The Borexino Detector:

•Construction

•Performances & Results

XI Pisa Meeting on Advanced Detectors

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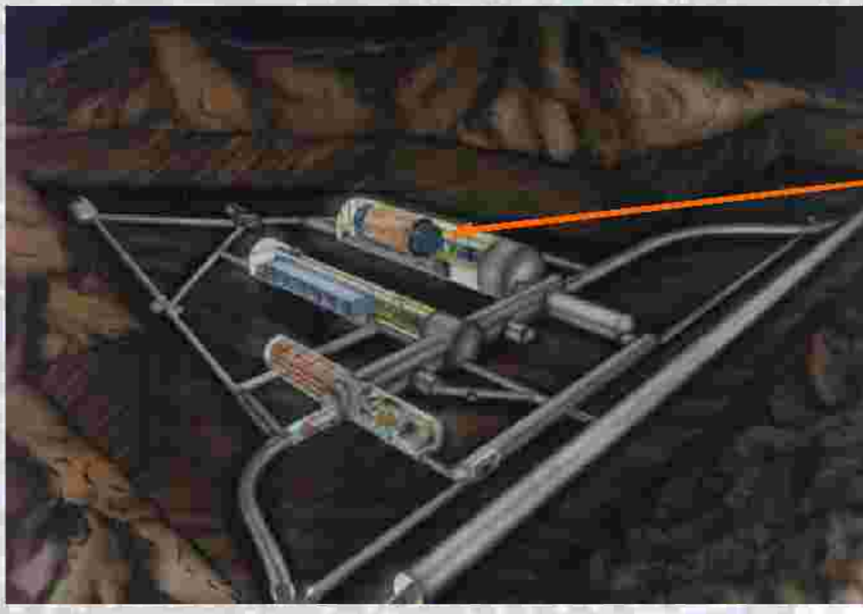
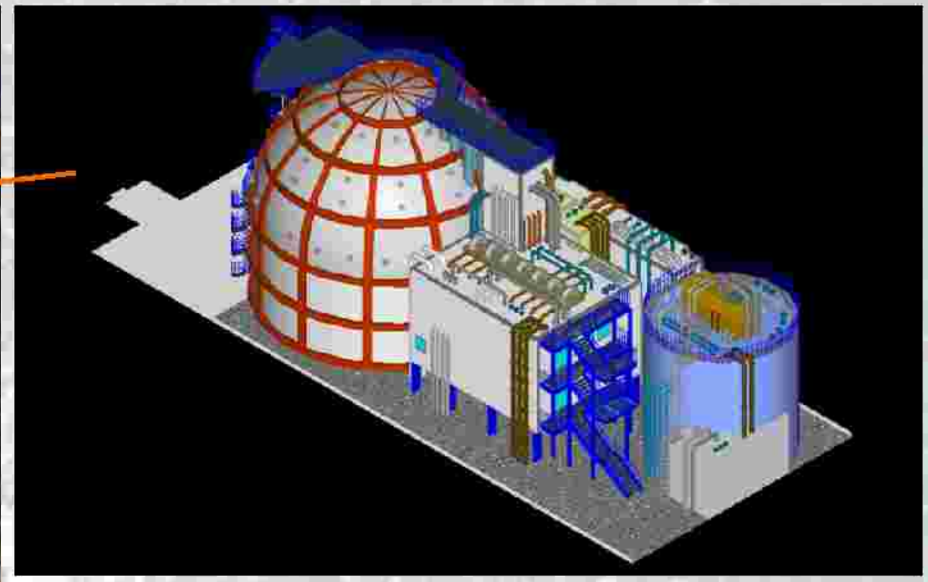
On behalf of the Borexino Collaboration

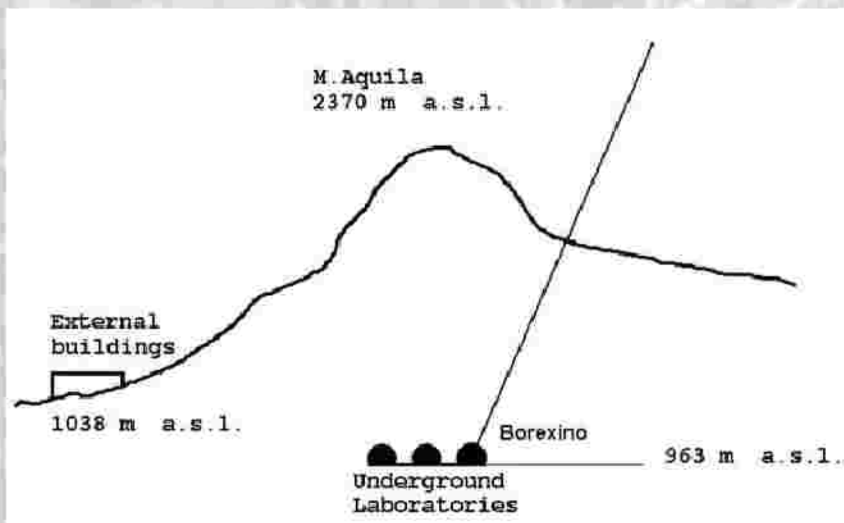
Experiment site



3D view of LNGS underground



3D view of Borexino Experiment

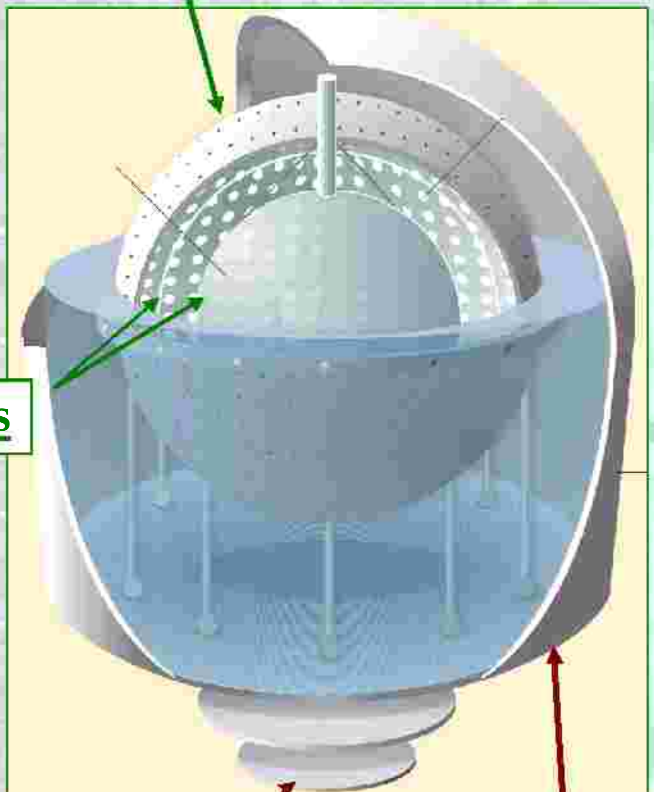


Borexino is located at Laboratori Nazionali of Gran Sasso (LNGS) near L'Aquila (Abruzzo), shielded by 1400 m of rocks (3500 m water equivalent)

