Supernovae Conference, Kyoto, October 31, 2013

Detection of supernova Neutrinos

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SN1987A

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Neutrino emission from core collapse supernova

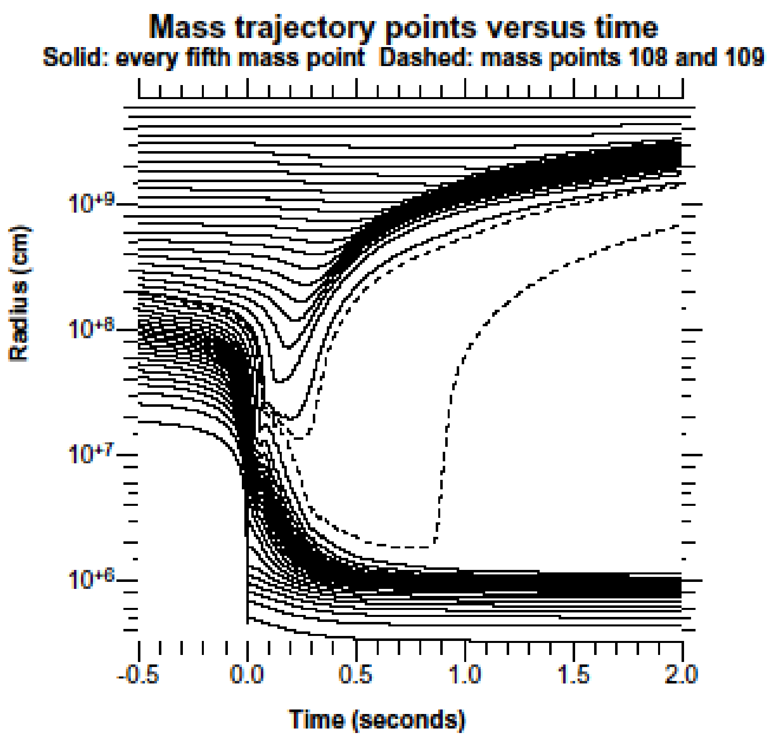
Released gravitational energy: ~3×10^{53} erg

Neutrinos carry almost all (99%) of the energy.

So, neutrino detection is important to investigate energy flow of the core collapse.

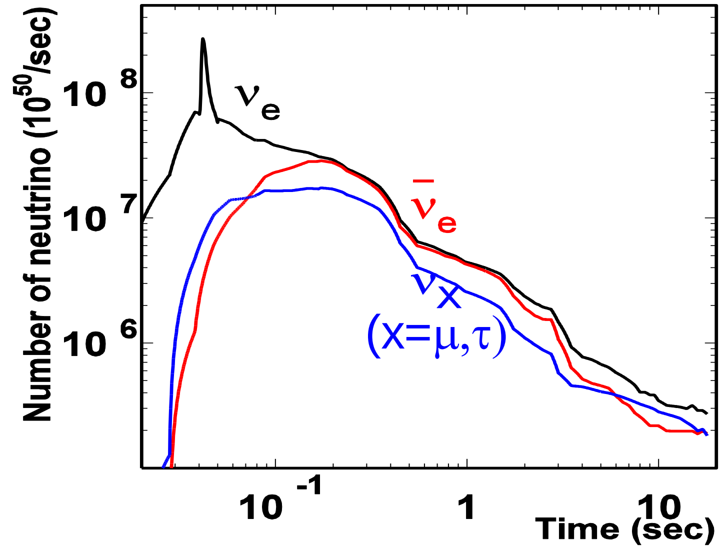
Livermore simulation

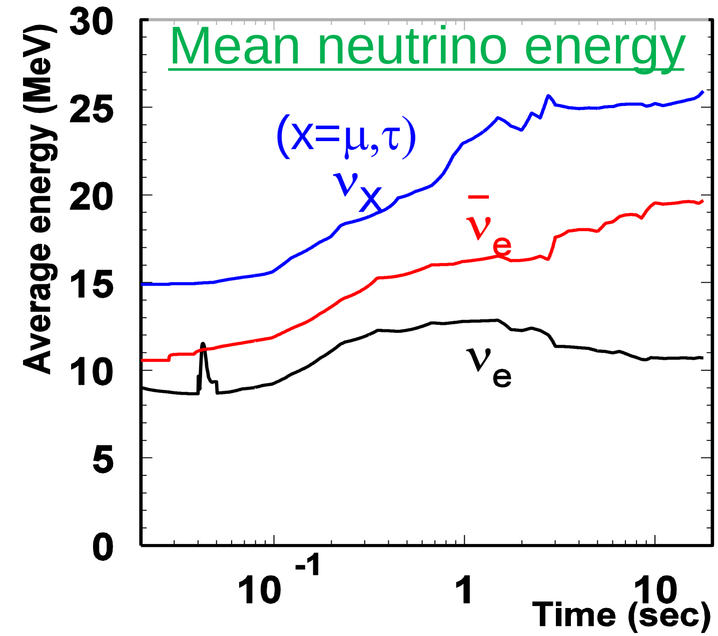
(often used for signal estimation for neutrino detectors)



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

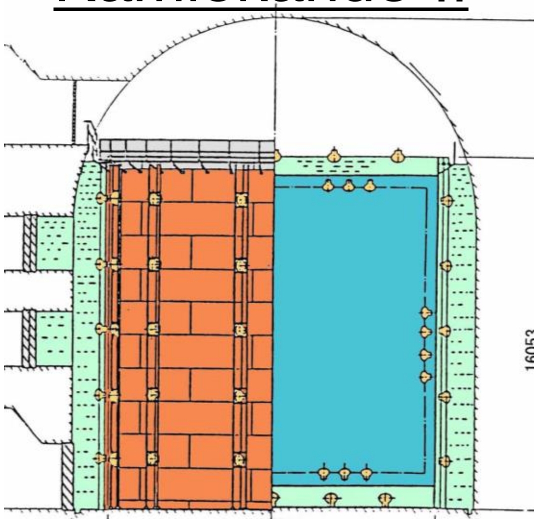
Expected time profile



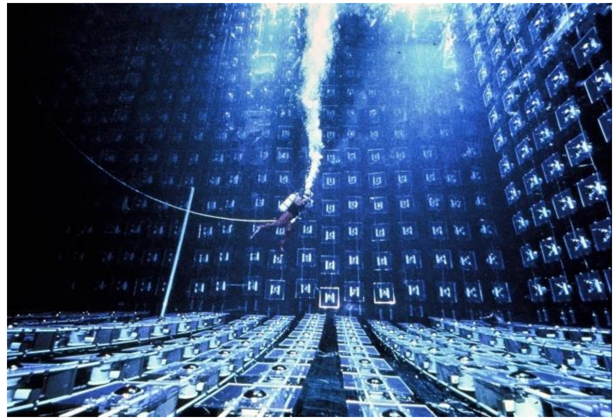


SN1987A: supernova at LMC(50kpc)

