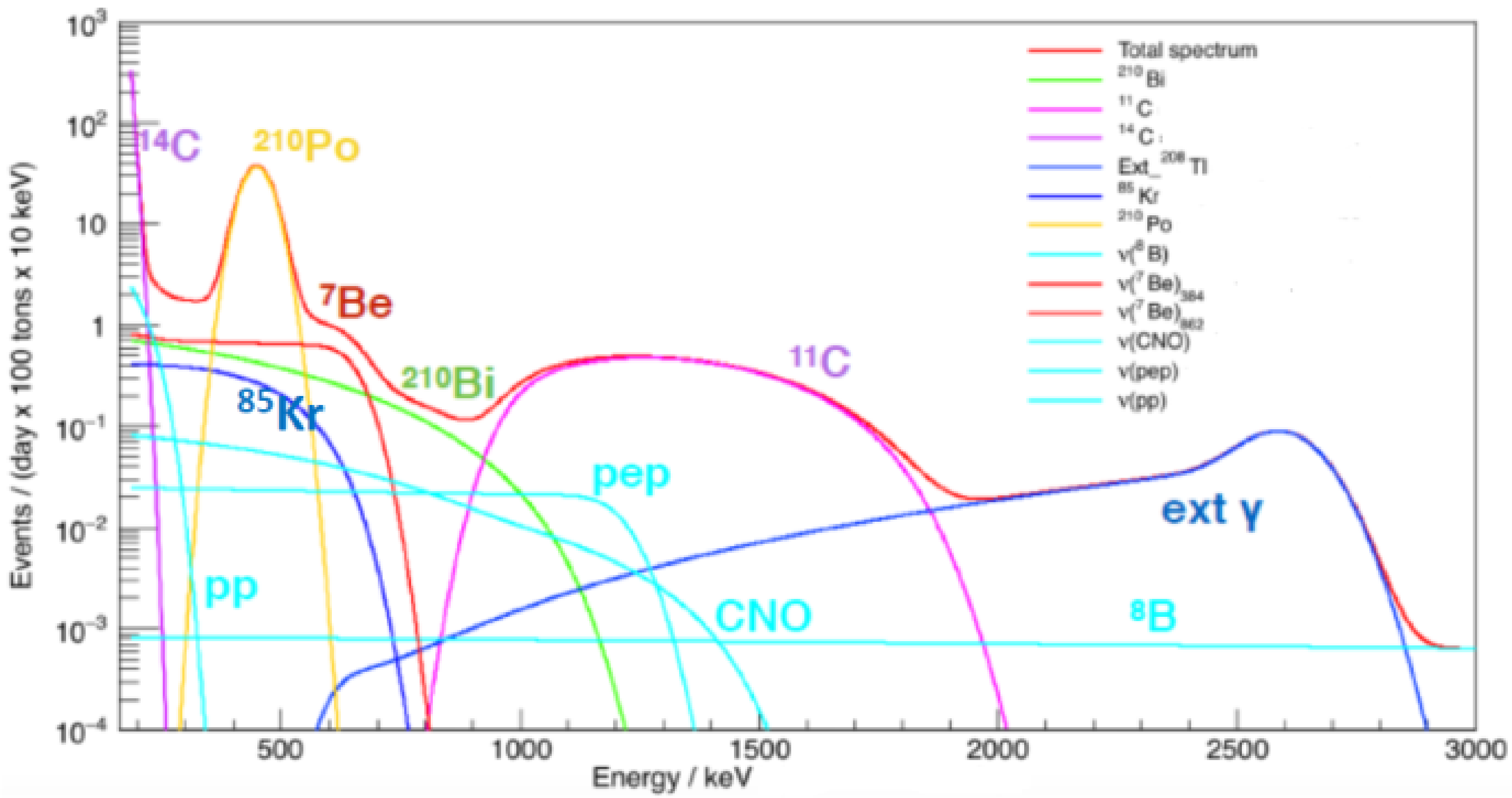
Heidelberg (Germany)

