Study of the penetrating component of cosmic rays underground using large scintillation detectors

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- Underground physics is the effective method to study broad class of rare processes in the cosmic ray and elementary particle physics especially concerning the role of neutrinos in Astrophysics.

The main problems of UP

I. Study of neutrino radiation

- Atmospheric neutrinos
- Solar neutrinos
- Neutrinos from collapsing stars

II. Construction of underground detectors

III. Detection of neutrino radiation from SN1987A

IV. Study of penetrating component of cosmic rays

- Energy spectrum
- Study of deep inelastic scattering
- Generation of nuclear active component underground
- Depth-intensity curve of muons
- Depth-intensity curve of neutrons
- Seasonal modulation of the cosmic ray muon flux and neutron flux from muons
- μ+/μ- ratio

Neutrino physics

- In the middle of 60th neutrino physics became to dominate in underground experiments. The sizes of detectors were increased and increased. The first underground laboratories were created.
- New methods for studying low-energy neutrinos, solar neutrinos, neutrinos from collapsing stars became to be developed .
- Neutrinos going in the horizontal direction by the use of scintillation detectors, and neutrinos, coming from the back side of the Earth (proposed by **M. Markov, G. Zatsepin, I. Zheleznykh, V. Kuzmin**, 1962) became to be studied.
- **M. Menon, A. Wolfendale et al**., Kolar Gold Fields, India, 1963-1971.

  Depth 7500 m.w.e. Horizontal muons, neutrinos.
- **F. Reines, W. Kropp et al.,** Johannesburg, South Africa, 1967-1971. Depth 8640 m.w.e.
- **J. Keuffel**, Utah, USA, 1967-1971. 1500 m.w.e. From the back side of the Earth.
- **A.E.Chudakov** et al. 1979-1980. 750 m.w.e. From the back side of the Earth
- Radio chemical methods for solar neutrino detection were developed.

  Cl-Ag experiment proposed by **B. Pontecorvo** in 1946, was realized by **R. Davis** in 1967.

1965 – elaboration of new liquid scintillator: transparency L>30m, stability >40 years, scintillator is bubbling by argon gas, after that the scintillation efficiency is increased in 2.5 times
<u>the price 30 kop/L (<30cent/L.)</u>

1965-80 – study of cosmic ray background

1979 - first detection of up-going atmospheric neutrino in Baksan.

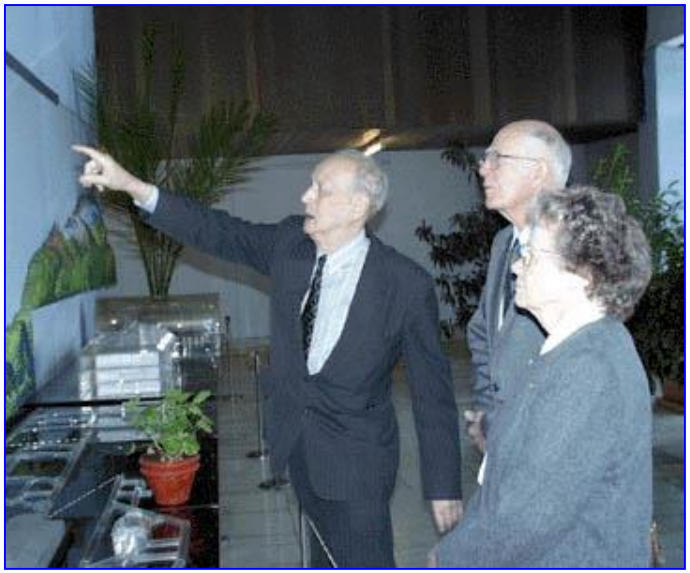
1979-80 – the beginning of search for neutrino from collapsing stars in Arteomovsk and Baksan.

3 detectors used the same liquid scintillator.

Background for solar neutrinos

$$\nu + Cl^{37} \rightarrow Ar^{37} + e^{-}$$

Statistics of ν events per 1 atom of the target per 1 sec is ~ 10^{-34} – 10^{-37} (ppe)



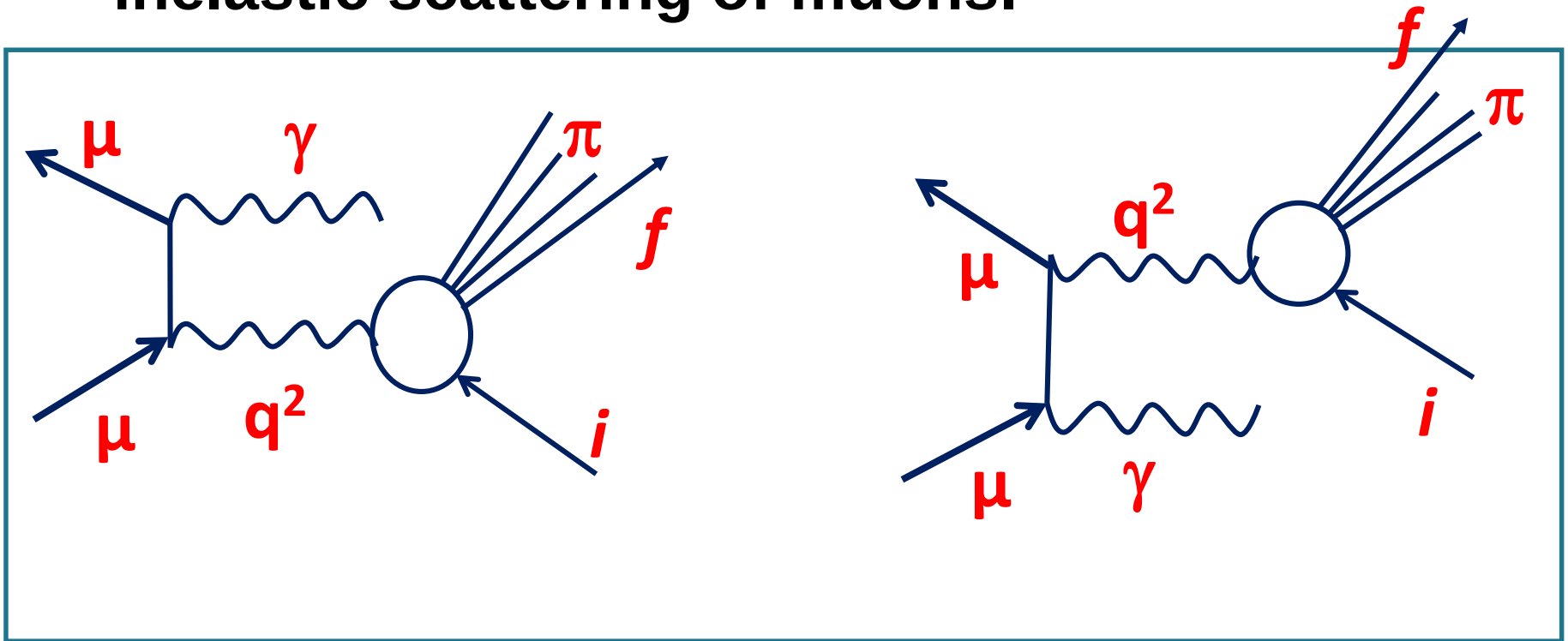
The questions of background play very important role.

Nuclear active component of the cosmic rays

$$p + Cl^{37} \rightarrow Ar^{37} + n$$

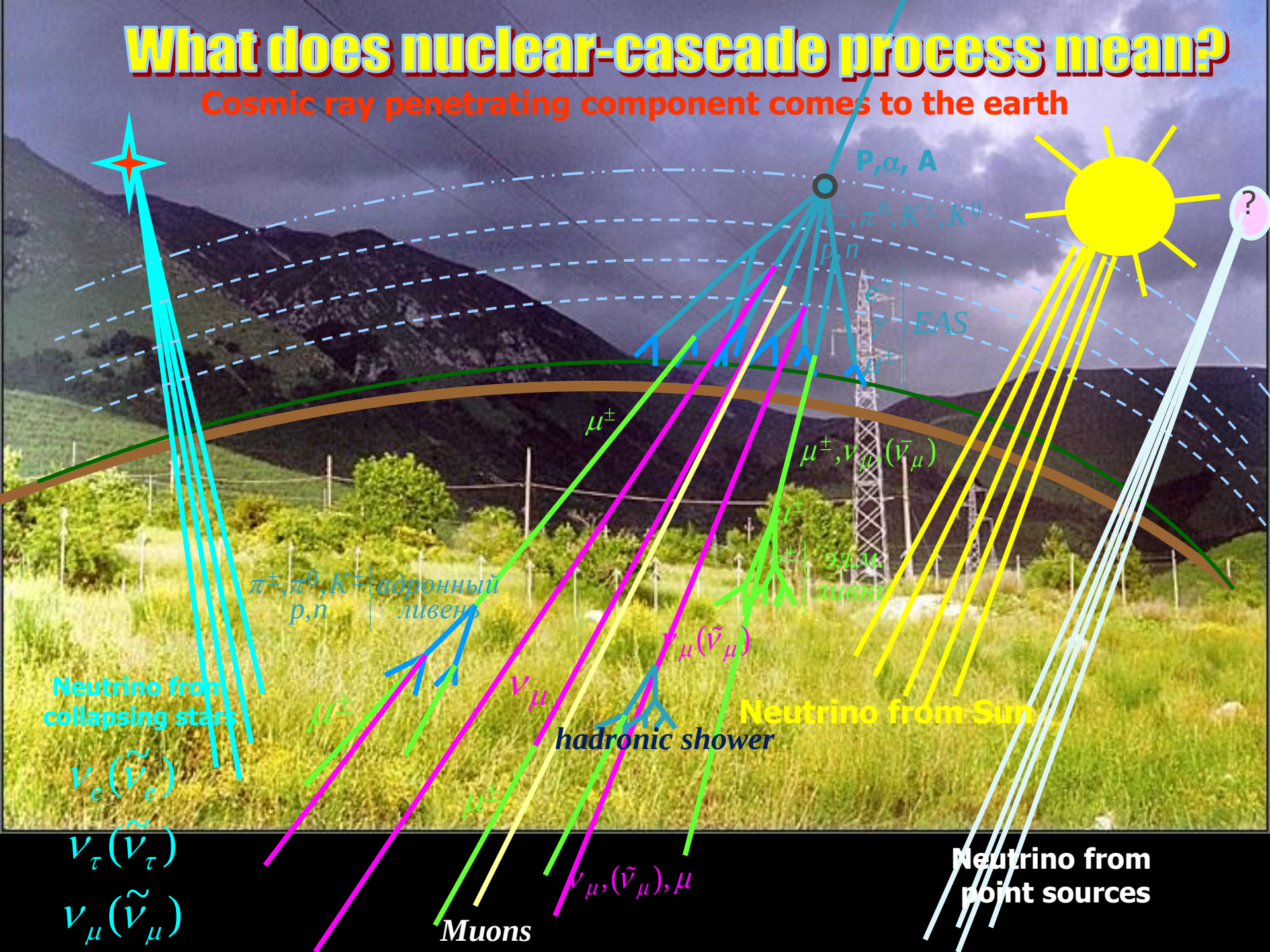
Before 1964 it was supposed that the nuclear active component is produced due to electromagnetic cascades generated by muons underground.

G.Zatsepin suggested to take into account the nuclear cascades developed after deep inelastic scattering of muons.

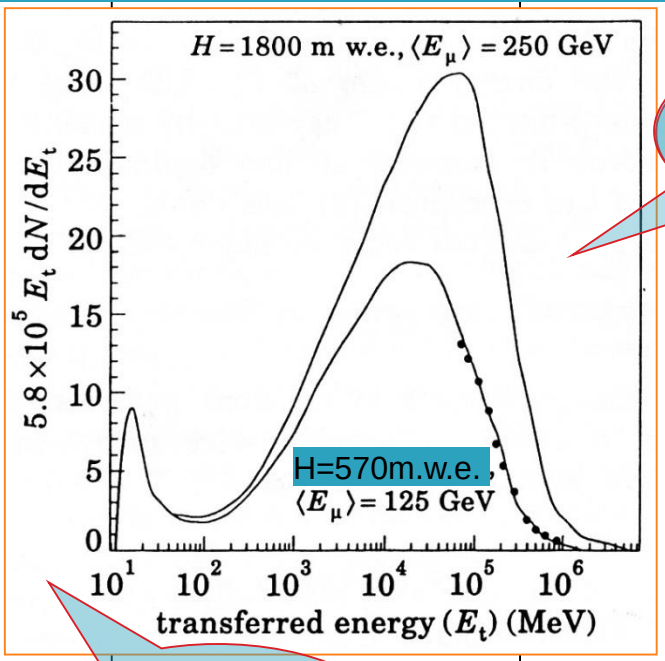


What does nuclear-cascade process mean?

Cosmic ray penetrating component comes to the earth



20-й семинар, Лаборатории Нейтрино, 1964 г. *(Апатиты, IX ICRC, London)*

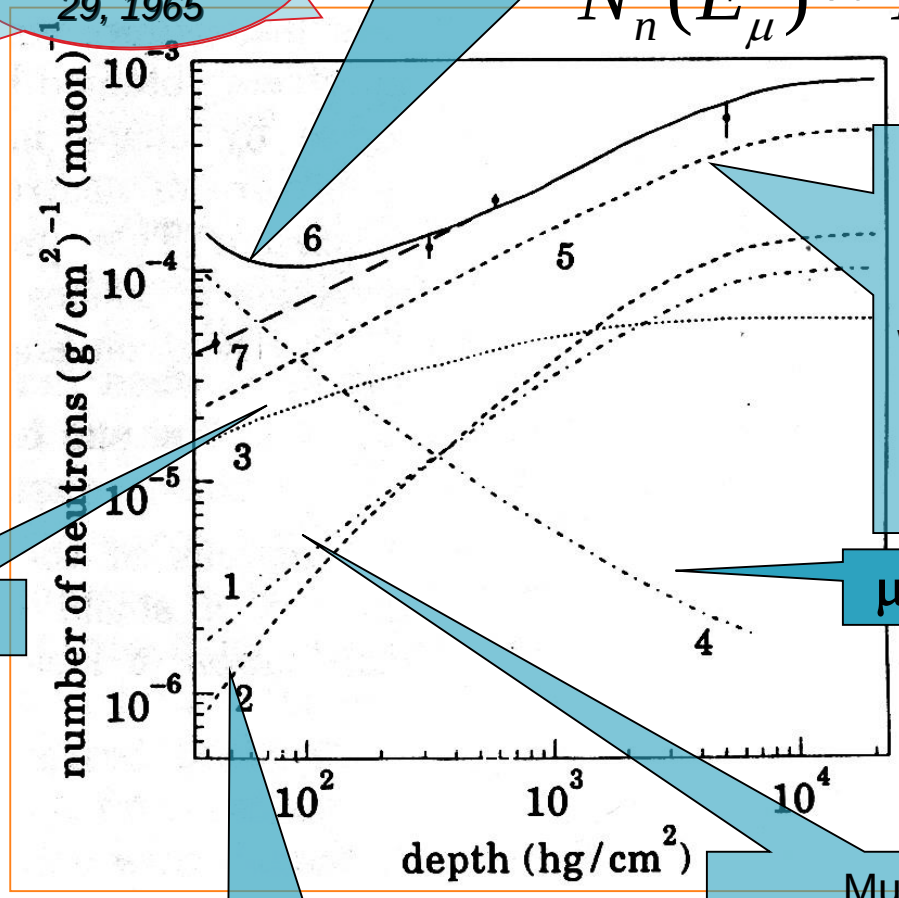


Z. R. Izv. AN SSSR, ser. Fiz. 29, 1965

Kh. M. R. R. JETP Lett., 36, 1982

The sum of all processes.

