Проблема нейтринного излучения от SN 1987A. Двадцать лет спустя.

Problems of Neutrino Radiation from SN 1987A 20 years later

О.Г. Ряжская

SN 1987A
23 February 1987

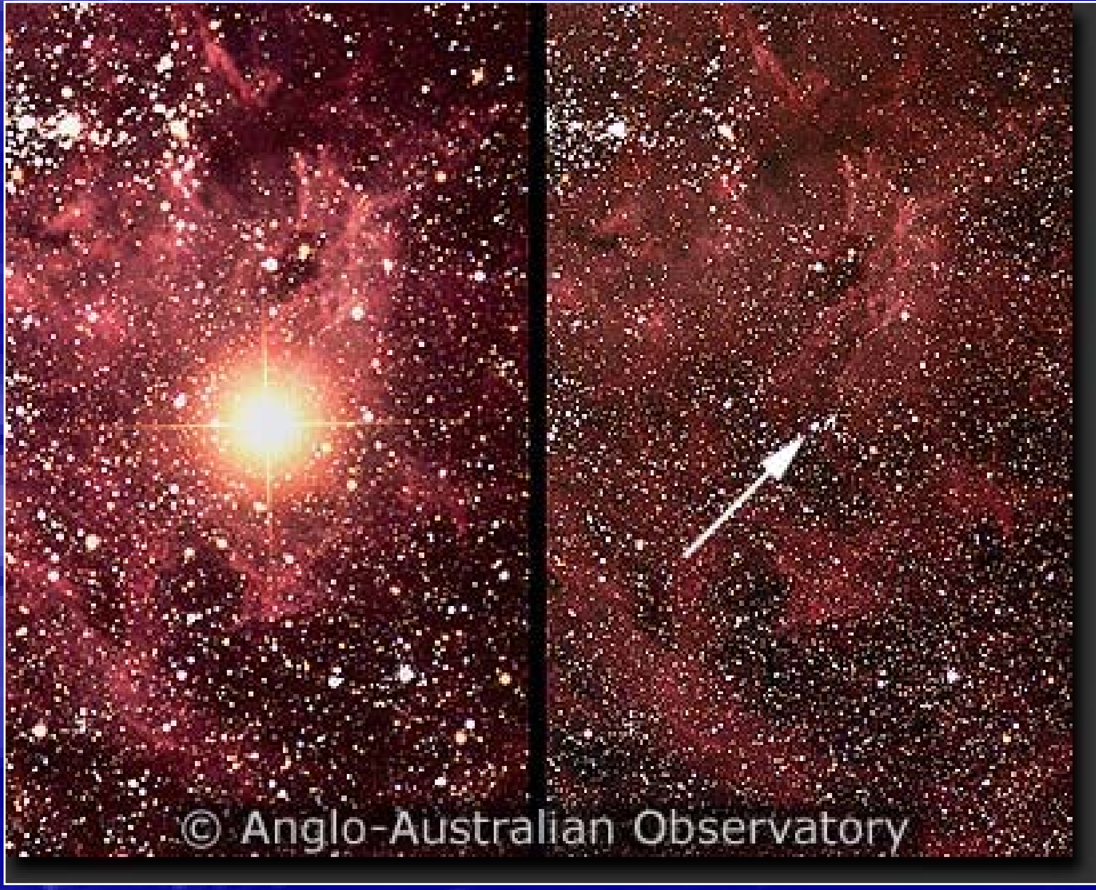
What was seen in underground neutrino detectors?

What were the questions on the neutrino detection at that time?

What are the answers on that now after 20 years?

Possible explanation of the results, obtained by underground detectors during Supernova SN1987A explosion.

The name "SN" came from the observational astronomy data and deals with an instant appearance of a very bright star, with luminosity of about tens billions of the solar one.



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

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

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

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

1941 *«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

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) at 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):

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

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

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

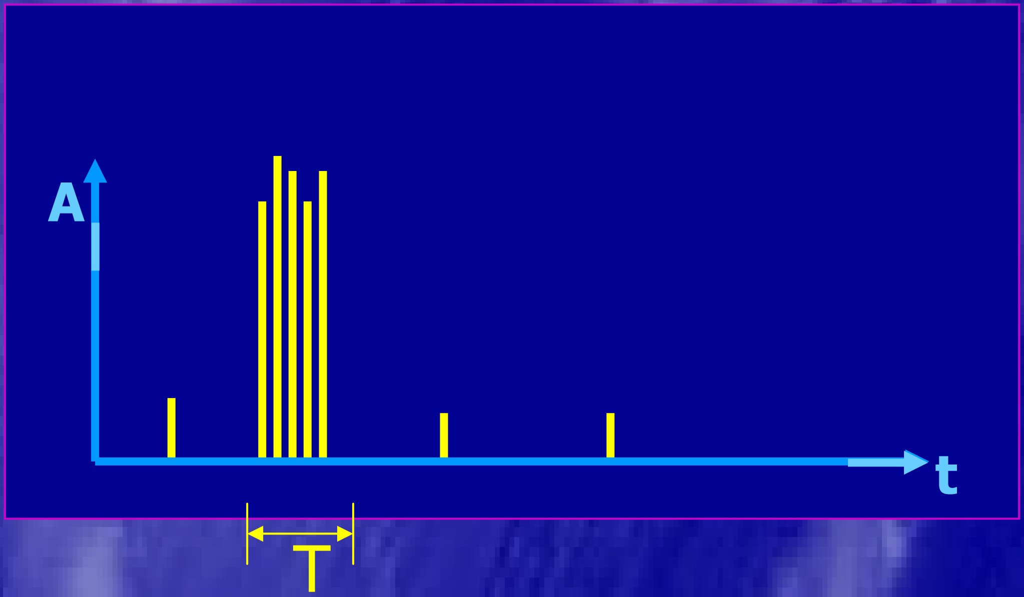
$$\sigma_{\tilde{\nu}_e p} \sim 9.3 E_{e^+}^2 \cdot 10^{-44} \, cм^2 \qquad E_{e^+} >> 0.5 \;\; MeV$$

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.

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

The specific signature of event

How can the neutrino burst be identified ?



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

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

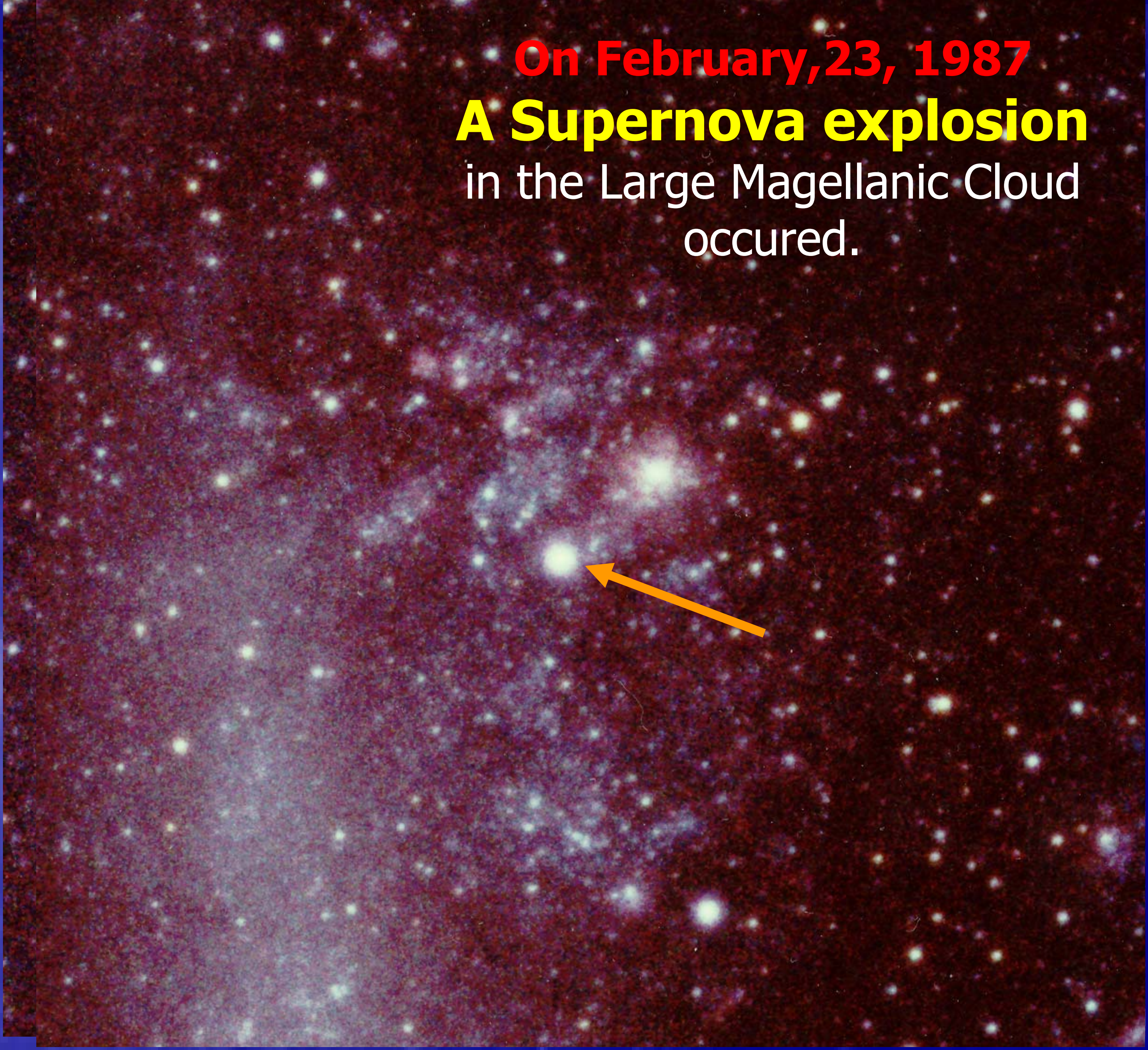
The possibility to observe the neutrino burst depends on background conditions

The source of background:

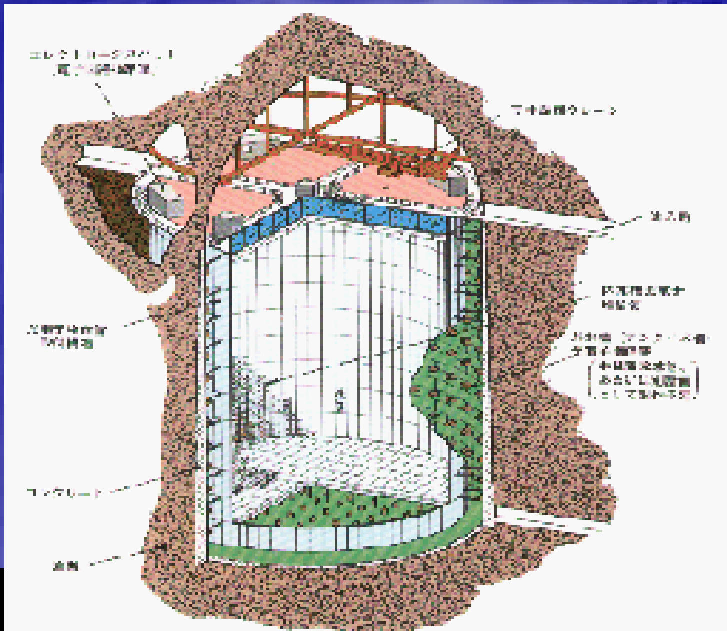
1. Cosmic rays $0<E<\infty$
   a) muons
   б) secondary particles generated by muons (e,γ,n and long-living isotopes)
   c) the products of reactions of nuclear and electromagnetic interactions
2. Natural radioactivity $E<30$ MeV, mainly $E<2.65$ MeV
   a) γ,
   b) n, (n γ), U^{238}, Th^{232}
   c) α,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

