Observation of Supernova Neutrinos
― Past and Now ―

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KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Kavli IPMU 10th anniversary symposium 16 - 18 October 2017

30th Anniversary of SN1987A

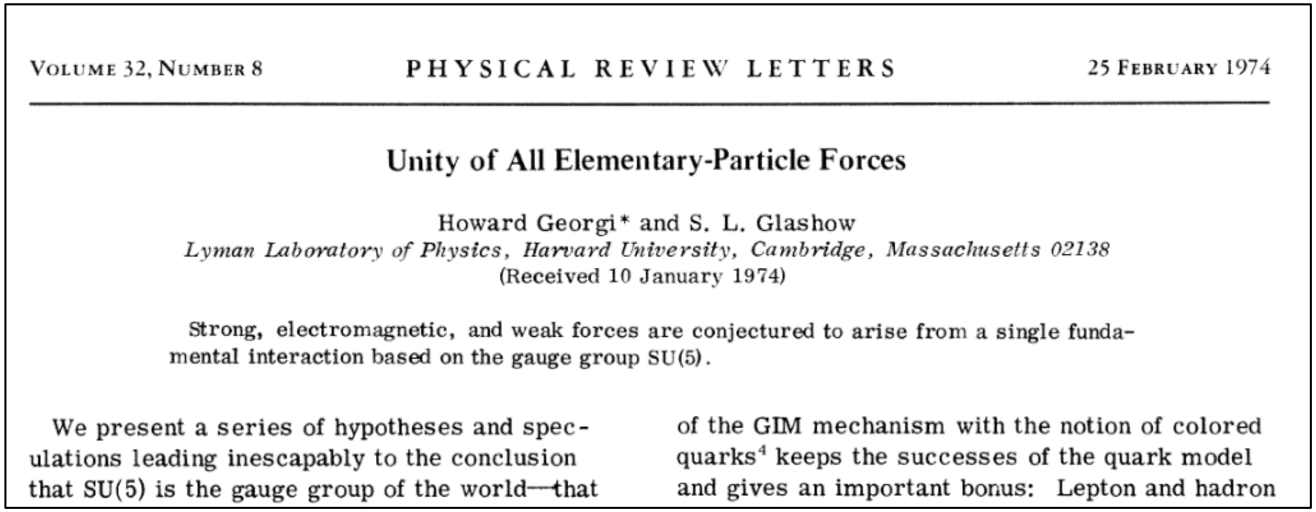
Cake made for an anniversary held on Feb.12, 2017 at the Univ. of Tokyo

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

Contents

- Why large underground detectors were constructed in 1980’s
- A little history of the Kamiokande detector
- Observation of neutrinos from SN1987A by Kamiokande, IMB and BAKSAN
- What we have learned from this observation
- Supernova detectors in the world now
- What Super-Kamiokande will measure for supernova
- SK-Gd project (if I have time)

Prediction of GUTs in 1970's



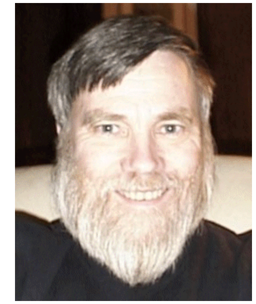
VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

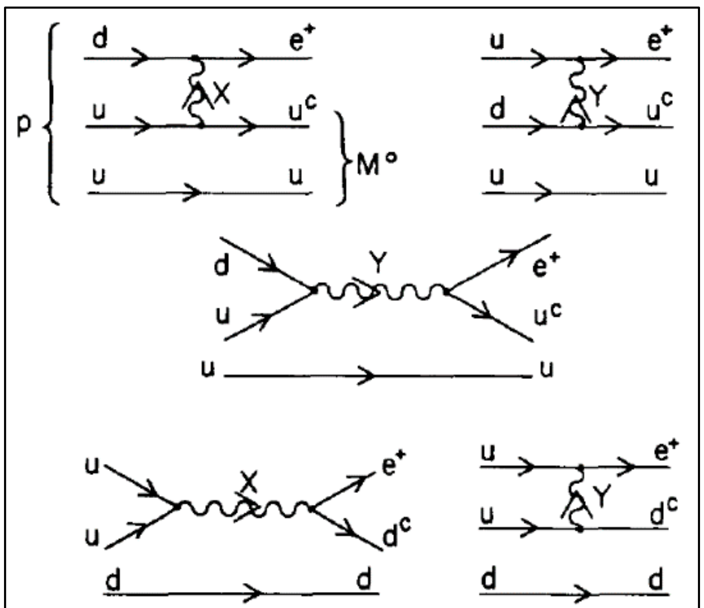
Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

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



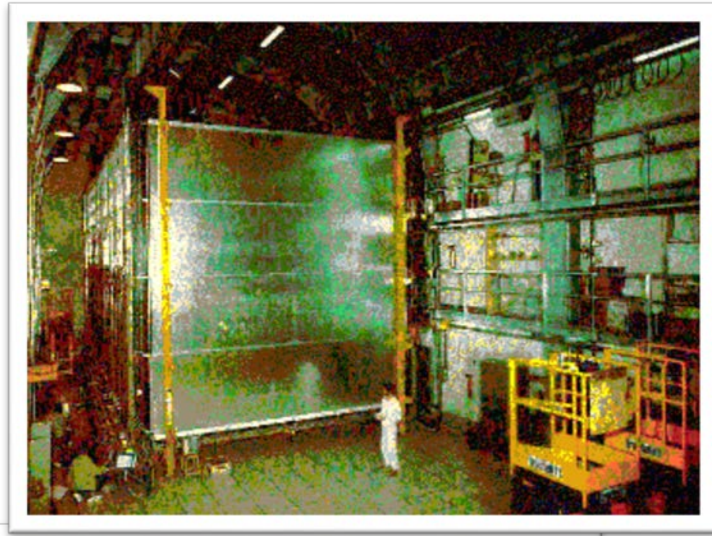
P. Langacker, Phys. Rep. 72, No.4(1981) 185.

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 proton decay detectors were constructed in 1980's

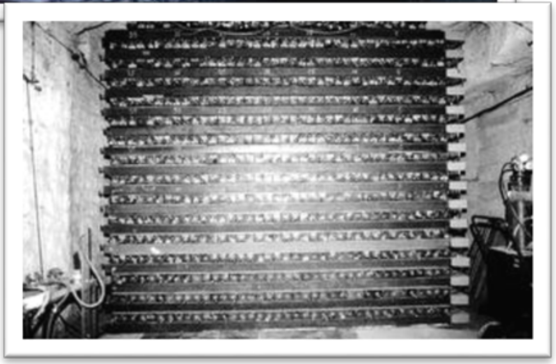
IMB (3300 ton)



Frejus
(700 ton)

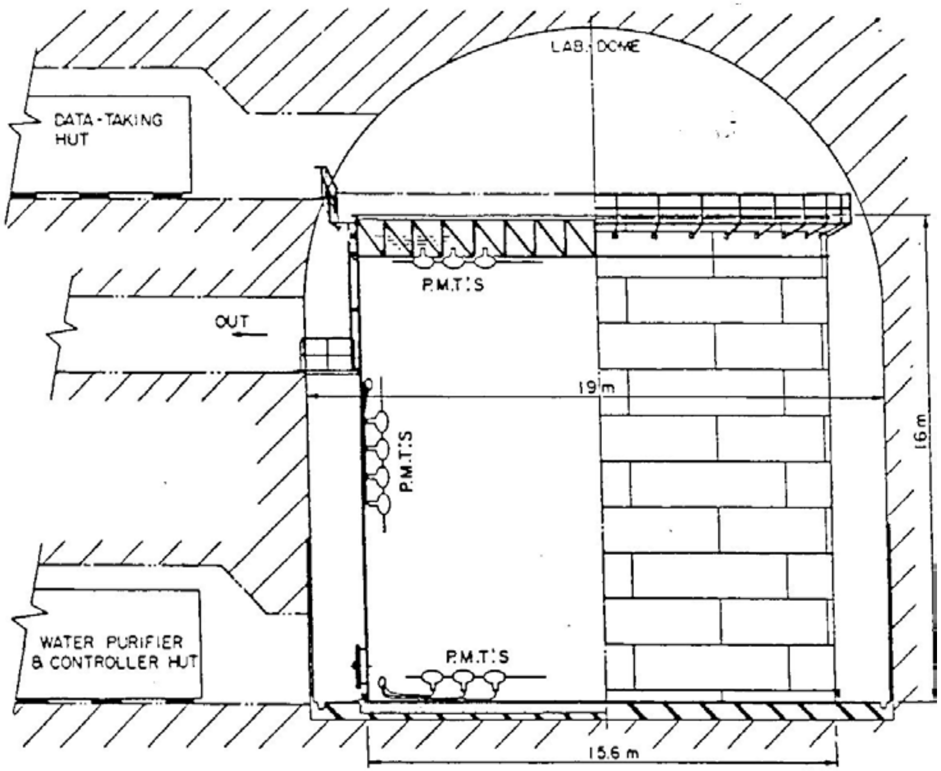
Kamiokande (1000 ton)

NUSEX
(130 ton)



KGF
(~100 ton)

Kamiokande-I detector（1983－1984）



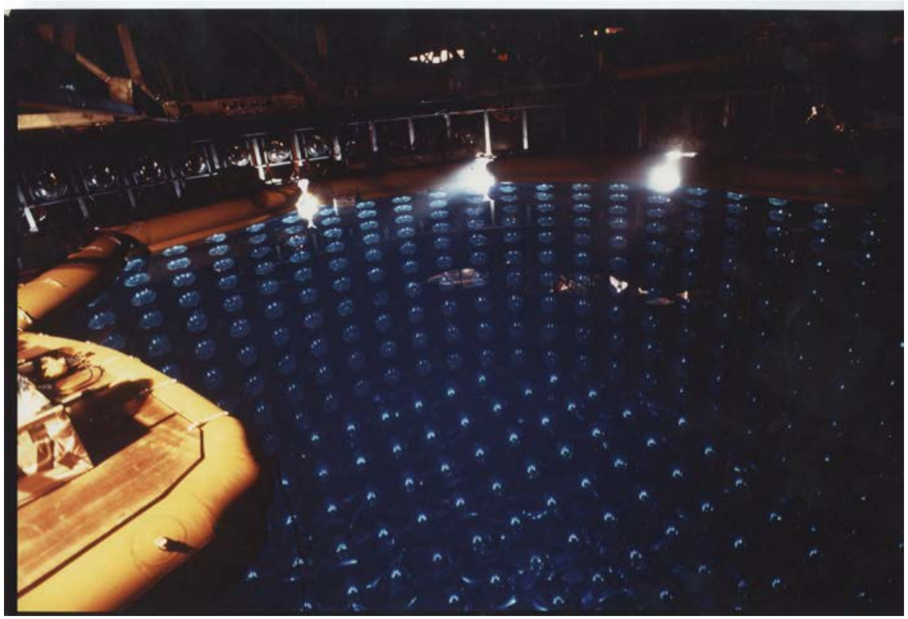
High resolution detector for measuring the branching ratio of proton decay.

However, proton decay was not observed.