$$N_n(\overline{E}_\mu) \sim \overline{E}_\mu^{0,75}$$



Neutron production in inelastic muon interactions with taking into account nuclear showers

δ-electrons

μ^- capture

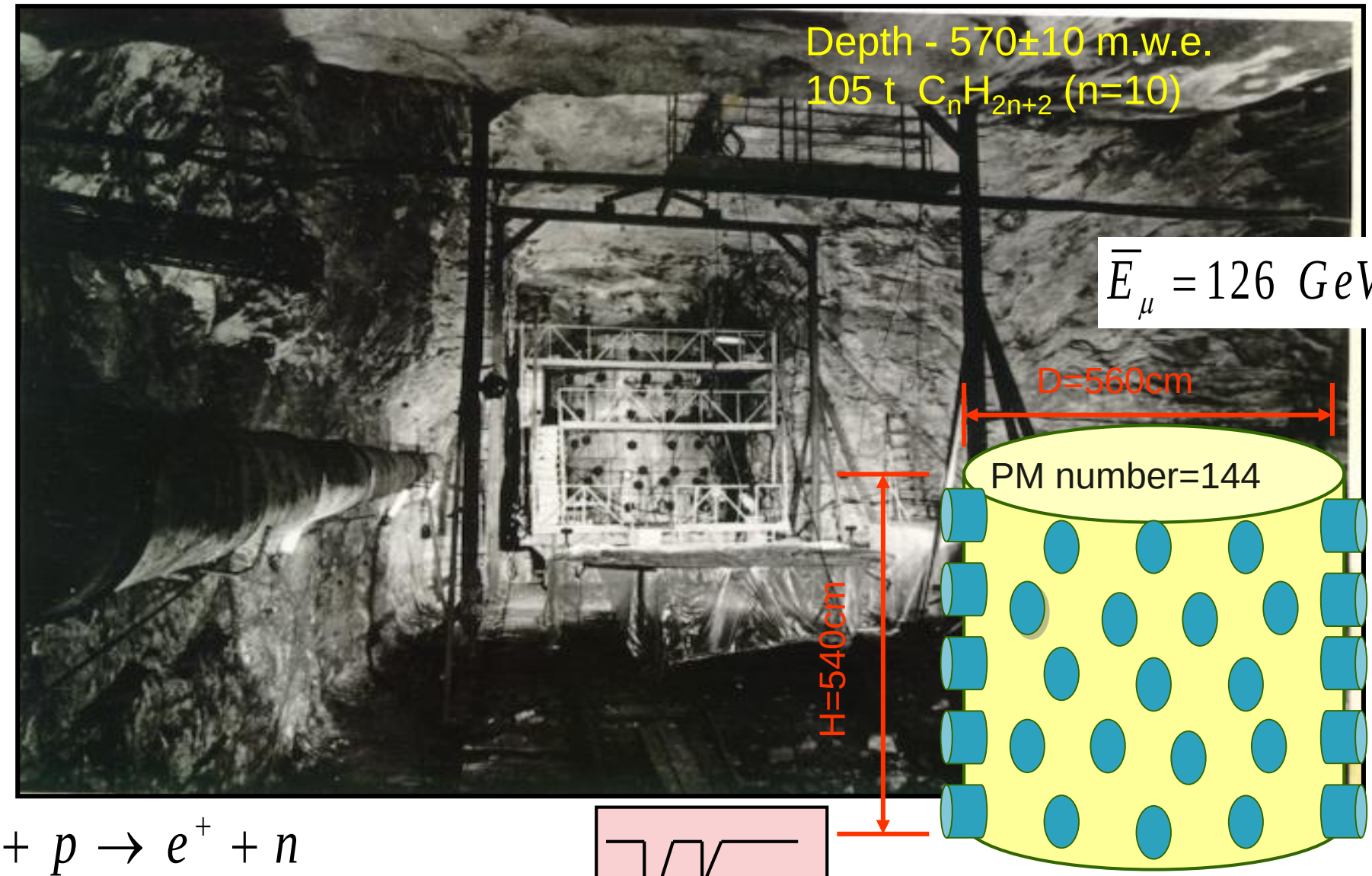
Muon bremsstrahlung

pair production

Dependence of the contribution of neutrons, produced in inelastic muon interactions, on the energy transfer in the interaction E_t

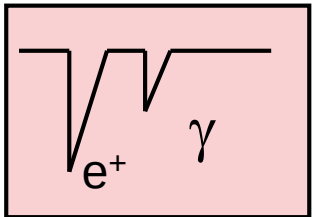
The number of generated neutrons per 1 muon per 1 g/cm^2 vs the depth from the top of the atmosphere.

ARTEOMOVSK



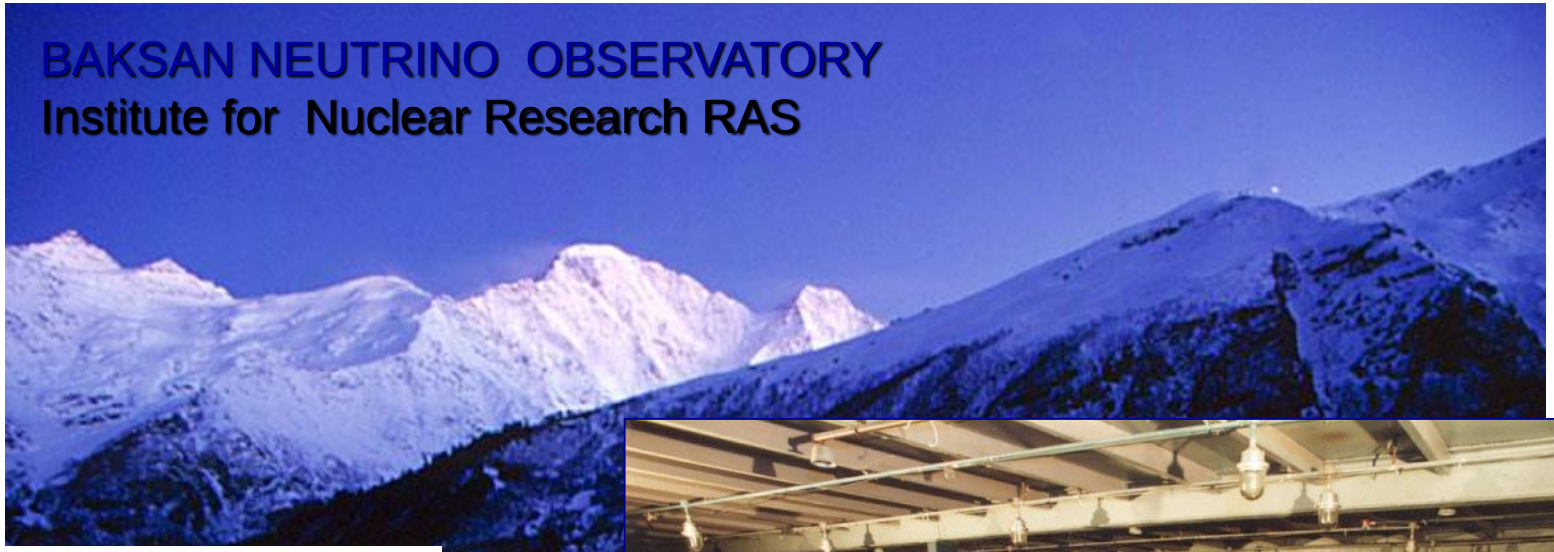
$$\tilde{\nu}_e + p \rightarrow e^+ + n$$

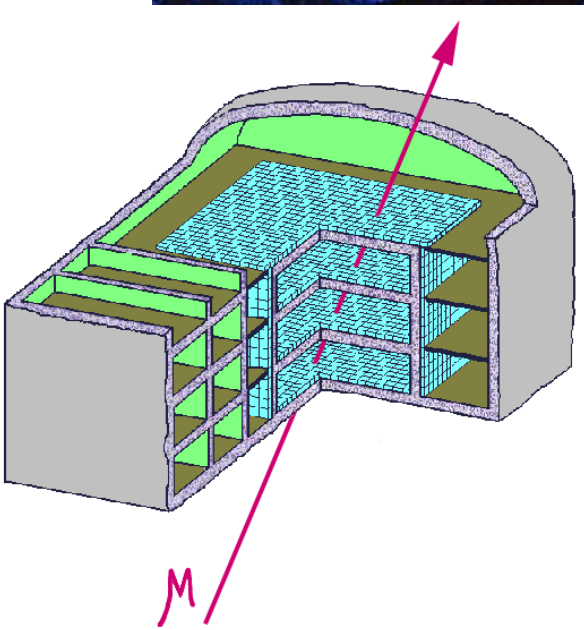
$$n + p \rightarrow d + \gamma,\ E_\gamma = 2.2 MeV$$



η_n ~87%

BAKSAN

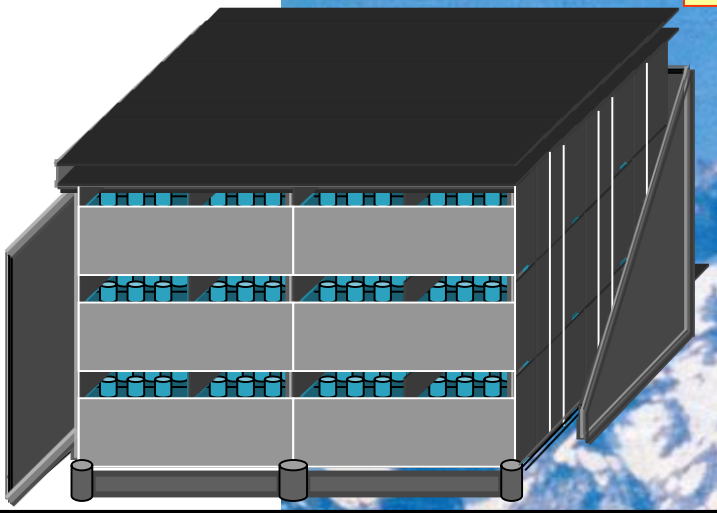

BAKSAN NEUTRINO OBSERVATORY
Institute for Nuclear Research RAS

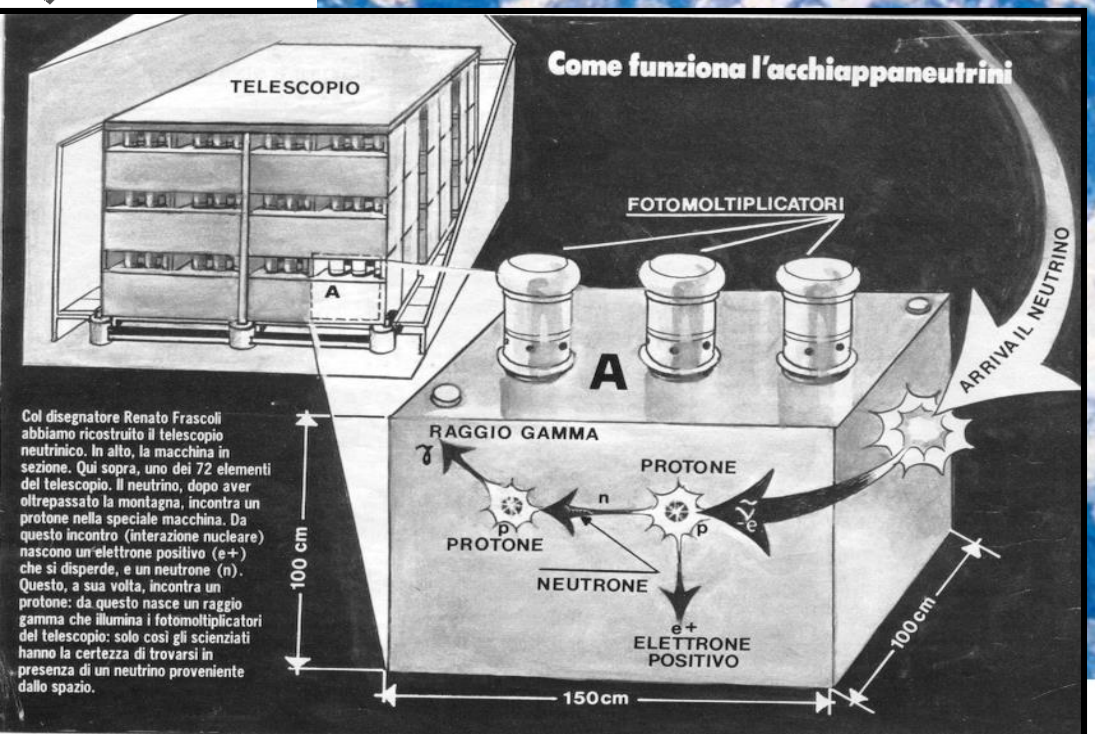

M

- *Discussion about underground physics, 1969.*

- *Discussion about Russian-Italian collaboration, 1977.*

LSD, Monte Bianco





Col disegnatore Renato Frascoli abbiamo ricostruito il telescopio neutrinico. In alto, la macchina in sezione. Qui sopra, uno dei 72 elementi del telescopio. Il neutrino, dopo aver oltrepassato la montagna, incontra un protone nella speciale macchina. Da questo incontro (interazione nucleare) nascono un elettrone positivo (e+) che si disperde, e un neutrone (n). Questo, a sua volta, incontra un protone: da questo nasce un raggio gamma che illumina i fotomoltiplicatori del telescopio: solo così gli scienziati hanno la certezza di trovarsi in presenza di un neutrino proveniente dallo spazio.

UP 85

1st Symposium on

Underground physics

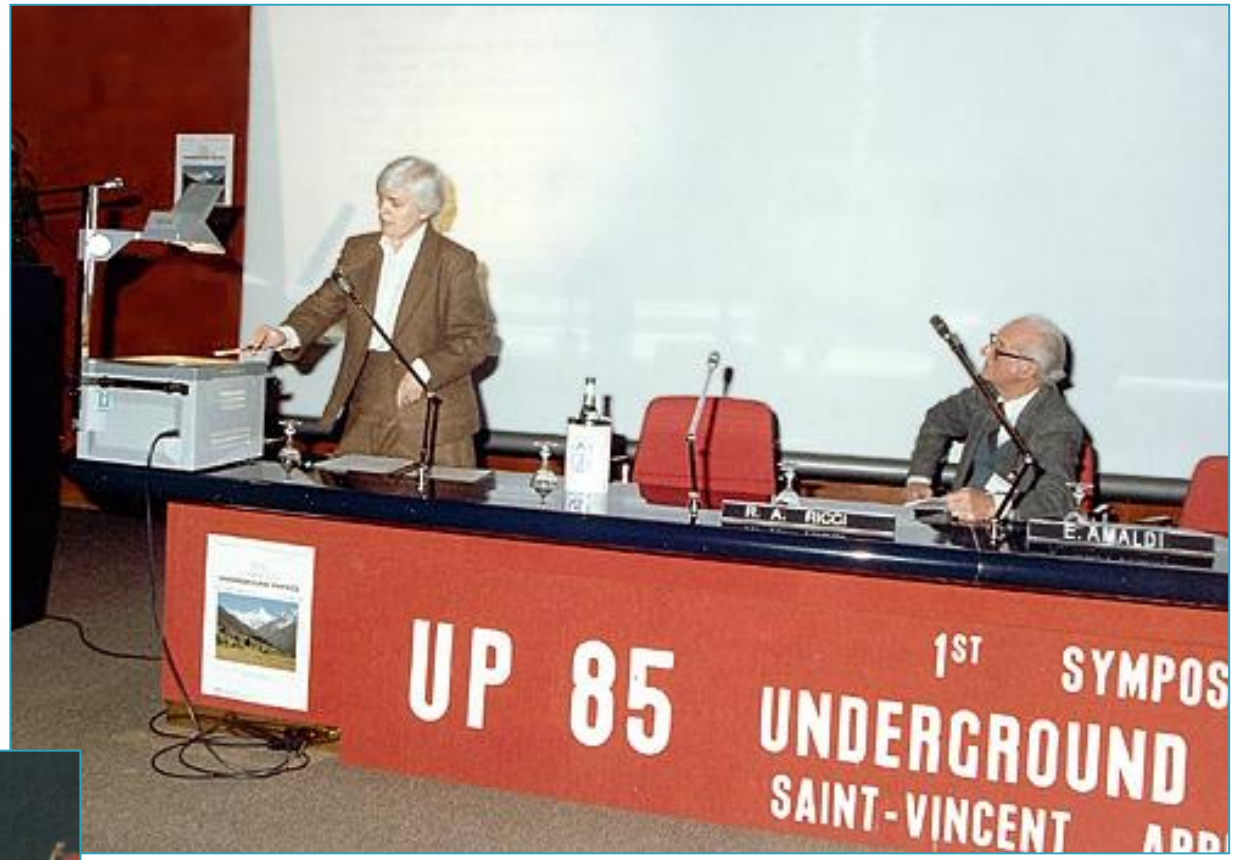
April 25-28, 1985

1985

The term

“**Underground Physics**”

was introduced in 1985 by prof. C.Castagnoli during the symposium dedicated to the opening ceremony of the LSD detector under Mont Blanc



1978: B.Pontecorvo about Gran Sasso lab:

“I regret not to be young enough to participate in this formidable project. The scientific content of the project appears to me extremely interesting”.