Background reduction:

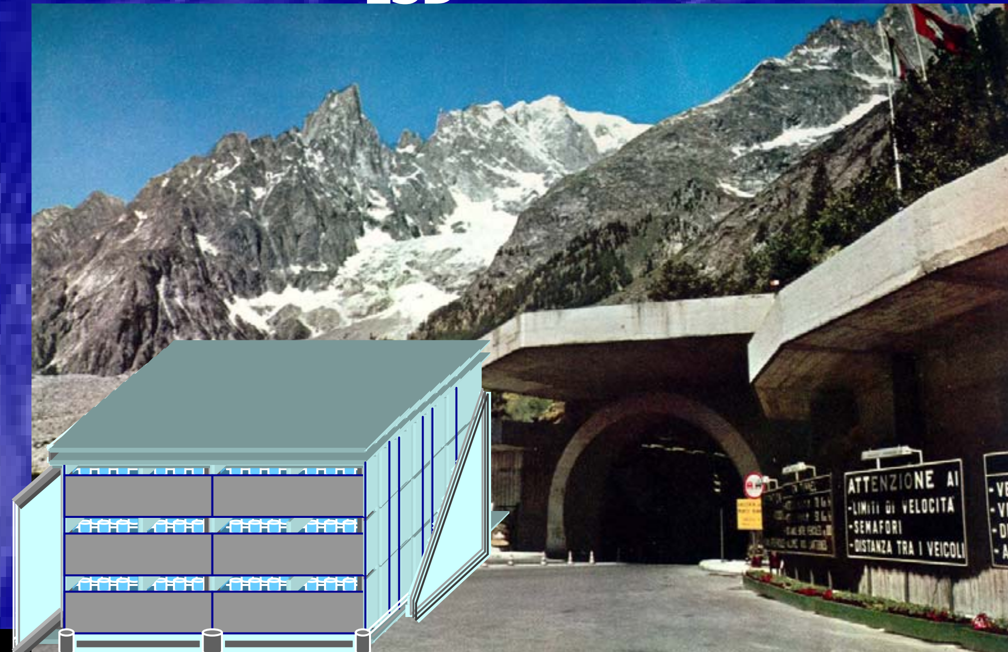
1. **Deep underground location**
2. **Using the low radioactivity materials**
3. **Anti-coincidence system**
4. **Using the reactions with good signature**
5. **The coincidence of signals in several detectors**

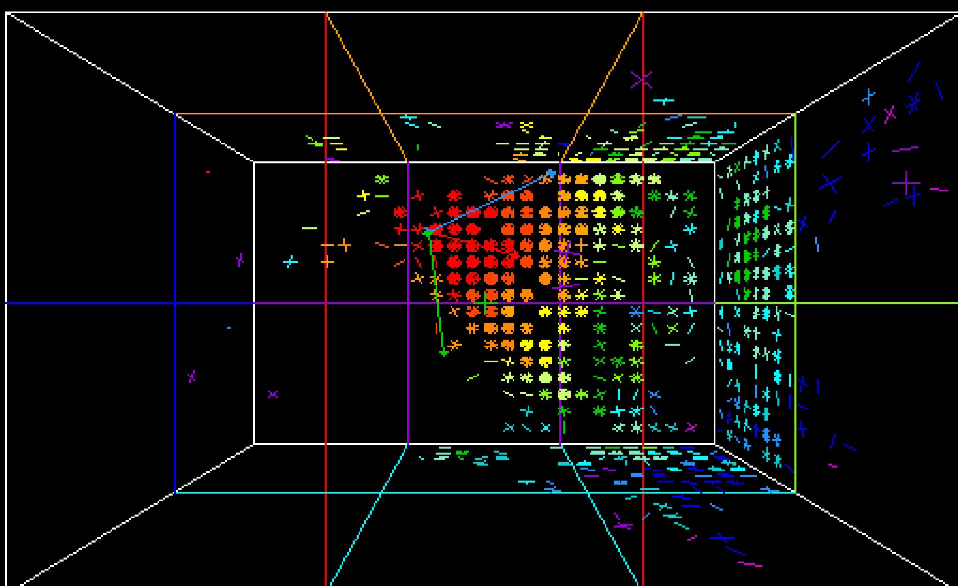

On February,23, 1987
A Supernova explosion
in the Large Magellanic Cloud
occured.