Fiducial volume: 880 ton
(2m from the wall)

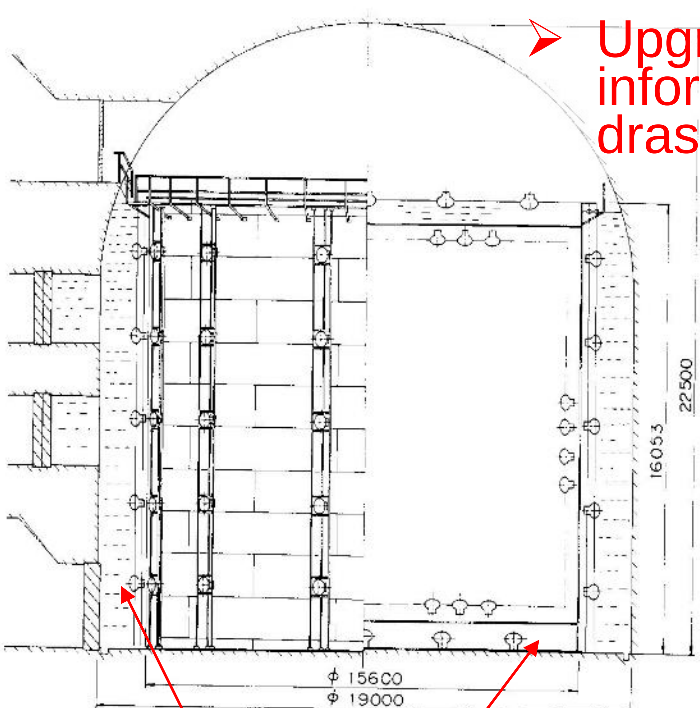
1000 20-inch PMTs were used

Photo-coverage: 20%

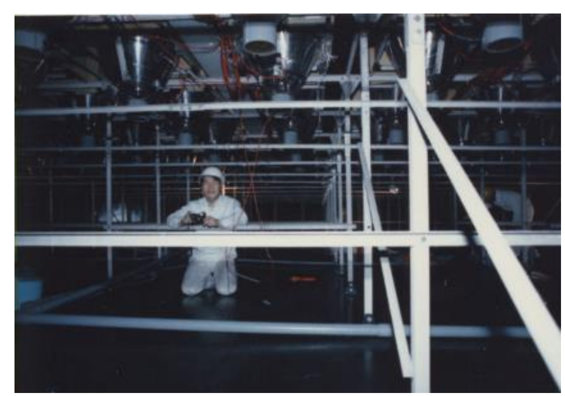


Upgrade to Kamiokande-II (1984-1985)

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.

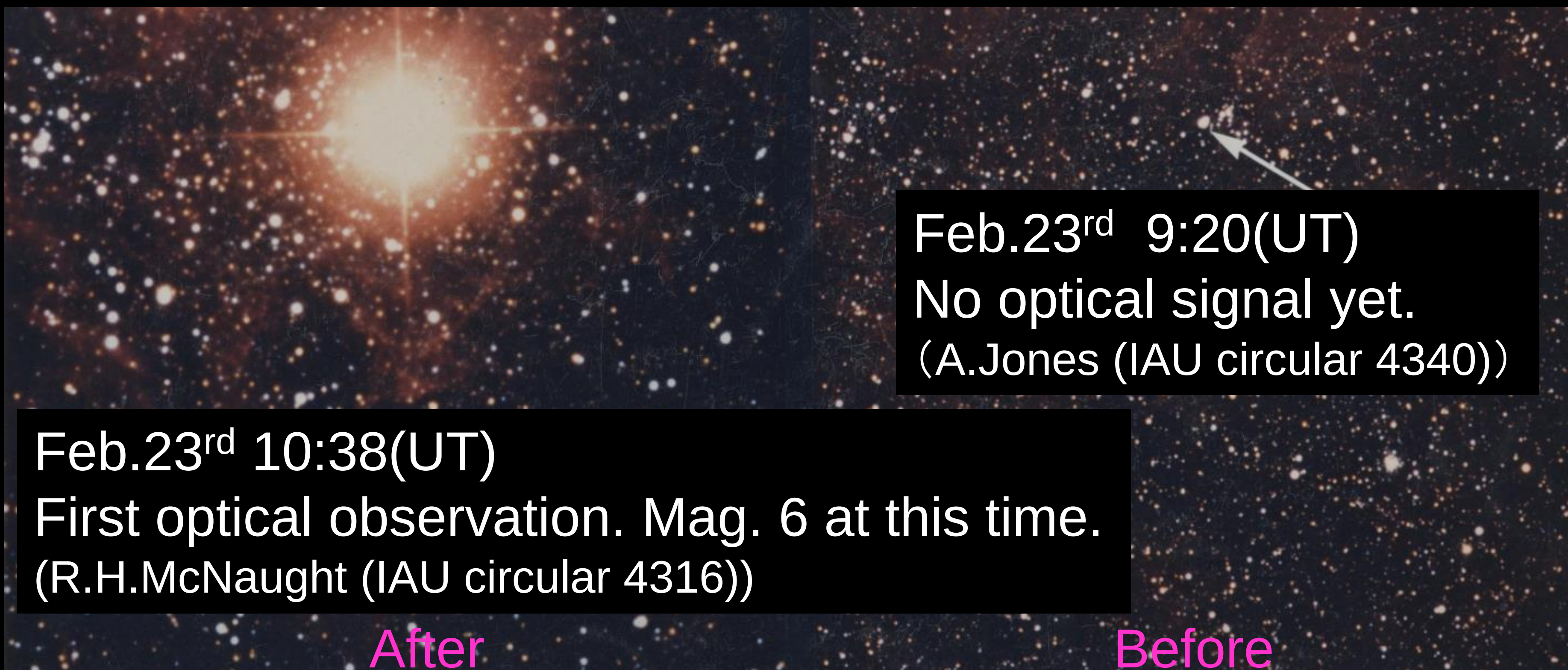


- ➢ Upgrade electronics for readout of timing information. It improved vertex reconstruction drastically.
- ➢ Made outer detector to shield external gamma rays and tag cosmic rays muons.



Optical observations of SN1987A

Feb.24th 5:30(UT): Ian Shelton announced mag. 5 object based on 3 hours observation from Feb.24th 1:30(UT) using 25cm telescope at Las Campanas Observatory in Chile. (IAU circular 4316)



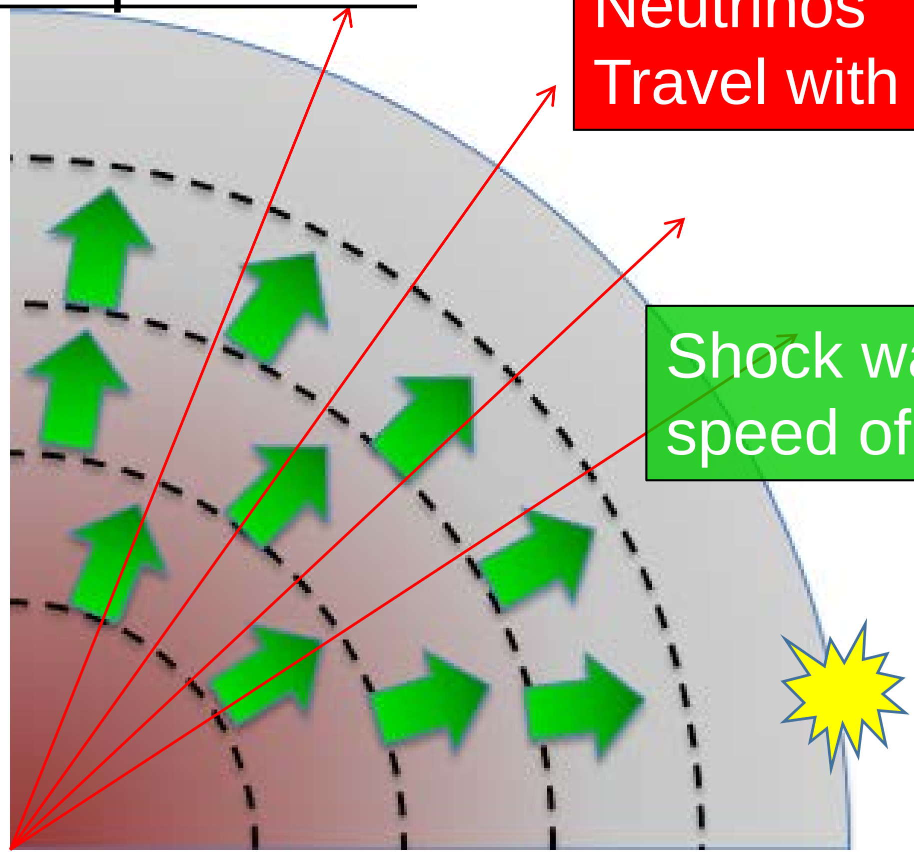
Feb.23rd 9:20(UT)
No optical signal yet.
（A.Jones (IAU circular 4340)）

Feb.23rd 10:38(UT)
First optical observation. Mag. 6 at this time.
(R.H.McNaught (IAU circular 4316))

Cf. Neutrino time：Feb.23rd, 7:35(UT)

Time order of neutrinos and optical signals

Collapsed star



core envelop surface

Neutrinos
Travel with speed of light ($3x10^5$ km/sec)

Shock wave travels with ~1/30 of speed of light (~10^4 km/sec).

Optical signals are produced when the shock wave arrives at surface.

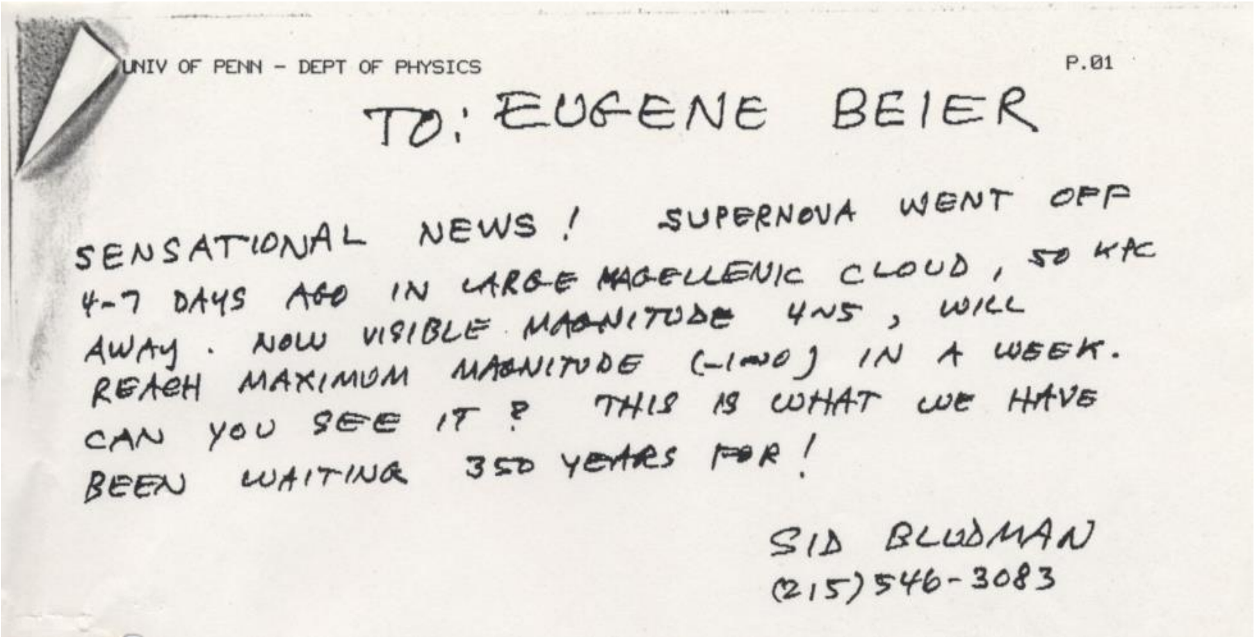
So, neutrinos arrive earlier than optical signals.