SOLAR PHYSICS

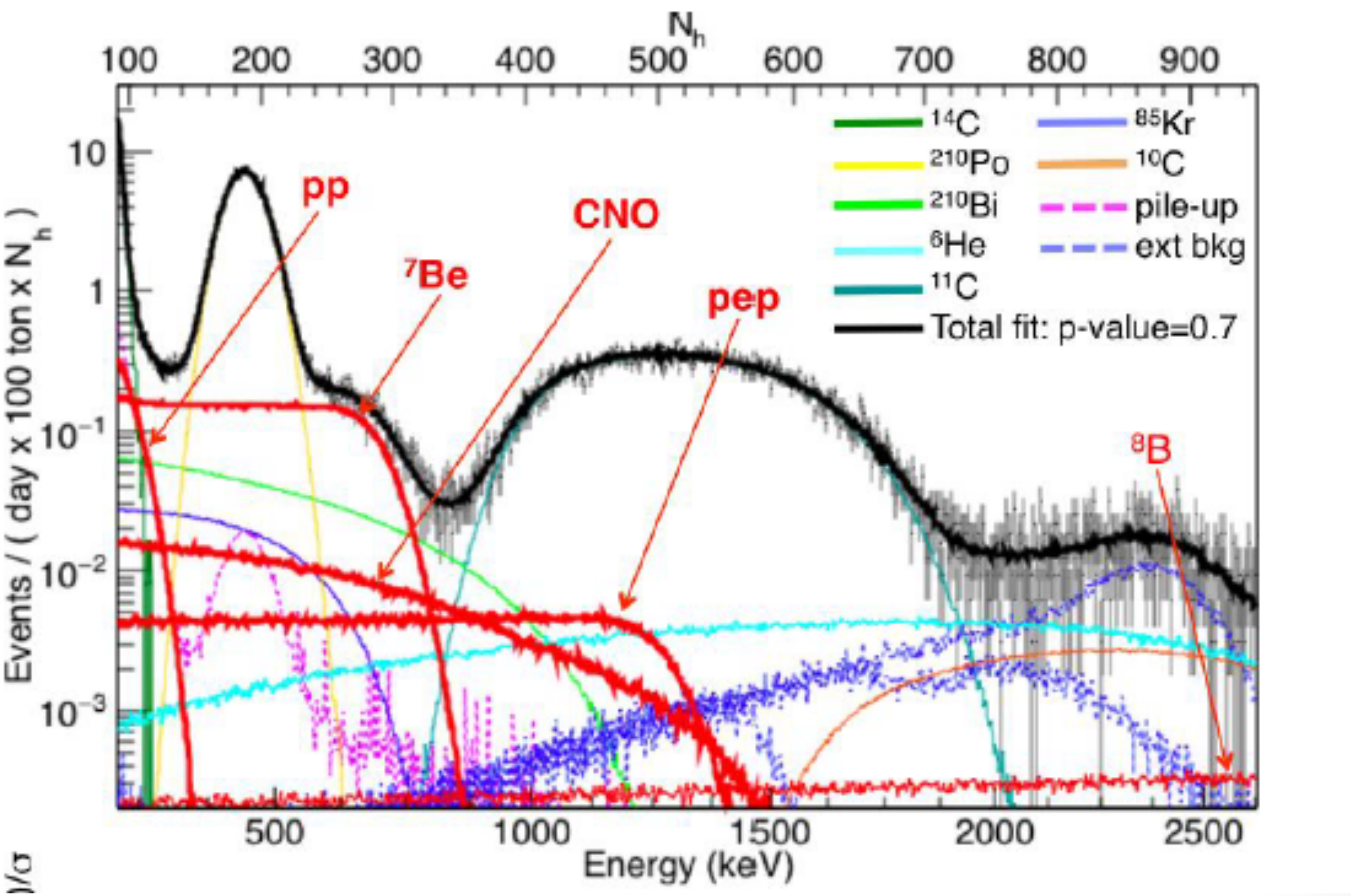
Solar Neutrinos



SIGNALS AND RESIDUAL BACKGROUND



1291.37 DAYS.   1.86-2.93 MEV

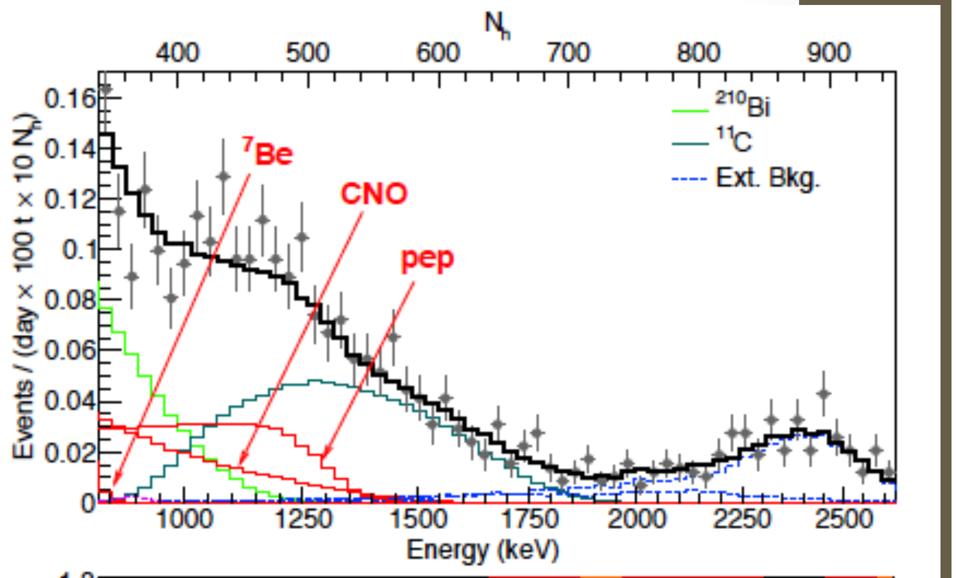


See B. Caccianiga talk

^{8}B

- 2062 live days of data acquisition; 1.5 kton year
- Fit of the radial distribution – Threshold at 3 MeV
- Main background: - ^{208}Tl (Q-value ~ 5 MeV- strongly reduced by the second purification campaign;
  - ^{212}Bi
  - radiogenic neutron capture

See D. Franco talk



pep

- Strong correlation with CNO and ^{210}Bi;
- to break the degeneracy CNO-^{210}Bi, CNO assumed as the SSM prevision.
- Then: pep flux:

  ⇨ pep (HZ)=$1.27 \pm 0.19^{+0.08}_{-0.12}$x 10^8

  ⇨ pep (LZ)=$1.3 \pm 0.19^{+0.08}_{-0.13}$ x10^8

Very good evidence of pep- not existence rejected at > 5 σ–

Not important role to check the SSM

Solar neutrino flux	GS 98 (cm^{-2} s^{-1}) High metallicity Z/X=0.0229 (*)	AGS09 (cm^{-2} s^{-1}) Low metallicity Z/X=0.0178 (*)	Experimental results (Borexino) Flux (cm^{-2} s^{-1})	Global fit including solar, reactor, accel. Data (cm^{-2} s^{-1}) (**)pp
pp	5.98 (1±0.006) x 10^{10}	6.03 (1 ± 0.005) x 10^{10}	$6.11 \pm 0.47^{+0.3}_{-0.5}$ x 10^{10}	$5.97^{+0.037}_{-0.033}$ X 10^{10}
^{7}Be (***)	4.93 (1 ± 0.06) x 10^{9}	4.50 (1 ± 0.06) x 10^{9}	$4.99 \pm 0.13^{+0.07}_{-0\text{-}01}$ x 10^{9}	$4.80^{+0.24}_{-0.22}$ X 10^{9}
pep	1.44 (1 ± 0.01) x 10^{8}	1.46 (1 ± 0.009) x 10^{8}	See previous slide	1.448± 0.013 x 10^{8}
^{8}B	5.46 (1 ± 0.12) x 10^{6}	4.50 (1 ± 0.12) x 10^{6}	5.6 ± 0.4 x 10^{6}	$5.16^{+0.13}_{-0.09}$ $^{+0.3}_{-0\text{-}26}$ x10^{6}
^{13}N **^{15}O** **^{17}F**	2.78 (1 ± 0.15) x 10^{8} 2.05 (1 ± 0.17) x 10^{8} 5.29 (1 ± 0.20) x 10^{6}	2.04 (1 ± 0.14) x 10^{8} 1.44 (1±0.16) x 10^{8} 3.26 (1 ±0.18) x 10^{6}	<7.9 x 10^{8} (95% C.L.) total CNO	≦13,7 x 10^{8} ≦2.8 x 10^{8} ≦8.5 x 10^{6}

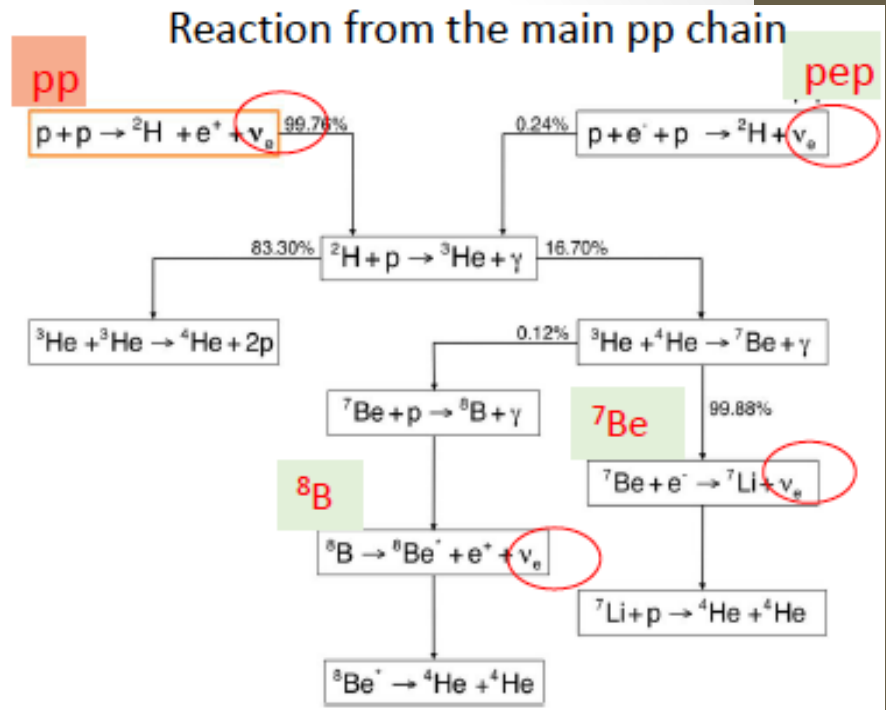
(*): HZ and LZ previsions of SSM from N. Vinyoles et al. Astrophys. J. 835 (2017) 202

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

(***): ^{7}Be flux includes both the lines at 384 and 862 keV.

From the previous data we can extract two important results:

1-The ratio R=^{3}He-^{4}He/^{3}He-^{3}He ≅
≅2Φ(^{7}Be)/[Φ(pp)-Φ(^{7}Be)]=**0.18 ± 0.02**
From SSM (*): 0.18 ± 0.11 (HZ)
0.16± 0.001 (LZ)
(*) C. Pena Garay private communication



2-Comparison between the measured fluxes and HZ vs LZ:

- combination of *pp, ^{7}Be, ^{8}B from Bx and ^{8}B from SK and SNO* prefer **HZ at about 2 σ (0.6 σ for LZ)**
- Only Bx:

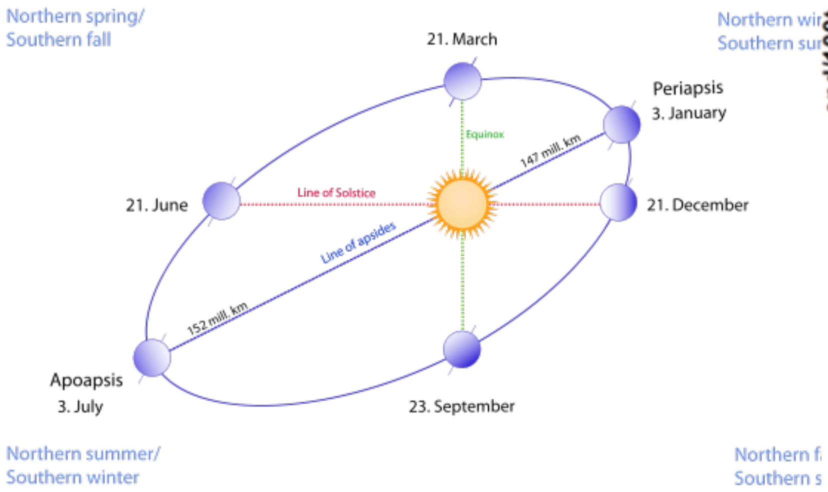
HZ preferred at 3.1 σ (LZ compatible at 0.3 σ)

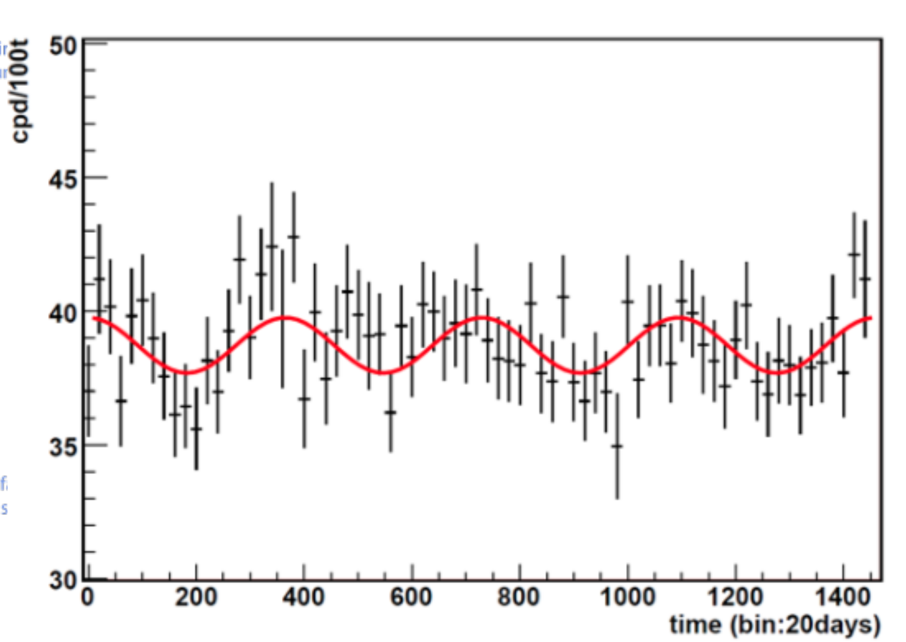
Good indication in favor of HZ

Borex10th 4

seasonal modulation

eccentricity of the Earth orbit- ± 3.5%





max flux: January 3rd

bins 20 days
December 2011- December 2015
1456 astronomical days of data).

total agreement with a Lomb-Scargle periodogram

energy range of ^{7}Be spectrum

the absence of annual modulation is rejected at 99.99% C.L.

Achievements in solar physics

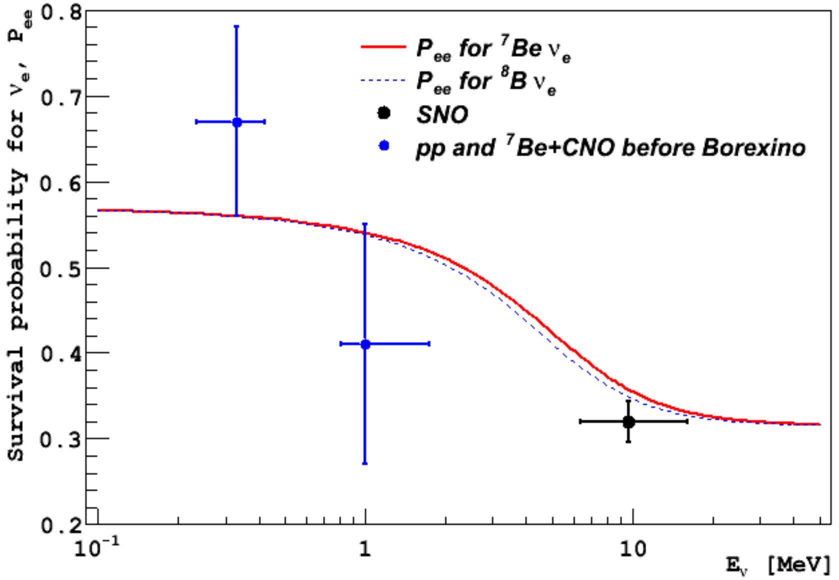
Borexino has measured all the nuclear reactions of the proton-proton solar cycle: **pp, ^{7}Be, pep, ^{8}B***

*the last one already measured by SNO and SuperK.

