Borexino detector performances

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On behalf of the Borexino Collaboration

16th Marcel-Grossman Meeting - July 5th – 10th 2021

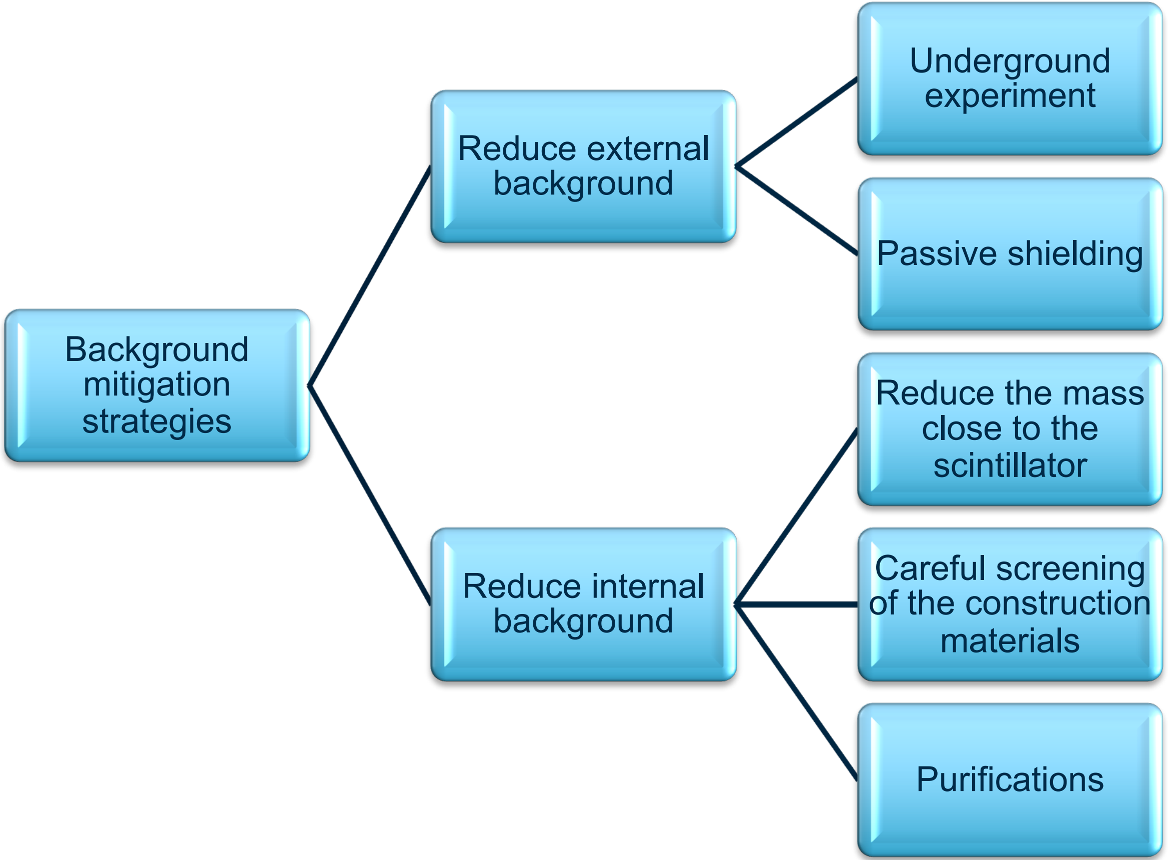
The Borexino experiment

- Main goal: the detection of low energy solar neutrinos, in particular ^{7}Be neutrinos
- Detection method: elastic scattering of neutrinos on electrons: $\nu_x + e \rightarrow \nu_x + e \quad x = e, \mu, \tau$
- Location: LNGS (Laboratori Nazionali del Gran Sasso), Italy
- Detection medium: large mass of organic liquid scintillator

$\sigma_{\nu e}$ is small: the expected rate of ^{7}Be solar neutrinos in 100 tons of Borexino scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/kg

Just for comparison, natural water is about 1 Bq/kg in ^{238}U, ^{232}Th, and ^{40}K
huge effort to achieve extremely high radiopurity levels

How to build a rare event search experiment



Background mitigation strategies

Reduce external background

Underground experiment

Passive shielding

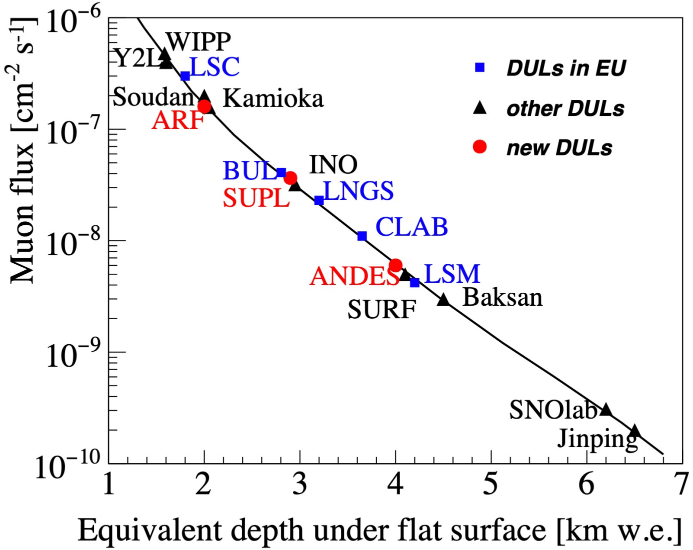
Reduce internal background

Reduce the mass close to the scintillator

Careful screening of the construction materials

Purifications

Laboratori Nazionali del Gran Sasso (Italy)



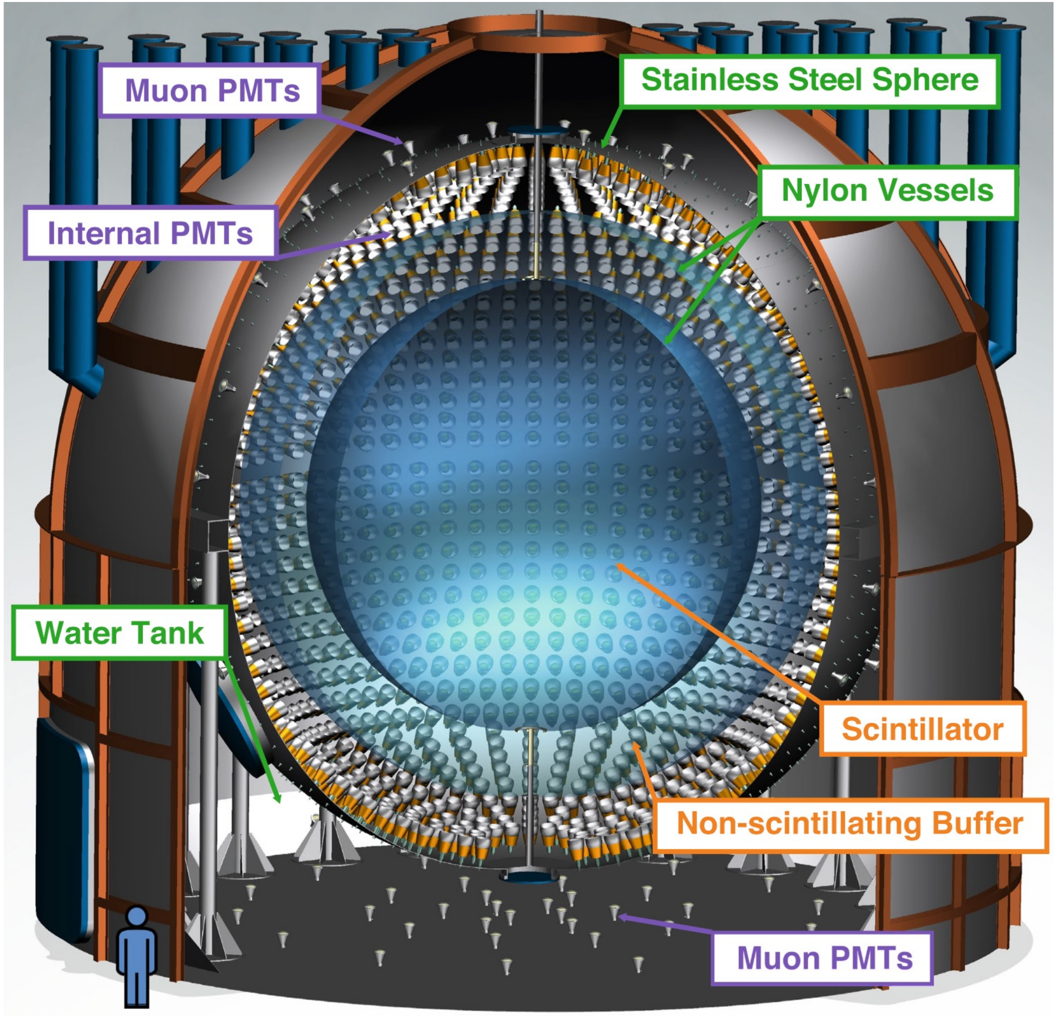
Source A. Ianni, Journal of Physics: Conference Series **1342** (2020) 012003

