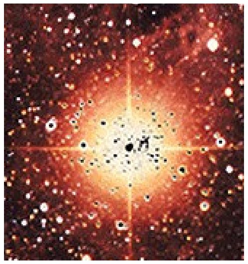
Supernova neutrino detection

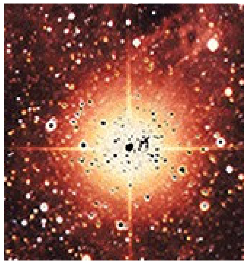
Marco Selvi
Bologna University
& INFN

Summary



- SN ν generalities
- ν oscillations in the SN and in the Earth
- SN ν detector generalities
- Existing and future detectors
- Some "new" ideas in the market
- LVD detector description
- ν interactions in iron

SN ν generalities



The main features of the ν flux originally produced in the star are:

1. Neutrinos of a given flavor ν_α have a Fermi-Dirac energy spectrum,
we assume no pinching (η=0) :

$$F_\alpha^0 \propto \frac{L_\alpha}{D^2 T_\alpha^4} \frac{E^2}{\exp(E/T_\alpha)+1}$$

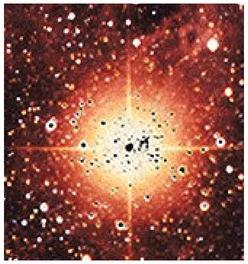
2. The hierarchy of the temperatures: $T_{\nu e} < T_{\overline{\nu e}} < T_{\nu x}$.
Recent studies with an improved treatment of neutrino transport, microphysics, the inclusion of nuclear bremsstrahlung, and the energy transfer by recoils find somewhat smaller differences between the ν_e and ν_x spectra
(see for example astro-ph/0303226).

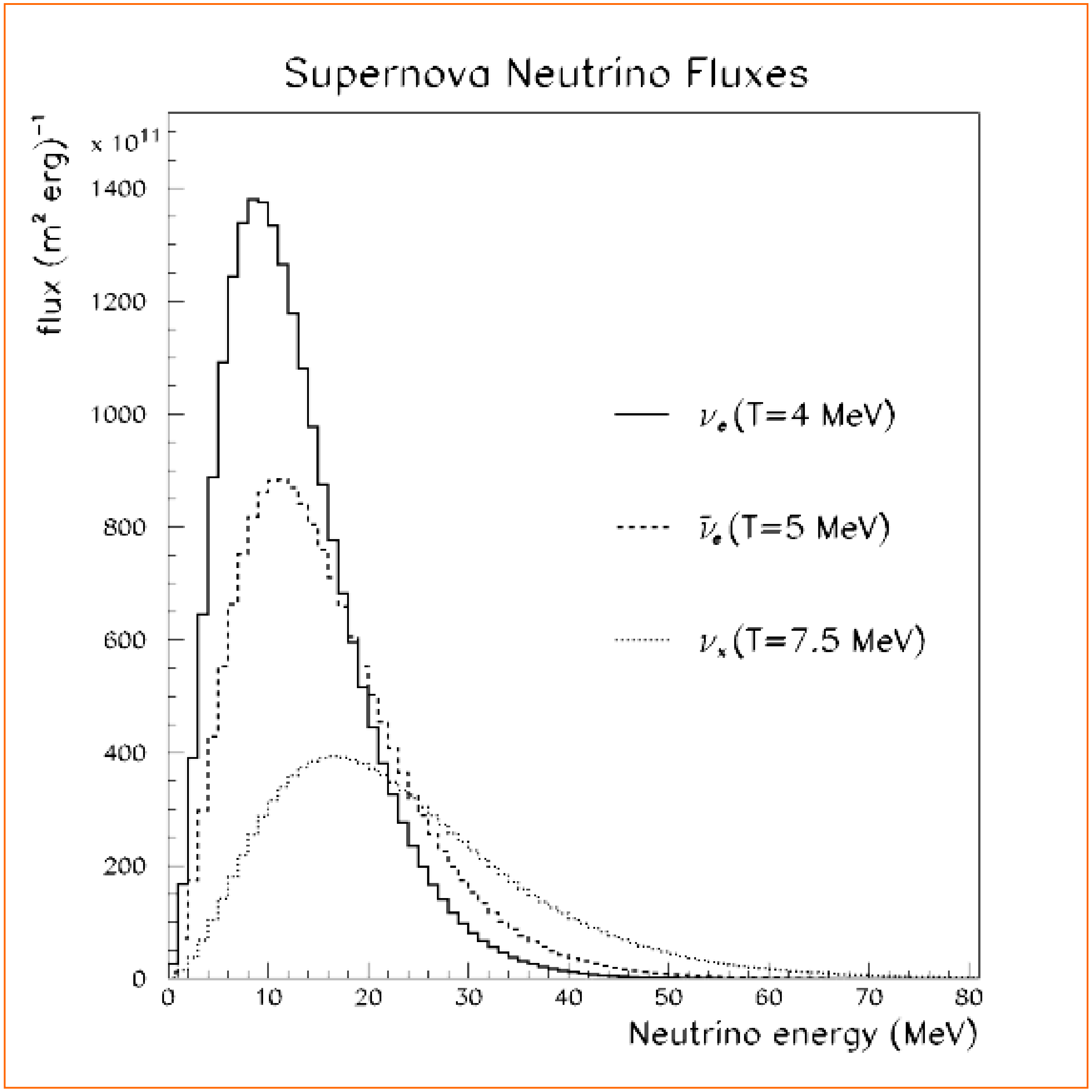
3. The approximate equipartition of energy among flavors: $L_{\nu e} \cong L_{\overline{\nu e}} \cong L_{\nu x} \cong E_B/6$.

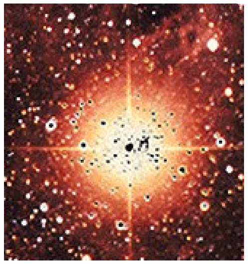
In the following we assume a future galactic SN explosion with:

- a typical distance of D=10 kpc,
- a binding energy of E_B= 3 x 10^{53} erg,
- perfect energy equipartition $L_{\nu e} = L_{\nu e} = L_{\nu x} = E_B/6$.
- assume that the fluxes $\nu_\mu \overline{\nu}_\mu \nu_\tau \overline{\nu}_\tau$ are identical ($\equiv \nu_x$),
- fix the ratio $T_{\nu x}/T_{\overline{\nu e}}$ =1.5 , $T_{\nu e}/T_{\overline{\nu e}}$ =0.8 and $T_{\overline{\nu e}}$ =5 MeV.

SN ν fluxes




Supernova Neutrino Fluxes
flux (m^2 erg)$^{-1}$
x 10^{11}
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
Neutrino energy (MeV)
ν_e (T=4 MeV)
$\bar{\nu}_e$ (T=5 MeV)
ν_x (T=7.5 MeV)



Neutrino oscillations in SN

Neutrino oscillations in SN

We consider the system of 3 active neutrinos $\nu_f=(\nu_e, \nu_\mu, \nu_\tau)$, mixed in vacuum such that $\nu_f=U\ \nu_m$ where $\nu_m=(\nu_1, \nu_2, \nu_3)$ is the vector of mass eigenstates and U is the mixing matrix.

If neutrinos have mass they could oscillate between flavors.

The oscillation is resonantly enhanced if a flavor-asymmetric medium is present (MSW matter effect).

The medium density ρ_{res} for the resonance to occur depends on the oscillation parameters.

$$\rho_{res} \approx \frac{1}{2\sqrt{2}G_F}\frac{\boxed{\Delta m^2}}{E}\frac{m_N}{Y_e}\cos\boxed{2\vartheta}$$

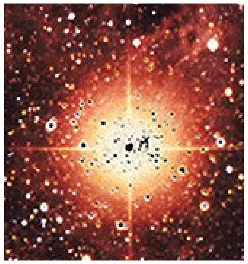
<u>The wide range of density values in the SN matter allows for 2 resonance levels.</u>

	ρ (g/cc)	Medium	Osc. parameters involved
ρ_H	10^3–10^4	He	"ATM" (Δm^2_{atm}, U_{e3}^2).
ρ_L	10–30	H	"MSW LMA" (Δm^2_{sol}, U_{e2}^2)

The resonance is expected for ν or $\overline{\nu}$ depending on the mass hierarchy (=sign of Δm^2_{atm})

sign of Δm^2_{atm}	Resonance in
+ (normal hierarchy)	ν
- (inverted hierarchy)	$\overline{\nu}$

Neutrino oscillations in SN



In the study of SN neutrinos, ν_μ and ν_τ are indistinguishable, →
the relevant oscillation parameters are just $(\Delta m^2_{sol}, U_{e2}^2)$ and $(\Delta m^2_{atm}, U_{e3}^2)$.

We will adopt the following numerical values:

$U_{e2}^2=0.33$, $\Delta m^2_{sol}= 7 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm}= 2.5 \times 10^{-3}\ eV^2$.

Given the energy range of SN ν (up to ~100 MeV), and considering a star density profile $\rho \propto 1/r^3$, the adiabaticity condition is always satisfied at the L resonance for any LMA solution, while at the H resonance, this depends on the value of U_{e3}^2.

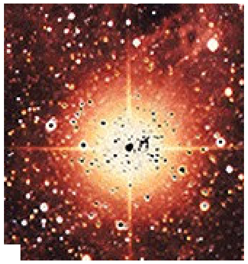
$$P_H \propto \exp\left[- const\ U_{e3}^2 (\Delta m^2_{atm}/E)^{2/3}\right]$$

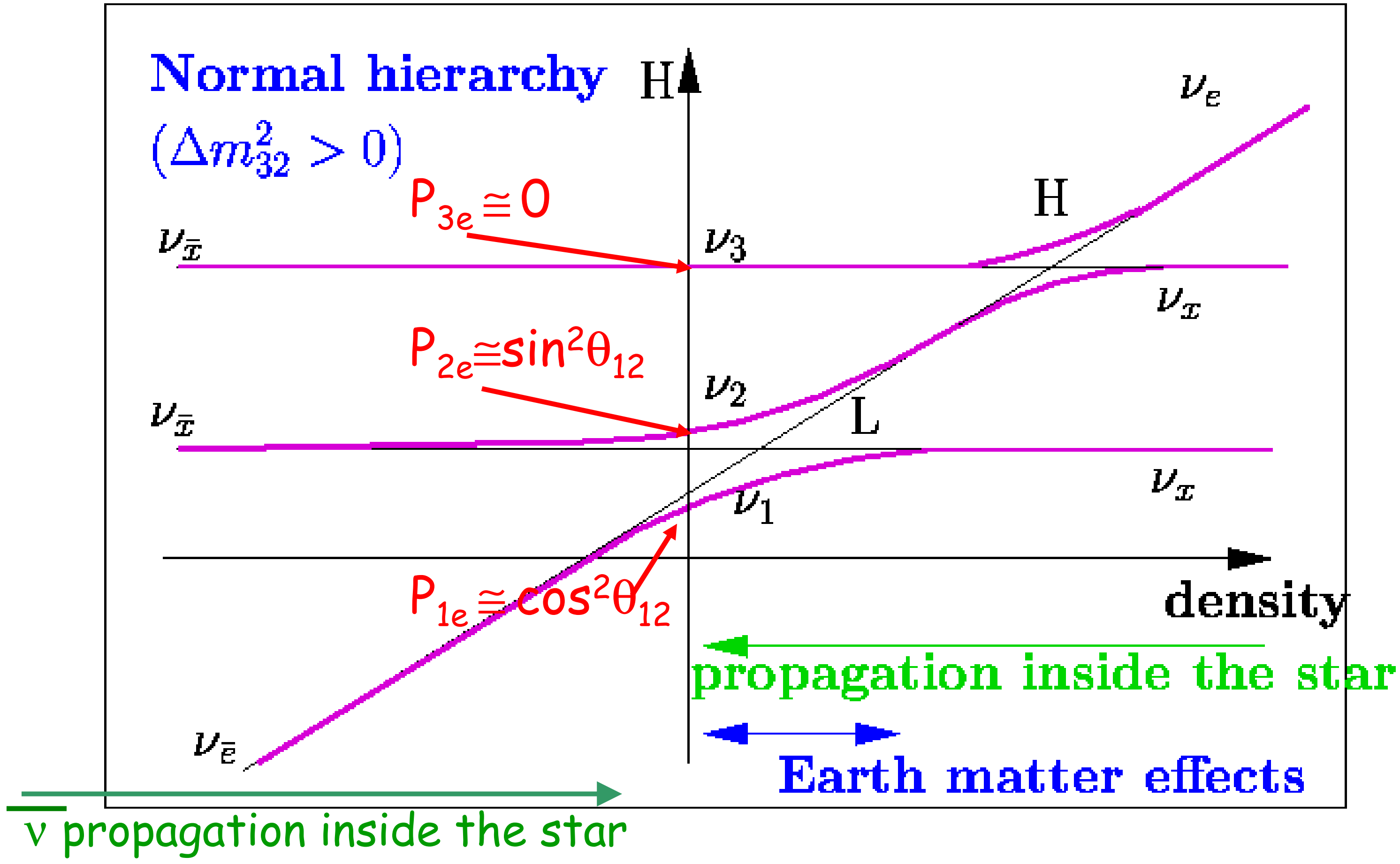
- $U_{e3}^2 \geq 5 \times 10^{-4}$ → completely adiabatic conversion → $P_H=0$
(the flip probability between two adiacent mass eigenstates is null)

- $U_{e3}^2 \leq 5 \times 10^{-6}$ → completely non adiabatic conversion → $P_H=1$.

We used in the calculation $U_{e3}^2 = 10^{-2}$, which is just behind the corner of the CHOOZ upper limit, for the adiabatic transition case, and $U_{e3}^2 = 10^{-6}$ for the non-adiabatic one.

Neutrino oscillations in SN

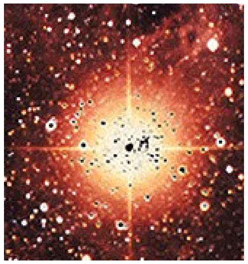


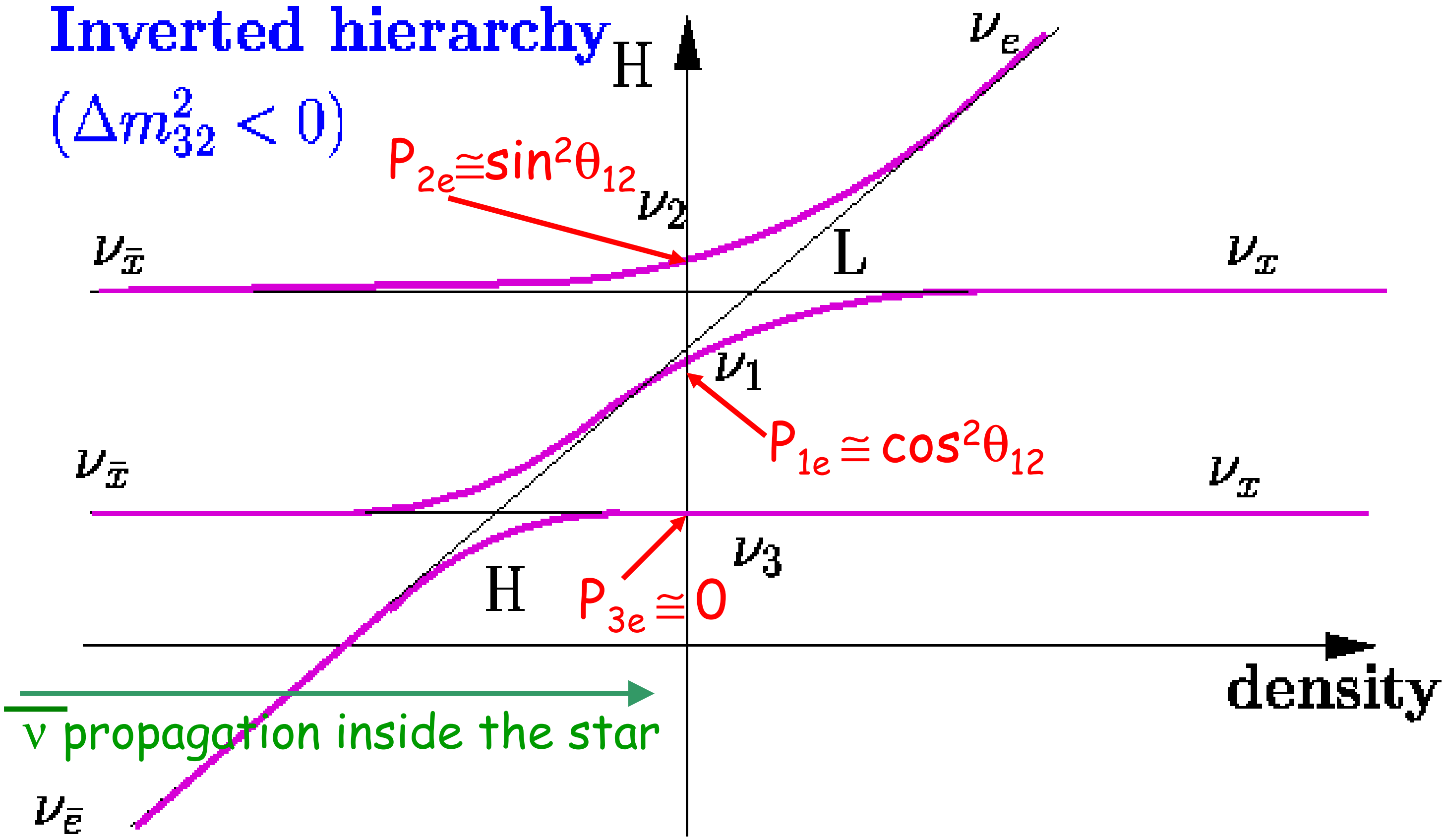


In the NH case a part ($\sin^2\theta_{12}$) of the detected $\bar{\nu}_e$ come from the original $\bar{\nu}_x$ flux in the star.

- $F_{\bar{e}} = \cos^2\theta_{12} \, F^0_{\bar{e}} + \sin^2\theta_{12} \, F^0_{\bar{x}}$

Neutrino oscillations in SN





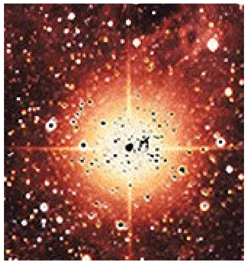
$P_{2e} \cong \sin^2\theta_{12}$

$P_{1e} \cong \cos^2\theta_{12}$

$P_{3e} \cong 0$

In the adiabatic-IH case ALL the detected $\overline{\nu}_e$ come from the original $\overline{\nu}_x$ flux in the star and both the number of interactions and the mean energy of the detected events are still greater.

Neutrino oscillations in SN



The observed ν_e and $\bar{\nu}_e$ fluxes (without Earth crossing) are:

$$\begin{cases} F_e = P_H \sin^2\theta_{12}\, F^0_e + (1 - P_H \sin^2\theta_{12})\, F^0_x \\ F_{\bar{e}} = \cos^2\theta_{12}\, F^0_{\bar{e}} + \sin^2\theta_{12}\, F^0_{\bar{x}} \end{cases}$$

for normal hierarchy

$$\begin{cases} F_e = \sin^2\theta_{12}\, F^0_e + \cos^2\theta_{12}\, F^0_x \\ F_{\bar{e}} = P_H \cos^2\theta_{12}\, F^0_{\bar{e}} + (1 - P_H \cos^2\theta_{12})\, F^0_{\bar{x}} \end{cases}$$

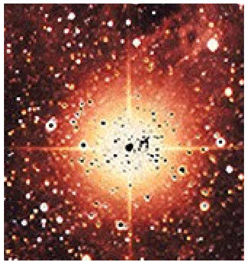
for inverted hierarchy

where F^0_e, $F^0_{\bar{e}}$, F^0_x are the original neutrino fluxes in the star and F_e, $F_{\bar{e}}$, F_x are the observed ν fluxes.

F_e and $F_{\bar{e}}$, have harder energy spectra than the original ν_e and $\nu_{\bar{e}}$ fluxes, due to the contribution of F^0_x.

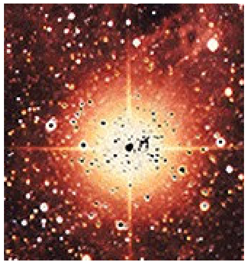
One can notice that, in the antineutrino channel, the non adiabatic (P_H=1), IH case, is equivalent to the NH case (which does not depend on the adiabaticity of the transition). Similar considerations are valid for the neutrino channel.

Indeed, it is possible to determine the sign of Δm^2_{atm}, if and only if P_H<1, that is θ_{13} is not too small.



Generalities of SN neutrino detectors

Detector requirements



Burrows' prescriptions, 1992:

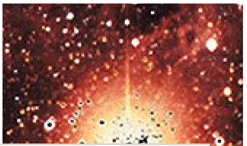
"Beyond material, mass and depth, a Supernova neutrino telescope must have:

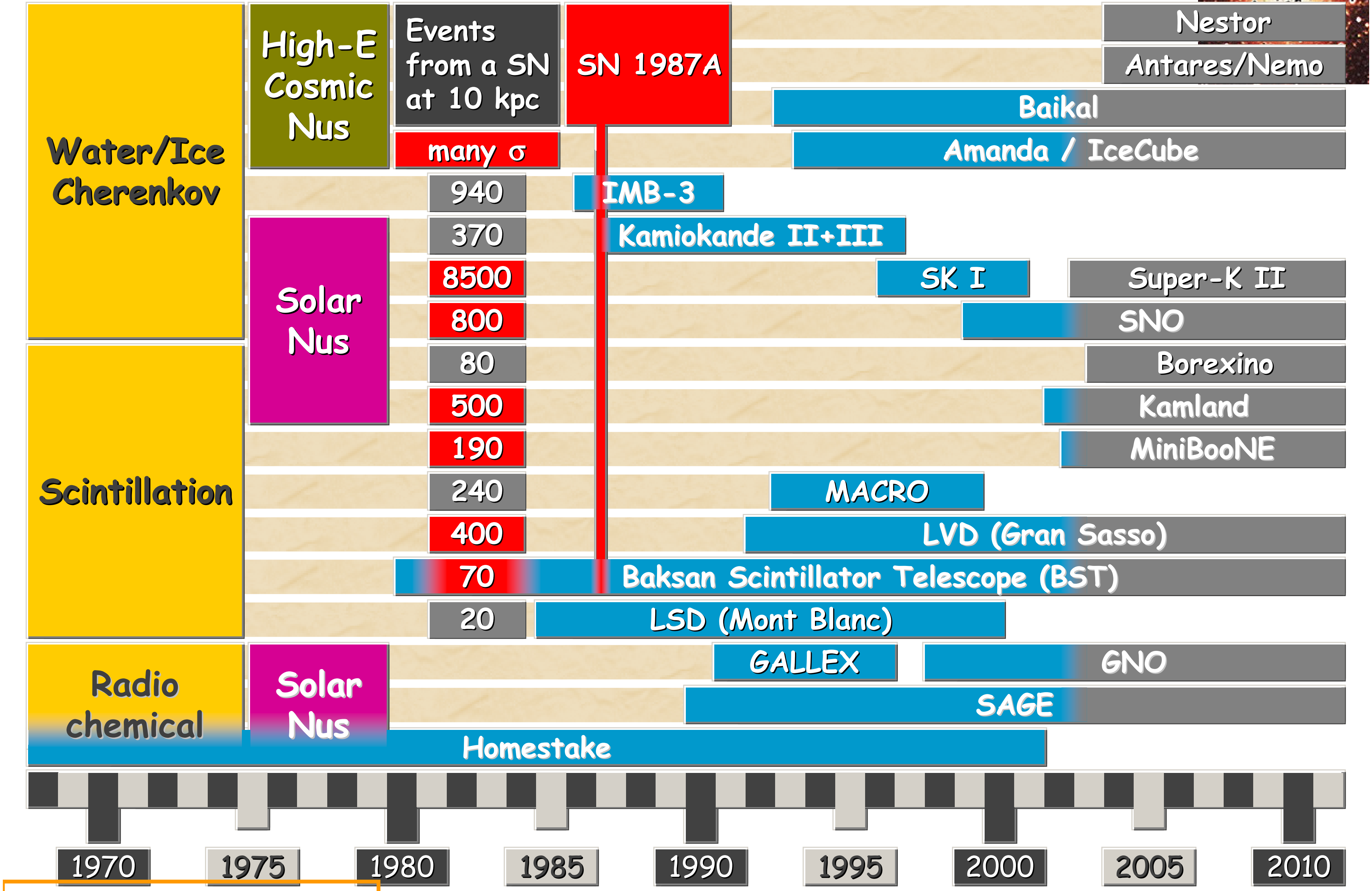
- buffers adequate to handle high throughoutput,
- short deadtime
- accurate absolute and relative timing
- good energy resolution
- low maintenance cost and a high duty cycle

I add :

- ability to distinguish among flavors

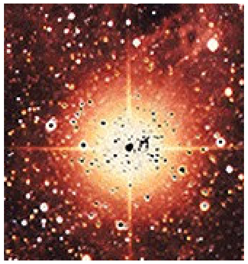
Brief History of neutrino Astronomy





Courtesy of G. Raffelt

Detectors for stellar collapse ν



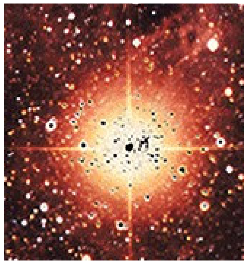
Experiment	Mass (t)	Target	Lab
Super-Kamiokande	32000	H_2O	Kamioka Mines
SNO	1400 , 1000	H_2O , D_2O	Sudbury
LVD	1000	"H_nC_{2n+2}"	LNGS
Kamland	1000	"H_nC_{2n+2}"	Kamioka
MiniBoone	500	"H_nC_{2n+2}"	FermiLab
Baksan	330	"H_nC_{2n+2}"	Russia

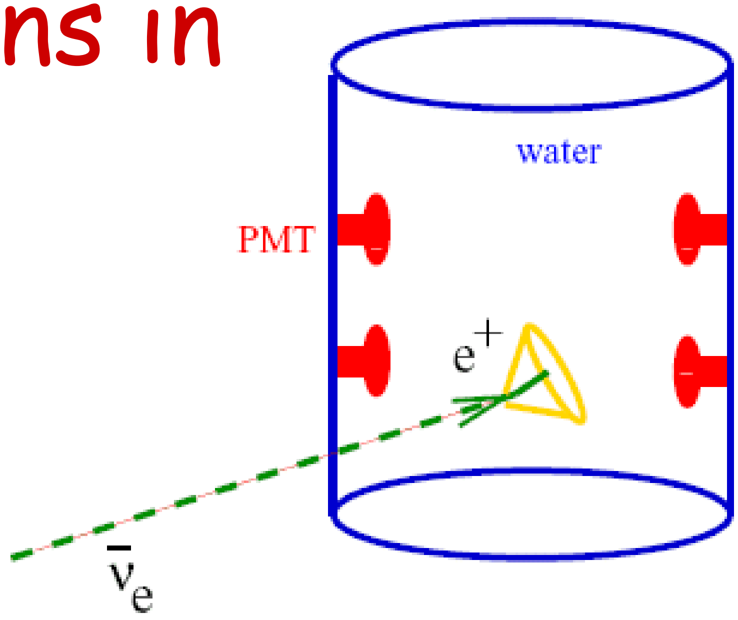
Others approved detector in costruction: Borexino (300 t of C_9H_{12}), Icarus (600 t of LAr)

(AMANDA may observe a statistical enhance in the PM counting rate).

