30 years after SN1987A

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Kamioka Observatory,
ICRR/IPMU, the Univ. of Tokyo

The 26th International Workshop on Weak Interactions and Neutrinos (WIN2017)

30th Anniversary of SN1987A

Cake made for an anniversary held on Feb.12, 2017 at the Univ. of Tokyo

Cake made by Kamioka local people on Feb.23, 2017

Contents

- Why big underground detectors were made
- Observed neutrino data of SN1987A
- What we have learned from the observation
- Supernova detectors in the world now
- Supernova relic neutrinos
- Future prospects

Prediction of GUTs in 1970's

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

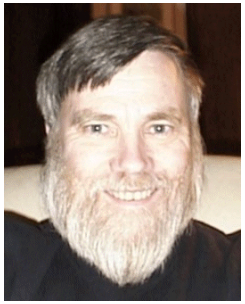
Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

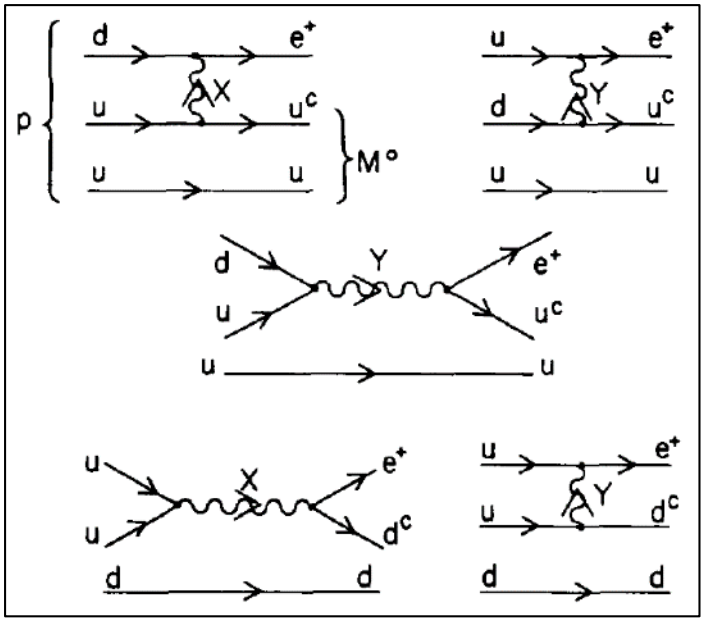
Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that

of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron



Georgi and Glashow



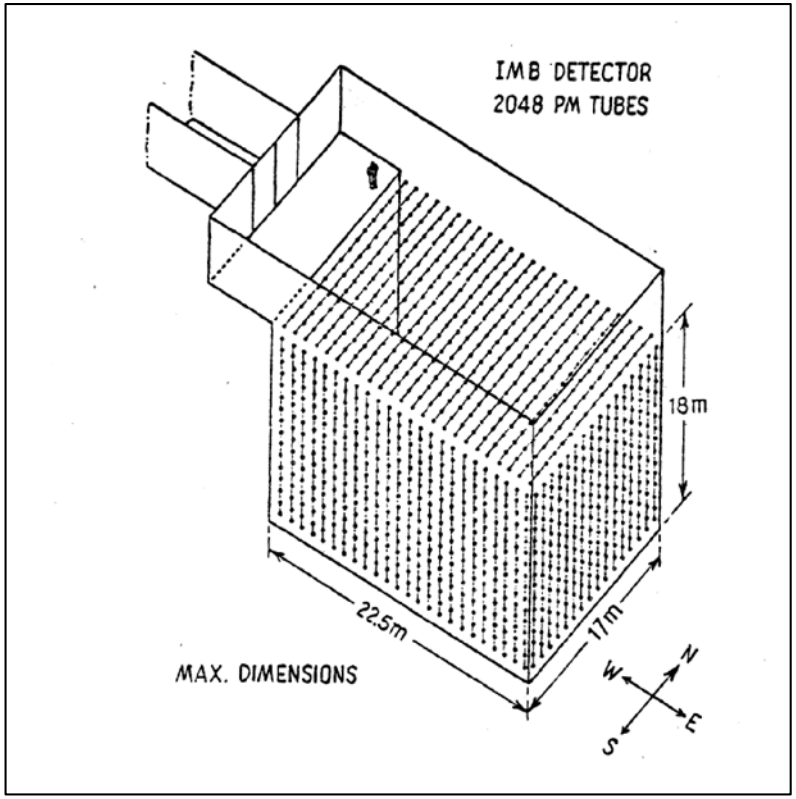
P. Langacker, Phys. Rep. 72, No.4(1981) 185.

Proton decay was predicted.

Expected number of proton decay events was 30 ~ 300 events/1000ton/year for 10^{31} ~ 10^{30} years of proton lifetime.

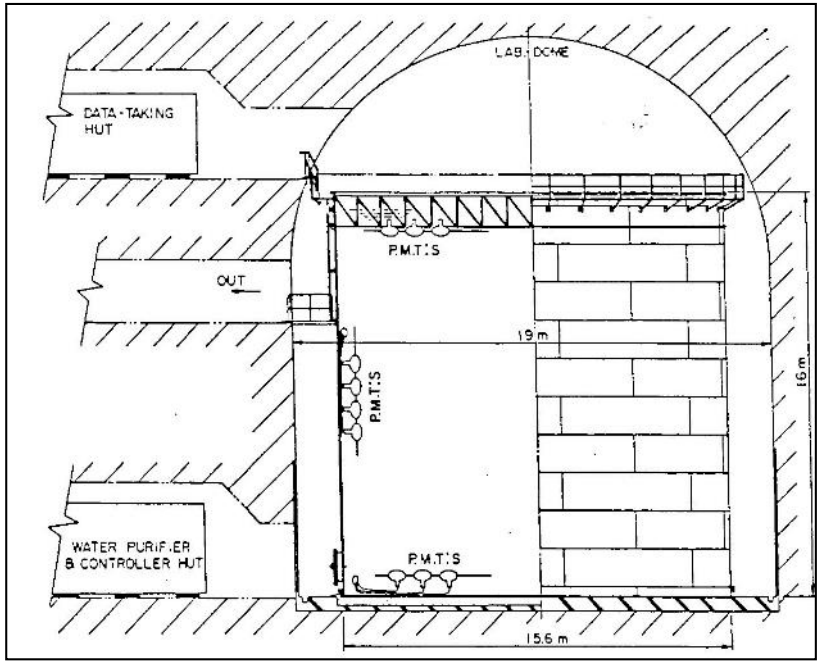
Large detectors were constructed in early 1980's

IMB (Irvine-Michigan-Brookhaven)



- 7,000 ton water Cherenkov detector
- 3,300 ton fiducial volume
- 2,048 5-inch PMTs
- Morton-Thiokol salt(1570 m.w.e.)
- Started operation in 1982

KAMIOKANDE



2,140 ton water Cherenkov detector
880 ton fiducial volume
1,000 20-inch PMTs
Kamioka Mine (2700 m.w.e.)
Started operation in 1983

Led by F. Reines and M. Koshiba

However, proton decay was not observed.

IMB group paper in 1983.

VOLUME 51, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

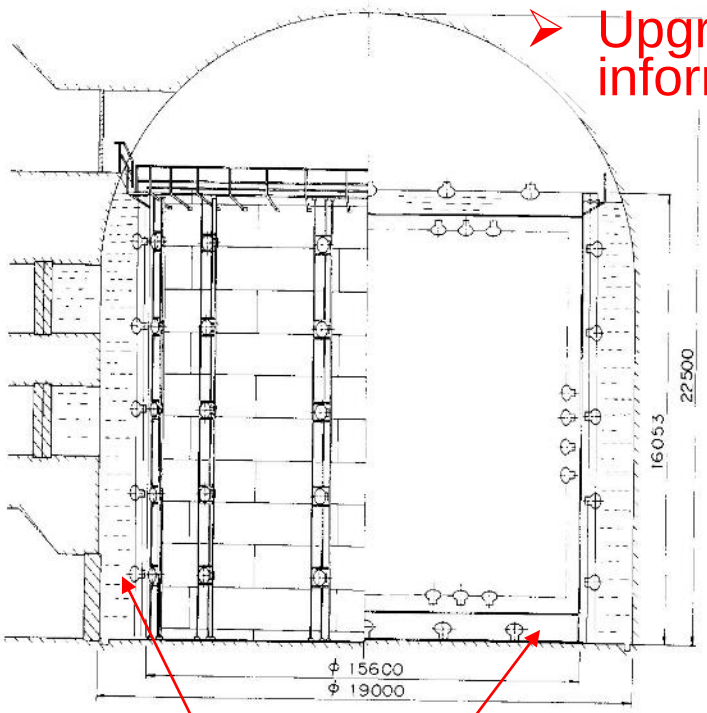
The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p \to e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5 \times 10^{31}$ yr; for free protons the limit is $\tau/B > 1.9 \times 10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

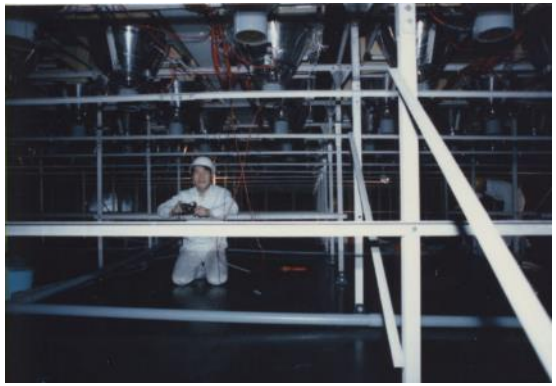
Upgrade to Kamiokande-II (1984-1985)

Thanks to large photo-coverage, it was found that the detector is sensitive to low energy events.
So, the detector was upgraded for solar neutrinos.



- Upgrade electronics for readout of timing information. It improved vertex reconstruction.

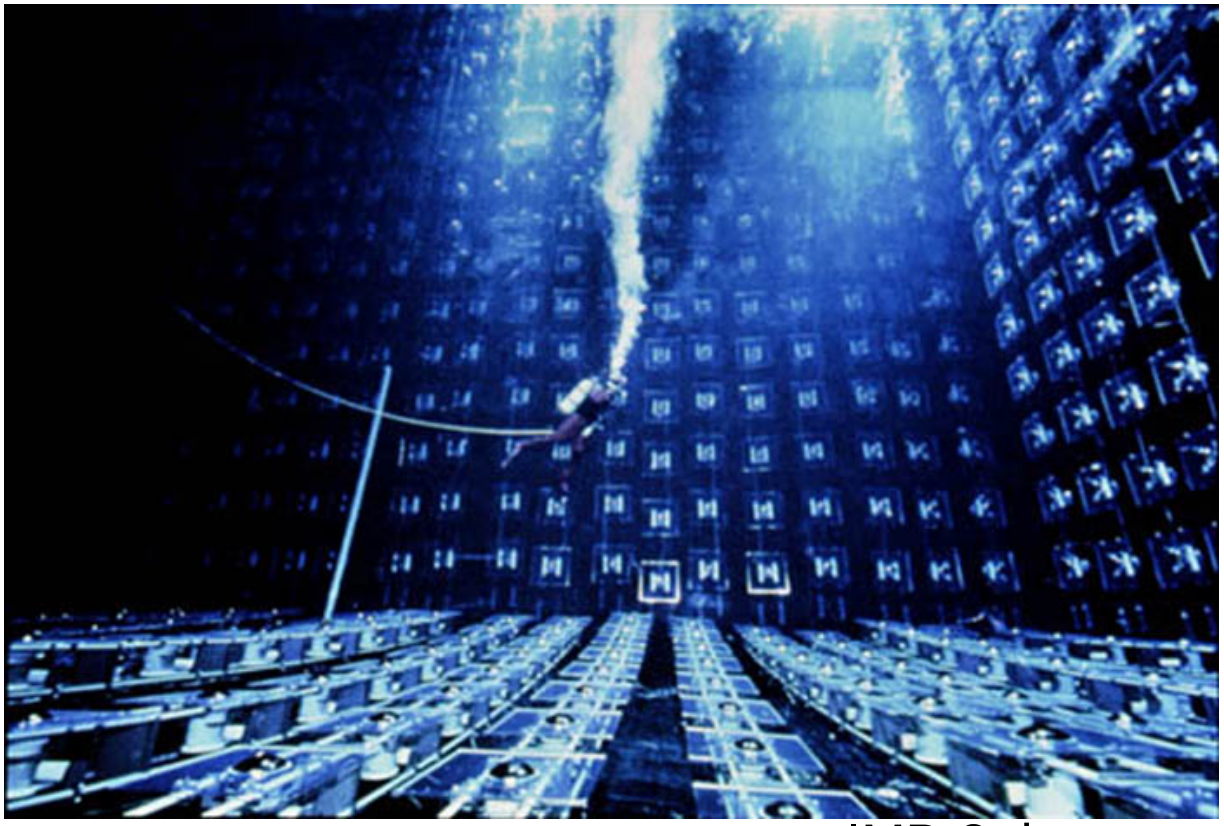
- Made outer detector to shield external gamma rays



Upgrade of IMB detector

Increased light collection efficiency in order to improve physics analysis.
One of the main motivations was to improve the particle identification capability.