- The LNGS altitude is 963 m and the average rock cover is about 1400 m
- The shielding capacity against cosmic rays is about 3800 m.w.e.
- The muon flux is reduced by a factor 10^6 with respect to the surface: $\Phi(\mu) \sim 1\ \mu/\mathrm{m}^2/\mathrm{h}$

The Borexino detector

Key elements

- Scintillator:
  280 ton of PC+PPO in a 125 μm thick nylon vessel, fiducial mass ~ 100 ton;
- Non scintillating Buffer:
  900 t of quenched scintillator
- Nylon Vessels: 4.25 m and 5.5 m radius
- 2212 Internal PMTs
- Stainless Steel Sphere holding PMTs
- 208 Muon PMts
- Water Tank:
  2.8 kton of pure H_2O, γ and n shield, μ water Čerenkov detector



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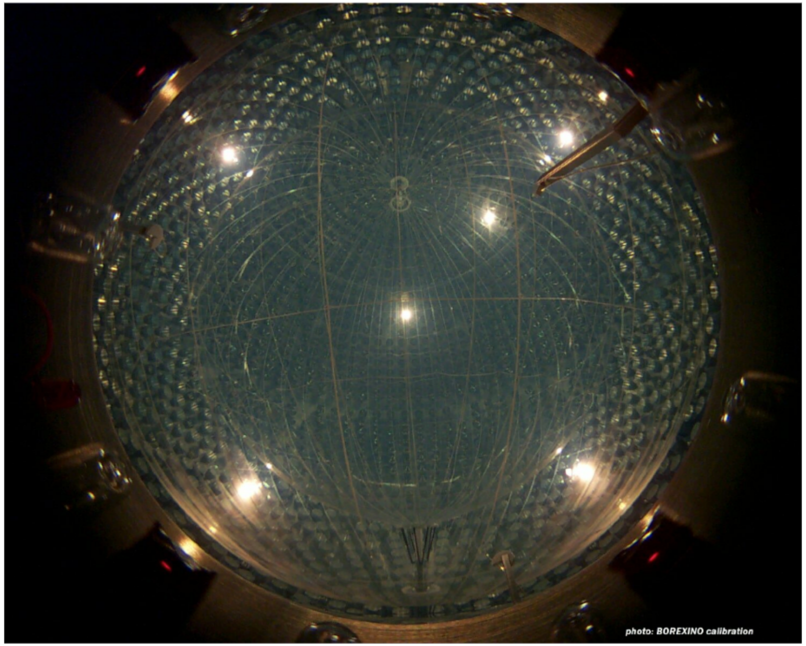
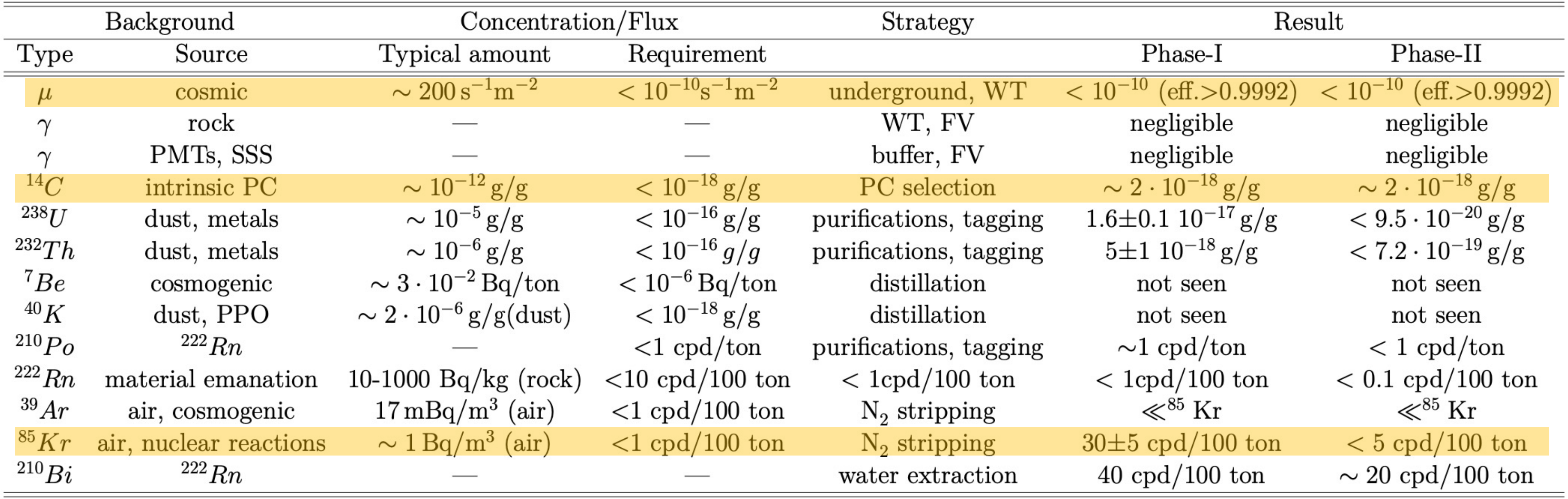


