LVD

Large Volume Detector

…from the beginning till nowadays

This talk is devoted to the memory of

Lelio Valeriani

7.10

Carlo Castagnoli

5.05

Giuliana Cini

5.03

Underground physics is the branch of physics studying:

I. COSMIC RAYS using their penetrating components;
II. ASTROPHYSIC OBJECTS with muon(μ) and neutrino(ν);
III.RARE PROCESSES predicted by the theory.

Underground physics Detectors

Reactor $\bar{\nu}$

Accelerator ν

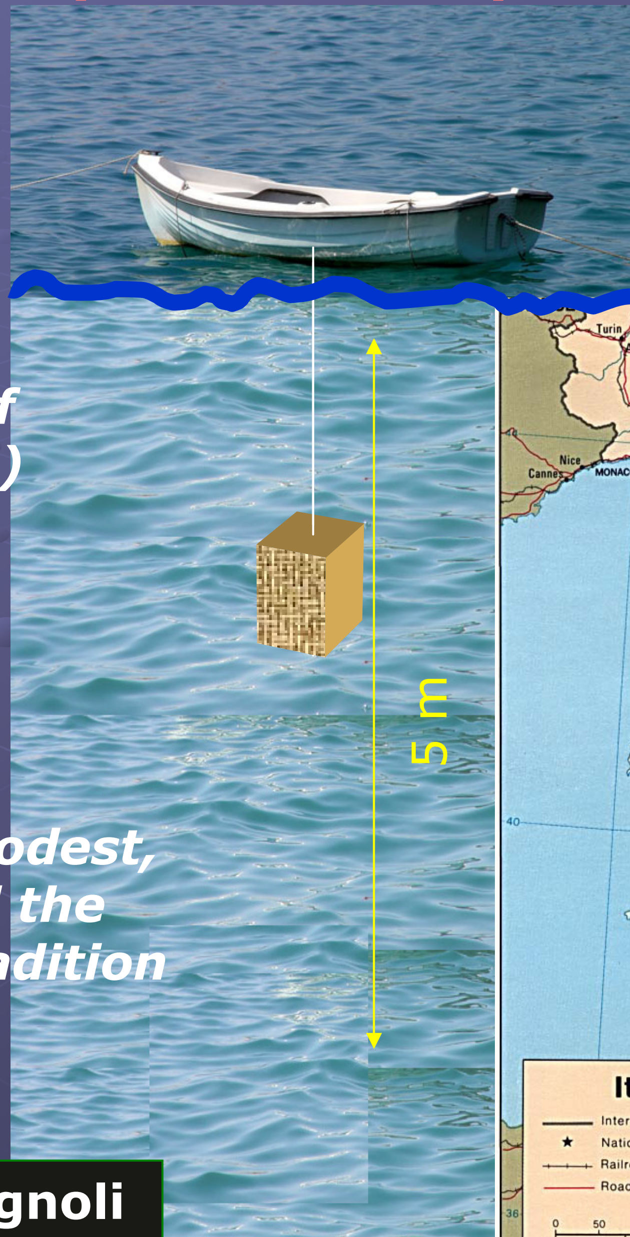
The term "Underground Physics" was introduced in 1985 by prof. C.Castagnoli during the symposium dedicated to the opening ceremony of the LSD detector under Mont Blanc

This year we can celebrate 100th anniversary of an experiment by Domenico Pacini which influenced the successive discovery of cosmic rays.

" In this experiment an ionization measurement carried out in the Tyrrhenian Sea, under 5 meters of water (5 m.w.e. !) allowed the discovery of penetrating radiation coming from above.

The depth was modest, but it established the beginning of a tradition of which we now represent the continuation."

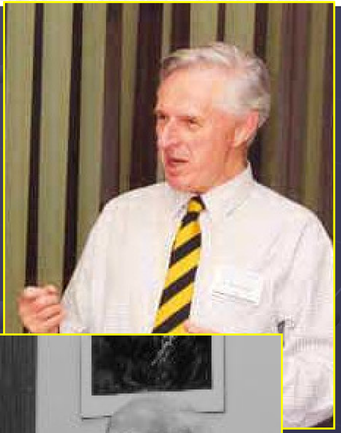
C. Castagnoli



This talk:

- Overview of experimental data of LVD
- Situation with atmospheric muons, muon bundles
- Muon produced background
- Problems of search for neutrinos from collapsing stars

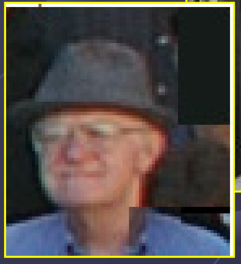
Several words about history



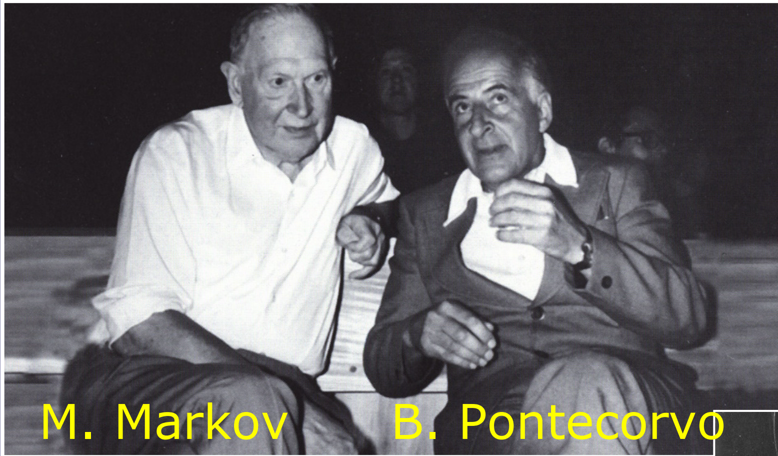
Big progress in μ,ν study begins from 60^{th} …

1965 – first detection of atmospheric neutrinos in the Kolar Gold Fields, 7500 m.w.e., (A.Wolfendale, M.G.K. Menon et al.)

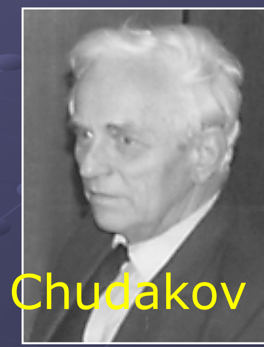
1964–1967 – experiment in South Africa,
depth: 8640 m.w.e., F.Reines, W.Kropp et al.



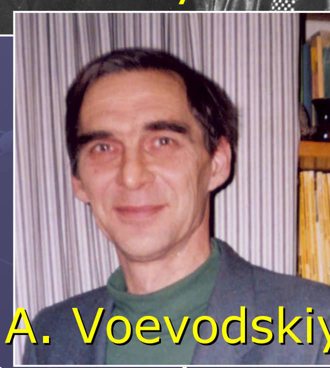
1968 – experiment in Utah for μ, ν detection,
depth: 1500m.w.e., S.W. Keuffel et al.

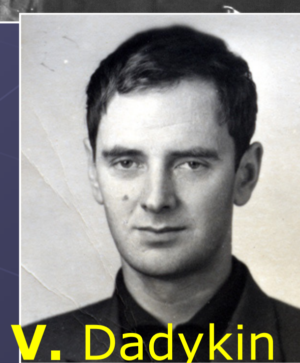


1963 – decision for constructing underground neutrino laboratory to study solar neutrino, atmospheric neutrino and … at Baksan valley. Creation of the neutrino laboratory (FIAN, from 1971 INR AS of the USSR)



1965 – elaboration of new liquid scintillator: transparency L~50m, stability >40 years,
the price 30 kop/L (<30cent/L.)





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 liquid scintillator.

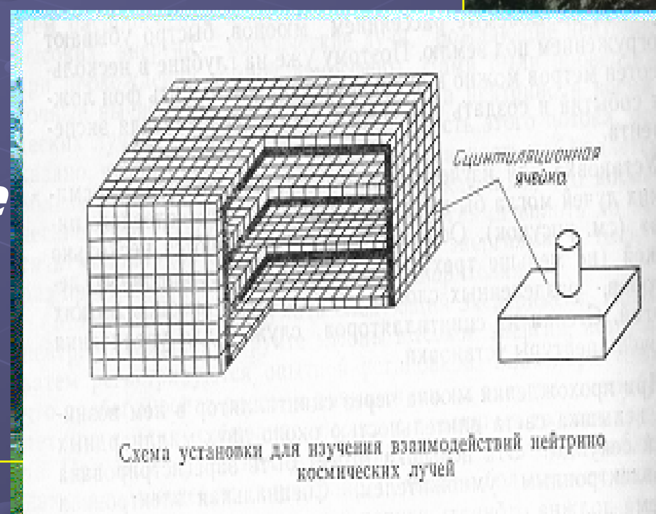
1977 ***Arteomovsk Scintillation Detector*** (INR RAS) has scintillator mass of 105 t, good signature of events (the possibility to detect both particles in the reaction)

$$\bar{\nu} + p \rightarrow e^{+} + n$$

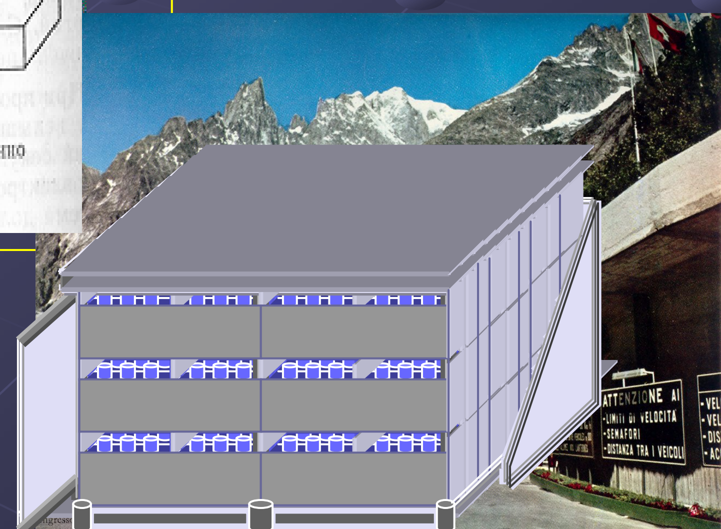
$$n + p \rightarrow d^{*}$$

$$\hookrightarrow d + \gamma \; E_{\gamma} = 2.2 \; MeV$$

1978 ***Baksan Underground Scintillation Telescope*** (INR RAS) with a total mass of 330 t



1984 ***LSD*** –
(Liquid Scintillation Detector, USSR – Italy), scintillator mass - 90 t, good signature of events (the possibility to detect both particles in the reaction : $\tilde{\nu} p \rightarrow n e^{+}$)



- Discussion about underground physics, 1969.

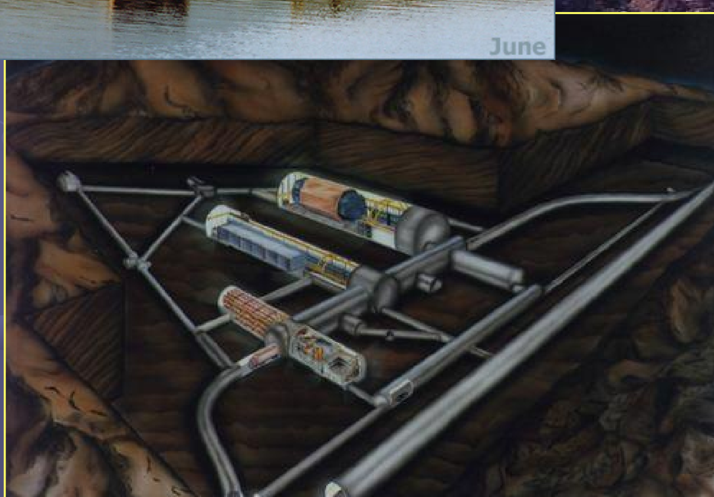
- Discussion about Russian-Italian collaboration, 1977.

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".

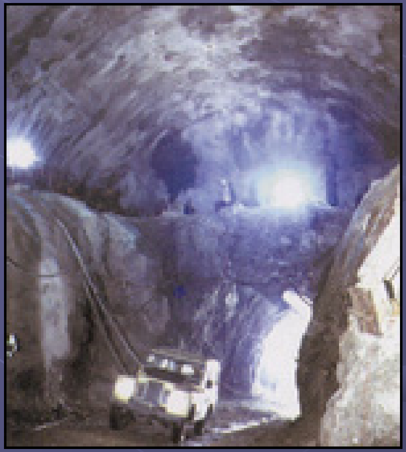
ISTITUTO NAZIONALE DI FISICA NUCLEARE INFN

LNGS Laboratori Nazionali del Gran Sasso

INFN

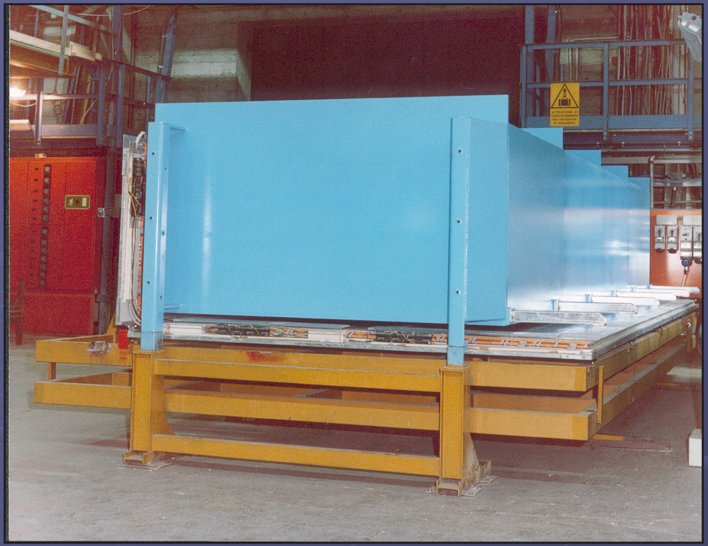


1980-1985



Gran Sasso tunnel building

1988-1990

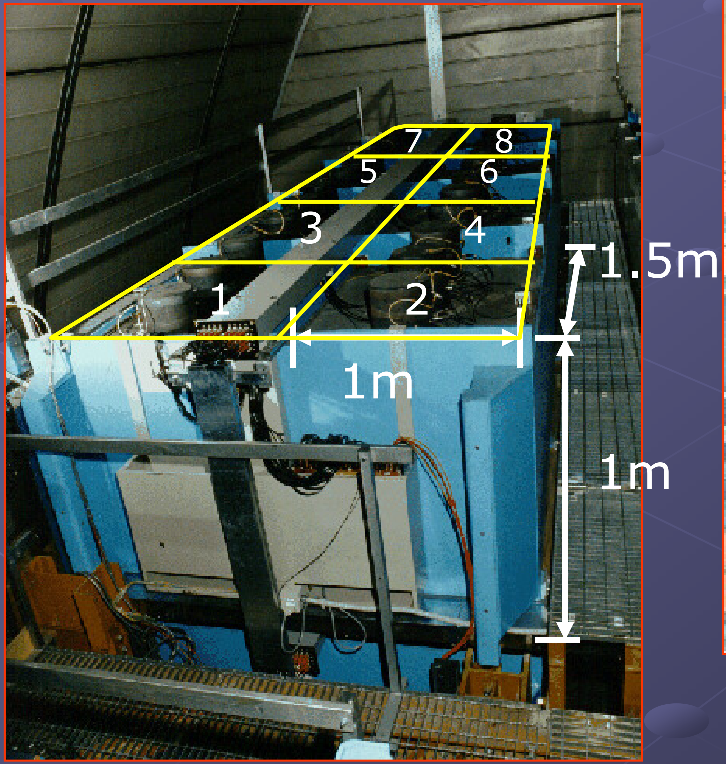


first montage works in Hall A

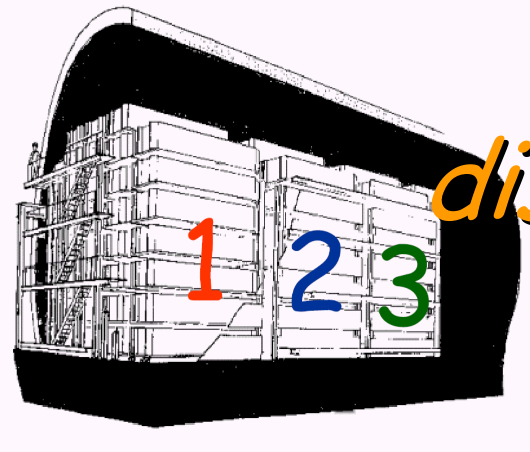
1992

first LVD tower begins to operate

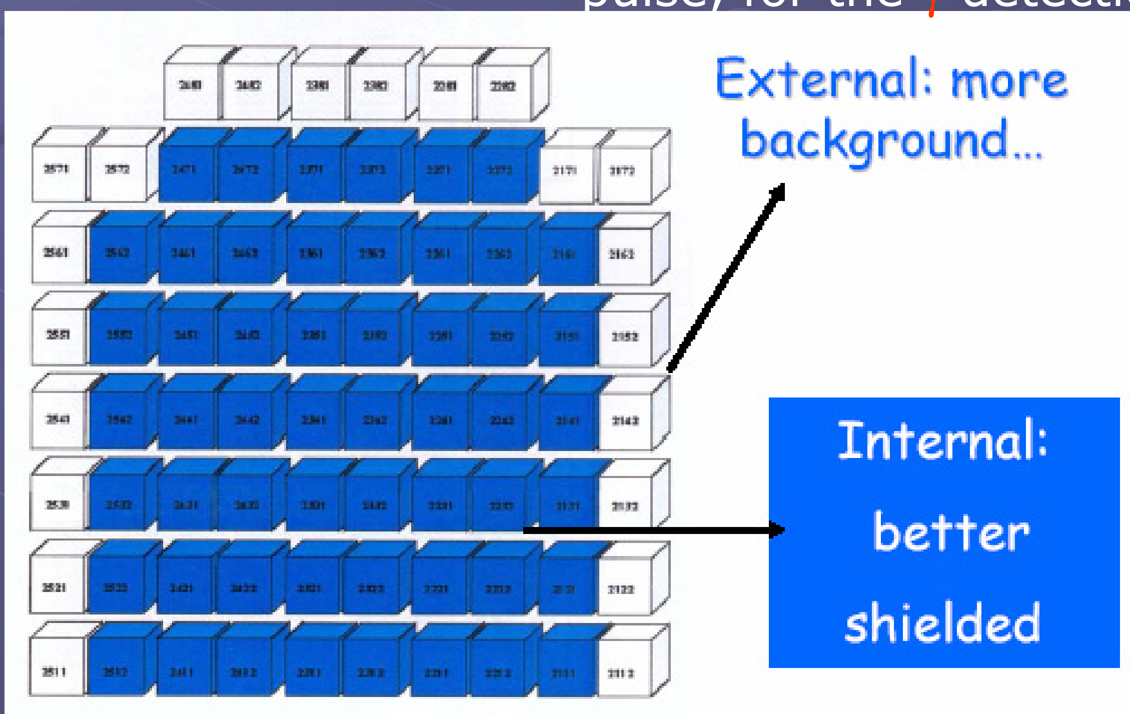
LVD, located in the hall A of the LNGS, is a neutrino observatory mainly designed to study low energy neutrinos from gravitational stellar collapses. It is in operation since 1992, under different larger configurations. The final

