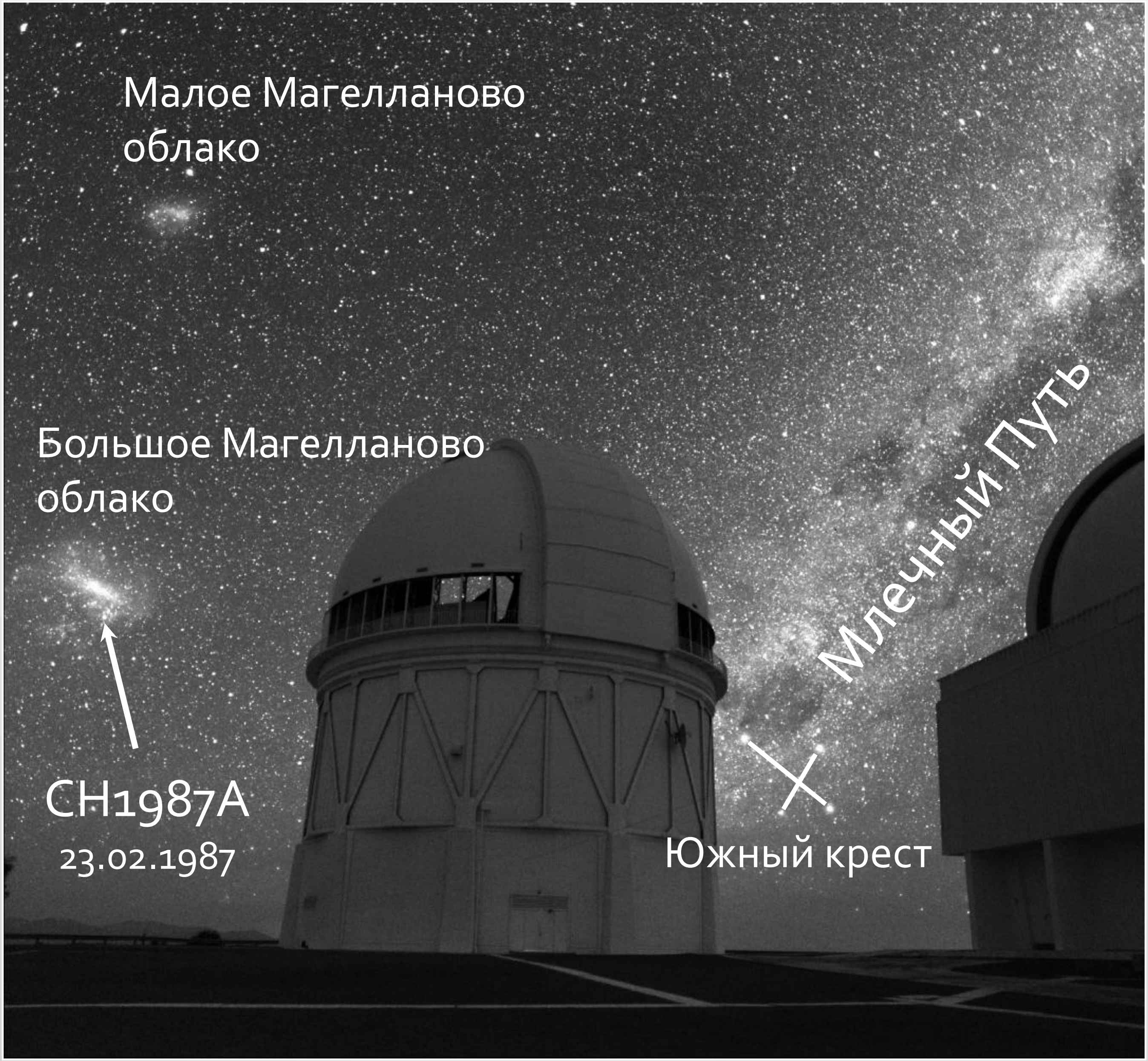
Нейтринный сигнал SN1987A. Моделирование отклика LSD.

Мануковский К.В

Десятые Зацепинские чтения

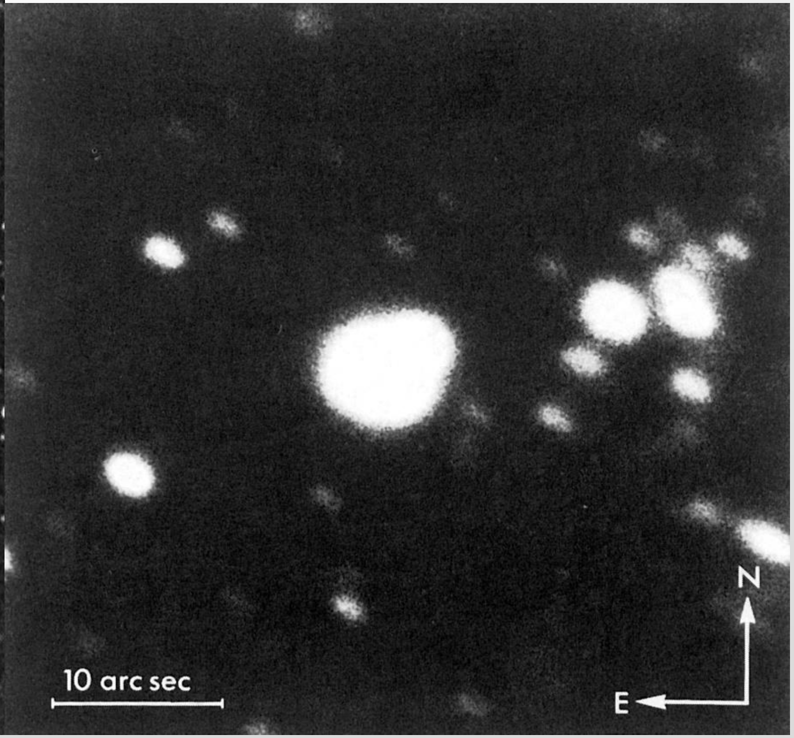
ФИАН им. П.Н. Лебедева, Москва
7 июня 2019 года

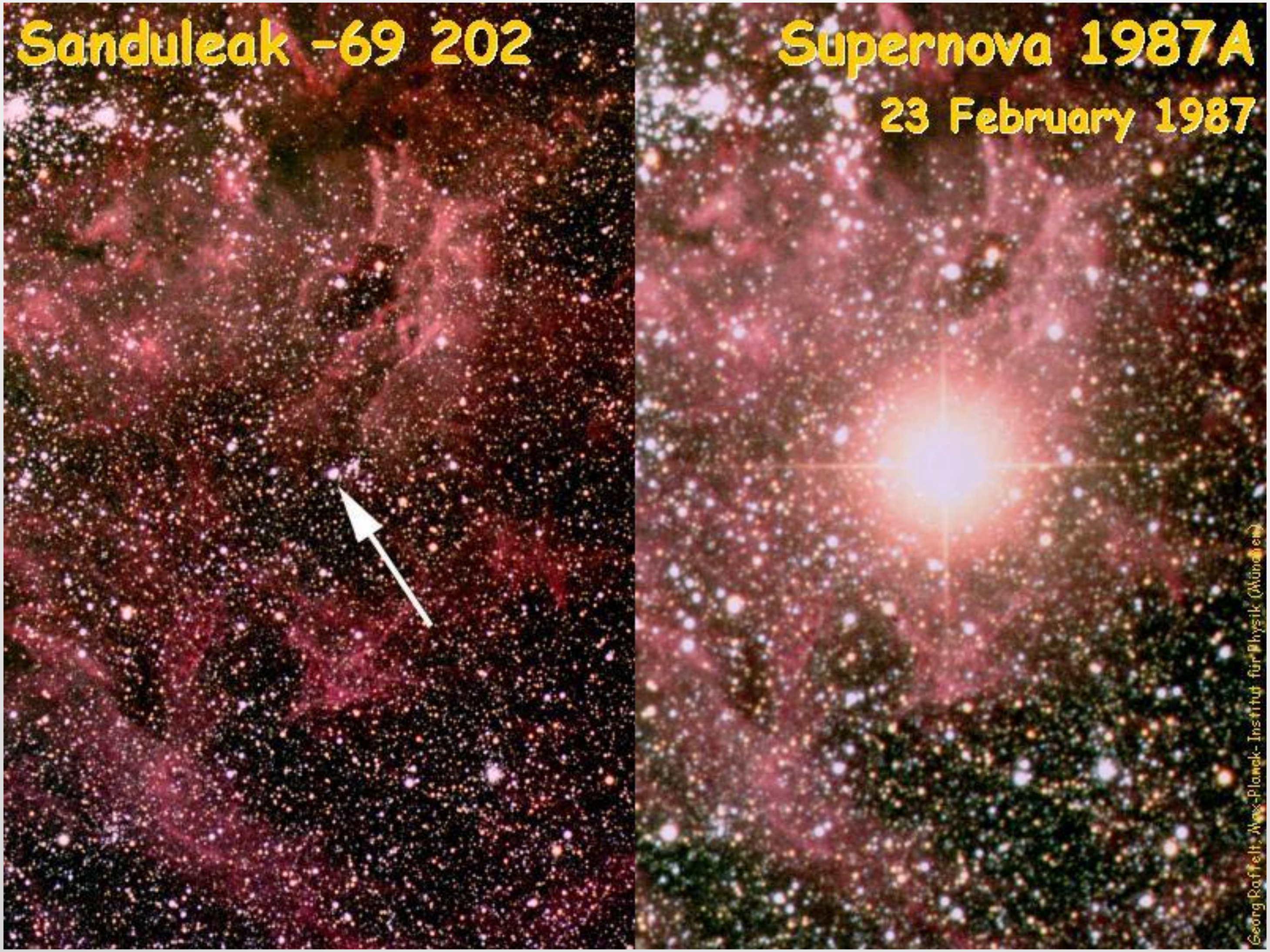


Межамериканская обсерватория Серро-Тололо, Чили

The star that exploded on February 23 in the Large Magellanic Cloud (the progenitor of supernova 1987A) has now been identified. It was catalogued by in 1969 as an OB star of 12th magnitude and given the designation **Sanduleak-69 202**.

Observations at the European Southern Observatory in the mid-1970's allowed to classify it as of spectral type B3 I, that is a very hot, supergiant star. **Credit:** ESO





Progenitor was a hot blue supergiant (BSG)

$M \sim 17M_\odot$ $R \sim 40R_\odot$ $L \sim 10^5 L_\odot$ $T_{eff} = 16000K$

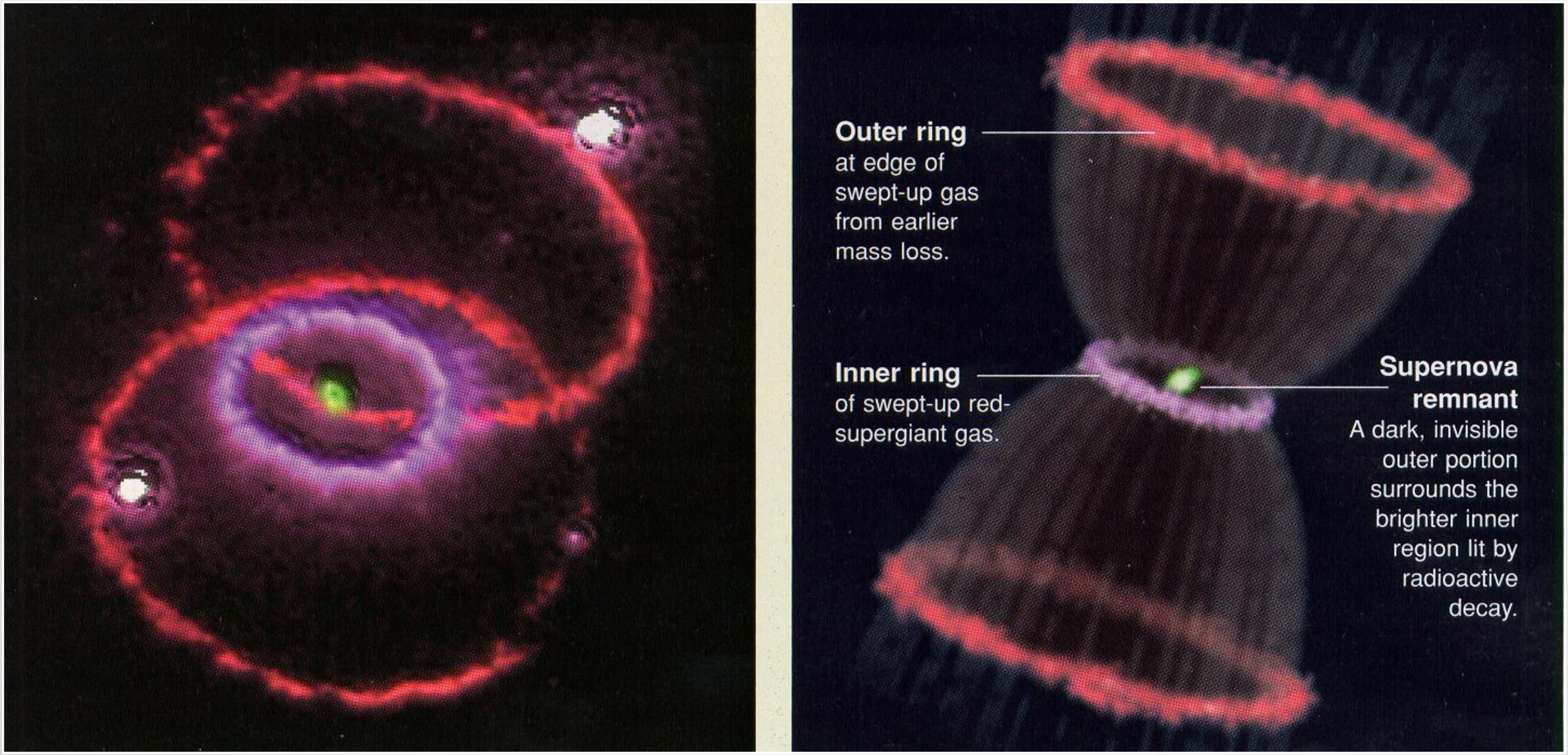
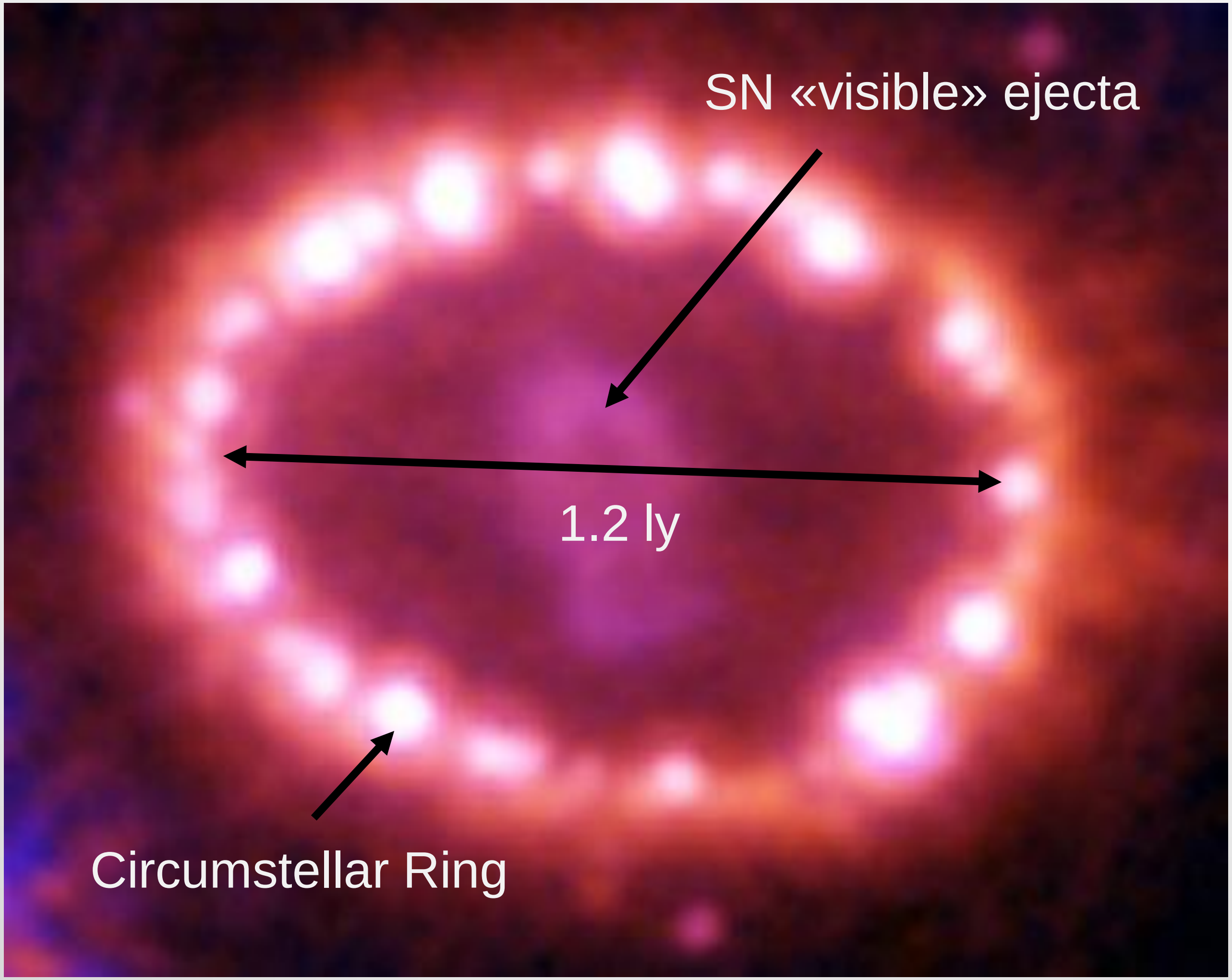
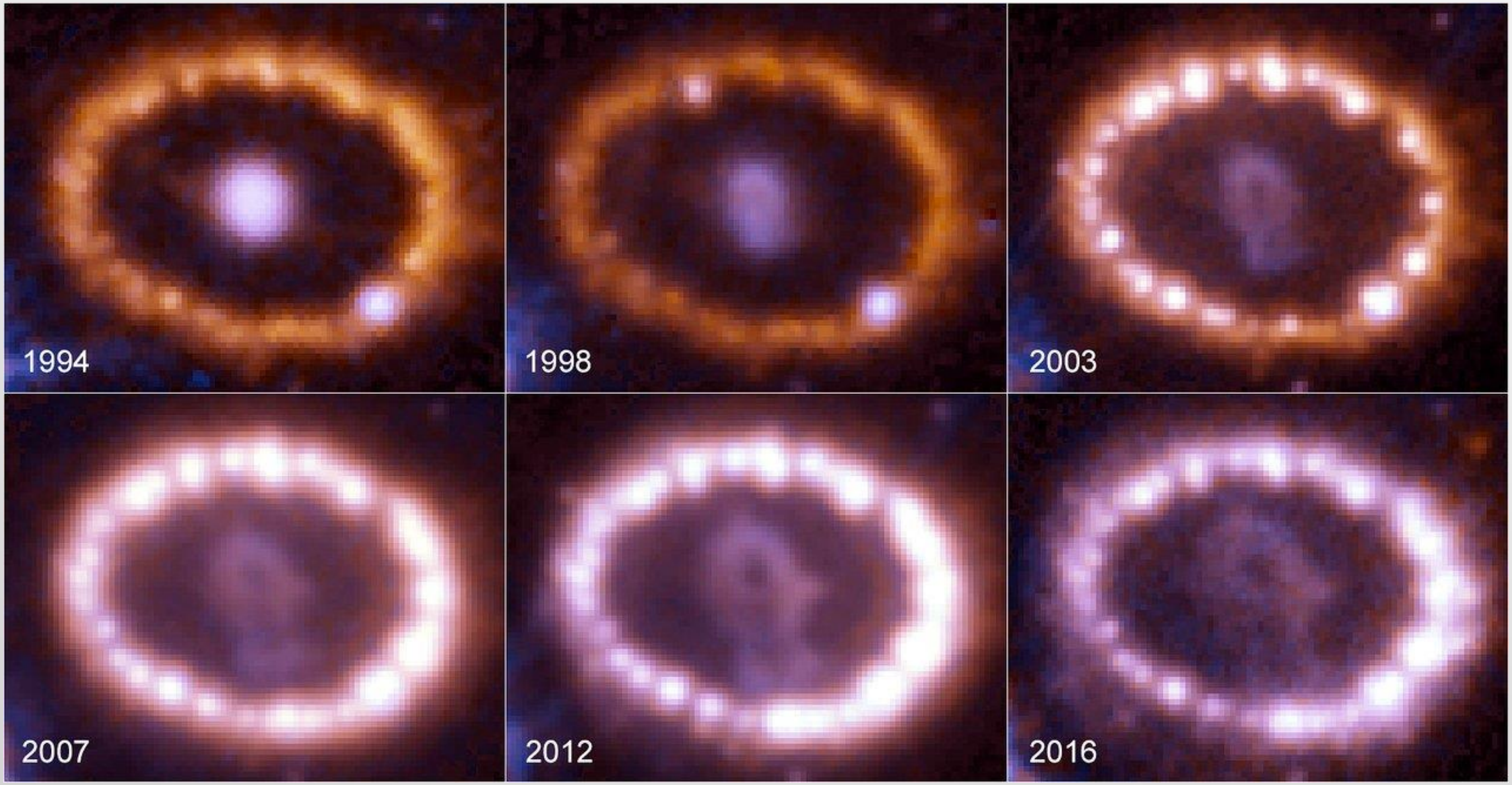


