Status of SN neutrino detectors

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Outline

- The neutrino signal
  - neutrino burst from core collapse SN
  - neutrino oscillations
  - open problems
- Core collapse neutrino detection
  - The strategy after SN1987A
  - Water Cherenkov
  - Long string Water Cherenkov
  - Scintillators
  - Liquid Ar

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Neutrino emission

..the shock spends energy, mostly by the photo dissociation of heavy nuclei into nucleons and stalls, before reaching the outer shells. This change in the matter composition increases the electron capture rate producing a first neutrino burst: the **shock break-out neutrino burst:** $e^- + p \rightarrow n + \nu_e$

The model predicts a second impulsive neutrino signal of the duration of ~ 500 ms related to the **accretion** phase just before the explosion.

The **cooling** of the hot interior of the proto-neutron star proceeds by neutrino-pair production and diffusive loss of neutrinos of all three lepton flavors: $e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i$

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The explosive nucleosynthesis process (r-process and νp-process) are thought to occur in this phase. They strongly depend upon the properties of the matter when the supernova was only a few seconds old, sampling directly the neutrino luminosity and temperatures.

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observable

1) ...as the density reaches $\rho_{trap} \sim 10^{12}$ g\cm^3, neutrinos interact efficiently with matter and are essentially trapped in the core.

This determines duration and spectra of the ν emission

(thermal spectra with average neutrino energy 10-20 MeV during some 10 seconds)

2) The proto-neutron star will liberate its binding energy radiating neutrinos of all flavors:

$$E_b = G_N M^2_{NS}/R_{NS} \sim (1 - 4) \times 10^{53} \text{ erg}$$

3) Due to their different interaction with the stellar matter, neutrinos decouple at different stellar radii and then at different temperatures following the hierarchy:

$$T_{\nu_e} \leq T_{\bar{\nu}_e} \leq T_{\nu_x}$$

with ν_x representing all non electron neutrino flavors.

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neutrino oscillations

On the basis of our present knowledge of neutrino oscillation (disregarding effects due to $\nu - \nu$ coherent interactions)...

.. In their path from the high density region where they are generated to the lower density one where they escape the star, neutrinos cross two resonance layers.

H resonance ($\Delta m^2_{atm}, \theta_{13}$), $\rho_H \sim 10^3 - 10^4$ g/cm^3

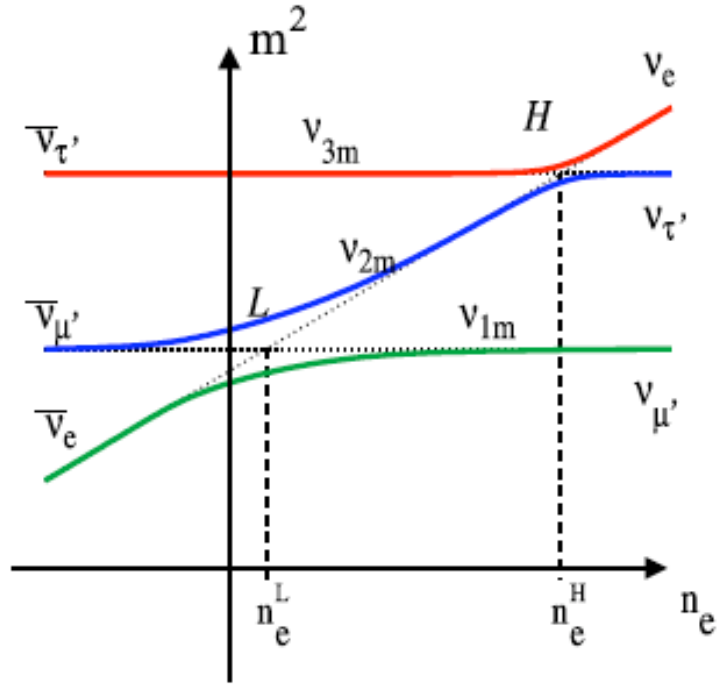
L resonance ($\Delta m^2_{sol}, \theta_{sol}$), $\rho_L \sim 10 - 100$ g/cm^3

..mixing their energy spectra.

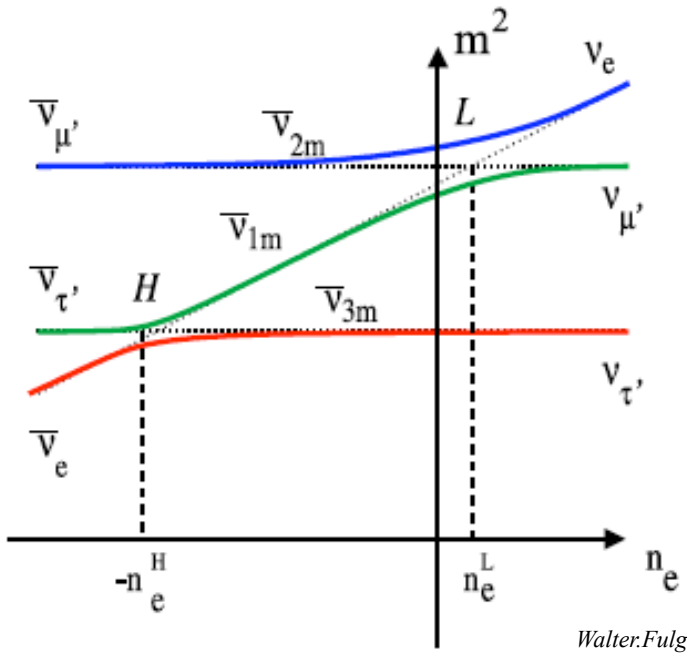
The temperature hierarchy at the detector will be modified depending on the values of the mixing angle θ_{13} and on the ν mass hierarchy, both unknown.

A. Dighe and A. Yu. Smirnov, Phys. Rev. D 62, 033007 (2000).

Normal mass ordering



Inverted mass ordering



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open problems

While successful in nature, in most numerical supernova models the shock stalls, so that the fate of the entire star is to produce a black hole, but no optical supernova.

Stars of 8-11 solar masses may be relatively easy to explode. These stars, however, do not eject enough mass to explain the origin of abundant heavy elements such as O, Mg, Si, S and Ca.)

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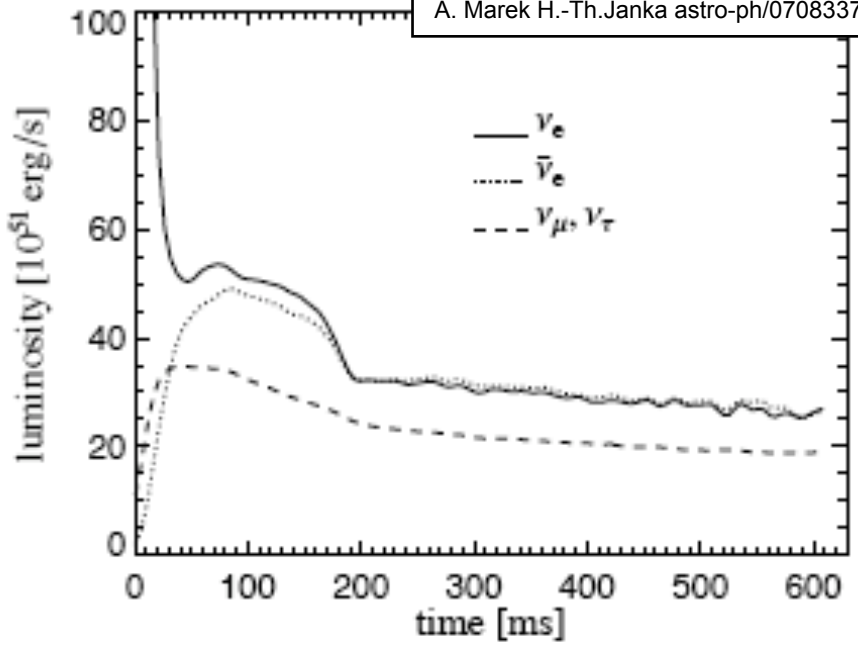
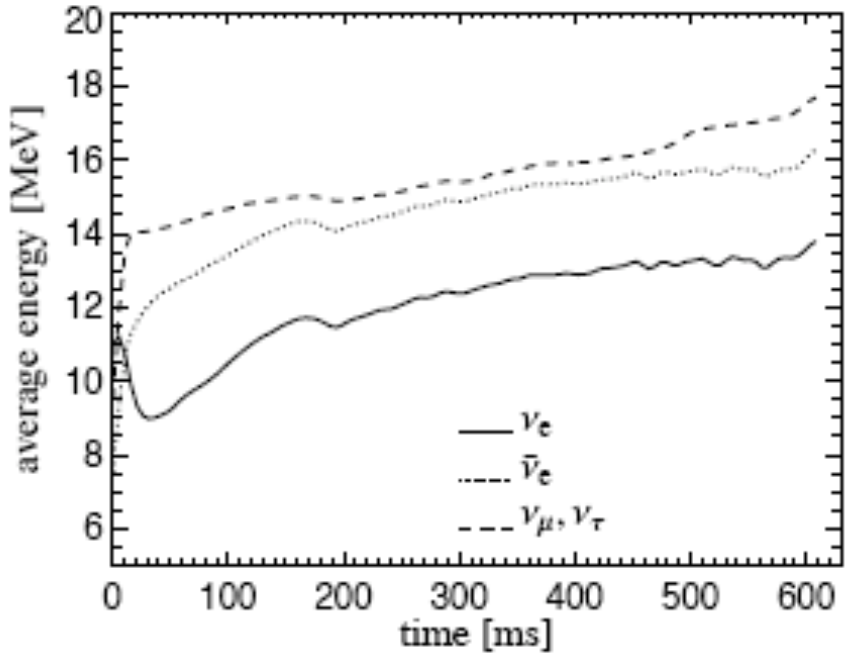
A. Marek H.-Th.Janka astro-ph/07083372





Core collapse dynamics and explosion mechanism must be stamped in the features of the neutrino signal.