Detector

Stainless Steel Sphere

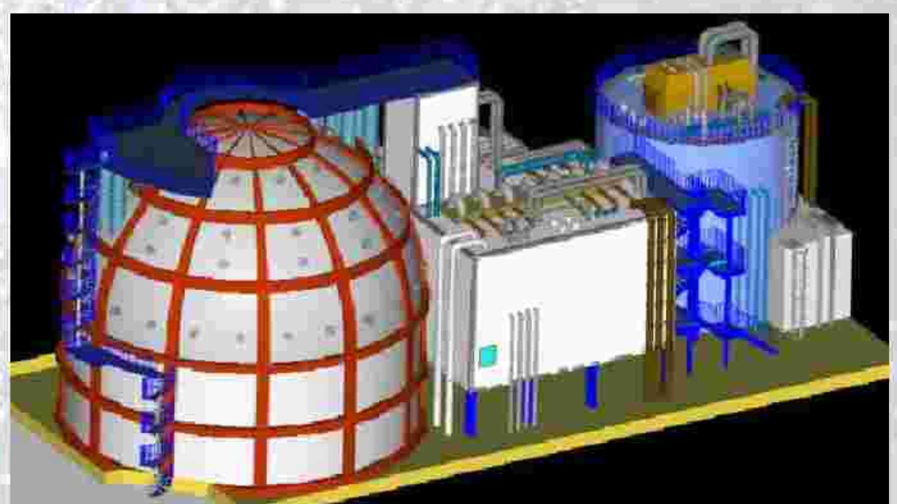
Nylon vessels



Carbon steel plates

Water Tank

Design Based on the principle of graded shielding



Detector

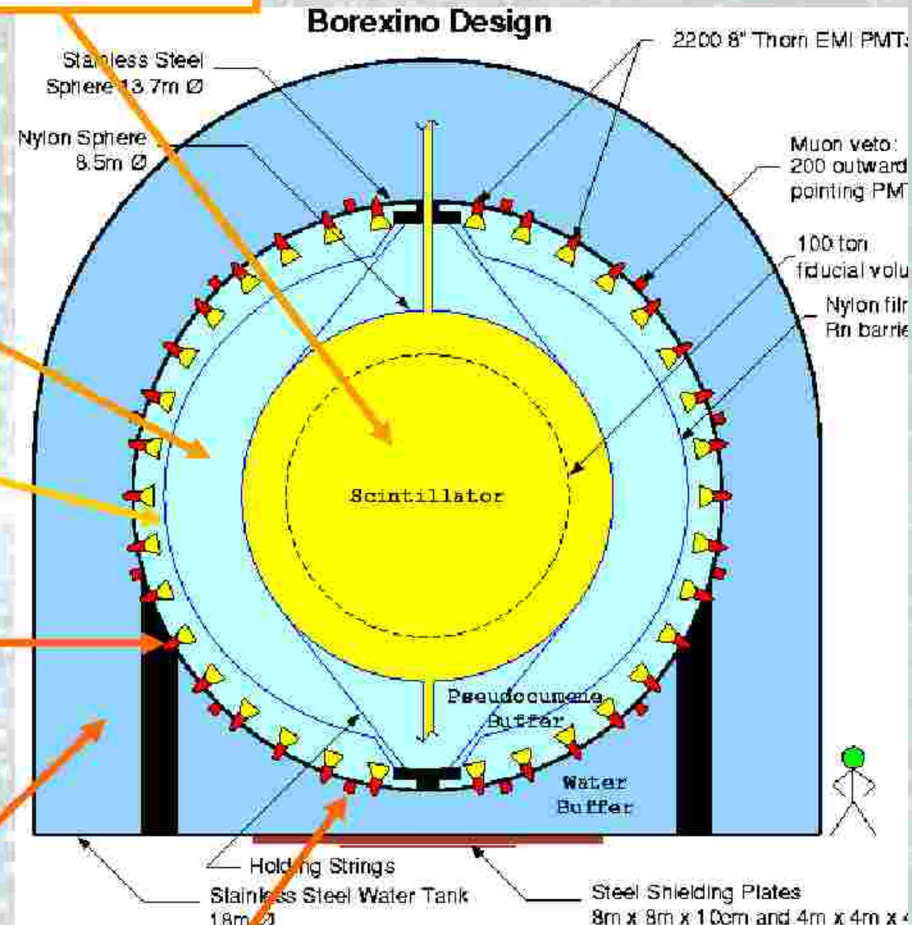
278 tons of pseudocumene (PC) added with 1.5 g/L of 2,5dipheniloxazole (PPO), contained in a 4.25 m radius nylon vessel (125µm thick) at the center of the detector, act as scintillator

890 tons of PC added with 5 g/L of dimethylphthalate , contained in a second 5.5 m radius nylon vessel (323t) and in a 6.85 m radius Stainless Steel Sphere (567t), act as first radioactive shielding.

The external nylon vessel works as additional barrier against Rn emitted by PMT and s.steel

2214 photomultipliers inside the SSS detect the scintillation light from the internal events(1843 with optical concentrator)

2400 tons of ultrapure water in an external tank act as second radioactive shielding.



200 photomultipliers outside the SSS detect the Cherenkov light from external muon events

Physics and detection principles

- Borexino aims to measure low energy solar neutrinos in **real time** by elastic neutrino-electron scattering in a volume of **highly purified liquid scintillator:**
  - Mono-energetic 0.862 MeV 7Be ? is the main target
  - pep, CNO and possibly pp ?
  - Geoneutrinos
  - Supernova ?

- Detection via scintillation light
  - Advantages:
    - ü Very low energy threshold (~200 keV)
    - ü Good position reconstruction (~ 15cm/1MeV)
    - ü Good energy resolution (~5%/1MeV)
  - Drawbacks:
    - ü No direction measurements
    - ü ? induced events can't be distinguished from other ß due to natural radioactivity

Extreme radiopurity of the scintillator

Borexino requirements

Radioisotope	Source	Typical level in scintillator without purification	Removal strategy	Design Level (<1cpd/100 ton)
^{14}C	Cosmic Ray activation of ^{14}N	$^{14}C/^{12}C$~10^{-12} (equilibrium from cosmic radiation at earth's surface)	Petroleum derivate (Old carbon)	$^{14}C/^{12}C$~10^{-18}
^{7}Be	Cosmic Ray activation of ^{12}C	2.7x10^{3} cpd/ton (equilibrium from cosmic ray activation of ^{12}C to ^{7}Be at earth's surface)	Distillation and Underground storage of scintillator	<0.01 cpd/ton <10^{-6} Bq/ton
^{222}Rn	Air and emanation from materials	1.3x10^{7} cpd/ton (equilibrium Rn absorption into PC from air with ^{222}Rn=10-100 Bq/m^3-air)	Nitrogen Stripping	<0.01 cpd/ton
^{210}Bi – ^{210}Po	^{210}Pb decay	2x10^{4} cpd/ton (^{210}Pb decay after exposing surface of the containment vessel to air with 10Bq/m^3 of ^{222}Rn for 1 year)	Surface cleaning	
^{238}U – ^{232}Th	**Suspended Dust, Organometallics**	**<10^{3} cpd/ton or <10^{-12}g-U(Th)/g-scintillator (1g-dust suspended in 1 ton of scintillator. Dust has U(Th) content equal to average of earth's crust, 10^{-6}g-U/g-dust (10^{-5}g-Th/g-dust)**	Distillation, Filtration	**<10^{-17}g-U(Th)/g-scintillator**
^{40}K	**Contaminant found in fluor**	**2700 cpd/ton~10^{-9}g-K/g-scintillator (scintillator with 1.5 g-PPO/L and PPO has 10^{-6}g-K/g-PPO)**	Water extration, filtration and distillation of fluor solution	**<10^{-14}g-K/g-scintillator**
^{39}Ar	Air	218 cpd/ton (equilibrium Ar absorption into PC from air with ^{39}Ar=16 mBq/m^3-air)	Nitrogen Stripping, leak tight system	<500 nBq/m^3-N_2
^{85}Kr	**Air**	**4.3x10^{4} cpd/ton (equilibrium Kr absorption into PC from air with ^{85}Kr=1 Bq/m^3-air)**	Nitrogen Stripping, leak tight system	**<100 nBq/m^3-N_2**

Borexino requirements

In order to achieve the requirements, Borexino developed a strategy consisting mainly in 4 points:

↓

Choice of materials and components

Purification of the scintillator

Cleaning and installation in clean room environment

Leak tightness

Materials

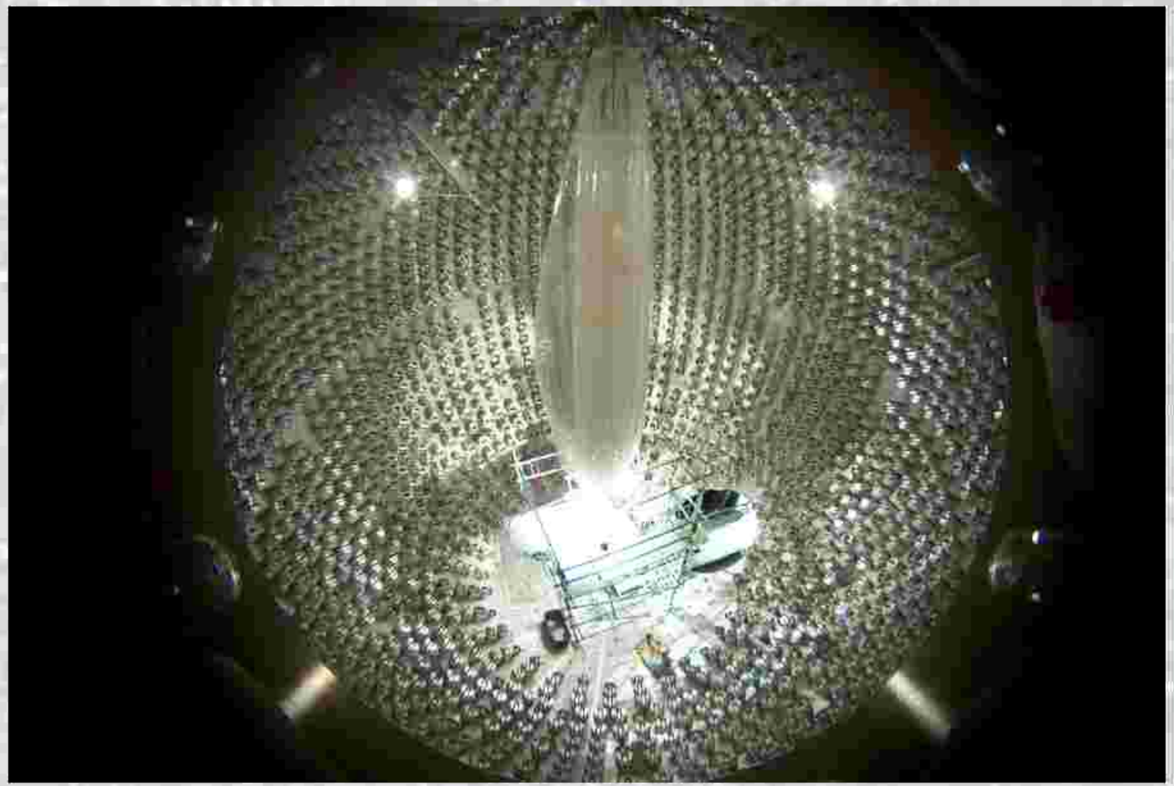
- Piping and vessels in AISI 316L electropolished stainless steel;
- Orbital welding with high pure Ar bottle or electrode without thorium for TIG welding;
- Connections using: VCR, ConFlat, Helicoflex gaskets and Double Teflon Encapsulated Viton O-rings.
- High quality teflon filters (0.1µm and 0.02µm for water, 0.05 µm for PC)