Image from skyandtelescope.com

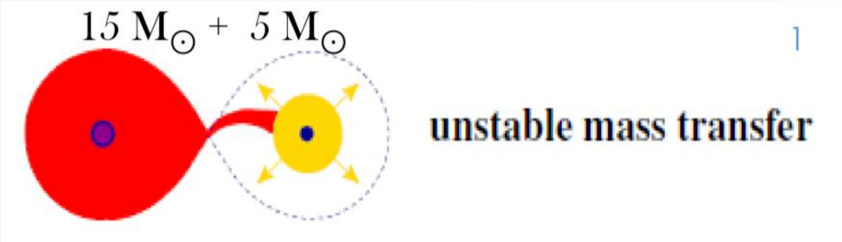


SN 1987A 16 years old (HST Nov. 28, 2003)
Interaction of shock wave with the circumstellar ring

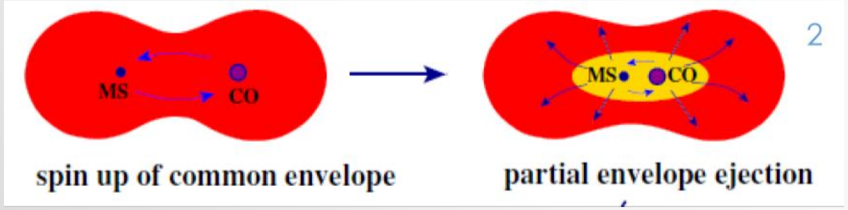
SN1987A ring evolution



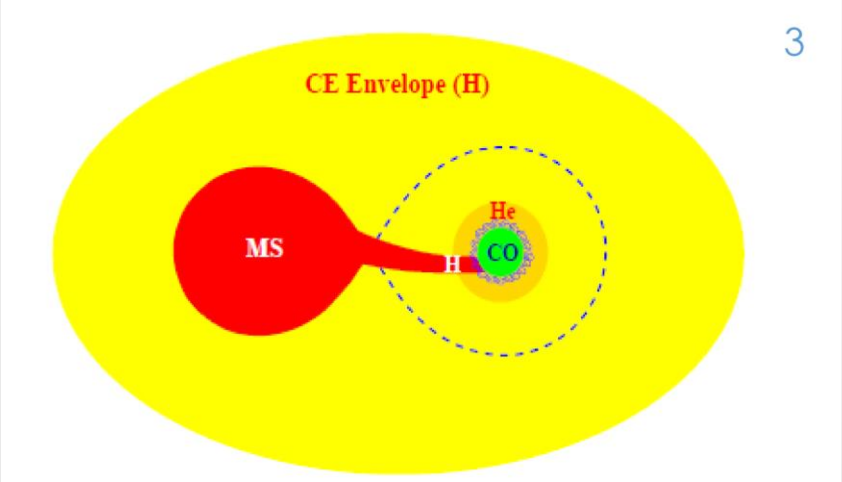
Binary merger scenario
(Podsiadlowski / Ivanova papers)



Primary Red supergiant with CO core +
Secondary main sequence

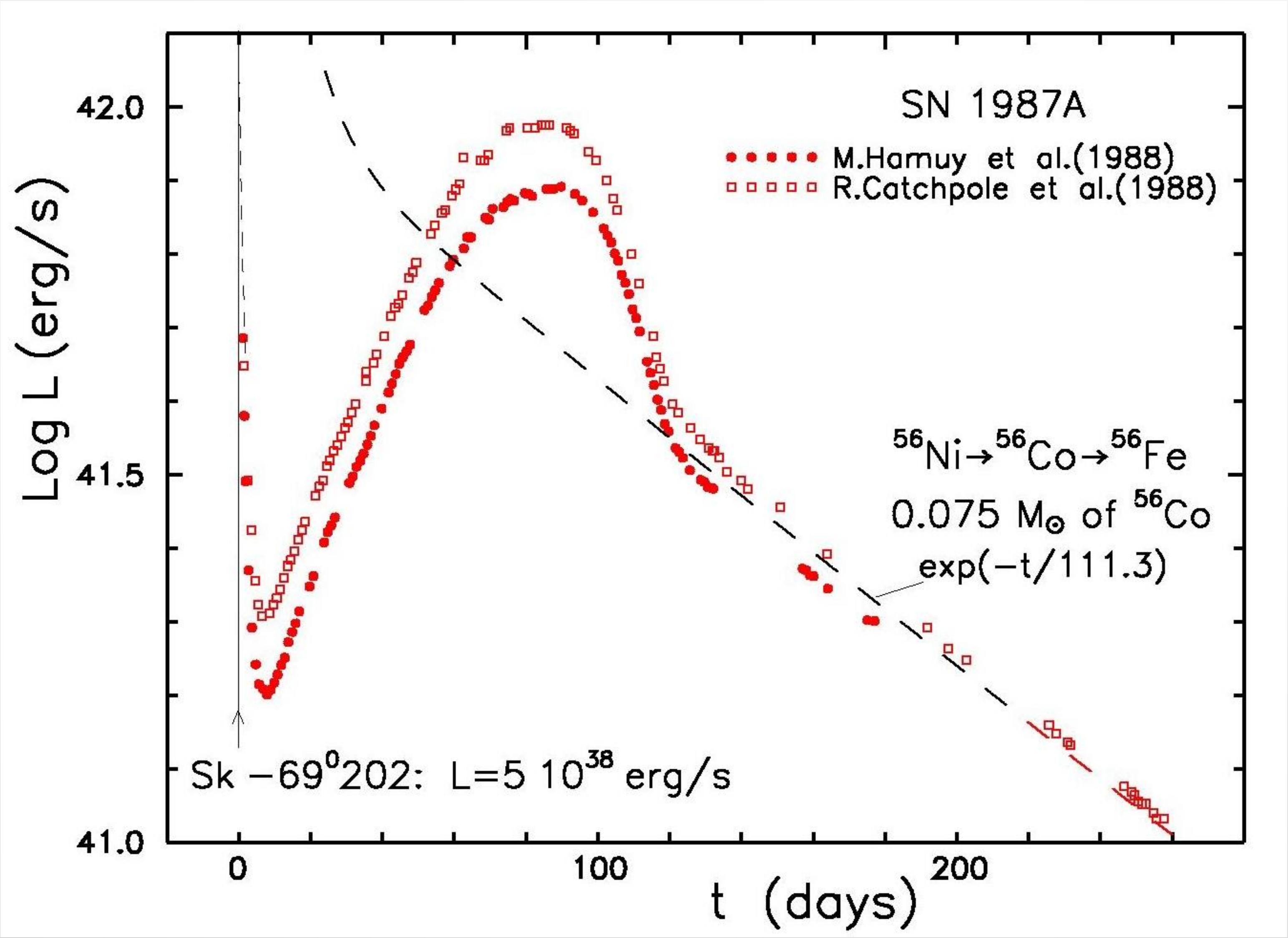


(Podsiadlowski et al. 2007)

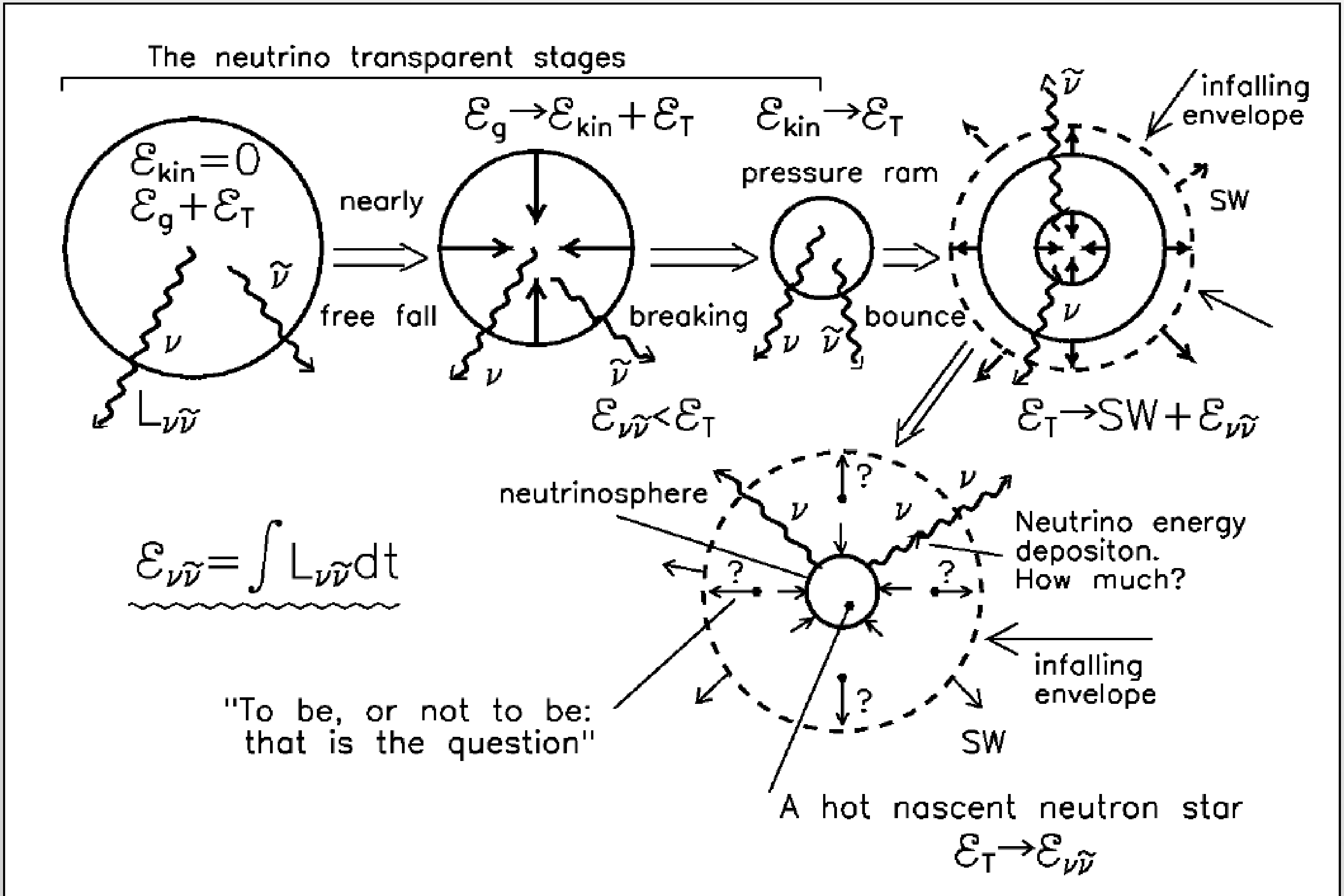


Blue Supergiant
pre-SN ?

Merger: Order of 100 years
3D simulations (Ivanova 2002, 2003)



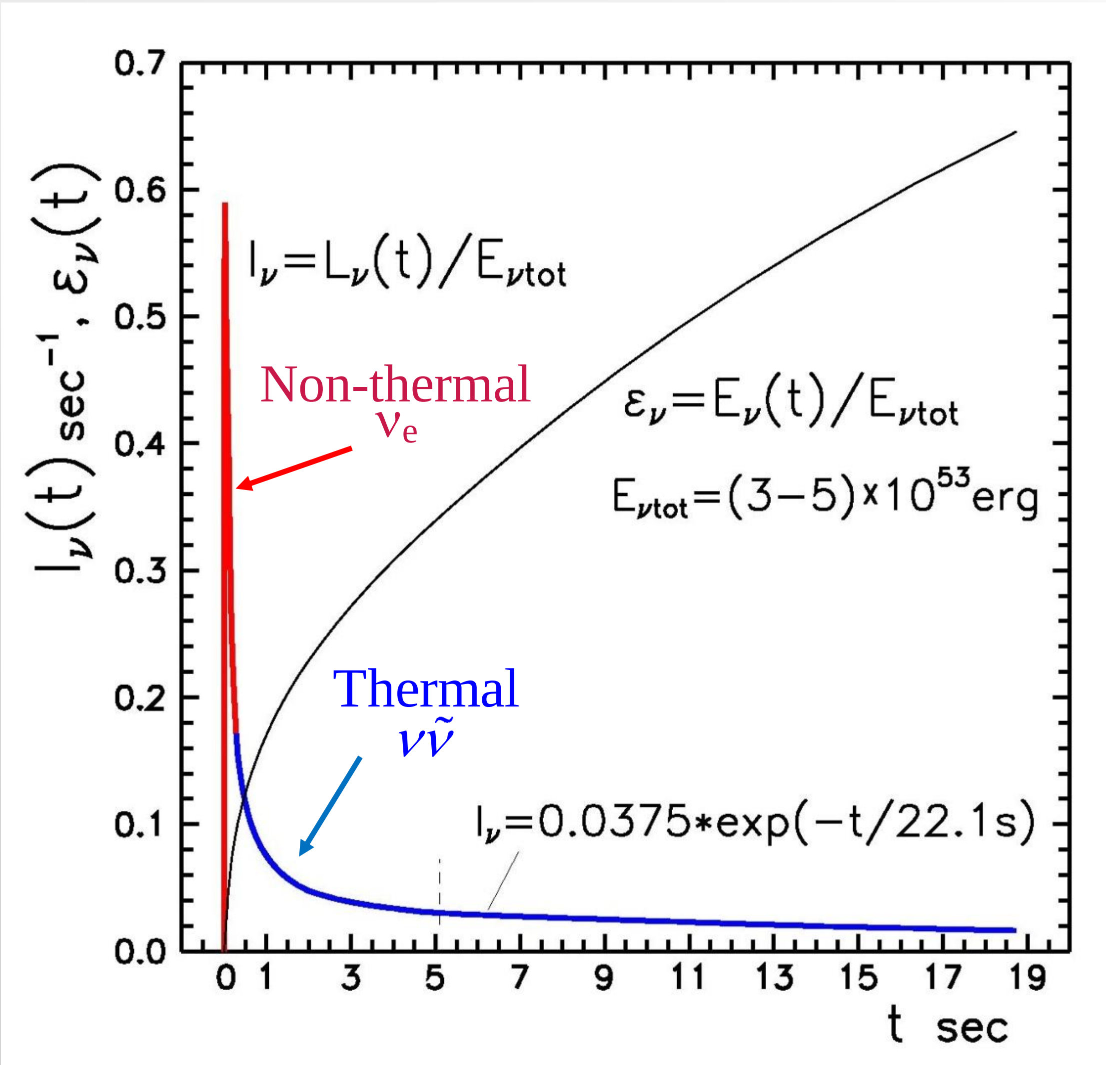
The Bolometric Light Curve of SN1987A



The neutrino transparent stages
$\mathcal{E}_{kin}=0$
$\mathcal{E}_g+\mathcal{E}_T$
$\tilde{\nu}$
ν
$L_{\nu\tilde{\nu}}$
nearly
free fall
$\mathcal{E}_g \rightarrow \mathcal{E}_{kin}+\mathcal{E}_T$
ν
$\tilde{\nu}$
$\mathcal{E}_{\nu\tilde{\nu}}<\mathcal{E}_T$
breaking
$\mathcal{E}_{kin} \rightarrow \mathcal{E}_T$
pressure ram
ν $\tilde{\nu}$
bounce
$\tilde{\nu}$
infalling envelope
SW
ν
$\mathcal{E}_T \rightarrow SW+\mathcal{E}_{\nu\tilde{\nu}}$
neutrinosphere
ν
ν
ν
?
?
?
?
Neutrino energy depositon. How much?
infalling envelope
SW
$\mathcal{E}_{\nu\tilde{\nu}}=\int L_{\nu\tilde{\nu}}dt$
"To be, or not to be: that is the question"
A hot nascent neutron star
$\mathcal{E}_T \rightarrow \mathcal{E}_{\nu\tilde{\nu}}$