SN ν interactions in

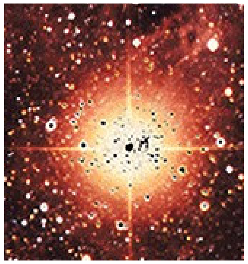
Water Čerenkov



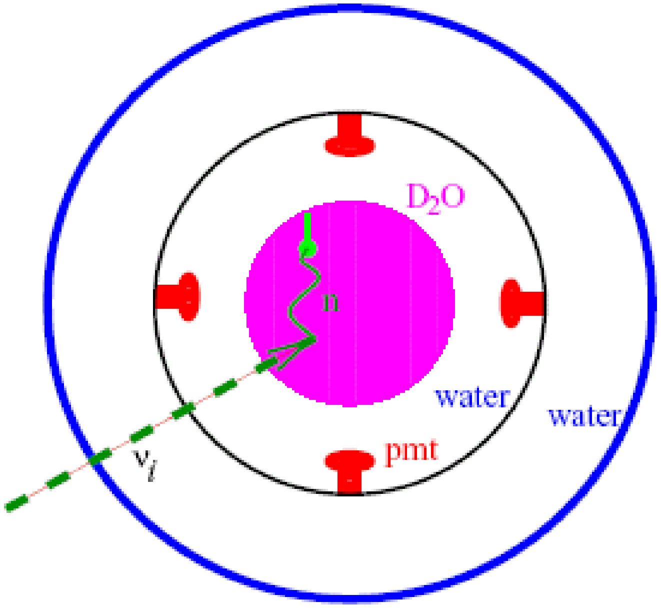


Interactions in H_2O	Int.	Energy threshold (MeV)
$\bar{\nu}_e + p \rightarrow n + e^+$	CC	1.8
$\nu_i + e^- \rightarrow \nu_i + e^-$	CC-NC	
$\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$	CC	15.4
$\nu_i + {}^{16}O \rightarrow \nu_i + \gamma + X$	NC	13.1 (1^-) 16.1(2^-)
$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$	CC	11.4

SN ν interactions in
heavy water Čerenkov



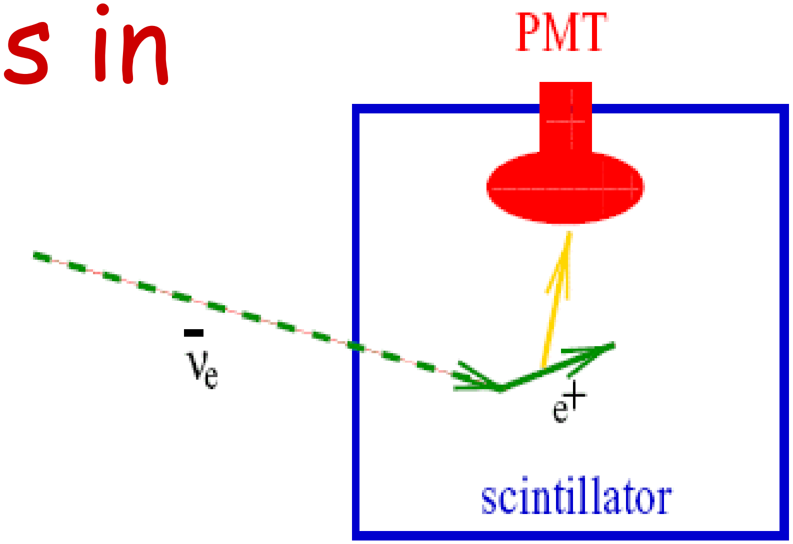
(SNO)

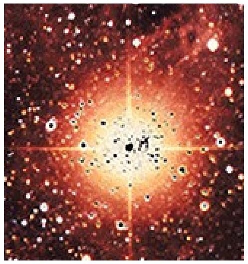


Interactions in D_2O	Int.	Energy threshold (MeV)
$\nu_i + d \rightarrow n + p + \nu_i$	NC	2.22
$\nu_e + d \rightarrow p + p + e^-$	CC	1.44
$\overline{\nu}_e + d \rightarrow n + n + e^+$	CC	4.03

High statistic sample of all-flavors neutrinos

SN ν interactions in Liquid Scintillator



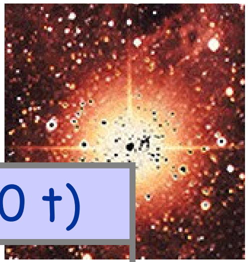


C_nH_{2n} volume surrounded by PMTs
(LENA, Kamland, LVD, Borexino,
MiniBoone, Baksan)

Signature of a high energy spectrum

Interactions in liquid scintillator	Int.	Energy threshold (MeV)
$\bar{\nu}_e + p \rightarrow n + e^+$	CC	1.8
$\nu_i + p \rightarrow \nu_i + p$	NC	
$\nu_i + e^- \rightarrow \nu_i + e^-$	CC-NC	
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	CC	17.3
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	CC	14.4
$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C^*$ ${}^{12}C^* \rightarrow {}^{12}C + \gamma$	NC	15.11

Nb of expected events



	D_2O (1000 t)	H_2O (34100 t)	LS (2500 t)
$\bar{\nu}_e + p \rightarrow n + e^+$		5540	500
$\nu_i\ (\nu_x) + e^- \rightarrow \nu_i\ (\nu_x) + e^-$	8 (2)	150 (52)	17 (4)
$\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$	1	38	
$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$	1	48	
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$			1
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$			1
$\nu_i + {}^{16}O \rightarrow \nu_i + \gamma + X$		40	
$\nu_i\ (\nu_x) + {}^{12}C \rightarrow \nu_i\ (\nu_x) + \gamma + {}^{12}C$			28 (22)
$\nu_e + d \rightarrow p + p + e^-$	82		
$\bar{\nu}_e + d \rightarrow n + n + e^+$	67		
$\nu_i\ (\nu_x) + d \rightarrow \nu_i\ (\nu_x) + n + p$	272 (200)		
TOTAL	≈ 430	≈ 5800	≈ 550

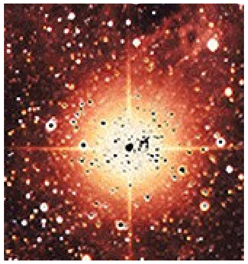
$E_{tot}=2.9 \cdot 10^{53}$ erg D=10 kpc

ν_i = all, $\nu_x = \bar{\nu}_\mu, \bar{\nu}_\tau, \nu_\mu, \nu_\tau$

$<E_{\nu e}> = 9.9$ MeV

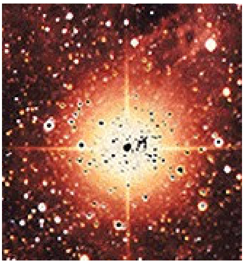
$<E_{\bar{\nu} e}> = 11.6$ MeV $<E_{\nu x}> = 15.4$ MeV

stime da W. Fulgione, Nucl. Phys. B 77, 435 (1999)



Miscellanea of "new" ideas in the market

Gd in Water Čerenkov



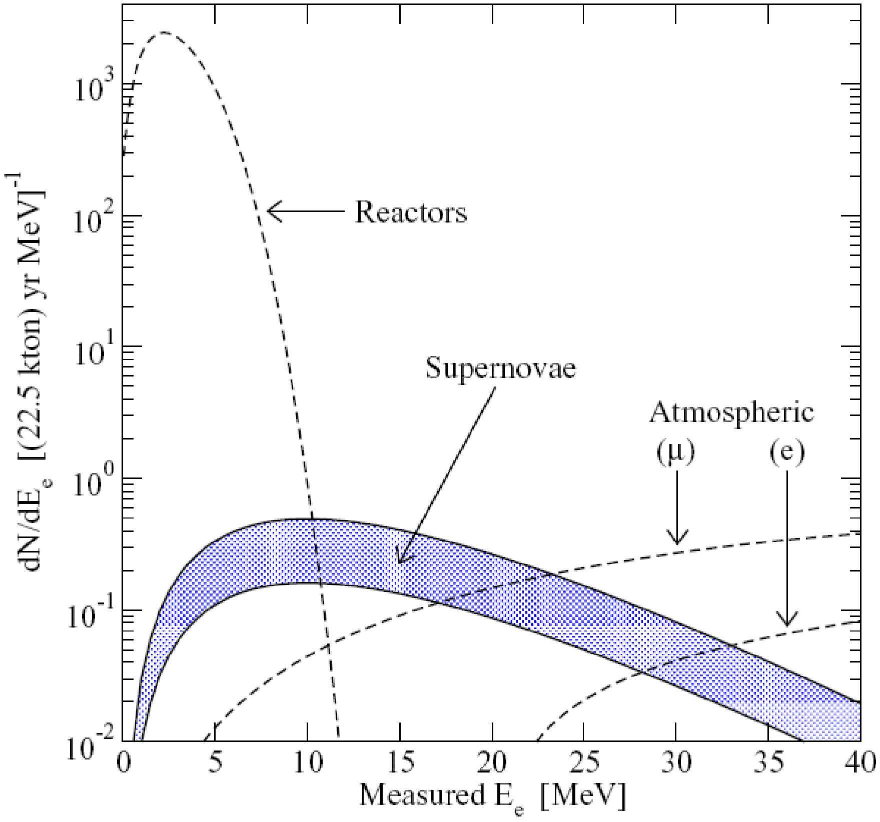
Adding a small amount of Gd (100 t of $GdCl_3$ in SK) a water Čerenkov detector can greatly enhance its performances. (J. Beacom and M. Vagins hep-ph/0309300)

$$\overline{\nu_e} + p \rightarrow n + e^+$$

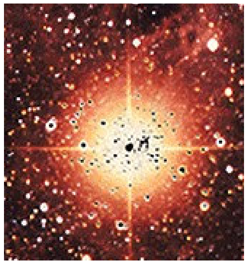
The high Gd neutron capture cross section allows to get 90% of the neutrons produced in the inverse beta decay interaction, as a gamma cascade with $\Sigma E\gamma \cong 8$ MeV

For the SN neutrino detection there are improvements in the:

- S/N ratio
- deconvolution of the various neutrino signals
- elastic scattering pointing accuracy
- clear ν_e detection through $\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$ interactions
- SN relic neutrinos
- SN prealarm (astro-ph/0311012) ...



SN self prealarm



- During the Silicon burning phase, about 2 days before the SN core-collapse, the star is hot enough ($T>10^9$ K) that the pair annichilation process

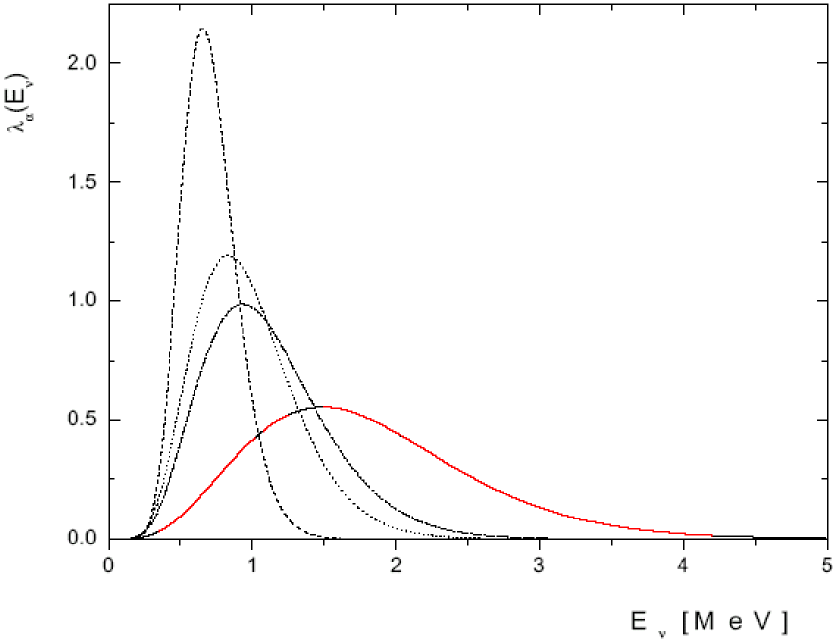
$$e^+ e^- \rightarrow \nu_x \bar{\nu}_x$$

starts to produce a large number of $\bar{\nu}_e$ with an average energy of 1.8 MeV.

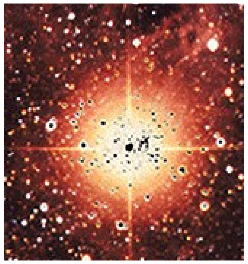
Thus, a large fraction of them is above the inverse beta decay threshold.

- Sk with Gd expects to see about 1000 neutron capture per day, which is ten times higher that their current bkg singles rate, assuming that the star is at 1 kpc.

- Of course this works only if the star is very close. With HK one can extend the distance up to 5 kpc.



ν elastic scattering on p



In hep-ph/0205220 J. Beacom et al. proposed that neutrino proton elastic scattering $\nu + p \rightarrow \nu + p$ can be used for the detection of SN neutrinos in scintillation detectors.

- The proton recoil kinetic energy spectrum is soft $T_p \cong 2E_\nu^2/M_p$

- Scintillation light from slow, heavily ionizing protons is quenched

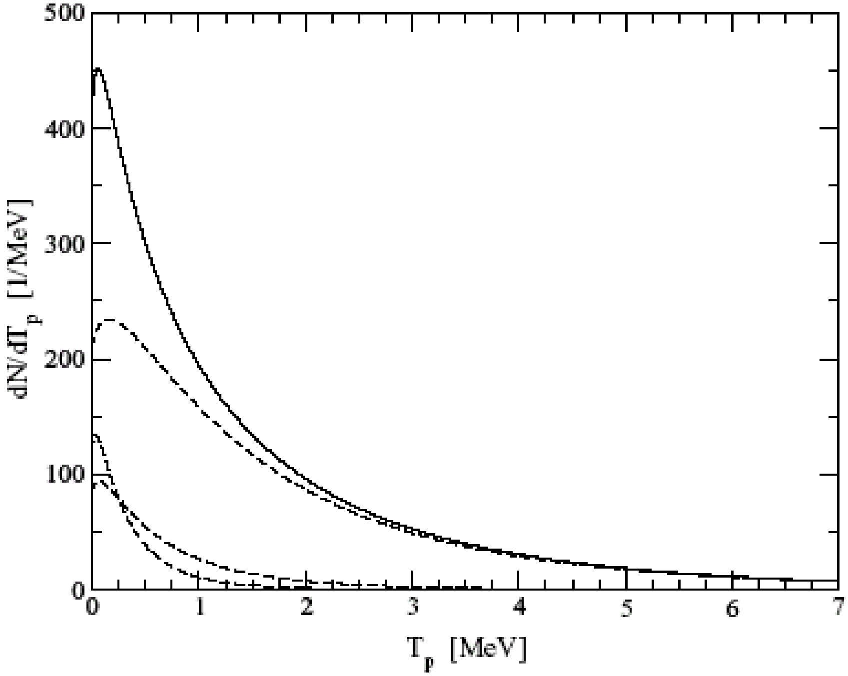


FIG. 4: The true proton spectrum in KamLAND, for a standard supernova at 10 kpc. In order of increasing maximum

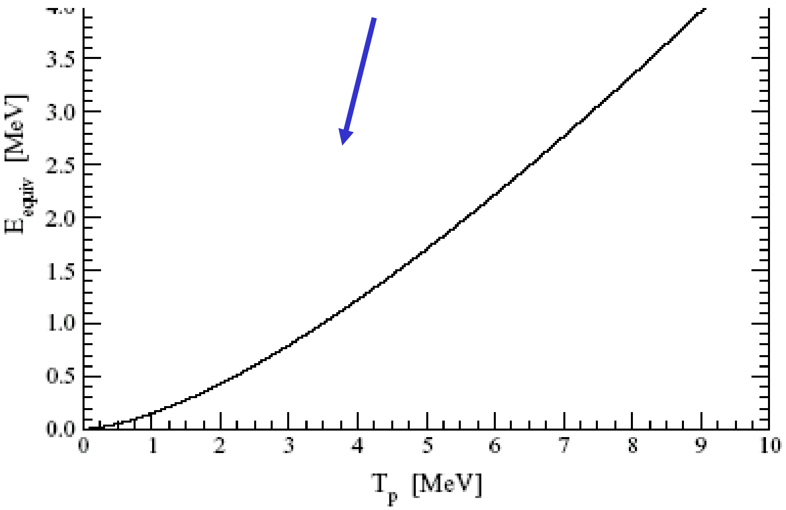
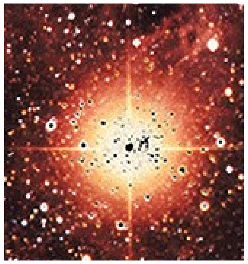
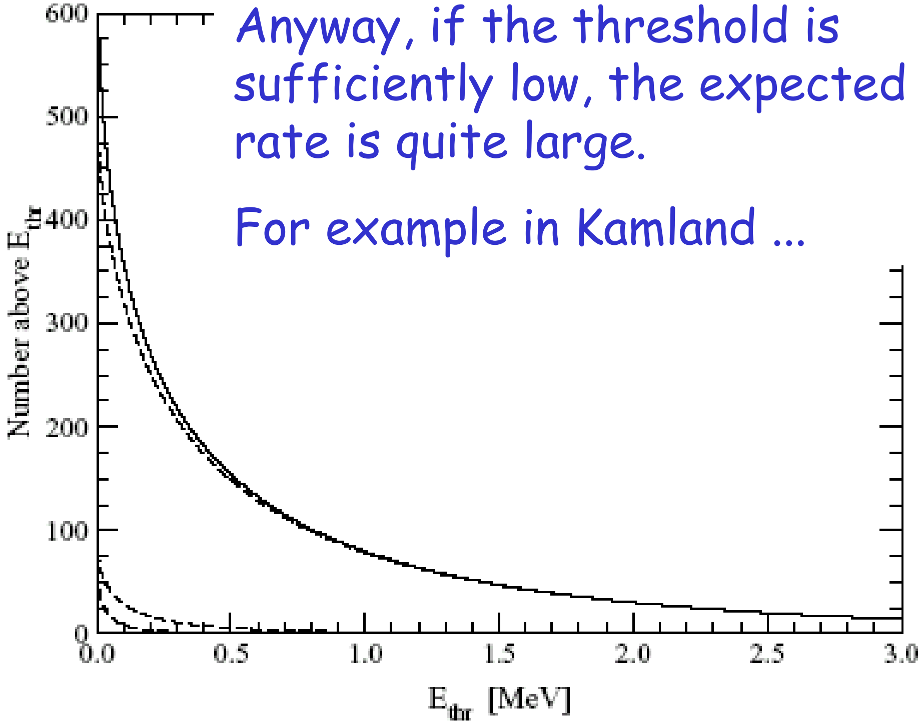


FIG. 5: The quenched energy deposit (equivalent electron energy) as a function of the proton kinetic energy. The KamLAND detector properties are assumed.

ν elastic scattering on p





Anyway, if the threshold is sufficiently low, the expected rate is quite large.

For example in Kamland ...

cluded.

Neutrino Spectrum	$E_{thr} = 0$	0.2 MeV
$\nu : T = 3.5$ MeV	57	3
$\bar{\nu} : T = 5$ MeV	80	17
$2\nu : T = 8$ MeV	244	127
$2\bar{\nu} : T = 8$ MeV	243	126
All	624	273

In addition, the measured proton spectrum is related to the incident neutrino spectrum.

Remind that this was not possible with the other NC interactions like

$$\nu_i + d \rightarrow n + p + \nu_i$$

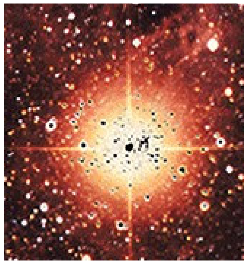
$$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C + \gamma$$

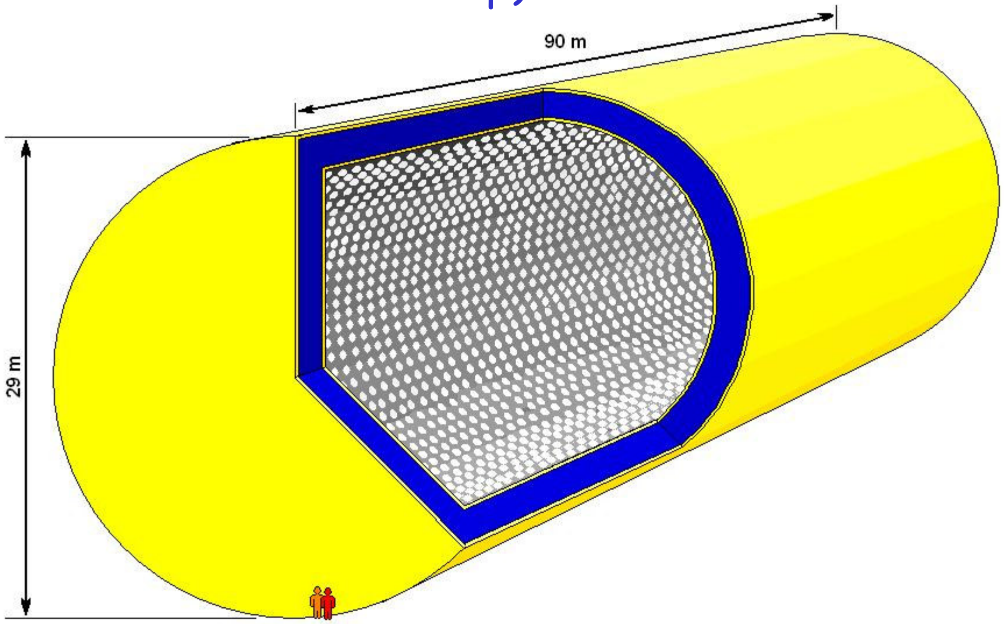
And NC are the only way to measure non electron SN ν.

