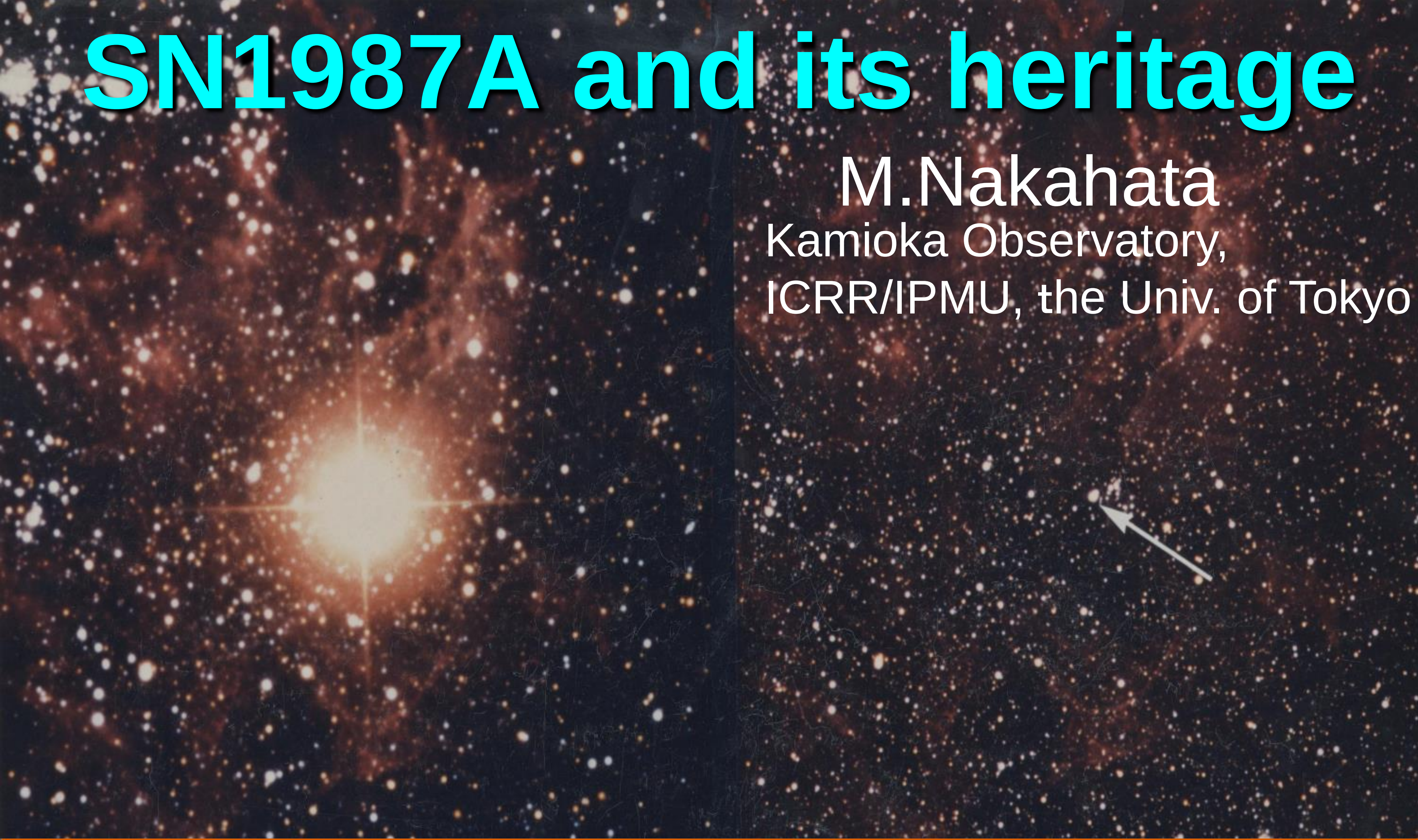
SN1987A and its heritage

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



RECENT DEVELOPMENTS IN NEUTRINO PHYSICS AND ASTROPHYSICS

4-7 September 2017 *LNGS and GSSI (Assergi and L'Aquila, Italy)*

30th Anniversary of SN1987A

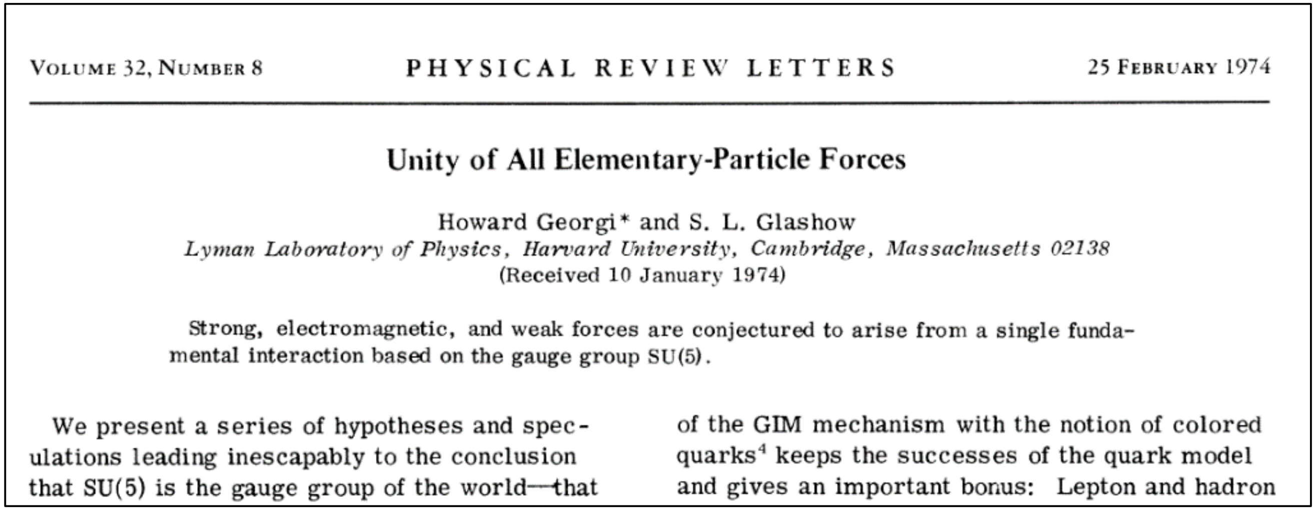
Cake made for an anniversary held on Feb.12, 2017 at the Univ. of Tokyo

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

Contents

- Why large underground detectors were constructed in 1980's
- Observed neutrino data of SN1987A
- What we have learned from this observation
- Supernova detectors in the world now
- Supernova relic neutrinos
- Future prospects

Prediction of GUTs in 1970's

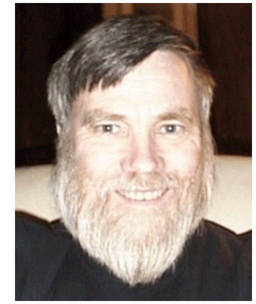

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

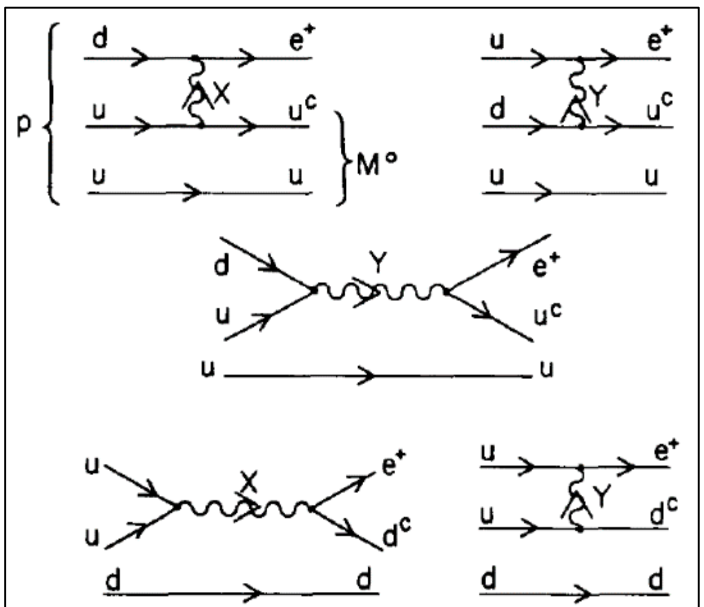
Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

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.

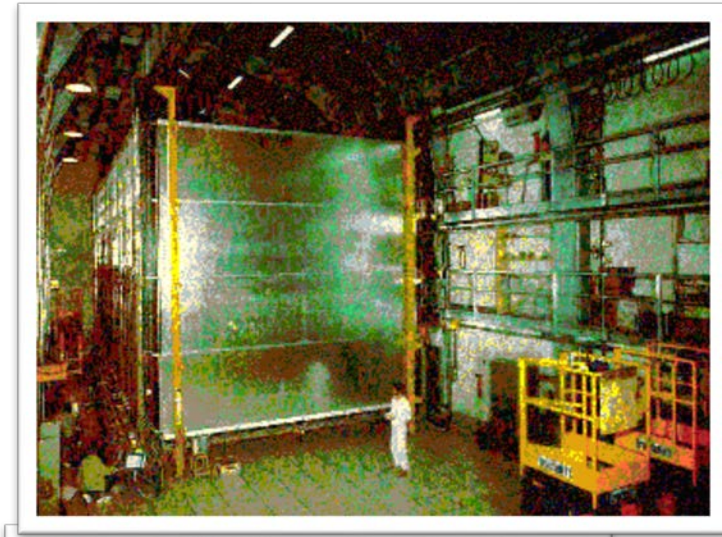
Proton decay was predicted.

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

Large proton decay detectors were constructed in 1980's

IMB (3300 ton)

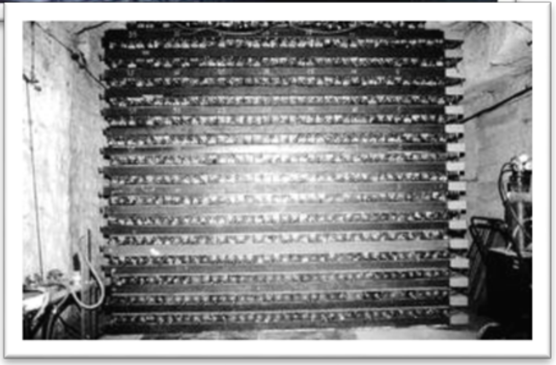
Frejus
(700 ton)



Kamiokande (1000 ton)

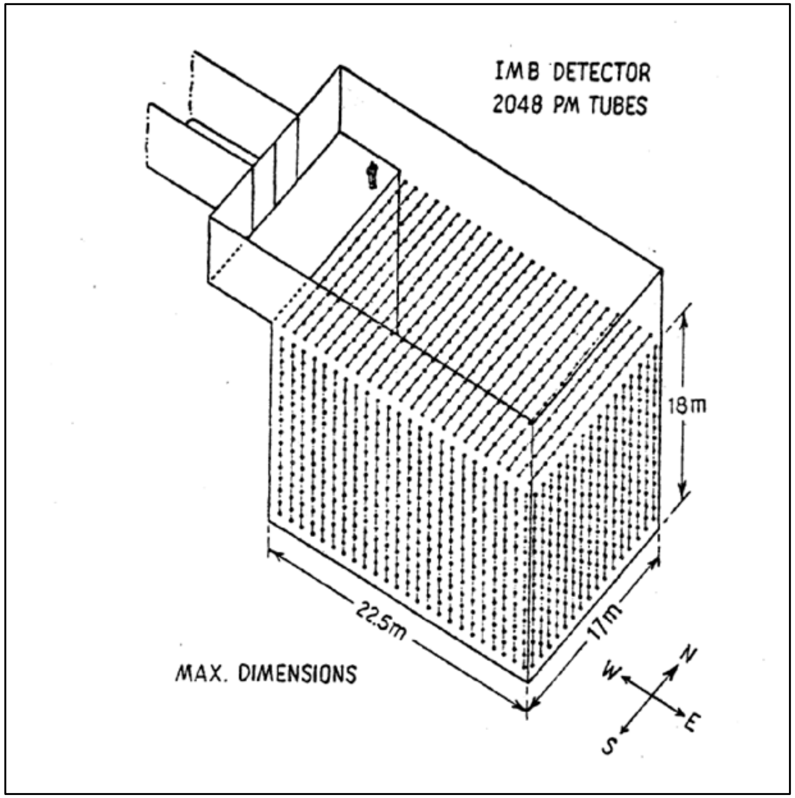
NUSEX
(130 ton)

KGF
(~100 ton)



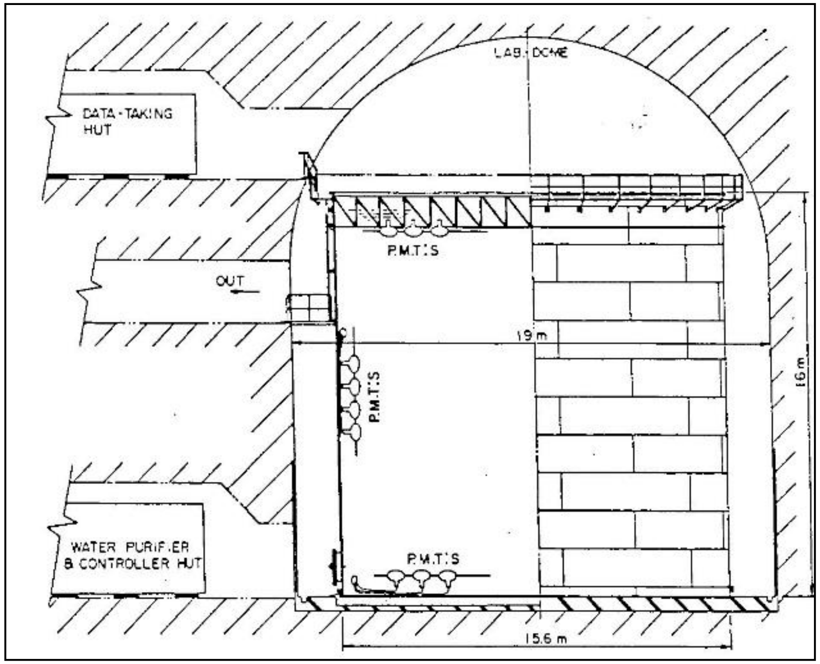
Large water Cherenkov detectors

IMB (Irvine-Michigan-Brookhaven)



- 7,000 ton photo-sensitive volume
- 3,300 ton fiducial volume
- 2,048 5-inch PMTs
- 1.3% photo-coverage
- Morton-Thiokol salt(1570 m.w.e.)
- Started operation in 1982

KAMIOKANDE



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

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

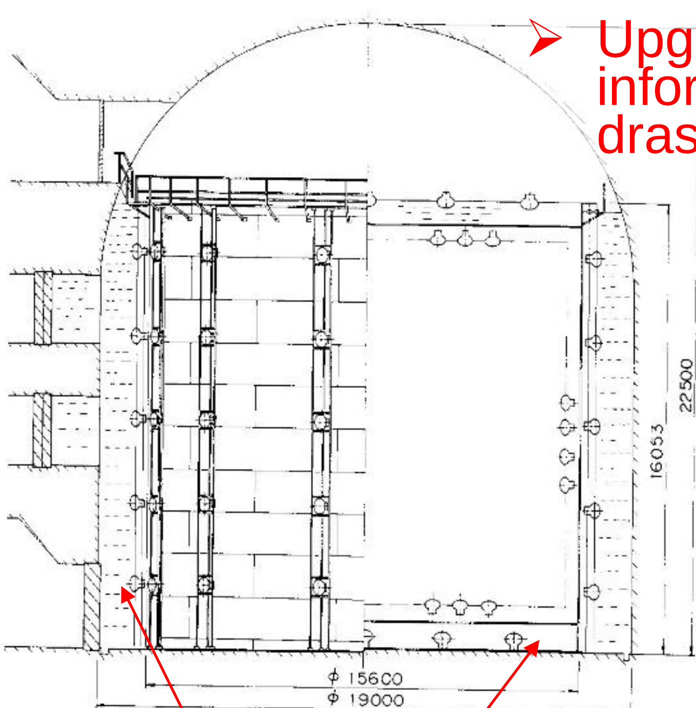
(Received 13 April 1983)

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 drastically.