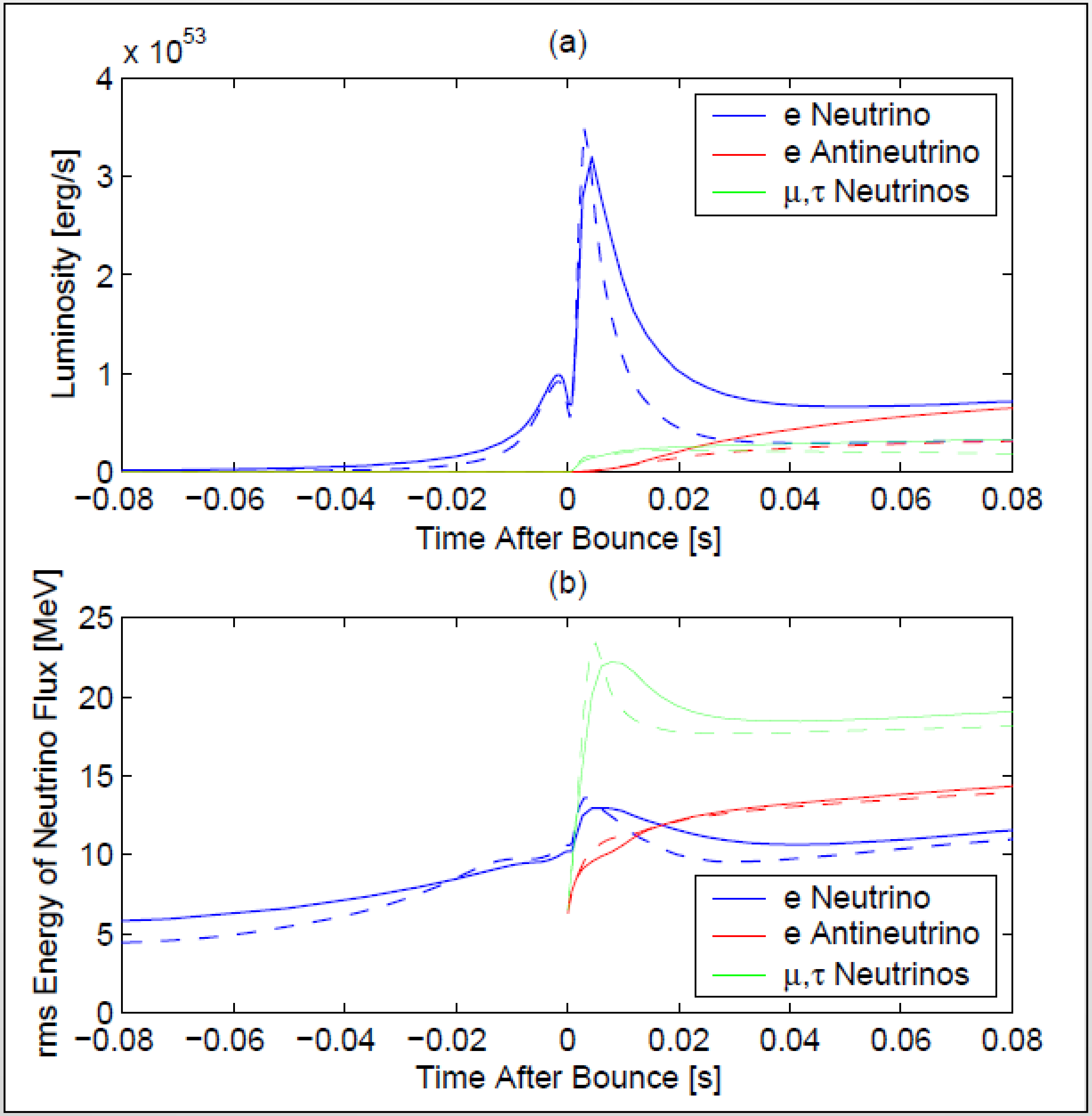
Cumulative neutrino «light» curve

(based on Nadyozhin 1978)



Neutrino reaction
$e^- + p \rightleftarrows n + \nu_e$
$e^+ + n \rightleftarrows p + \bar{\nu}_e$
$e^- + \langle A, Z\rangle \rightleftarrows \langle A, Z-1\rangle + \nu_e$
$\nu + N \rightleftarrows \nu' + N$
$\nu + \langle A, Z\rangle \rightleftarrows \nu' + \langle A, Z\rangle$
$\nu + e^\pm \rightleftarrows \nu' + e^\pm$
$e^- + e^+ \rightleftarrows \nu + \bar{\nu}$
$N + N \rightleftarrows N + N + \nu + \bar{\nu}$
$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$

Liebendoerfer et al., ApJS 150, 1 (2004)



Solid lines: $40\ M_\odot$

Dashed: $13\ M_\odot$

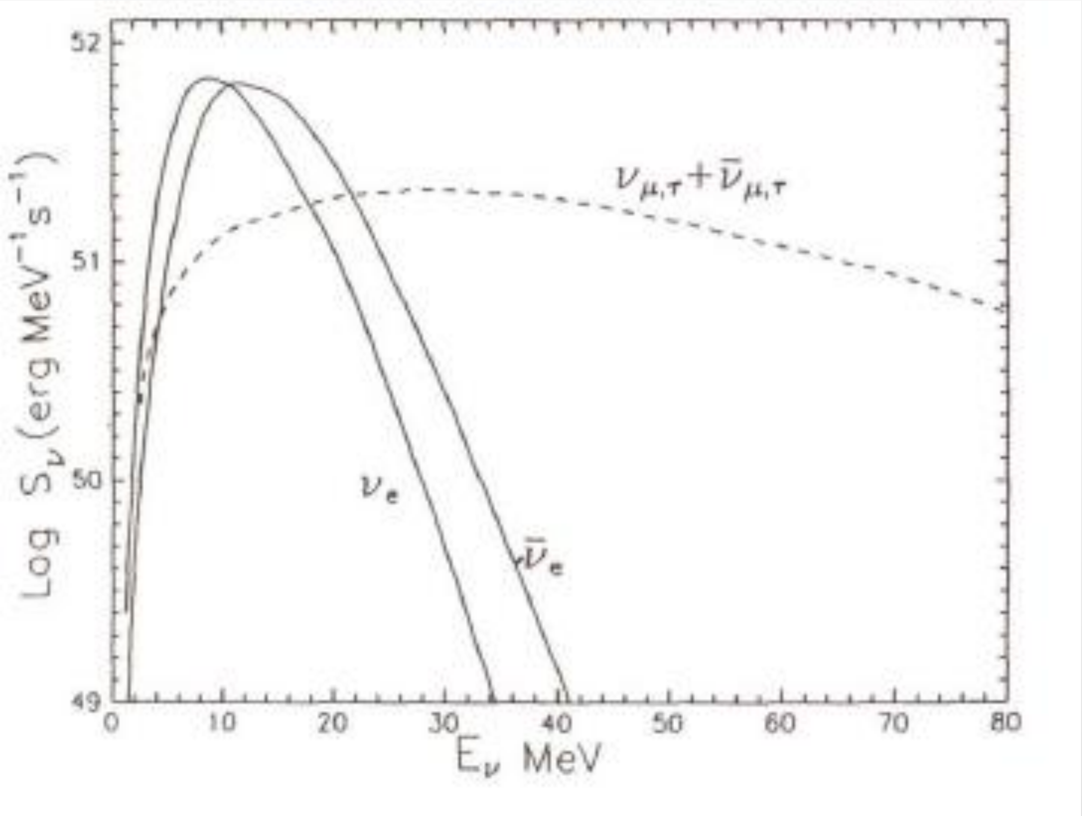
Neutrino spectra for thermal phase

Energy spectra

Fermi−Dirac law:

$$S_\nu \sim \frac{\varepsilon_\nu^3}{1 + exp\left(\frac{\varepsilon_\nu}{kT_{\nu ph}} - \psi_{\nu ph}\right)}\ ,$$

$$(\psi_{\nu ph} \approx 0)\ .$$



High-energy cutoff

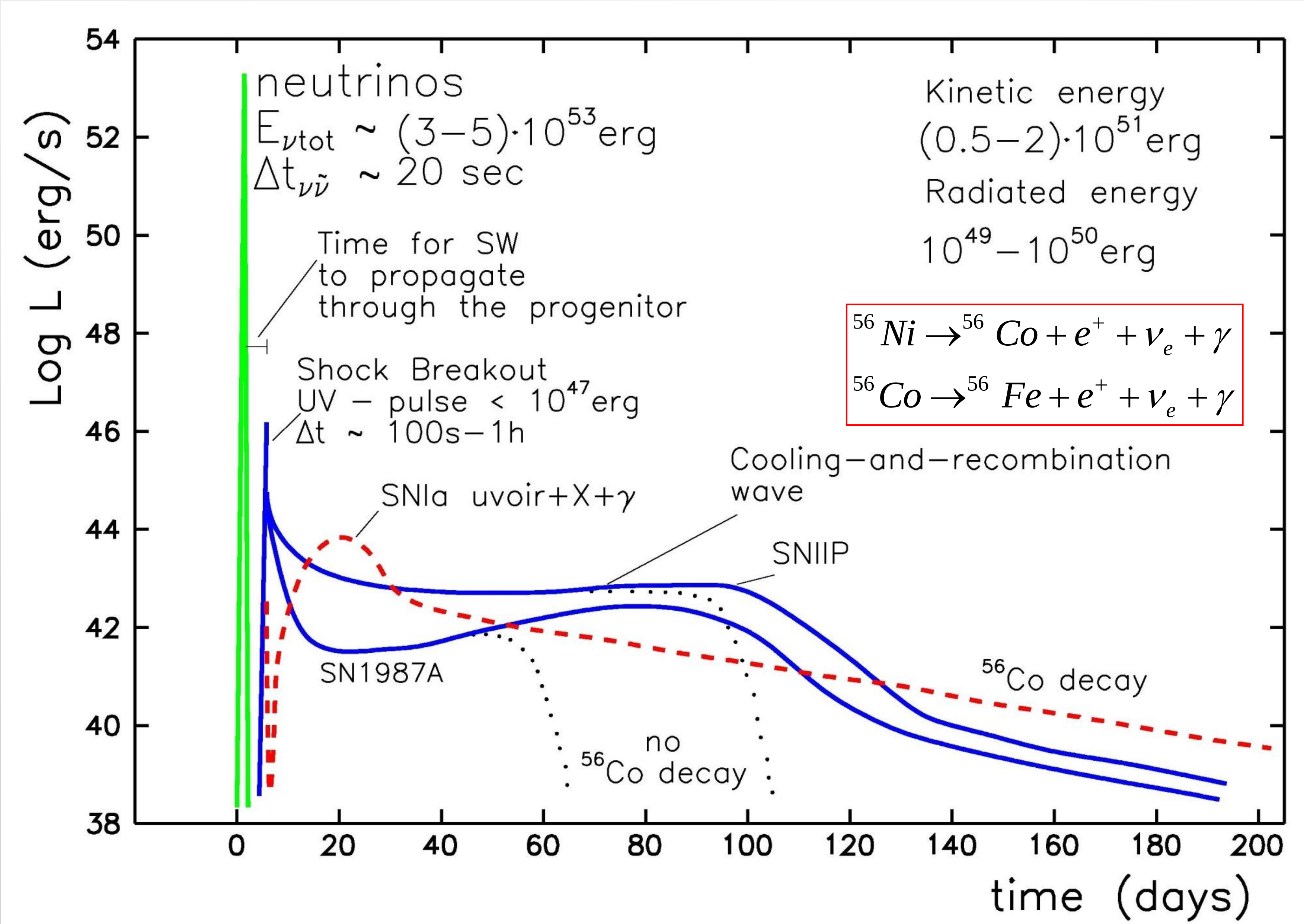
(relevant to $\nu_e, \tilde{\nu}_e$):

$$S_\nu \sim \frac{\varepsilon_\nu^3\ exp\left[-\alpha\left(\frac{\varepsilon_\nu}{kT_{\nu ph}}\right)^2\right]}{1 +\ exp\left(\frac{\varepsilon_\nu}{kT_{\nu ph}}\right)}\ ,\ (\alpha \approx 0.02 - 0.04).$$

$$T_{\nu ph} \approx 4\ MeV\ \ for\ \nu_e, \tilde{\nu}_e$$

$$T_{\nu ph} \approx 8\ MeV\ \ for\ \nu_\mu, \nu_\tau$$

Schematic Supernova «light curves»



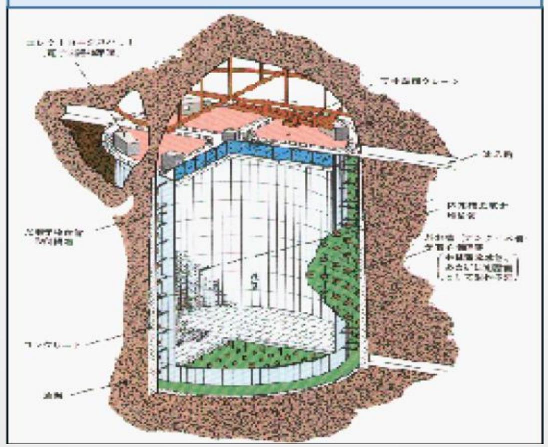
Signals from SN1987A on 23 Feb.1987

Baksan

- ❑ 330 tons liquid scint
- ❑ threshold ~10 MeV
- ❑ 5 events in 9.1 sec.

Kamioka

- ❑ water Cerenkov
- ❑ 2140 tons fiducial
- ❑ threshold ~6 MeV
- ❑ 12 events in 12.4 sec.

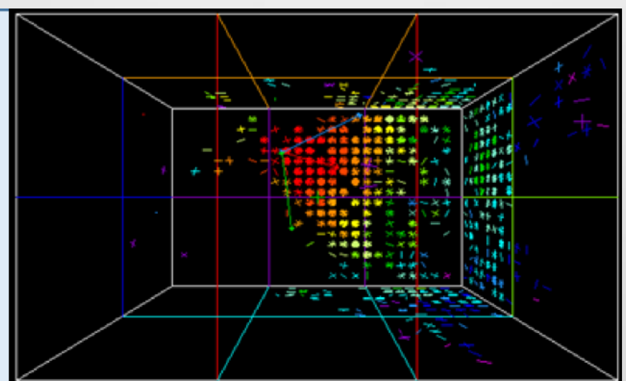


$$\tilde{\nu}_e + p \rightarrow e^+ + n$$

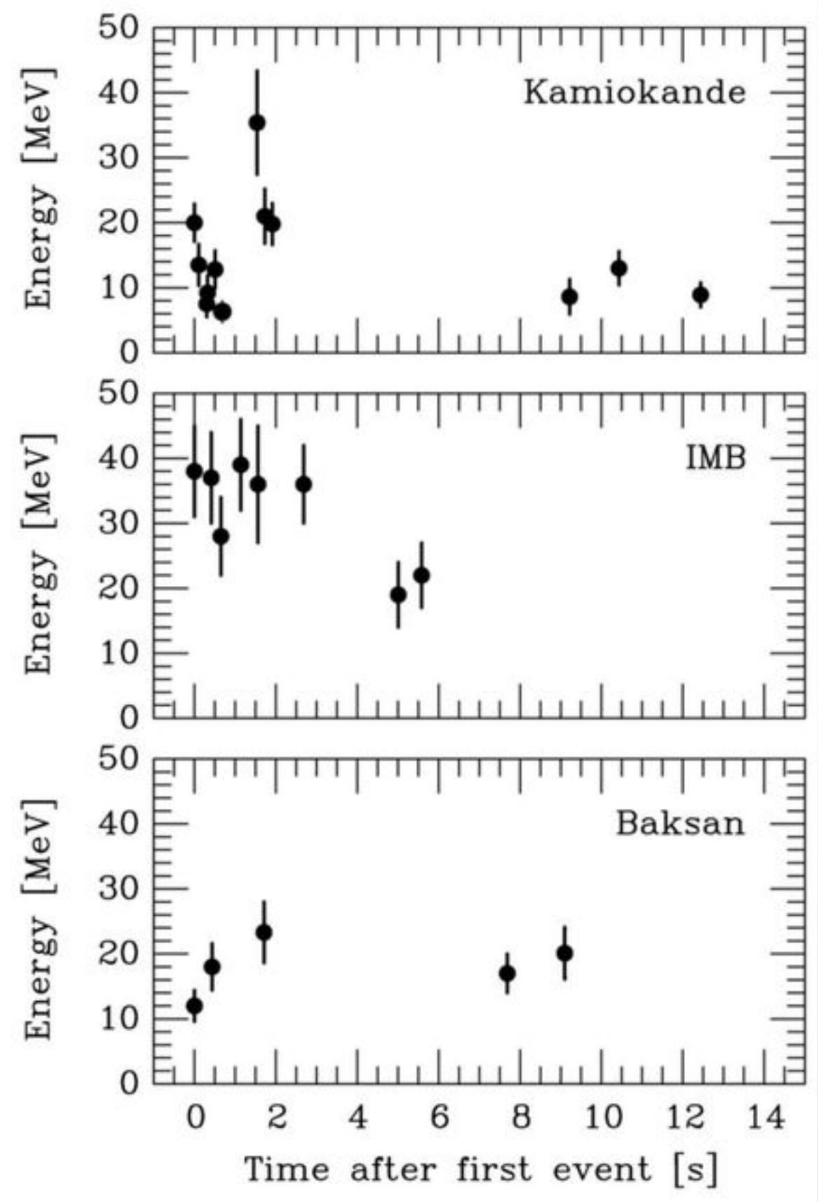
All three detectors saw a cluster of events at ~7:35 UT

IMB

- ❑ water Cerenkov
- ❑ 5000 tons fiducial
- ❑ threshold 20 MeV
- ❑ 8 events in 6 seconds