This allows to separately measure their temperature and fraction of binding energy

LENA

(L. Oberauer et al. , see for example, No-Ve 2003 workshop)



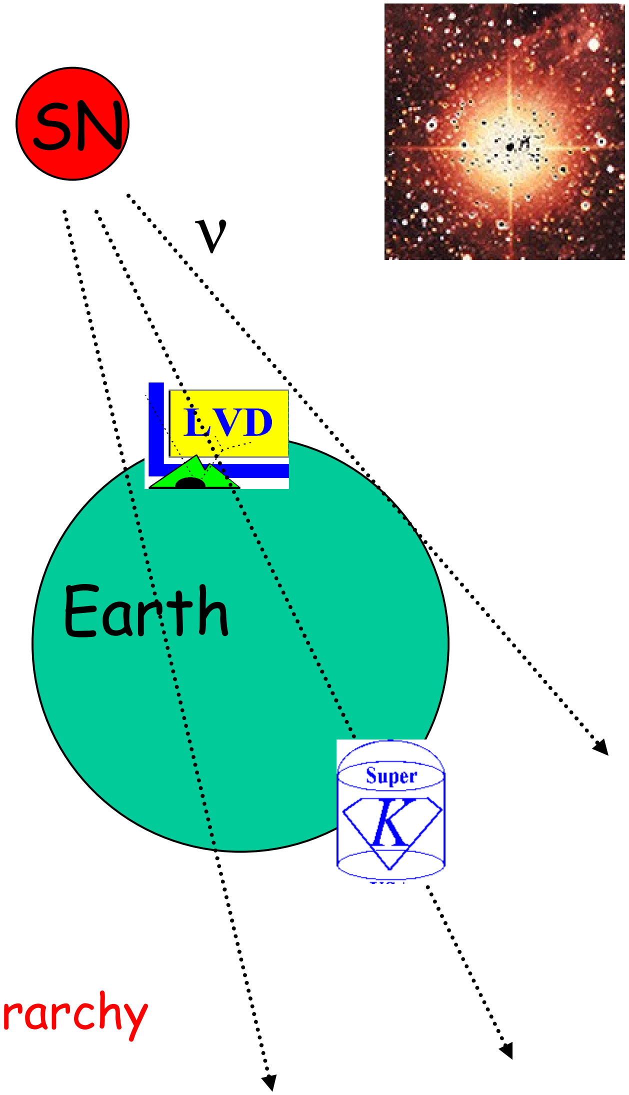


A large (30 kt) liquid scintillator underground detector

Beyond the obvious scaling of the nb of expected events (wrt KamLand or LVD) the idea could be interesting to study:

- Neutrino proton elastic scattering
- Silicon burning neutrinos
- Earth matter effect with a single detector
- Distinguish between nu and anti-nu CC off Carbon nuclei (see LVD discussion)

Earth matter effects



If we consider the effect of Earth in the neutrino path to the detector, we must replace, in the detected flux estimation, U^2_{ei} with P_{ei} (i=1,2), the probability for the mass eigenstate ν_i to be detected as ν_e after path in the Earth, which depends on the solar oscillation parameters and on the travelled density profile through the Earth.

$$\begin{cases} F_e = P_H \; P_{e2} \; F^0_e + (1 - P_H \; P_{e2}) \, F^0_x \\ F_{\bar{e}} = P_{e1} \; F^0_{\bar{e}} + P_{e2} \; F^0_{\bar{x}} \end{cases}$$

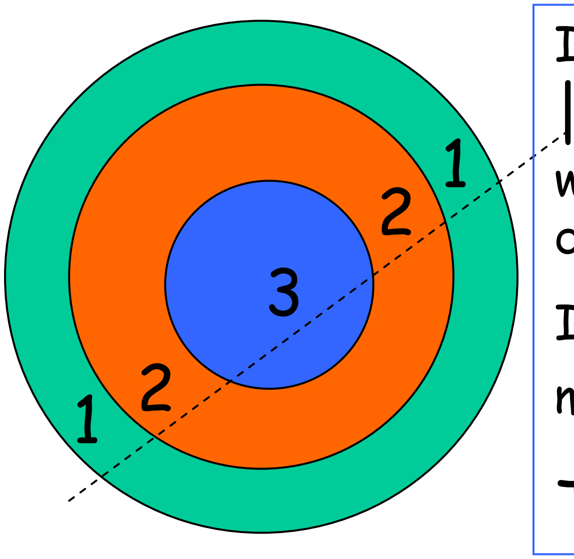
for normal hierarchy

$$\begin{cases} F_e = P_{e2} \; F^0_e + P_{e1} \; F^0_x \\ F_{\bar{e}} = P_H \; P_{e1} \; F^0_{\bar{e}} + (1 - P_H \; P_{e1}) \, F^0_{\bar{x}} \end{cases}$$

for inverted hierarchy

Earth matter effects

We developed a complete 3-flavour calculation, describing the earth interior as made of 12 equal density steps, following the PREM matter density profile. For each constant density step we compute the exact propagator of the evolution matrix and we get the global amplitude matrix by multiplying the propagators of the traversed density layers, following the strategy of Akmedov hep-ph/0001264.



In constant density:

$$|\nu_\alpha(t)> = U_m e^{-iDt} U_m^{-1} |\nu_\alpha(0)> = S(t)|\nu_\alpha(0)>$$

where U_m is the matter mixing matrix and D is the diagonal matrix of the eigenvalues in matter.

If we consider the Earth density as made of steps, we must replace $S(t) = S_1(t)\, S_2(t)\, S_3(t)\, S_2(t)\, S_1(t)$

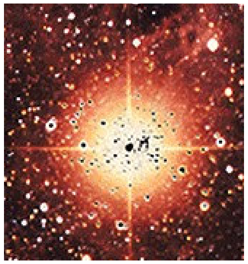
Then $P_{2e} = P_{(2\to e)} = |<\nu_2(0)|\nu_e(t)>|^2$

A parametrization of the Earth regeneration effect, valid in the costant density case (mantle) is (Vissani):

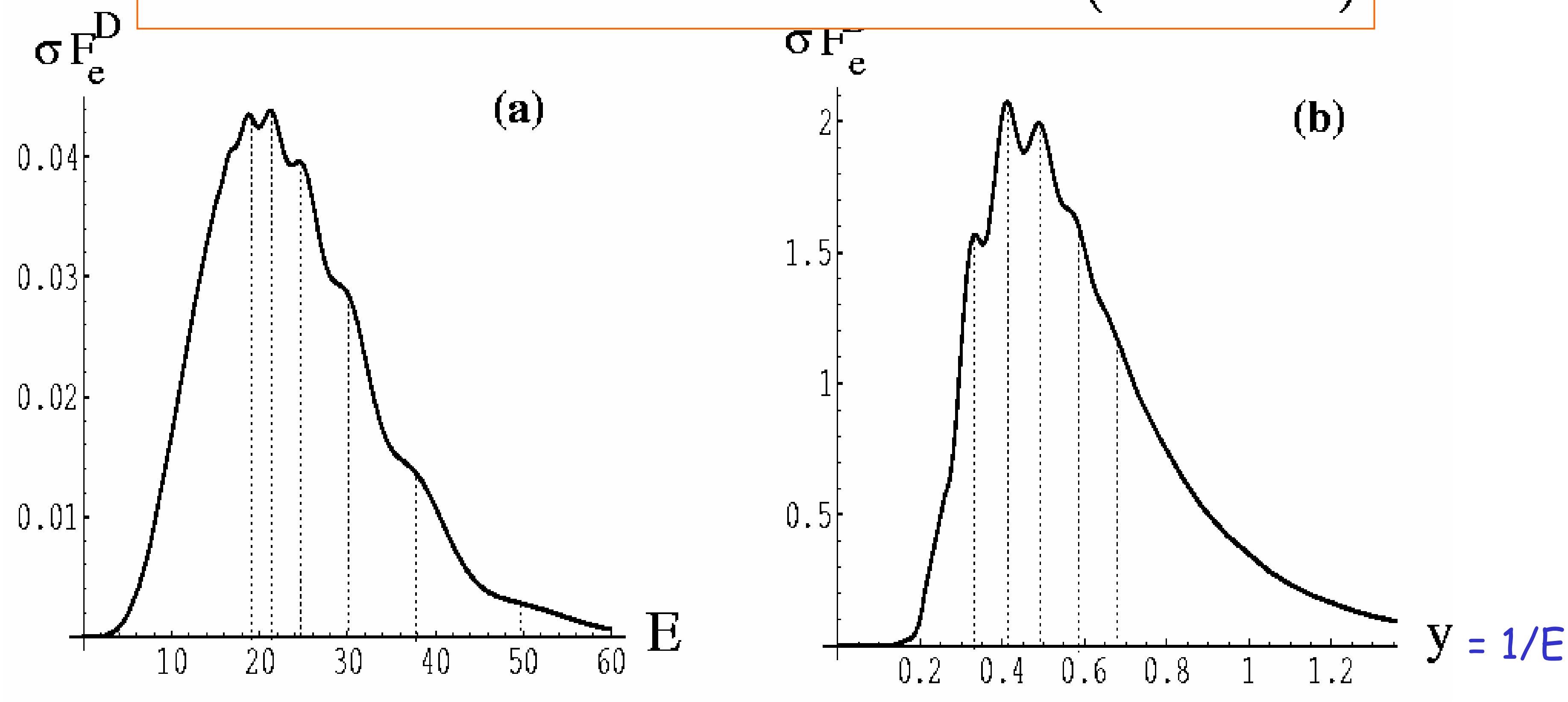
$$P_{ee} = \sin^2\theta_{12}\left[1 + \frac{4\varepsilon\cos^2\theta_{12}}{(1+\varepsilon)^2 - 4\varepsilon\cos^2\theta_{12}} \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\sqrt{(1+\varepsilon)^2 - 4\varepsilon\cos^2\theta_{12}}\right)\right] \qquad \varepsilon = \frac{\sqrt{2}G_F N_e}{\Delta m^2/2E}$$

For antineutrinos, just replace $\theta_{12} \rightarrow 90° - \theta_{12}$.

Earth matter effects with one detector (Dighe, Keil, Raffelt hep-ph/0304150)



$$\bar{p}^D \approx \cos^2\theta_{12} - \sin 2\bar{\theta}^{\oplus}_{e2}\ \sin(2\bar{\theta}^{\oplus}_{e2} - 2\theta_{12})\ \sin^2\left(12.5\,\frac{\overline{\Delta m^2_{\oplus} L}}{E}\right)$$

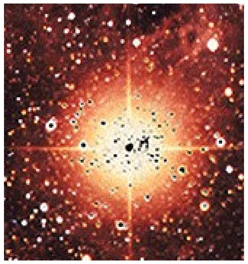


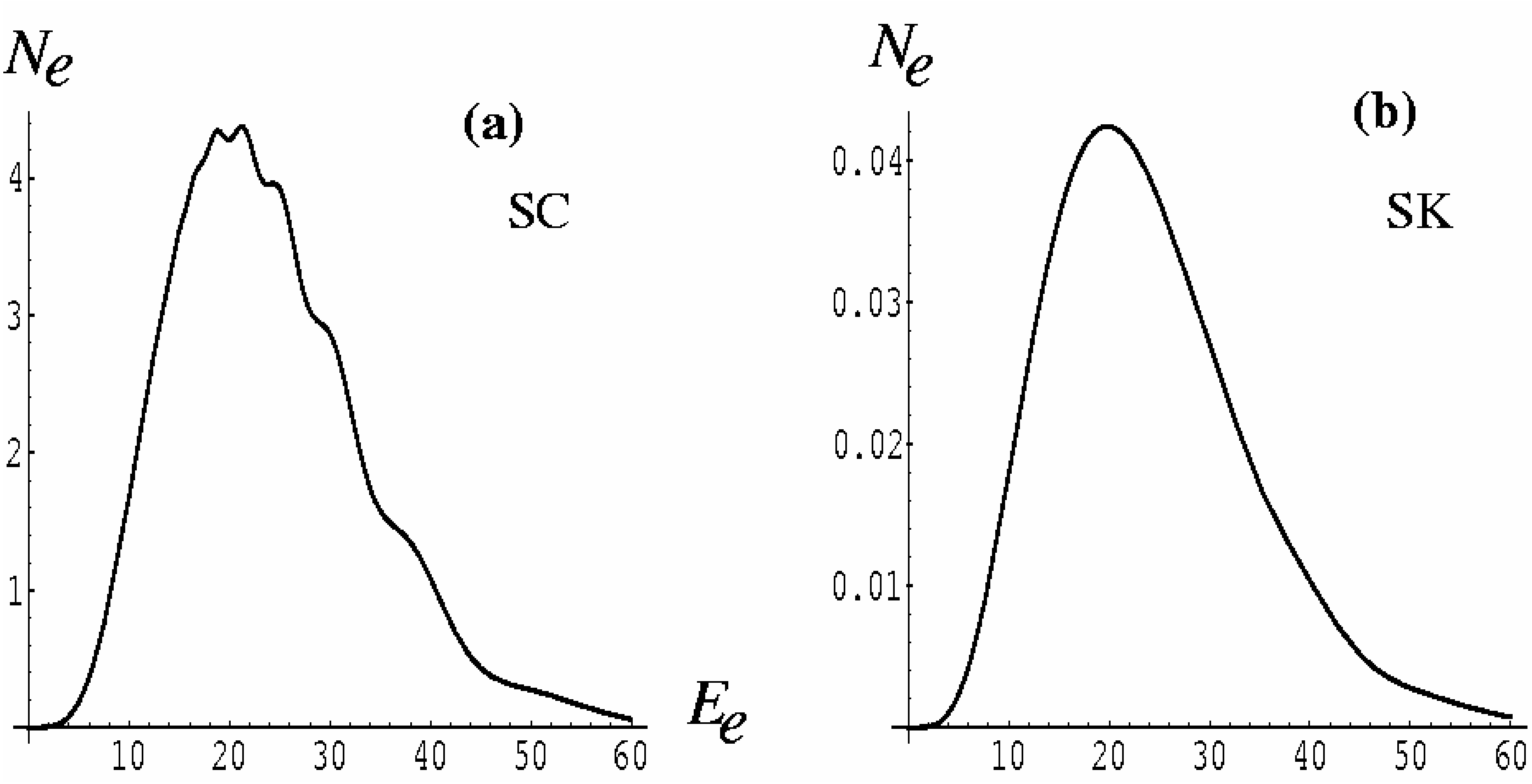
Modulations in the energy spectrum due to matter effects in the Earth

$$k_{\oplus} \equiv 2\overline{\Delta m^2_{\oplus} L}$$

Earth matter effects with one detector

(Dighe, Keil, Raffelt hep-ph/0304150)

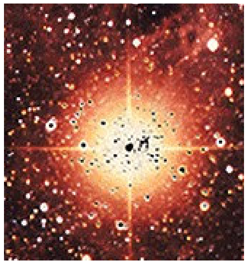




The modulation can be seen by one single detector only if the energy resolution is good enough → scintillator detectors

Liquid Argon

(Botella et al. hep-ph/0307222 0307244)



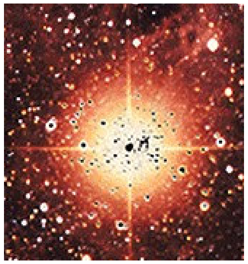
A liquid Argon TPC has the ability to detect SN neutrinos via three processes:

• elastic scattering by electrons (all neutrino species)	41
• ν_e CC absorption on Ar with production of excited K (E_{thr}=4.4 MeV)	188
• $\bar{\nu}_e$ CC absorption on Ar with production of excited Cl	15

The numbers are referred to the 3 kt ICARUS detector, for a "standard" SN at 10 kpc, without considering oscillations.

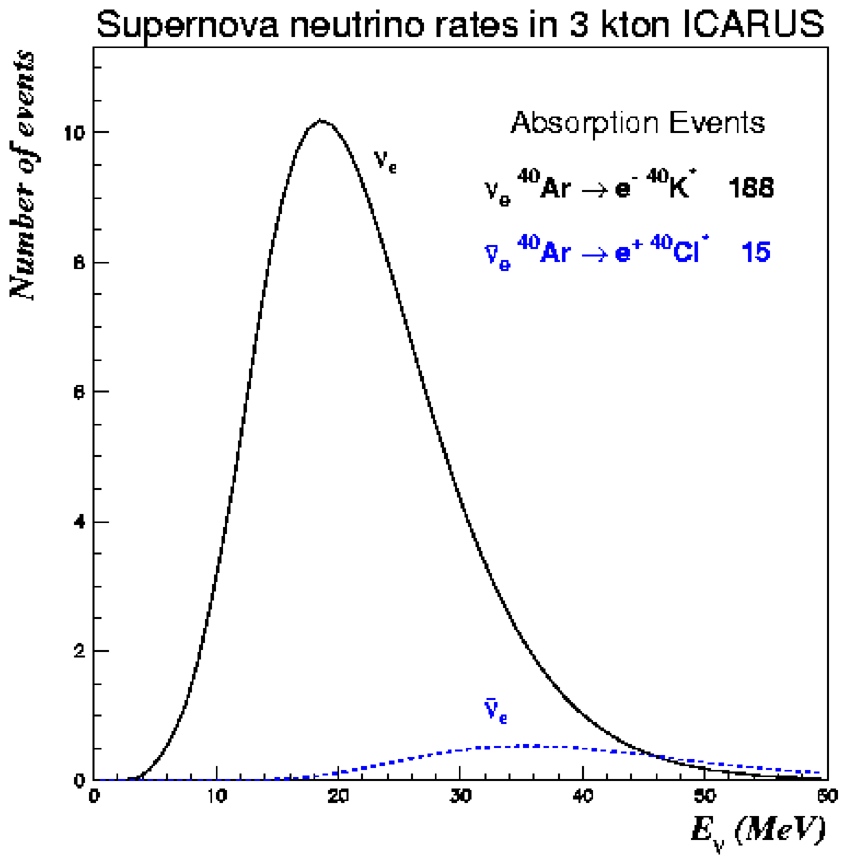
Liquid Argon

(Botella et al. hep-ph/0307222 0307244)



- Good sample of “rare” electron ν

- Sensitive to the ν_e breakout burst



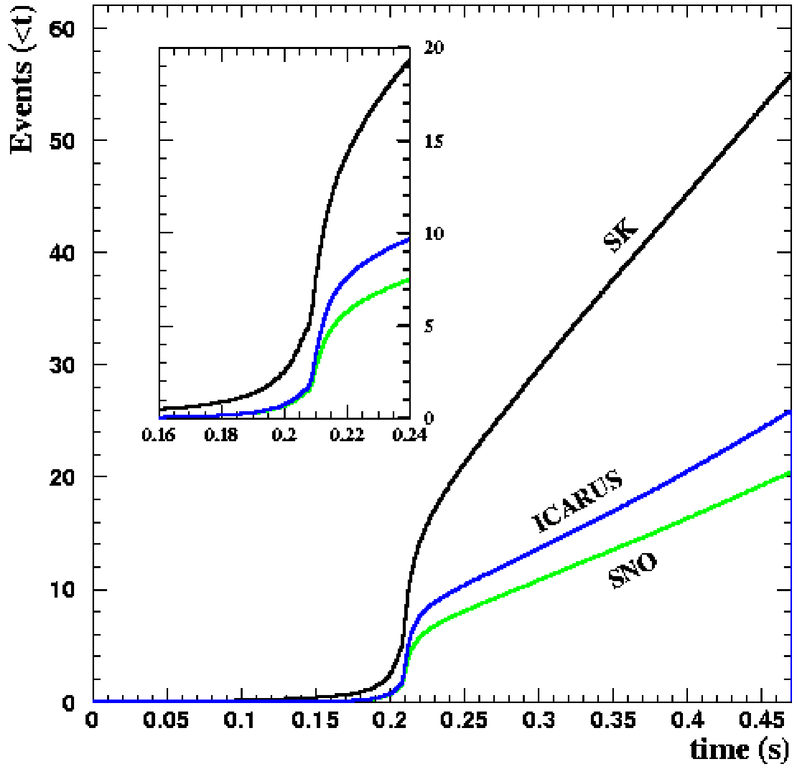
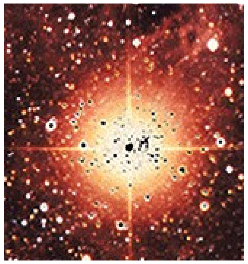
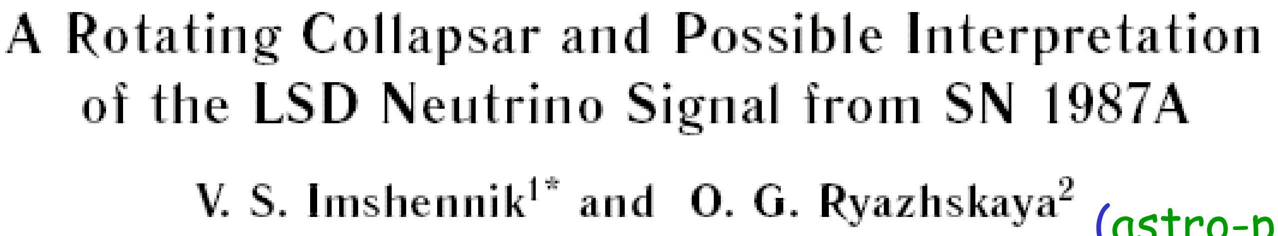


Figure 13: Comparison of the expected number of events from the ν_e breakout burst in a 3 kton ICARUS, SK and SNO experiments. In the first 40 ms after bounce a total of 20 events are expected in SK, 10 in ICARUS and 7 in SNO. No oscillation effects are included.

A rotating collapsar





A Rotating Collapsar and Possible Interpretation of the LSD Neutrino Signal from SN 1987A

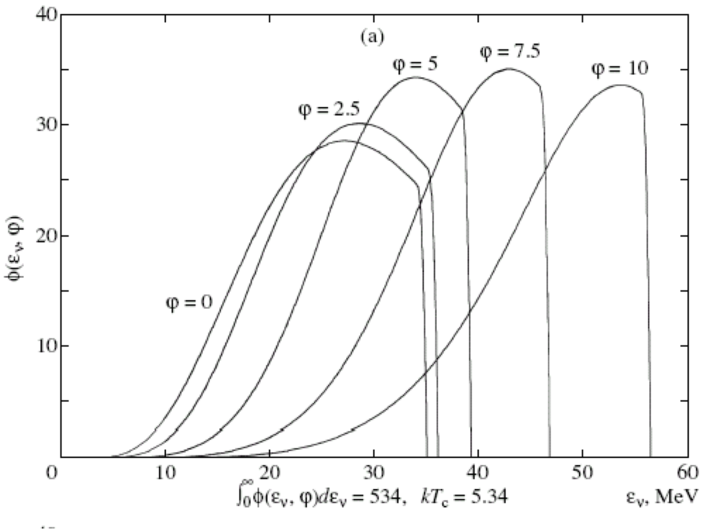
V. S. Imshennik[1*] and O. G. Ryazhskaya[2]

(astro-ph/0401613)

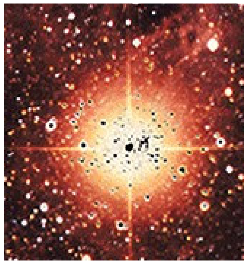
Pre-collapse phase of neutrino emission when only non-thermal ν_e of E = 30-40 MeV are emitted, a few hours before the “standard” core collapse.

They could be detected in LSD better than in IMB or KII because of its huge iron mass (200 t).

Infact the neutrino-iron cross section is large and the efficiency to release energy in the liquid scintillator is not small (see LVD discussion)



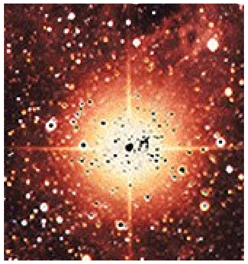
E (MeV)	σ (ν_e O) (cm^2)	σ (ν_e Fe) (cm^2)
30	200 10^{-44}	18000 10^{-44}



What can we learn from a SN core collapse ?

A lot of informations, but many of them are mixed together !