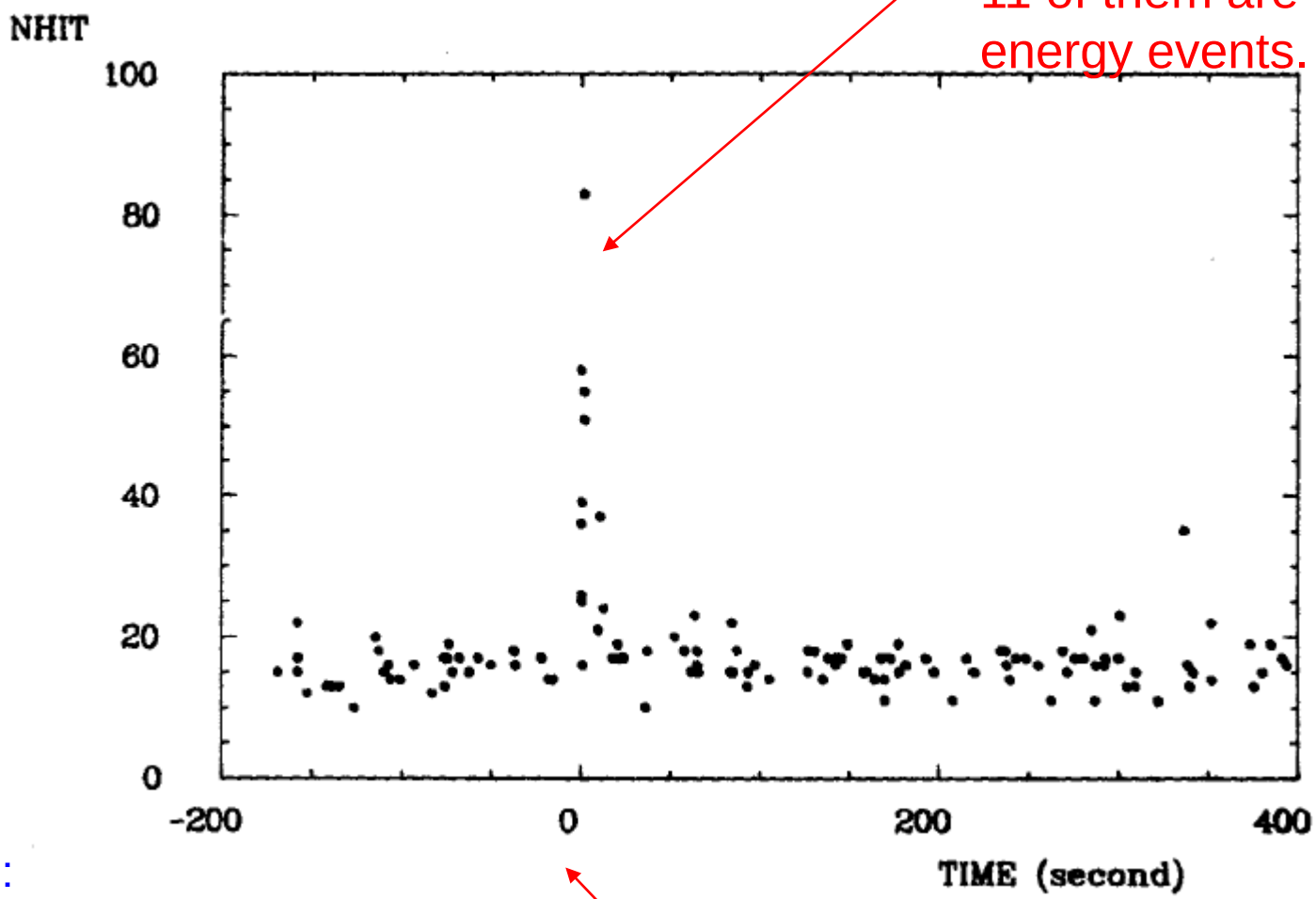
- IMB-1:
  5-inch PMT
  Photo-coverage(1.3%)
- IMB-2:
  Added WLS plates for a factor of ~1.5 increase
- IMB - 3:
  In 1986 shut down to add 8-inch PMTs to bring coverage to effectively about 5%. Also added a WWVB clock to get absolute time to better than 50 milliseconds.



IMB-3 detector

Kamiokande data

12 events within 13sec.
11 of them are higher energy events.

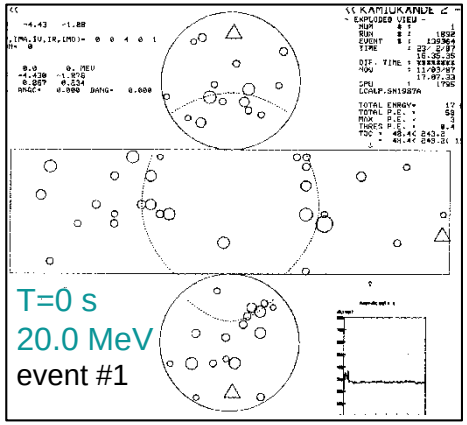


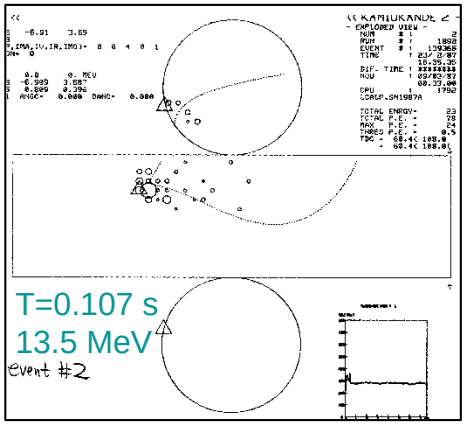
Vertical axis:
Number of hit PMTs for each event, which is almost proportional to energy