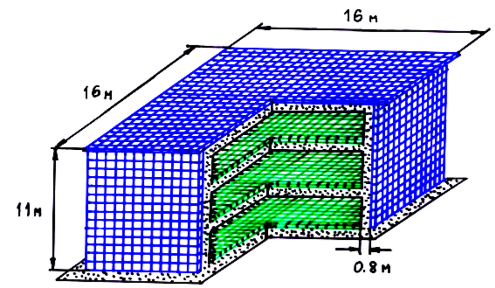
Kamiokande-II



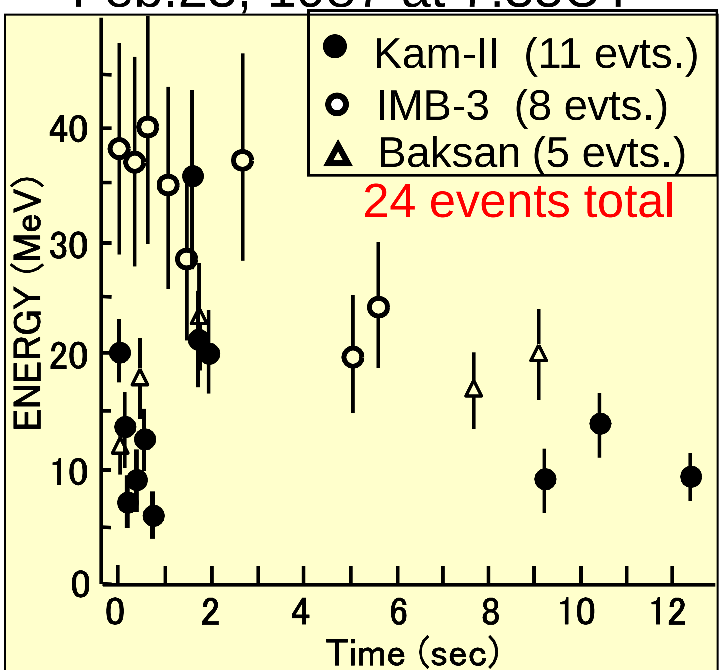
IMB-3



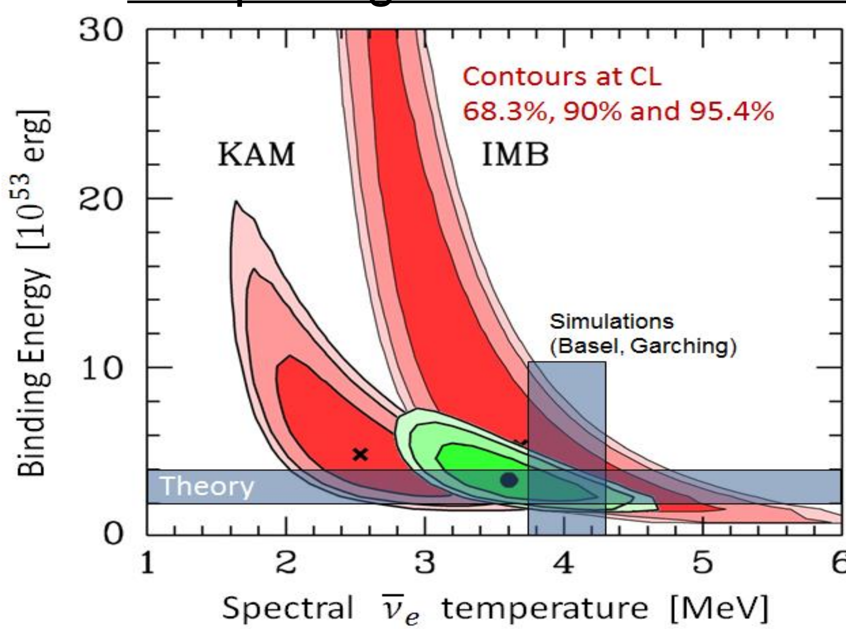
BAKSAN



Feb.23, 1987 at 7:35UT

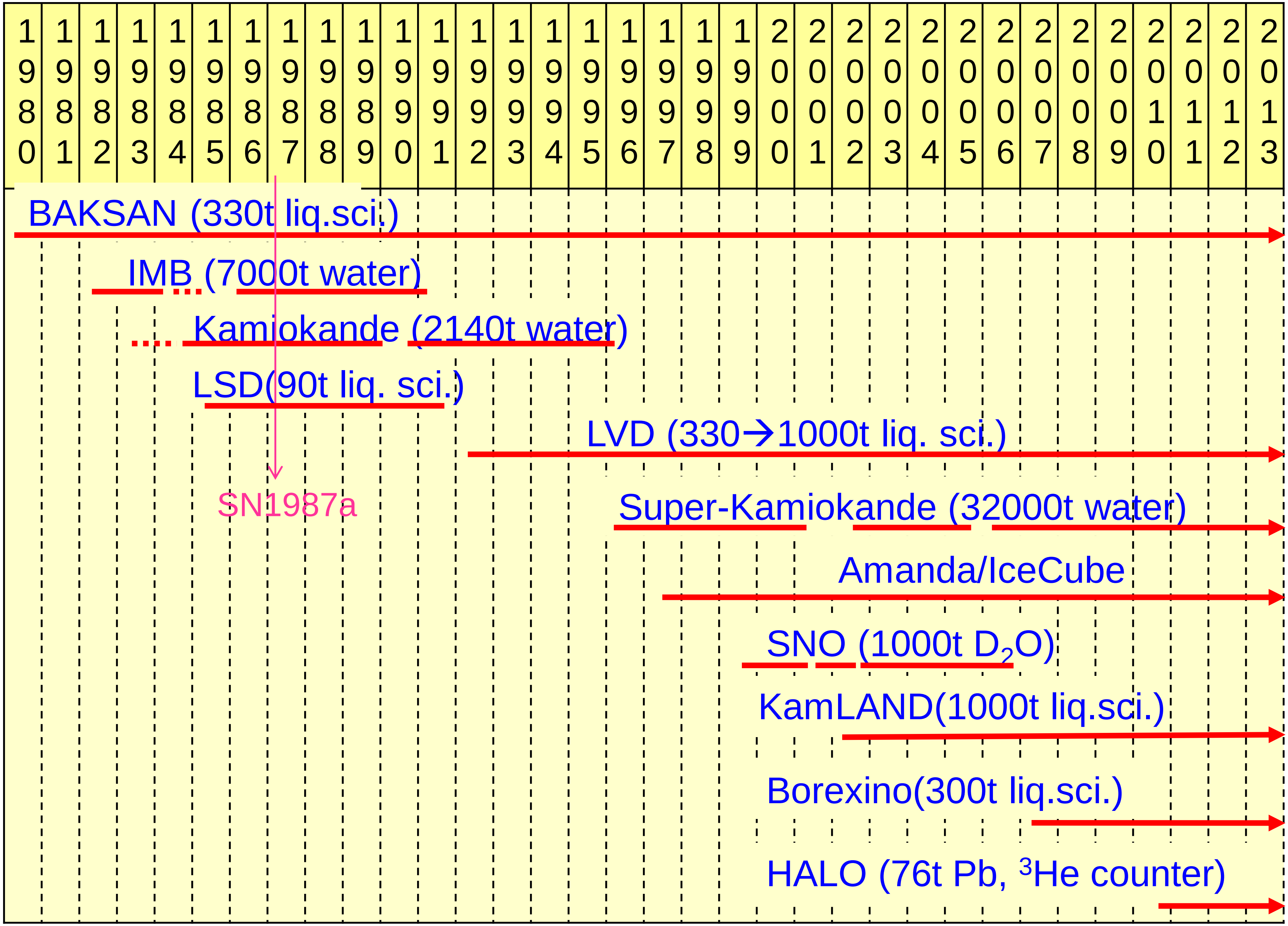


Interpreting SN 1987A Neutrinos



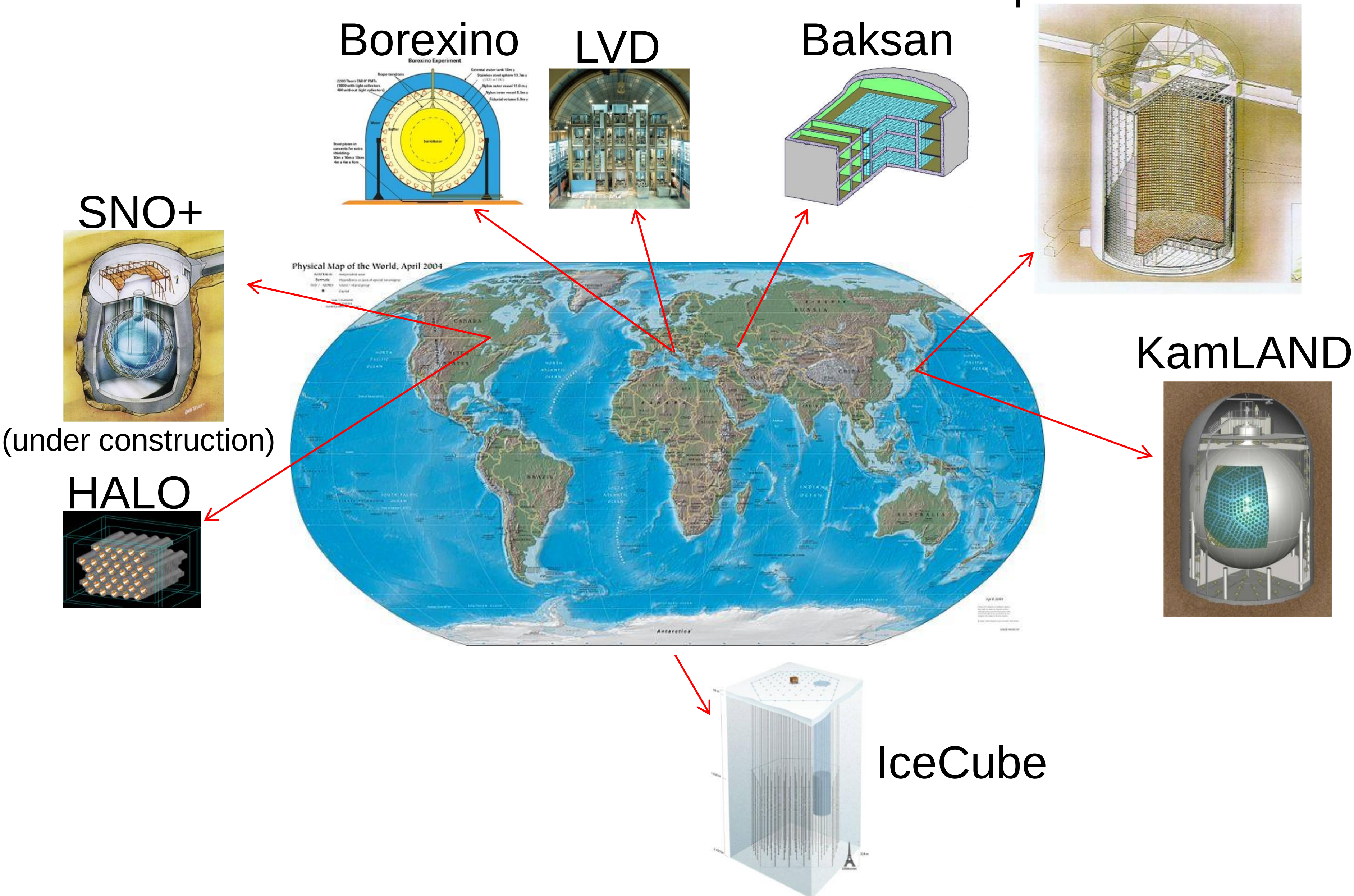
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

History of supernova detectors

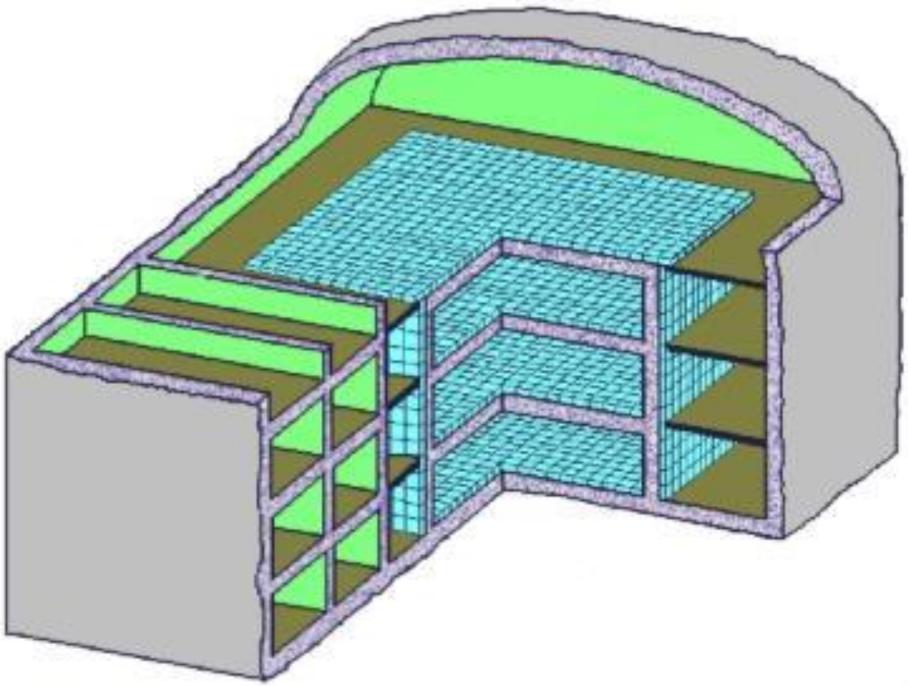


Supernova burst detectors in the world

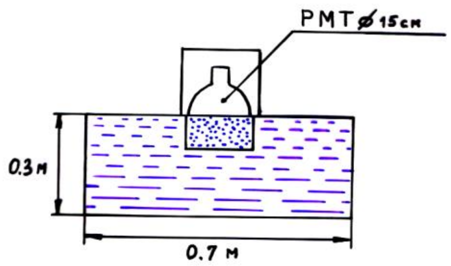
(running and near future experiments)



The Baksan underground scintillation telescope (Russia)



Each detector



E.N.Alexeyev, L.N.Alexeyeva, astro-ph/0212499
A. Gaponenko et al., ICRC2013, Paper ID: 621

Total number of standard detectors…………..3150

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

~100 $\overline{\nu}_e p \rightarrow e^+ n$ events expected for 10 kpc SN.
Running since 1980 with ~90% live time.

No candidate for 28 years' observation time from 1980 to 2013.
Upper limit of SN rate: < 0.082 /yr

From E.N.Alexeyev, A. Gaponenko

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.

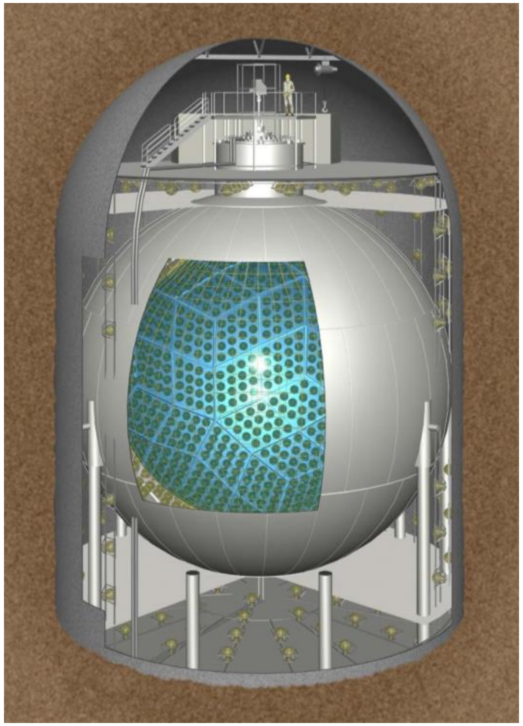
No candidate for 19.3 years from 1992 to 2013.
Upper limit of SN rate: < 0.12 /yr

C.Vigorito et al., ICRC2013, Paper ID: 453

From W.Flugione

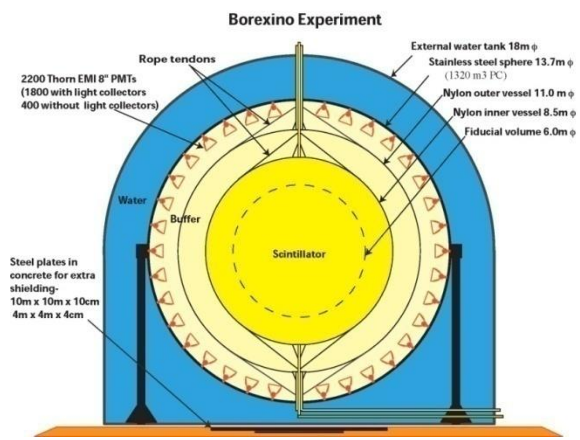
Single volume liquid scintillator detectors

KamLAND
(Kamioka, Japan)



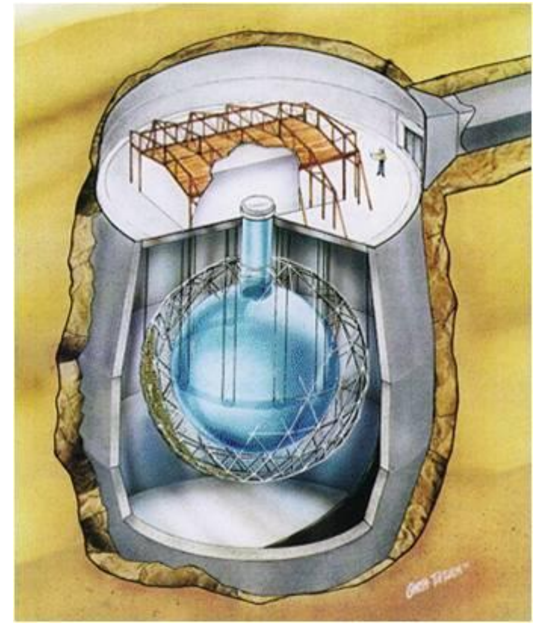
1000ton liq.sci.
Running since 2002.

Borexino
(Gran Sasso, Italy)



300ton liq.sci.
Running since 2007.

SNO+
(SNO Lab.,Canada)



1000ton liq.sci.
Under construction.