Kamiokande

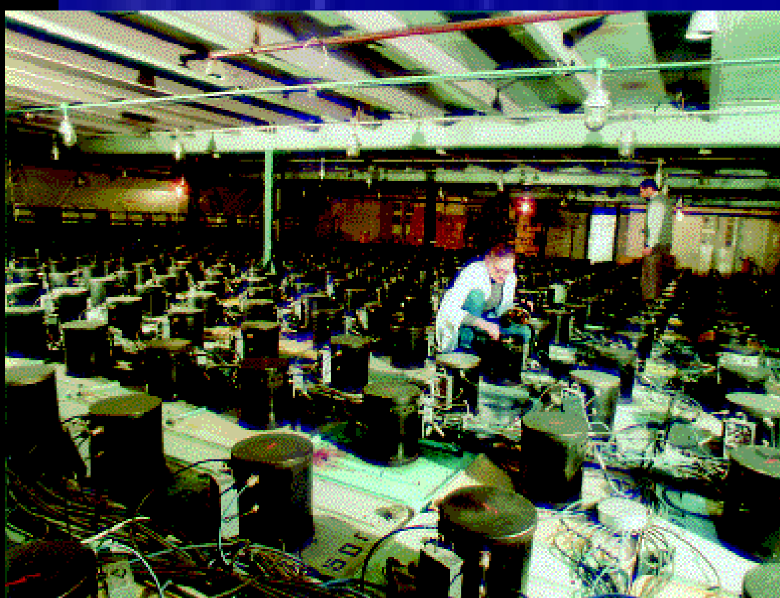


LSD





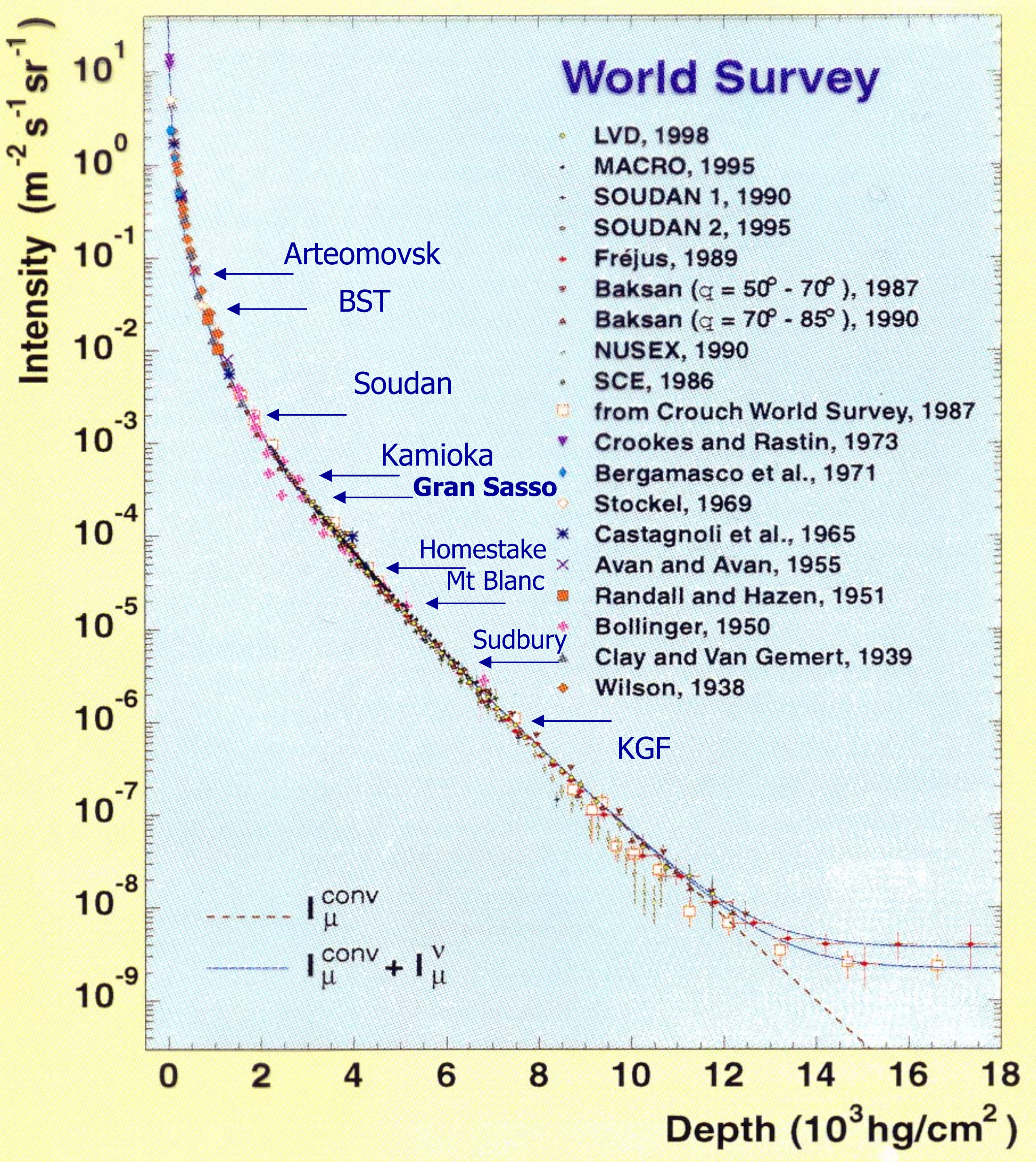
IMB

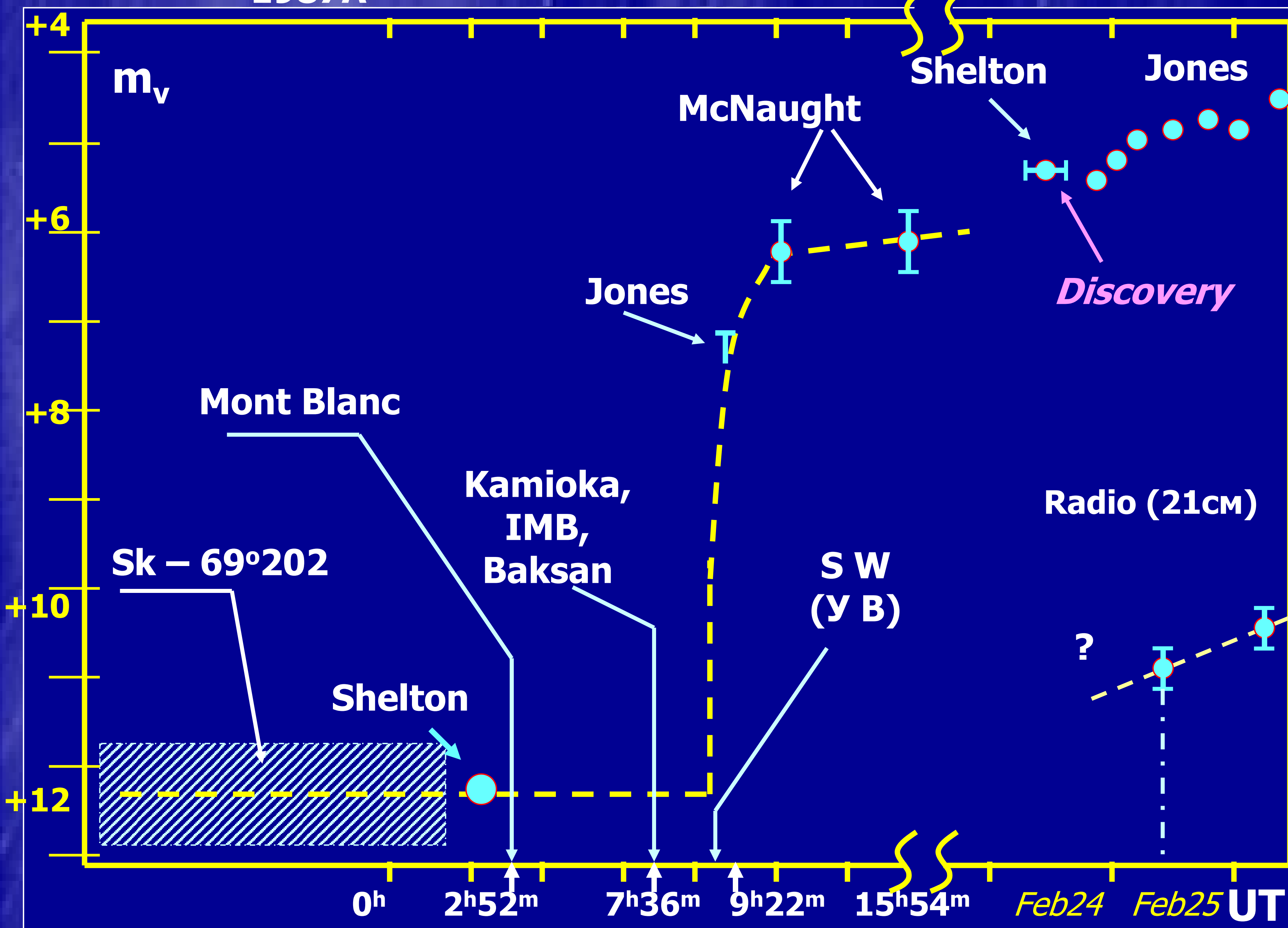


Баксан

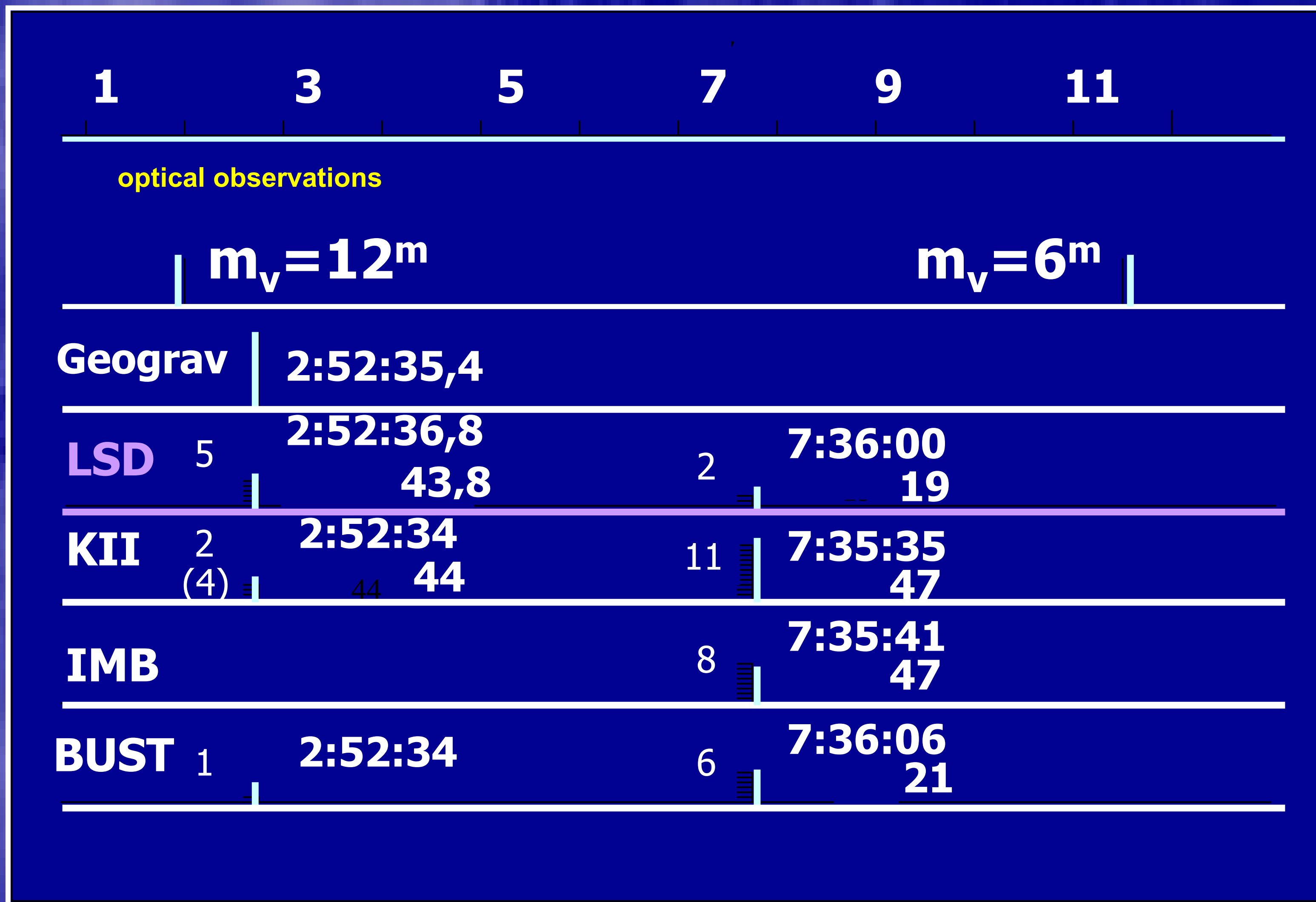
Detector	Depth, meters of water equivalent	Fiducial volume, tons	Material	Energy threshold, MeV	Detection efficiency		Background rate s^{-1}
					e^+ spectrum of reaction $\tilde{\nu}_e p \to e^+ n$	e^- spectrum of reaction $\nu_i e^- \to \nu_i e^-$	
BUST USSR	850	130 (200) 160	C_nH_{2n} Fe	10	0.6	0.15 (0.54)	0.013 (0.033)
LSD USSR – Italy	5200	90 200	C_nH_{2n} Fe	5-7	0.9	0.4(0.7)	0.01
KII Japan – USA	2700	2140	H_2O	7-14	0.7	0.17 (0.54)	0.022
IMB USA	1570	5000	H_2O	20-50	0.1	0.02 (0.18)	3.5×10^{-6}

The muon depth-intensity curve (underground data): curves are calculated by Bugaev et al., 1998




1987A
+4
+6
+8
+10
+12
m_v
McNaught
Shelton
Jones
Discovery
Jones
Mont Blanc
Kamioka,
IMB,
Baksan
Radio (21см)
Sk – 69°202
S W
(У В)
?
Shelton
0h
2h52m
7h36m
9h22m
15h54m
Feb24
Feb25
UT

February 23, 1987



The detector responses to the standard stellar collapse in the Large Magellanic Cloud

Detector	K_{e^+} (1)	K_{e^-} $(2a)+(2b)$	K_{e^-} $(2b)$
LSD	1.5	0.043	0.024
BUST	2	0.052	0.036
KII	17	0.53	0.36
IMB	6	0.4	0.35

$$\Phi_{\tilde{\nu}}(s^{-1}MeV^{-1}) \sim \frac{\varepsilon^2}{1+\varepsilon^2} e^{-\alpha\varepsilon^2} \quad (\varepsilon = \frac{E_{\tilde{\nu}}}{kT})$$

if $kT \sim 2MeV$

kT, MeV	α	$W_{\tilde{\nu}_e} \cdot 10^{54}$, эрг	k_i			
			LSD	BUST	KII	IMB
1.7	0.1	2.1±1.0	5	0.2	5±2.5	0
2.1	0.1	1.8±0.8	5	0.5	12±6	0

The total energy of neutrino radiation from SN1987A is more than an order of magnitude higher than the binding energy of neutron star with a baryon mass of about $2M_\odot$

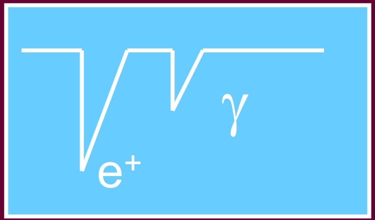
$$E_{tot} = 6W_{\tilde{\nu}_e} \approx (1 \div 2) \cdot 10^{55} erg$$

Spherically symmetrical model

$\tilde{\nu}_e$ – detection → LSD - 5; KII - 50 (4?)

LSD event is not similar to $\tilde{\nu}p$ -detection

$\rightarrow e^+ + n$

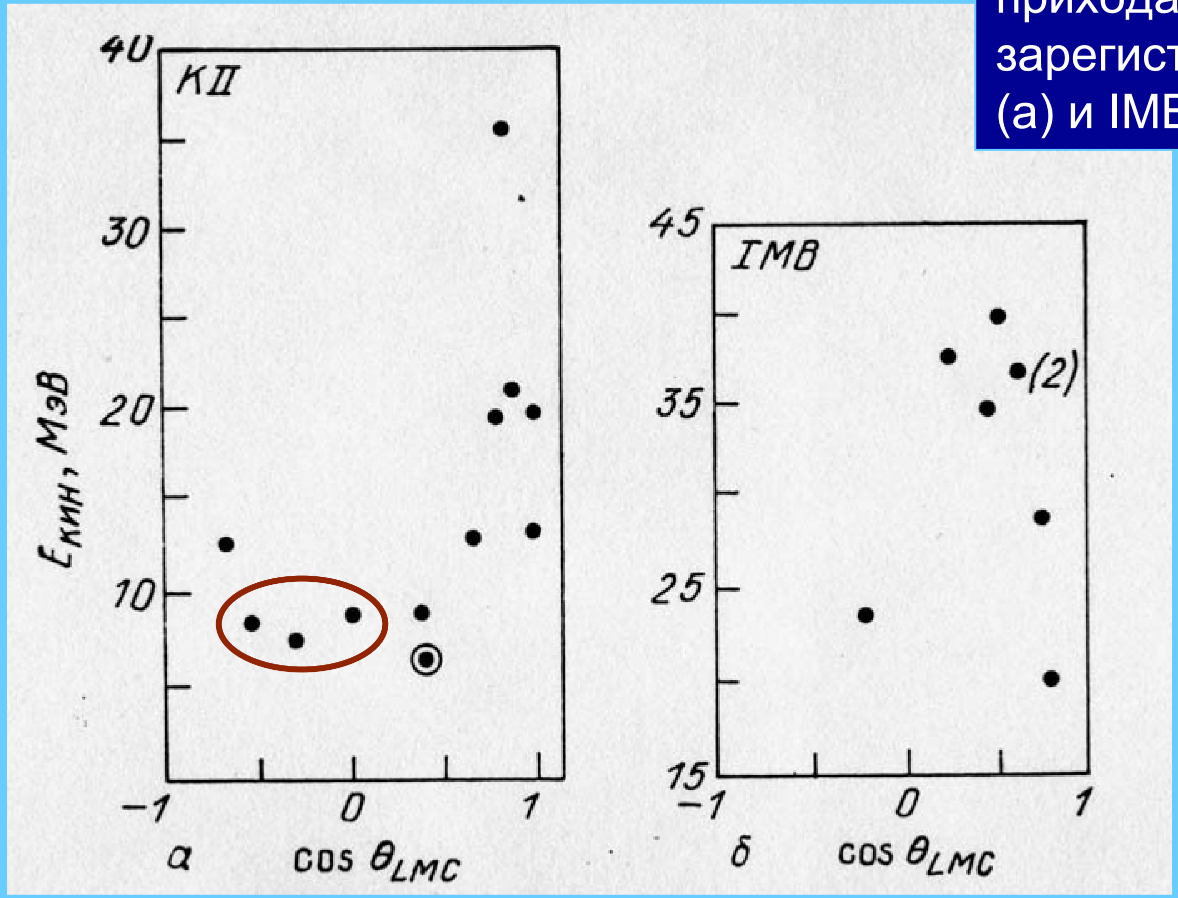


$$n + p \rightarrow d + \gamma \qquad \tau \sim 180\mu s$$

Only 1 trigger has small pulse with $\Delta t = 278\ \mu sec$

1. 2 years of observations N (≥5 pulses, deltaT ≤7s) = 0
2. Coincidence with SN < 1 per 1000 years
3. Distribution of pulses is uniform
4. Noises in the low energy channel (E>0.5 MeV) are absent
5. Counting rate of high energy pulses (E>25 MeV) is normal

The LSD event is not due to fluctuations.