1985 – official start of LSD running

New concept of cosmic ray physics

Underground physics

In this year we can celebrate
30 years of
UNDERGROUND PHYSICS

Neutrino from the Collapsing stars

General idea

How can one detect the neutrino flux from collapsing stars?

Until now, **Cherenkov (H_2O)** and **scintillation (C_nH_{2n})** detectors which are capable of detecting mainly $\tilde{\nu}_e$, have been used in searching for neutrino radiation, This **choice is natural and connected with large $\tilde{\nu}_e$- p cross-section**

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

$$\sigma_{\tilde{\upsilon}_e p} \sim 9.3 E_{e^+}^2 \cdot 10^{-44} \, cm^2 \qquad E_{e^+} >> 0.5 \ MeV$$

As was shown at the first time by G.T.Zatsepin, O.G.Ryazhskaya, A.E.Chudakov (1973), the proton can be used for a neutron capture with the following production of deuterium (d) with γ - quantum emission with τ~180 – 200 μs.

$$n + p \rightarrow d + \gamma \quad E_\gamma = 2.2 \ MeV$$

The specific signature of event

During last 40 years the following underground detectors were constructed by the Institute for Nuclear Research of the USSR:

1. **ASD (Collapse)** : (INR RAS, Arteomovsk), 105 t of liquid scintillator, 1 kt of NaCl, 1977

2. **BUST** (INR RAS, Baksan), 200 t of liquid scintillator and 160 t of iron, 1978

3. **LSD** (INR RAS together with Institute of Cosmo Geophysics of CNR) Mt. Blanc, 90 t of scintillator and 200 t of iron, 1984

4. **LVD** (INR RAS and LNGS INFN, Gran Sasso) ,
   0,35 кt scintillator and 0,33кt iron , 1992
   last version (1 kt of scintillator and 1 kt of iron), 2001

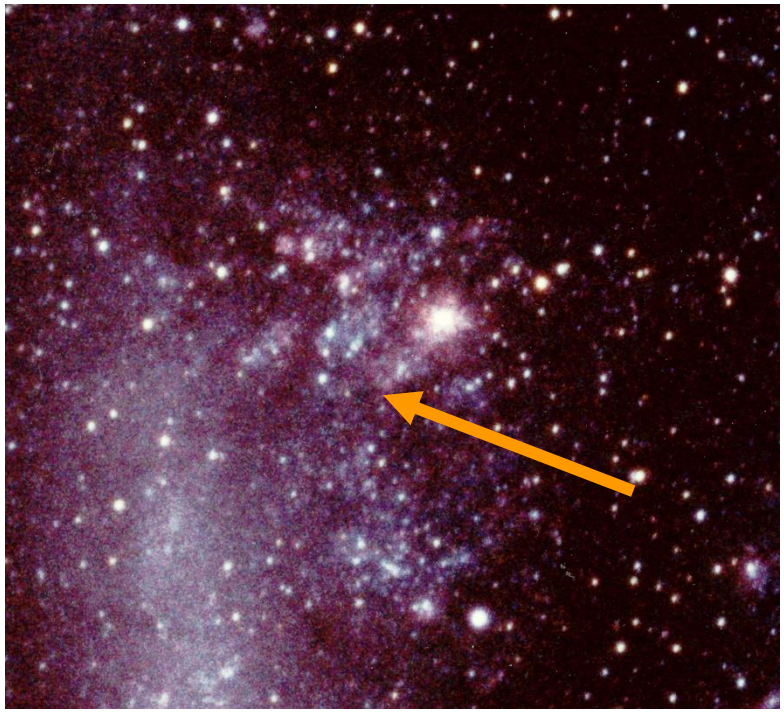
One of main goals of the experiment is the search for neutrino burst from collapsing stars.

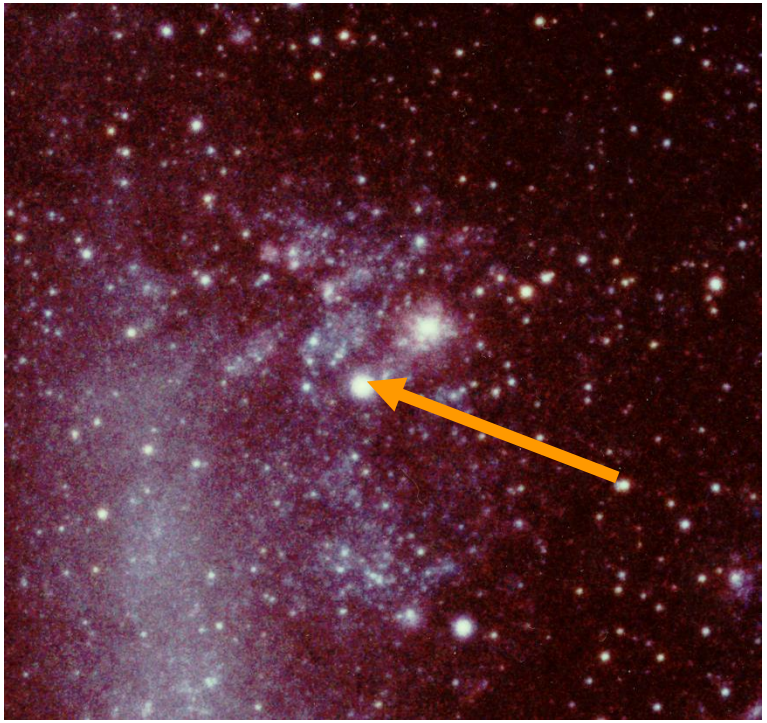
These detectors also are used for different studies in the field of underground physics. The possibility of a simultaneous detection of a neutrino burst by several detectors located in different places on the Earth strongly reduces noise and increases the reliability of results.

On February,23, 1987

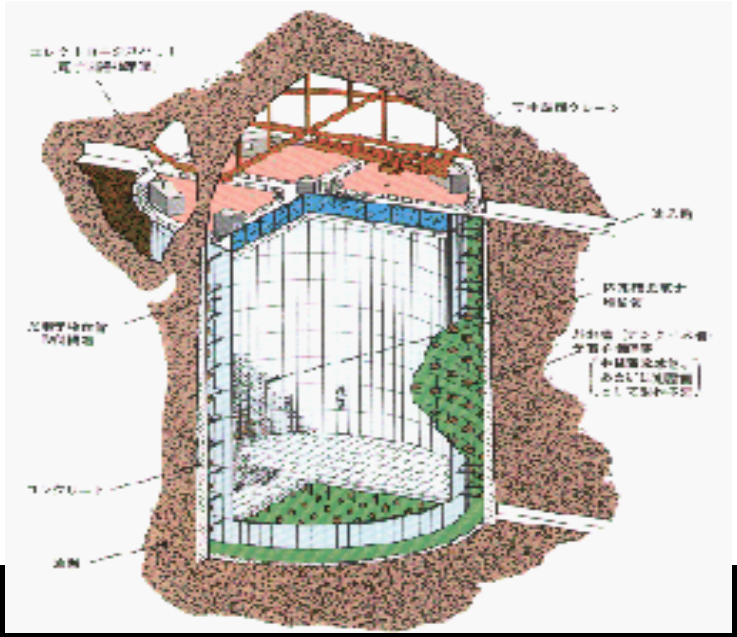
A Supernova explosion

in the Large Magellanic Cloud occured.