Components: Nylon Vessels

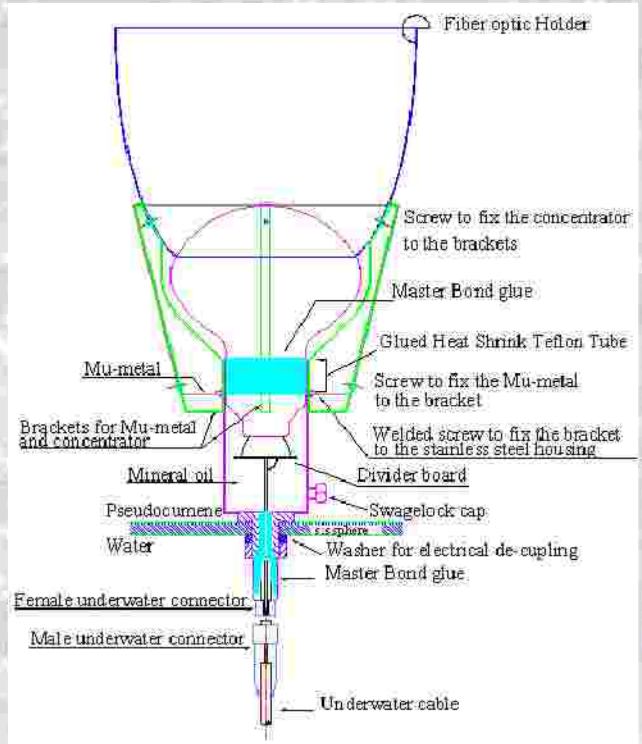
Nylon Vessels constructed in a radon-free Clean Room:

- **Sniamid Nylon-6 film, 125 µm tickness**
- **Index of refraction = 1,53 with transmittance >90%**
- **Nylon radioactive content (radium -^{222}Rn progenitor- level < 21 mBq/kg).**

Vessels installation into the SSS, in a clean room environment class 1000



Components: Inner PMTs tubes



Sealing:

PC and water proof

All material selected for low radioactivity

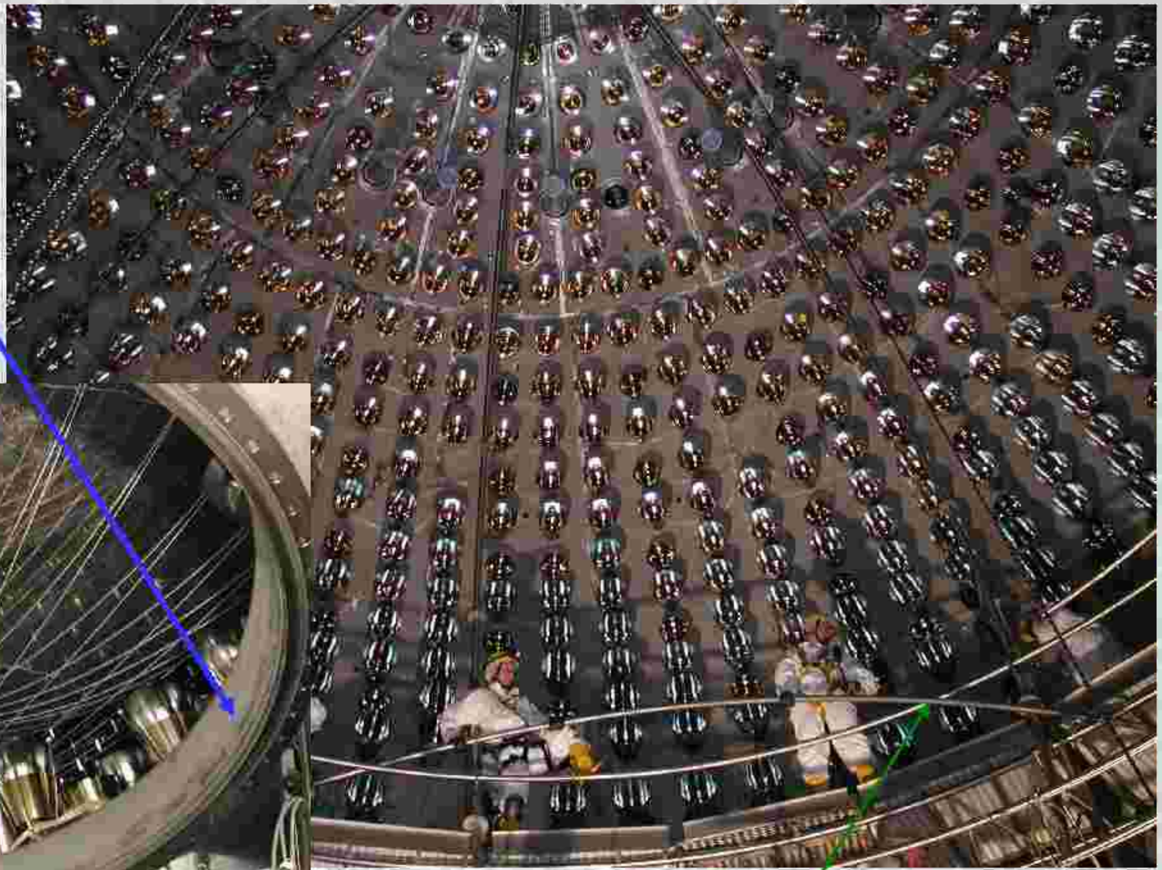
Thermal and mechanical ageing test

Complete fine elements simulation

- **Photomultiplier ETL former Thorn-EMI**
  - **8" ETL 9351 with 12 linear focused dynods (BeCu)**
  - **SbKCs hemispherical cathode~ 26% quantum efficiency**
  - **10^7 voltage gain with low dark rate (~1 kHz)**
  - **After pulses < 5%**
  - **Single p.e. transit time spread ~ 1.1 ns**
  - **Peak to valley ratio > 1.5**

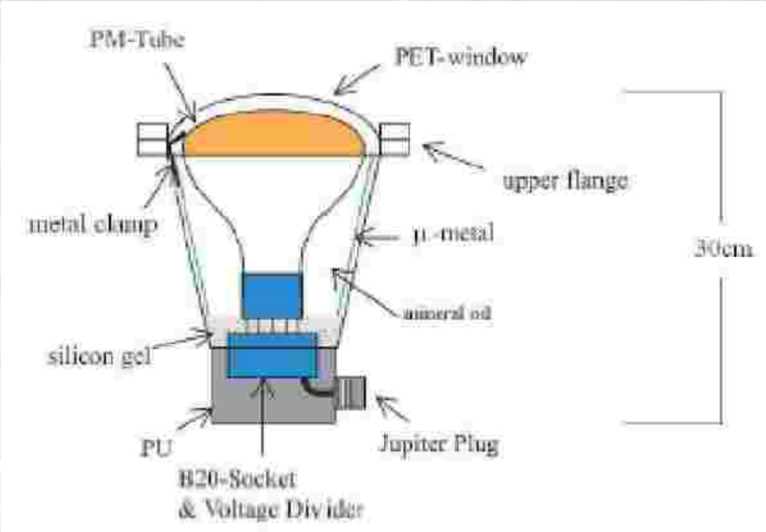
Components: PMTs installation

3 meter flange on the sphere
Double seal
helicoflex metal gasket



Scaffold dismounting

Components: Outer Detector



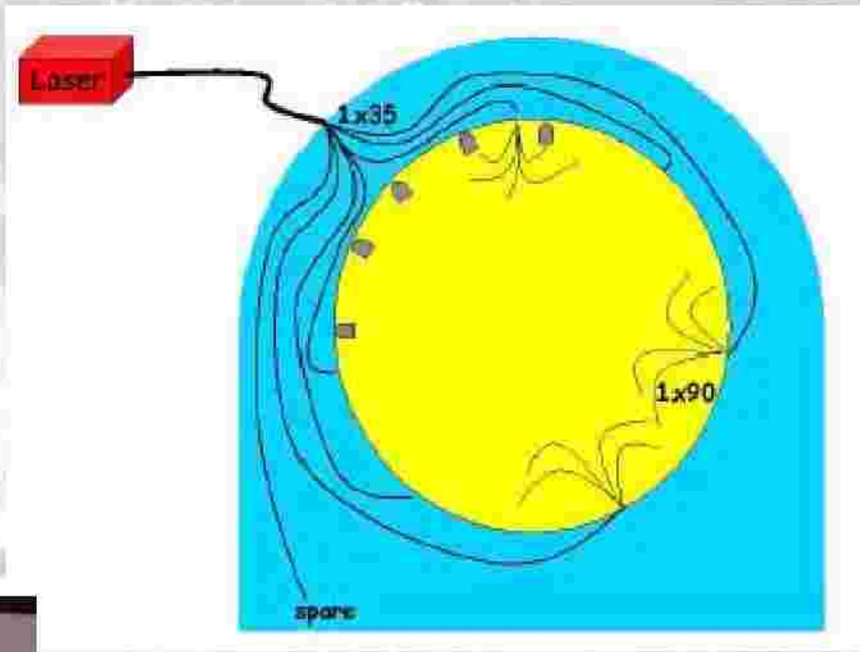
High energy muons still constitute a relevant source of background for the experiment.