Neutrino signal of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/–54 s

Within clock uncertainties,
all signals are contemporaneous

Georg Raffelt, MPI Physics, Munich

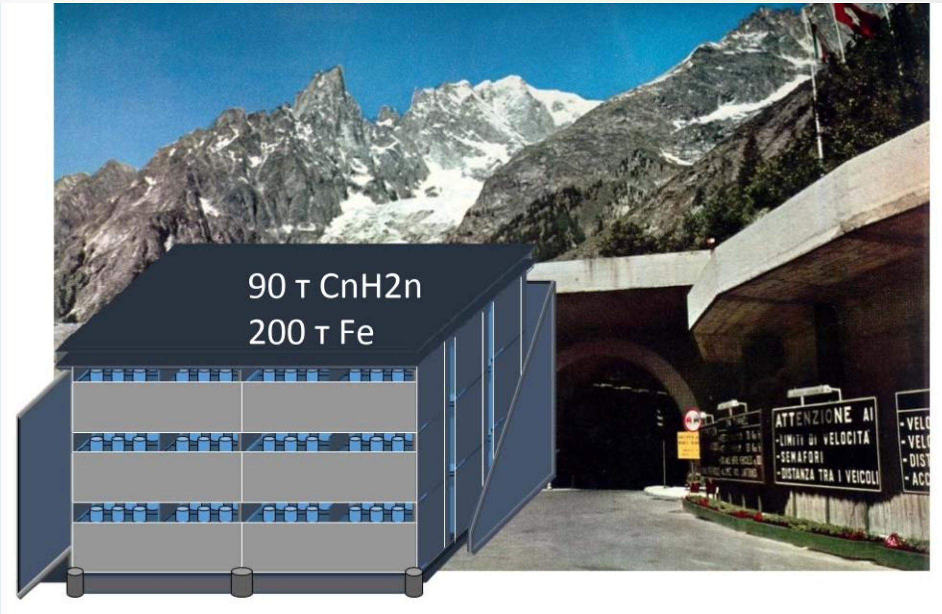
LSD

- 90 tons liquid scintilator
- 220 tons Fe
- threshold ~ 5 MeV
- 5 events in 7 sec – 2:52
- 2 ev. In 18 sec. – 7:36

On the Event Observed in the Mont Blanc Underground Neutrino Observatory during the Occurrence of Supernova 1987*a*

M. Aglietta, G. Badino, G. Bologna, C. Castagnoli, A. Castellina, V. L. Dadykin, W. Fulgione, P. Galeotti, F. F. Kalchukov, B. Kortchaguin, P. V. Kortchaguin, A. S. Malguin, V. G. Ryassny, O.G. Ryazhskaya, O. Saavedra, V. P. Talochkin, G. Trinchero, S. Vernetto, G. T. Zatsepin and V. F. Yakushev *EuroPhys. Lett.* **3** (1987) 1315

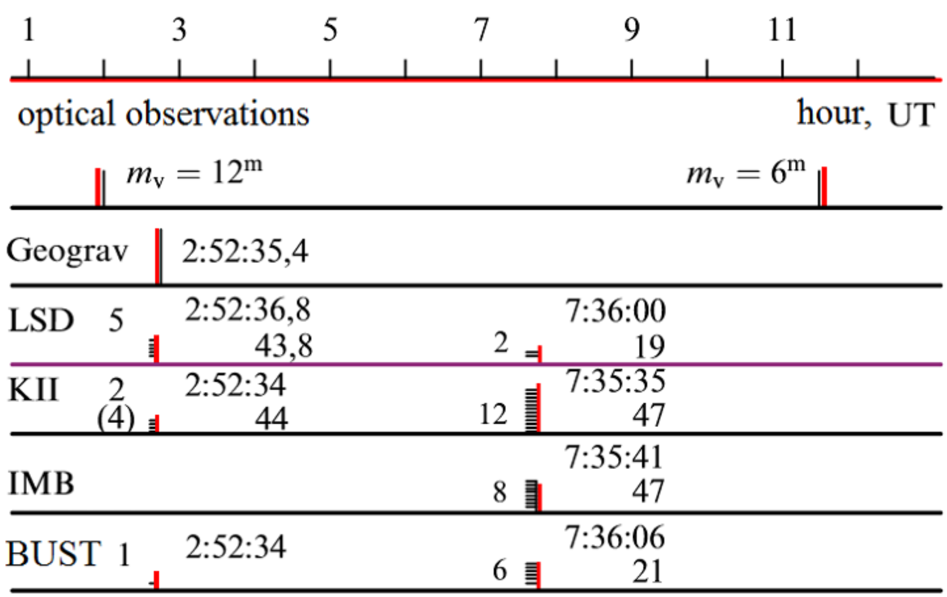
№	Time, UT ± 2ms	Energy, MeV
1	2:52:36,79	6,2 – 7
2	40,65	5,8 – 8
3	41,01	7,8 –11
4	42,70	7,0 – 7
5	43,80	6,8 – 9
1	7:36:00,54	8
2	7:36:18,88	9

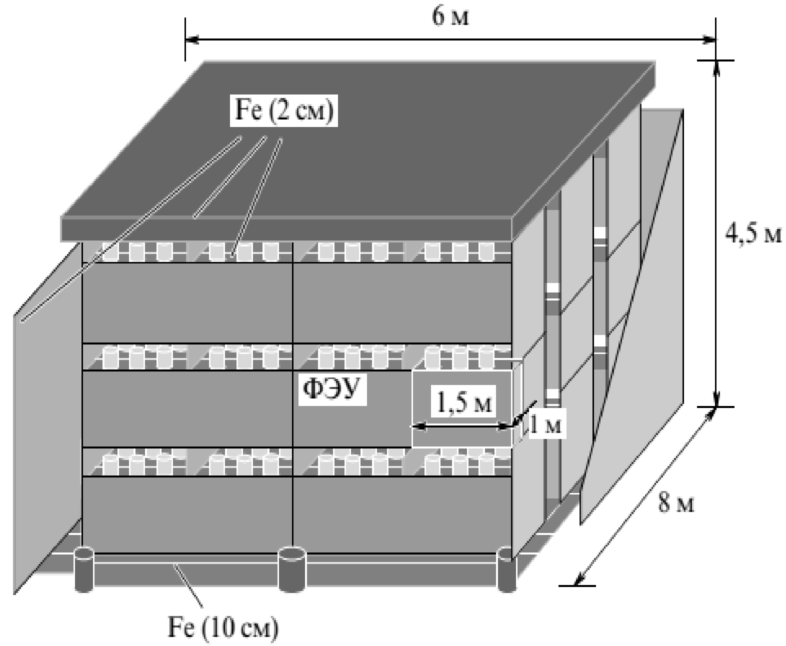


Нейтринный сигнал от СН1987А

О.Г. Ряжская, УФН **176**, №10 (2006)

LSD, Mot Blanc





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

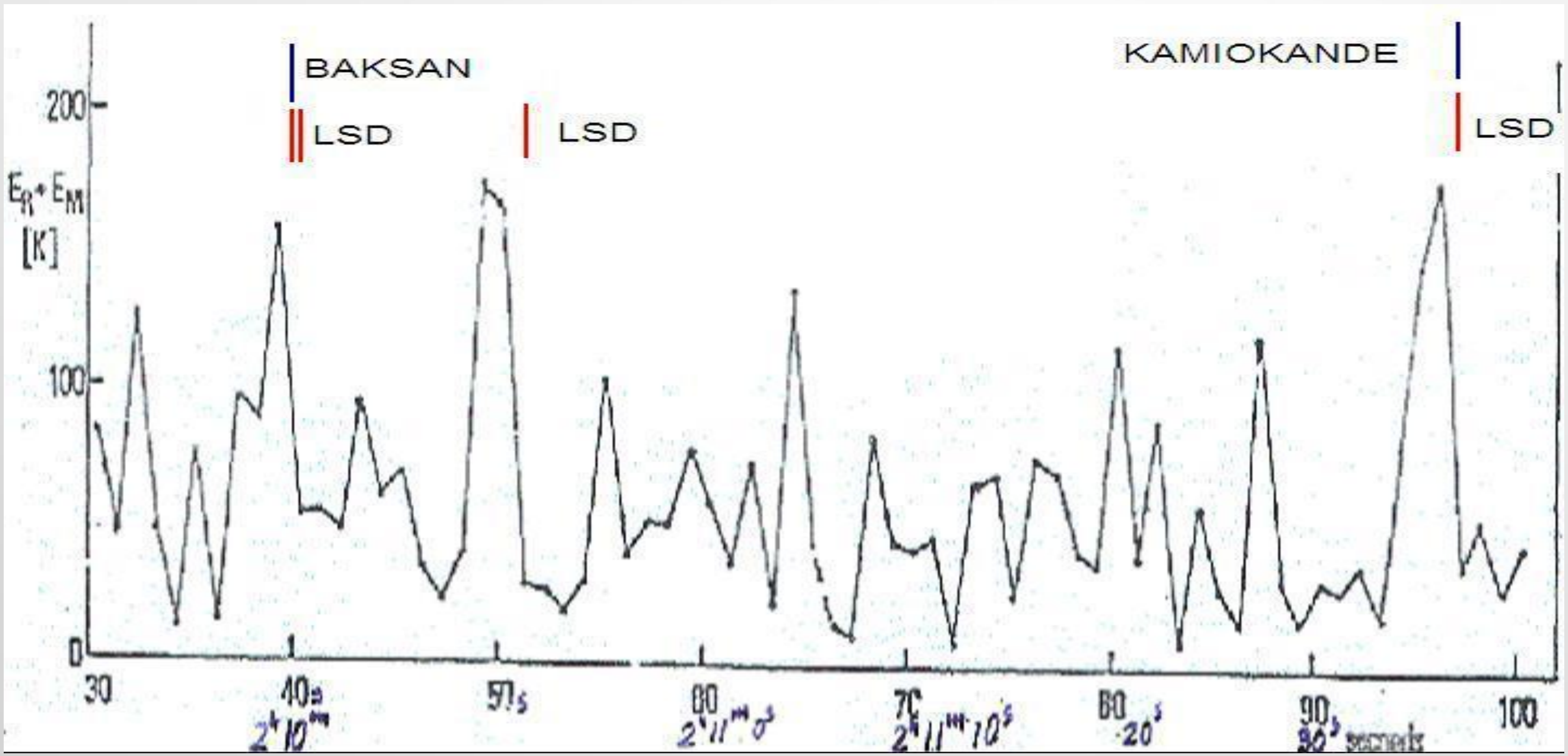
$$n + p \to d + \gamma, \quad E_\gamma = 2.2 \text{ МэВ}.$$

$$\sigma_{\tilde{\nu}_e p} \cong 9.3 E_{e+}^2 \times 10^{-44} \text{ см}^2, \quad E_{e+} \gg 0.5 \text{ МэВ}.$$

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

$$\nu_e + (A, Z) \to \nu'_e + (A, Z)^*.$$

Coincidences (GWR + GWM) with LSD, BST and Kamiokande II (70 seconds of data taking)



P. Galeotti

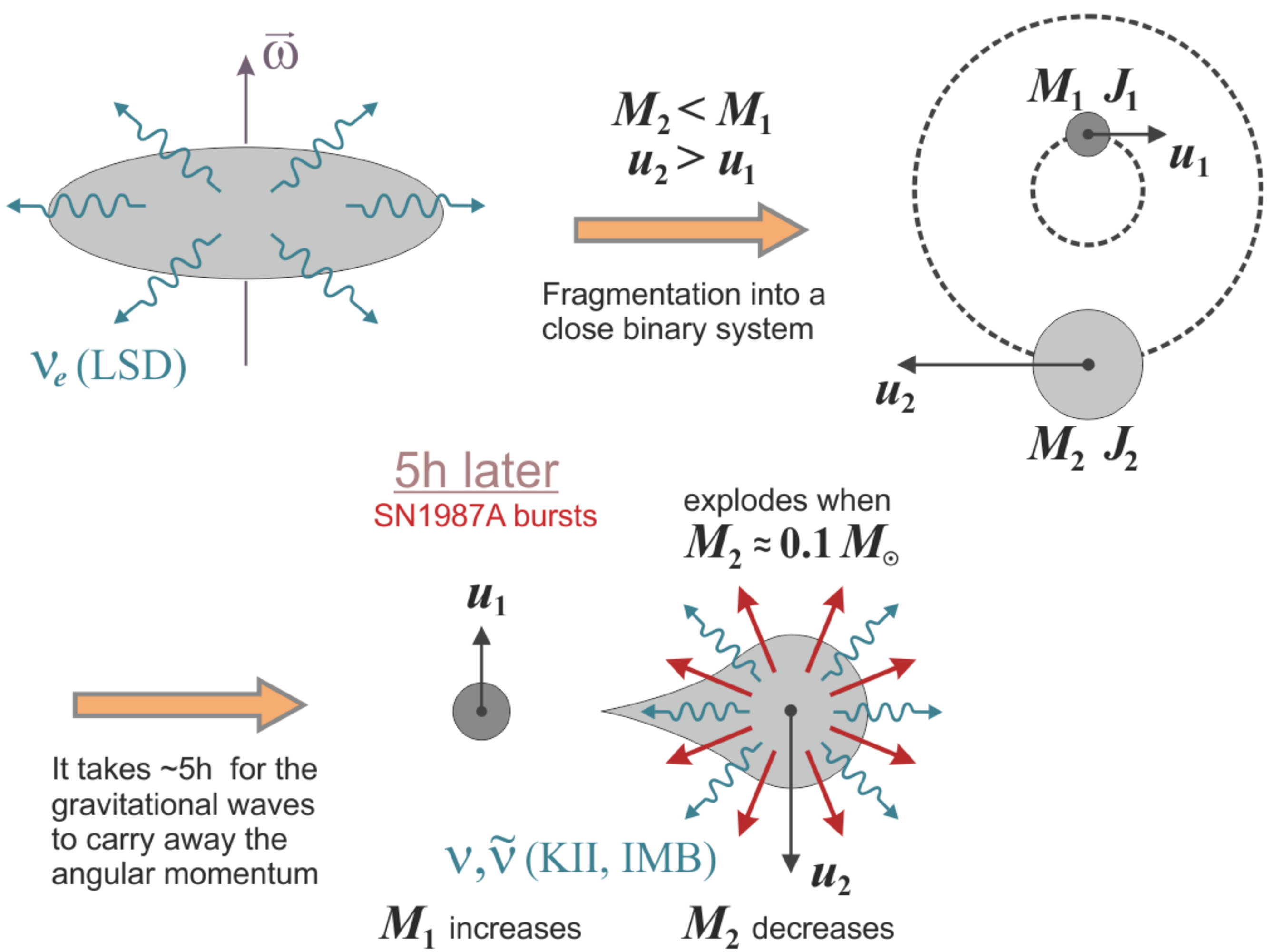
Scenario for a supernova explosion in the gravitational collapse of a massive stellar core

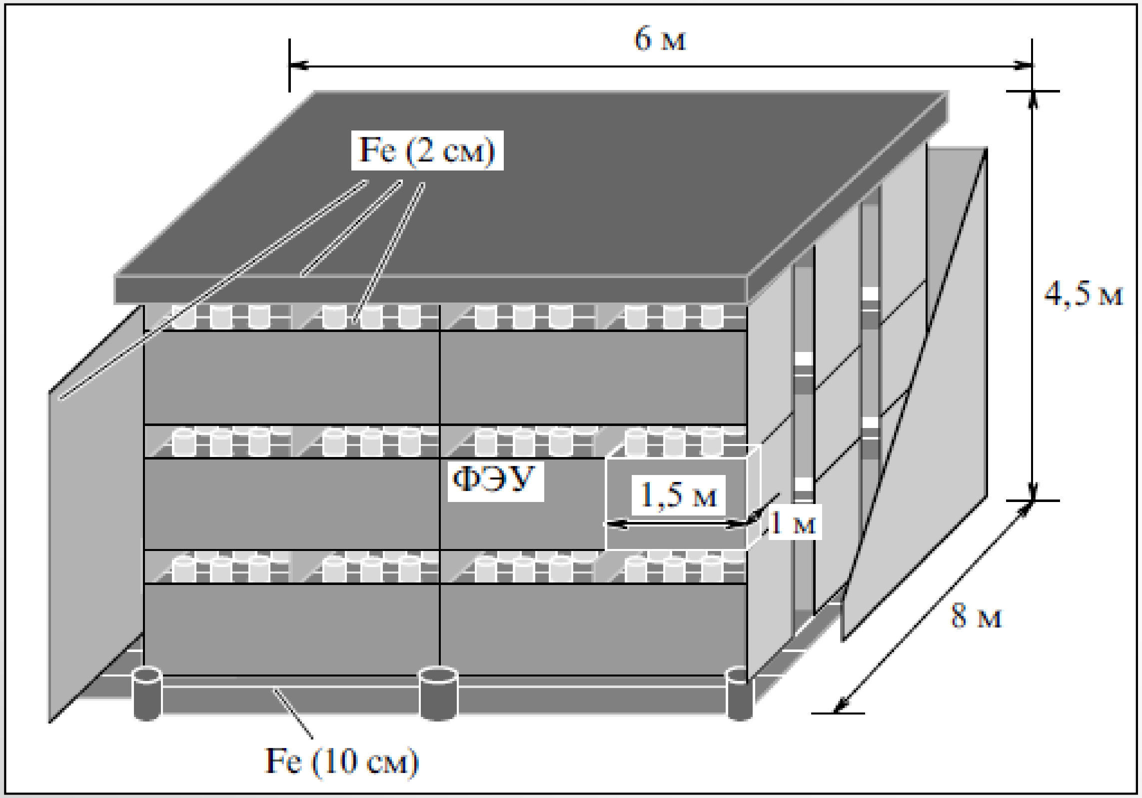
V. S. Imshennik

Institute of Experimental and Theoretical Physics, Moscow

(Submitted February 20, 1992)

Pis'ma Astron. Zh. **18**, 489–504 (June 1992)