The pp cycle produces the 99% of the whole solar energy: therefore a comparison with the solar photon luminosity shows a good agreement and demonstrates the Sun stability on ~10^5 years time scale

Borexino has given a contribution to the solution of the metallicity puzzle in the SSM- good indication in favor of the high metallicity

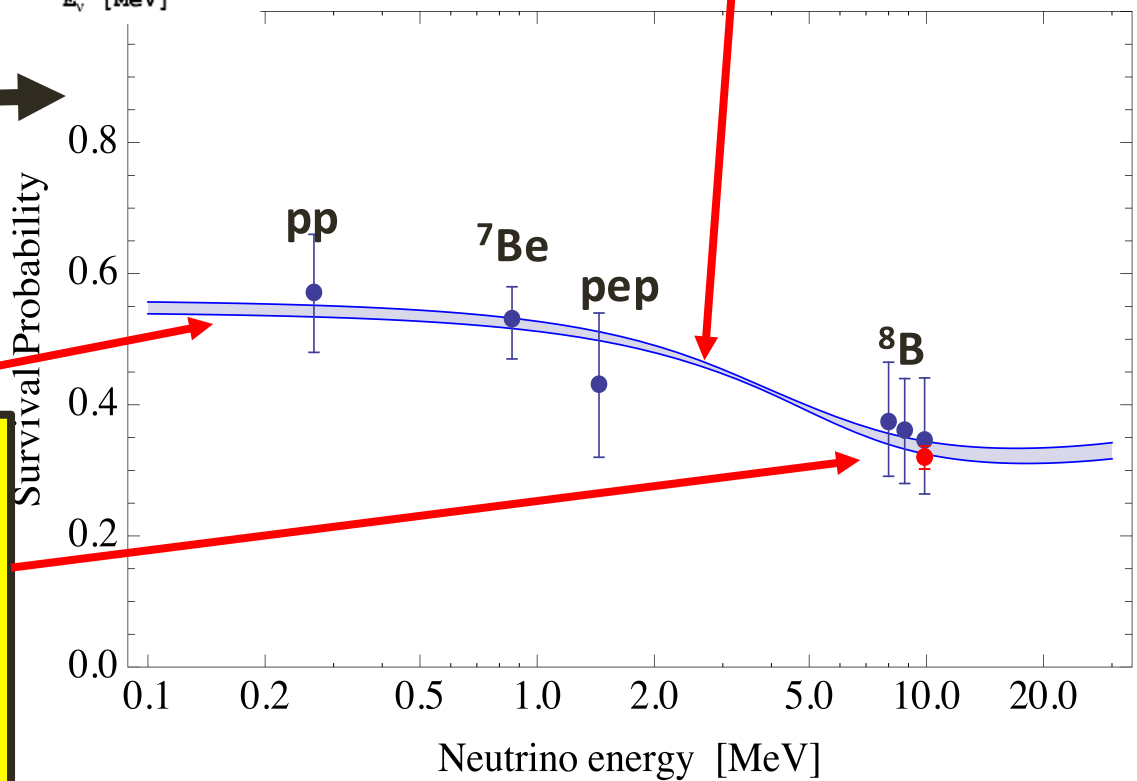
Neutrino physics



Before Borexino

1σ uncertainty MSW prediction

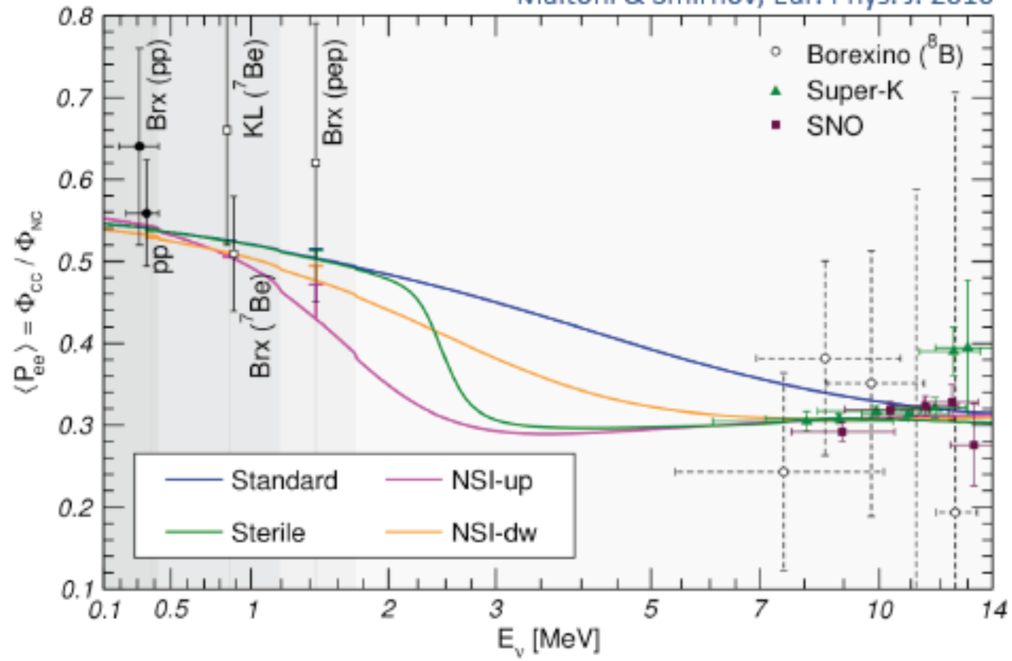
After Borexino



 # Flavor conversion vacuum dominated and relative P_{ee}
 # ratio P_e vacuum / matter =1.58 ± 0.43

<u>Transition</u> region between the vacuum and matter regime

Maltoni & Smirnov, Eur. Phys. J. 2016



The results of SUPERK and BOREXINO agree with the upturn, but within about 1σ