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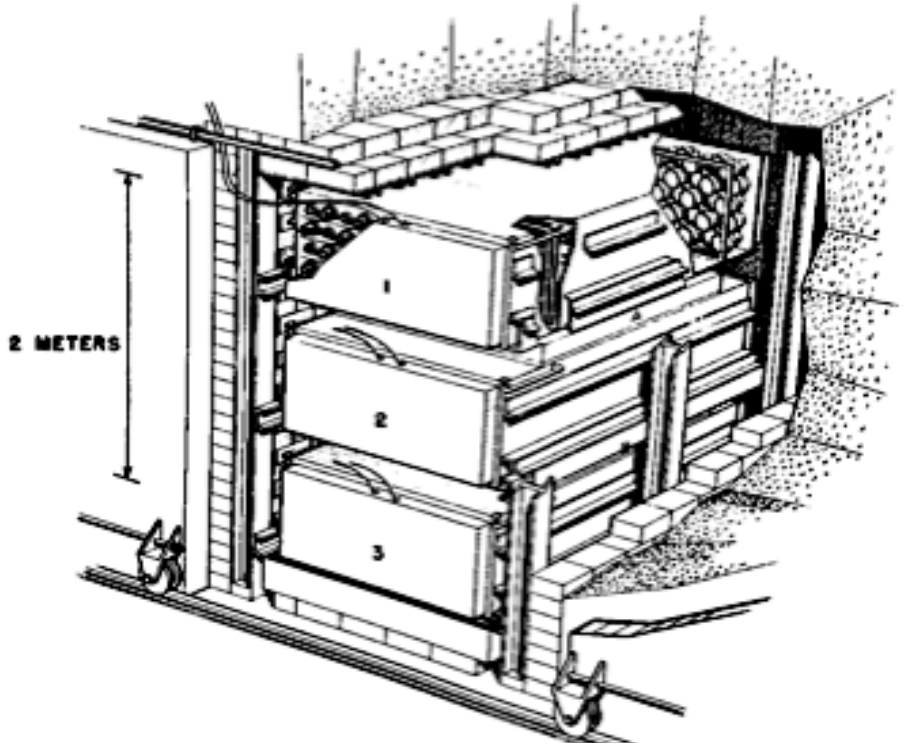
Core collapse neutrino detection

G.V. Domogatsky and G.T. Zatsepin,
in Proc. of the 9th ICRC, London, 1965

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

$$n + p \rightarrow d + \gamma_{[2.2\mathrm{MeV}]}$$



PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection of the Free Antineutrino*

F. Reines,† C. L. Cowan, Jr.,‡ F. B. Harrison, A. D. McGuire, and H. W. Kruse
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

Golden channel: inverse beta decay

Main difficulties

Small cross section.

For scintillators and water Cherenkov detectors and for a "1987A-like" core collapse at 10 kpc.

$$N_{ev} \approx 0.2 \div 0.3 \times [M/1\ \text{ton}] \times [D/10\ \text{kpc}]^{-2}$$

hundreds tons of target are required to observe the entire Galaxy.

The rate of gravitational collapses in our Galaxy is 2±1 event/100 years.

The absence of a firm model.

Which does not allow a fine tuning of the ν burst search.

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new strategy

..after the detection of neutrinos from SN1987A:

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new strategy

..after the detection of neutrinos from SN1987A:

neutrino detectors must be able to recognize SN explosions independently of any other signal

- The only neutrino burst detected (SN1987A) have been recognized thanks to its correlation with the electromagnetic signal.
- We need experiments able to disentangle the ν burst in the absence of any other signal and promptly, to be used as a trigger for all others detectors (gw, em and particle detectors), allowing the study of this rare event since its first instant. → **SNEWS**

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The ideal experiment should have the capabilities to measure:

- $L_{\nu_e}(t)$, $L_{\bar{\nu}_e}(t)$, $L_{\nu_x}(t)$;
- $\bar{E}_{\nu_e}(t)$, $\bar{E}_{\bar{\nu}_e}(t)$, $\bar{E}_{\nu_x}(t)$; and
- pointing

Table 1. Supernova neutrino detector types and their primary capabilities.

Detector type	Material	Energy	Time	Point	Flavour
Scintillator	C, H	y	y	n	$\bar{\nu}_e$
Water Cherenkov	H_2O	y	y	y	$\bar{\nu}_e$
Heavy water	D_2O	NC: n	y	n	All
		CC: y	y	y	ν_e, $\bar{\nu}_e$
Long string water Cherenkov	H_2O	n	y	n	$\bar{\nu}_e$
Liquid argon	Ar	y	y	y	ν_e
High Z/neutron	Pb, Fe	y	y	n	All
Radio-chemical	^{37}Cl, ^{127}I, ^{71}Ga	n	n	n	ν_e

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Water Cherenkov

Super-Kamiokande

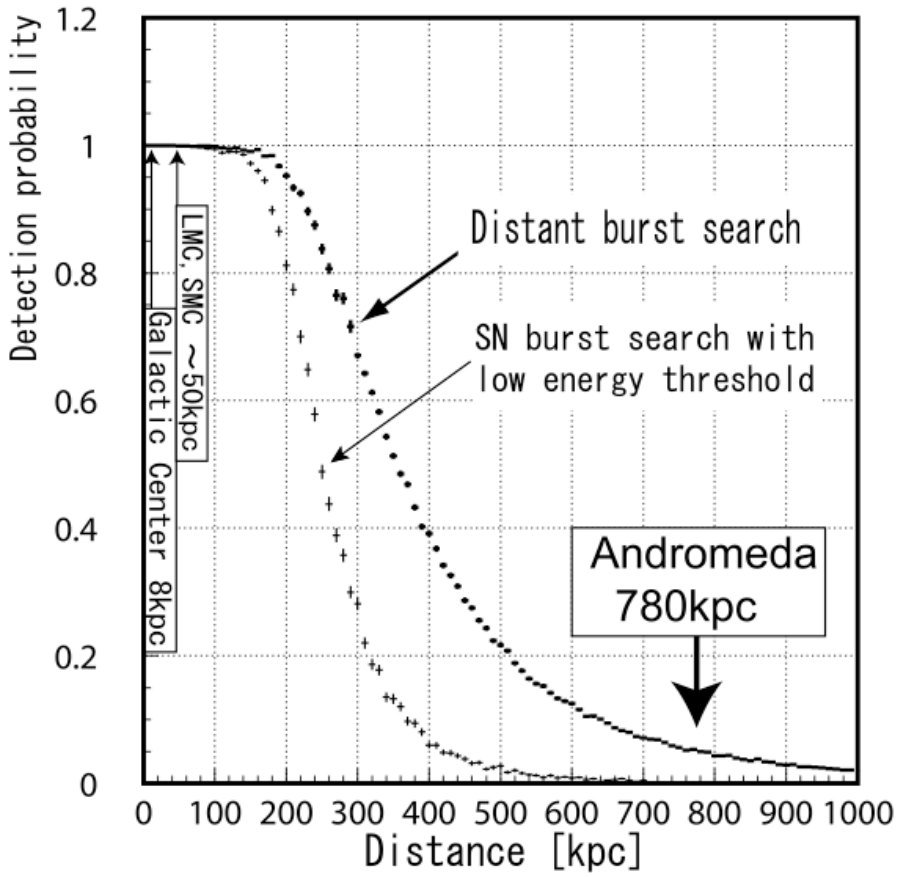
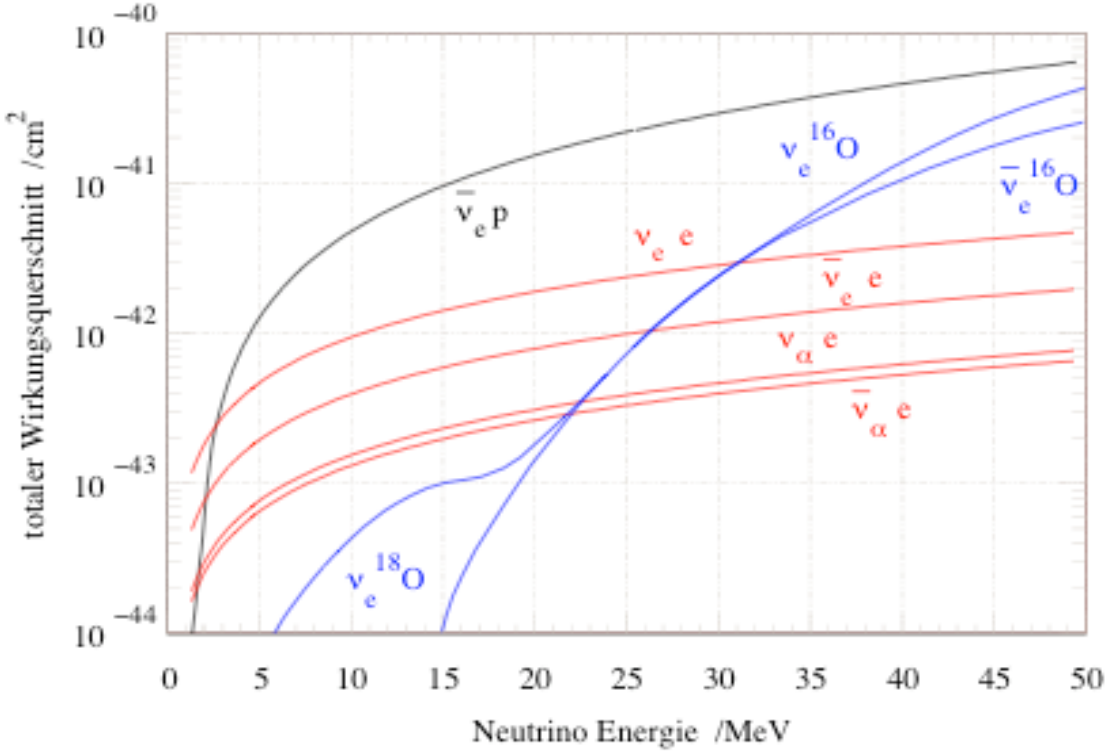


FIG. 6.—Probability of detecting supernovae assuming a specific supernova model at SK. Full (100%) detection probability is retained out to around 100 kpc.



22.5 kton H_2O fiducial mass

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (88\%/89\%), \quad (1)$$

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad (1.5\%/1.5\%), \quad (2)$$

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- \quad (<1\%/<1\%), \quad (3)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (1\%/1\%), \quad (4)$$

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F} \quad (2.5\%/<1\%), \quad (5)$$

$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N} \quad (1.5\%/1\%), \quad (6)$$

$$\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + \mathrm{O}^*/\mathrm{N}^* + \gamma \quad (5\%/6\%), \quad (7)$$

SEARCH FOR SUPERNOVA NEUTRINO BURSTS AT SUPER-KAMIOKANDE
M. Ikeda, et al. The Astrophysical Journal, 669:519Y524, 2007 November 1