From K.Inoue, G.Bellini, M.Chen

Liquid scinitillator detectors

Expected number of events(for 10kpc SN)

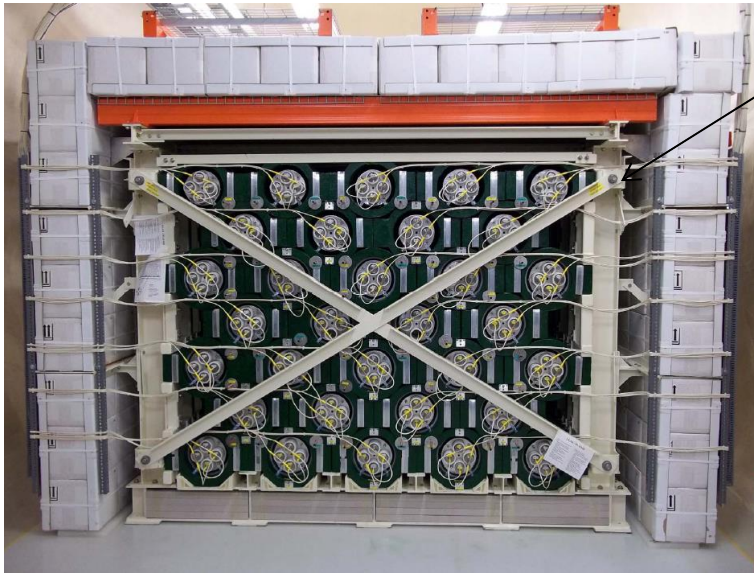
Events/1000 tons

- Inverse beta($\bar{\nu}_e + p \rightarrow e^+ + n$) : ～300 events
  Spectrum measurement with good energy resolution, e.g. for spectrum distortion of earth matter effect.
- CC on ^{12}C ($\nu_e + {}^{12}C \rightarrow e + {}^{12}N({}^{12}B)$) : ～30 events
  Tagged by $^{12}N(^{12}B)$ beta decay
- Electron scattering ($\nu + e^- \rightarrow \nu + e^-$) : ～20 events
- NC γ from ^{12}C ($\nu + {}^{12}C \rightarrow \nu + {}^{12}C + \gamma$): ～60 events
  Total neutrino flux, 15.11MeV mono-energetic gamma
- ν+p scattering（$\nu + p \rightarrow \nu + p$）: ～300 events
  Sensitive to all types of neutrinos.
  (Independent from neutrino oscillation)
  Spectrum measurement of higher energy component.

From K.Inoue, G.Bellini, M.Chen

HALO (SNOLAB, Canada)

SNO ^{3}He neutron detectors with lead target



$$\text{CC:} \quad \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$$

$$\text{NC:} \quad \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$$

HALO is using 76 tonnes of Pb

For a SN @ 10kpc†,

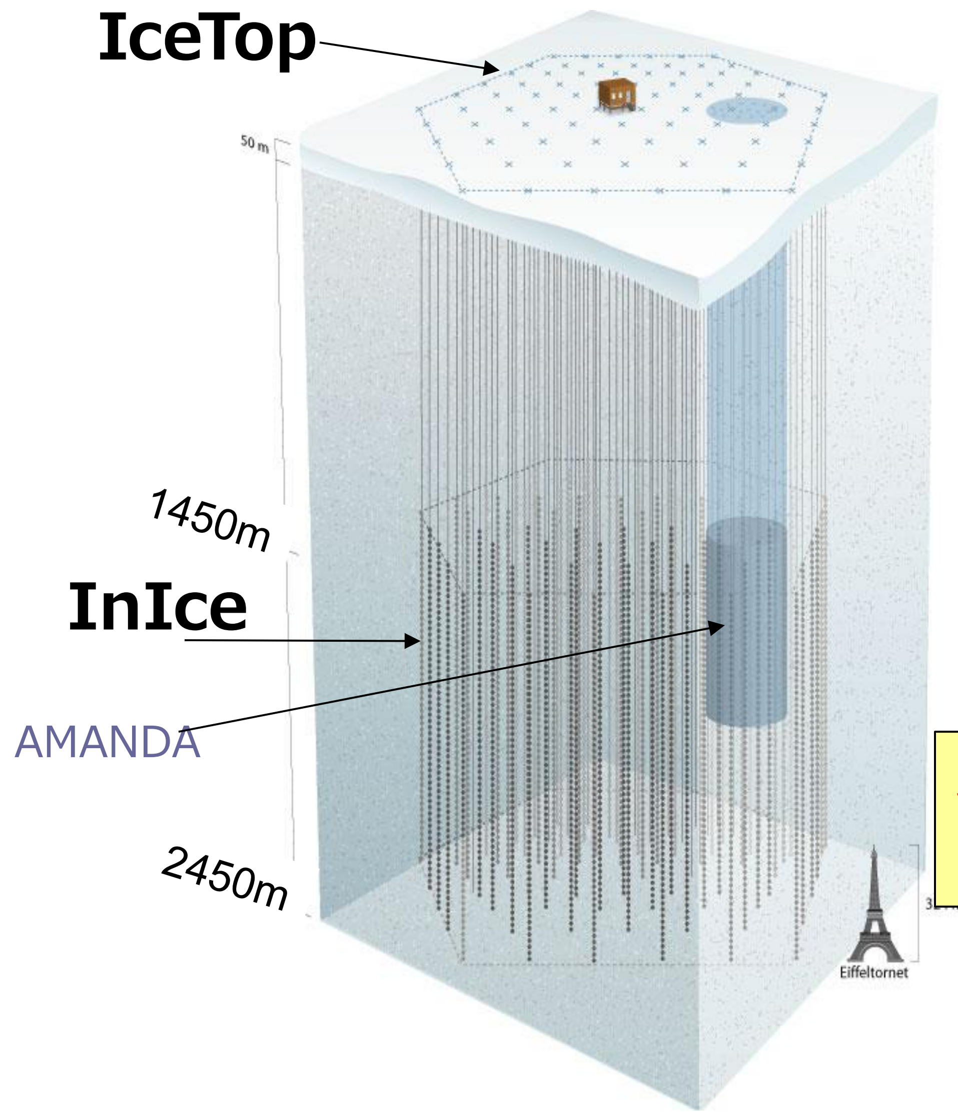
- Assuming FD distribution with T=8 MeV for ν_μ's, ν_τ's.
- 68 neutrons through ν_e charged current channels
- 20 neutrons through ν_x neutral current channels

~ 88 neutrons liberated;

with ~50% of detection efficiency, ~40 events expected.

From C.Virtue

IceCube (South pole)



Design Specifications

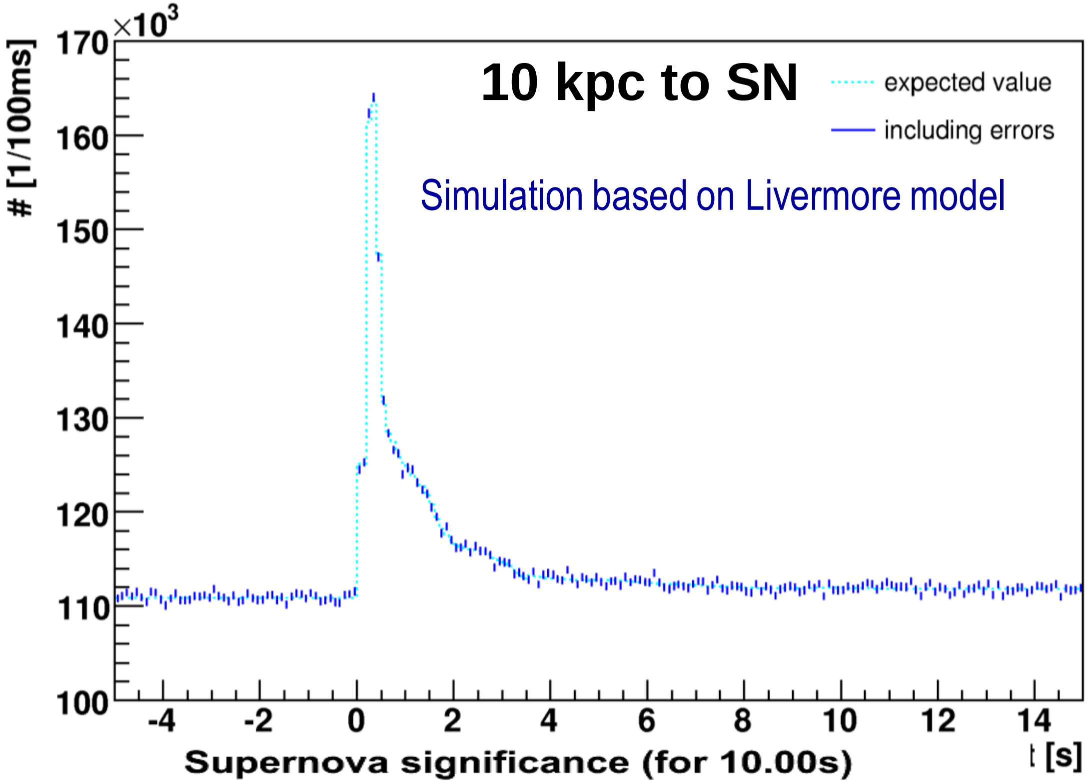
- Fully digital detector concept
- Number of strings – 75
- Number of surface tanks – 160
- Number of Optical modules (DOMs) – 4820
- Instrumented volume – 1 km^3

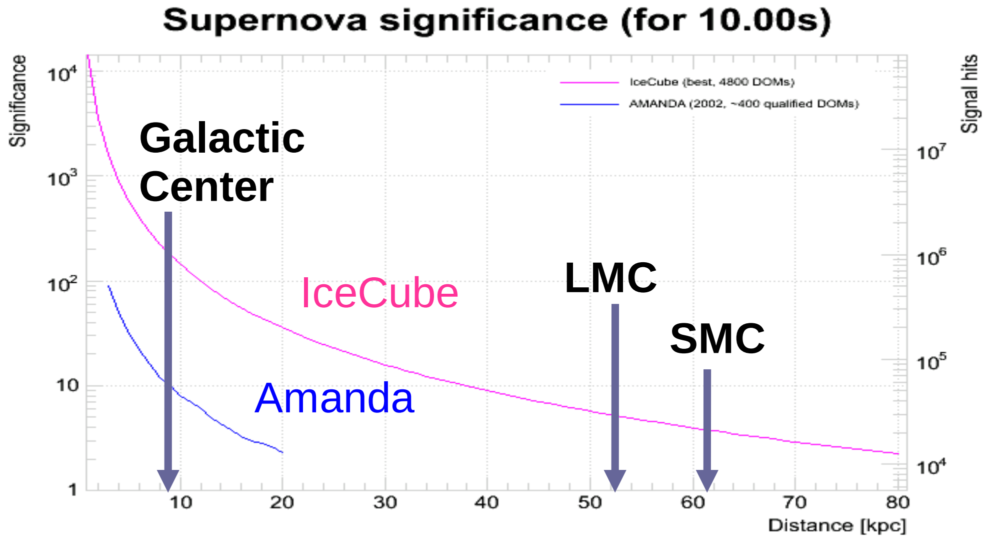
Supernova neutrinos coherently increase single rates of PMTs.

Running with full detector configuration since Dec., 2010.

From L.Koepke, S.Yoshida

IceCube signal





Advantage:

☞ high statistics
(0.75% stat. error
@ 0.5s and 100ms bins)

Good for fine time structures (noise low)!

