Instrumented shielding detectors as general infrastructure in Deep Underground Laboratories: the example of Borexino and DarkSide-50

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Borexino and its shielding veto : general features

- ✓ Borexino @ LNGS paradigmatic example of the need of an effective vetoing system against cosmic radiation for underground rare events search

- ✓ 278 t liquid-scintillator detector designed for real-time measurements of low energy (<20 MeV) neutrinos: solar neutrinos and geo-neutrinos

- ✓ Unprecedented challenge and achievements : the extremely low background in the scintillator target → careful pre-selection of detector materials and extensive purification of the organic scintillator

- ✓ **Shielding from external, and especially cosmic, radiation is of comparable importance**

- ✓ Detector located deep underground (3800 meters of water equivalent, m. w.e.) in the Hall C of the Laboratori Nazionali del Gran Sasso (LNGS, Italy) → the cosmic muon flux suppressed by about six orders of magnitude

Other general considerations

Large factor but not enough : residual muons still an important source of background for neutrino detection

- muon signals themselves can under certain circumstances appear as ν signal
- neutrons or radioactive isotopes by spallation reactions in target materials, e.g. ^{12}C, which also can produce signals which mimic the observation of a reaction of interest

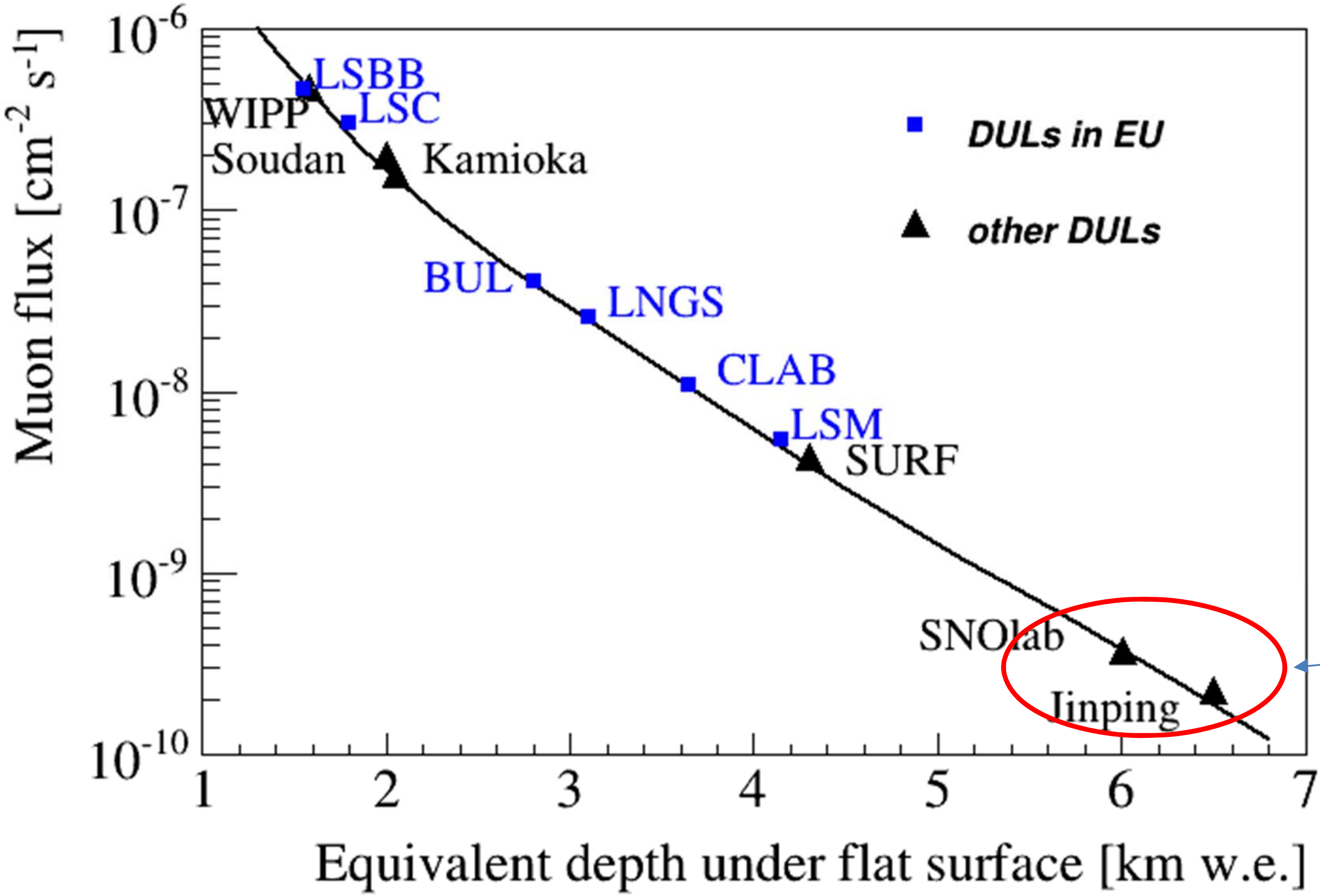
In general understanding and mitigation of muon-induced backgrounds of great relevance to all investigations of rare processes carried out in underground Laboratories

In direct dark matter searches → neutron interactions with signature very similar to those induced by WIMPs - careful shielding and vetoing must be employed

In 0ββ decay experiments decays of long-lived cosmogenic radioisotopes produced in-situ can be significant background components

It is expected that cosmogenic backgrounds will be even more important in the next generation of low-background experiments as the detector sizes and sensitivities are increasing - thus sophisticated muon vetoes as well as extensive shielding will be mandatory

Muon flux and equivalent depth of the worldwide underground laboratories

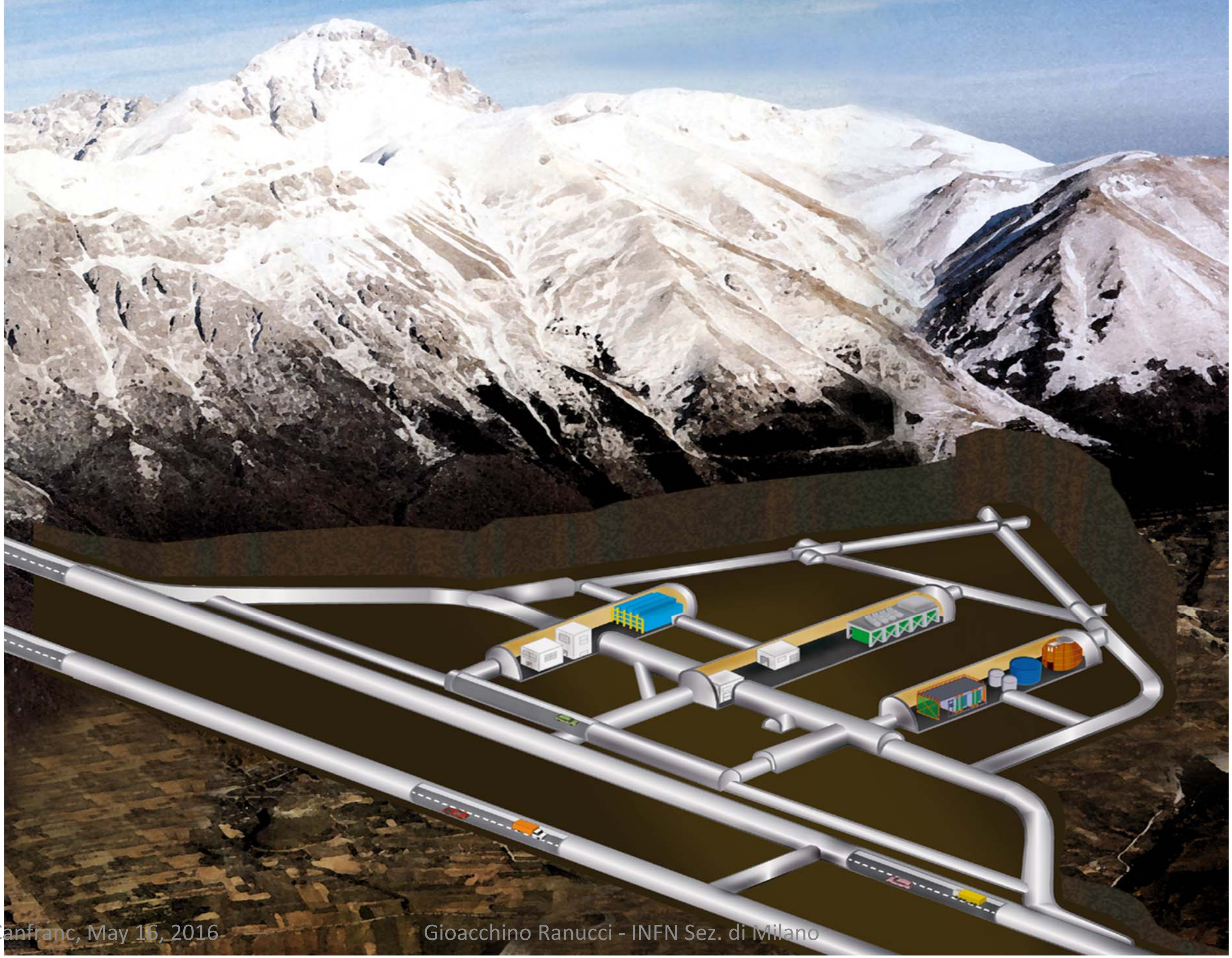


Plot from the Director

Our competing friends in Canada and China

Effective shielding strategies will allow a successful future scientific program of the European Laboratories even at shallow depths than that of SNOLAB and Jinping