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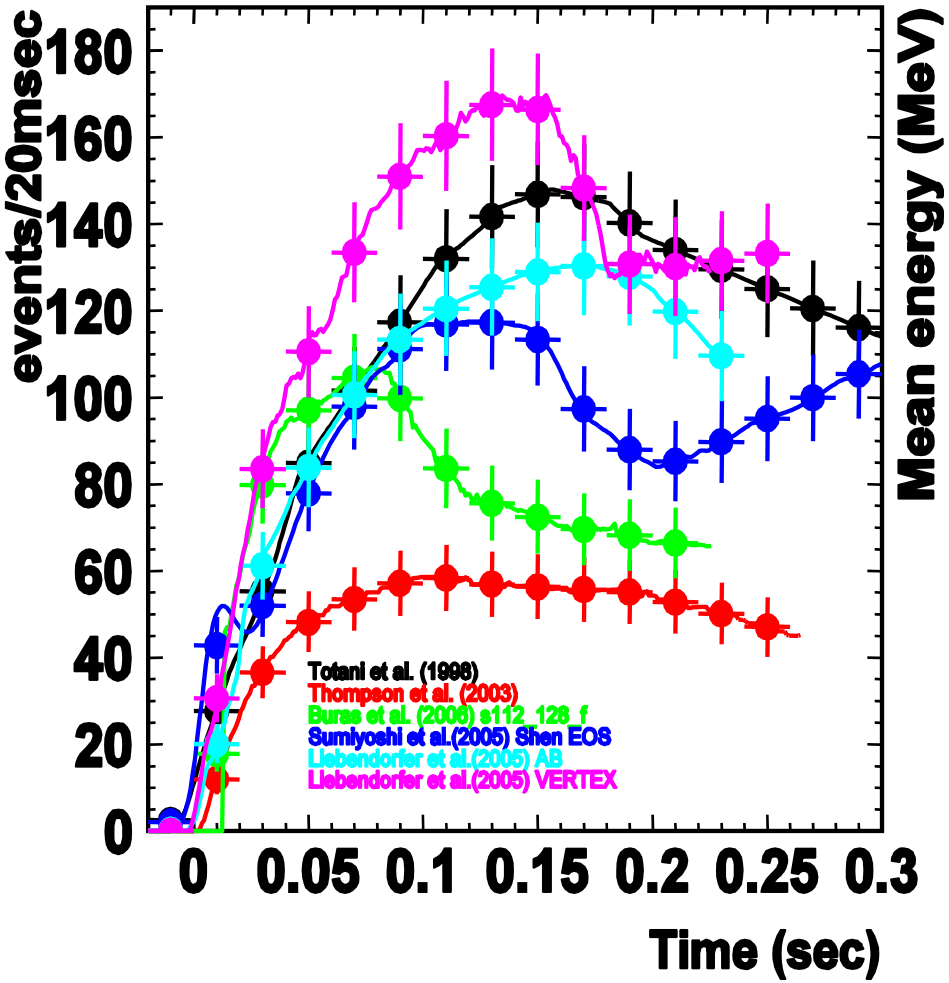
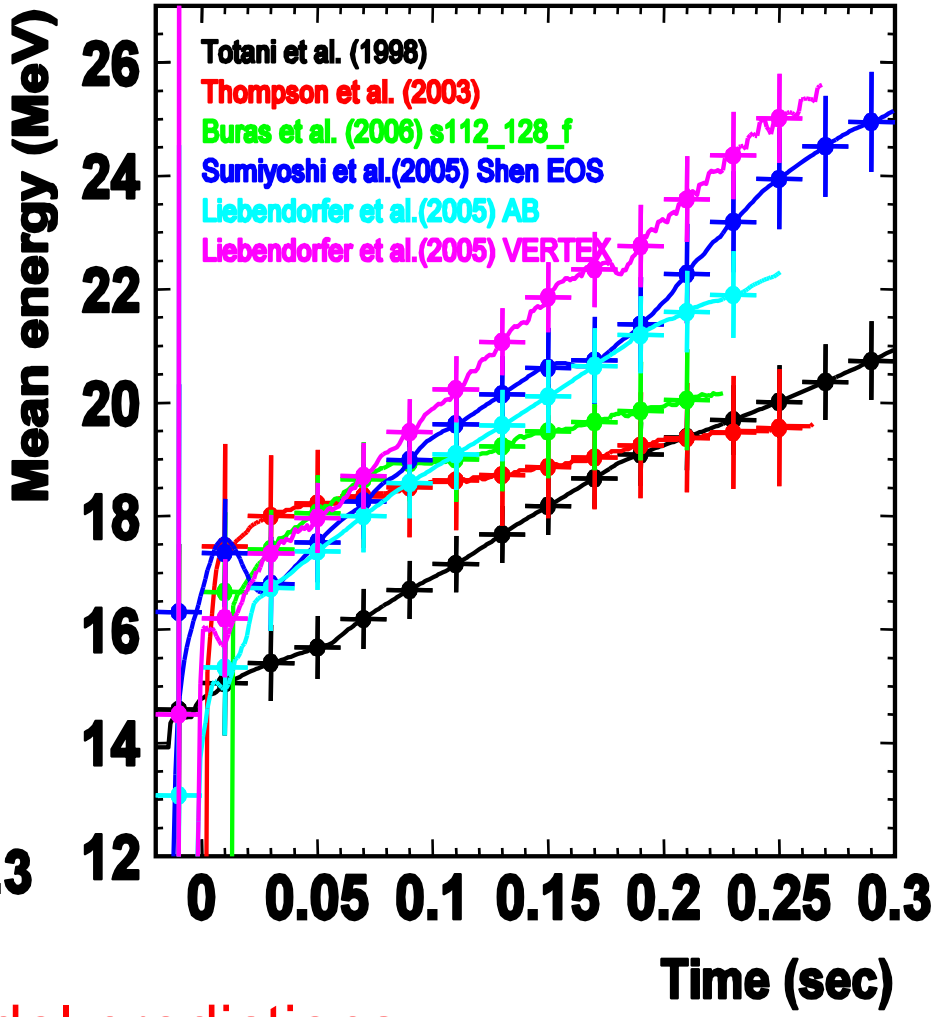
Super-K: Time variation measurement by $\bar{\nu}_e$+p

Assuming a supernova at 10kpc.
$\bar{\nu}_e p \rightarrow e^+ n$ events give direct energy information ($E_e = E_\nu - 1.3$MeV).

Time variation of event rate



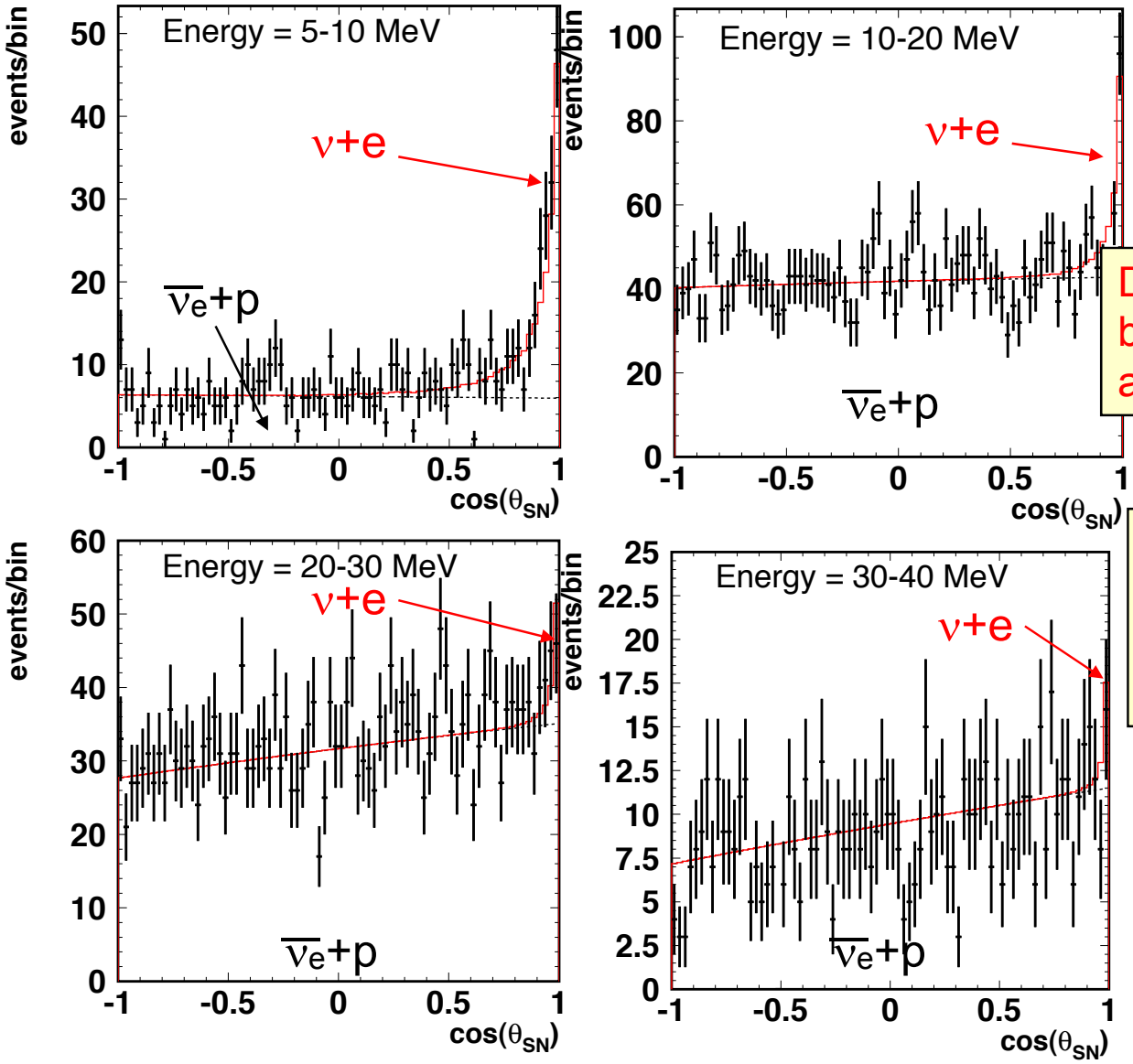
Time variation of mean energy



Enough statistics to discuss model predictions

Pointing

Super-K: ν+e scattering events



SN at 10kpc

Direction of supernova can be determined with an accuracy of ~5 degree.

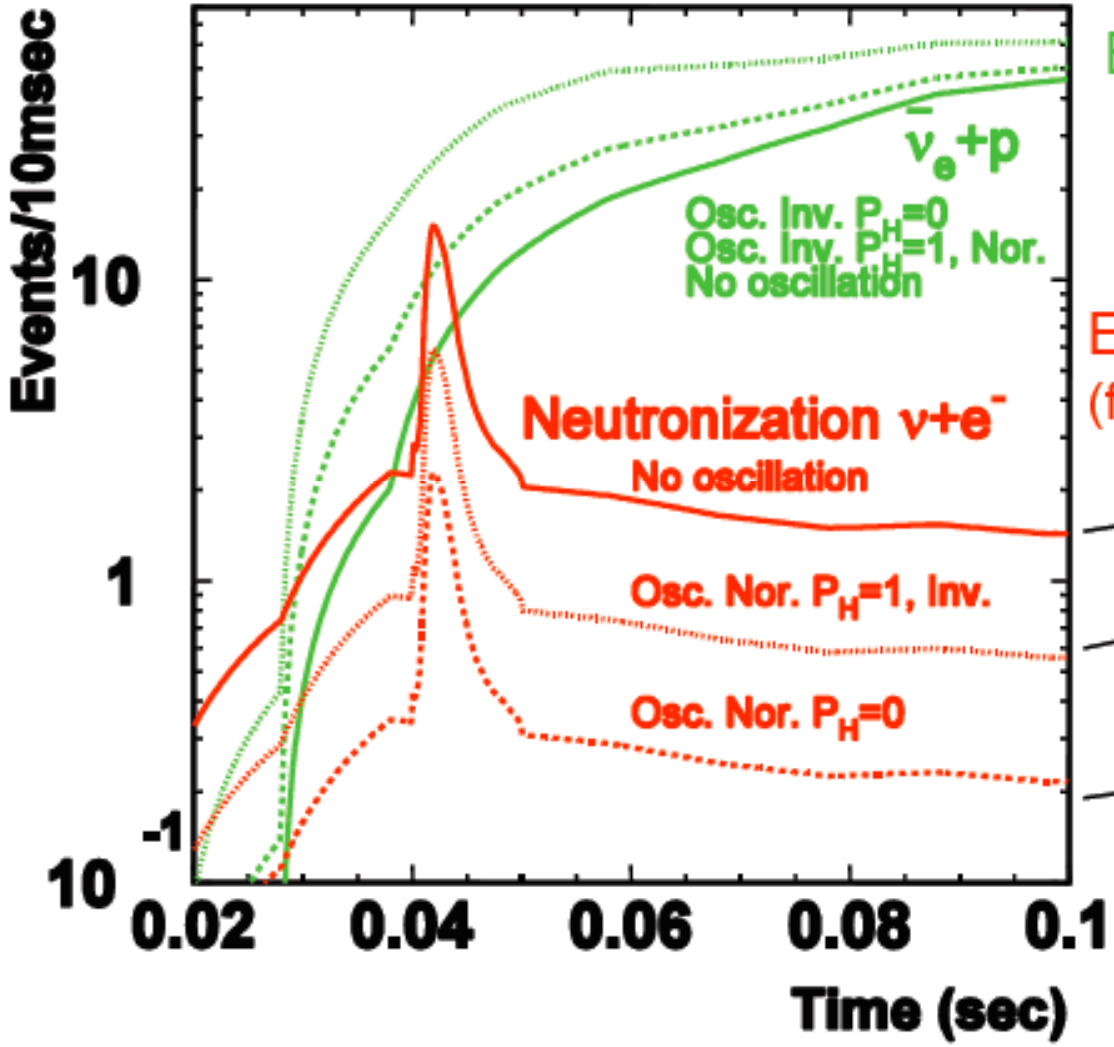
Spectrum of ν+e events can be statistically extracted using the direction to supernova.