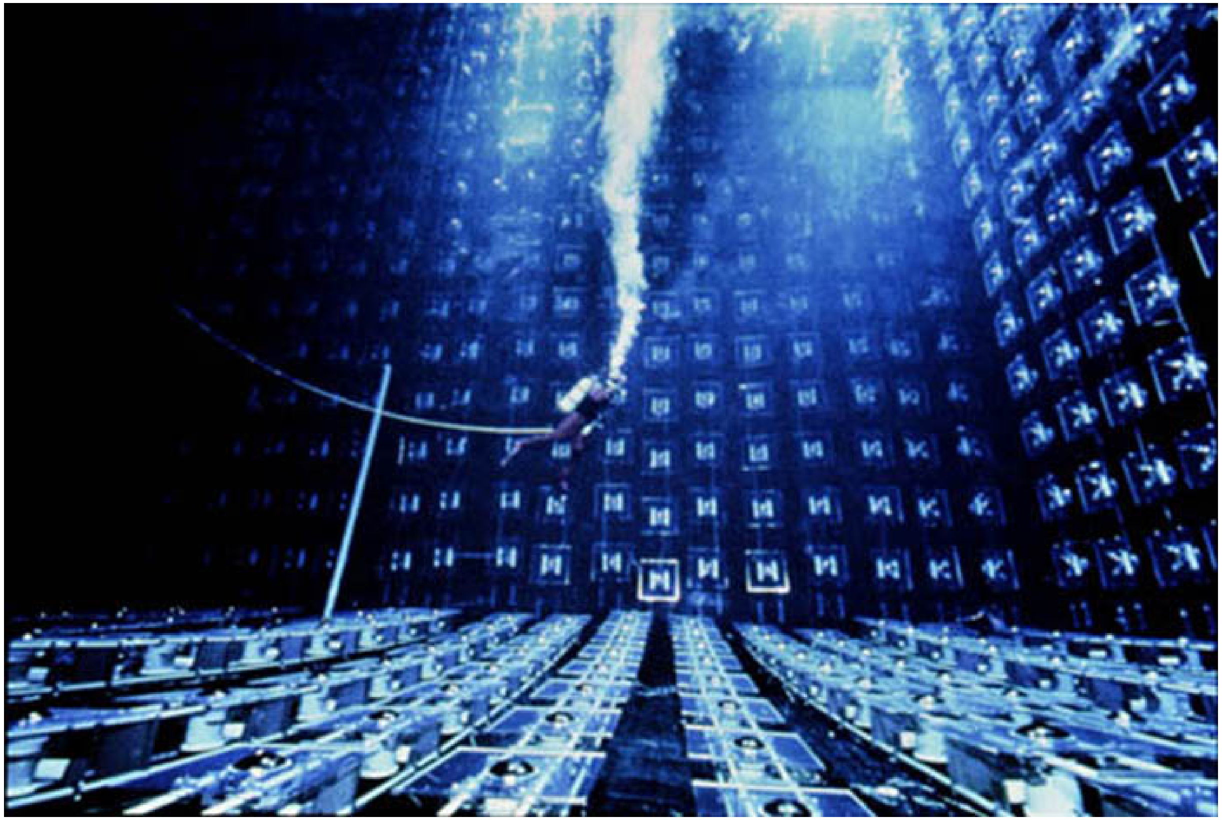


- Made outer detector to shield external gamma rays and tag cosmic rays muons.

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.

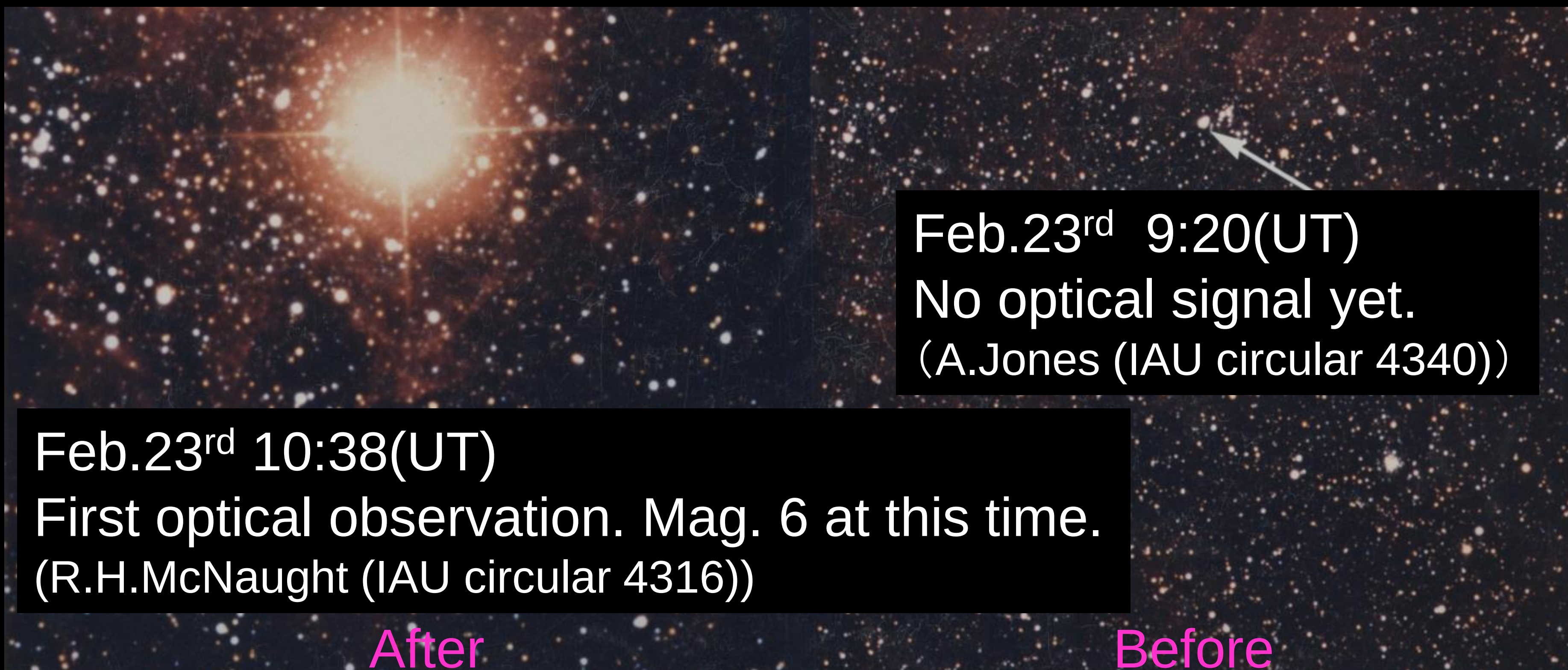
- **IMB-1:**
  5-inch PMT
  Photo-coverage(1.3%)
- **IMB-2:**
  Added WLS plates for a factor of ~1.5 increase
- **IMB - 3:**
  In 1986 shut down to add 8-inch PMTs to bring coverage to effectively about 5%. Also added a WWVB clock to get absolute time to better than 50 milliseconds.



IMB-3 detector

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)



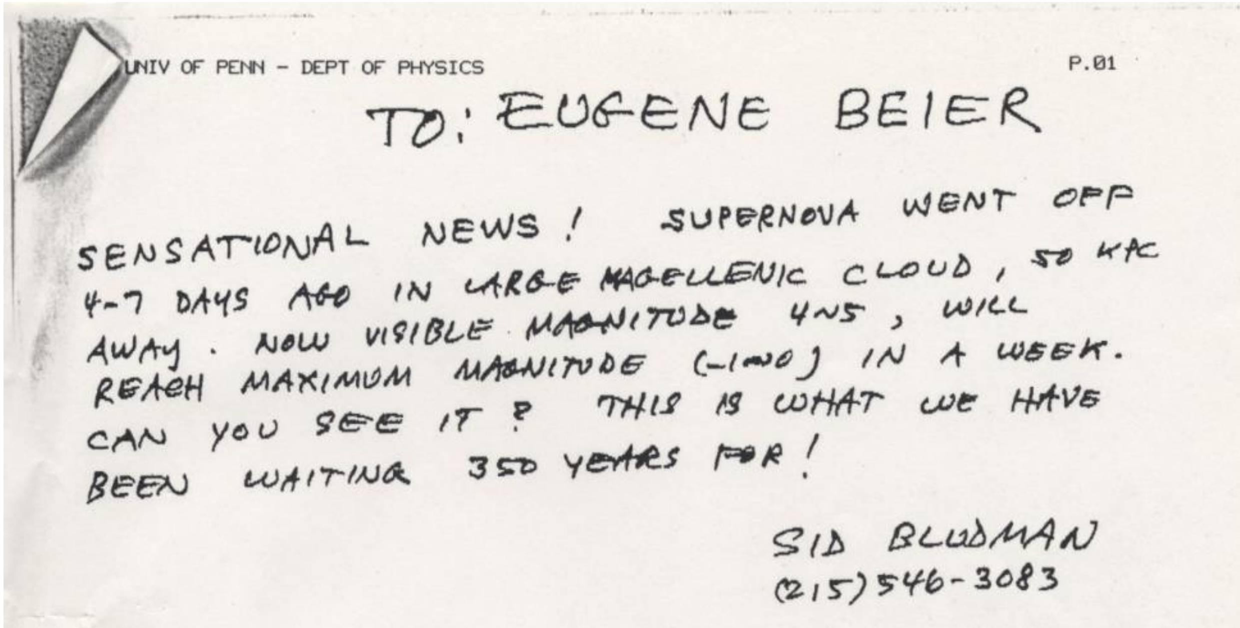
Feb.23rd 9:20(UT)
No optical signal yet.
（A.Jones (IAU circular 4340)）

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)

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

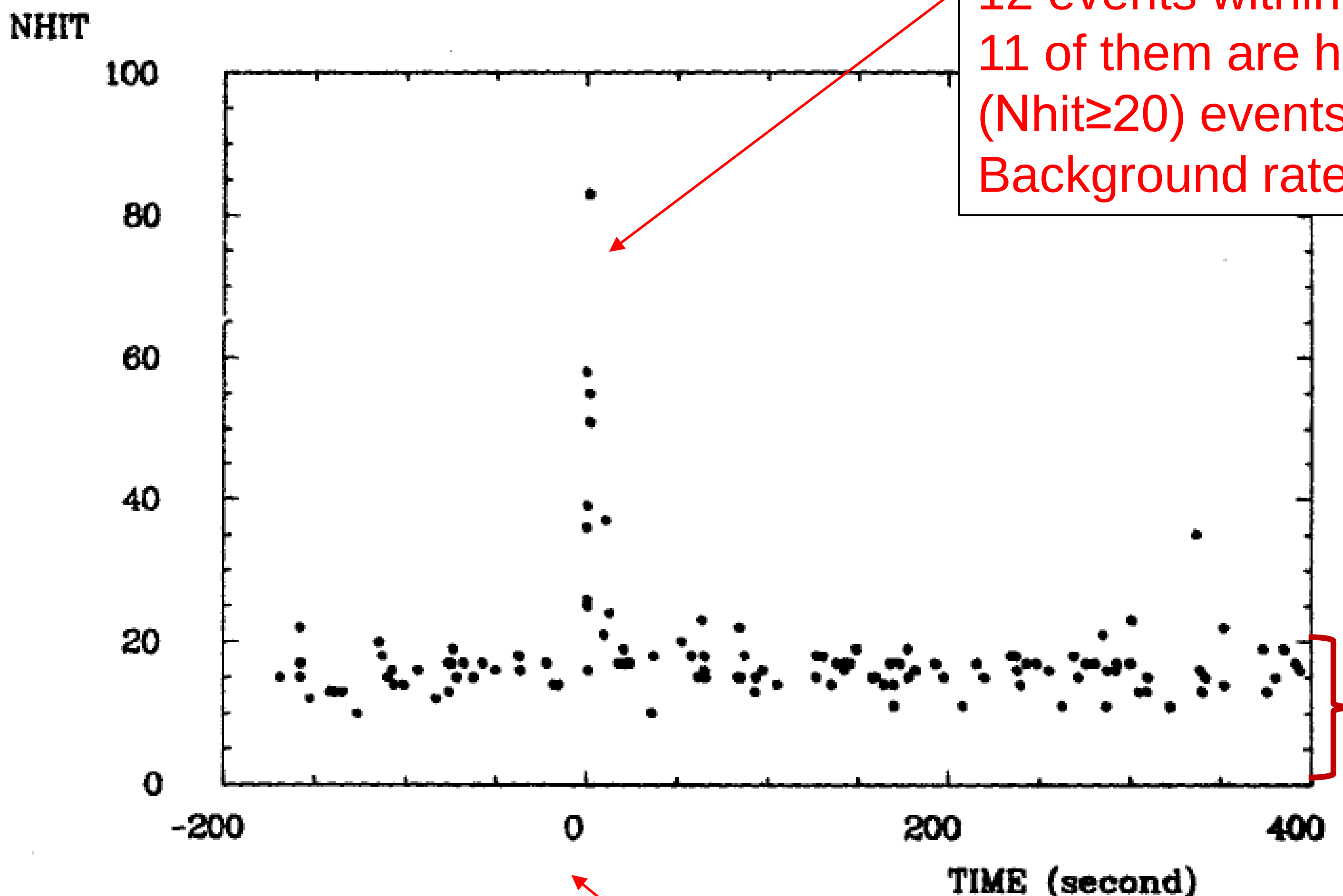
→ *Totsuka asked Kamioka shift to send recent data tapes.*

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

Feb. 28th(Sat): Hirata and Nakahata found the neutrino signals and made plots with Totsuka and Oyama.