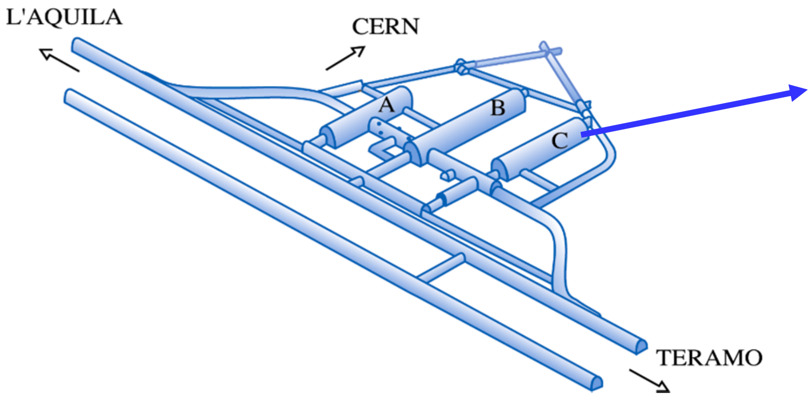
Laboratori Nazionali del Gran Sasso

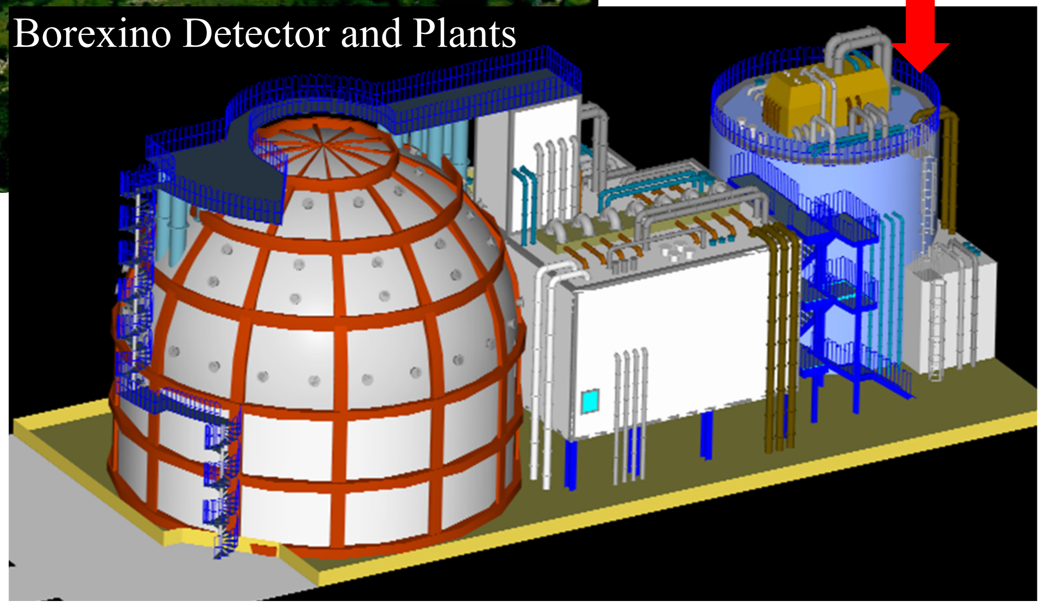


Laboratori
Nazionali del
Gran Sasso

Assergi (AQ)
Italy
~3800 m.w.e

DarkSide-50
within CTF





Borexino at Gran Sasso: low energy real time detection

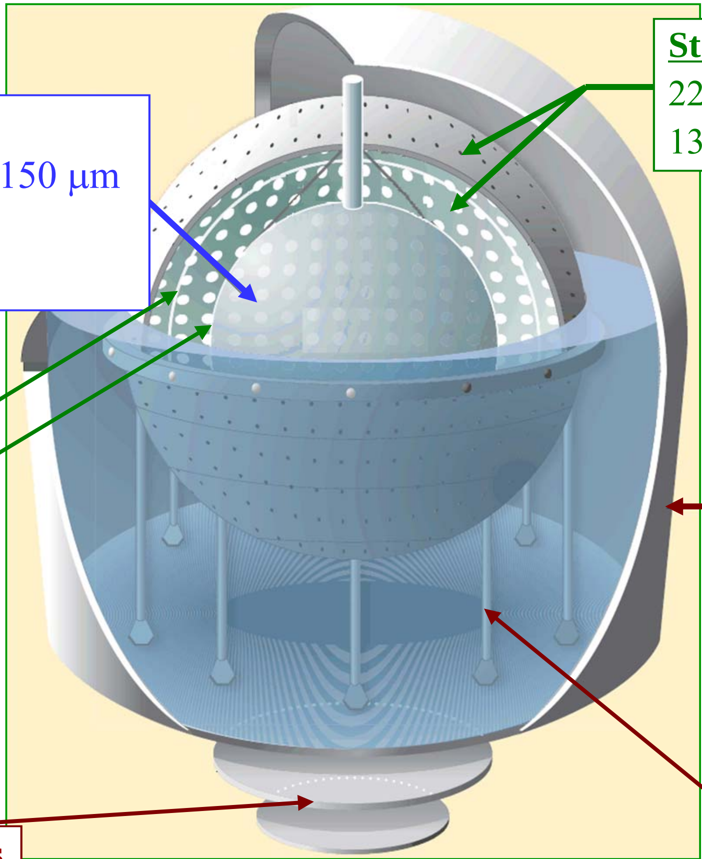
Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel
Nominal FV 100 t

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Neutrino electron scattering

ν e –> ν e

Carbon steel plates

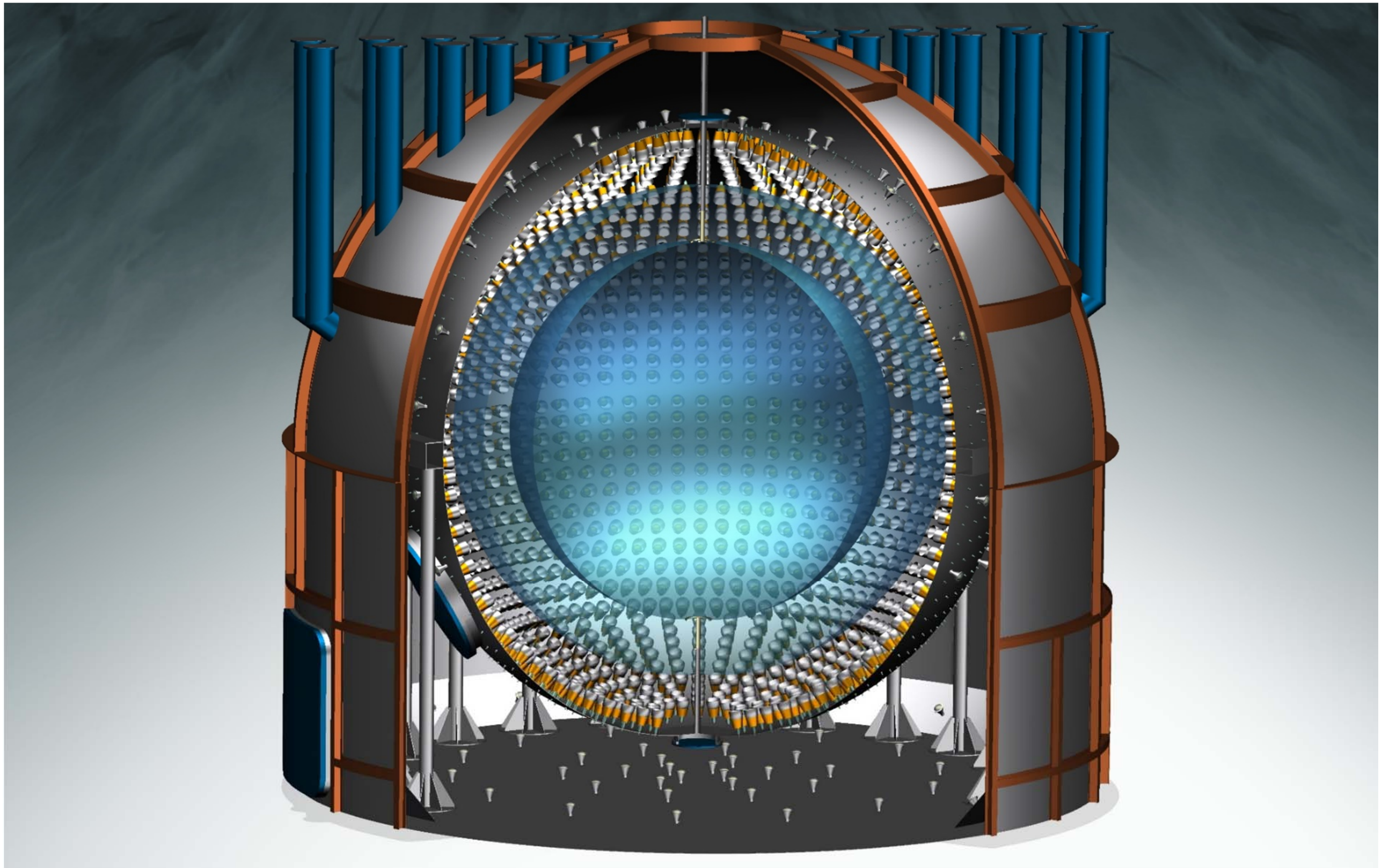


Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Design based on the principle of graded shielding

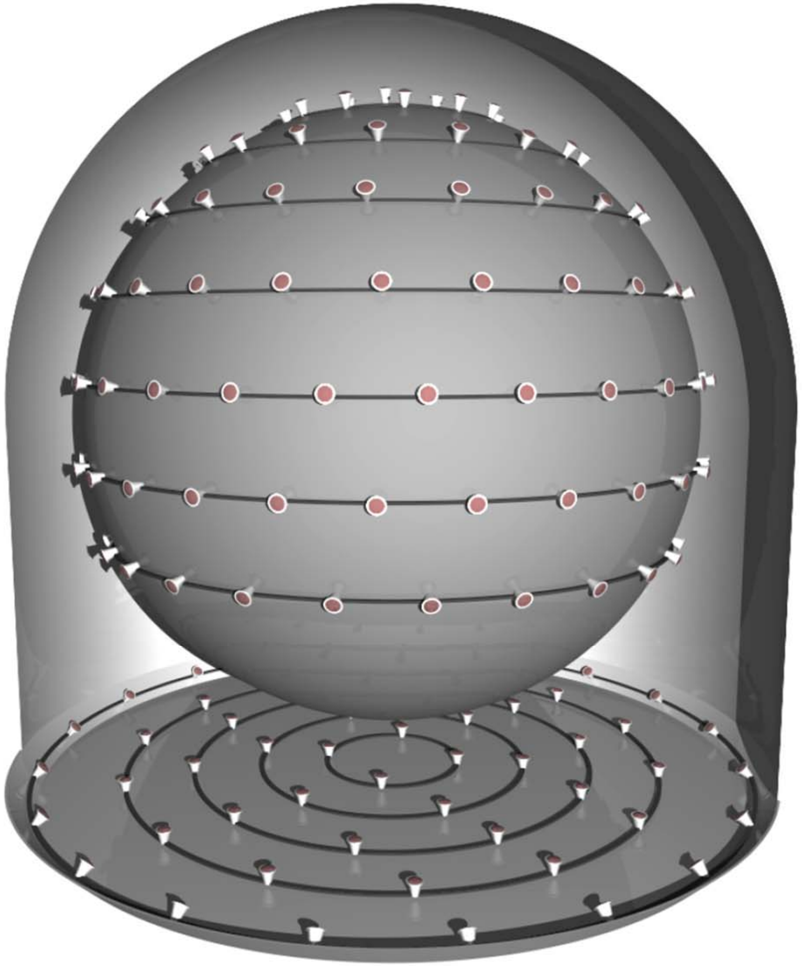
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

20 legs



Veto PMT's on middle/top part of the sphere and on the floor

Precise map of the veto PMTs



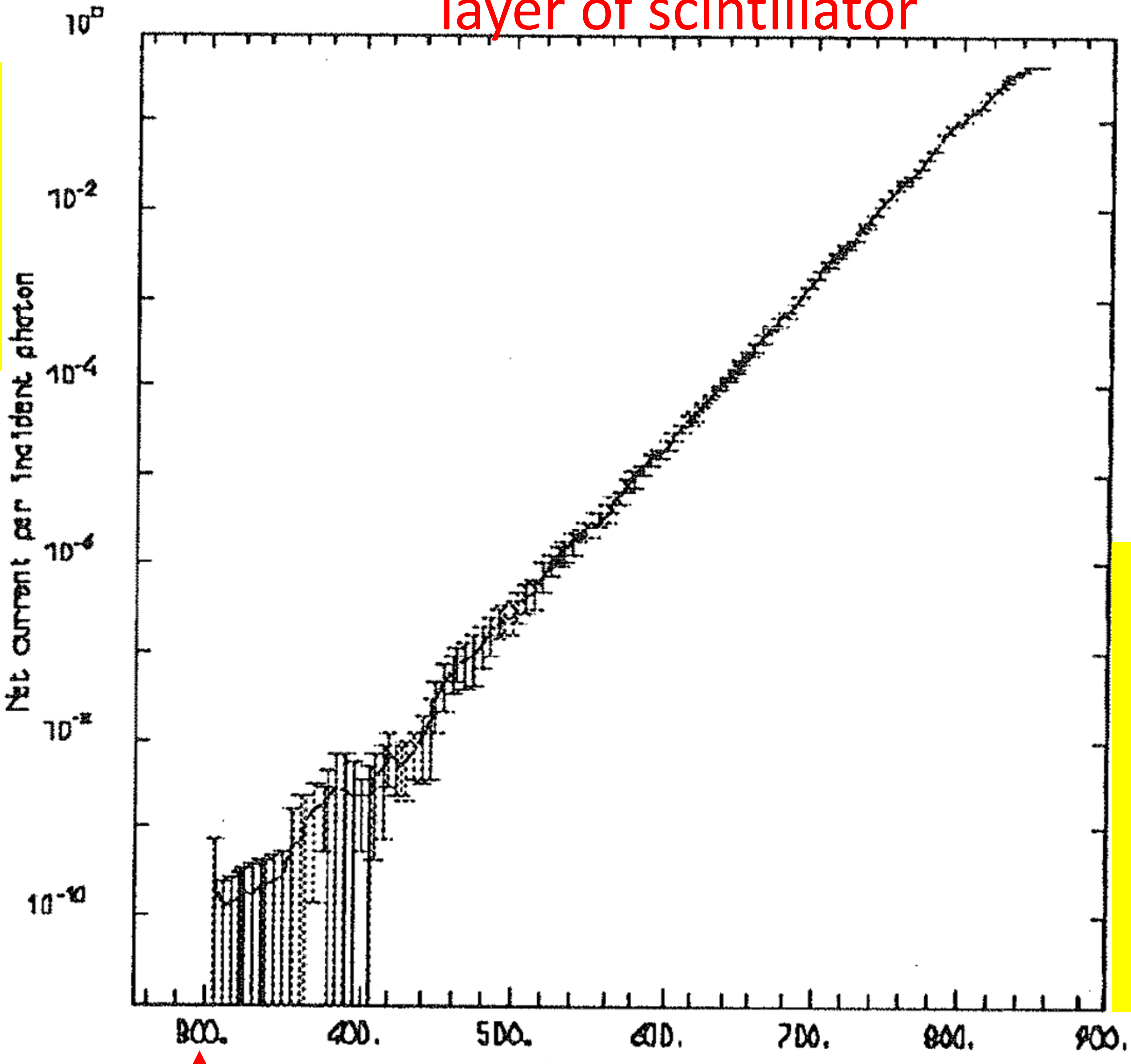
Ring	Position	z [m]	# of PMTs
+6	SSS-UH	+7.0	4
+5	SSS-UH	+6.6	12
+4	SSS-UH	+5.6	17
+3	SSS-UH	+4.4	21
+2	SSS-UH	+2.7	24
+1	SSS-UH	+0.9	26
−1	SSS-LH	−1.0	26
−2	SSS-LH	−2.8	24
−3	45°-slope	−6.8	20
−4	floor	−7.6	14
−5	floor	−7.6	10
−6	floor	−7.6	6
−7	floor	−7.6	4