Type II: a few hours - several tens of hours earlier

Type Ib/Ic: several minutes earlier

Time order of information (from a diary of Kamiokande)

Feb. 25th, 1987: A fax was sent to Univ. of Tokyo



UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF
4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC
AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL
REACH MAXIMUM MAGNITUDE (-1~0) IN A WEEK.
CAN YOU SEE IT? THIS IS WHAT WE HAVE
BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215)546-3083

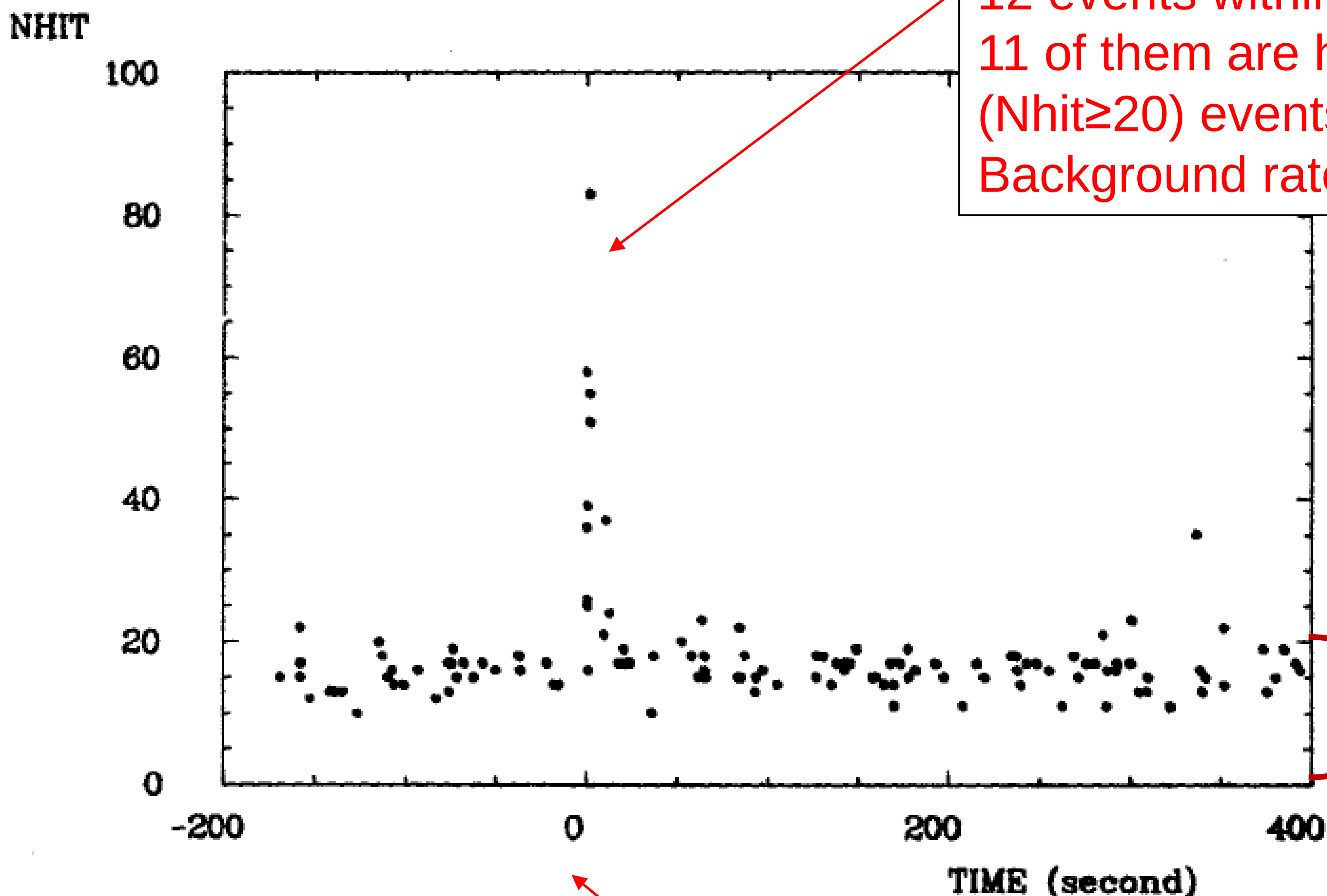
➡ *Asked Kamioka shift to send recent data tapes.*

Feb. 27th(Fri): The data tapes arrived at Univ. of Tokyo and data was analyzed.

Feb. 28th(Sat): We found the neutrino events from SN1987A!

Mar. 7th(Sat): Announced to the world. Submit paper to PRL.

Kamiokande data



12 events within 13sec.
11 of them are higher energy (Nhit≥20) events.
Background rate is 0.219/10sec.

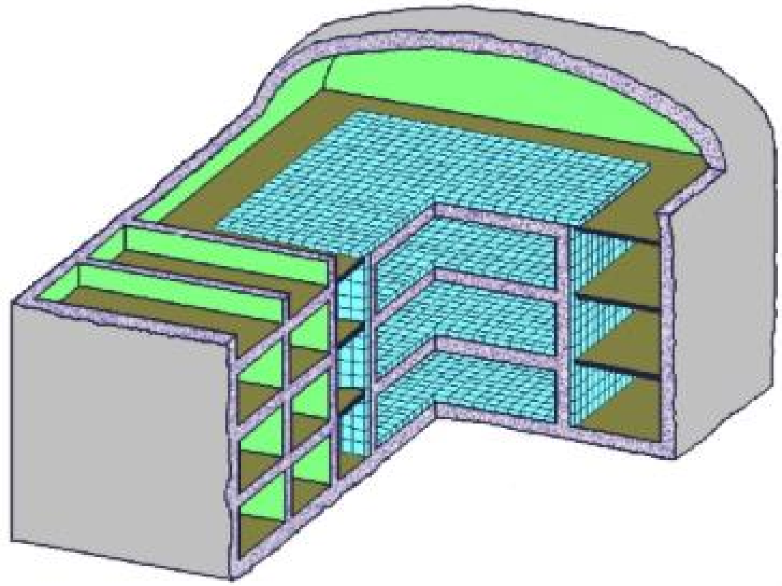
Event with Nhit≤20 are mostly radioactive BG like ^{214}Bi from Rn decay.

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

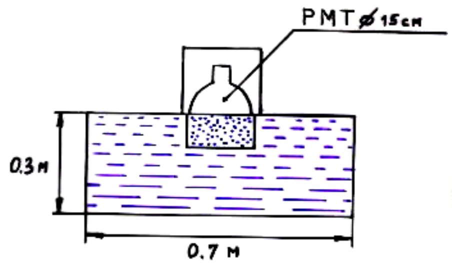
at 7:35:35(±1min)(UT) on Feb.23, 1987

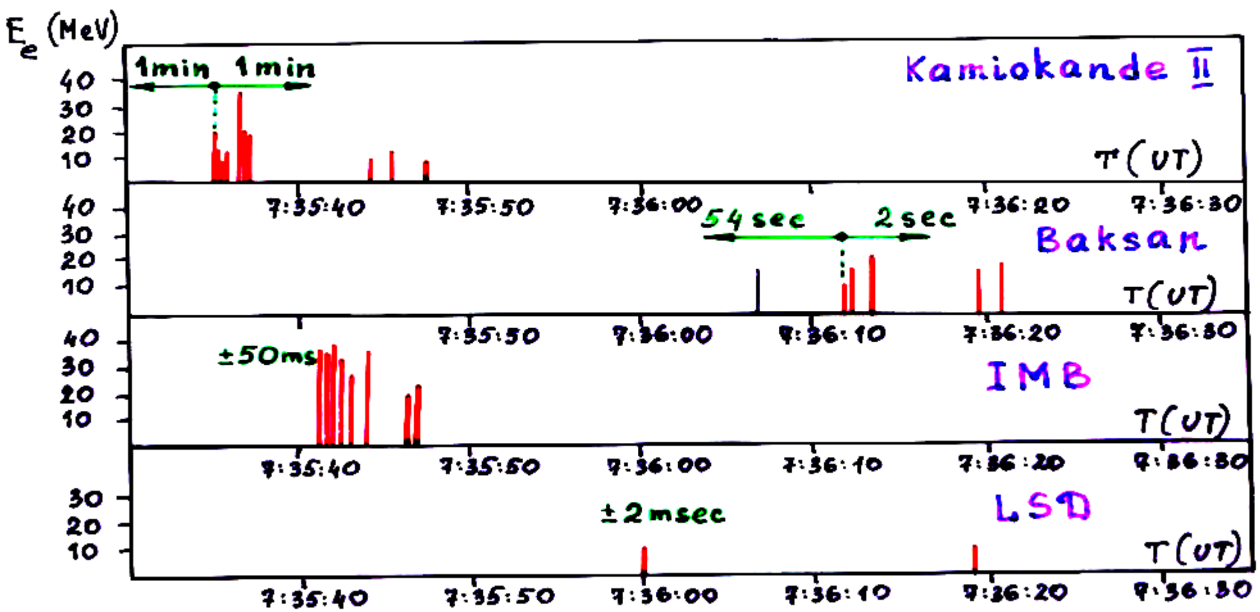
The Baksan underground scintillation telescope (Russia)