Mar. 7th(Sat): 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

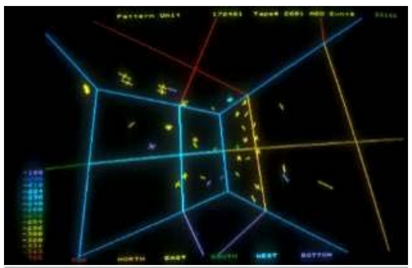
Kamiokande events

From 7:35:35(UT)(±1min.)
Feb.23, 1987

IMB events

SN 1987A Events in IMB Detector
February 23, 1987

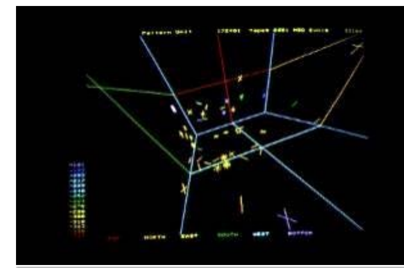
UT 7:35:41.4



UT 7:35:41.8

UT 7:35:42.0

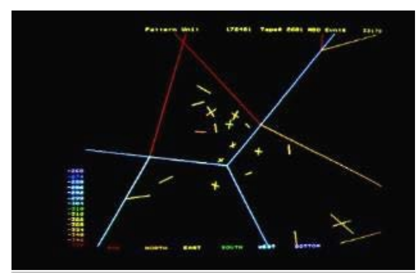
UT 7:35:42.5



UT 7:35:42.9

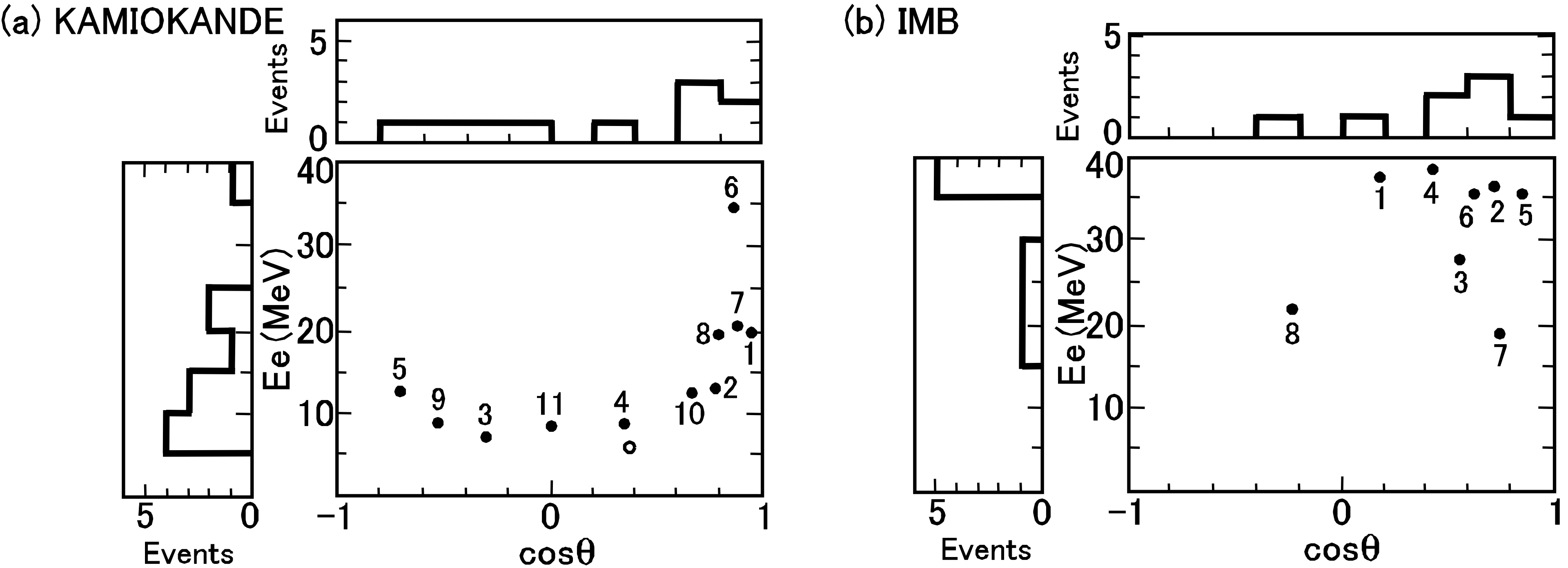
UT 7:35:44.1

UT 7:35:46.4



UT 7:35:46.9

Angular and energy distributions of Kamiokande and IMB events

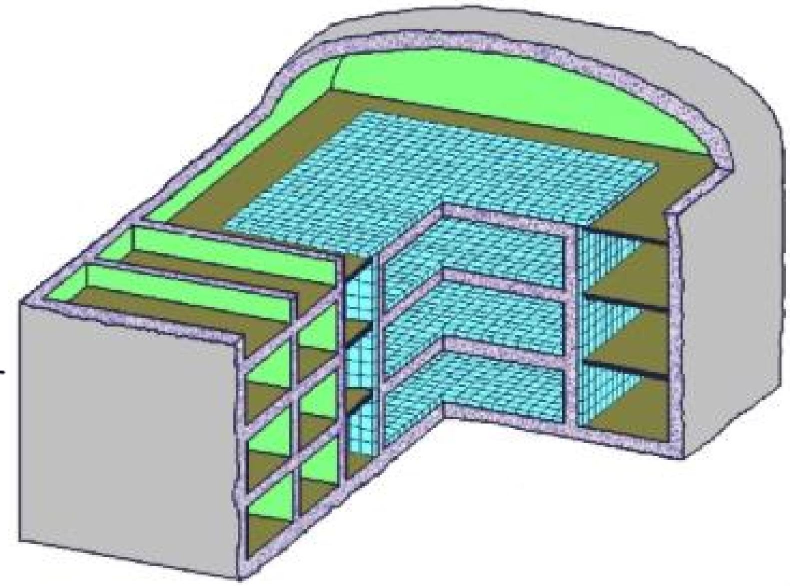


- Essentially, uniform angular distribution in Kamiokande as expected from inverse-beta-reactions.
- The 1st Kamiokande event is in the direction from SN1987A. Note that expected number of electron-scattering events is about 0.1 and that of neutronization burst is 0.002.
- 7 out of 8 IMB events are in forward hemisphere.

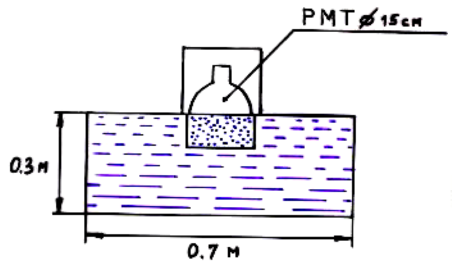
Are they just statistical fluctuation?
We cannot discuss further because of low statistics.

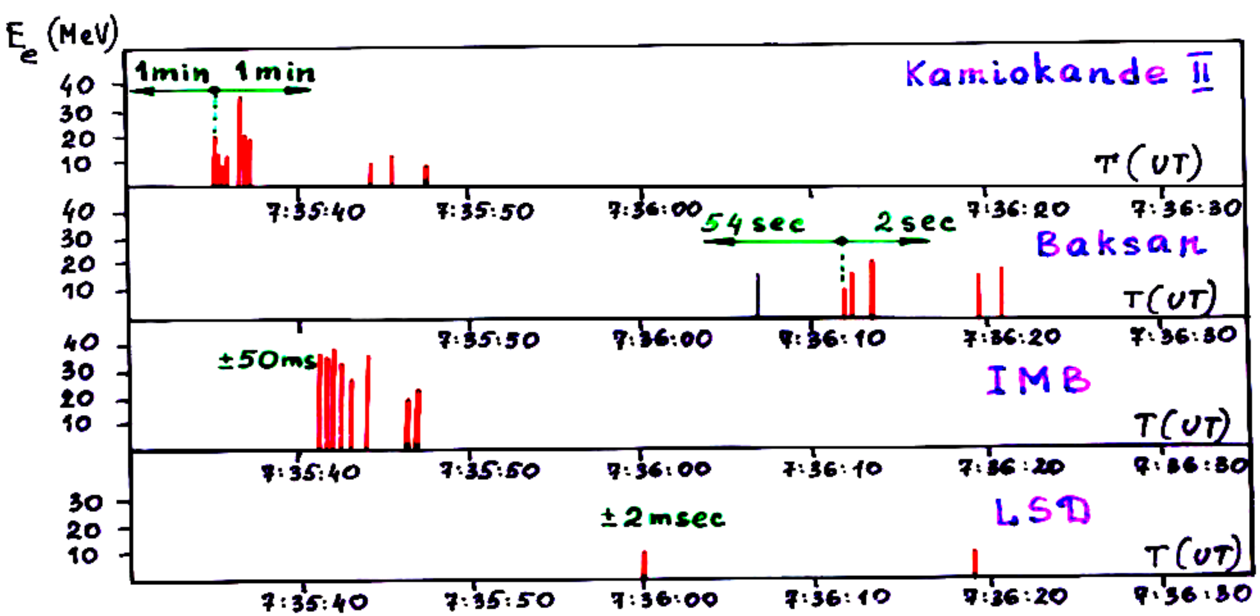
The Baksan underground scintillation telescope (Russia)

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



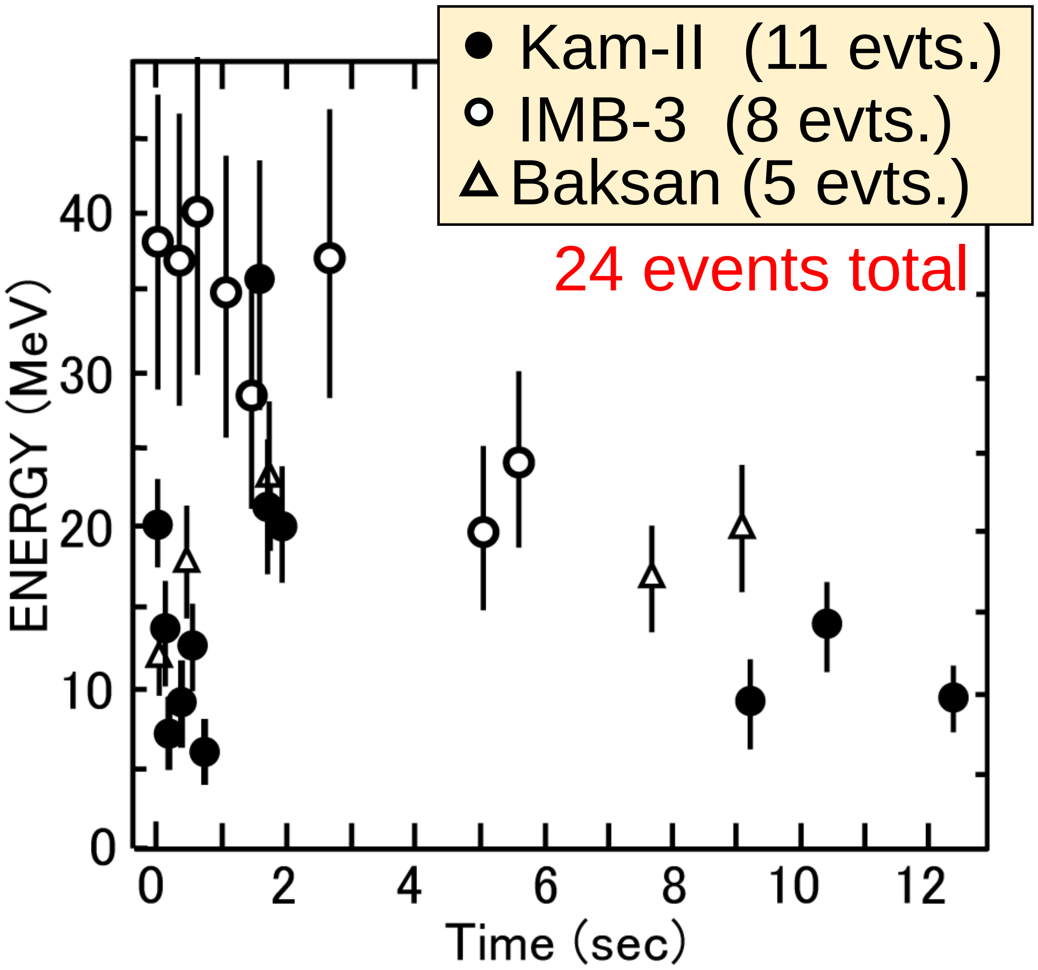
Each detector



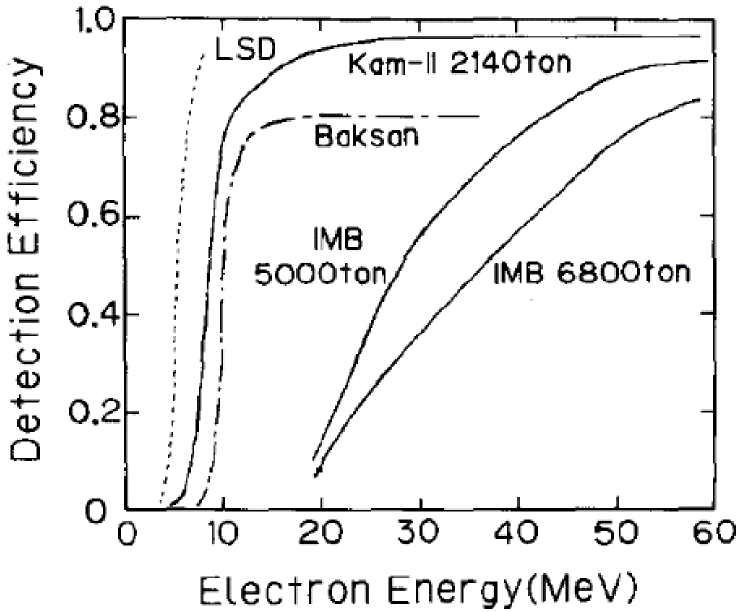


5 events in Baksan detector

Adjusting the 1st events from Kamiokande, IMB and Baksan



Detection efficiency



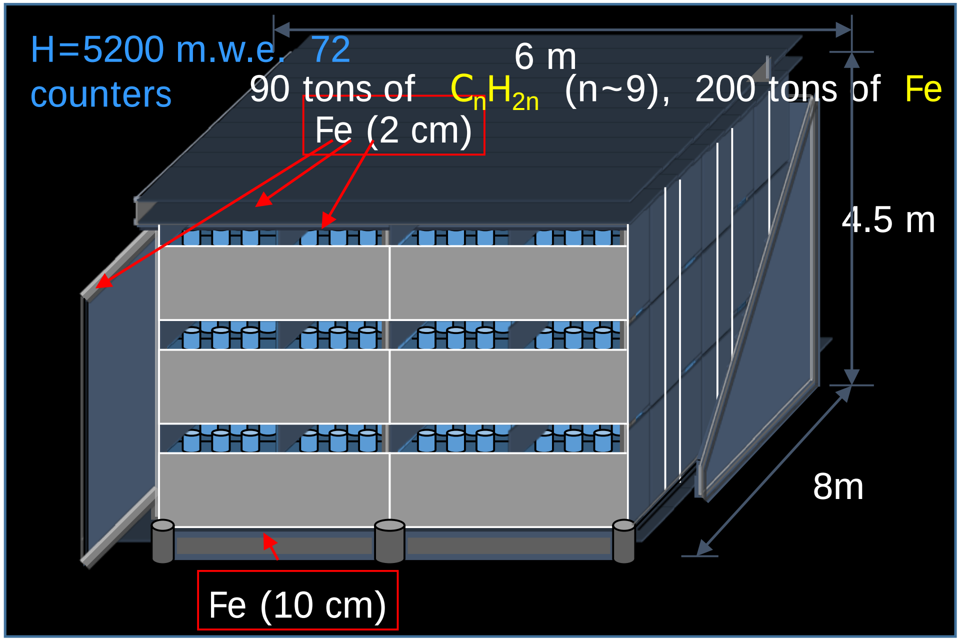
Energy threshold (at 50% eff.)

~8.5 MeV @ Kamiokande

~28 MeV @ IMB

~10 MeV @ Baksan

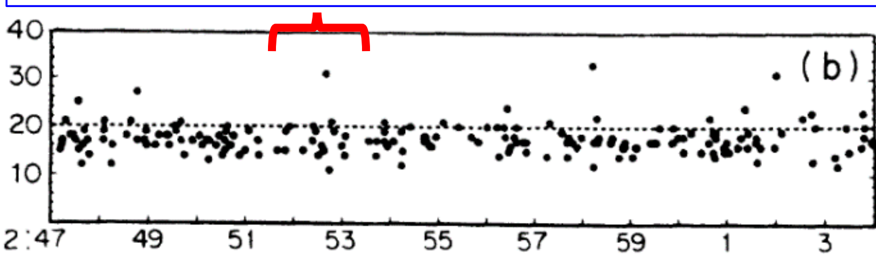
LSD(Liquid Scintillator Detector) signals



90 ton liq. scintillator detector at Mt. Blanc tunnel claimed 5 events at 2:52(UT).

# of event	Time, UT±2ms	Energy, MeV
1	2:52:36,79	6,2 – 7
2	40,65	5,8 – 8
3	41,01	7,8 –11
4	42,70	7,0 – 7
5	43,80	6,8 – 9

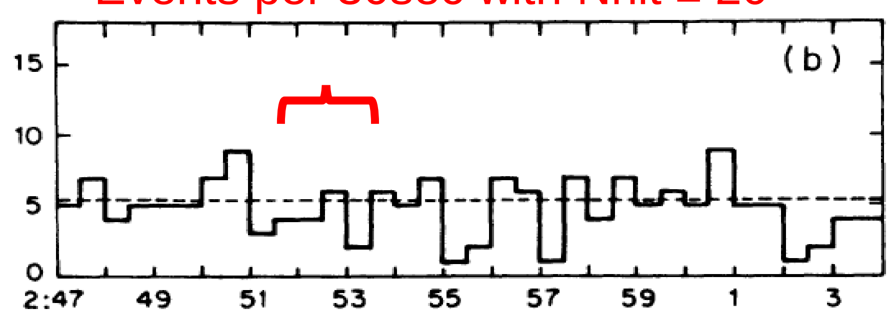
Kamiokande data at 2:52(UT) ±1min.