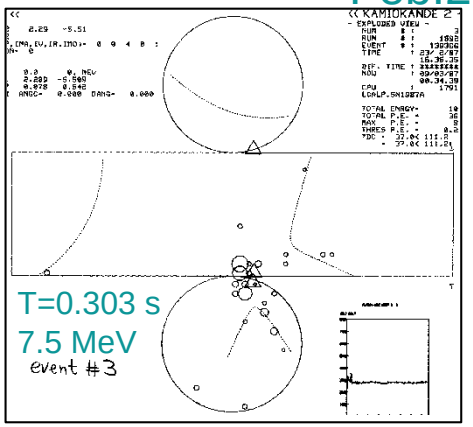
at 7:35:35(±1min)(UT) on Feb.23, 1987

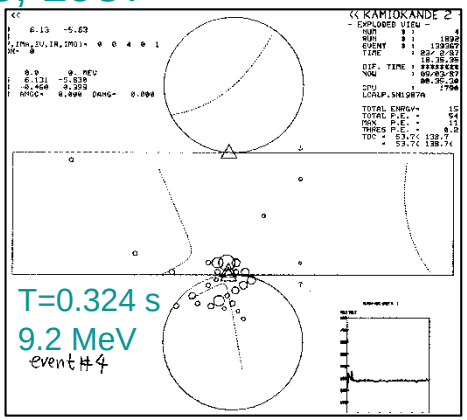
Kamiokande events

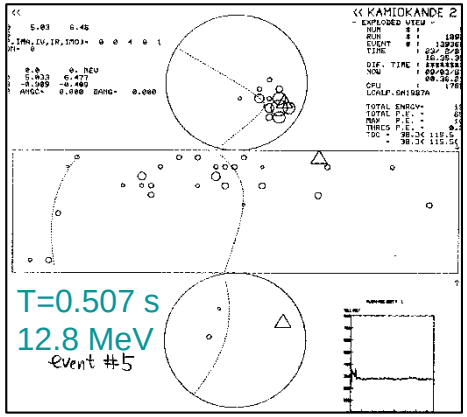
From 7:35:35(UT)(±1min.)
Feb.23, 1987

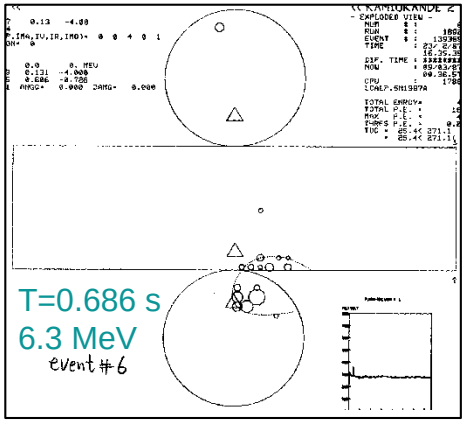


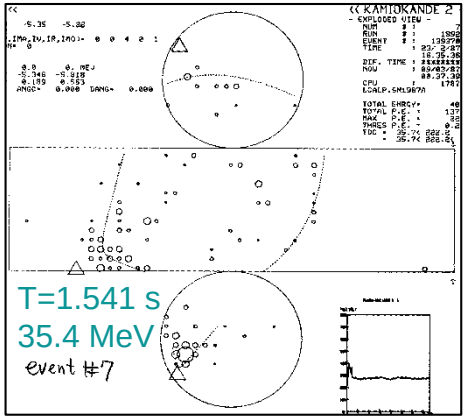


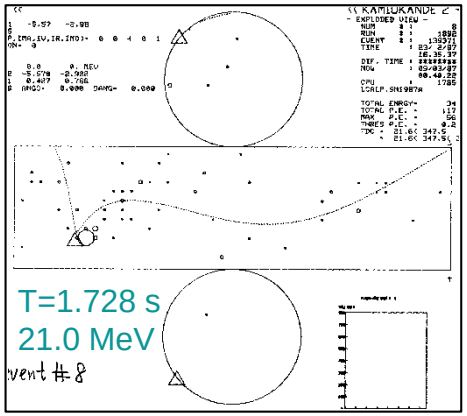


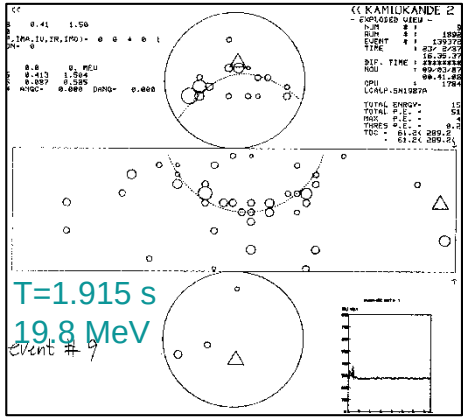


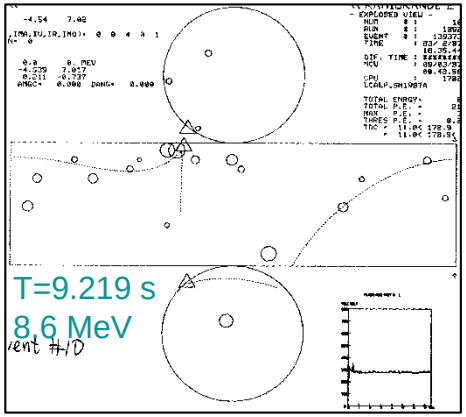


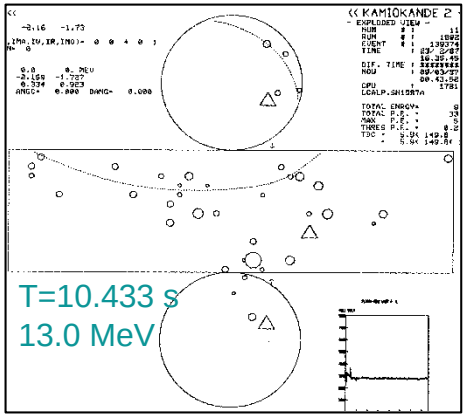


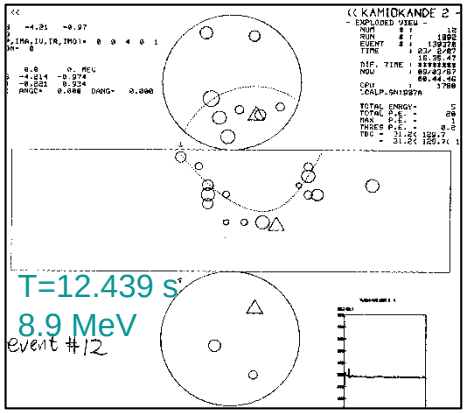












IMB events

SN 1987A Events in IMB Detector
February 23, 1987

UT 7:35:41.4

UT 7:35:41.8

UT 7:35:42.0

UT 7:35:42.5

UT 7:35:42.9

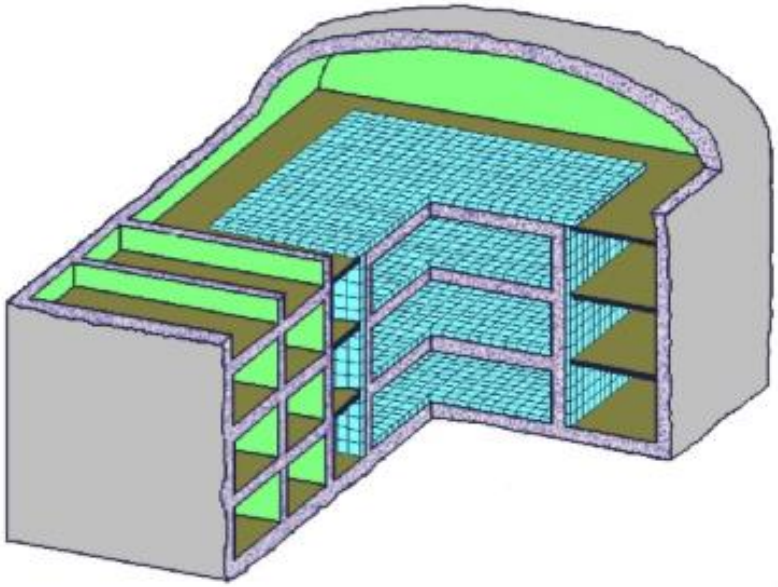
UT 7:35:44.1

UT 7:35:46.4

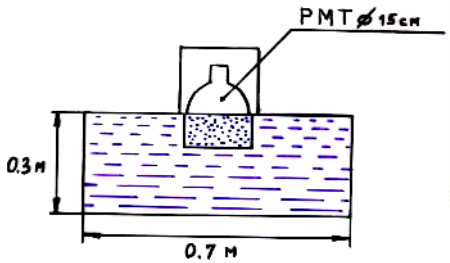
UT 7:35:46.9

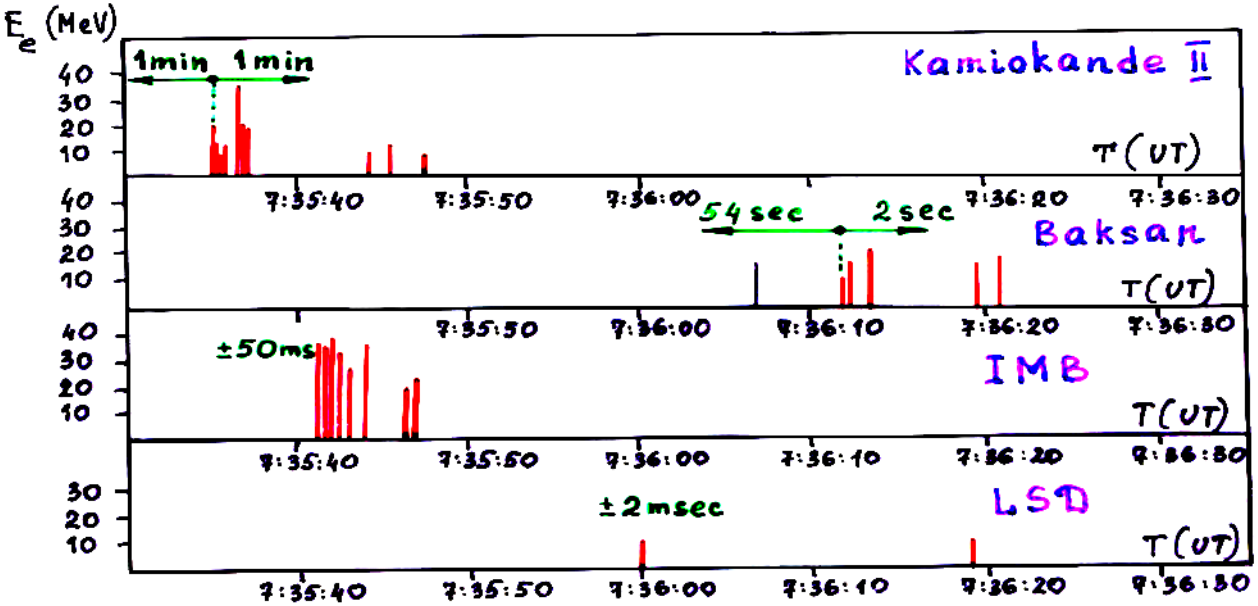
The Baksan underground scintillation telescope (Russia)

- 3184 segmented liquid scintillator detectors
- 330 tons total target mass



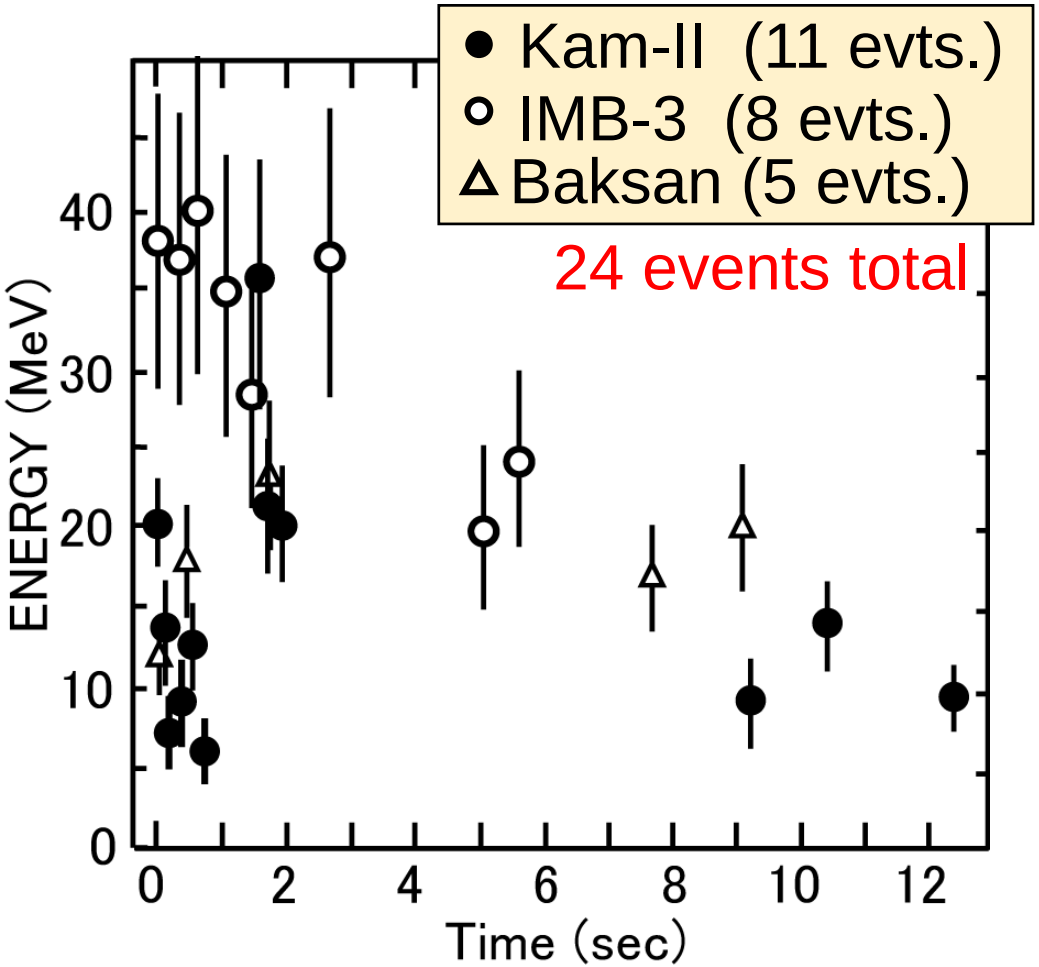
Each detector



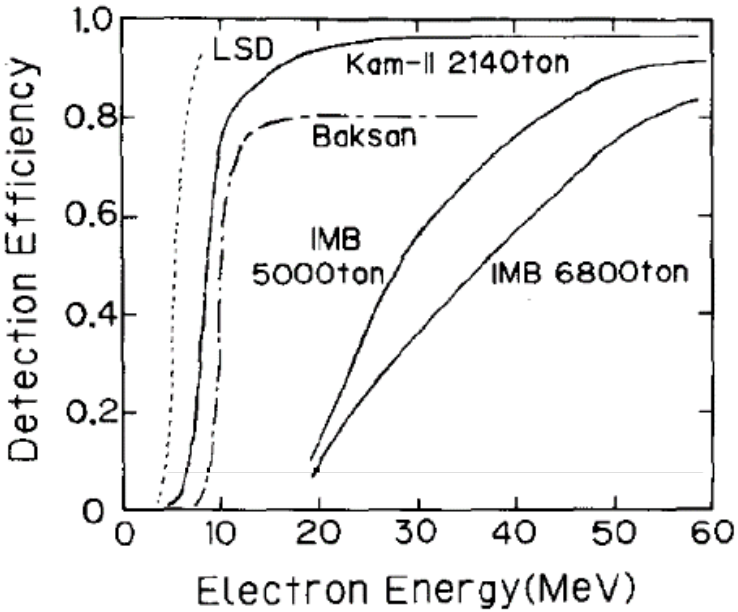


5 events in Baksan detector

Adjusting the 1st events from Kamiokande, IMB and Baksan



Detection efficiency



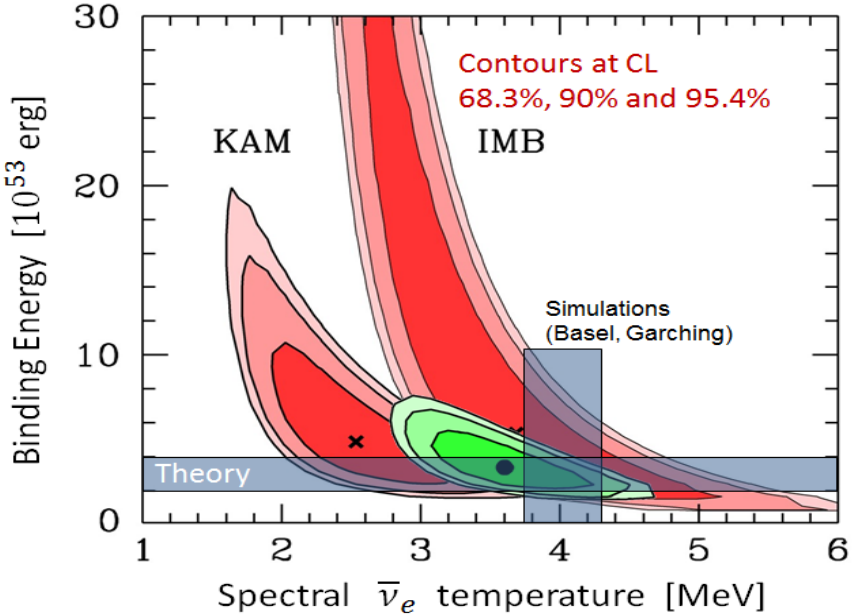
Energy threshold (at 50% eff.)