Careful MC determination of the PMTs arrangement in the design phase

Shielding performances of the Water Buffer plus external layer of scintillator

The water acts as shield against the gammas and neutrons from the rock

Extremely purified water
Also degassed from Radon



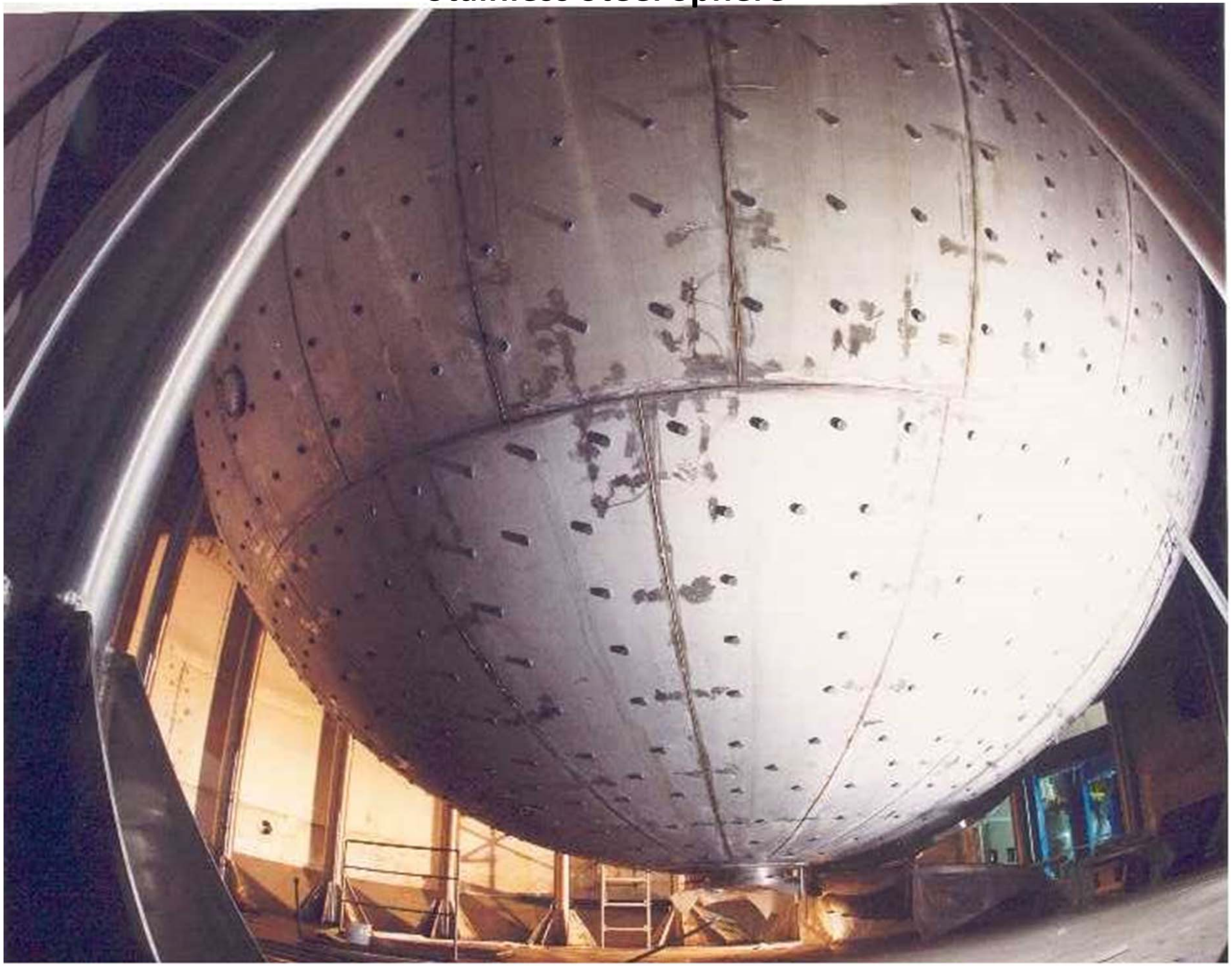
Boundary of the fiducial volume

Attenuation of high energy gamma rays from the rock << 1 ev/day in the fiducial volume

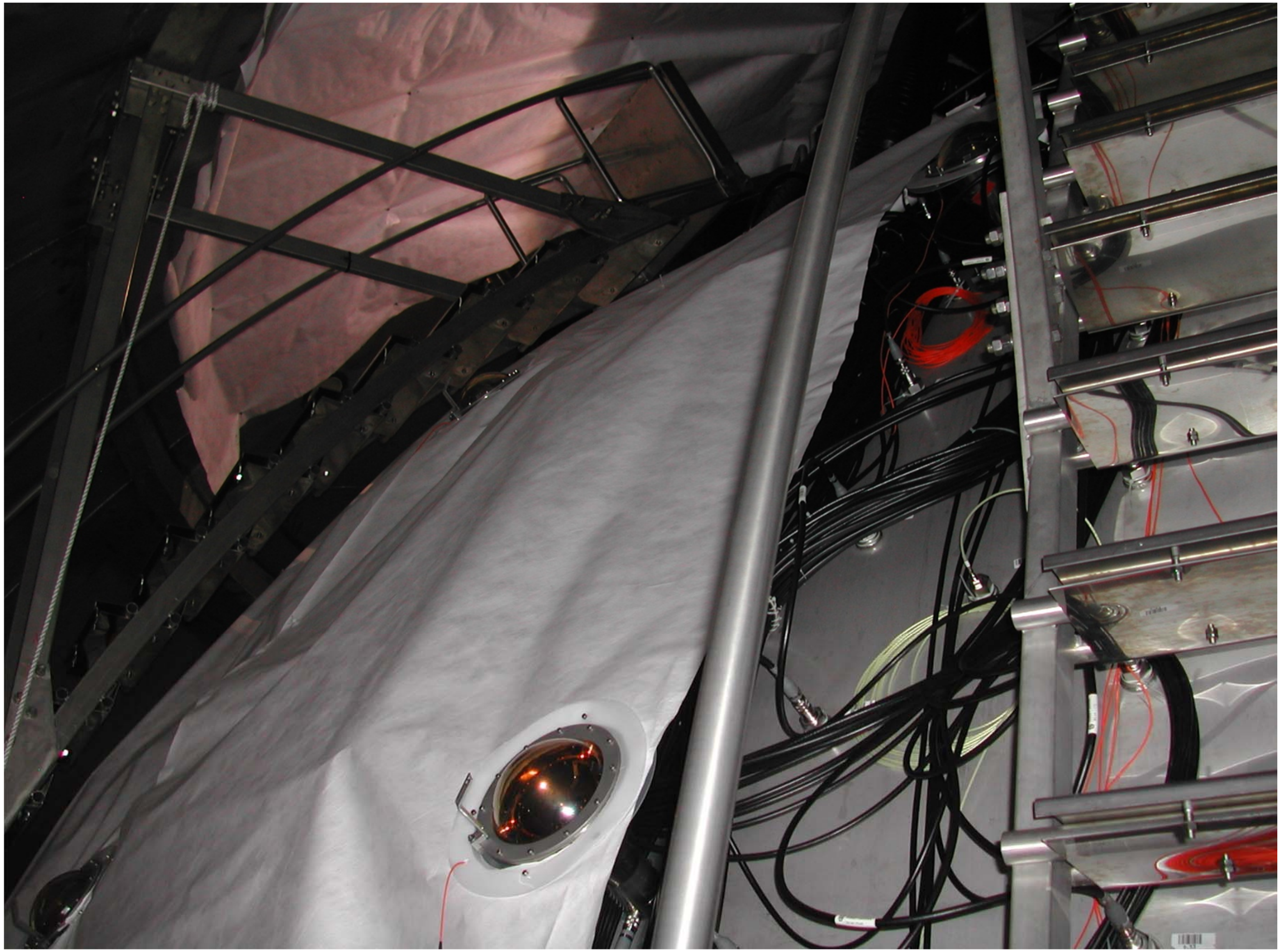
External Water Tank

Height 18 m
Diameter 20 m

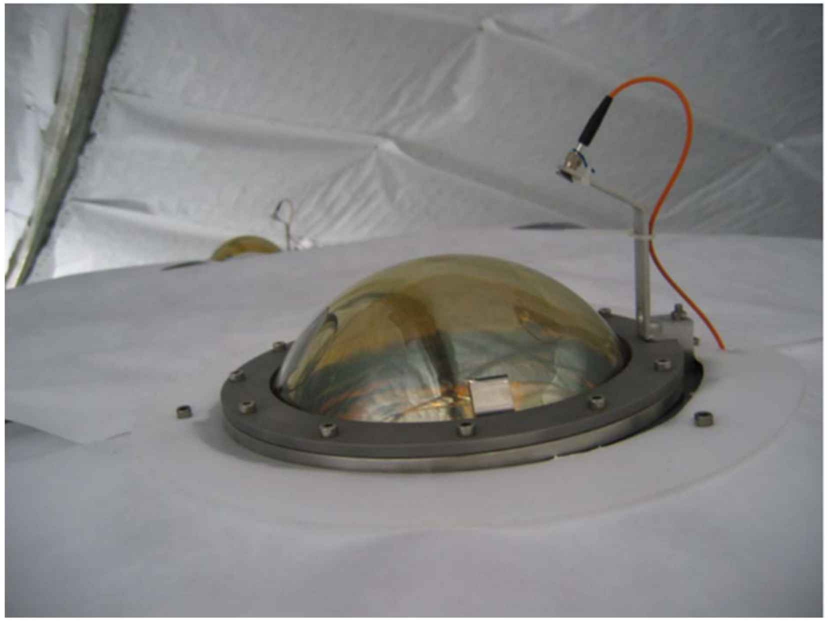
Stainless Steel Sphere



Detail of the muon veto during the installation



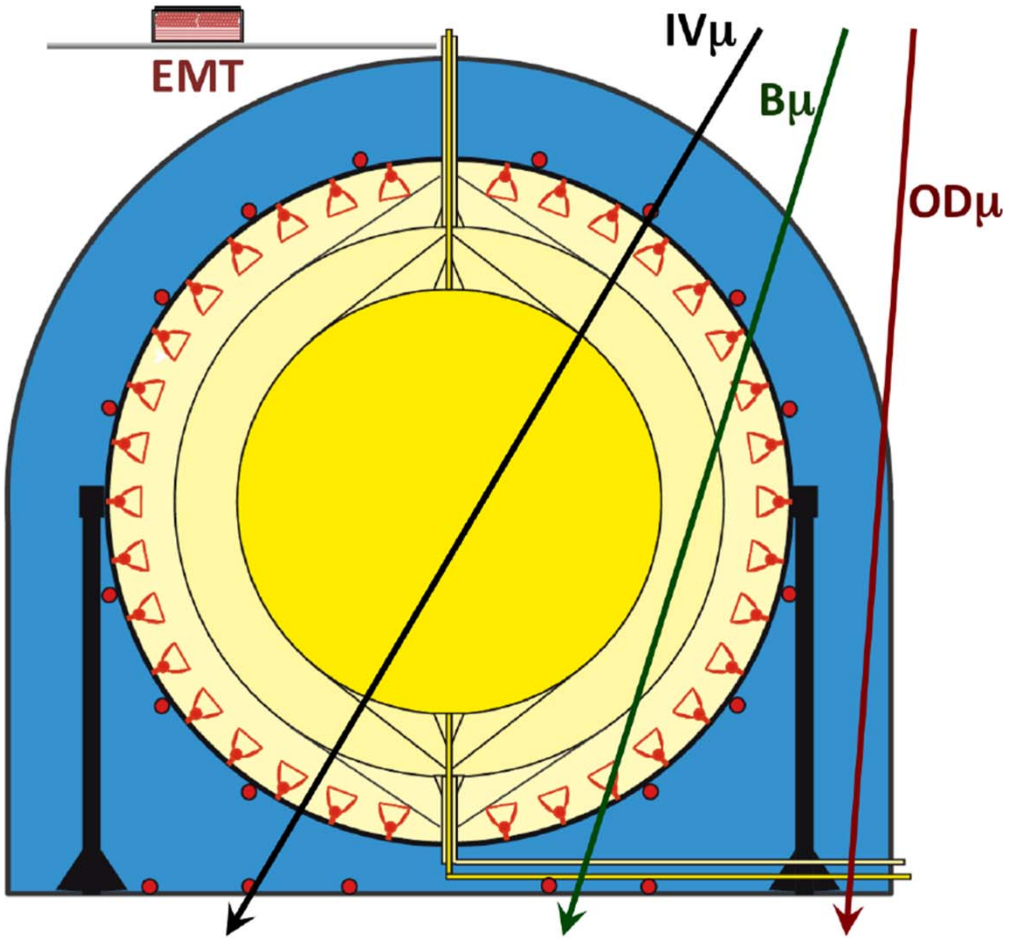
Tyvek and PMTs



Light diffusion to enhance the photoelectron yield

Categories of muons with respect to the detector

Inner detector ID
Outer detector OD



Mons crossing the inner vessel IVμ
Buffer muons Bμ
Muons only traversing water ODμ