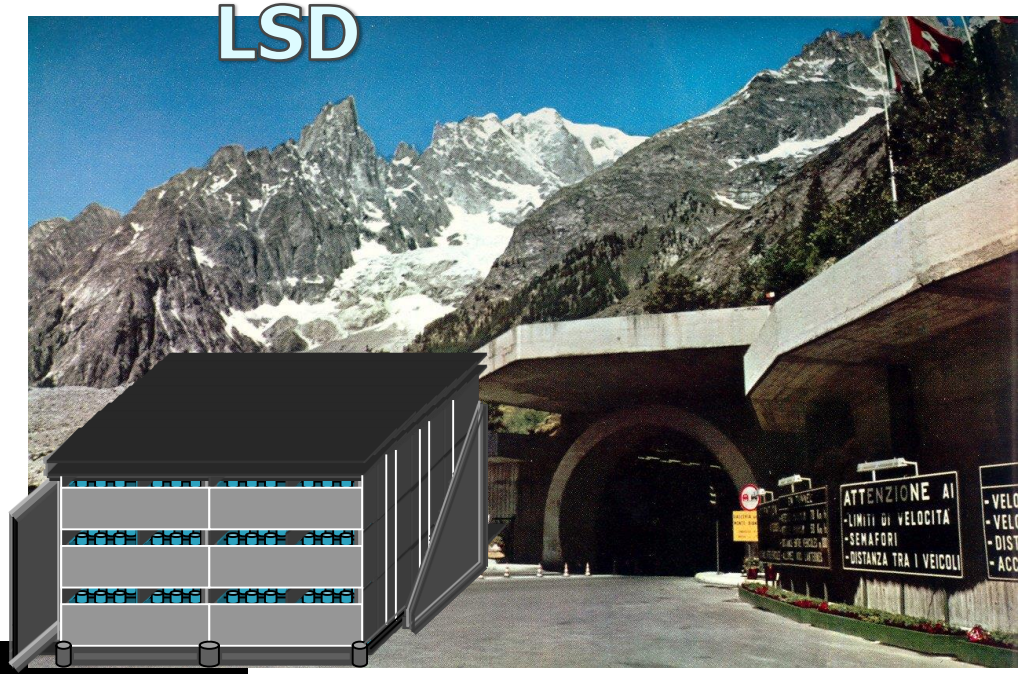


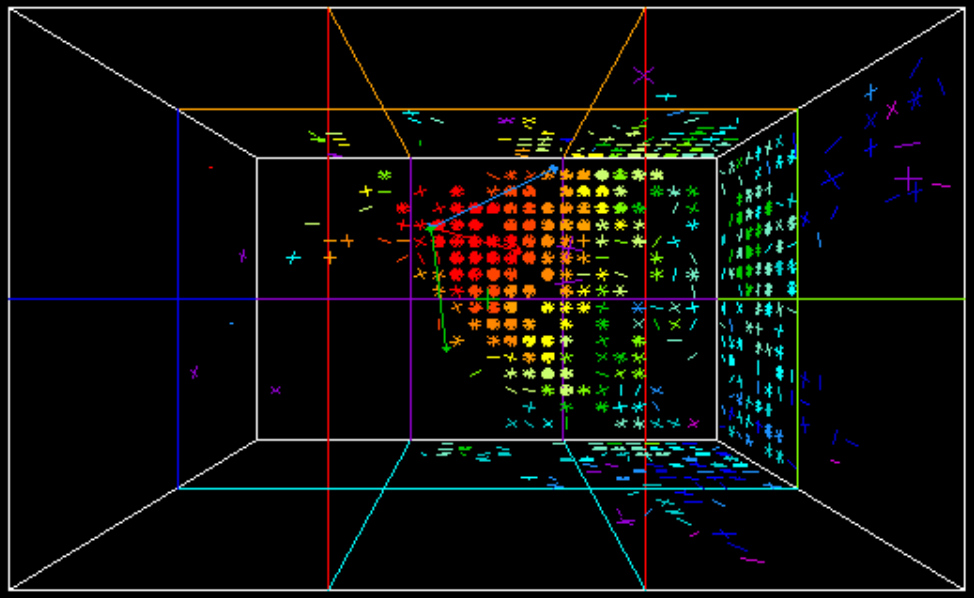


Kamiokande

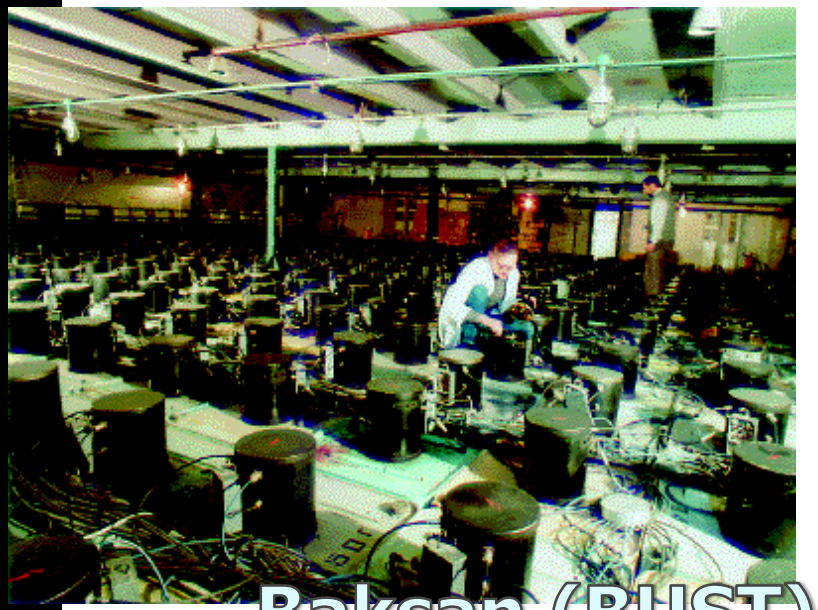


LSD



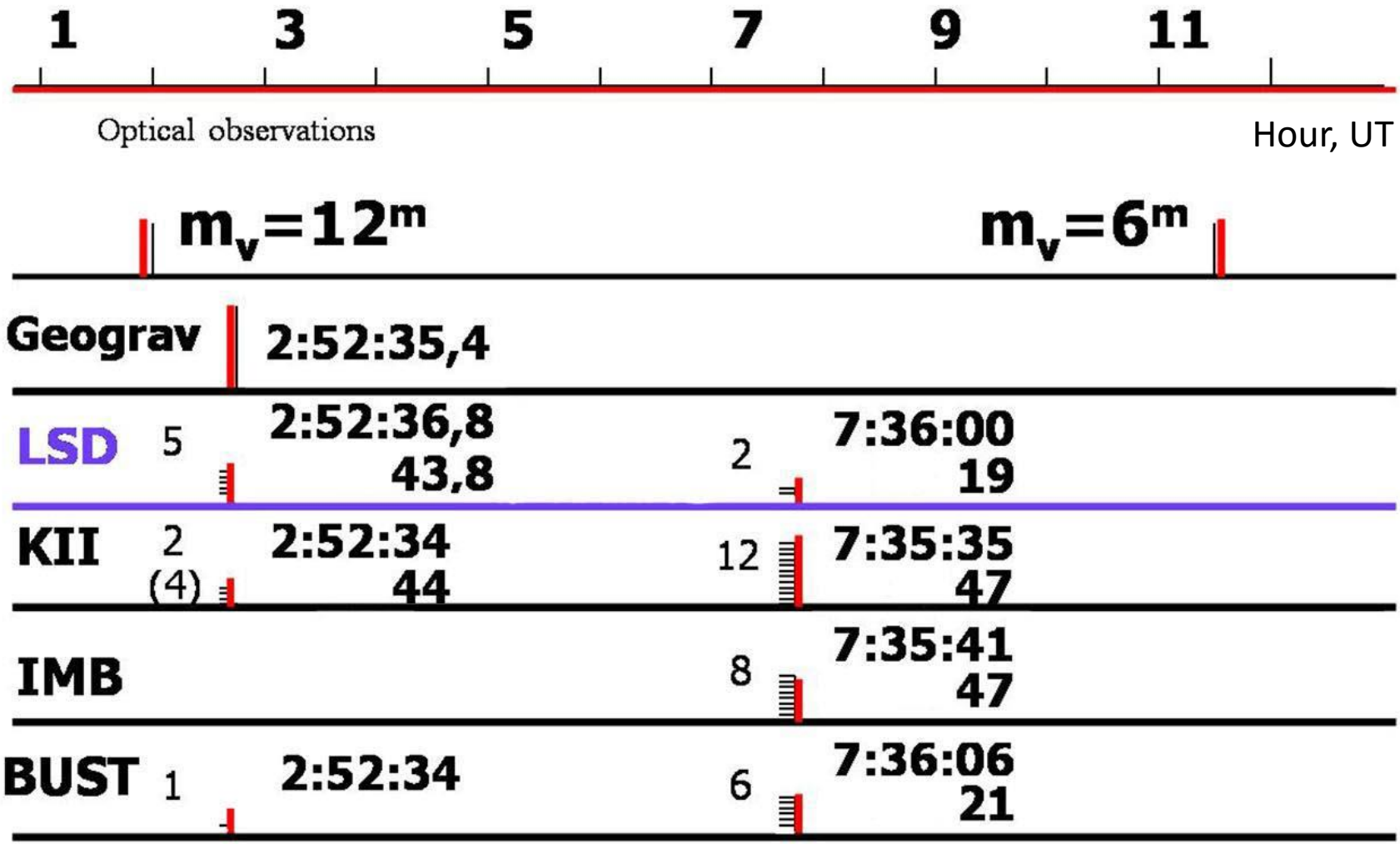


IMB



Baksan (BUST)

February 23, 1987



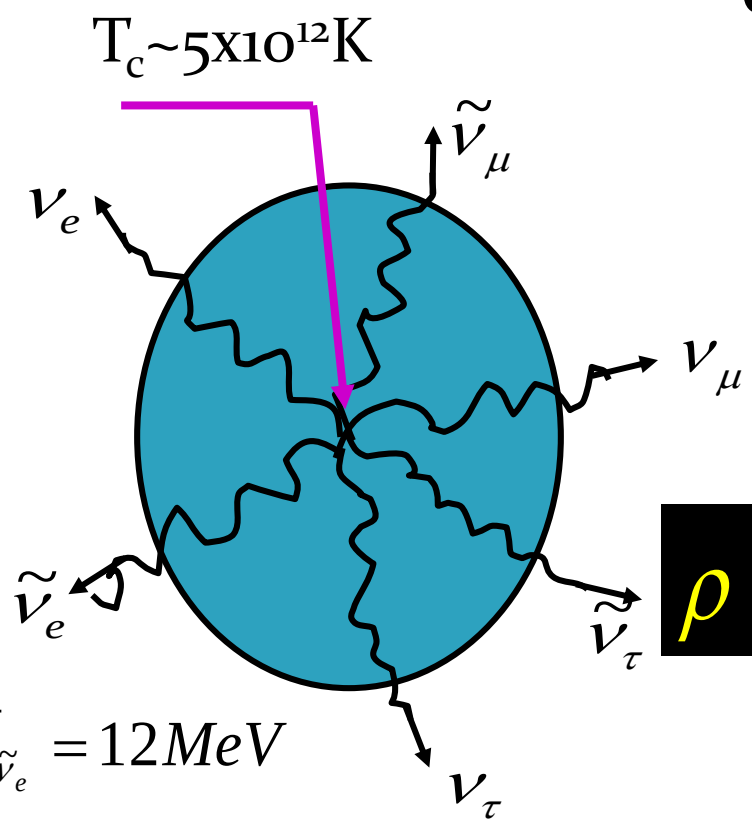
The results are not explained in the frame of the standard collapse model, but can be naturally explained by rotating collapsar model (*V.Imshennik,O. Ryazhskaya, Astron. Lett. 30, 14 (2004)*) which predicts two-stage collapse. **LSD detected neutrino from the stage of neutronization of the star due to the presence of the iron in LSD. The first stage was ~ 5 hours early then second one.**

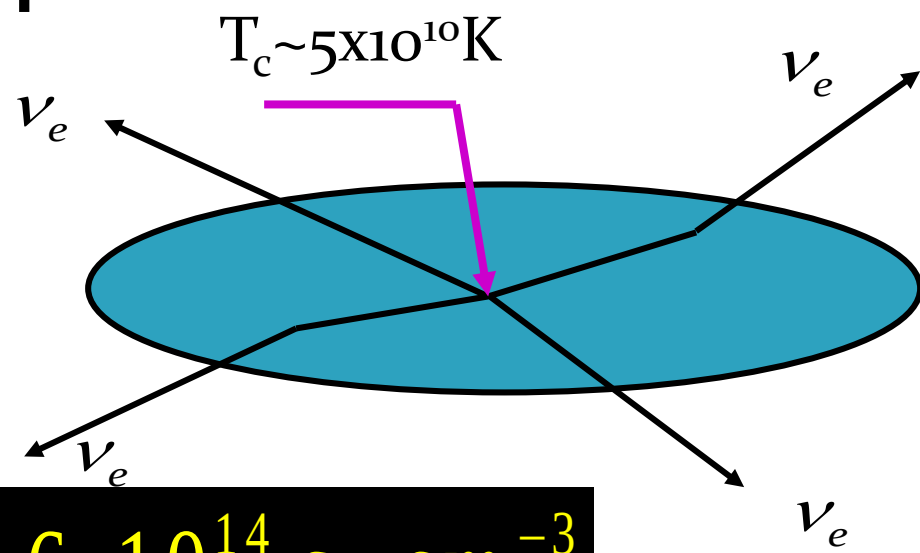
The rotation effects make it possible:

1. To resolve the problem of the transformation of collapse into an explosion for high-mass and collapsing supernovae (all types of SN, except the type Ia – thermonuclear SN)

2. To resolve the problem of two neutrino signals from SN 1987A, separated by a time interval of 4.7 h.

The difference of neutrino emission in the standard model and in the model of rotating collapsar.





$$\rho \sim 2.6 \cdot 10^{14} g \cdot cm^{-3}$$

$$\overline{E}_{\tilde{\nu}_e} = 12 MeV$$

$$\overline{E}_{\nu_e} = 10 MeV$$

$$\overline{E}_{\nu_\mu, \tilde{\nu}_\mu, \nu_\tau, \tilde{\nu}_\tau} = (20 - 25) MeV$$

$$\varepsilon_{\nu, \tilde{\nu}} = 5.3 \cdot 10^{53} erg$$

The main reaction – URCA-process:

$$p + e^- \rightarrow n + \nu_e$$

$$\overline{E}_\nu = (30 - 50) MeV$$

$$\varepsilon_{\nu_e, \tilde{\nu}_e} \approx \varepsilon_{\nu_e} = 8.9 \cdot 10^{52} erg$$

The experiments running to search for neutrino radiation from collapsing stars up to now traditionally take one's bearings for the detection of the inverse β-decay reaction and, accordingly, for the use of the hydrogenate targets. The observation of neutrino radiation from SN1987A showed that it is important to have in the composition of the targets beside the hydrogen also other nuclei suitable to neutrino radiation detection. In particular the presence of iron nuclei in the LSD (200 t) provided for the sensational detection of electron neutrino at 2:52 UT on February 23 1987 when other more powerful detectors with their hydrogenate targets could not respond to this type of neutrino.

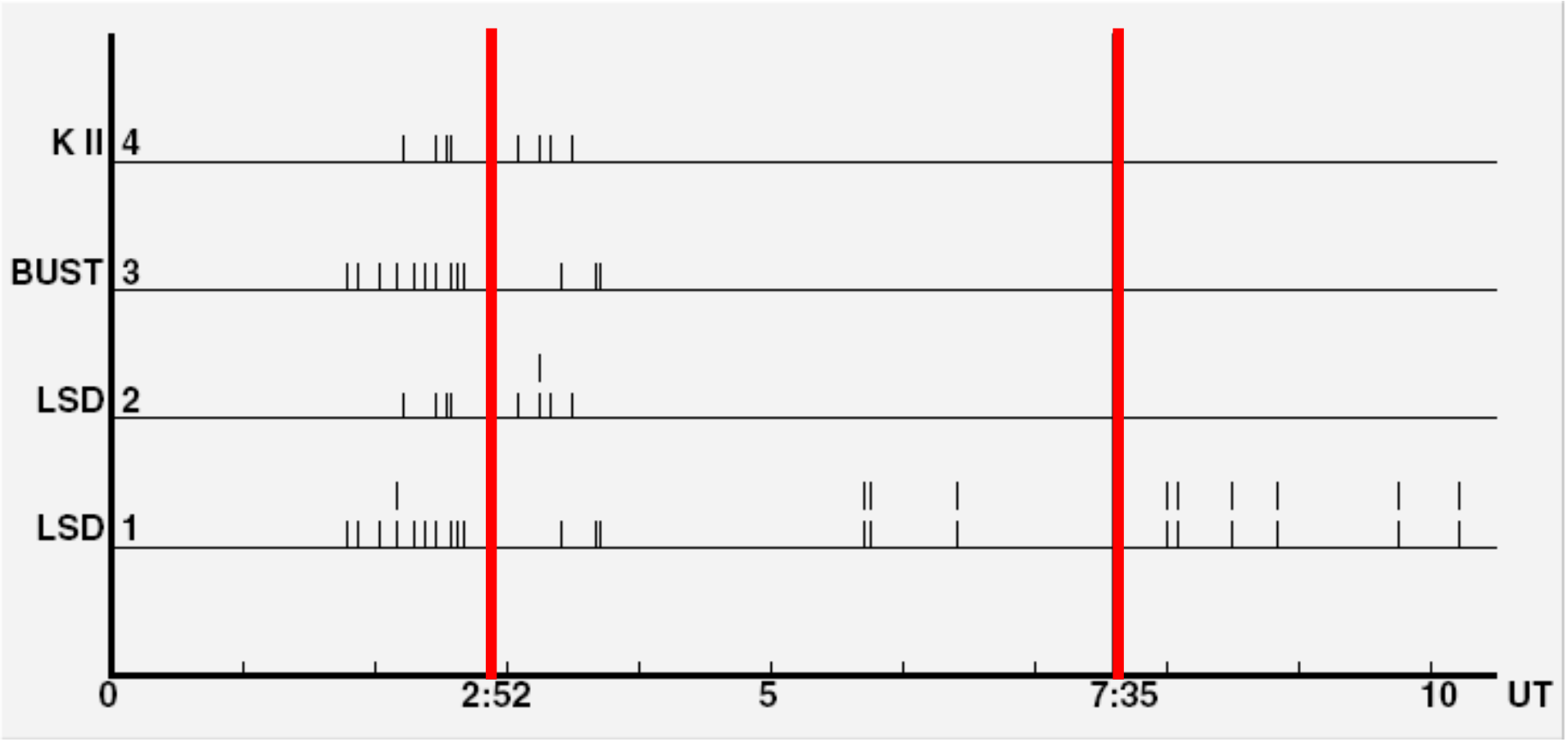
2:52 UT results and 7:35 UT results correspond to a certain extent to the model of standard collapse (7:35 UT)

Review by Imshennik V.S., Nadyozhin D.K. // Inter. J. Mod. Phys. A **20,** 6597 (2005),

the model of rotating collapsar (2:52 UT; 7:35 UT)

Imshennik V.S., Space Sci Rev, **74**, 325-334 (1995); Astronomy Lett., 34, 375 (2008); Imshennik V.S., Ryazhskaya O.G. // Astronomy Lett., **30**, 14 (2004)

However, a number of questions still remains!



Timing diagram of the BUST pulses coincident with the LSD pulses within 1 s and similar coincidences for the K2 and LSD detectors as well as double pulses in LSD over the period from 0:00 to 10:00 UT on February 23, 1987.

N_c (LSD-K2) = 8; $N_{c.by\ chance}$ = 2

N_c(LSD-BUST) = 13; $N_{c.by\ chance}$ = 3

$N_{pairs\ by\ chance}$ = 1,2

Coincidence by chance with SN 1/3000 years

It was made the analysis of the BUST and LVD data obtained during 2013-2014 yy. to study experimental search for BUST and LVD coincidences of pulses within 1 s.

The average number of coincidences within the 1 second time interval is less than 1 event per day (total 294 evens for 2013 year and 297 events for 2014 year was obtained). The results are correspond to random coincidences.

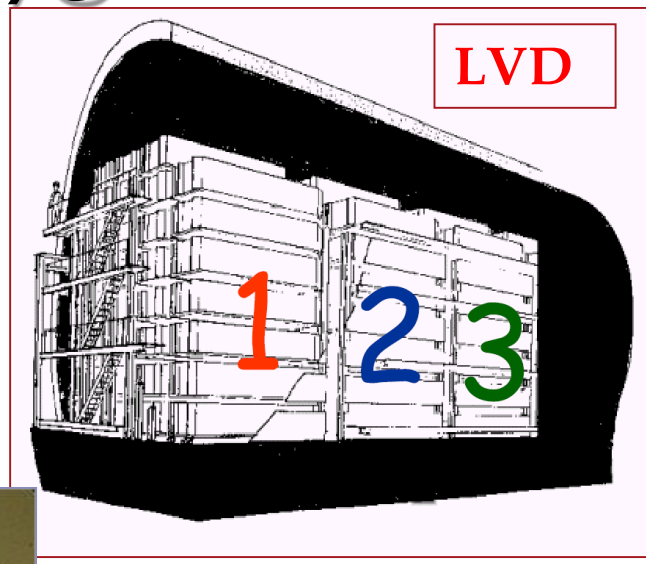
On February 23, 1987 13 events in time interval from 1:50 UT till 3:50 UT were detected, number of random events is 3.

LVD – detector under Gran Sasso (LNGS) @ 3300 m.w.e.