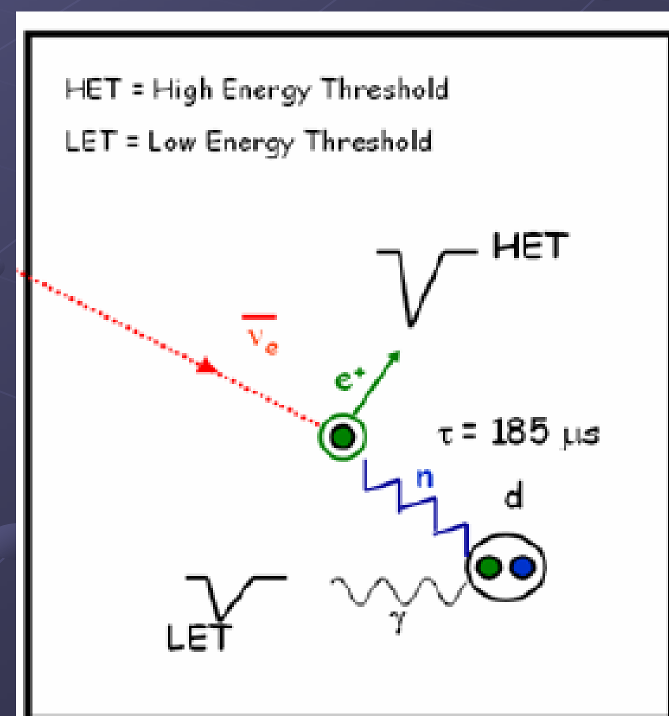


Two different discrimination channels

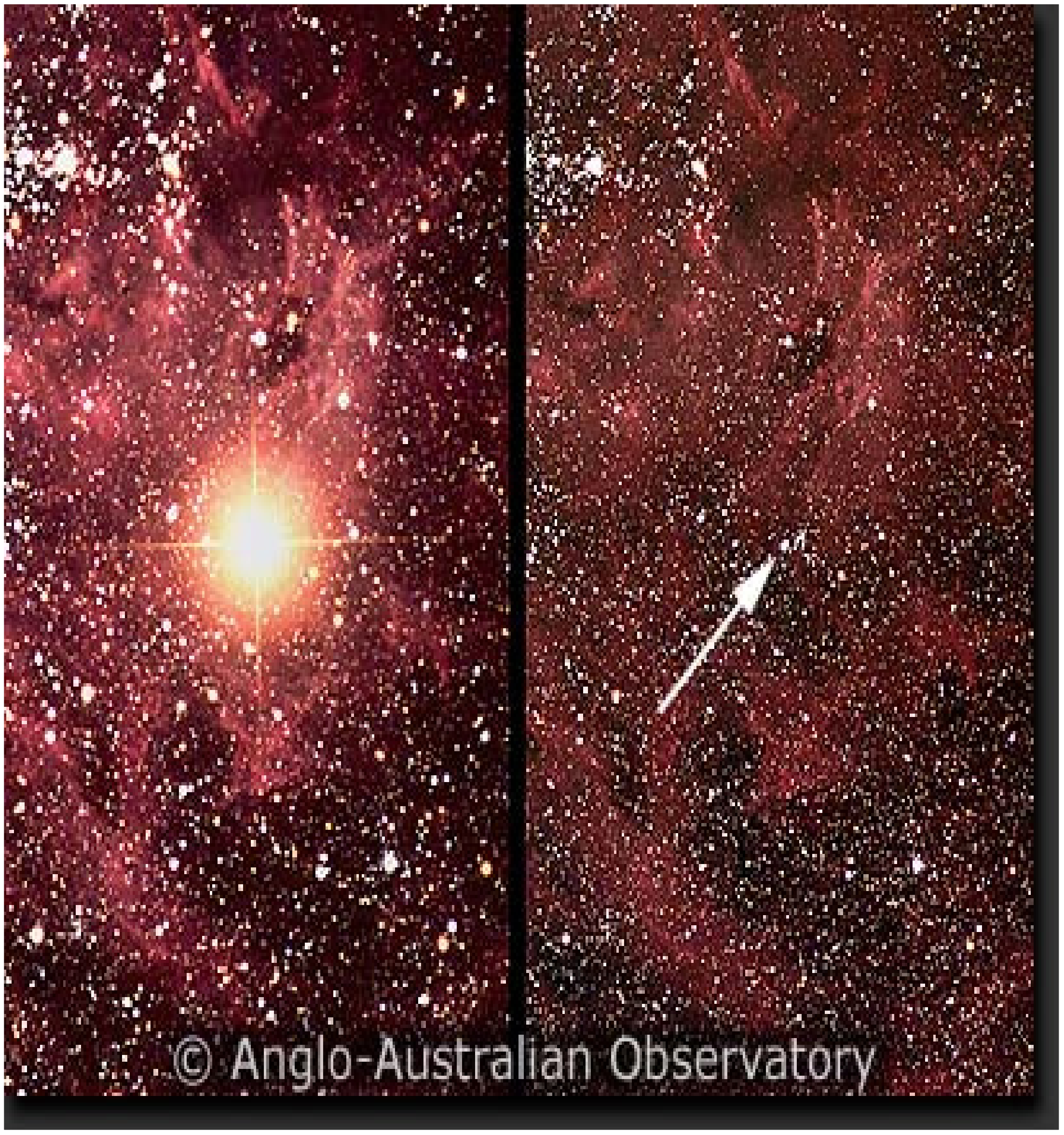


1. High energy threshold at HET=7 MeV for the external counters (43%), and at HET=4 MeV for internal ones (57%) better shielded from rock radioactivity
2. All counters are equipped with an additional discrimination channel,set at a lower threshold, LET=0.8 MeV which is active for 1 ms after HET pulse, for the γ detection





COLLAPSE



~60 years ago the problem looked like the science fiction mixed with a some joke.

On April 1st, 1941 Phys. Rev. has published «Neutrino Theory of Stellar Collapse» by G. Gamov and M. Schoenberg

«The processes of absorption and reemission of free electrons by atomic nuclei which are abundant in stellar matter may lead to such tremendous energy losses through the neutrino emission that the collapse of the entire stellar body with an almost free-fall velocity becomes quite possible»

$$\left.\begin{array}{l} {}_{Z}N^{A} + e^{-} \rightarrow {}_{Z-1}N^{A} + \nu \\ {}_{Z-1}N^{A} \rightarrow {}_{Z}N^{A} + e^{-} + \tilde{\nu} \end{array}\right\}$$

URCA-process

The idea was born in Rio casino "Urca" where it was possible to lose a lot of money very quickly.

$$p + e^{-} \rightarrow n + \nu_{e}$$

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

«We have developed the general views regarding the role of neutrino emission in the ***vast stellar catastrophes*** *known to astronomy, while the neutrinos are still considered as highly hypothetical particles because of the failure of all efforts made to detect them».*

G.Gamov, M.Schoenberg

1957 F. Reines and C. Cowan detect antineutrinos from reactor.

1959 An active discussion of the role of neutrinos in astrophysics starts. B. Pontecorvo states, that *νe*-scattering may lead to macroscopic effects.

1965 Ya.B. Zel'dovich and O.H.Guseinov show, that gravitational collapse is accompanied by powerful and short (~10 ms) pulse of neutrino radiation.

1965 The first proposal to search for collapsing starts (c.s.) using neutrino detectors by G.V.Domogatsky and G.T. Zatsepin

1965 ***The birth of an experimental neutrino astrophysics.***

1964-1966 W. Fowler, F. Hoyle investigate the role of neutrinos in the last stages of stellar evolution. The dissociation of iron core plays an important role in stability loss by massive stellar envelopes.

1966 The first calculation of collapse dynamics by S. Colgate, R.White

1966-1967 The process of an implosion for stars with 32; 8; 4; or 2 solar masses has been studied. The parameters of neutrino radiation are obtained (W. Arnett).

1967-1978 The structure of neutrino burst , υ_e and $\tilde{\upsilon}_e$ energy spectra was studied by V.S.Imshennik, L.I.Ivanova, D.K.Nadyozhin, I.V.Otroshenko (Model I) in the first time . Also it was shown that the main flux of the neutrinos is emitted during the cooling stage of a new born neutron star. The duration of neutrino pulse was shown to be ~ 10 s.

1980-1982 The time structure and energy spectra of $\tilde{\upsilon}_e, \upsilon_e, \upsilon_\mu, \upsilon_\tau$ for the initial stage of collapse (<0.1 ms) are obtained by R.Bowers, J.Wilson (Model II).

1987 S. Bruenn’s calculations

Neutrino detection from a collapsing star makes it possible:

- To detect gravitational collapse even it is “silent” (isn’t accompanied by Supernova explosion);
- To investigate the dynamics of collapse;
- To estimate the temperature in the star center.

If the star is nonmagnetic, nonrotating, spherically symmetrical the parameters of neutrino burst are the following (Standard model):

<table>
<tr><th>Model</th><th>Total energy, $10^{53}\,erg$</th><th>Total energy of $\tilde{\nu}_e$,$10^{53}\,erg$</th><th>Total energy of ν_e ,$10^{53}\,erg$ neutronization stage,t=3*10^{-2} sec</th><th>$\overline{E}_{\tilde{\nu}_e}, MeV$</th><th>$\overline{E}_{\nu_e}, MeV$</th><th>$E(\nu_e)$ MeV</th><th>Duration, s</th></tr>
<tr><td>Model I</td><td rowspan="2">3-14</td><td rowspan="2">0.5-2.3</td><td rowspan="2">0.1</td><td>12.6</td><td>10.5</td><td>-</td><td>~20</td></tr>
<tr><td>Model II</td><td>10</td><td>8</td><td>25</td><td>5</td></tr>
</table>

From the theory of the Standard collapse it follows that the total energy,carried out by all types of neutrinos $\nu_e, \tilde{\nu}_e, \nu_\mu, \tilde{\nu}_\mu, \nu_\tau, \tilde{\nu}_\tau$, corresponds to ~ 0.1 of star core mass and is divided among these 6 components in equal parts.

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

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

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

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 $\tau \sim 180 - 200\ \mu s$.

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

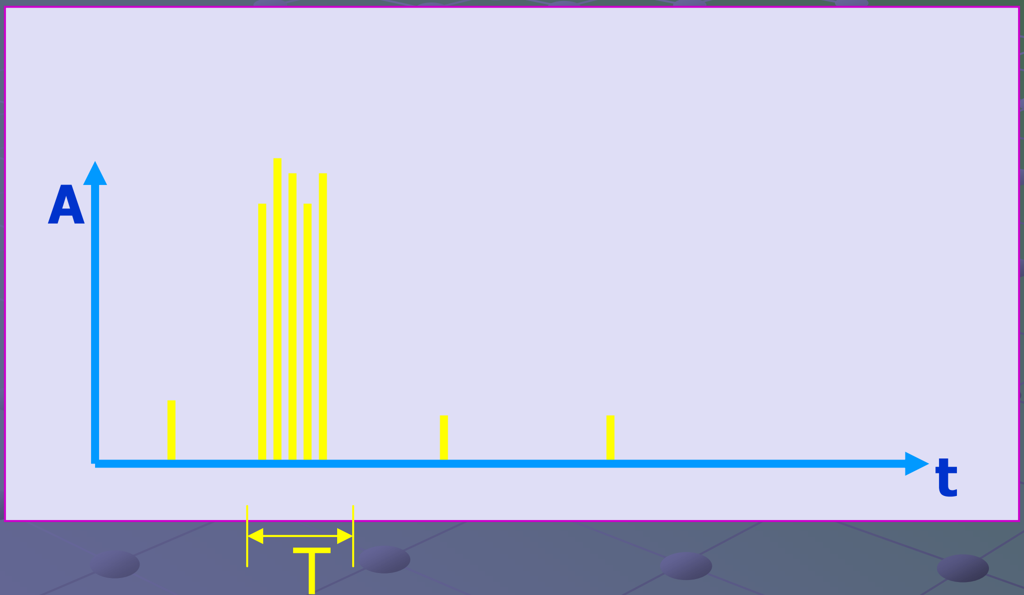
The specific signature of event

C_nH_{2n} H_2O

Reactions for scintillation and Cherenkov counters

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

How can the neutrino burst be identified ?



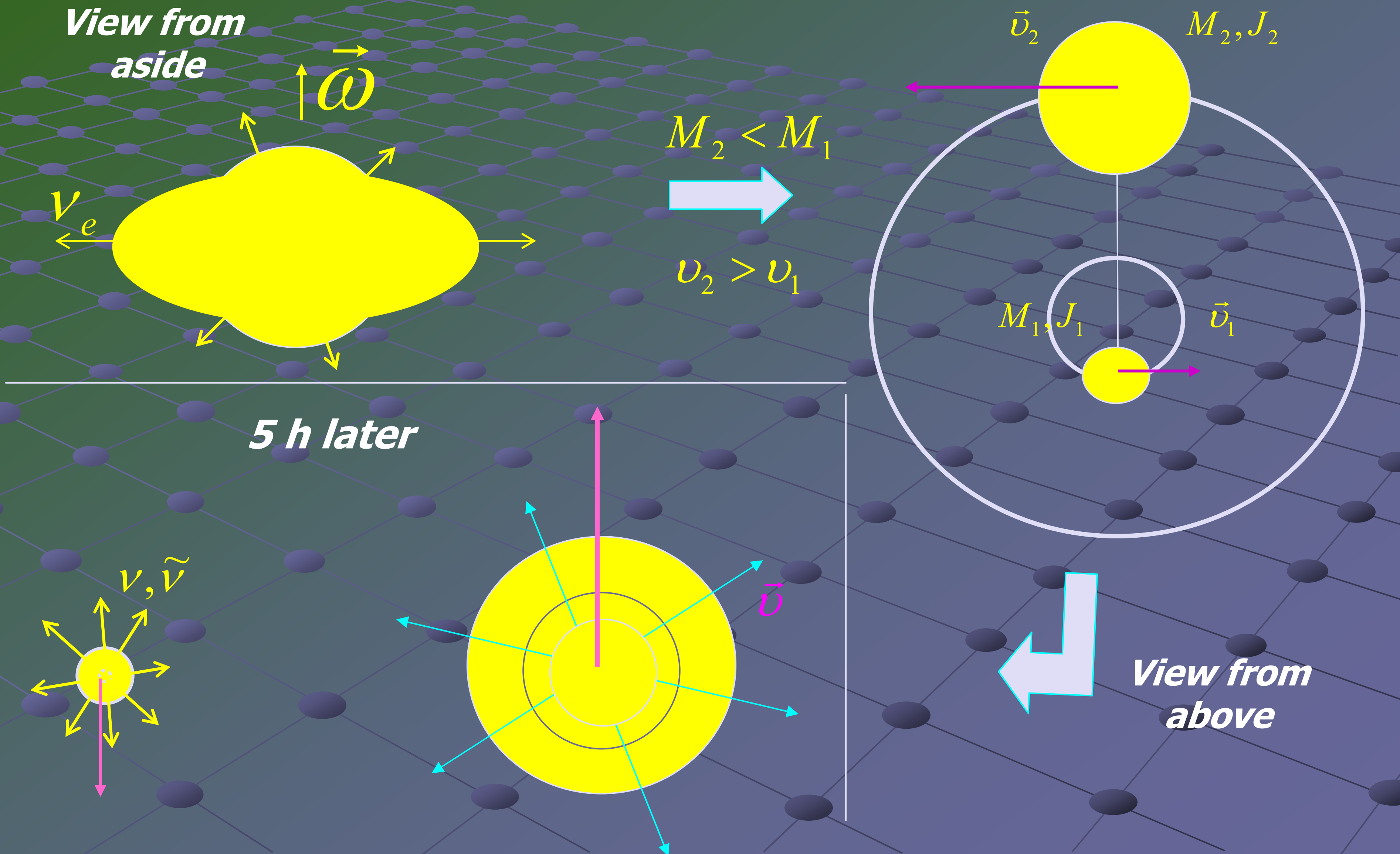
The detection of the burst of N impulses in short time interval T

$$N \sim \frac{1}{4\pi R^2} \cdot \sum_i \int_{E_{thr}}^{\infty} I_{\nu_i}(E_{\nu_i}) \cdot \sigma(E_{\nu_i}) dE \cdot M$$

A rotating collapsar

The Two-Stage Gravitational Collapse Model

[Imshennik V.S., Space Sci Rev, **74**, 325-334 (1995)]

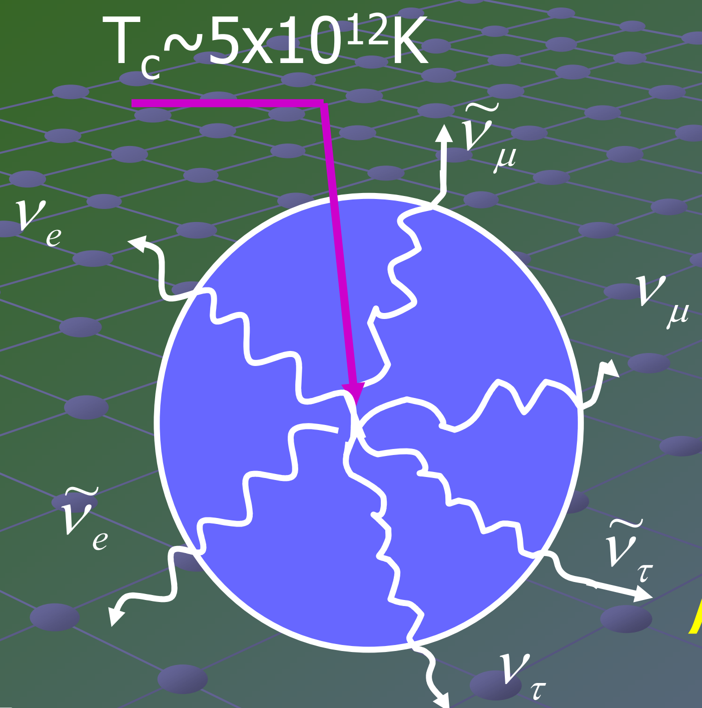


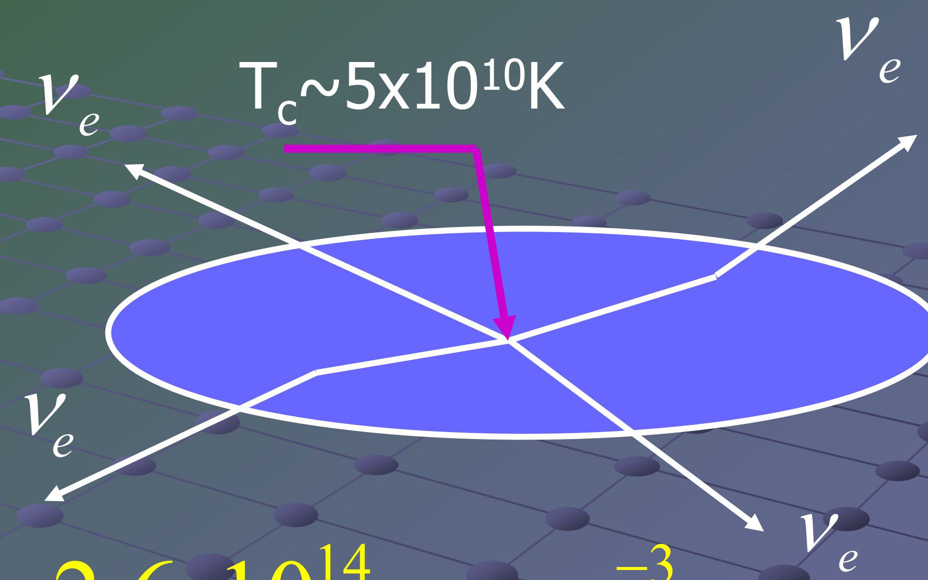
The rotation effects make it possible:

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.