External Muon Tracker to select a reference sample of muons

Muon Induced Background at Borexino

- Cosmic radiation produces $\pi^{\pm}$ and $\mathrm{K}^{\pm}$ that decay in flight via

$$\mathrm{K}^{\pm}, \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

- Residual muon flux $1.2\,\mathrm{m}^{-2}\mathrm{h}^{-1}$ with $\langle E \rangle \sim 270\,\mathrm{GeV}$ at LNGS compared to $180\,\mathrm{cm}^{-2}\mathrm{h}^{-1}$ and $1\,\mathrm{GeV}$ at surface

Muon Induced Background at Borexino

Direct Background

- Muons crossing IV: No background for neutrino analyses
- Buffer muons important

Indirect Background

- Cosmic radionuclides produced in spallation processes on $^{12}\mathrm{C}$ and neutrons
- Background suppression relies on very efficient muon identification

Muon Detection at Borexino

- Two OD tags
- Muon Trigger Board (MTF)
  Hardware tag
  $\geq$ 6 OD PMT hits within 150 ns
- Muon Clustering (MCF)
  Software tag

  $\geq$ 4 OD PMT hits on at least SSS or floor
  within 150 ns

Muon Detection at Borexino

- ID tag
  Pulse Shape Discrimination (IDF)

  → peak-, mean time & Gatti parameter to discriminate between μ and point-like events

Number of Hits	Mean Time t_{m}	Peak Time t_{p}	Pulse Shape Gatti Parameter g
100 – 900	×	>40 ns	>0.2 (if z>4 m)
900 – 2100	×	>30 ns	×
> 2100	>100 ns	×	<0.55

Pulse shape discrimination in practice

Muon identification efficiency

Two approaches for efficiency evaluation

- ✓ samples of muon events selected independently of any tagging flag used to find directly the identification efficiencies

  Direct OD flags efficiency via high energy ID events - events with more than 7000 hits

  Direct ID flag efficiency via CNGS (CERN to LNGS beam) muon events

- ✓ each flag tested against a muon sample selected by either of the remaining two flags

Numerical efficiencies

Tag	E_{vis} [hits]	Direct Efficiencies vs. High E	Direct Efficiencies vs. CNGS	Mutual Efficiencies vs. IDF	Mutual Efficiencies vs. MTF	Mutual Efficiencies vs. MCF
ε_{IDF}	$\geq$80	X	$0.9586^{(24)}_{(25)}$	X	0.9890(1)	0.9891(1)
ε_{MTF}	$\geq$80	0.9925(2)	X	0.9933(1)	X	0.9997
ε_{MCF}	$\geq$80	0.9928(2)	X	0.9935(1)	0.9997	X
ε_{IDF}	80-110	X	$0.1315^{(529)}_{(423)}$	X	$0.1325^{(108)}_{(103)}$	$0.1355^{(111)}_{(105)}$
	110-500	X	$0.5500^{(244)}_{(246)}$	X	0.7188(37)	0.7211(37)
	500-7k	X	$0.9912^{(15)}_{(17)}$	X	0.9962(1)	0.9963(1)
	$\geq$7k	X	$1.0000_{(4)}$	X	1.0000	1.0000

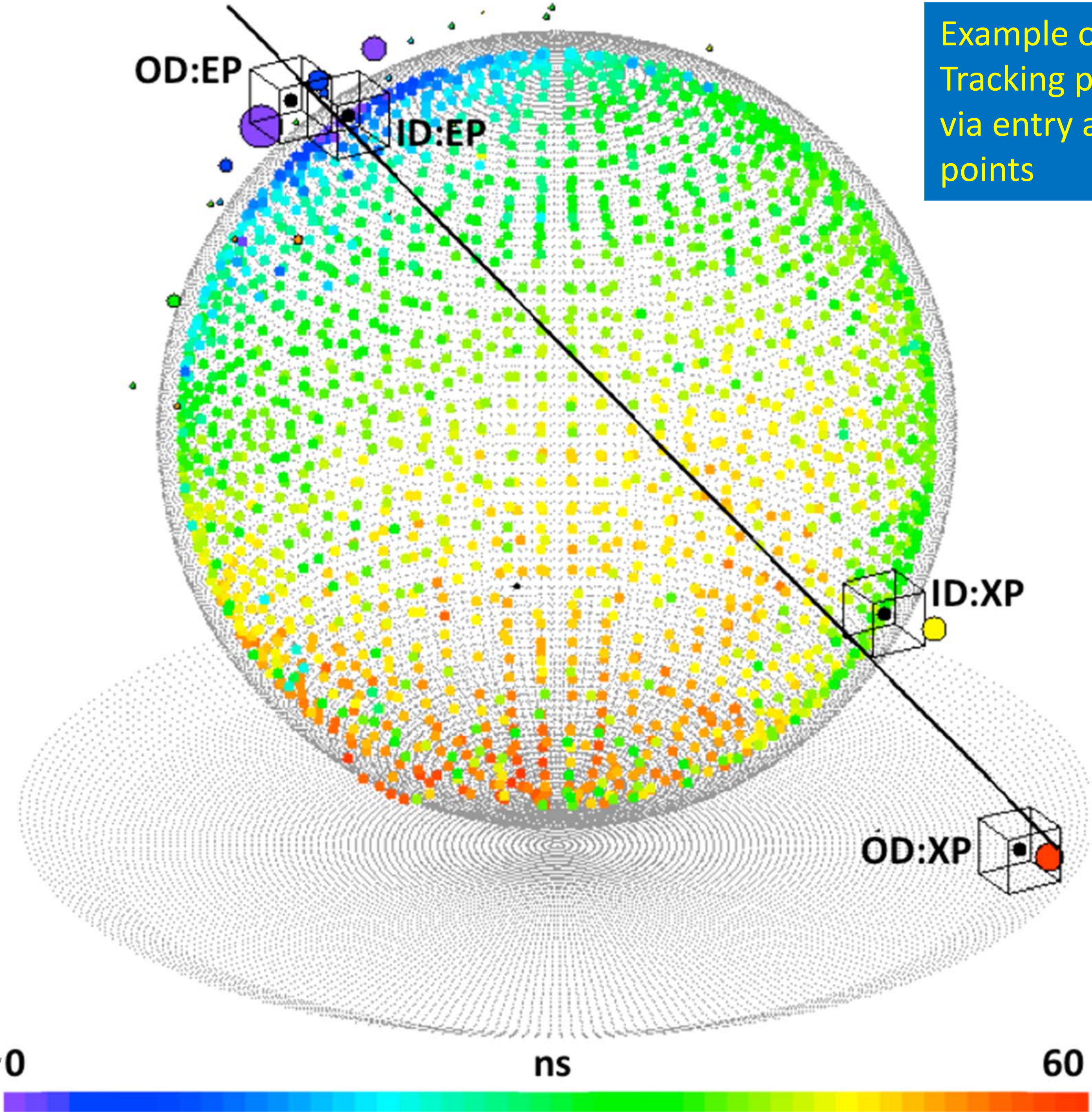
The muon veto efficiency from the application of the combined tags is better than 99.992 % design value

arXiv:1101.3101

MUON TRACK

- Three tracking algorithms:
- OD tracking based on OD position reconstruction, only available for tracks crossing the ID as well
- ID tracking based on ID hit time data
- Global tracking combining OD and ID tracking information

Example of a track
Tracking performed
via entry and exit
points



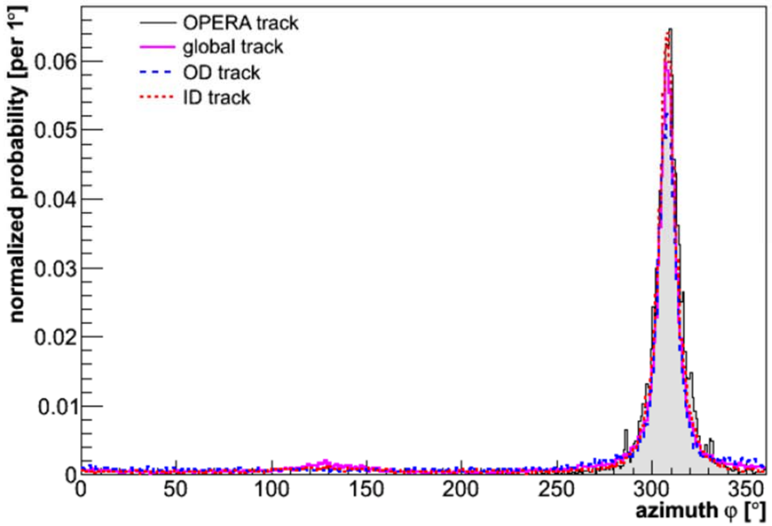
Precision and accuracy of muon tracking

- Via CNGS muon events generated in the rock upstream of the Borexino detector and crossing both Borexino and OPERA

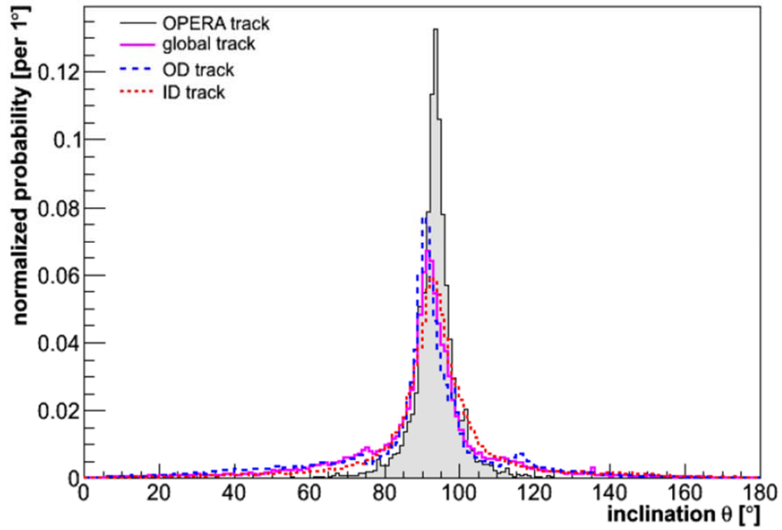
- Events selected through the External Muon Tracker (EMT)

- Comparison with previous MACRO results on cosmic muons

Angular distributions of muons produced by the CNGS ν_μ beam



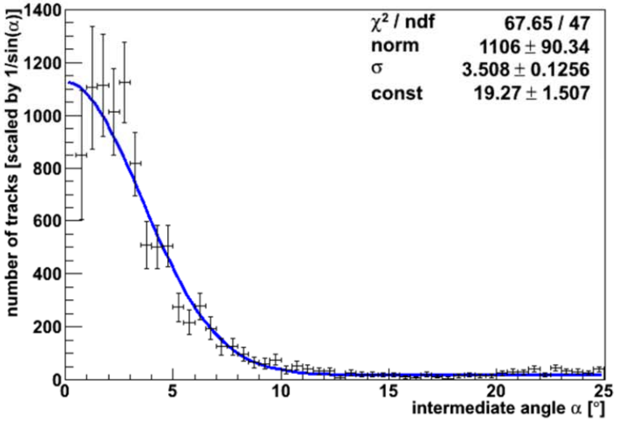
Azimuth



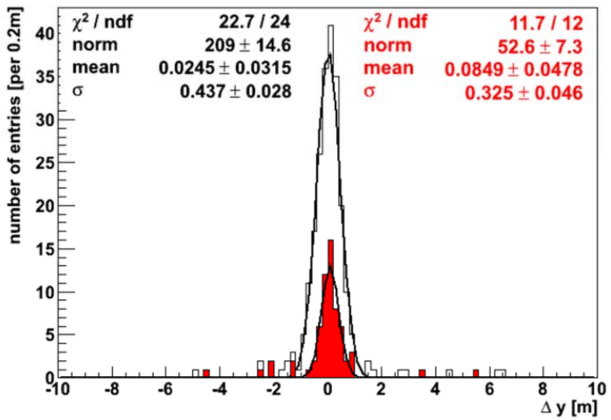
Inclination

tracks in Borexino are required to cross both ID and OD
the distributions reconstructed by OPERA are shown for comparison – grey area
Very good match