✓the largest iron-scintillation telescope in the world

✓3 towers:

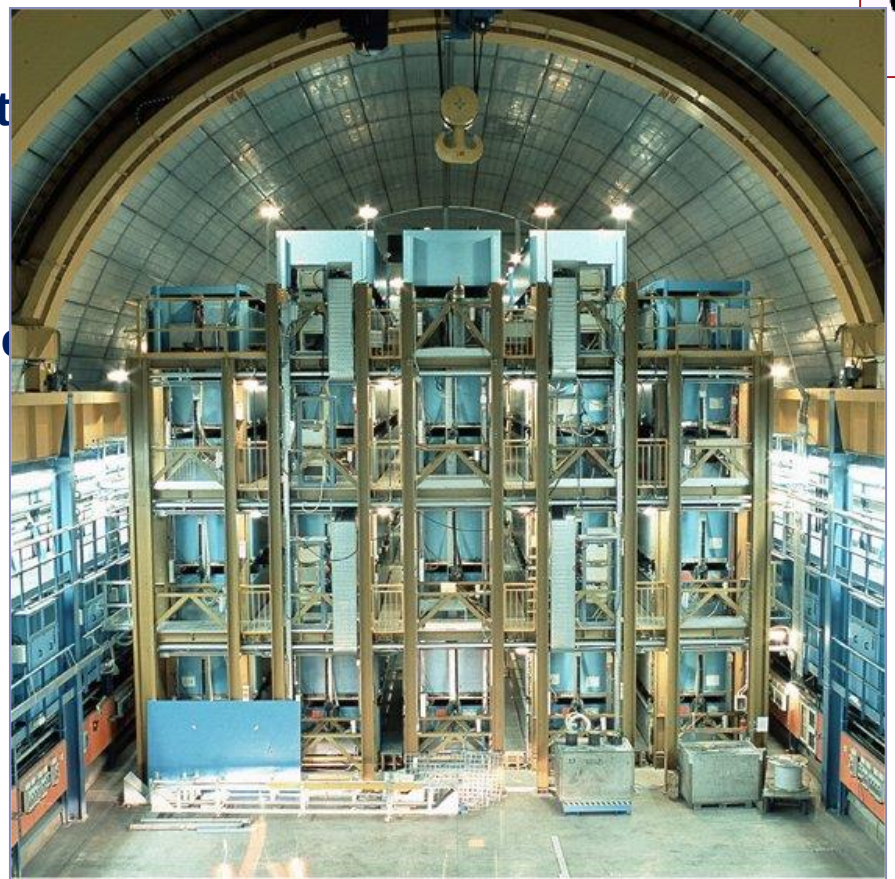
- ✓840 scintillation counters (1010 tons of scintillator)
- ✓1000 tons of iron



Study & important results in:

- neutrino physics
- astrophysics
- cosmic ray physic
- search for rare processes

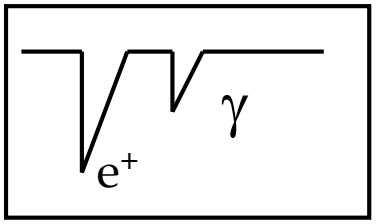
The main goal is to search for ν bursts from collapsing stars



LVD is 10 times expanded version of the LSD (Mont Blanc) apparatus which has detected the ν-burst from SN 1987A at 2:52 UT on February, 23, 1987. LSD & LVD are Russian-Italian projects. Scintillator & scintillation counters were elaborated and produced in INR, Russia

LVD can measure all types of neutrinos from collapsing stars

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



$$\left.\begin{array}{l} n + p \rightarrow d + \gamma \ (E_\gamma = 2.2 MeV) \\ n + {}^{56}Fe \rightarrow {}^{57}Fe + \sum \gamma \ (E_\gamma = 10.16 MeV) \end{array}\right\} \tau \approx 185 \mu s$$

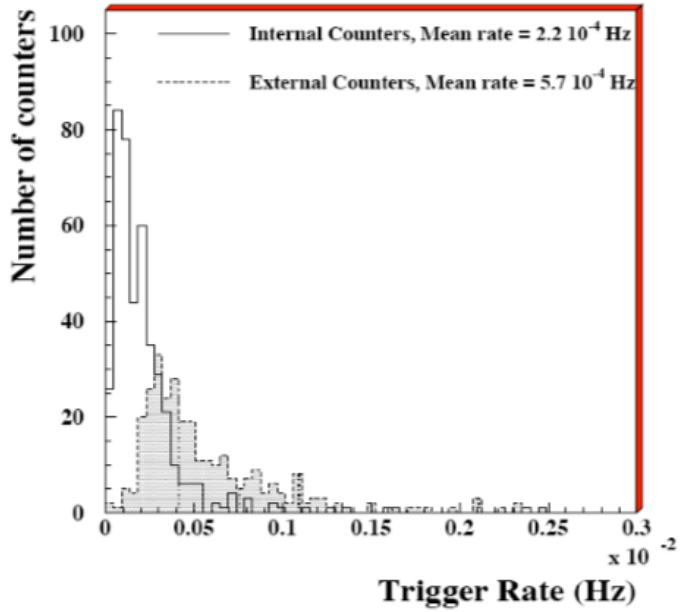
$$\nu_e + {}^{56}_{26}Fe \rightarrow {}^{56}_{27}Co^* + e^-, \quad {}^{56}Co^* \rightarrow {}^{56}Co + \Sigma\gamma, \ E_\gamma = 7 \div 11 MeV$$

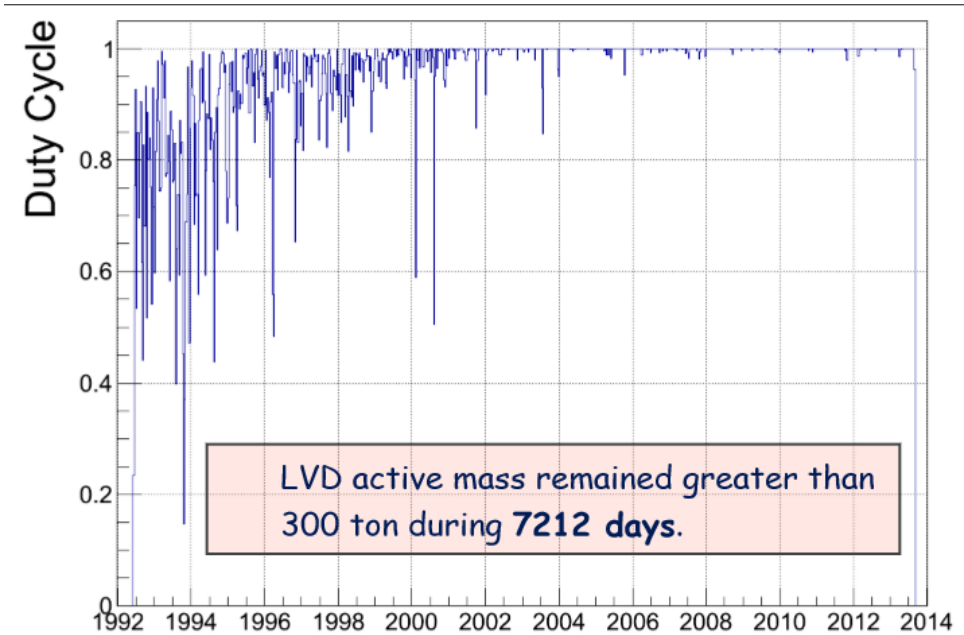
and $\nu_i + {}^{12}C \rightarrow {}^{12}C^* + \nu_i, \ (i = e, \mu, \tau); \ {}^{12}C^* \rightarrow {}^{12}C + \gamma, \ E_\gamma = 15.1 \ MeV$

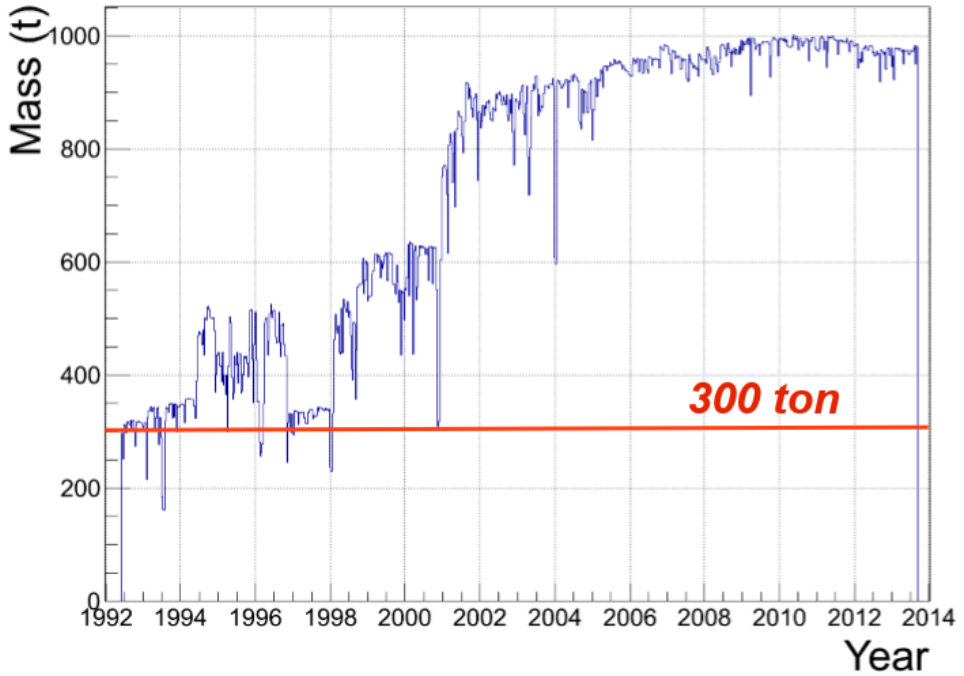
data set

The detector active mass, M_{act}, is updated every 8 hours:

- **The response to atmospheric muons is used to identify and discard bad working counters.**
- **Counters with a background rate: $R(E \geq 7MeV) \geq 3 \cdot 10^{-3}$/s are rejected as noisy.**



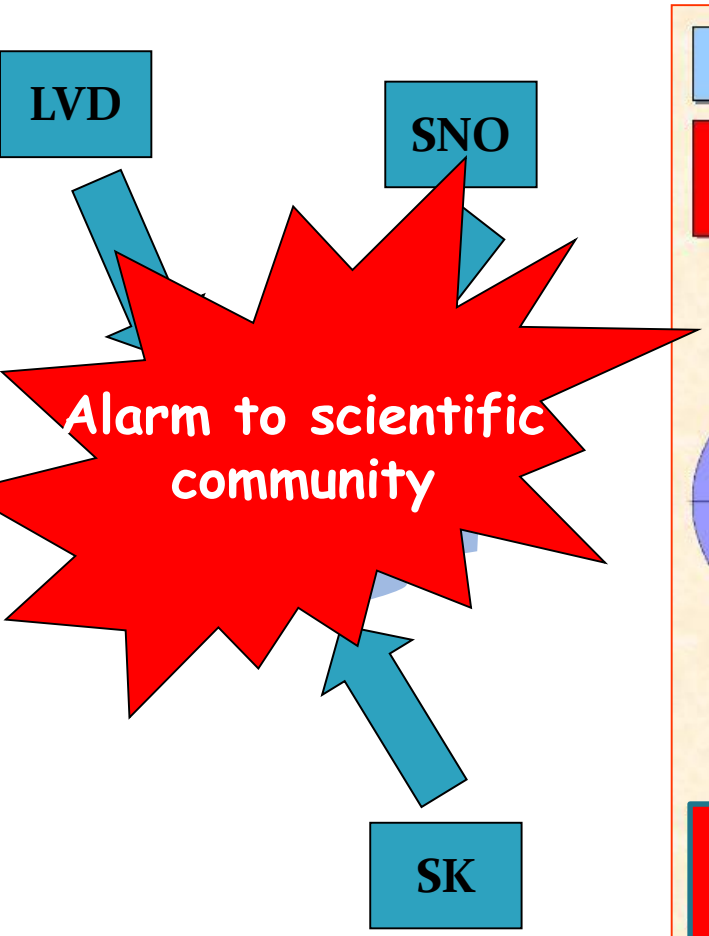


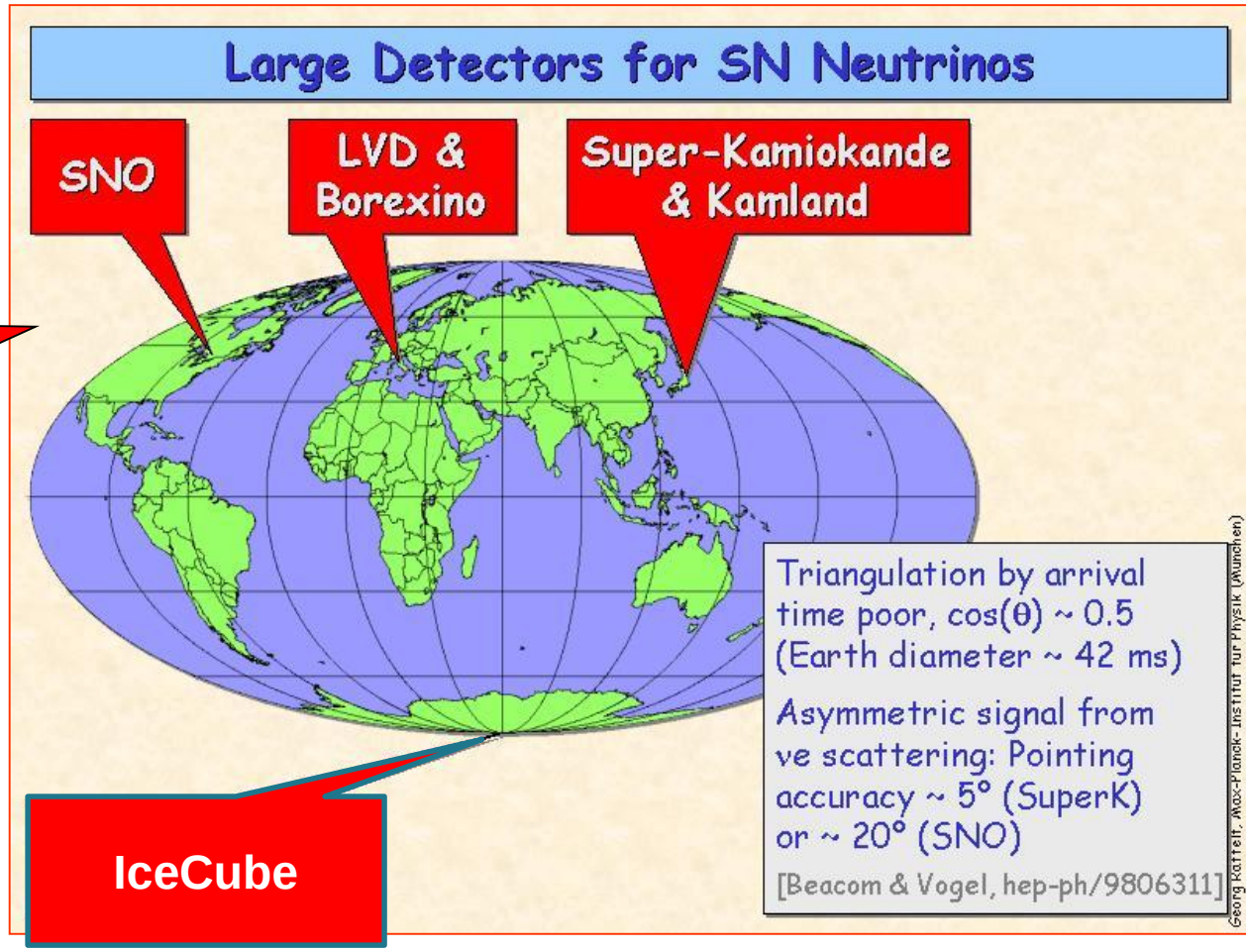


During 38 years ["Collapse" – 1977, LSD – 1984-2002, LVD – 1992(1 tower), 1998 (3 towers)] there were no observation of ν radiation from collapsing stars in the Galaxy. The collapse rate is less than 1 / 16 years at 90% c.l.

