Current status of LVD experiment

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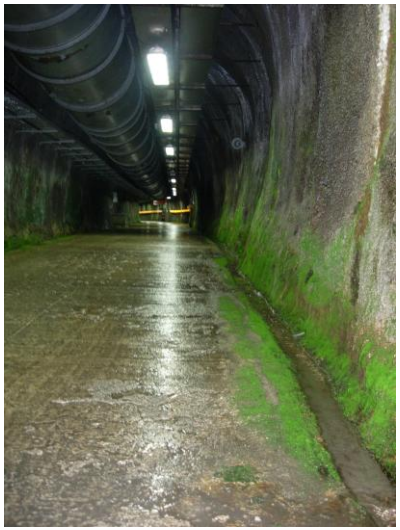
LVD - Multi-Purpose Detector

1. Search for neutrinos from supernovae
- Registration of neutrinos from collapses of stellar cores
- Latest results

2. Muon physics
- depth-intensity curve, muon charge ratio
- reconstruction of multiple events
- muon intensity variations

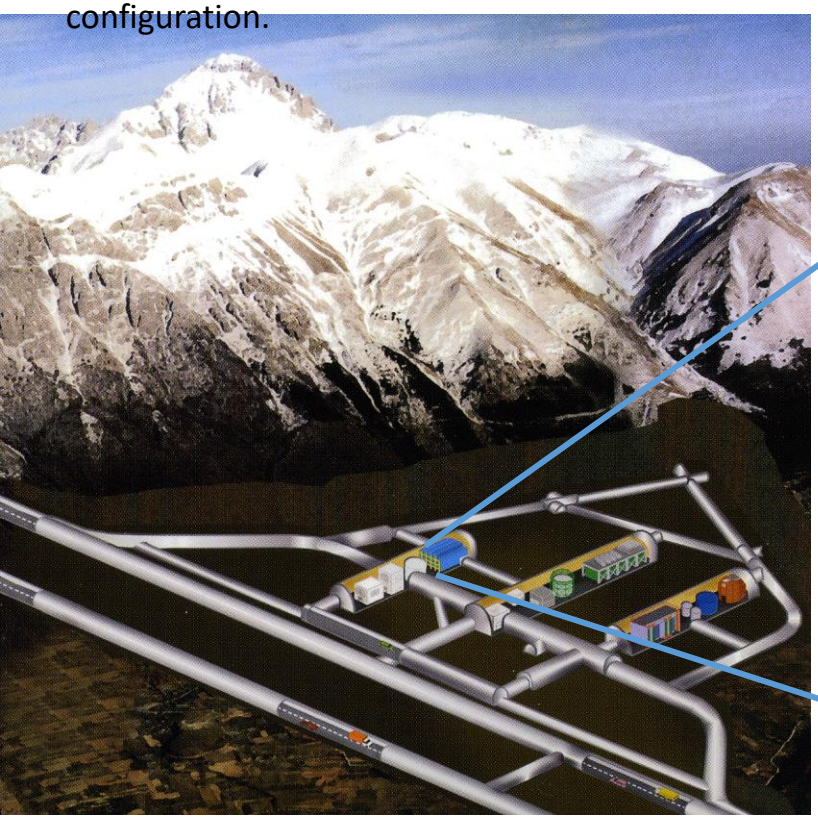
3. Neutron physics
- neutron yield from muons
- neutron variations

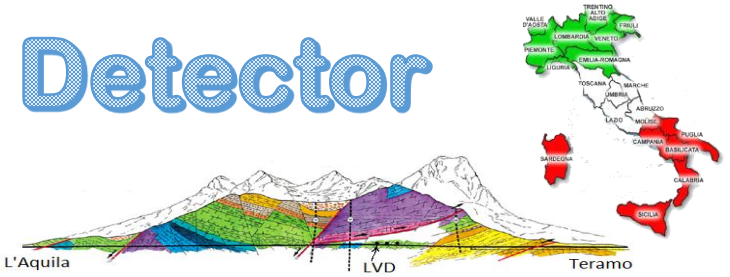
4. Detector gamma background
- background variations
- earthquake prediction



LVD - Large Volume Detector

LNGS Underground Laboratory (H=3620 m w.e.), Gran Sasso, Italy.
The detector has been operating since 1991, since 2001 in full configuration.