Disadvantage:

☞ no pointing
☞ no energy
☞ intrinsic noise

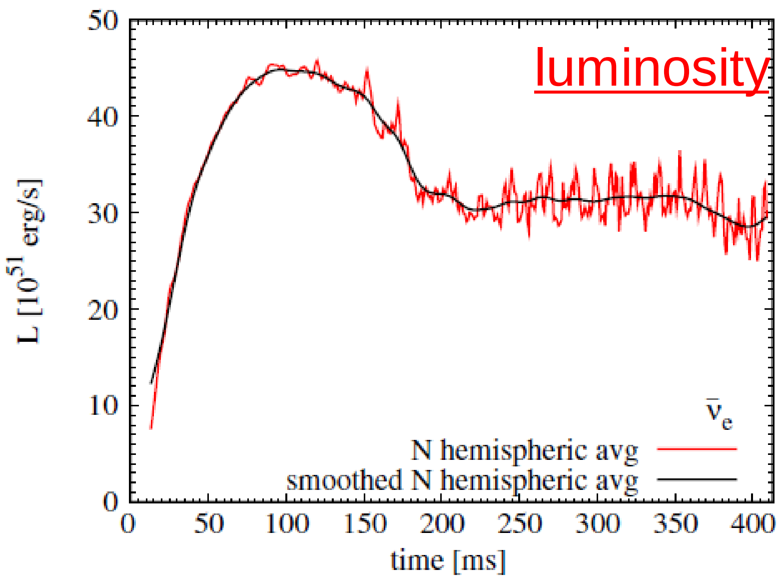
Significance:

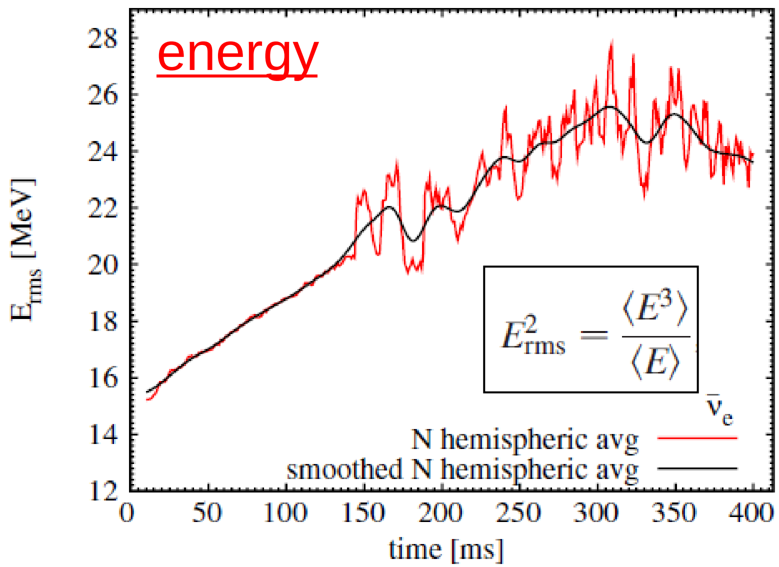
Galactic center: ~200 σ
LMC : ~5 σ
SMC : ~4 σ

From L.Koepke

High frequency signal variation by SASI

SASI=standing accretion shock instability

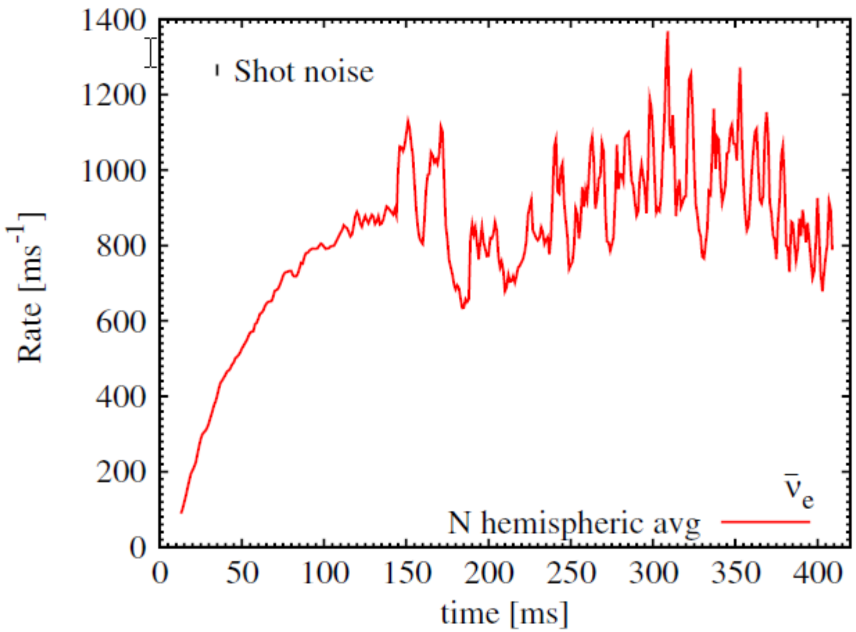




2-D(axially symmetric) simulation with PROMETHEUS-VERTEX code

Supernova at 10kpc

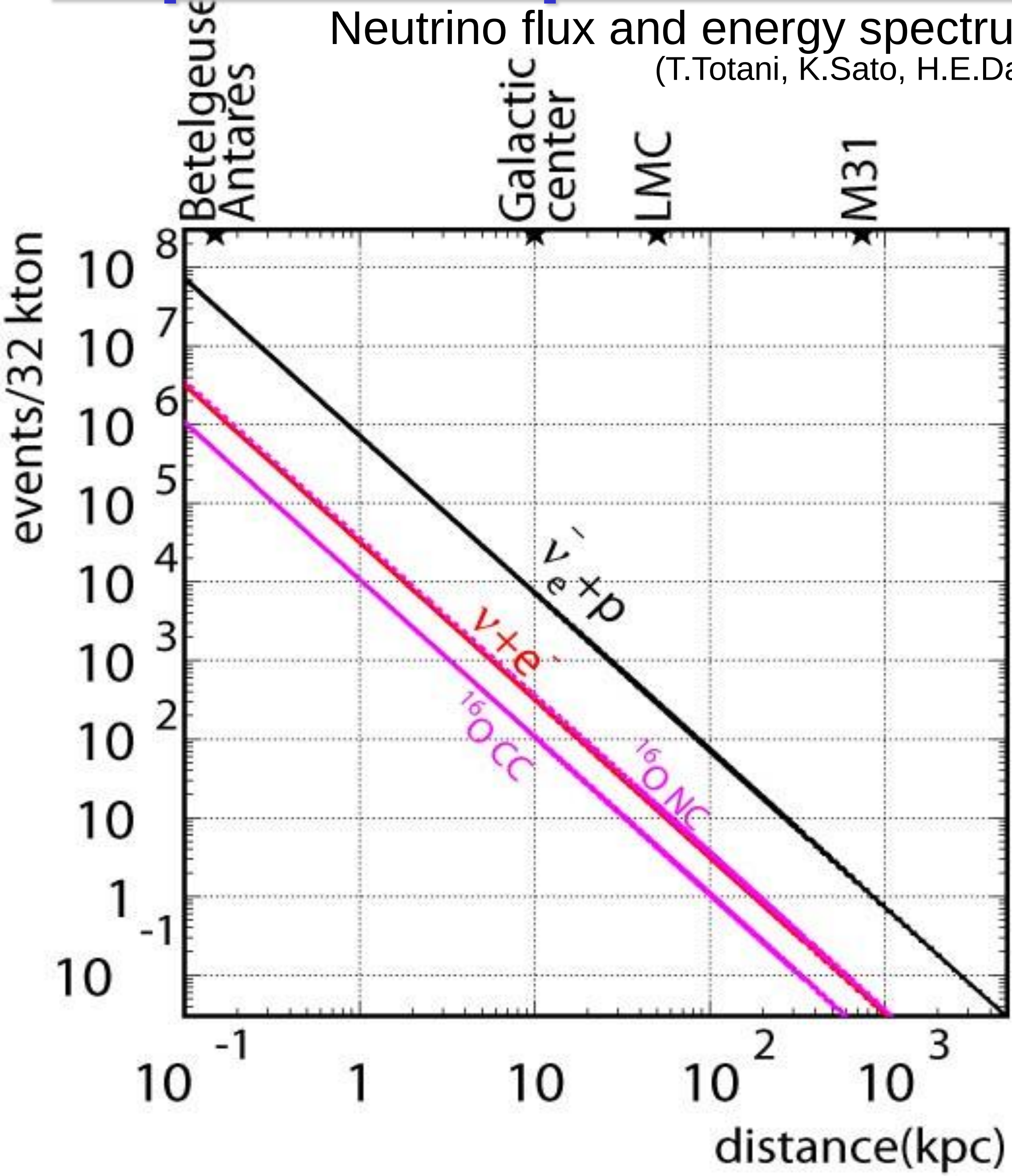
IceCube "event" rate

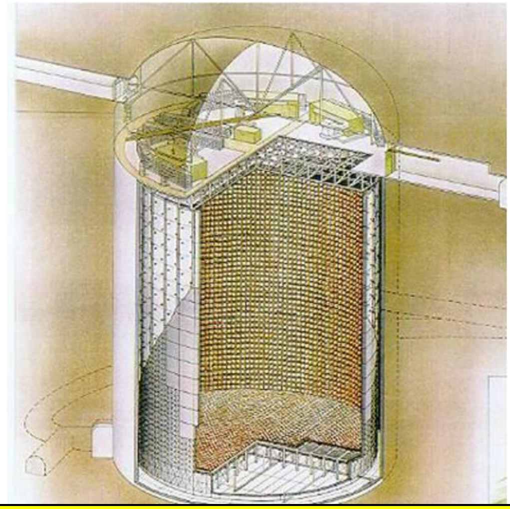


T.Lund et al., Phys. Rev. D82, 063007(2010).

Super-K: Expected number of events

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





32kton water Cherenkov

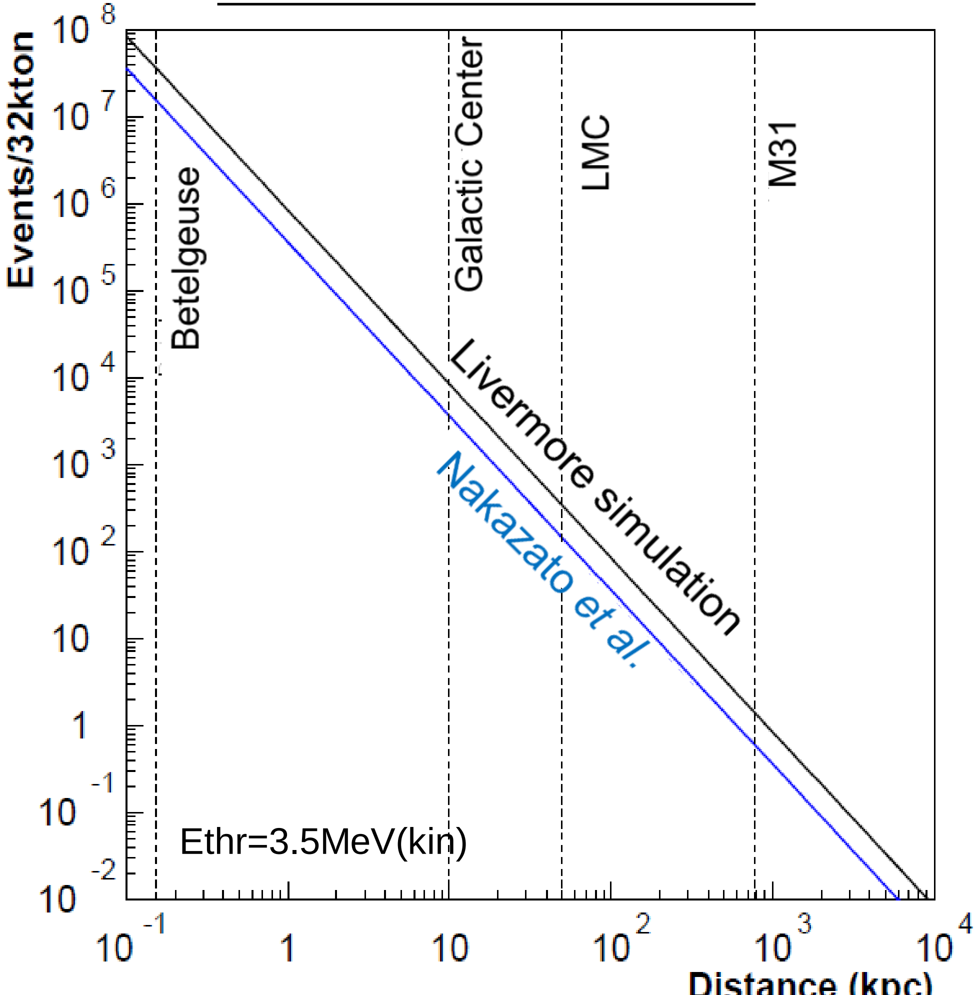
~7,300 $\overline{\nu}_e$+p events
~300 ν+e events
~360 ^{16}O NC γ events
~100 ^{16}O CC events
(with 5MeV thr.)
for 10 kpc supernova

Model dependence of Super-K prediction

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)

Total number of events



Number of events comparison

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

for 10 kpc supernova
32kton SK volume
4.5MeV(kin) threshold
without ν oscillation