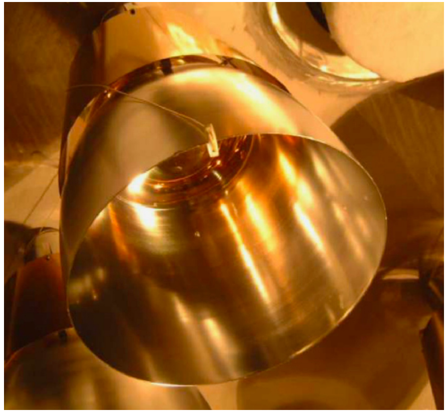
photo: BOREXINO calibration

Radiopurity of the materials



Background		Concentration/Flux		Strategy	Result	
Type	Source	Typical amount	Requirement		Phase-I	Phase-II
μ	cosmic	$\sim 200\,\mathrm{s^{-1}m^{-2}}$	$< 10^{-10}\mathrm{s^{-1}m^{-2}}$	underground, WT	$< 10^{-10}$ (eff.>0.9992)	$< 10^{-10}$ (eff.>0.9992)
γ	rock	—	—	WT, FV	negligible	negligible
γ	PMTs, SSS	—	—	buffer, FV	negligible	negligible
^{14}C	intrinsic PC	$\sim 10^{-12}\,\mathrm{g/g}$	$< 10^{-18}\,\mathrm{g/g}$	PC selection	$\sim 2 \cdot 10^{-18}\,\mathrm{g/g}$	$\sim 2 \cdot 10^{-18}\,\mathrm{g/g}$
^{238}U	dust, metals	$\sim 10^{-5}\,\mathrm{g/g}$	$< 10^{-16}\,\mathrm{g/g}$	purifications, tagging	$1.6 \pm 0.1\ 10^{-17}\,\mathrm{g/g}$	$< 9.5 \cdot 10^{-20}\,\mathrm{g/g}$
^{232}Th	dust, metals	$\sim 10^{-6}\,\mathrm{g/g}$	$< 10^{-16}\,g/g$	purifications, tagging	$5 \pm 1\ 10^{-18}\,\mathrm{g/g}$	$< 7.2 \cdot 10^{-19}\,\mathrm{g/g}$
^{7}Be	cosmogenic	$\sim 3 \cdot 10^{-2}\,\mathrm{Bq/ton}$	$< 10^{-6}\,\mathrm{Bq/ton}$	distillation	not seen	not seen
^{40}K	dust, PPO	$\sim 2 \cdot 10^{-6}\,\mathrm{g/g(dust)}$	$< 10^{-18}\,\mathrm{g/g}$	distillation	not seen	not seen
^{210}Po	^{222}Rn	—	<1 cpd/ton	purifications, tagging	~1 cpd/ton	< 1 cpd/ton
^{222}Rn	material emanation	10-1000 Bq/kg (rock)	<10 cpd/100 ton	< 1cpd/100 ton	< 1cpd/100 ton	< 0.1 cpd/100 ton
^{39}Ar	air, cosmogenic	$17\,\mathrm{mBq/m^3}$ (air)	<1 cpd/100 ton	N_2 stripping	$\ll{}^{85}$ Kr	$\ll{}^{85}$ Kr
^{85}Kr	air, nuclear reactions	$\sim 1\,\mathrm{Bq/m^3}$ (air)	<1 cpd/100 ton	N_2 stripping	30±5 cpd/100 ton	< 5 cpd/100 ton
^{210}Bi	^{222}Rn	—	—	water extraction	40 cpd/100 ton	~ 20 cpd/100 ton

The scintillation light



Scintillation light detected by 2212 PMTs

Information from detected light:

- Particle identification -> light vs time
- Energy of the event -> total light collected
- Event position -> time of flight algorithms

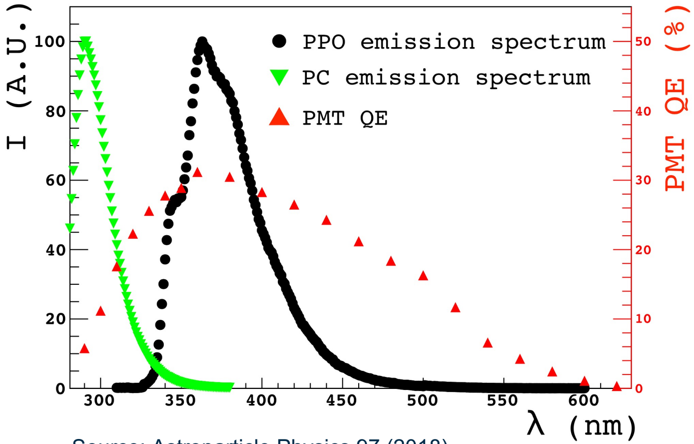
Scintillation light is isotropic

- No directionality

Performances

- σ(E) ~ 50 keV @ 1 MeV
- σ(r) ~ 10 cm @ 1 MeV

} From calibration campaign



Source: Astroparticle Physics 97 (2018)

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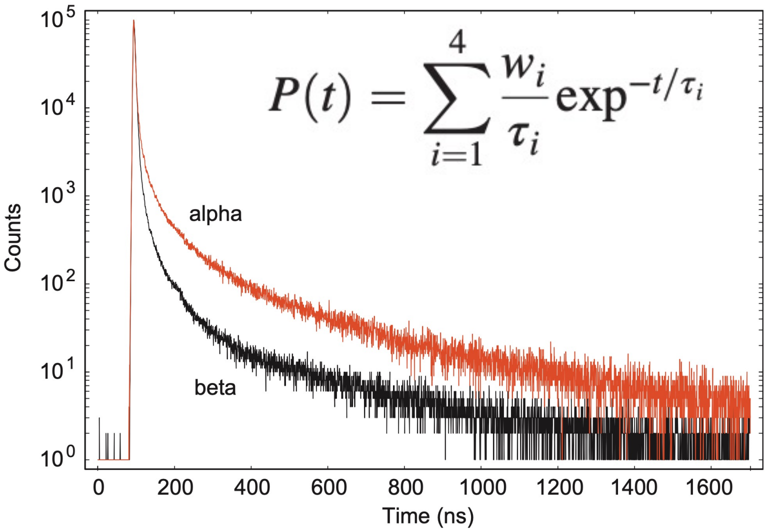
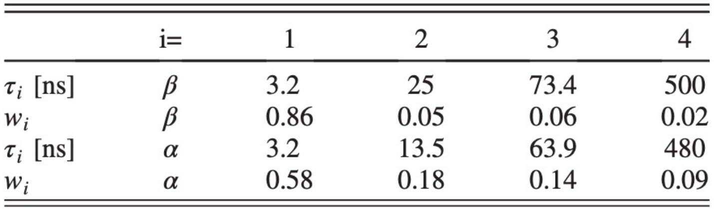


$$P(t) = \sum_{i=1}^{4} \frac{w_i}{\tau_i} \exp^{-t/\tau_i}$$

Source: NIM A 600 (2009)



	i=	1	2	3	4
τ_i [ns]	β	3.2	25	73.4	500
w_i	β	0.86	0.05	0.06	0.02
τ_i [ns]	α	3.2	13.5	63.9	480
w_i	α	0.58	0.18	0.14	0.09

Source: PHYSICAL REVIEW D 89, 112007 (2014)

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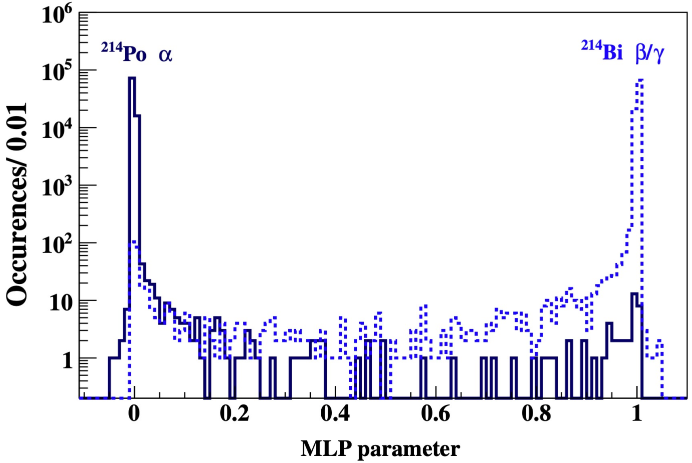
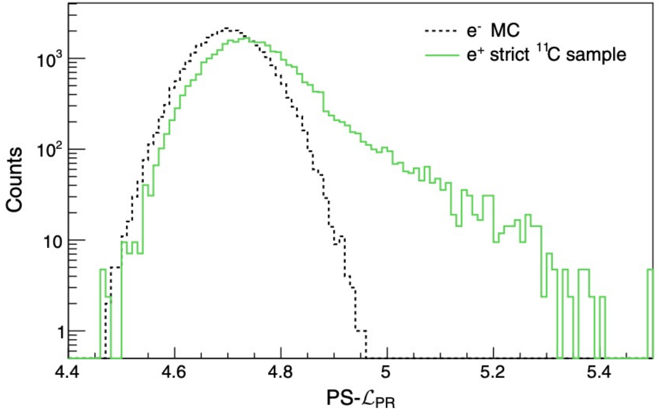