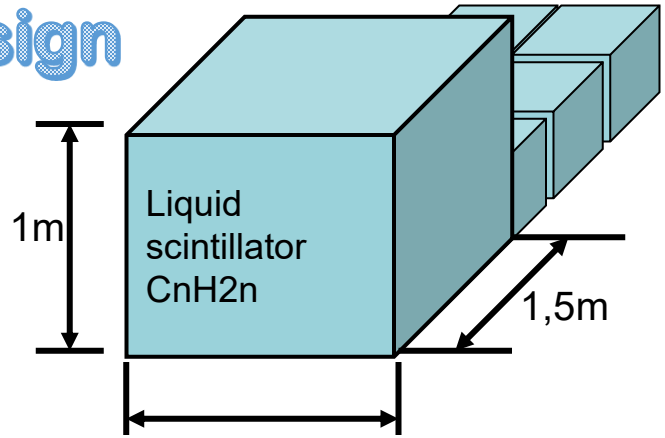


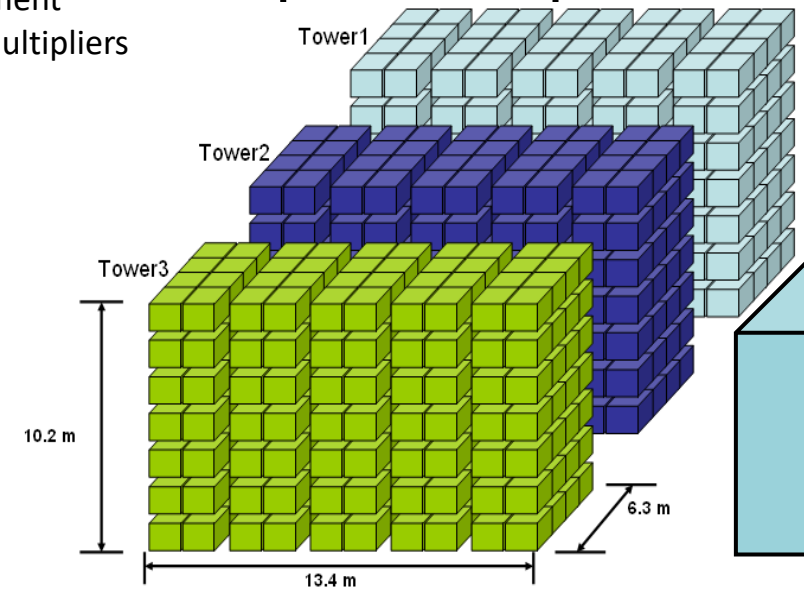
The main goal of LVD is searching for neutrino radiation from stellar core collapse.

22×13×10 m
M_{Fe}=1020 t
M_{sc}=1008 t
counters=840
H=3620 m w.e.
E_{μ}=280 GeV
$E_{s.l.}$=1.3 TeV
CR_{μ}~ 120 h^{-1}
ε_{th} = 4 MeV

LVD design

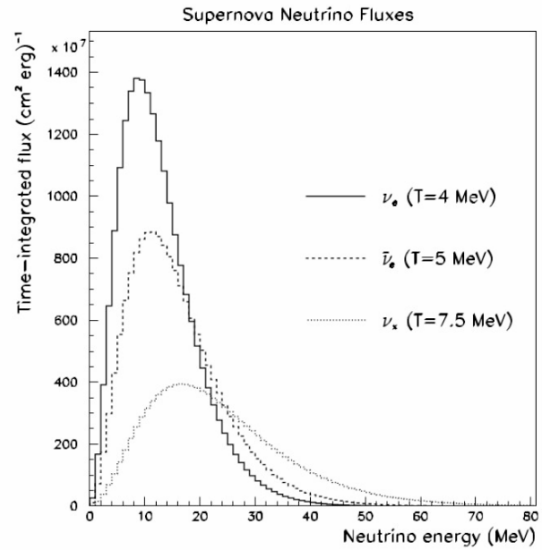
- modular structure
- main element
- 3 photomultipliers