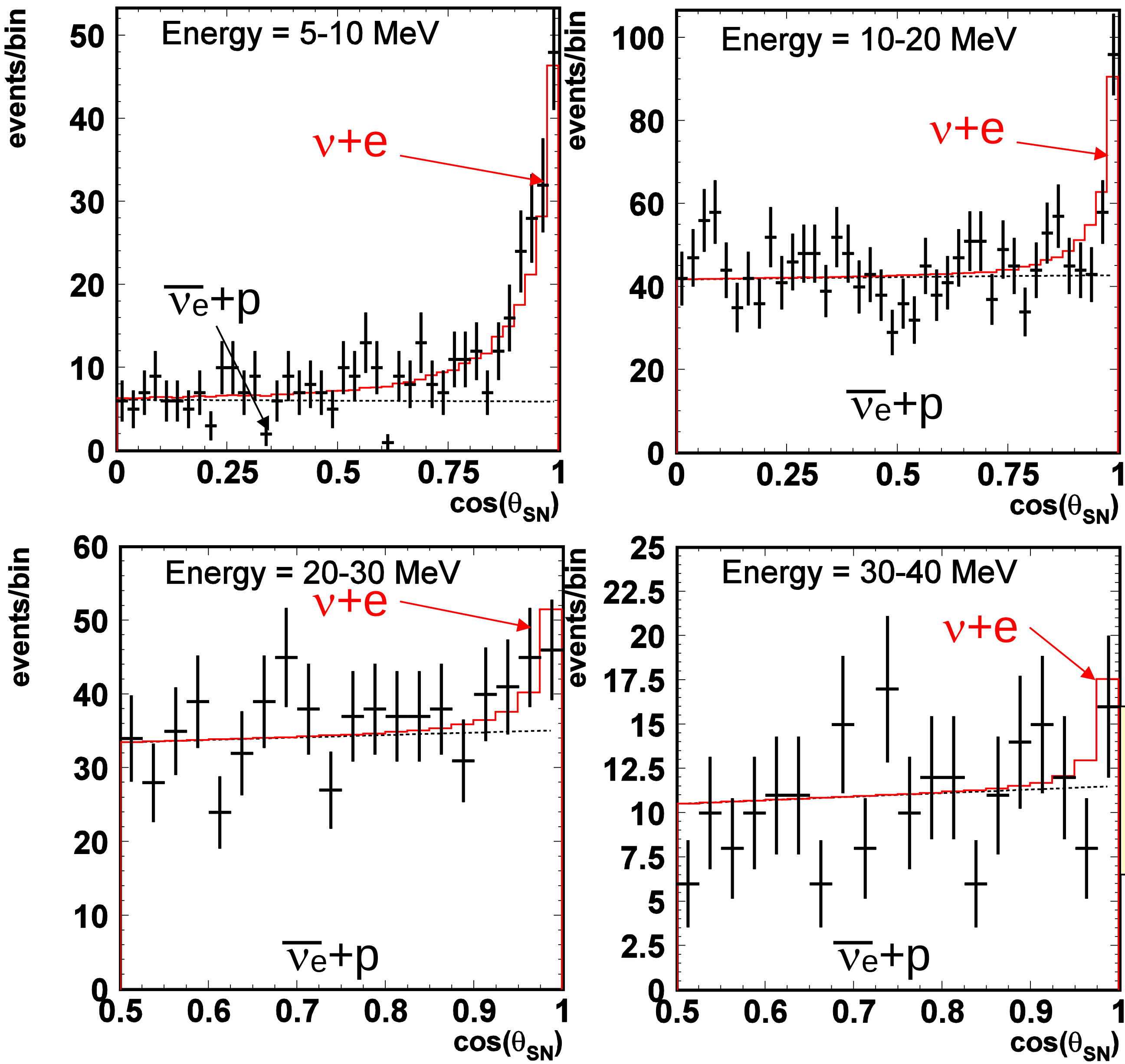
Factor of ~2 difference

Summary of current supernova ν detectors

of events expected for 10kpc. Directionality

Baksan (1980-)	330 ton liquid scintillator ~100 $\bar{\nu}_e p \rightarrow e^+ n$ events.	No
LVD (1992-)	1000 ton liquid scintillator. 840 counters 1.5m^3 each. 4 MeV thres., ~50% eff. for tagging decayed signal. ~300 $\bar{\nu}_e p \rightarrow e^+ n$ events.	No
Super-K (1996-)	32,000 tons of water target. ~7300 $\bar{\nu}_e p \rightarrow e^+ n$, ~300 $\nu e \rightarrow \nu e$ scattering events.	Yes
KamLAND (2002-)	1000 ton liquid scintillator, single volume. ~300 $\bar{\nu}_e p$, several 10 CC on ^{12}C, ~60 NC γ, ~300 $\nu p \rightarrow \nu p$	No
ICECUBE (2005-)	Gigaton ice target. By coherent increase of PMT single rates. High precision time structure measurement.	No
BOREXINO (2007-)	300 ton liquid scintillator, single volume. ~100 $\bar{\nu}_e p$, ~10 CC on ^{12}C, ~20 NC γ, ~100 $\nu p \rightarrow \nu p$	No
HALO (2010-)	SNO ^{3}He neutron detectors with 76 ton lead target. ~40 events expected.	No

Super-K: simulation of angular distribution

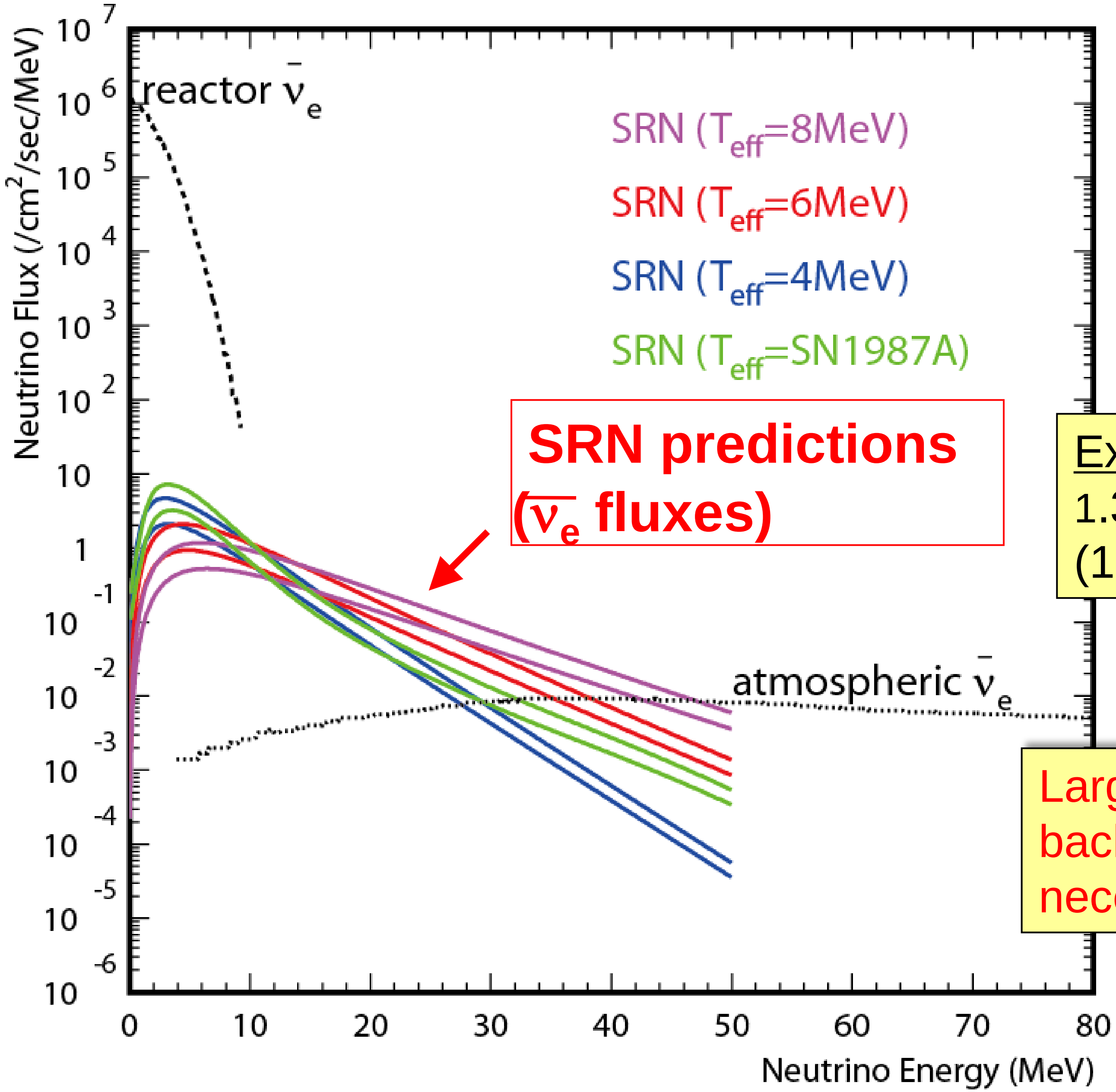


SN at 10kpc

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

Neutrino flux and spectrum from Livermore simulation

Supernova Relic Neutrinos



SRN flux from Horiuchi et al.
PRD, 79, 083013 (2009)

<u>Expected SRN events</u>
1.3 -6.7 events/year/22.5kt
(10-30MeV)

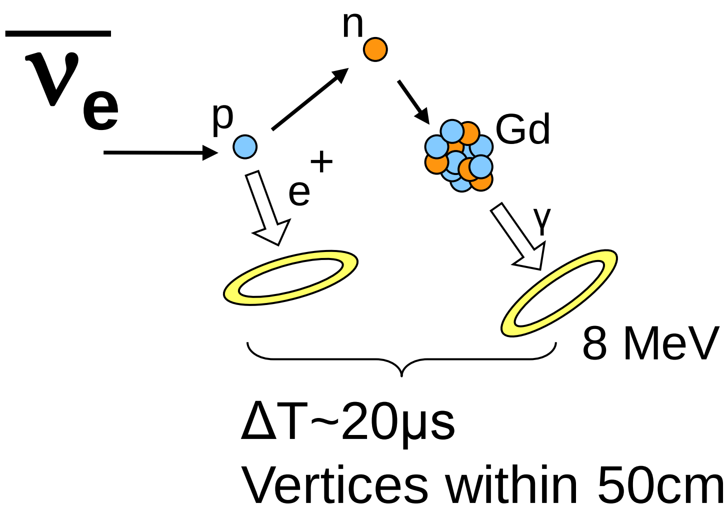
SK fiducial volume

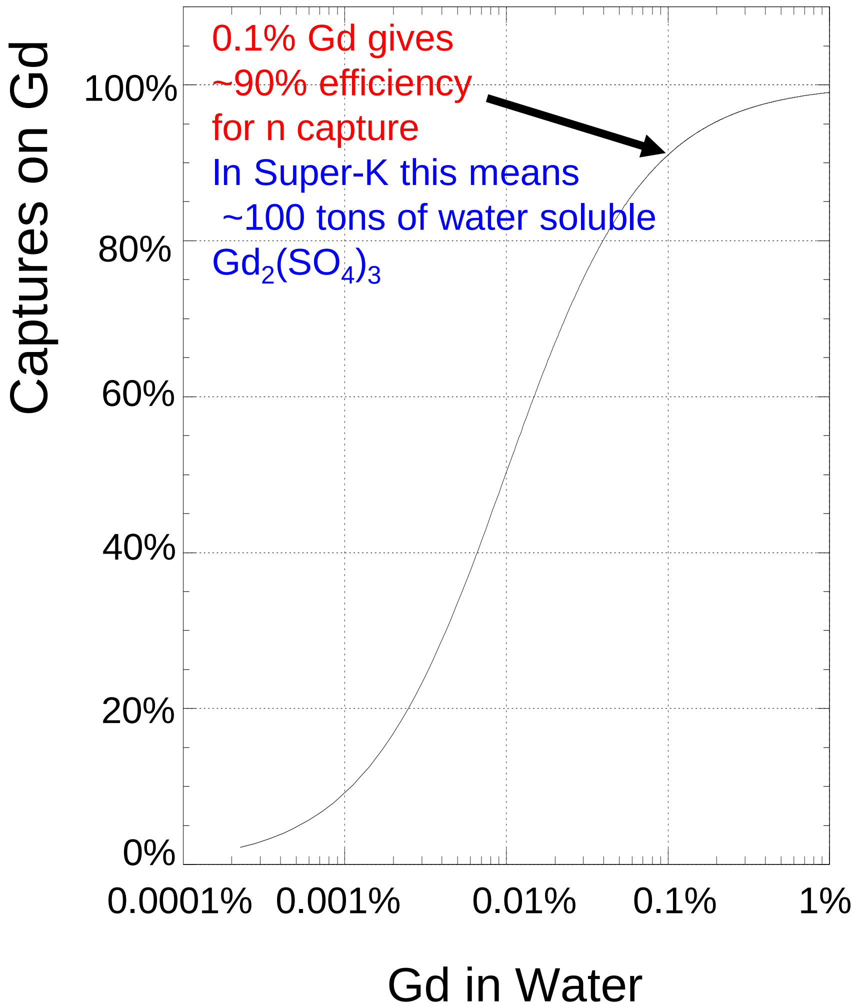
Large target mass and high background reduction are necessary.