H=5200 m.w.e.
72 counters
90 tons of C_nH_{2n}
200 tons of Fe

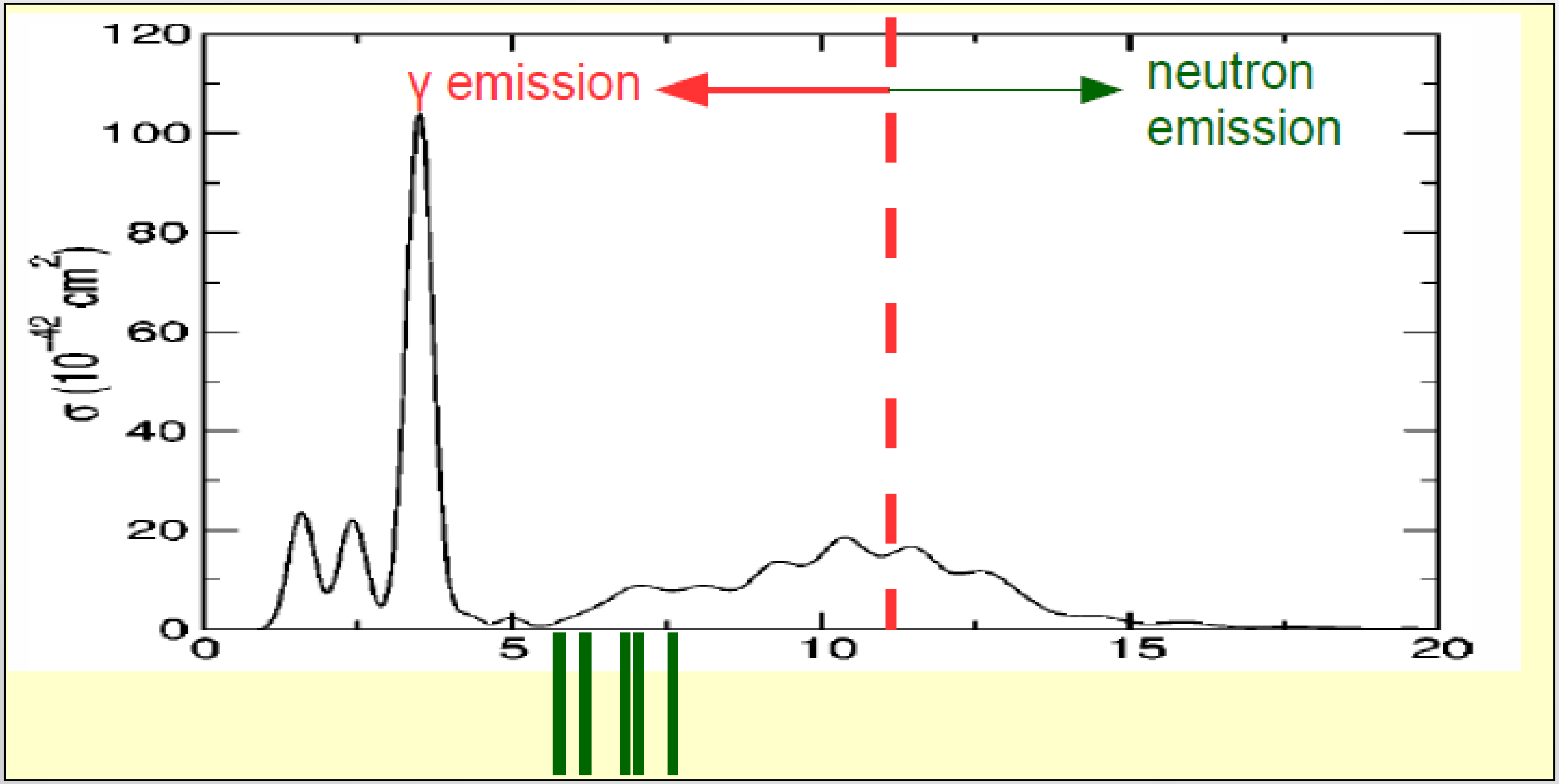
Table I - Characteristics of the pulses in the burst detected on February 23rd, 1987

Event no.	Counter no.	Time (UT)	E_{vis} (MeV)
994	31	$2^h 52^m 36^s.79$	6.2
995	14	40.65	5.8
996	25	41.01	7.8
997	35	42.70	7.0
998	33	43.80	6.8

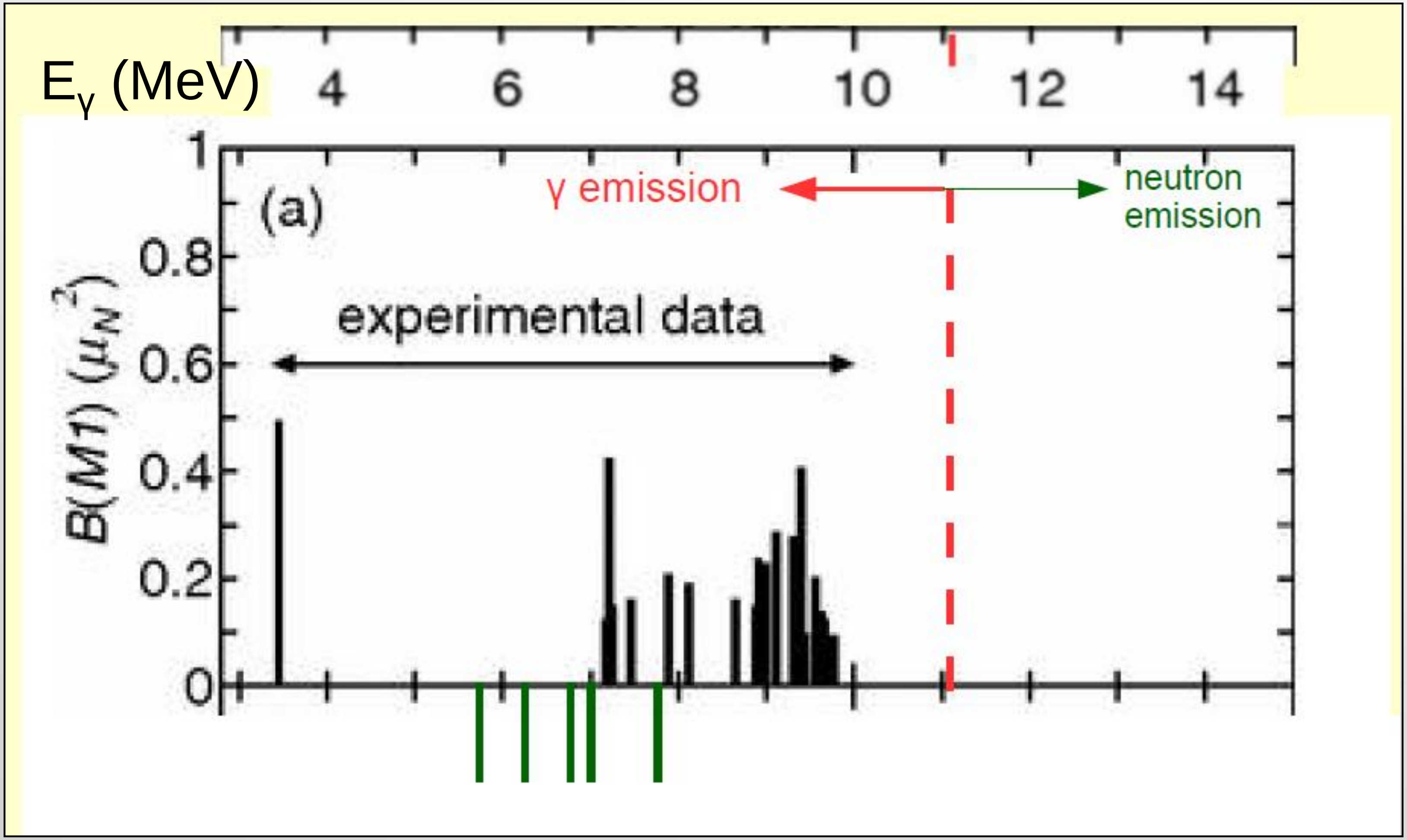
Aglietti et al. 1988

$$\nu_e + {}^{56}Fe \rightarrow e^- + {}^{56}Co^*$$
$$\searrow {}^{56}Co + \gamma$$

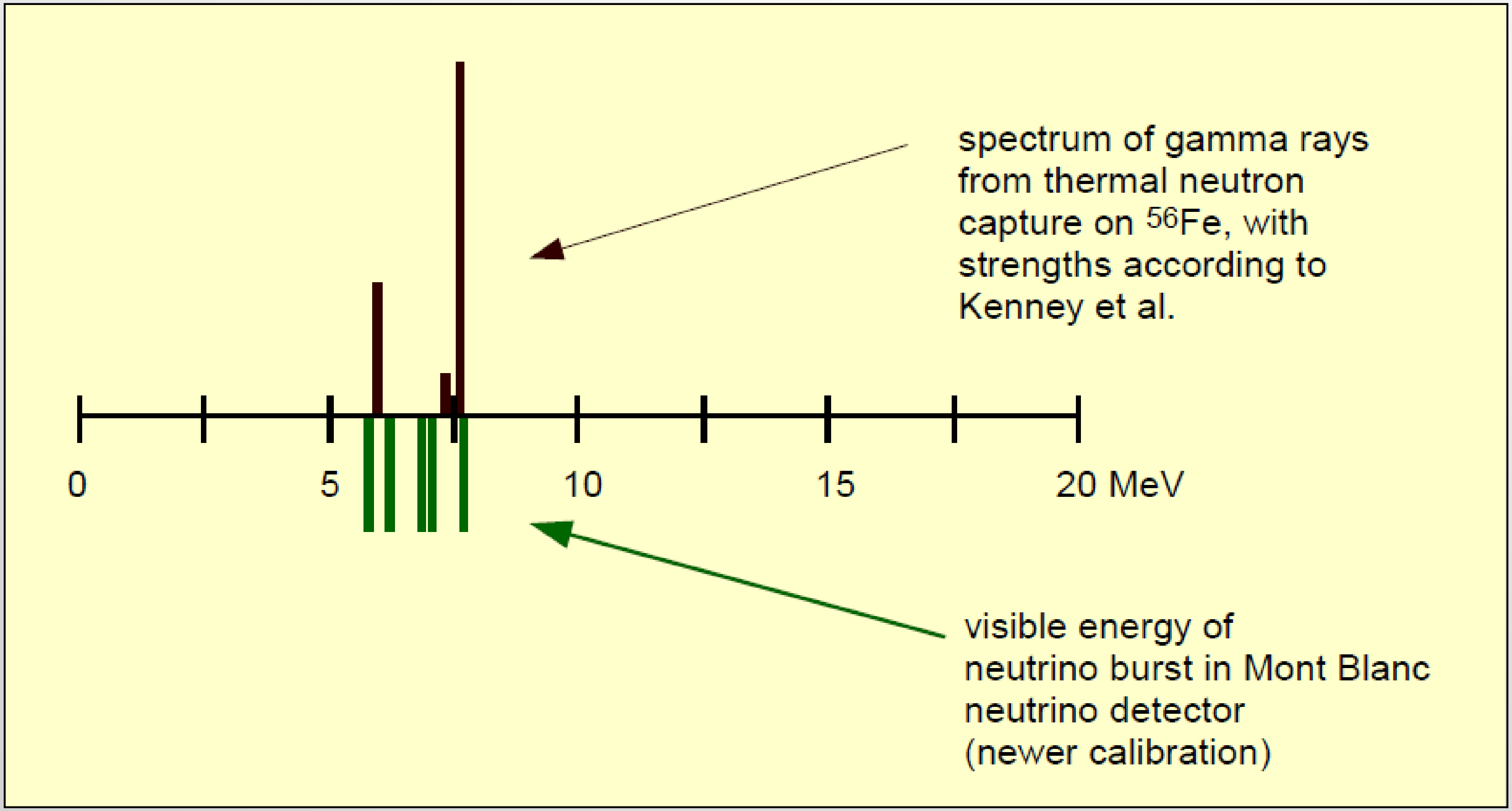
$$\tilde{\nu}_e + {}^{56}Fe \rightarrow e^+ + {}^{56}Mn^*$$
$$\searrow {}^{56}Mn + \gamma$$



$$\nu_{any} + Fe \rightarrow \nu'_{any} + Fe^{*}$$
$$\searrow Fe + \gamma$$



$$n + {}^{56}Fe \rightarrow {}^{57}Fe^{*}$$
$$\searrow {}^{57}Fe + \gamma$$



GEANT4 simulation

- GEANT4 version 9.4.
- Detailed geometry.
- Physics list (essentials for muon-induced neutrons):

Electromagnetic

mu- G4QCaptureAtRest

Photonuclear

mu+/-		1 GeV < E
gamma	CHIPS	E < 3.5 GeV
	QGSC	3 GeV < E < 100 TeV
e+/-	CHIPS	E < 10 TeV

Hadronics

HP	n	0 < E < 19.9 MeV
BiC	n	19.5 MeV < E < 6.1 GeV
BiC	p	0 < E < 6.1 GeV
LEP	p, n	6.1 GeV < E < 12 GeV
QGSP	p, n	12 GeV < E < 100 TeV
BiC	pi	0 < E < 1.5 GeV
LEP	pi	1.4 GeV < E < 12.1 GeV
QGSP	pi	12 GeV < E < 100 TeV
LEP	H2, H3, He4	0 < E < 100 MeV
BiC	He3, GenIon	0 < E < 10 GeV

Lindote A. et al., Astropart. Phys., **31**, p.366, 2009.

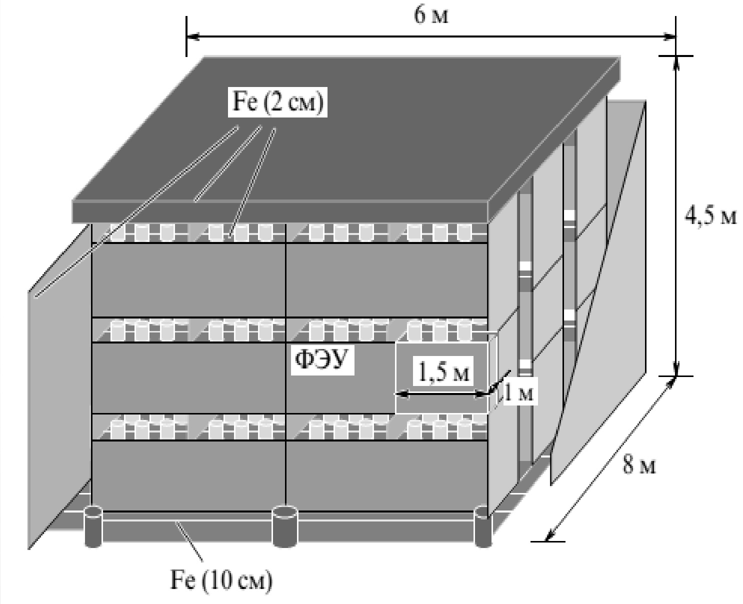
Evolution of the neutron yield in GEANT4

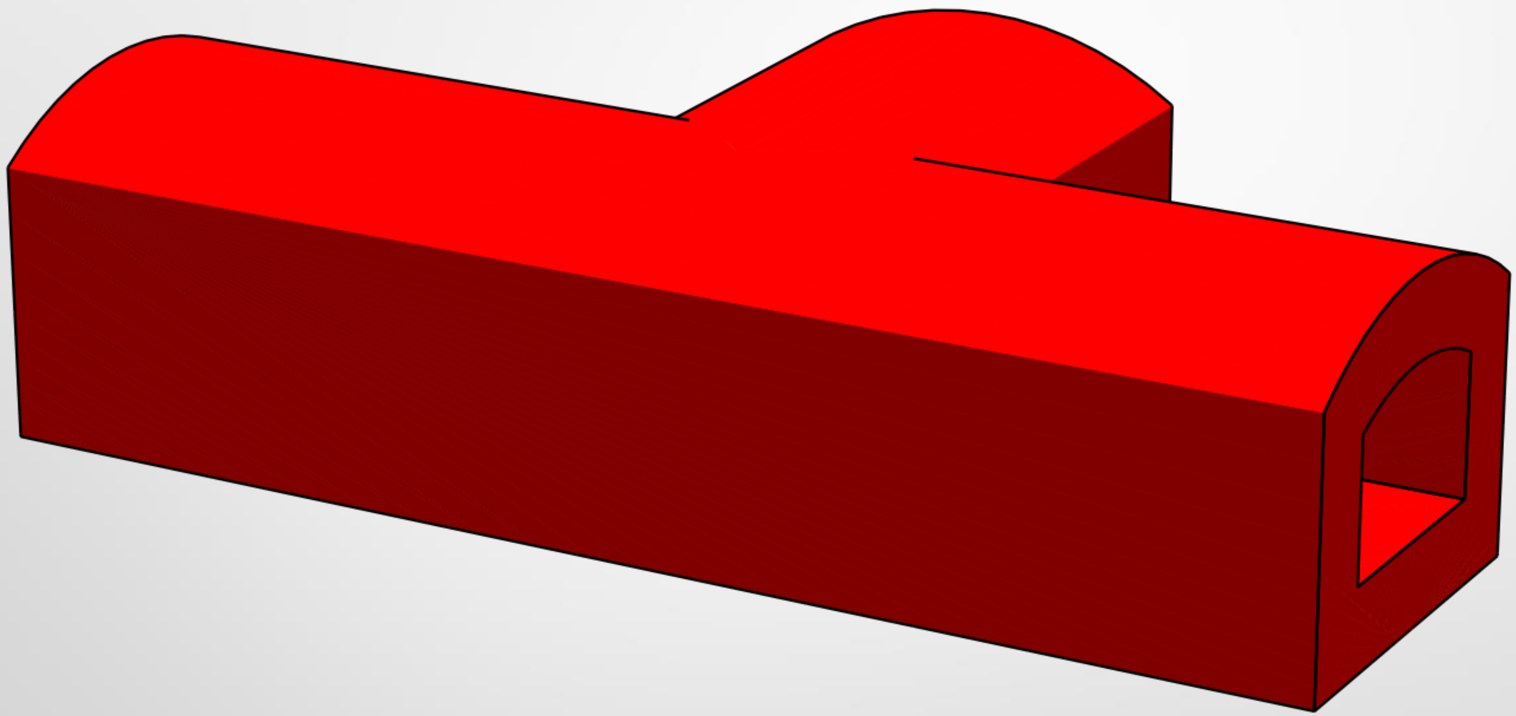
GEANT4 version	physics list	muon-induced neutron yield [neutrons/muon/(g/cm^2)]
8.2	custom list	$(2.846\pm0.006)\times10^{-3}$
9.4	custom list	$(3.304\pm0.003)\times10^{-3}$
9.4	QGSP_BIC_HP	$(3.376\pm0.003)\times10^{-3}$
9.4	Shielding	$(3.682\pm0.003)\times10^{-3}$
9.5	QGSP_BIC_HP	$(3.993\pm0.004)\times10^{-3}$
9.5	QGSP_BERT_HP	$(4.369\pm0.004)\times10^{-3}$
9.5	FTFP_BERT	$(4.467\pm0.004)\times10^{-3}$
9.5	Shielding	$(4.594\pm0.004)\times10^{-3}$