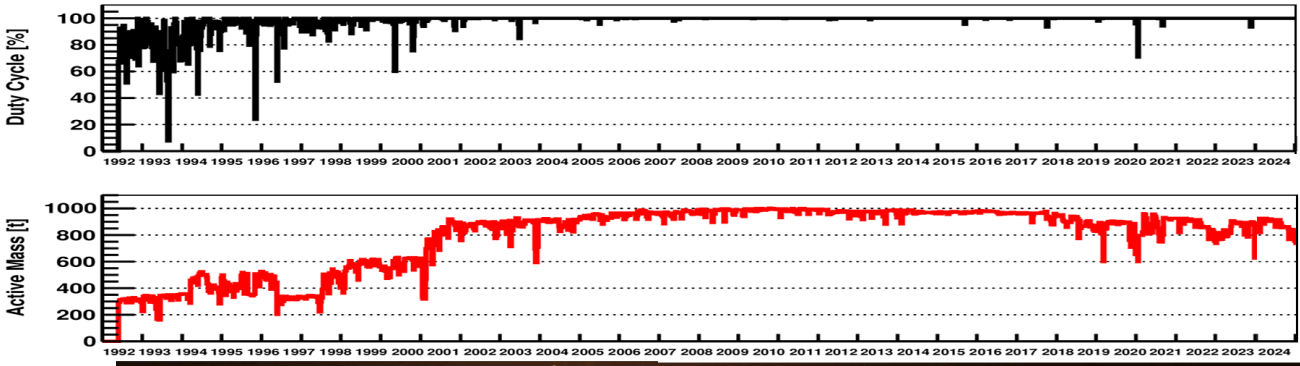


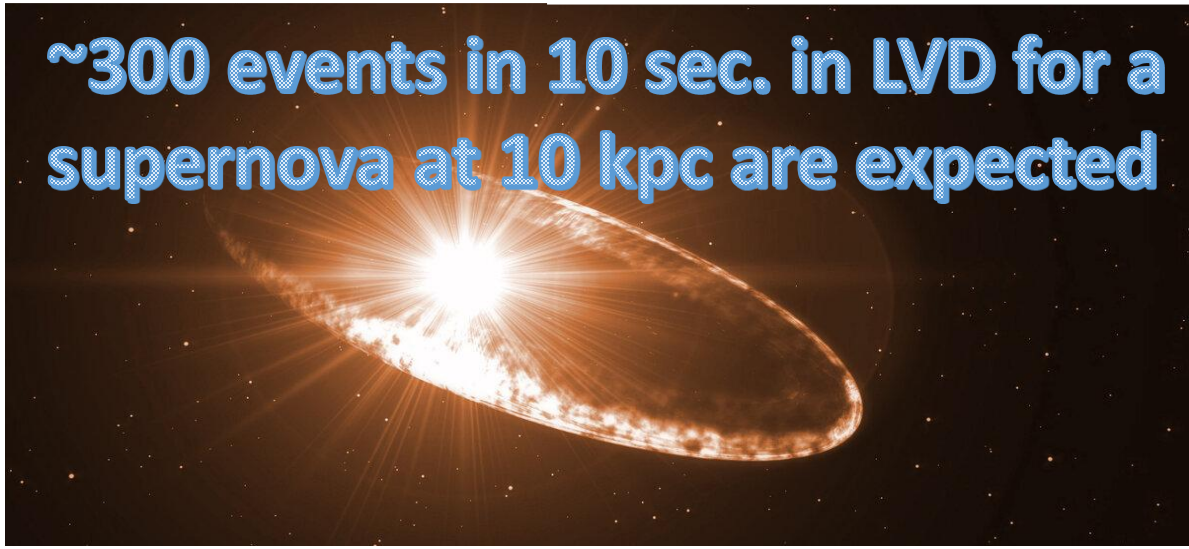


Neutrino burst from supernova

The LVD has been operating under the program to search for neutrinos from the collapse of stellar cores in our galaxy since 1992.







Core-collapse of stars with mass M>8 M_{sun}
ν and anti-ν of all flavours are produced.
Duration of the burst is O(10 s).

$\langle E\nu_e \rangle \sim$ 10-12 MeV

$\langle E\bar{\nu}_e \rangle \sim$ 12-18 MeV

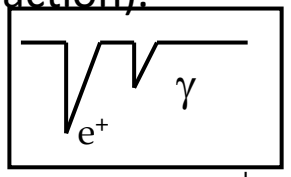
$\langle E\nu_{\mu\tau} \rangle \sim$ 15-25 MeV

The neutrino interaction channels in LVD

	ν Interaction Channel	E_ν Threshold	%
1	$\bar{\nu}_e + p \rightarrow e^+ + n$	(1.8 MeV)	(88%)
2	$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	(17.3 MeV)	(1.5%)
3	$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	(14.4 MeV)	(1.0%)
4	$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C^* + \gamma$	(15.1 MeV)	(2.0%)
5	$\nu_i + e^- \rightarrow \nu_i + e^-$	(-)	(3.0%)
6	$\nu_e + {}^{56}Fe \rightarrow {}^{56}Co^* + e^-$	(10. MeV)	(3.0%)
7	$\bar{\nu}_e + {}^{56}Fe \rightarrow {}^{56}Mn + e^+$	(12.5 MeV)	(0.5%)
8	$\nu_i + {}^{56}Fe \rightarrow \nu_i + {}^{56}Fe^* + \gamma$	(15. MeV)	(2.0%)

Note. Cross sections of different interactions are obtained referring to Strumia & Vissani (2003) for interaction 1, Fukugita et al. (1988) for interactions 2–4, Bahcall et al. (1995) for interaction 5, and Kolbe & Langanke (2001) and Toivanen et al. (2001) for interactions 6–8.

The main reaction of antineutrino interaction is the inverse beta decay (Cowan-Reines reaction).



$$\tilde{\nu}_e + p \rightarrow e^+ + n$$

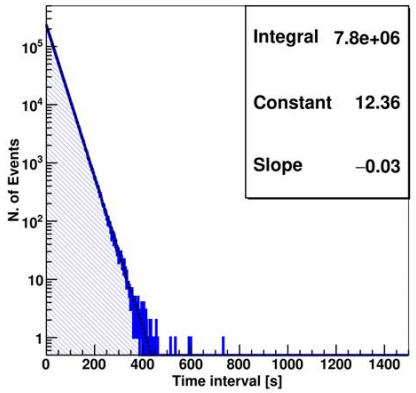
$$n + p \rightarrow d + \gamma$$
$$n + {}^{56}Fe \rightarrow {}^{57}Fe + \Sigma\gamma$$

$\tau \cong 150\mu s$

Due to the presence of carbon and iron nuclei in detector composition, the LVD is also sensitive to neutrinos of all flavors.