Связь между энергией E и углом прихода для частиц зарегистрированных детекторами KII (а) и IMB (б)

Dadykin V.L., Zatsepin G.T., R.O.G., 1989, UFN

Correspondence between energy E and angle to SN1987A for pulses detected by KII and IMB

The possible solution is :

A rotating collapsar

The short review of the rotational mechanism:

On the threshold of gravitational collapse the Fe-O-C stellar core

M_t – total mass, I_0 – total angular momentum

are conserved

during the collapse of the core into a rotating collapsar

The collapsar with the high probability falls into the region of the dynamical instability.

The criterion:

$$\beta = \varepsilon_{rot} / |\varepsilon_{grav}| \geq 0.27$$

ε_{rot} – Total rotational energy

$|\varepsilon_{grav}|$ – Total gravitational energy

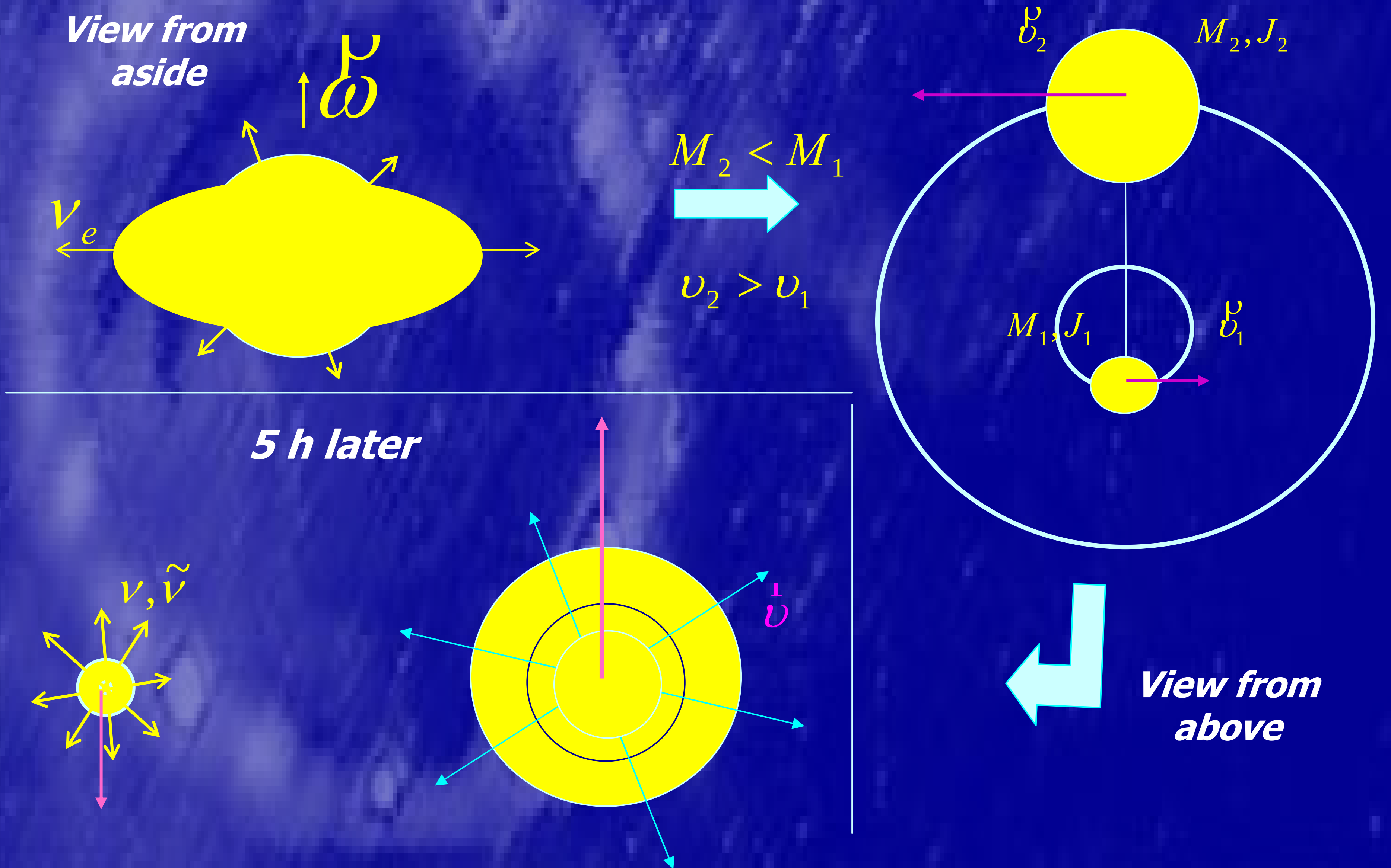
During the collapse ε_{rot} increases greatly compared to $|\varepsilon_{grav}|$, which is also an increasing quantity

This instability grows with the characteristic hydrodynamic time and leads to the breakup of the collapsar into pieces.

A rotating collapsar

The Two-Stage Gravitational Collapse Model

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



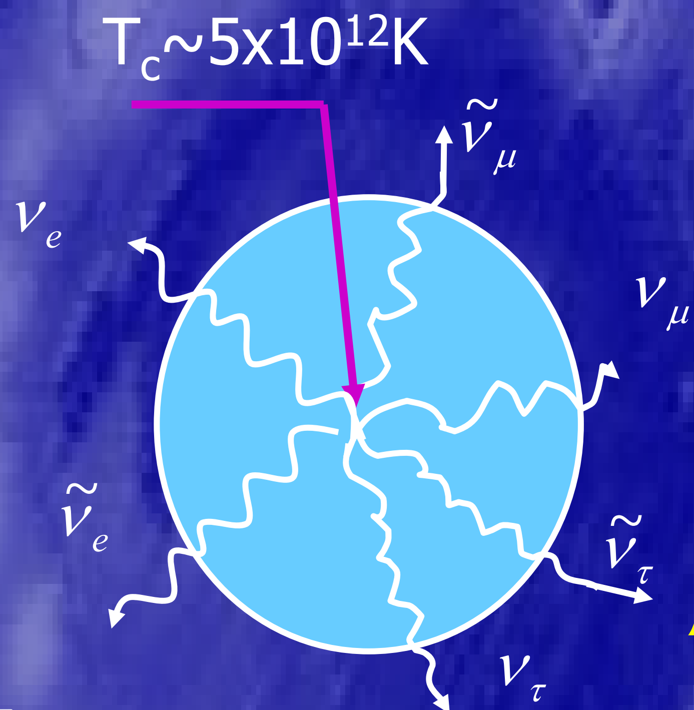
The rotation effects make it possible:

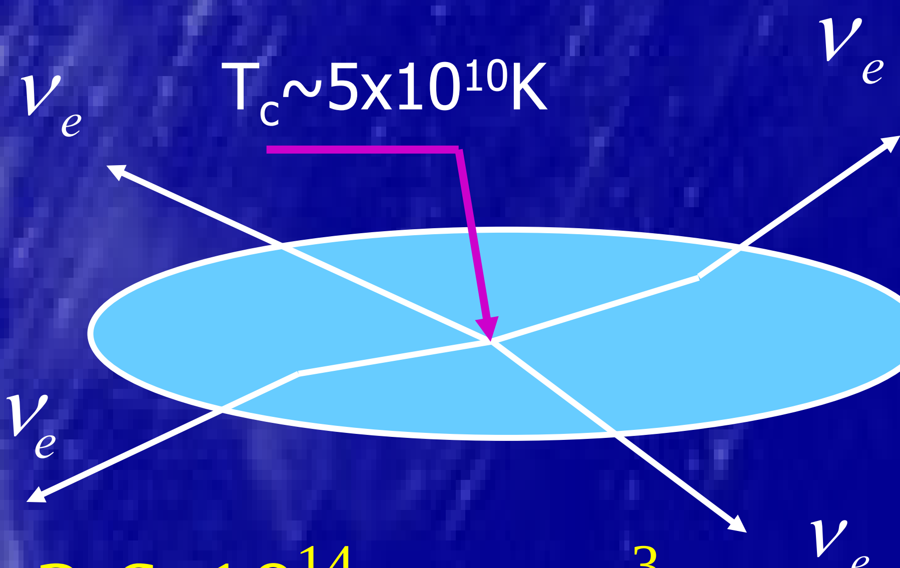
1. To resolve the problem of the transformation of collapse into an explosion for high-mass and collapsing supernovae (all types of SN, except the type Ia – thermonuclear SN)

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.

Imshennik V.S., R.O.G., 2004





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

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

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

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

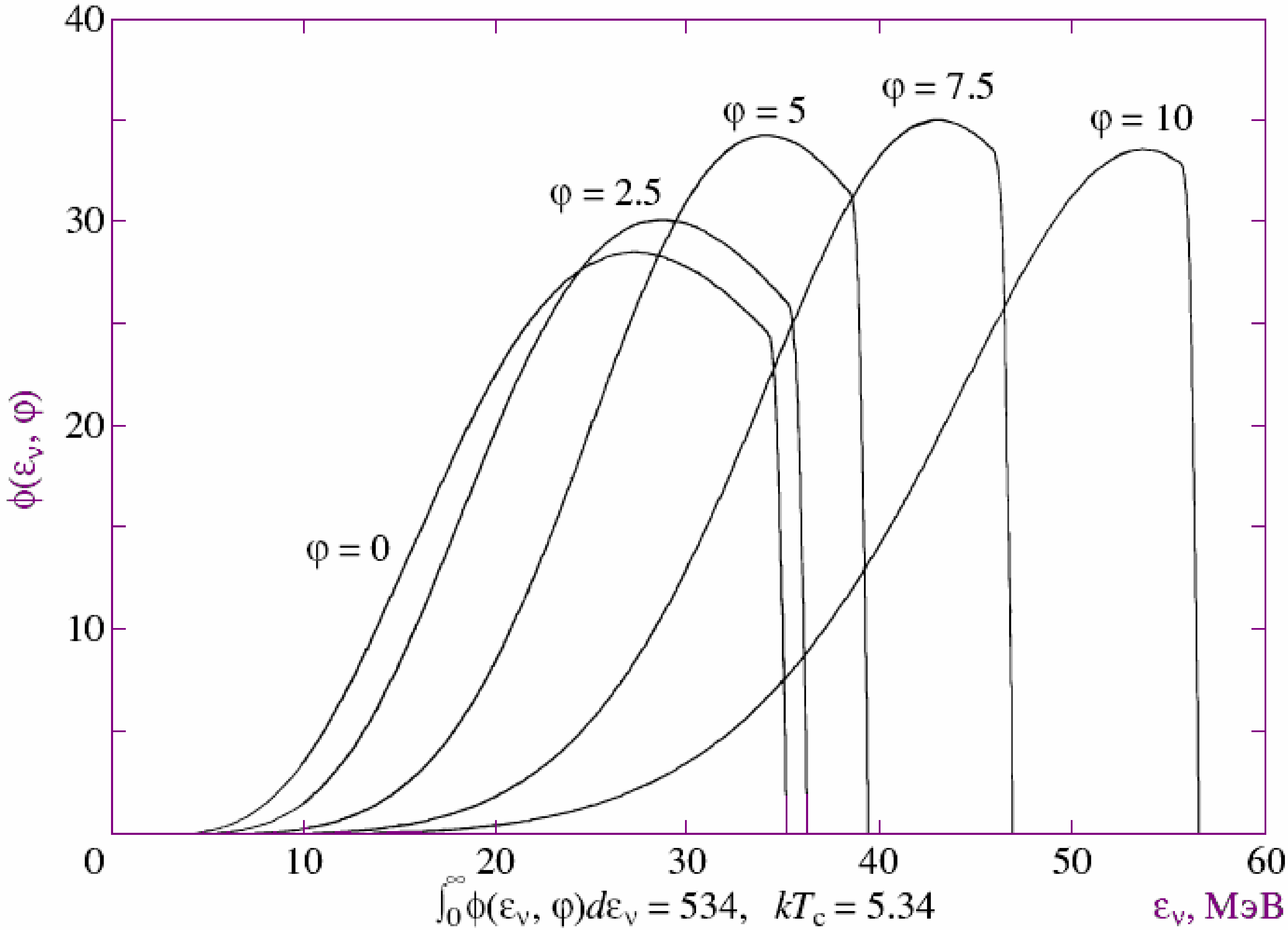
$$\varepsilon_{\nu, \tilde{\nu}} = 5.3 \cdot 10^{53} erg$$

