Accounting for atmospheric neutrinos background in Borexino's results

Viktor Atroshchenko on behalf of the Borexino collaboration
National Research Center "Kurchatov Institute"

What?

Borexino is a particle physics experiment with a large liquid scintillator neutrinos detector, located in Gran Sasso National Laboratory (LNGS), Italy. Together with its main goal – studying solar neutrinos – the exceptional levels of radiopurity have made it possible to also to produce many other interesting results both within and beyond the Standard Model of particle physics.

Atmospheric neutrinos are generated in decays of secondary particles produced in cosmic rays interactions with atomic nuclei of atmosphere.

$$p(\alpha,\dots) + A \rightarrow \pi^{\pm}(K^{\pm}) + \dots + X$$

$$\pi^{\pm}(K^{\pm}) \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow \begin{matrix} e^{+} + \nu_e + \bar{\nu}_{\mu} \\ e^{-} + \bar{\nu}_e + \nu_{\mu} \end{matrix}$$

Why?

Atmospheric neutrinos interact in many ways with matter, including detector target medium. They have small flux, but potentially *can mimic any event signature.*

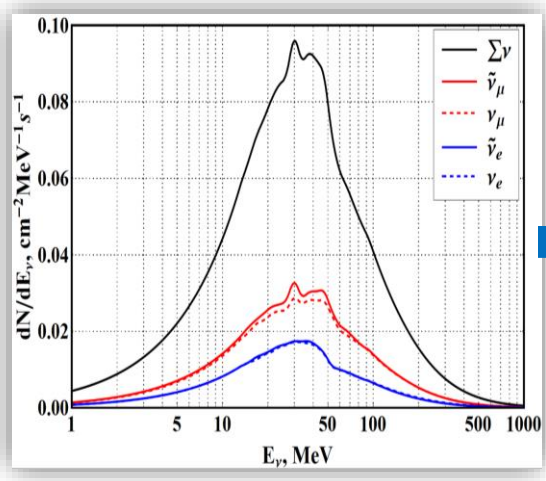
Atmospheric neutrinos are major background for processes with yield of few events per year, such as *diffuse supernova neutrino background* (DSNB) and *geo-neutrinos.*

How?

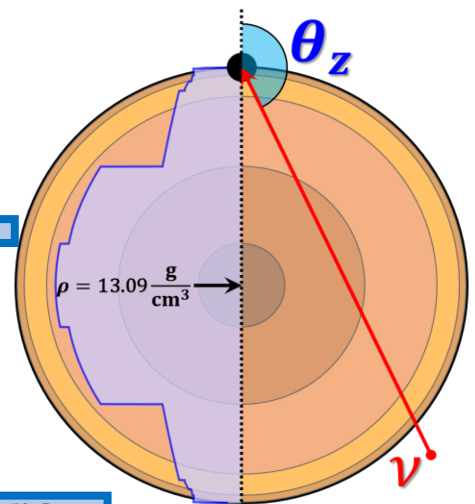
Calculation

Initial fluxes

Combination of HKKM2014 [1] (for energies above 100 MeV) and FLUKA [2] (below 100 MeV) models for LNGS.



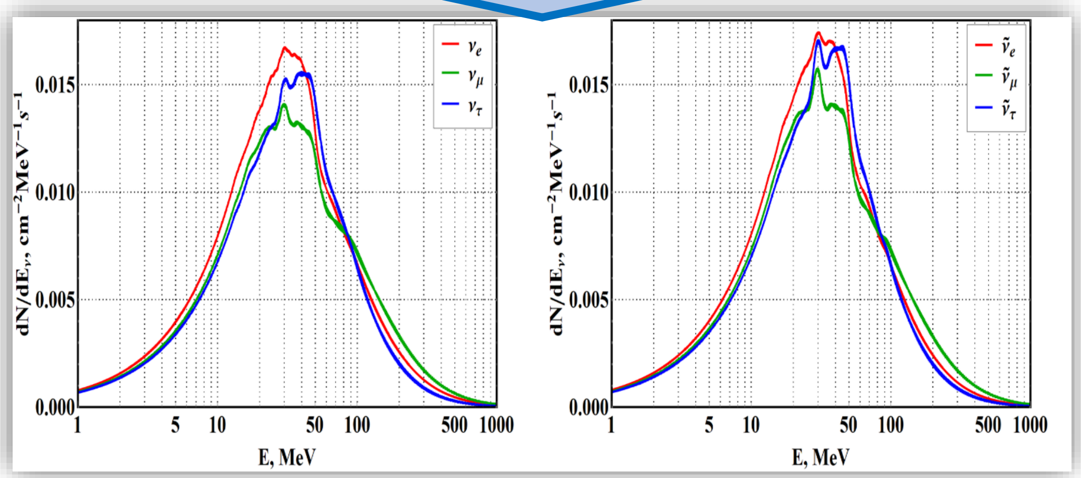
$\nu_e : \nu_\mu : \nu_\tau \approx 1:2:0$