Parameters



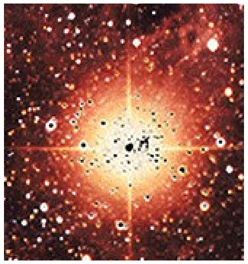
Astrophysical parameters:

• $E_B = 1\text{-}5\ 10^{53}$ erg	Gravitational binding energy
• $T_{\nu\, ae}$	Electron anti-neutrinosphere temperature
• r_e	Ratio between e and anti-e neutrinosphere T
• r_x	Ratio between x and anti-e neutrinosphere T
• f_e	Fraction of total energy carried away by nu e
• η	“pinching” parameters (one per flavor)

Oscillation parameters:

• θ_{12}	”solar” mixing angle
• P_H related to θ_{13}	Adiabaticity in the H density resonance
• sign of Δm^2_{13}	mass hierarchy

Analysis methods

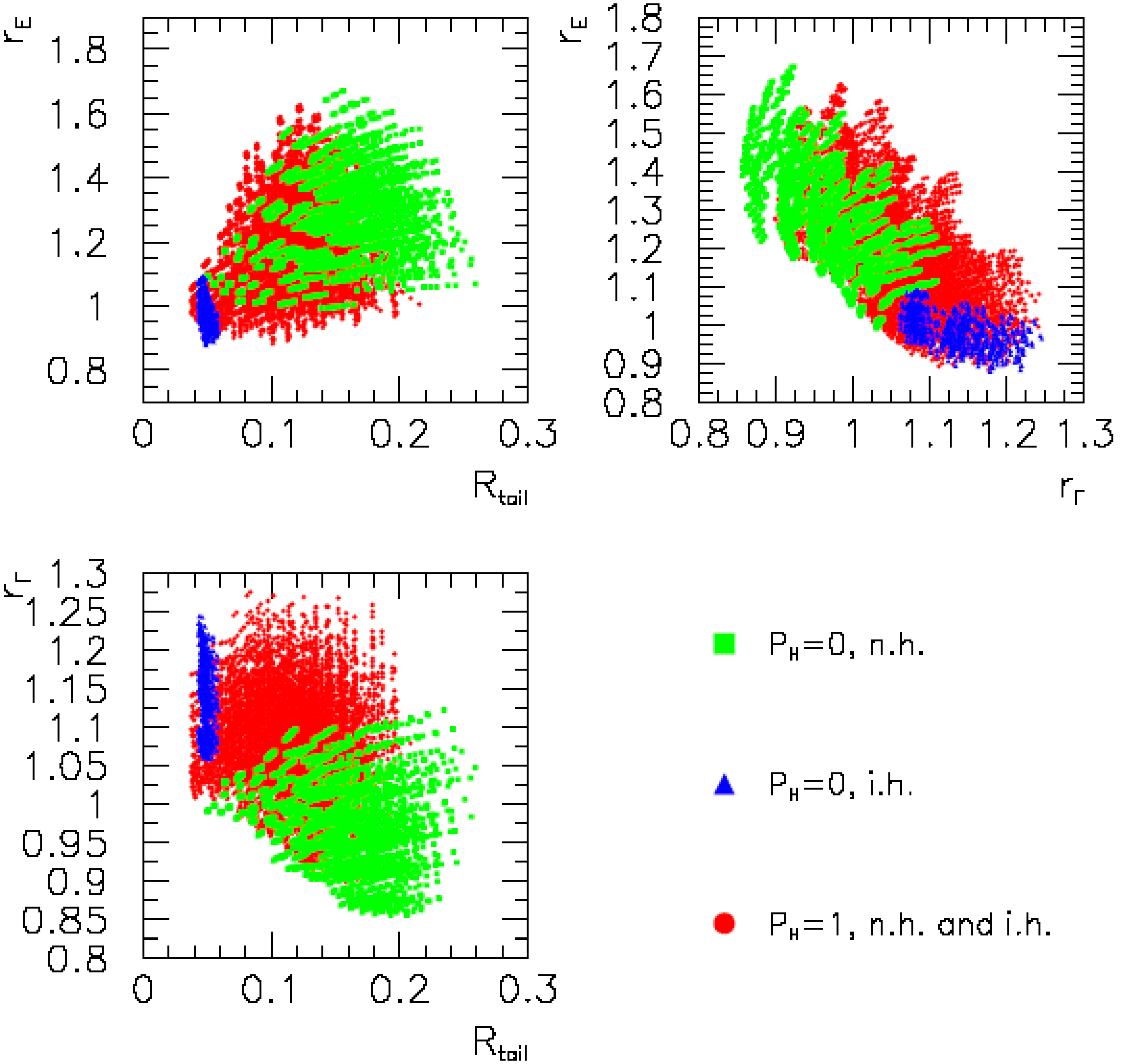


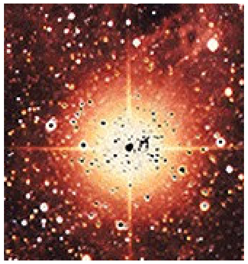
There are two approach:

- perform a global fit to t
oscillation parameters. Th
can produce the same obs
example in hep-ph/011212

- perform an analysis on
example from IBD and ν

    - Ratio of average en
    - ratio of the widths
    - ratio of total numbe
    - ratio of total numbe





LVD detector description

Detector description

The Large Volume Detector (LVD) in the INFN Gran Sasso National Laboratory, Italy, consists of an array of 840 liquid scintillator (LS) counters, 1.5 m^3 each. These are interleaved by streamer tubes, and arranged in a compact and modular geometry. The active scintillator mass is M=1000 t.

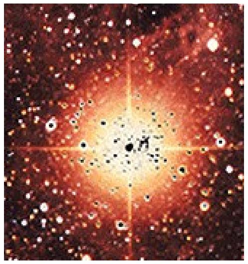
LVD, with KamLand, is the biggest liquid scintillator neutrino detector in the world

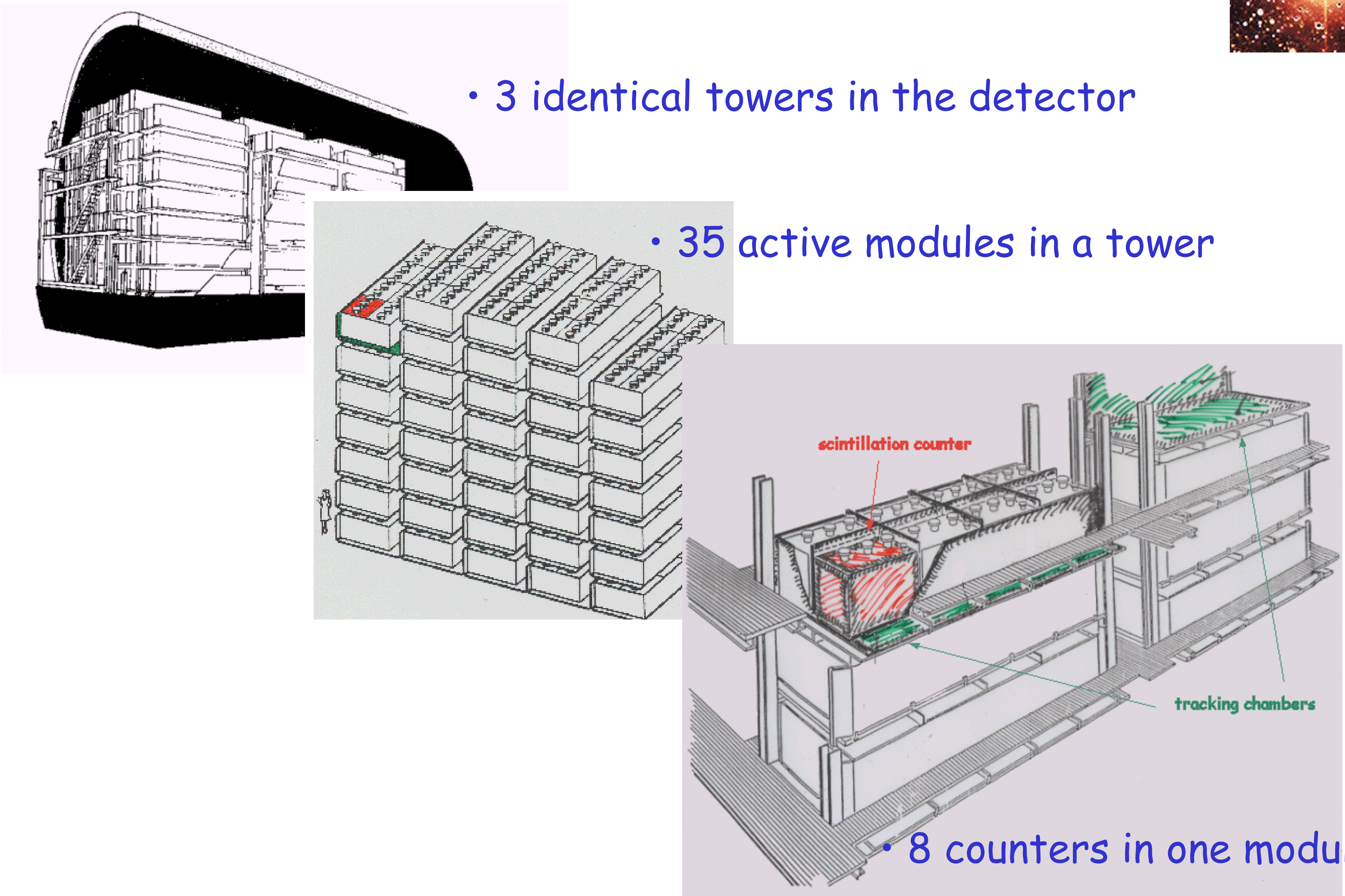
There are two subsets of counters: the external ones (43%), operated at energy threshold $\varepsilon_h \leftrightarrow 7$ MeV, and inner ones (57%), better shielded from rock radioactivity and operated at $\varepsilon_h \leftrightarrow 4$ MeV. In order to tag the delayed γ pulse due to n-capture, all counters are equipped with an additional discrimination channel, set at a lower threshold, $\varepsilon_l \leftrightarrow 1$ MeV.

Relevant features of the detector are:

- good event localization;
- accurate absolute and relative timing: $\Delta t_{abs} = 1\ \mu s$, $\Delta t_{rel} = 12.5$ ns;
- short dead time (2 μs for each counter)
- uptime greater than 99%
- energy resolution: $\sigma(E)/E = 0.07 + 0.23\ (E/MeV)^{-0.5}$.

LVD detector





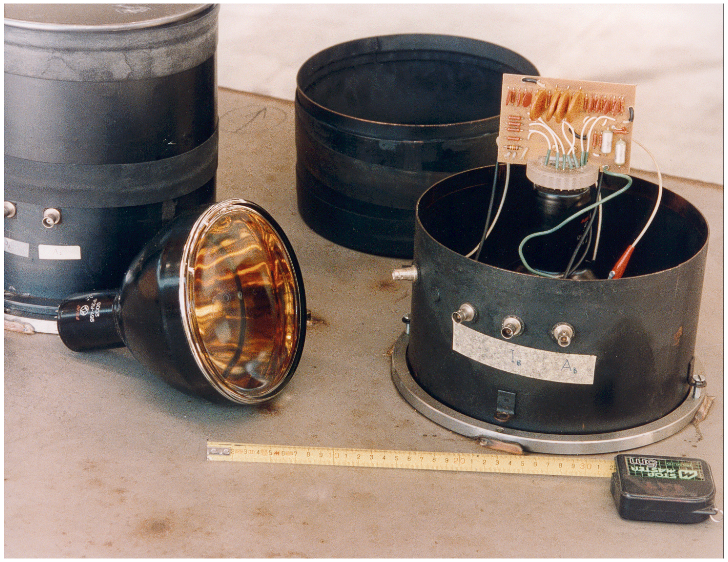
- 3 identical towers in the detector
- 35 active modules in a tower
- 8 counters in one module

Liquid scintillator

External dimensions:	1.5 x 1 x 1 m^3

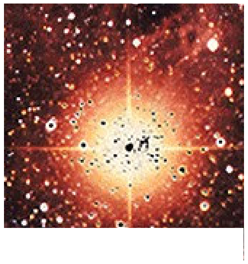
Scint. composition:
C_nH_{2n+2} $\langle n \rangle = 9.6$ +1 g/l PPO + 0.03 g/l POPOP

Scint. density:	~ 0.8 g/cm^3
Attenuation lenght:	> 15m @ λ=420 nm
Flash point at:	~39°C



PMT:	FEU-49B
Photocathode diameter:	d=15 cm
Quantum efficiency:	10-15%

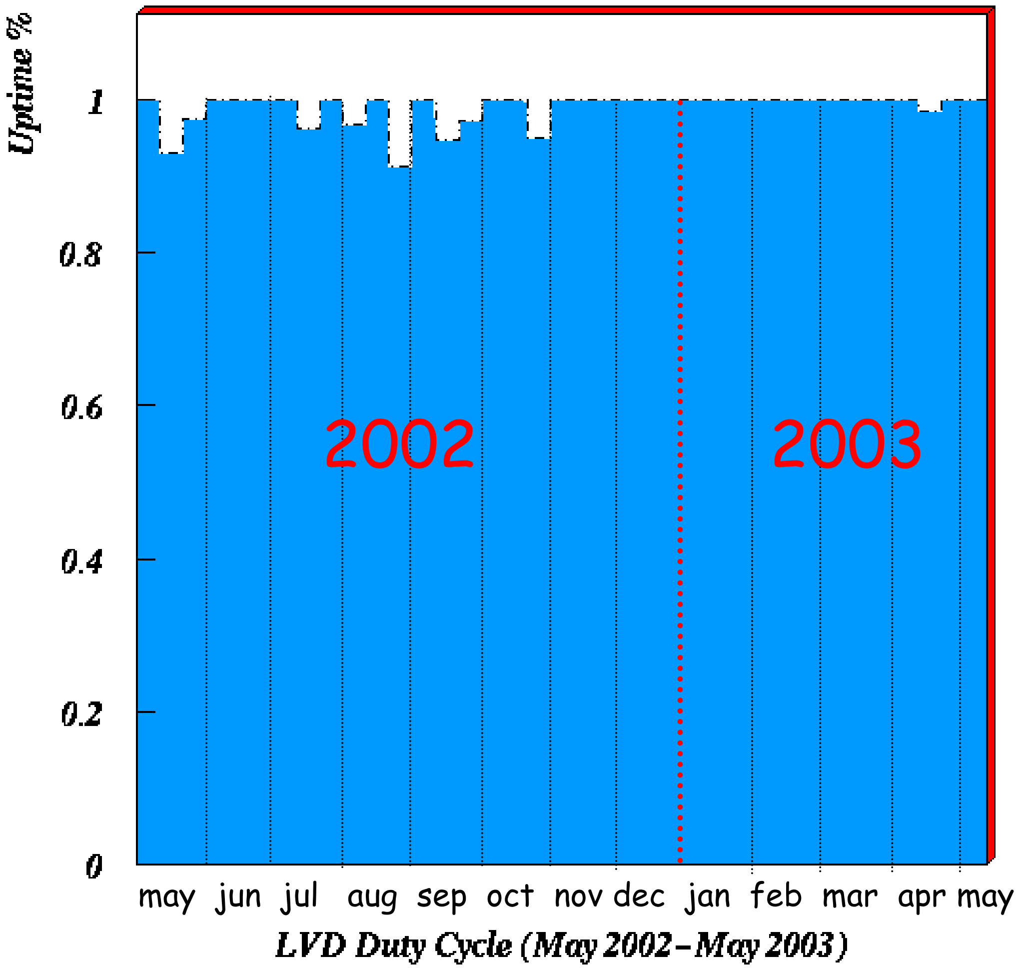
Up time

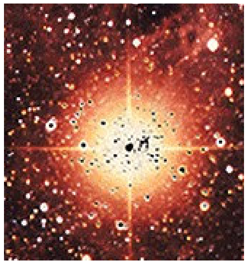


ν beam characteristics:

- 1 bunch each 20-30 years
- Bunch duration: 10 – 60 s
- $\blacklozenge_0 = ?$

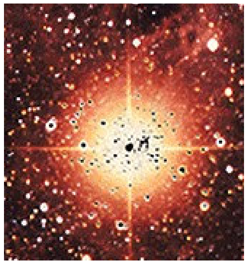
<u>High duty cicle needed!</u>





ν interactions in LS

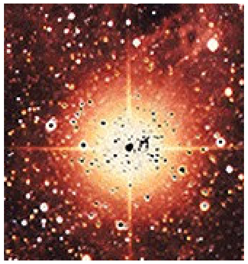
Neutrino interactions in LS



ν interactions in LVD (mass = 1000 tons)	Energy threshold (MeV)	Detection Efficiency above threshold (%)
$\bar{\nu}_e + p \to n + e^+$	1.8	95
$\overset{(-)}{\nu}_x + e^- \to \overset{(-)}{\nu}_x + e^-$	/	/
$\nu_e + {}^{12}C \to {}^{12}N + e^-$	17.8	85
$\bar{\nu}_e + {}^{12}C \to {}^{12}B + e^+$	13.9	70
$\overset{(-)}{\nu}_x + {}^{12}C \to \overset{(-)}{\nu}_x + \gamma + {}^{12}C$	15.11	55

Target	Contained in	Mass	Number of targets
Free protons	Liquid Scintillator	1000 t	9.34×10^{31}
Electrons	Liquid Scintillator	1000 t	3.47×10^{32}
C Nuclei	Liquid Scintillator	1000 t	4.23×10^{31}
Fe Nuclei	Support structure	710 t	7.63×10^{30}

Inverse beta decay (double signature)

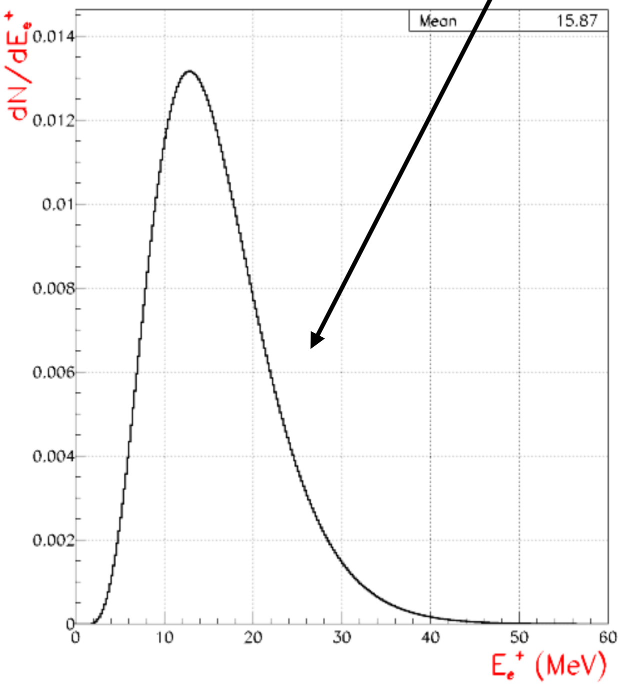


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

1. Positron detection

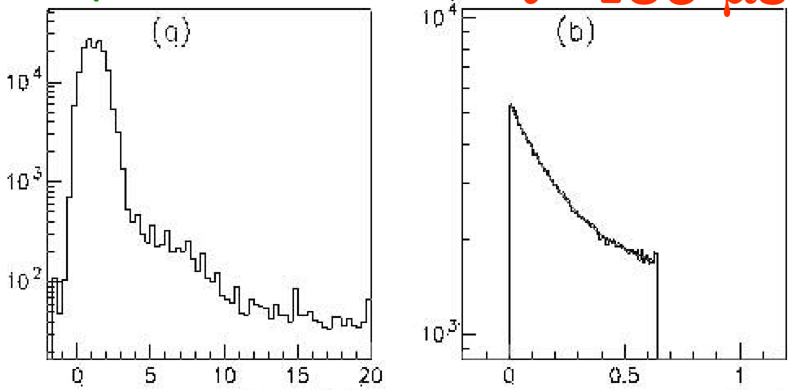
followed by ...



2. Gamma (2.2 MeV) from neutron capture (τ = 185 μs)

E_γ = 2.2 MeV

τ= 185 μs

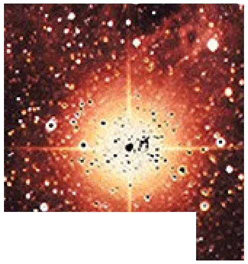


Energy (MeV)

Delay (ms)

Neutron capture efficiency = 60% (from ^{252}Cf measurement)

SN burst event filtering

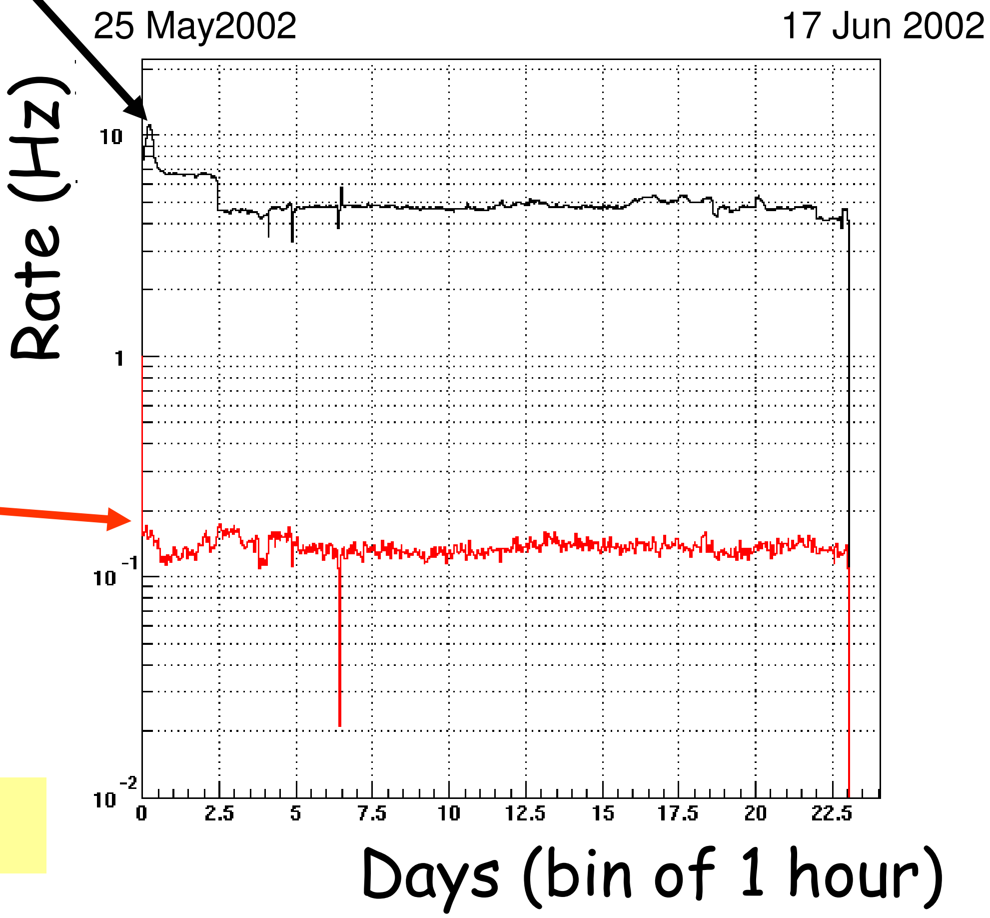


<u>After muon rejection</u>

(muon = at least 2 high energy threshold in coincidence within 250 ns) raw input rate to SN monitor

- Filter noisy counters and
- accept pulses with 7 MeV < E < 100 MeV

Final input rate stable!



SN Signal / background

High threshold
average rate = 1 Hz

Low threshold
average rate = 120 Hz

$\bar{\nu}_e$ signature

Neutron capture
efficiency = 60%

300 events burst

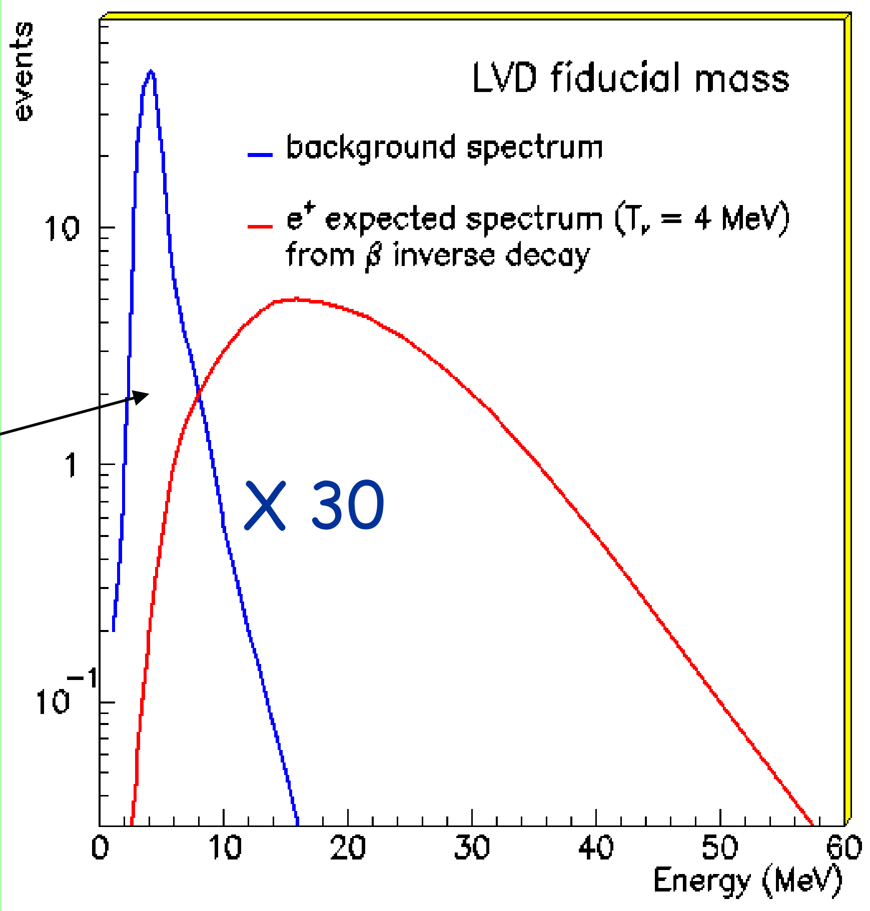
burst due to
background:
300 ·(120 Hz) ($6\cdot10^{-4}$ s)
= **22± 5**
low en. pulses expected

burst due to $\bar{\nu}_e$
interactions
300·0.6 + 22 ± 5 =
202 ± 14
low en. pulses expected

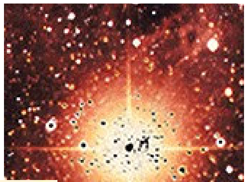
Normalized to same number of events!