The main reaction:

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

$$\overline{E}_\nu = (30 - 55) MeV$$

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

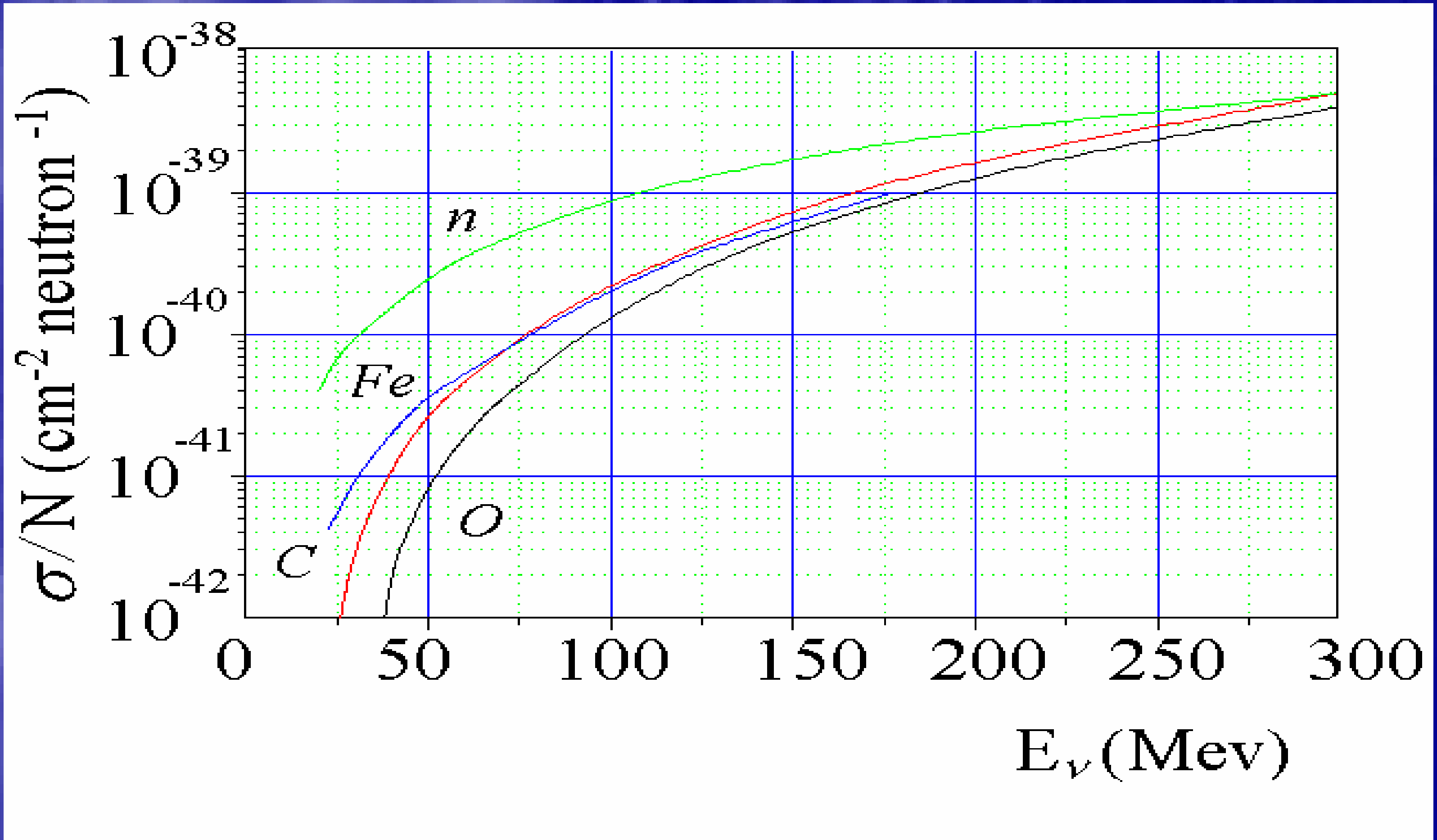


0
10
20
30
40
50
60
10
20
30
40
φ(ε_ν, φ)
φ = 0
φ = 2.5
φ = 5
φ = 7.5
φ = 10
$\int_0^\infty \phi(\varepsilon_\nu, \varphi) d\varepsilon_\nu = 534, \quad kT_c = 5.34$
ε_ν, МэВ

Let us consider how the various detectors operated during the explosion of SN1987A could record the neutrino signals in terms of the model of a rotating collapsar, which reduces to the following:

1. Two neutrino bursts separated by a time t_{grav}~5 h must exist.
2. The neutrino flux during the first burst consists of electron neutrino with a total energy of 8.9×10^{52} erg: the neutrino energy spectrum is hard and asymmetric with mean energies in the range of 25-50 MeV; the duration of the neutrino radiation is t ~ 2.4 - 6 s.
3. The second neutrino burst corresponds to the theory of standard collapse.

Bugaev E.V., Bisnovaty-Kogan G.S. et al., 1979

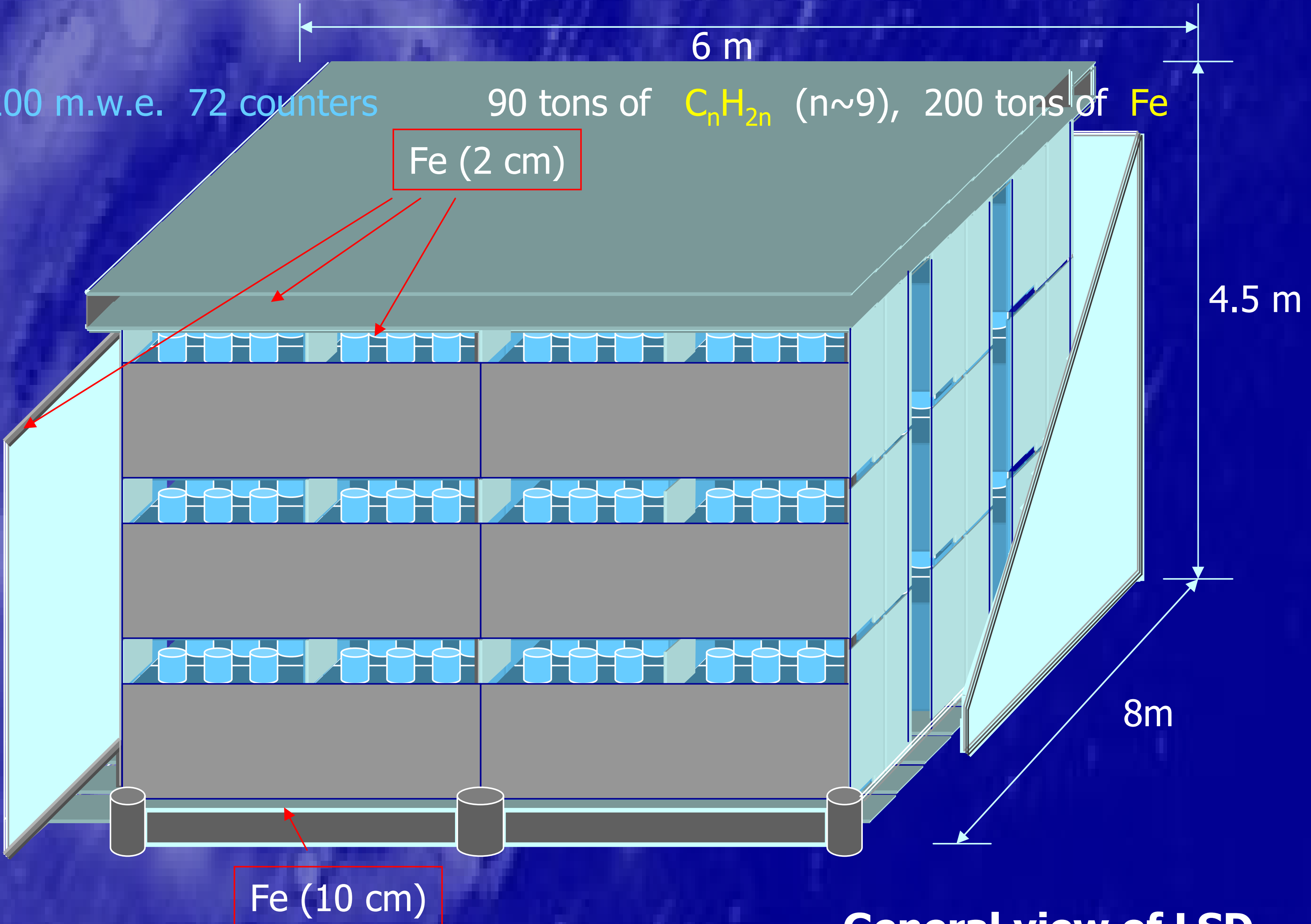


The comparison of the total reduced cross-sections with νn cross-section on a free neutron for the reaction

$$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)^*$$

Liquid Scintillator Detector (LSD)

H=5200 m.w.e. 72 counters   90 tons of C_nH_{2n} (n~9), 200 tons of Fe



General view of LSD

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	2-4*
BUST	10	2.8	5.2			~1	1**