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

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

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

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

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

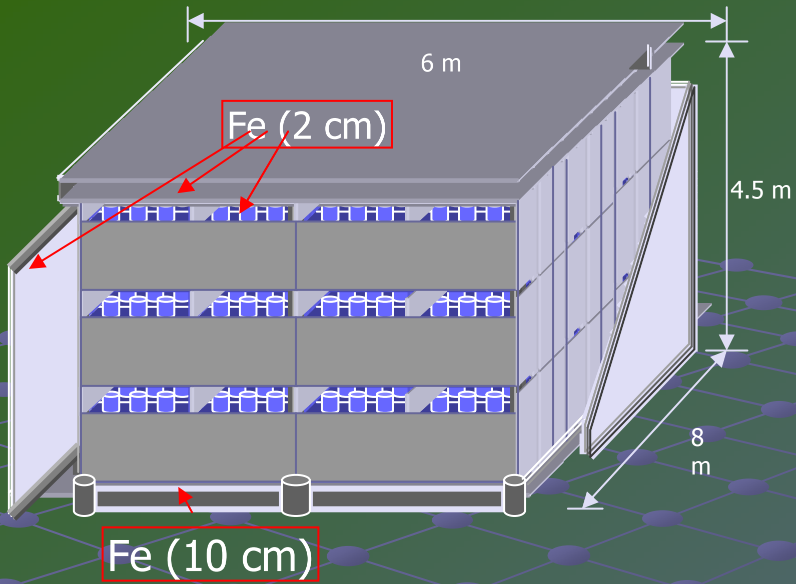
The main reaction:

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

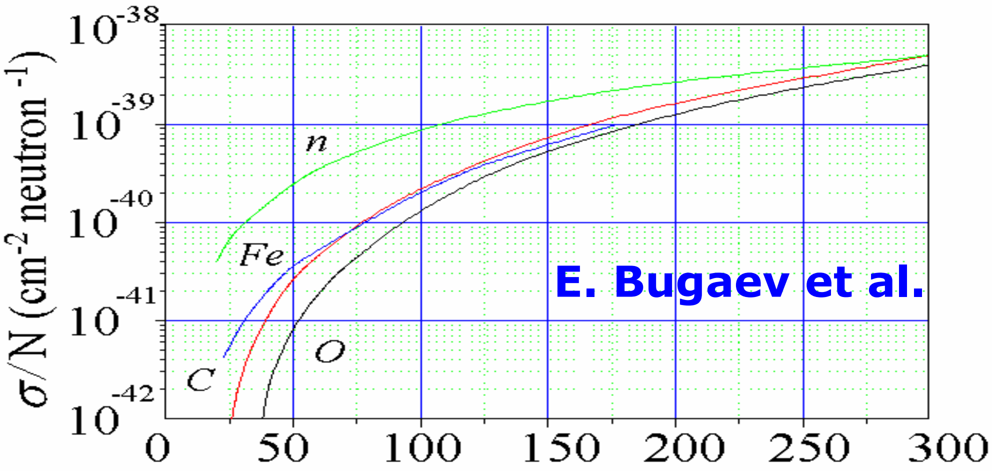
$$\overline{E}_\nu = (30-40) MeV$$

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

Liquid Scintillator Detector (LSD)



90 tons of C_nH_{2n} (n~9), 200 tons of Fe



The comparison of the total reduced cross-sections with νn cross-section on a free neutron for the reaction $\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)^*$

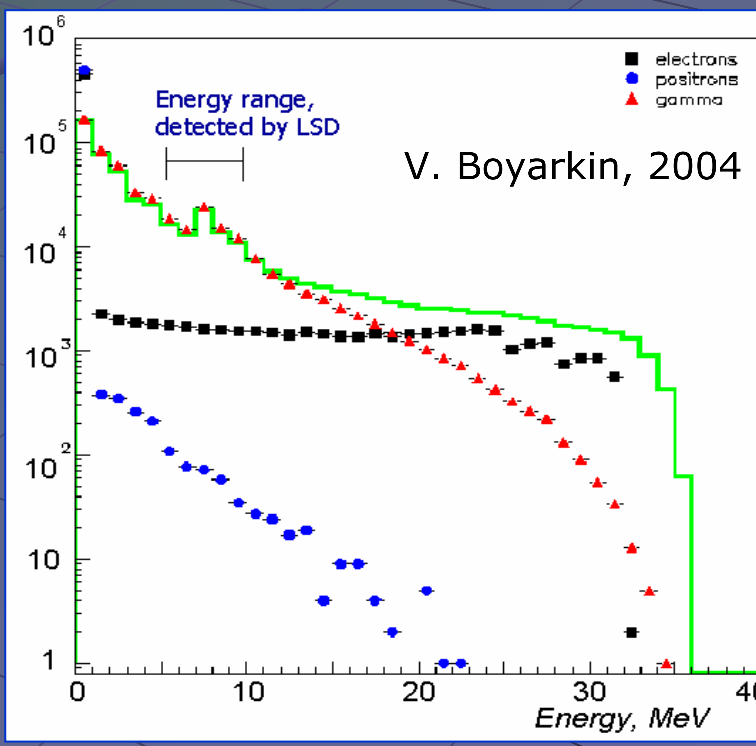
$$\nu_e + {}^{56}_{26}Fe \rightarrow {}^{56}_{27}Co + e^- \quad \sigma_{tot}(40MeV) = 4.24E{-40}cm^2$$

0^+

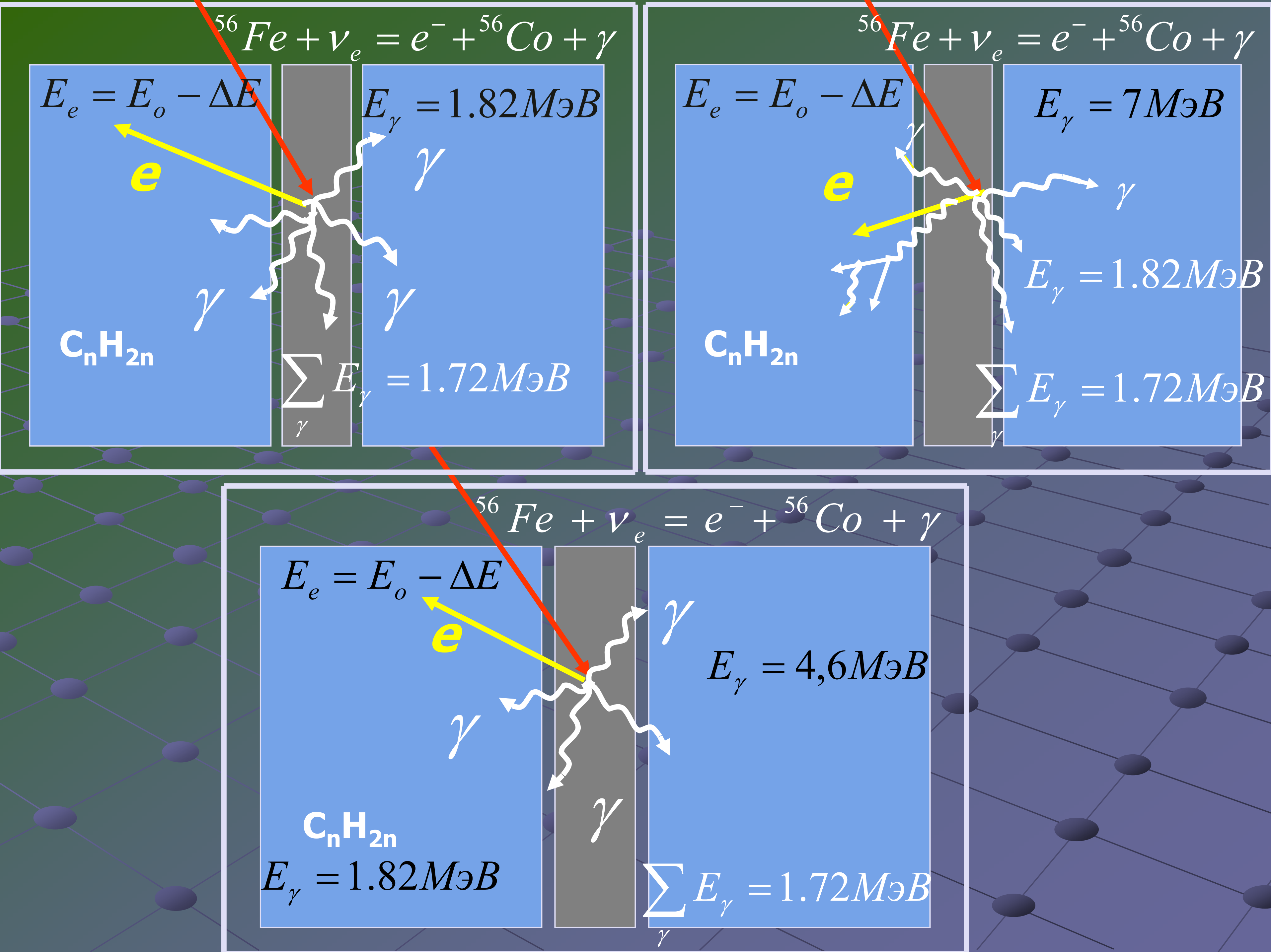
$$E\left({}^{56}_{27}Co\right) - E\left({}^{56}_{26}Fe\right) = 4.056\,MeV$$

Yu.V. Gaponov, S.V. Semenov

1^+ GT	10,7
1^+ GT	8,2
1^+ GT	7,2
0^+ IAS	3,6
1^+	1,72
4^+	${}^{56}_{27}Co$



Energy spectrum of the particles, coming from 2,8 cm iron plate (Geant4 calculations; histogram – total energy depos



$^{56}Fe + \nu_e = e^- + {}^{56}Co + \gamma$
$E_e = E_o - \Delta E$
$E_\gamma = 1.82 MэВ$
e
γ
γ
γ
C_nH_{2n}
$\sum_\gamma E_\gamma = 1.72 MэВ$
$^{56}Fe + \nu_e = e^- + {}^{56}Co + \gamma$
$E_e = E_o - \Delta E$
$E_\gamma = 7 MэВ$
γ
e
γ
$E_\gamma = 1.82 MэВ$
C_nH_{2n}
$\sum_\gamma E_\gamma = 1.72 MэВ$
$^{56}Fe + \nu_e = e^- + {}^{56}Co + \gamma$
$E_e = E_o - \Delta E$
e
γ
$E_\gamma = 4,6 MэВ$
γ
γ
C_nH_{2n}
$E_\gamma = 1.82 MэВ$
$\sum_\gamma E_\gamma = 1.72 MэВ$

Detector	Energy threshold	Estimated number of $\nu_e A$ interaction				Estimated Effect $N_2 \cdot \eta$	Exp.
		N_1	N_2	N_3	N_4		
LSD	5 – 7	3.2	5.7	3.5	4.9	3.2	5
KII	7 – 14	0.9	3.1	1.2	2.5	2.7	2*
BUST	10	2.8	5.2			~1	1**

$$E_{\upsilon_e} = 30 MeV \; (N_1) \qquad E_{\upsilon_e} = 40 MeV \; (N_2)$$

$$f\left(E_{\upsilon_e}\right) \; with \;\; \varphi = 5 \;\; (N_3)$$

$$f\left(E_{\upsilon_e}\right) \; with \;\; \varphi = 7.5 \;\; (N_4)$$

$$\varphi = \frac{\mu_e}{kT}$$

$$kT_c = 5.34 \;\; MeV$$

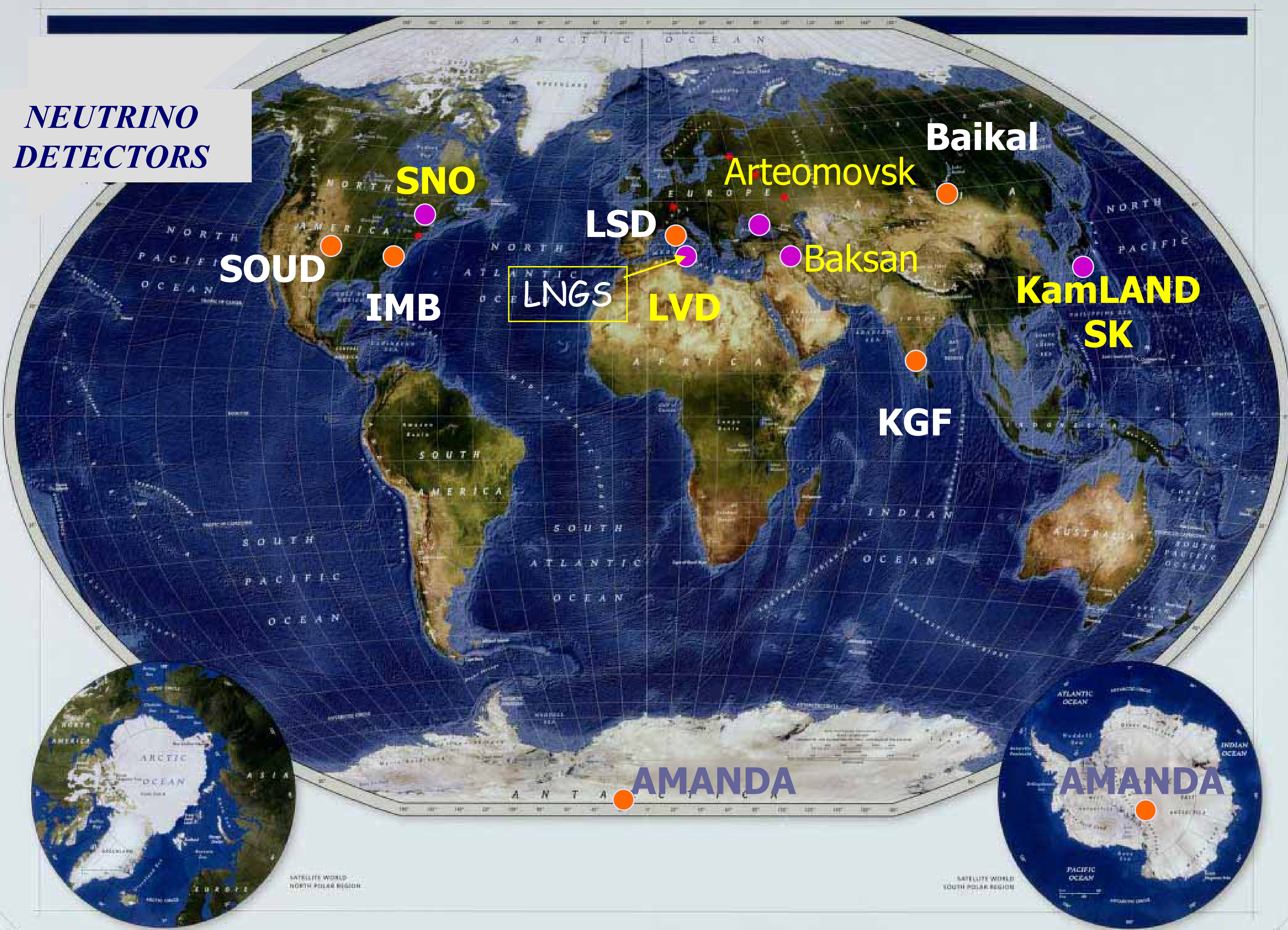
$$\rho = 2.6 \cdot 10^{14} \;\; g/cm^3$$

* De Rujula, 1987

** Alexeyev, 1987

Detector	Depth m.w.e	Mass, ktons	Thre-shold, MeV	Efficiency			Number of events			Back-ground s^{-1}
				η_{e^+}	η_n	η_γ	$\tilde{\nu}_e p$	$\nu_e A$	$\nu_e C$	
Arteomovsk **ASD** Russia	570	0.1 C_nH_{2n}	5	0.97	0.8	0.85	57	2.1	9.5	0.16
Baksan **BUST** Russia	850	0.13 (0.2) C_nH_{2n}	10	0.6	-	0.2	45 (67)	1.4 (2.2)	2.8 (4.3)	0.013 (0.033)
KamLAND USA Japan	2700	1. C_nH_{2n}	~ 4				- 500	22	300 54	
Gran Sasso **LVD** Italy,Russia	3300	0.95 Fe 1.1 C_nH_{2n}	4 – 6	0.9	0.6	0.5	- 550	470 24	300 60	< 0.1
Kamioka **Super-K** Japan,USA	2700	22.5 H_2O	5.5	0.7	-	-	- 6000	750 220	-	
SNO Canada	6000	1.4 H_2O 1 D_2O	5				530	37 770		

NEUTRINO DETECTORS



- **From 1978 up to now there were no observations of gravitational collapse in our Galaxy with "Collapse" (Arteomovsk), LSD, LVD, BUST and other detectors.**
- **It means that the frequency of collapses in our Galaxy is less than 1/(16 years) at 95% c.l.**

The possibility to observe the neutrino burst depends on background conditions

The source of background:

1. Cosmic rays $0<E<\infty$
   a) muons
   b) secondary particles generated by muons (e,γ,n and long-living isotopes)
   c) the products of reactions of nuclear and electromagnetic interactions
2. Natural radioactivity E<30 MeV, mainly E<2.65 MeV
   a) γ,
   b) n, (n γ), U^{238}, Th^{232}
   c) α, (αn) d) Rn^{222}

Background reduction:

1. Deep underground location
2. Using the low radioactivity materials
3. Anti-coincidence system
4. Using the reactions with good signature
5. The coincidence of signals in several detectors

