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
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: $\Phi(\mu) \sim 1 \, \mu$/m$^2$/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 H₂O, γ and n shield, μ water Čerenkov detector
The Borexino detector
Radiopurity of the materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Concentration/Flux</th>
<th>Strategy</th>
<th>Phase-I</th>
<th>Phase-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ</td>
<td>cosmic</td>
<td>~ 200 s⁻¹ m⁻²</td>
<td>&lt; 10⁻¹⁰ s⁻¹ m⁻²</td>
<td>underground, WT</td>
<td>&lt; 10⁻¹⁰ (eff.&gt;0.9992)</td>
</tr>
<tr>
<td>γ</td>
<td>rock</td>
<td>—</td>
<td>—</td>
<td>WT, FV</td>
<td>negligible</td>
</tr>
<tr>
<td>γ</td>
<td>PMTs, SSS</td>
<td>—</td>
<td>—</td>
<td>buffer, FV</td>
<td>negligible</td>
</tr>
<tr>
<td>¹⁴C</td>
<td>intrinsic PC</td>
<td>~ 10⁻¹² g/g</td>
<td>&lt; 10⁻¹⁸ g/g</td>
<td>PC selection</td>
<td>~ 2 · 10⁻¹⁸ g/g</td>
</tr>
<tr>
<td>²³⁸U</td>
<td>dust, metals</td>
<td>~ 10⁻⁵ g/g</td>
<td>&lt; 10⁻¹⁶ g/g</td>
<td>purifications, tagging</td>
<td>1.6±0.1 10⁻¹⁷ g/g</td>
</tr>
<tr>
<td>²³²Th</td>
<td>dust, metals</td>
<td>~ 10⁻⁶ g/g</td>
<td>&lt; 10⁻¹⁶ g/g</td>
<td>purifications, tagging</td>
<td>5±1 10⁻¹⁸ g/g</td>
</tr>
<tr>
<td>⁷Be</td>
<td>cosmogenic</td>
<td>~ 3 · 10⁻² Bq/ton</td>
<td>&lt; 10⁻⁶ Bq/ton</td>
<td>distillation</td>
<td>not seen</td>
</tr>
<tr>
<td>⁴⁰K</td>
<td>dust, PPO</td>
<td>~ 2 · 10⁻⁶ g/g (dust)</td>
<td>&lt; 10⁻¹⁸ g/g</td>
<td>distillation</td>
<td>not seen</td>
</tr>
<tr>
<td>²¹⁰Po</td>
<td>²²²Rn</td>
<td>—</td>
<td>&lt; 1 cpd/ton</td>
<td>purifications, tagging</td>
<td>~1 cpd/ton</td>
</tr>
<tr>
<td>²²²Rn</td>
<td>material emanation</td>
<td>10-1000 Bq/kg (rock)</td>
<td>&lt; 10 cpd/100 ton</td>
<td>&lt; 1 cpd/100 ton</td>
<td>&lt; 1 cpd/100 ton</td>
</tr>
<tr>
<td>³⁹Ar</td>
<td>air, cosmogenic</td>
<td>17 mBq/m³ (air)</td>
<td>&lt; 1 cpd/100 ton</td>
<td>N₂ stripping</td>
<td>≪⁸⁵ Kr</td>
</tr>
<tr>
<td>⁸⁵Kr</td>
<td>air, nuclear reactions</td>
<td>~ 1 Bq/m³ (air)</td>
<td>&lt; 1 cpd/100 ton</td>
<td>N₂ stripping</td>
<td>30±5 cpd/100 ton</td>
</tr>
<tr>
<td>²¹⁰Bi</td>
<td>²²²Rn</td>
<td>—</td>
<td>—</td>
<td>water extraction</td>
<td>40 cpd/100 ton</td>
</tr>
</tbody>
</table>
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**
- $\sigma(E) \sim 50 \text{ keV} @ 1 \text{ MeV}$
- $\sigma(r) \sim 10 \text{ cm} @ 1 \text{ MeV}$

![Graph showing scintillation light emission spectrum and PMT quantum efficiency](image-url)

Source: Astroparticle Physics 97 (2018)
The scintillation light

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\[ P(t) = \sum_{i=1}^{4} \frac{w_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right) \]
The scintillation light

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From calibration campaign
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)
Calibration campaign

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

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

\[ T_{\text{flight}}^i(\vec{r}_0, \vec{r}_i) = \frac{|\vec{r}_0 - \vec{r}_i|}{v_g} \]
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 N_{pe} = (290-350)pe [800-900]keV (mostly $^{210}$Bi, $^{40}$K, $^{208}$Tl) on the vessel
- Precision of the method: $\pm 1\%$ ($\pm 5$ cm)
- Vessel shape updated every 3 weeks

Source: PHYS. REV. D 101, 012009 (2020)
A trigger is fired when a minimum of $K$ of inner detector PMTs detect at least a photoelectron in 99 ns.