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



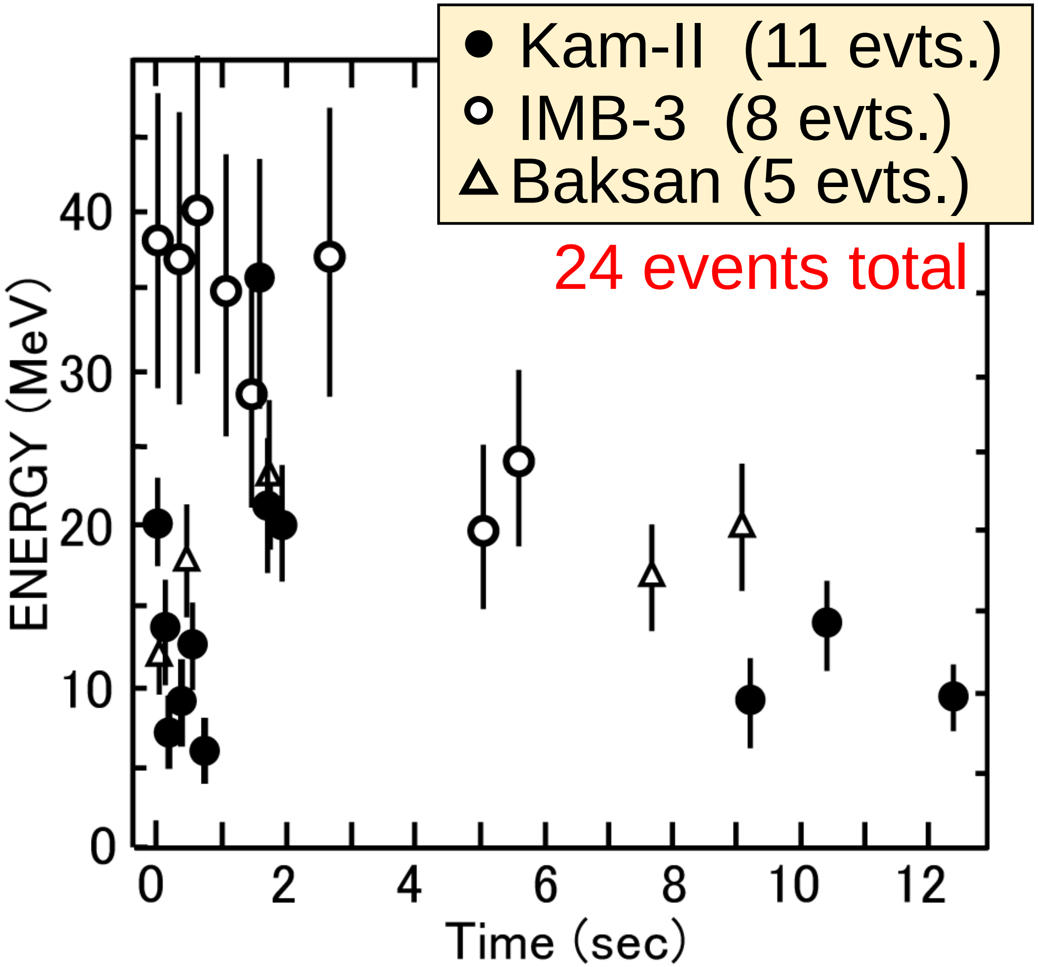
Each detector





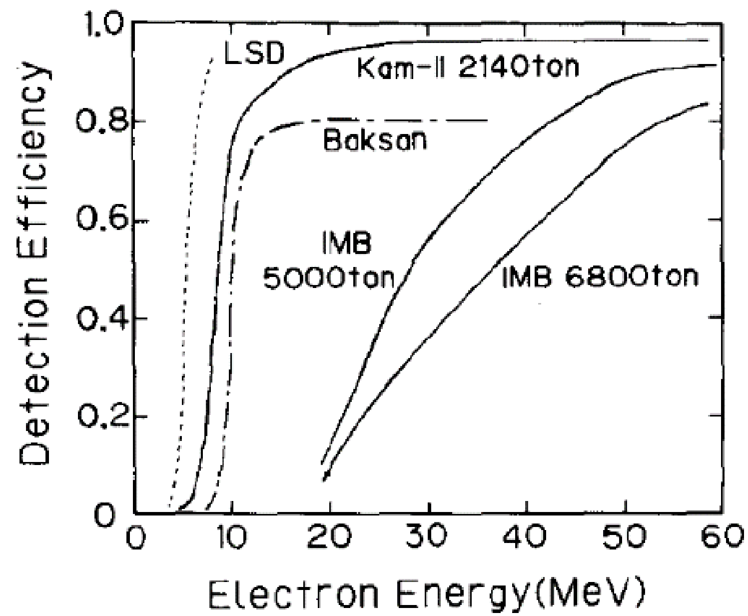
5 events in Baksan detector

Events observed at Kamiokande, IMB and Baksan



Adjusting the 1st events from the experiments

Detection efficiency



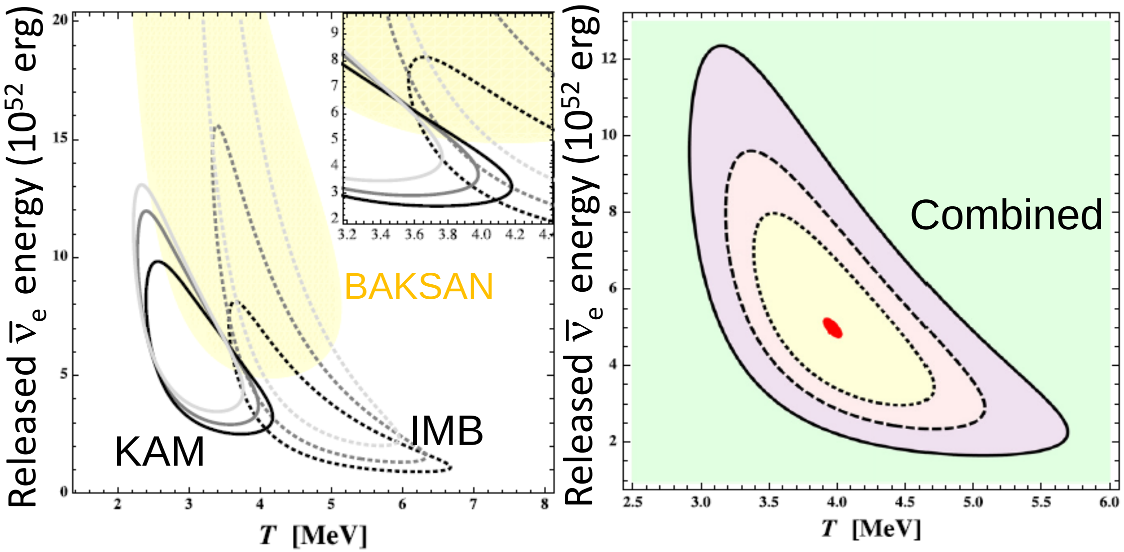
Energy threshold (at 50% eff.)

~8.5 MeV @ Kamiokande

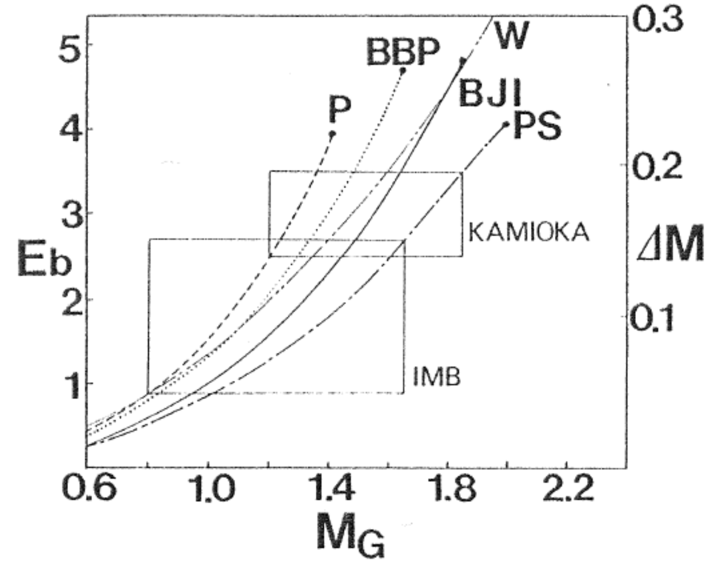
~28 MeV @ IMB

~10 MeV @ Baksan

What we have learned from SN1987A



Vissani, J. Phys. G: Nucl. Part. Phys. 42 (2015) 013001

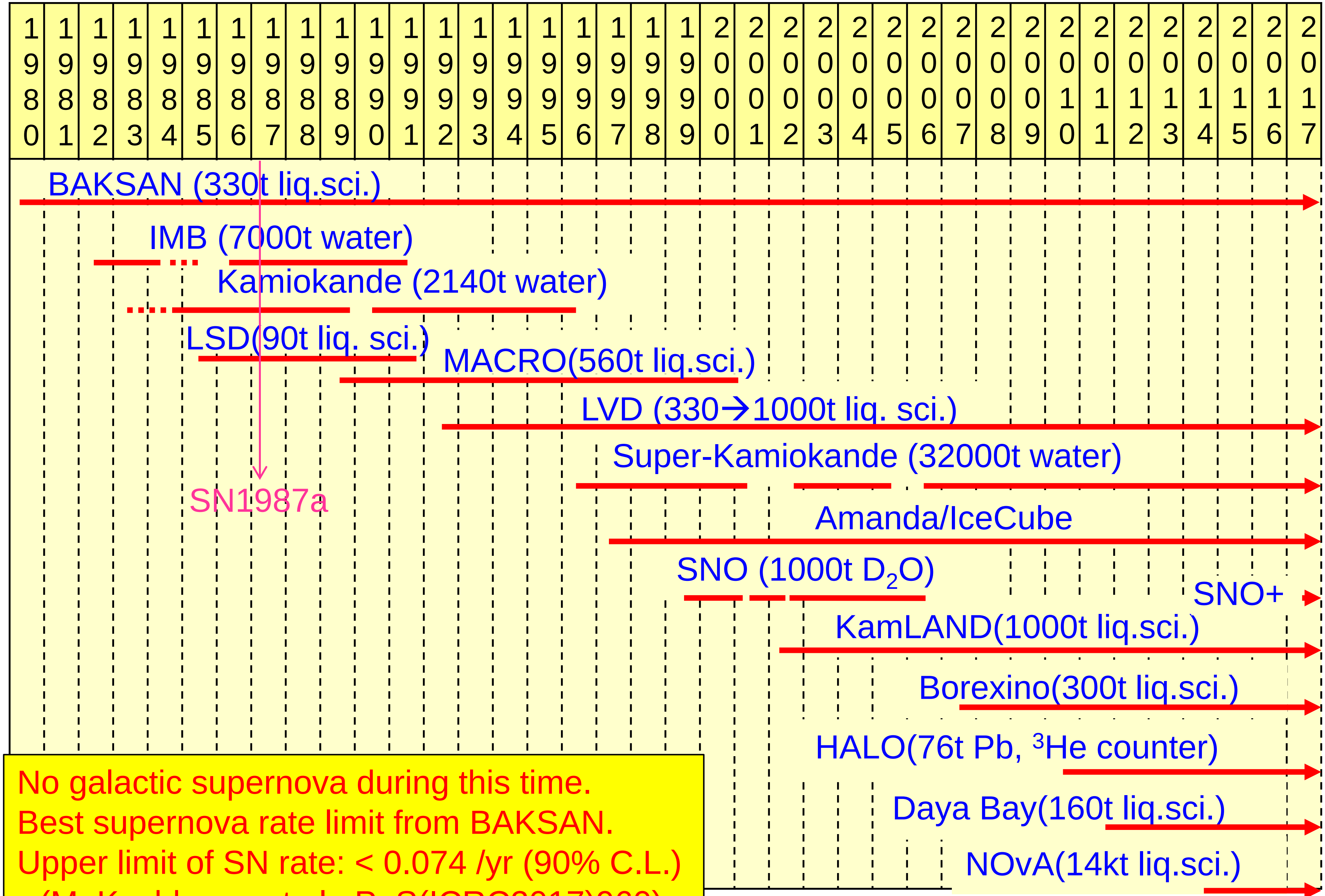


Sato and Suzuki, Phys.Lett.B196 (1987) 267

- 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.
- The observed released energy and explosion time scale were consistent with predictions from the supernova theory.

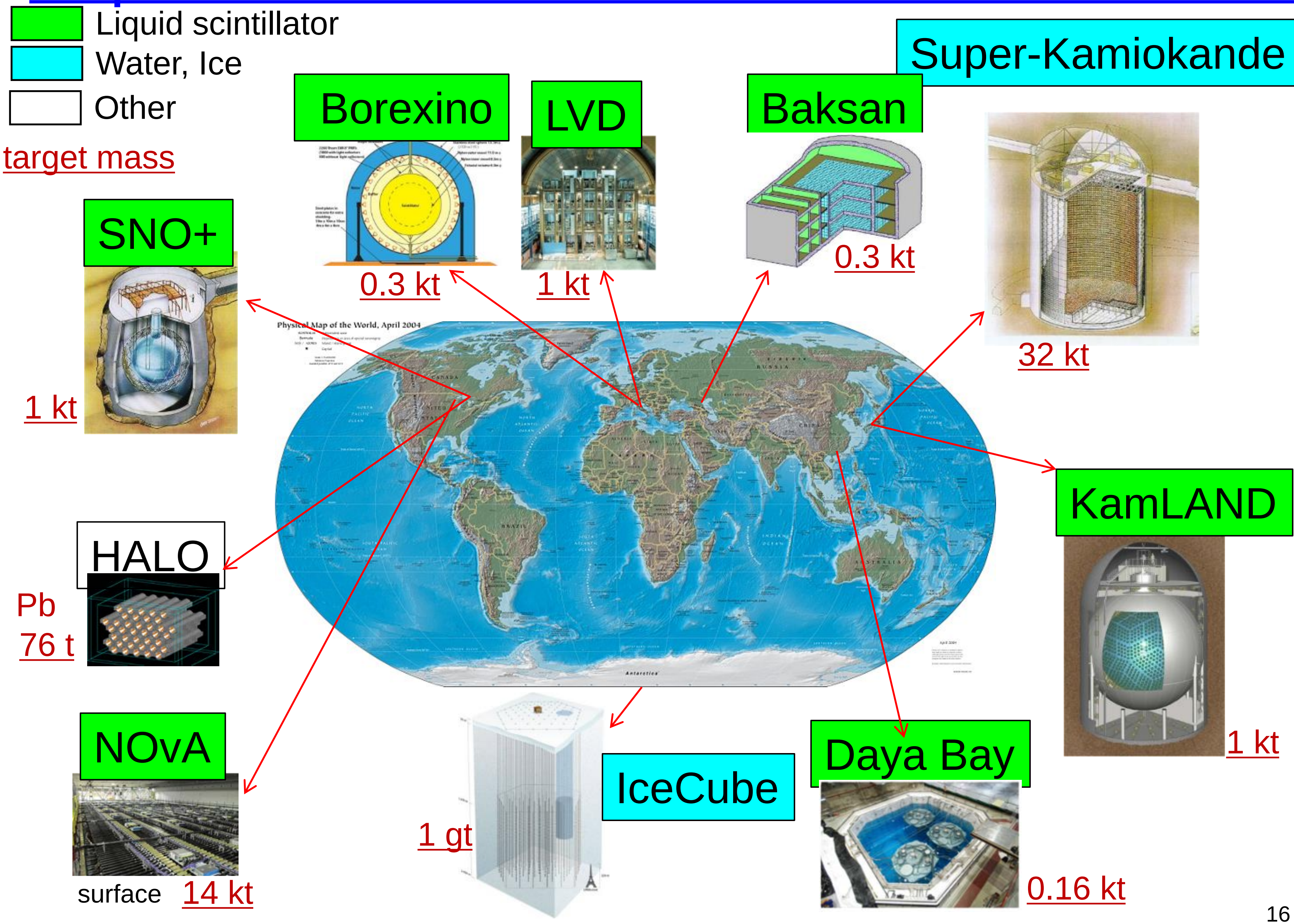
However, no detailed information of burst process was observed because of low statistics.

