The LVD Experiment: 1992 to present

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on behalf the LVD Collaboration

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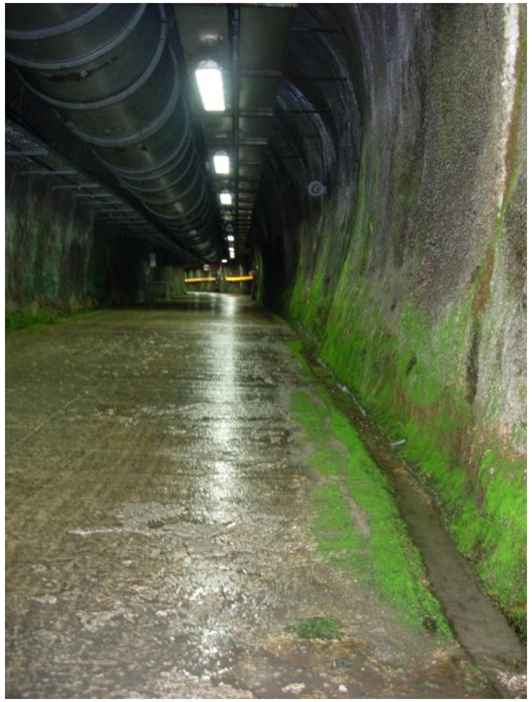
LVD - Multi-Purpose Detector

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

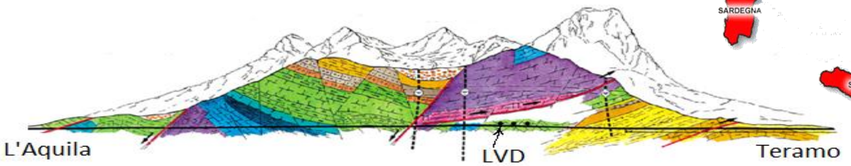
3. Neutron physics
- neutron yield from muons
- neutron variations

4. Detector gamma background
- background variations
- earthquake prediction



LVD - Large Volume Detector

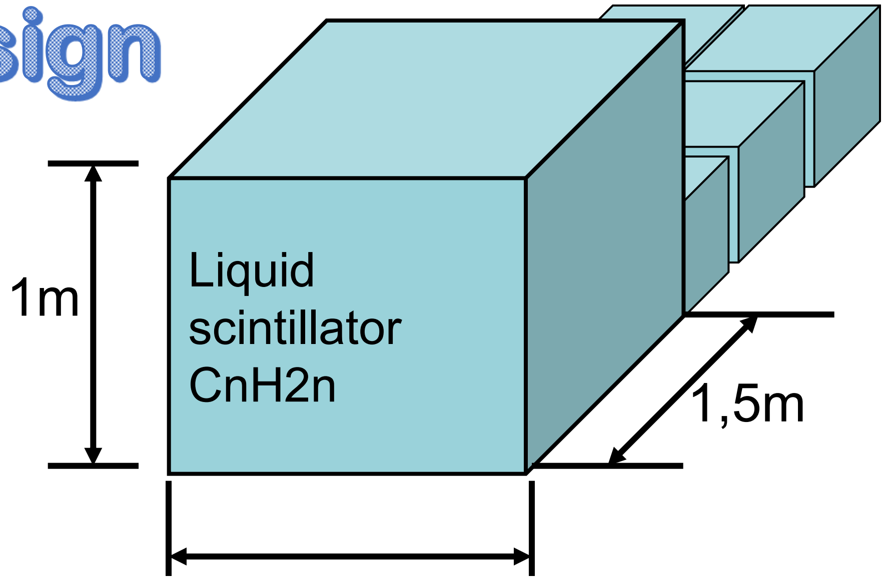
LNGS Underground Laboratory (H=3620 m w.e.), Gran Sasso, Italy.
The detector has been operating since 1991, since 2001 in full configuration.



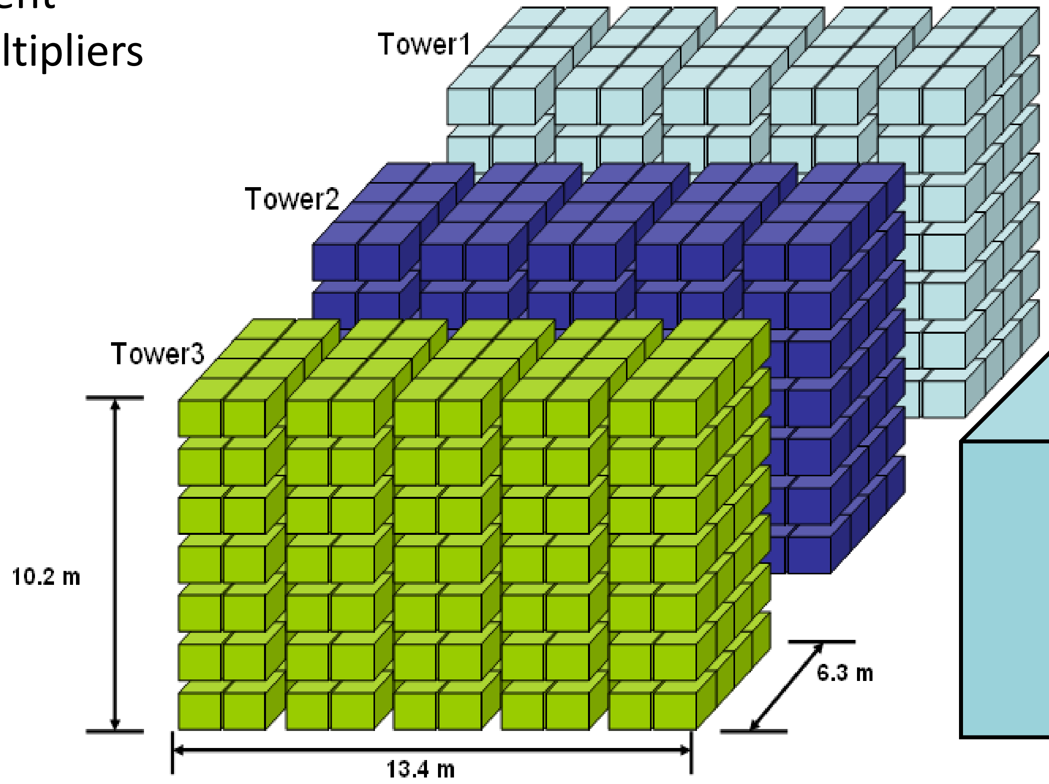
The main goal of LVD is searching for neutrino radiation from stellar core collapse.

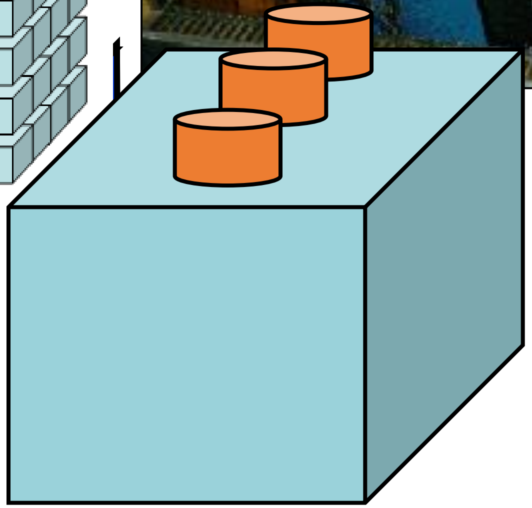
22×13×10 m
M_{Fe}=1020 t
M_{sc}=1008 t
counters=840
H=3620 m w.e.
E_{μ}=280 GeV
$E_{s.l.}$=1.3 TeV
CR_{μ}~ 120 h^{-1}
ε_{th} = 4 MeV

LVD design



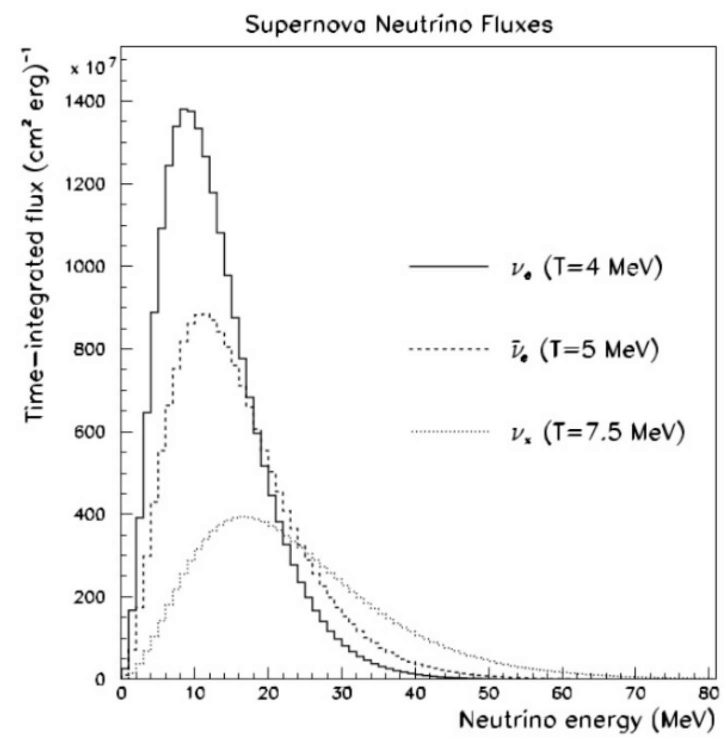
- modular structure
- main element
- 3 photomultipliers

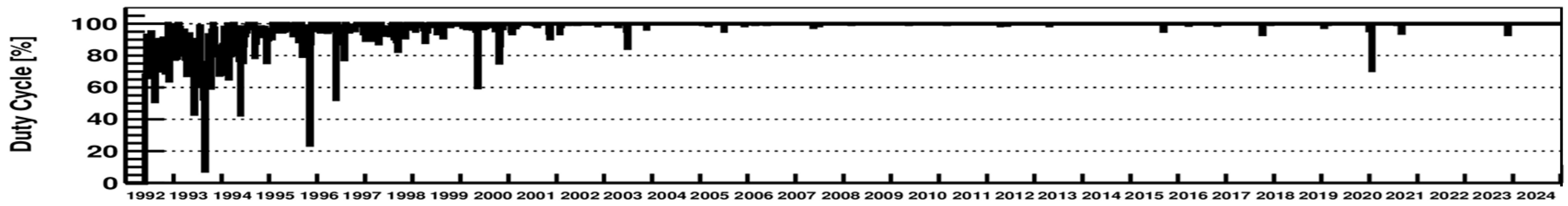


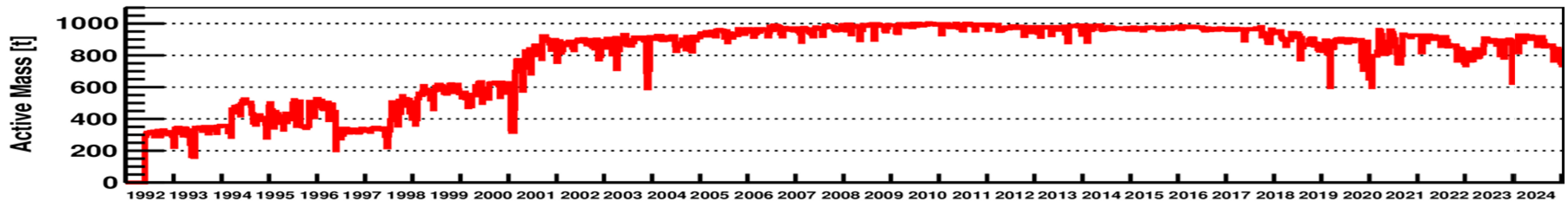


Neutrino burst from supernova

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







~300 events in 10 sec. in LVD for a supernova at 10 kpc are expected

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).

$<E\nu_e> \sim$ 10-12 MeV

$<E\bar{\nu}_e> \sim$ 12-18 MeV

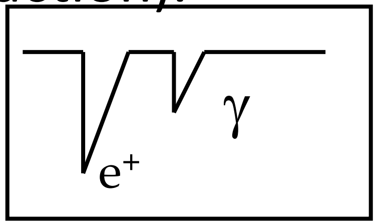
$<E\nu_{\mu\tau}> \sim$ 15-25 MeV

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).



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

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

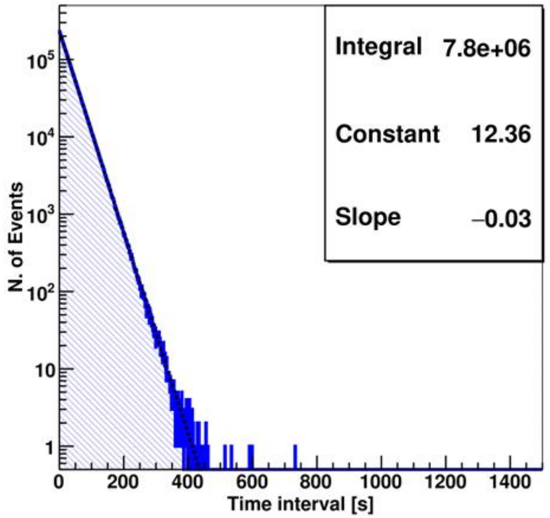
$\tau \cong 150\mu s$

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

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

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} = $3 \cdot 10^{-2}$ s^{-1}

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]