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

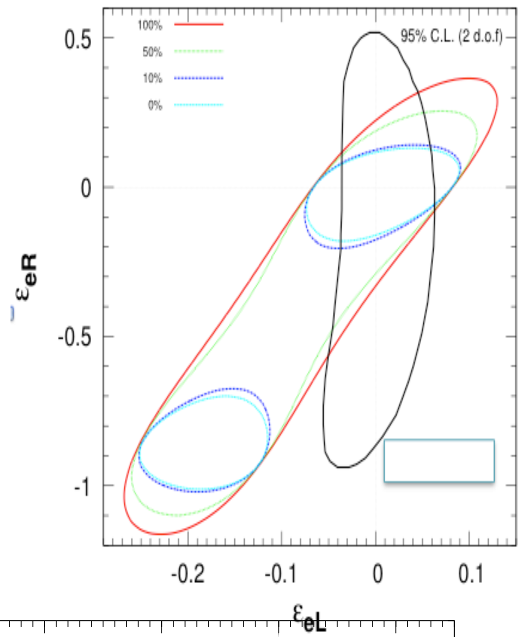
$$\Delta m^2_{21} = 7.5 \bullet 10^{-5} eV^2 \quad \Delta m^2_{01} = 1.2 \bullet 10^{-5} eV^2 \quad \sin^2\alpha = 0.005 \quad \sin^2\theta_{12} = 0.31$$

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)

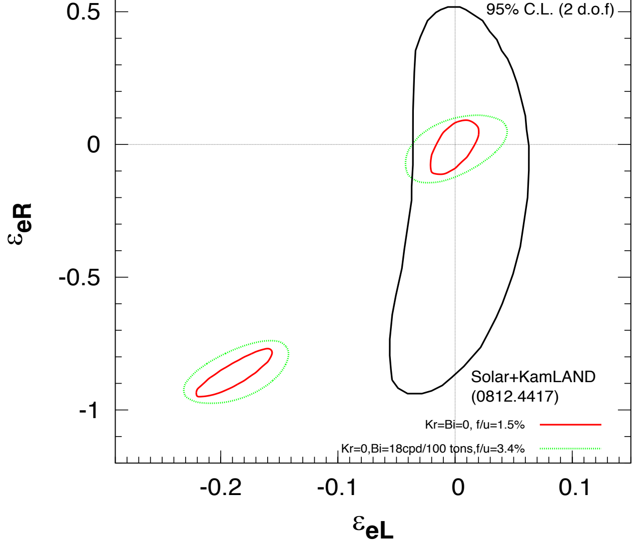
The study of a possible NSI can be done more easily analyzing the energy spectrum of the recoiled electron from the ν-e scattering, in particular for the ^{7}Be neutrinos, which is mono-energetic and then does not need convolution with the incident neutrino spectrum, as for instance is the case of ^{8}B.

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



Bx phase 1

Phase 2:
Kr < 6.4 cpd/100 t
Bi from ~40 to ~15 cpd/100t
^{7}Be flux uncertainty from 5% to 2.6%.