Data selection and method for Searching for neutrino bursts

All triggers with energy in **[10,100] MeV** are included in the dataset



After quality cuts are applied, **the background is well described by Poisson statistics** with event rate $f_{bk} = 3*10^{-2}$ s^{-1}

The basis of the search for ν bursts is the identification of events clusters with a low probability of simulating events due to background fluctuations.
Any cluster with imitation frequency less then 10^{-2} / year is a neutrino burst candidate

A cluster is a set of *m* events in a time window Δt (up to Δt_{max} = 100 s)

For each cluster *i* we calculate the frequency with which it can be produced by background fluctuactions (Imitation Frequency) $F_{im,i}$ [3]

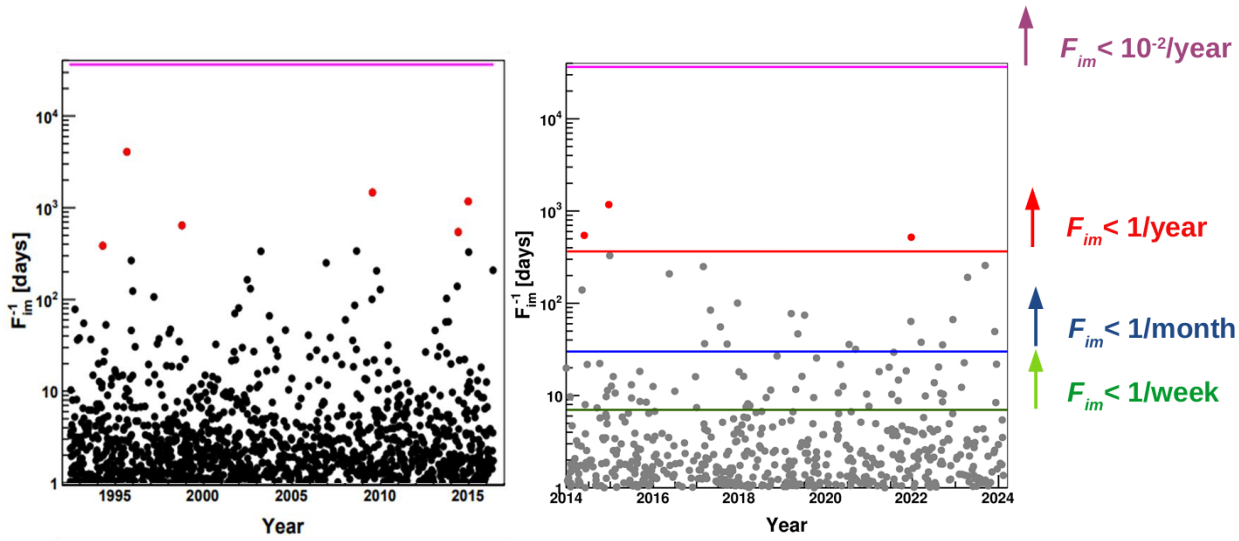
$$F_{im_i} = f_{bk}^2 \Delta t_{max} \sum_{k \geq m_i - 2} P(k, f_{bk} \Delta t_i)$$

Where f_{bk} is the event rate and *P* is the Poisson probability

Statistical selection

Any cluster with $F_{im} < 10^{-2}$ / year is a neutrino burst candidate

Latest results of the search for neutrino bursts in the LVD



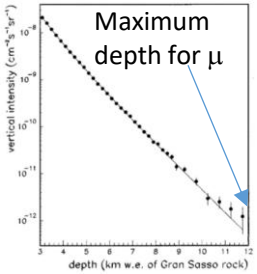
Clusters with F_{im} < 1/day detected vs time (2014 – 2024).
Clusters with high significance are marked in red (**with F_{im} < 1/year)**

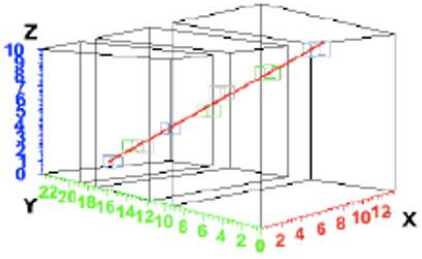
Analysis of the LVD data taking period **from 2014 to 2024.**
The LVD active mass has been M > 300 t for 3711 days , exposure 8.86 kt*y , <M>= 871 t
A total of ~17 M clusters are found, of which:
497 with Fim < 1/day,
77 with Fim < 1/week,
24 with Fim < 1/month,
3 with Fim < 1/year

Inspection of the 3 clusters with F_{im} < 1/year: Energy spectrum, temporal distribution of events and number of low energy signals following a trigger are compatible with background characteristics

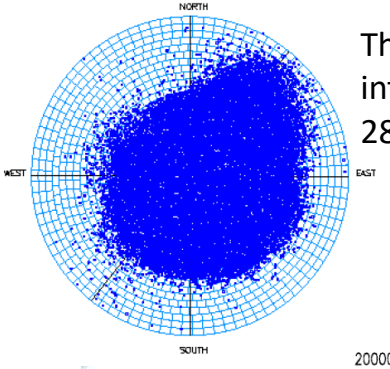
LVD detects muons and muon bundles

Depth-intensity curve



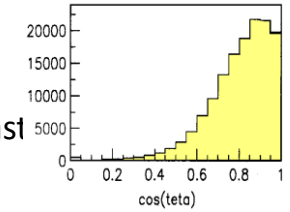


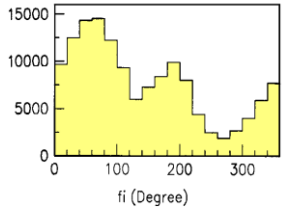
Large θ angles toward the northeast correspond to depths of about 5 km w.e.