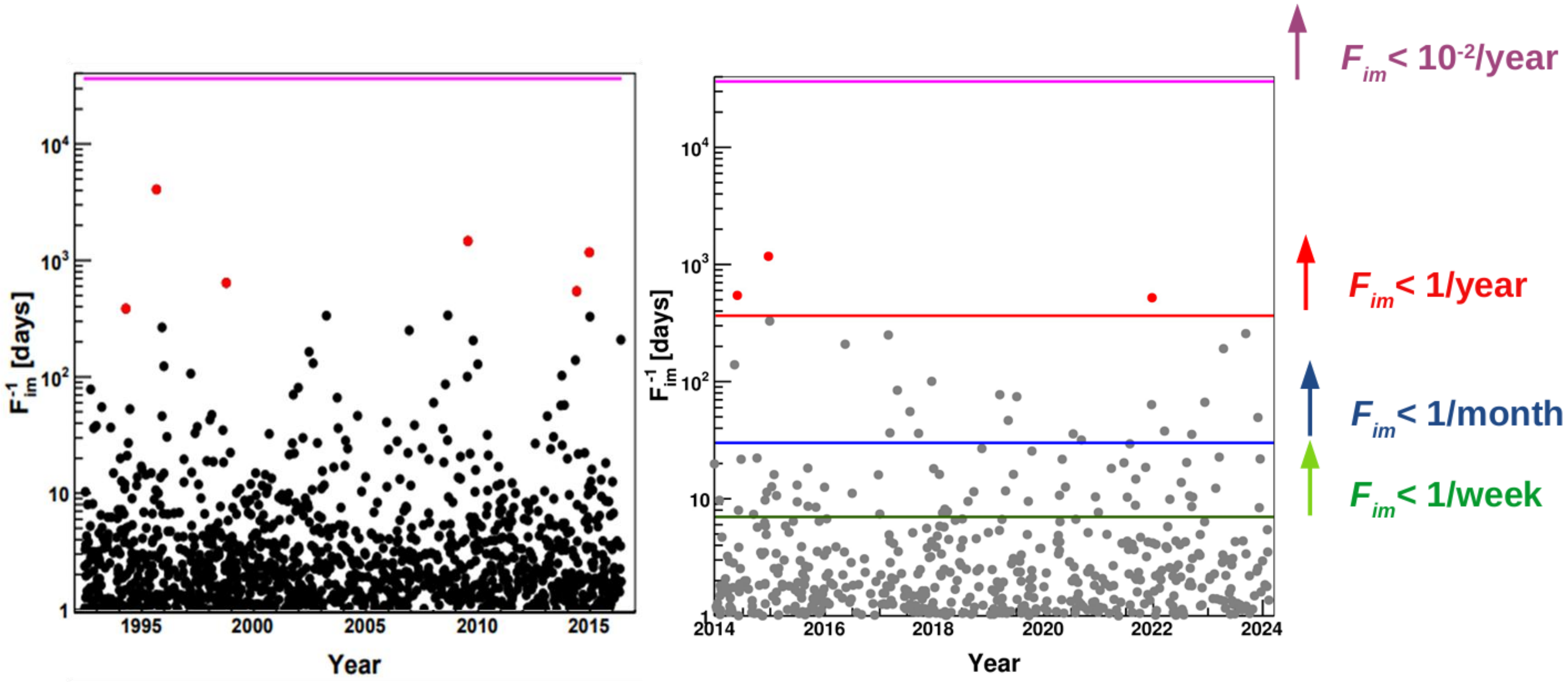
$$F_{im_i} = f_{bk}^2 \Delta t_{max} \sum_{k \geq m_i - 2} P(k, f_{bk} \Delta t_i)$$

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



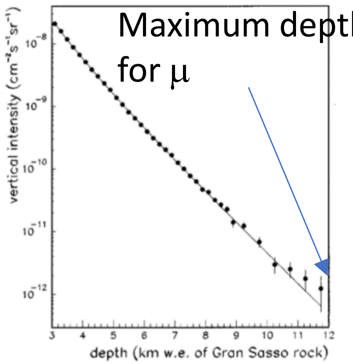
Analysis of the LVD data taking period **from 2014 to 2024.**
The LVD active mass has been M > 300 t for 3711 days , exposure 8.86 kt*y , <M>= 871 t
A total of ~17 M clusters are found, of which:
497 with Fim < 1/day,
77 with Fim < 1/week,
24 with Fim < 1/month,
3 with Fim < 1/year

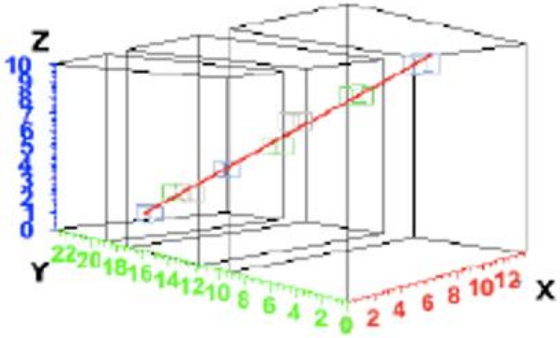
Clusters with F_{im} < 1/day detected vs time (2014 – 2024).
Clusters with high significance are marked in red (**with F_{im} < 1/year)**

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

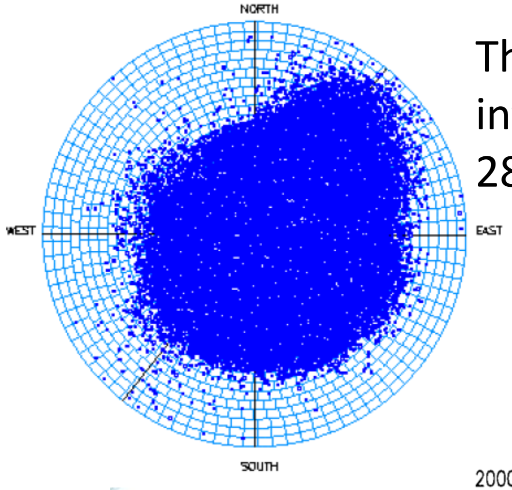
LVD detects muons and muon bundles

Depth-intensity curve



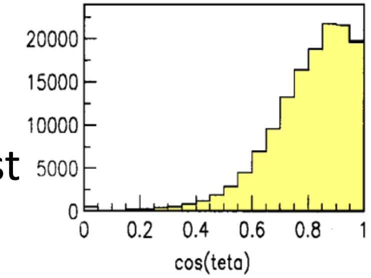


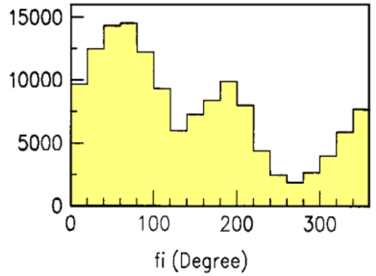
Large θ angles toward the northeast correspond to depths of about 5 km w.e.

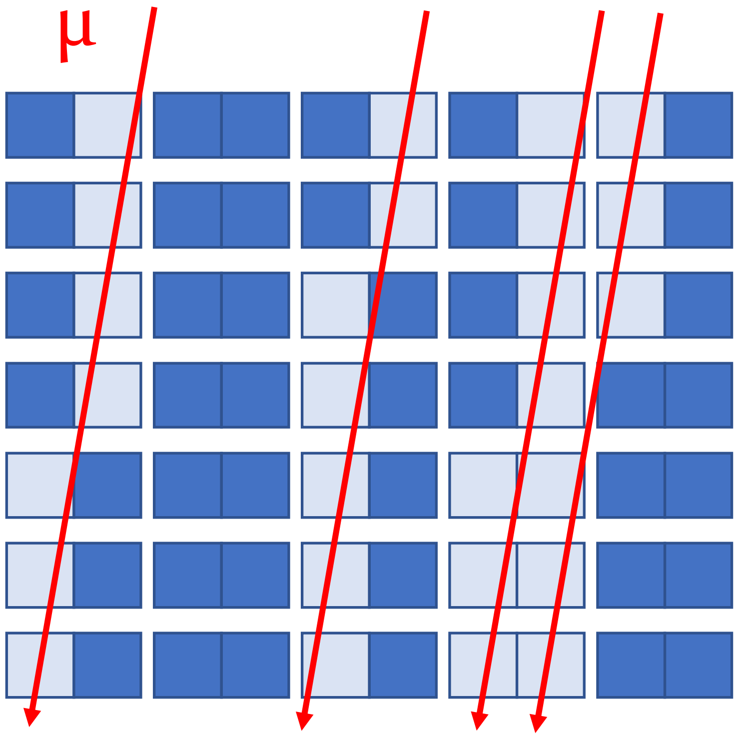


The maximum intensity angle is 28 degrees.

Angular distribution

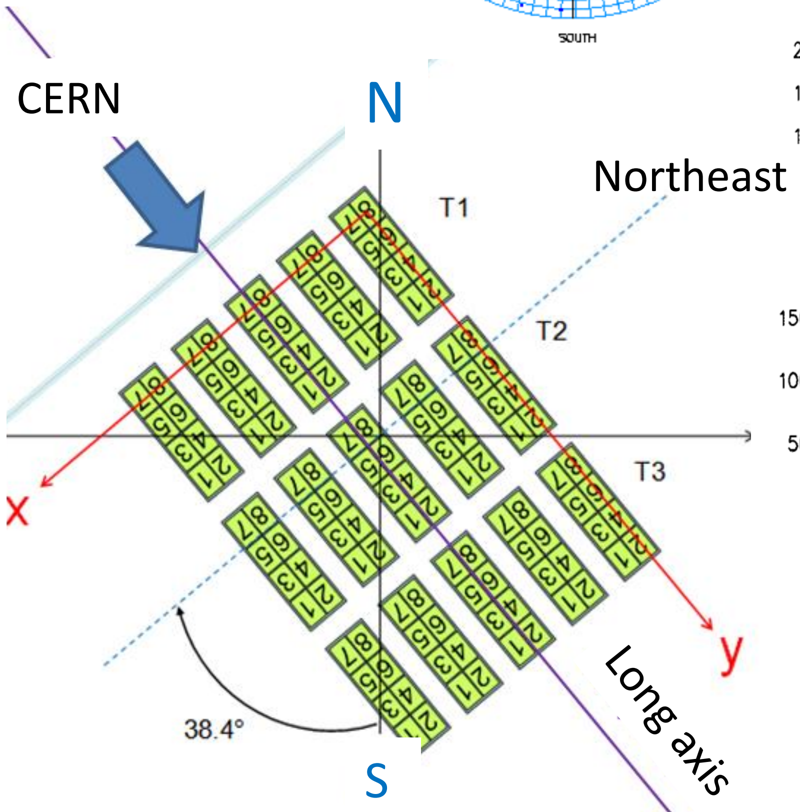






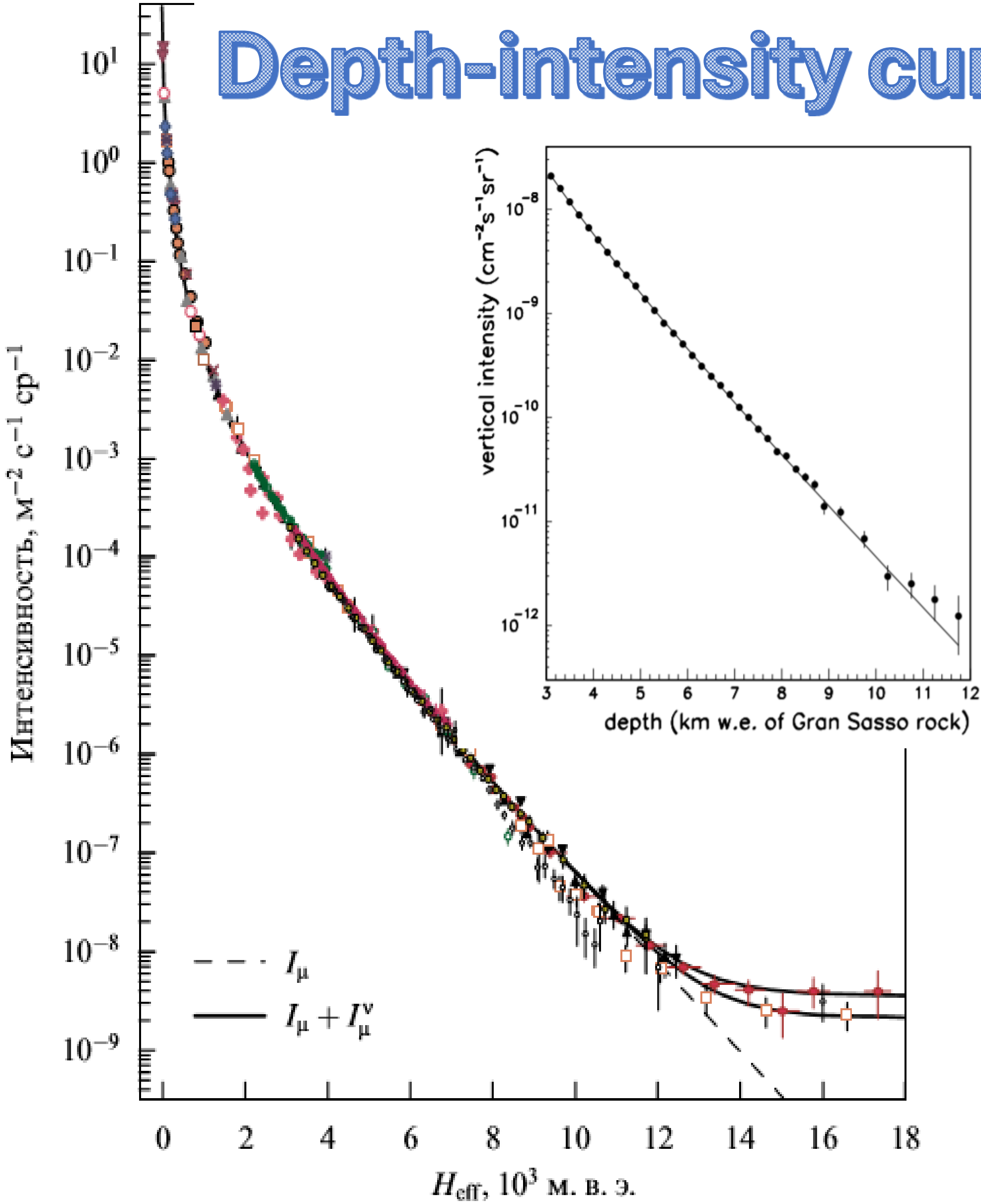
Мюонное событие – группа из 4 мюонов

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

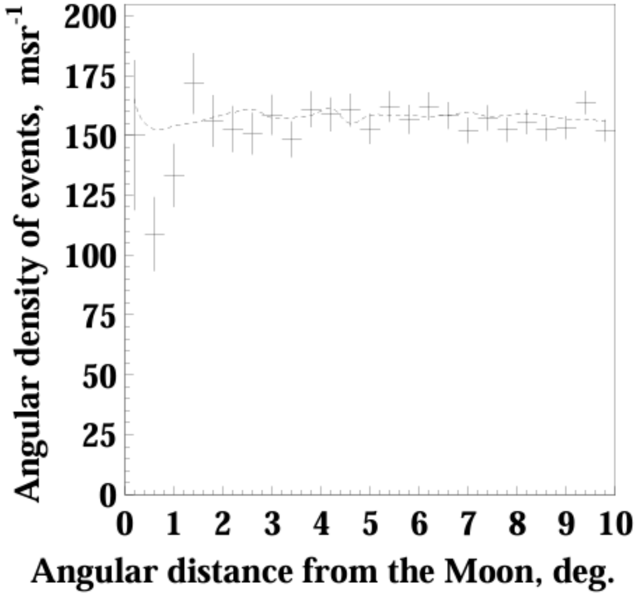


Scheme of the setup

Depth-intensity curve



*M. Aglietta et al. (LVD Collaboration) Muon "depth-intensity" relation measured by the LVD underground experiment and cosmic-ray muon spectrum at sea level Phys. Rev. D **58**, 092005 – Published 1 October 1998*



Moon shadow

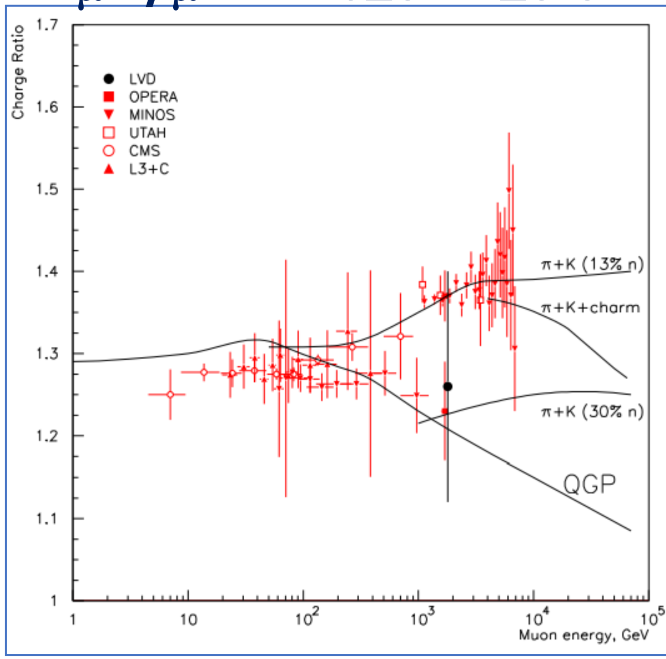
We used the shadowing of cosmic rays by the Moon to confirm the pointing accuracy of the LVD detector.