History of supernova detectors



No galactic supernova during this time.
Best supernova rate limit from BAKSAN.
Upper limit of SN rate: < 0.074 /yr (90% C.L.)
(M. Kochkarov et al., PoS(ICRC2017)960)

Supernova burst detectors in the world now



Supernova neutrino detectors

Detector	Type	Mass (kt)	Location	Events	Status
Super-Kamiokande	H_2O	32	Japan	7,000	Running
LVD	C_nH_{2n}	1	Italy	300	Running
KamLAND	C_nH_{2n}	1	Japan	300	Running
Borexino	C_nH_{2n}	0.3	Italy	100	Running
IceCube	Long string	(600)	South Pole	(10^6)	Running
Baksan	C_nH_{2n}	0.33	Russia	50	Running
HALO	Pb	0.08	Canada	30	Running
Daya Bay	C_nH_{2n}	0.33	China	100	Running
NOνA*	C_nH_{2n}	15	USA	4,000	Running
MicroBooNE*	Ar	0.17	USA	17	Running
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
DUNE	Ar	40	USA	3,000	Future
Hyper-Kamiokande	H_2O	374	Japan	75,000	Future
JUNO	C_nH_{2n}	20	China	6000	Future
RENO-50	C_nH_{2n}	18	Korea	5400	Future
PINGU	Long string	(600)	South Pole	(10^6)	Future

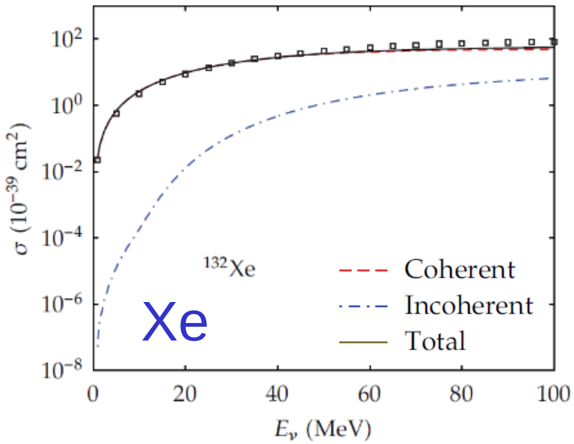
Neutrino event estimates are approximate for 10 kpc. An asterisk indicates a surface detector, which have more cosmogenic background. Numbers in parentheses indicate long-string Cherenkov detectors which do not reconstruct individual interactions.

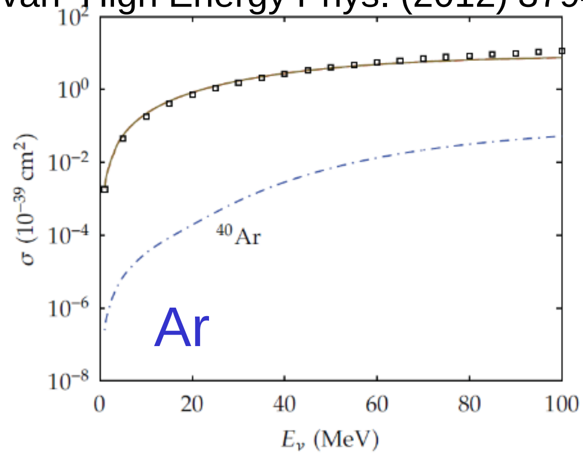
From K. Scholberg, arXiv:1707.06384

Supernova signals by Dark Matter detectors

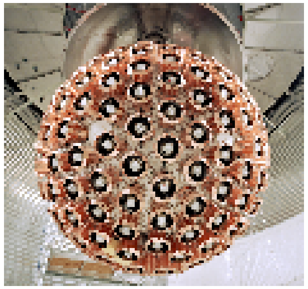
Coherent elastic neutrino-nucleus scattering

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



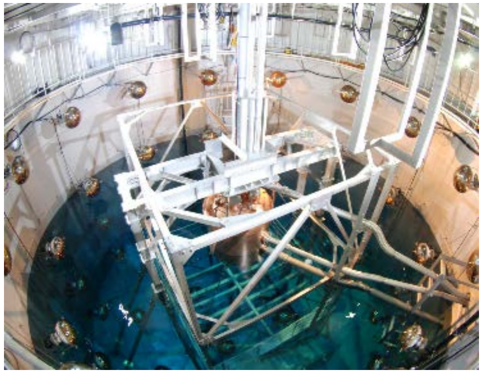


DEAP3600
(Ar 3.6ton)

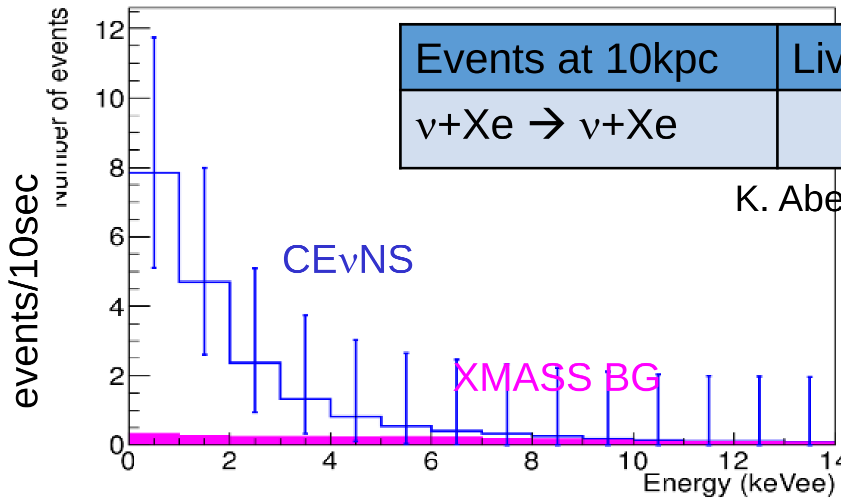


XENON1T
(Xe 1ton)

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



Supernova at 10 kpc



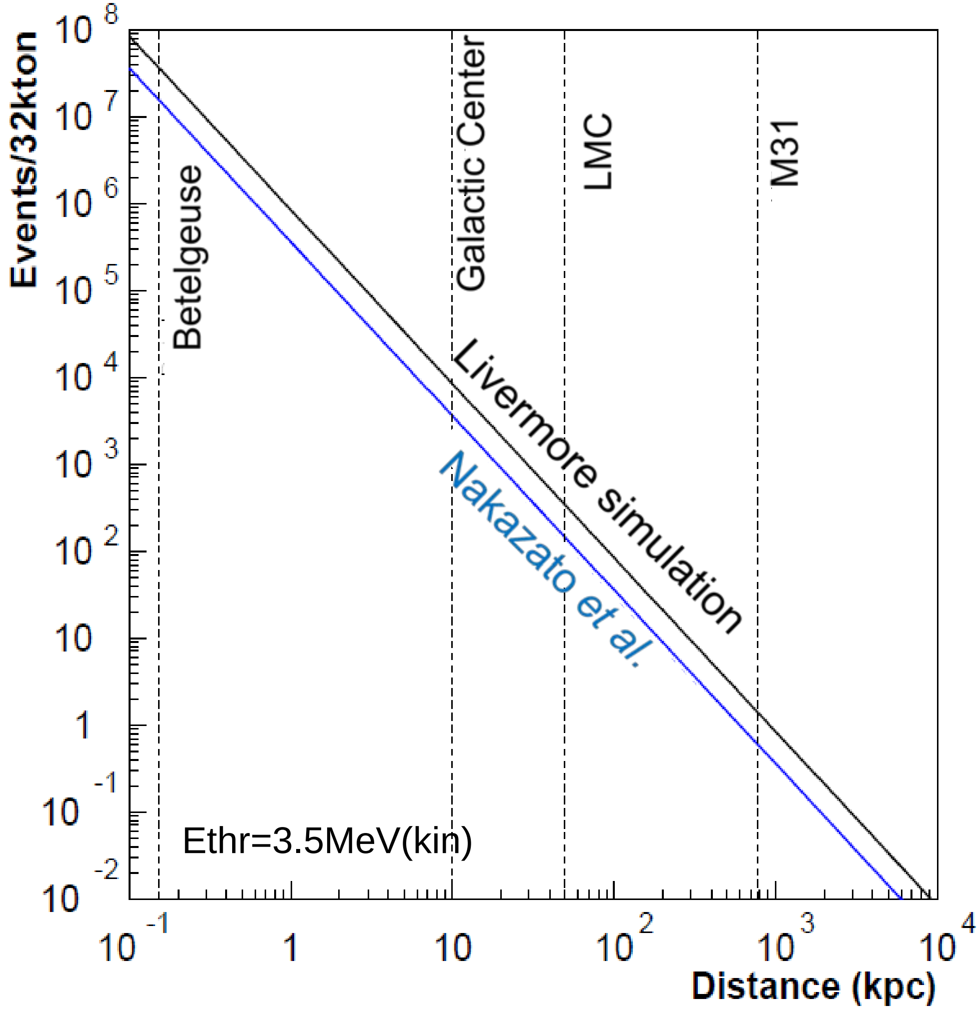
Events at 10kpc	Livermore	Nakazato
ν+Xe → ν+Xe	15	3.5 ~ 21

K. Abe et al., arXiv:1604.01218

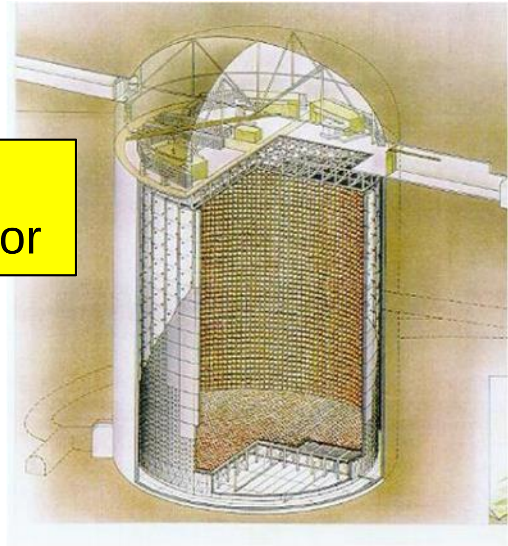
Remark: Coherent interaction itself was experimentally observed by the COHERENT experiment in this year. (science.aao0990)

Super-K: Number of events

Number of events vs. distance



32kton water Cherenkov detector



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.