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

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

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

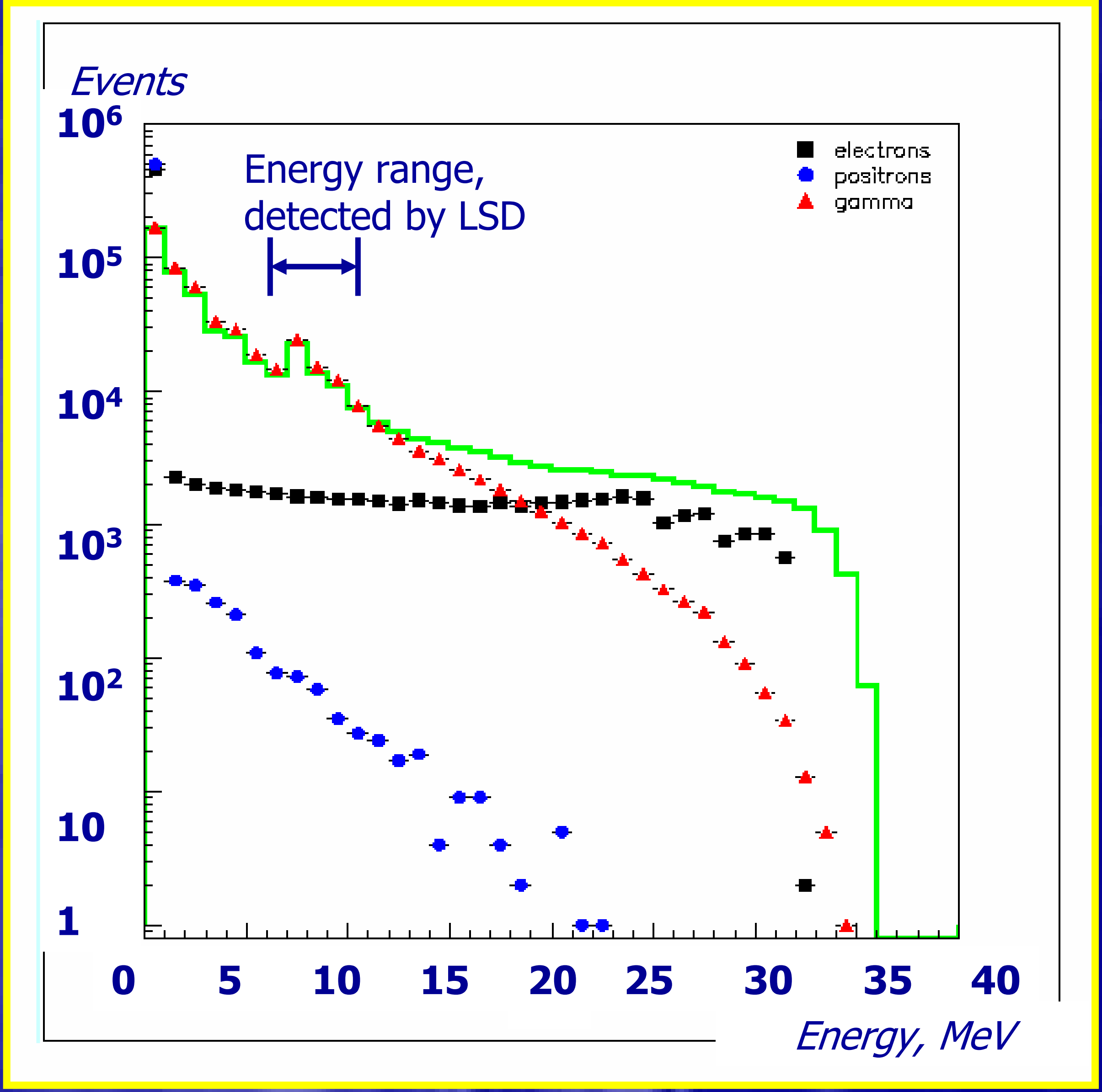
$$\varphi = \frac{\mu_e}{kT}$$

$$kT_c = 5.34 \ \ MeV$$

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

* De Rujula, 1987

** Alexeyev, 1987



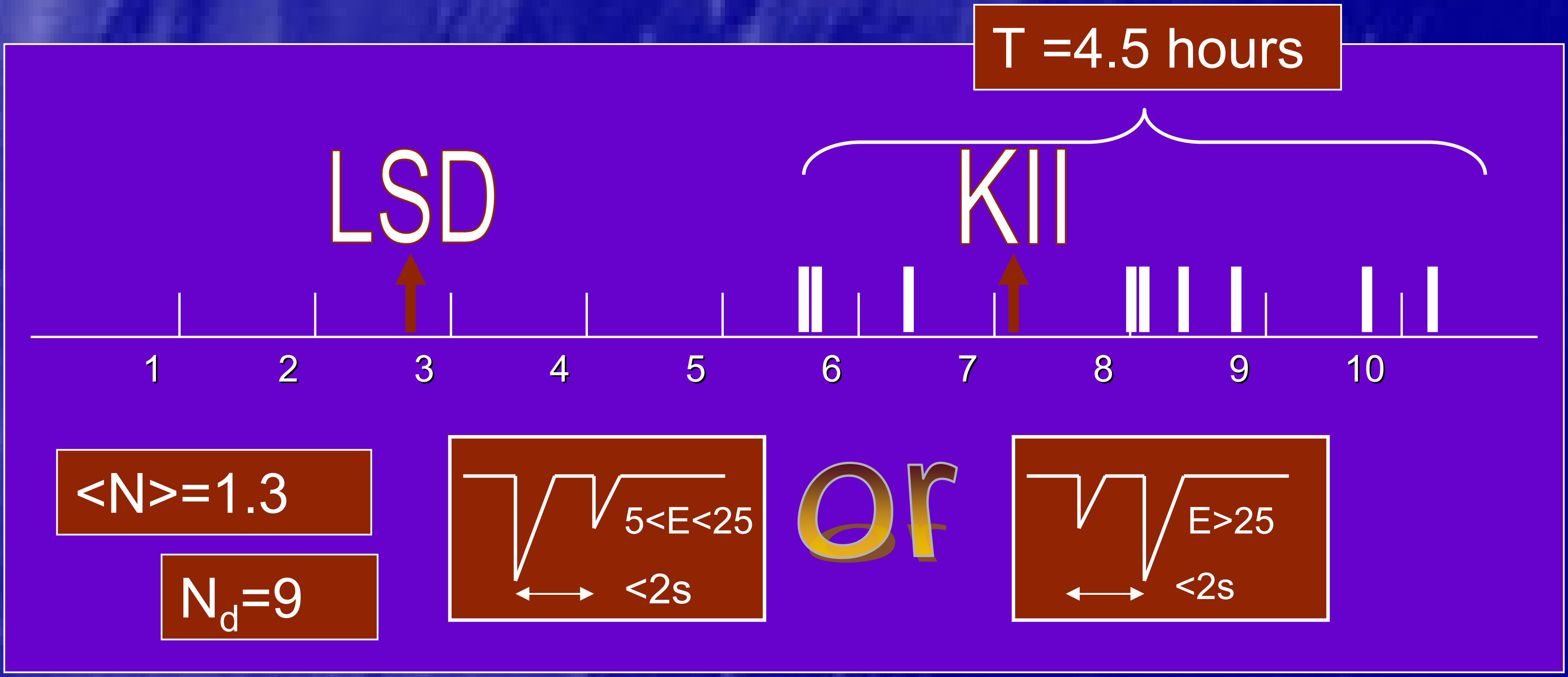
Energy spectrum of the particles, coming from 2,8 cm iron plate

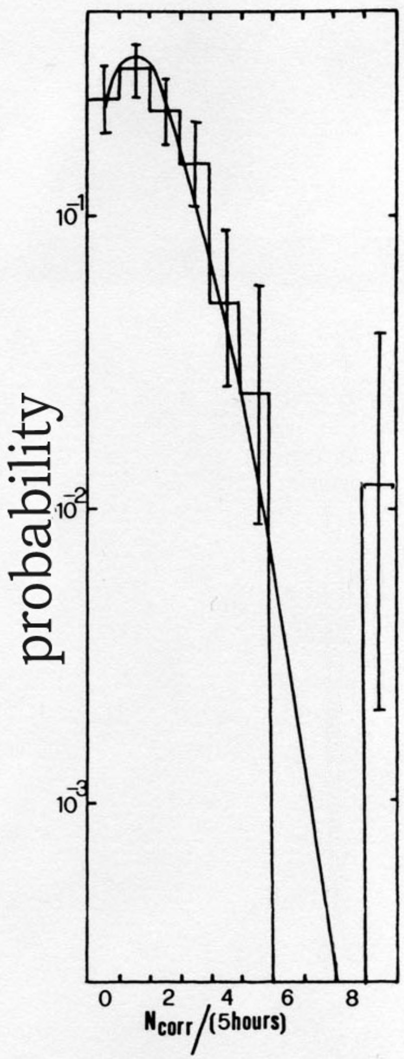
(Geant4 calculations; histogram – total energy deposit)

V. Boyarkin, 2004

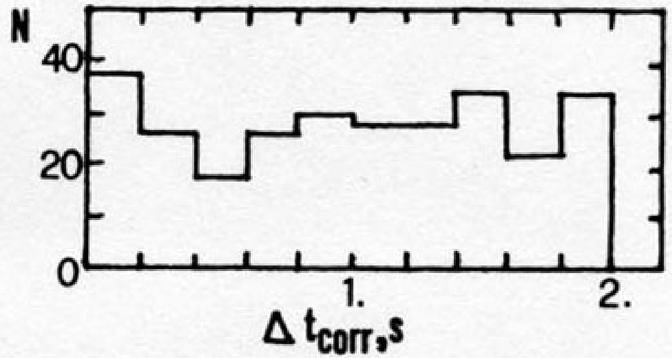
KII

№	Time UT±1min	E, MeV	Theta, degree
1	2:52:34	5.3	59
2	37	5.8	47
3	40	11.4	15
4	2:52:44	4.8	130

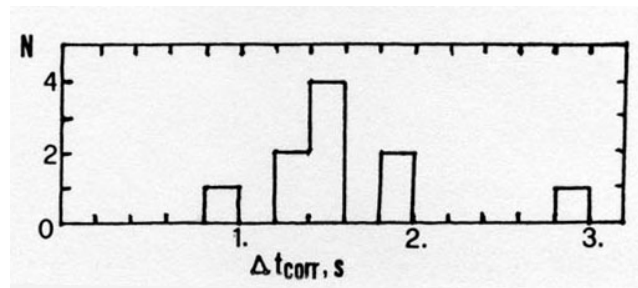




The probability distribution of the counting rate of pairs of correlated pulses per 5 hours and the poissonian fit to this distribution; $<n_{corr}>=1.46/(5$ hours), $\Delta T=2$ s



The distribution of time differences between the pulses in the pairs ($\Delta t=2$ s) for the whole data set excluding the interval of interest



For 10 pairs ($\Delta t=3$ s) from 5:42 UT to

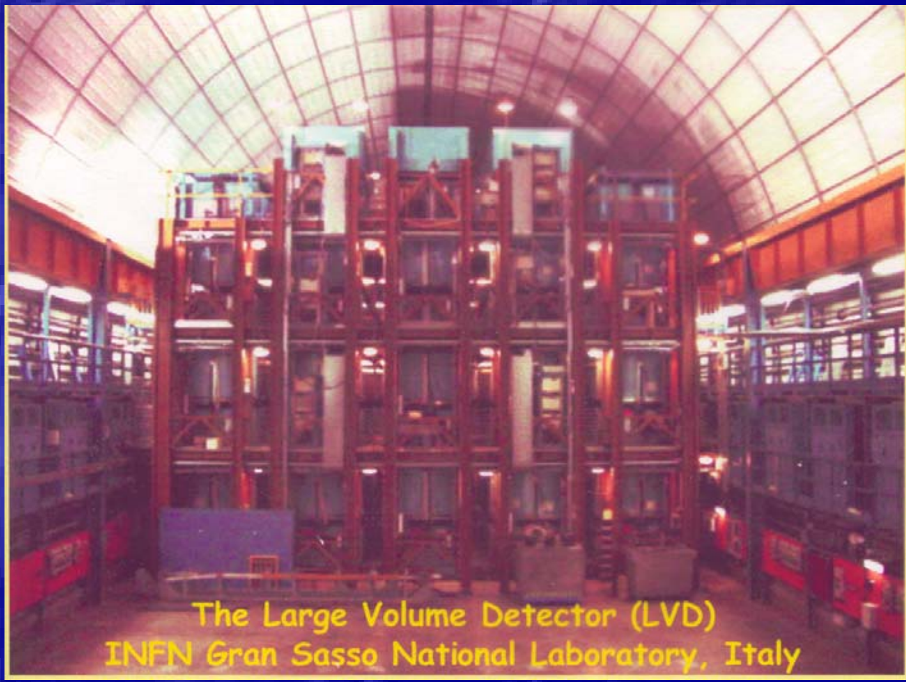
9 pairs ($\Delta t=2$ s)

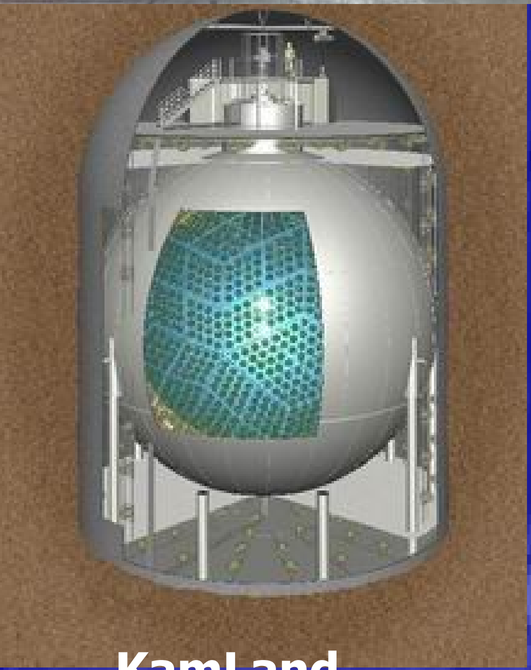
10:13UT on February 23, 1987 .