Phase 2- expected

Analysis in progress

See A. Formozov poster
S. Agarwalla talk

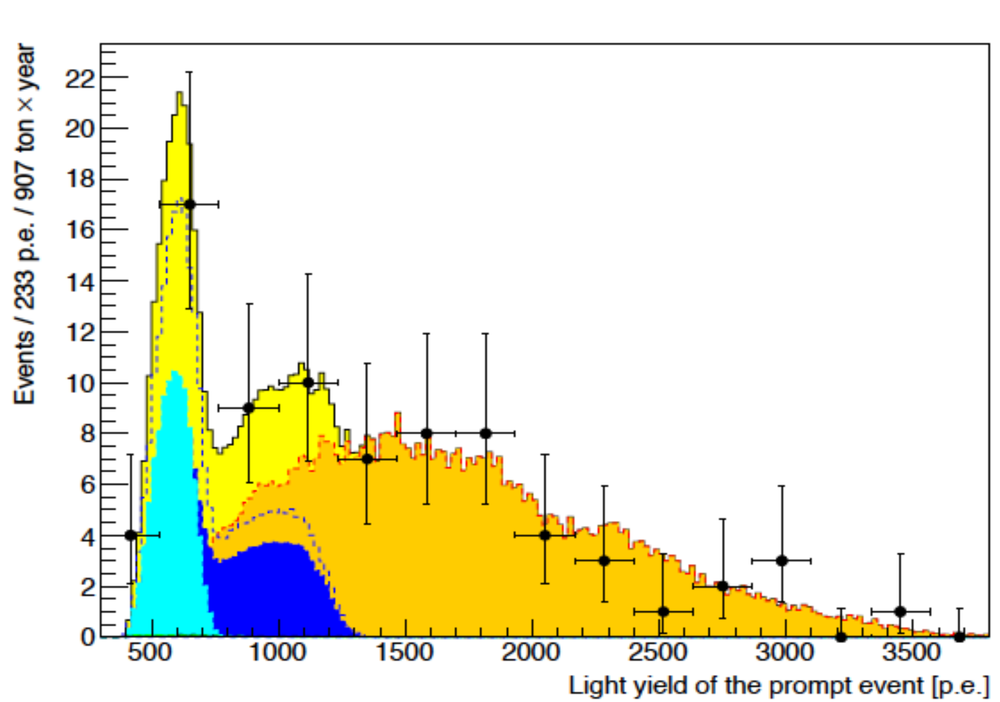
See B. Fujikawa talk

Geoneutrinos

Detected only by KAMLAND and BOREXINO

One disadvantage: # size of the detector
1.5 events/2 months

Two advantages: # very small background
low flux of antineutrino from reactors at the Gran Sasso site



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

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

Evidence of 5.9 σ C.L. reached by Borexino

Main goals: # presence of radioactive nuclides in the Earth mantle
percentage of the total Earth heat due to radioactive decays
discriminate among the **Bulk Silicate Earth** (BSE) models

Borexino reached also the following limits:

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

see Oleg Smirnov talk

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: $\tau(^{12}C \rightarrow ^{12}C^{NP}+\gamma) \geq 5.0 \cdot 10^{31}$ y, $\tau(^{12}C \rightarrow ^{11}B^{NP}+p) \geq 8.9 \cdot 10^{29}$ y, $\tau(^{12}C \rightarrow ^{11}C^{NP}+n) \geq 3.4 \cdot 10^{30}$ y, $\tau(^{12}C \rightarrow ^{12}N^{NP}+e+\nu) \geq 3.1 \cdot 10^{30}$ y, $\tau(^{12}C \rightarrow ^{12}B^{NP}+e^{+}+\nu) \geq 2.1 \cdot 10^{30}$ y, **BEST LIMITS**

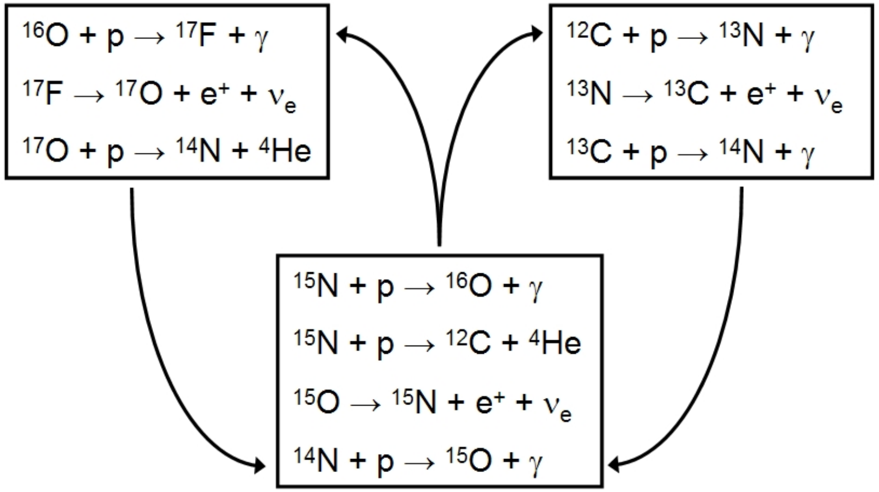
Stability of the electron: $e^- \rightarrow \gamma + \nu$ - search for 256 keV γ peak – consistent with zero- $\tau \geq 6.4 \bullet 10^{28}\ years\ (90\%\ C.L.)$ **BEST LIMIT**

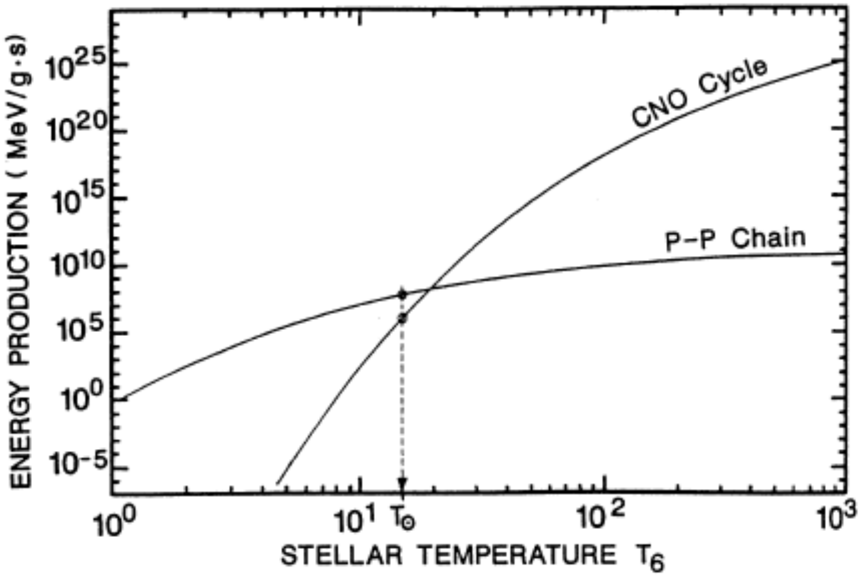
Search for heavy sterile neutrino- The Borexino constrains the mixing of a heavy neutrino with mass 1.5 MeV< **m** <14 MeV appearing in ^{8}B-decay to be $|U_{eH}|^2 \leq (10^{-3} - 4 \bullet 10^{-6})$ -- respectively--10 to 1000-fold stronger than those obtained searching for decay $\nu_H \rightarrow \nu_L + e + e^-$ at nuclear reactors and 1.5-4 times stronger than those inferred from $\pi \rightarrow e + \nu$