2 events with Nhit ≥ 20 within the ±1min while expected BG is 2.6 .

How about lower energy events at Kamiokande.

Events per 30sec with Nhit ≤ 20



So, no excess at the LSD time in Kamiokande. No event at IMB as well.

History of theoretical works of supernova (before SN1987A)

From D. Arnett, “Supernovae and Nucleosynthesis”, 1996 and etc.

1934 Baade and Zwicky: Proposed the idea of neutron stars and that these objects were produced in supernova explosion.

1939 Oppenheimer and Snyder: Examined continued collapse to black holes.

1941 Gamov and Schönberg: Identified importance of neutrino emission and nuclear weak interactions for supernovae and core collapse.

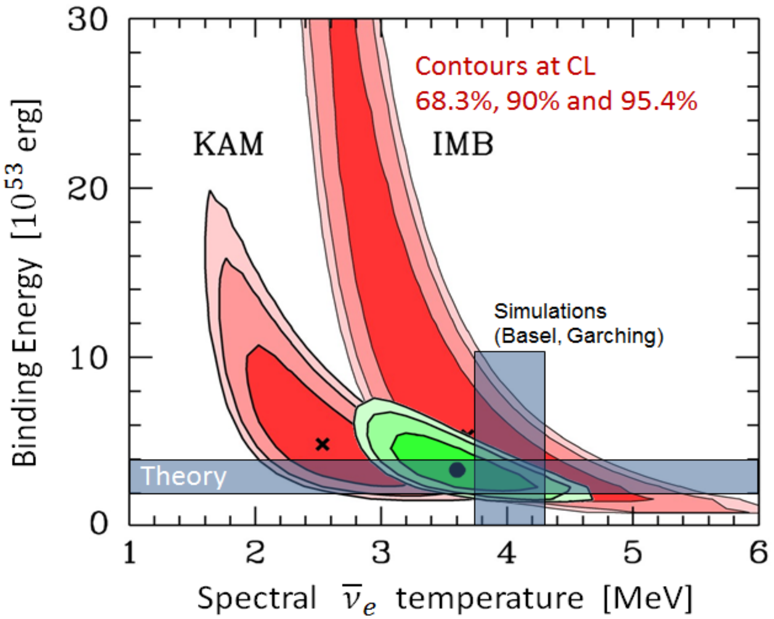
1961, 1966 Colgate et al.: Early examples of numerical hydrodynamics: transfer of energy, from the gravitational potential to exploding mantle, took place by emission and deposition of neutrinos.

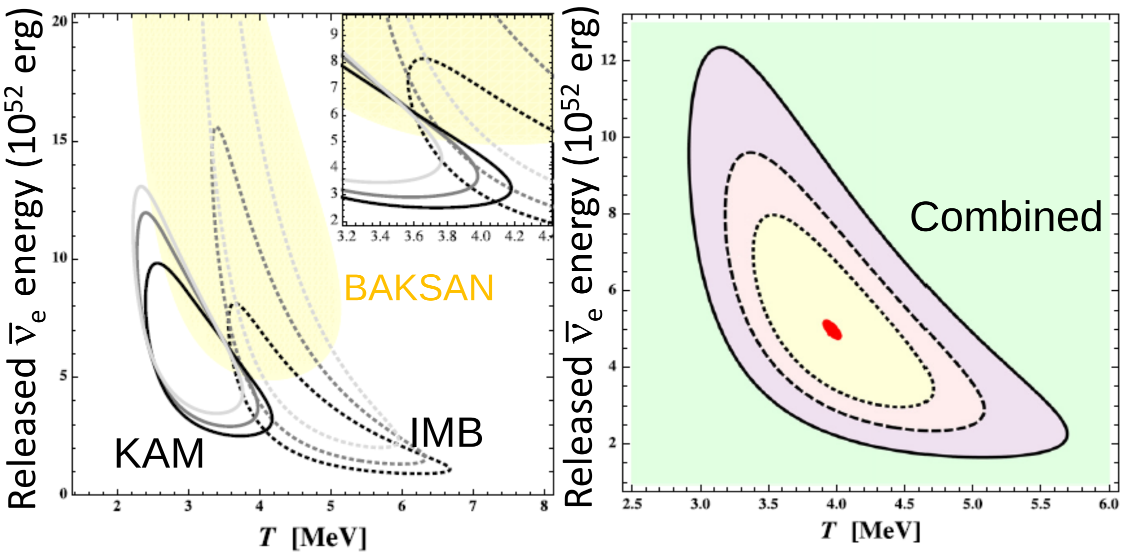
1967 Schwartz, May and White: Improvement of numerical techniques by adding general relativity to the dynamics.

1974, 1975 Wilson, Schramm and Arnett, Mazurek, Sato: Effect of neutral current interaction(coherent ν-nucleus scattering) on the core collapse.

1986 Mayle, Wilson and Schramm: Delayed explosion models by numerical simulation

What we have learned from SN1987A





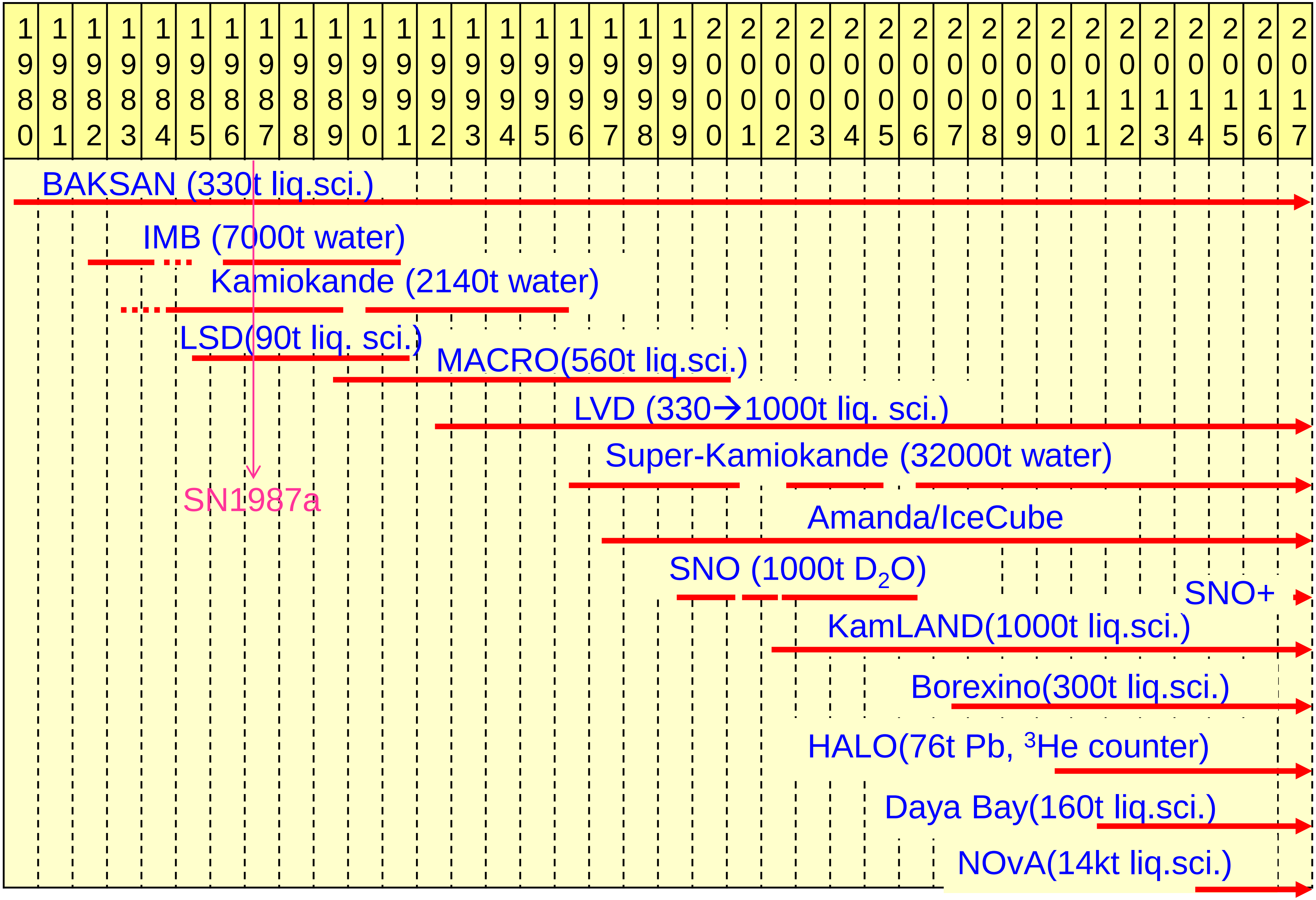
Vissani, J. Phys. G: Nucl. Part. Phys. 42 (2015) 013001

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

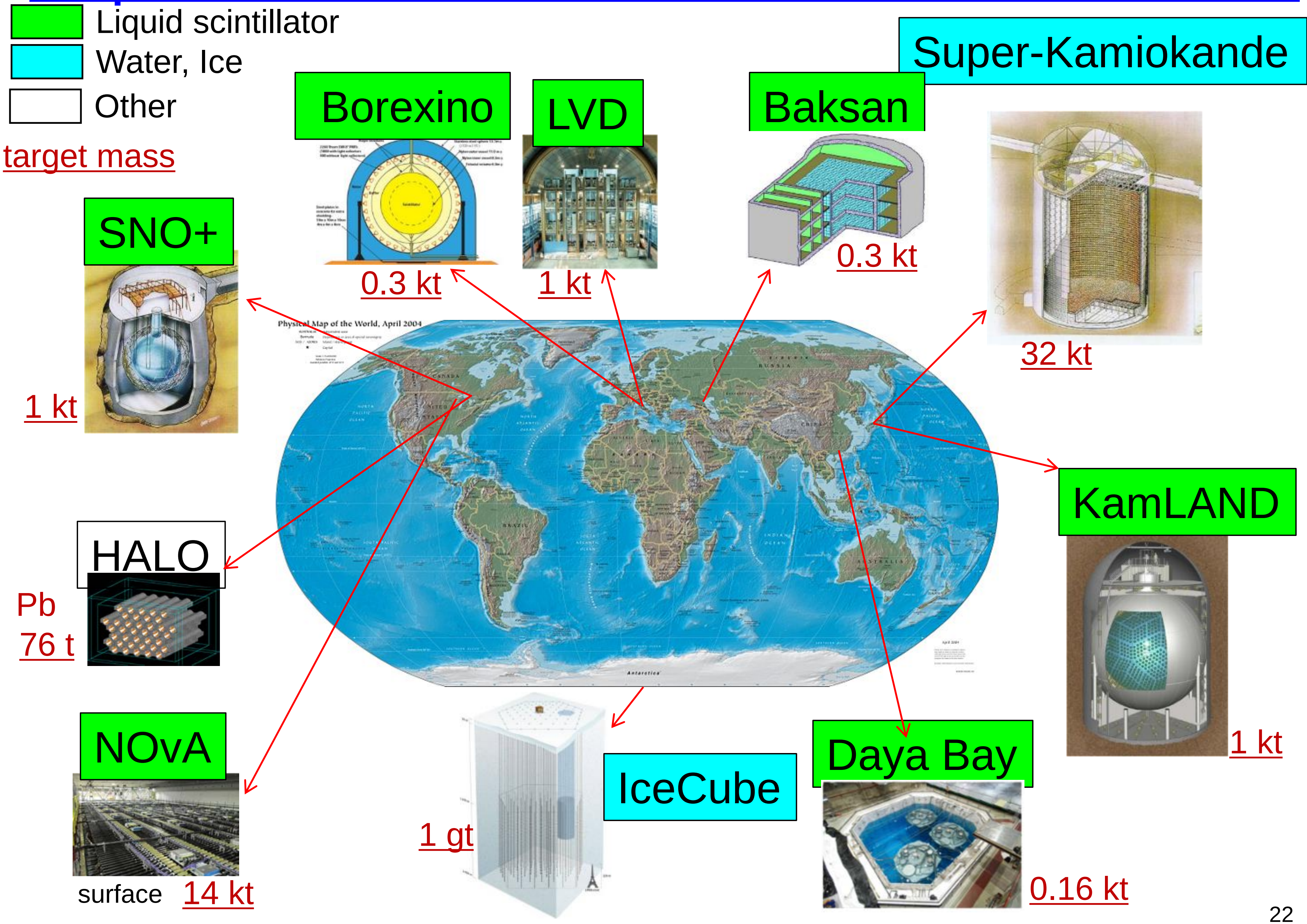
- Total energy released by $\bar{\nu}_e$ was measured to be ~5x10^{52} erg.
- Assuming equipartition, binding energy was estimated to be ~3x10^{53} erg.
- The observed released energy and explosion time scale were consistent with predictions from the supernova theory.

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

History of supernova detectors



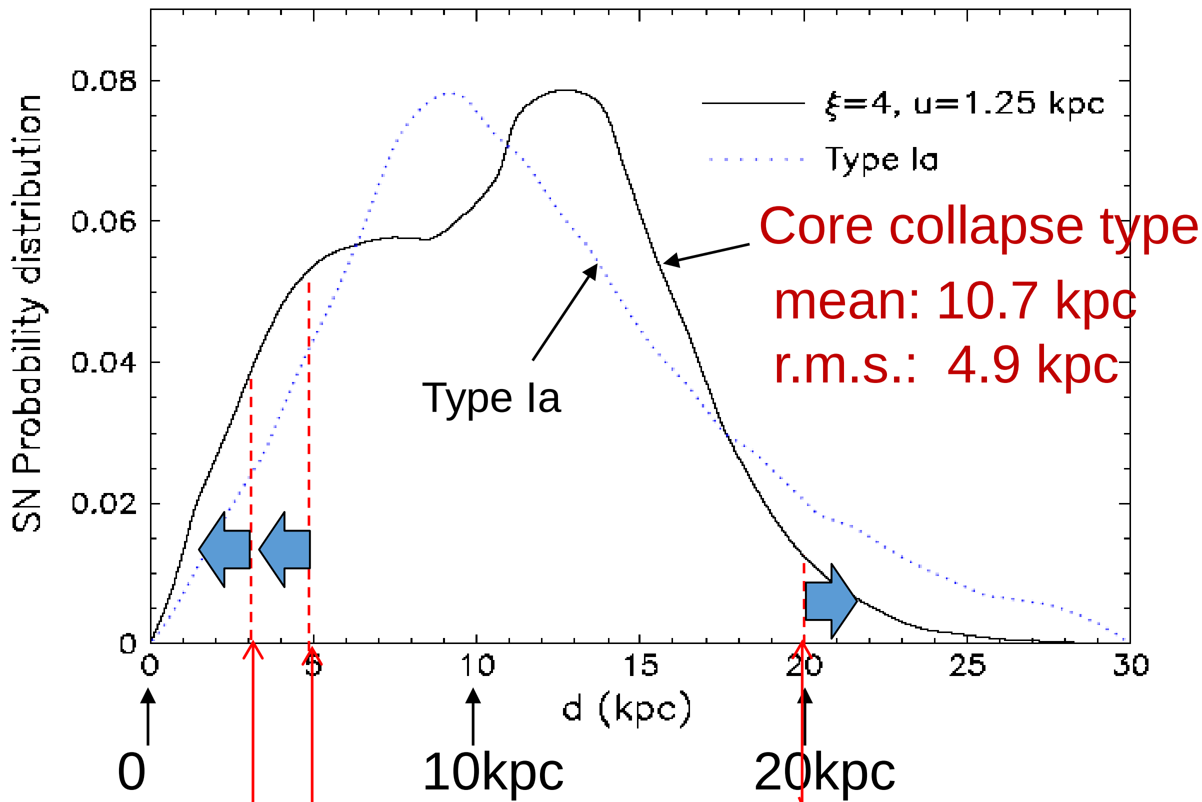
Supernova burst detectors in the world now



Distance to Galactic supernova

Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006), astro-ph/0604300

Based on birth location of neutron stars

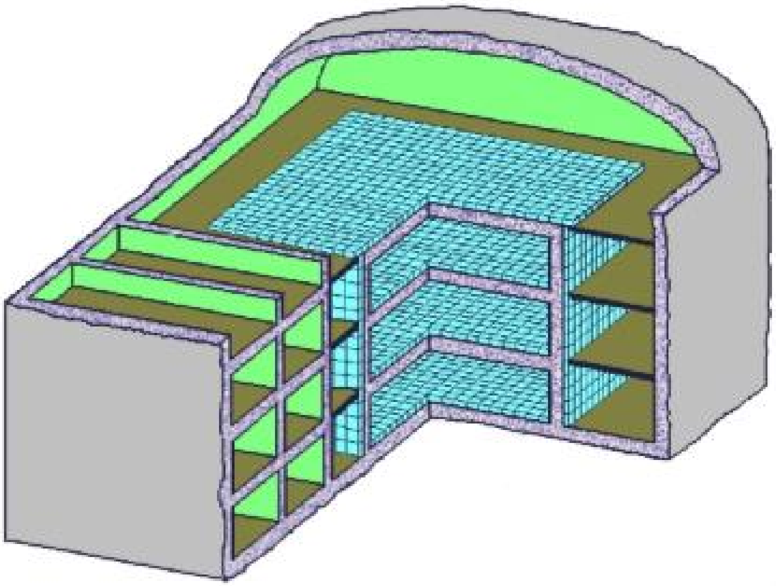


7% probability
< 3.16 kpc
> x10 statistics

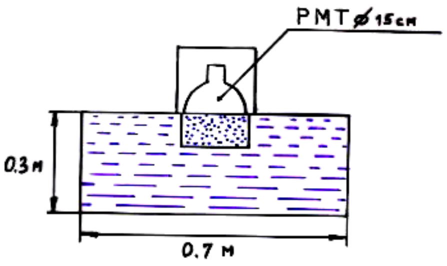
16% probability
< 5 kpc
> x 4 statistics

3% probability
> 20 kpc
< 1/4 statistics

The Baksan underground scintillation telescope (Russia)



Each detector



Total number of standard detectors…………..3184

Total target mass………………………...330 tons of oil-based scintillator

Lower horizontal layer …………………..130 tons is used for supernova monitor

~30 $\bar{\nu}_e p \rightarrow e^+ n$ events expected for 10 kpc SN.
Running since 1980. Sensitive up to ~20 kpc.