Neutrino flux and spectrum from Livermore simulation

Super-K: Neutronization burst ($e^- + p \rightarrow n + \nu_e$)

SN at 10kpc

Neutrino flux and spectrum from Livermore simulation



Event rate of $\bar{\nu}_e$+p events

Event rate of neutronization burst
(forward peaked ν+e scattering events)

No oscillation

Normal P_H=1 or
Inverted hierarchy

Normal hierarchy P_H=0

P_H: crossing probability at H resonance
(P_H=0: adiabatic)

Number of events from neutronization burst is 0.9~6 events for SN@10kpc.

$\bar{\nu}_e$p events during this 10msec is about 8 - 30 events.

N.H. +adiamacitc case: neutronization=0.9ev., $\bar{\nu}_e$p = 14 ev.(1.4 for SN direction).

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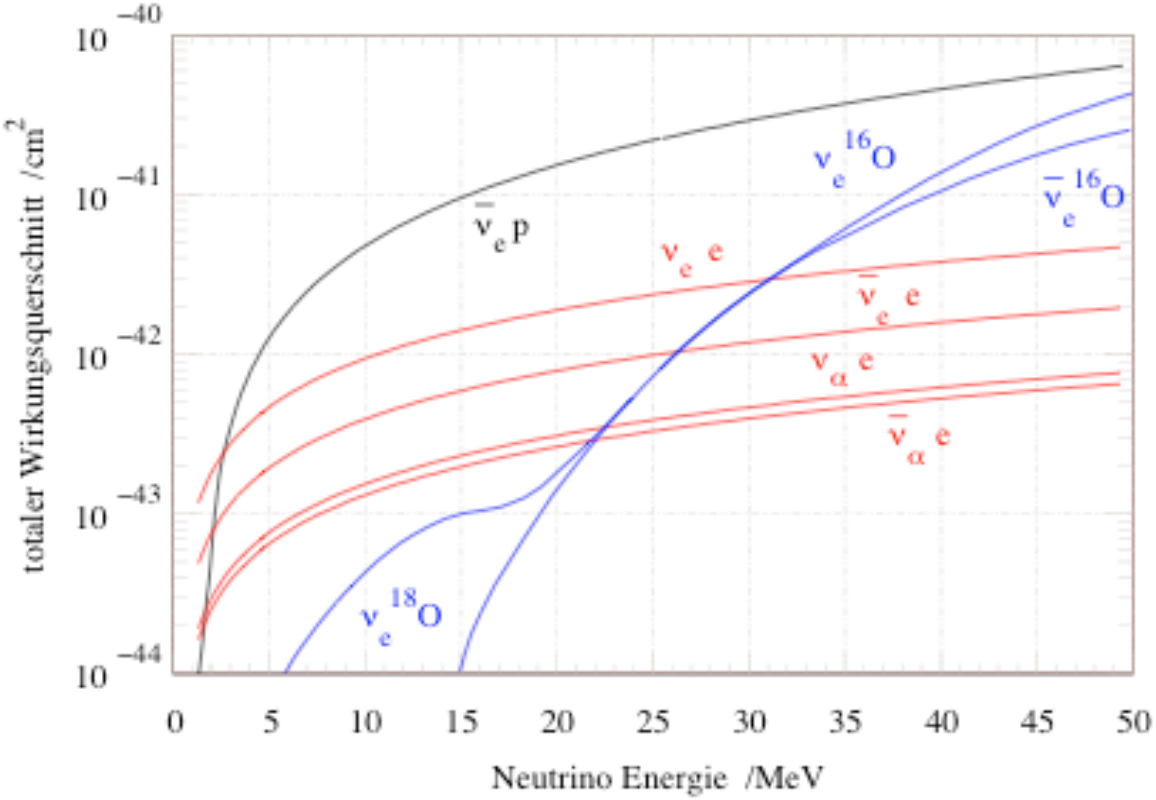
Long string

AMANDA / IceCUBE

Jacobsen, Halzen, Zas PRD **49** (1994) 1758 first proposed.

Follow-up calculation for IceCube presented in JCAP **6** (2003) - Dighe, Keil, Raffelt.

AMANDA Ph.D. thesis by T. Feser



- The detection comes from increase in background counts across the entire array.
- Principal detection channel is IBD. The observable signal is totally dominated by events where a e^+ shower yields a single photoelectron hit in a single DOM.

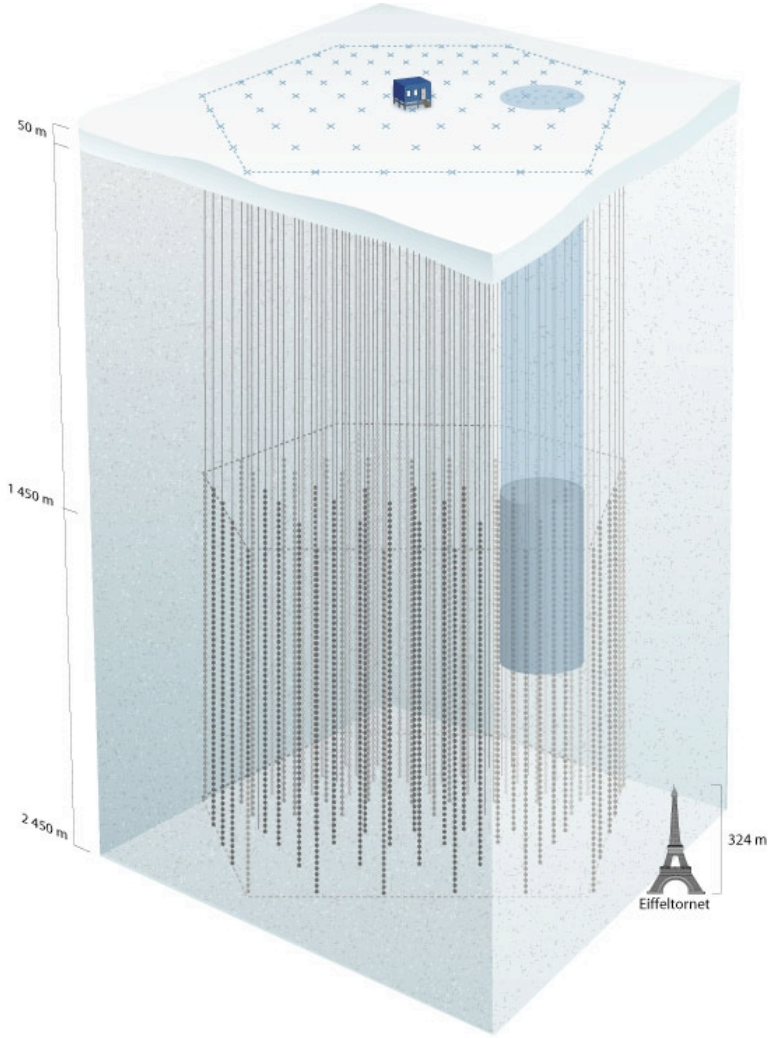
Amanda/IceCube

- Effective volume, V_{eff}, approximate a sphere around each module of 5 m radius.

- Currently, with ~ 3500 deep ice modules (59/86 strings) detector mass ~ 2 Mton.
  (Full IceCube ~ 5000 modules detector mass ~ 3 Mton)

$$V_{eff} \propto N_{\gamma} \cdot A \cdot \Lambda_{abs} \propto E_{e+} \cdot A \cdot \Lambda_{abs} \propto E_{\nu}^{3} \cdot A \cdot \Lambda_{abs}$$

- Neutrino effective volume is proportional to:
  - E_{ν}^{3} : 2 powers from σ 1 power from e^+/e^- track length;
  - Λ the optical pathlength in the ice that depends on depth (each module may be treated independently);
  - A, the photocatode area of the OM.



- Thus, detection is sensitive to neutrino energy spectra - or, stated another way, effective volumes are all dependent on SN models / oscillations, & c.

Amanda/IceCube

Disadvantages

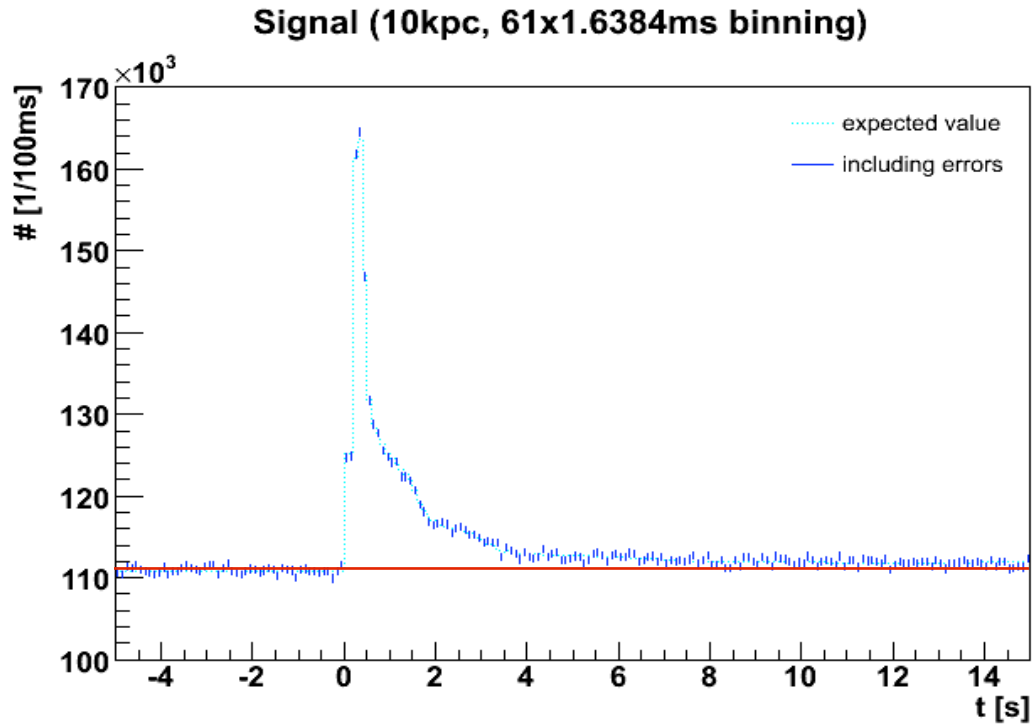
- you have no pointing or energy reconstruction.