Oscillations + MSW effect

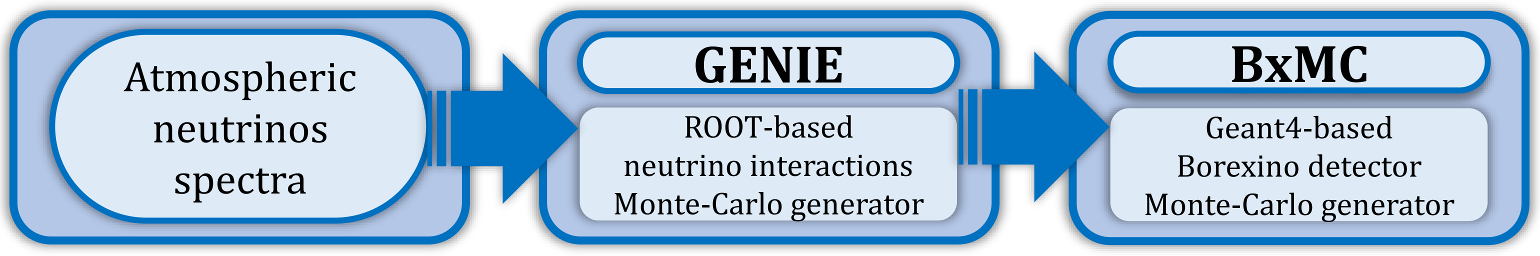
Fluxes in detector

Using ROOT [3] and modified Prob3++ software [4] we developed special software to calculate the neutrinos flavor oscillations during propagation through the Earth.



$\nu_e : \nu_\mu : \nu_\tau \approx 1:1:1$

Simulation



Calculated atmospheric neutrinos spectra are then used in GENIE [5] (version 3.0.0, tune G18_10b) to generate neutrinos interactions with ^{1}H, ^{12}C and ^{13}C nuclei of Borexino target medium. GENIE output final state particles are used as input particles for the BxMC – Borexino Monte-Carlo [24] that allows us to reproduce the detector response.

Events selection

"Normal" IBD	$\bar{\nu}_e + p \rightarrow n + e^{+}$
"Fake" IBD	$\nu + A \rightarrow \nu + n + \dots + X$

Inverse beta decay (IBD) is a good reaction to detect neutrinos, even if only $\bar{\nu}_e$. Both it has high cross-section and provides very clear event signature of the space-time coincidence of prompt and delayed signals. Positron gives prompt signal by scattering and annihilation. Neutron looses its energy on protons and then is thermalized. After an average time of ~260 μs it is captured by proton, with emission of 2.2 MeV gamma, what gives the delayed signal. Atmospheric neutrinos can mimic this signature mostly in neutral current interactions with one or more neutrons produced.

Since our simulation software provides the same data format as used for the real data from detector, by using real data analysis algorithms we've automatically applied the same event selection criteria, which described in detail in [6, 7].

Uncertainties

The uncertainty comes mostly from two sources. Atmospheric fluxes are known with ~25% precision [1, 2]. To quantify the uncertainty related to the interaction cross sections we repeated the calculation by using GENIE version 2.12.10 and the rest of the simulation chain unchanged: the expected number of events decreased by 36%, probably because of the cross sections and intranuclear cascade models' differences between GENIE versions. To account for other small and unknown uncertainty sources, and assuming that these uncertainties are independent, we consider a conservative *uncertainty of 50%.*