GADZOOKS! project at Super-K

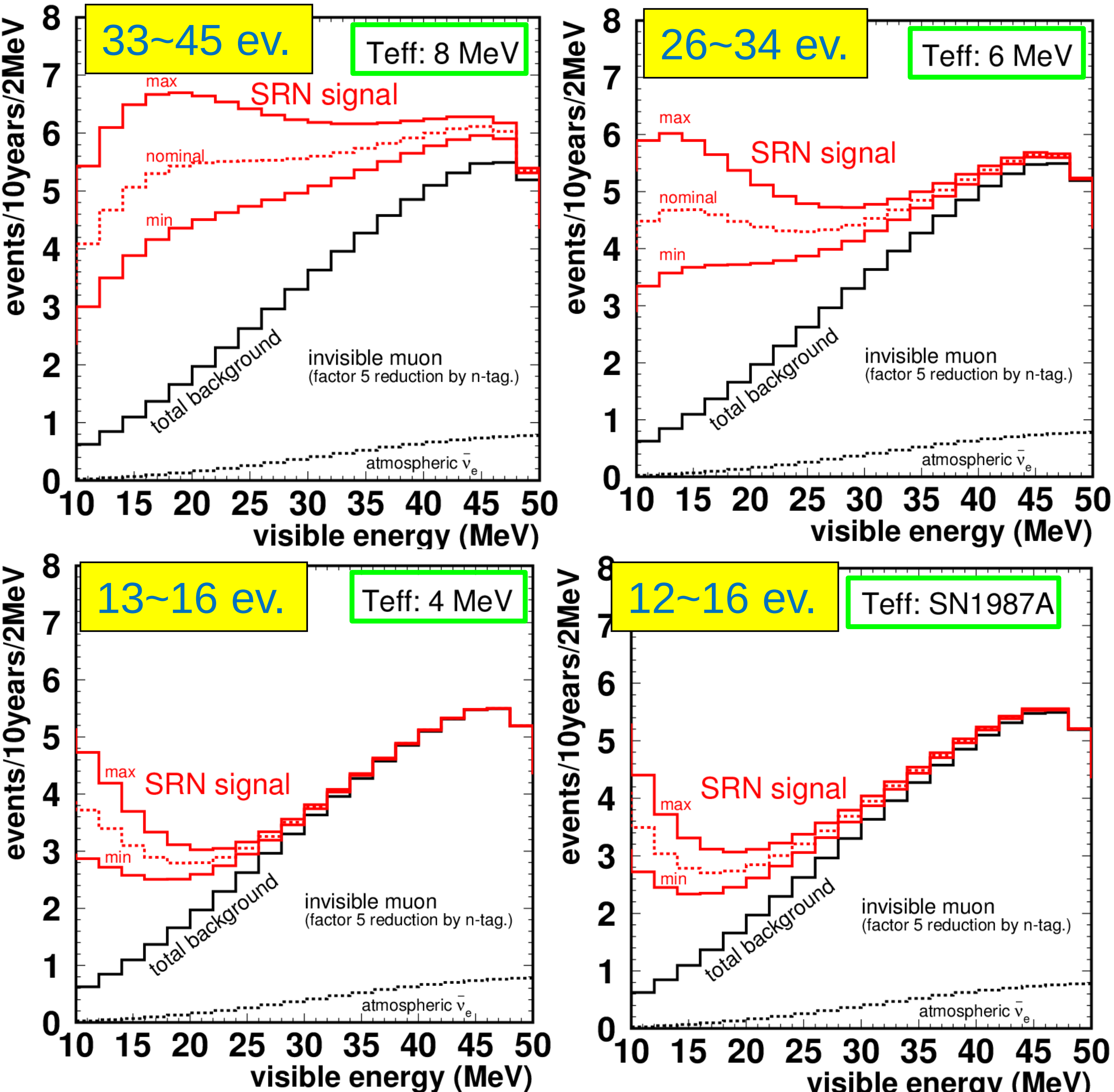
Identify $\overline{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.





Expected SRN signal and background at Super-K



Expect number of events in 10 years in E_{total} =10-30 MeV

Assuming

Capture efficiency of 90% and Gd gamma detection efficiency of 74%.

Invisible muon B.G. is 35% of the SK-IV invisible muon BG.

Min/nominal/Max are due to uncertainties in astronomy.

Background: ~18 ev.

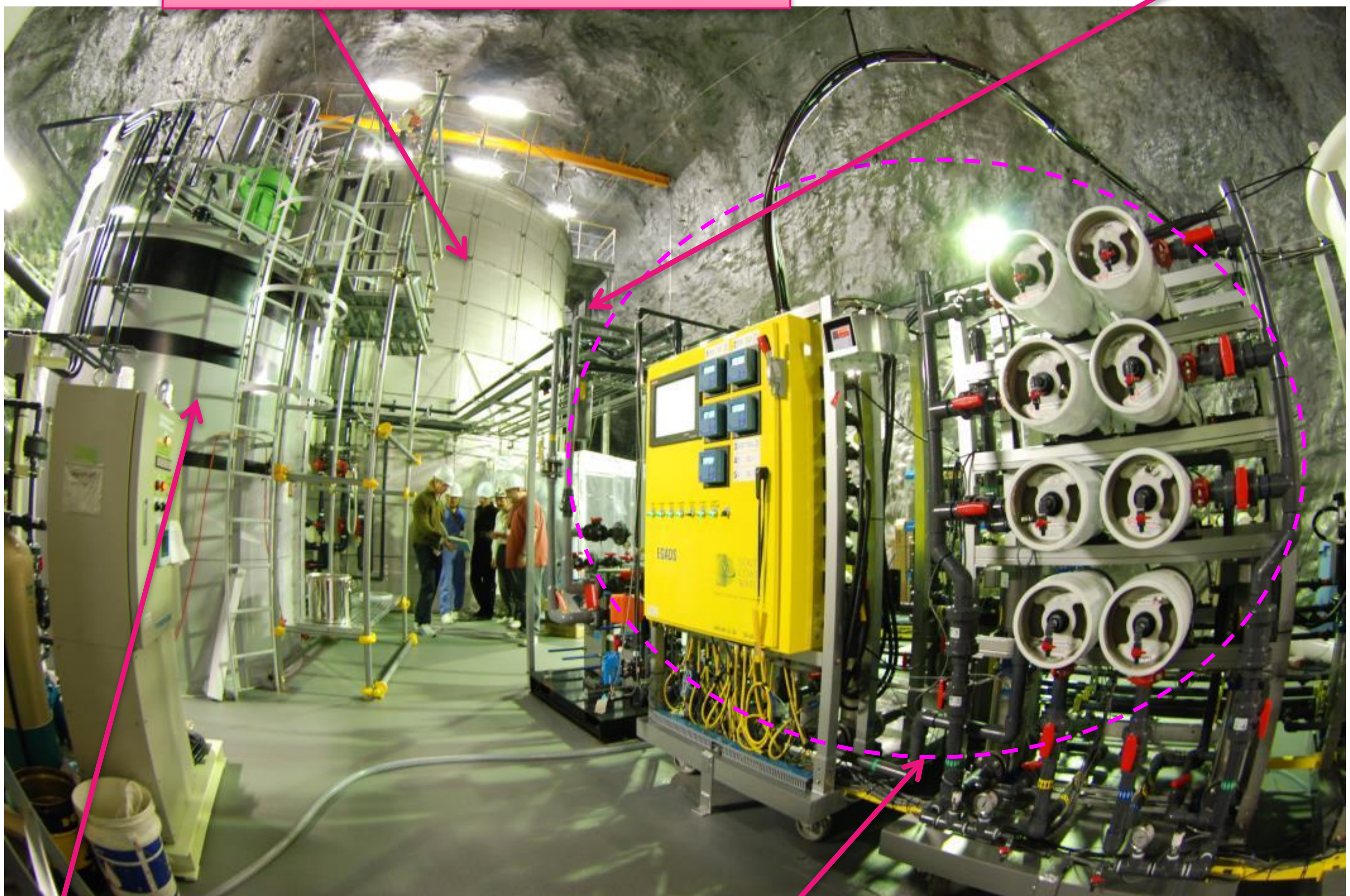
SRN flux from Horiuchi et al. PRD, 79, 083013 (2009)

EGADS

Evaluating Gadolinium's Action on Detector Systems

Transparency measurement (UDEAL)

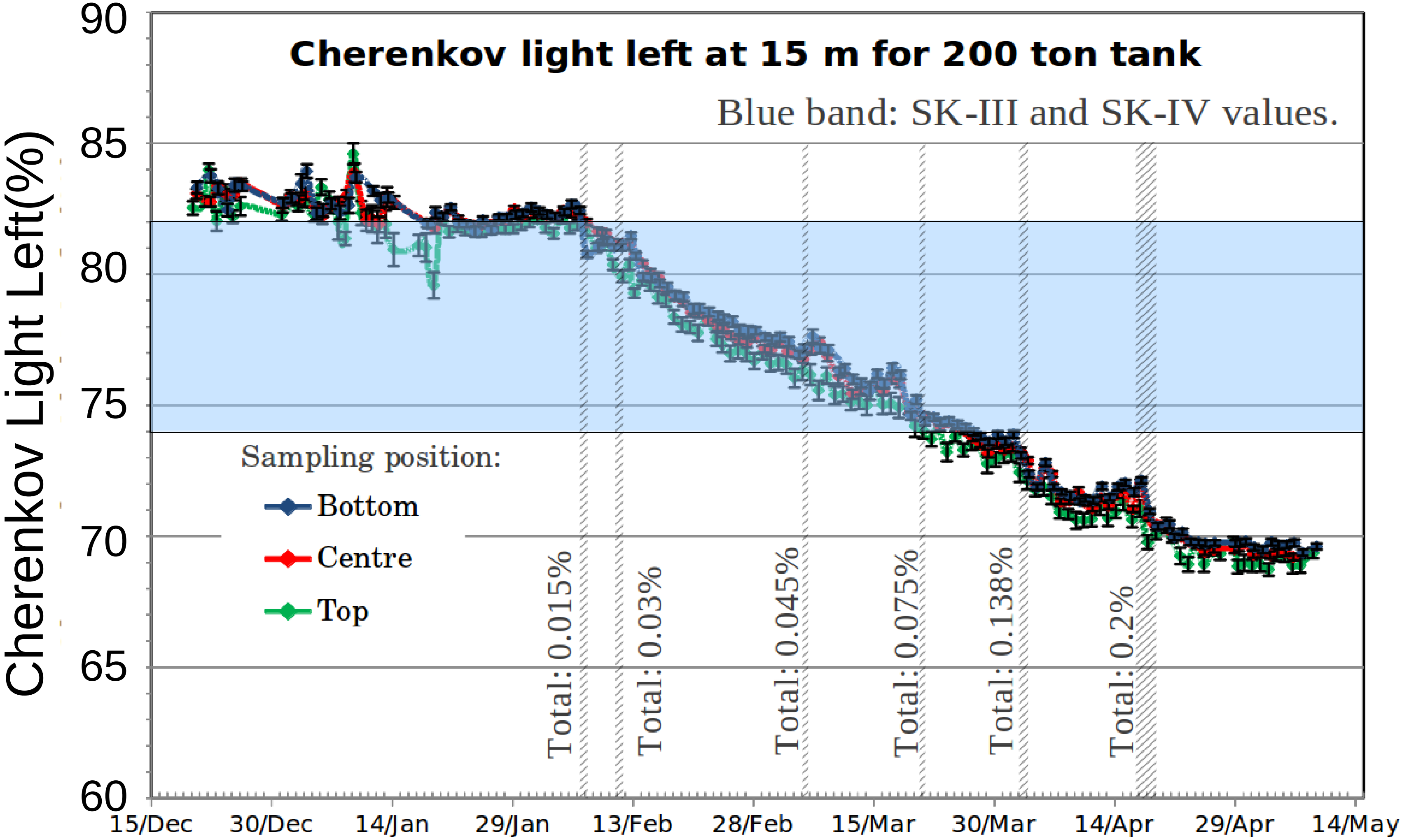
200 m^3 tank with 240 PMTs



15m^3 tank to dissolve Gd

Gd water circulation system (purify water with Gd)

Transparency of Gd-loaded water (before mounting PMTs)