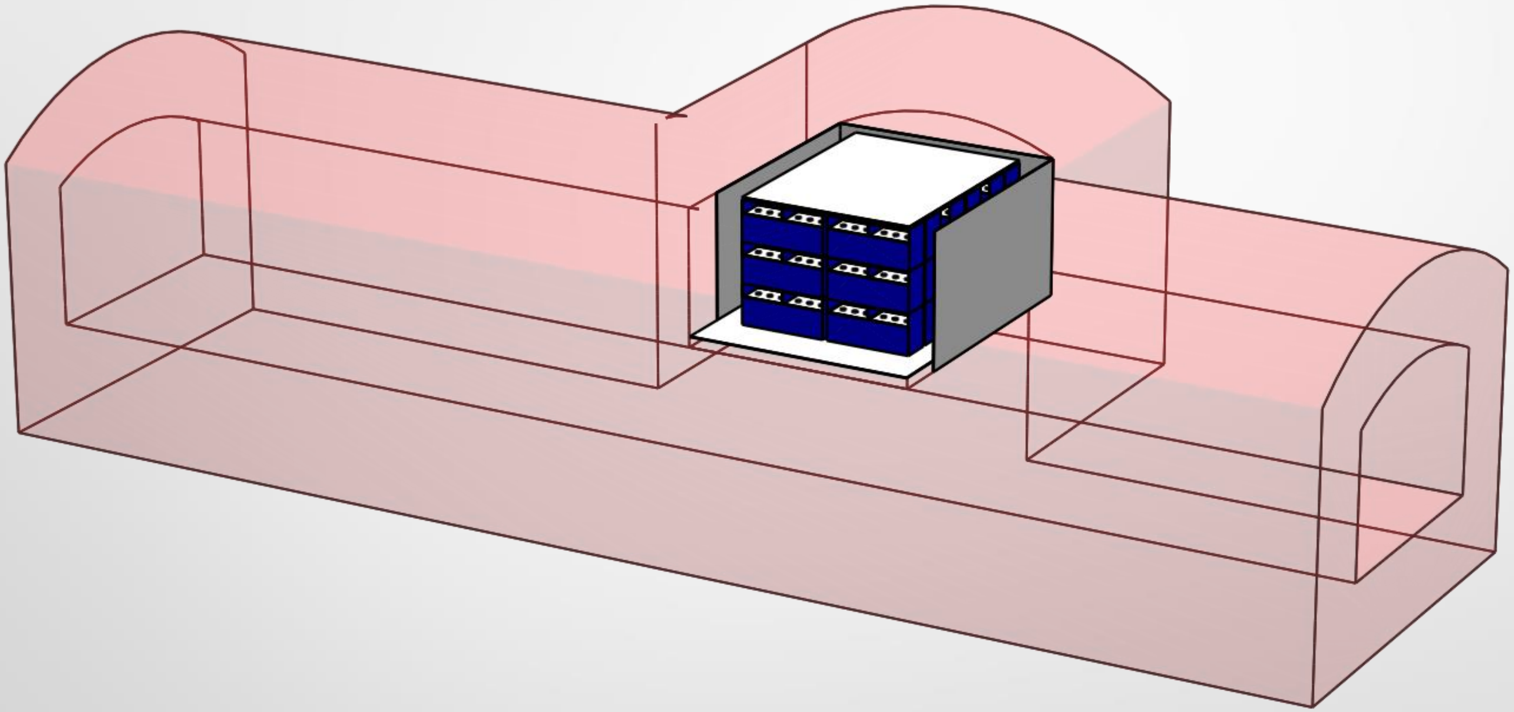
Reichhart L. et al., Astropart. Phys., **47**, p.67, 2013.

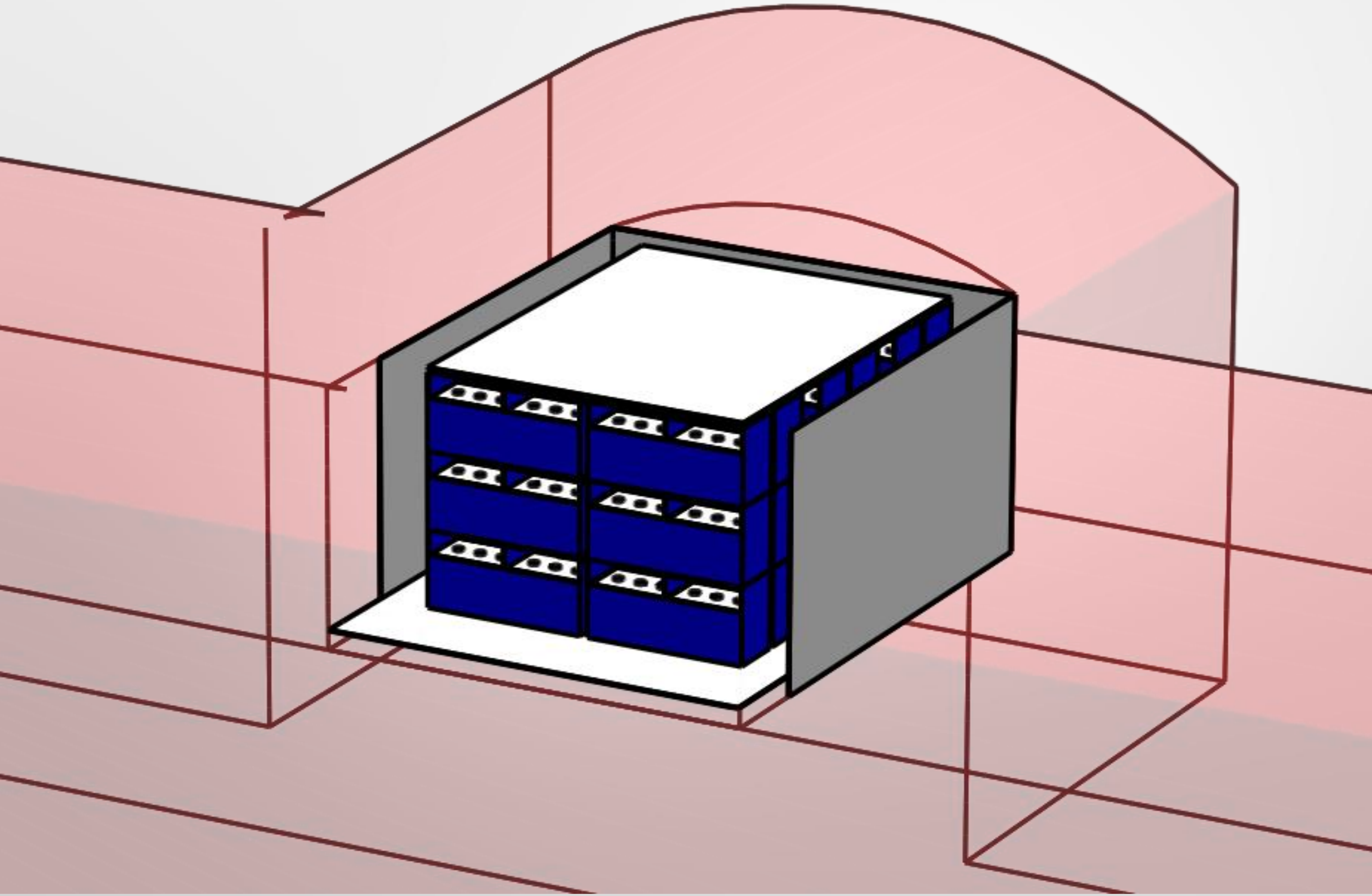
Chemical composition of Mont Black rock

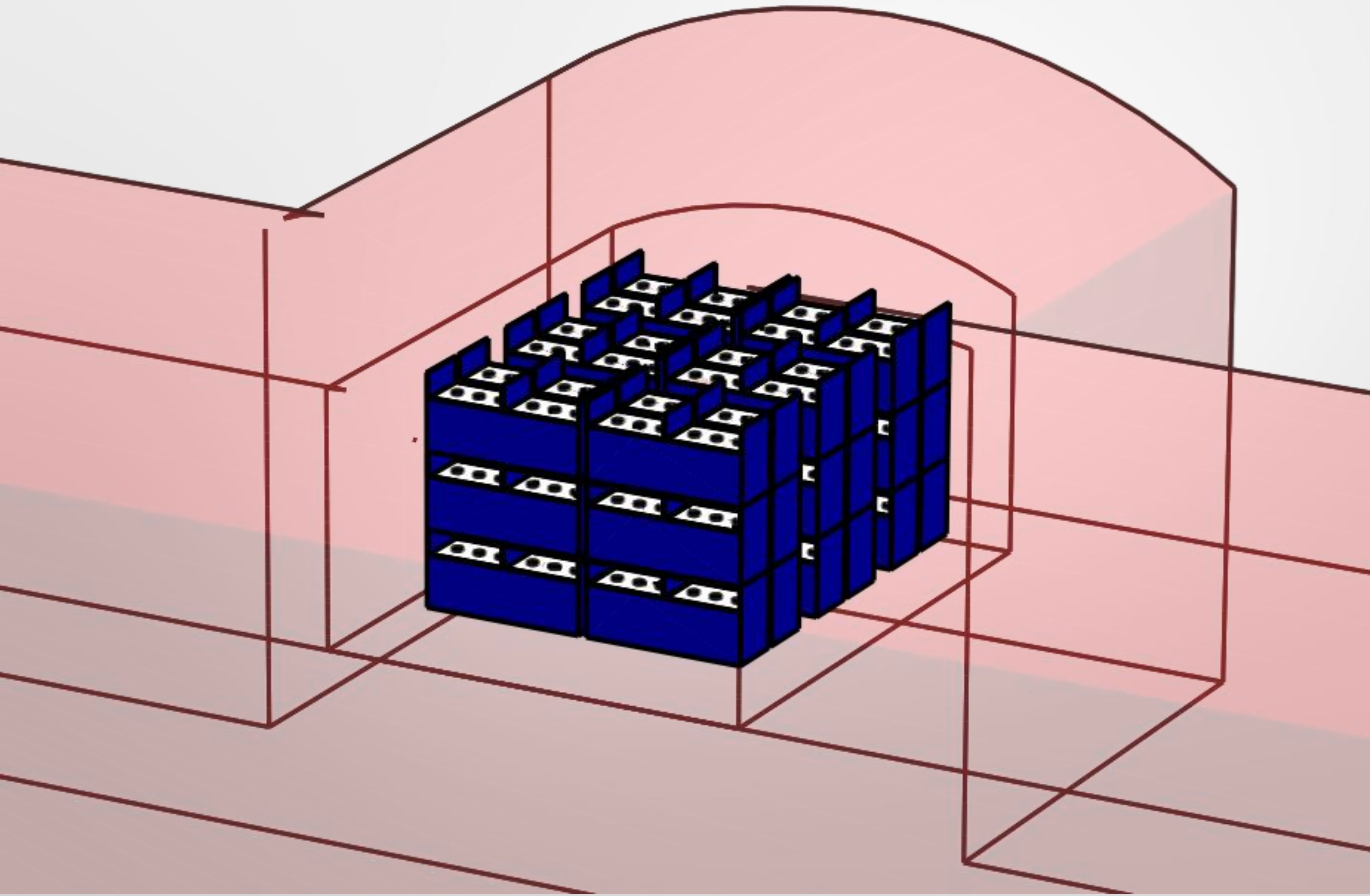
Element	Mass fraction %
SiO_2	75.4
AlO	13.7
FeO	0.99
NaO	3.73
KO	5.66
CaO	0.74
MgO	0.24