2004

Spectral indices obtained in various experiments

muons

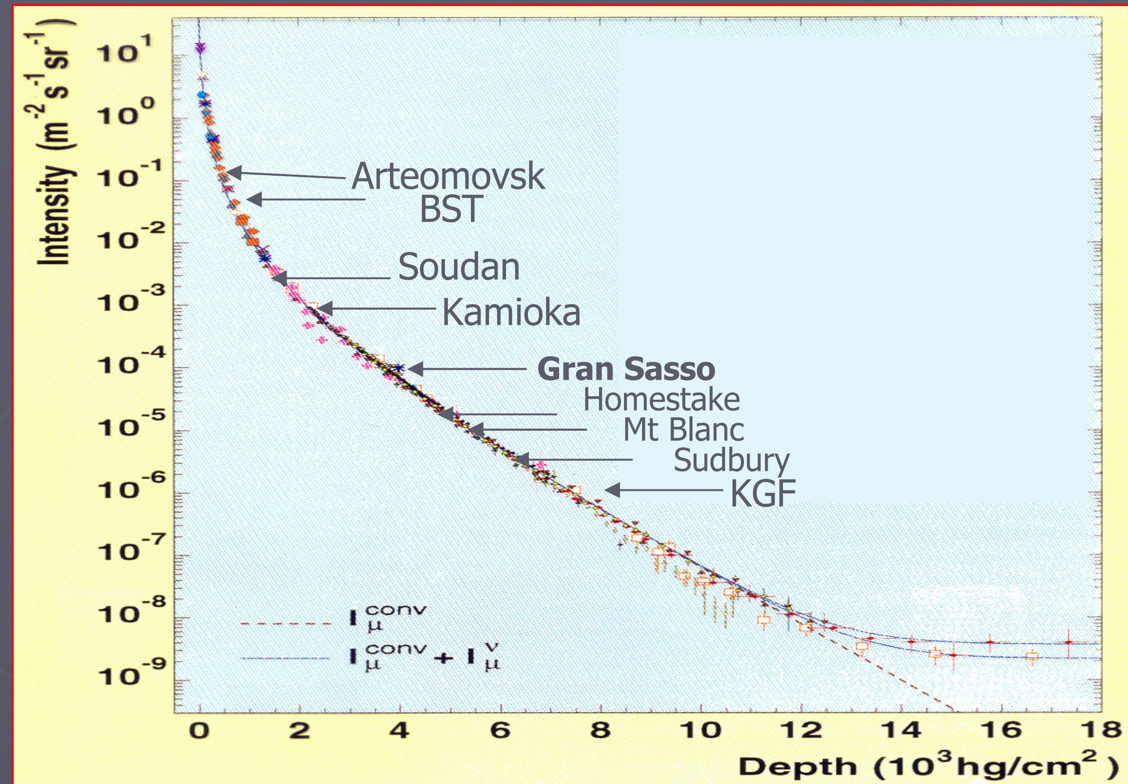
Experiment	Spectral index	Method
LVD	$\gamma_{\pi,K}$ =2.72±0.05	DIC
MACRO	$\gamma_{\pi,K}$ =2.78±0.09	DIC
BUST	γ_{p} =2.65±0.05	DIC
	γ_{μ} =3.80*	SC
KGF	γ_{μ} =3.60±0.05*	DIC
NUSEX	γ_{p} =2.79±0.03	DIC
ASD	$\gamma_{\pi,K}$ =2.75±0.08	SC
MEPhI	$\gamma_{\pi,K}$ =2.68-2.75	SC
MSU	$\gamma_{\pi,K}$ =2.67±0.03	SC
	γ_{p} =2.64±0.03	SC
DEIS	$\gamma_{\pi,K}$ =2.74±0.03	MS
MUTRON	$\gamma_{\pi,K}$ =2.71±0.03	MS
AMANDA	$\gamma_{\pi,K}$ =2.70±0.02	DIC
SNO	$\gamma_{\pi,K}$ =2.70	DIC

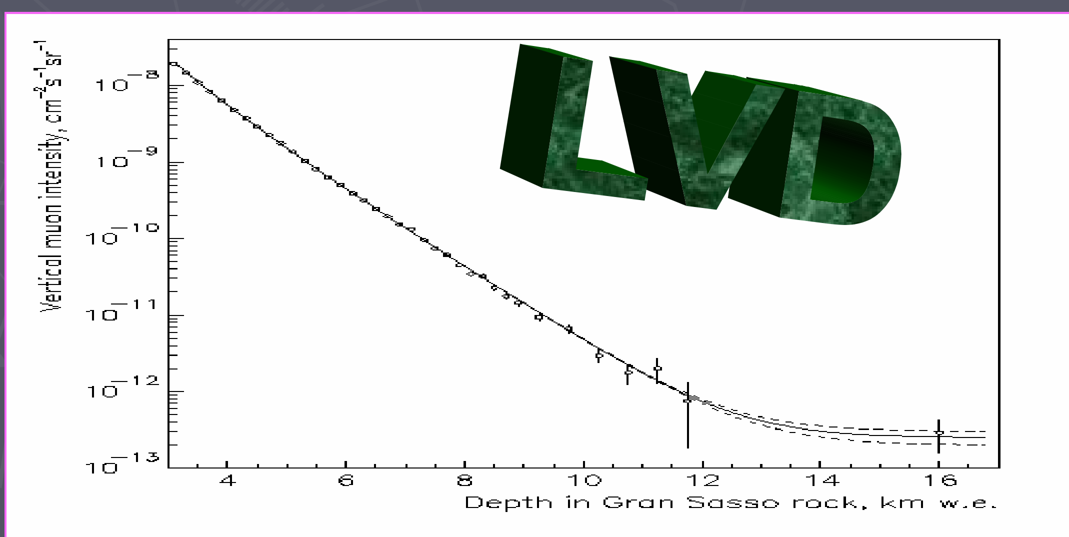
DIC - Depth-intensity curve
SC - spectrum of cascades
MS - magnetic spectrometer

* - *for high-energy muons* $\gamma_p=\gamma_{\pi,K}=\gamma_\mu-1$

1998

depth-intensity curve





2004

PHYSICS LETTERS B review of particle physics Volume 592, Issues 1-4, 15 July 2004

Muon bundles

Muon bundles (MB) are generated in EAS with E>100TeV.
They were discovered by G.V. Wataghin in 1941 and independently by E. Amaldi, C. Castagnioli et. al in 1952.

MB and muons in EAS

- composition
- Energy spectrum
- Cross section

of CR with E>100TeV

Experimental results

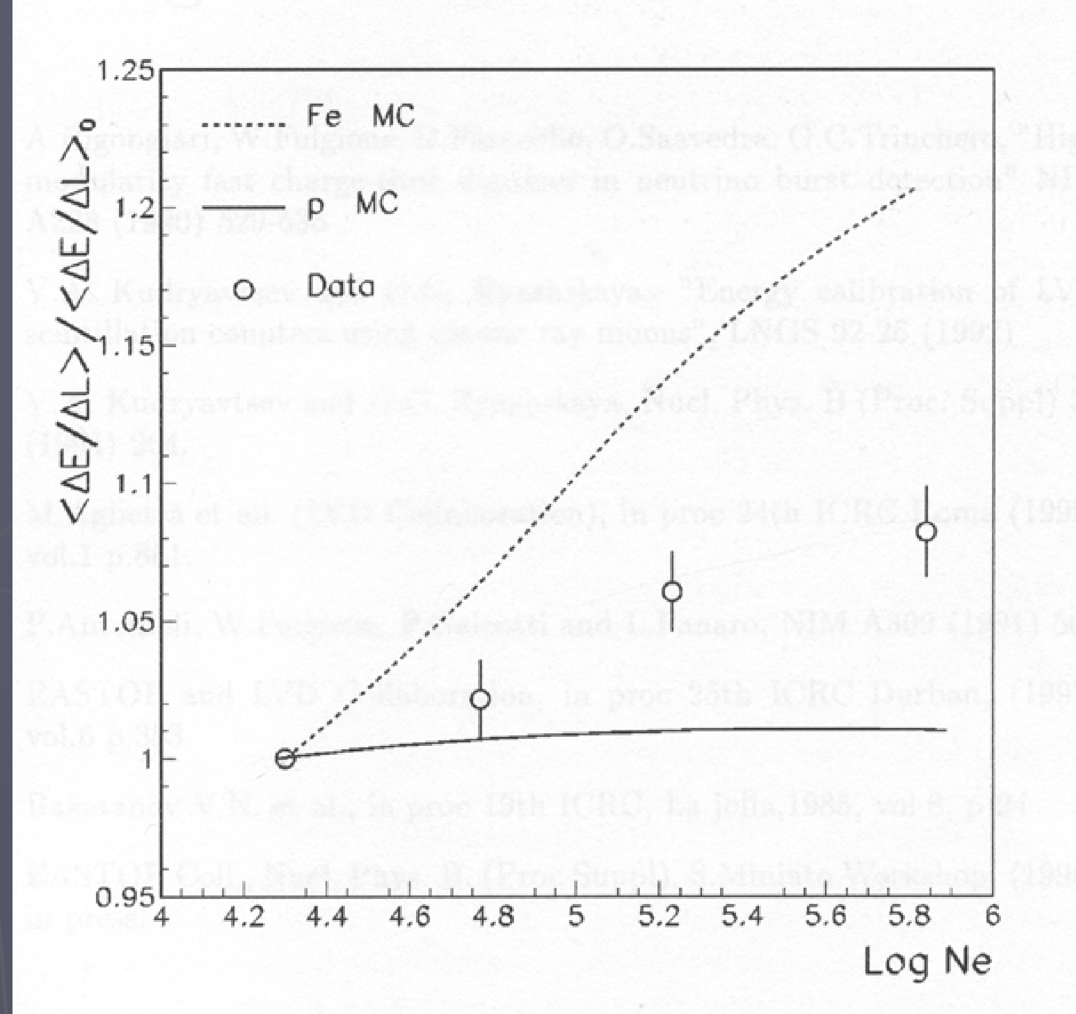
- Distribution of the distances between any muon pair in the MB
- Muon multiplicity distribution

BUST, MACRO, LVD, L_3+C, CosmoALEPH

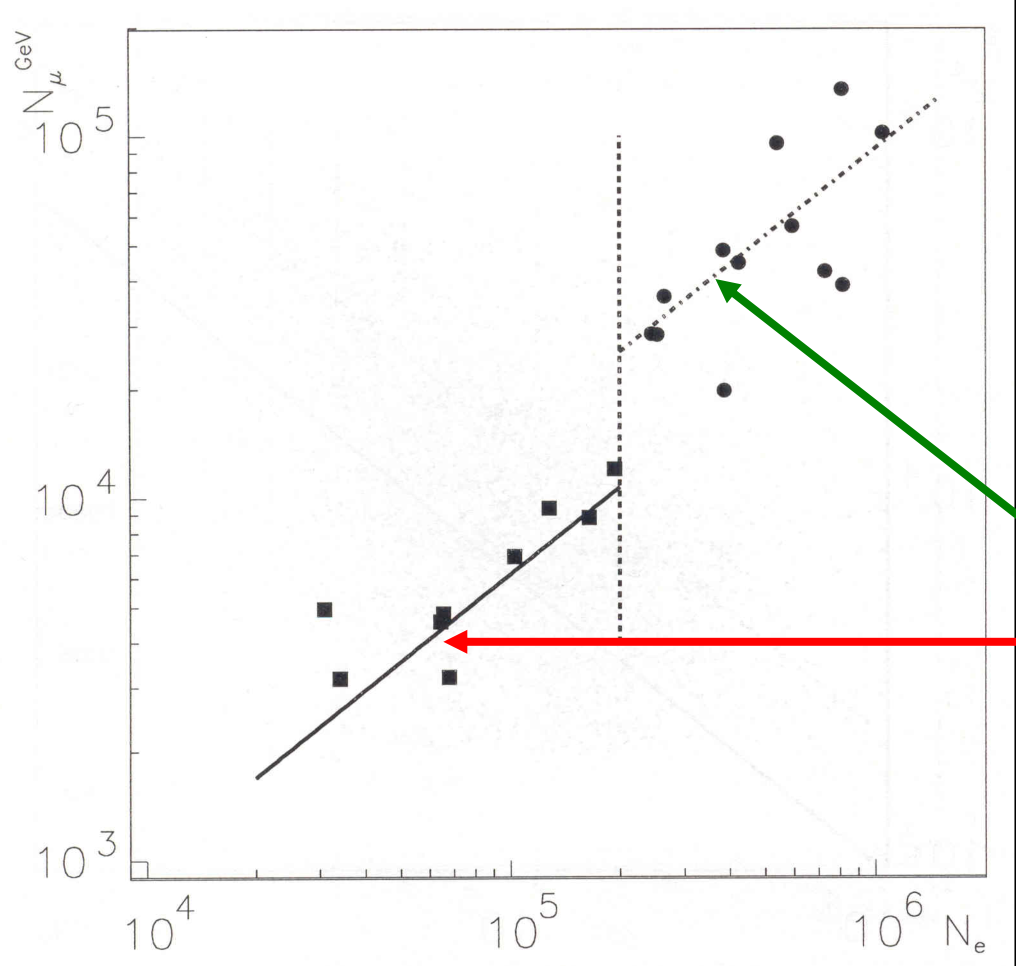
Time delays between muons in the MB, the dependence of the relative angle between muons, search for muon clusters in the events with high multiplicity

1998

Expected mean muon energy at LVD level (3000 m.w.e. depth) as a function of shower size N_e at EAS-TOP level (2000 m a.s.l.), for different primaries, i.e. protons (p) and iron nuclei (Fe). We sample over a spectral index $\gamma=2.7$ between $1.*10^{14}$ eV and $1.*10^{16}$ eV for proton primaries and between $2.1*10^{14}$ eV and $1.4*10^{16}$ eV for iron nuclei. The shower sizes plotted correspond to the shower size bins used in the data analysis.



There is an evidence for a dependence of the average deep underground muon energies on shower size in the coincident EAS-TOP and LVD data at the Gran Sasso laboratories. The measured relation agrees with a mixed chemical composition of the cosmic ray primary spectrum at energies around 10^{15} eV.



Dependence of muon number on electron number at EAS-TOP level for events selected by LVD

Iron

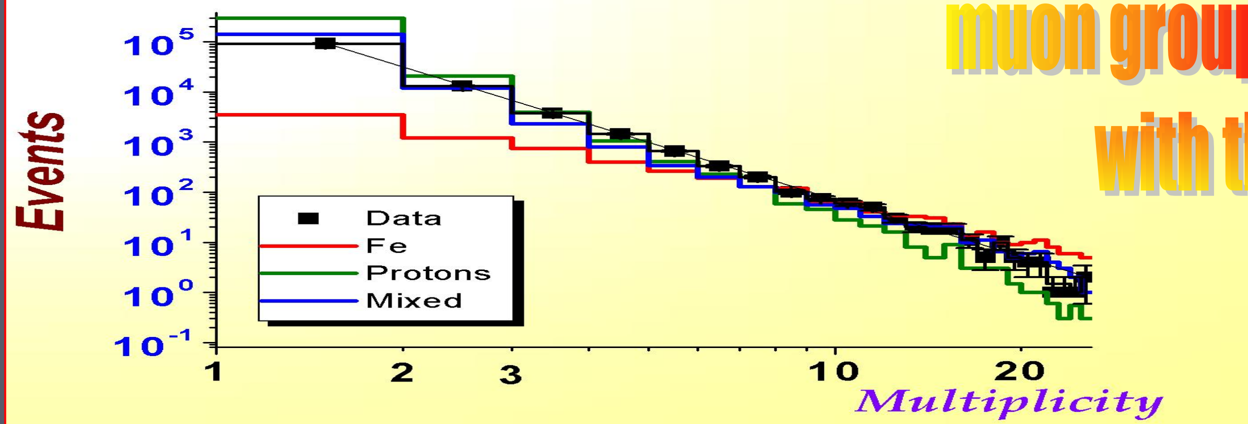
Hydrogen

■ Low number of muons (in LVD); larger energy losses (in LVD)

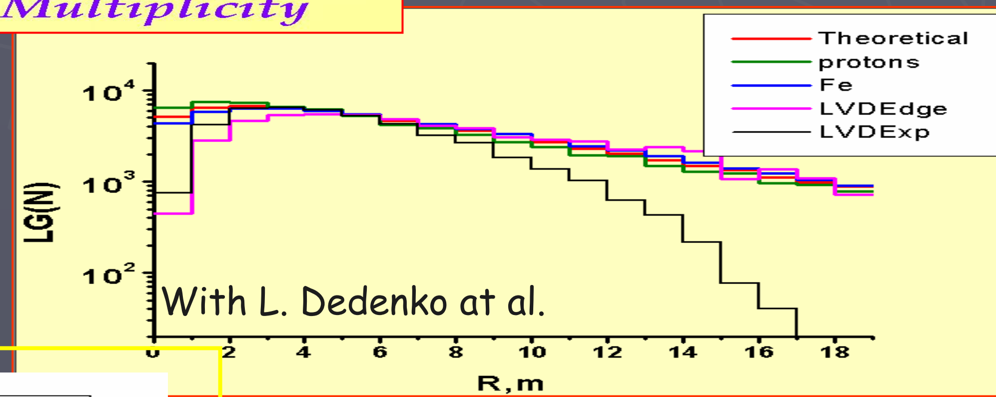
● High number of muons (LVD); low energy losses (LVD)