SNEWS

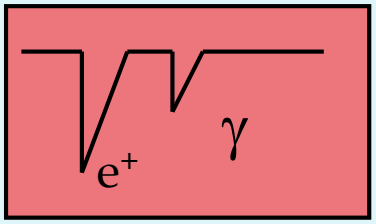
SuperNova Early Warning System





ASD and LVD can detect all types of neutrinos

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



$$\left.\begin{array}{l} n + P \rightarrow d + \gamma \ (E_\gamma = 2.2MeV) \\ n + {}^{56}Fe \rightarrow {}^{57}Fe + \sum\gamma \ (E_\gamma = 10.16MeV) \end{array}\right\} \tau \approx 185\mu s$$

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma \ (E_\gamma = 8.56MeV, \bar{k}_\gamma = 3.1) \ \tau \approx 170\mu s$$

$$\nu_e + {}^{56}_{26}Fe \rightarrow {}^{56}_{27}Co^* + e^-, \quad {}^{56}Co^* \rightarrow {}^{56}Co + \Sigma\gamma, \ E_\gamma = 7 \div 11MeV$$

and $\nu_i + {}^{12}C \rightarrow {}^{12}C^* + \nu_i, \ (i = e, \mu, \tau); \ {}^{12}C^* \rightarrow {}^{12}C + \gamma, \ E_\gamma = 15.1 \ MeV$

Reactions for scintillation and Cherenkov counters

$\tilde{\upsilon}_e + p \rightarrow e^+ + n$	$\sigma_{\tilde{\nu}_e p} \sim 9.3 E_{e^+}^2 \cdot 10^{-44}\ cm^2$	$E_{e^+} >> 0.5 MeV$
$\nu_e + e^- \rightarrow \nu_e + e^-$ $\nu_i + e^- \rightarrow \nu_i + e^-$ $\tilde{\nu}_i + e^- \rightarrow \tilde{\nu}_i + e^-$	$\sigma_{\nu_e e^-} \sim 9.4 E_{\nu_e} \cdot 10^{-45} cm^2$ $\sigma_{\nu_i e^-} \sim 1.6 E_{\nu_i} \cdot 10^{-45} cm^2$ $\sigma_{\tilde{\nu}_e e^-} \sim 1.3 E_{\tilde{\nu}_i} \cdot 10^{-45} cm^2$	
$\nu + {}^{12}C \rightarrow {}^{12}C^* + \nu - 15.1\ MeV$ $\hookrightarrow {}^{12}C + \gamma\ (15.1\ MeV)$	$\bar{\sigma}_{\nu_e}(\bar{E}_{\nu_e} = 10 MeV) = 0.066 \cdot 10^{-42} cm^2$ $\bar{\sigma}_{\mu,e}(\bar{E}_{\nu_\mu} = 20 MeV) = 1.23 \cdot 10^{-42} cm^2$	
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$ $\hookrightarrow {}^{12}C + e^+ + \nu_e$	$E_{thr} = 17.34\ MeV$	$\tau = 15.9\ ms$
$\tilde{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$ $\hookrightarrow {}^{12}C + e^- + \tilde{\nu}_e$	$E_{thr} = 14.4\ MeV$	$\tau = 29.3\ ms$

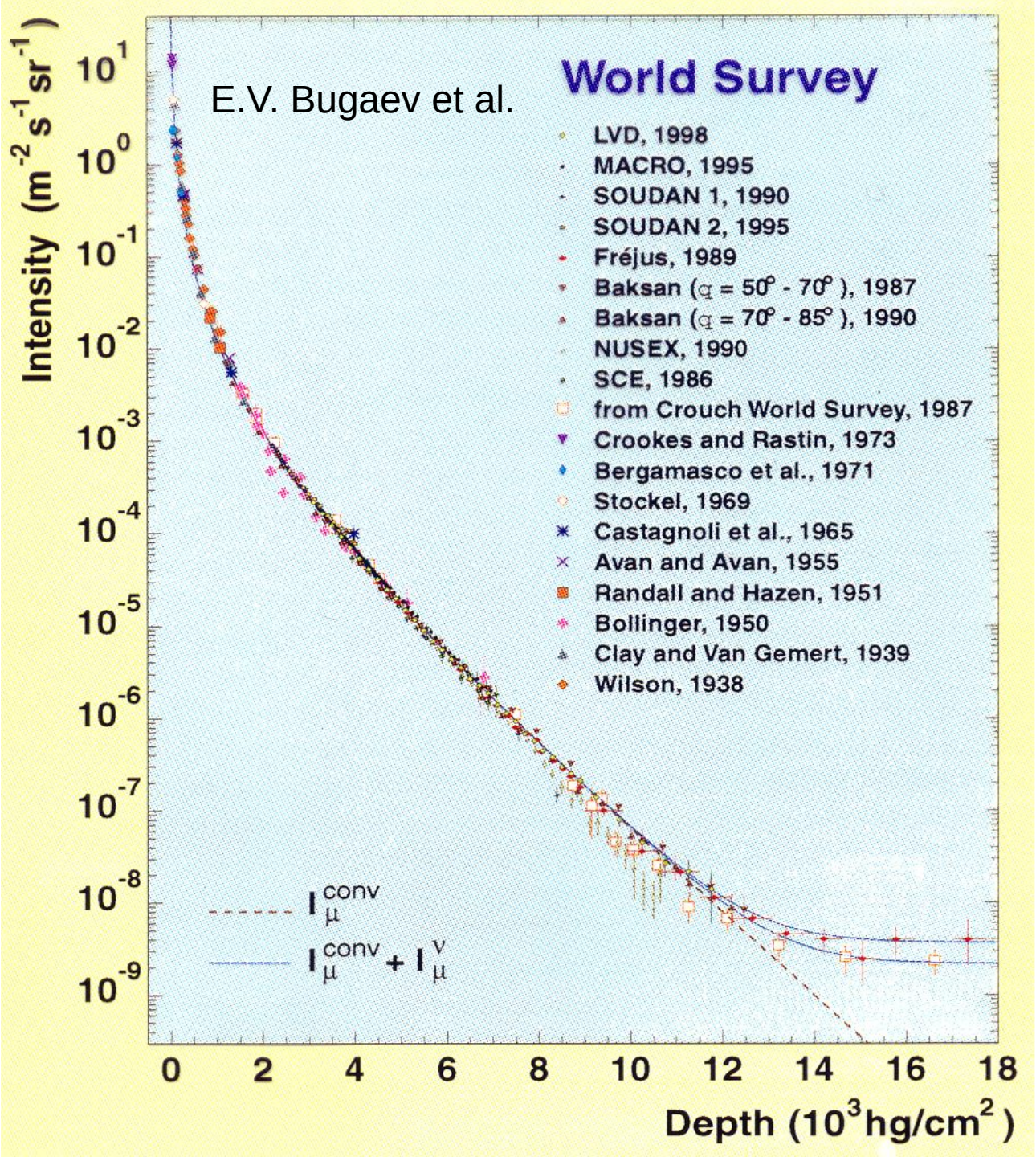
Detector	Depth, m.w.e.	Mass, ktons	Threshold	Efficience			Expected number of events					Back-ground, s^{-1}
							Standart model			Rotating collapsar model		
				$\eta_{e\pm}$	η_n	η_γ	$\nu_e p$	$\nu_i e$	$\nu_i C$	$\nu_e A$	$\nu_e A_{in}$	
ASD Artyomovsk Russia	570	0.1 C_nH_{2n} 1.0 NaCl	5	0.97	0.80 0.07	0.85 0.05	57	2.1	9.5	25	19	0.16
BUST Baksan Russia	850	0,2 C_nH_{2n} 0.16 Fe	8	0.6	-	0.2	67	2.2	4.3		8	0.033
KamLAND Kamioka Japan	2700	1.0 C_nH_{2n}	0.35	0.9			500	48	85		180	
Borexino Gran Sasso Italy	3300	0.3 C_9H_{12}	0.2	0.9	0.85		120	12	28		60	
LVD Gran Sasso Italy	3300	1.0 C_nH_{2n} 0.95 Fe	4-6	0.9	0.6	0.55 0.45	500	22	55	250	160	0.1
Super-K Kamioka Japan	2700	22.5 H_2O	7	0.9	-	-	9400	400	-		650	

We should be able:

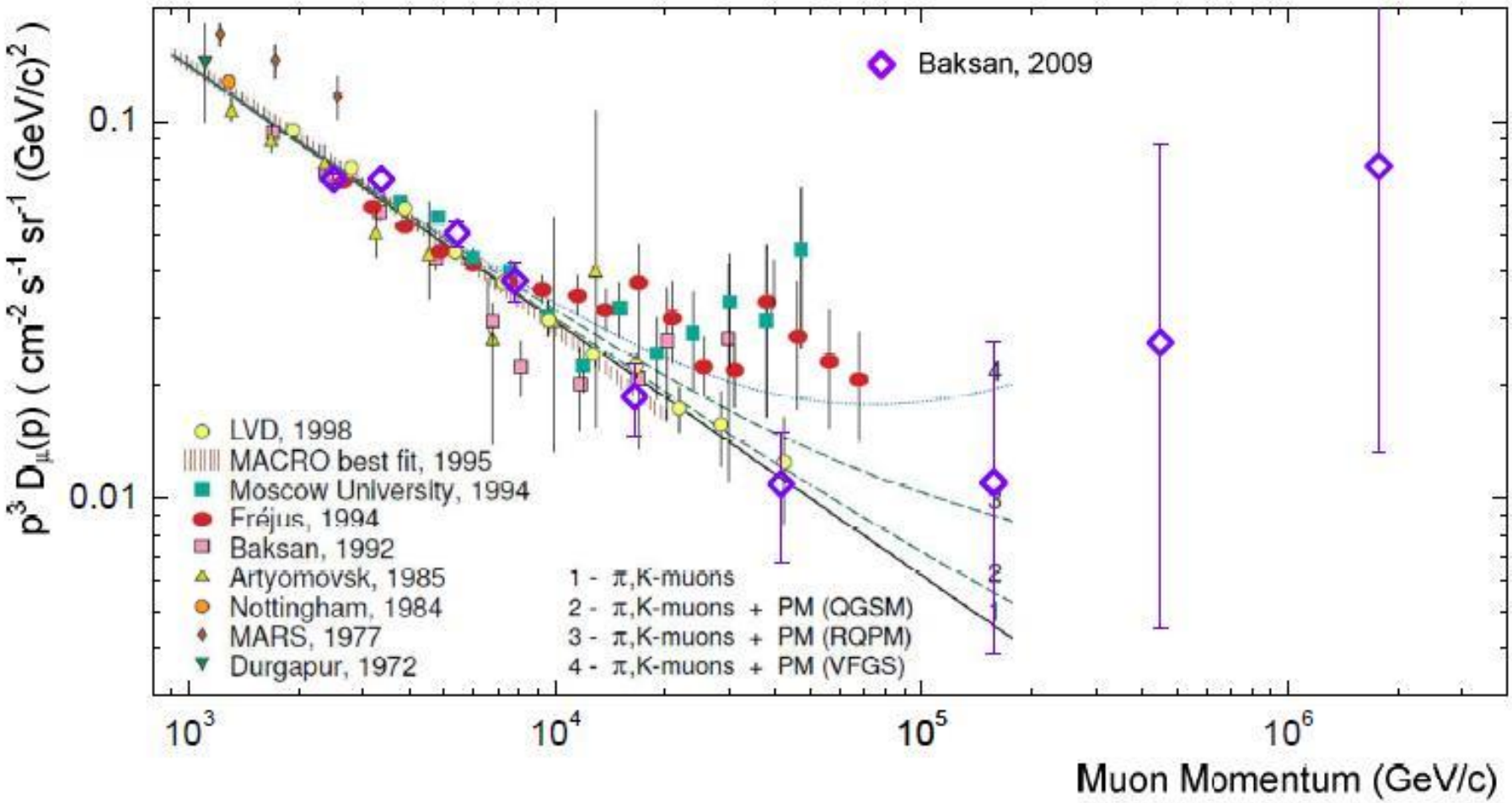
- ❑ to separate events appearing from neutrinos of different types;
- ❑ to measure energy spectrum and time distribution of neutrinos;
- ❑ to put new limits on the neutrino mass or to measure it;
- ❑to look for neutrino oscillations.

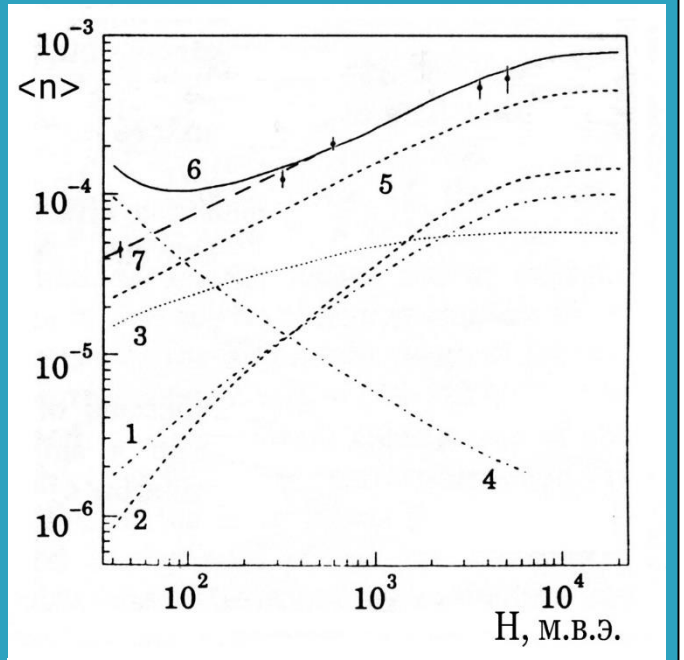
We are waiting for new Supernova

The results of cosmic ray penetrating component study

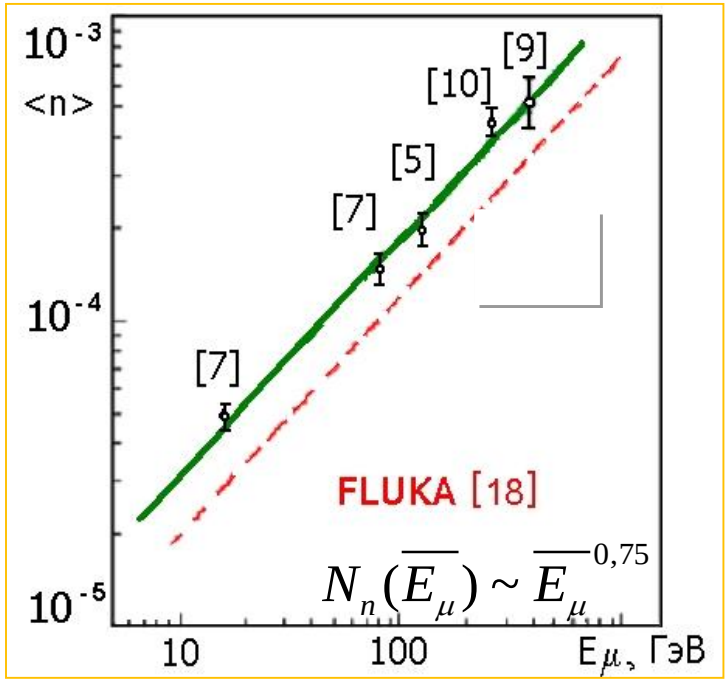

E.V. Bugaev et al.
World Survey
LVD, 1998
MACRO, 1995
SOUDAN 1, 1990
SOUDAN 2, 1995
Fréjus, 1989
Baksan (q = 50° - 70°), 1987
Baksan (q = 70° - 85°), 1990
NUSEX, 1990
SCE, 1986
from Crouch World Survey, 1987
Crookes and Rastin, 1973
Bergamasco et al., 1971
Stockel, 1969
Castagnoli et al., 1965
Avan and Avan, 1955
Randall and Hazen, 1951
Bollinger, 1950
Clay and Van Gemert, 1939
Wilson, 1938
I_μ^{conv}
$I_\mu^{conv} + I_\mu^{\nu}$
Intensity ($m^{-2} s^{-1} sr^{-1}$)
Depth ($10^3 hg/cm^2$)