Water Cherenkov detector

- **208 PMTs installed in the external tank**
- **Tyvek foil to increase light reflection/collection**
- **Encapsulation specially designed for water**
- **High efficiency > 99%**
- **Independent acquisition system**
- **Provide trigger information for main Borexino electronic**

Components: Calibration

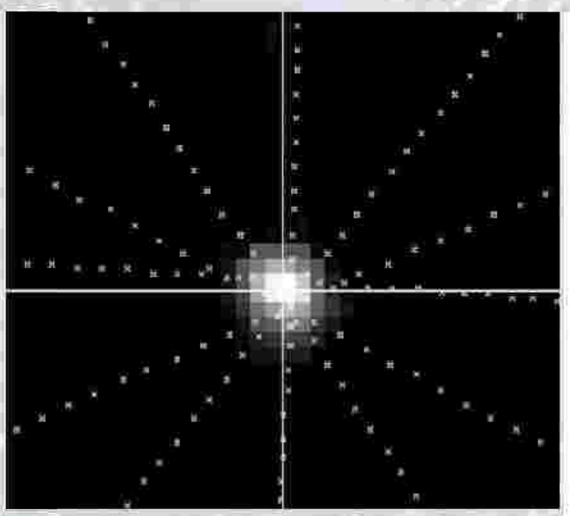
- **Requirements:**
  - **Single electron response for energy cal. µ ˜ 0.05 p.e./laser pulse**
  - **Precise timing calibration < 1 ns**
  - **Adjustable illumination level (linearity)**
  - **Calibration rate ˜ 100 Hz**
  - **High level of automation**
  - **Low radioactivity of fibers and support**
  - **Long term stability and reliability (10 y)**

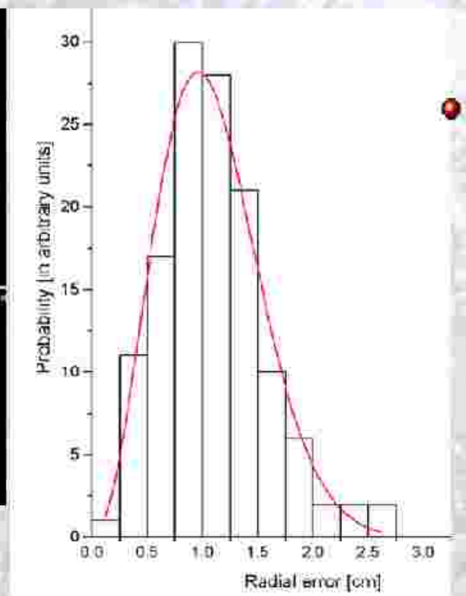


- **Solutions:**
  - **Picoseconds diode laser (50 ps, l =394nm)**
  - **Air/water: a bundle of 35 fibers 40 m long**
  - **Water/PC: 35 leak tight feed-through with SMA connectors**
  - **PC: a bundle of 90 fibers 6 m long (10 spares) 110 µm core quartz Teflon coating**
  - **High uniformity of distributed light tested with a power meter**

Components: CCD cameras

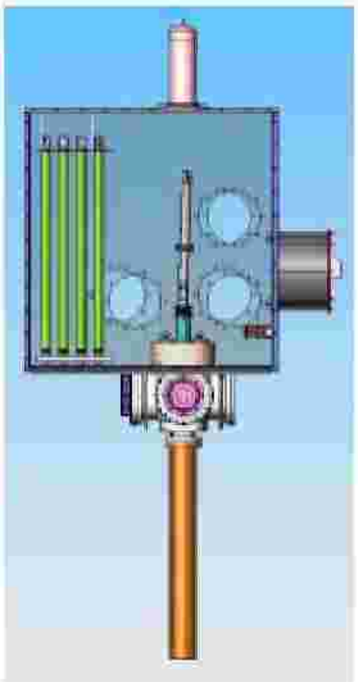
- Source position determination for fiducial volume definition required to see 7% annual variation in ? flux due to Earth orbit.
- LED connected to the source insertion system arm to perform visual calibration

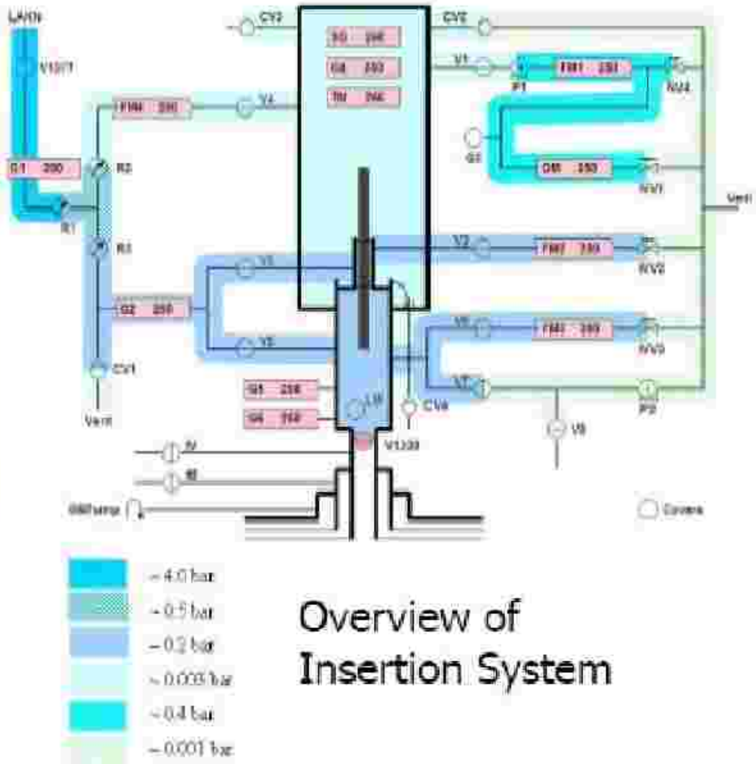




- Camera system:
  - 7 Kodak DC290 digital cameras with Nikon fish-eye lens
  - USB connection to electronic control box
  - Stainless steel housing with spherical glass dome
  - 8 Halogen light for each camera
  - 2 cm resolution achieved
  - PMT cone position for absolute calibration

Components: Source Insertion S.





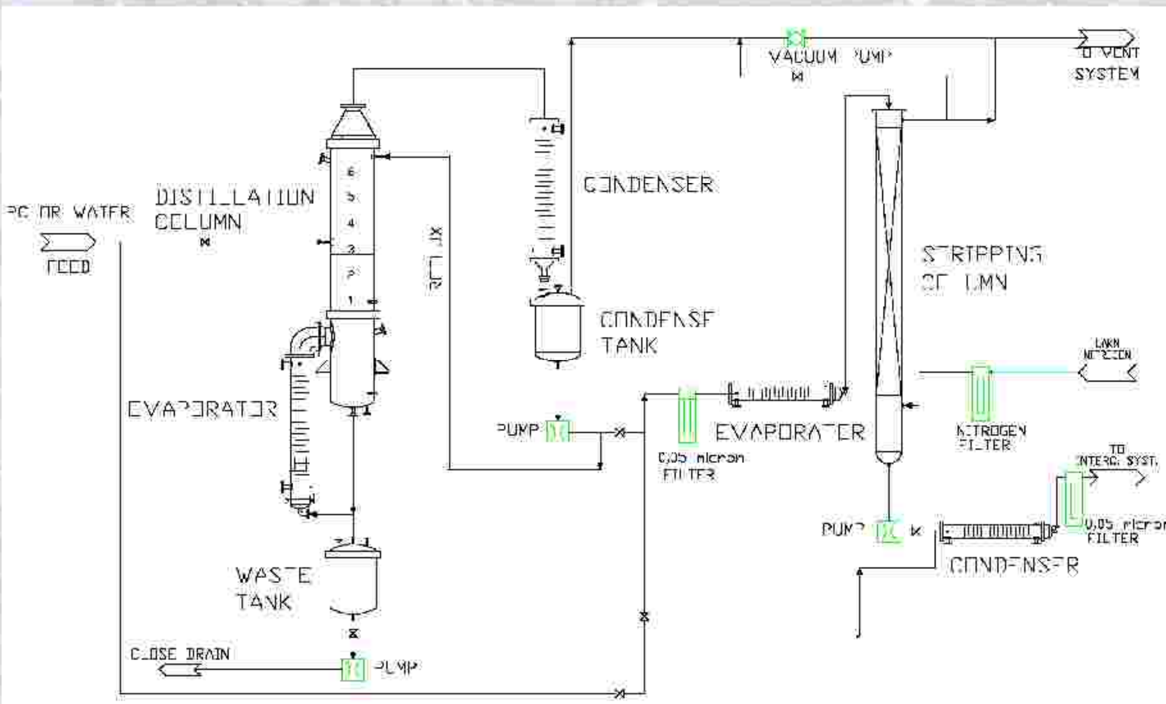
CALIBRATION:

- **Position reconstruction**
- **Energy calibr. and resolution**
- **Light Yield determination**
- **a/ß discrimination perfor.**
- **Fiducial volume determination**