Angular and lateral resolution obtained from CNGS muon tracks
OPERA assumed as reference



Angle between the directions reconstructed in OPERA and Borexino



Y-distance between reconstructed tracks in Borexino yz plane , comparing OPERA and Borexino

Exploitation of the OD only

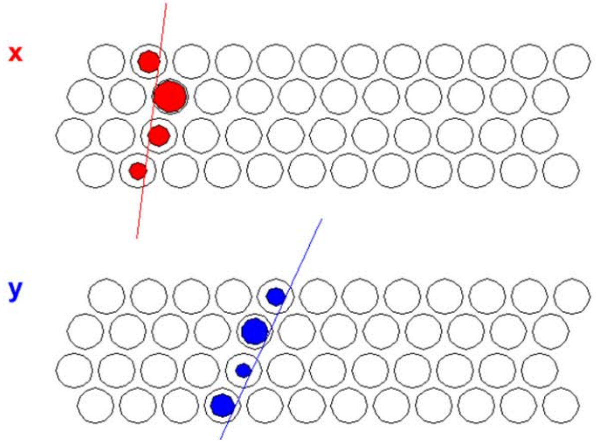
Overall muon tracking capability from CNGS muon tracks

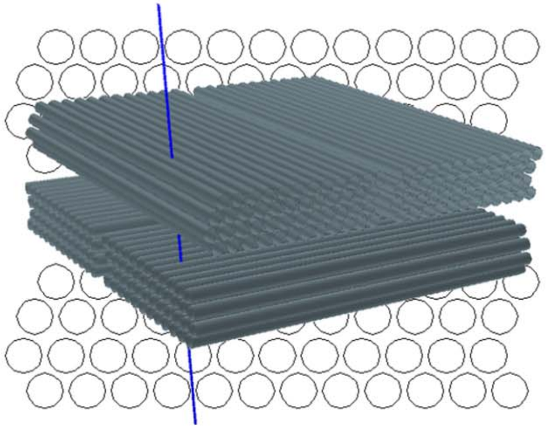
IDμ's	σ_α [°]	σ_y [cm]	σ_z [cm]
OD tracking	3.51±0.13	53±4	198±13
ID tracking	5.13±0.25	42±3	40±5
global tracking	2.83±0.13	44±3	87±12

IVμ's	σ_α [°]	σ_y [cm]	σ_z [cm]
OD tracking	3.01±0.15	28±7	45±7
ID tracking	2.44±0.19	36±5	31±6
global tracking	2.31±0.13	33±5	35±7

Very good performance considering that a scintillator detector is surely not optimized for tracking

Tracking capability cross check with the External Muon Tracker

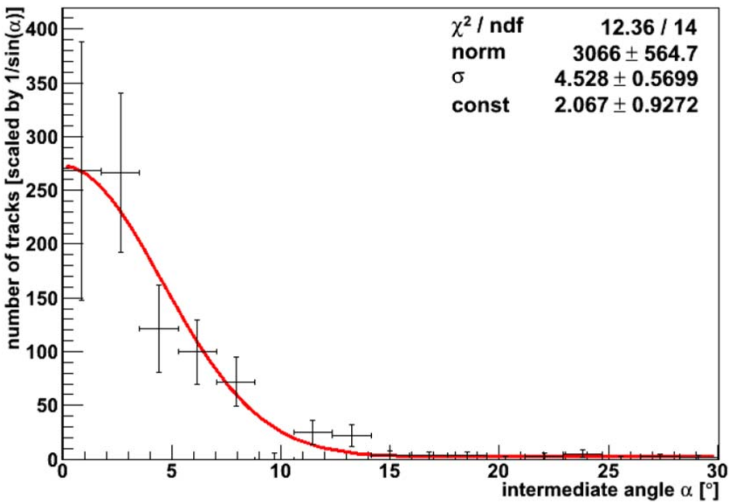




Layers of drift tubes

originally developed as OPERA prototype

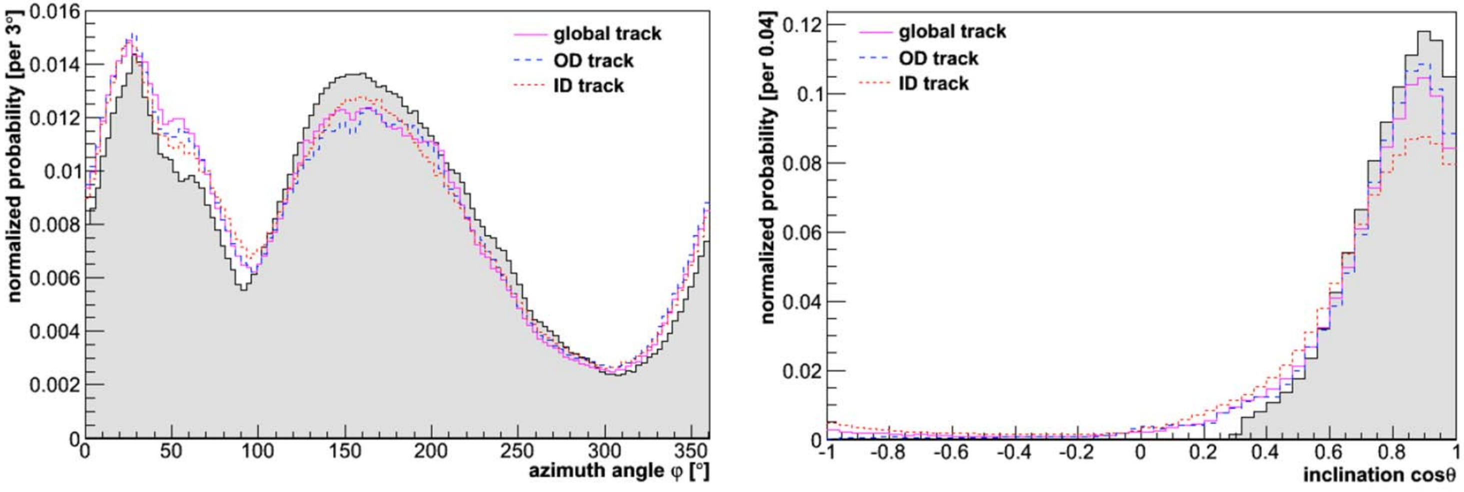
From the observed drift times track projections in the yz- and xz-plane



	σ_α [°]	N
OD tracking	3.9±0.3	125
ID tracking	4.5±0.6	82
global tracking	3.4±0.1	125

In spite of the low statistics the obtained angular resolution is comparable to the CNGS results

Third check - MACRO



Azimuth and inclination distributions for cosmic muon tracks detected at the LNGS – comparison of the three Borexino tracking modules with the results of MACRO grey area

- The distributions reflect the influence of the local mountain topology
- The differences in the thickness of the overlaying rock are imprinted as angle-dependent variations in the residual muon flux
- Globally good tracking features for a scintillator detector inherently not optimized for this property

Study of cosmogenic isotopes and neutrons

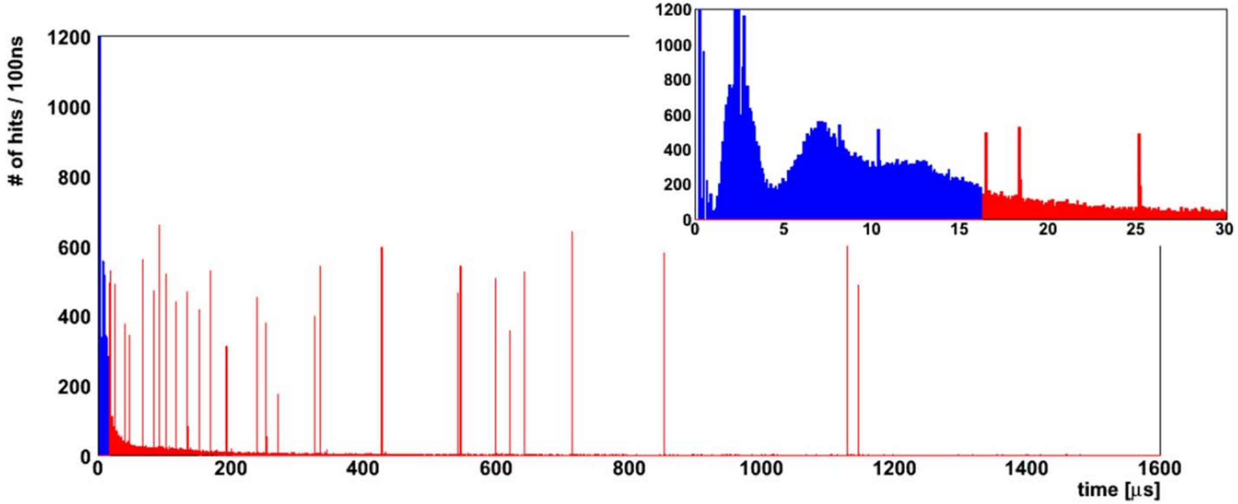
Muon identification and vetoing capability used for

Careful understanding of the potential backgrounds

Precise definition of the cut strategy

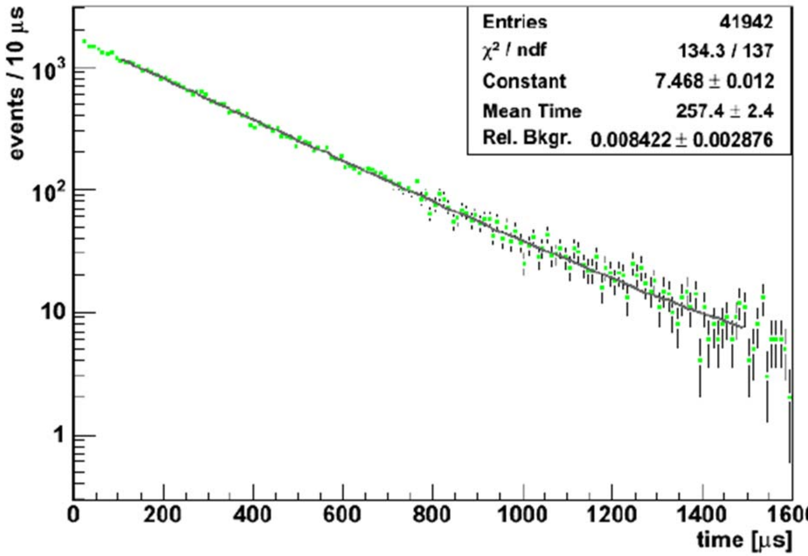
arXiv:1304.7381

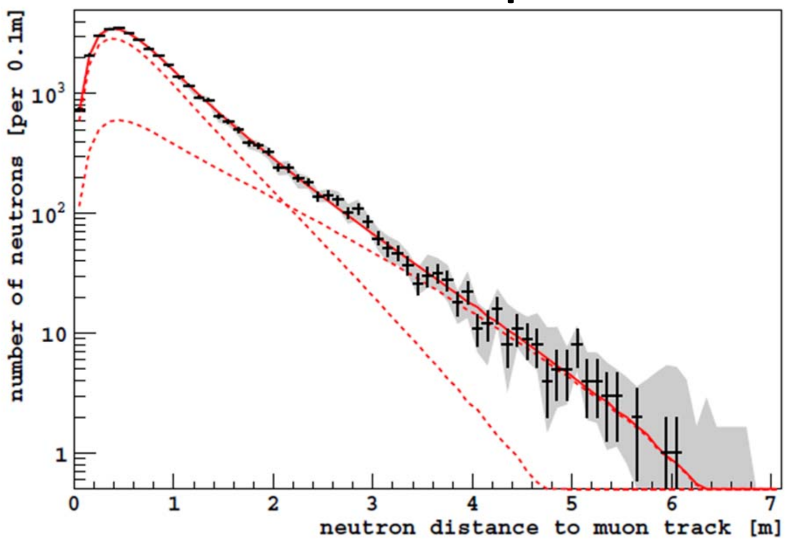
Neutrons



Example of many neutrons after a muon

Muon-neutron lateral distance – important to define spatial associations





Neutron capture time 257.4 +/- 2.4 μs

List of cosmogenic isotopes

Cosmogenic Isotope	Lifetime	Q-Value [MeV]	Decay Type	Cosmogenic Isotope	Lifetime	Q-Value [MeV]	Decay Type
^{12}**N**	15.9 ms	17.3	β^-	^{6}**He**	1.16 s	3.51	β^-
^{12}**B**	29.1 ms	13.4	β^+	^{8}**Li**	1.21 s	16.0	β^-
^{8}**He**	171.7 ms	10.7	β^-	^{11}**Be**	19.9 s	11.5	β^-
^{9}**C**	182.5 ms	16.5	β^+	^{10}**C**	27.8 s	3.65	β^+
^{9}**Li**	257.2 ms	13.6	β^-	^{11}**C**	29.4 min	1.98	β^+
^{8}**B**	1.11 s	18.0	β^+				