No candidate (except for SN1987A) for 31.27 years' observation time from June 1980 to December 2016. Upper limit of SN rate: < 0.074 /yr (90% C.L.)
(M. Kochkarov et al., PoS(ICRC2017)960)

LVD detector (at Gran Sasso, Italy)

LVD consists of an array of 840 counters, 1.5 m^3 each.

Total target:
1000 t liquid scintillator

4MeV threshold

With <1MeV threshold for delayed signal (neutron tagging efficiency of 50 +- 10 %)

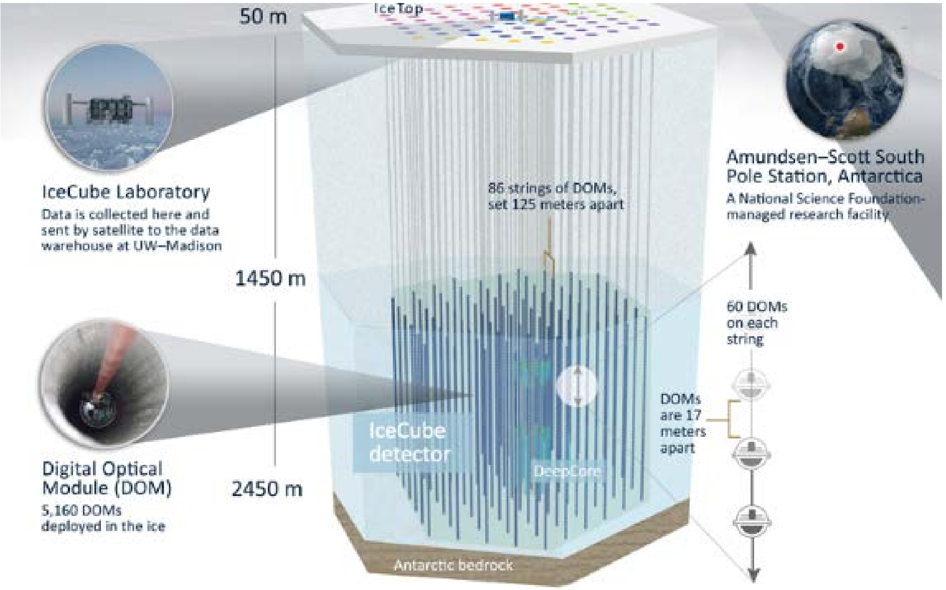
E resolution: 13%(1σ) at 15MeV

~300 $\bar{\nu}_e p \rightarrow e^+ n$ events expected for 10 kpc SN.

No candidate for 8577 days from 1992 to May 2017.
Upper limit of SN rate: < 0.098 /yr (90% C.L.)

C.Vigorito et al., PoS(ICRC2017)1017

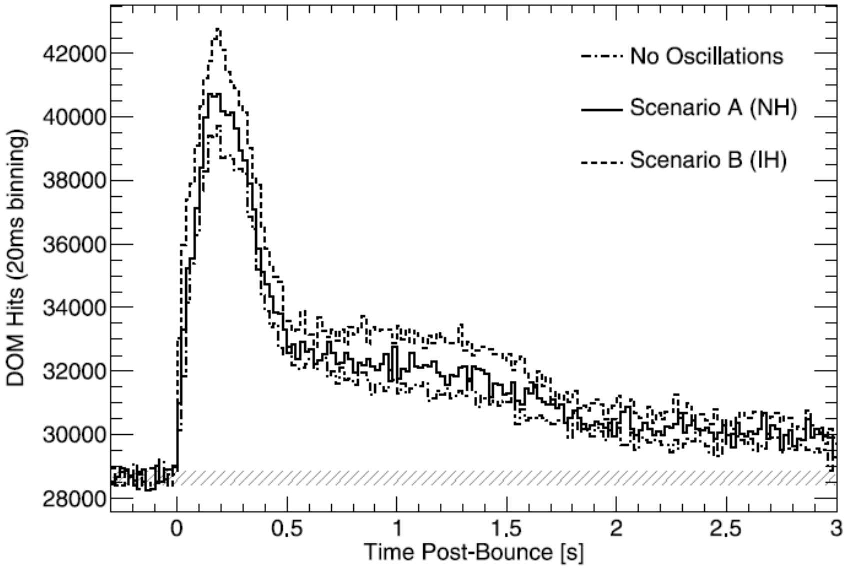
IceCube (South pole)

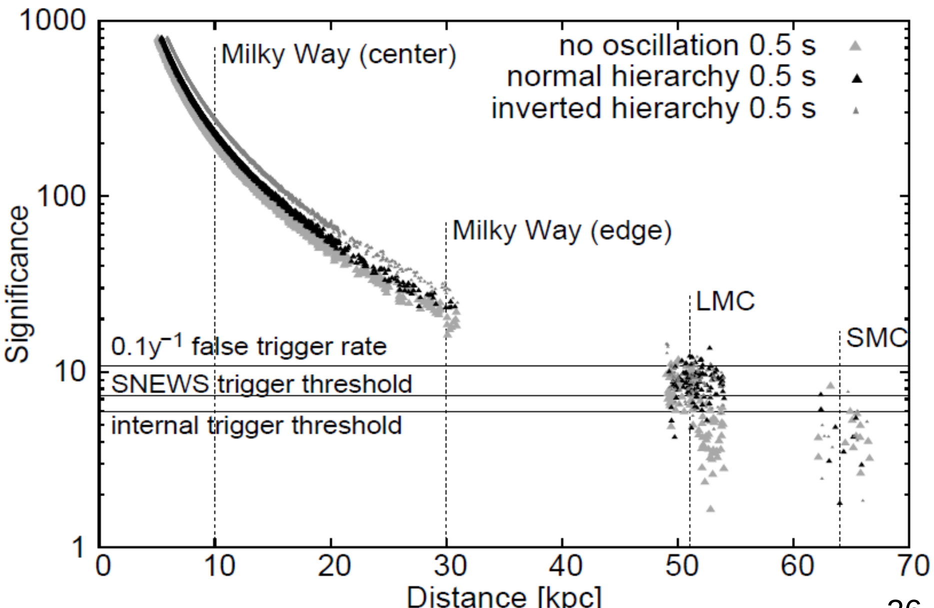


IceCube detector

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

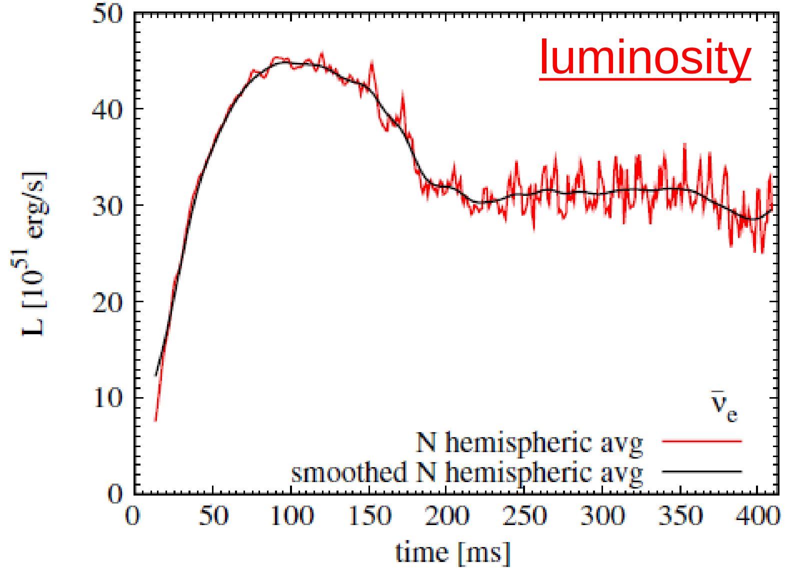
Supernova neutrinos coherently increase single rates of PMTs.

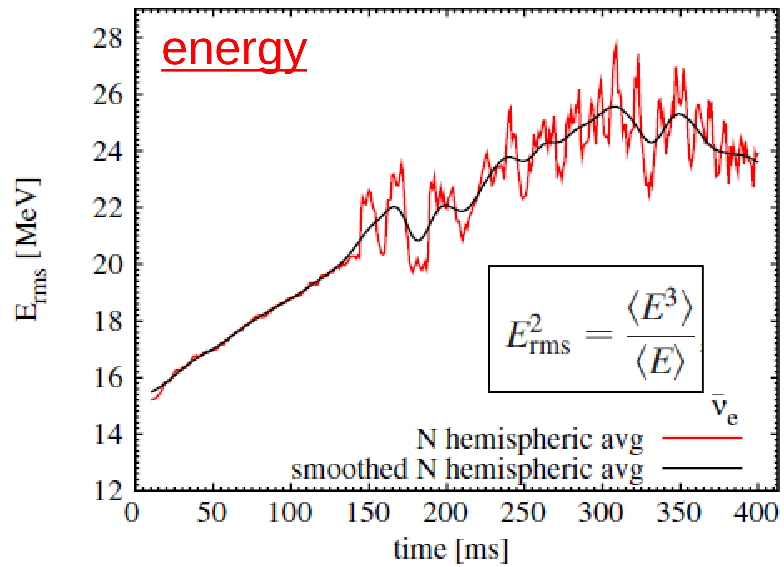




High frequency signal variation by SASI

SASI=standing accretion shock instability

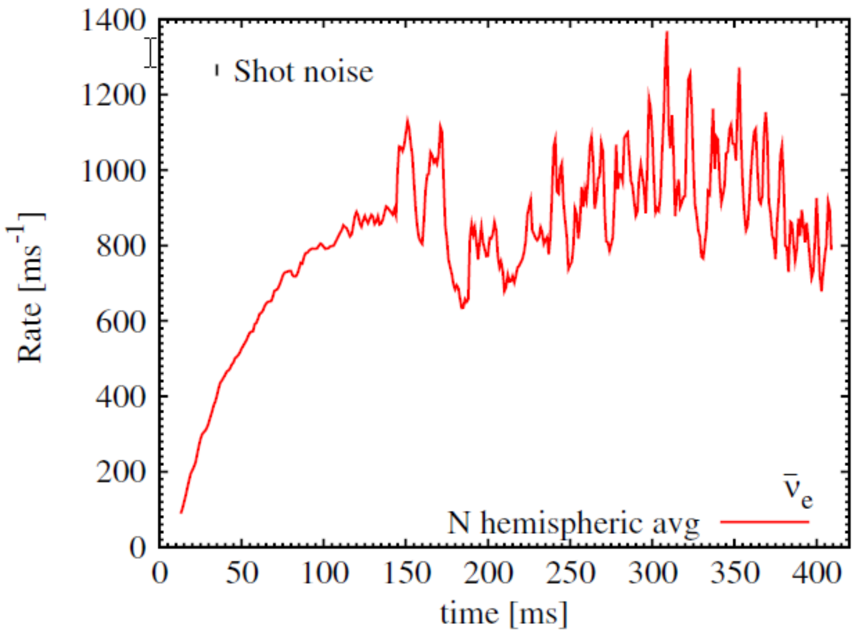




2-D(axially symmetric) simulation with PROMETHEUS-VERTEX code

Supernova at 10kpc

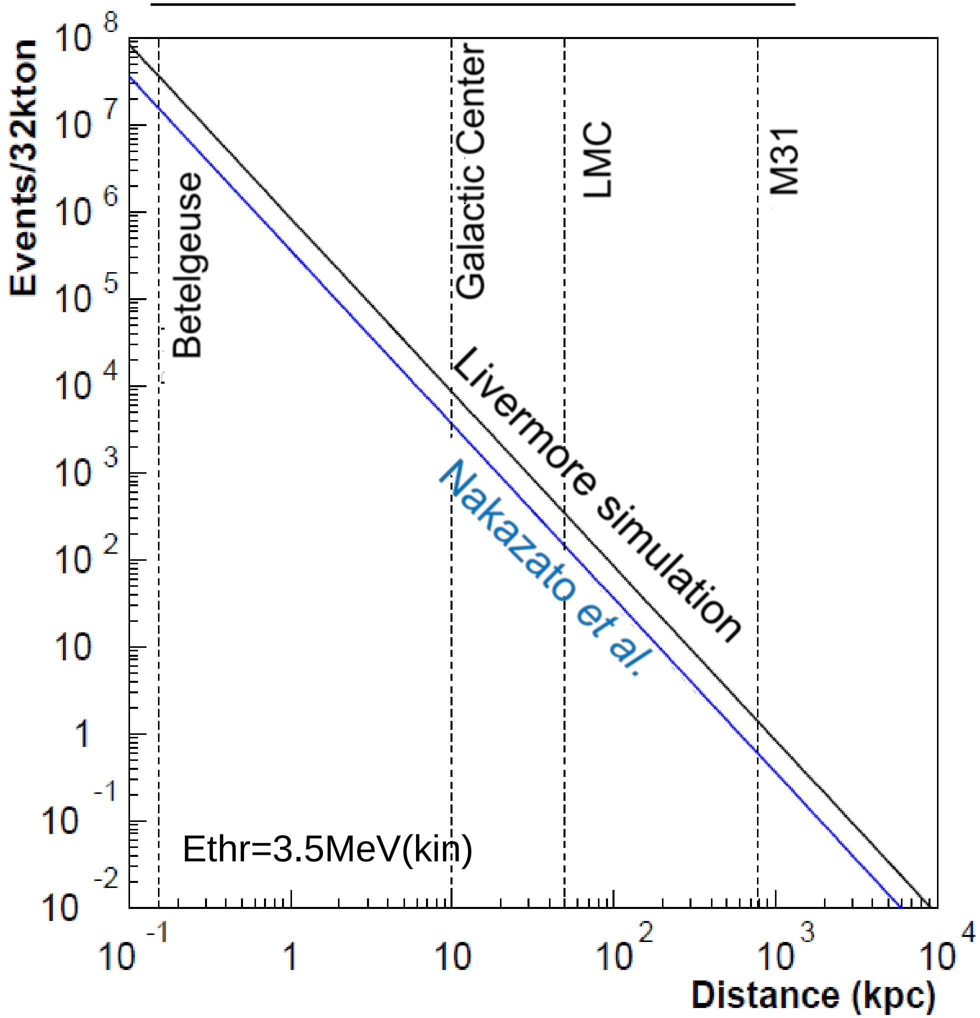
IceCube "event" rate



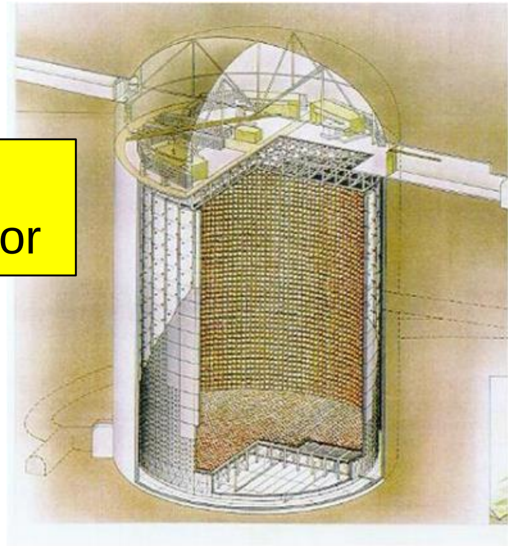
T.Lund et al., Phys. Rev. D82, 063007(2010).