~8.5 MeV @ Kamiokande

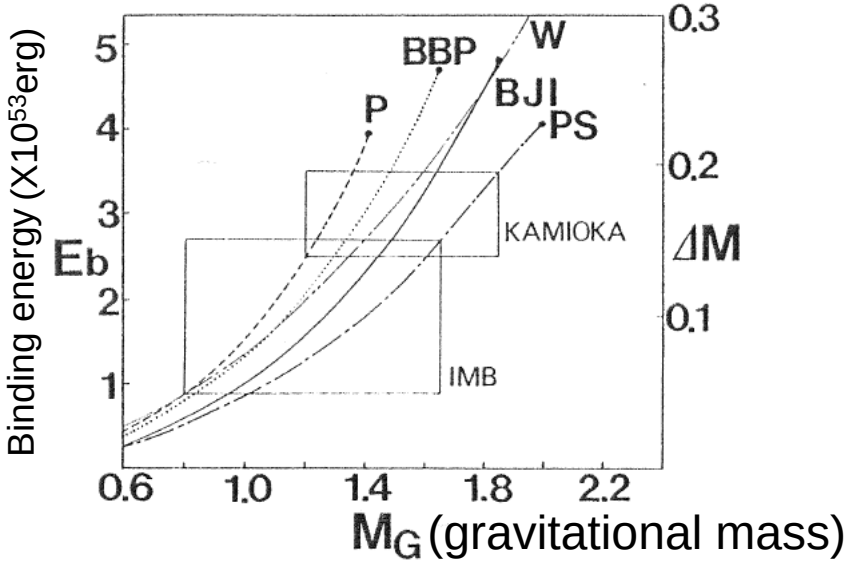
~28 MeV @ IMB

~10 MeV @ Baksan

What we have learned from SN1987A



Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

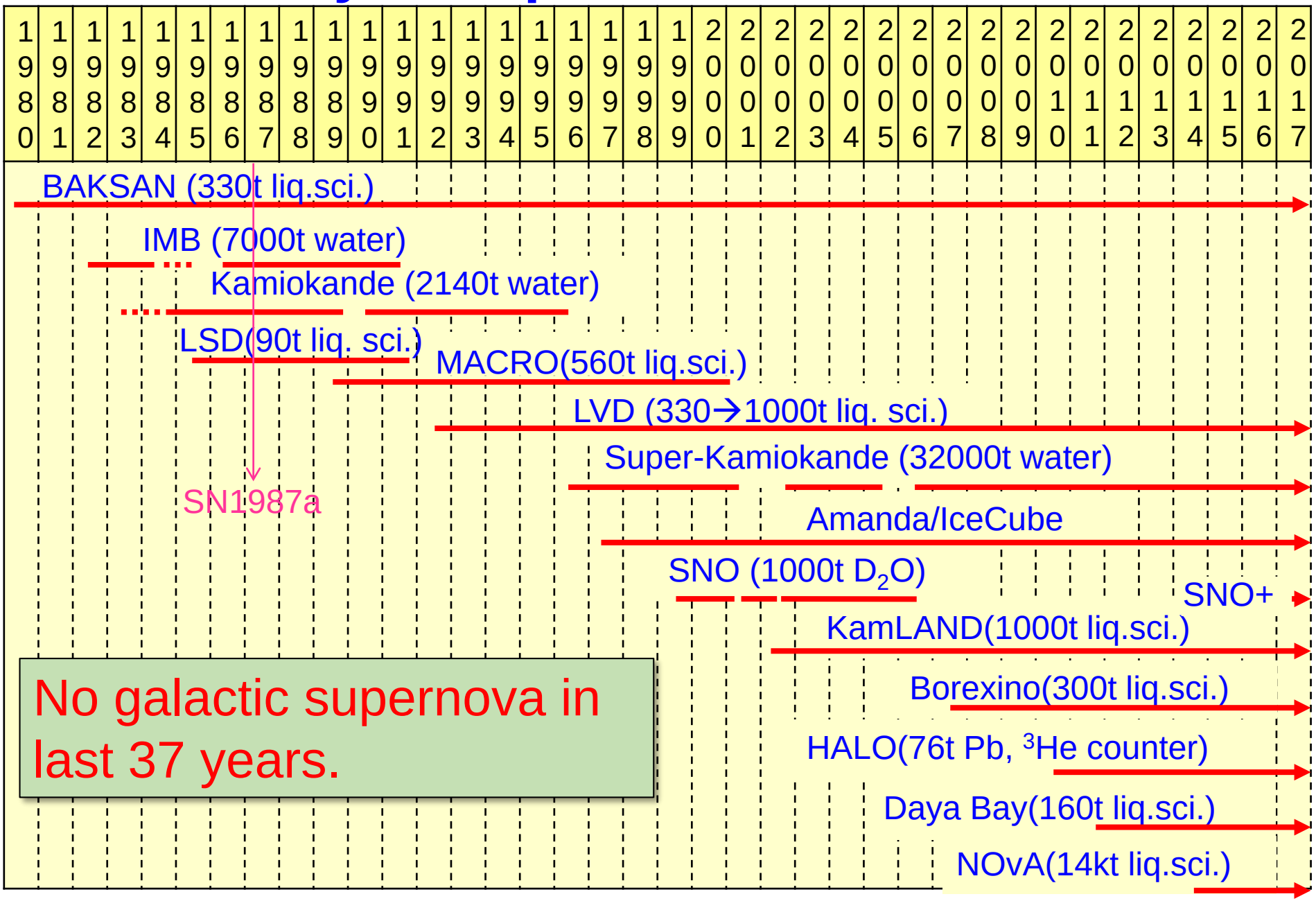


Sato and Suzuki, Phys.Lett.B196 (1987) 267

- Total energy released by $\bar{\nu}_e$ was measured to be ~5x10^{52} erg.
- Assuming equipartition, binding energy was estimated to be ~3x10^{53} erg.
- This binding energy was consistent with core-collapse scenario.

However, no detailed information of burst process was observed because of low statistics.

History of supernova detectors



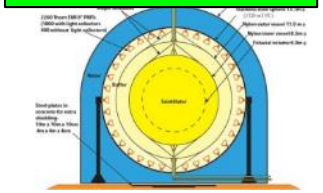
No galactic supernova in last 37 years.

Supernova burst detectors in the world now

Liquid scintillator
Water, Ice
Other

target mass

Borexino

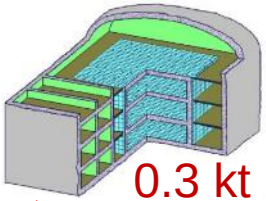


0.3 kt

LVD

1 kt

Baksan



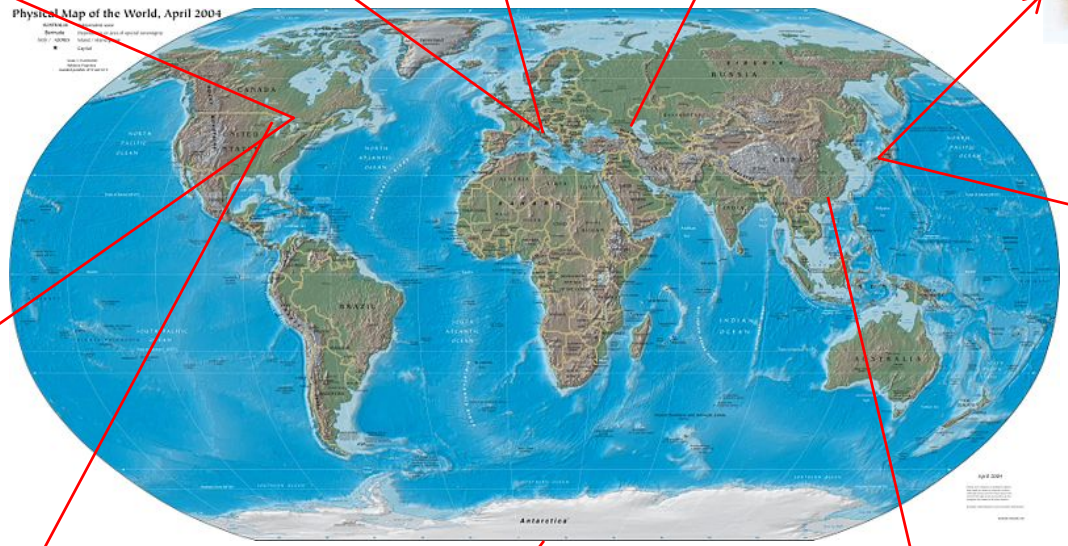
0.3 kt

Super-Kamiokande

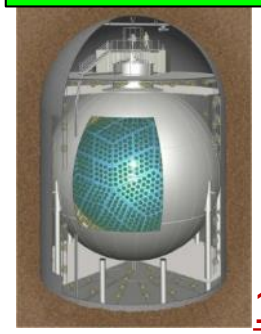
32 kt

SNO+

1 kt



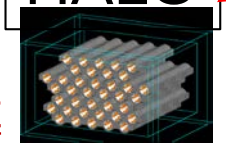
KamLAND



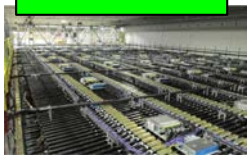
1 kt

HALO

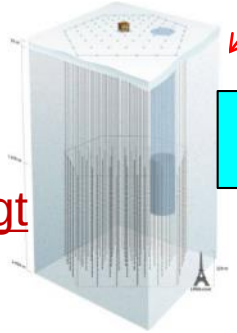
Pb
76 t



NOvA



surface 14 kt



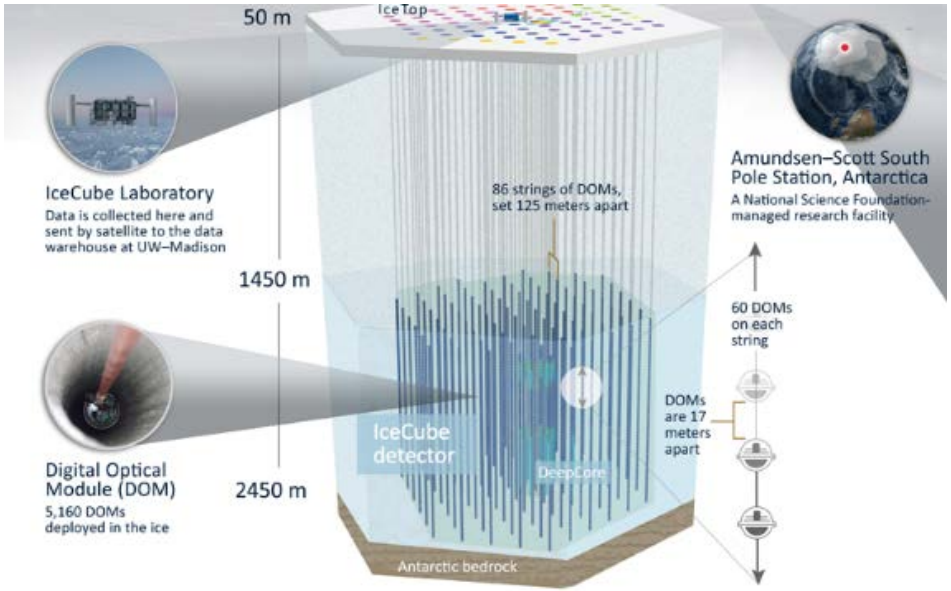
1 gt

IceCube

Daya Bay

0.16 kt

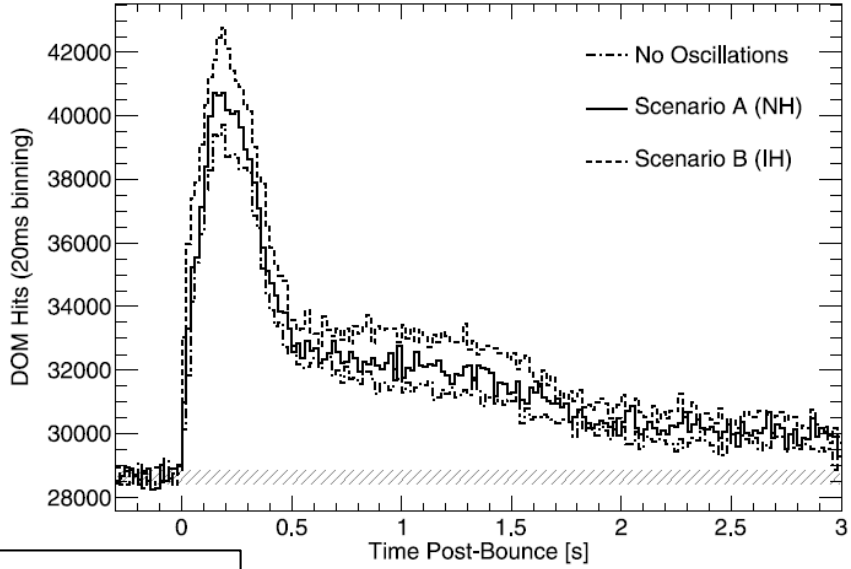
IceCube (South pole)

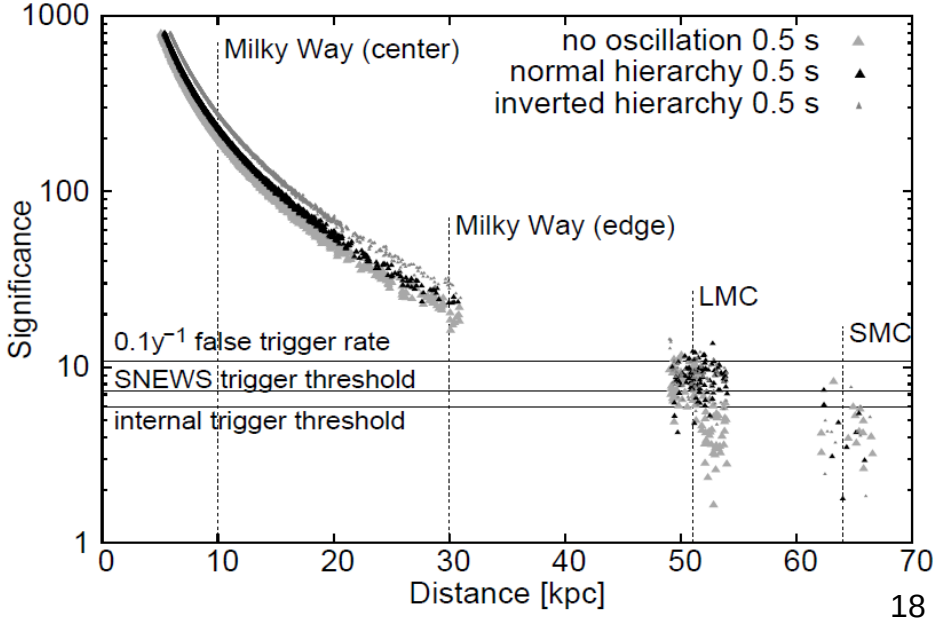


IceCube detector

- Number of Optical modules: 5160
- 25cm diameter PMTs in each optical module
- Number of strings: 86
- Instrumented volume: 1 km^3

Supernova neutrinos coherently increase single rates of PMTs.