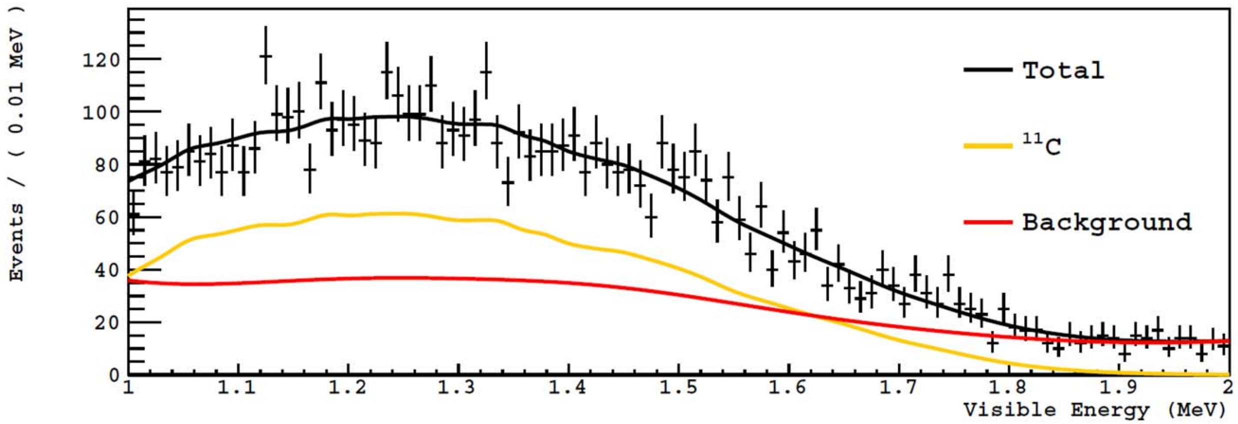
^{9}Li/^{8}He relevant for geoneutrino study

The more relevant isotopes as solar neutrino background for the pep and CNO fluxes

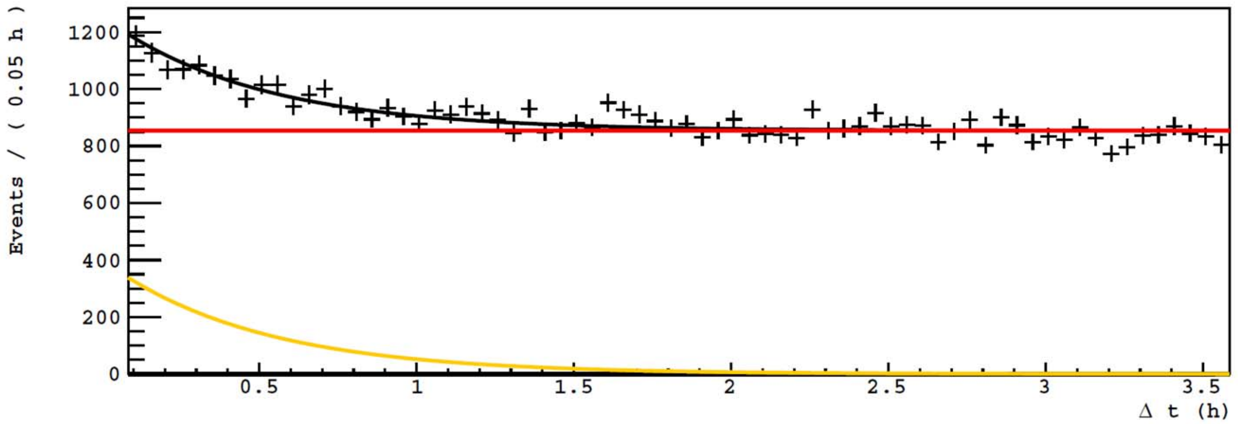
Extensively studied through proper time spatial and energy selections

Example - ^{11}C detection

Threefold coincidence selection: $\Delta t \in [0:1; 3:6]$ h and a distance of 1m to a preceding μn - coincidence



Energy distribution



Time distribution

Both consistent with the properties of ^{11}C

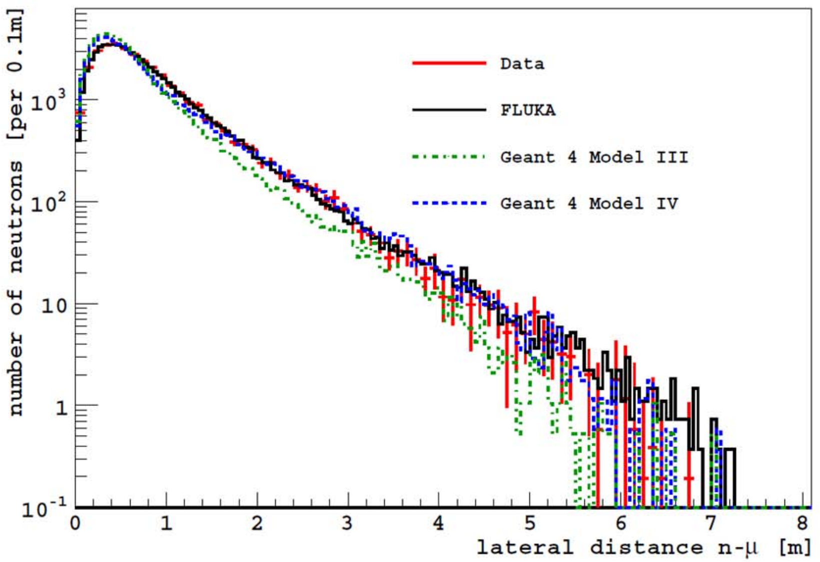
MC and KamLAND comparisons

	GEANT4 Model III	GEANT4 Model IV	FLUKA	Borexino	KamLAND
	— $\langle E_\mu \rangle = 283 \pm 19$ GeV —				$\langle E_\mu \rangle = 260 \pm 8$ GeV
Isotopes	Yield $[10^{-7}\,(\mu\,g/cm^2)^{-1}]$				
^{12}**N**	1.11 ± 0.13	3.0 ± 0.2	0.5 ± 0.2	< 1.1	1.8 ± 0.4
^{12}**B**	30.1 ± 0.7	29.7 ± 0.7	28.8 ± 1.9	56 ± 3	42.9 ± 3.3
^{8}**He**	< 0.04	0.18 ± 0.05	0.30 ± 0.15	< 1.5	0.7 ± 0.4
^{9}**Li**	0.6 ± 0.1	1.68 ± 0.16	3.1 ± 0.4	2.9 ± 0.3	2.2 ± 0.2
^{8}**B**	0.52 ± 0.09	1.44 ± 0.15	6.6 ± 0.6	14 ± 6	8.4 ± 2.4
^{6}**He**	18.5 ± 0.5	8.9 ± 0.4	17.3 ± 1.1	38 ± 15	not reported
^{8}**Li**	27.7 ± 0.7	7.8 ± 0.4	28.8 ± 1.0	7 ± 7	12.2 ± 2.6
^{9}**C**	0.16 ± 0.05	0.99 ± 0.13	0.91 ± 0.10	< 16	3.0 ± 1.2
^{11}**Be**	0.24 ± 0.06	0.45 ± 0.09	0.59 ± 0.12	< 7.0	1.1 ± 0.2
^{10}**C**	15.0 ± 0.5	41.1 ± 0.8	14.1 ± 0.7	18 ± 5	16.5 ± 1.9
^{11}**C**	315 ± 2	415 ± 3	467 ± 23	886 ± 115	866 ± 153
Neutrons	Yield $[10^{-4}\,(\mu\,g/cm^2)^{-1}]$				
	3.01 ± 0.05	2.99 ± 0.03	2.46 ± 0.12	3.10 ± 0.11	2.79 ± 0.31

Expected 10 to 20 % difference between KamLAND and Borexino →production yields depend on the number of carbon atoms per weight and the muon energy spectrum – different depth

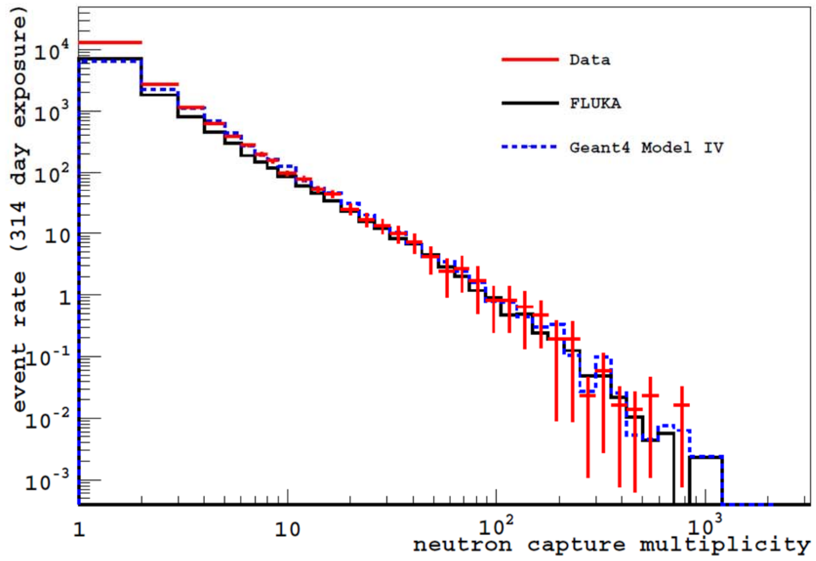
On ^{11}C the most notable data MC-discrepancy

Neutrons spatial distribution and multiplicity vs MC

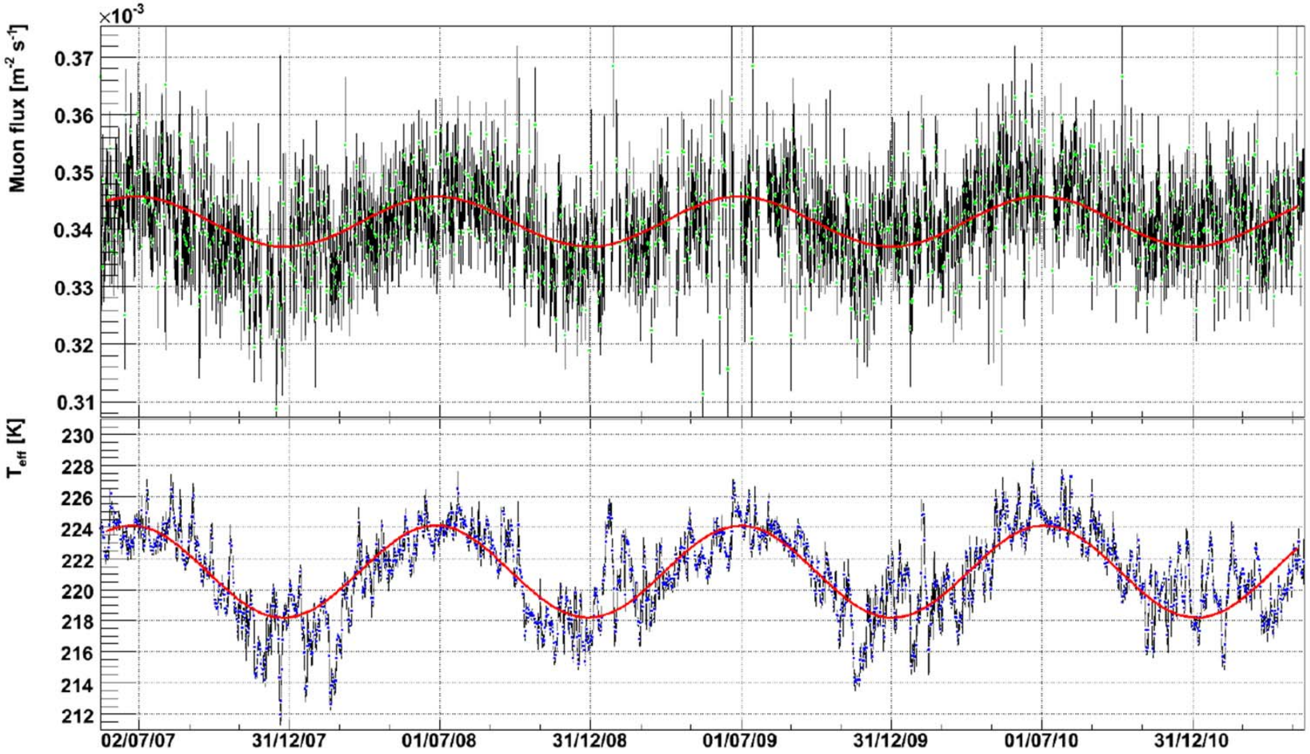


Globally a satisfactory agreement with the predictions

Total yield however different
67 ±1 measured against around 40 predicted



Muon flux variation



Muon flux vs time

Effective Atmospheric temperature

Average muon rate $(4310 \pm 2_{stat} \pm 10_{syst})\ d^{-1} \rightarrow (3.41 \pm 0.01)\ 10^{-4} m^{-2} s^{-1}$