Advantages

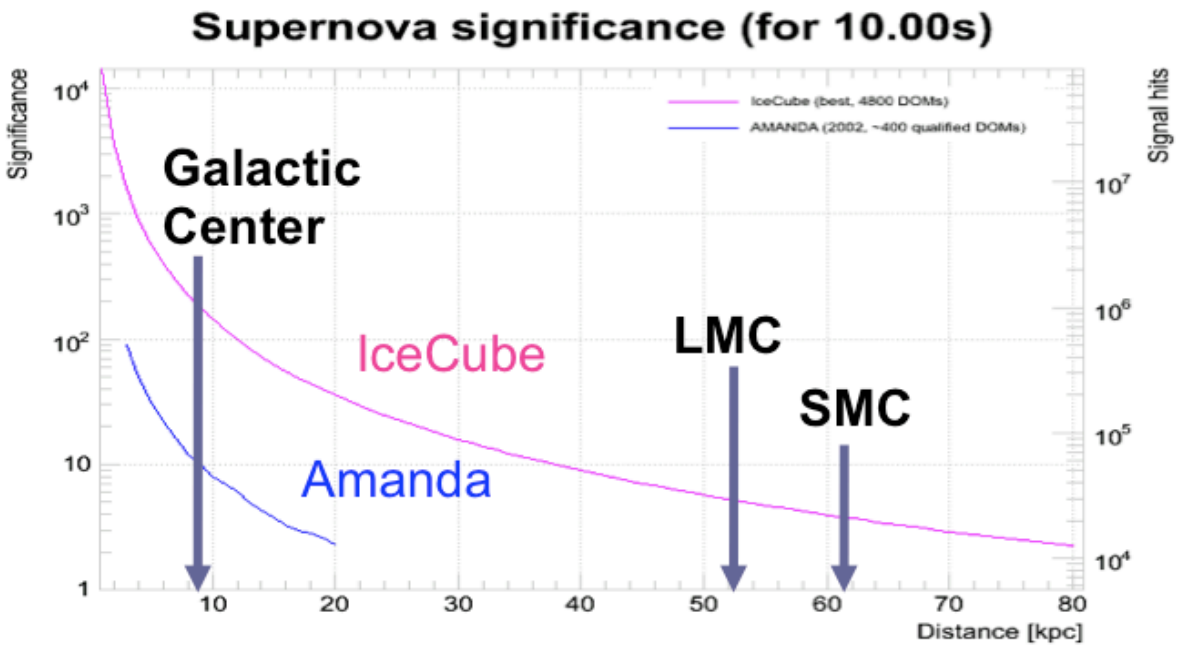
- enormous volume provides high-statistics measurement.

  Time binning can be made fine:

  the hardware limit being 1.6ms



- Signal from 1987A SN at galactic center would produce 475000 excess counts in ~10 sec window on a background of 12 ×10^6 counts from noise - S/N ~ 150 in full IceCube;



Scintillators - modular

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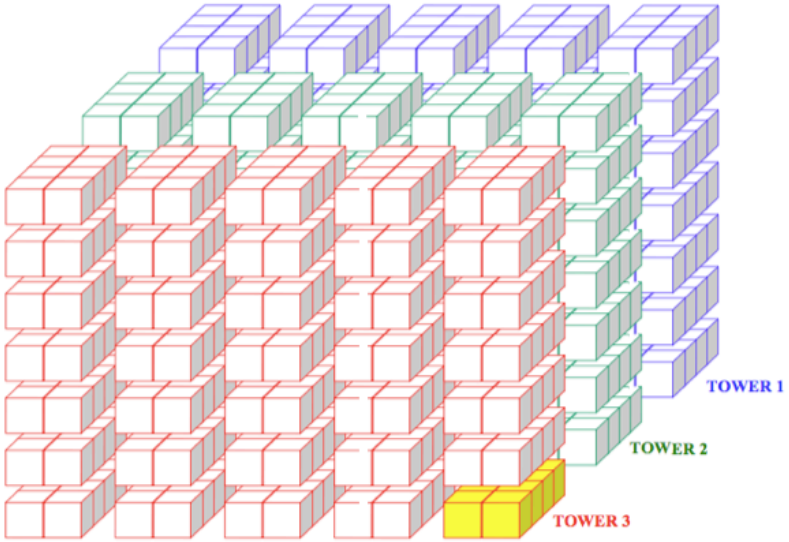
Scintillators - modular

LVD at LNGS



LVD is an array of 840 counters 1.5 m^3 each,
total target: 1000 ton of C_nH_{2n+2}
900 ton of Fe
divided in three independent, identical "towers".

Main purpose of LVD is detecting neutrinos from core collapse SN in our Galaxy.

$\bar{\nu}_e + p \rightarrow e^+ + n$
$(n,p) \rightarrow d + \gamma$

$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$

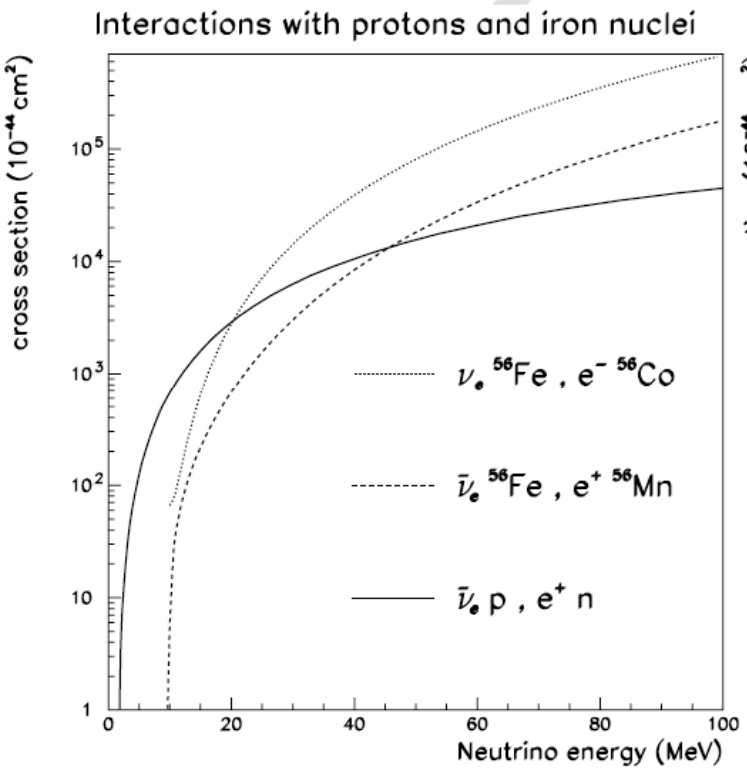
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$

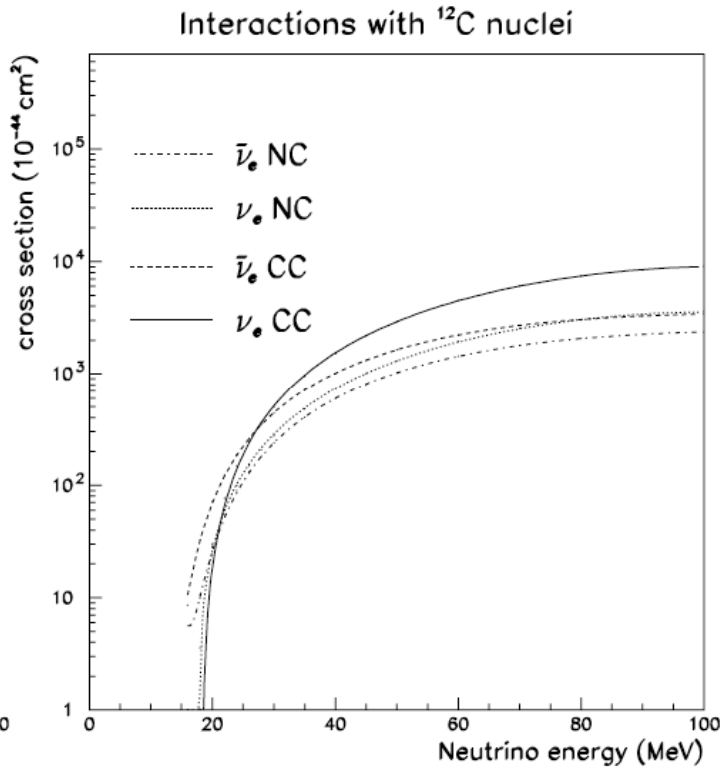
$\nu_i + {}^{12}C \rightarrow \nu_i + {}^{12}C + \gamma$

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

$\bar{\nu}_e + {}^{56}Fe \rightarrow {}^{56}Mn + e^+$

$\nu_i + Fe \rightarrow \nu_i + Fe + \gamma$





LVD on-line sensitivity

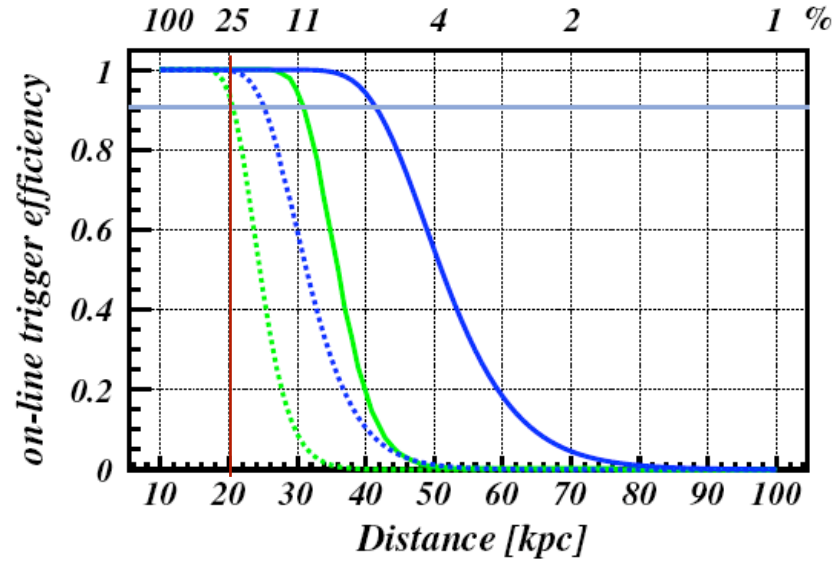
The detector sensitivity has been evaluated assuming the signal from SN1987A as a standard candle:

- total emitted energy $E_b = 2.4 \cdot 10^{53}$ erg;
- average $\bar{\nu}_e$ energy = 14 MeV
- $T_{\nu_x} / T_{\bar{\nu}_e} = 1.1$