Super-K: Number of events

Number of events vs. distance



32kton water Cherenkov 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.

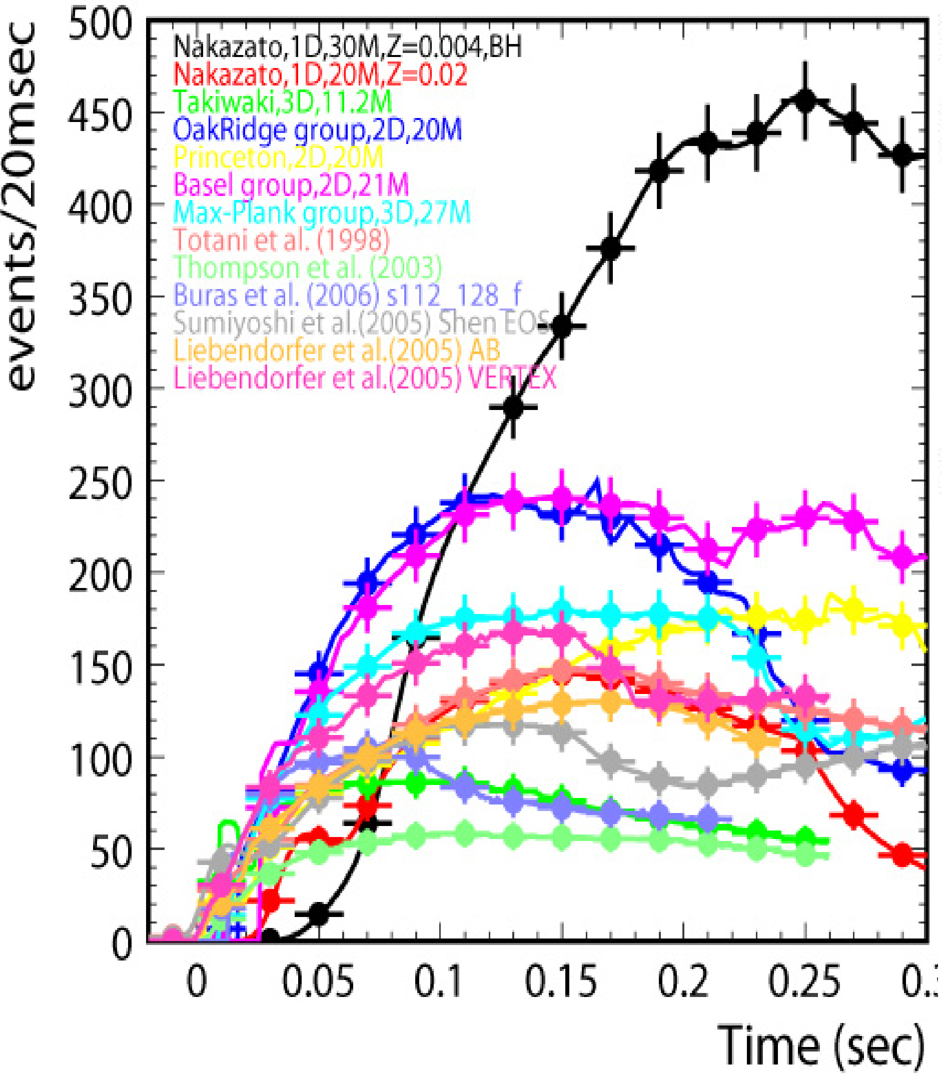
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

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)

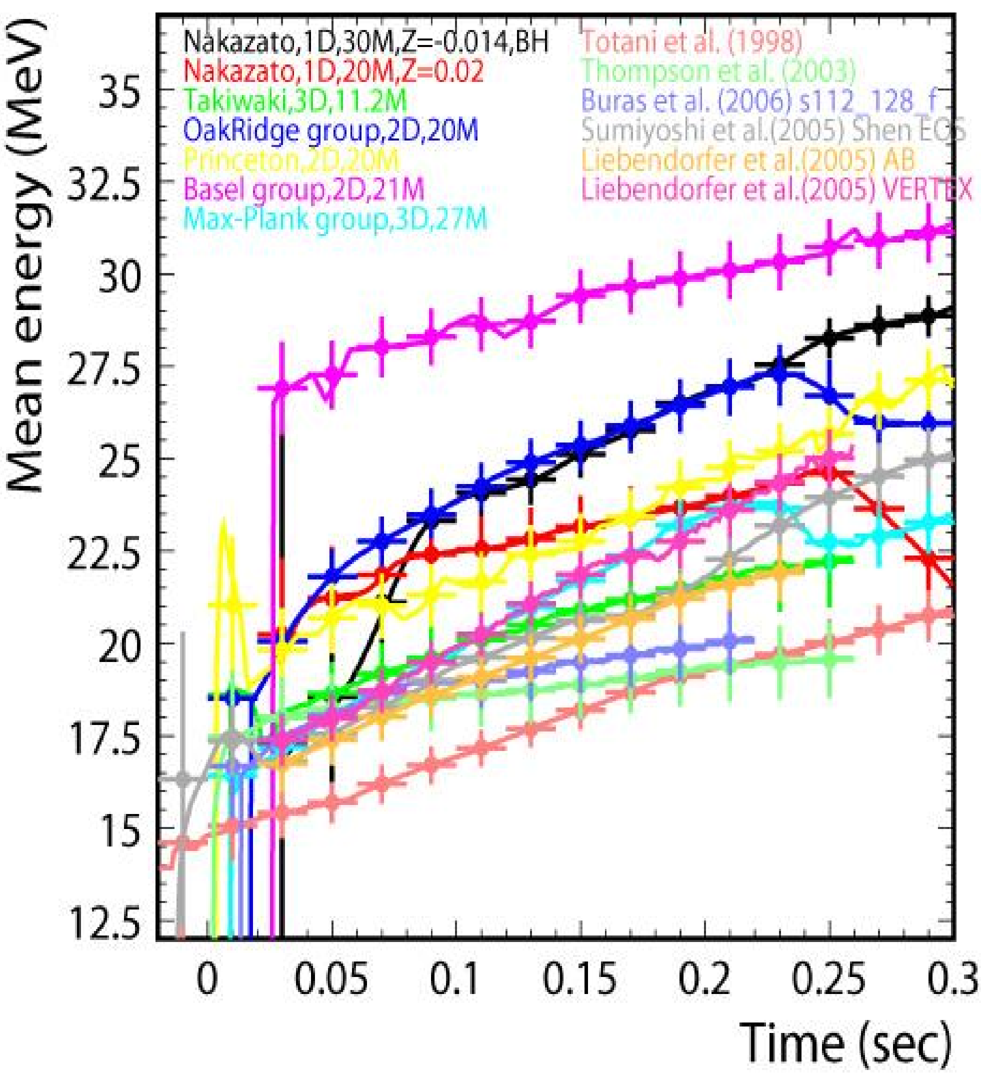
Sensitivity of Super-K for the model discrimination

For 10kpc supernova

Time variation of event rate



Time variation of mean energy



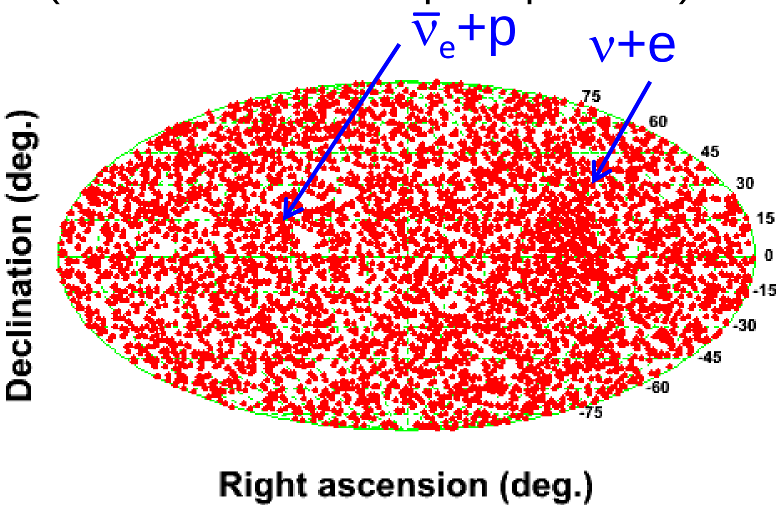
High statistics enough to discriminate models

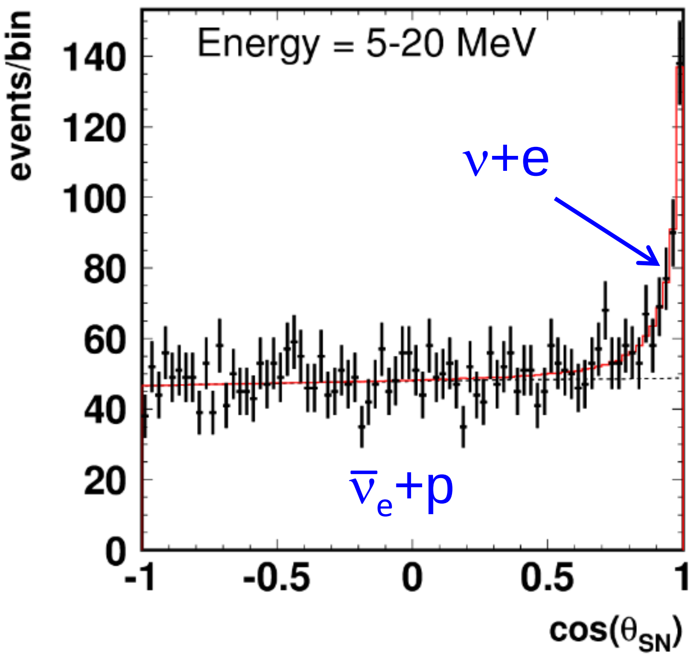
Cooperation: H. Suzuki

Super-K: directional information

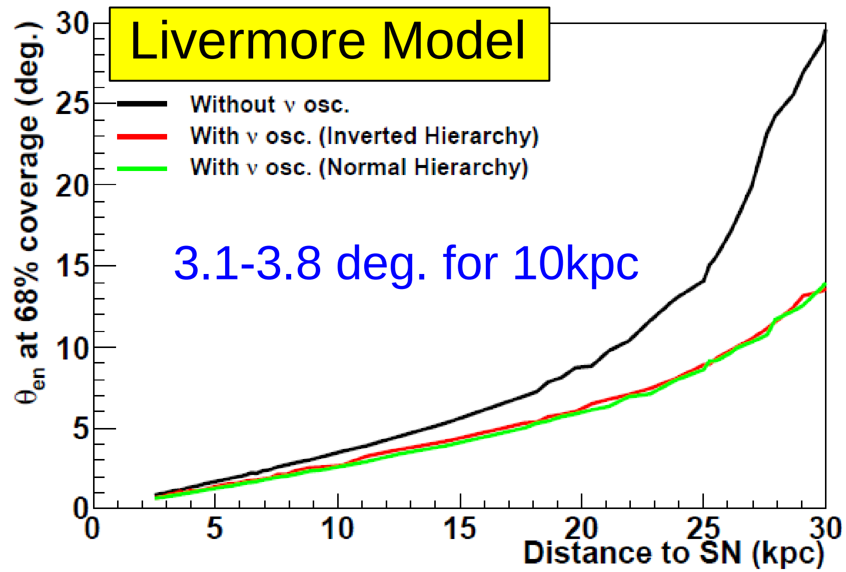
Reconstructed direction

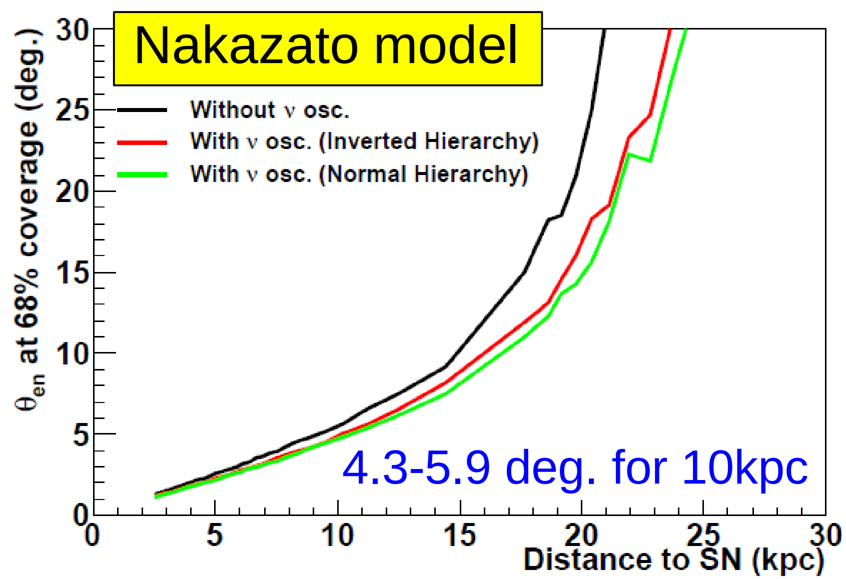
(Simulation of a 10kpc supernova)





Distance vs. pointing accuracy

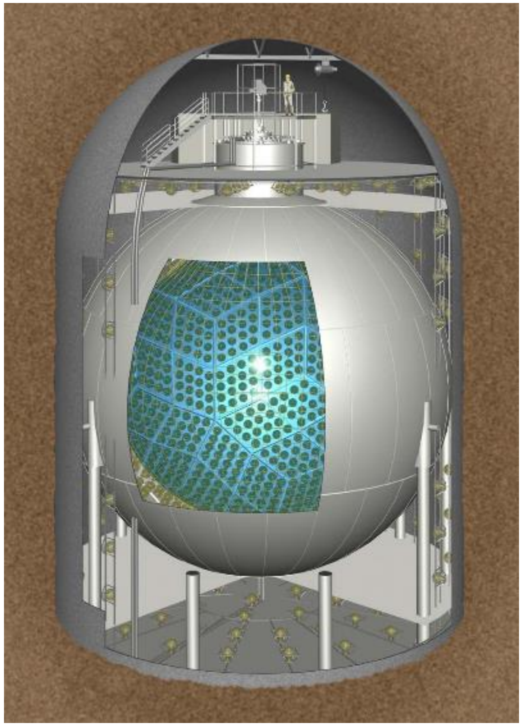




Single volume liquid scintillator detectors

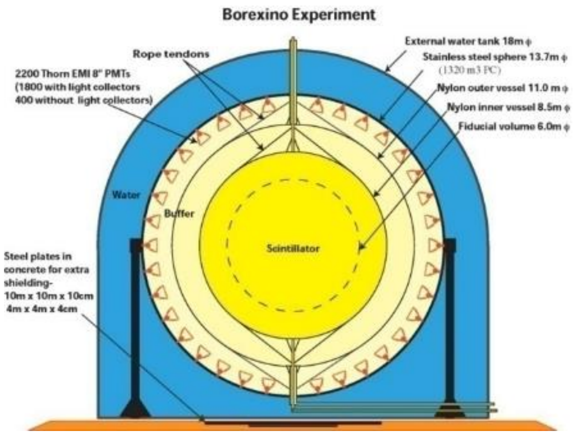
KamLAND (Kamioka, Japan)	Borexino (Gran Sasso, Italy)	SNO+ (SNO Lab.,Canada)

KamLAND
(Kamioka, Japan)



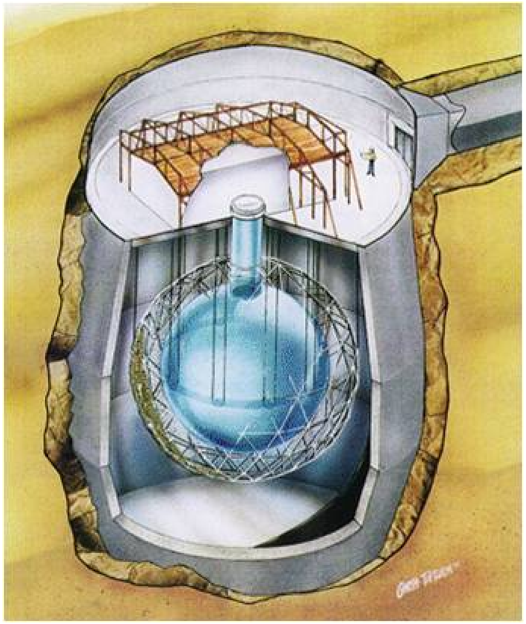
1000ton liq.sci.
Running since 2002.