Strong atmospheric temperature correlation

arXiv:1202.6403

How the muon veto features are used in the neutrino and anti-neutrino analysis

- ✓ Scintillation signals identified as directly due to muons removed from the dataset

- ✓ Global veto over the whole detector with no spatial «segmentation»

  For external muons in the Buffer and in the Outer Detector → detector software blinded for 2 millisec to veto the signals induced by cosmogenic neutrons

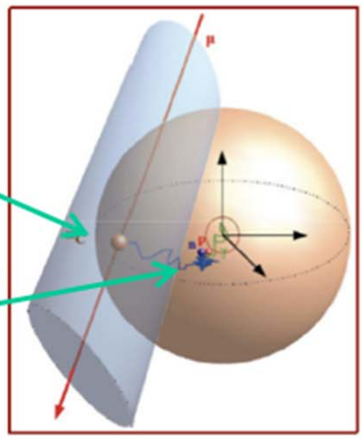
  For internal muons → detector software blinded for 300 millisec for solar neutrino analysis and 2 s for antineutrino analysis (to cope in particular with $^{9}Li/^{8}He$ isotopes which mimic the antineutrino signature)

- ✓ Spatial veto for ^{11}C → study of the pep and CNO solar neutrino fluxes

Application of the tracking capability to avoid excessive dead time

Interaction point and ^{11}C production point

Position of the γ



$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$

$t \sim 30min$

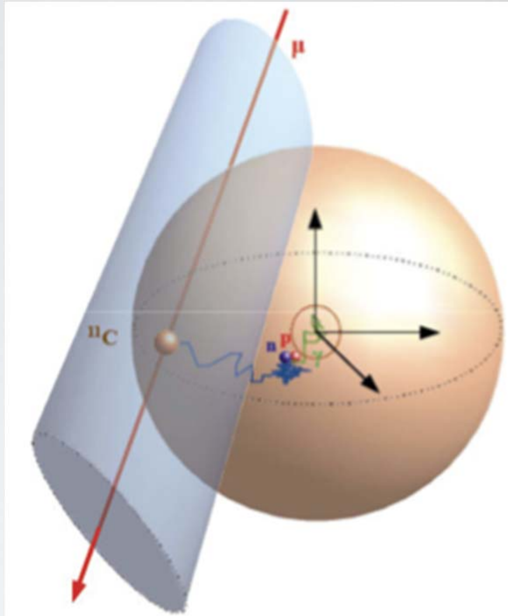
$n + p \rightarrow d + \gamma$

$\tau \sim 260 \mu s$

Threefold coincidence for ^{11}C rejection

FIRST DETECTION of PEP neutrinos

- Borexino obtained first evidence of **pep neutrinos**
  - Thanks to the very low background and analysis tools developed for ^{11}C rejection
    - Three fold coincidence tagging of ^{11}C events
    - **β+ - β** separation exploiting **positronium** induced pulse shape distortion
    - Multivariate maximum likelihood test using all available information



- **Three-fold coincidence**

$\mu + {}^{12}C \rightarrow n + {}^{11}C + \mu$

236 μs

No convection
^{11}C doesn't move

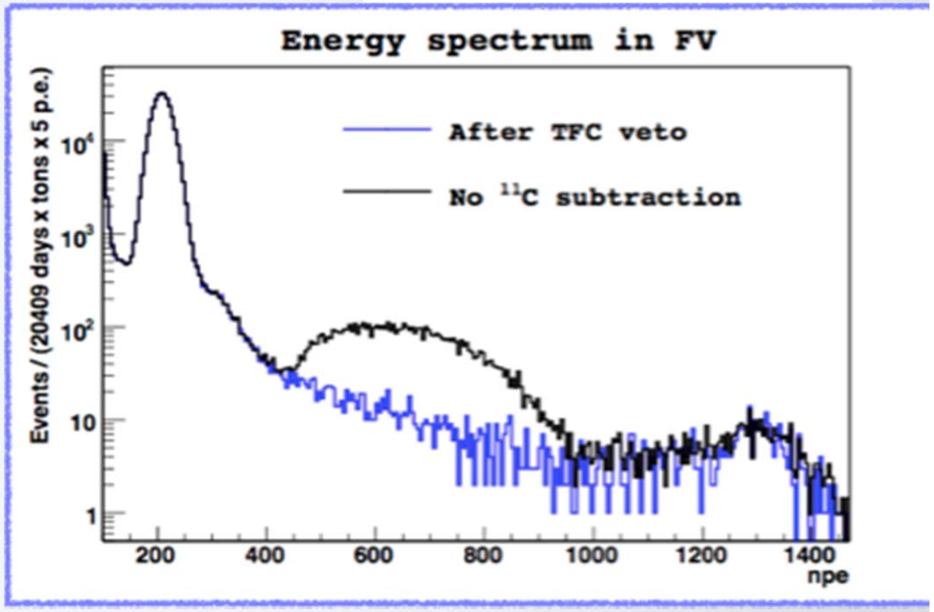
29.4 min

$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$

Quick neutron thermalization and capture yields clear tag

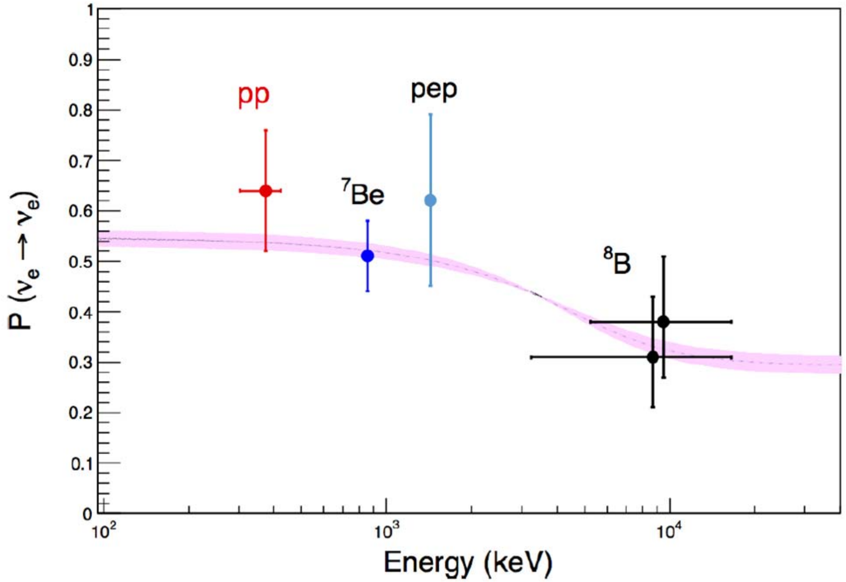
$n + p \rightarrow D + \gamma$ (2.2 MeV)

PHYSICAL REVIEW C 74, 045805 (2006)

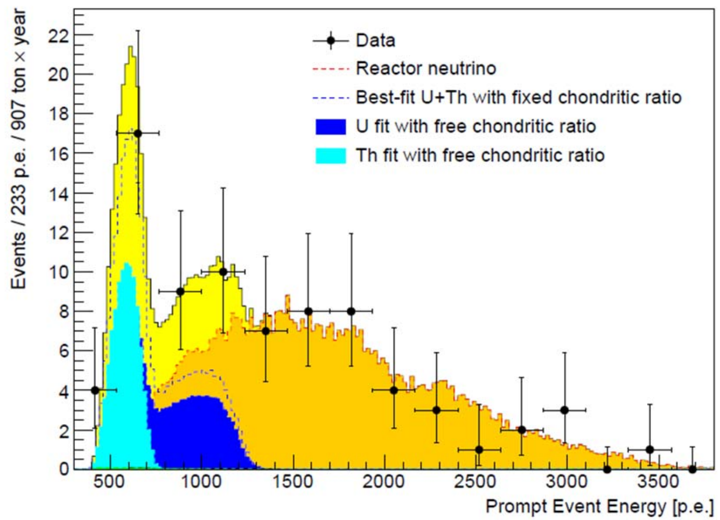


arXiv:1110.3230

Summary of the low energy neutrino physics achievements of Borexino



Borexino alone provides the validation of the MSW – LMA neutrino oscillation paradigm over the entire solar neutrino spectrum



High significant geoneutrino detection paving the way to the effective use of geoneutrinos as indicator of geophysical properties of our Planet

Darkside-50

Twofold veto implementation

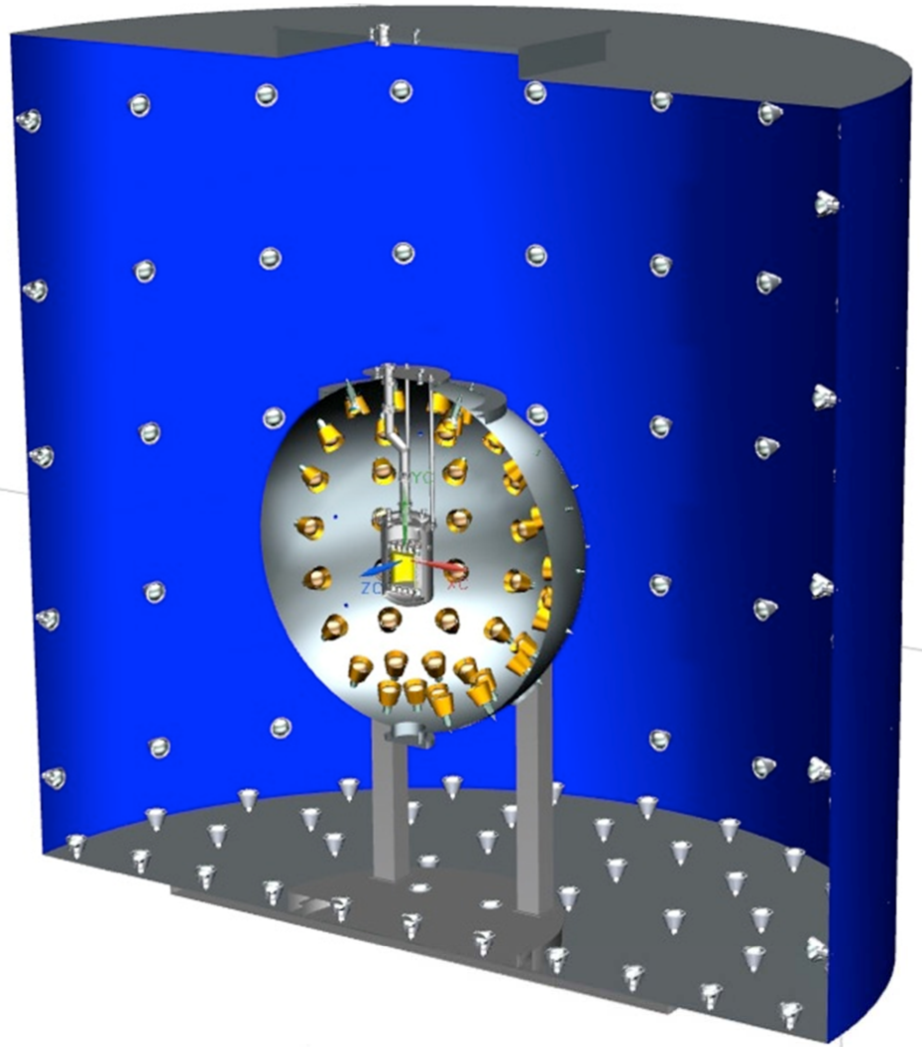
- External water shield instrumented for Cherenkov detection
- Inner scintillation optimized for neutron capture loaded with TMB (trimethylborate)