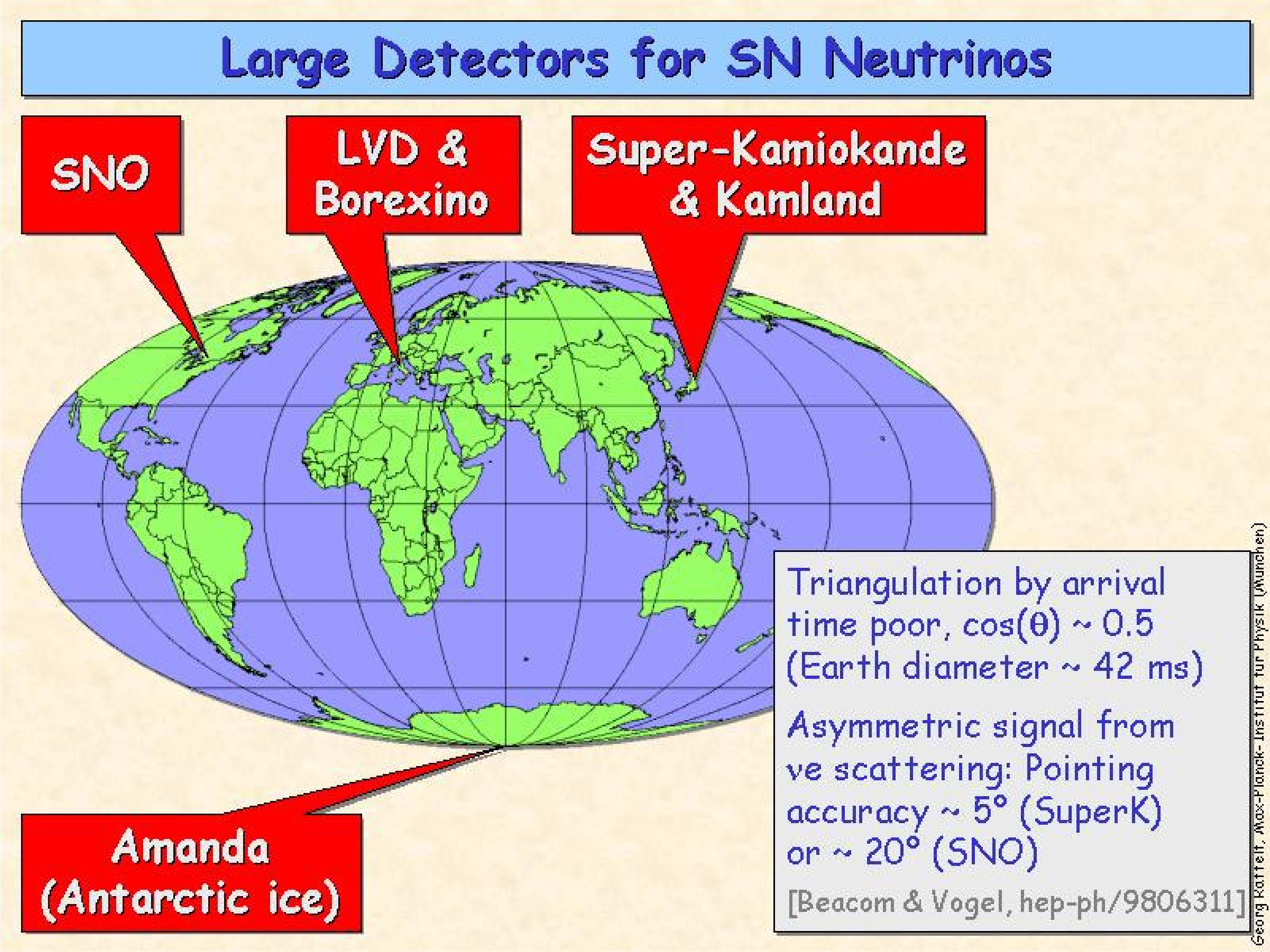
In a 10 s burst, 10 events expected from background with high threshold cut

Energy spectrum



SNEWS





Large Detectors for SN Neutrinos

Triangulation by arrival time poor, cos(θ) ~ 0.5 (Earth diameter ~ 42 ms)

Asymmetric signal from νe scattering: Pointing accuracy ~ 5° (SuperK) or ~ 20° (SNO)

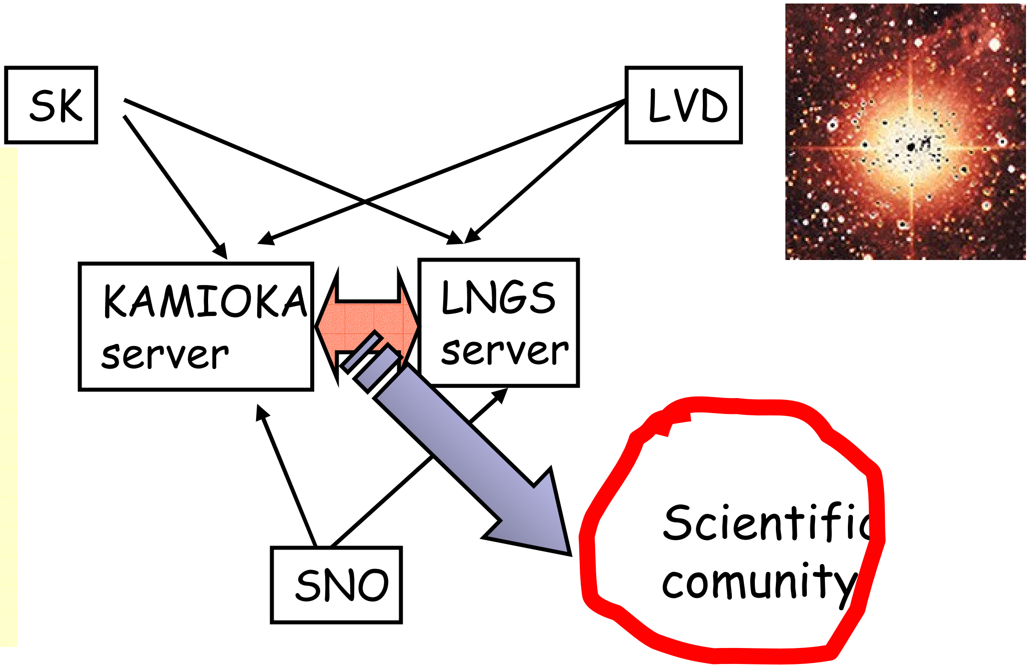
[Beacom & Vogel, hep-ph/9806311]

Georg Raffelt, Max-Planck-Institut für Physik (München)

The SNEWS system

SuperNova Early Warning System: working group between experiments looking for SN burst

(currently LVD, SK, SNO, but Borexino, Amanda, MiniBoone, KamLand expected to join)

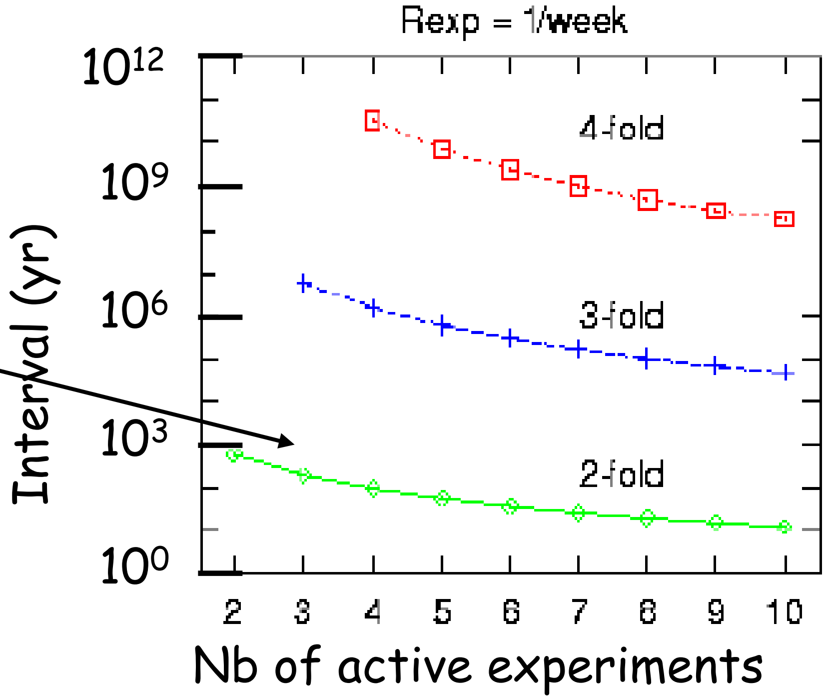


Every experiment looks for SN burst and send alarm at average rate of 1/week
Network as much as possible fault tolerant

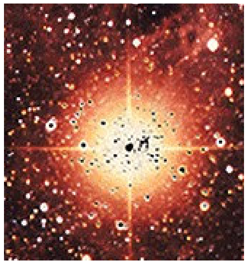
Give prompt information to astronomical comunity.

Doing online twofold coincidence allows to send a prompt alarm and to reduce to zero fake alarm!

Triangulation possible but $\delta\theta \approx 50\%$

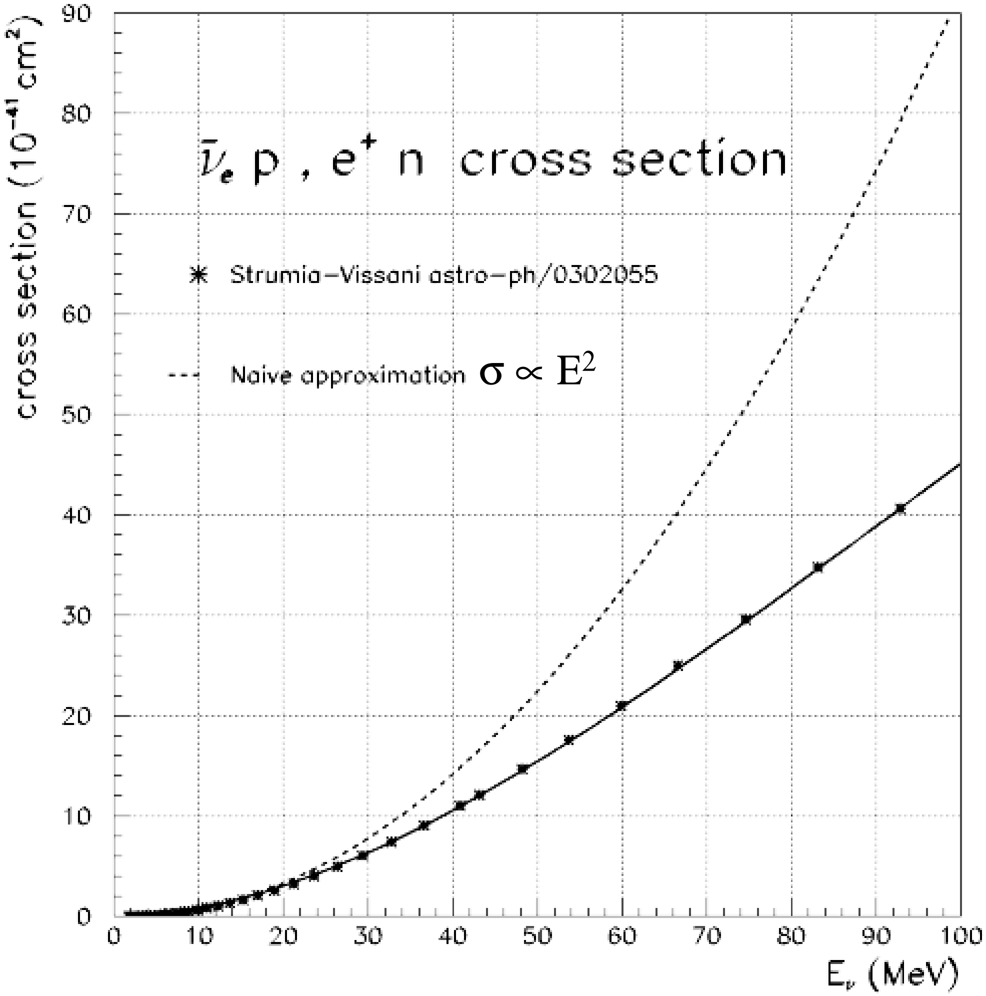


Inverse beta decay



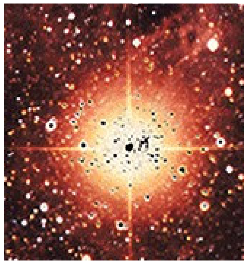
The most important reaction in LS is:

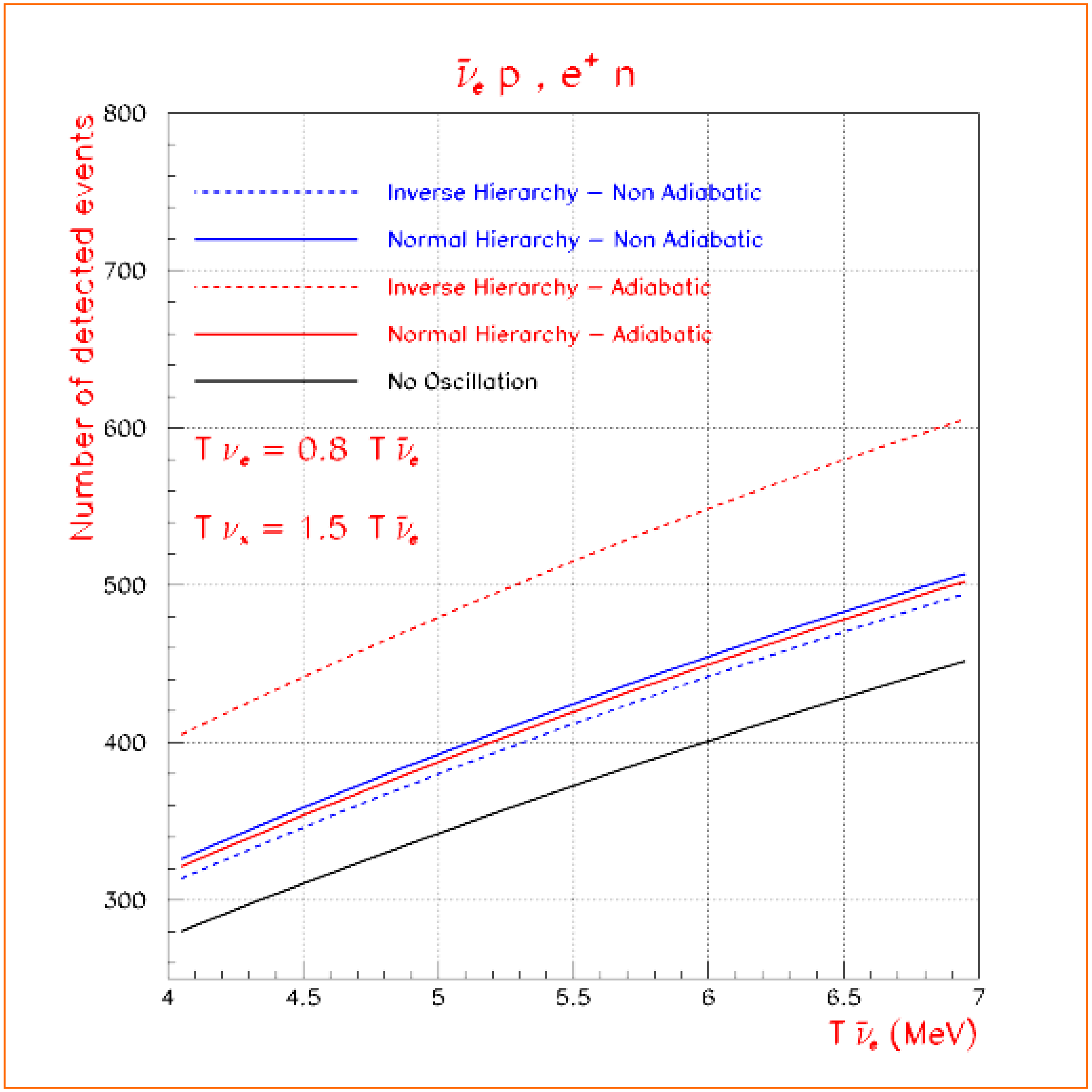
- $\bar{\nu}_e$ p,n e^+ observed through
  - a prompt signal from e^+ above threshold ε_h (detectable energy $E_d \leftrightarrow E_{\bar{\nu}e}$ - 1.8 MeV + 2 $m_e c^2$), followed by
  - the signal from the n p,d γ capture ($E\gamma$ = 2.2 MeV), above ε_l and with a mean delay $\Delta t \leftrightarrow$ 180 μs.



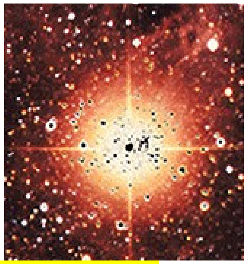
The cross section for this reaction has been recently recalculated (astro-ph/0302055) with a better treatment of the 10-100 MeV region, very important for the SN neutrino signal. This result in a lower rate at high energy with respect to older calculations.

Inverse beta decay





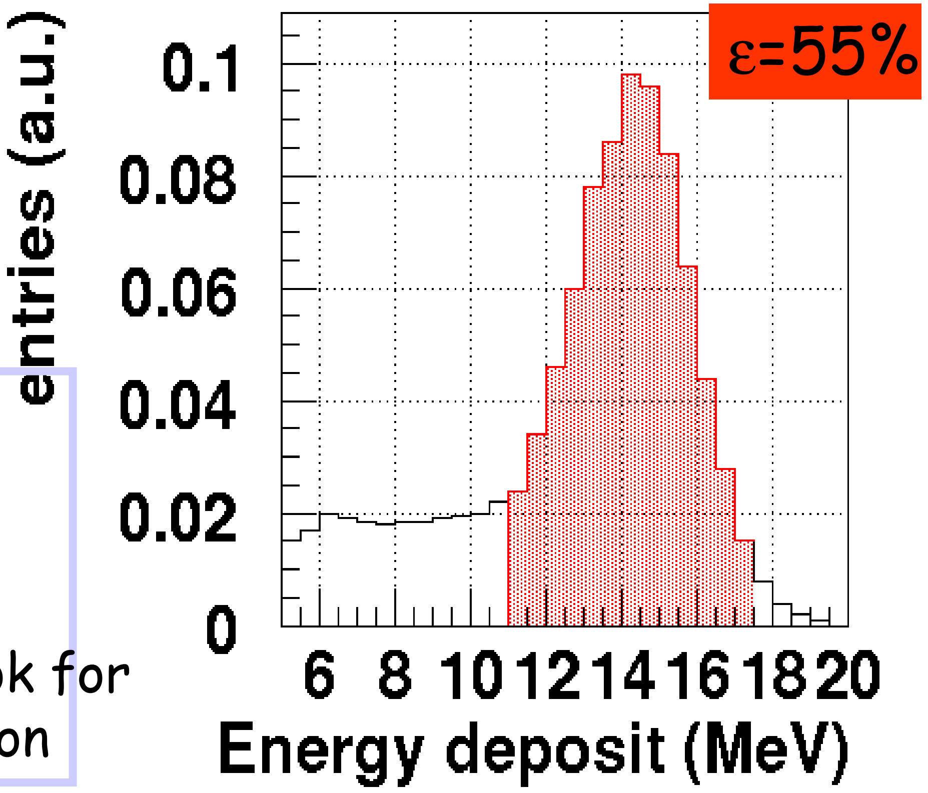
ν interactions on Carbon nuclei



Interaction	
$\overline{\nu}_e + p \rightarrow n + e^+$	CC
$\nu_i + e^- \rightarrow \nu_i + e^-$	CC-NC
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	CC
$\overline{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	CC
$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C^*$ ${}^{12}C^* \rightarrow {}^{12}C + \gamma$	NC

Elastic scattering

γ 15.11 MeV energy deposit

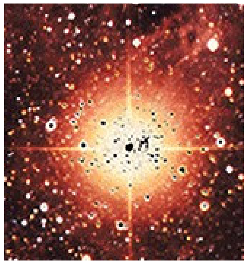


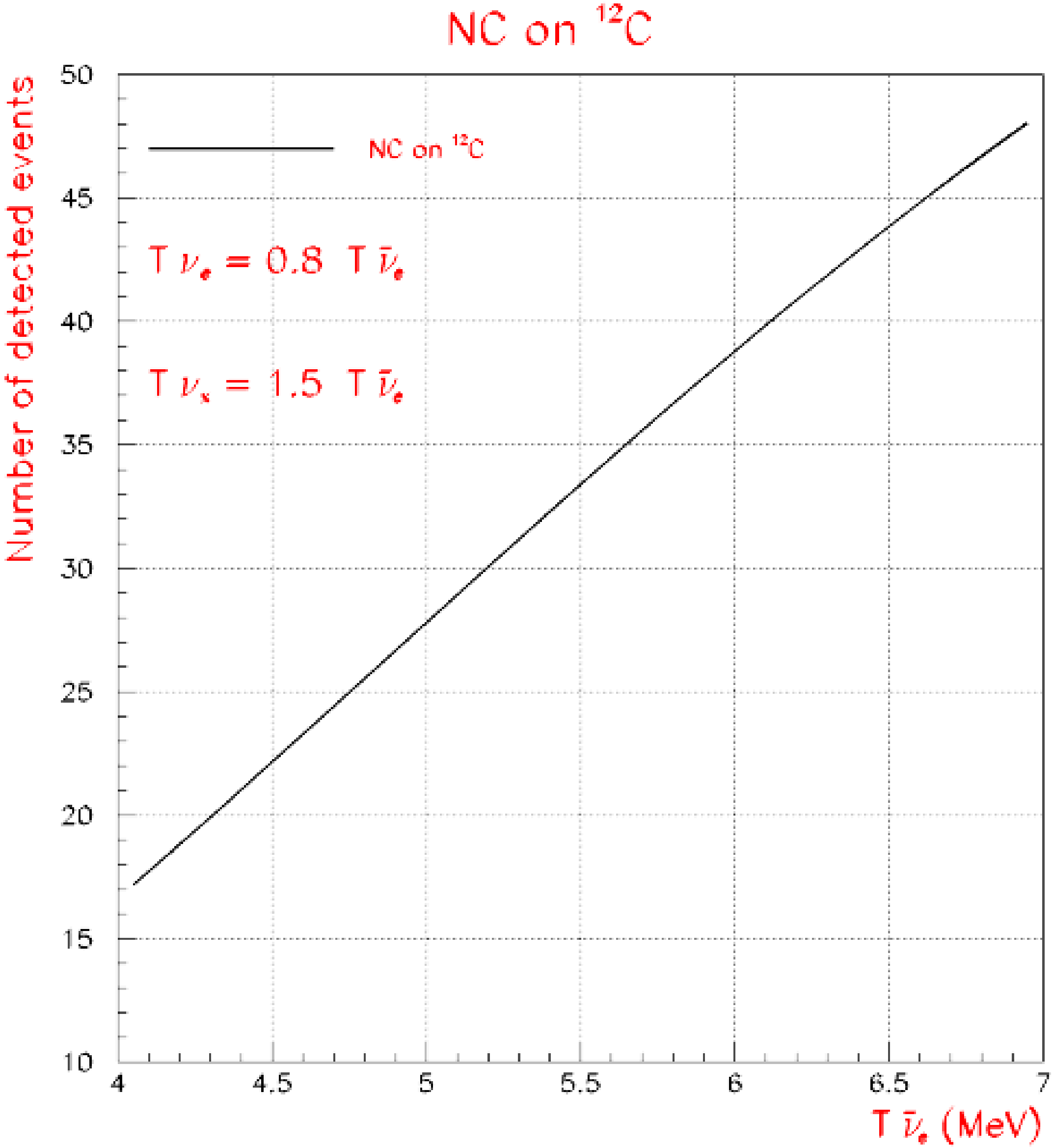
P. Antonioli et al., NIM A309 (1991) 5

The NC carbon reaction allows a bolometric flux measurement, “oscillation” independent.