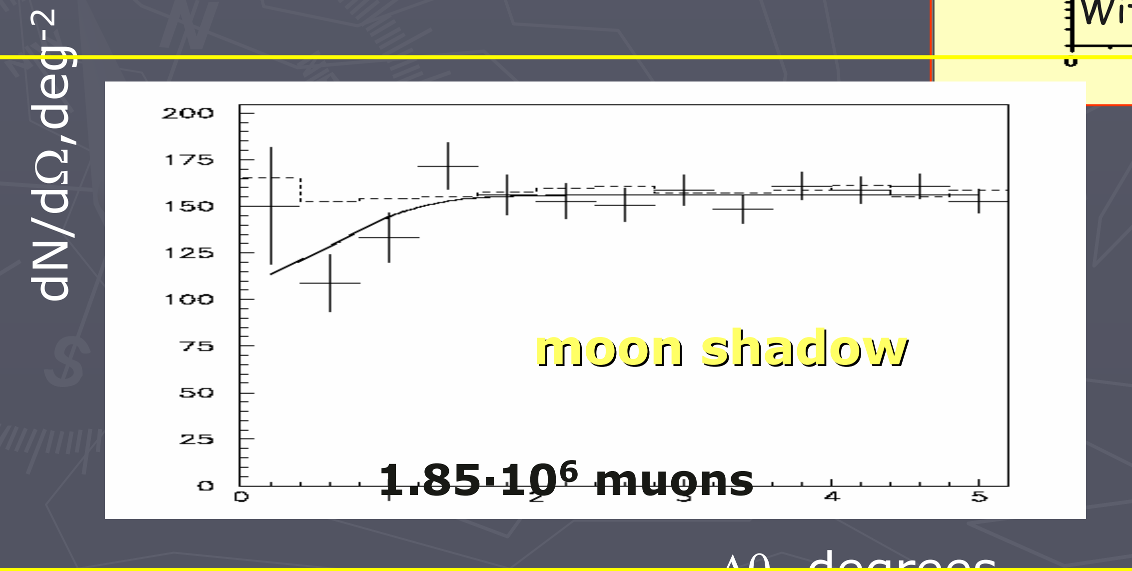
2003

generation of high energy muon groups by primary particles with the energy > 1 PeV



distributions of distances among muon pairs in muon groups

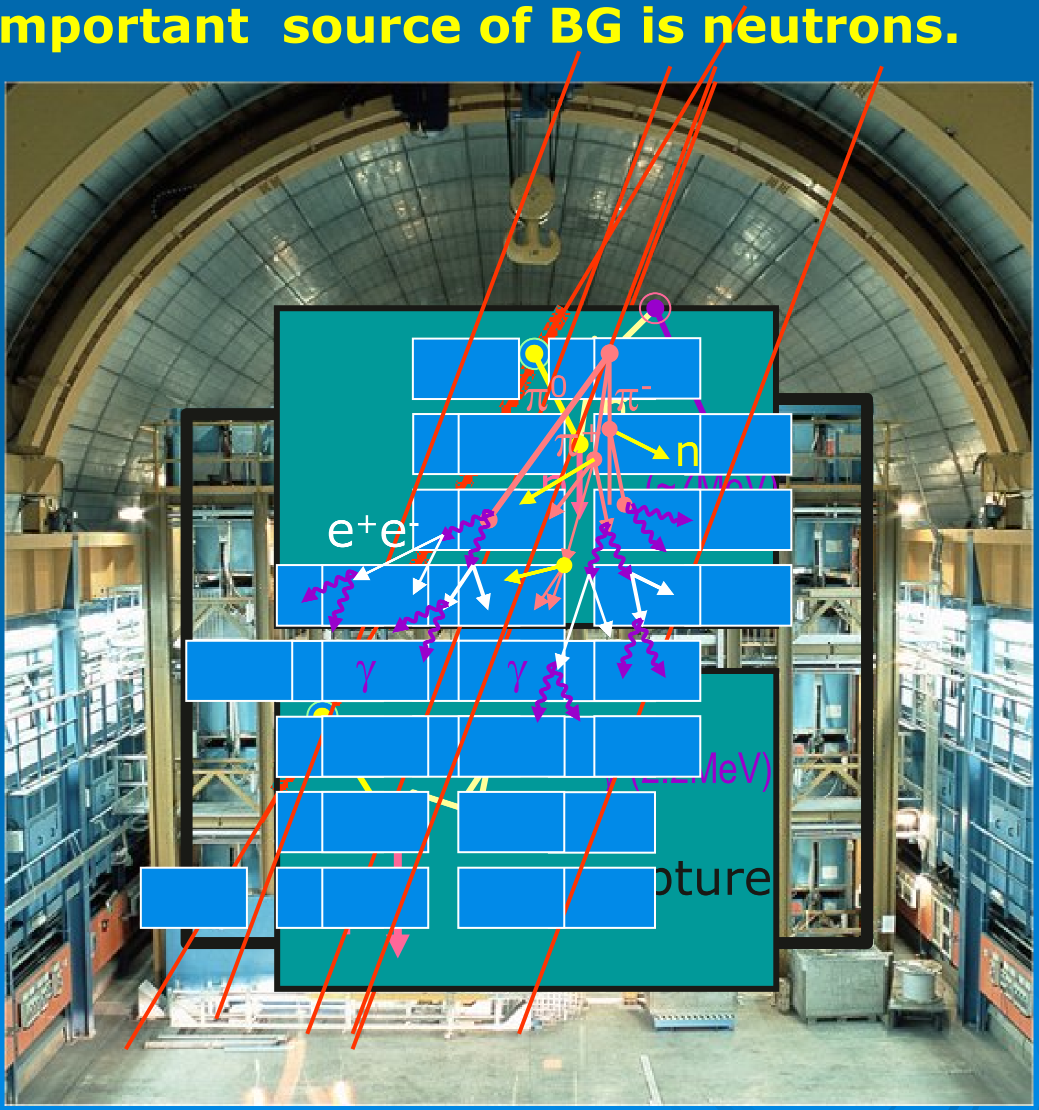




moon shielding of cosmic radiation

LVD results: neutrons

The possibility to observe rare processes strongly depends on background conditions.
Important source of BG is neutrons.



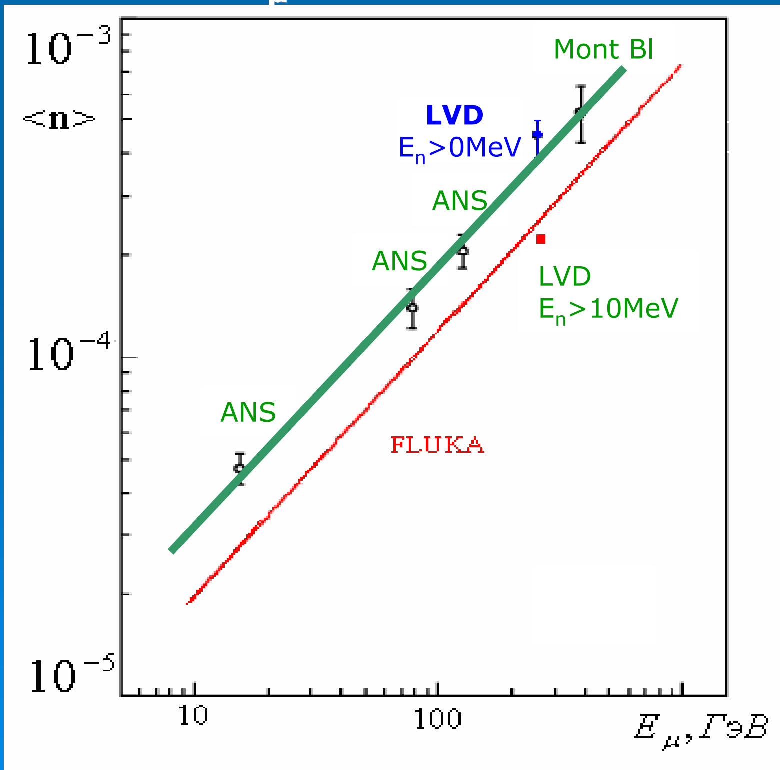
single muon ⇨ $\langle n \rangle = 0.155$

muon bundle (kμ) ⇨ $\langle n \rangle = 0.547$

per 1 muon (k=3.54) $\langle n \rangle = 0.154$

cascade ⇨ $\langle n \rangle = 2.03$

$\langle n \rangle \propto \langle E_\mu \rangle^{0.75}$ (R.Z.,1965)

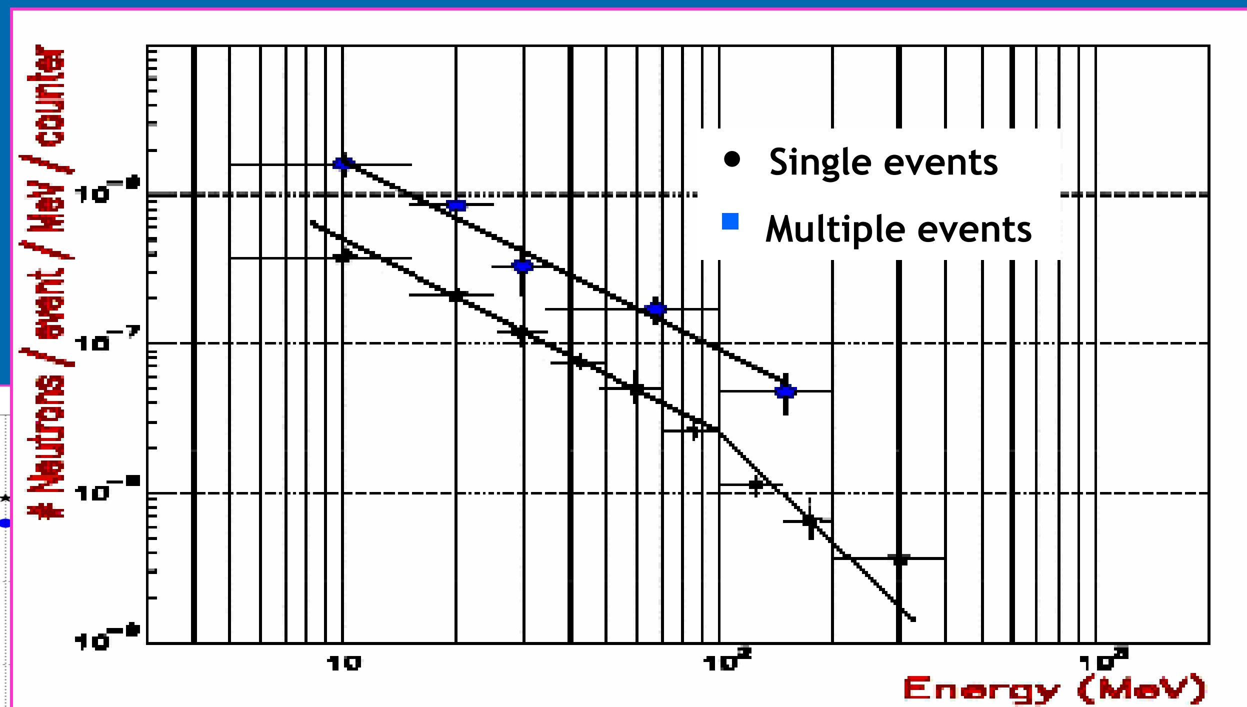


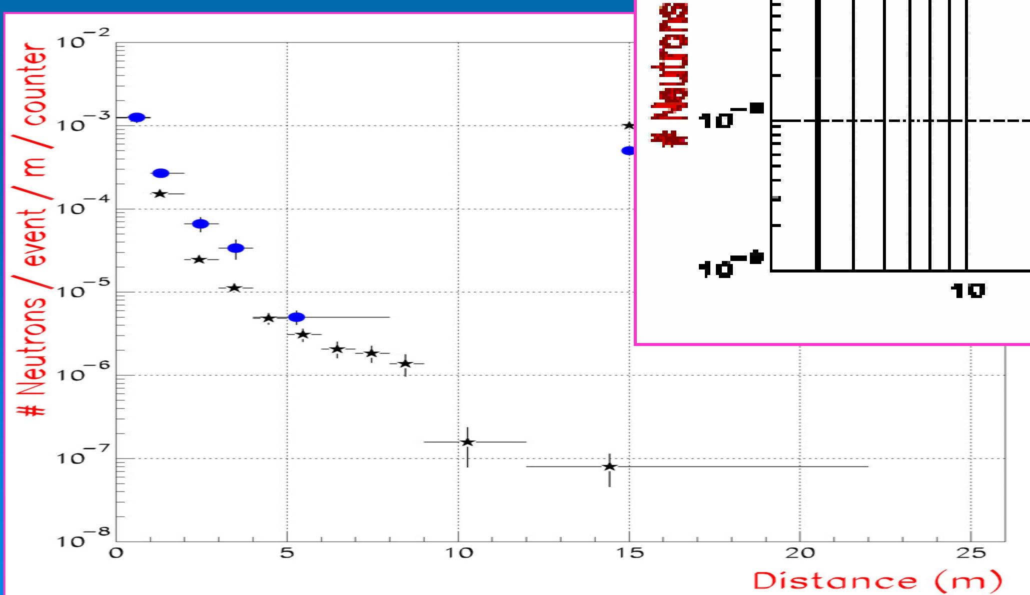
$\delta=0.07$

muons	0-4 MeV	4-12 MeV	N. of ev. neutron	$\bar{N}n$/ev.	$\bar{n}_{Fe,sc}$ (cm²/g)±δ	$\bar{n}_{sc}$ (cm²/g)±δ
Single 1μ 72294	5704	1124	6828	0.155	$3.06\cdot10^{-4}$	$1.84\cdot10^{-4}$
Muon bundles 23502	6611	1211	7822	0.547	$10.85\cdot10^{-4}$	$6.51\cdot10^{-4}$
k_μ (k=3.54) 83264				0.154		$1.84\cdot10^{-4}$
cascades 19603	20597	3580	24177	2.03	-	-
Total 116710	33423	6148	39571	0.557	$11\cdot10^{-4}$	$6.6\cdot10^{-4}$

Per 1 μ (all processes) → $4.38\cdot10^{-4}$

Energy spectra of neutron-produced events till 300 MeV and neutron space distribution till 22 m from muon track are measured





Muon Decay and Muon Capture

Goal of measurements:

The charge composition (positive excess) of primary cosmic rays at energy ≥10 TeV.

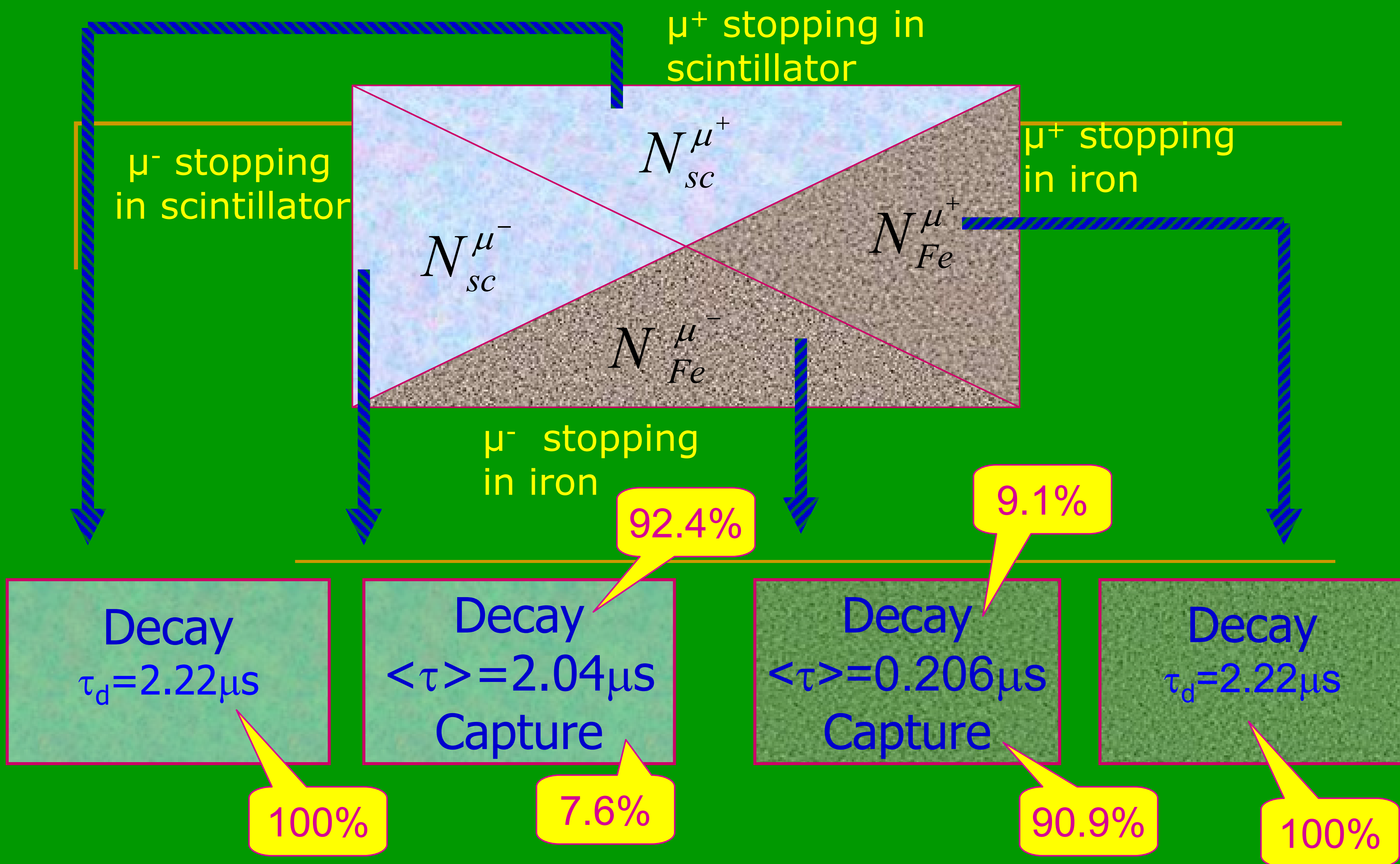
→ The ratio of $\nu / \tilde{\nu}$ of atmospheric neutrinos

Method:

Study of charge composition of stopping atmospheric muon flux underground

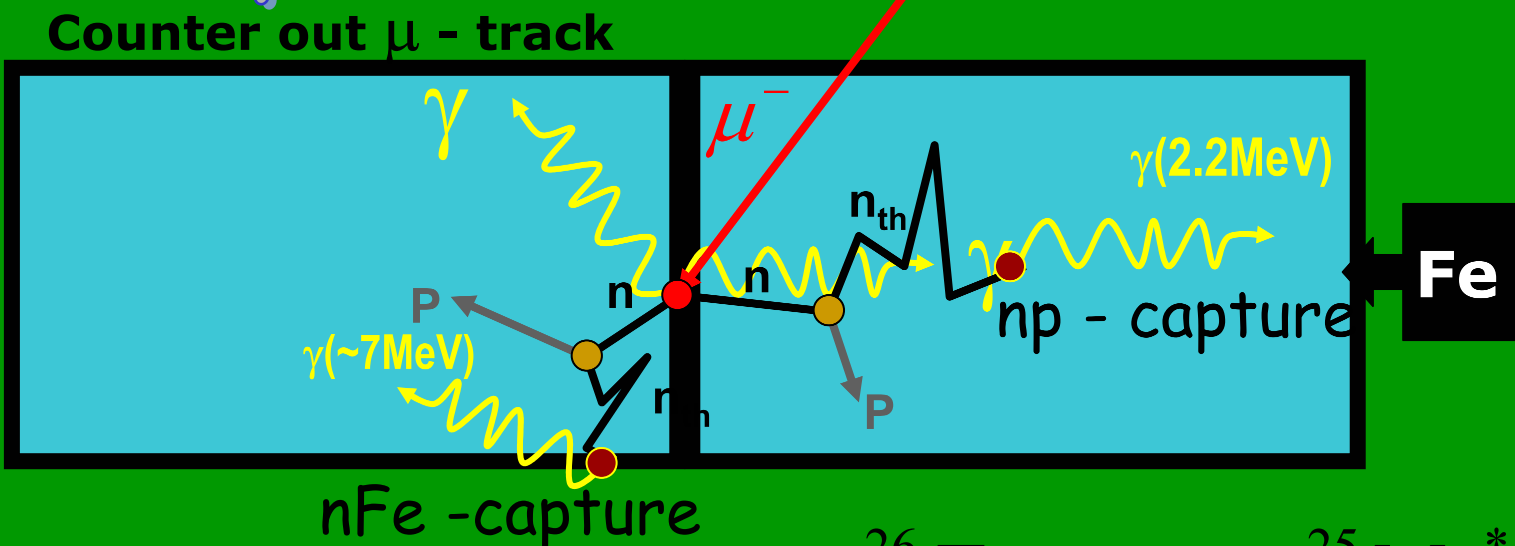
Technique:

Separation of μ^-Fe – captures and μ^+ - decays in the iron structure of LVD



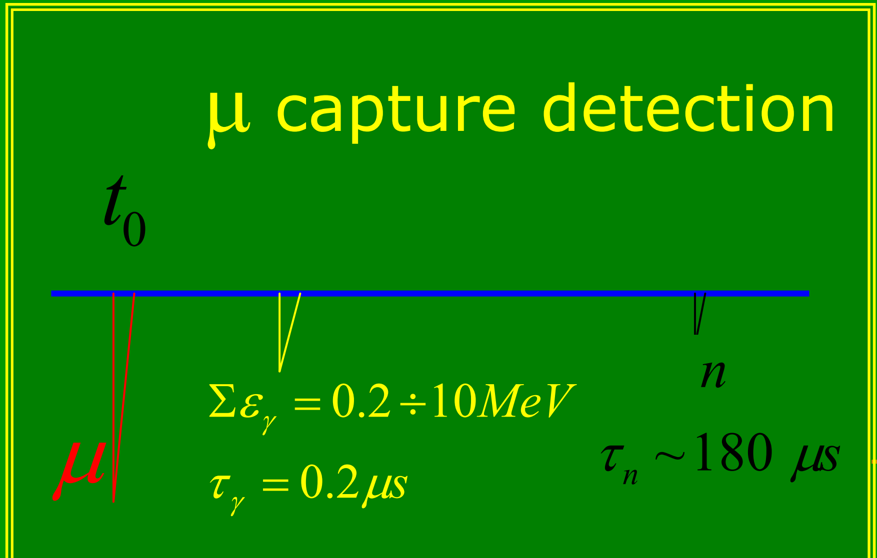
Detection: $\Sigma(N_d^{sc^+} + N_d^{sc^-}),\ N_c^{Fe^-},\ N_d^{Fe^+}$

μ⁻ capture in iron



$$ {}^{26}_{56}Fe + \mu^- \rightarrow {}^{25}_{56}Mn^* + \nu $$

$$ {}^{25}_{56}Mn^* \begin{cases} \rightarrow {}^{25}_{56}Mn + k\gamma \ (\sim 30\%) \\ \rightarrow {}^{25}_{55}Mn + n \ (\sim 70\%) \end{cases} $$



$$ \Sigma\varepsilon_\gamma \geq 0.2 \div 10\ MeV $$

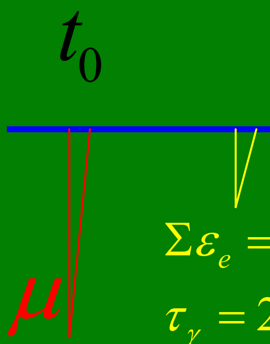
μ^+ decay

$$\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu$$

$$\tau_d = 2.22\mu s, \qquad E_{e^+}^{\max} = 52.8 MeV$$

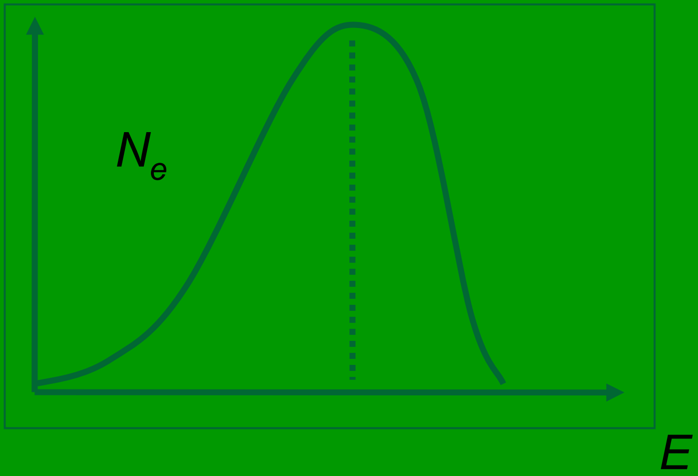
$$E_{e^+}^{prob} = 37\ MeV$$

μ^+ decay detection



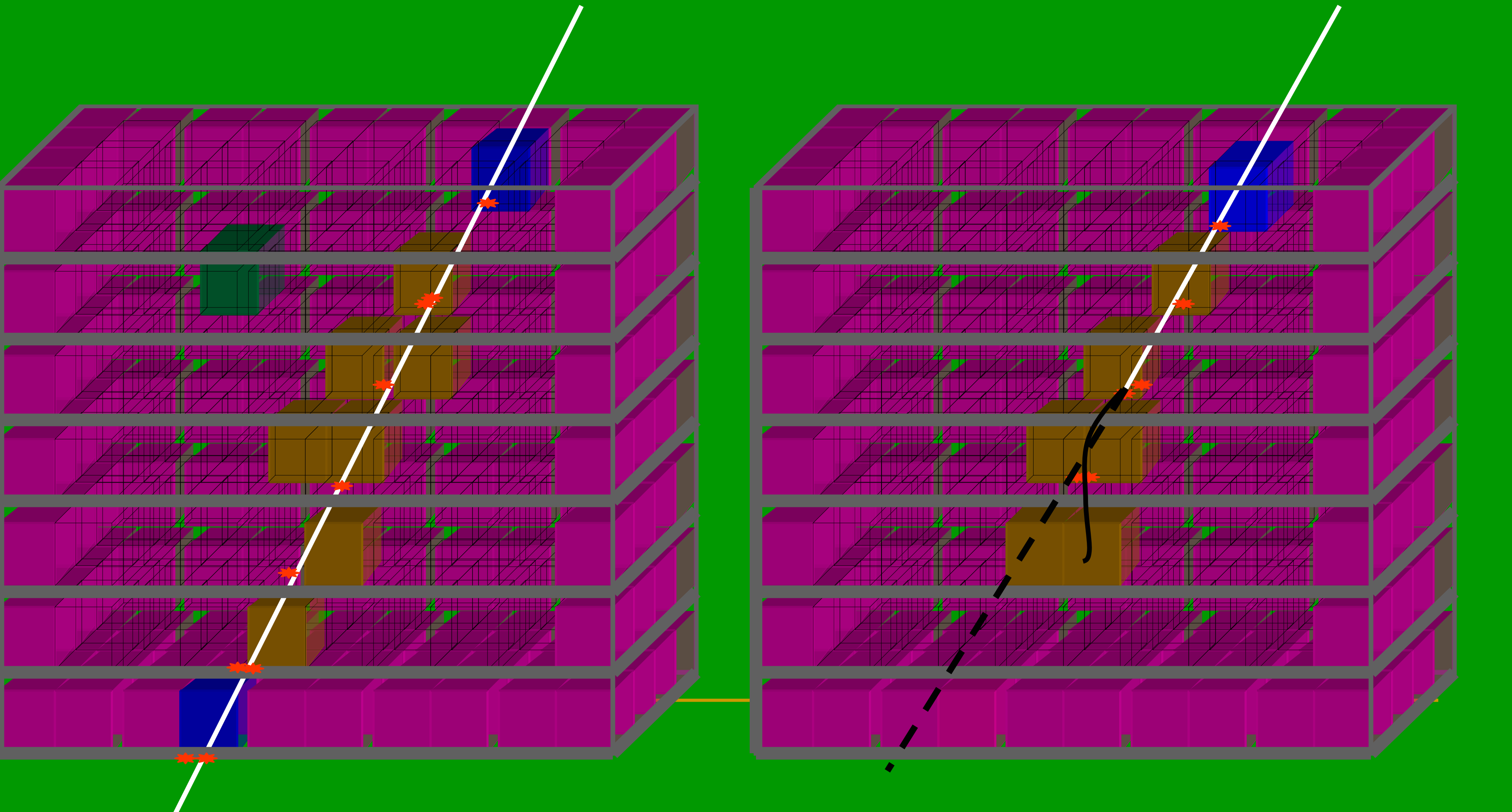
$\Sigma\varepsilon_e = 0 \div 52.8 MeV$

$\tau_\gamma = 2.22 \mu s$



through-going muon

quasi-stopping and stopping muons



RESULTS

The **first** tower data

39843 single muon reconstructed tracks

(172 expected stoppings)

8887 non reconstructed muon events

47 of 72 inner counters of 2nd, 3rd, 4th levels

$\mu^{\pm}$ decays in scintillator	36	$\eta \sim 40\%$
μ^{+} decays in iron	10	$\eta \sim 20\%$
μ^{-} captures by Fe	4	$\eta \sim 10\%$

$$\mu^{+}/\mu^{-} = 1.2^{+0.4}_{-0.3}$$

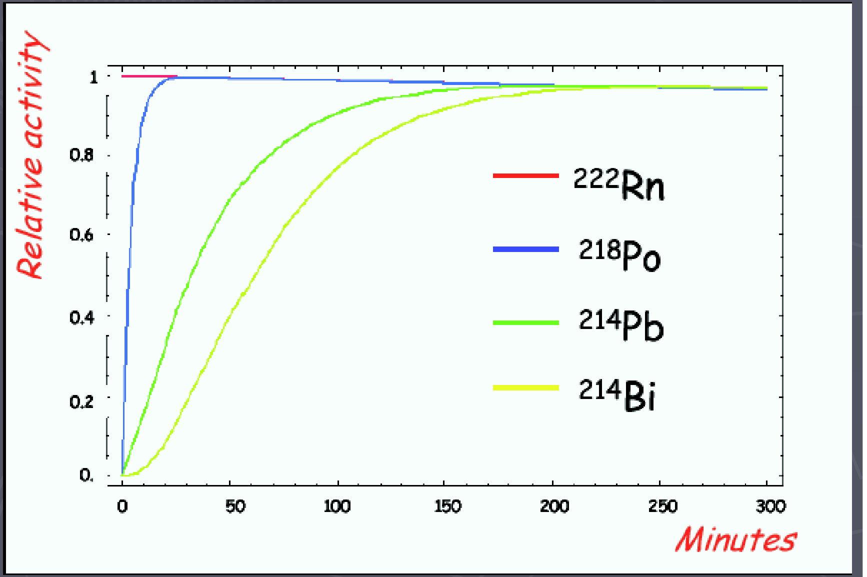
Radon problem

- Radon decay chain:

$$^{222}_{86}Rn \xrightarrow{\alpha} {}^{218}_{84}Po \xrightarrow{\alpha} {}^{214}_{82}Pb \xrightarrow{\beta^-} {}^{214}_{83}Bi \xrightarrow{\beta^-} {}^{214}_{84}Pb \xrightarrow{\alpha} {}^{210}_{82}Pb$$

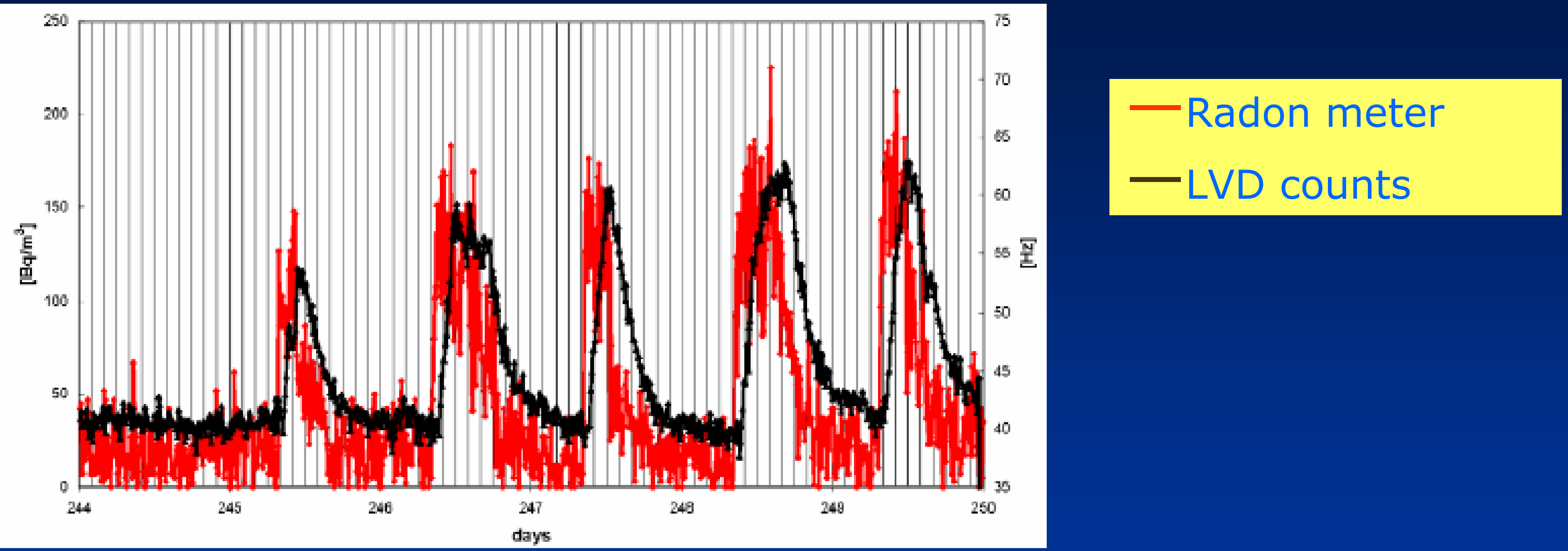
3.82 d | 3.05 min | 26.8 min | 19.7 min | 1.6×10^{-4} sec | 22.3 y

- ^{214}Bi gamma-quanta spectrum:

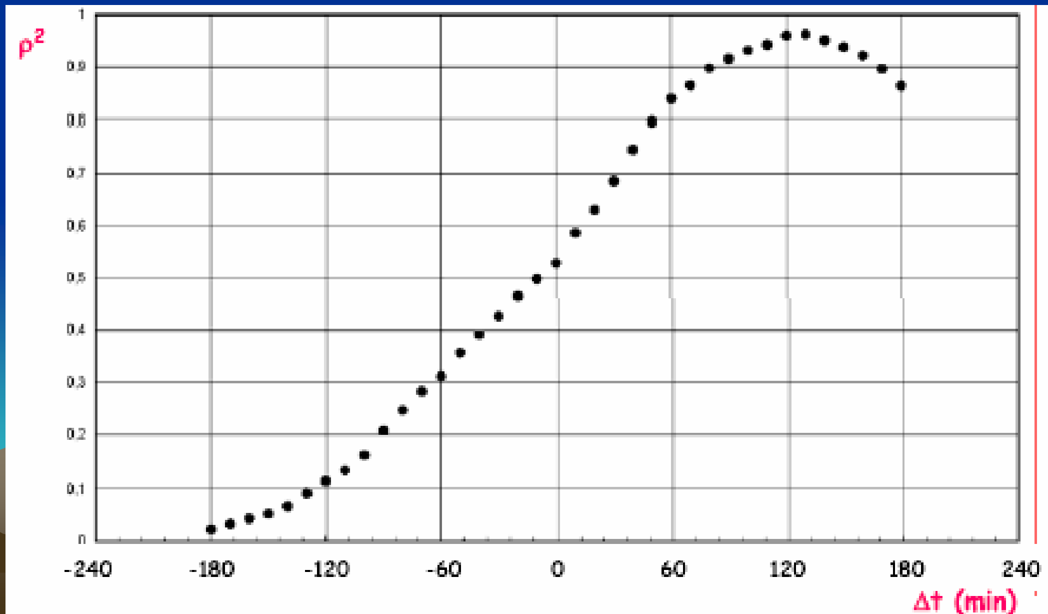


Gamma-quantum energy, MeV	Amount of quanta per 100 nuclei of Bi
0.609	47
1.764	17
1.120	17
1.238	6
2.204	5
1.378	5
0.769	5
1.400	4
2.445	2