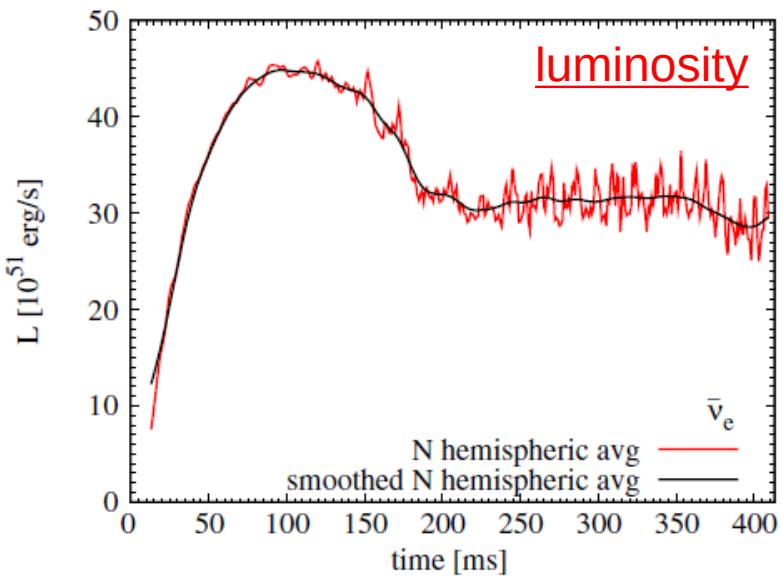


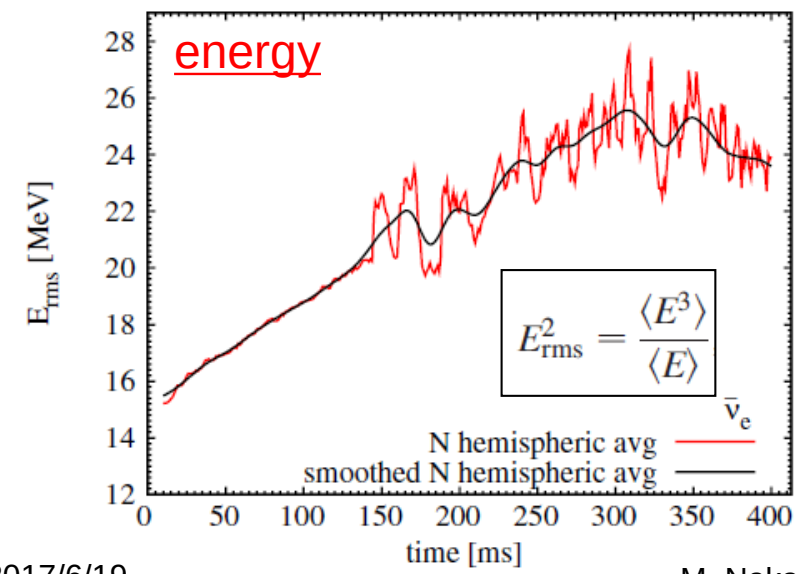


From L.Koepke

High frequency signal variation by SASI

SASI=standing accretion shock instability

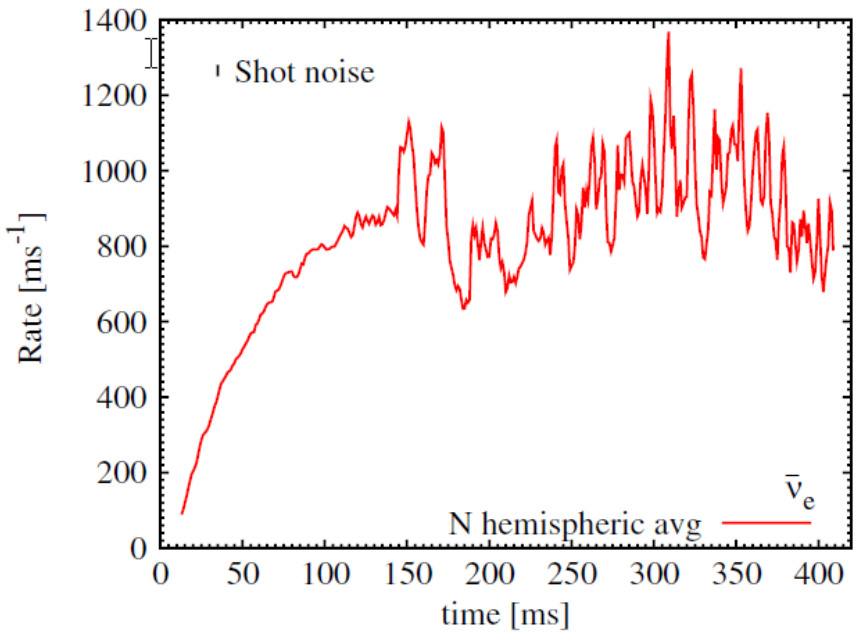




2-D(axially symmetric) simulation with PROMETHEUS-VERTEX code

Supernova at 10kpc

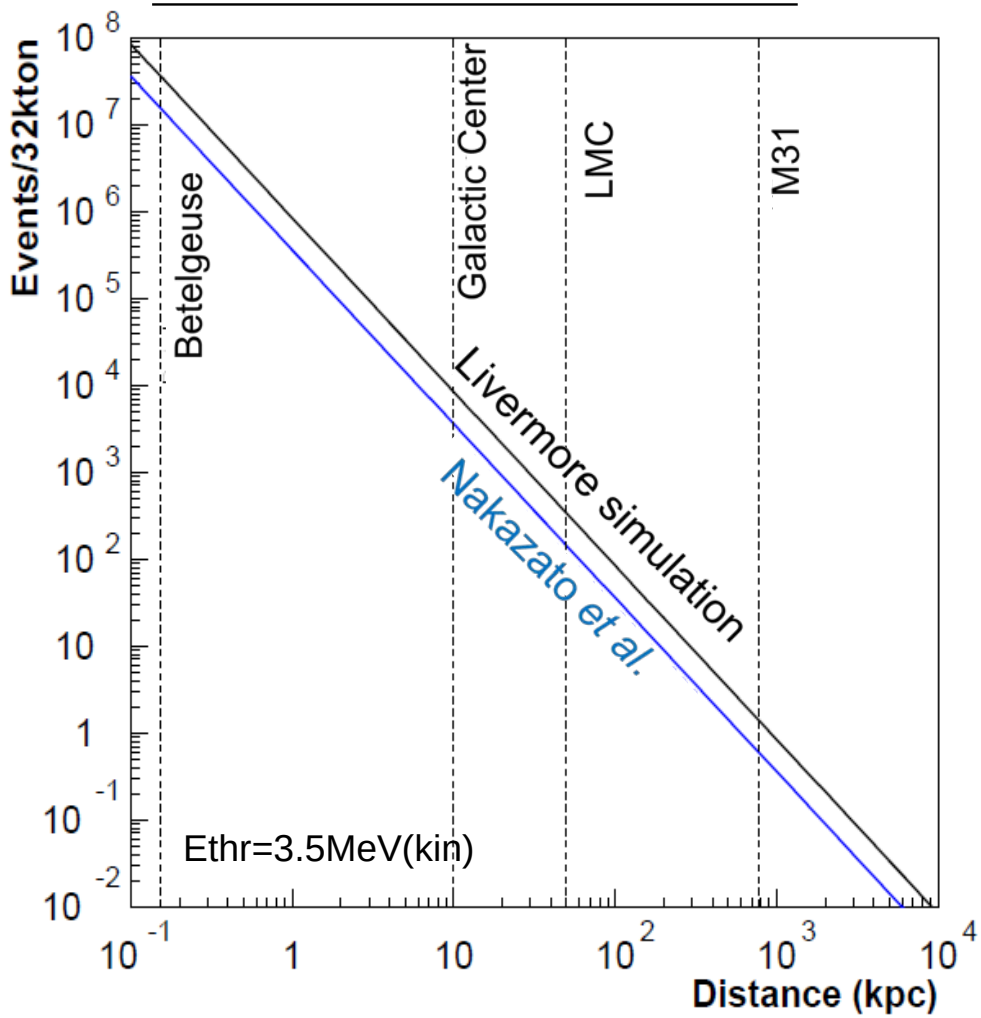
IceCube "event" rate



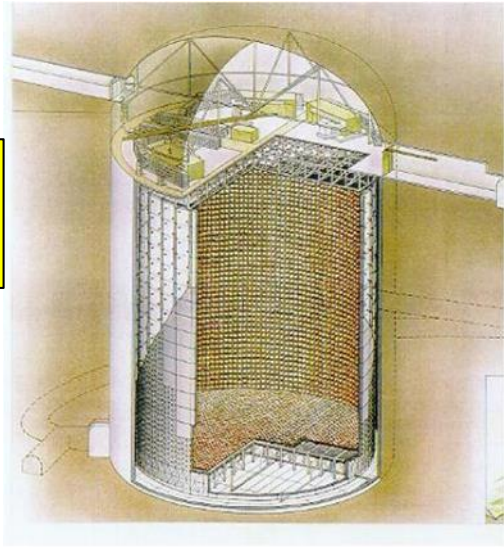
T.Lund et al., Phys. Rev. D82, 063007(2010).

Super-K: Number of events

Number of events vs. distance



32kton water Cherenkov



For each interaction

	Livermore	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

Directional information

Supernova at 10 kpc

32kton SK volume

4.5MeV(kin) threshold

No oscillation case.

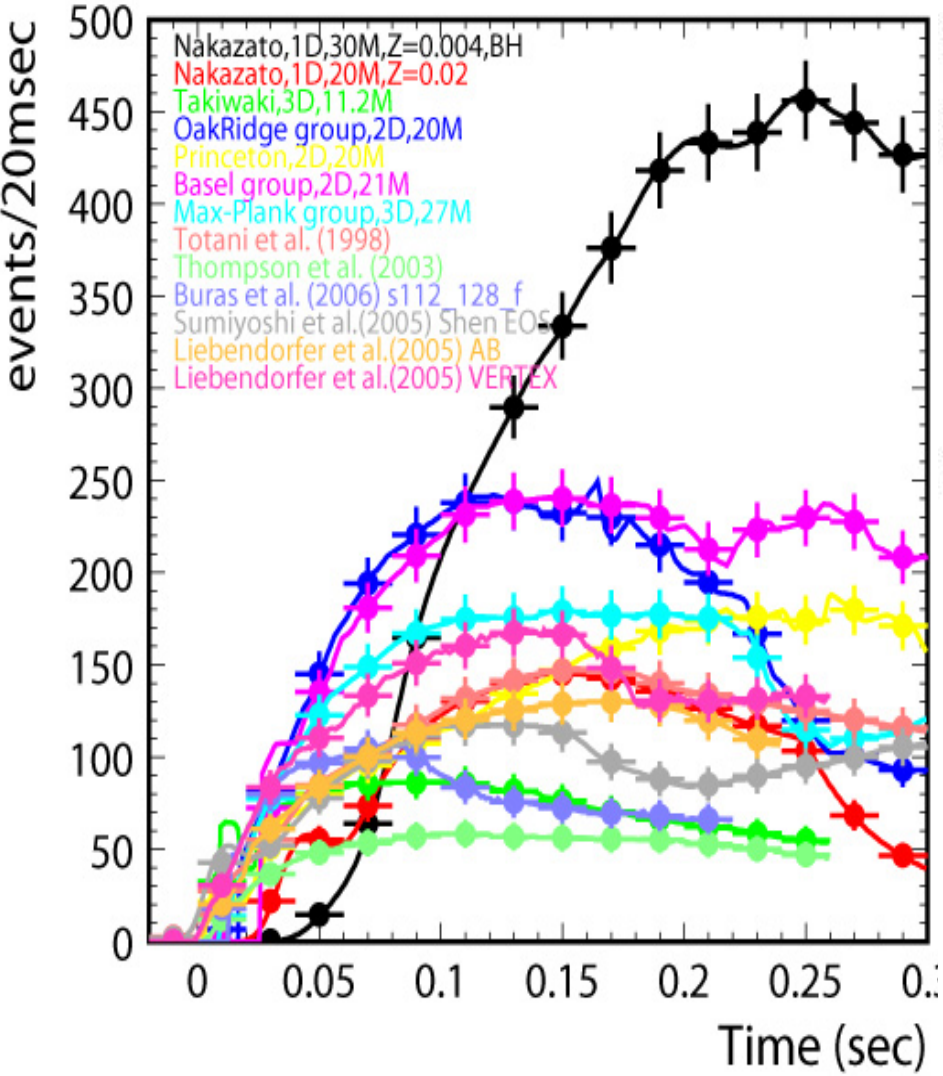
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

Nakazato et al. K.Nakazato, K.Sumiyoshi, H.Suzuki, T.Totani, H.Umeda, and S.Yamada, ApJ.Suppl. 205 (2013) 2, ($20M_{sun}$, trev=200msec, z=0.02 case)