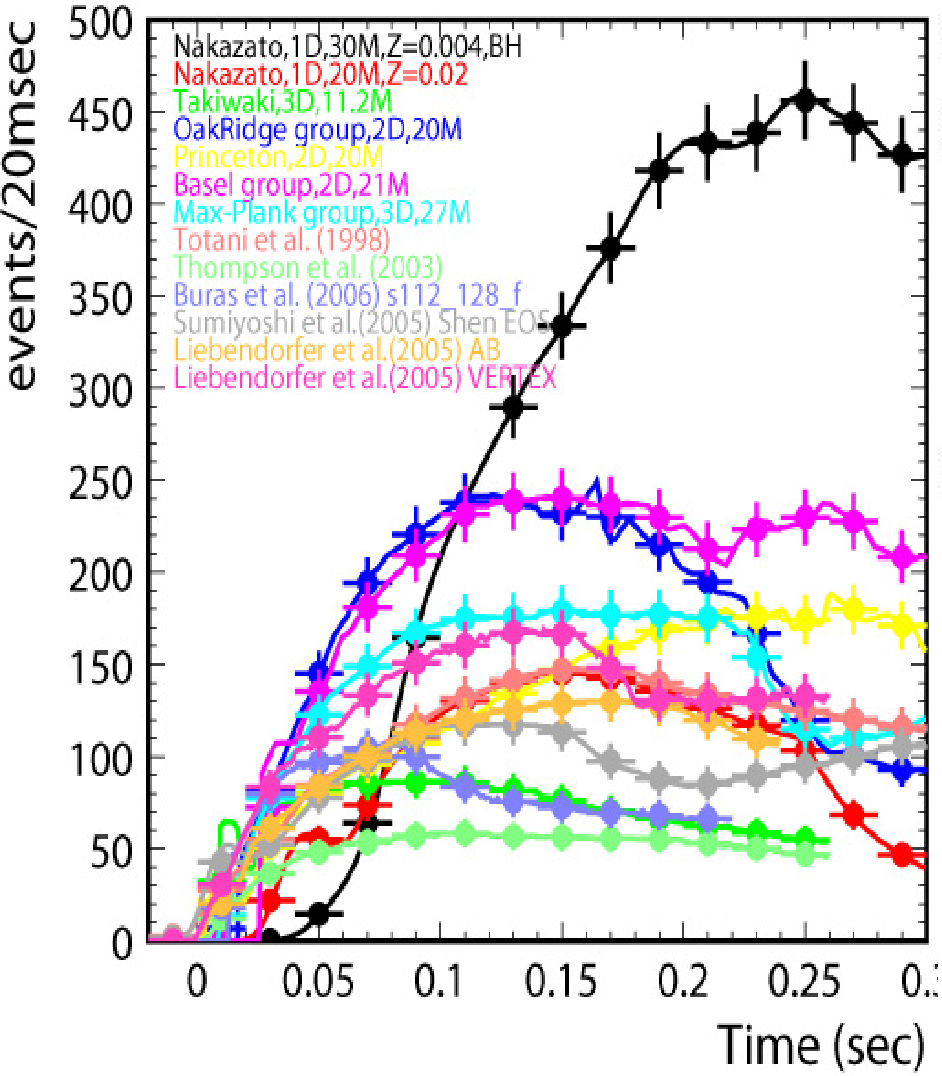
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

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)

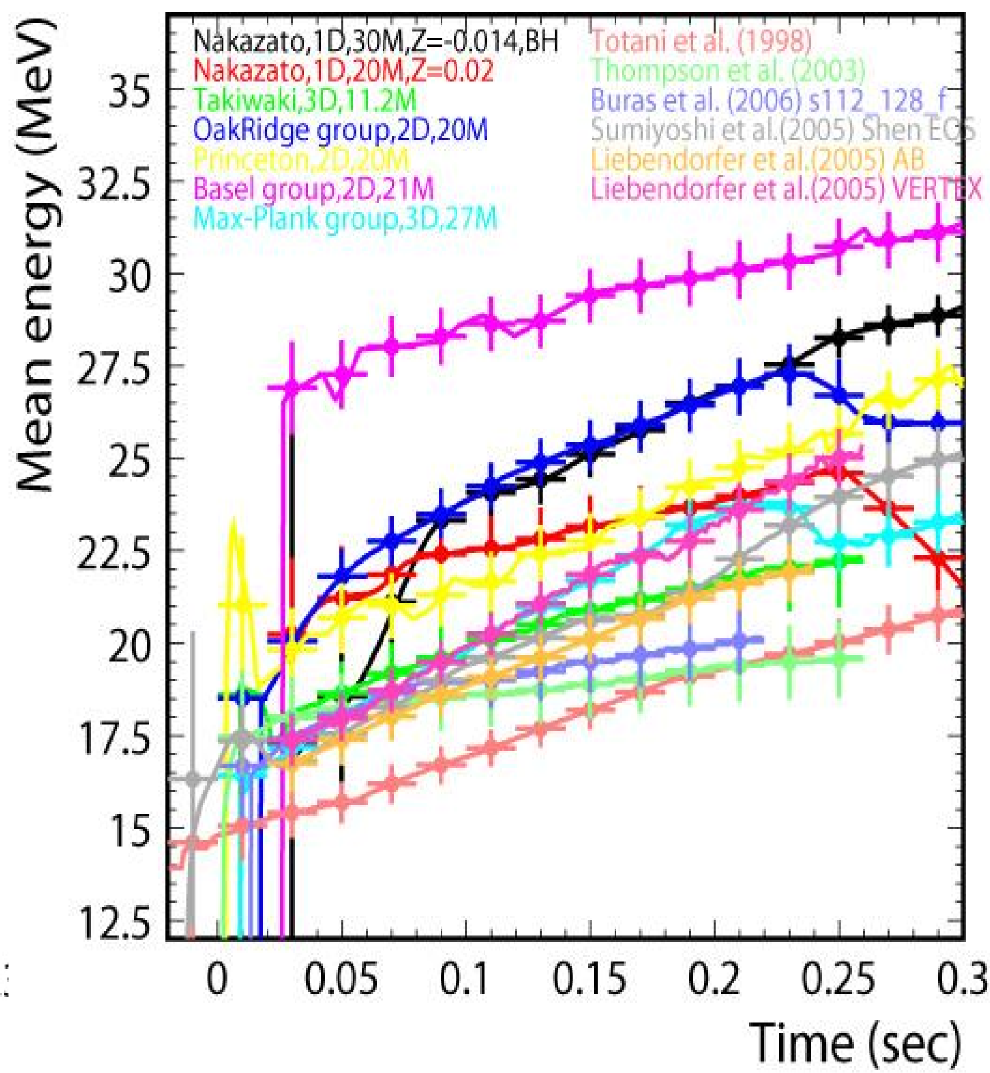
Sensitivity of Super-K for the model discrimination

For 10kpc supernova

Time variation of event rate



Time variation of mean energy



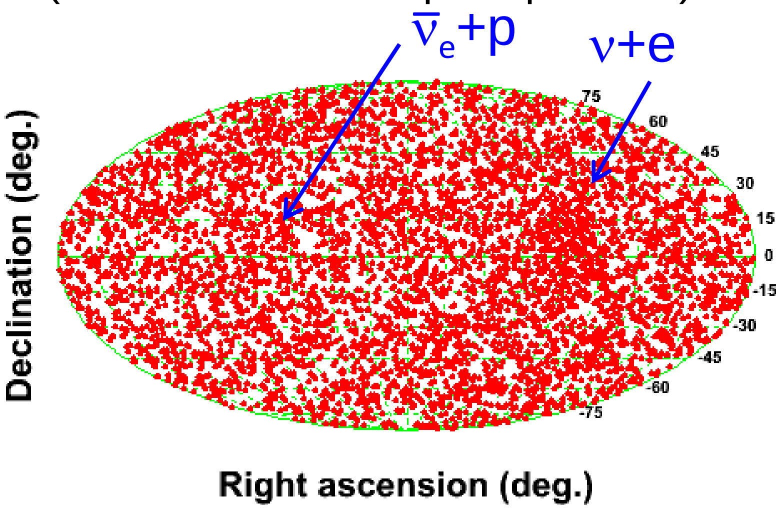
High statistics enough to discriminate models

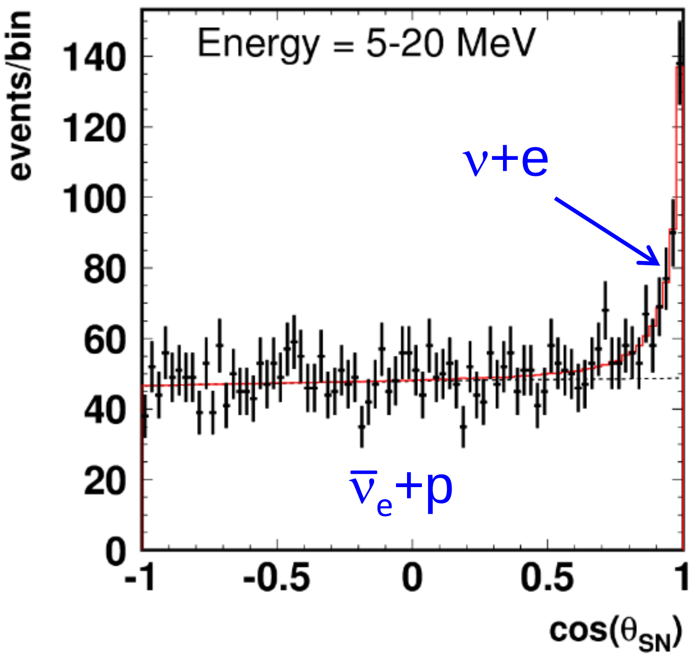
Cooperation: H. Suzuki

Super-K: directional information

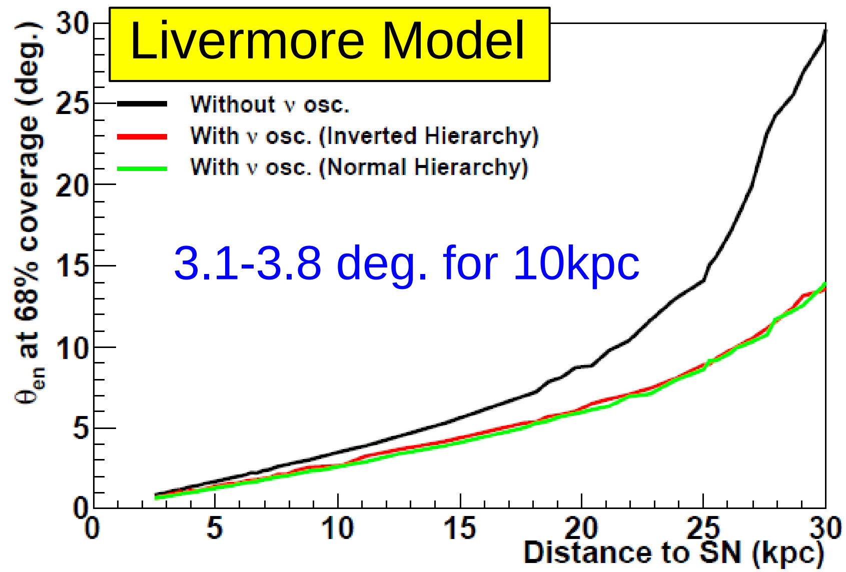
Reconstructed direction

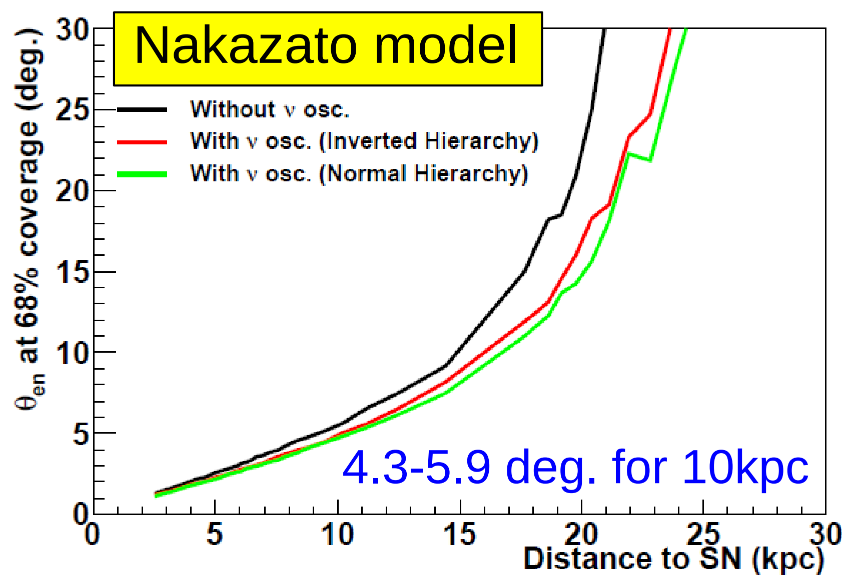
(Simulation of a 10kpc supernova)