- $K$ is chosen to have a threshold of 50-60 keV.
- Trigger efficiency measured with dedicated laser runs of variable laser intensity.
- Trigger efficiency crosschecked with $^{85}\text{Sr}$ 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)
  - No bias in position reconstruction

Source: Astroparticle Physics 97 (2018) 136-159
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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

\[
\mu = \frac{\bar{N}_{ne}(E)}{N_{tot}},
\]
\[
\bar{N}_{ne}(E) = Y_{n}^{pe} \cdot \left[ Q(E) \cdot E + f_{Ch} \cdot F_{Ch}(E) \right]
\]
\[
\bar{N}_{p}(E) = N_{tot}[1 - e^{-\mu}(1 + p_{t}\mu)](1 - g_{C}\mu)
\]
\[
\sigma_{p}^{2} = f_{eq}[1 - (1 + v_{1})p_{1}]\bar{N}_{p}(E) + v_{T}^{0}\bar{N}_{p}^{3}(E)
\]
\[
+ v_{T}^{q}\left(\mu \frac{P_{0}}{P_{1}}\right)^{2} \bar{N}_{p}^{2}(E) + v_{N}\bar{N}_{p}(E) + \sigma_{d}^{2}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fix/Free</th>
<th>Meaning/Approach to fixing</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{n}^{pe}$</td>
<td>Free/Free</td>
<td>Photodetector yield [p.e./MeV] for events in the detector center and with $N_{tot} = 2000$ PMTs</td>
<td>$551 \pm 1$</td>
</tr>
<tr>
<td>$g_{C}$</td>
<td>Fixed</td>
<td>Fit $N_{n}^{pe}$ vs true $N_{p}$ of MC with Eq. (11) using MC mono-energetic electron samples at 4 energies, simulated along the whole data-set.</td>
<td>0.101</td>
</tr>
<tr>
<td>$p_{t}$</td>
<td>Fixed</td>
<td>Fraction of a single photoelectron charge spectrum below the electronics threshold; fixed from the earlier calibration measurements and calculations.</td>
<td>0.12</td>
</tr>
<tr>
<td>$f_{Ch}$</td>
<td>Fixed</td>
<td>Relative weight of the scintillation and Cherenkov light; fixed by performing many analytical fits on data with it as a fixed parameter.</td>
<td>1.0</td>
</tr>
<tr>
<td>$F_{Ch}(E)$</td>
<td>Fixed</td>
<td>$F_{Ch}(E) = (C_{0} + C_{1} \cdot x + C_{2} \cdot x^{2} + C_{3} \cdot x^{3})(1 + C_{4} \cdot E)$; $E_{0} = 0.165$ MeV.</td>
<td>$C_{0} = 1.415$; $C_{1} = -3.397$; $C_{2} = 1.107$; $C_{3} = 0.072$; $C_{4} = 1.337$</td>
</tr>
<tr>
<td>$Q(E)$</td>
<td>Fixed</td>
<td>Quenching term summarizing the effects related to nonlinearity of the scintillator response according to Birk’s quenching model [18]; $Q(E, k_{B}) = \frac{E^{2}}{E_{0} + k_{B}E/E_{0}}$, where $k_{B}$ is the Birk’s constant, and $Q(E)$ can be parameterized as: $Q(E, k_{B}) = \frac{k_{B}}{1 + k_{B}E/E_{0}}$, fixed from the fit of $N_{p}$ vs $E$ with MC simulation of $\gamma$ calibration data.</td>
<td>$k_{B}[cm/MeV] = 0.0109$; $A_{1} = 0.972$; $A_{2} = 0.201$; $A_{3} = 0.0105$; $A_{4} = 0.195$; $A_{5} = 0.014$</td>
</tr>
<tr>
<td>$v_{1}$</td>
<td>Fixed</td>
<td>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 LEER.</td>
<td>0.16</td>
</tr>
<tr>
<td>$v_{p}^{'}$</td>
<td>Free</td>
<td>Spatial nonuniformity of the number of triggered PMTs.</td>
<td>$0.50 \pm 0.37$</td>
</tr>
<tr>
<td>$v_{n}$</td>
<td>Free</td>
<td>Scintillator intrinsic resolution parameter for $\beta_{b}$ (caused by $\delta$-electrons) that also effectively takes into account other contributions at low energies.</td>
<td>$11.5 \pm 1.0$</td>
</tr>
<tr>
<td>$v_{p}^{'}$</td>
<td>Fixed</td>
<td>Nonuniformity of the light collection, calculated from MC events uniformly distributed in FV.</td>
<td>7.0</td>
</tr>
<tr>
<td>$v_{p}$</td>
<td>Free</td>
<td>Spatial nonuniformity resolution, corresponding to the width of $^{37}$Ko-\alpha peak.</td>
<td>$4.73 \pm 0.21$</td>
</tr>
<tr>
<td>$\sigma_{d}$</td>
<td>Fixed</td>
<td>PMT dark noise contribution.</td>
<td>$0.23 N_{p}^{0.6}$, $0.4 N_{p}^{0.6}$</td>
</tr>
</tbody>
</table>

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
  - $\sigma(E) \sim 50$ keV @ 1 MeV
  - $\sigma(r) \sim 10$ 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