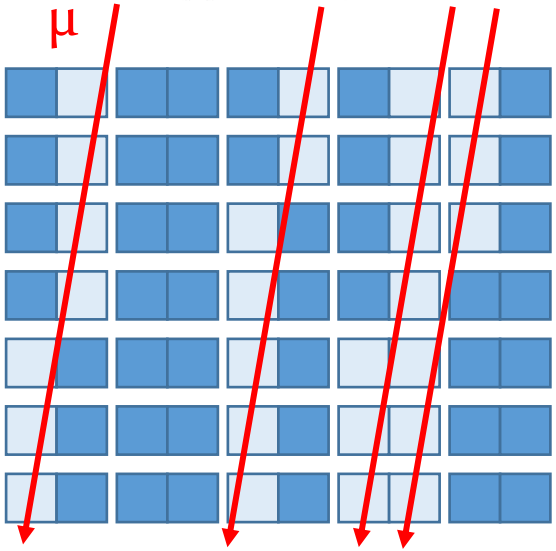


The maximum intensity angle is 28 degrees.

Angular distribution

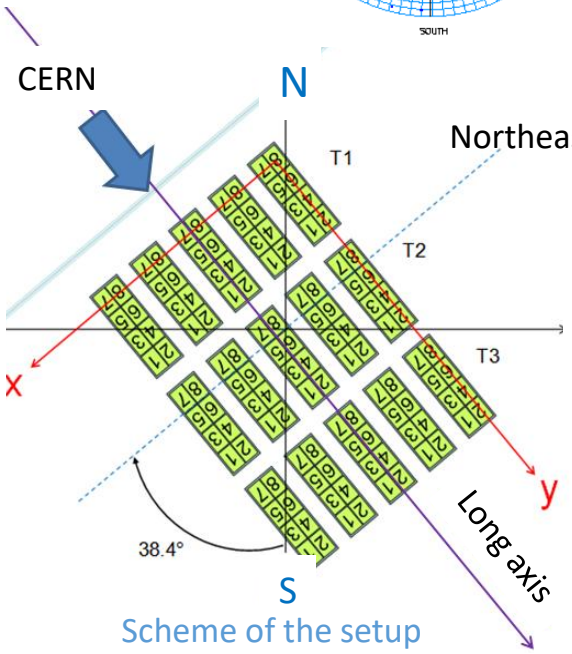






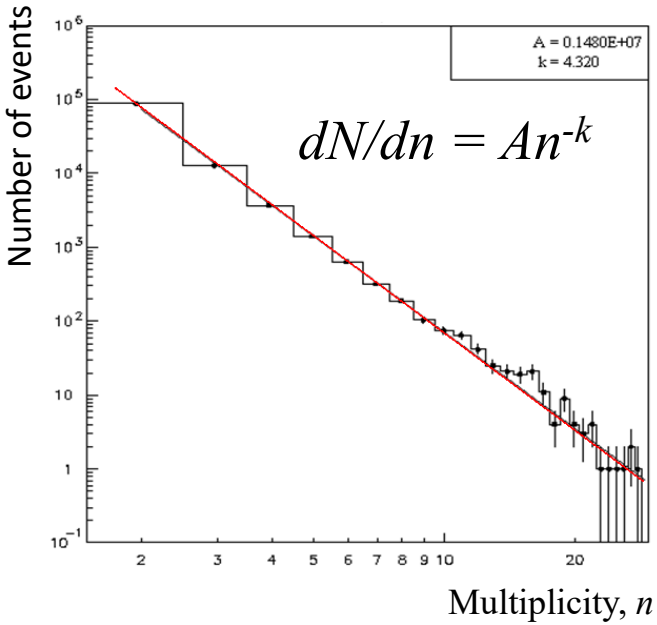
Мюонное событие – группа из 4 мюонов

The direction and multiplicity of muons were reconstructed using the detector's tracking system.