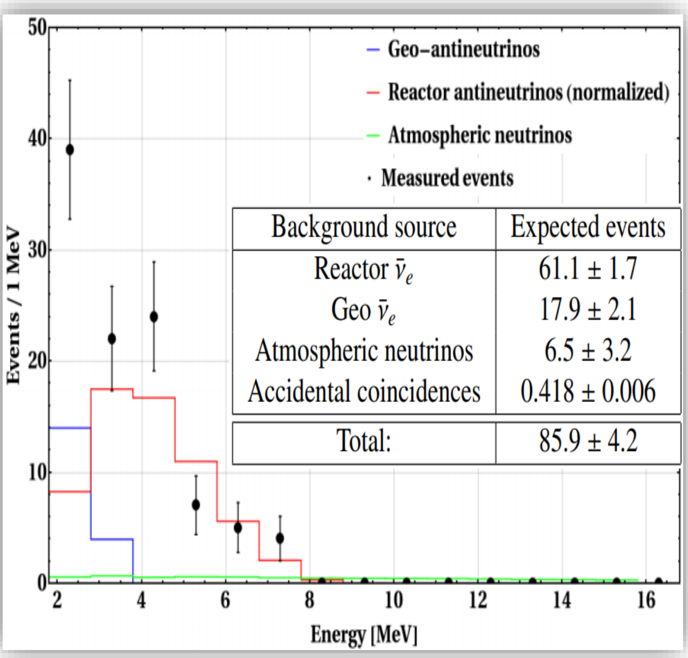
References:

[1] M. Honda, et al., Phys. Rev. D 92 (2015) 023004
[2] G. Battistoni, et al., Astropart. Phys. 23 (2005) 526
[3] R. Brun, F. Rademakers, Nucl. Inst. & Meth. in Phys. Res. A 389 (1997) 81-86; https://root.cern
[4] R. Wendell, http://www.phy.duke.edu/~raw22/public/Prob3++/ (2012)
[5] C. Andreopoulos et al., Nucl. Instrum. Meth. A 614 (2010) 87
[6] M. Agostini et al., Search for low-energy neutrinos from astrophysical sources with Borexino, Astropart. Phys. 125 (2021) 102509
[7] M. Agostini et al., Comprehensive geoneutrino analysis with Borexino, Phys. Rev. D 101, 012009 (2020)

Results

DSNB-search

Measured IBD candidate events and expected backgrounds



Observed events, expected background events and 90% C.L. upper limits on the $\bar{\nu}_e$ DSNB flux. Without or (with) atmospheric neutrinos contribution

E[MeV]	N_{ev}	N_{bkg}	$\Phi[cm^{-2}s^{-1}]$
1.8	39	22.4 (23.0)	$1.40\ (1.37) \times 10^{5}$
2.8	22	21.5 (22.2)	$1.07\ (1.00) \times 10^{4}$
3.8	24	16.7 (17.2)	$8.39\ (8.13) \times 10^{3}$
4.8	7	10.9 (11.5)	$6.92\ (7.07) \times 10^{2}$
5.8	5	5.55 (6.10)	$8.08\ (7.21) \times 10^{2}$
6.8	4	2.04 (2.52)	$8.29\ (7.68) \times 10^{2}$
7.8	0	0.28 (0.72)	$2.02\ (1.65) \times 10^{2}$
8.8	0	0.01 (0.44)	$1.75\ (1.44) \times 10^{2}$
9.8	0	0.00 (0.41)	$1.40\ (1.17) \times 10^{2}$
10.8	0	0.00 (0.39)	$11.4\ (9.59) \times 10^{1}$
11.8	0	0.00 (0.35)	$9.50\ (8.12) \times 10^{1}$
12.8	0	0.00 (0.32)	$8.05\ (7.01) \times 10^{1}$
13.8	0	0.00 (0.31)	$6.91\ (6.03) \times 10^{1}$
14.8	0	0.00 (0.27)	$6.00\ (5.34) \times 10^{1}$
15.8	0	0.00 (0.24)	$5.27\ (4.74) \times 10^{1}$

Geo-ν analysis

Expected number of atmospheric $\bar{\nu}_e$ events	
Energy range [p.e.]	Signal [events]
408-1500	2.2±1.1
408-4000	3.3±1.6
408-8000	9.2±4.6

We estimate the respective systematic uncertainty due to atmospheric neutrinos on geoneutrinos as $^{+0.00}_{-0.38}$ % and on reactor antineutrinos as $^{+0.00}_{-3.90}$ %.

Constrained fit of expected spectra shapes to data			
$\bar{\nu}_e$	Fit 0 – without atm. ν	Fit 1 – 4000 p.e.	Fit 2 – 7500 p.e.
Atmospheric	–	4.6±3.2	1.2±4.1
Reactor	91.9±1.6	89.0±11.3	~ unchanged
Geo	many values (model dependent)	~ unchanged	~ unchanged