Surrounding the active core of the detector → a two phase liquid argon TPC

Mirror the implementation of Borexino vs cosmogenic neutrons and muon induced backgrounds

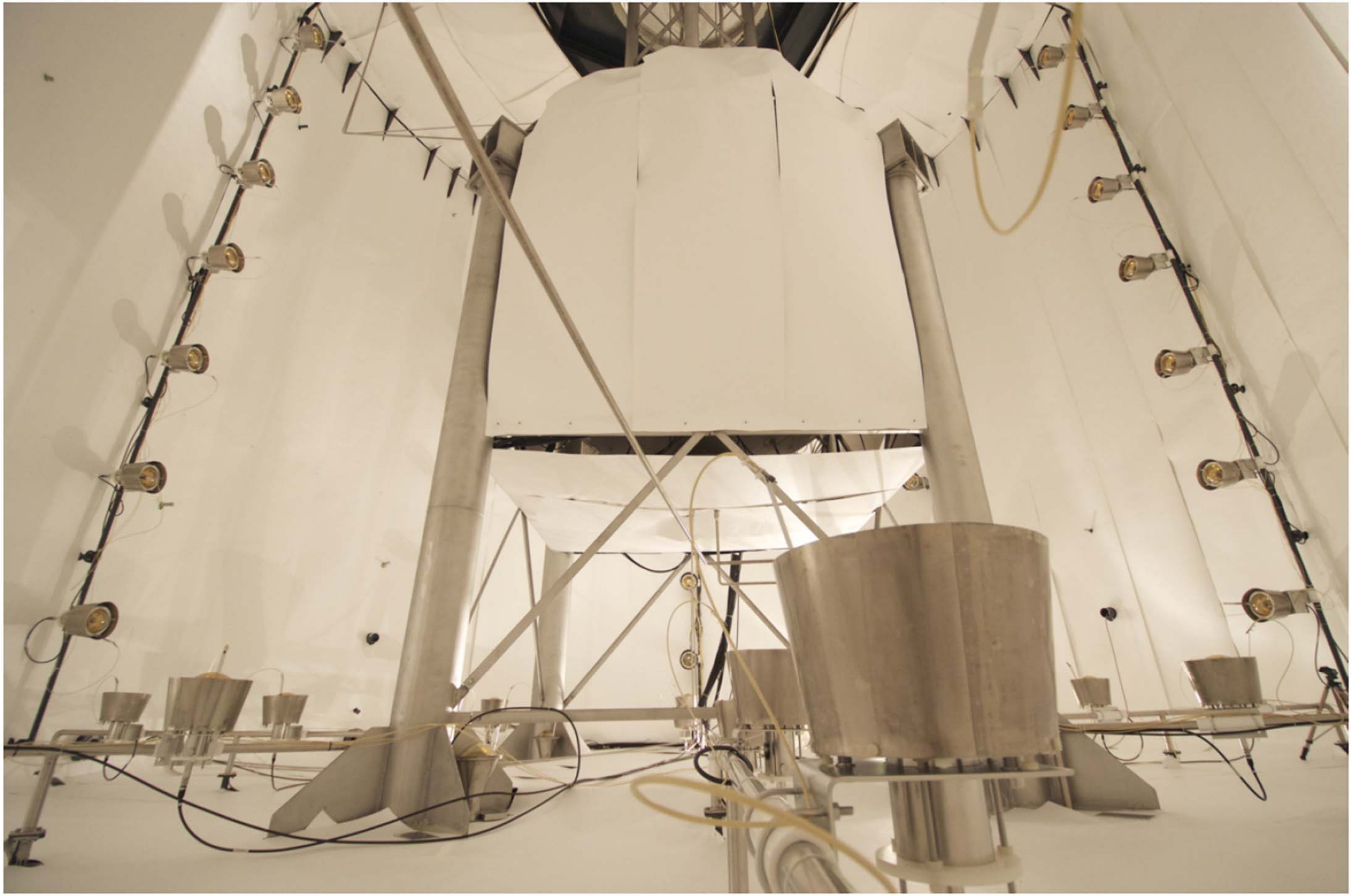
But in addition focused to providing a tag for the radiogenic neutrons from the construction materials in the TPC

Neutrons recoil off Argon nuclei mimicking the WIMP signal – well known background issue in the direct dark matter searches



The external CTF tank 11 x 10 m
and the stainless steel sphere 4 m diameter
reproduce the Borexino layout

Tyvek and PMTs on the wall of the Water Tank



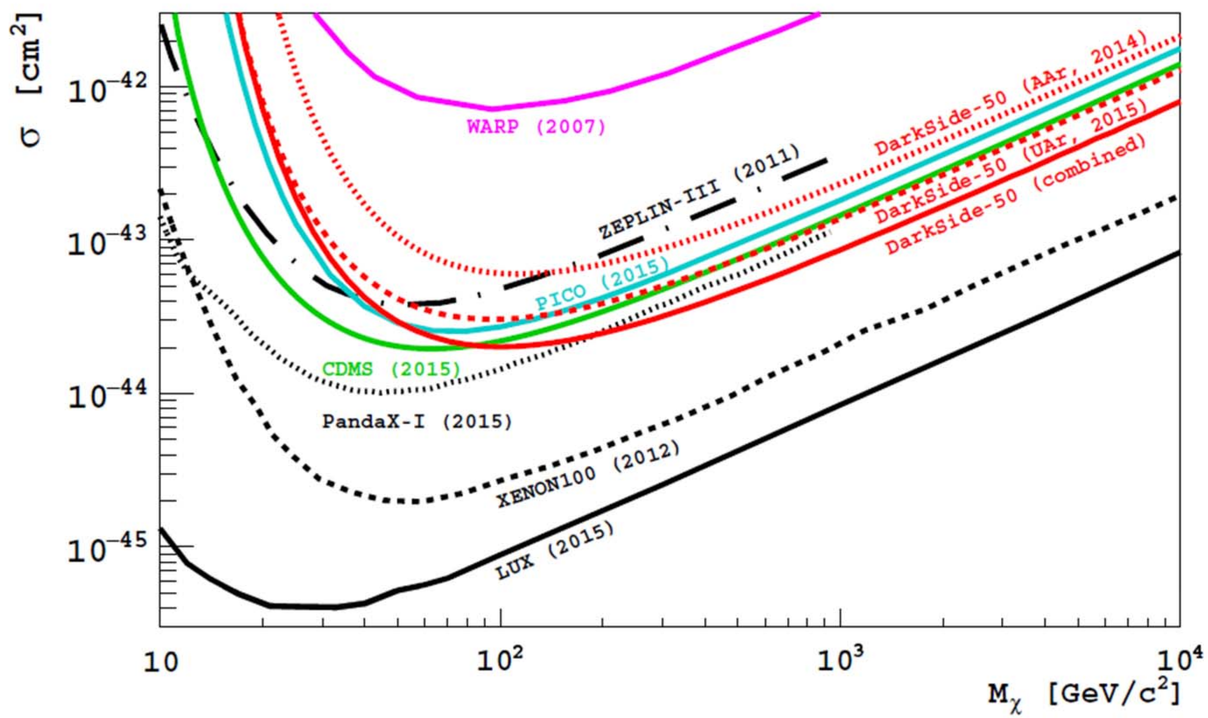
TPC deployed at the center of the neutron veto

Neutron detection efficiency greater than the design value of 99.5 %
arXiv:1512.07896

DarkSide-50 achievement

Background-free null result in arXiv:1510.00702 exploiting low-radioactivity argon

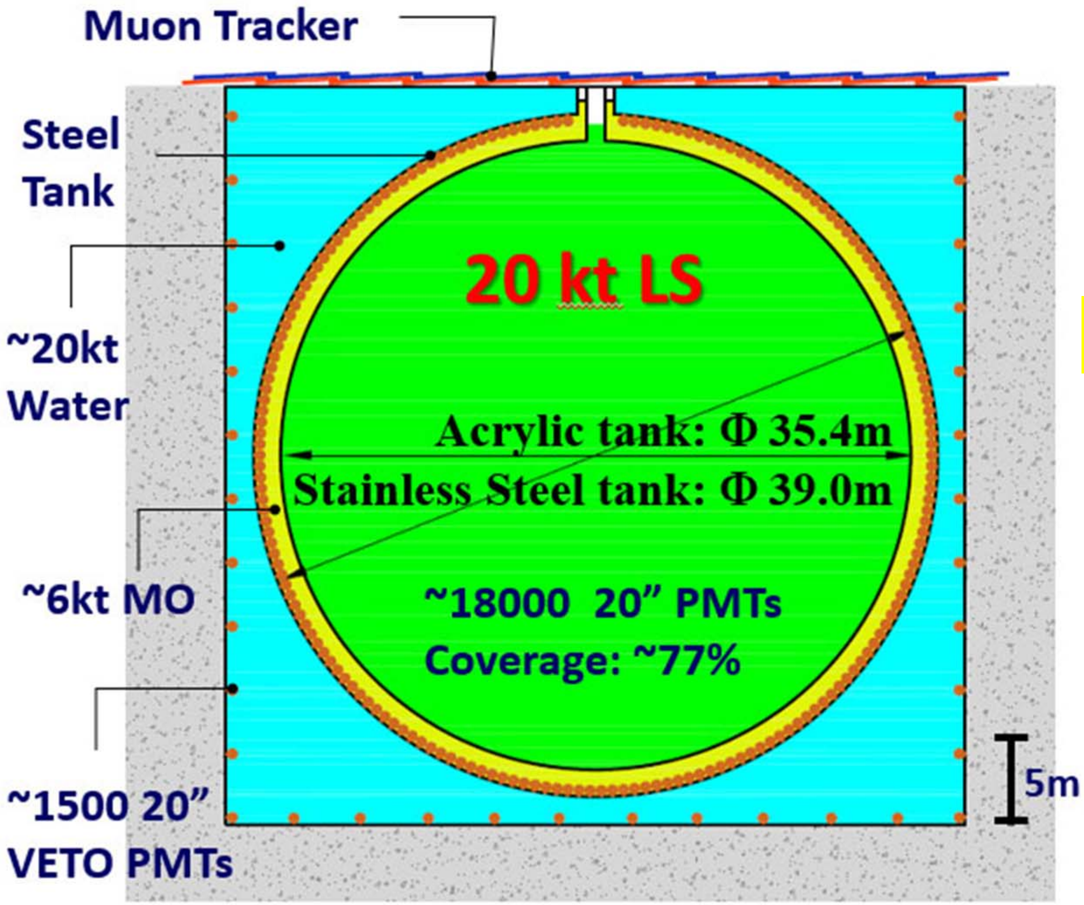
Muon and neutron vetoes crucial for this accomplishment

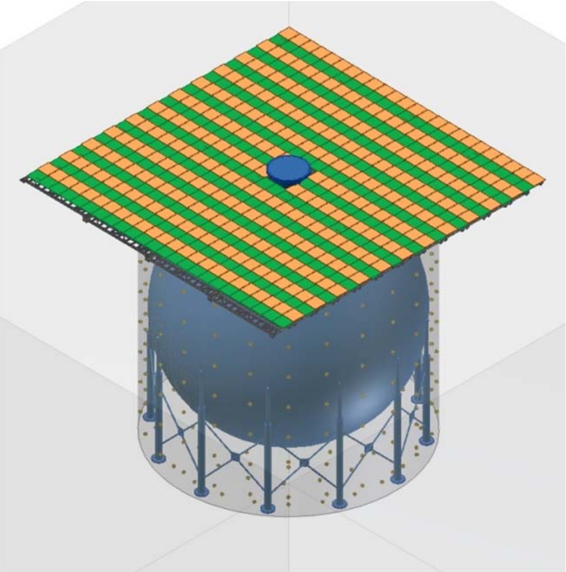


Most sensitive dark matter search performed with an argon target

JUNO: a future large LS detector

- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution





Muon Tracker -> Opera tracker

Conclusions

An effective shielding and veto strategy is an essential prerequisite for any sensitive state of the art underground rare event search

Borexino and DarkSide-50 represent very successful examples of the implementation of such a strategy

All future set-ups focused to move forward along the long standing quest to probe some yet undiscovered “secrets” of the nature e.g. dark matter search and $0\beta\beta$ decay investigation, as well as experiments designed to deepen the understanding of the already unraveled neutrino oscillation phenomenon, will require the adoption of sophisticated and effective shielding methodologies and techniques to enable the accomplishment of successful science

Cutting edge shielding infrastructures for ultimate frontier underground physics research