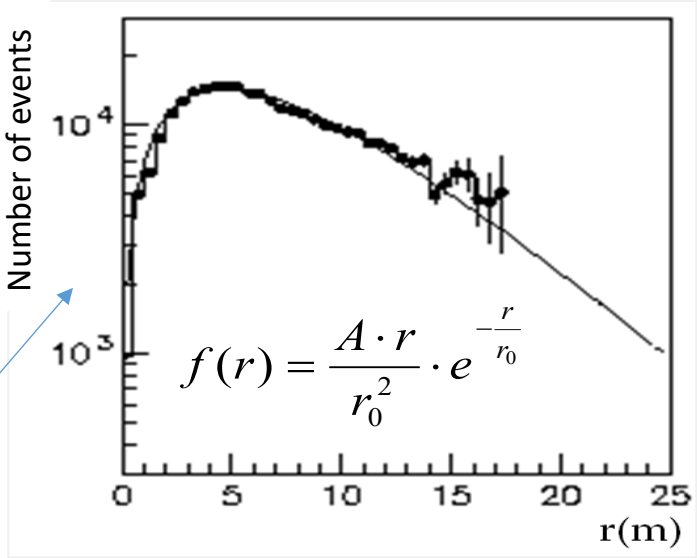
Scheme of the setup

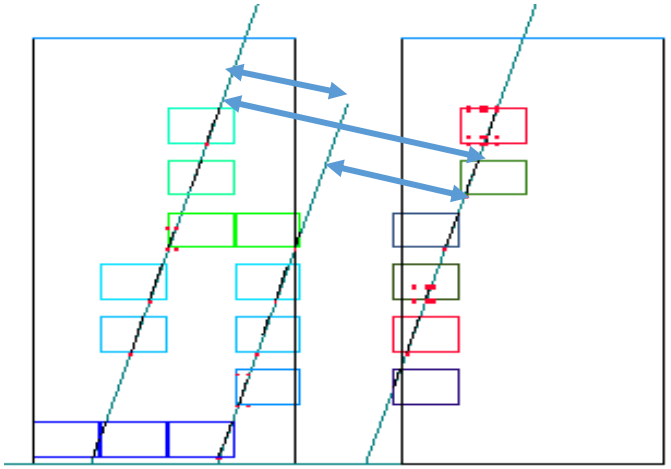
Multiple muon events



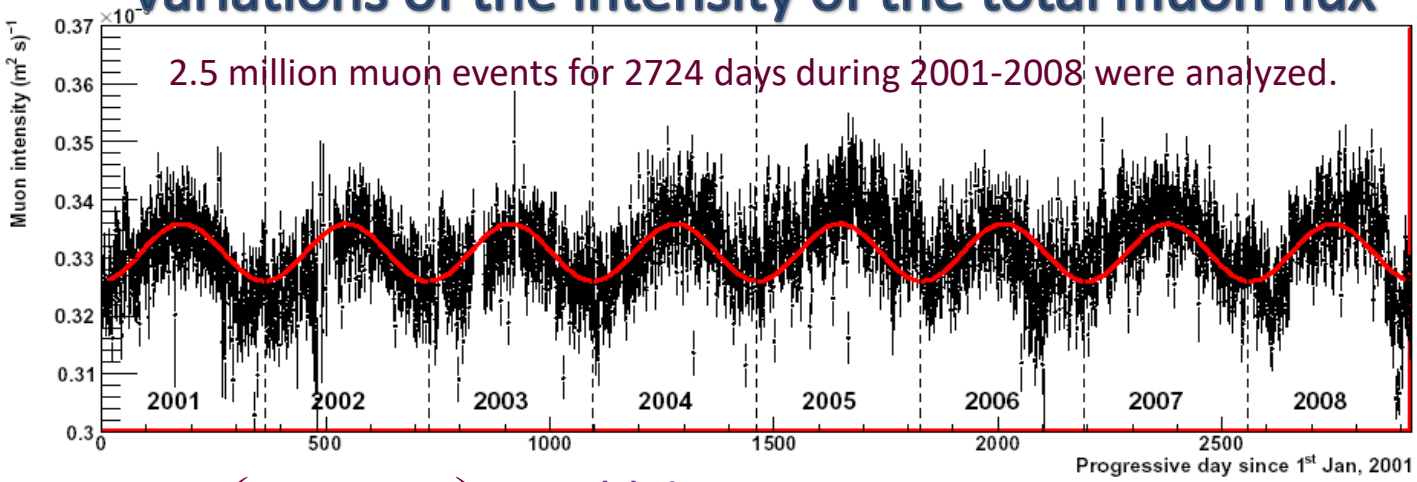
Using the muon event reconstruction program, distribution by muon group multiplicity was obtained. The maximum muon multiplicity through 2 LVD towers is 27 in one event.

Decoherence curve - Distribution of pair combinations by the distance between muons in a pair for all groups





Variations of the intensity of the total muon flux



$$I_\mu = I_0^\mu + \delta I^\mu \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$

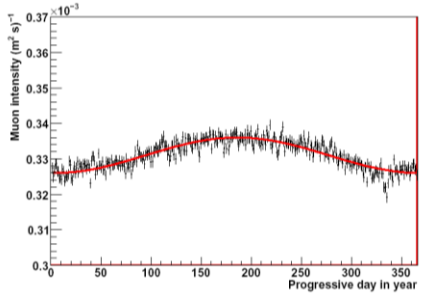
Modulation phase
t_0= 185±15 дней

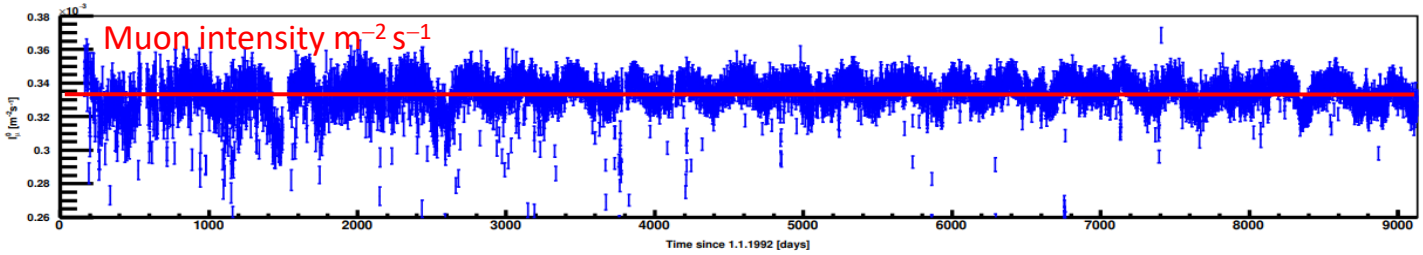
Average intensity
$I_0^\mu = (3.31 \pm 0.03) \cdot 10^{-4}\, м^{-2} c^{-1}$