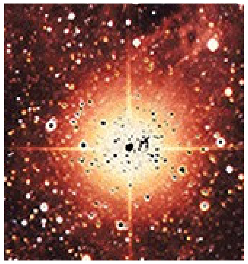
An energy window is selected to look for excess of events due to this reaction

Neutral Current with ^{12}C

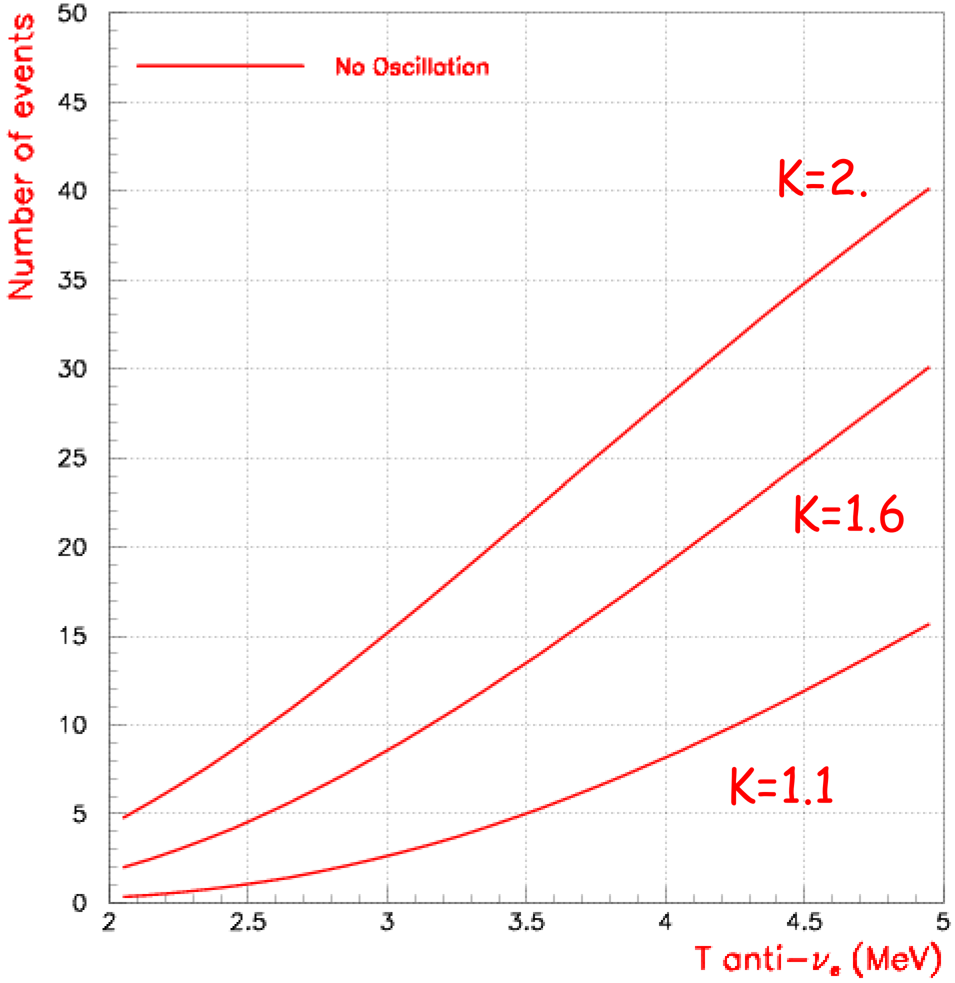




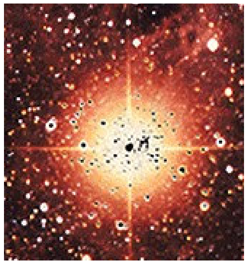
Neutral Current with ^{12}C

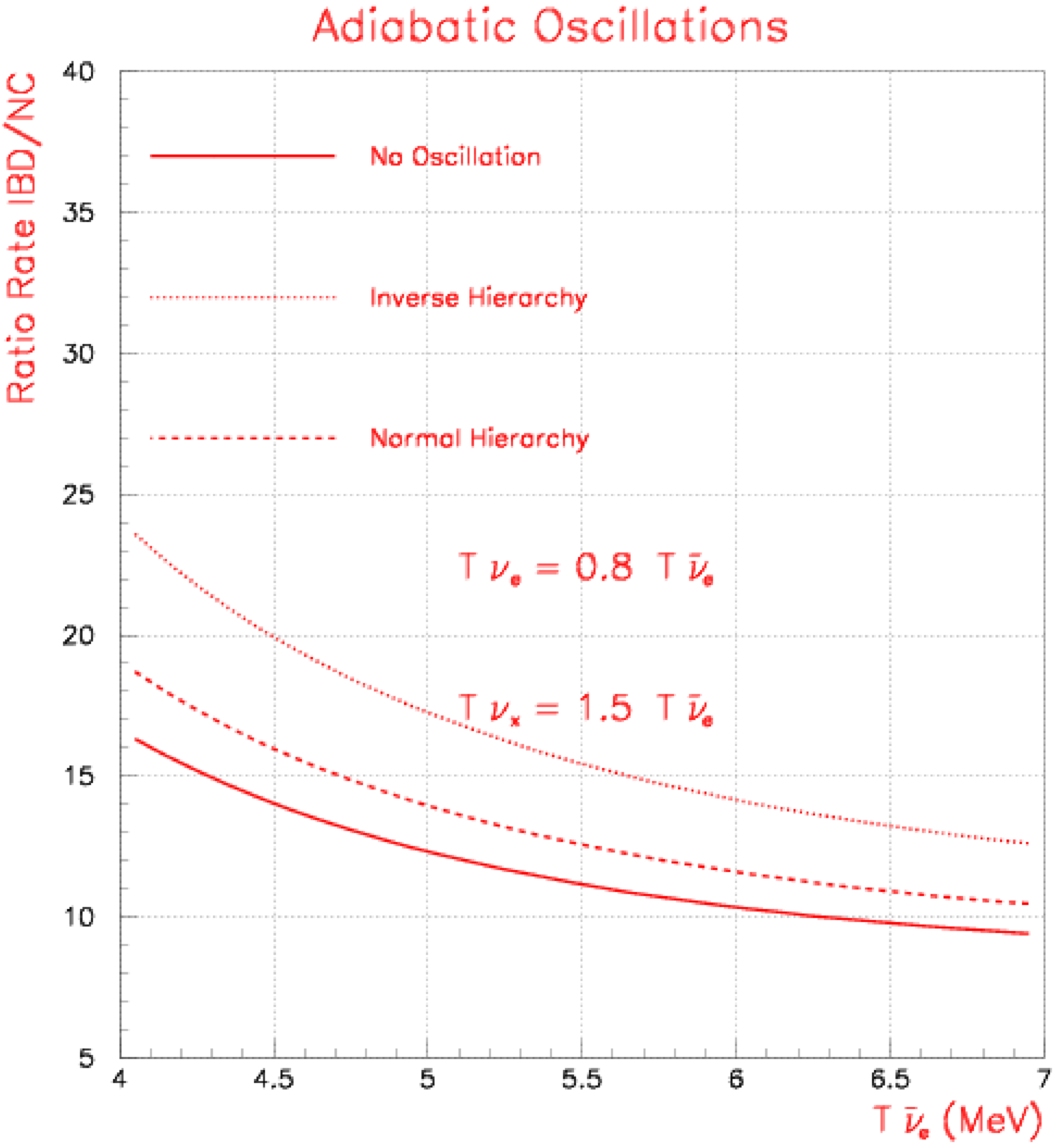


- $T_{\nu x}/T_{\overline{\nu e}} = k$

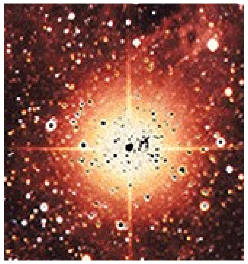


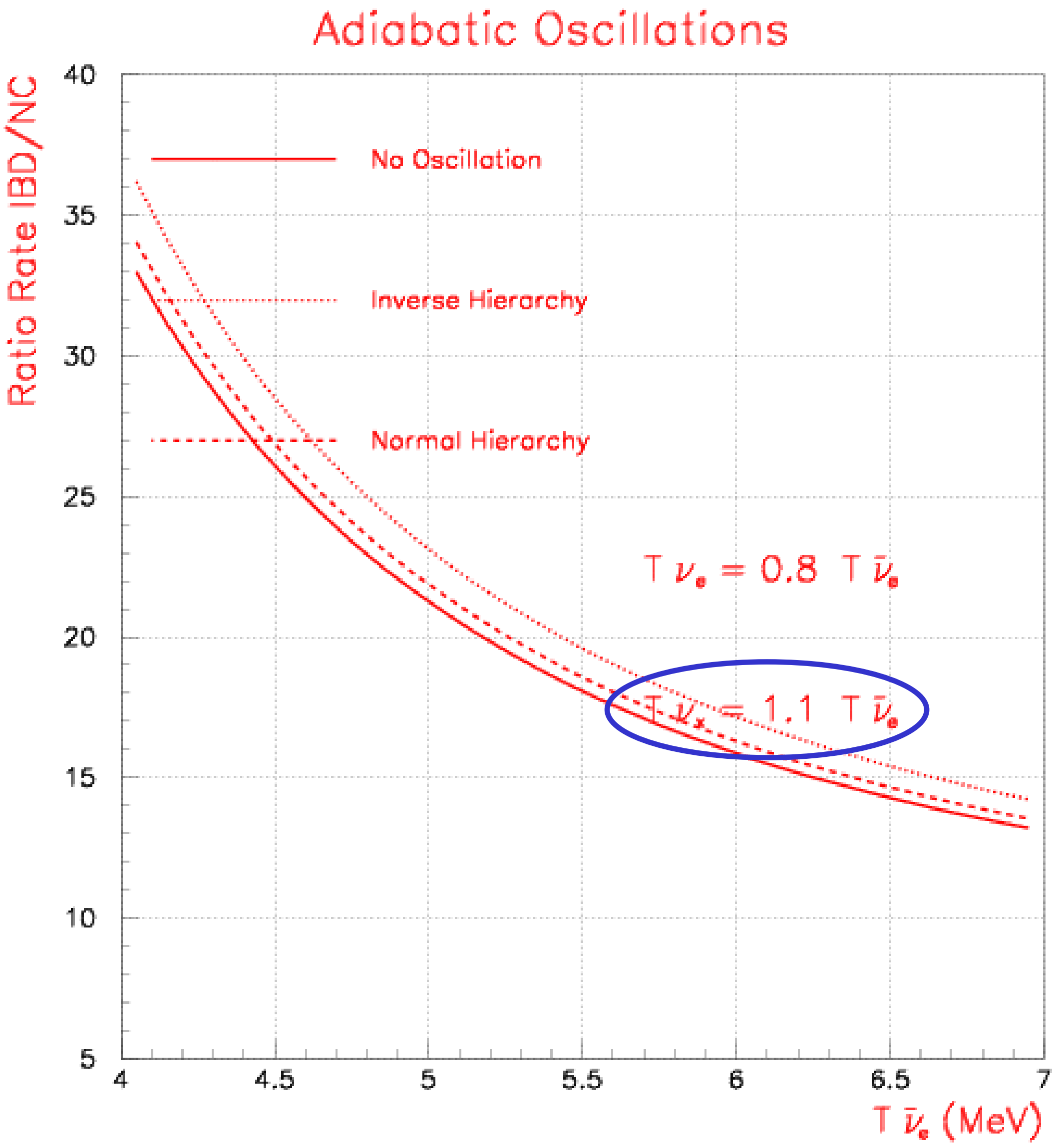
Ratio IβD/NC




Adiabatic Oscillations
Ratio Rate IBD/NC
40
35
30
25
20
15
10
5
4
4.5
5
5.5
6
6.5
7
T $\bar{\nu}_e$ (MeV)
No Oscillation
Inverse Hierarchy
Normal Hierarchy
T ν_e = 0.8 T $\bar{\nu}_e$
T ν_x = 1.5 T $\bar{\nu}_e$

Ratio IβD/NC




Adiabatic Oscillations
Ratio Rate IBD/NC
T $\bar{\nu}_e$ (MeV)
No Oscillation
Inverse Hierarchy
Normal Hierarchy
T ν_e = 0.8 T $\bar{\nu}_e$
T ν_x = 1.1 T $\bar{\nu}_e$
40
35
30
25
20
15
10
5
4
4.5
5
5.5
6
6.5
7

ν interactions on Carbon nuclei

Interaction	
$\bar{\nu}_e + p \rightarrow n + e^+$	CC
$\nu_i + e^- \rightarrow \nu_i + e^-$	CC-NC
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	CC
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	CC
$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C^*$ ${}^{12}C^* \rightarrow {}^{12}C + \gamma$	NC

Elastic scattering

E_{th}=17.8 MeV

ε=85%

ν_e ${}^{12}C$, ${}^{12}N$ e^-, observed through two signals: the prompt one due to the e^- above ε_h (detectable energy $E_d \leftrightarrow E_{\nu e}$ - 17.8 MeV) followed by the signal, above ε_h, from the β decay of ${}^{12}N$ (mean life time τ = 15.9 ms).

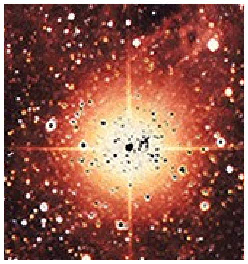
E_{th}=13.9 MeV

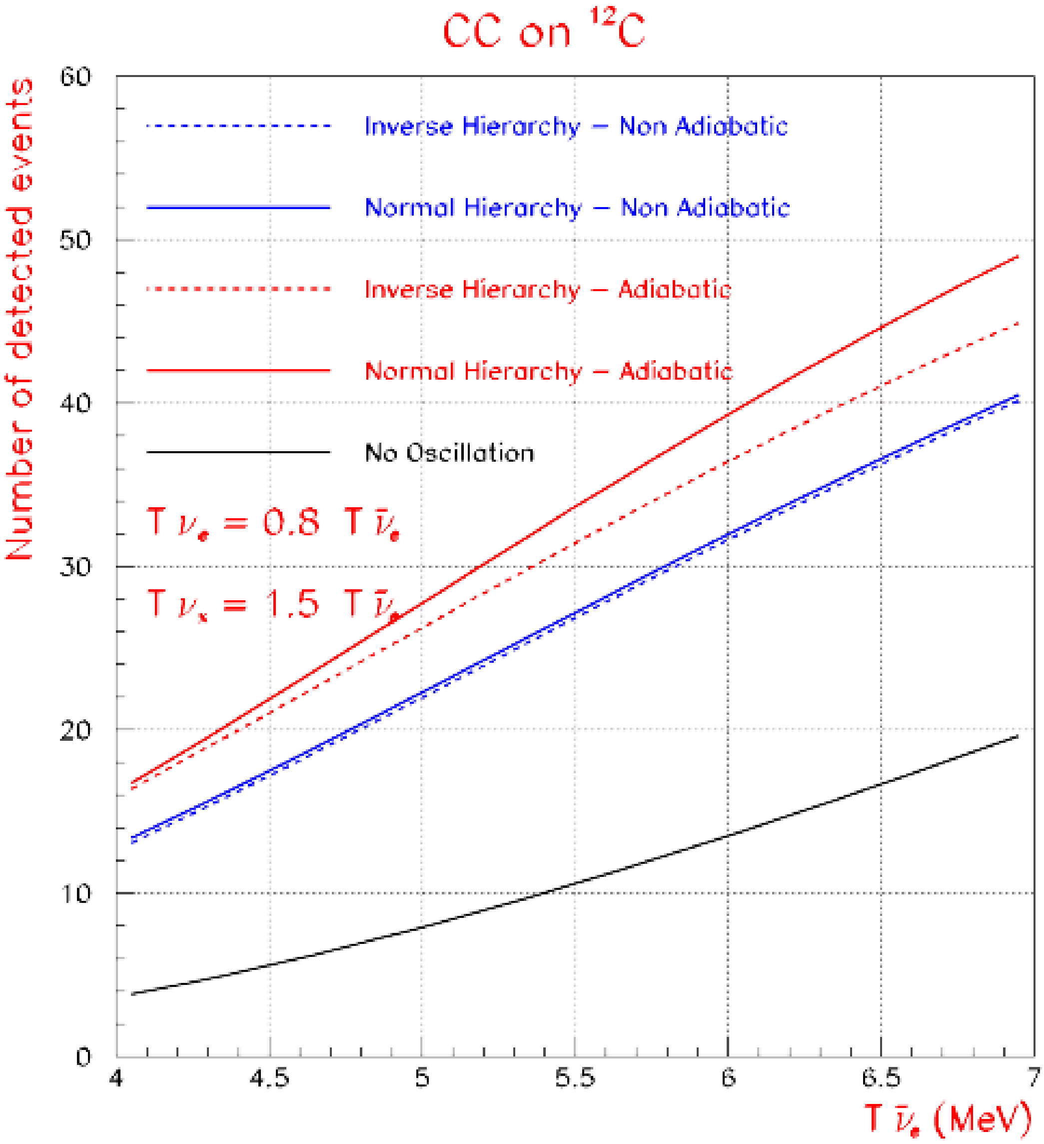
ε=70%

$\bar{\nu}_e$ ${}^{12}C$, ${}^{12}B$ e^+, observed through two signals: the prompt one due to the e^+ above ε_h (detectable energy $E_d \leftrightarrow E_{ne}$ - 13.9 MeV + 2 $m_e c^2$), followed by the signal, above ε_h, from the β^- decay of ${}^{12}B$ (mean life time t = 29.4 ms).

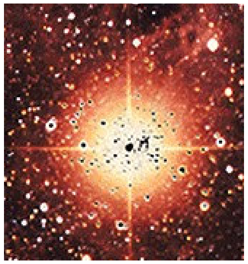
Detector modularity allows precise event tagging

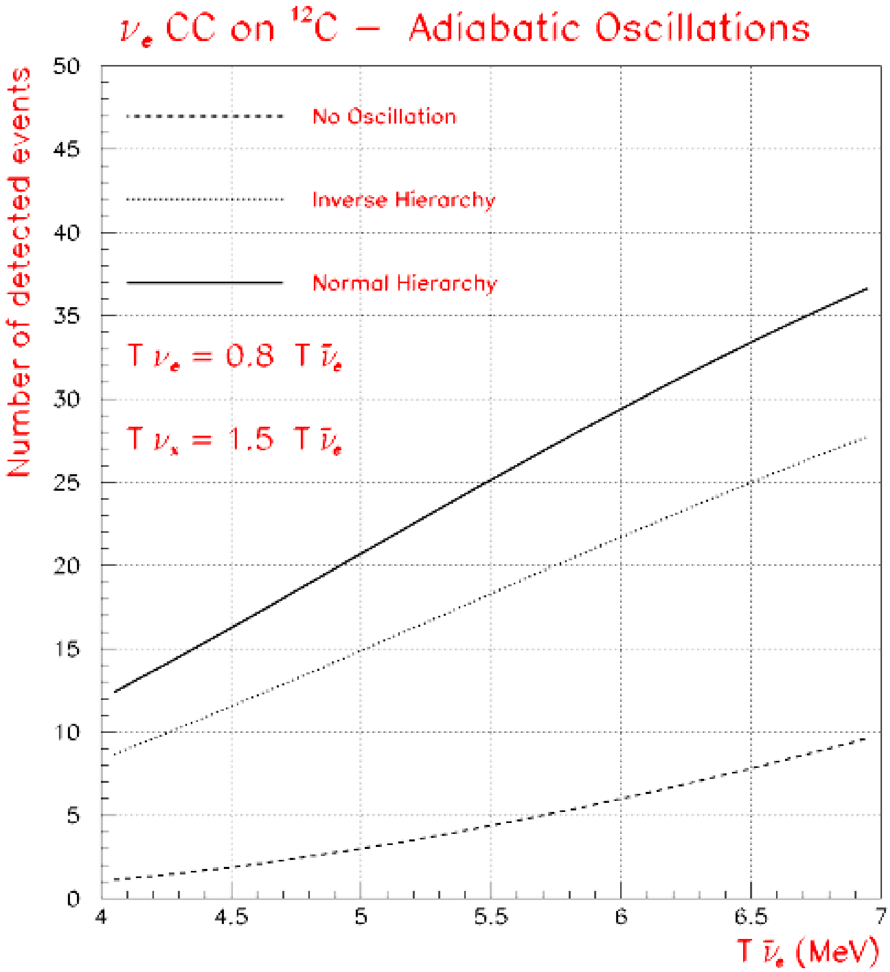
CC with ^{12}C

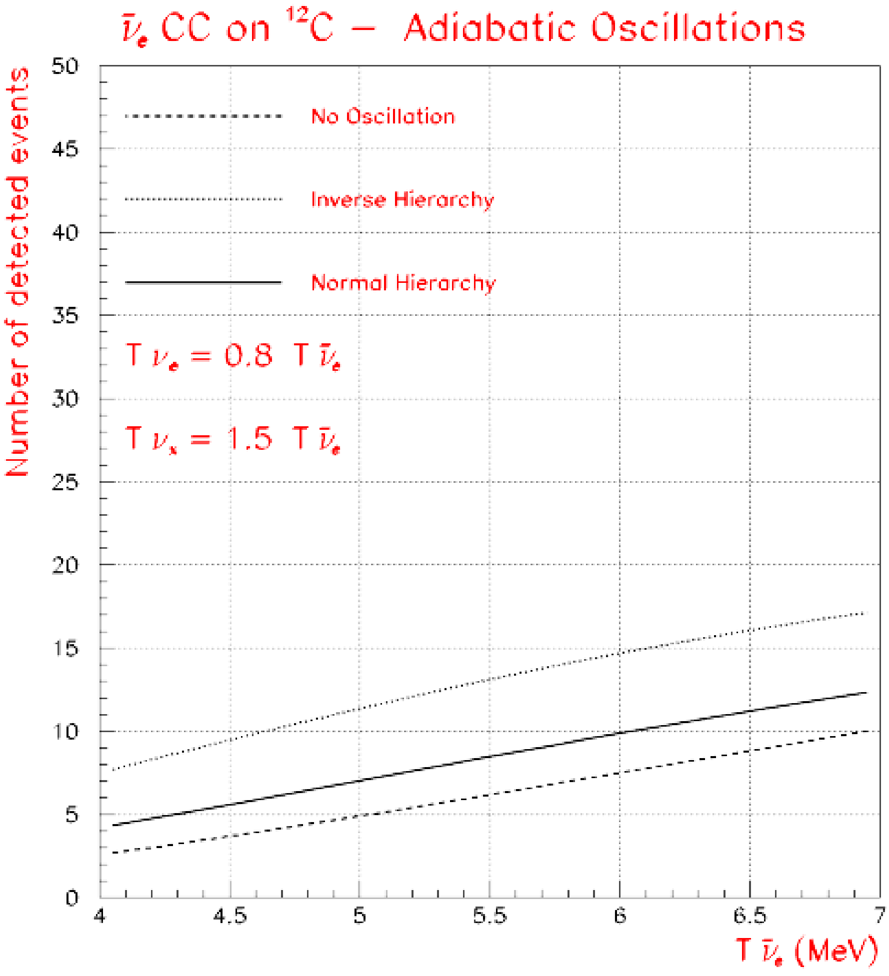



CC on ^{12}C
Number of detected events
60
50
40
30
20
10
0
4
4.5
5
5.5
6
6.5
7
Inverse Hierarchy – Non Adiabatic
Normal Hierarchy – Non Adiabatic
Inverse Hierarchy – Adiabatic
Normal Hierarchy – Adiabatic
No Oscillation
$T\,\nu_e = 0.8\ T\,\bar{\nu}_e$
$T\,\nu_x = 1.5\ T\,\bar{\nu}_e$
$T\,\bar{\nu}_e$ (MeV)

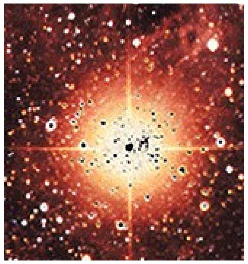
CC with ^{12}C




ν_e CC on ^{12}C – Adiabatic Oscillations


$\bar{\nu}_e$ CC on ^{12}C – Adiabatic Oscillations

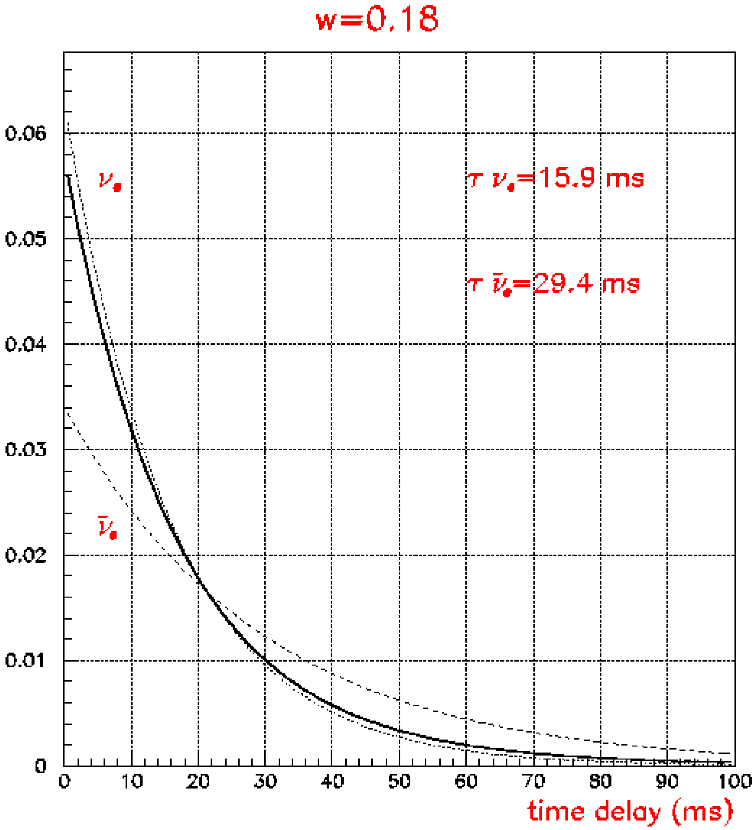
CC with ^{12}C

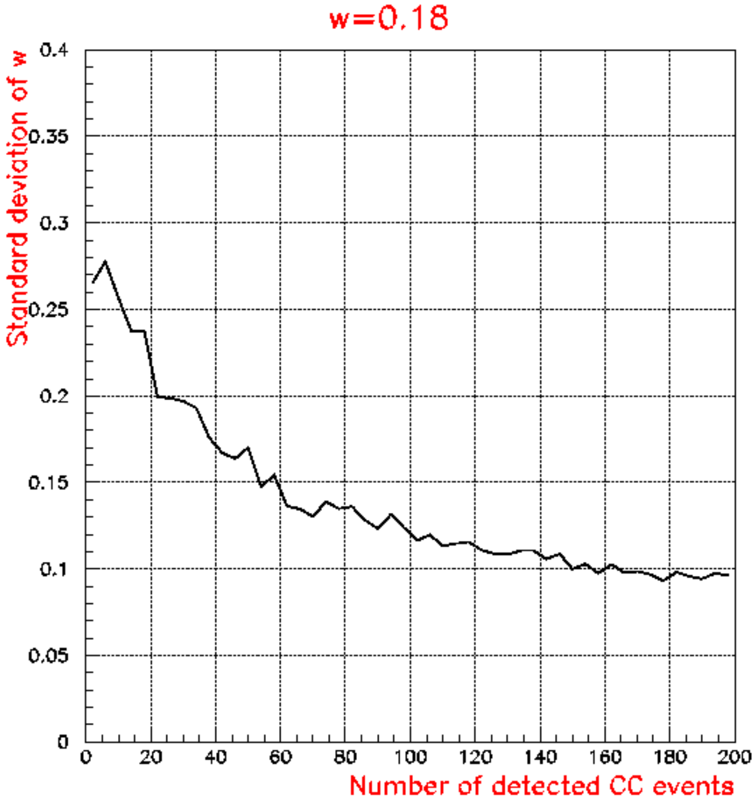


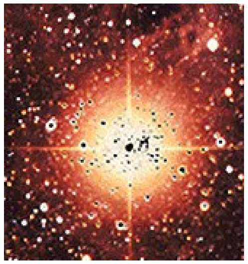
At T_{anue}=5 MeV

	ν_e	$\bar{\nu}_e$	tot	w
NH	22	6	28	0.2
IH	15	11	26	0.4

W = # antinue /
(# antinue + # nue)







ν interactions in Fe

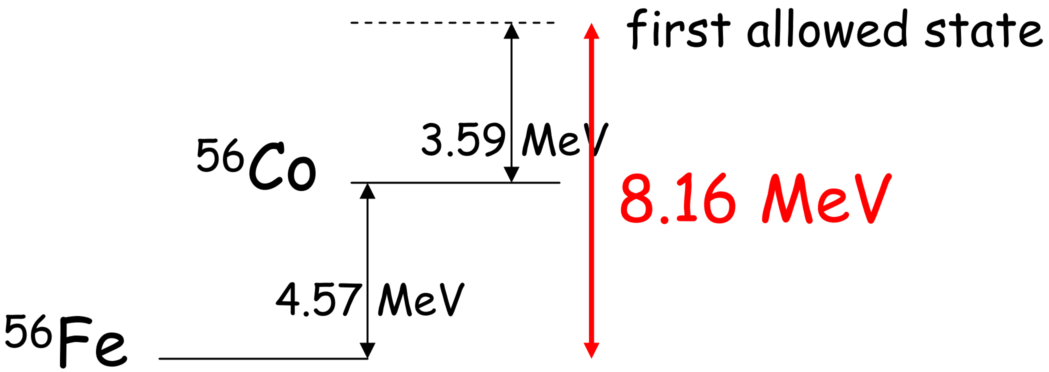
Neutrino interactions in iron

The LVD detector presents an iron support structure made basically by two components: the tank (mean thickness: 0.4 cm) which contains the LS and the portatank (mean thickness: 1.5 cm) which hosts a cluster of 8 tanks. Indeed, the higher energy part of the ν flux could be detected also with the ν–Fe interaction, which results in an electron (positron) that could exit iron and release energy in the LS.