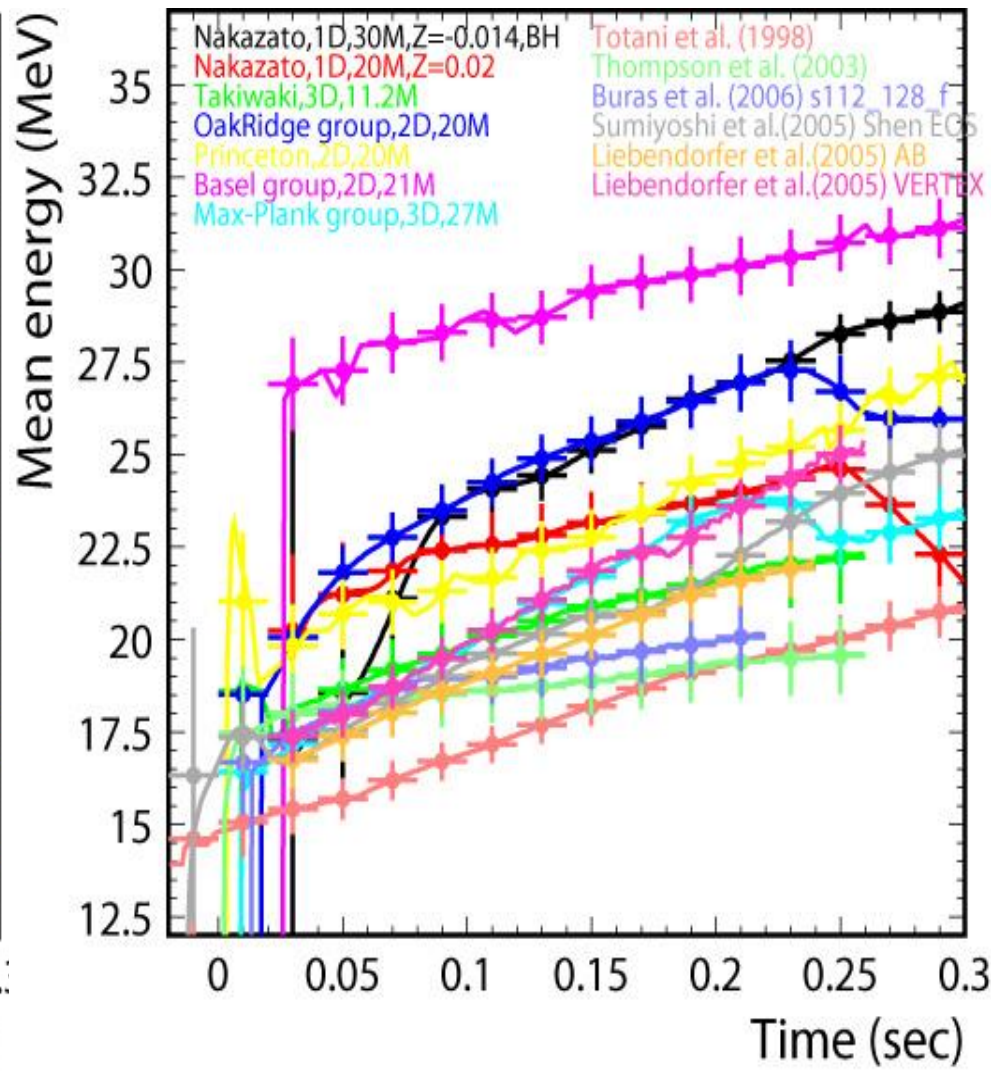
Sensitivity of Super-K for the model discrimination

For 10kpc supernova

Time variation of event rate



Time variation of mean energy

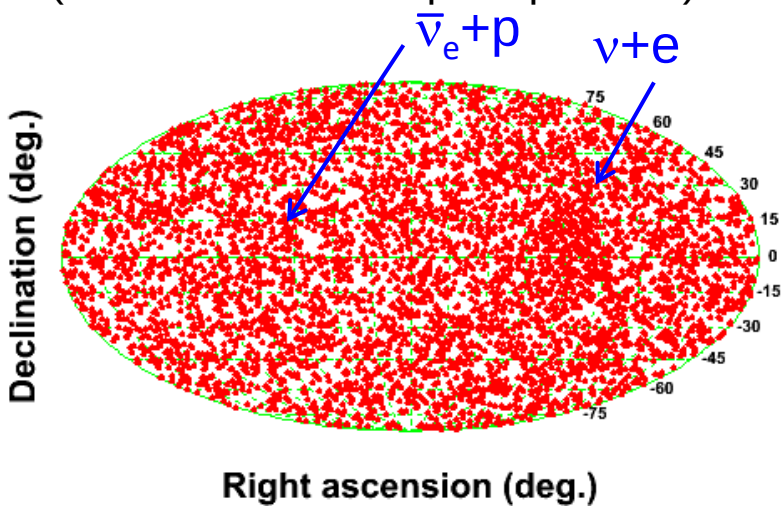


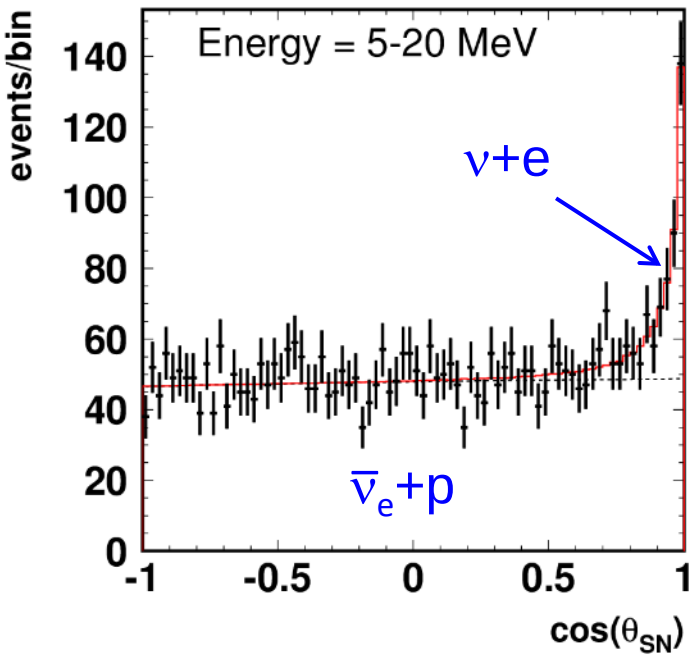
High statistics enough to discriminate models

Cooperation: H. Suzuki

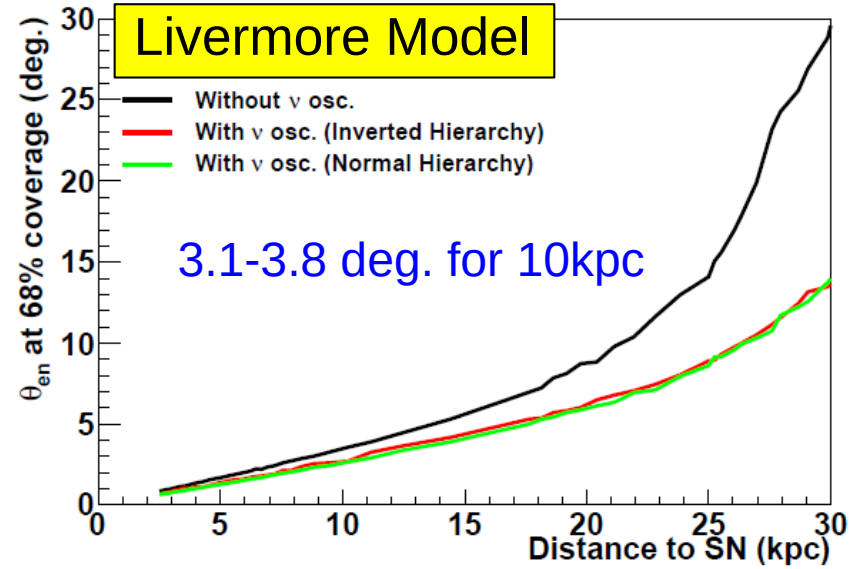
Super-K: directional information

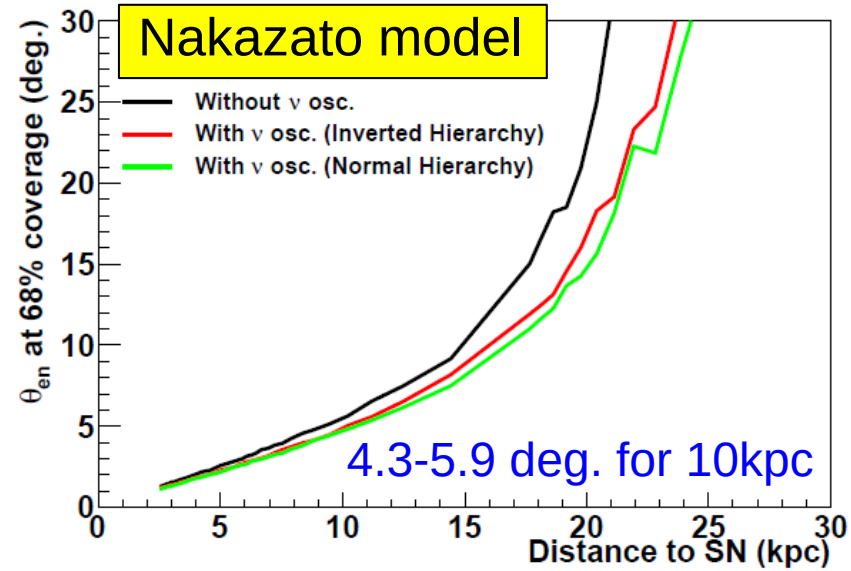
Reconstructed direction
(Simulation of a 10kpc supernova)





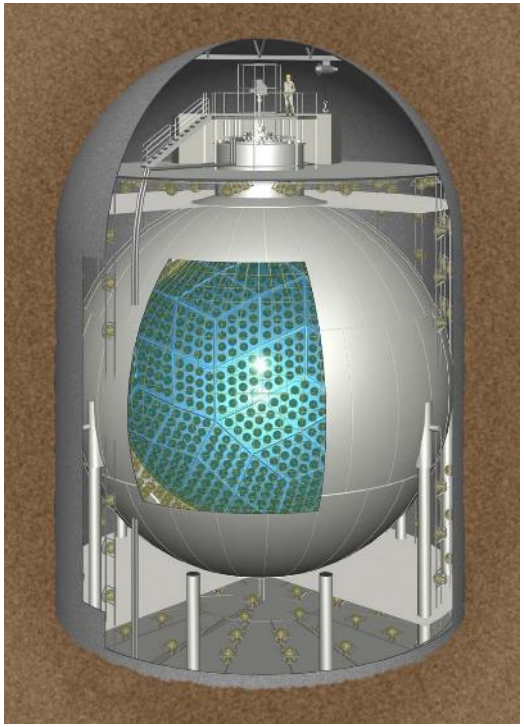
Distance vs. pointing accuracy





Single volume liquid scintillator detectors

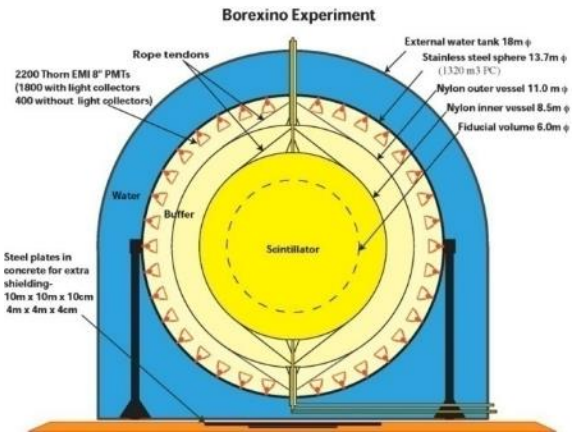
KamLAND
(Kamioka, Japan)



1000ton liq.sci.

Running since 2002.

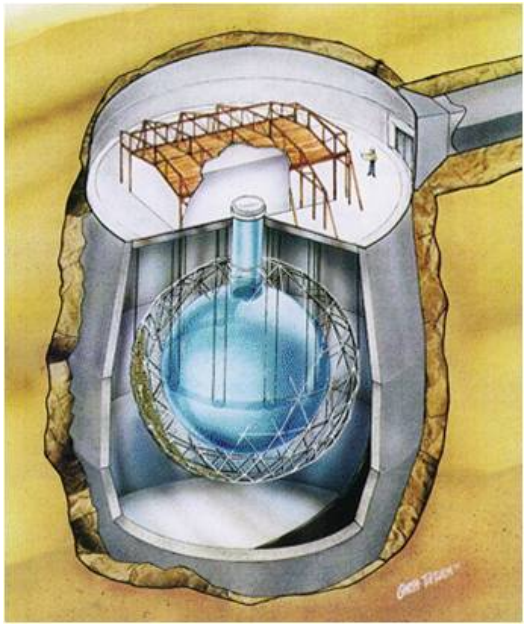
Borexino
(Gran Sasso, Italy)



300ton liq.sci.

Running since 2007.

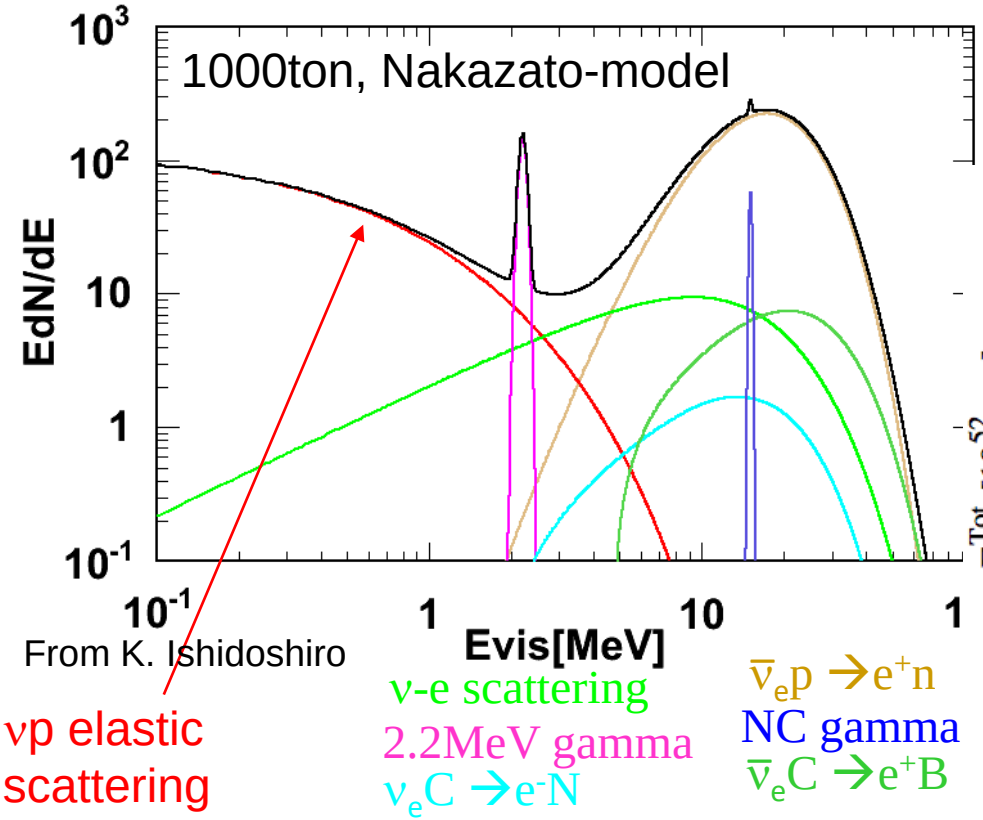
SNO+
(SNO Lab.,Canada)



1000ton liq.sci.