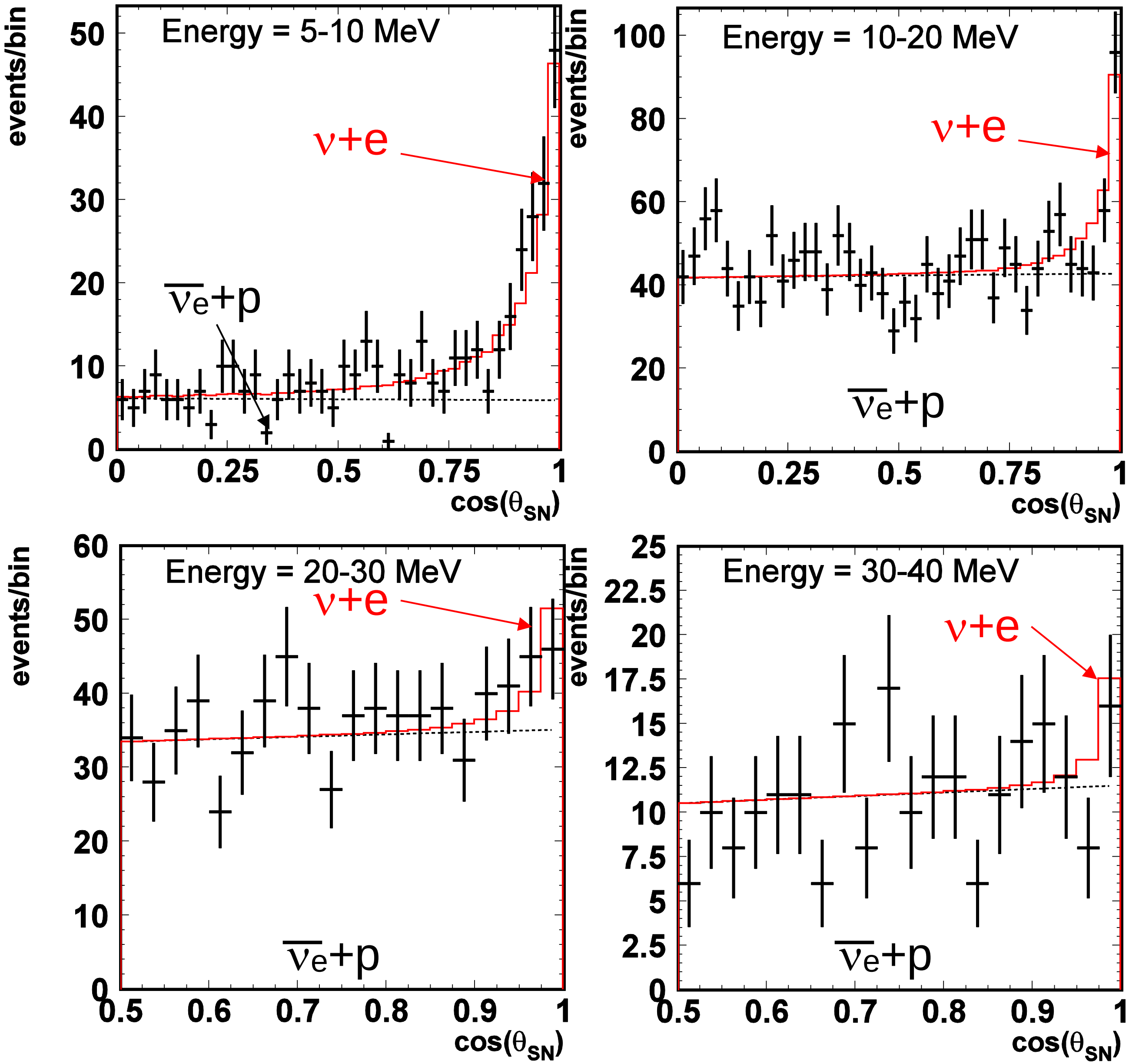


The light left at 15 m in the 200m^3 tank (stainless steel) was ~69% for 0.2% $Gd_2(SO_4)_3$, which corresponds to ~84% of pure water.

240 PMTs were mounted in the 200 m^3 tank in this summer.

Pure water circulation was started.
Gd-loaded test is expected start soon.

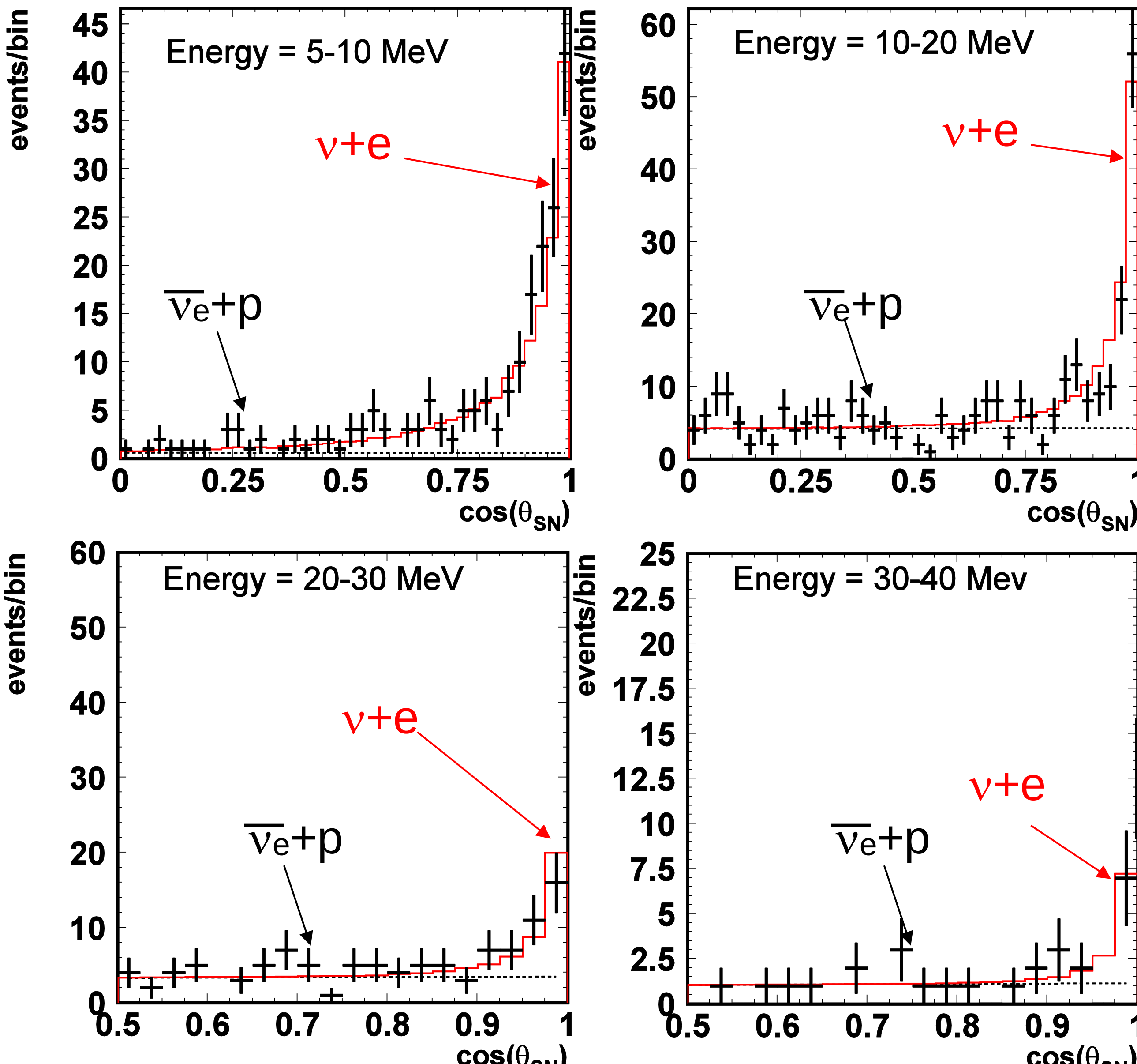
Super-K: Angular distribution (without Gd)



Without $\overline{\nu}_e p$ identification by neutron tagging

SN at 10kpc

Super-K: Angular distribution (with Gd)



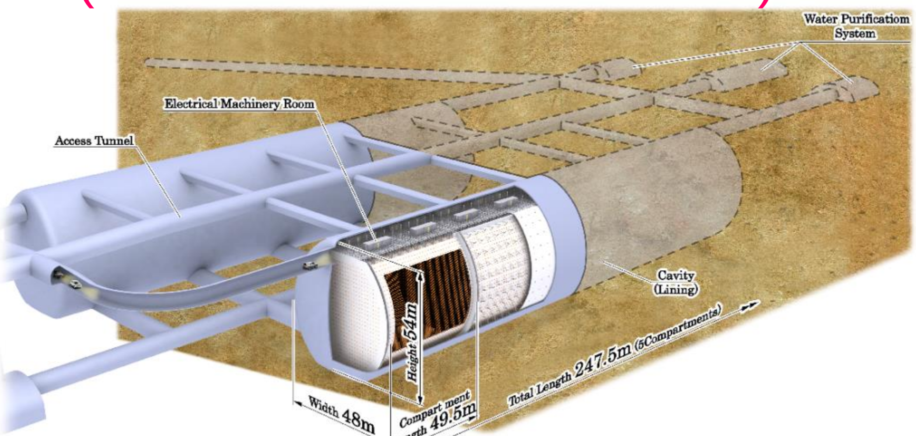
With $\overline{\nu}_e p$ identification by neutron tagging

Direction accuracy can be improved to ~3 degree.

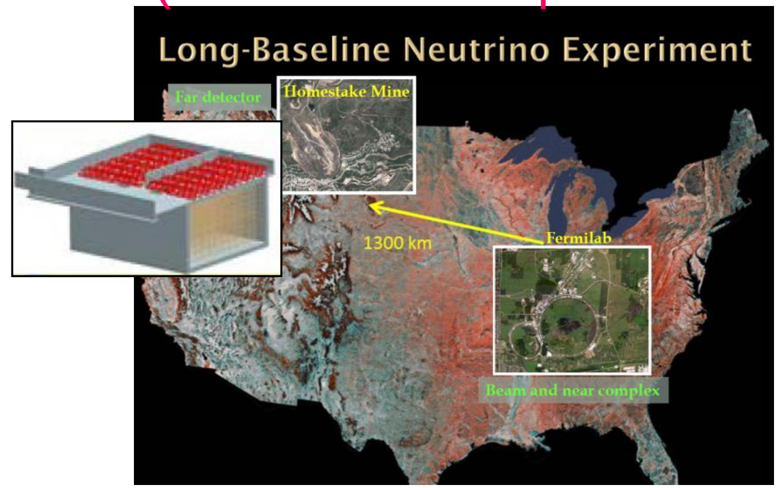
SN at 10kpc

Future Large Volume Detectors

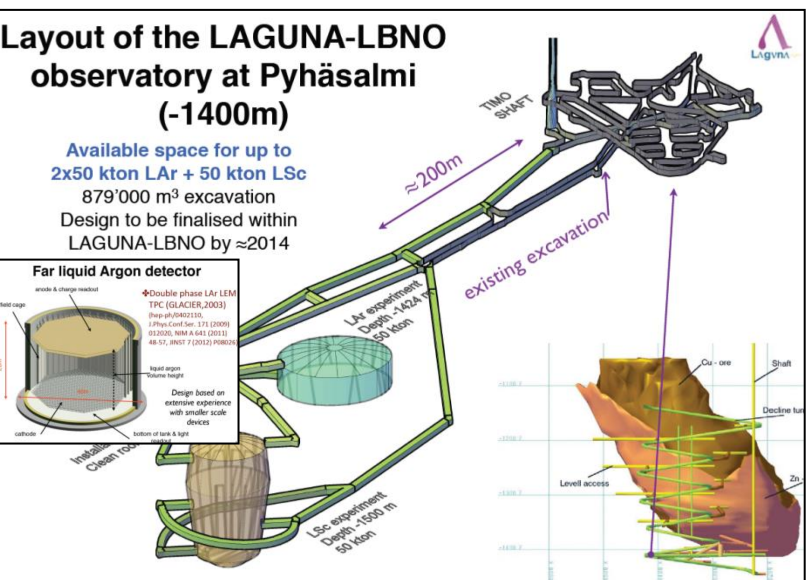
Hyper-Kamiokande
(0.74 Mton Water Cherenkov)



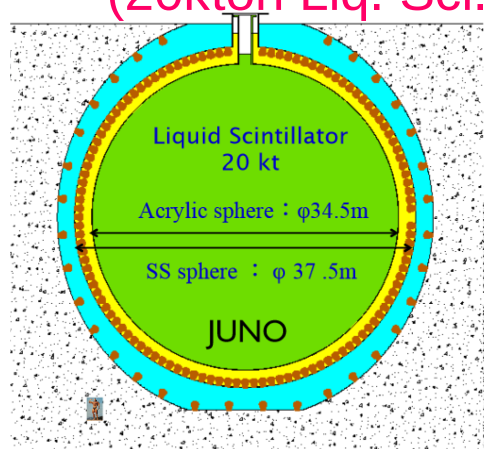
LBNE (US)
(10 – 34 kton Liq. Ar detector)



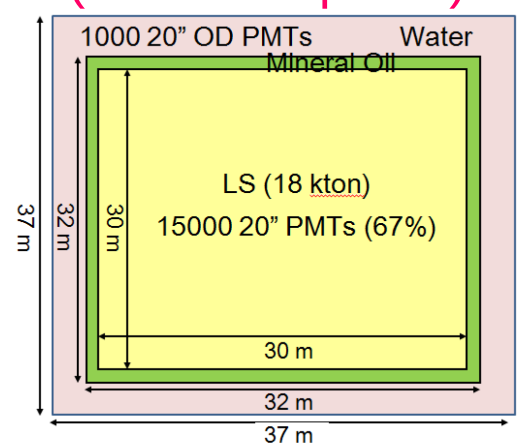
LBNO (Europe)
(20kton Liq. Ar, 50kton Liq. scintillator)