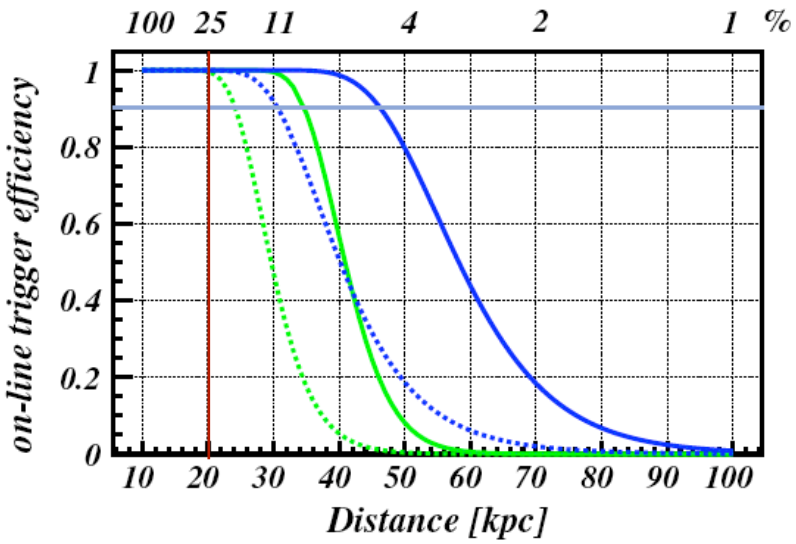
M.L. Costantini, A. Ianni, G. Pagliaroli, F. Vissani, JCAP 05 (2007) 404 astro-ph/0608399(2006)

STAND ALONE
(<1 fake event/100 years)
E_{cut} = 7 MeV
E_{cut} = 10 MeV

LVD Collaboration, "On-line recognition of supernova neutrino bursts in the LVD detector", Astropart. Phys. 28, 516-522 (2008) [arXiv:0710.0259].



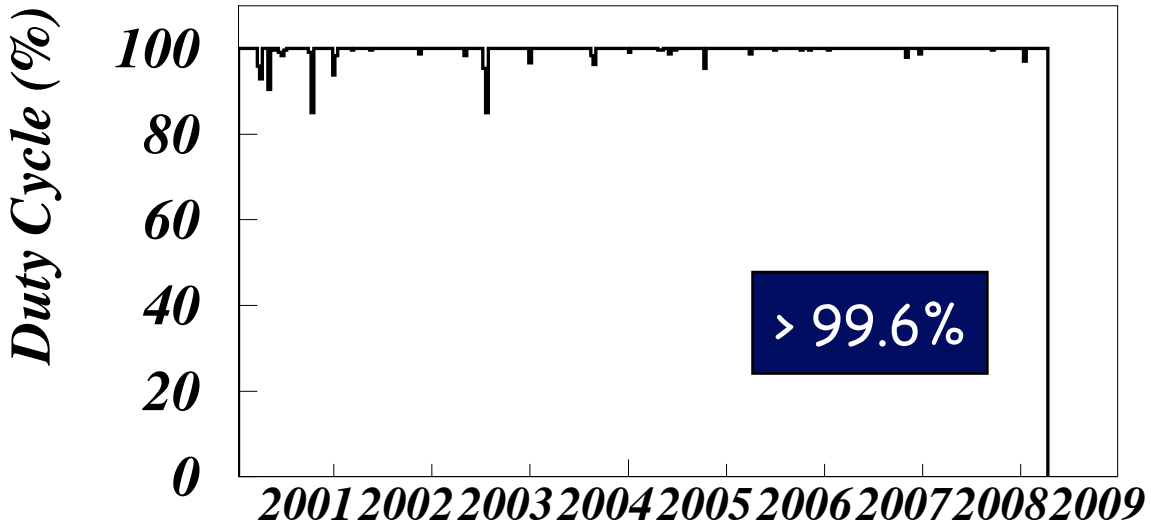
SNEWS
(<1 fake event/month)
E_{cut} = 7 MeV
E_{cut} = 10 MeV



Active Mass and Duty Cycle

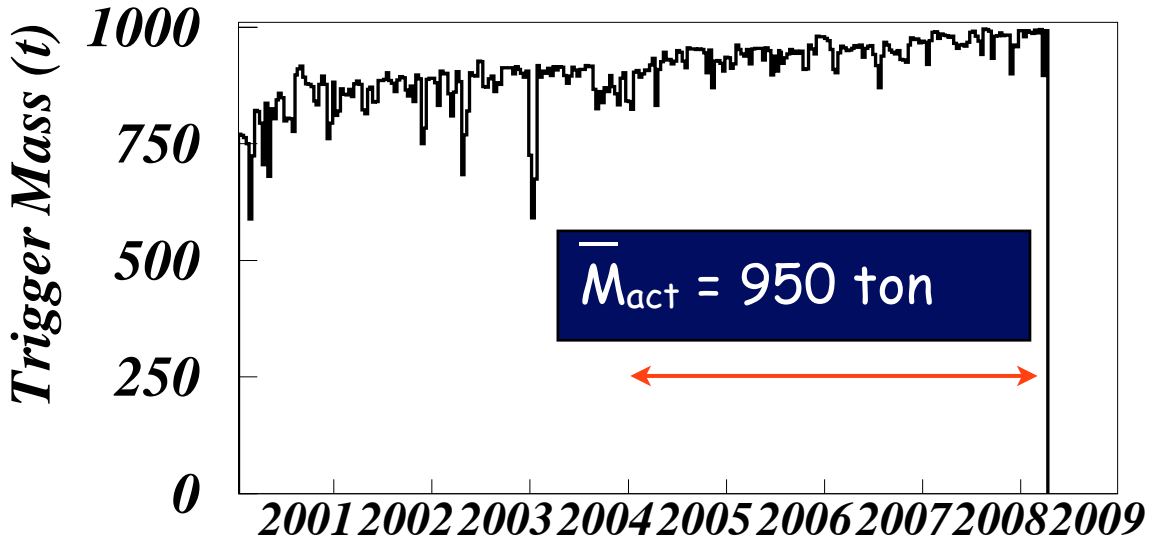
LVD

The ν observatory reached its final configuration at the end of 2000.



..because of its modularity, LVD can be serviced during data taking.

In case of failures, the telescope automatically remove the not properly working region and reconfigures itself at lower mass.