Charge ratio

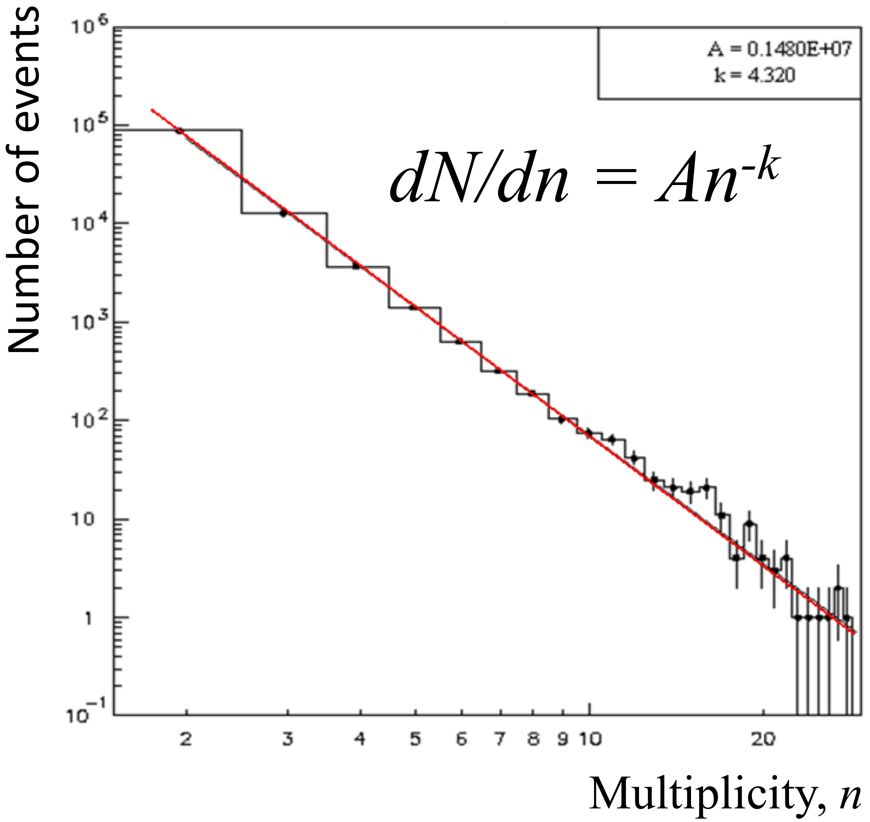
of vertical cosmic ray muons with E > 1.3 TeV at sea level

LVD Collaboration // Proc. of 31st ICRC, 2009

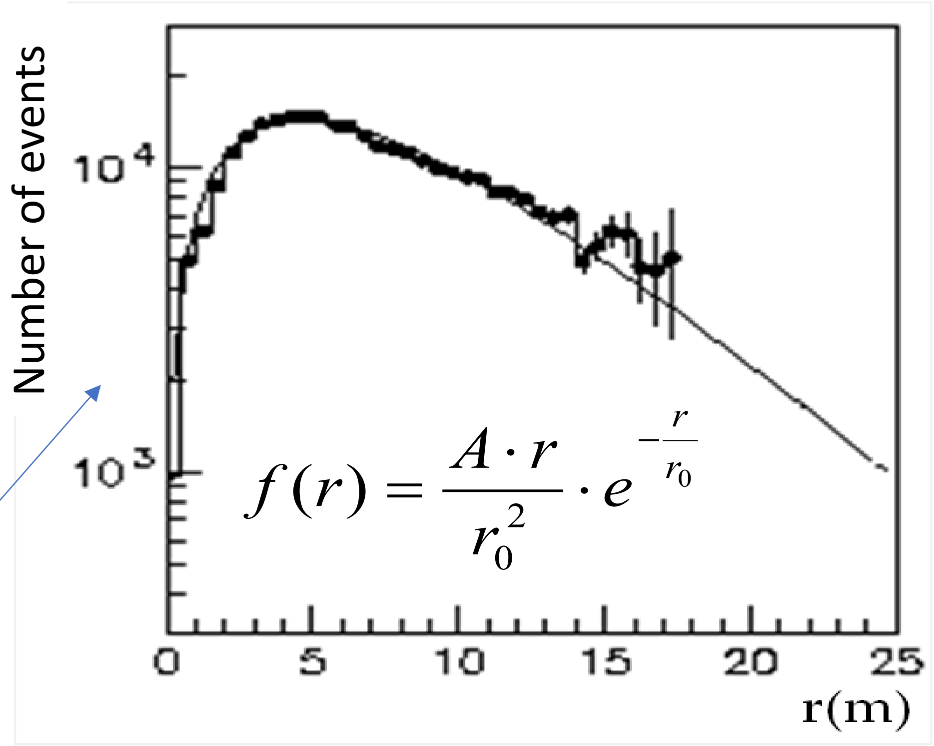
$\mu+/\mu- = 1.26 \pm 0.11 \pm 0.04$

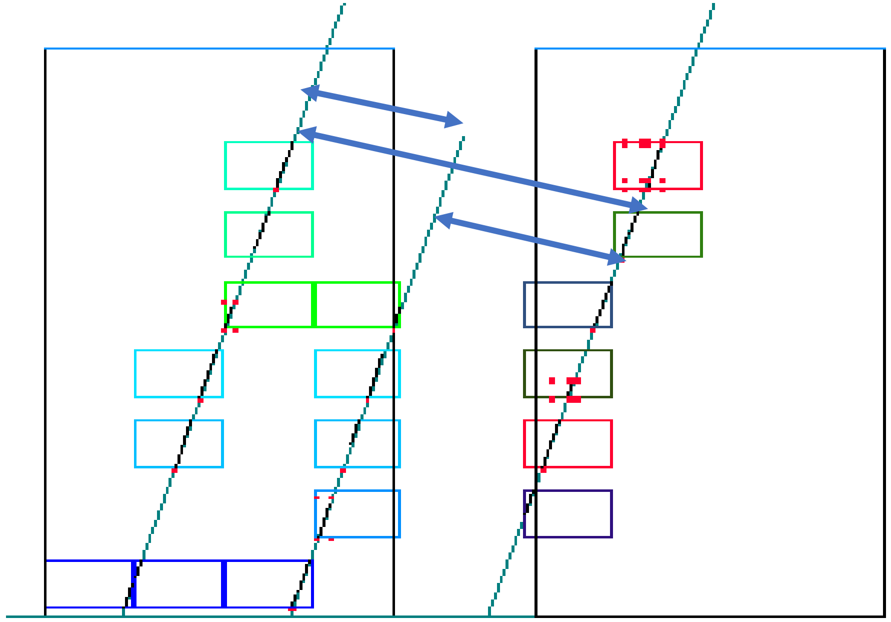


Multiple muon events



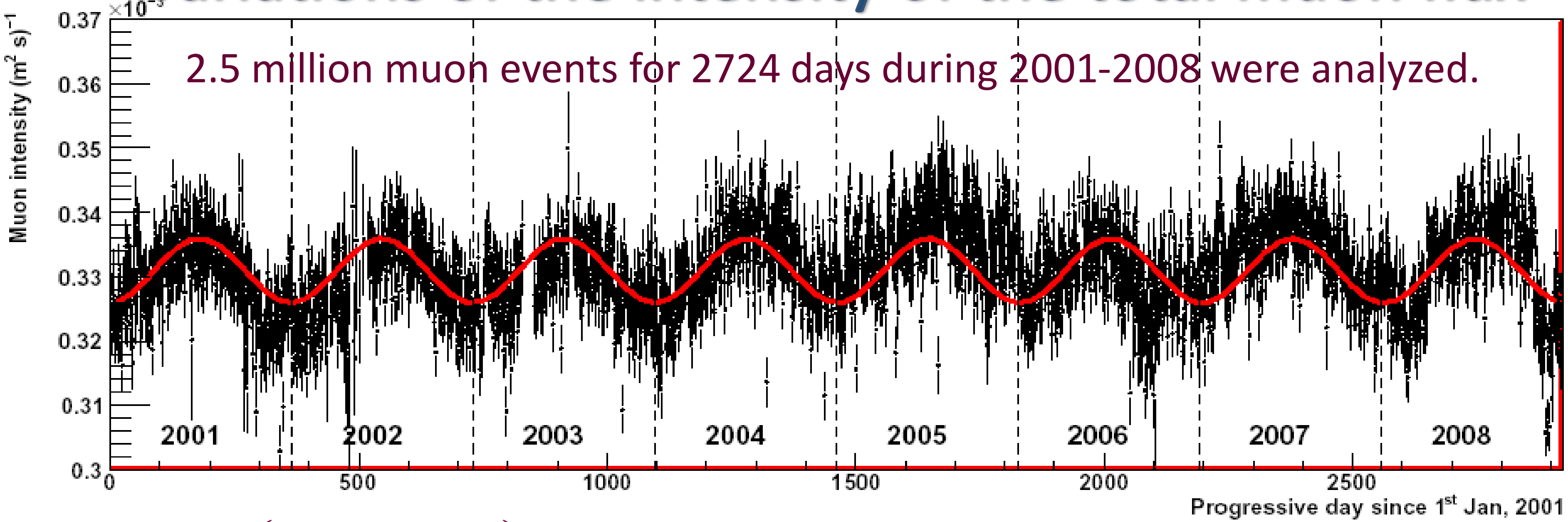
Decoherence curve - Distribution of pair combinations by the distance between muons in a pair for all groups





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.

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

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

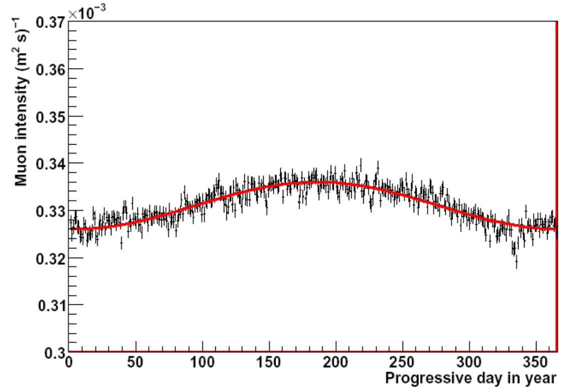
Modulation value

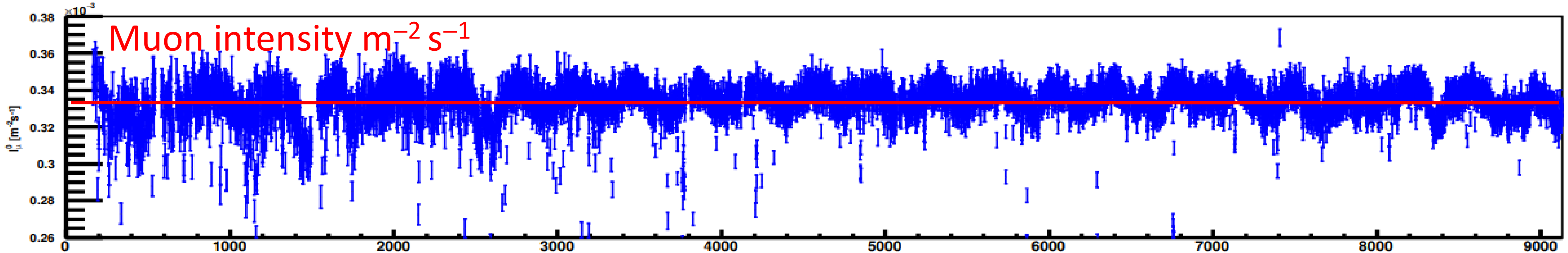
δI = (1.5±0.1)%

Modulation period

T= 367±15 дней

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



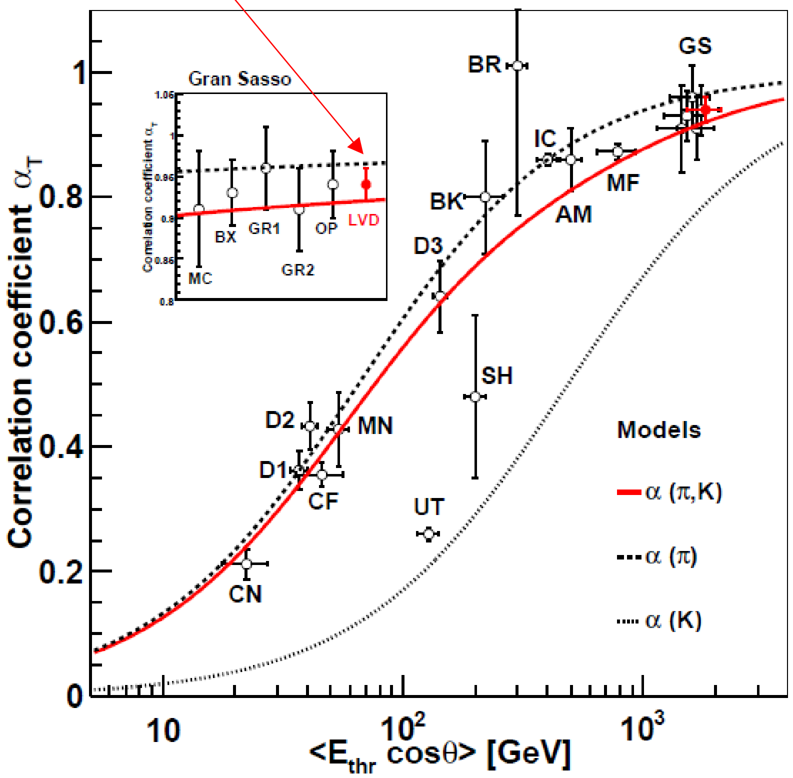


Temperature effect

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

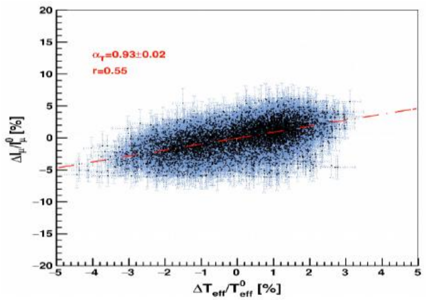
Muons that reach great depths are produced, generally, in the decays of pions of the first generation. The number of these decays increases with the expansion of the atmosphere and the fall of its density in the upper layers (at an altitude of ~ 30 km).