Energy spectrum expected at the liquid scintillation detectors

Expected energy spectrum (10kpc)

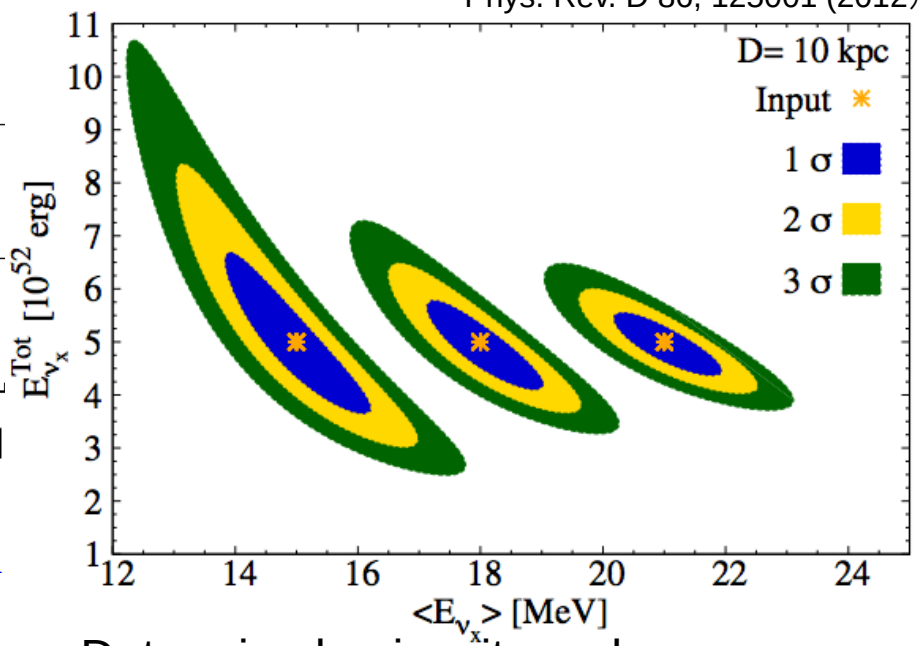


From K. Ishidoshiro

Expected number of events	for 1kton, 10kpc
$\bar{\nu}_e p \rightarrow e^+ n$	~300
$\nu + e^- \rightarrow \nu + e^-$	~20
$\nu + p \rightarrow \nu + p$	~80 (>200keV)
^{12}C CC	60

ν_x parameter measurement with νp elastic scattering events (3000t eqv.)

Phys. Rev. D 86, 125001 (2012)



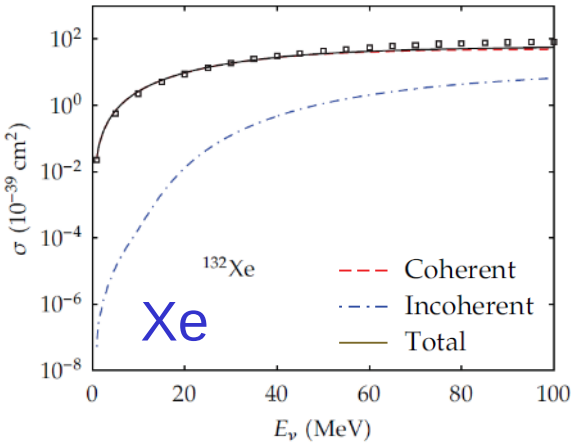
Determine luminosity and mean energy of ν_x

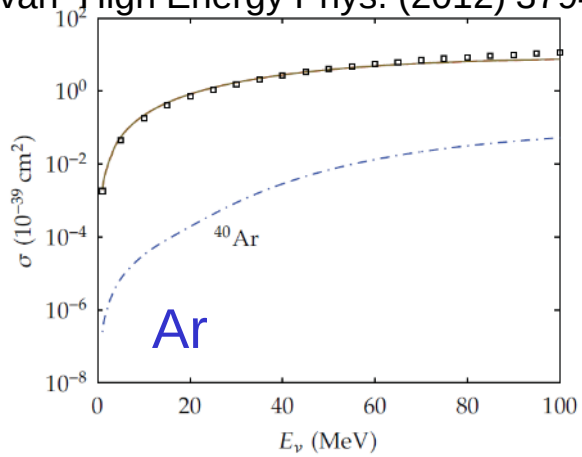
(ν_x : ν_μ , ν_τ at the source)

Supernova signals by Dark Matter detectors

Coherent elastic neutrino-nucleus scattering

CEνNS cross section P. C. Divari High Energy Phys. (2012) 379460

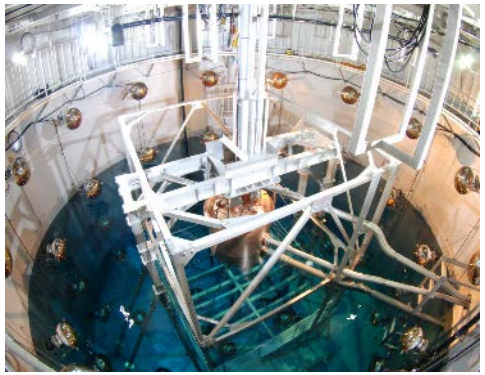




DEAP3600 (Ar 3.6ton)

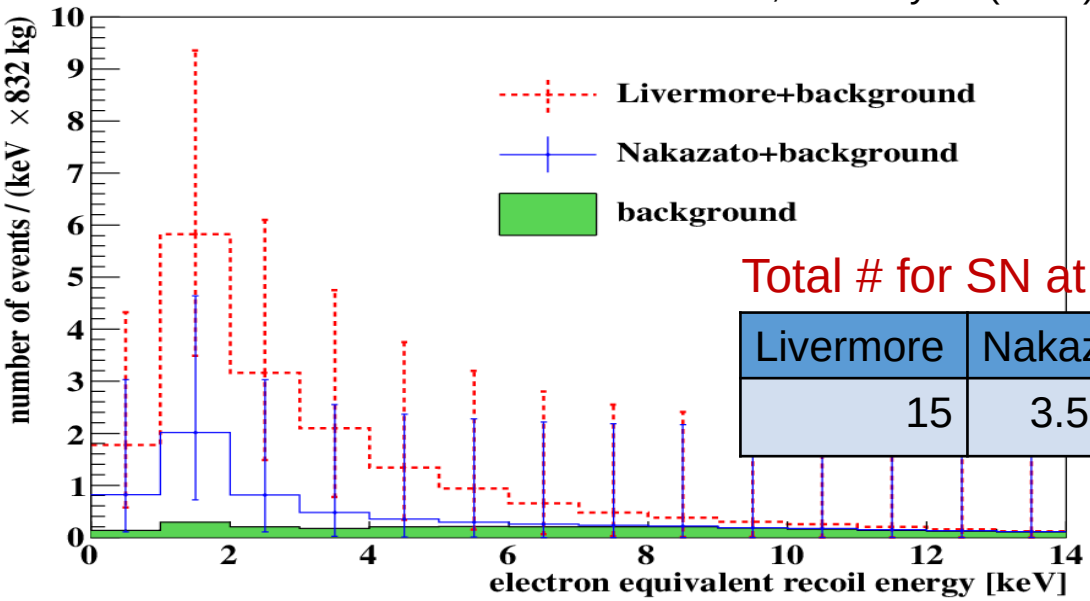
XENON1T (Xe 1ton)

- **XMASS** (Xe 0.83ton)
  - >300eV threshold



K. Hiraide from 15:40 on June 21

K. Abe et al., Astr.Phy.89 (2017) 51-56

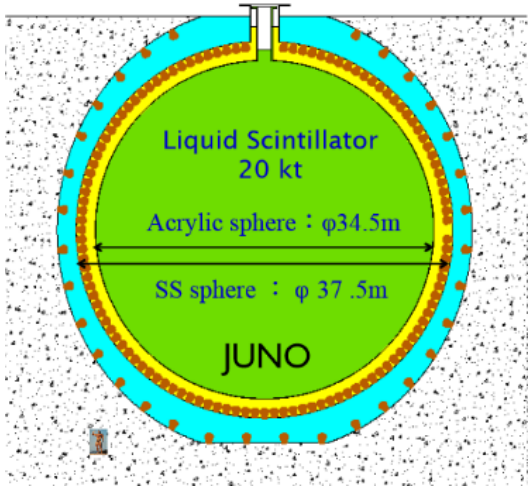


Total # for SN at 10 kpc

Livermore	Nakazato
15	3.5 ~ 21

Future Large Volume Detectors

JUNO(China)
(20kton Liq. Sci.)

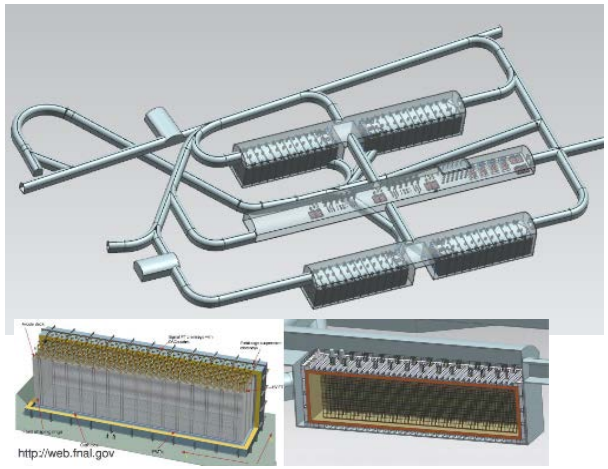


Precise measurement of average energy and luminosity for all neutrino flavors.

~1% for <E> for $\bar{\nu}_e$
~10% for <E> for ν_e
~5% for <E> for ν_x

H. Li from 16:50 on June 21

DUNE/LBNF (US)
(40 kton Liq. Ar)

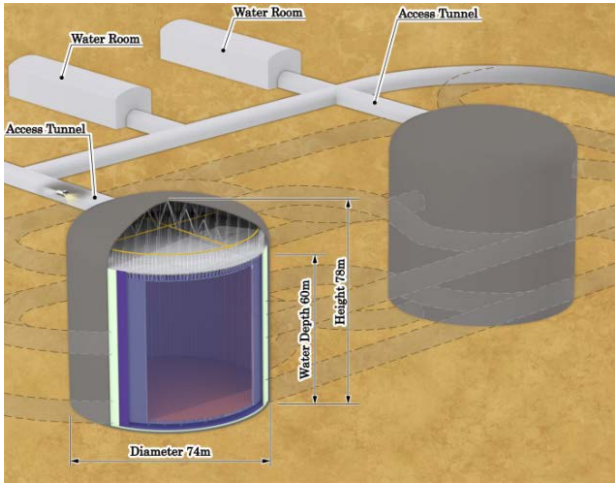


$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ is the dominant interaction.

~4000 events for 10kpc SN. ~60 events for from neutronization burst for IH case (~0 for NH).

J.Reichenbacher from 17:10 on June 21

Hyper-Kamiokande
(440 kton Water)



~120k $\bar{\nu}_e p$,~5k ν+e events for 10 kpc supernova. Precise measurement of time variation.