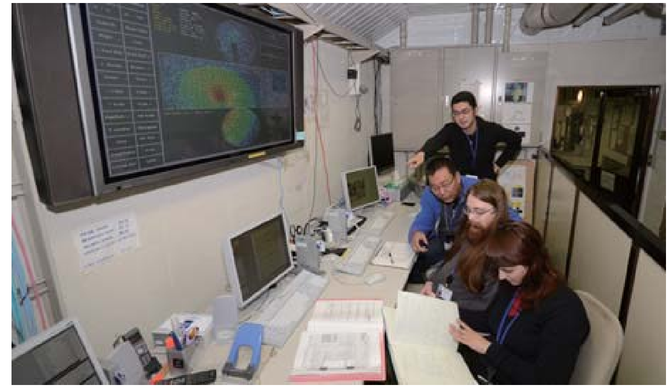


Distance vs. pointing accuracy

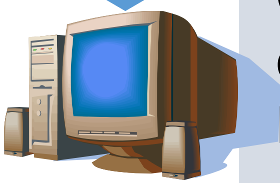




Real time supernova monitor in Super-K



Raw data

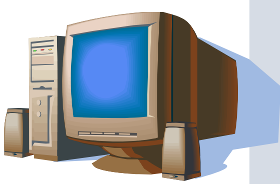


Real Time Process

Quickly analyze events.
Reconstruct vertex, energy and direction.

SK shift people always keep watch whether the processes are running.

Processed data



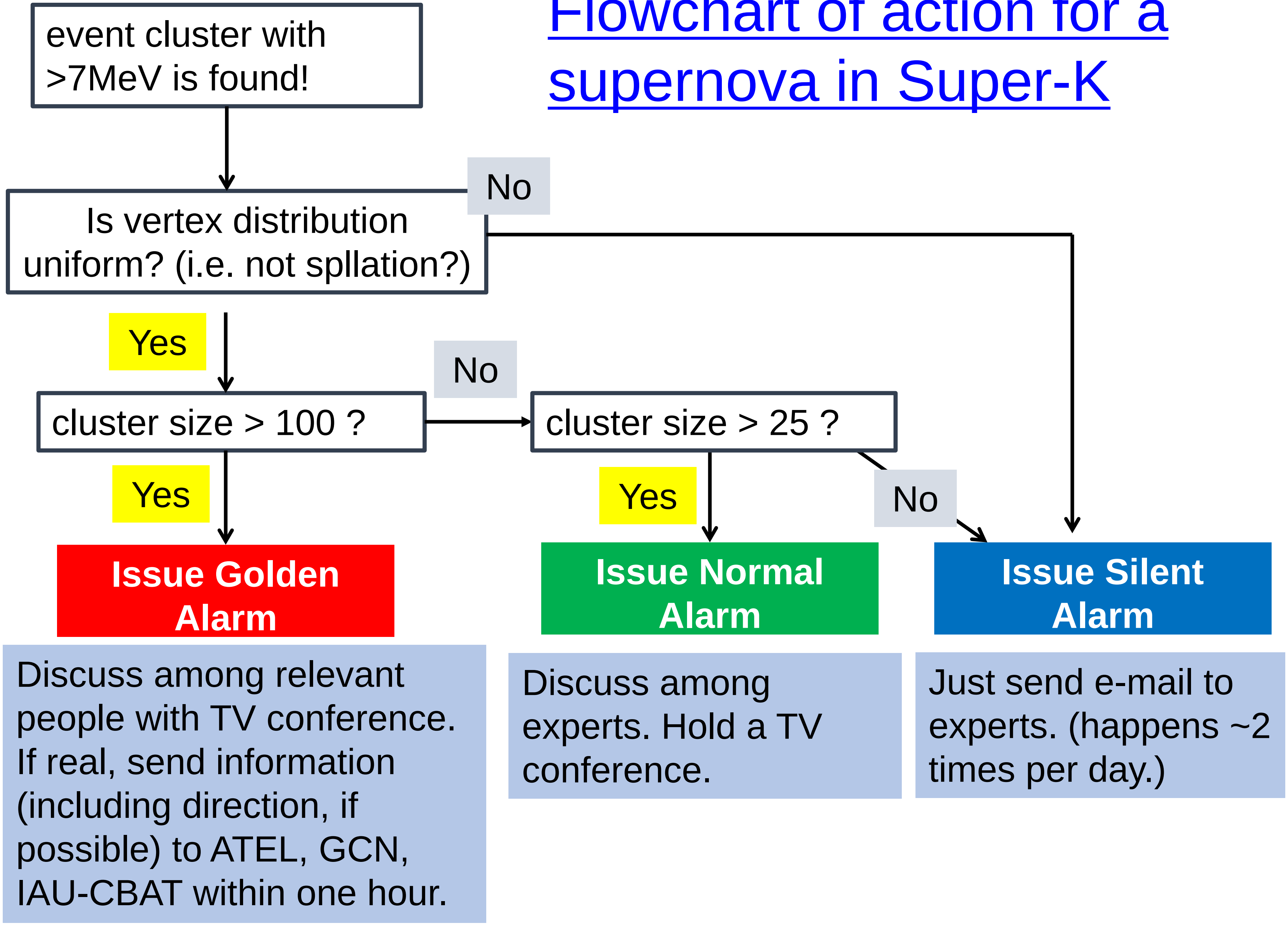
Supernova Watch

Search for time-clustered events.
Get initial result within 200 sec after a burst.

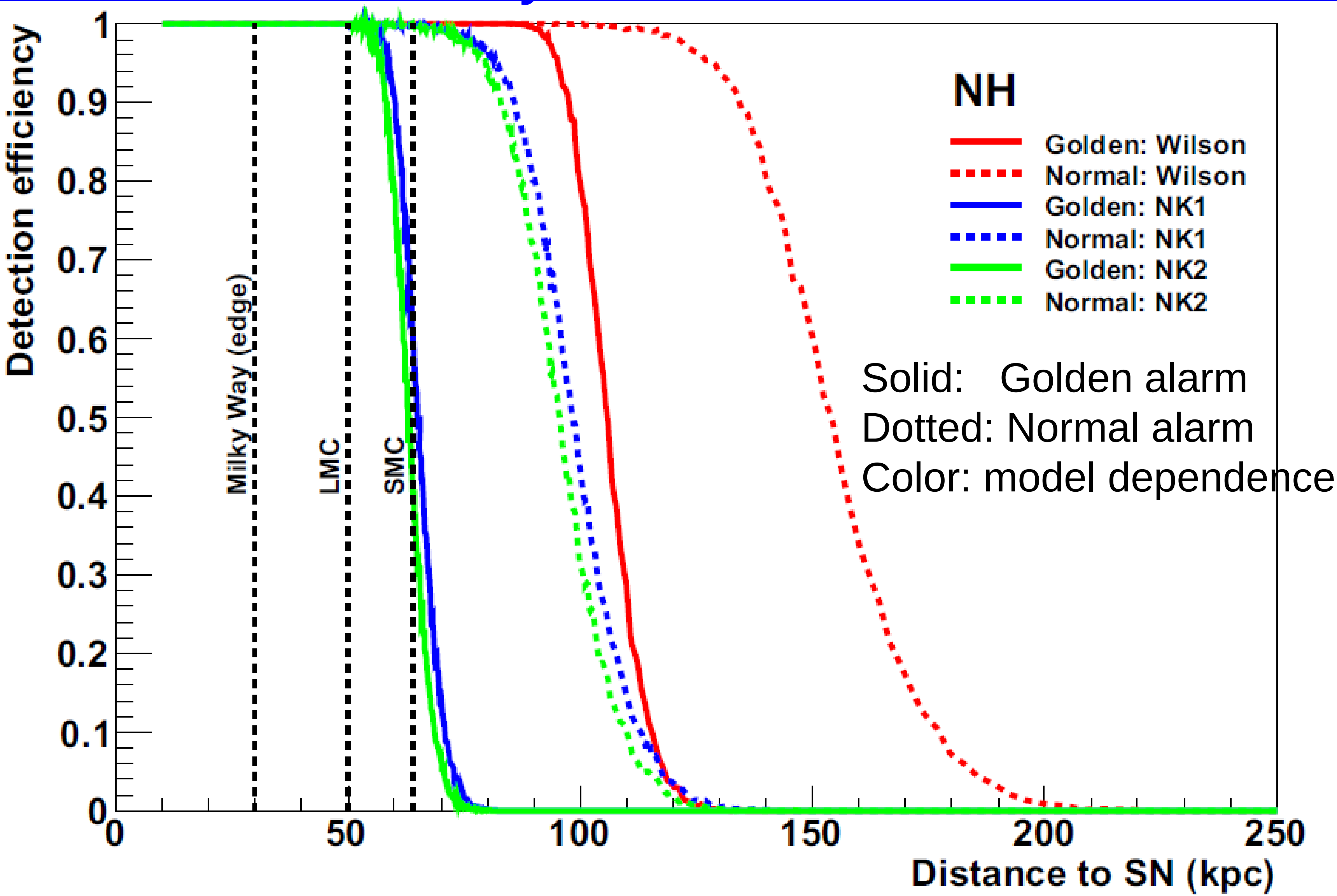
If significant time-clustered events are found, send e-mails to experts (PC and portable phone e-mails.)
Also, send signal to SNEWS.