Modulation value
δI = (1.5±0.1)%

Modulation period
T= 367±15 days

N. Agafonova et al. (LVD Collaboration),// Phys. Rev. D 100, 062002 (2019)



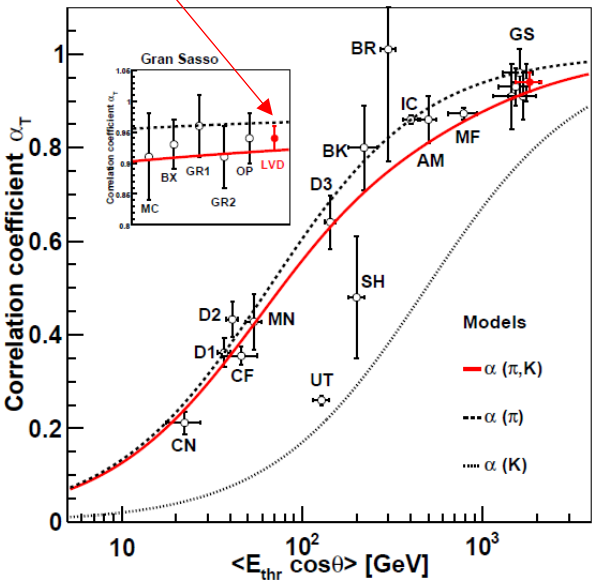


Temperature effect

For high-energy muons (~ 280 GeV), which we are detecting underground, there is a positive temperature effect.

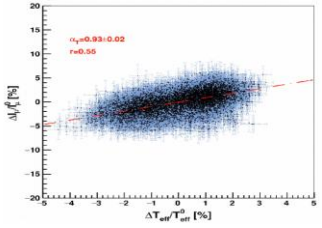
Muons that reach great depths are produced, generally, in the decays of pions of the first generation. The number of these decays increases with the expansion of the atmosphere and the fall of its density in the upper layers (at an altitude of ~ 30 km).

$\alpha_T = 0.93 \pm 0.02$

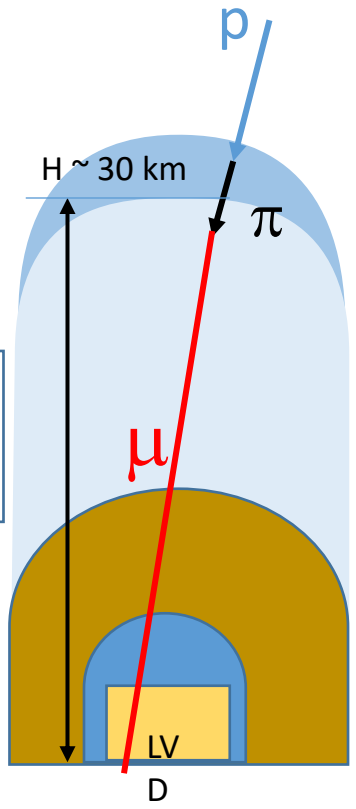


The correlation of the change in the muons intensity and the change in temperature

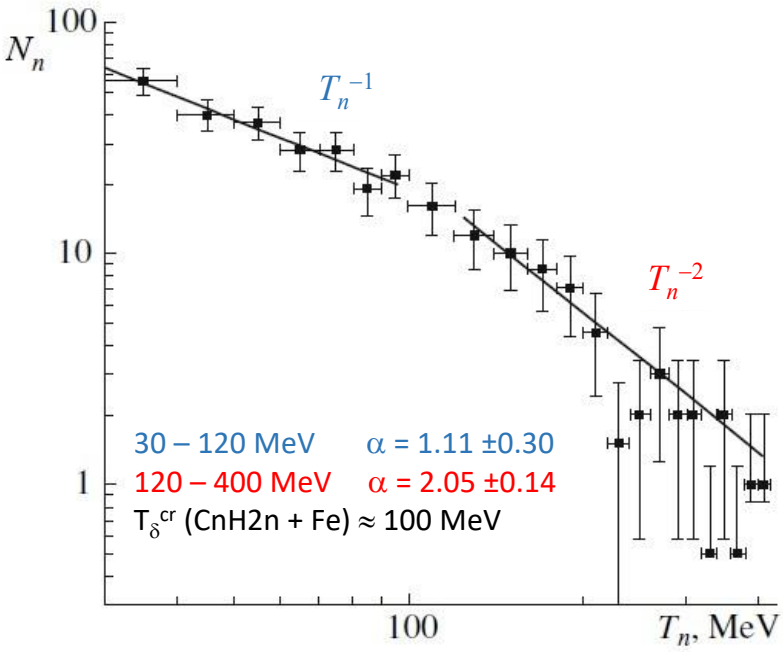
$$\Delta I_\mu / I^0_\mu = \alpha_T \frac{\Delta T_{eff}}{T^0_{eff}}$$