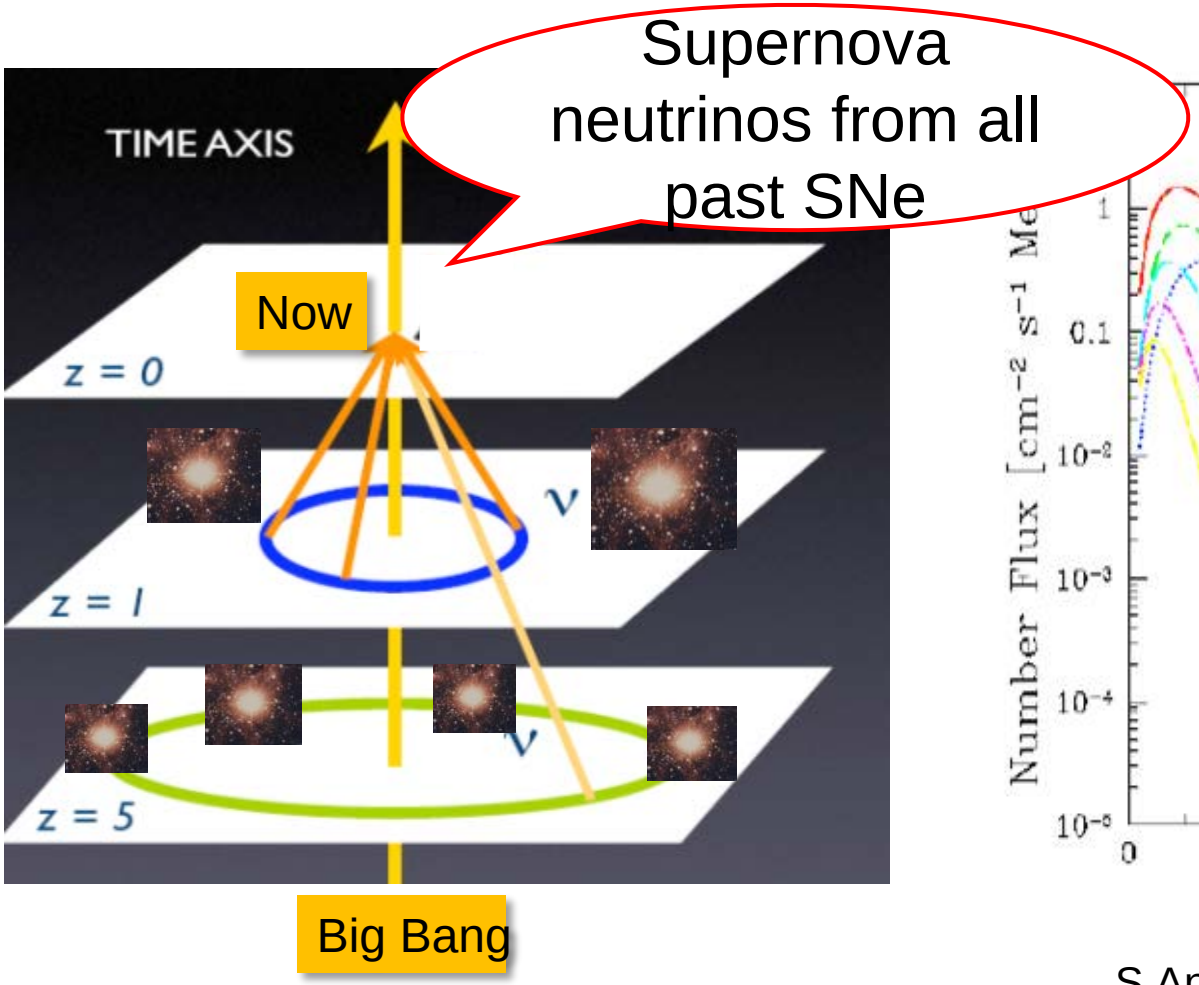
~1 deg. pointing accuracy.

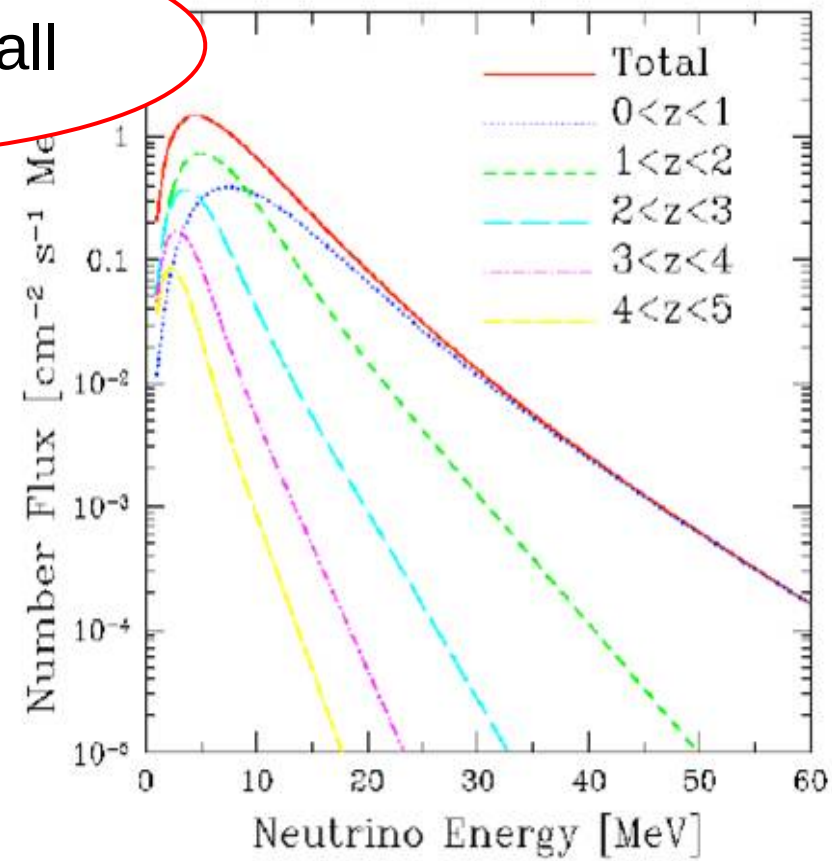
Detection of supernova neutrinos at nearby galaxies.

S.Nakayama from 14:50 on June 20

Supernova Relic Neutrinos

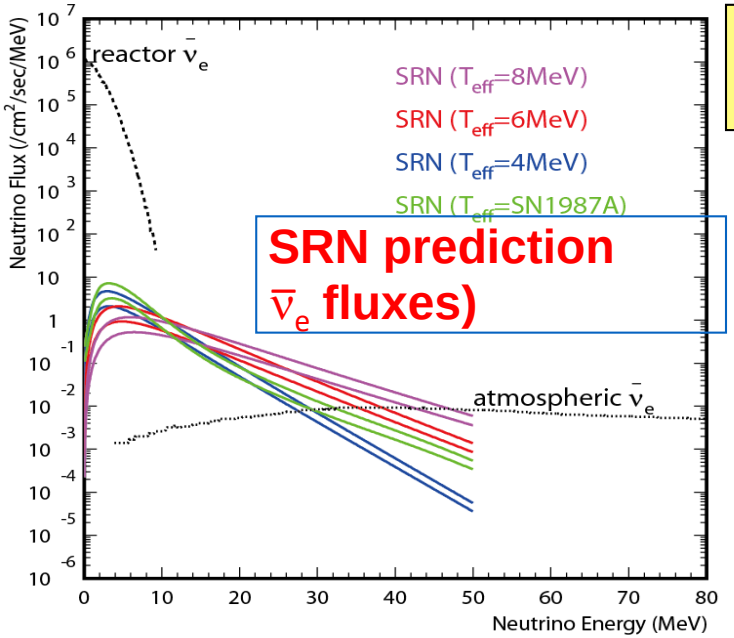
~10^{10} stars/galaxy × ~10^{10} galaxy × 0.3%(massive star->SN) ~$O(10^{17})$SNe



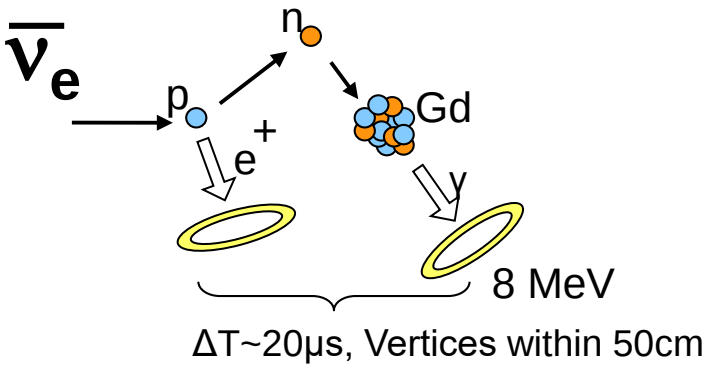


S.Ando, Astrophys.J. 607, 20(2004)

SK-Gd project for Supernova Relic Neutrino



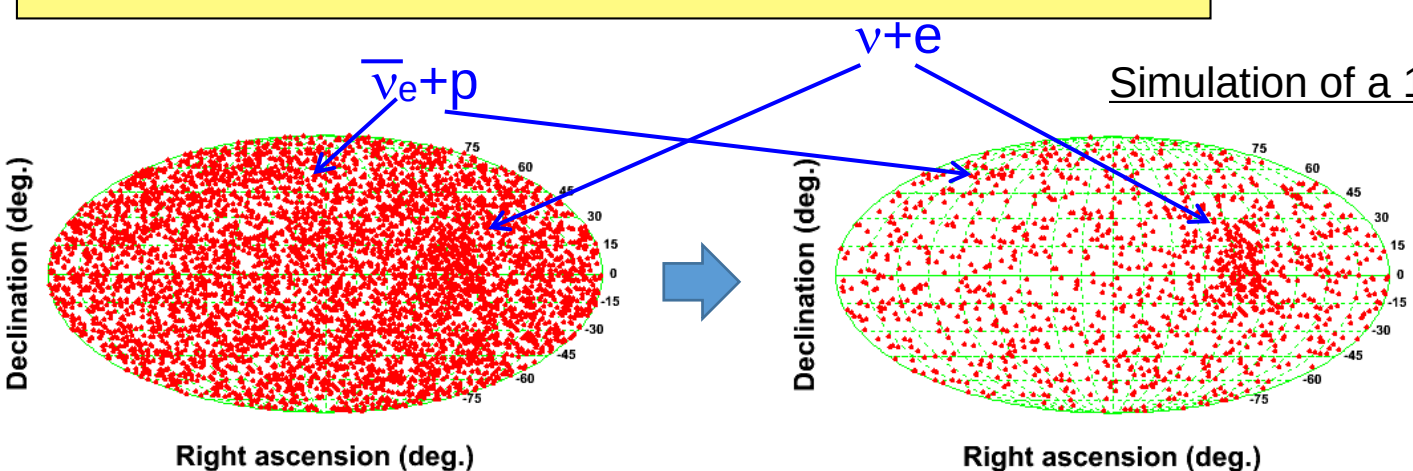
Open widow for SRN at 10-30MeV
Expected rate 1.3 -6.7 events/year/22.5kt(10-30MeV)



Identify $\bar{\nu}_e$+p events by neutron tagging with Gd. 90%(50%) capture efficiency with 0.1% (0.01%) Gd in water.

Improve pointing accuracy for supernova bursts, e.g. 4~5°→ 3°(90%C.L.) for 10kpc

Simulation of a 10kpc supernova

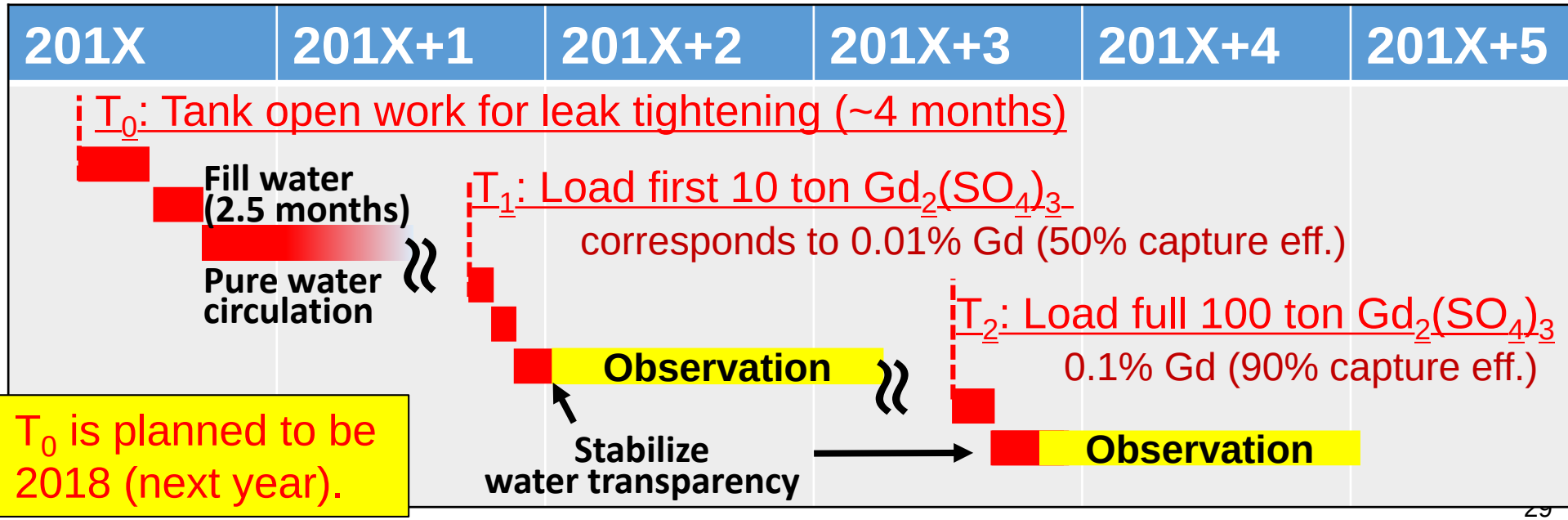


Preparation and plan for SK-Gd project

Y. Takeuchi from 16:30 on June 21

Gd-loading, pre-cleaning and Gd-water circulation systems were constructed.

Low radioactive $Gd_2(SO_4)_3$ power has been developed and getting close to our goals. Uranium and radium removal resins have been developed.



T_0 is planned to be 2018 (next year).

Conclusions

- Large volume detectors were built in order to search for proton decay and they detected SN1987A neutrinos.
- The observation of the SN1987A neutrinos proved the basic scenario of supernova explosions.
- The supernova detectors in the world now and future are able to obtained detailed information to reveal explosion mechanism.
- SK-Gd for supernova relic neutrinos will start in a few years.