$\alpha_T = 0.93 \pm 0.02$

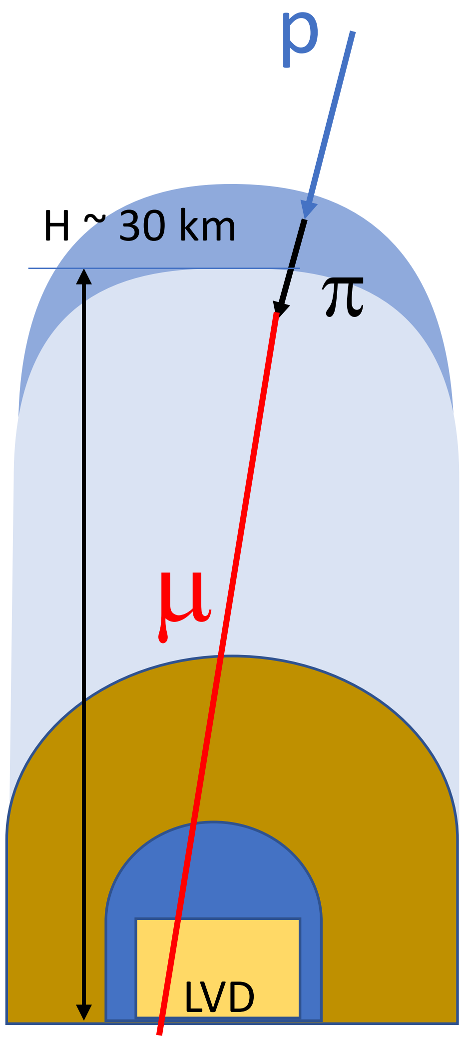


The correlation of the change in the muons intensity and the change in temperature

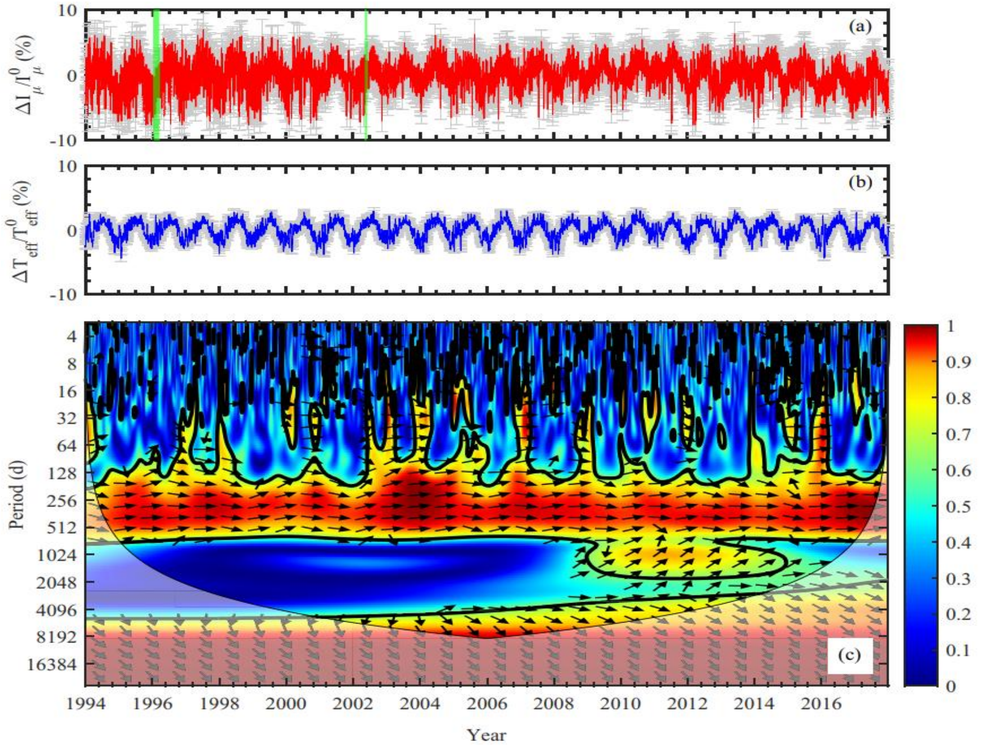
$$\Delta I_\mu / I_\mu^0 = \alpha_T \frac{\Delta T_{eff}}{T_{eff}^0}$$



correlation between muon flux and temperature changes



Exploration of the stratosphere with cosmic-ray muons detected underground



Using a 24-year muon data series**, variations with periods of about 4 and 10 years are found**, related to temperature variability in the lower stratosphere.

Analysis of the muon flux series also reveals evidence for diurnal and monthly variations, especially during the highly variable **winter period (sudden stratospheric warmings).** *Although such short-term modulations are also found in the effective temperature series, we show that the variations of these two series are brought to a better agreement when considering only certain atmospheric layers depending on the specific event.*

The amplitudes of the long-term variations are significantly larger than expected based on the temperature modulations. Our study shows that the subsurface muon flux can be used as a powerful tool to study stratospheric temperature variability around the tropopause**.**

C. Taricco et al. (LVD Collaboration) «Exploration of the stratosphere with cosmic-ray muons detected underground» Phys. Rev. Research 4, 023226 – Published 21 June 2022

Используя 24-летнюю серию мюонных данных обнаружены вариации с периодами около 4 и 10 лет, связанные с изменчивостью температуры в нижних слоях стратосферы.

Анализ рядов потока мюонов выявляет также свидетельства суточных и месячных вариаций, особенно во время сильно изменчивого зимнего периода. Хотя такие кратковременные модуляции также обнаруживаются в рядах эффективной температуры, мы показываем, что вариации этих двух рядов приводятся к лучшему согласованию при рассмотрении только определенных слоев атмосферы в зависимости от конкретного события.

Амплитуды многолетних вариаций значительно больше, чем ожидаемые на основе температурных модуляций. Наше исследование показывает, что поток подземных мюонов можно использовать как мощное средство для изучения изменчивости стратосферной температуры вокруг тропопаузы.

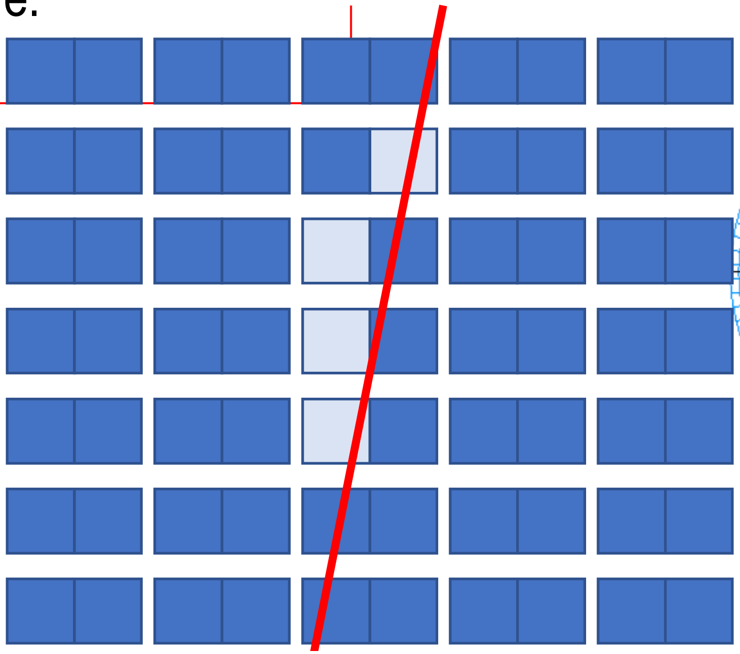
Near Vertical Muons

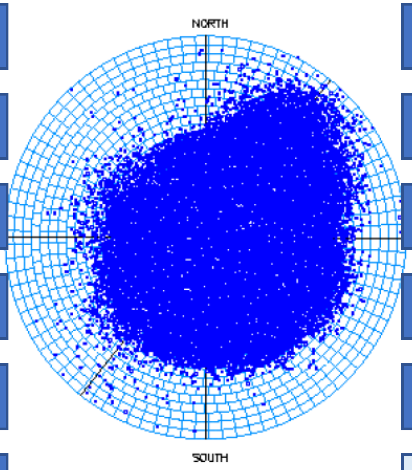
$\langle E_\mu \rangle \approx 270$ GeV
$\langle H \rangle \approx 3.3$ km w.e.
$\langle \theta \rangle \approx 13°$

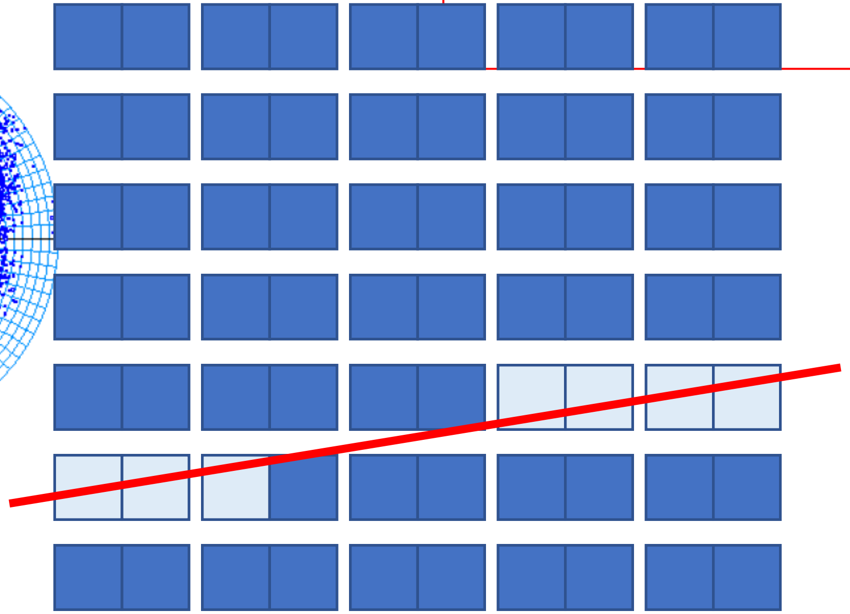
Near horizontal muons

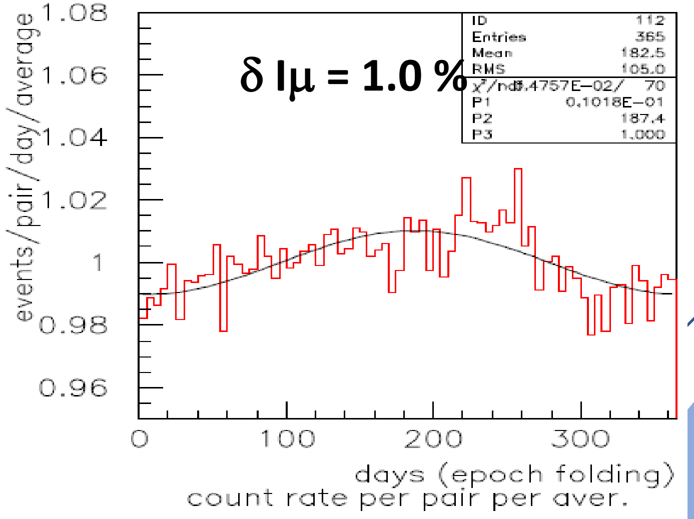
$\langle E_\mu \rangle \approx 340$ GeV
$\langle H \rangle \approx 5$ km w.e.
$\langle \theta \rangle \approx 75°$

The modular structure of the detector allows us to select muons in the horizontal and vertical directions.