Borexino
(Gran Sasso, Italy)



300ton liq.sci.
Running since 2007.

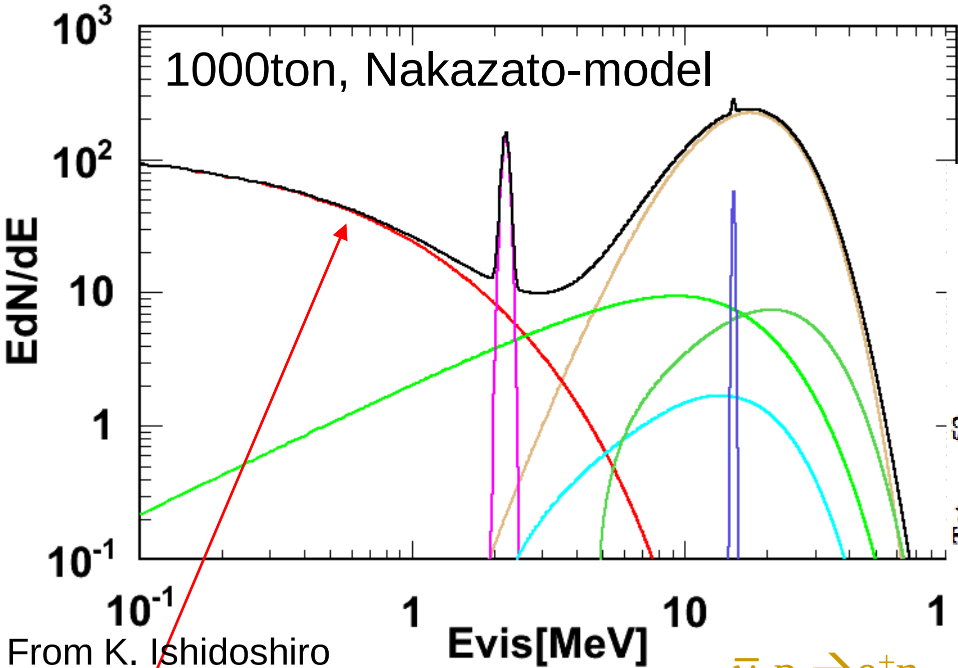
SNO+
(SNO Lab.,Canada)



1000ton liq.sci.
Start soon.

Energy spectrum expected at the liquid scintillation detectors

Expected energy spectrum (10kpc)



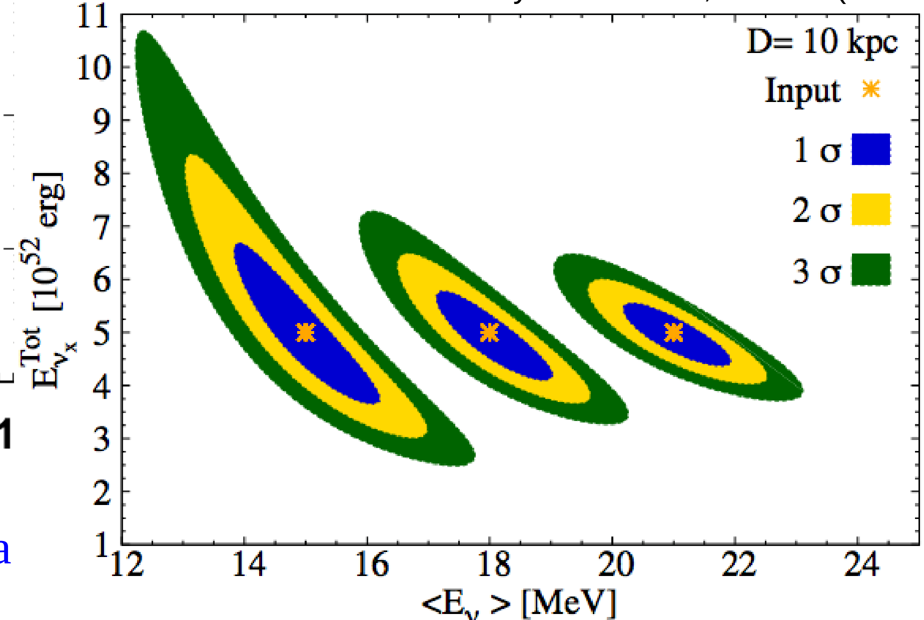
From K. Ishidoshiro

νp elastic scattering

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)



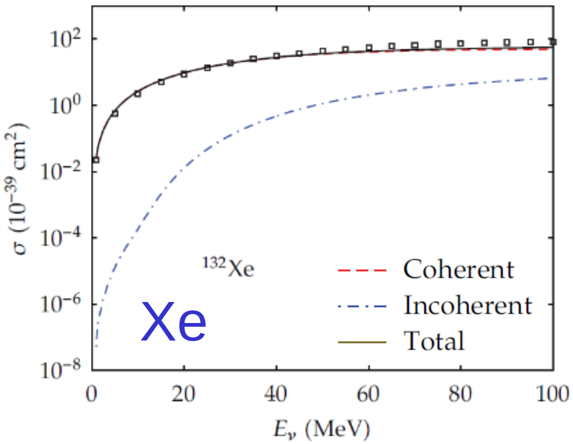
Determine luminosity and mean energy of ν_x

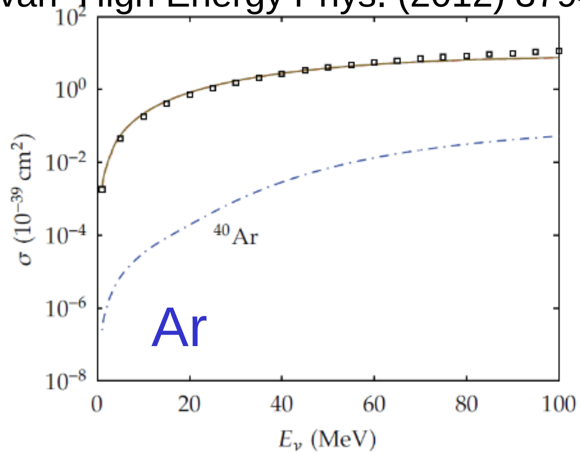
(ν_x : ν_μ , ν_τ at the source)

Supernova signals by Dark Matter detectors

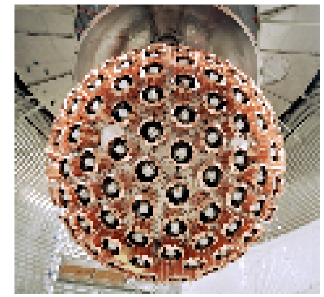
Coherent elastic neutrino-nucleus scattering

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



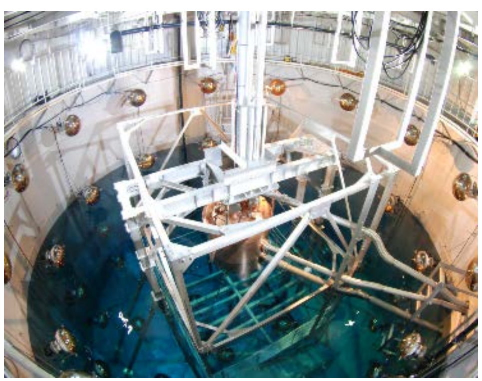


DEAP3600
(Ar 3.6ton)

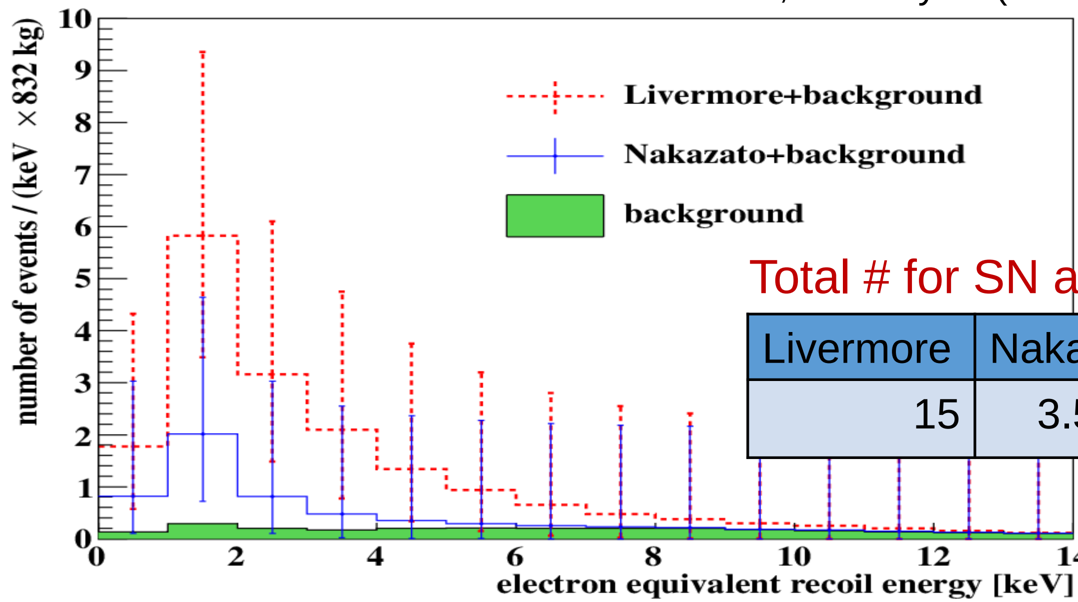


XENON1T
(Xe 1ton)

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



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

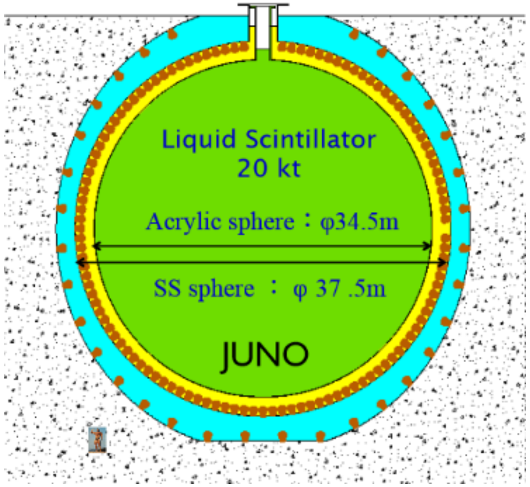


Total # for SN at 10 kpc

Livermore	Nakazato
15	3.5 ~ 21

Future Large Volume Detectors

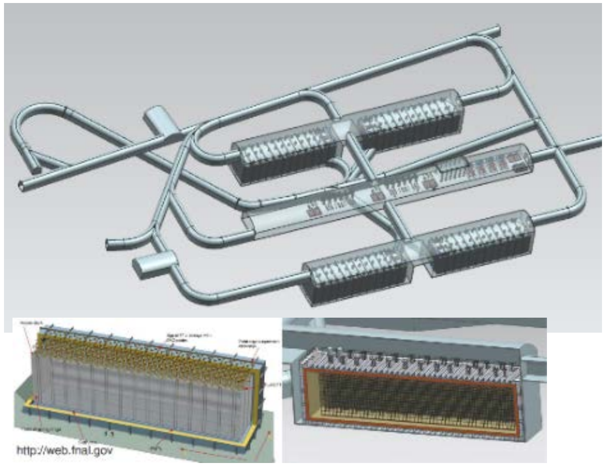
JUNO(China)
(20kton Liq. Sci.)



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

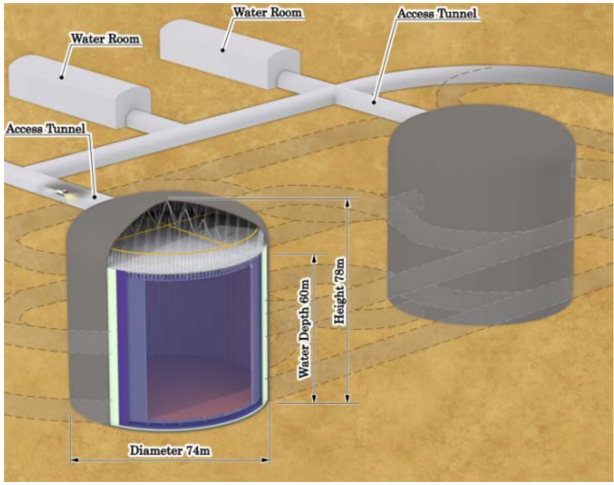
DUNE/LBNF (US)
(40 kton Liq. Ar)



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

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

Hyper-Kamiokande
(440 kton Water)



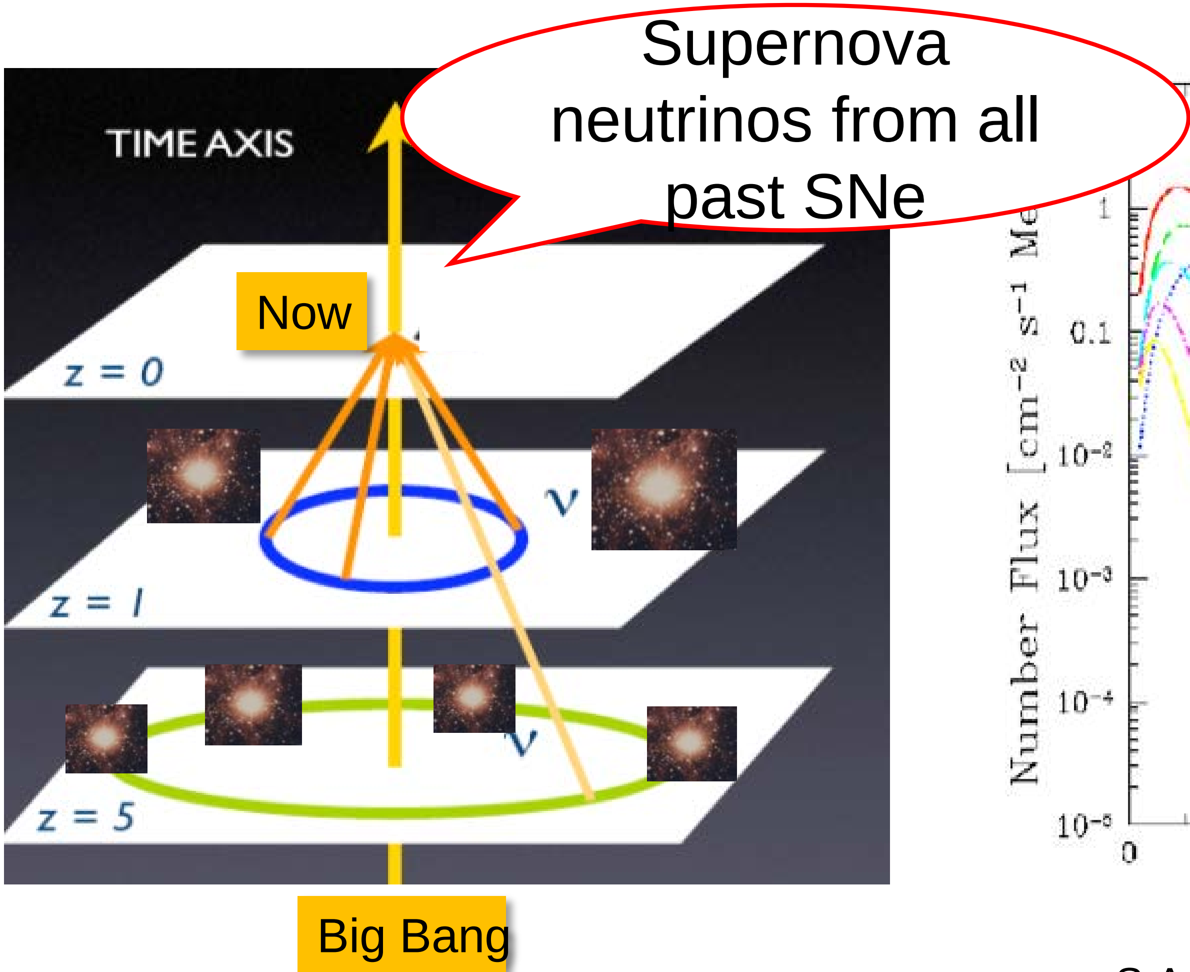
~120k $\bar{\nu}_e p$,~5k ν+e events for 10 kpc supernova. Precise measurement of time variation.