Source: PHYS. REV. D 101, 012009 (2020)

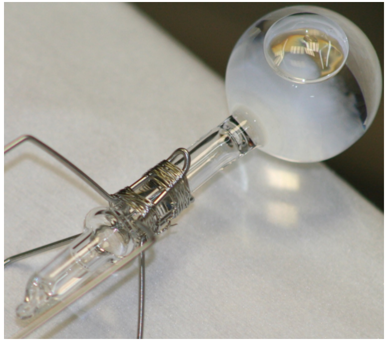


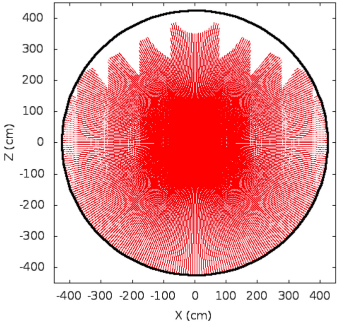
Source: PHYS. REV. D 100, 082004 (2019)

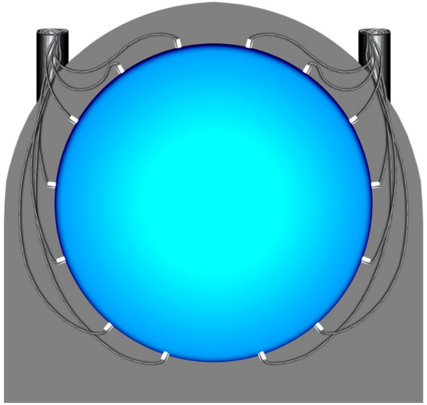
Calibration campaign

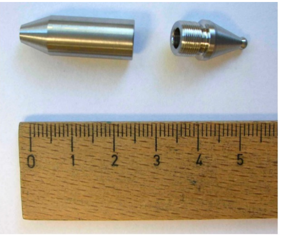
- Extensive detector calibration campaigns from 2008 to 2010
- Source deployment systems in scintillator and in SSS
- Different sources investigate different aspects of the detector's response

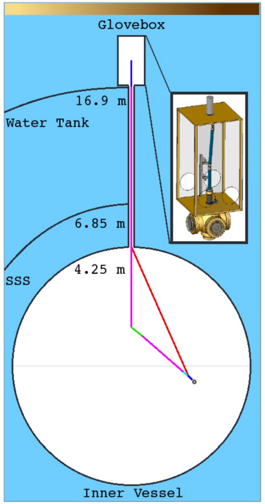
Source: JINST 7 P10018 (2012)











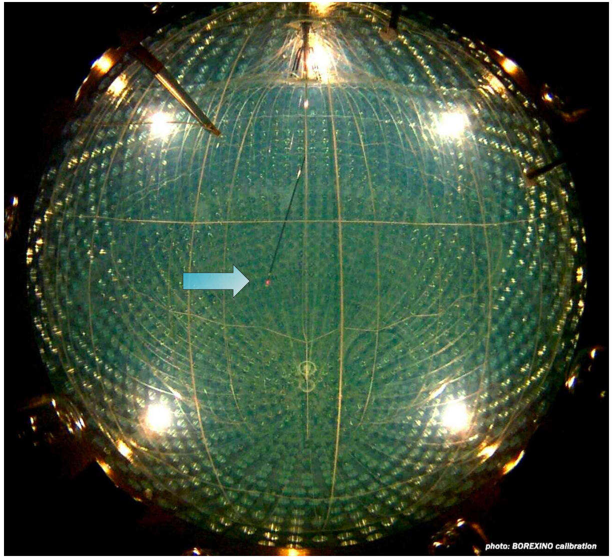
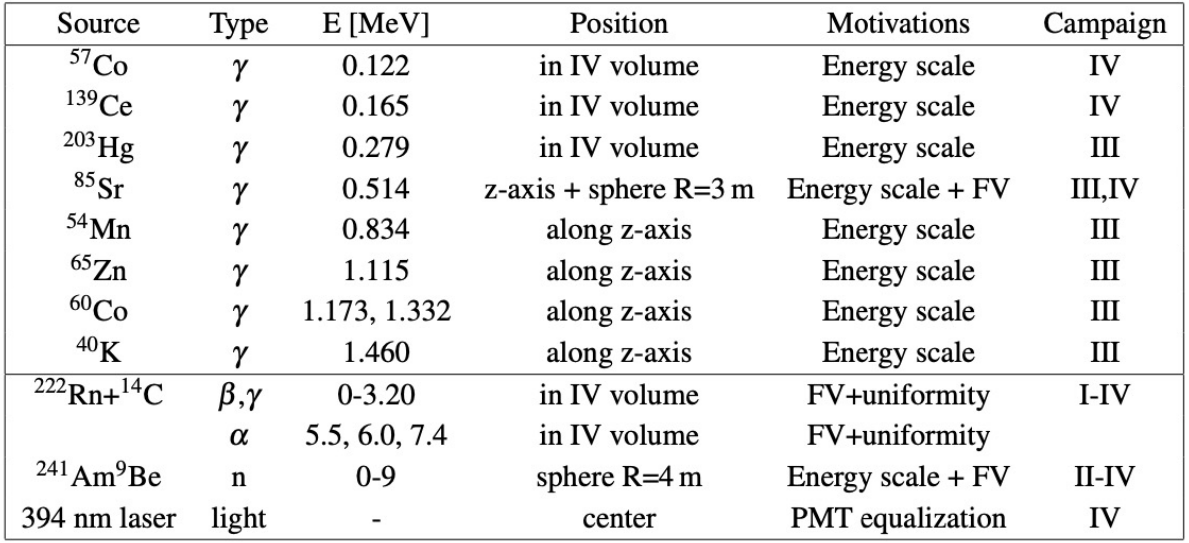