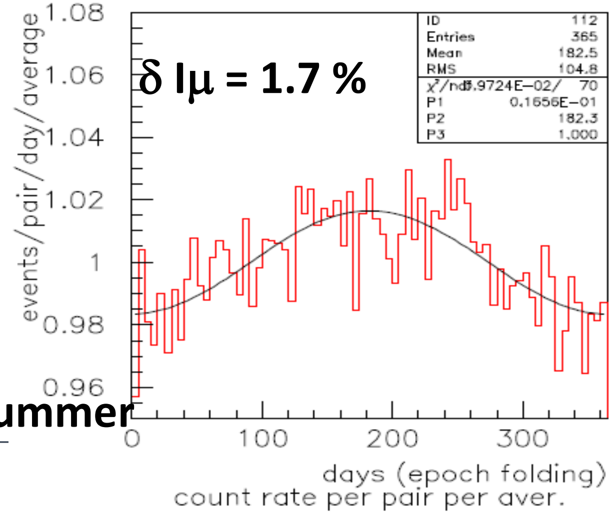


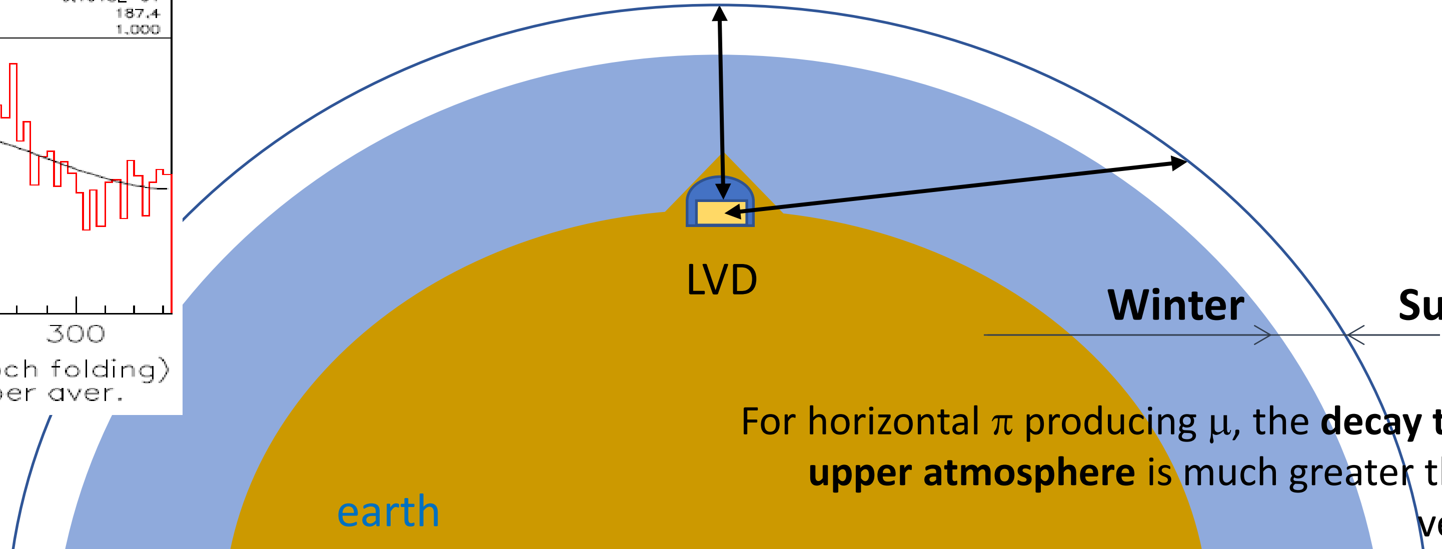






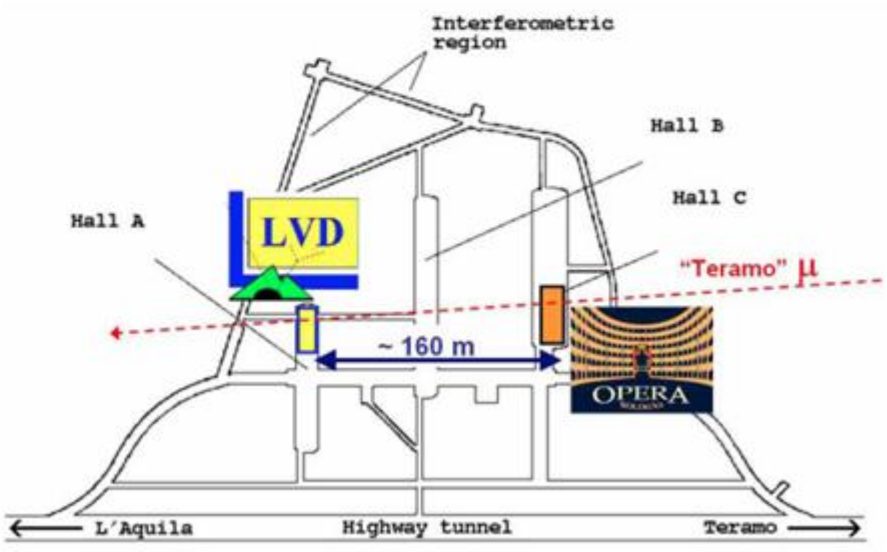
N. Agafonova (LVD Coll.)// Yad.Fiz, 2020, V 83, P. 70–75



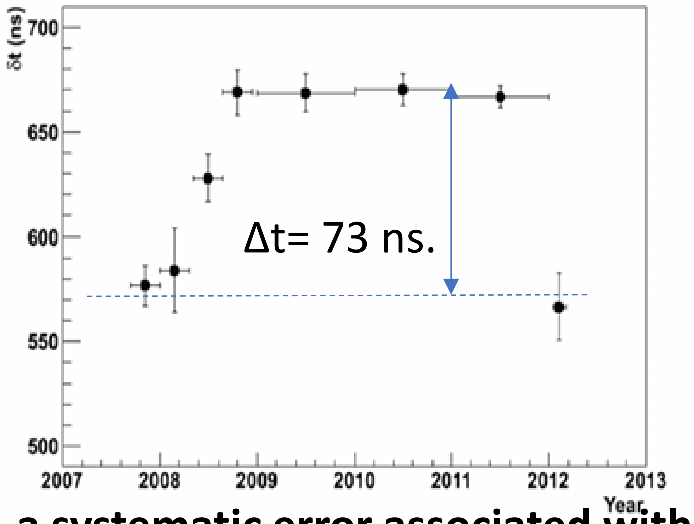


For horizontal π producing μ, the **decay thickness in the upper atmosphere** is much greater than for pions in vertical direction

Monitoring neutrino from the CERN



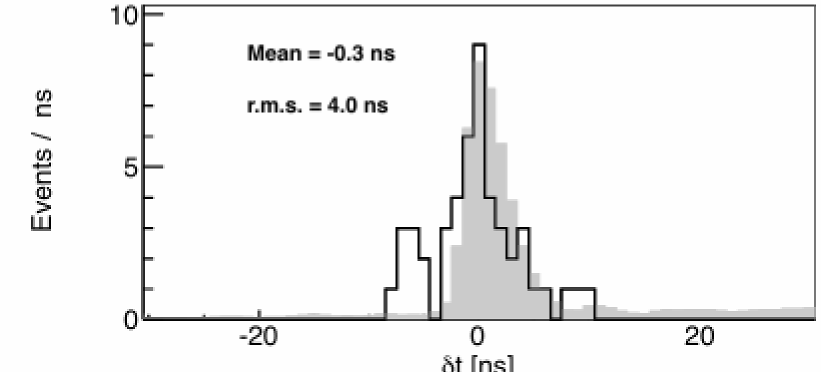
As a result of the analysis of horizontal muons of far beams, **which passed through the LVD and OPERA**, which move at a distance of 160 m from each other, **the difference in detectors clock response times was obtained**.
It was determined that from mid-2008 to the end of 2011 the difference exceeded the muon flight time by Δt=73ns. This helped to find a systematic error associated with the measurement of absolute time in the OPERA experiment.



a systematic error associated with the measurements of absolute time in the OPERA experiment.

The relative deviation of the neutrino velocity from the speed of light

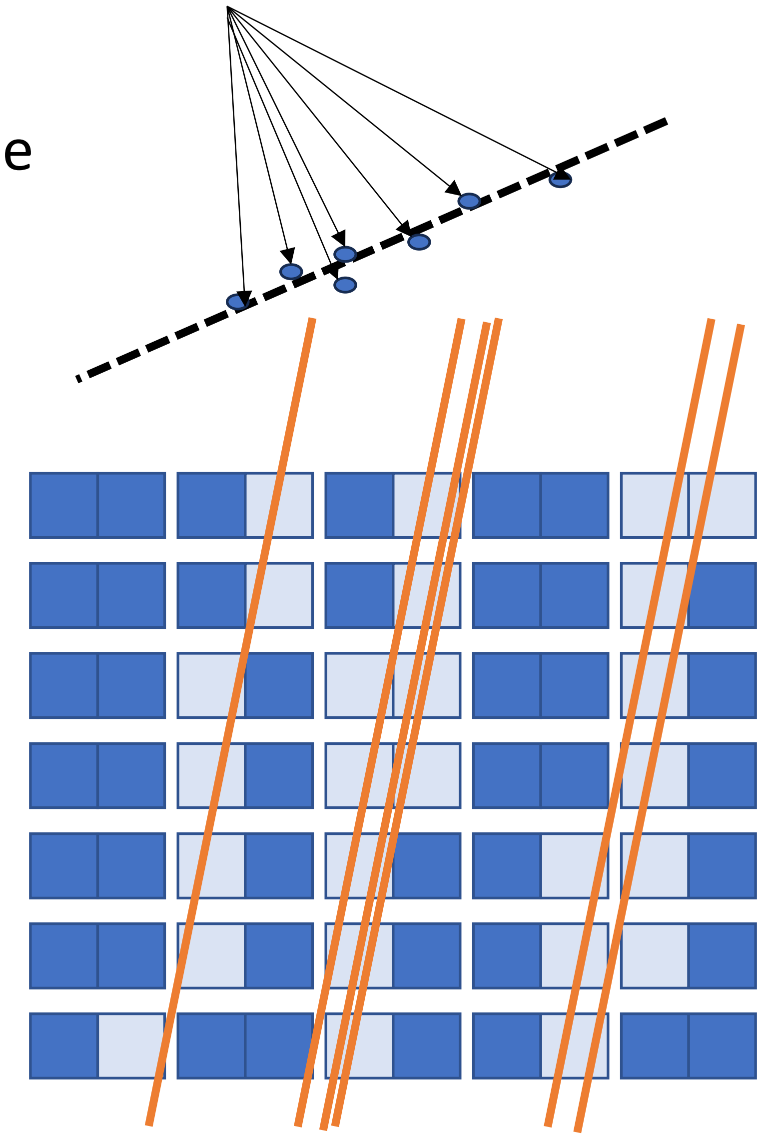
Измерена величина относительного отклонения скорости нейтрино от скорости света на установке LVD



Using the neutrino beam from CERN - Gran Sasso, with short bunches of 3 ns width and an interval between them of 100 ns, the relative deviation of the neutrino speed from the speed of light **was measured** at the LVD : $-3.3 \cdot 10^{-6} < (v_{\nu}-c)/c < 3.5 \cdot 10^{-6}$ (at the 99% confidence level).

The tasks with LVD that our group is solving today

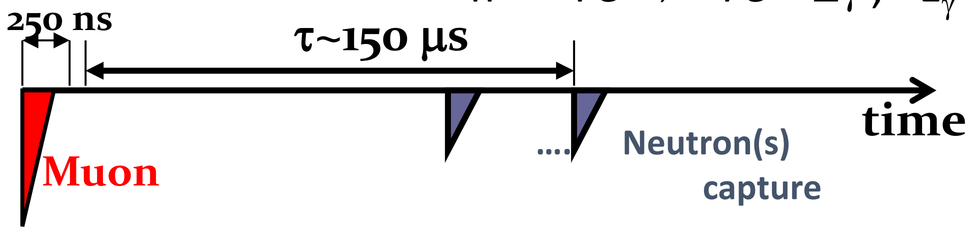
1. Reconstruction of muon events using counter response time delays.
2. Search for aligned (coplanar) events in muon groups, using archive data with a detector tracking system.
3. Analysis of events with high energy release and high multiplicity depending on the direction of events (from the zenith angle and/or great depths).
4. Study of narrow muon groups



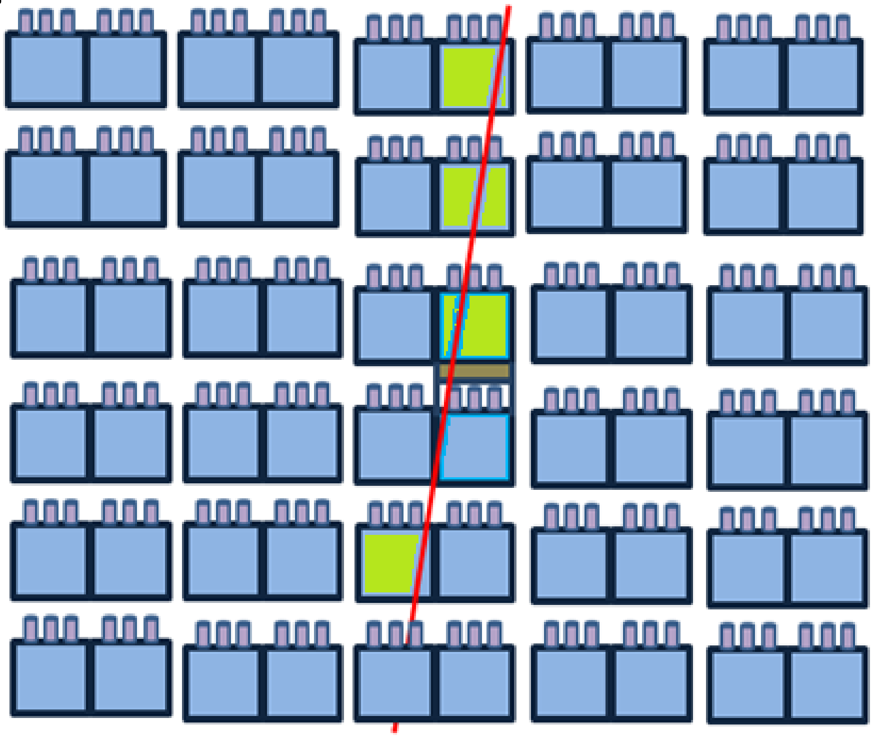
Neutrons generated by muons

$n + p \rightarrow d + \gamma$, $E_\gamma = 2.2$ МэВ

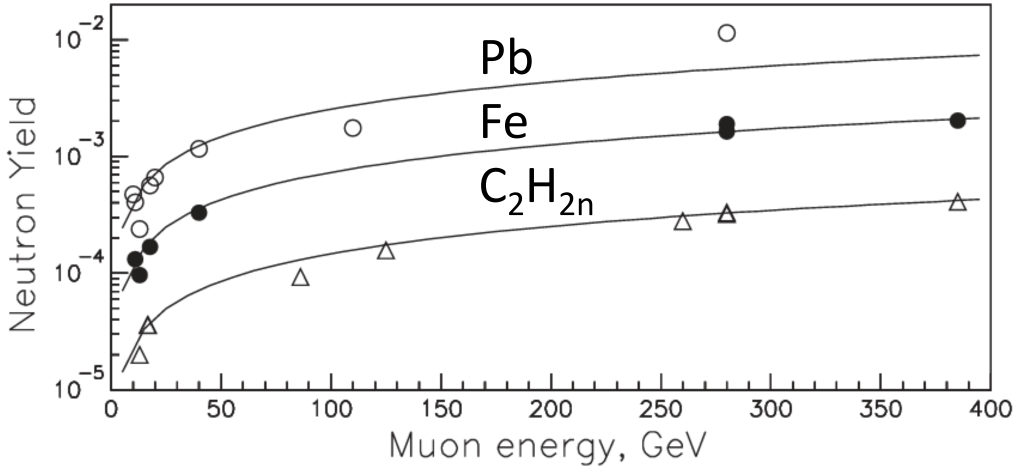
$n + {}^{56}Fe \rightarrow {}^{57}Fe + \Sigma\gamma$, $\langle E_\gamma \rangle \approx 7$ МэВ



Neutrons are detected by γ-quanta emitted after radiative capture of thermal neutrons mainly by scintillator protons and by iron nuclei.