- **Insertion system:**
  - **Glove box mounted on a steel cross above the inner vessel gate valve**
  - **Stainless steel insertion rods with a tight feed-trough continually purged with LAK nitrogen**
  - **Gas system to evacuate, purge and pressurize the cross with LAK nitrogen**
  - **Vial source, LED and Teflon tube for liquid sampling can be easily mounted on the system**

Purification

All the 1168 ton of PC have been vacuum distilled and nitrogen stripped during the Detector filling



Columns properties:

Distillation
- **6m tall**
- **0.75m diameter**
- **6 trays**

Nitrogen Stripping
- **8m tall**
- **0.15m diameter**
- **filled with stainless steel structured packing**

Process parameters:

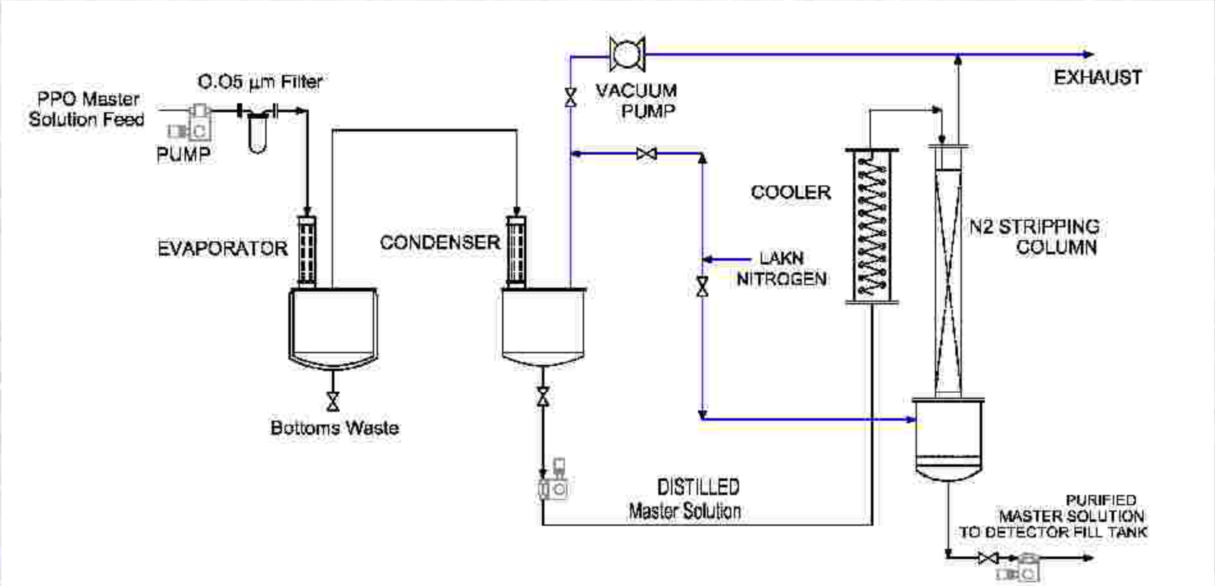
***Disillation*: 80mbar abs, 92(C, 850L/h, reflux 200L/h**

***Nitrogen Stripping*: 300mbar abs , 9Kg/h-N_2, 850L/h-PC, 35 °C**

Purification

The PPO has been added during the filling by a mixing inline between the purified PC and a pre-purified Master Solution (PC+120 g/L-PPO).

The Master Solution has been purified by Water Extraction, vacuum Distillation and Nitrogen stripping



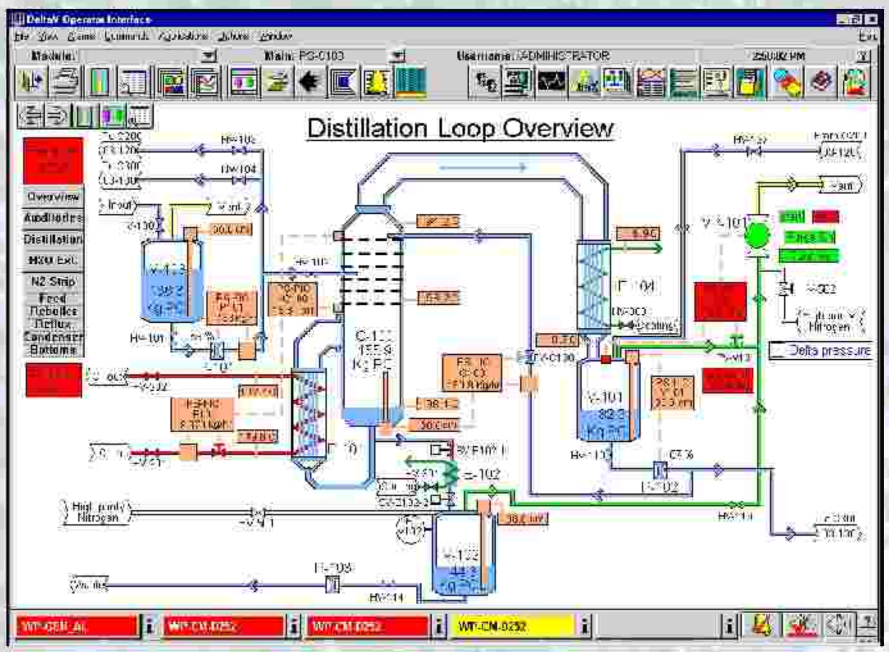
Process parameters:

Water extraction: **4 cycles per batch**

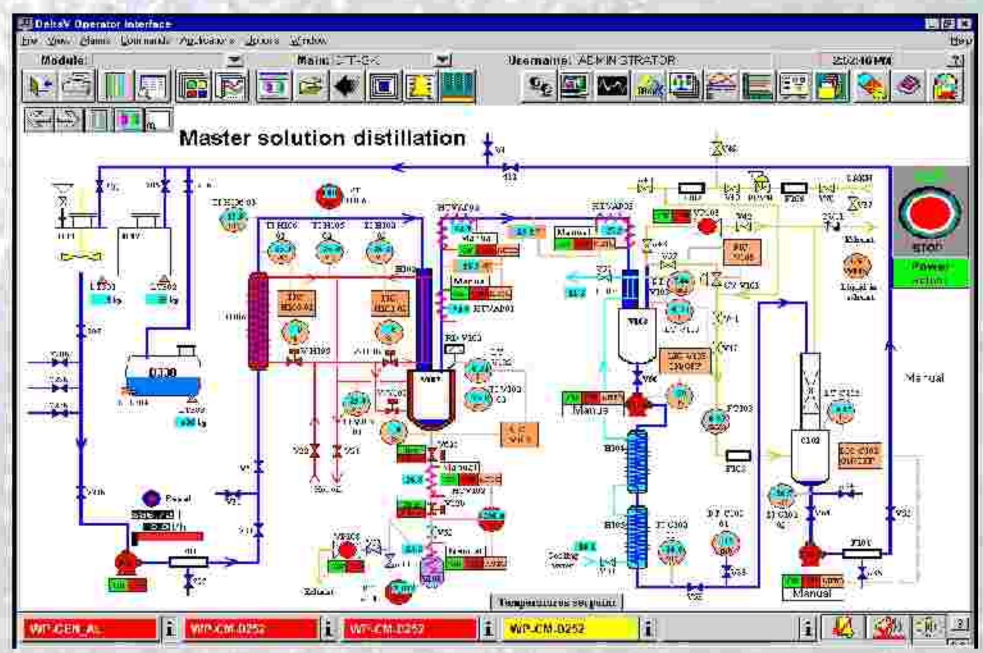
Distillation**: 30mbar abs, 200°C, 20L/h**

Nitrogen Stripping**: 1 bar abs , 2Kg/h-N_2, 20L/h-MS, ambient temperature**

Purification

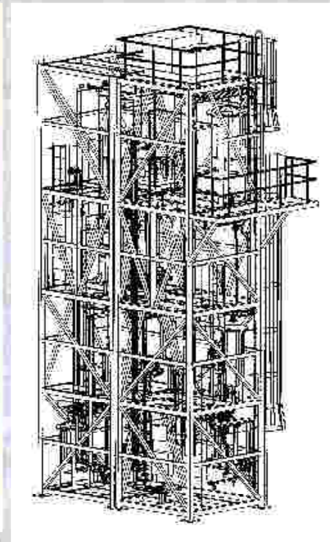


Graphical page of the PC distillation process



Graphical page of the Master Solution distillation

Purification



Some picture and a 3D drawing of the purification skids

Assembly of distillation & water extraction columns in clean room

Cleaning

- Remove surface contaminants and particulates
- Detailed procedures for the cleaning process (following ASTM A380-99 and A967-01 for pickling and passivation)
- Detailed procedures for the particle counting (following MIL STD 1246C)

Internal surface of the distillation column

Stripping column assembly in clean room

Cleanliness Level	Total Particulate Mass (g-particulates/g-liquid)	^{238}U Background from Particulates (cpd/ton)	^{238}U Background with filtration (cpd/ton)
1	1.0×10^{-14}	1.0×10^{-5}	1×10^{-8}
5	1.5×10^{-12}	1.5×10^{-3}	2×10^{-6}
10	1.5×10^{-11}	1.5×10^{-2}	2×10^{-5}
25	3.1×10^{-10}	0.31	3×10^{-4}
50	3.6×10^{-9}	3.6	4×10^{-3}
100	3.9×10^{-8}	39	8×10^{-2}
200	8.2×10^{-7}	820	1
300	4.2×10^{-6}	4200	5

The table is a summary of the total mass concentration of particulates and the expected background from U decay chain

ALL BOREXINO PLANTS HAVE BEEN CLEANED AT CLASS 30 OR BETTER

Leak tightness

Requirements

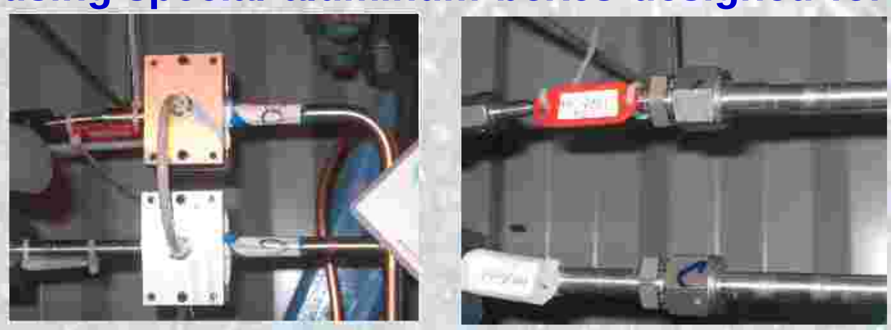
The atmospheric Krypton (~1 Bq/m^3) drives the leak tightness requirements.