correlation between muon flux and temperature changes

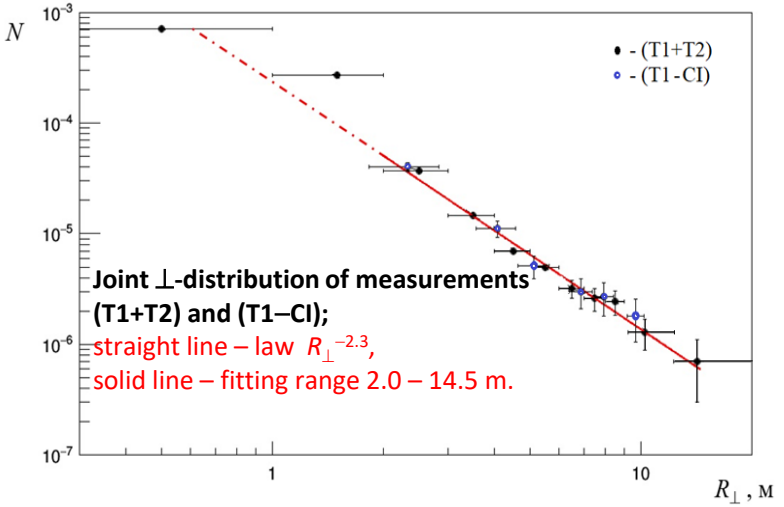


Energy spectrum of neutrons



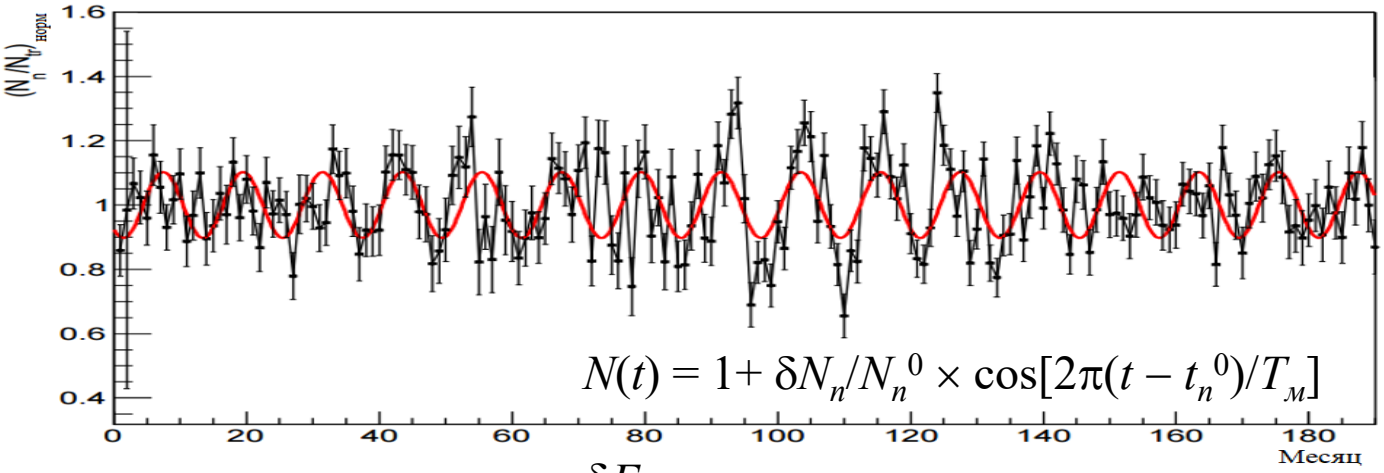
Spectrum of $F^s(T_n)$, measured in the LVD experiment (2009)

Spatial distribution (distance from muon track) of neutrons



The transverse distribution of neutrons in matter at a distance greater than 2 m from the muon track is described by the dependence $R_\perp^{-2.3}$.

Seasonal Variation of neutrons generated by muons



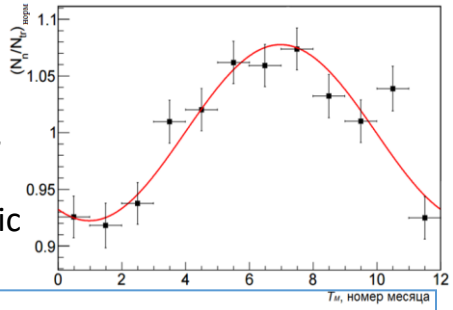
Variations in the specific number of neutrons at LVD over 15 years;
statistical errors of measurements with a step of 1 month are indicated, the curve is the best approximation of the data by a harmonic function

$$\frac{\delta N_n}{N_n} = 7.7\%$$

$$Y_n(E_\mu) \propto E_\mu^{0.78}$$

$$\frac{\delta E}{E_\mu} \sim (1+0.08)^{1/0.78} - 1 = 0.10$$

The amplitude of variations was 7.7%, which allowed us to determine variations in the energy of atmospheric muons underground.



$$E_\mu^{\mathrm{LVD}} = 280 \pm 28 \text{ GeV}$$

N.Yu. Agafonova, A.S. Malgin "On the Mechanism of Temperature Variations in the Average Energy of Muons at Large Depths", JETP, Vol. 132, No 1, pp. 73–78 (January 2021).

Thank you for your attention