$E_\mu = 280$ GeV



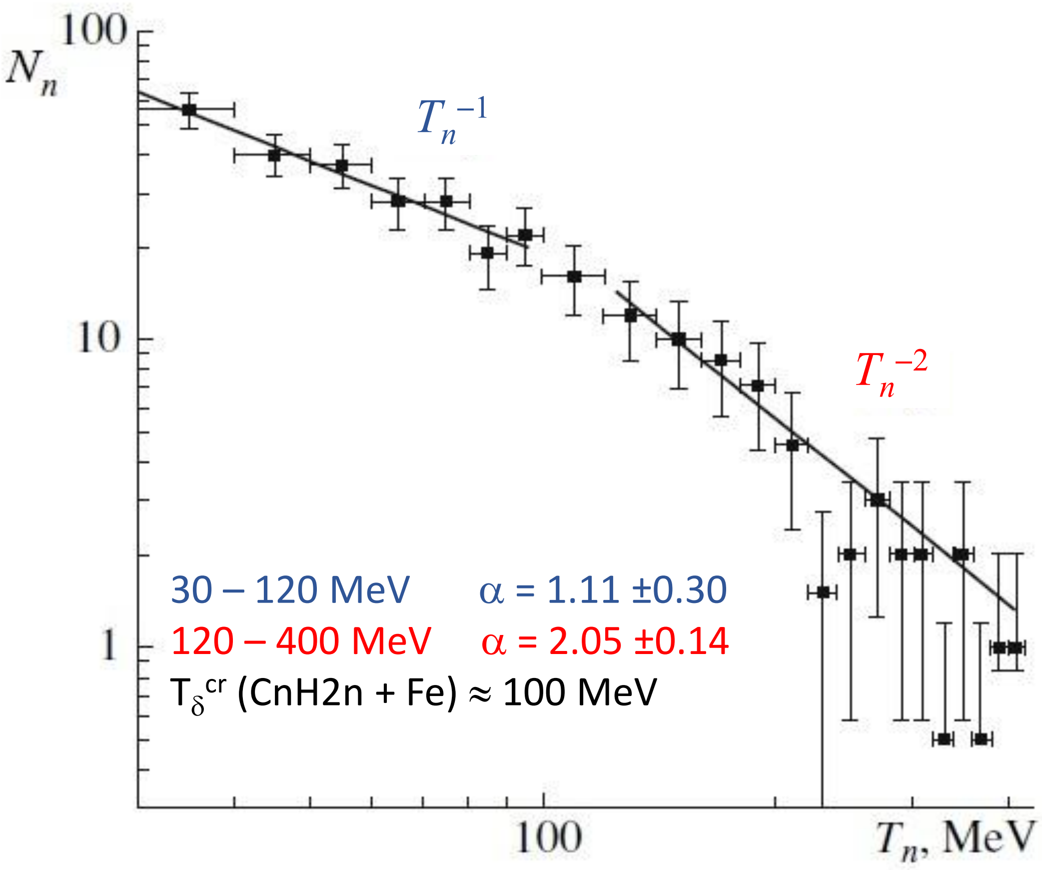
Measurement of neutron yield at LVD in different substances is consistent with the dependence :

$$Y_n\,(E_\mu, \mathrm{A}) = 4.4 \cdot 10^{-7}\,(\mathrm{g/cm^2})^{-1}\,A^{\beta}\,E_\mu^{\ \alpha}\,(E \text{ - GeV}),$$

$$\alpha = 0.78,\ \ \beta = 0.95$$

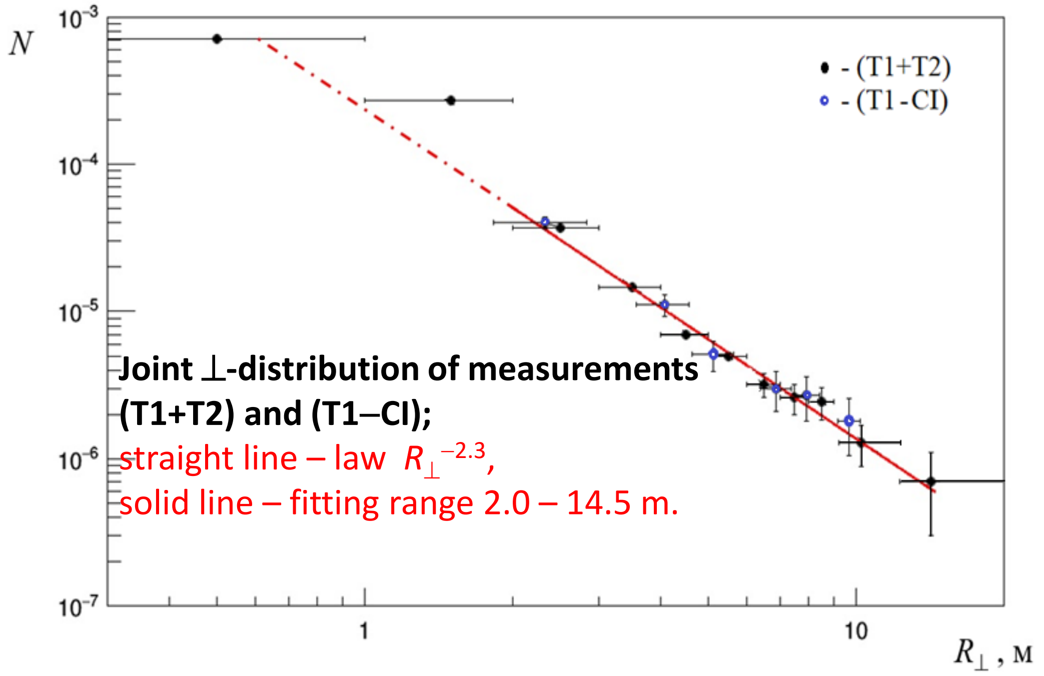
substance	Neutron yield from muons measured with LVD
CnH2n	$(3.2 \pm 0.2) \times 10^{-4}$
Fe	$(15 \pm 2) \times 10^{-4}$
Pb	$(55 \pm 20) \times 10^{-4}$

Energy spectrum of neutrons



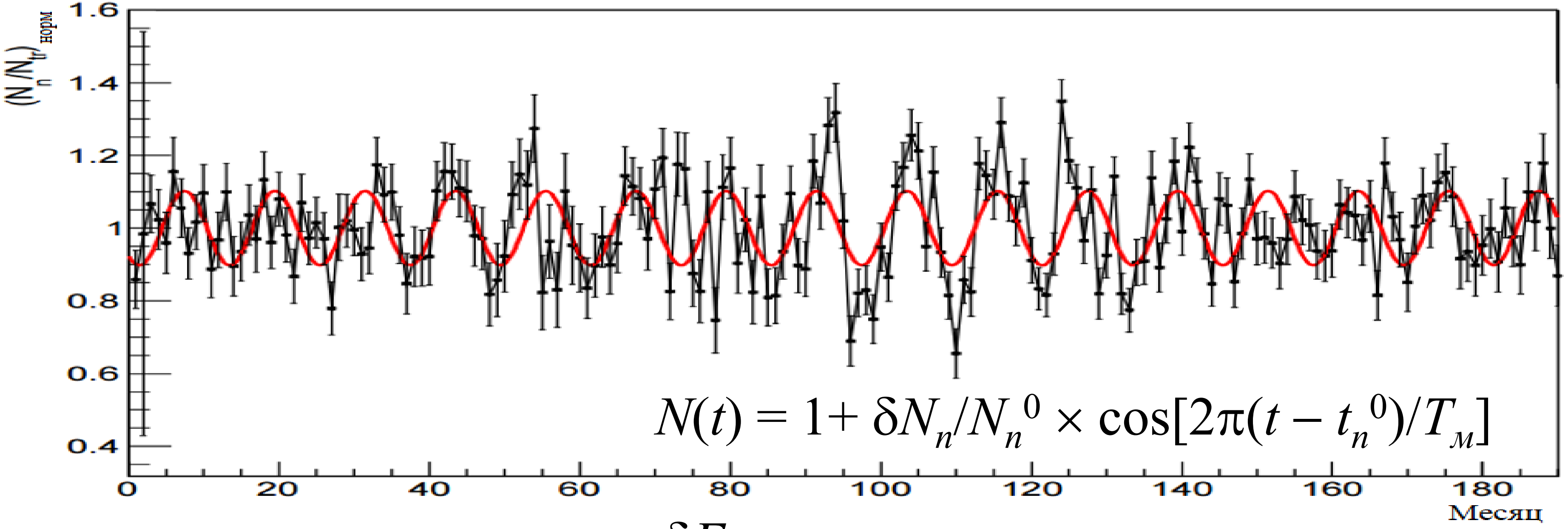
Spectrum of $F^s(T_n)$, measured in the LVD experiment (2009)

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



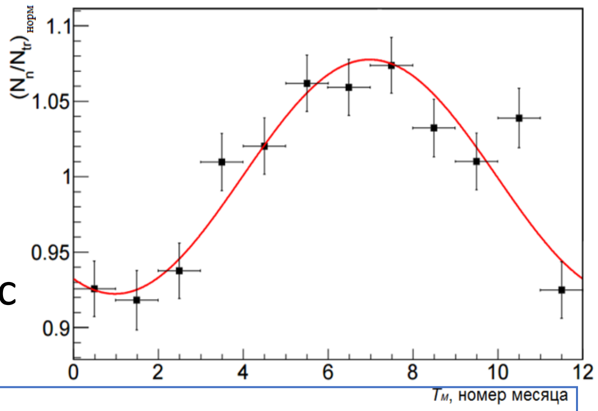
Variations in the specific number of neutrons at LVD over 15 years;
statistical errors of measurements with a step of 1 month are indicated, the curve is the best approximation of the data by a harmonic function

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

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

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

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



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

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).

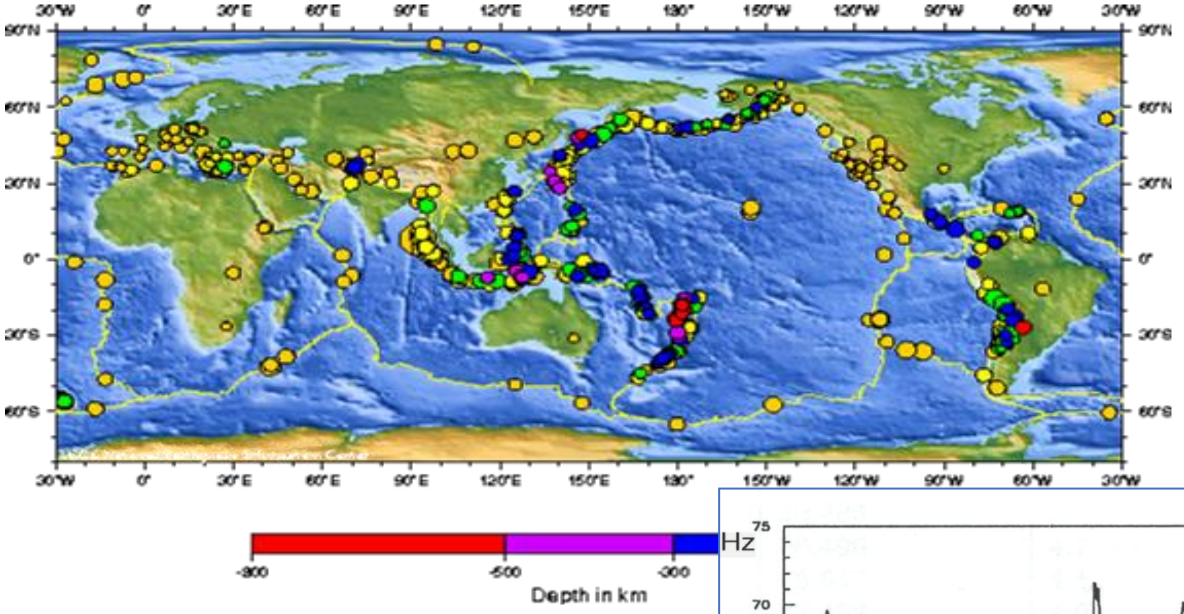
Earthquake observation

$$ {}^{222}_{86}Rn \xrightarrow{\alpha} {}^{218}_{84}Po \xrightarrow{\alpha} {}^{214}_{82}Pb \xrightarrow{\beta^-} {}^{214}_{83}Bi $$

3. 82 d — 3. 05 min — 26 .8 min — 19. 7 min

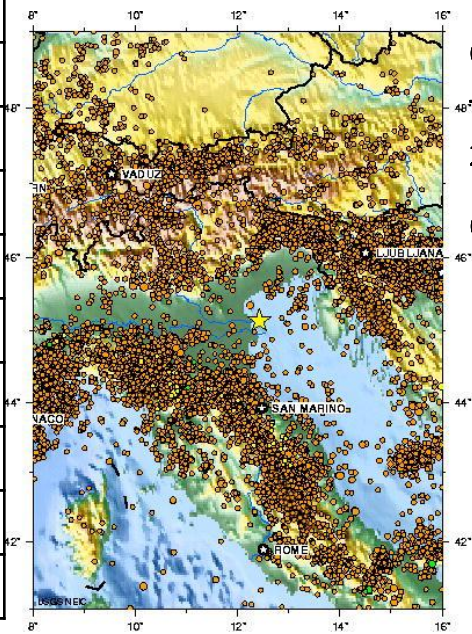
$$ \xrightarrow{\beta^-} {}^{214}_{84}Po \xrightarrow{\alpha} {}^{210}_{82}Pb $$

1.6×10^{-4} sec — 22. 3 y

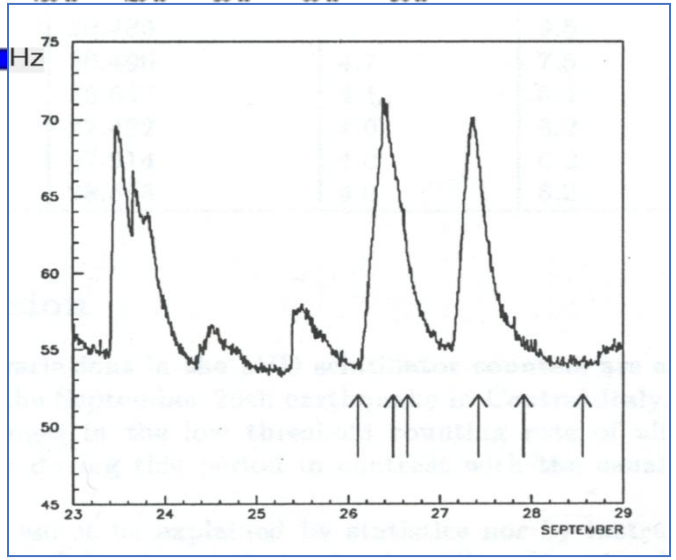


Changes in low-energy background are important for experiments to search for rare events, such as DM.