Gianpaolo Bellini
Borex10th 4-7 September 2017

CNO cycle
in the Sun only 1%

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

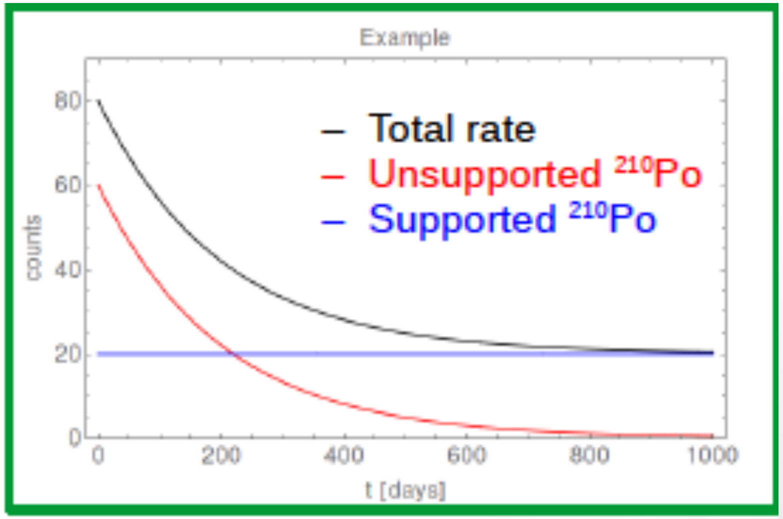




strategy: need of an independent constraint on ^{210}Bi rate (remove degeneracy with CNO spectrum)

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

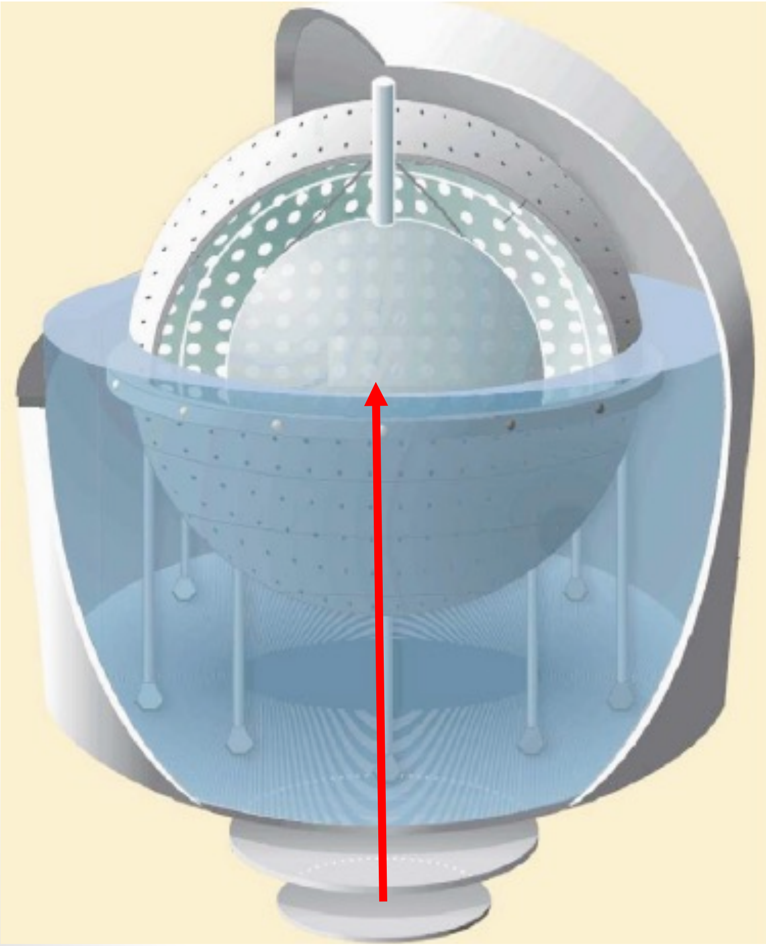


Detector insulation see **D. Bravo poster**

Search for sterile ν in Borexino: SOX

SOX: Short distance neutrino Oscillations with BoreXino **see S. Shoenert talk**

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
Claimed Gallex and Sage source anomaly –
Deficit of the detected ν_e- R= 0.76+-0.09- 2.8σ

Borexino Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

TUM Technische Universität München

JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

University of Houston

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH FORSCHUNGSZENTRUM

UH Universität Hamburg

Virginia Tech

НИИЯФ МГУ SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

Joint Institute for Nuclear Research

GSSI GRAN SASSO SCIENCE INSTITUTE CENTER FOR ADVANCED STUDIES Istituto Nazionale di Fisica Nucleare

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