The goal is to have less than 0.01 cpd/t (1 cpd/FV => 10cc-air/FV).

Considering the purification and filling flow (~1 m^3/h), the number of joints and a factor 10 as safe margin, the tolerable Borexino leak rate per connection is 10^{-8} std cc/s.

To prevent leaks due to possible fails of the sealings, additional precautions have been taken:

- **Continuous nitrogen purging in the gap of the double gasket sealings**
- **Continuous nitrogen purging around all the joints of the filling path, using special aluminum boxes designed for this purpose.**



Aluminum boxes around VCR fittings

Flange with double sealing

Filling Steps

Purging

To reduce the Oxygen, Radon, Argon and Krypton content, several volumes of the detector have been replaced with a Low Argon and Krypton Nitrogen ($LAKN_2$).

$LAKN_2$ is a particular nitrogen found on the market after a search between different companies:

^{222}Rn=6.8μBq/m^3

^{39}Ar=0.01ppm

^{85}Kr=0.02ppt

Water Filling

August – November 2006

The water filling has been done with ultra pure water a Borexino plant composed by a reverse osmosis and an ion exchanged beds unit followed by a nitrogen stripping column:

- Resistivity 18 MW/cm at 20ºC
- Radon content ~300 mBq/m^3
- Radium content <0.8 mBq/m^3

To remove dissolved gases (Ar, Kr, Rn, N_2), the used water has been stripped with $LAKN_2$ in the purification plant. The measured Rn content was ~1mBq/m^3 showing a 300 reduction factor in the stripping column.

Filling Steps

PC filling

January – May 2007

How?

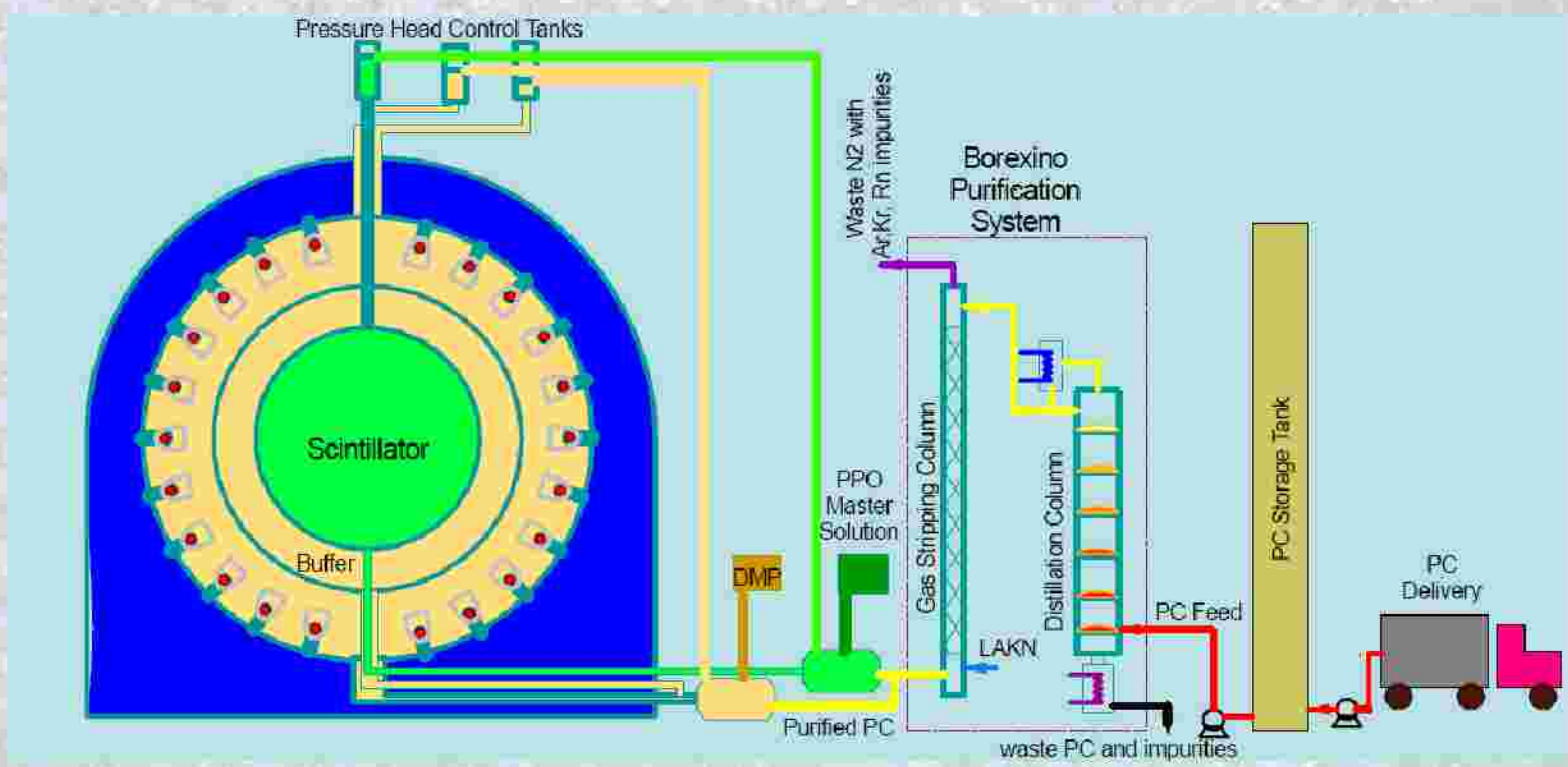
- **Replacing the water removed from the bottom with PC+PP and PC+DMP from the top**
- **PC vacuum distillation and nitrogen stripping with $LAKN_2$**
- **PC mixing inline with the pre-purified Master Solution to reach 1.5g/L of PPO for the scintillator**
- **PC mixing inline with the DMP to reach 5g/L concentration for the buffer shielding**
- **Following a calculated table and monitoring several instruments to keep a level difference between the nylon vessels <0.5 cm**
- **Regulating the differential gas pressure between the vessels by a continuous nitrogen flow with $LAKN_2$**

All the Borexino plants are monitored and controlled by a DCS System (DeltaV – Emerson Process Management).

The DCS has been fundamental to implement all the plants regulation and to automize all the Filling phases.