Energy of γ, MeV	Number of γ per 100 nuclei of ^{214}Bi
0,609	47
1,764	17
1,120	17
1,238	6
2,204	5
1,378	5
0,769	5
1,400	4
2,445	2



Radon concentration monitoring is carried out by recording γ-quanta from the decay of daughter nuclei ^{222}Rn, the half-life of which is 3.8 days



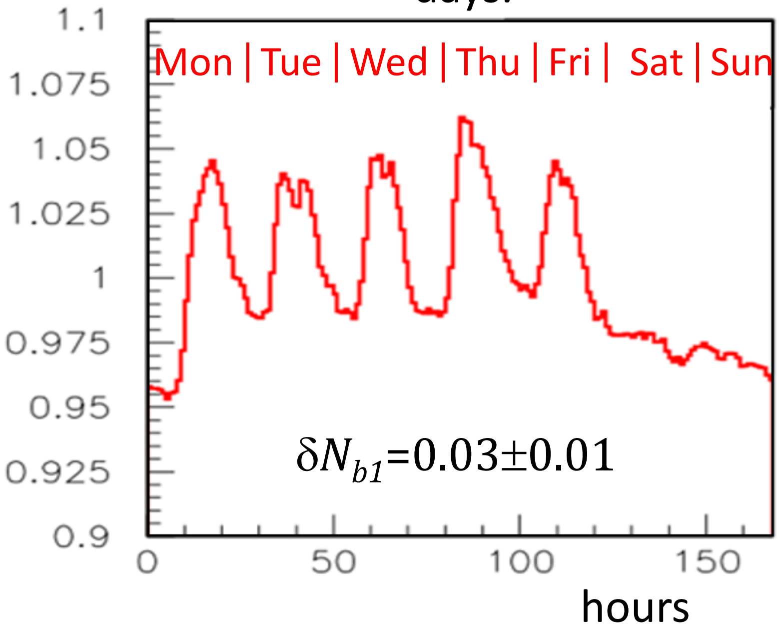
Counting rate of LVD during earthquake in Italy (1997).
The moments of shocks are given by arrows.

Periodic variations in the gamma-quantum count rate = underground radon concentration

$$f(t) = 1 + \delta N_b \cdot \cos(\frac{2\pi}{T}(t - \varphi))$$

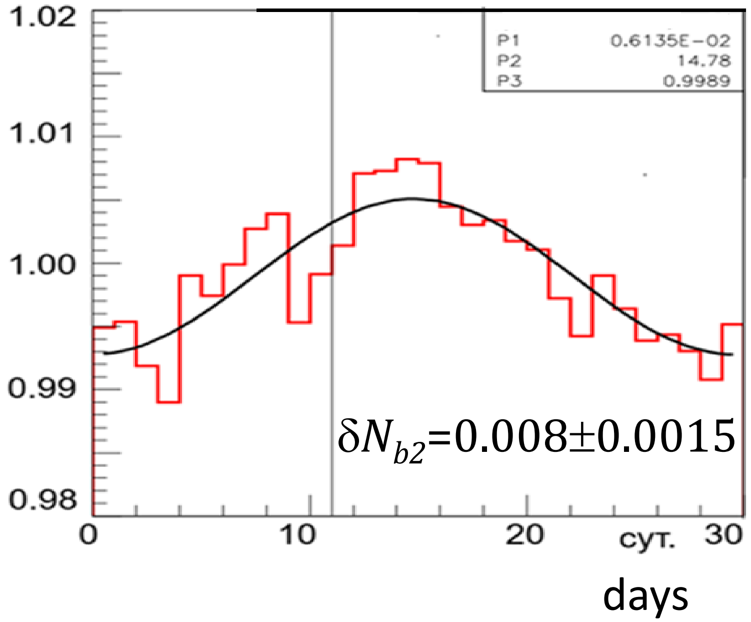
Daily-weekly

variations are due to the daily work of laboratory personnel, opening of gates on working and non-working days.



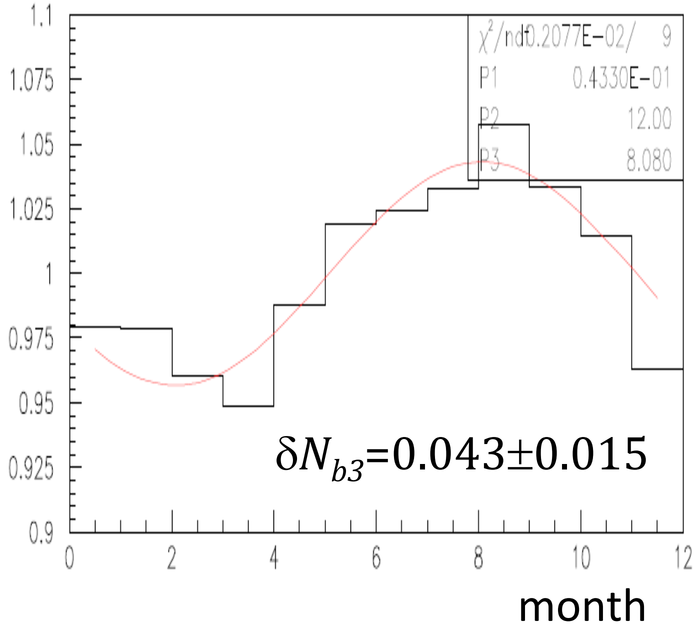
Lunar-monthly

variations are due to tidal forces associated with the movements of the moon and sun.

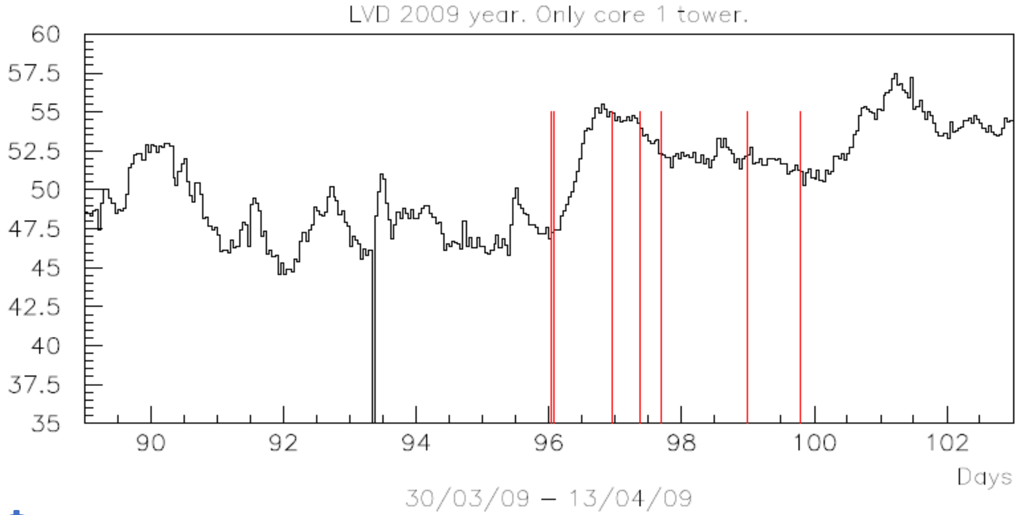


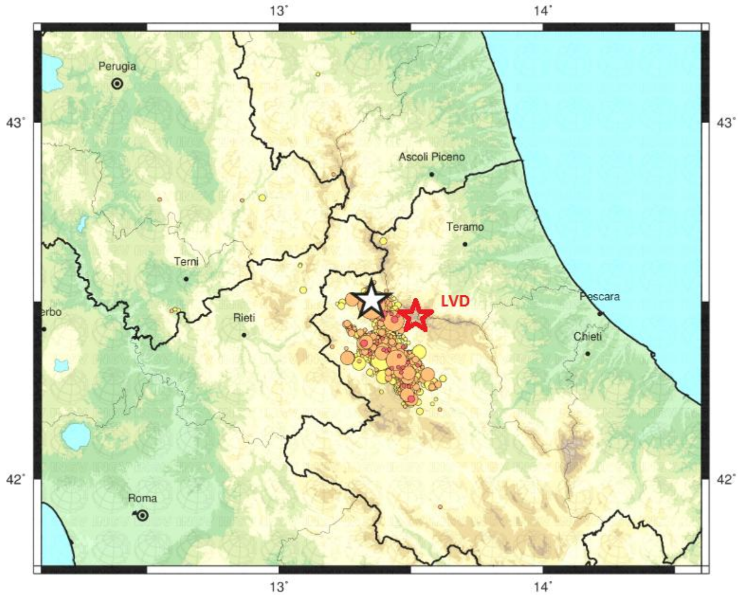
Seasonal-annual

variations are due to seasonal variations in precipitation and the rate of snowmelt in the mountains during the summer in the Italian region.



Earthquake 6/04/2009 in L’Aquila





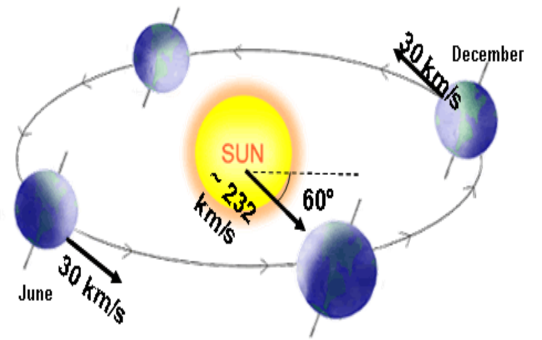
Факторы, влияющие на концентрацию радона в подземной лаборатории
Factors Affecting Radon Concentration in an Underground Laboratory.

1. Открывание и закрывание ворот в зал, где находится установка/ Opening and closing the gate to the hall where the installation is located
2. Прохождение машин по транспортному туннелю/ Passage of cars through a transport tunnel
3. Сезонные вариации концентрации радона/ Seasonal variations in radon concentration
4. Приливные силы, связанные с лунным циклом/ Tidal forces associated with the lunar cycle
5. **Сейсмическая активность/ Seismic activity => In general, we want to detect earthquake precursors using the gammas counting rate on the LVD**

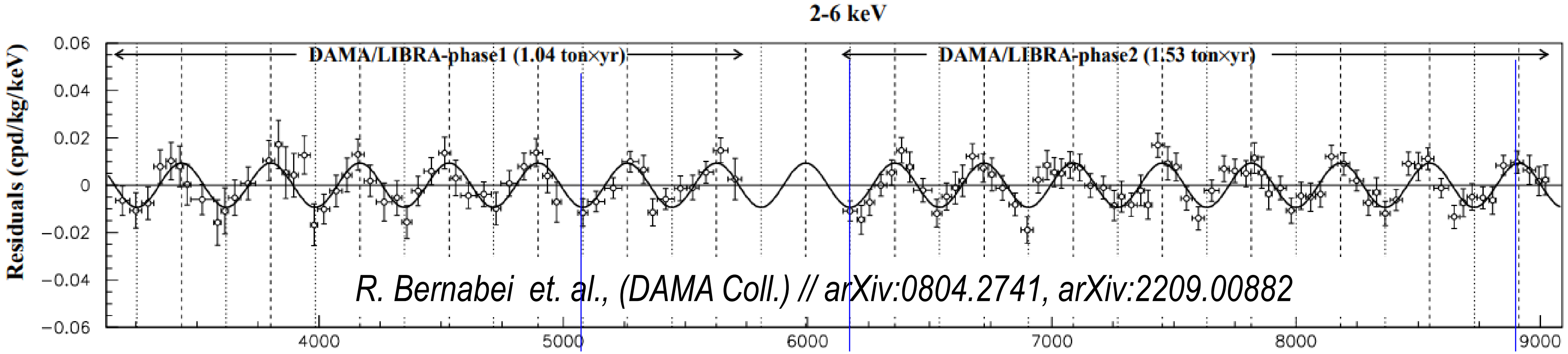
http://cnt.rm.ingv.it/

Thank you for your attention

Вариации Темной Материи и Нейтронов под землей, обнаруженные в подземной лаборатории



Вариация сигналов ТМ имеет синусоидальный характер и связан с движением земли в солнечной системе относительно гало нашей галактики. 2 июня скорость движения Земли сквозь гало мак



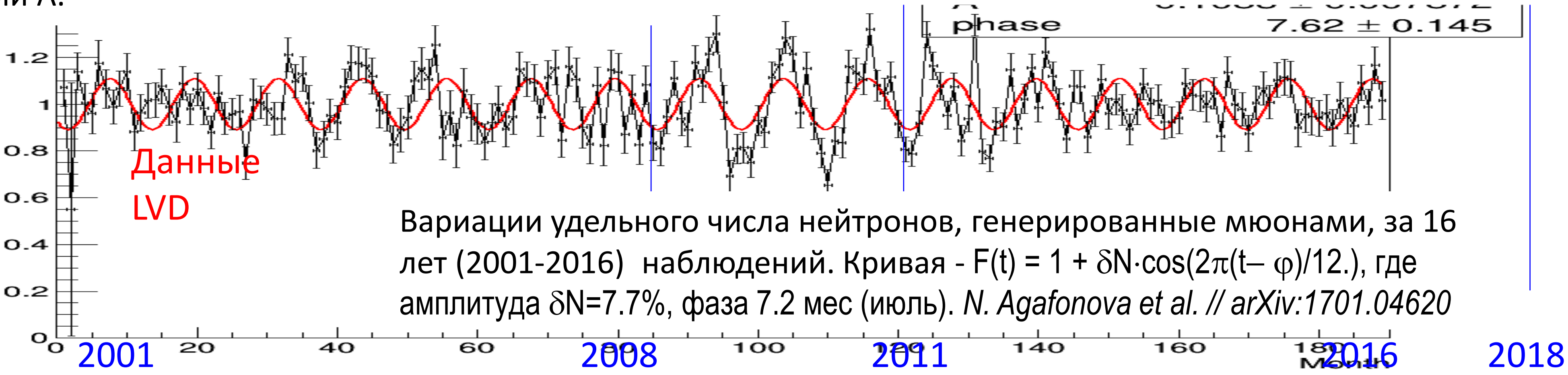
R. Bernabei et. al., (DAMA Coll.) // arXiv:0804.2741, arXiv:2209.00882

Экспериментальная скорость одиночных сцинтилляционных событий, измеренная с помощью DAMA/LIBRA-phase1 и DAMA/LIBRA-phase2 в интервалах энергий (2–6) кэВ, как функция времени. Наложенная кривая представляет собой косинусоидальные функциональные формы T = Acosω(t − t_0) с периодом T = 2π/ω = 1 год, фазой t_0 = 152,5 дня (2 июня) и амплитудой модуляции A.