NEUTRINO DETECTORS

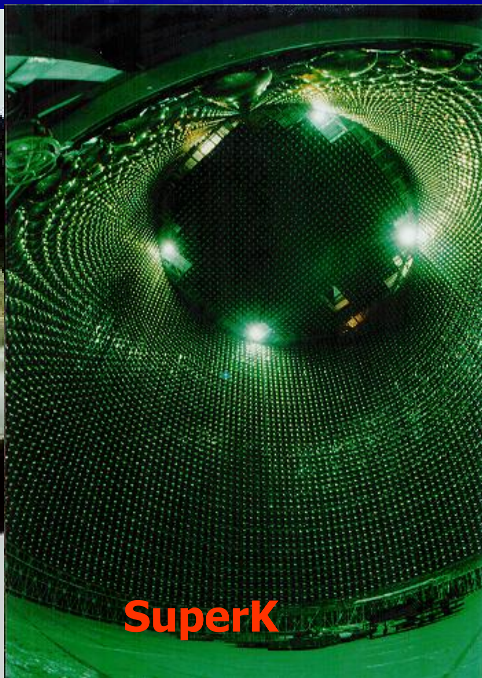
SNO

LVD





KamLand



C_nH_{2n} H_2O Reactions for scintillation and Cherenkov counters

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

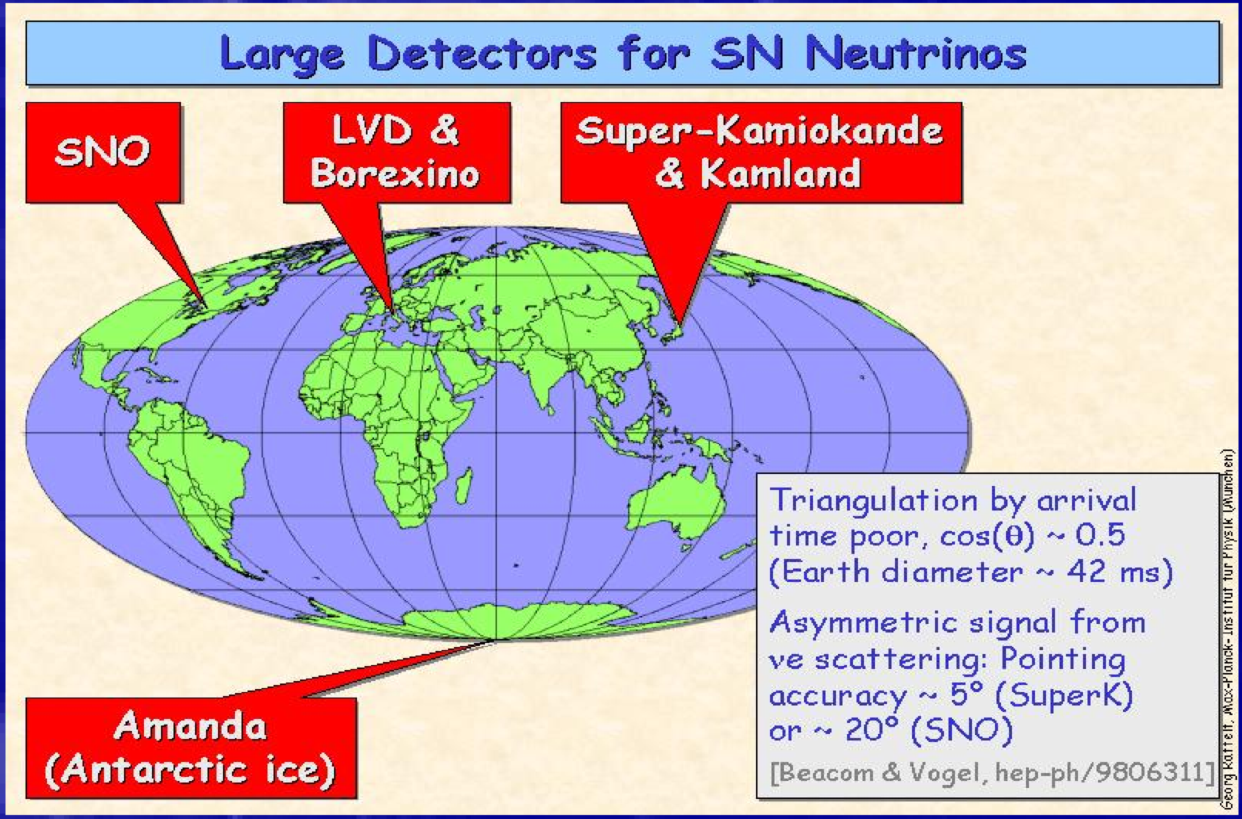
Detector	Depth m.w.e	Mass, ktons	Threshold, MeV	Efficiency			Number of events			Background s^{-1}
				η_{e^+}	η_n	η_γ	$\tilde{\nu}_e p$ $\tilde{\nu}_e D + \nu_e D$	$\nu_e A$	$\nu_e C$	
Arteomovsk **ASD** Russia	570	0.1 C_nH_{2n}	5	0.97	0.8	0.85	57		19* 9**	0.16
Baksan **BUST** Russia	850	0.13 (0.2) C_nH_{2n}	10	0.6	-	0.2	45 (67)		5*(8) 3**(4)	0.013 (0.033)
KamLAND USA Japan	2700	1. C_nH_{2n}	~ 4				500		180* 80**	
Gran Sasso **LVD** Italy,Russia	3300	0.95 Fe 1. C_nH_{2n}	4 – 6	0.9	0.6	0.55	500	250* 100**	110* 50**	< 0.1
Kamioka **Super-K** Japan,USA	2700	22.5 H_2O	5.5	0.9	-	-	9400	650* <160**		
SNO Canada	6000	1 D_2O	5				700	600* 350**		

* - E=40 MeV
** - E=30 MeV

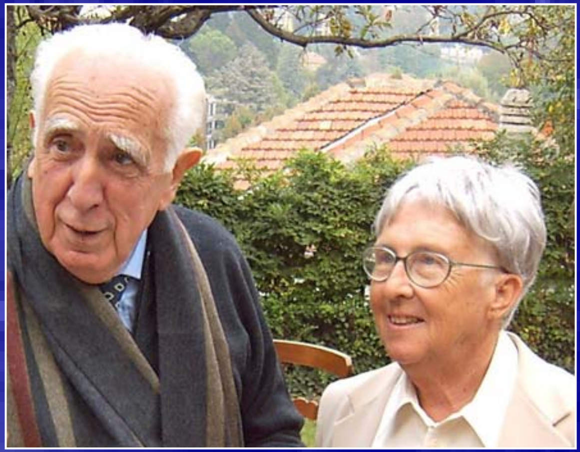
The search for neutrino bursts from collapsing stars was started ~ 29.5 years ago.

Upper limit of collapse rate in Galaxy is less than 12 years at 90% confidence level

Collapse (Arteomovsk, 1977 - now),
BUST (1978 - now),
LSD (1984 - 1999),
LVD (1991 - now).



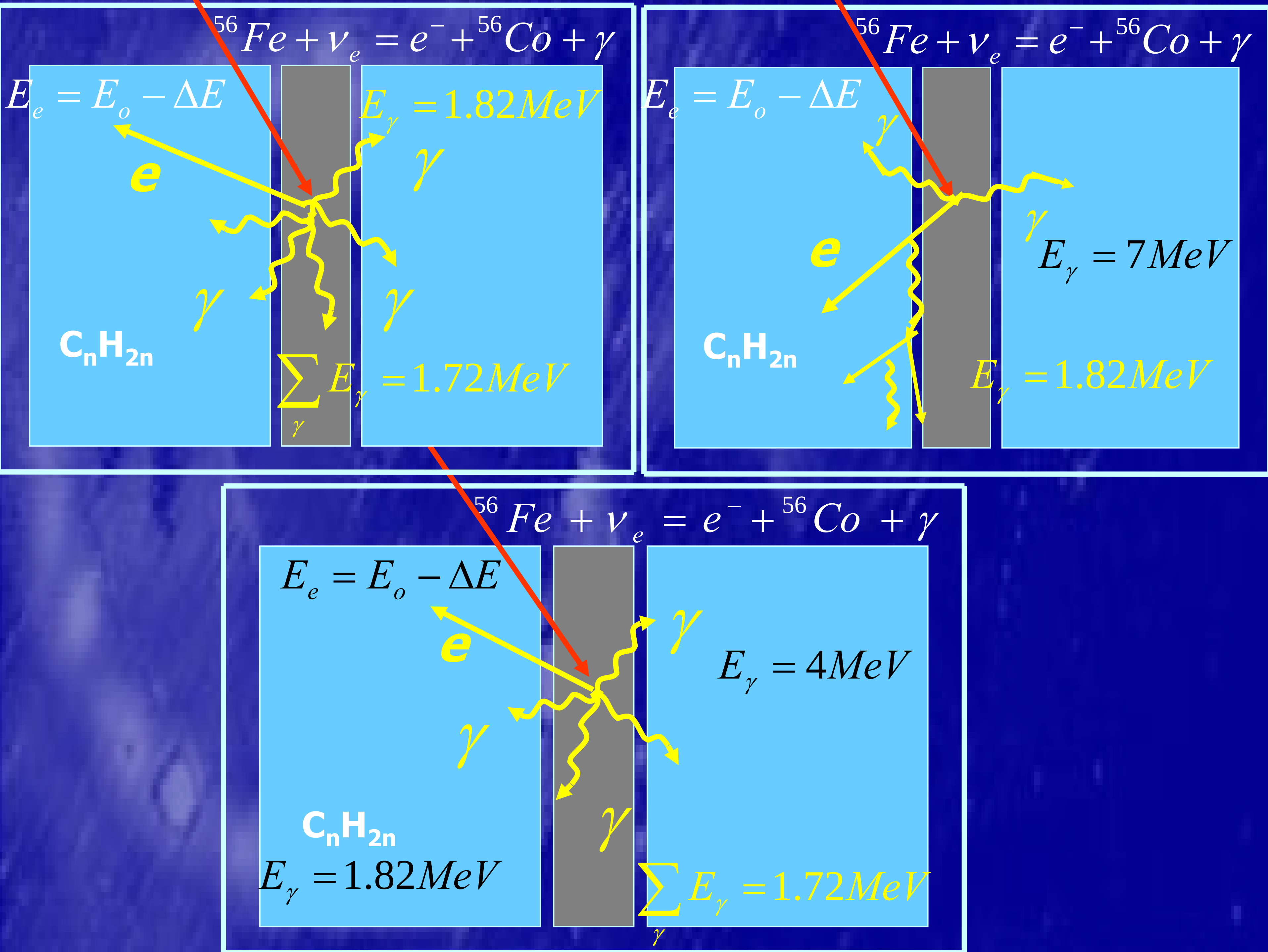

We are waiting for
SN's . . . .