Details in K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Flowchart of action for a supernova in Super-K



Detection efficiency of the real time SN monitor

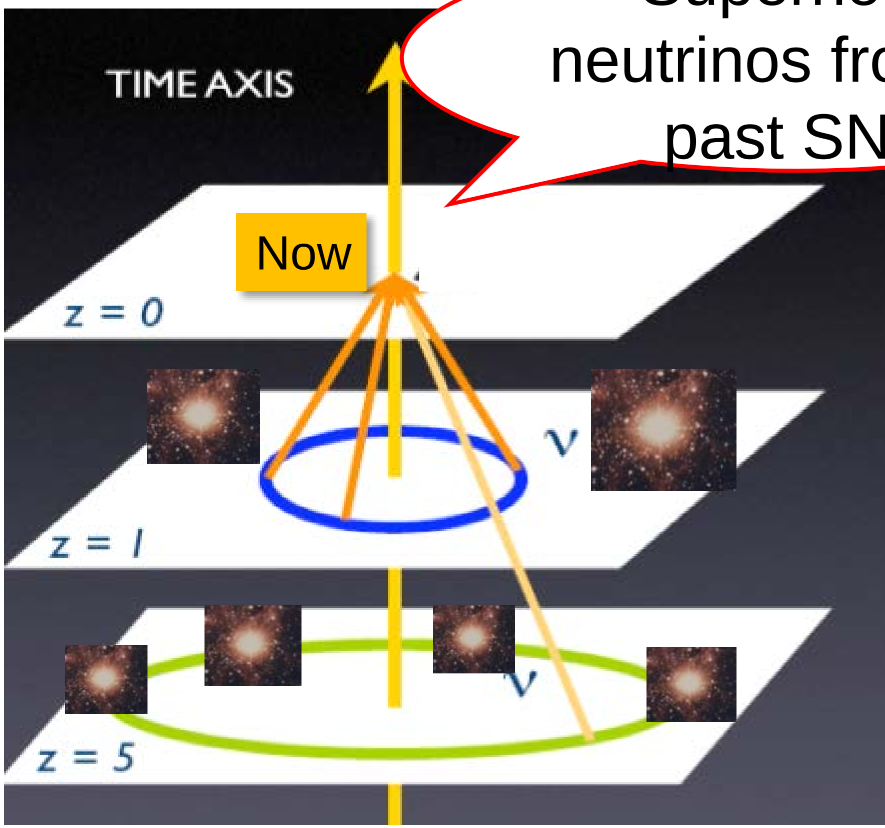


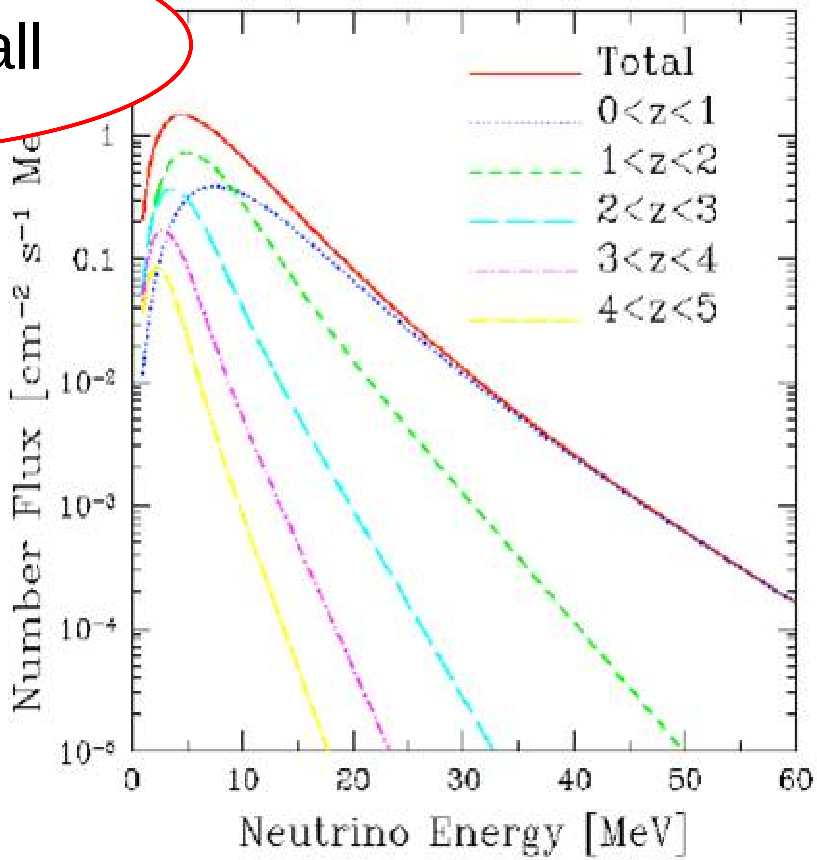
100% efficient for our galaxy and LMC for various models.

K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Supernova Relic Neutrinos

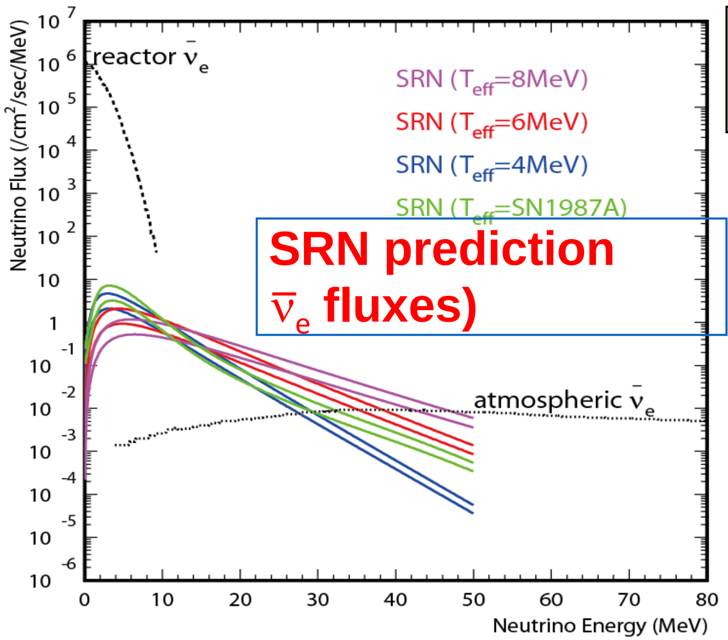
~10^{10} stars/galaxy ×~10^{10} galaxy × 0.3%(massive star->SN) ~$O(10^{17})$SNe



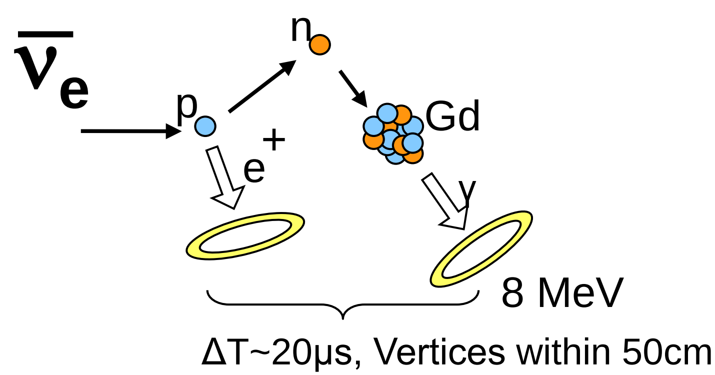


S.Ando, Astrophys.J. 607, 20(2004)

SK-Gd project for Supernova Relic Neutrino



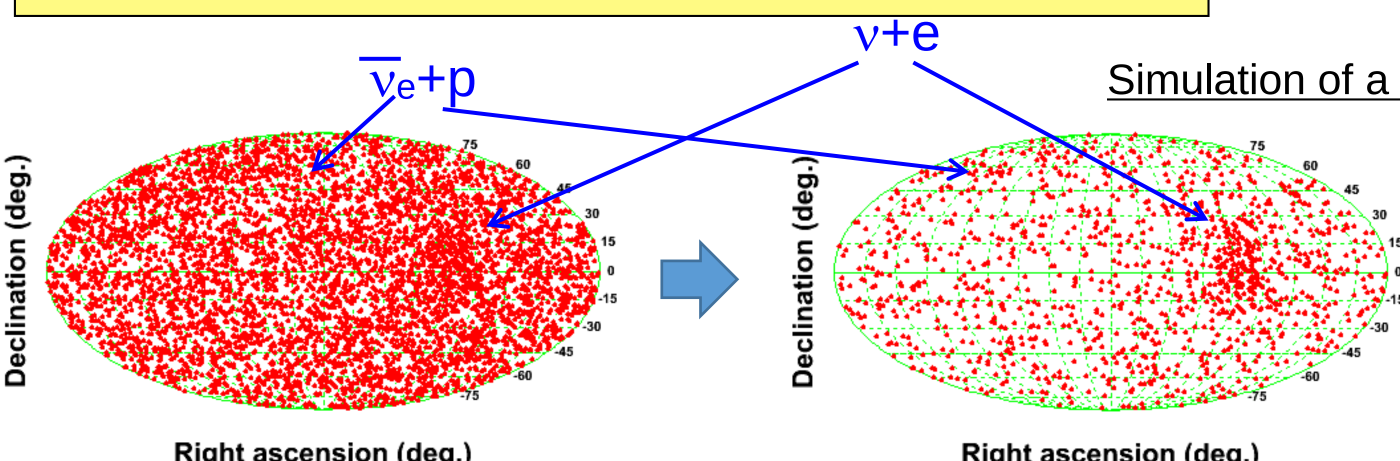
Open widow for SRN at 10-30MeV
Expected rate 1.3 -6.7 events/year/22.5kt(10-30MeV)



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

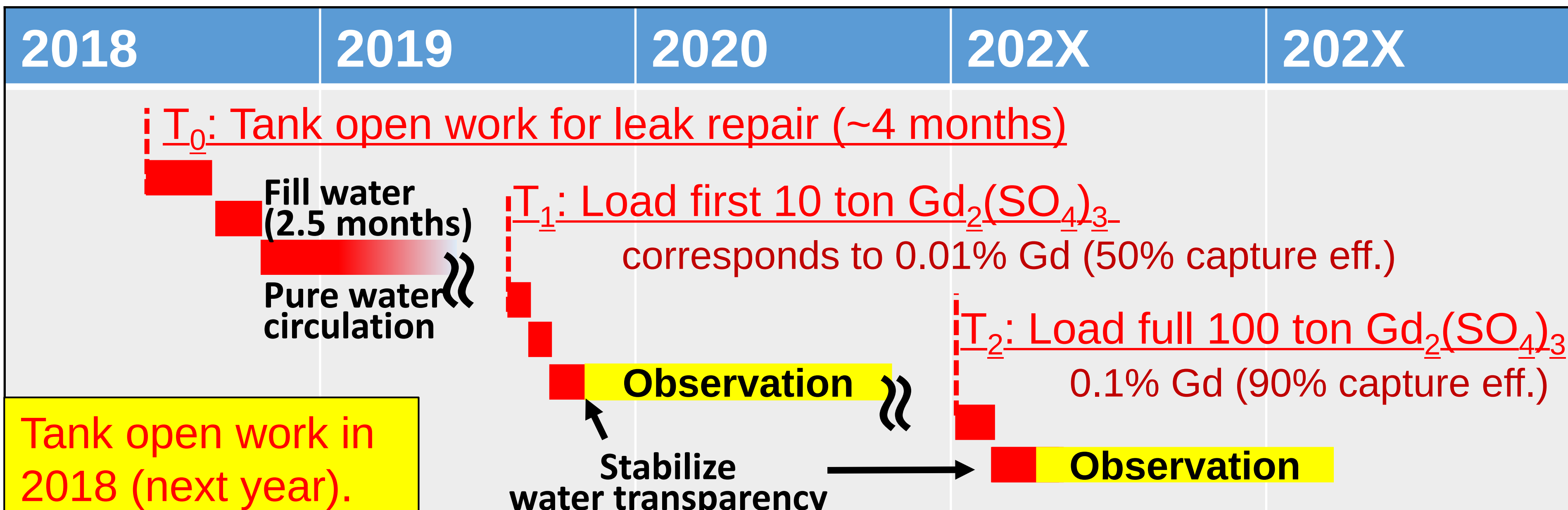
Simulation of a 10kpc supernova



Preparation and plan for SK-Gd project

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.



Conclusions

- Large volume detectors were constructed in order to search for proton decay. Without this strong motivation neutrinos from SN1987A may not have been observed.
- The observation of the SN1987A neutrinos proved the basic scenario of supernova explosions.
- Super-K will observe many events for a galactic supernova and they will tell us detailed information to reveal explosion mechanism.
- SK-Gd for supernova relic neutrinos will start in a few years.