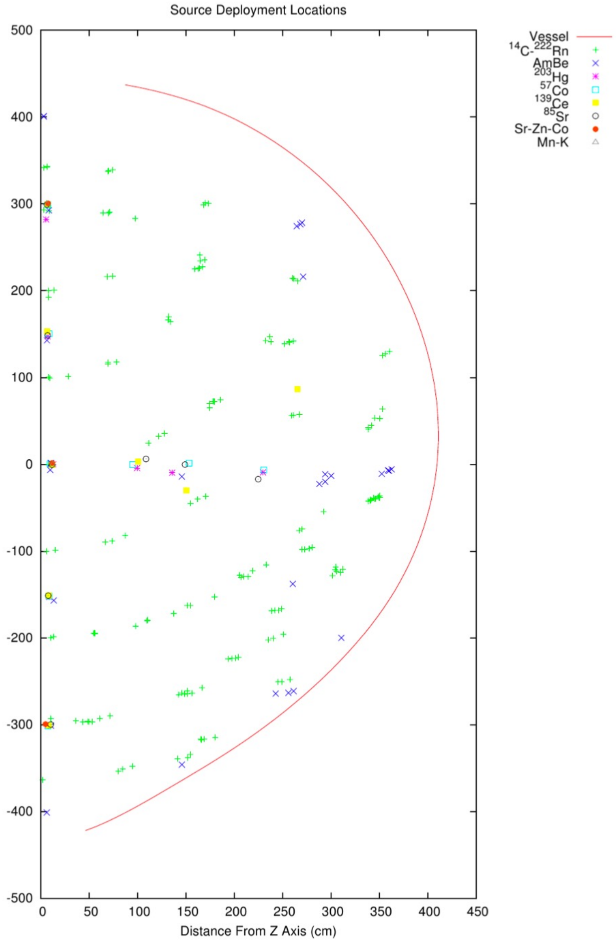
photo: BOREXINO calibration

Calibration campaign

- Position of the source measured by looking with cameras at the LED attached to the source



Source	Type	E [MeV]	Position	Motivations	Campaign
^{57}Co	γ	0.122	in IV volume	Energy scale	IV
^{139}Ce	γ	0.165	in IV volume	Energy scale	IV
^{203}Hg	γ	0.279	in IV volume	Energy scale	III
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV	III,IV
^{54}Mn	γ	0.834	along z-axis	Energy scale	III
^{65}Zn	γ	1.115	along z-axis	Energy scale	III
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale	III
^{40}K	γ	1.460	along z-axis	Energy scale	III
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity	I-IV
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity	
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV	II-IV
394 nm laser	light	-	center	PMT equalization	IV



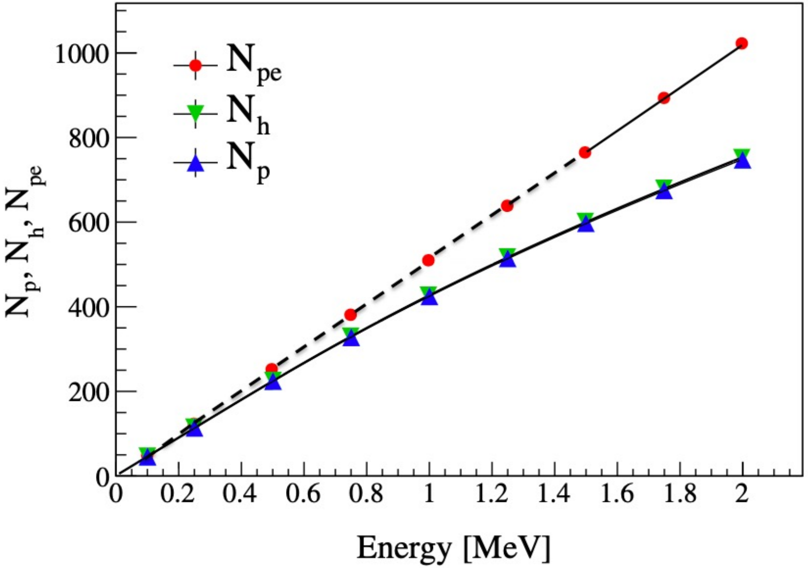
Energy reconstruction

- Energy of the event calculated from the number of hits on PMTs, number of hit PMTs or photoelectrons on PMTs

$$N_p^m = \sum_{j=1}^{N'} p^j,$$

$$N_h^m = \sum_{j=1}^{N'} h^j,$$

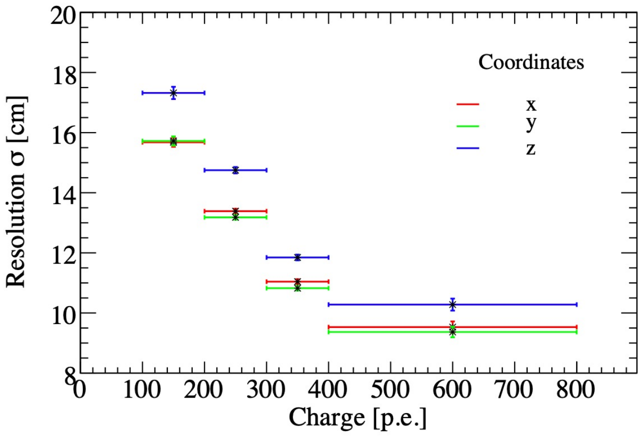
$$N_{pe}^m = \sum_{i=1}^{N_h^m} q_i^j.$$

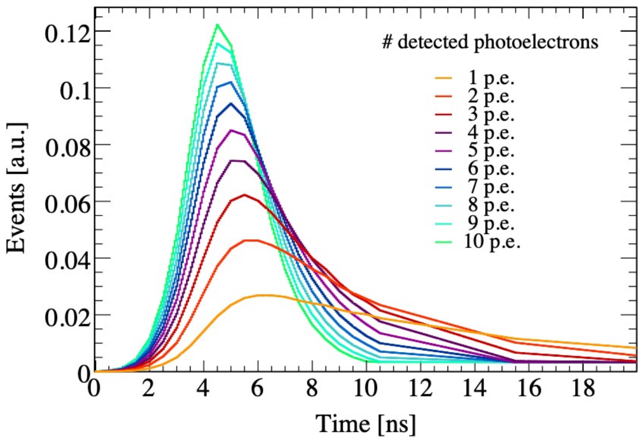


Position reconstruction

- Position calculated using time of flight information
- Time of arrival of the first hit corrected by hit multiplicity
- Position of the event obtained minimizing a likelihood function

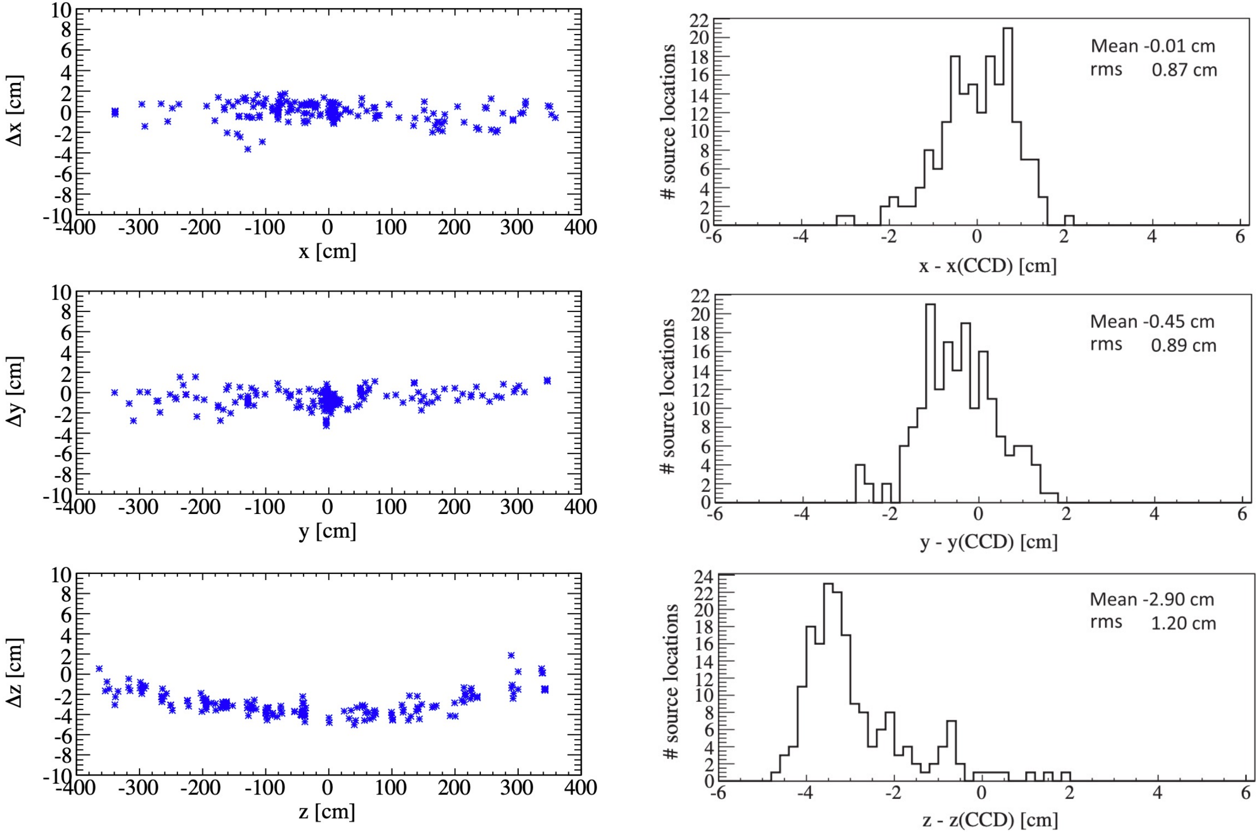
$$T^i_{\text{flight}}(\vec{r}_0, \vec{r}_i) = \frac{|\vec{r}_0 - \vec{r}_i|}{v_g}$$