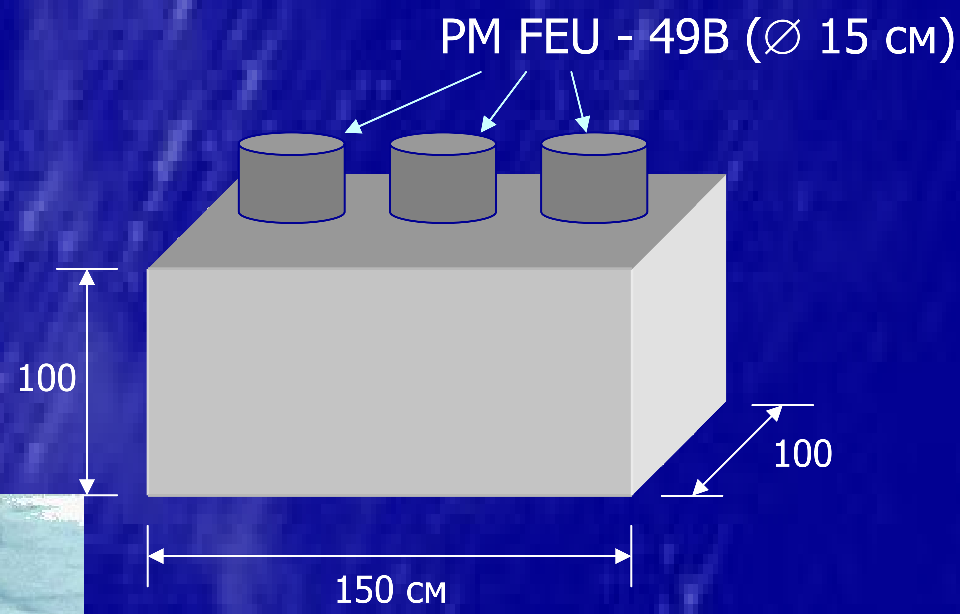
Cari amici!

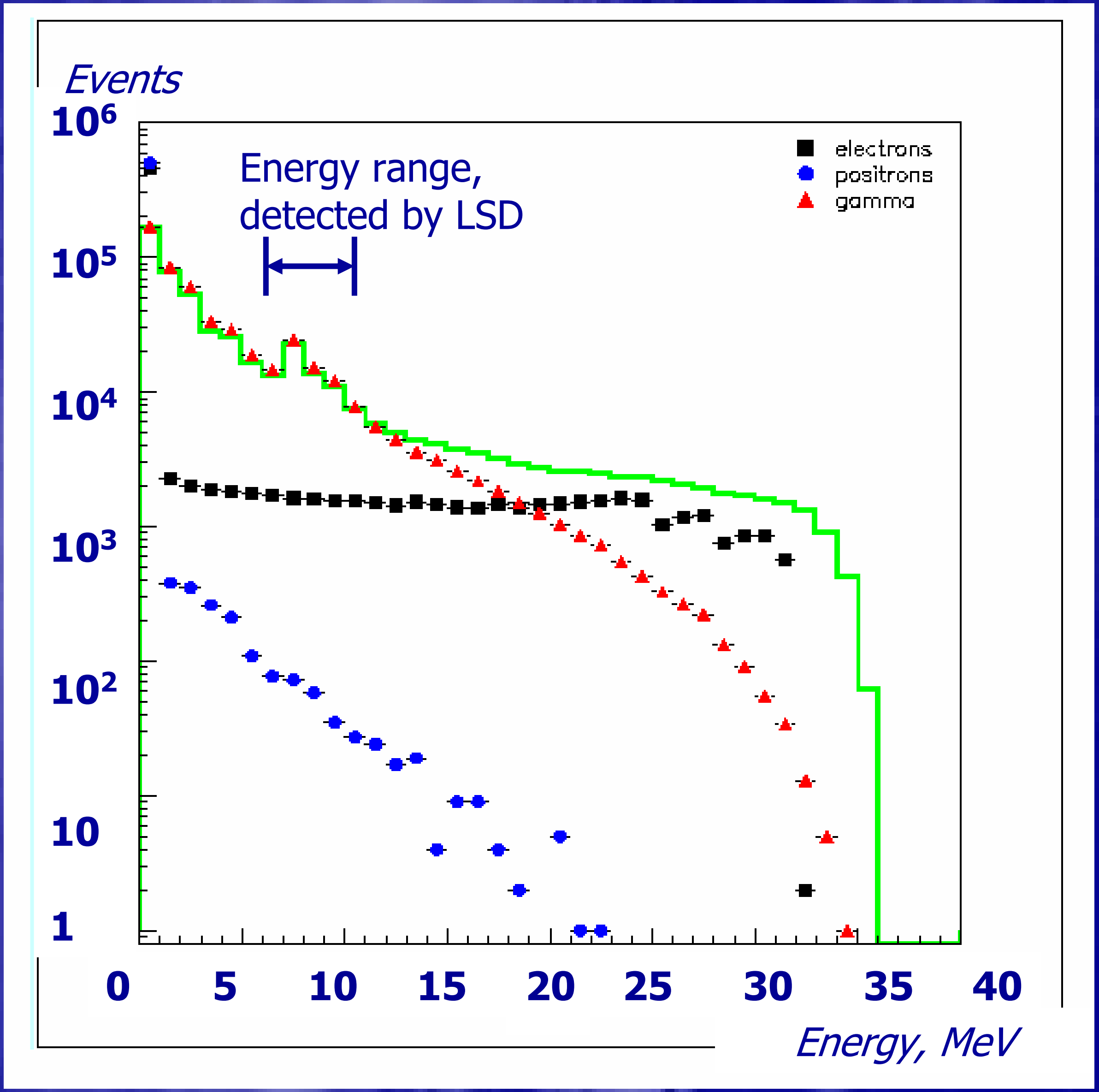
Grazie mille per la nostra collaborazione perfetta e la nostra amicizia di piu di 30 anni. ☺

Спасибо



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


PM FEU - 49B (∅ 15 см)
100
100
150 см



Energy spectrum of the particles, coming from 2,8 cm iron plate

(Geant4 calculations; histogram – total energy deposit)

Yu.V. Gaponov, S.V. Semenov

1^+ GT	10,589
1^+ GT	7,589
1^+ GT	4,589
0^+ IAS	3,589
1^+	1,72
4^+	

$^{56}_{27}Co$

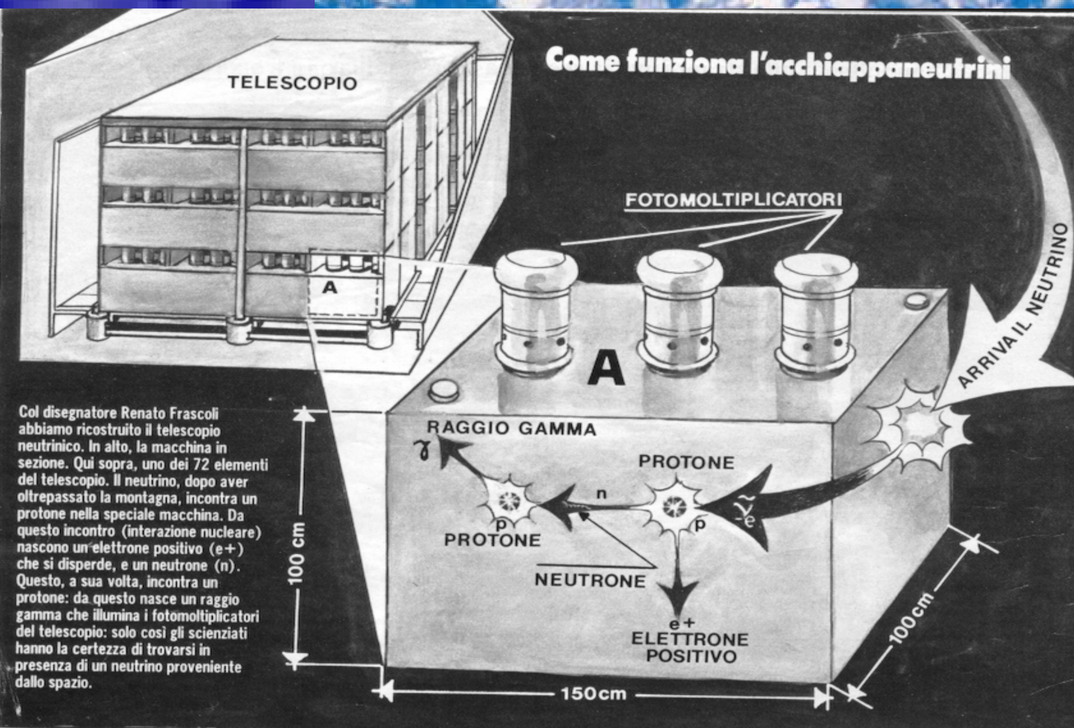
$$\nu_e + {}^{56}_{26}Fe_{0^+} \rightarrow {}^{56}_{27}Co + e^-$$

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

$$\sigma_{tot} = 4.24E^{-40} cm^2$$

$$E_\nu = 40\ MeV$$

F	$\sigma = 1.27 \cdot 10^{-40}\ cm^2$	$E_{K,e^-} = 31.84\ MeV$ E $E_\gamma = 1.82\ MeV$ $\sum_n E_\gamma = 1.72\ MeV$
GT	$\sigma = 6.41 \cdot 10^{-41}\ cm^2$	$E_{K,e^-} = 30.84\ MeV$ $E_\gamma = 1\ MeV$ $E_\gamma = 1.82\ MeV$ $\sum_n E_\gamma = 1.72\ MeV$
GT	$\sigma = 1.05 \cdot 10^{-40}\ cm^2$	$E_{K,e^-} = 27.84\ MeV$ $E_\gamma = 4\ MeV$ $E_\gamma = 1.82\ MeV$ $\sum_n E_\gamma = 1.72\ MeV$
GT	$\sigma = 1.27 \cdot 10^{-40}\ cm^2$	$E_{K,e^-} = 24.84\ MeV$ $E_\gamma = 7\ MeV$ $E_\gamma = 1.82\ MeV$ $\sum_n E_\gamma = 1.72\ MeV$



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.

Events, detected by LSD

February,23, 1987 г. (SN 1987 A)

# of event	Time, UT±2ms	Energy, MeV
1	2:52:36,79	6,2 – 7
2	40,65	5,8 – 8
3	41,01	7,8 –11
4	42,70	7,0 – 7
5	43,80	6,8 – 9
1	7:36:00,54	8
2	7:36:18,88	9

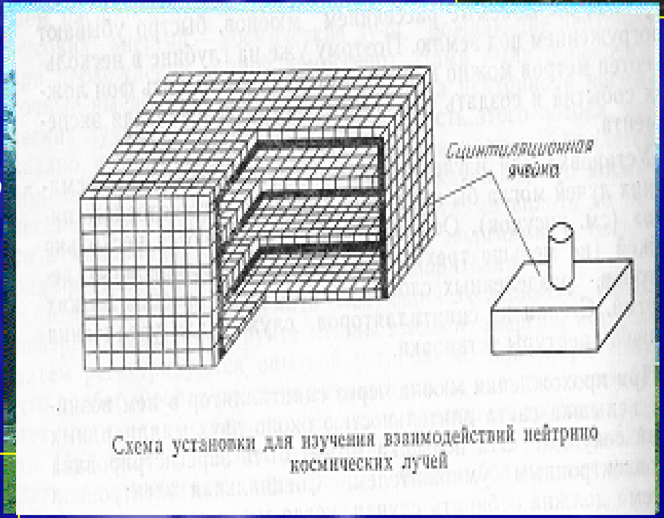
1977 ***Arteomovsk Scintillation Detector*** (INR RAS) has scintillator mass of 105 t, good signature of events (the possibility to detect both particles in the reaction)

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

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

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

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 : $\tilde{\nu} p \to n e^{+}$)