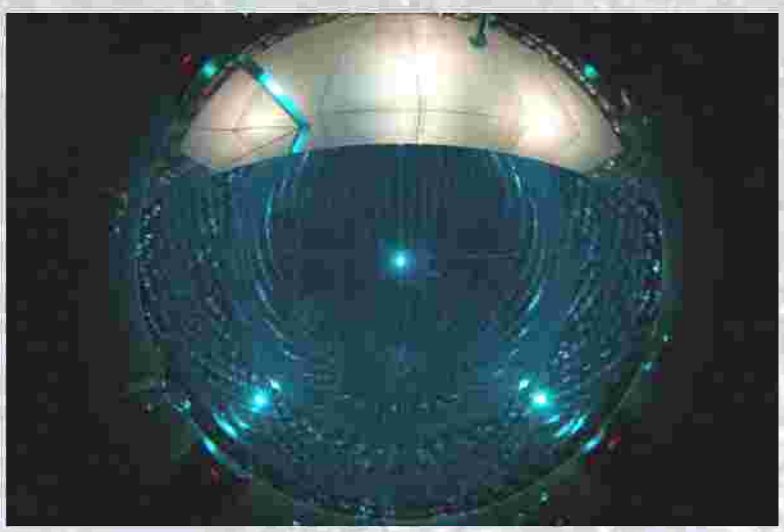
Filling Steps

PC filling

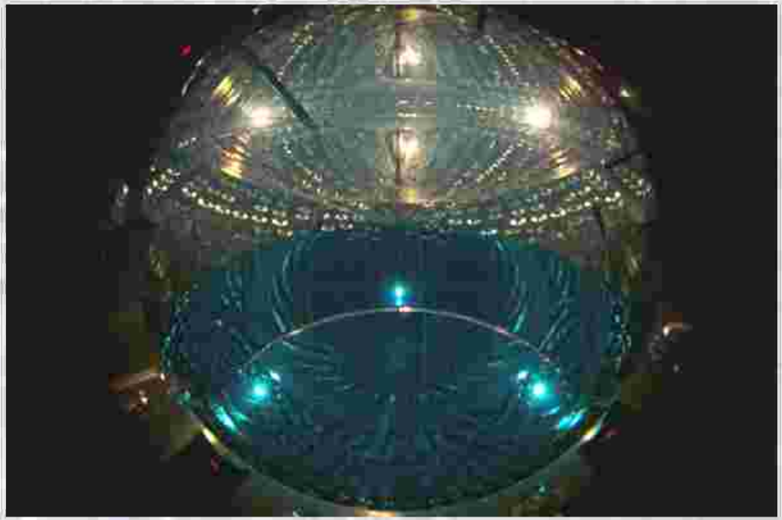


Borexino filling scheme

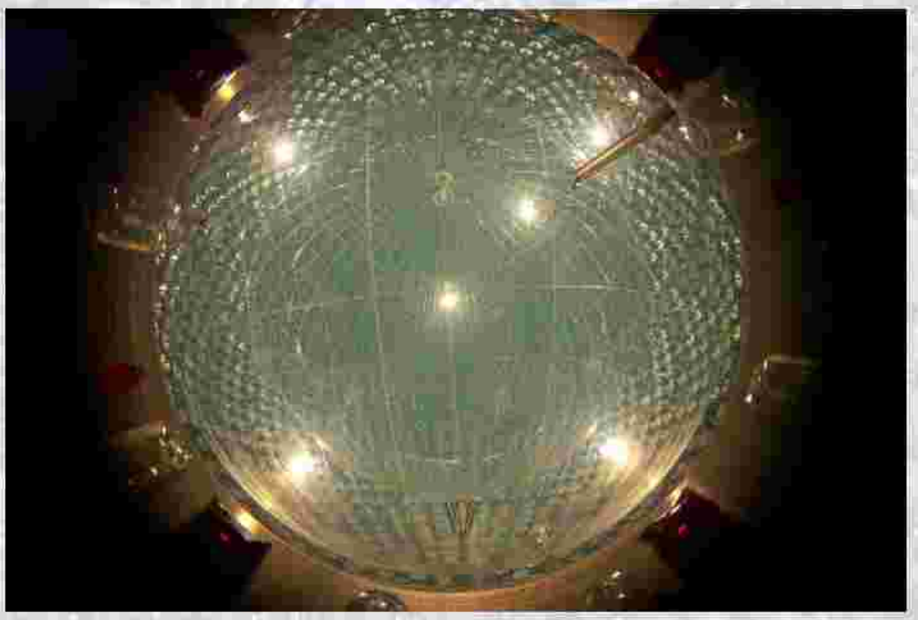
Filling Pictures



Water filling of the Detector



PC filling of the Detector



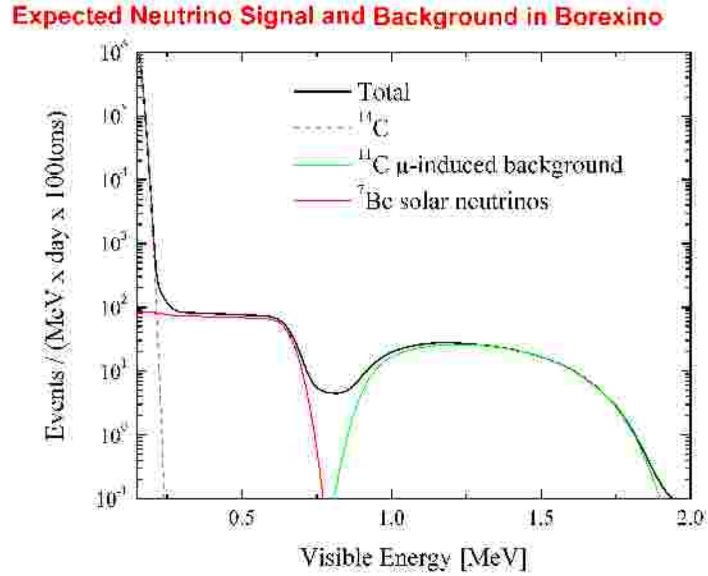
Detector now!

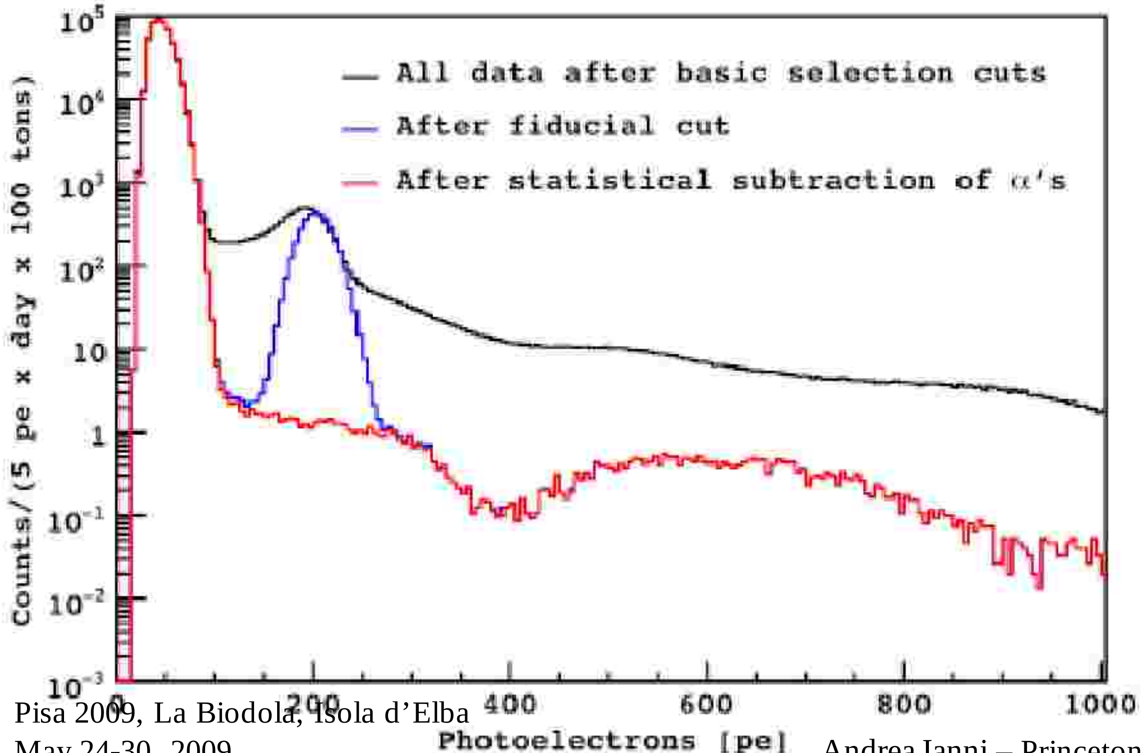
Level achieved

Radioisotope	Typical concentration in equilibrated organic	Design level	Level achieved in Borexino
^{14}C	$^{14}C/^{12}C \sim 10^{-12}$ 10^{10} cpd/ton	$^{14}C/^{12}C \leq 10^{-18}$ 10^{4} cpd/ton	$^{14}C/^{12}C \leq 2.7\times10^{-18}$ 3 x 10^{4} cpd/ton
^{7}Be	2.7x10^{3}cpd/ton	<0.01 cpd/ton	Undetermined
^{238}U	**10^{-6} g-U/g-dust** **10^{3} cpd/ton**	**<10^{-17} g-U(Th)/g-scintillator** **<0.01 cpd/ton**	**< 2 x 10^{-17} g/g** **< 0.02 cpd/ton**
^{232}Th	10^{-5} g-U/g-dust 10^{3} cpd/ton	<10^{-16} g-U(Th)/g-scintillator <0.01 cpd/ton	< 10^{-17} g/g < 0.003 cpd/ton
^{210}Pb	2 x 10^{4} cpd/ton (as ^{210}Bi & ^{210}Po)	<0.01 cpd/ton ^{210}Bi & ^{210}Po	0.15 cpd ^{210}Bi+CNO/ton 60 cpd ^{210}Po/ton
^{40}K	**10^{-6}g-K/g-PPO** **2700 cpd/ton**	**<10^{-14}g-K/g-scintillator** **<0.027 cpd/ton**	**<3x10^{-14} g-K/g-scintillator** **<0.06 cpd/ton**
^{39}Ar	16 mBq/m^{3}-air 218 cpd/ton	<500 nBq/m^{3} – N_2 <0.01 cpd/ton	Undetermined
^{85}Kr	**1 Bq/m^{3}-air** **4.3 x 10^{4} cpd/ton**	**<100 nBq/m^{3}-N_2** **<0.01 cpd/ton**	**<0.35 cpd/ton**