The considered reactions are:

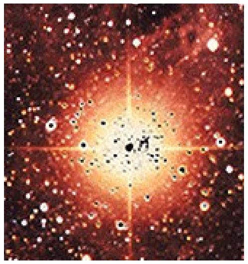
$\nu_e\ ^{56}Fe,\ ^{56}Co\ e^-$

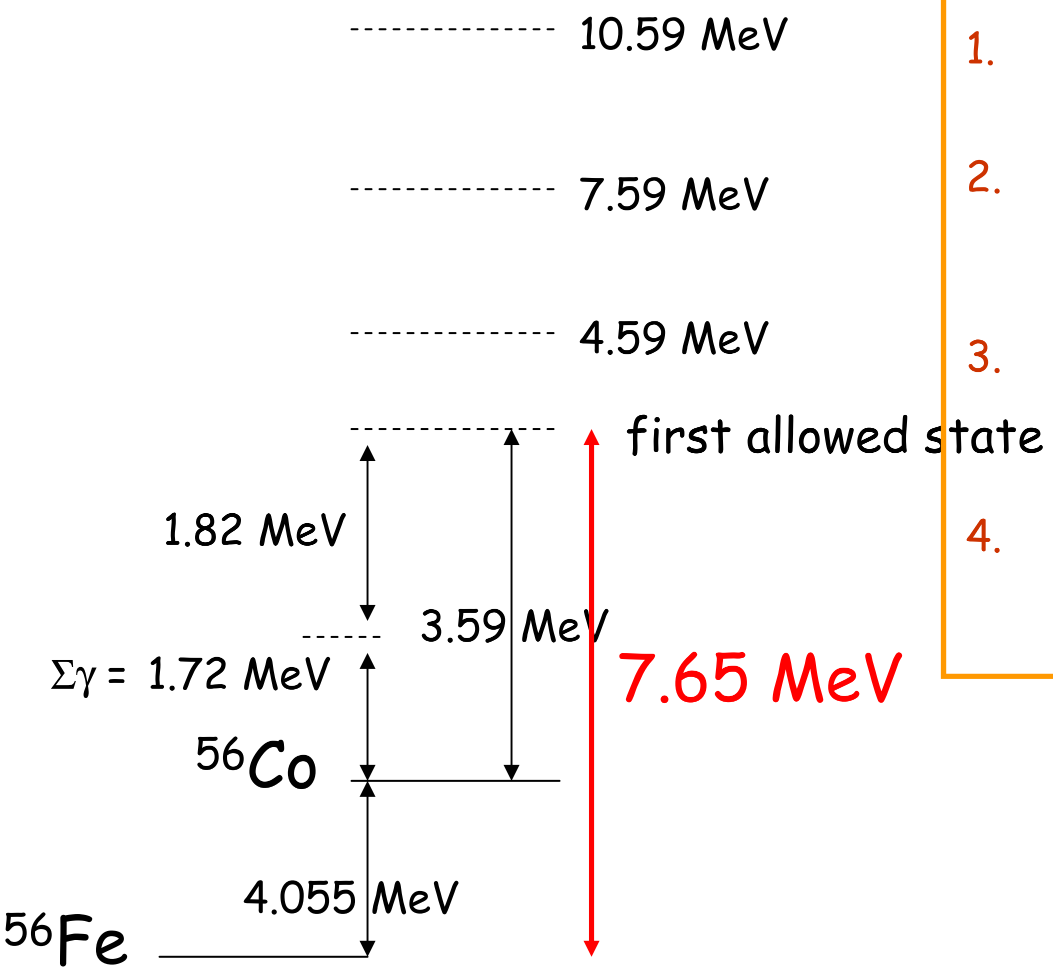
the binding energy difference between the ground levels is $E_b^{Co} - E_b^{Fe} = 4.57$ MeV; moreover the first Co allowed state is at 3.59 MeV.
Indeed, in this work we considered $E_{e-} = E_{\nu e} - 8.16\ \text{MeV} - m_e$.



$\bar{\nu}_e\ ^{56}Fe,\ ^{56}Mn\ e^+$; the energy threshold is very similar to the previous reaction and the same considerations could be done.

Neutrino interactions in iron

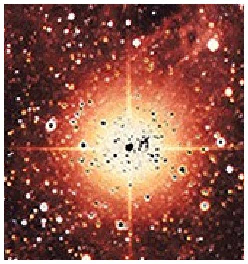


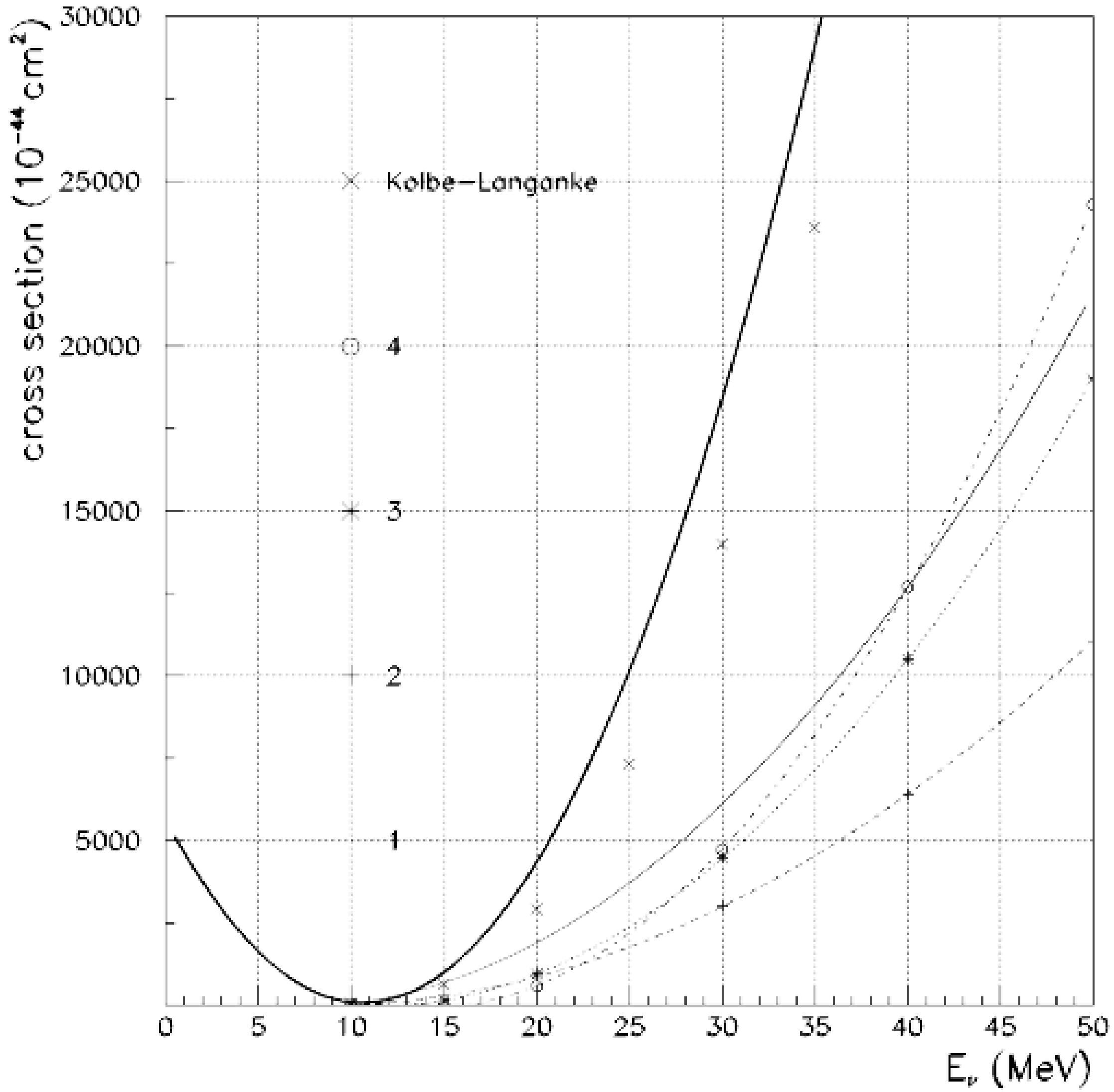


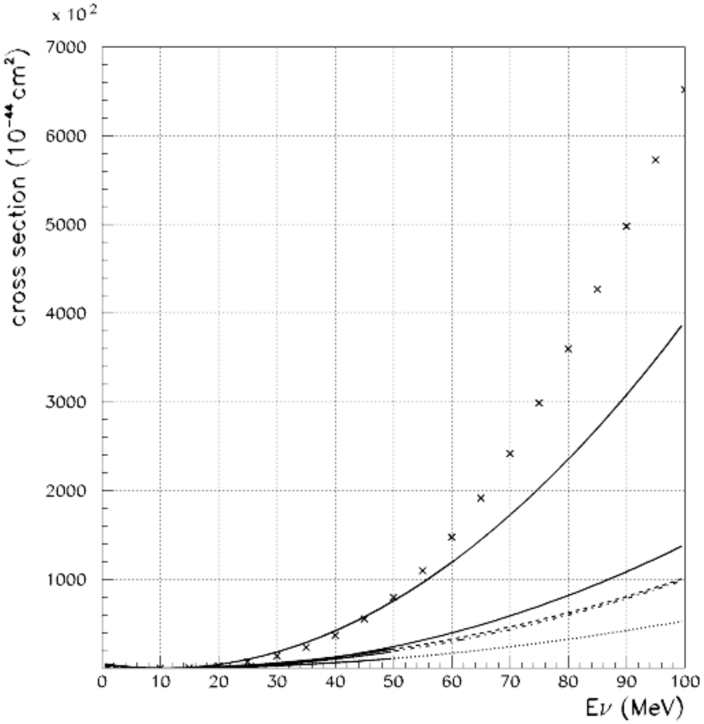
Example Eν=40MeV … 4 scenarios

1. E^{kin}_{e-} = 40 – 7.65 – 0.511 = 31.33 MeV
   Eγ = 1.82 MeV ΣEγ = 1.72 MeV
2. E^{kin}_{e-} = 40 – 8.65 – 0.511 = 30.33 MeV
   Eγ = 1 MeV
   Eγ = 1.82 MeV ΣEγ = 1.72 MeV
3. E^{kin}_{e-} = 40 – 11.65 – 0.511 = 27.33 MeV
   Eγ = 4 MeV
   Eγ = 1.82 MeV ΣEγ = 1.72 MeV
4. E^{kin}_{e-} = 40 – 14.65 – 0.511 = 24.33 MeV
   Eγ = 7 MeV
   Eγ = 1.82 MeV ΣEγ = 1.72 MeV