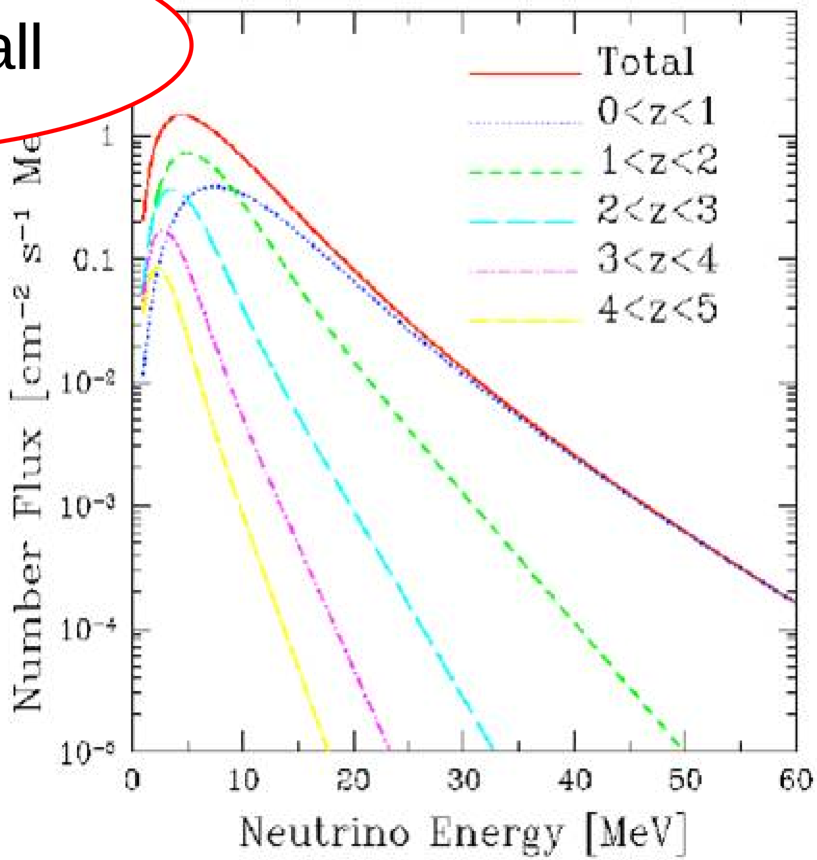
~1 deg. pointing accuracy.

Detection of supernova neutrinos at nearby galaxies.

Supernova Relic Neutrinos

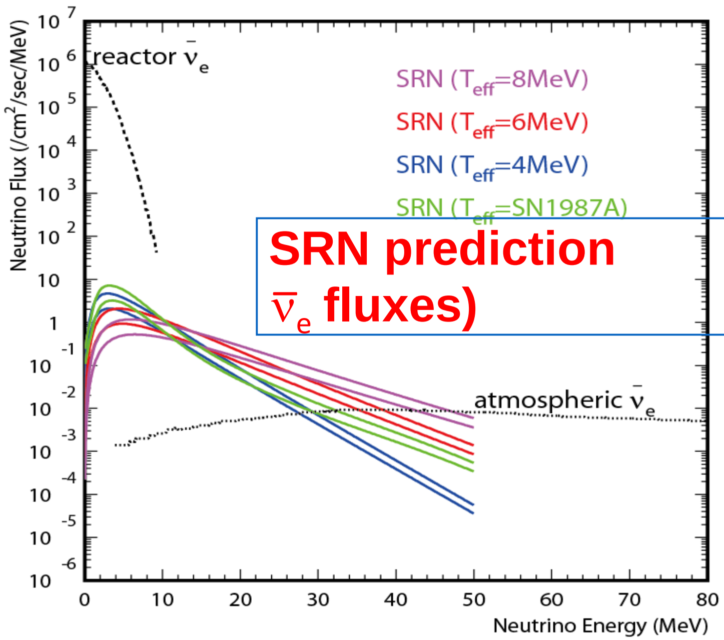
~10^{10} stars/galaxy ×~10^{10} galaxy×0.3%(massive star->SN) ~*O*(10^{17})SNe



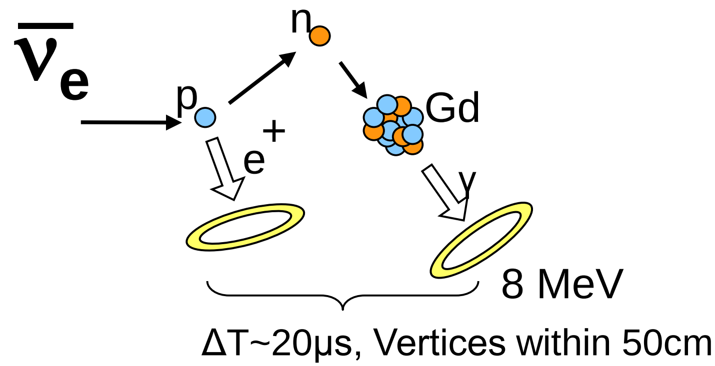


S.Ando, Astrophys.J. 607, 20(2004)

SK-Gd project for Supernova Relic Neutrino



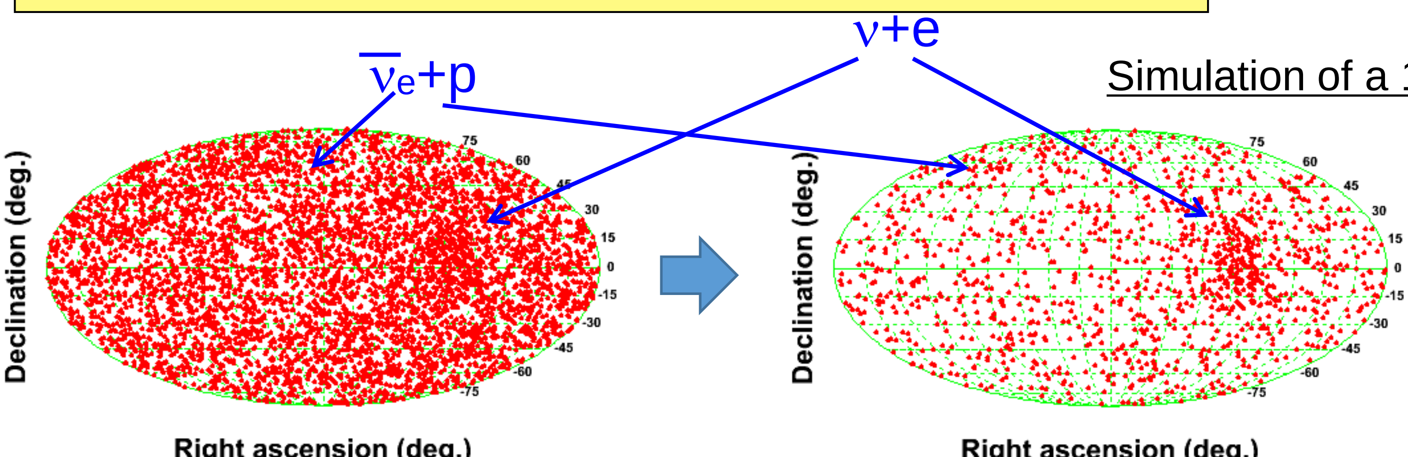
Open widow for SRN at 10-30MeV
Expected rate 1.3 -6.7 events/year/22.5kt(10-30MeV)



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

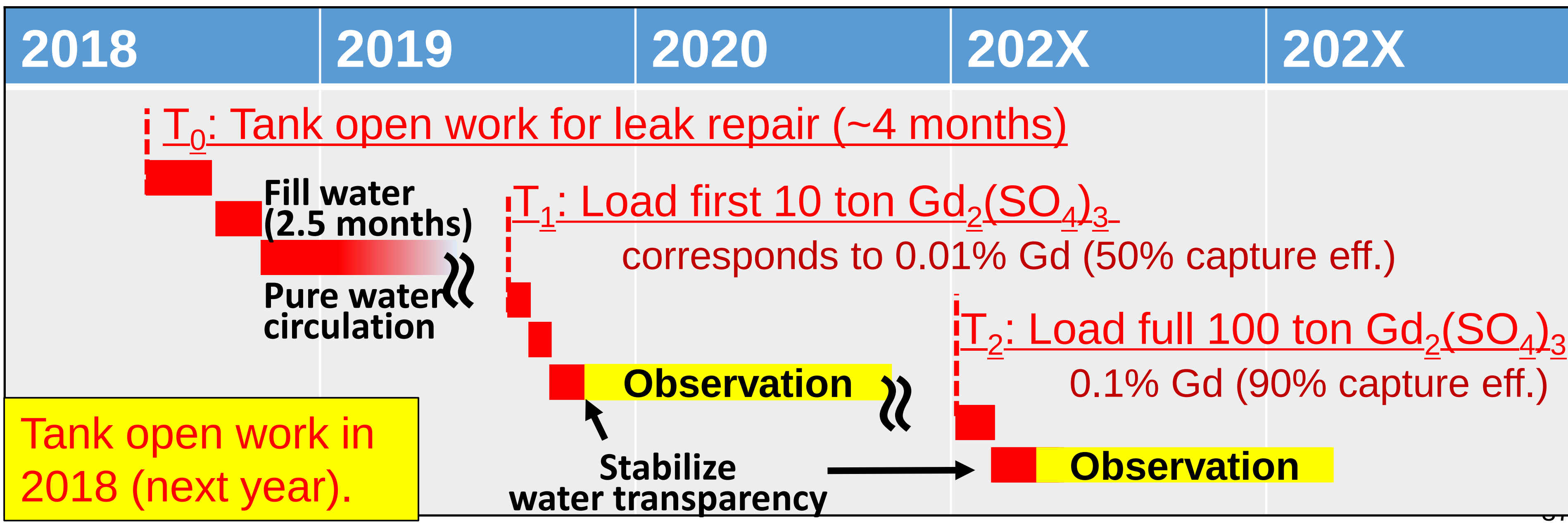
Simulation of a 10kpc supernova



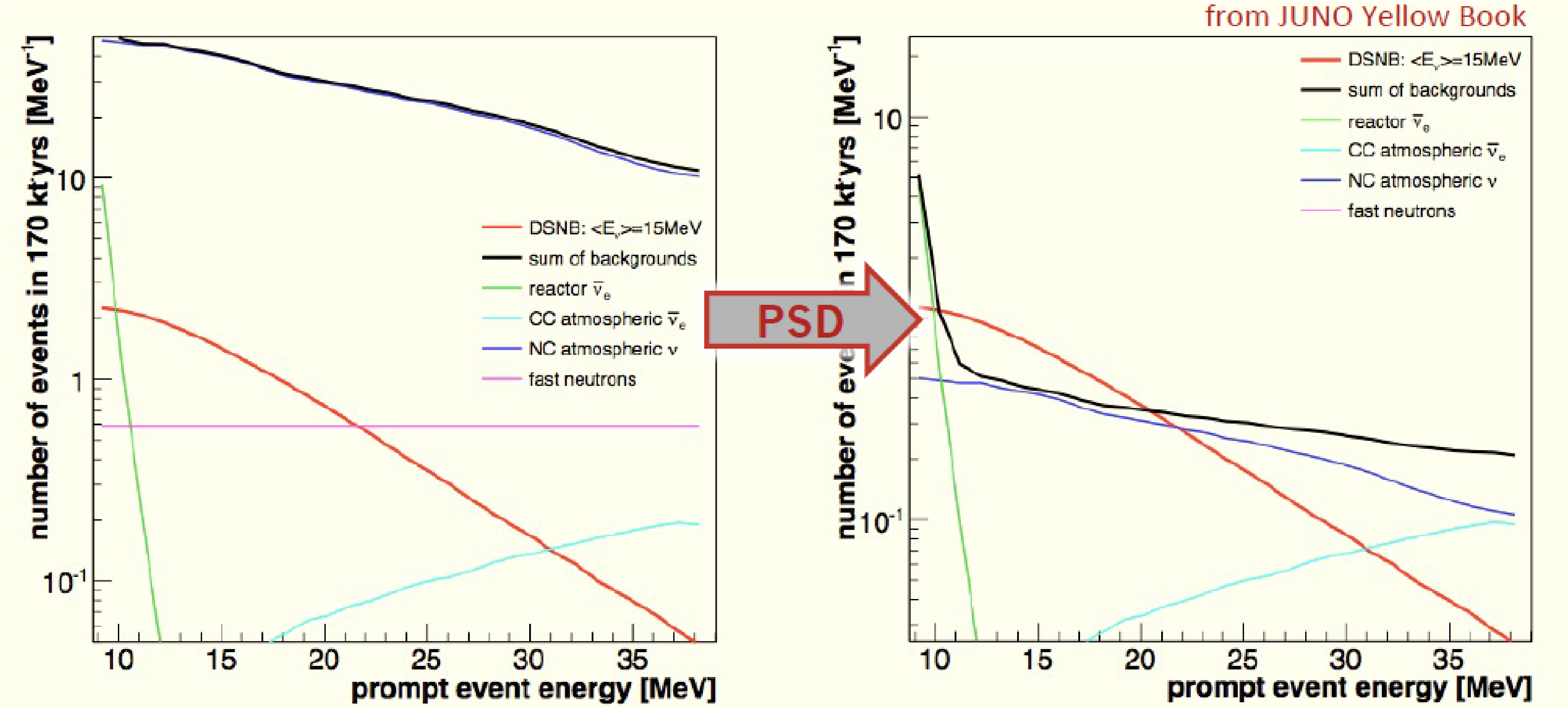
Preparation and plan for SK-Gd project

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.



JUNO: Expectation for supernova relic neutrinos



before PSD:

- atmospheric ν NC reactions
- fast neutrons

dominate the DSNB signal

after PSD:

- atm. NC & FN greatly reduced
- reactor & atmospheric IBDs define observation window

From M. Wurm, International Symposium on "Revealing the history of the universe with underground particle and nuclear research 2016"

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.
- The supernova detectors in the world now are able to obtained detailed information to reveal explosion mechanism.
- SK-Gd and JUNO for supernova relic neutrinos will start in a few years.