Spectral fit in ~ 192 days

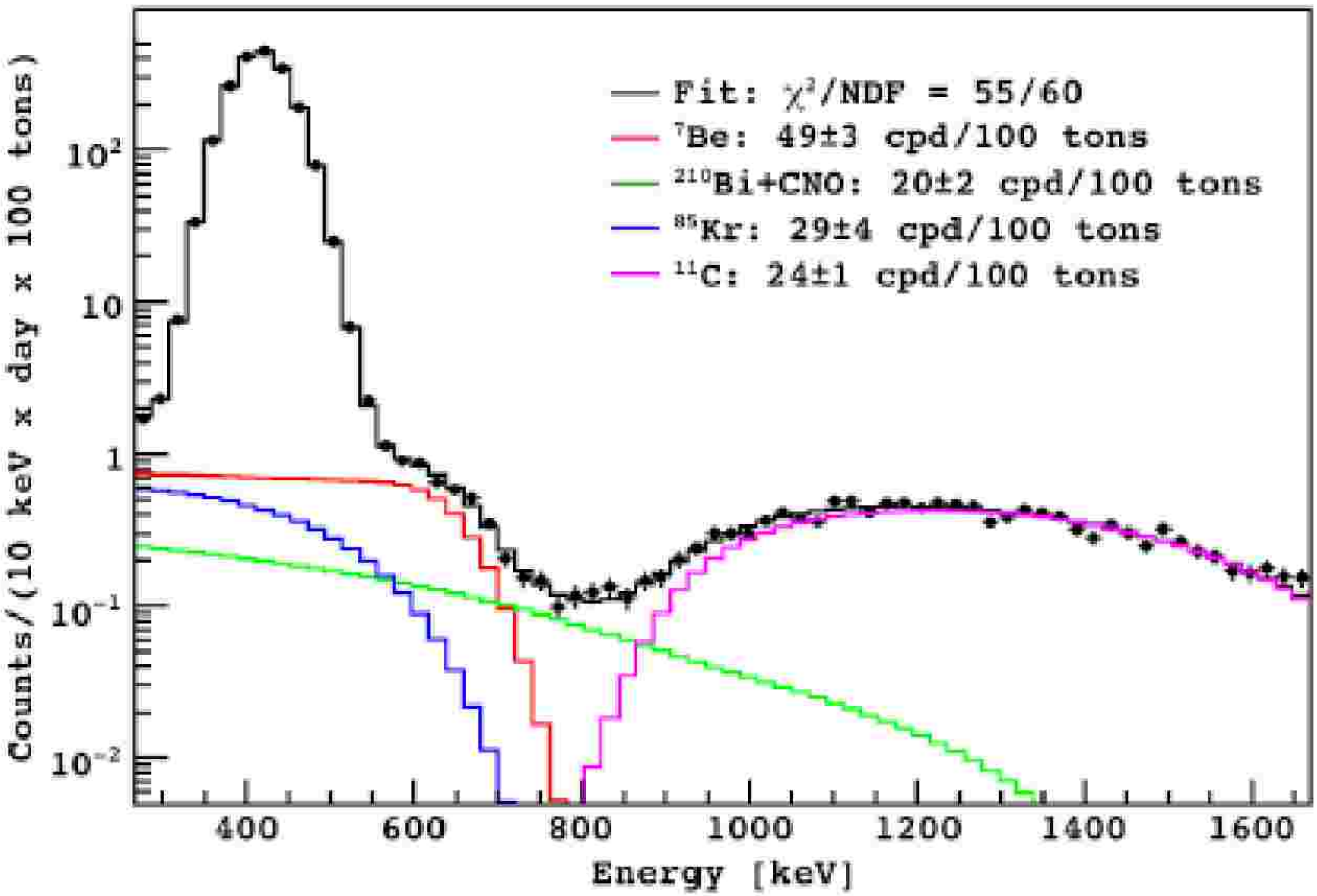
PRL 101, 091302 (2008)

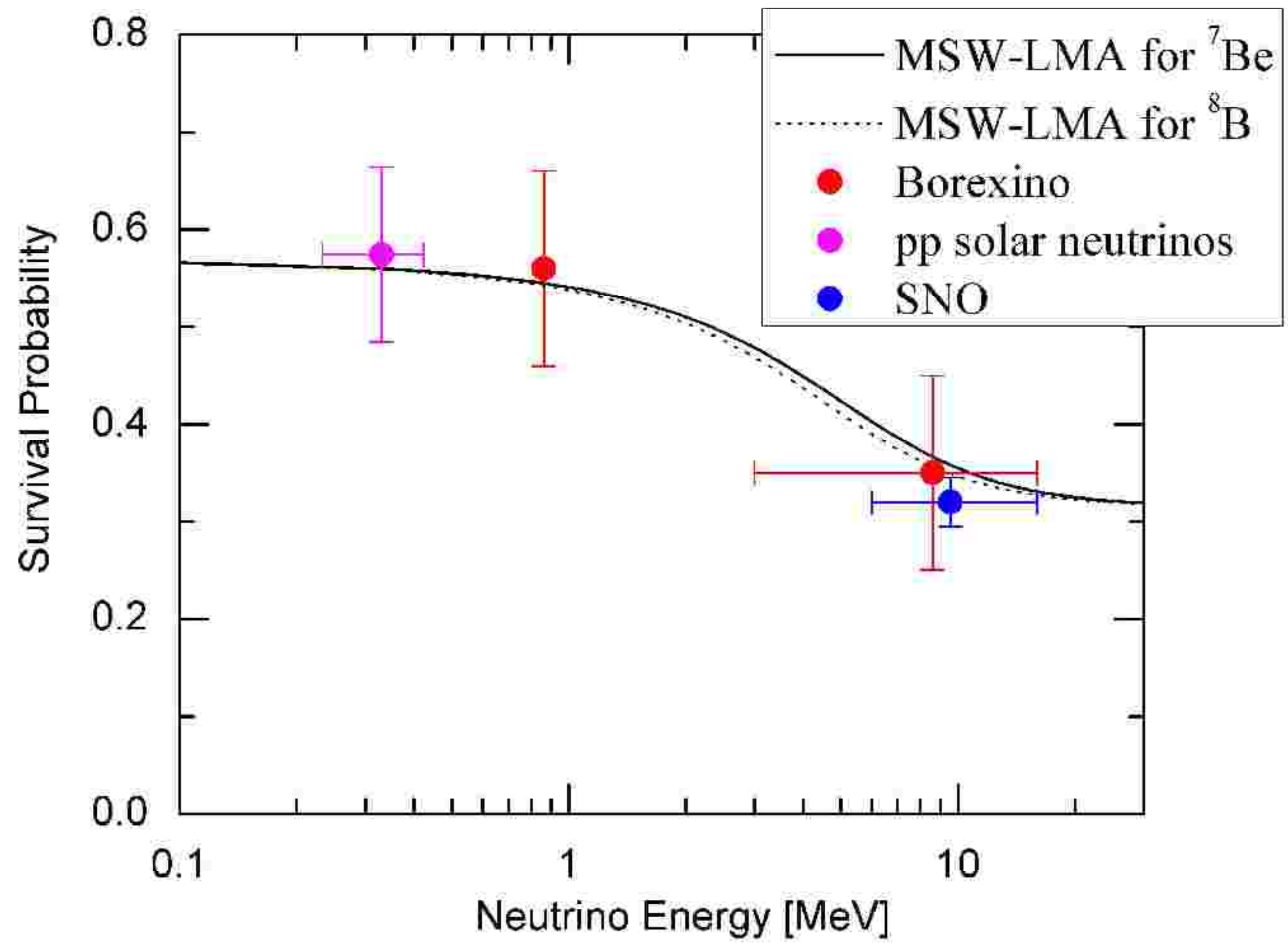




> muons and all events within 2 ms after a muon
> ^{222}Rn daughters subtracted
> Fiducial Volume cut
> a – ß discrimination

BOREXINO: 192 days




0.8
0.6
0.4
0.2
0.0
0.1
1
10
Survival Probability
Neutrino Energy [MeV]
MSW-LMA for ^{7}Be
MSW-LMA for ^{8}B
Borexino
pp solar neutrinos
SNO

Conclusions

- First Real-Time measurement of sub-MeV solar neutrino (^{7}Be).
- Very high level of radiopurity reached (U,Th~10^{-17} g/g).
- Due to the very high radiopurity, Borexino has measured directly the ^{7}Be flux and it is working to measure the other solar ? fluxes: CNO, pep, ^{8}B from 2.5 MeV, and perhaps pp.
- In this way it is possible to probe the ? oscillation model in the vacuum and in the transition region.
- Performed calibration on-axis and off-axis to reduce systematic error on fiducial volume and energy scale.
- Calibration sources: ^{222}Rn, ^{14}C, ^{85}Sr, ^{54}Mn, Am-Be.
- Next goal: measure ^{7}Be at 5%.
- Further purification campaign to remove Kr and improve sensitivity in CNO region.
- Geoneutrino measurement in progress.

Borexino Collaboration

France
- **APC_ Paris**

Germany
- **Max-Planck Institute fuer Kernphysik _ Heidelberg**
- **Technische Universitaet _ Muenchen**

Italy
- **INFN Laboratori del Gran Sasso-Assergi**
- **INFN e Dipartimento di Fisica dell'Universita'_ Genova**
- **INFN e Dipartimento di Fisica dell'Universita'_ Milano**
- **INFN e Dipartimento di Chimica dell'Universita' _ Perugia**

Poland
- **Institute of Physics, Jagellonian University _ Cracow**

Russia
- **JINR _Dubna**
- **Institute for Nuclear Research_Gatchina**
- **Kurchatov Institute _Moscow**
- **University of Moscow_Moscow**

USA
- **Princeton University _ Princeton**
- **Virginia Tech,_Blacksburg**