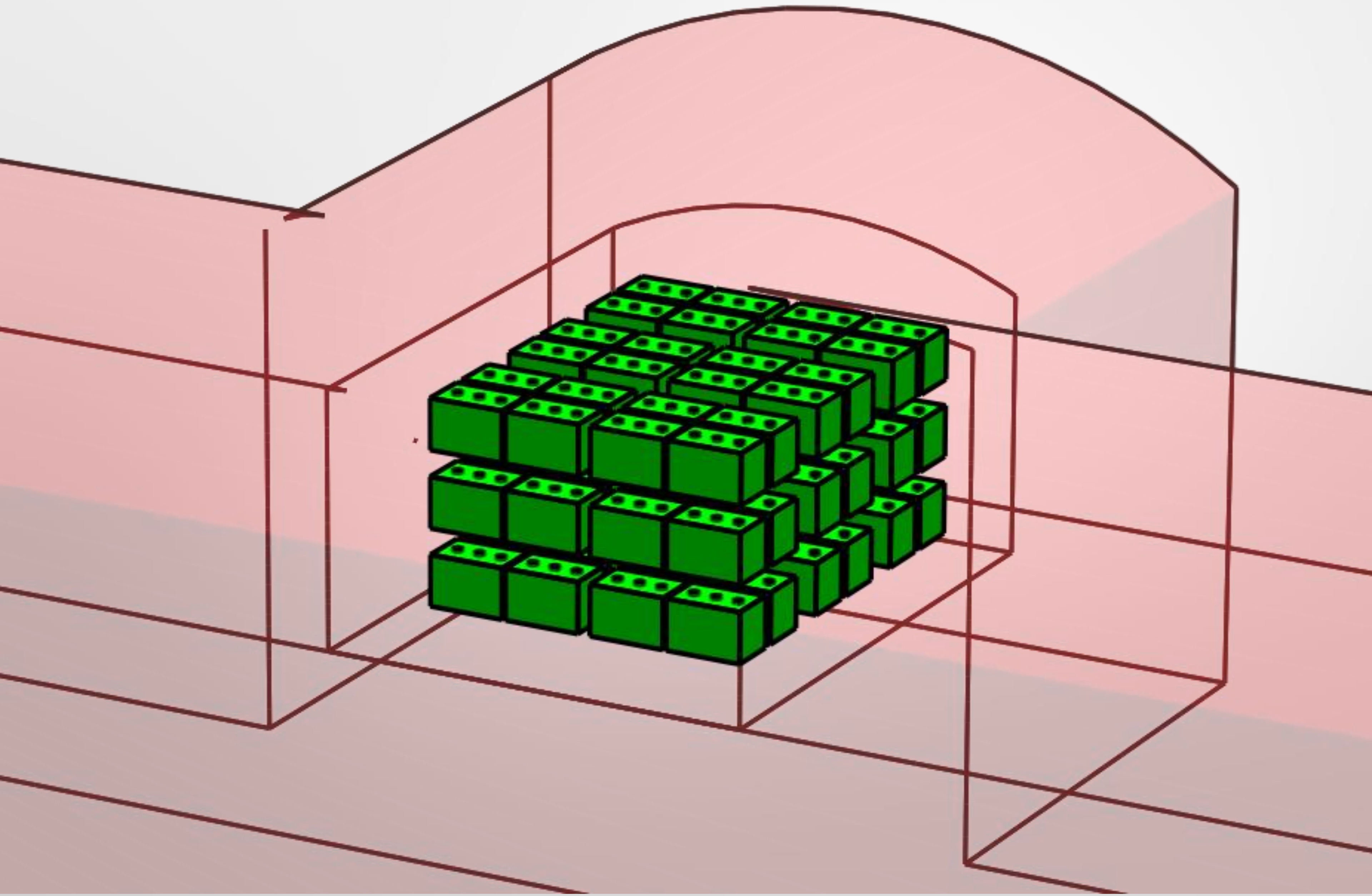


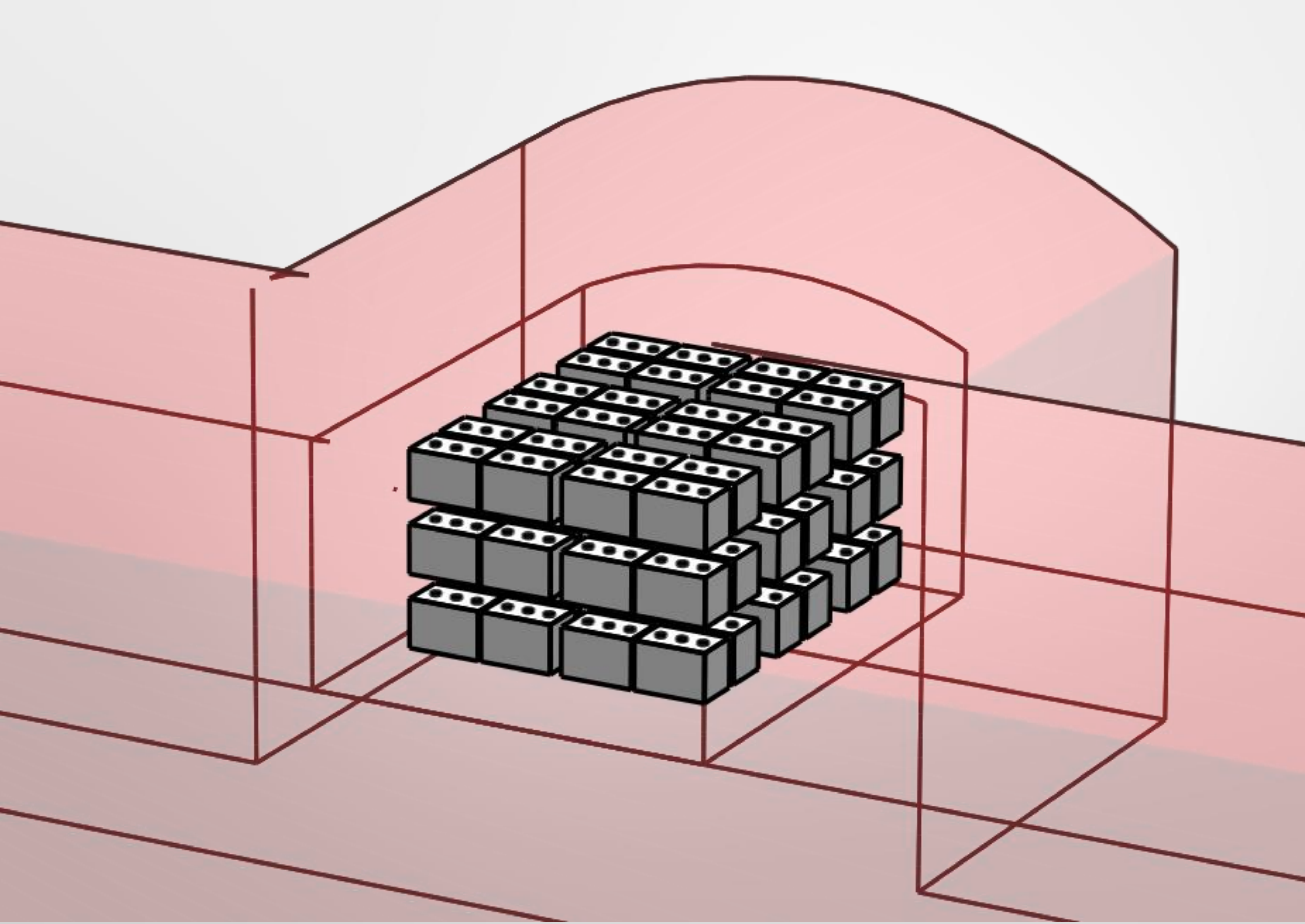






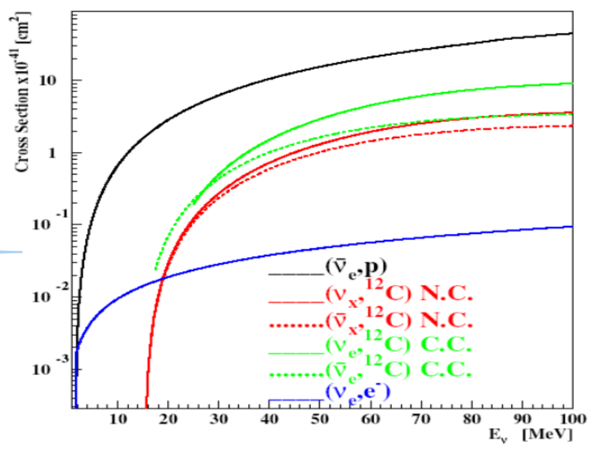


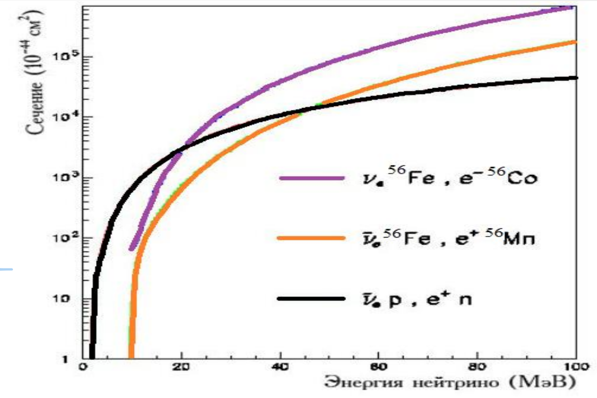


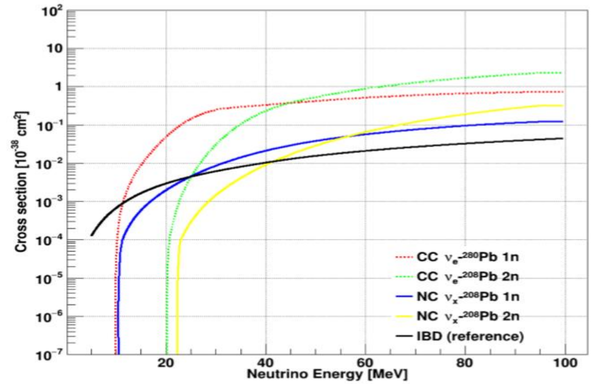


Neutrino interaction with LSD materials

$\bar{\nu}_e + p \to e^+ + n$	E_{th} = 1.8 МэВ
$n + p \to d + \gamma$	E_γ = 2.2МэВ
$n + \mathrm{Fe} \to \mathrm{Fe} + \Sigma\gamma.$	$\langle E_\gamma \rangle \approx$ 7МэВ
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	E_{th} = 17.3 МэВ
${}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e$	
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	E_{th} = 14.4 МэВ
${}^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$	
$\nu_i + {}^{12}\mathrm{C} \to \nu_i + {}^{12}\mathrm{C}^*$	E_{th} = 15.1 МэВ
${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma$	E_γ = 15.1 МэВ
${}^{12}\mathrm{C}^* \to {}^{11}\mathrm{C} + n$	E_n = 8 – 9 МэВ
${}^{12}\mathrm{C}^* \to {}^{11}\mathrm{B} + p$	E_p = 8 – 9 МэВ
$\nu_i + e^- \to \nu_i + e^-$	-
$\nu_e + {}^{56}\mathrm{Fe} \to e^- + {}^{56}\mathrm{Co}^*$	E_{th} = 10 МэВ
${}^{56}\mathrm{Co}^* \to {}^{56}\mathrm{Co} + \Sigma\gamma$	E_γ = 7-11 МэВ
${}^{56}\mathrm{Co}^* \to {}^{55}\mathrm{Co} + n$	
${}^{56}\mathrm{Co}^* \to {}^{55}\mathrm{Fe} + p$	
$\bar{\nu}_e + {}^{56}\mathrm{Fe} \to e^+ + {}^{56}\mathrm{Mn}^*$	E_{th} = 12.5 МэВ
${}^{56}\mathrm{Mn}^* \to {}^{56}\mathrm{Mn} + \gamma$	
${}^{56}\mathrm{Mn}^* \to {}^{55}\mathrm{Mn} + n$	
${}^{56}\mathrm{Mn}^* \to {}^{55}\mathrm{Cr} + p$	
$\nu_i + {}^{56}\mathrm{Fe} \to \nu_i + {}^{56}\mathrm{Fe}^*$	E_{th} =15.0 МэВ
${}^{56}\mathrm{Fe}^* \to {}^{56}\mathrm{Fe} + \gamma$	$E_\gamma \approx$ 7.6 МэВ
${}^{56}\mathrm{Fe}^* \to {}^{55}\mathrm{Fe} + n$	
${}^{56}\mathrm{Fe}^* \to {}^{55}\mathrm{Mn} + p$	







Detecting supernova neutrinos with iron and lead detectors

Abhijit Bandyopadhyay,[1,*] Pijushpani Bhattacharjee,[2,†] Sovan Chakraborty,[3,4,‡] Kamales Kar,[1,§] and Satyajit Saha[2,¶]

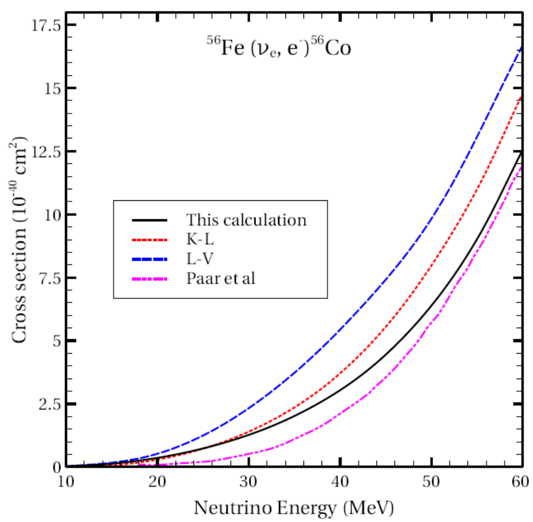
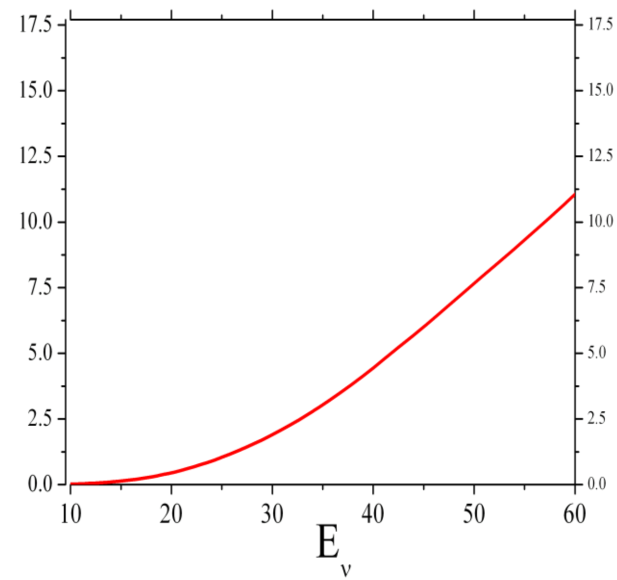
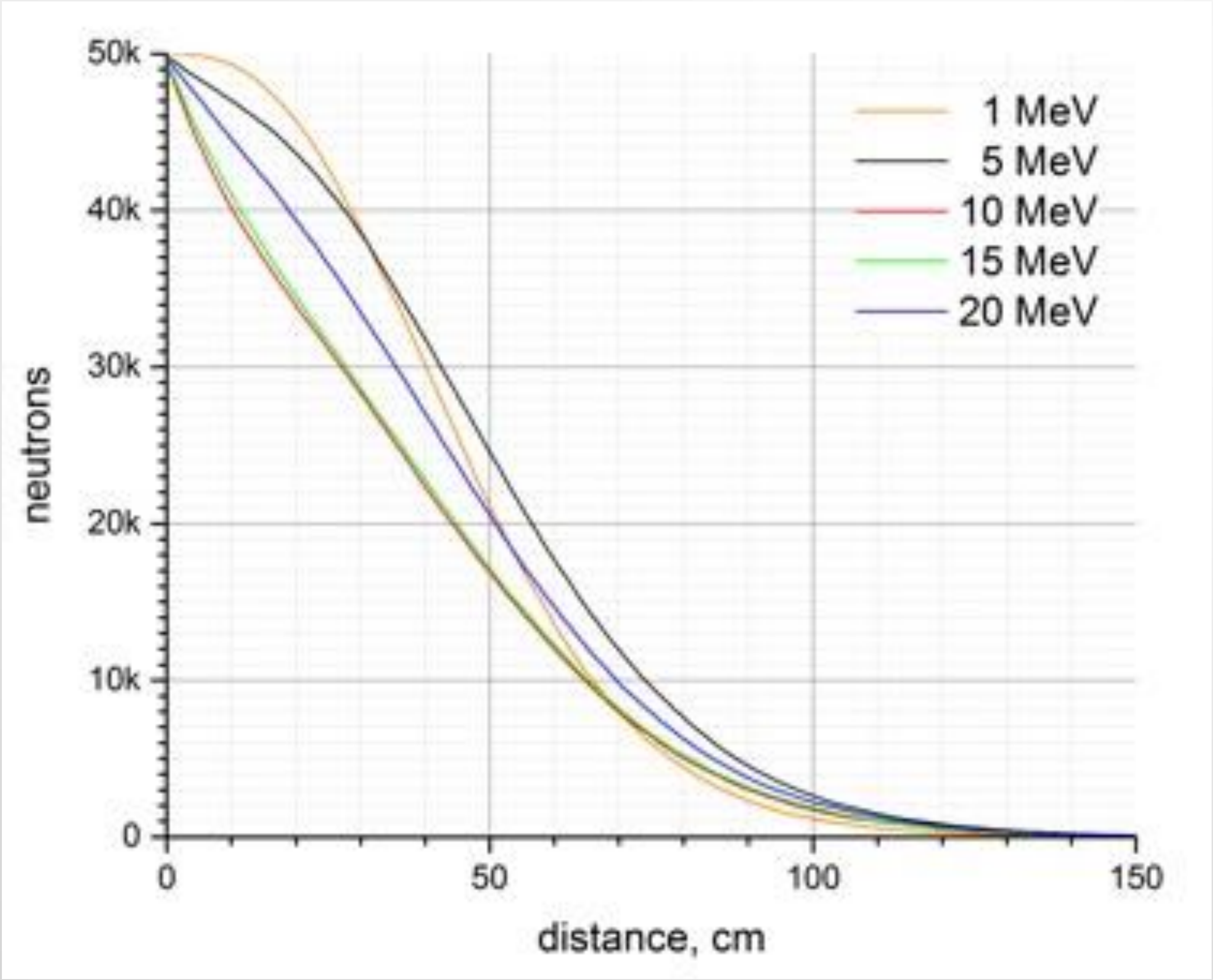


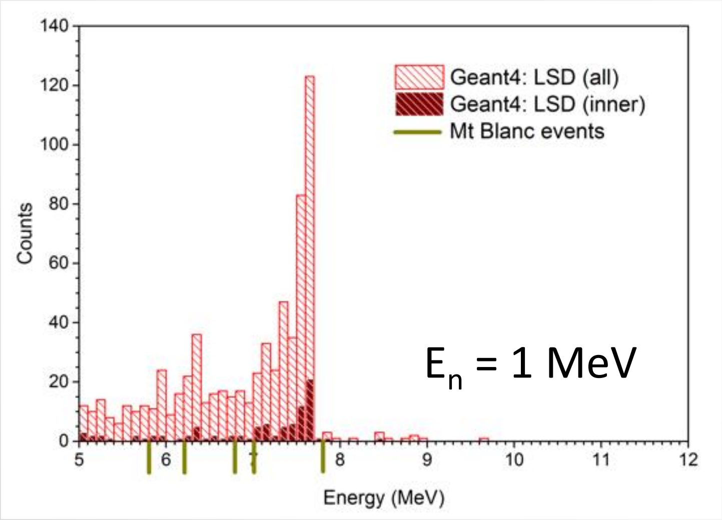
FIG. 5: Total ^{56}Fe$(\nu_e, e^-)^{56}$Co cross section as a function of neutrino energy. For comparison, the cross sections obtained in Refs. [9] (K-L), [41] (L-V) and [42] (Paar et al) are also shown.

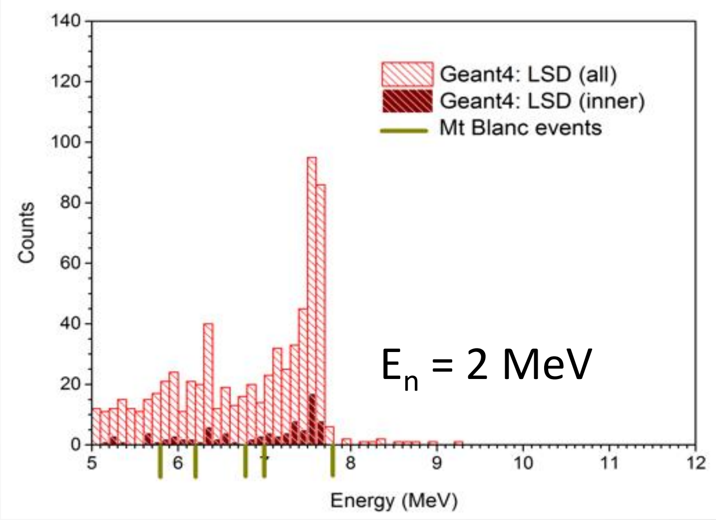


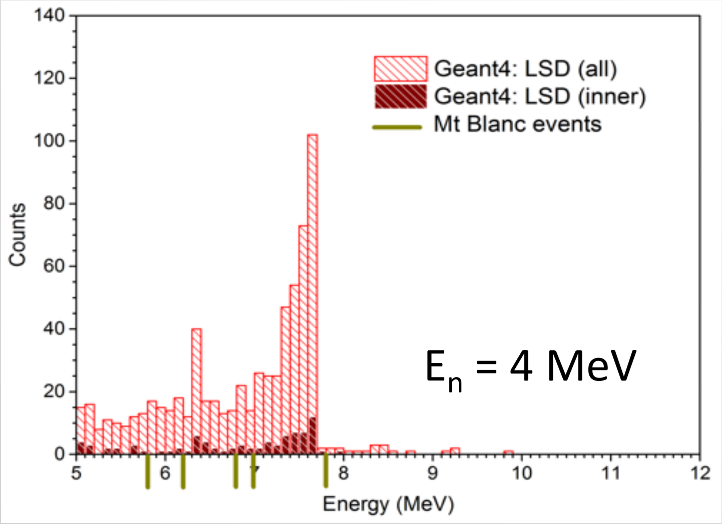
Neutrons propagation in granite

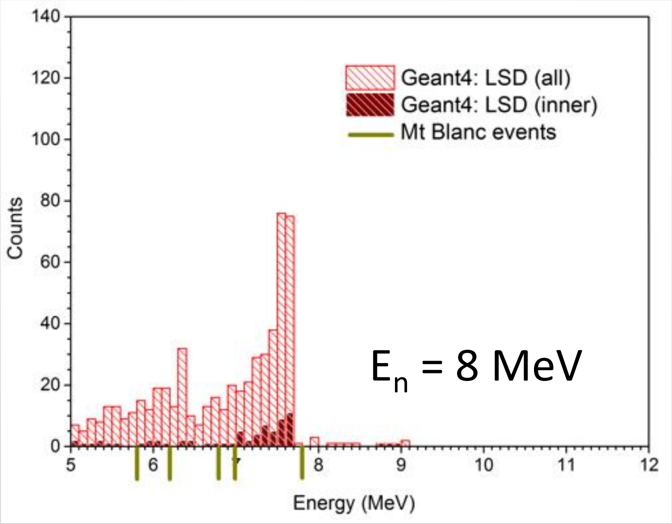


Geant4 simulation of detector response to neutrons produced in the granite layer

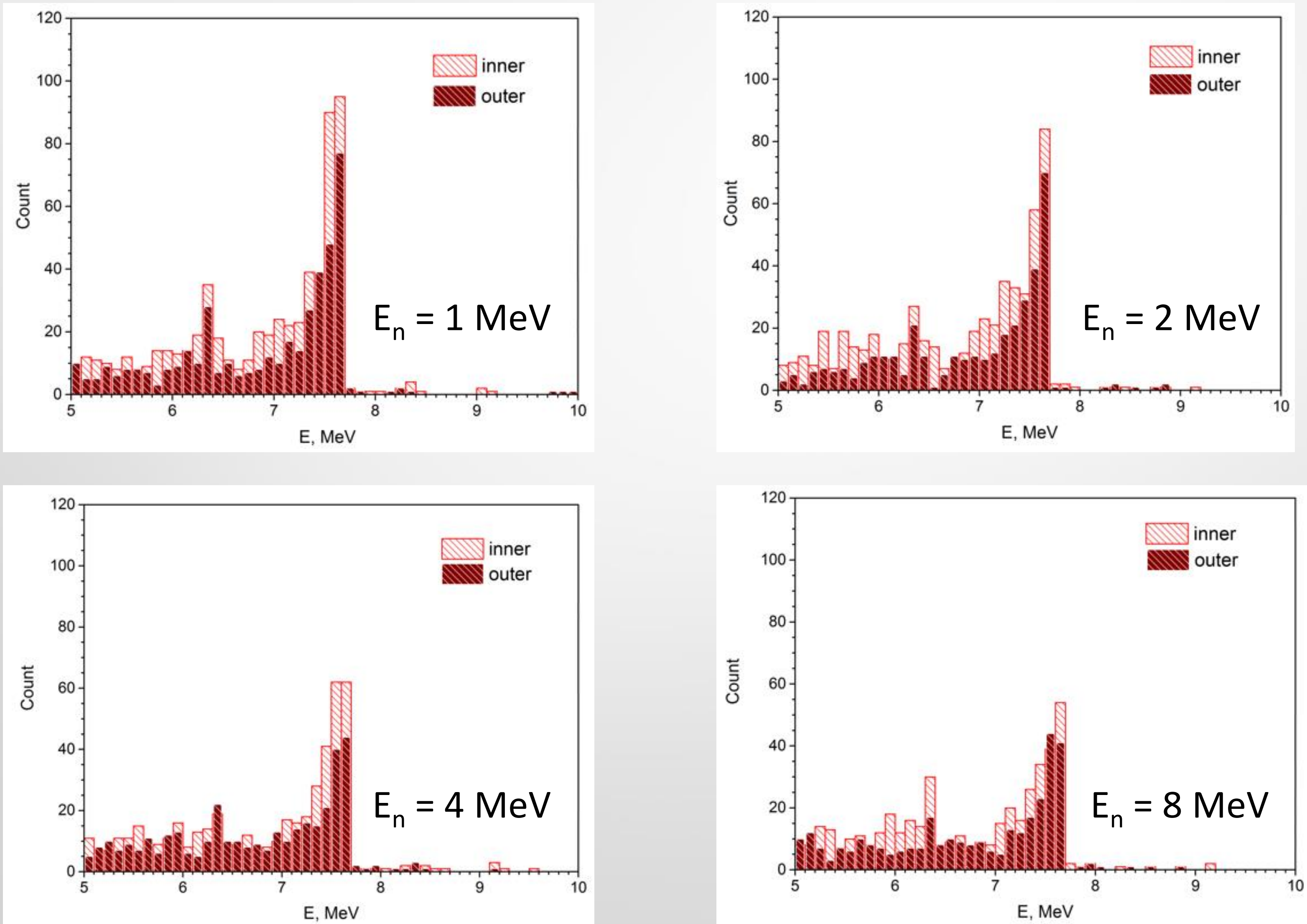








Geant4 simulation of detector response to neutrons produced in the LSD iron



Примеры реакций

$\langle E_\nu \rangle = 15$ MeV

Eν=22.34, place=Scint, nucleus=H1

run: e+, neutron

N 5222 E = 20.978, t = 2.687E-6
N 5222 E = 0.1089, t = 0.0105
N 5222 E = 1.2259, t = 160.54
N 4222 E = 0.1771, t = 160.55