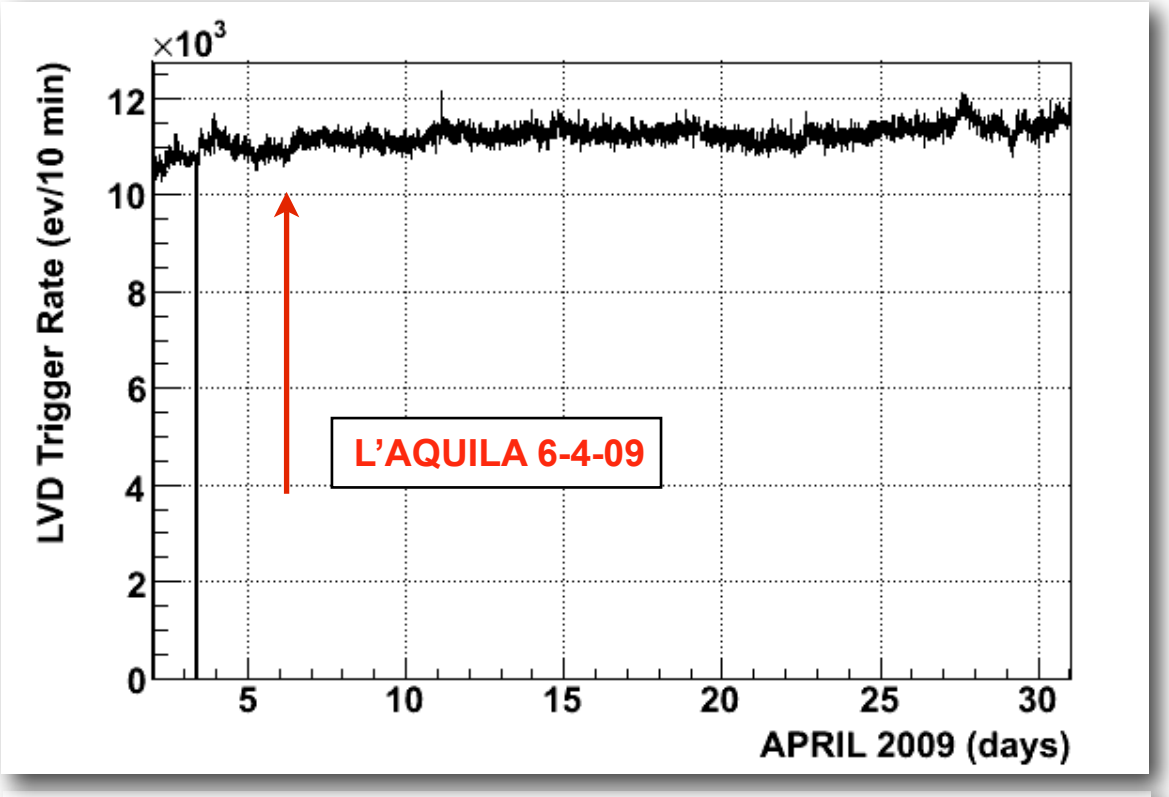


The effect is to adjust dynamically the LVD active mass, M_{act}

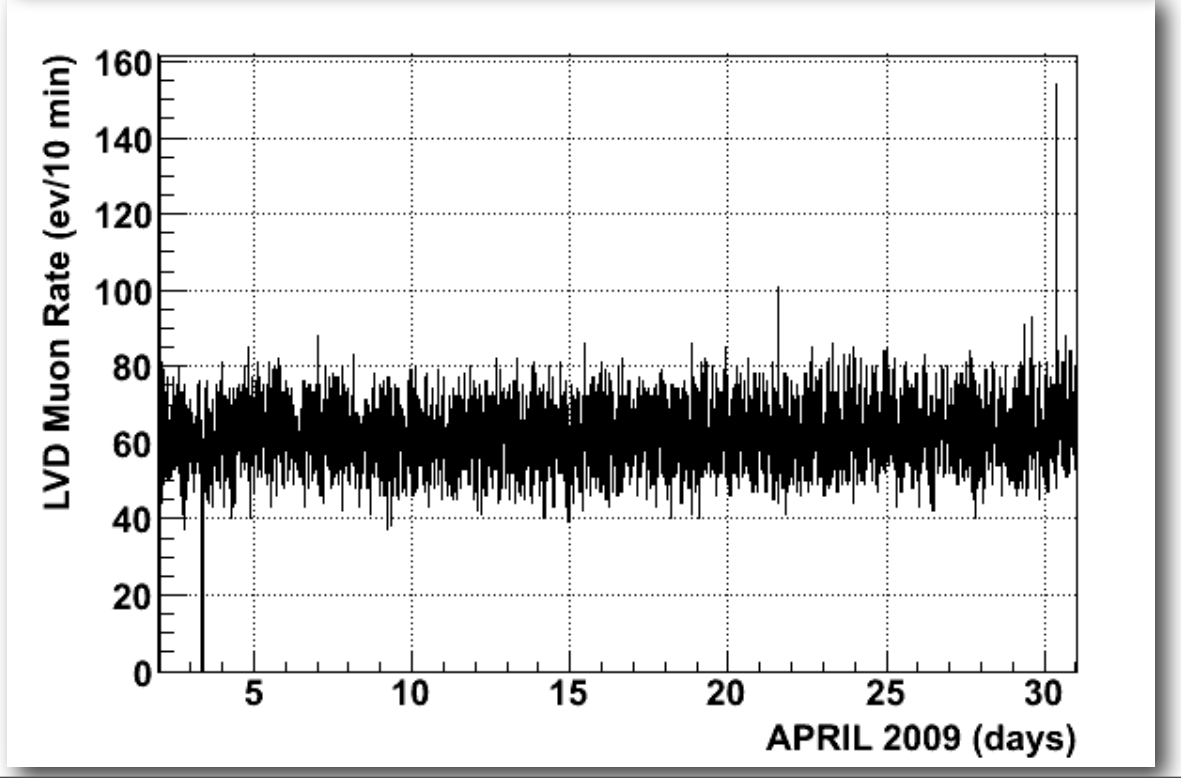
April 6th 2009

LVD

LVD monitoring task



Trigger rate



muon rate

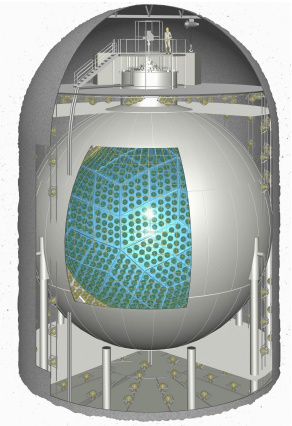
SEARCH FOR ν BURSTS

Run	Start	End	Time (*days*)	Uptime (%)	Mass (*t*)
1	June 6th 1992	May 31st1993	285	60	310
2	Aug.4th 1993	Mar.11th1995	397	74	390
3	Mar.11th 1995	Apr.30th 1997	627	90	400
4	Apr.30th 1997	Mar.15th1999	685	94	415
5	Mar.16th 1999	Dec.11th 2000	592	95	580
6	Dec.12th 2000	Mar.24th 2003	821	98	842
7	Mar.25th 2003	Feb.4th2005	666	>99	881
8	Feb.4th 2005	May 31st 2007	846	>99	936
9	**May 31st 2007**	**Apr.30th 2009**	**699**	**>99**	**967**
Σ	June 6th 1992	Apr.30th 2009	5618	94	

90% C.L. Upper Limit to gravitational stellar collapses in the Galaxy is

0.15 /year

Scintillators - single volume



KamLAND

Reaction	# Events
$\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$	~300
$\nu_x + \mathrm{p} \rightarrow \nu_x + \mathrm{p}$ (for 0.2MeV thr)	~270
$\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}(15.11\mathrm{MeV})$	~60

Assuming 1KT and "Standard Supernova"

The old trigger system (pre ~2008) had a SN trigger, the normal threshold was E_{thr} ~ 0.9MeV.

After purifying the detector (i.e. removing radioactive isotopes) the trigger threshold is now E_{thr} ~ **0.35 MeV** and the SN trigger is not longer used.

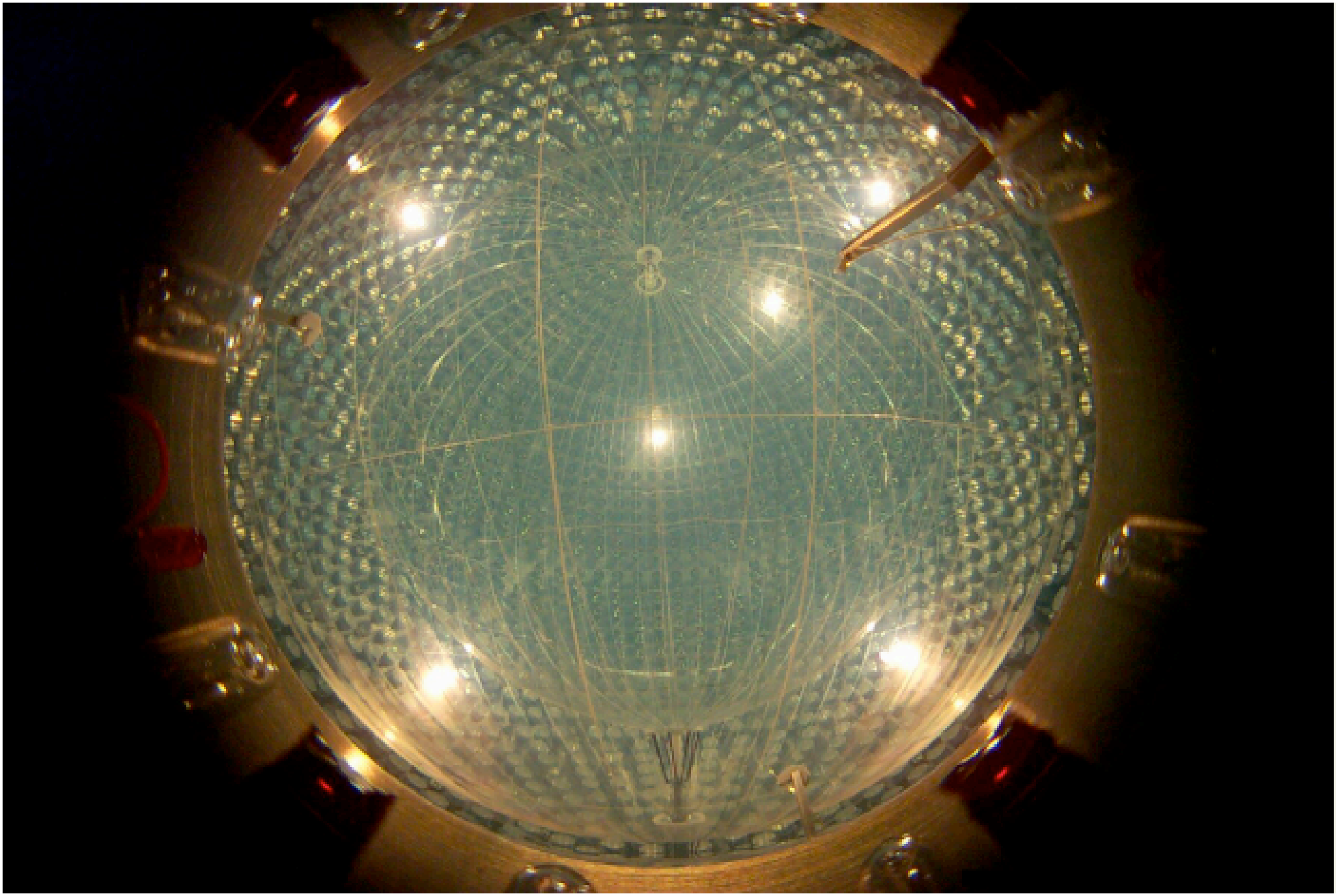
An algorithm, similar to the old SN trigger, runs online to notify shift personnel of a possible SN event.

Thanks to Patrick Decowski

Walter.Fulgione@gmail.com

Borexino

Thanks to:
A.Chavarria, A.Ianni and A.Razeto



Walter.Fulgione@gmail.com

Scintillators - single volume

Thanks to:
A.Chavarria, A.Ianni and A.Razeto

Borexino

Interaction	Prompt E_{vis} (MeV)	Delayed E_{vis} (MeV)	Delay (ms)	Number of events $E_{vis} > 0.2$ MeV
$\nu + e^- \rightarrow \nu + e^-$	$0 - 30$	–	–	5
$\bar{\nu}_e + p \rightarrow e^+ + n$	$0.9 - 50$	1.9	0.26	78
$^{12}C\ (\nu_e, e^-)\ ^{12}N$	$0 - 40$	$0.9 - 17$	11	9
$^{12}C\ (\bar{\nu}_e, e^+)\ ^{12}B$	$0.9 - 50$	$0 - 13$	20	3
$^{12}C\ (\nu, \nu')\ ^{12}C^*$	–	13	–	15
$\nu + p \rightarrow \nu + p$	$0 - 2$	–	–	52

The golden channel gives the temperature of the $\bar{\nu}_e$ (at the detector).

The ν_x+ p channel can give the temperature of ν_x (at the neutrinosphere),

other N.C. detection channels cannot break the degeneracy: $N \sim E^{tot} \frac{\langle \sigma \rangle}{T}$

J. Beacom, W.Farr and P.Vogel, Phys. Rev. D **66**, 033001 (2002)

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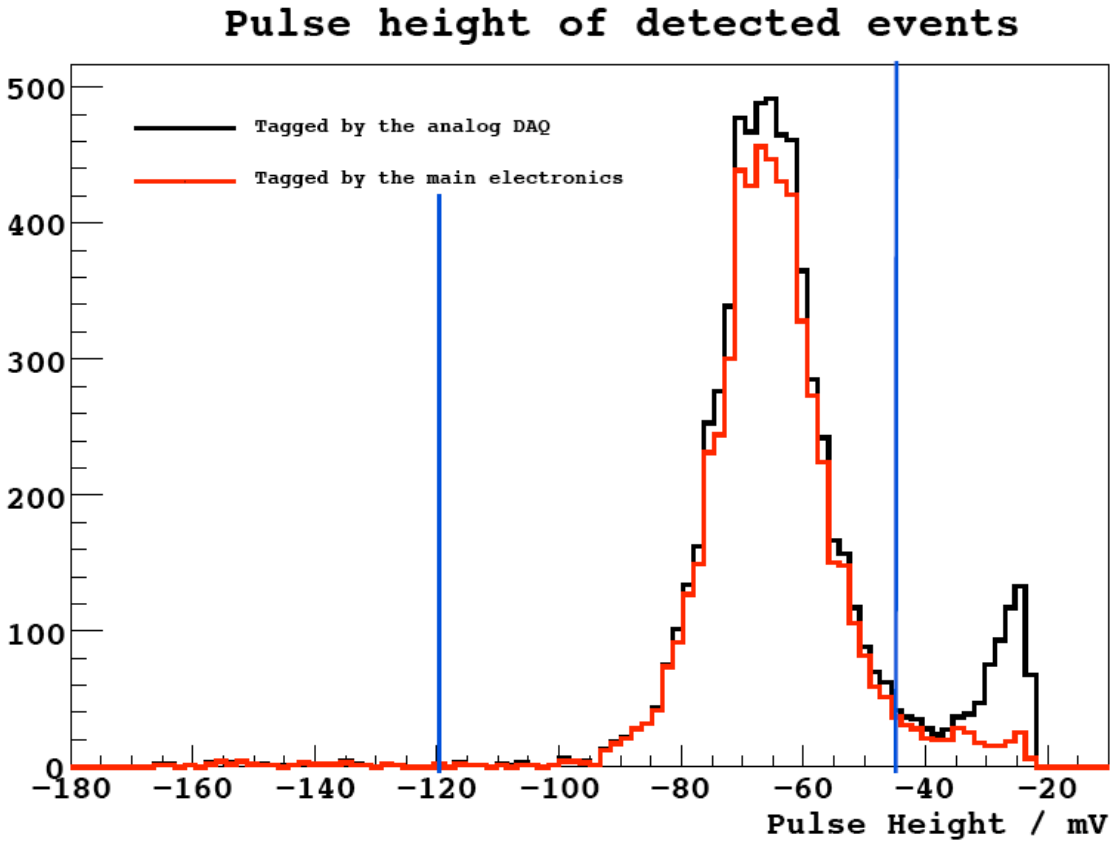
Borexino on-line

The system consists of the acquisition of individual pulses in the energy region of the neutron capture...
Noise cuts are made on the pulses based on the position and stability of the baseline.