Position reconstruction bias

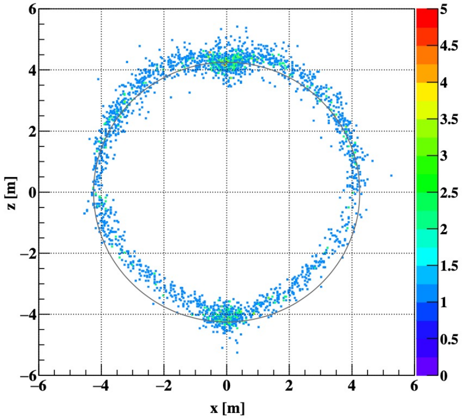
- Comparison between known source position (detected by cameras) and reconstructed position
- Bias in z considered during systematic studies
- Impact on the fiducial volume determination <0.2%

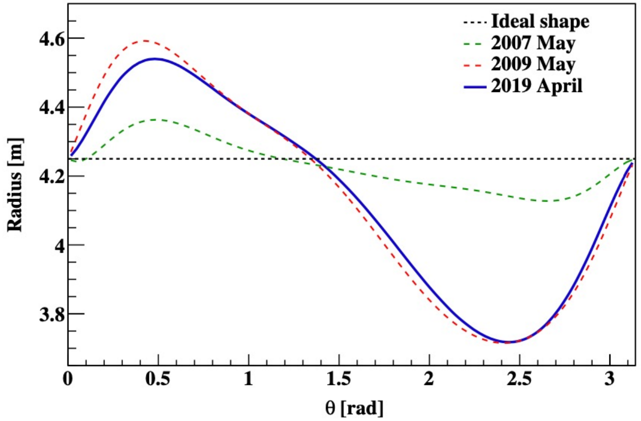


Sources: JINST 7 P10018 (2012), PHYSICAL REVIEW D 89, 112007 (2014)

Vessel shape reconstruction

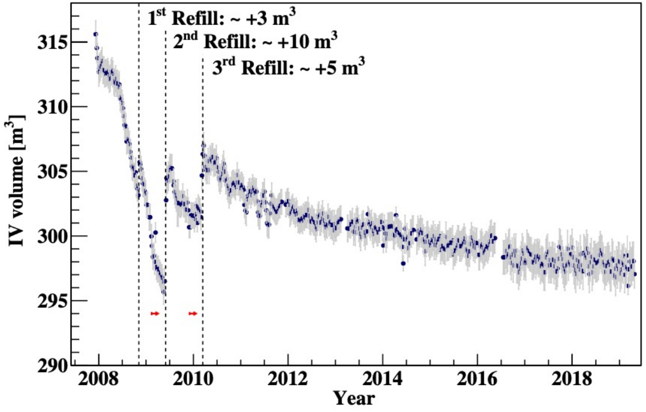
- Due to a small leak in the vessel, the vessel shape evolves with time
- Reconstructed selecting events in Npe=(290-350)pe [800-900]keV (mostly ^{210}Bi, ^{40}K, ^{208}Tl) on the vessel
- Precision of the method: ± 1% (± 5 cm)
- Vessel shape updated every 3 weeks





(a)

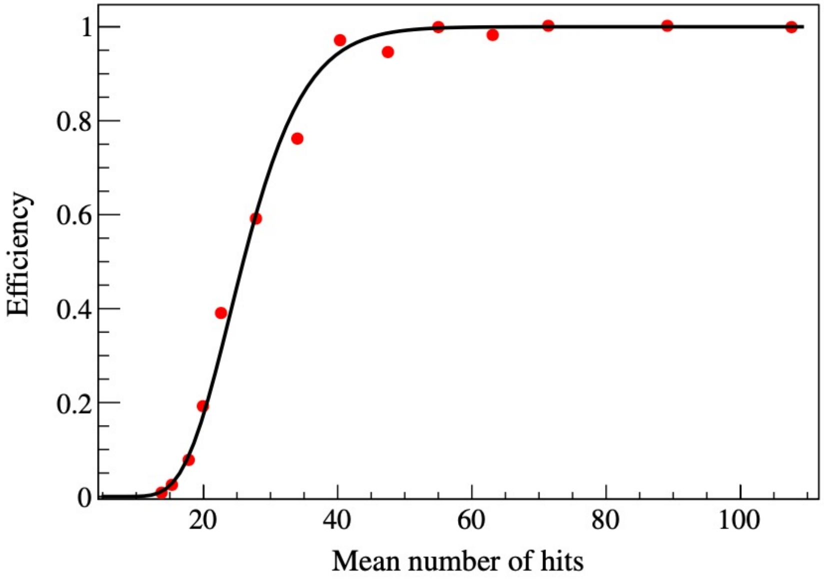
Source: PHYS. REV. D 101, 012009 (2020)



(b)

Trigger efficiency

- Borexino is a self triggering experiment
- A trigger is fired when a minimum of K of inner detector PMTs detect at least a pe in 99 ns.
- K chosen to have a threshold of 50-60 keV
- Trigger efficiency measured with a dedicated laser runs of variable laser intensity
- Trigger efficiency crosschecked with ^{85}Sr source, compatible with 100% efficiency



Source: PHYSICAL REVIEW D 89, 112007 (2014)