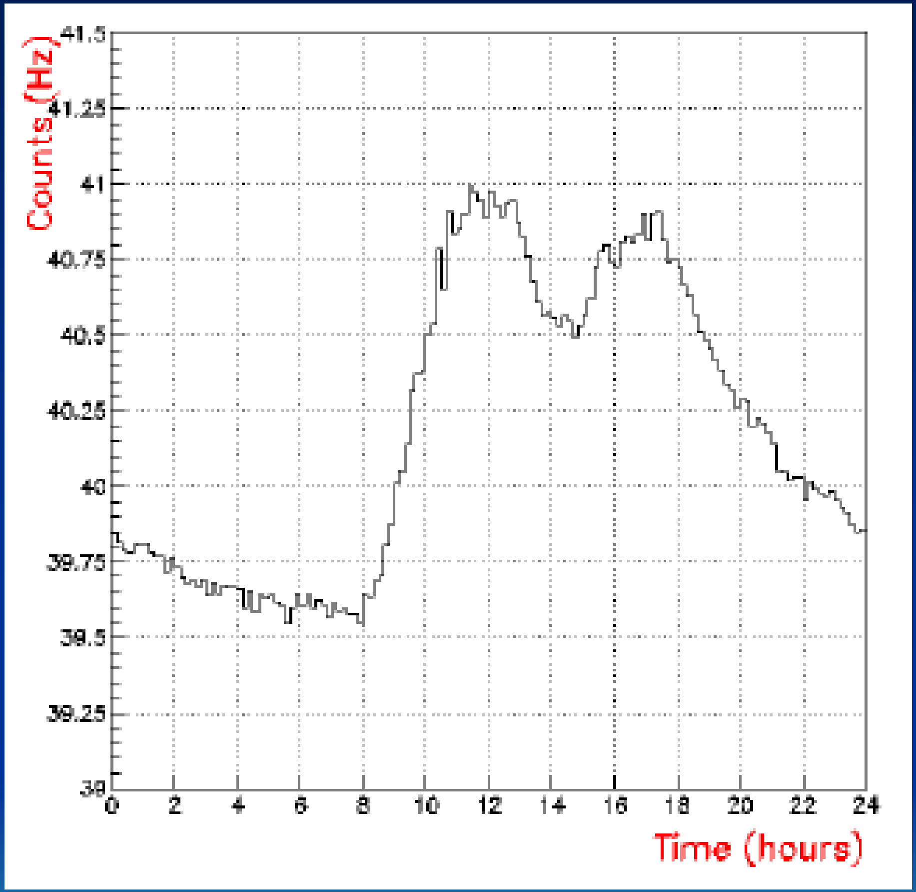
Correlation LVD-Radonmeter

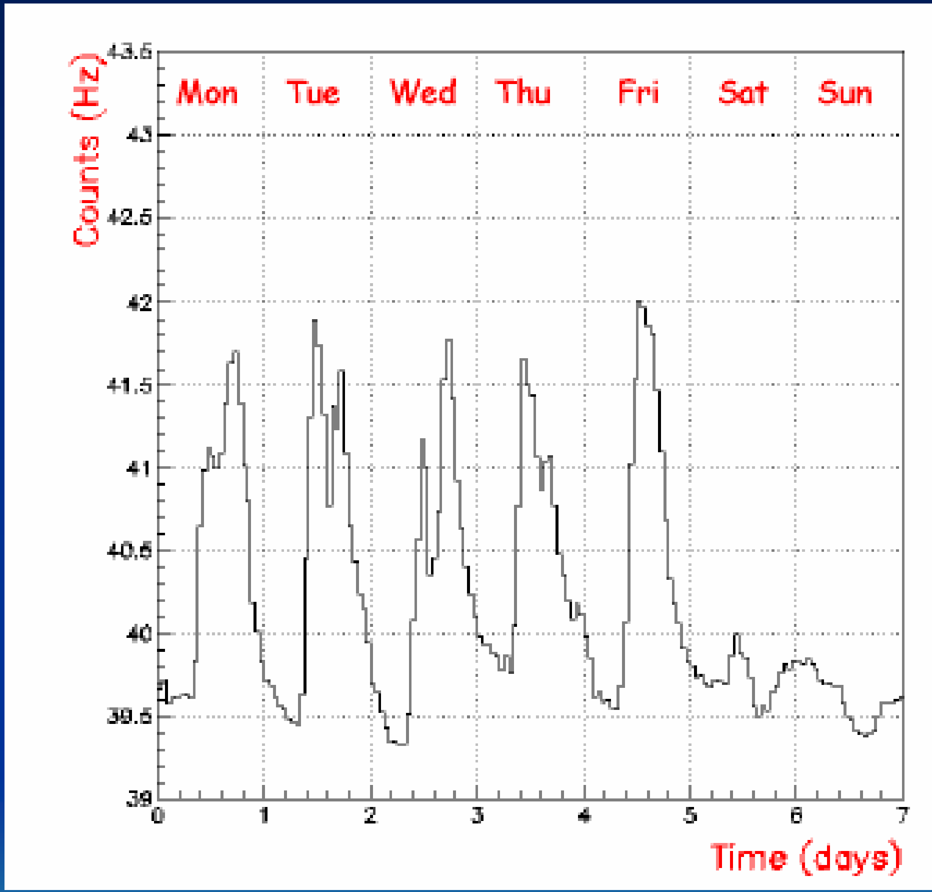


Maximum correlation: when LVD data go with delay of 2 hours to Radonmeter

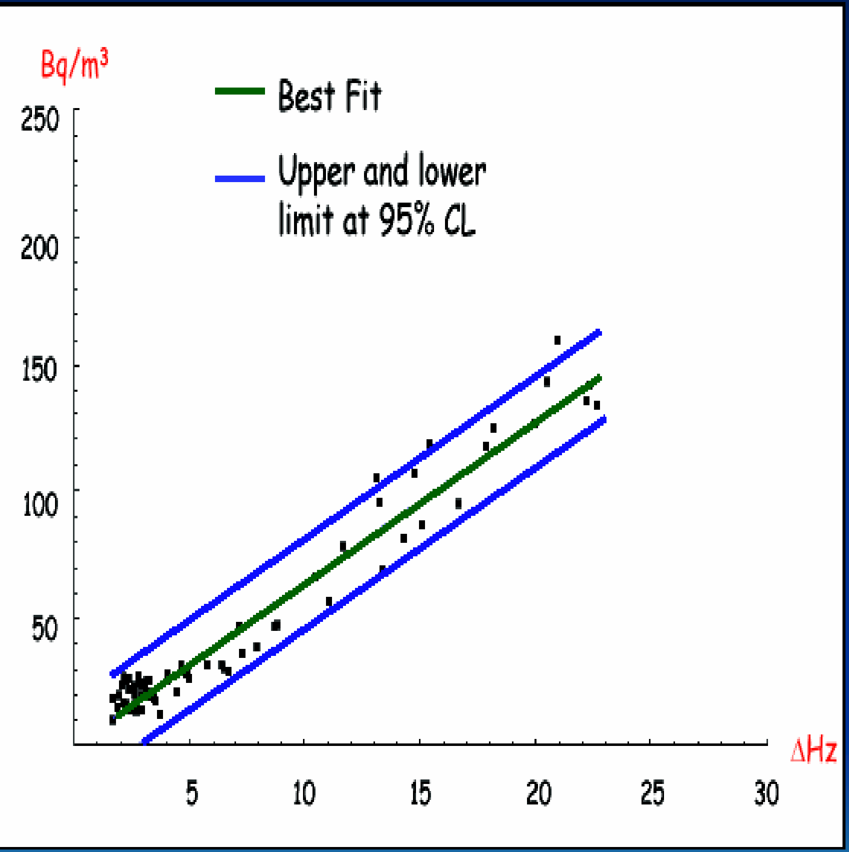


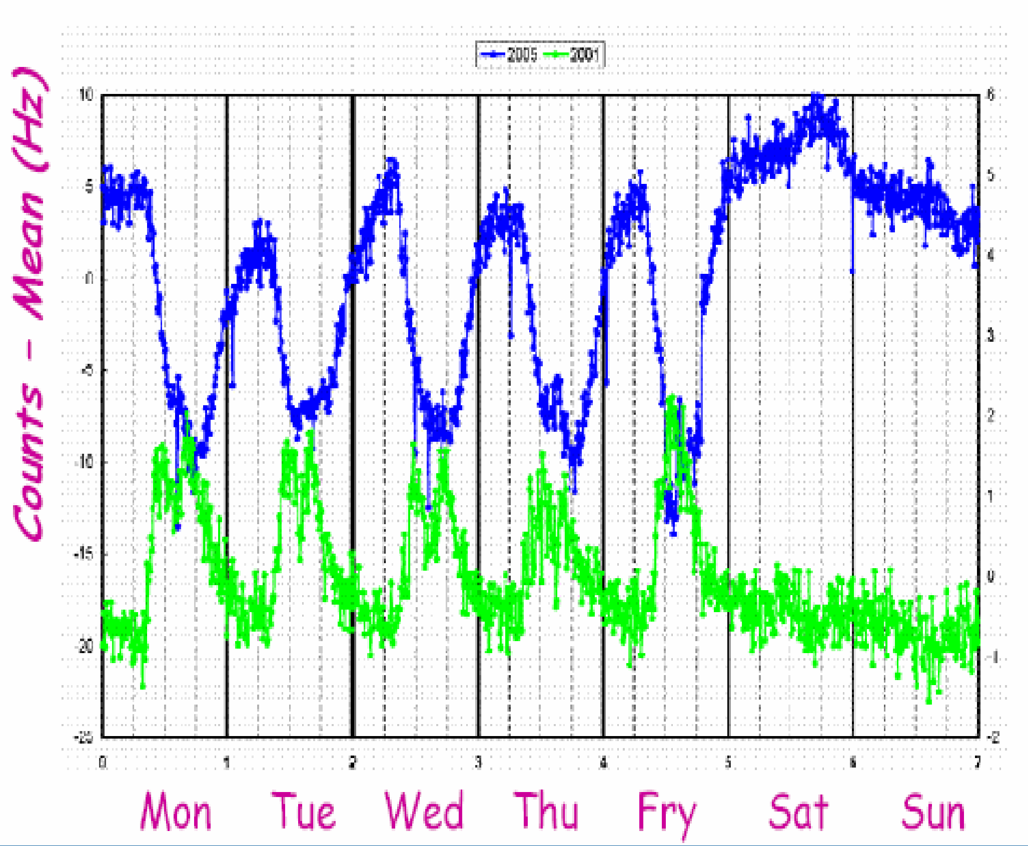
Daily and Weekly Modulations





Calibration, Low threshold counting rate & Ventilation system





Variation of 6.91±0.26 Bq/m³ in ^{222}Rn concentration leads to average variation of 1 Hz in LVD low threshold counting rate.

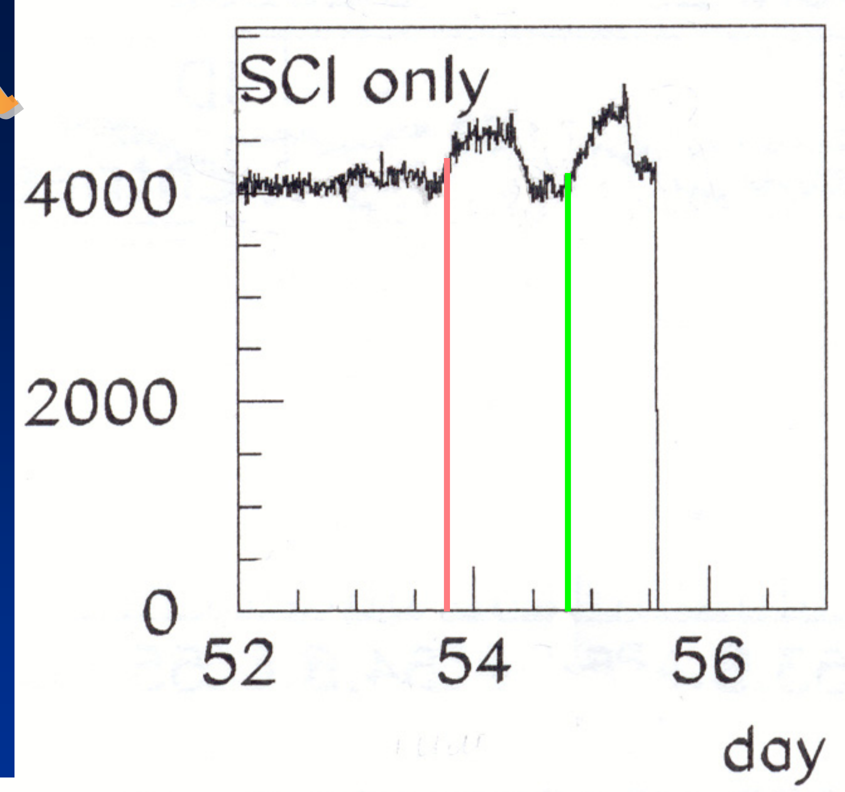
Comparison of low threshold counting rate between 2001 & 2005

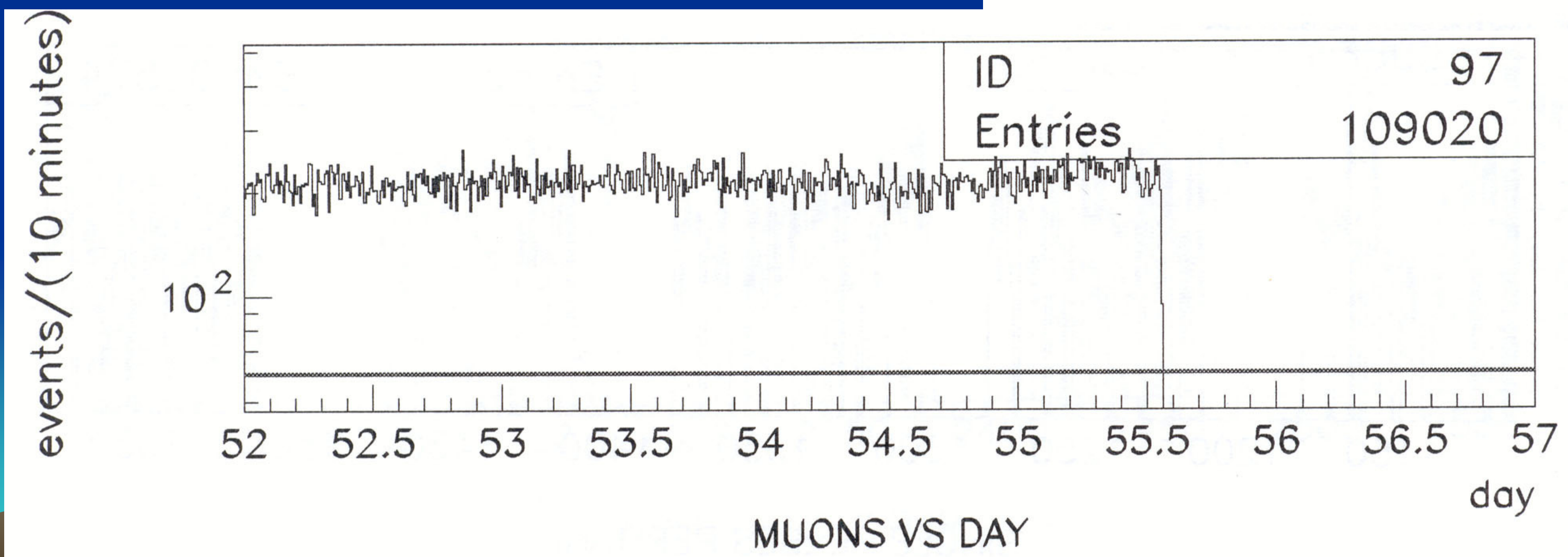
2005

august

Rome 4.5 R

Teramo 2.6 R



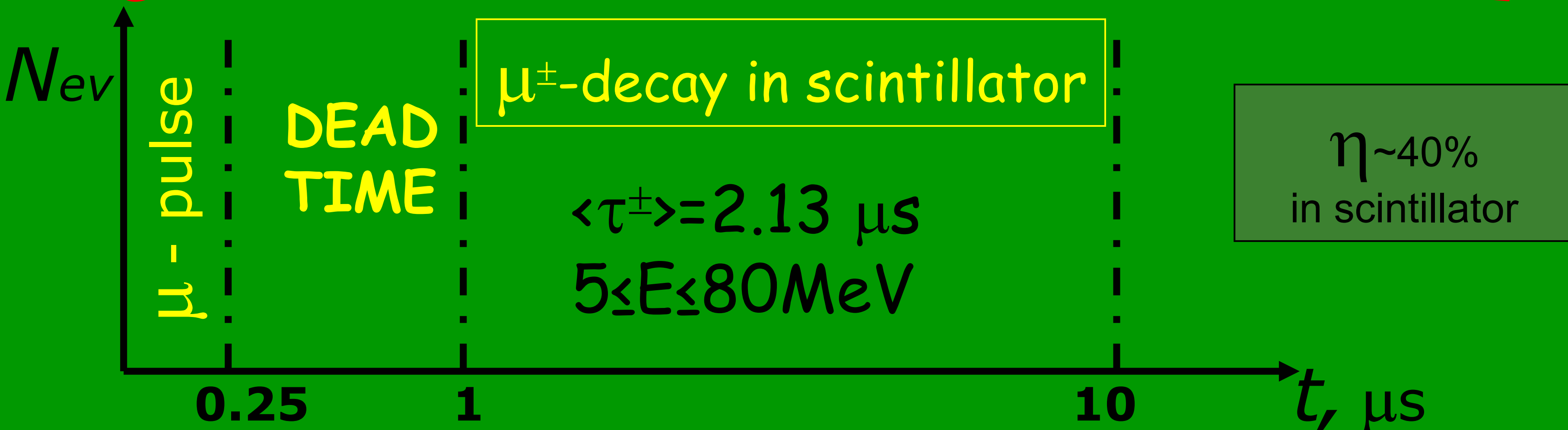


Conclusions

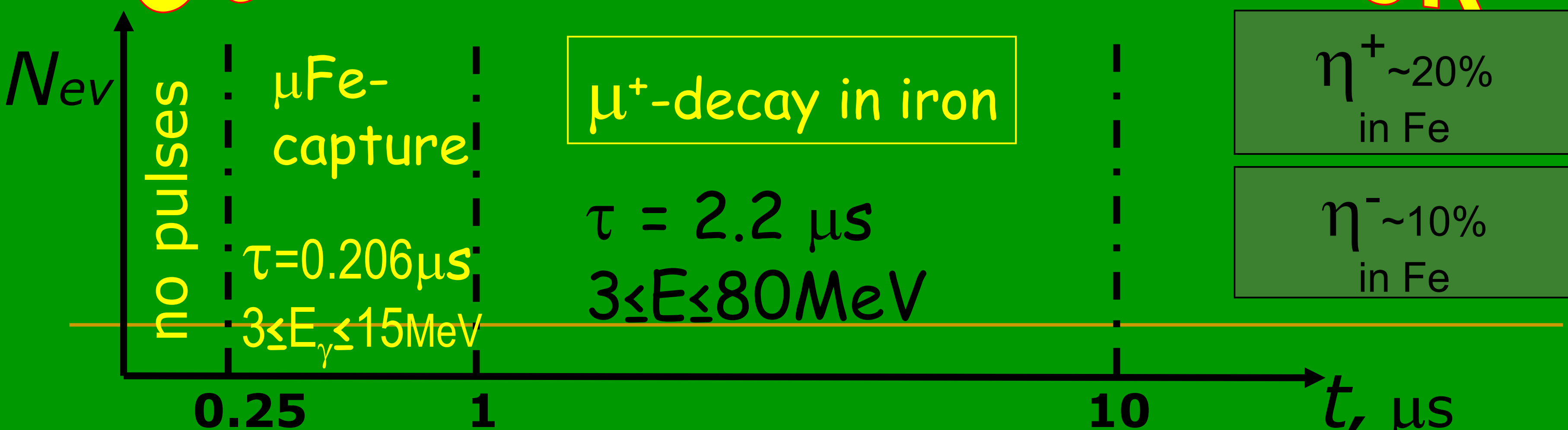
1. Life-time of LVD operation is 98%.
2. LVD is able to detect not only $\bar{\nu}_e$ but also ν_e. It is very important for rotating collapsars.
3. The duration of search for neutrino bursts from collapsing stars is 14 years. Taking into account the results of other detectors the frequency of collapses in our Galaxy is less than 1/(16 years) at 95% c.l.
4. LVD + Super-Kamiokande+SNO form a global network to search for neutrino bursts from collapses (SNEWS) which is working during 4 years.
5. Study of multiple muons shows a mixed composition of primary cosmic rays.
6. The muon depth-intensity curve is measured, what is important for primary cosmic rays studying and background understanding.
7. Average number of neutrons generated by muons at the depth of 3300 m.w.e. is $4.38 \cdot 10^{-4}$. Energy spectra and neutron space distribution till 22 m from muon track are measured.
8. The method of measuring μ^+/μ^- ratio is developed. $R = 1.2^{+0.4}_{-0.3}$
9. The variation of Ra concentration underground is studied using LVD.