Energy spectrum of cosmic ray muons

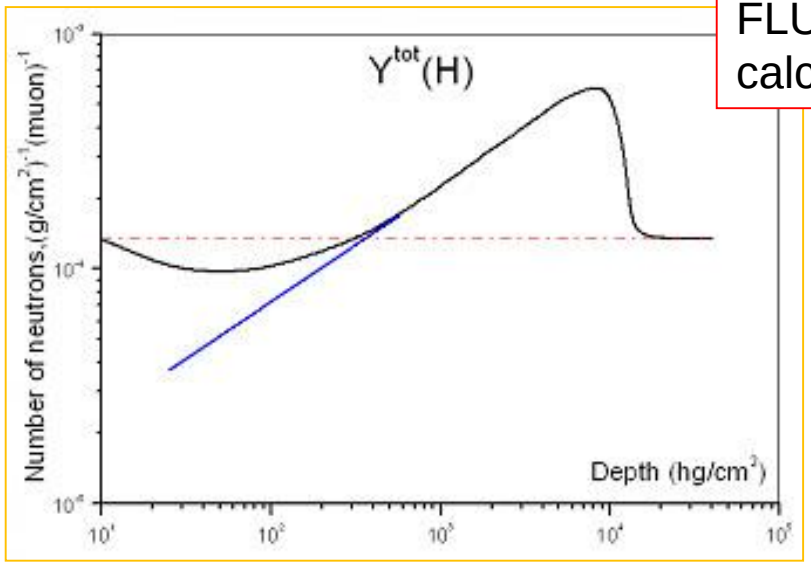




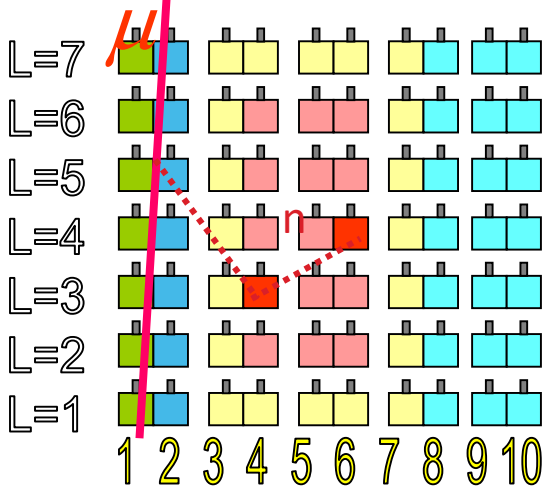
Dependence of neutron number per 1 muon per 1 g/cm^2 vs. the depth from the top of the atmosphere



Dependence of neutron number per 1 muon per 1 g/cm2 on average muon energies at a depths of 25 [7, 8], 316 [7, 8], 570 [5], 3650 [10] and 5200 [9] m.w.w.; solid line – calculation [1], dash line – FLUKA calculation [18].

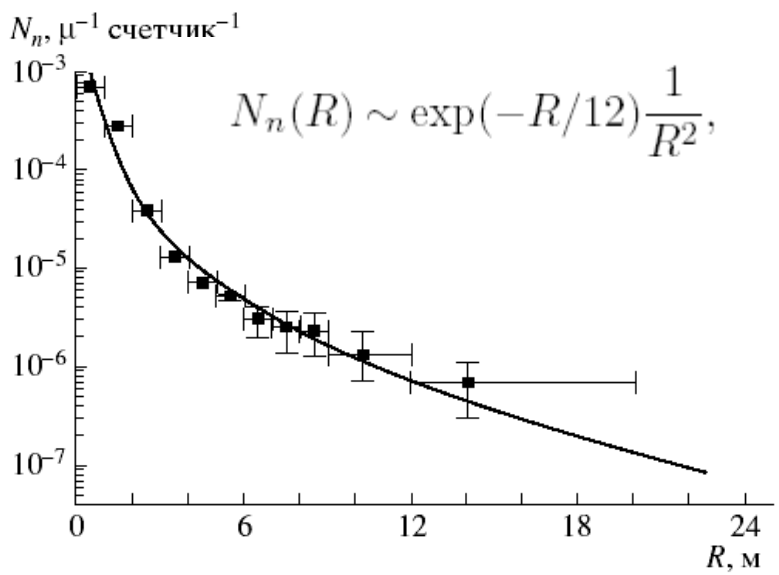


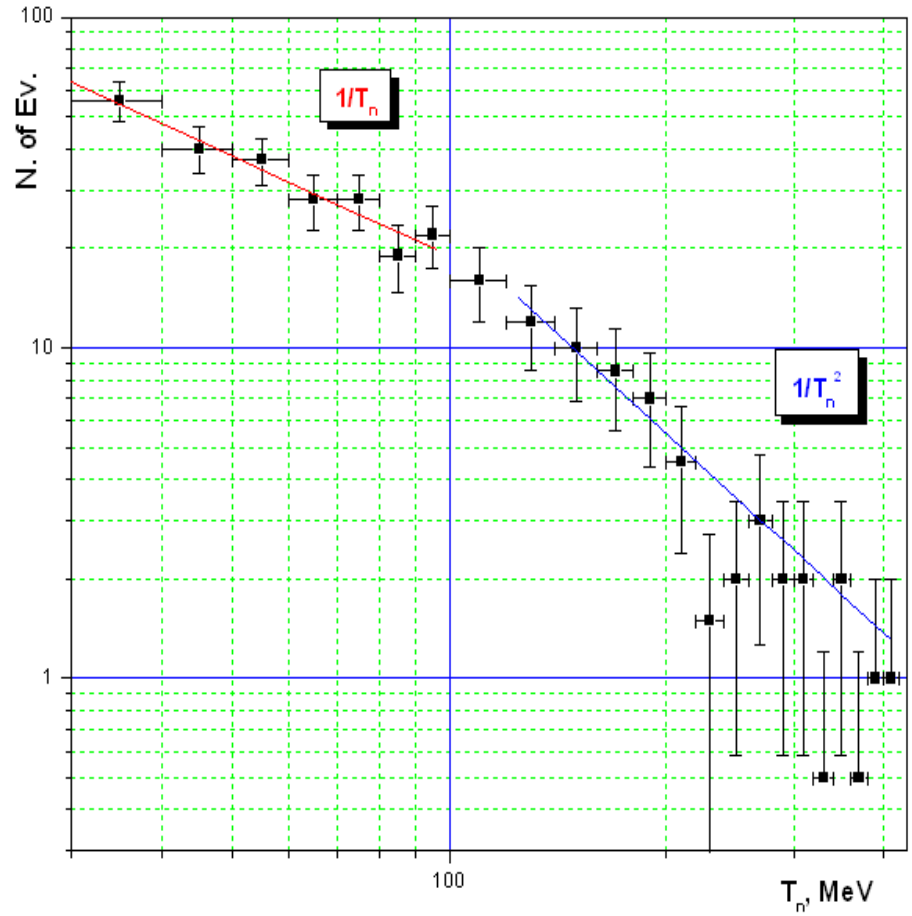
Dependence of neutron number per 1 muon per 1 g/cm2 vs. the depth from the top of the atmosphere



Energy spectra of neutron-produced events till 400 MeV

Neutron space distribution till 22 m from muon track are measured

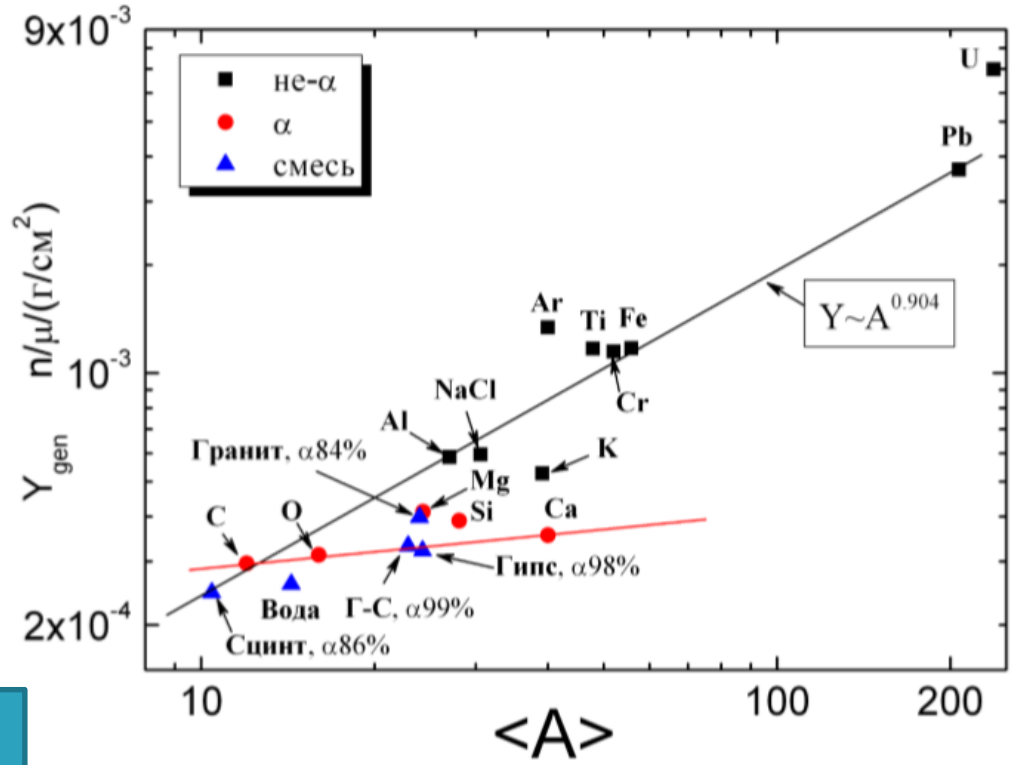




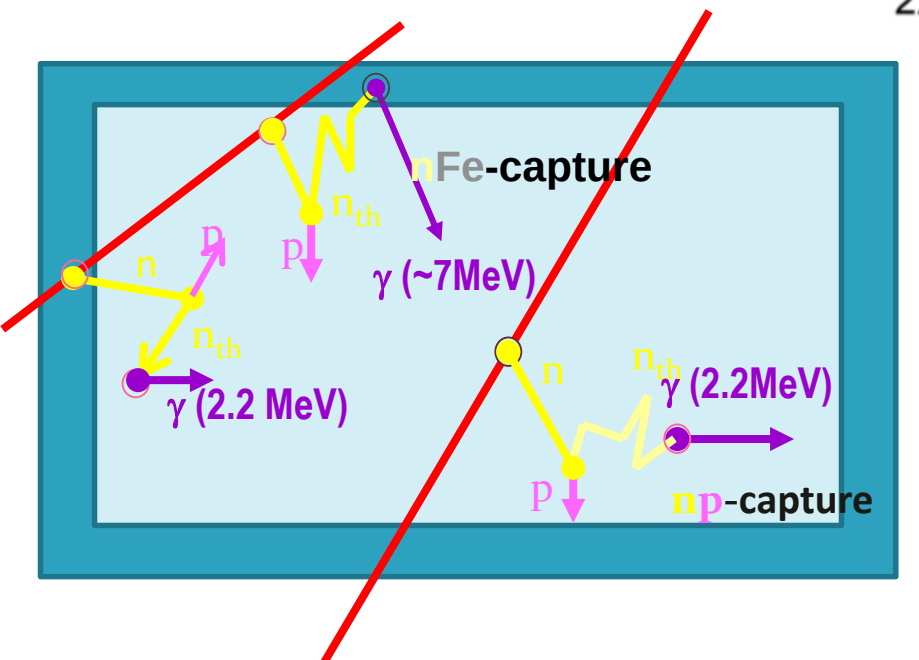
Neutrons in the muon events

Monte Carlo – GEANT4

2014 y.



Neutron generation by muons in Fe and Sc



Dependence of the neutron generation on atomic number for muons with energy 280 GeV

Analysis of the seasonal modulation of the cosmic muon flux and neutrons from muons.

The muon intensity in each run is defined as:

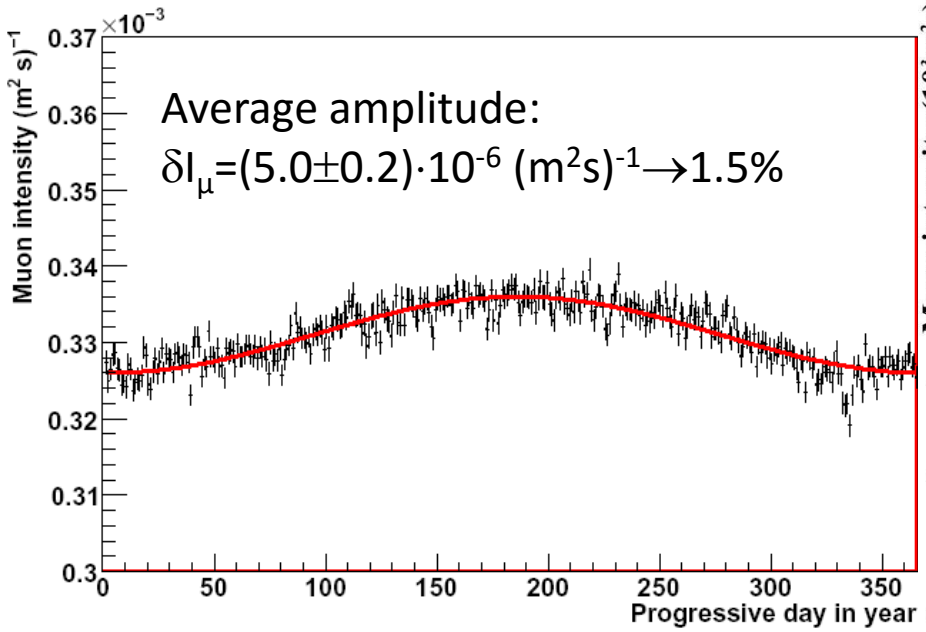
$I_i = N_i / A\varepsilon_i t_i$

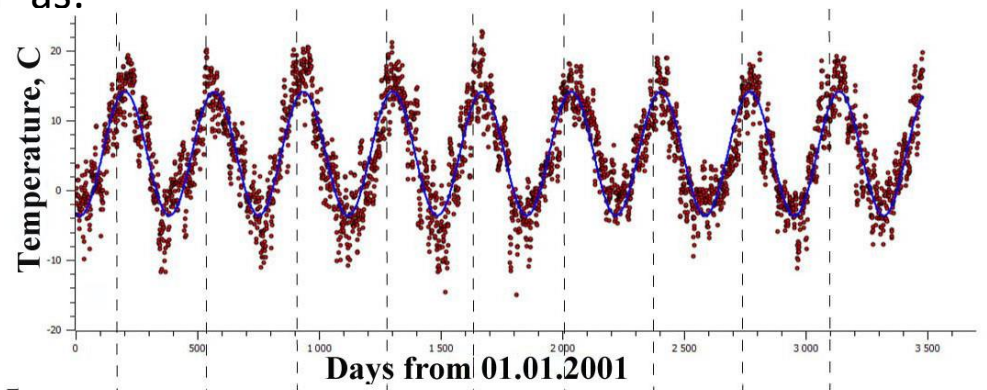
Average muon intensity:

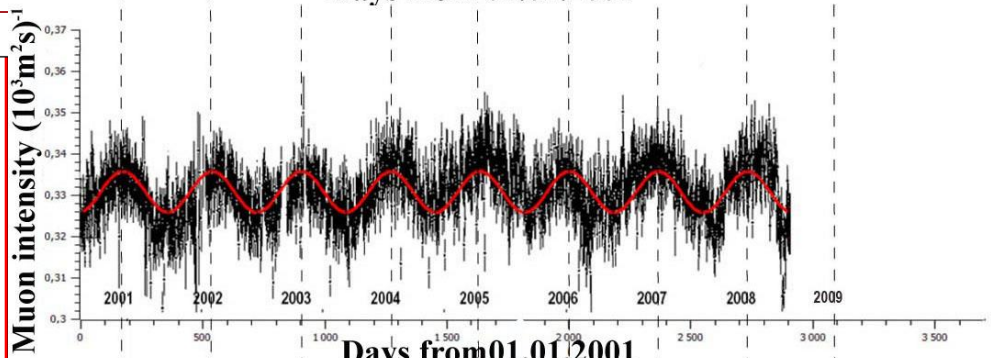
$I_\mu = (3.31 \pm 0.03) \cdot 10^{-4} (m^2 s)^{-1}$

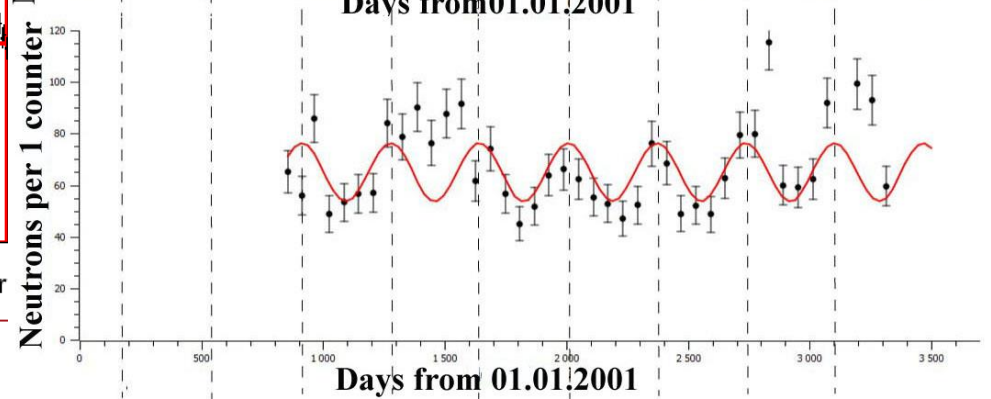
Period: $T = (367 \pm 15)$ days

Superposition of the whole muon data set into one year:

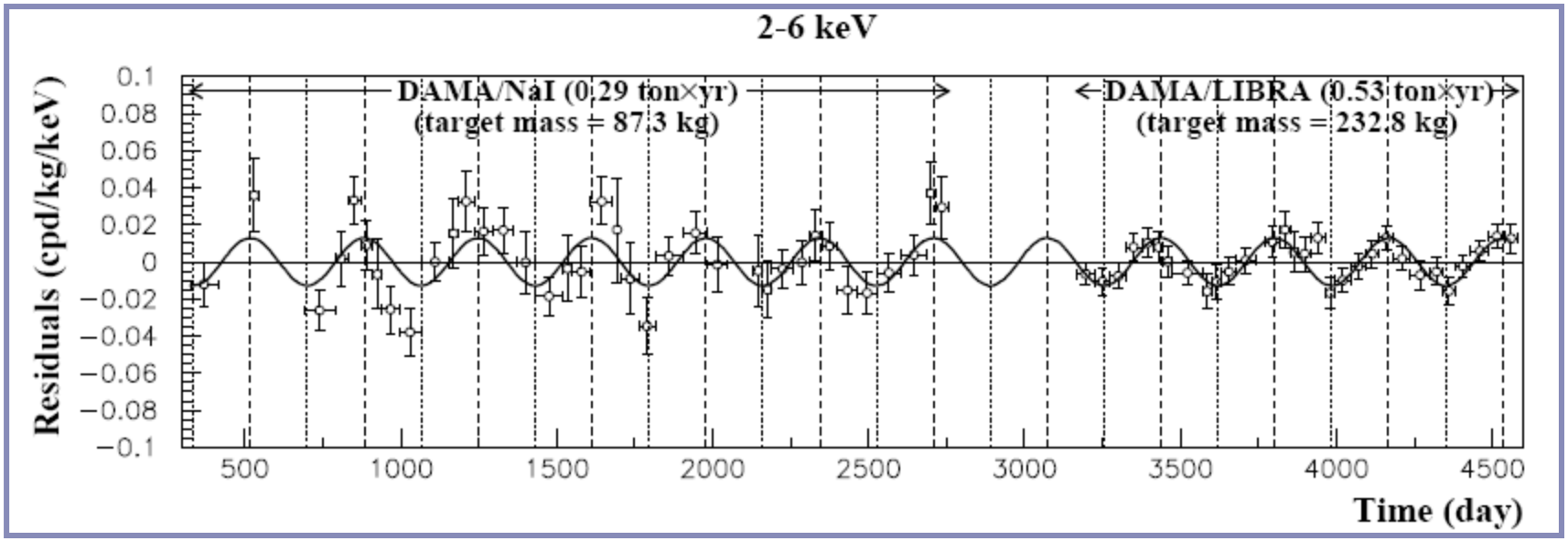








For studying the rare processes, as search for dark matter (for example) it is necessary to take into account the existing of the muon variation at the higher depth underground



The superimposed curves represent the cosinusoidal functions behaviours Acos $\omega(t - t_o)$ with a period T = 1 yr, with a phase t_o = 152.5 day (June 2nd). The dashed vertical lines correspond to the maximum of the signal (June 2nd), while the dotted vertical lines correspond to the minimum.

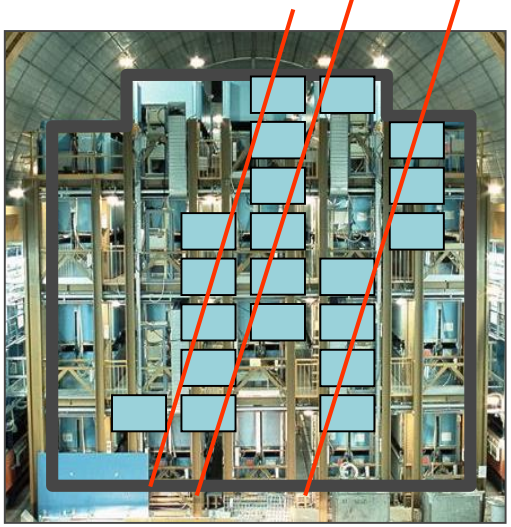
R. Bernabei et. al., (DAMA Coll.) // arXiv:0804.2741v1 [astro-ph]

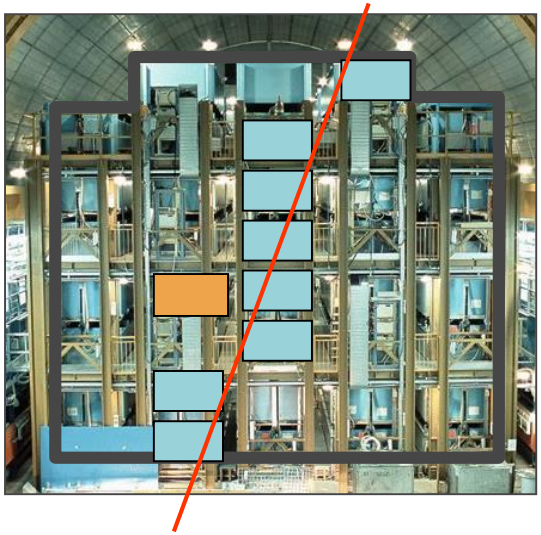
The results of muon counting rate measurements obtained in 2001 – 2009 by LVD detector in LNGS are shown before previous slide. In this work published in 2011 the authors draw attention to taking into account temperature muon modulations in experiments of dark matter search.

If the effect of the DAMA experiment is connected with the temperature mechanism the position of modulation curve maximum values obtained in the Northern and Southern hemispheres will be shifted in relation to each other for half a year.

If the effect is connected with WIMP registration the curve will be the same for experiments in both hemispheres. And this will serve an important indication to the nature of this effect.

Muons in LVD

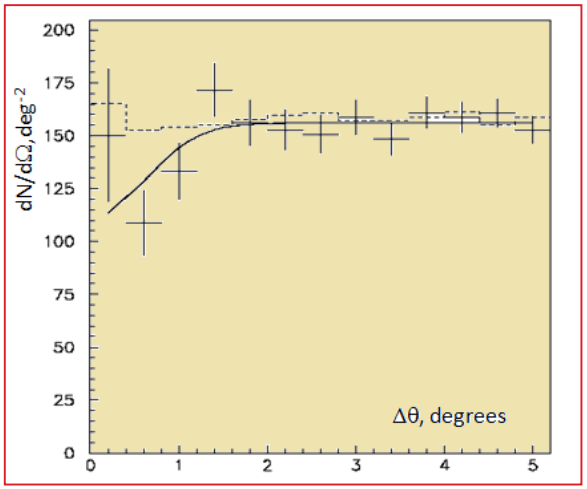


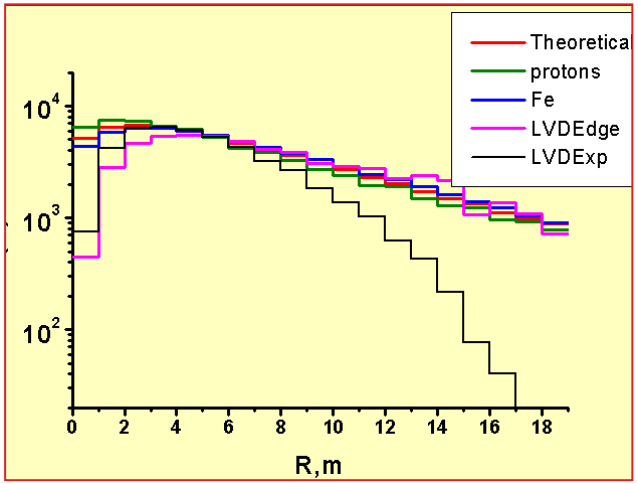


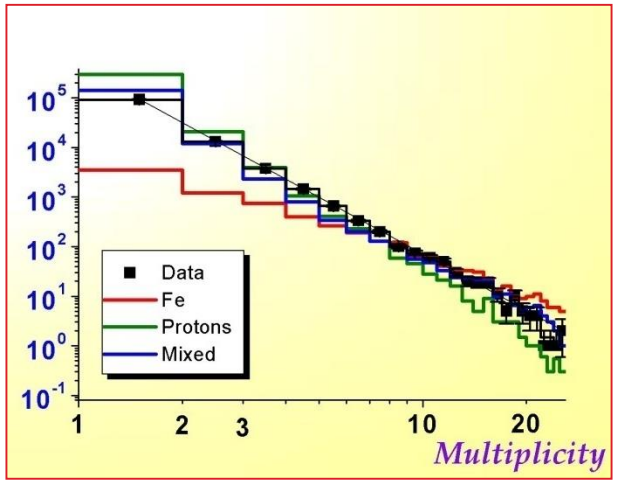
Cosmic ray screening by moon

Distance distribution between muon pairs

Multiplicity of muon groups

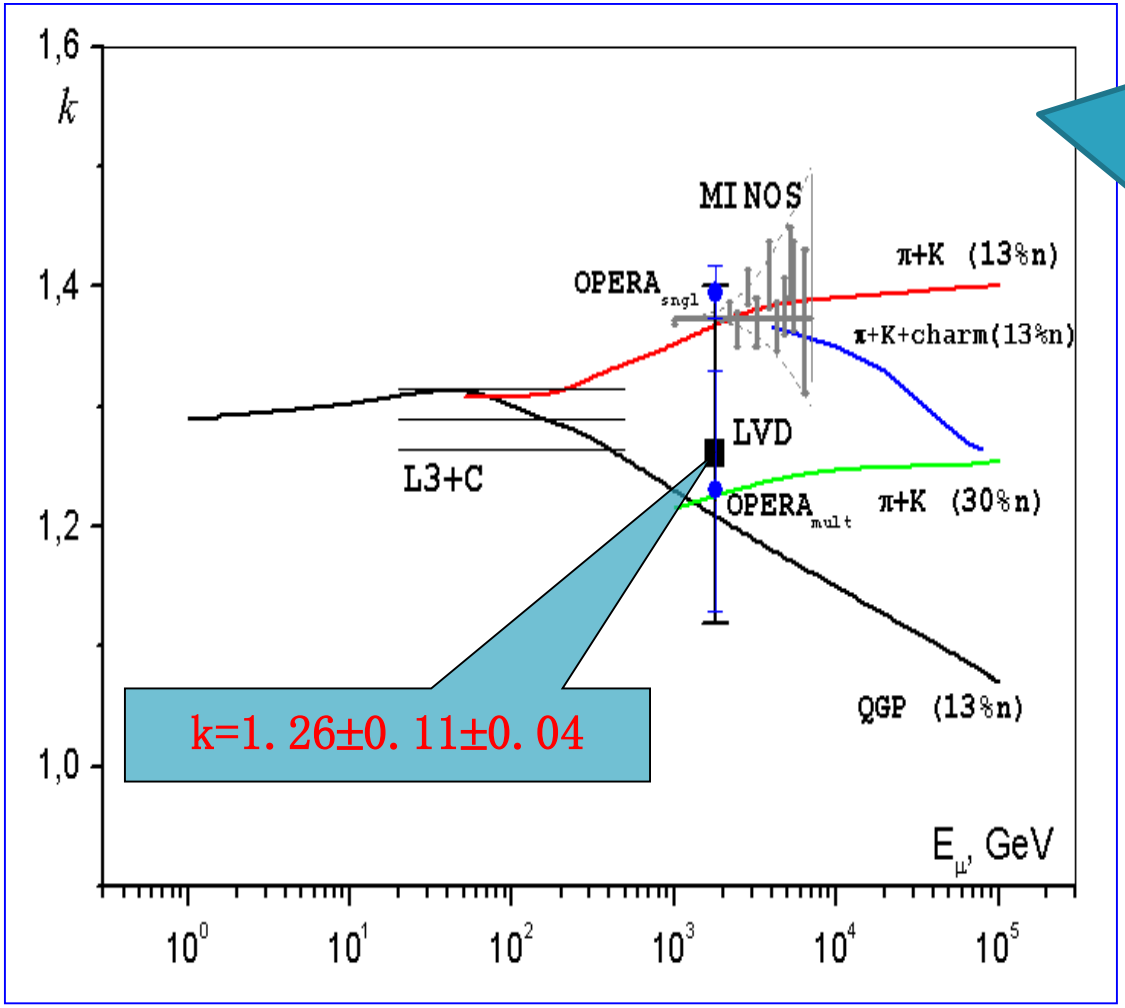






The μ^+/μ^- Ratio

ICRC 2009, Lodz, Poland; **The muon decay and muon capture detection with LVD** - LVD Coll. - *In:* 29th ICRC, Pune, **6**, 69-72, 2005.



Curve – L. Volkova Phys. Of Atomic Nuclei (2008), 71, 1782;

MINOS – Mufson S.L. and Rebel V.J. for the MINOS Coll., 30th ICRC, Mexico, 2007;

L3+C – The L3 Coll., arhiv: hep-ex/0408114 v1, 2004

OPERA – M.Sioli for the OPERA Coll, in ICRC2009

LVD – LVD result, ICRC2009

Thank you for your attention!