Basically, a list of candidate pulses is considered a supernova signal if it has six or more pulses where the time between subsequent pulses is less than 10 s and the time difference between first and last pulse is > 2 ms (to avoid cosmogenic neutrons).



..with this settings, the system is able to trigger on only 6 neutron captures, which corresponds to ≈ 1/10 of the expected signal from a "typical" galactic supernova and therefore, even a supernova considerably weaker or further away can potentially be detected.

55 clusters with m=4 during a 34 days test

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ν_e

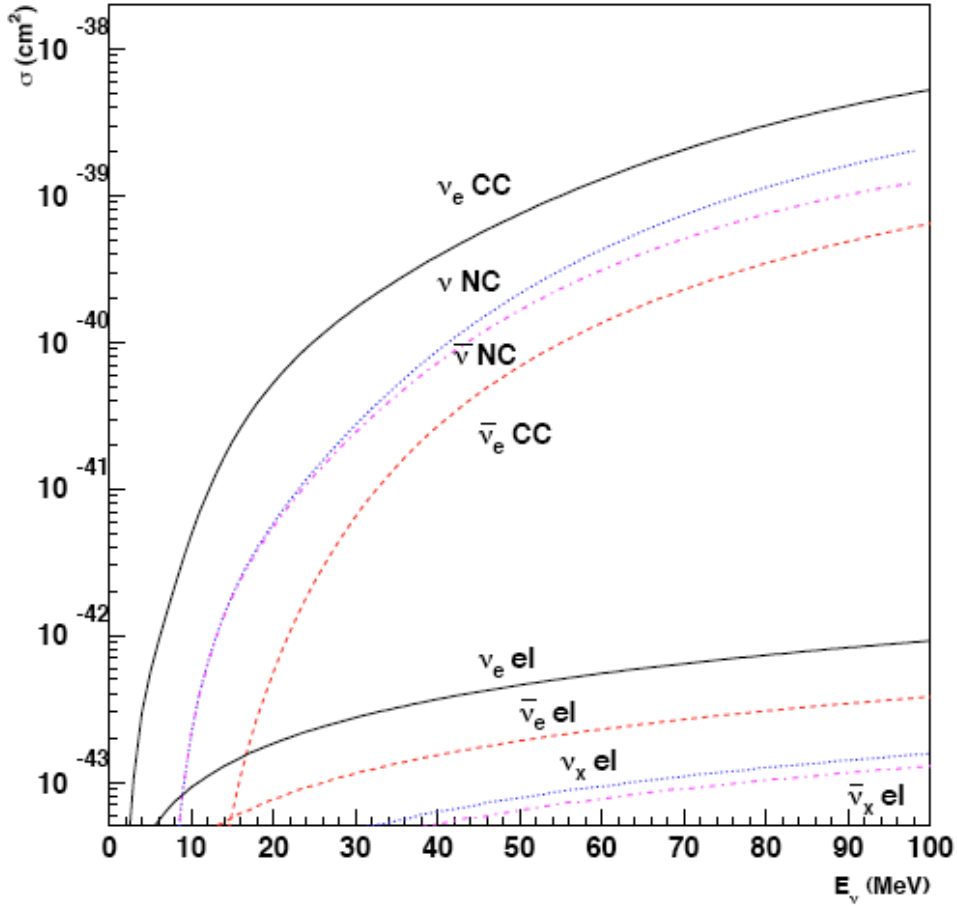
Liquid Ar

SNO studyed ν_e through:

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

ICARUS T600 is going to start data taking during 2009:

$\nu_e + {}^{40}Ar \rightarrow {}^{40}K + e^-$



n.c.:	$\nu_x + p \rightarrow \nu_x + p$	Borexino
c.c.:	$\nu_e + {}^{40}Ar \rightarrow {}^{40}K + e^-$	Icarus
c.c.:	$\bar{\nu}_e + p \rightarrow e^+ + n$	LVD

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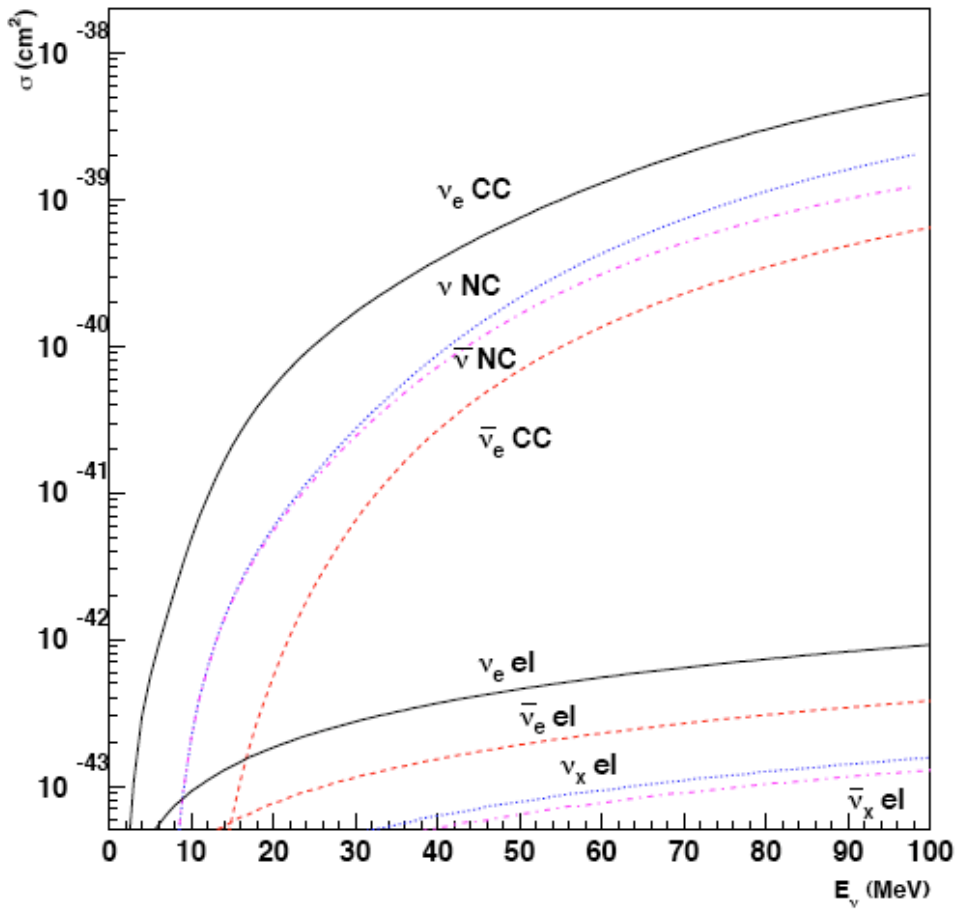

n.c.:	$\nu_x + p \rightarrow \nu_x + p$	Borexino
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c.c.:	$\bar{\nu}_e + p \rightarrow e^+ + n$	LVD

The number of expected events in 600 tons of Ar is not so big, nevertheless nobody knows the distance of the next galactic SN.

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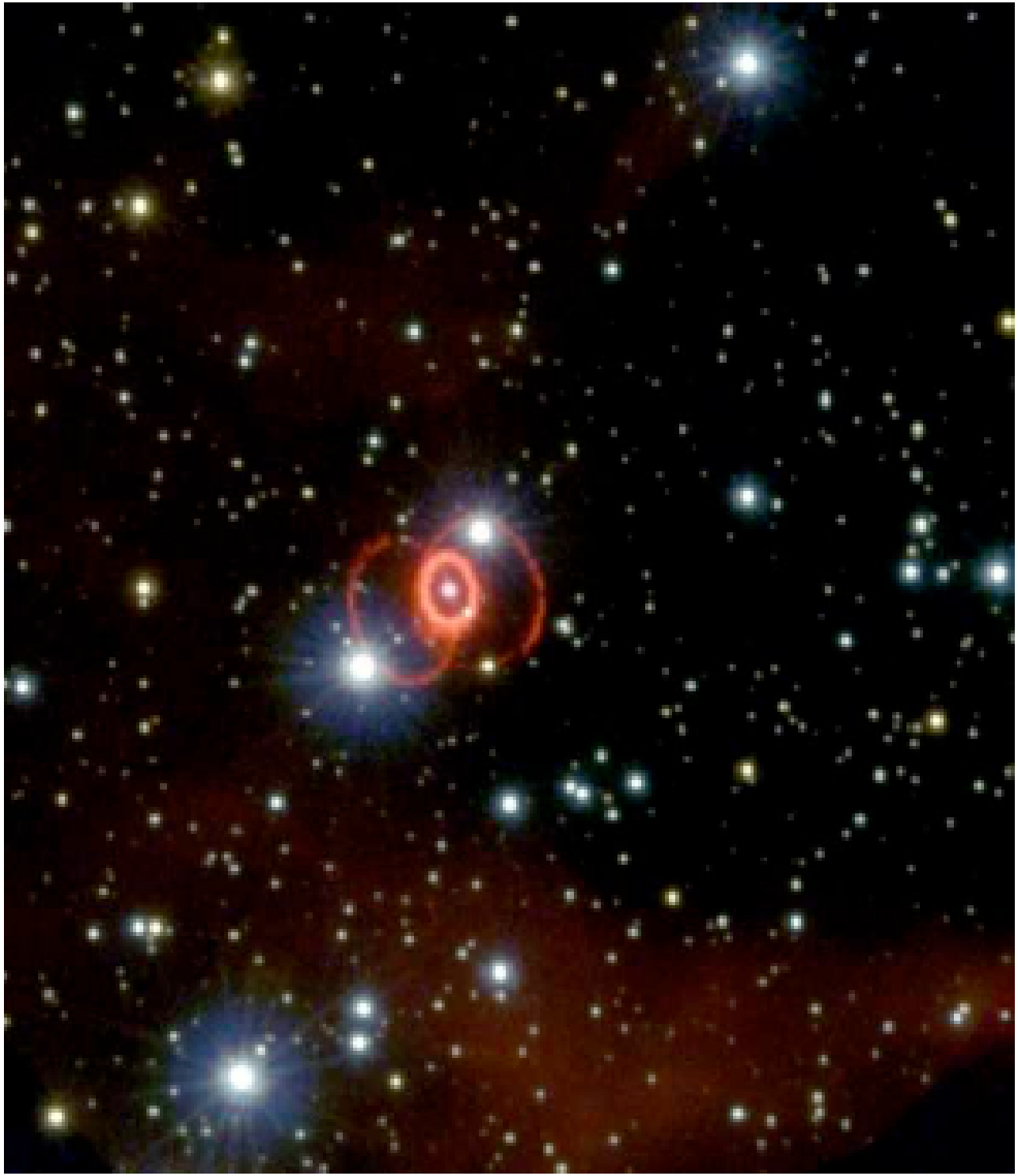

Hubble image

Thank you

Walter.Fulgione@gmail.com