LVD

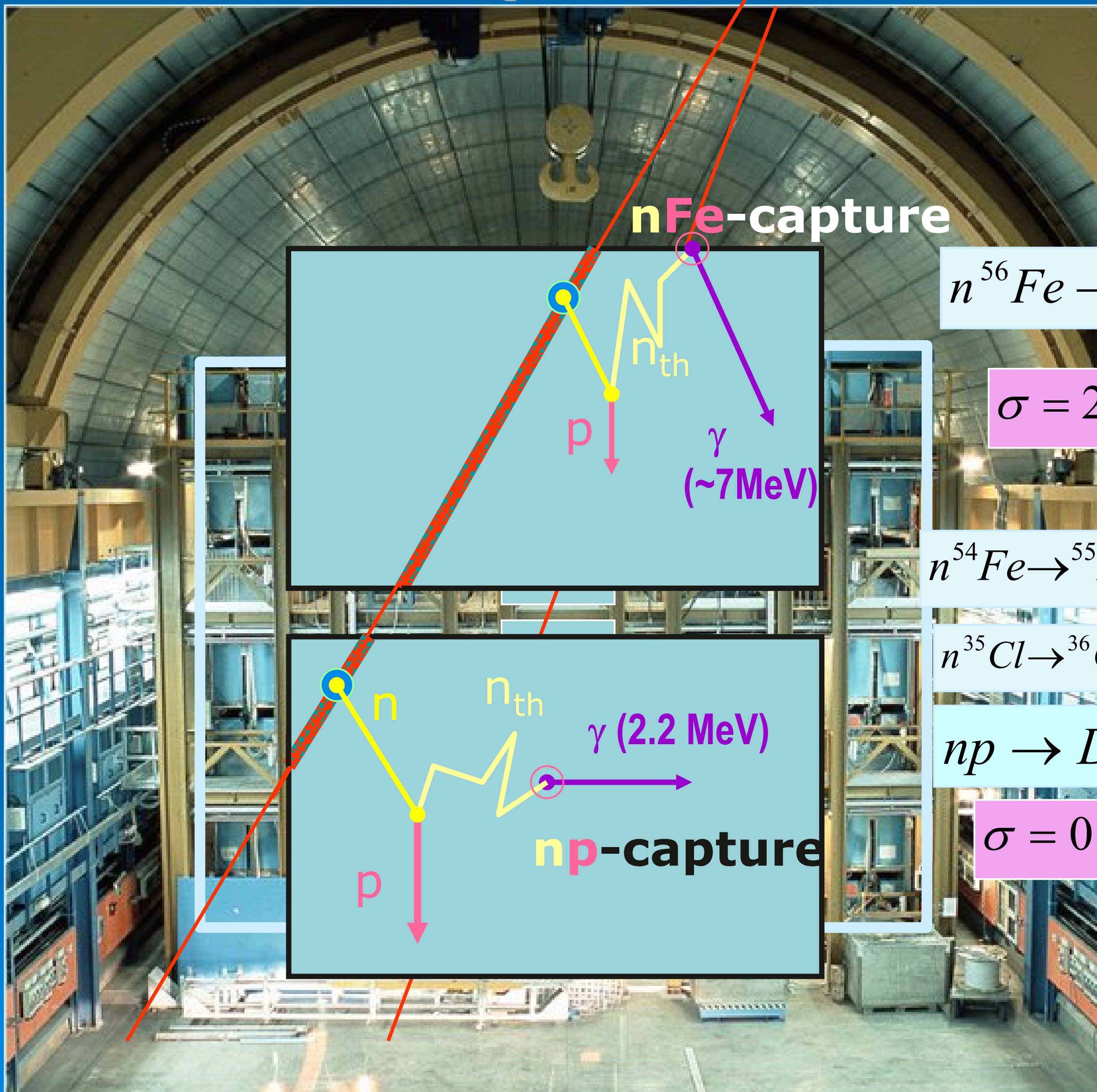
Counters along muon track



Counters out muon track



muon-produced neutrons



$$n\,^{56}Fe \to {}^{57}Fe^{*} \to {}^{57}Fe\ (k\gamma),\ 91.7\%$$

$\sigma = 2.55\ barn$ $\tau_{sc+Fe} \approx 130\ \mu s$

$$n\,^{54}Fe \to {}^{55}Fe^{*} \to {}^{55}Fe\ (\gamma),\ 5.8\%$$

$$n\,^{35}Cl \to {}^{36}Cl^{*} \to {}^{36}Cl\ (k\gamma),\ 75.8\%$$

$$np \to D^{*} \to D\gamma$$

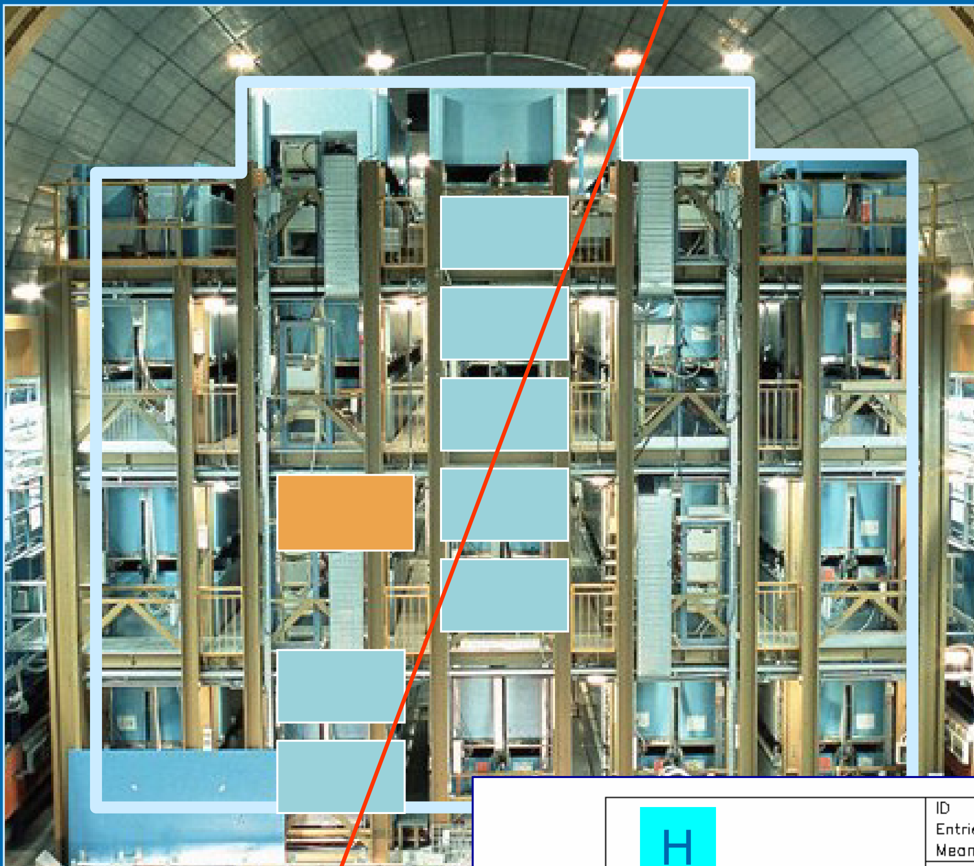
$\sigma = 0.334\ barn$ $\tau_{sc} = 185\ \mu s$

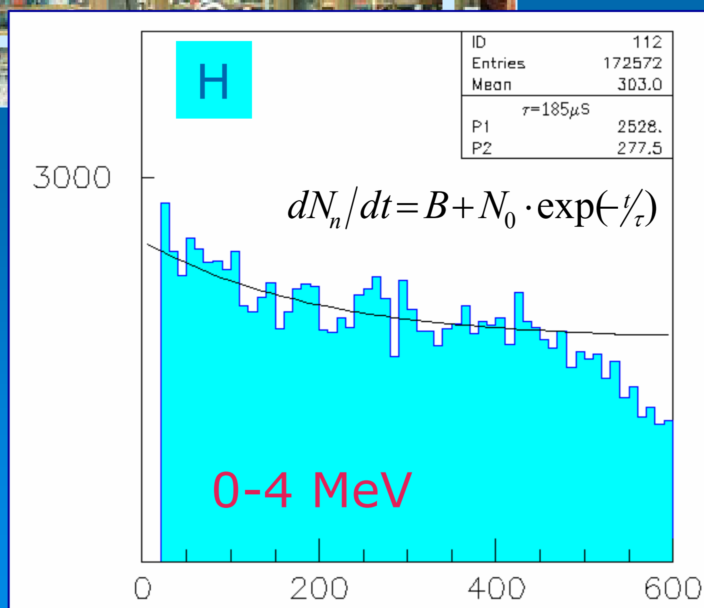
single muon

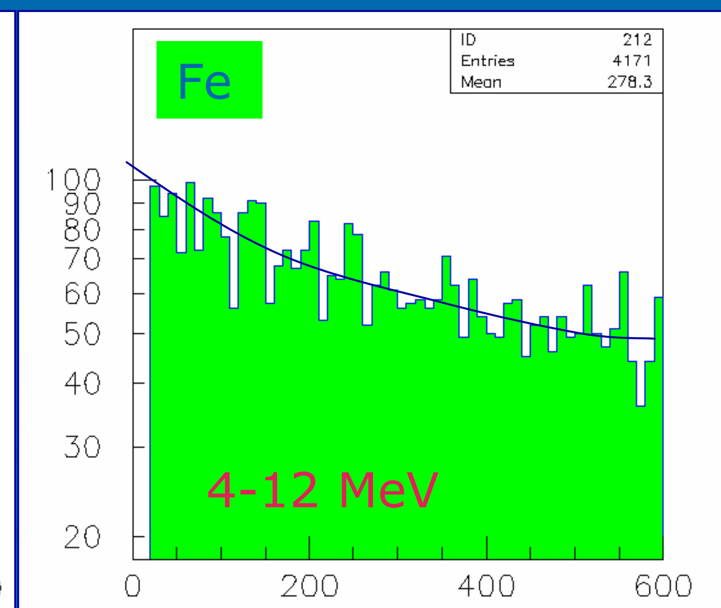
72294

Neutrons= 5133.7

843.4







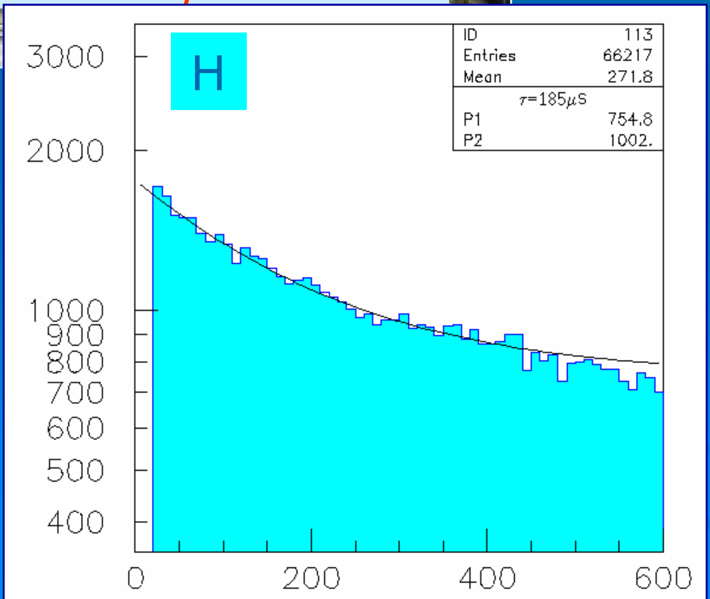
muon bundles

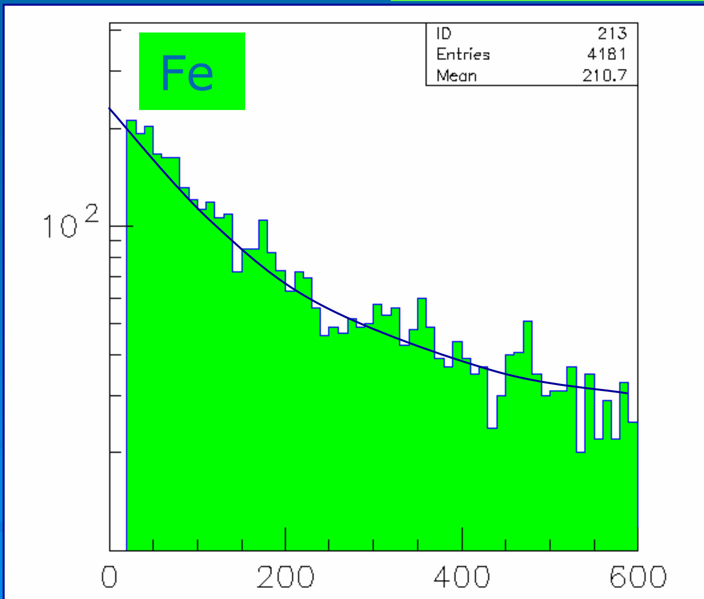
23502

Nμ=72294

Neutrons= 5949.6

908.2



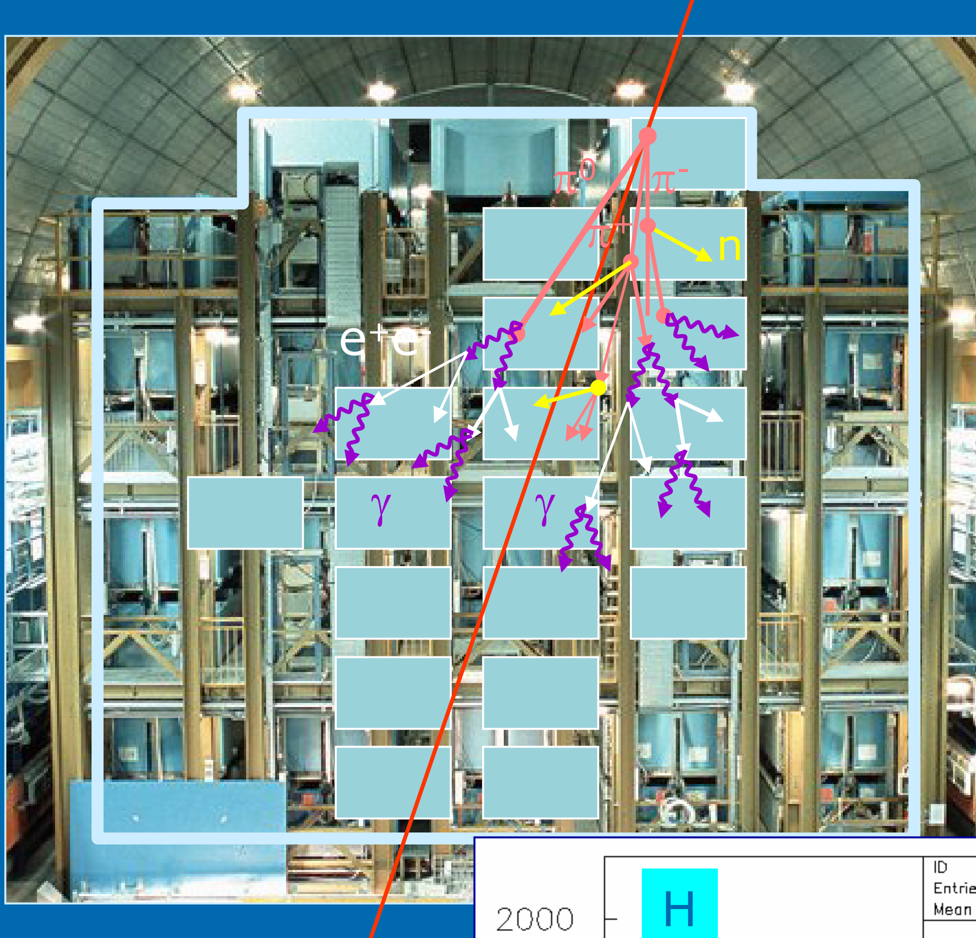


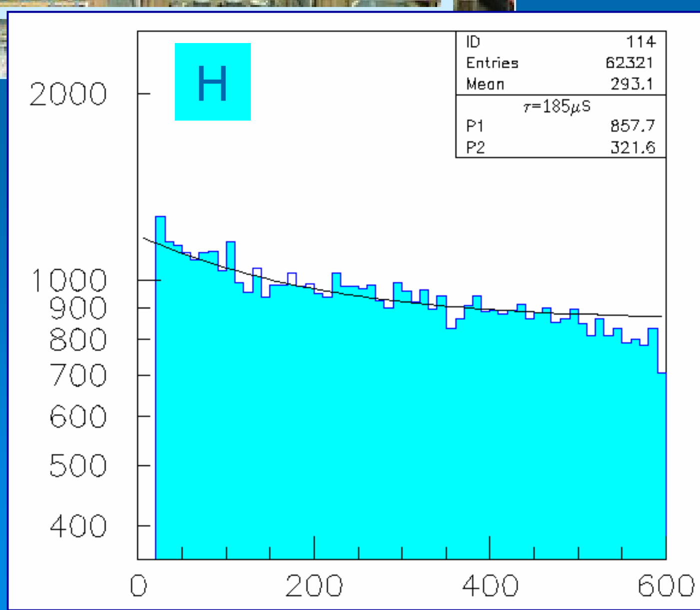
hadronic and electromagnetic cascades

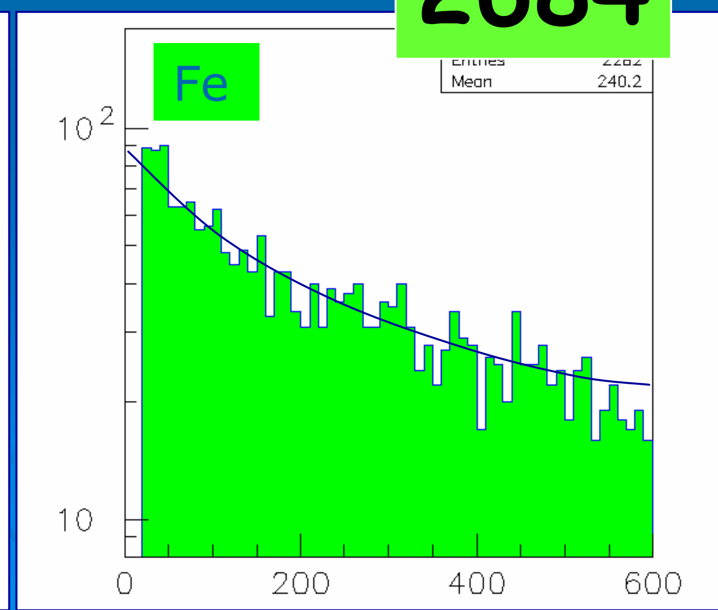
19603

Neutrons= 18537

2684







For determining the specific neutron yield number we used the formula:

$$< n >= N_n^{tot} \big/ < l_\mu > \cdot N_\mu^{ev}$$

the number of searched events

$$N_n^{tot} = N_n^{sc} + N_n^{Fe,Cl}$$

the average muon path length

$$< l_\mu >= L_\mu^{in} \cdot \overline{\rho}$$

total number of muon events both single muons and groups, and electromagnetic and hadronic cascades

$$N_\mu^{event}$$

$$< n > = 11 \cdot 10^{-4} \left(g \big/ cm^2 \right)^{-1}$$