Eν=31.808, place=Granite, nucleus=O16

run: e+, neutron, neutron, gamma, N14

N 1221 E = 0.13513, t = 0.49344
N 1221 E = 6.7123, t = 124.63

$\langle E_\nu \rangle = 40$ MeV

Eν=19.36018, place=Steel, nucleus=Fe56

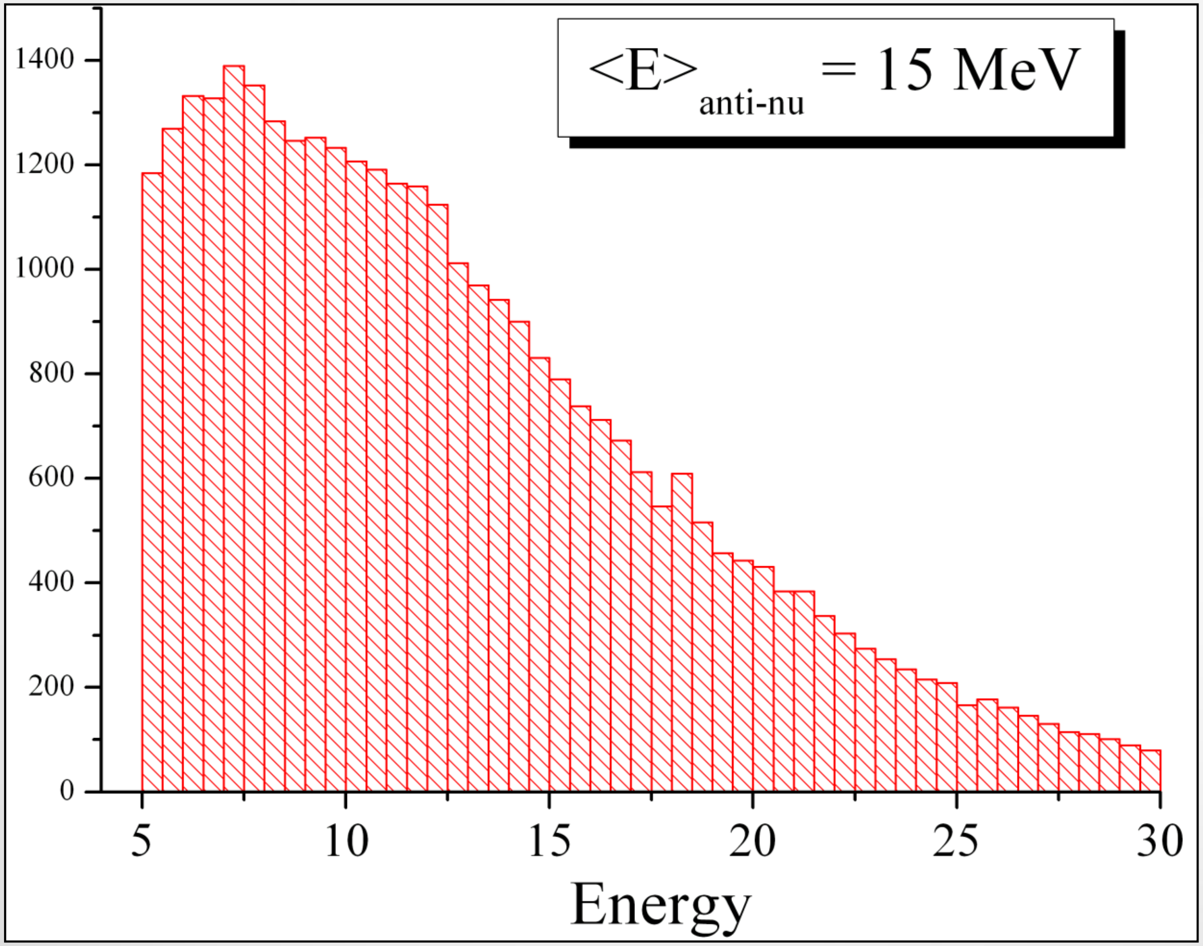
run: e-, gamma, gamma, gamma, Co56

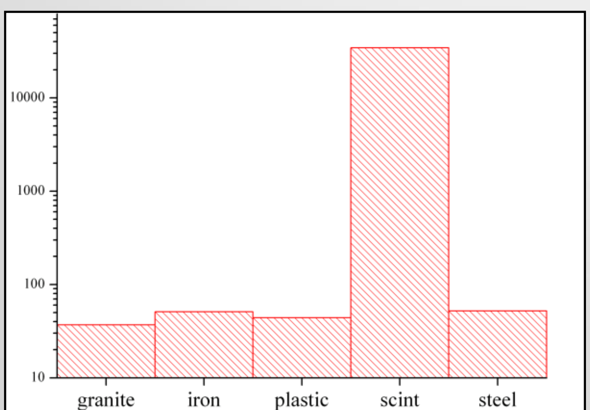
N 1121 E = 5.8699, t = 1.409E-5
N 1121 E = 0.64718, t = 3.3193E13
N 2121 E = 1.8593, t = 3.3193E13

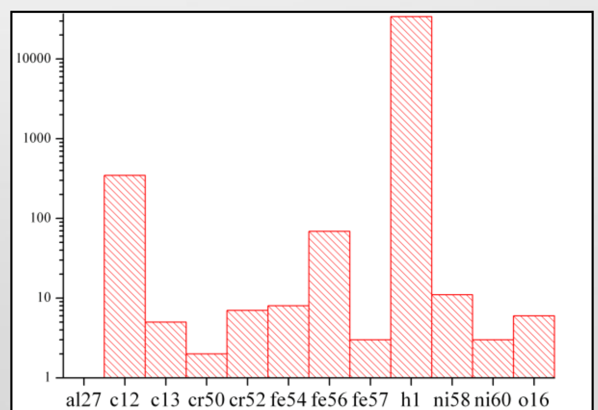
Eν = 55.84111, place=Scint, nucleus=C12

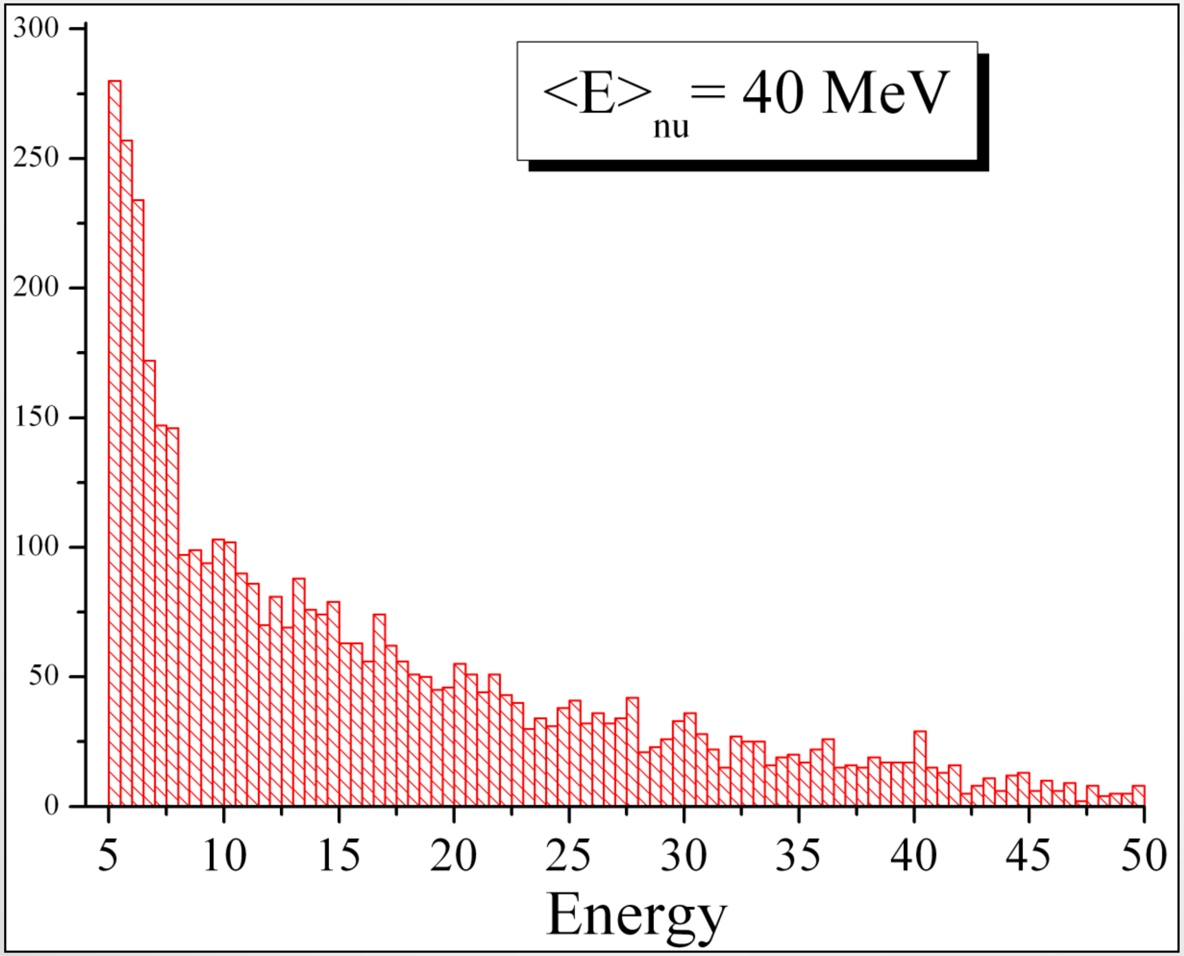
run: proton, gamma, B11

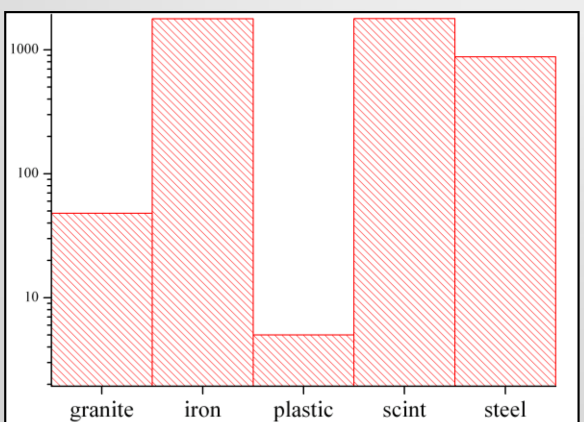
N 4231 E = 0.46383, t = 2.8714E-7
N 4231 E = 7.0736, t = 2.5414E-6

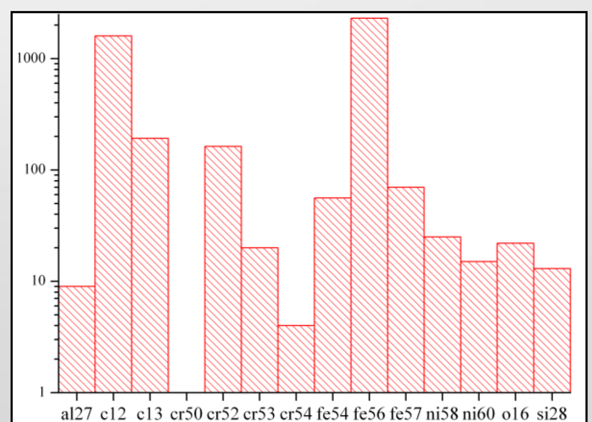

<E>anti-nu = 15 MeV
1400
1200
1000
800
600
400
200
0
5
10
15
20
25
30
Energy

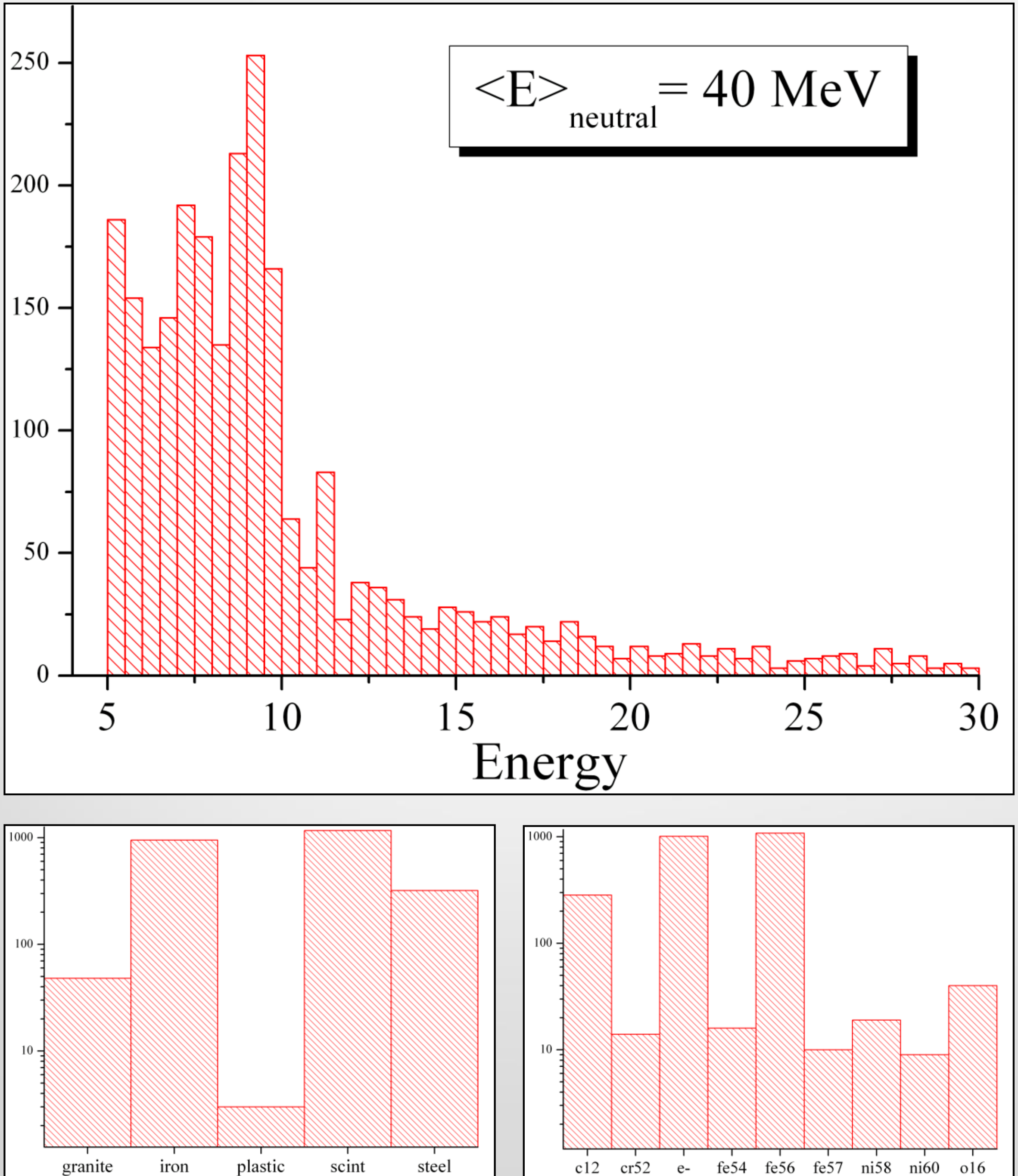

10000
1000
100
10
granite
iron
plastic
scint
steel


10000
1000
100
10
1
al27
c12
c13
cr50
cr52
fe54
fe56
fe57
h1
ni58
ni60
o16


<E> nu = 40 MeV
300
250
200
150
100
50
0
5 10 15 20 25 30 35 40 45 50
Energy


1000
100
10
granite iron plastic scint steel


1000
100
10
1
al27 c12 c13 cr50 cr52 cr53 cr54 fe54 fe56 fe57 ni58 ni60 o16 si28



<E>neutral = 40 MeV
250
200
150
100
50
0
5
10
15
20
25
30
Energy
1000
100
10
granite
iron
plastic
scint
steel
1000
100
10
c12
cr52
e-
fe54
fe56
fe57
ni58
ni60
o16

Тип реакции	Ожидаемое число энерговыдел.	Вероятность 5<E<10 МэВ	Доля событий, пришедших из грунта	Доля событий с нейтронами
15 МэВ anti-nu-e	**1.92**	**0.379**	**0.0011**	**6.4e-4**
30 МэВ anti-nu-e	**5.6**	**0.175**	**0.0029**	**9.2e-3**
40 МэВ anti-nu-e	**8.46**	**0.135**	**0.0054**	**1.96e-2**
15 МэВ nu-e	**0.08**	**0.635**	**0.0017**	**1.1e-2**
30 МэВ nu-e	**1.1**	**0.449**	**0.0045**	**2.43e-2**
40 МэВ nu-e	**2.6**	**0.371**	**0.0093**	**2.86e-2**
15 МэВ neutral	**0.046**	**0.69**	**0.0006**	**6.8e-3**
30 МэВ neutral	**0.22**	**0.69**	**0.0092**	**1.64e-2**
40 МэВ neutral	**0.41**	**0.69**	**0.0193**	**3.52e-2**

Спасибо за внимание!