Monte Carlo modelling of detector’s response

- Code based on Geant4 and custom C++ simulation
- Performances validated with data from calibration campaign
- Performances:
    - Energy response in agreement within 1% in the solar analysis fiducial volume (^{210}Po events)
    - Discrepancy lower than 2% in the whole scintillator (studied with 2.2 MeV gammas from neutron capture on hydrogen)
    - Data from external calibration campaign well reproduced (ad hoc methods implemented, fundamental for modelling of external background)
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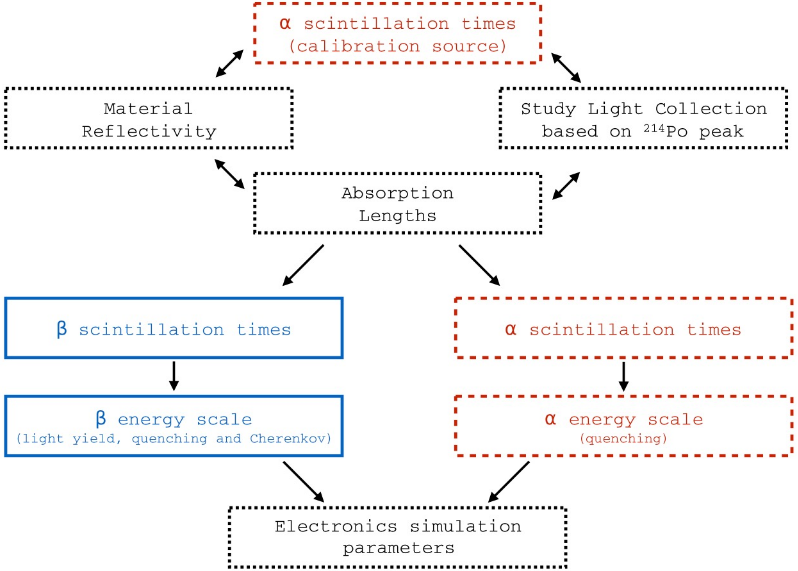

α scintillation times (calibration source)

Material Reflectivity

Study Light Collection based on ^{214}Po peak

Absorption Lengths

β scintillation times

α scintillation times

β energy scale (light yield, quenching and Cherenkov)

α energy scale (quenching)

Electronics simulation parameters

Source: Astroparticle Physics 97 (2018) 136-159

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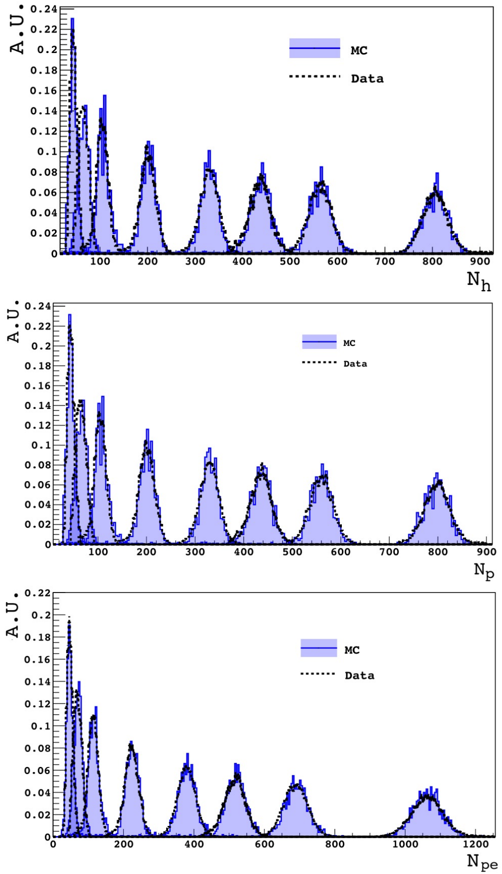

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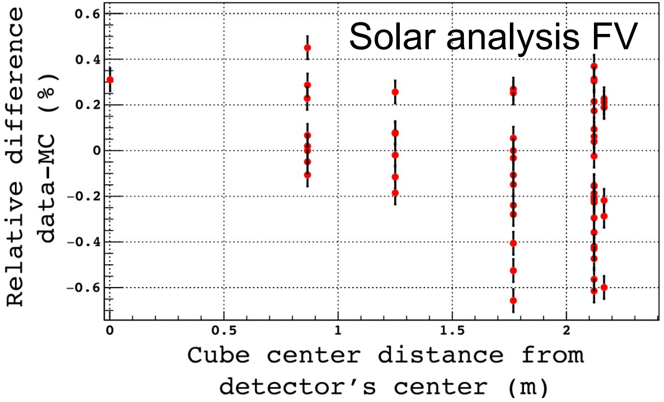

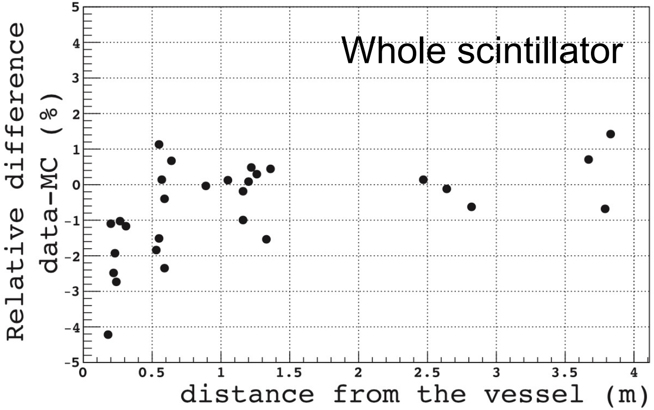

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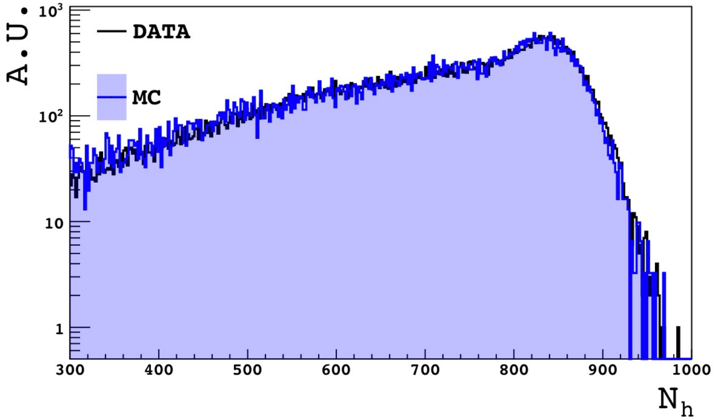