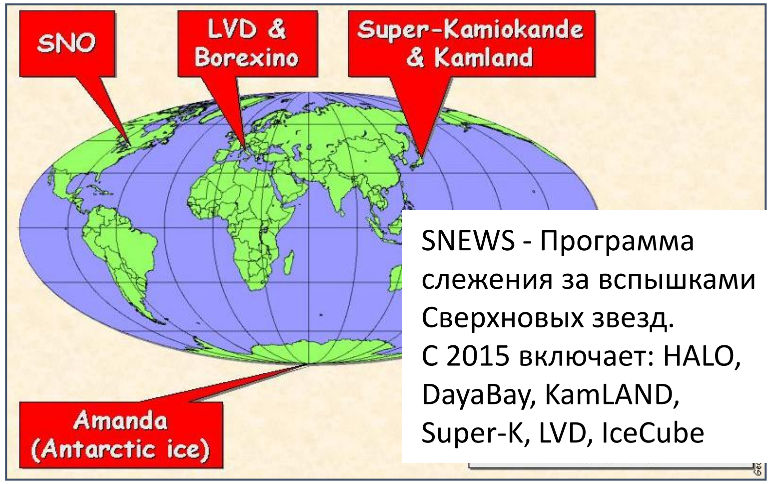
Характеристики годовых вариаций, измеренных на экспериментах LVD и DAMA/LIBRA

	Амплитуда	Фаза	Положение в году	Период,
Тёмная материя	1-2%	(145±5) дней	июнь	2010-2017
Мюоны	1.5%	(187±3) суток	июль	2001-2008
Нейтроны	7.7%	(7.0±0.5) мес.	июль	2001-2016
Гамма-кванты	(3.0±1.1)%	(8.5±0.5) мес.	август	2009-2021

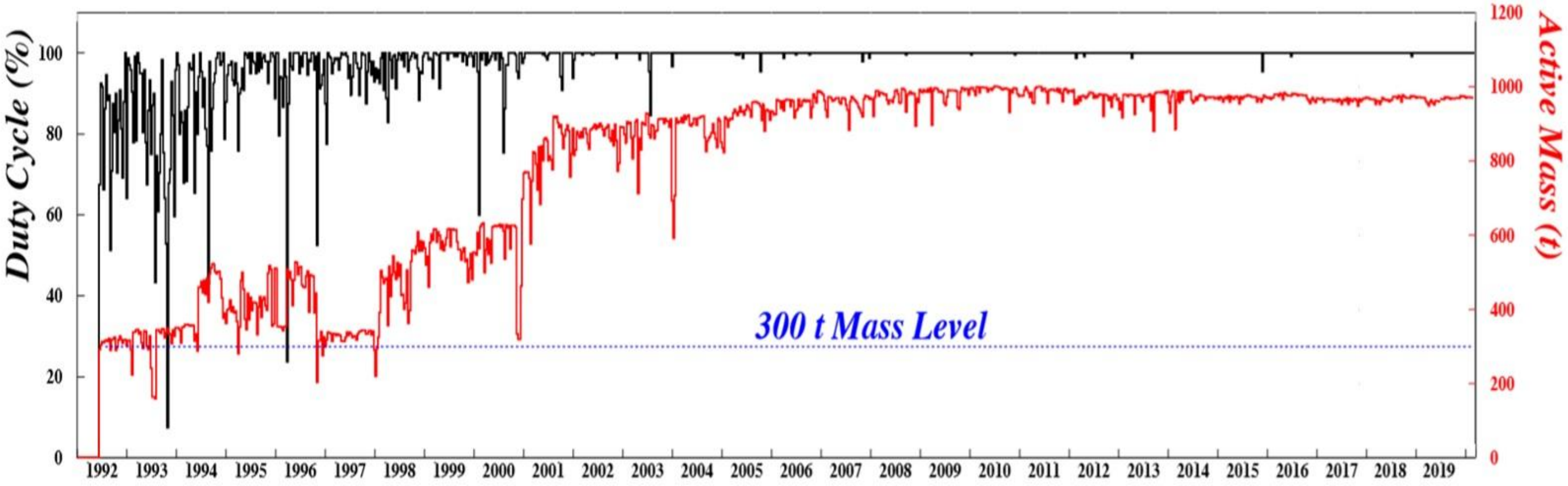
Экспериментальное наблюдение редких событий – нетривиальная задача, требующая точного знания фона под землей.



Вариации удельного числа нейтронов, генерированные мюонами, за 16 лет (2001-2016) наблюдений. Кривая - F(t) = 1 + δN·cos(2π(t– φ)/12.), где амплитуда δN=7.7%, фаза 7.2 мес (июль). *N. Agafonova et al. // arXiv:1701.04620*



SNEWS - Программа слежения за вспышками Сверхновых звезд.
С 2015 включает: HALO, DayaBay, KamLAND, Super-K, LVD, IceCube



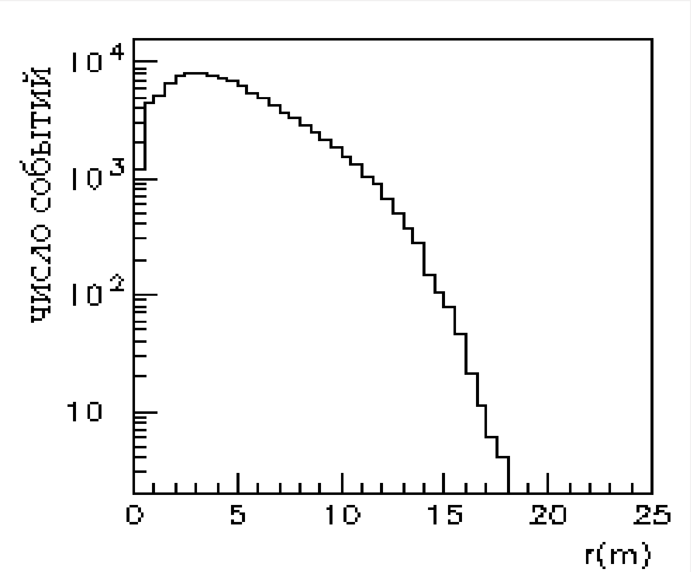
Цель SNEWS – предоставить астрономическому сообществу раннее предупреждение о вспышке сверхновой в нашей Галактике с тем, чтобы экспериментаторы могли наблюдать астрономические следствия гравитационного коллапса звезды.

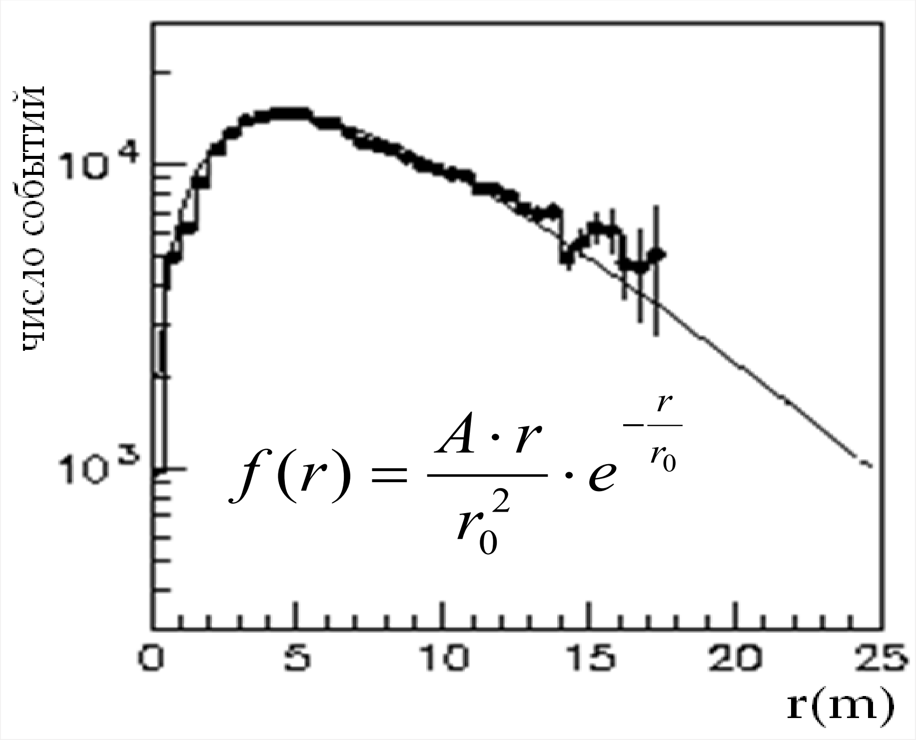
SuperNova Early Warning System

По данным работы нейтринного телескопа LVD за 33 года работы (1992 - 2025), получено экспериментальное ограничение на частоту нейтринных всплесков от гравитационных коллапсов звёзд в Галактике: менее 1 события за 14.3 г. на 90% уровне достоверности.

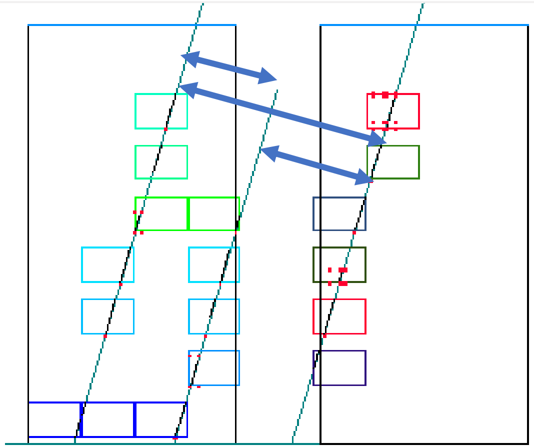
Декогерентная кривая

Распределение парных комбинаций по расстоянию между мюонами в паре для всех групп.





Зависимость расстояния между мюонами в группе дает информацию о поперечных импульсах. Вместе с множественностью мюонов можно получить информацию об энергетическом спектре адронов. Измерения спектров и распределения атмосферных мюонов по расстояниям позволяют тестировать модели ядерного каскада в атмосфере, то есть параметры первичного космического излучения (энергетический спектр и химический состав) и взаимодействия частиц при высоких энергиях.

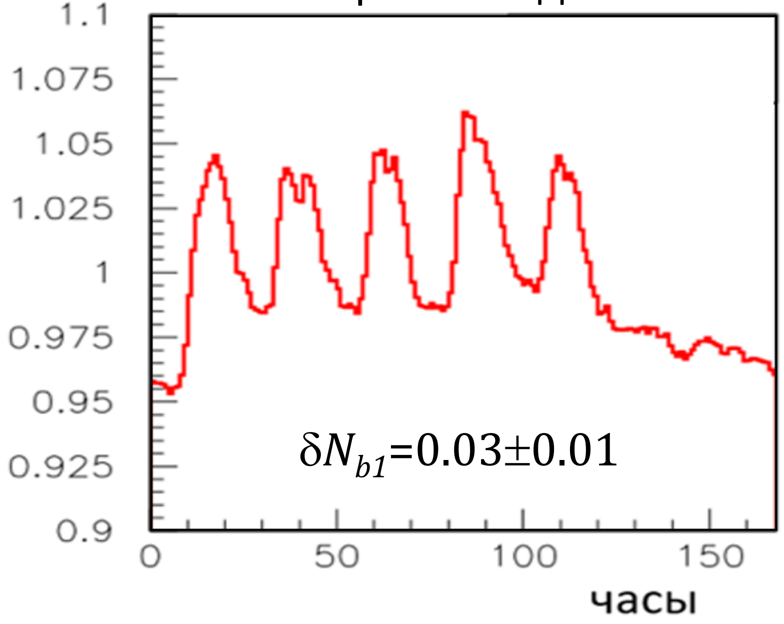


Периодические вариации скорости счета гамма-квантов = концентрации радона под землей

$$f(t) = 1 + \delta N_b \cdot \cos(\frac{2\pi}{T}(t - \varphi))$$

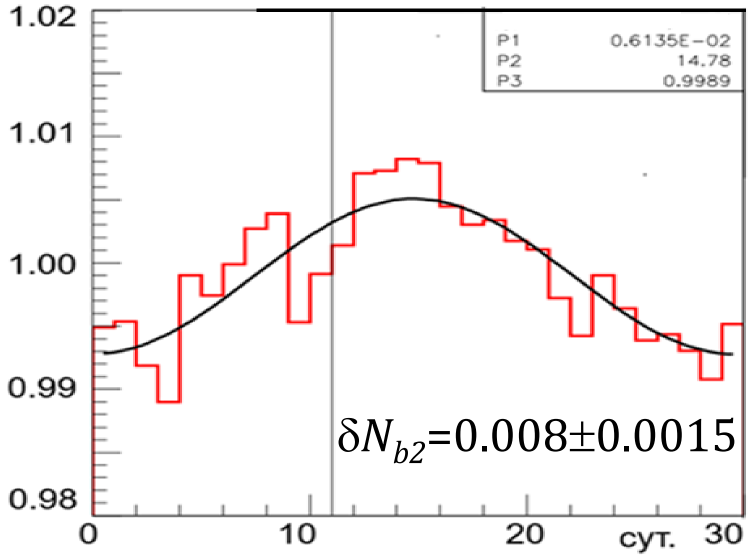
Суточные-недельные

Обусловлены каждодневной работой персонала лаборатории, открыванием ворот в рабочие и нерабочие дни.



Лунно-месячные

обусловлены приливными силами, связанные с движением луны и солнца



Сезонно-годовые

Обусловлены сезонными колебаниями осадков и скоростью таяния снега в горах в летний период в Итальянском регионе