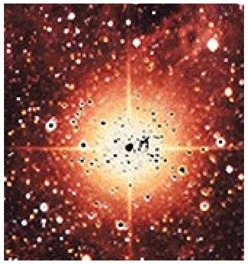
Neutrino cross sections

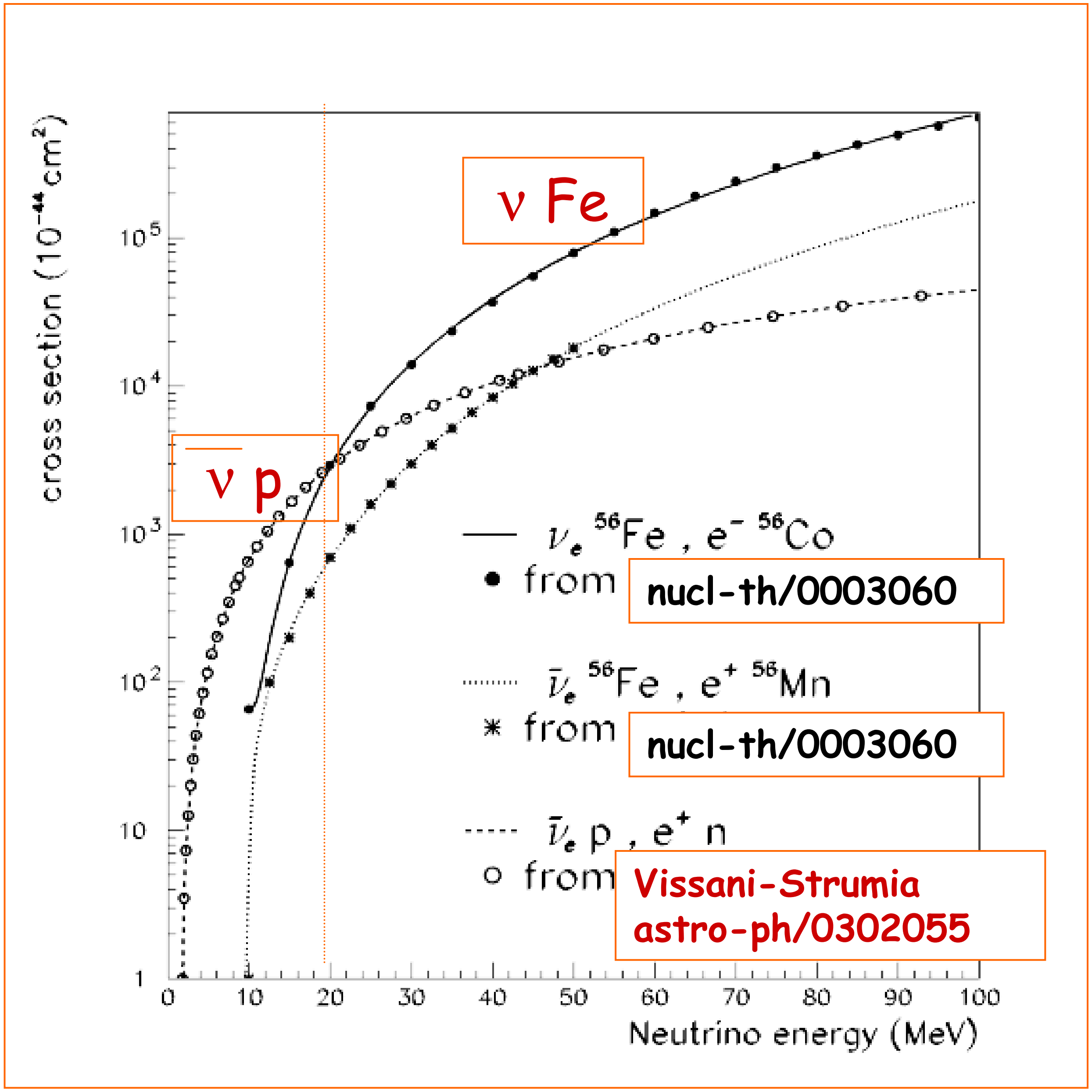




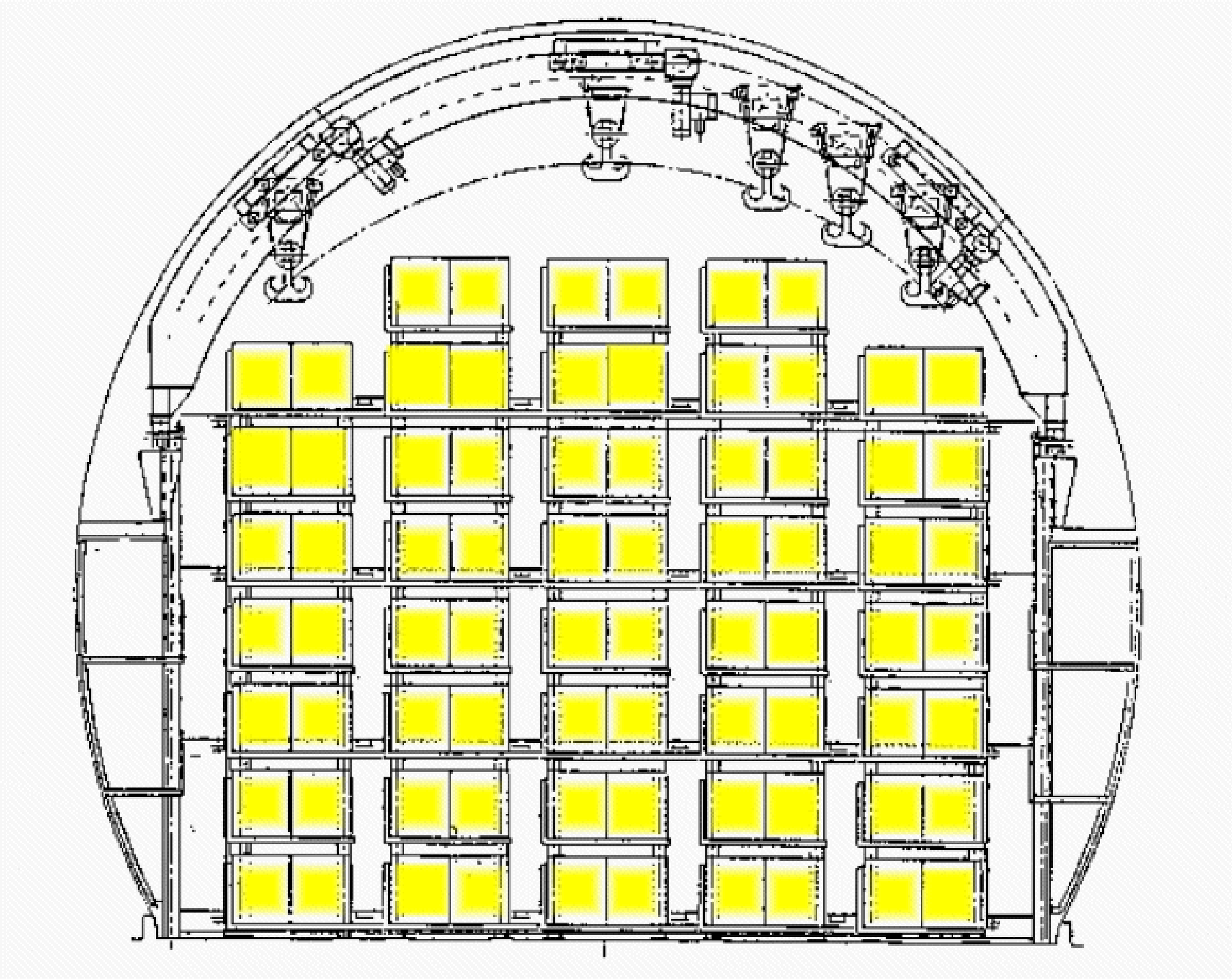


Neutrino cross sections

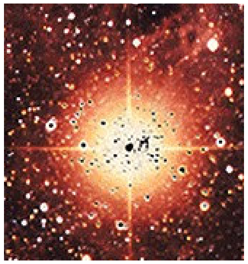


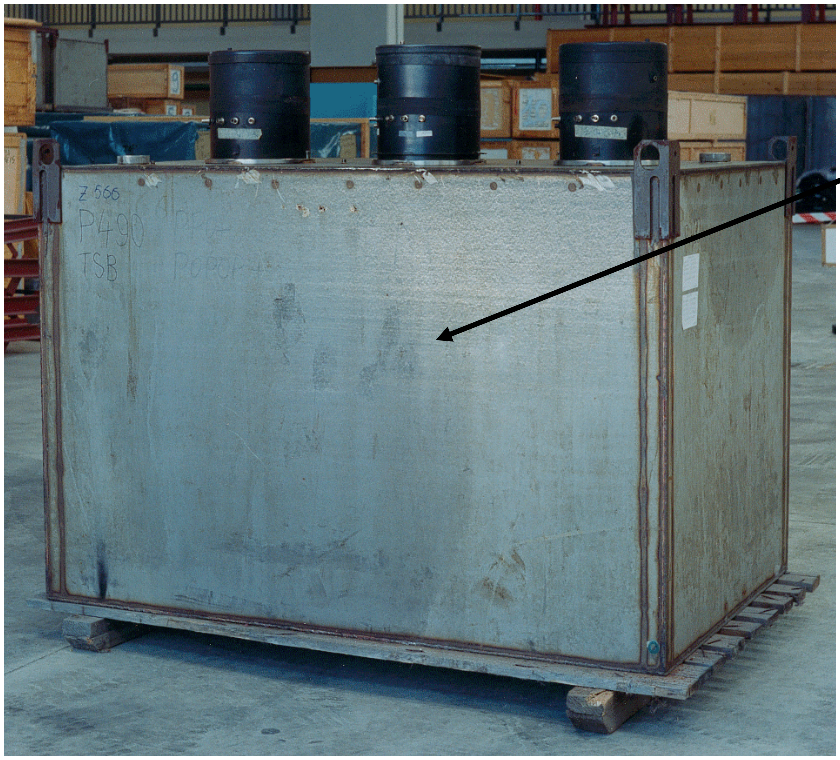


LVD support structure

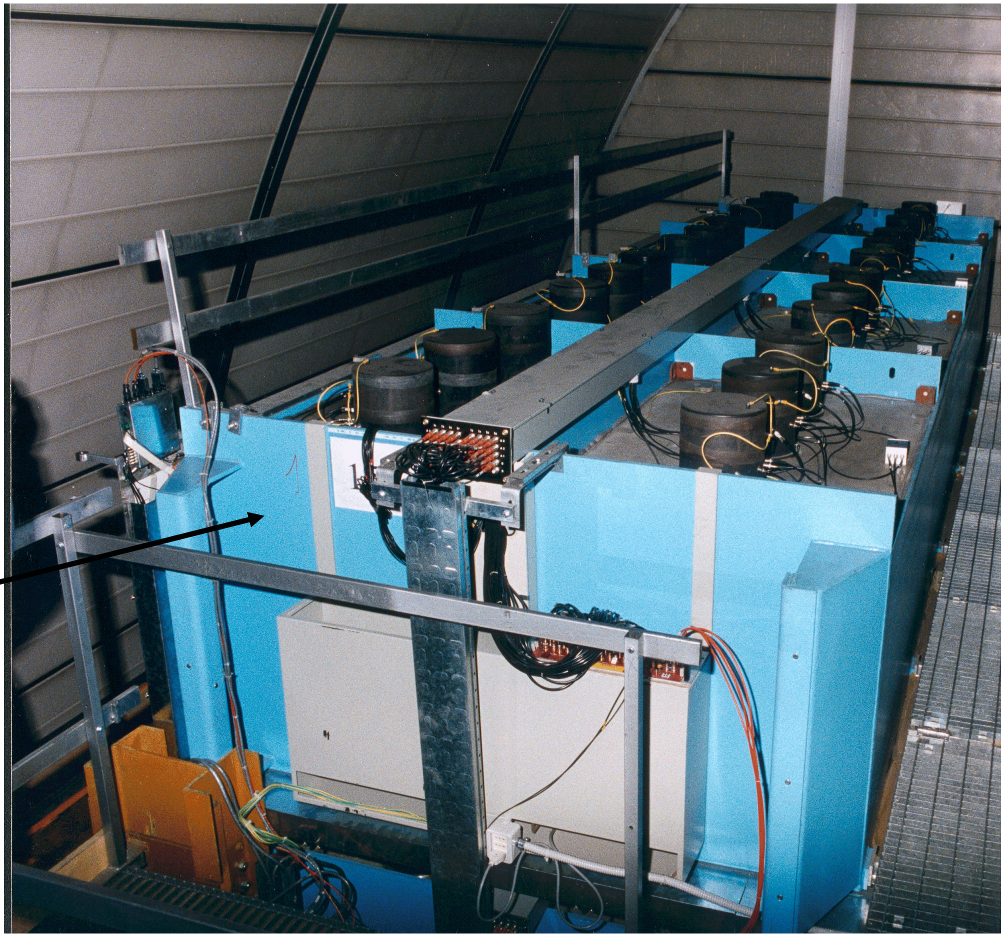


LVD support structure



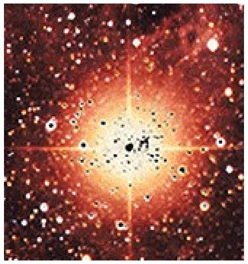


Tank:
mean thickness = 0.4 cm



PortaTank:
mean thickness=
1.5 cm

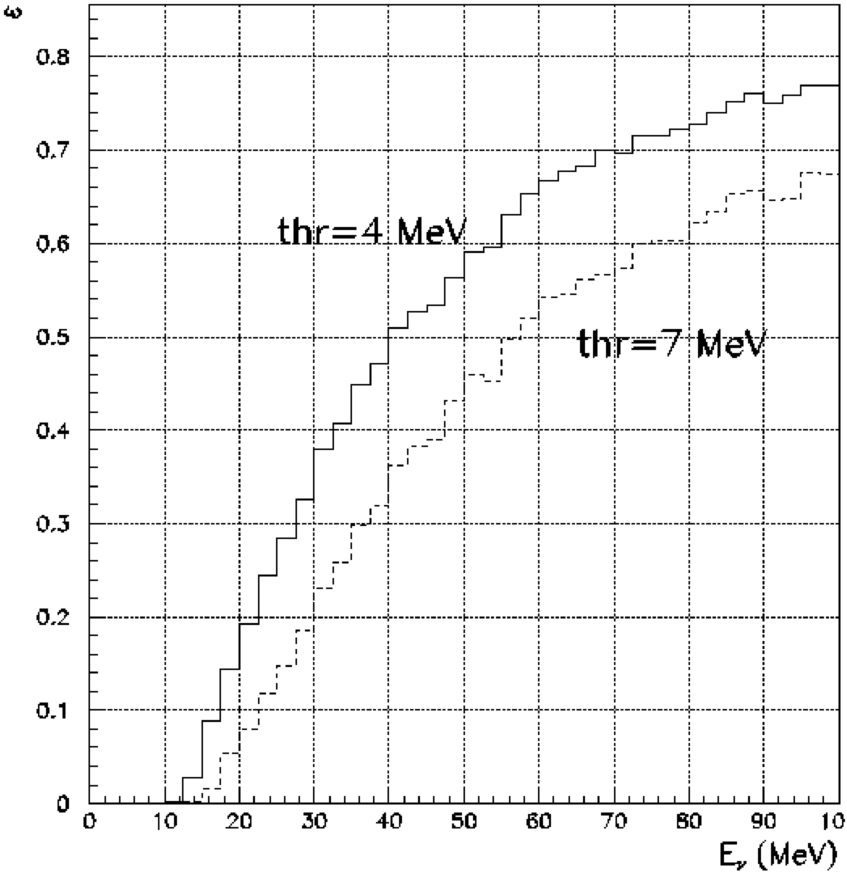
Detection efficiency



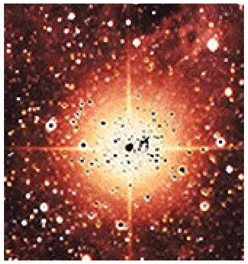
A full simulation of the LVD support structure and LS geometry has been developed in order to get the efficiency for an electron, generated randomly in the iron structure, to reach the LS with energy higher than ε_h. The efficiency is greater than 20% for $E_{\nu e} > 30$ MeV and grows up to 70% for $E_{\nu e} > 100$ MeV. On average, the electron energy detectable in the LS is $E_d \sim 0.45 \times E_{\nu e}$.

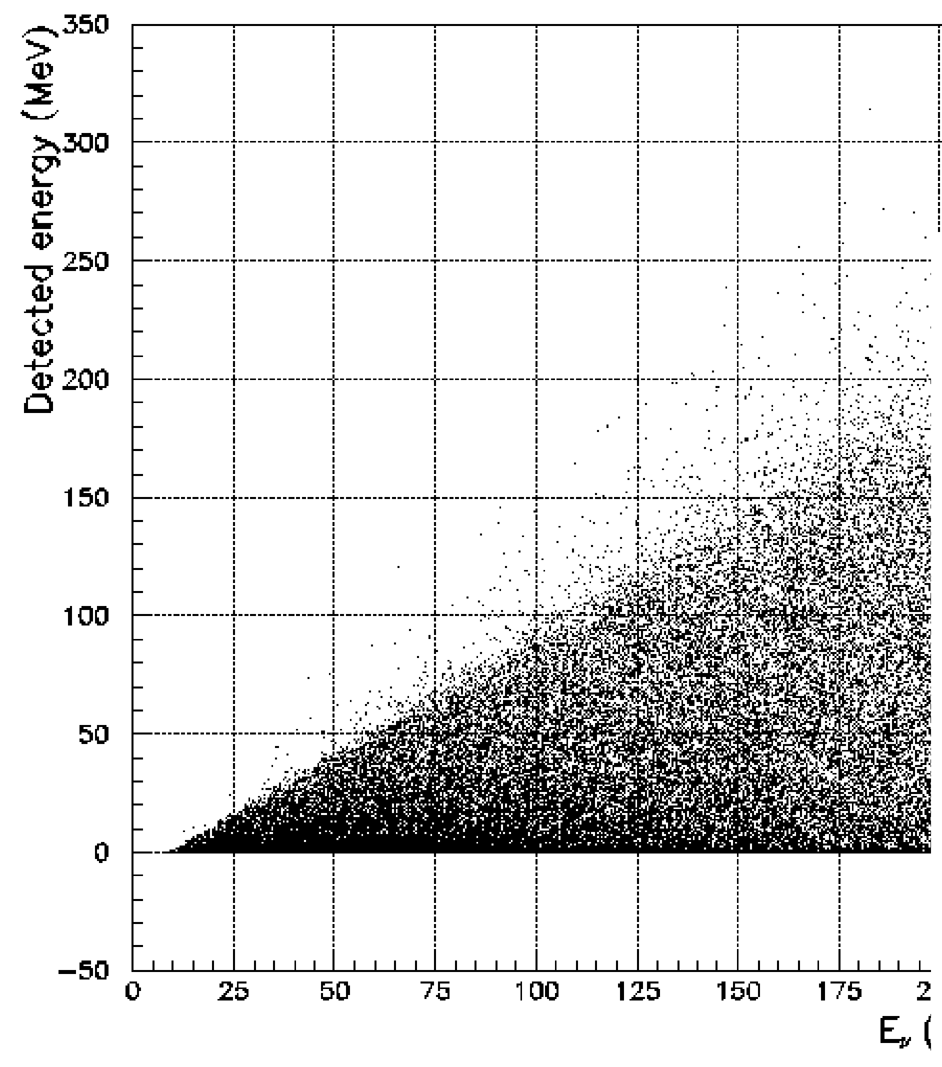
The total support structure mass is 710 t.

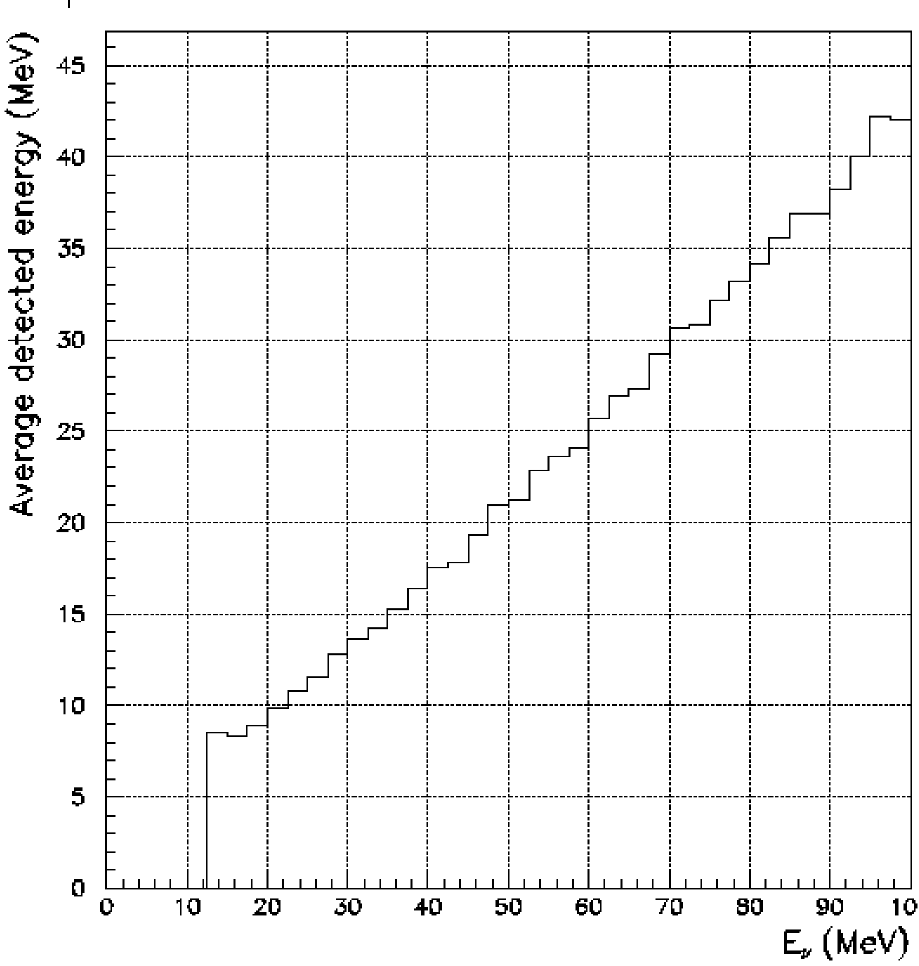
The total number of iron nuclei in the whole structure is 7.63×10^{30}.



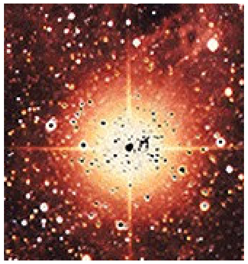
Detected energy

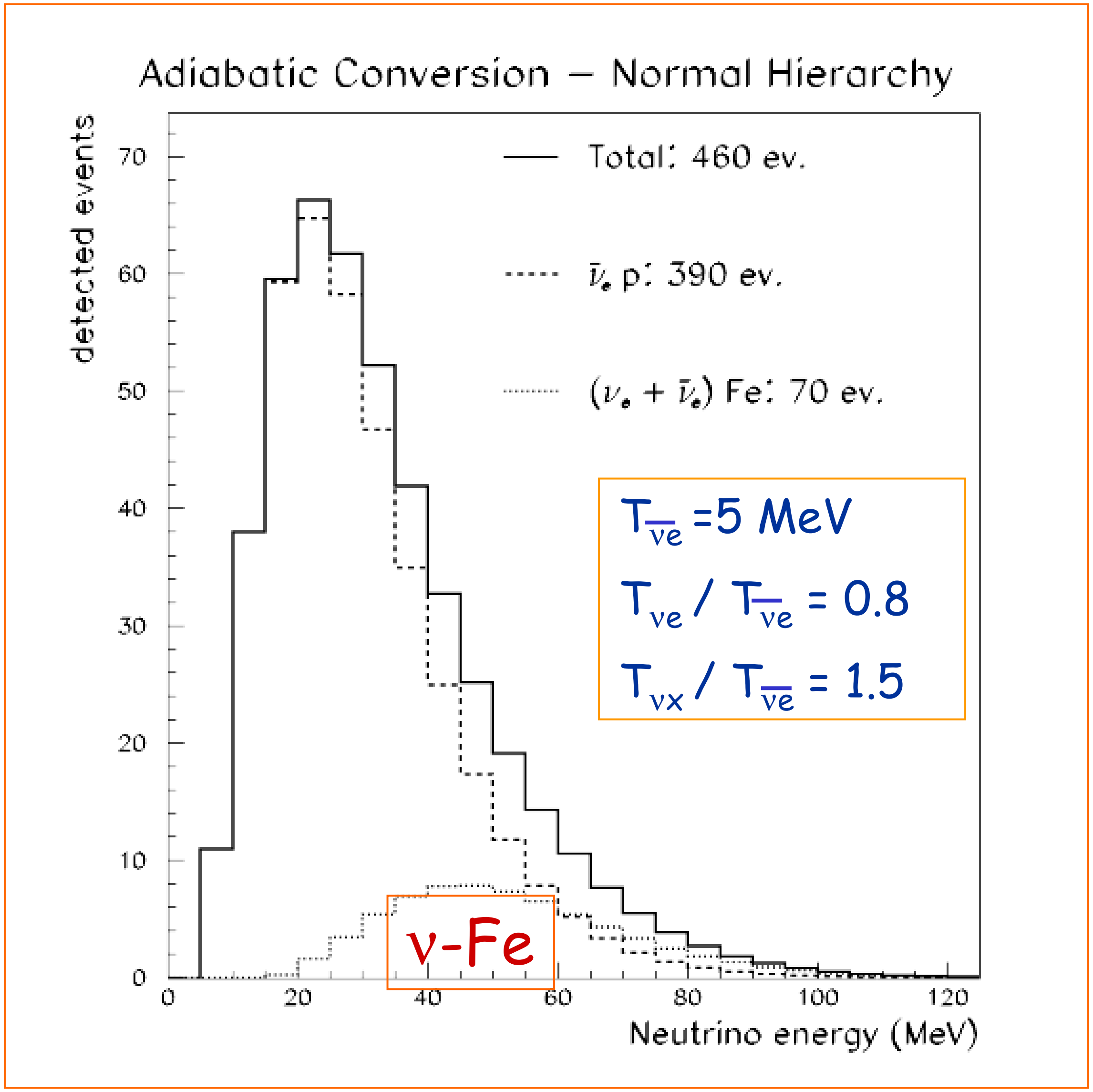






Results





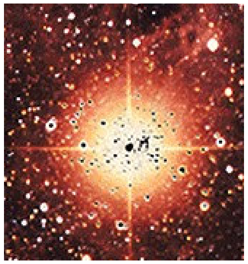
$T_{\overline{\nu e}}$ =5 MeV

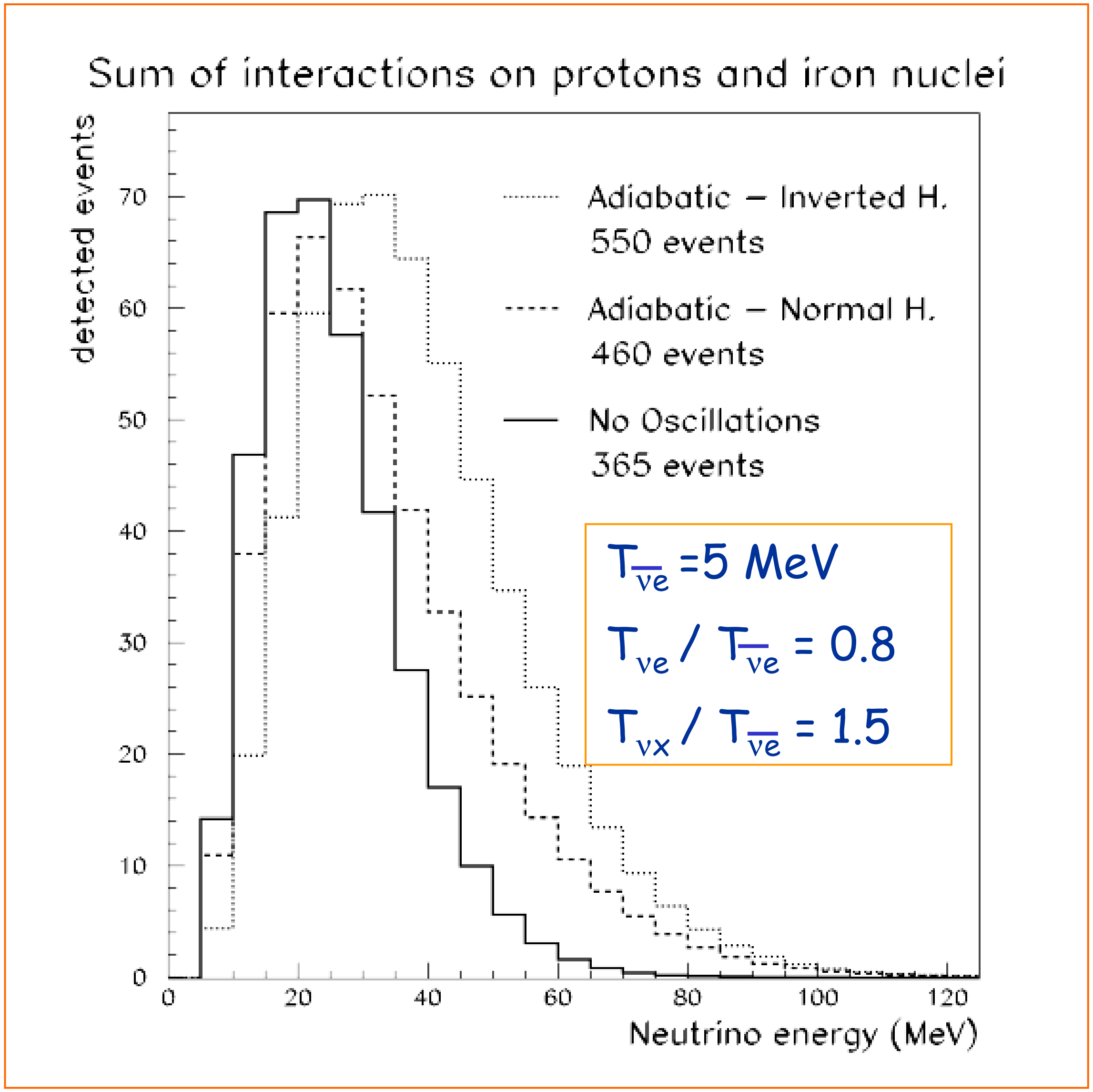
$T_{\nu e}$ / $T_{\overline{\nu e}}$ = 0.8

$T_{\nu x}$ / $T_{\overline{\nu e}}$ = 1.5

- the nb of interaction in iron is 18% of the number of inverse beta decay interactions

Results



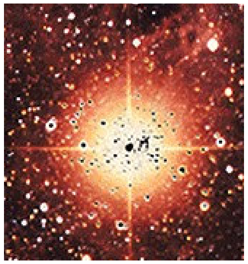


$T_{\bar{\nu}_e} = 5$ MeV

$T_{\nu_e} / T_{\bar{\nu}_e} = 0.8$

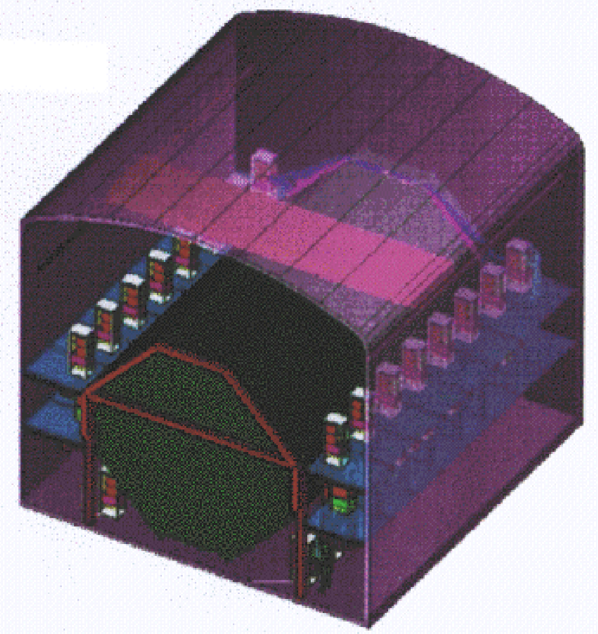
$T_{\nu_x} / T_{\bar{\nu}_e} = 1.5$

What about MINOS ?



The MINOS far detector has the following characteristics:

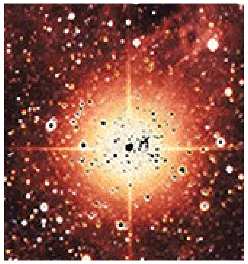
- 486 iron plates of 2.54 cm Fe
- Separated by 1 cm scintillator bars
- Total mass: 5.4 kt



Half of the MINOS Far Detector

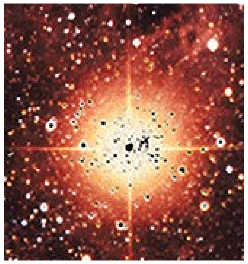
In case of a "standard" SN, the events in which the electron (or the positron) can exit iron and get the scintillator bar are:

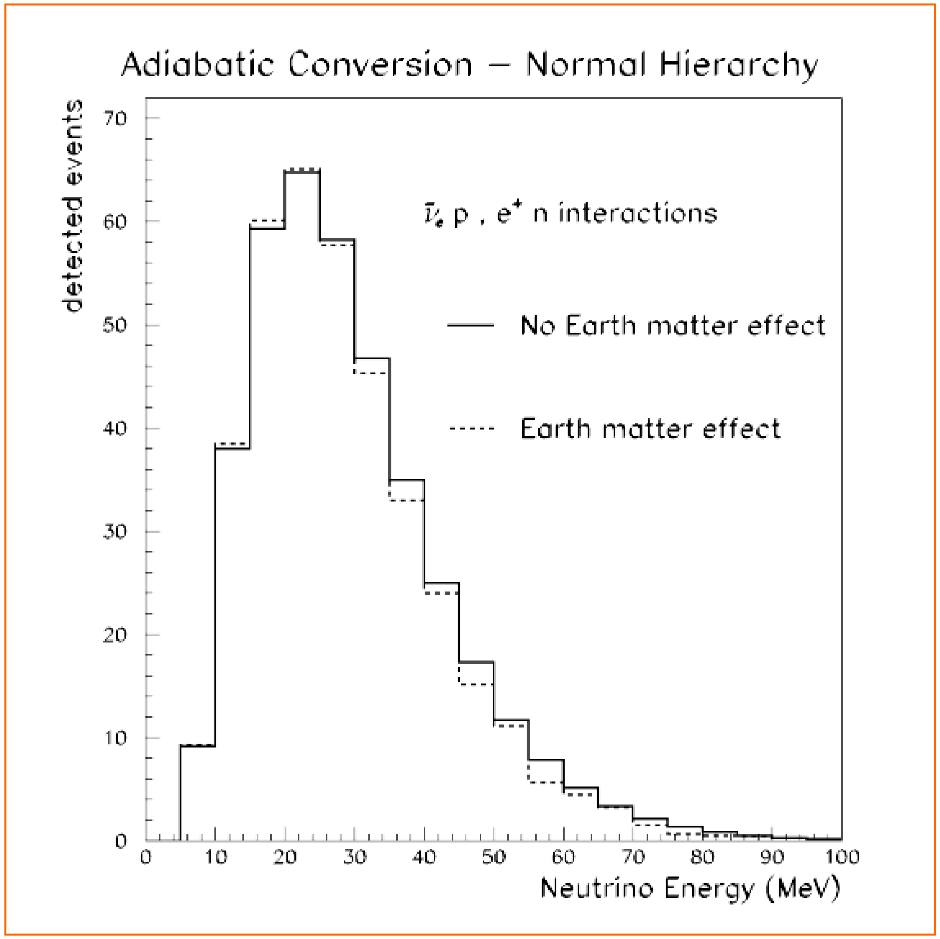
•No Osc	190
•Adiabatic, Normal Hierarchy	884
•Adiabatic, Inverted Hierarchy	866



Earth matter effects

Earth matter effects



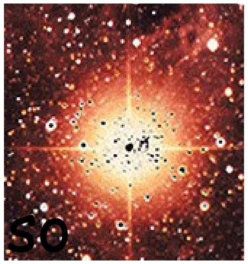


Earth matter effects are a very powerful tool, because we don't need to measure it precisely, it is enough to exclude or establish the effect.

For example, if we can exclude the effect in the antineutrino channel, we immediately infer that the hierarchy is inverse and the conversion adiabatic.

In the figure the effect is shown for a nadir angle $\theta_n=50°$, which corresponds to neutrinos passing through the mantle only. Earth matter effect are more relevant in the ν than in the $\bar{\nu}$ channel, so the effect in reaction $\bar{\nu}_e$ p,n e^+ is quite weak (it also depends on the rather high Δm^2_{sol}), but it could be detected if compared with a high statistic sample (i.e. the one coming from SuperKamiokande) or if a larger number of events is available, i.e. a closer SN.

Summary



- The concept for detecting SN n have not changed so much ... but some new ideas can contribute to get the most from the next SN core collapse in our galaxy.
- The observed number of events highly depends on oscillation parameters: the neutrino mass hierarchy and on the adiabaticity of the high density resonance (i.e. the order of magnitude of θ_{13}).
- It is difficult to infer any oscillation parameter because of the astrophysical uncertainties.
- Neutrino interactions with Fe nuclei could be as high as 18% of the IBD ones.
- Earth matter effects are an important tool to learn more on the oscillation scheme, but, at least with the current detectors, the effect is weak.