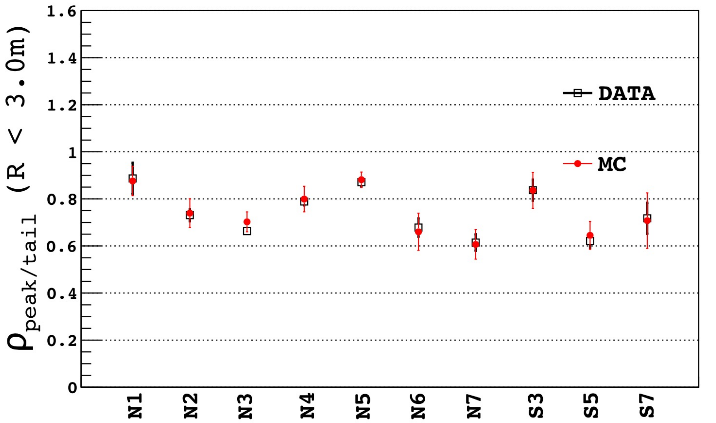

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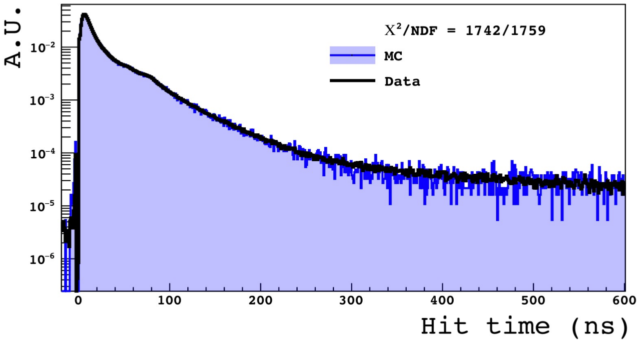
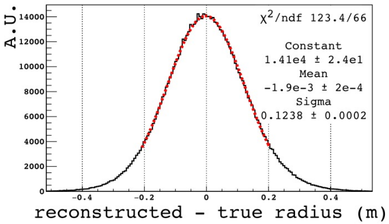
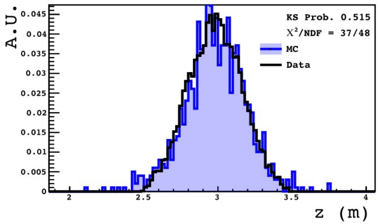
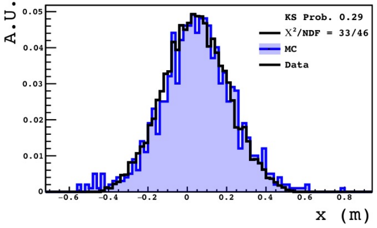
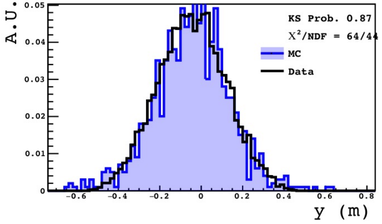










Analytical modeling of detector’s response

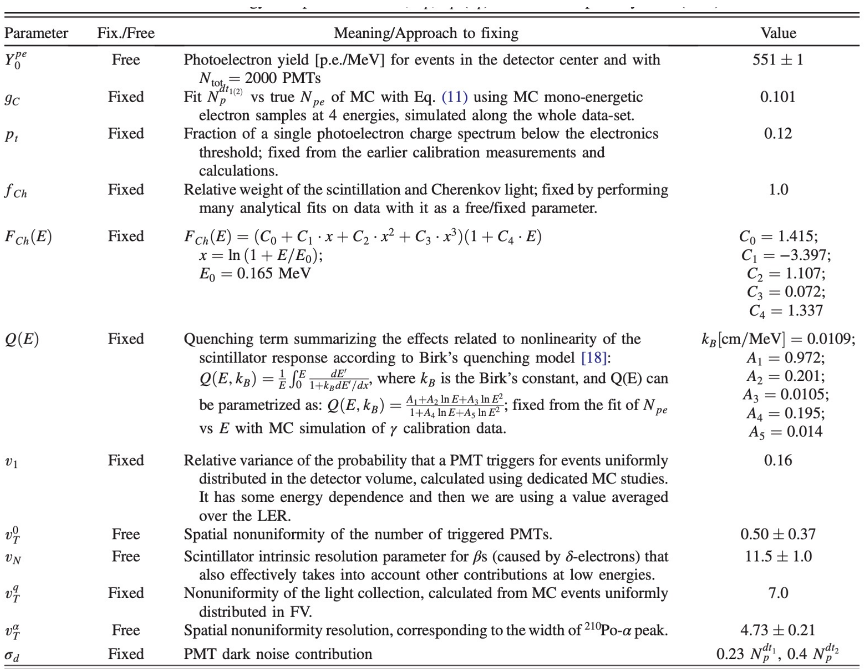
- In parallel to the Monte Carlo modeling we developed an analytical response function for determining energy PDF
- Effects taken into account:
    - Scintillation light
    - Cherenkov photons
    - Non uniformity of light collection

$$\mu = \frac{\bar{N}_{pe}(E)}{N_{\text{tot}}},$$

$$\bar{N}_{pe}(E) = Y_0^{pe} \cdot [Q(E) \cdot E + f_{Ch} \cdot F_{Ch}(E)]$$

$$\bar{N}_p(E) = N_{\text{tot}}[1 - e^{-\mu}(1 + p_t\mu)](1 - g_C\mu)$$

$$\sigma_p^2 = f_{eq}[1 - (1 + v_1)p_1]\bar{N}_p(E) + v_T^0\bar{N}_p^3(E) + v_T^q\left(\mu\frac{p_0}{p_1}\right)^2\bar{N}_p^2(E) + v_N\bar{N}_p(E) + \sigma_d^2$$



Parameter	Fix./Free	Meaning/Approach to fixing	Value
Y_0^{pe}	Free	Photoelectron yield [p.e./MeV] for events in the detector center and with $N_{\text{tot}} = 2000$ PMTs	551 ± 1
g_C	Fixed	Fit $N_p^{dt_{1(2)}}$ vs true N_{pe} of MC with Eq. (11) using MC mono-energetic electron samples at 4 energies, simulated along the whole data-set.	0.101
p_t	Fixed	Fraction of a single photoelectron charge spectrum below the electronics threshold; fixed from the earlier calibration measurements and calculations.	0.12
f_{Ch}	Fixed	Relative weight of the scintillation and Cherenkov light; fixed by performing many analytical fits on data with it as a free/fixed parameter.	1.0
$F_{Ch}(E)$	Fixed	$F_{Ch}(E) = (C_0 + C_1 \cdot x + C_2 \cdot x^2 + C_3 \cdot x^3)(1 + C_4 \cdot E)$ $x = \ln(1 + E/E_0)$; $E_0 = 0.165$ MeV	$C_0 = 1.415$; $C_1 = -3.397$; $C_2 = 1.107$; $C_3 = 0.072$; $C_4 = 1.337$
$Q(E)$	Fixed	Quenching term summarizing the effects related to nonlinearity of the scintillator response according to Birk’s quenching model [18]: $Q(E, k_B) = \frac{1}{E}\int_0^E \frac{dE'}{1+k_B dE'/dx}$, where k_B is the Birk’s constant, and Q(E) can be parametrized as: $Q(E, k_B) = \frac{A_1+A_2\ln E+A_3\ln E^2}{1+A_4\ln E+A_5\ln E^2}$; fixed from the fit of N_{pe} vs E with MC simulation of γ calibration data.	k_B[cm/MeV] $= 0.0109$; $A_1 = 0.972$; $A_2 = 0.201$; $A_3 = 0.0105$; $A_4 = 0.195$; $A_5 = 0.014$
v_1	Fixed	Relative variance of the probability that a PMT triggers for events uniformly distributed in the detector volume, calculated using dedicated MC studies. It has some energy dependence and then we are using a value averaged over the LER.	0.16
v_T^0	Free	Spatial nonuniformity of the number of triggered PMTs.	0.50 ± 0.37
v_N	Free	Scintillator intrinsic resolution parameter for βs (caused by δ-electrons) that also effectively takes into account other contributions at low energies.	11.5 ± 1.0
v_T^q	Fixed	Nonuniformity of the light collection, calculated from MC events uniformly distributed in FV.	7.0
v_T^α	Free	Spatial nonuniformity resolution, corresponding to the width of ^{210}Po-α peak.	4.73 ± 0.21
σ_d	Fixed	PMT dark noise contribution	$0.23\ N_p^{dt_1}$, $0.4\ N_p^{dt_2}$

Source: Physical Review D 100, 082004 (2019)

Conclusions

- Borexino is a liquid scintillator detector tailored for the solar neutrino detection currently in phase of data taking at LNGS
- Performances:
  - Triggering efficiency
  - σ(E) ~ 50 keV @ 1 MeV
  - σ(r) ~ 10 cm @ 1 MeV
- Energy response model in agreement within 1% with data

- These performances allow Borexino to deliver important results in neutrino and solar physics as shown in the next talks


Thank you for your attention