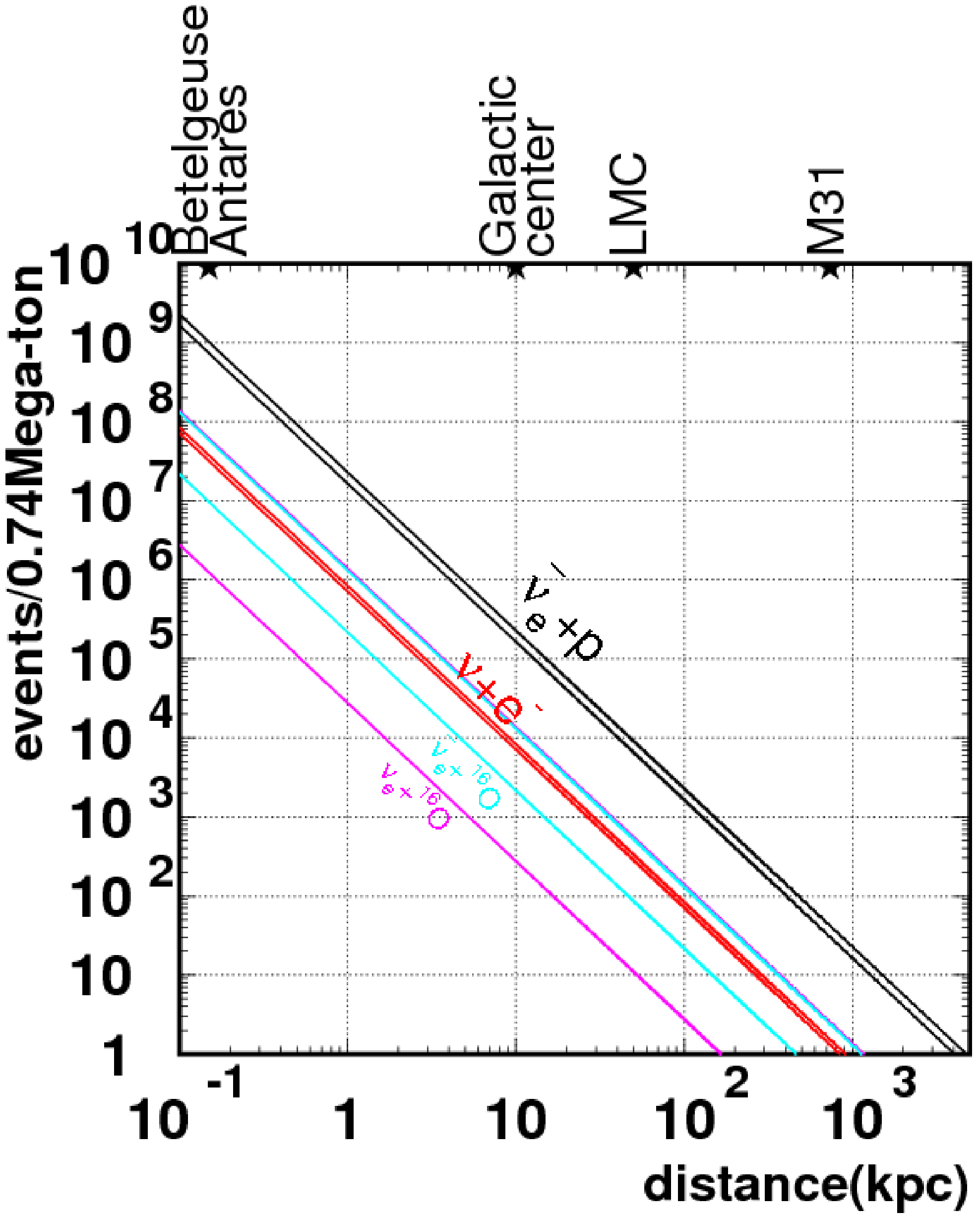
JUNO(China)
(20kton Liq. Sci.)



RENO-50(Korea)
(18kton Liq. Sci.)



Supernova events at Hyper-Kamiokande



~200,000 $\overline{\nu}_e$+p events

7,000~8000 ν+e events

~10,000 $\overset{(-)}{\nu}_e$+^{16}O events

for 10 kpc supernova

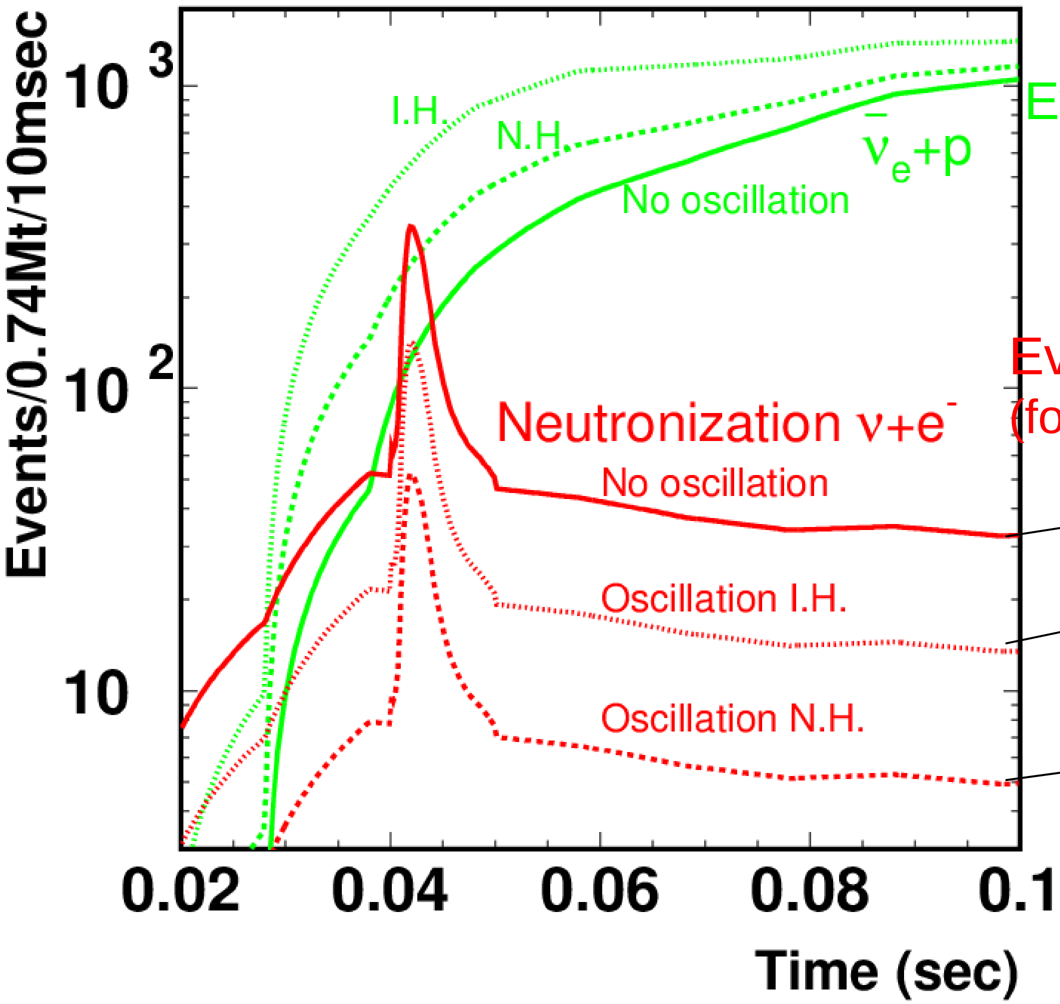
30~50 events even for M31 supernova

Each band covers, no osc., N.H. and I.H. cases

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

Neutrino flux and spectrum from Livermore simulation

SN at 10kpc



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)

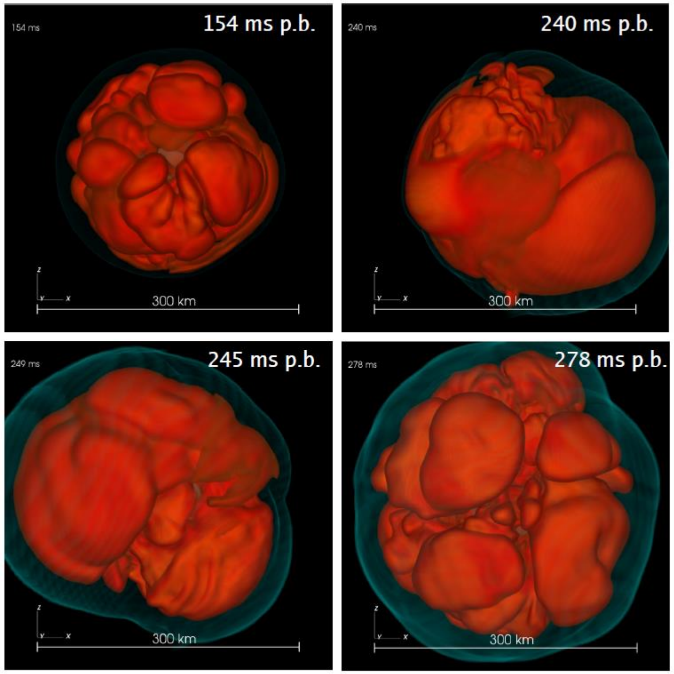
Number of events from neutronization burst is 20~130 events for SN@10kpc.

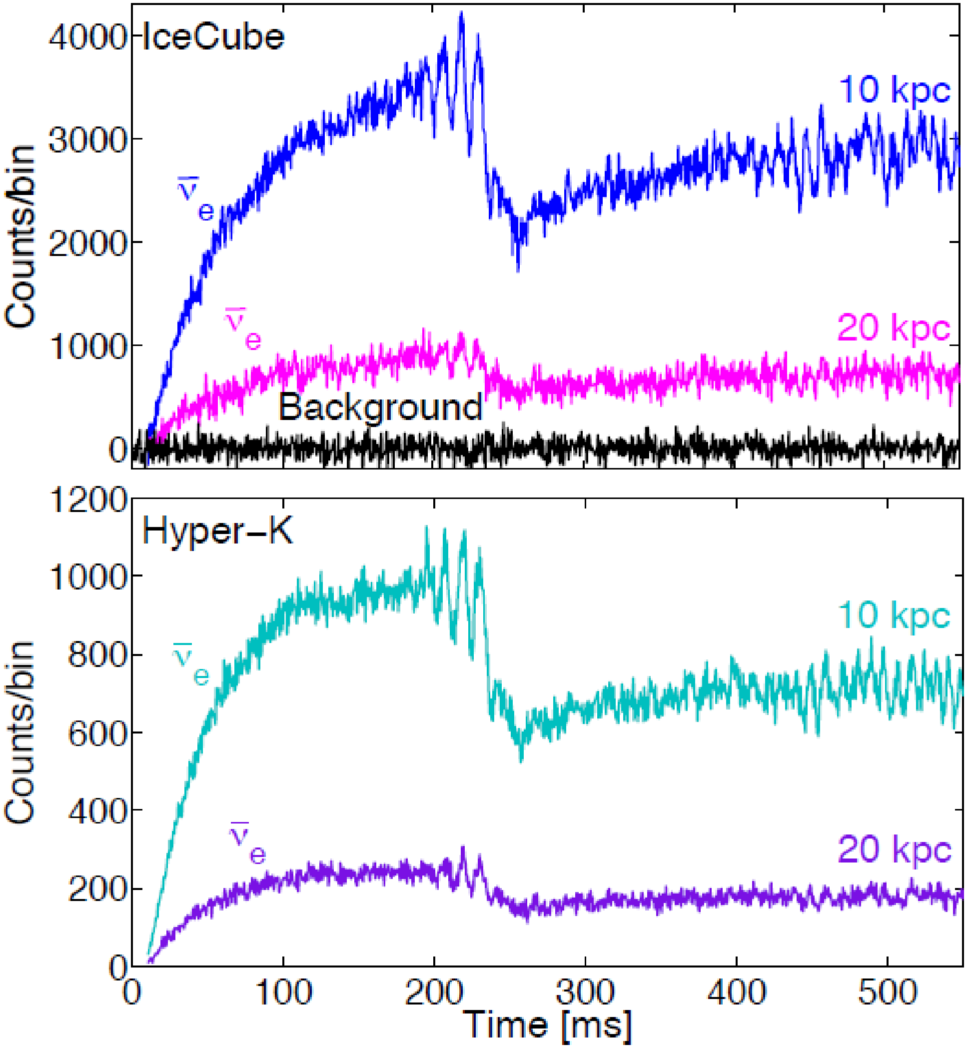
$\bar{\nu}_e$p events during this 10msec is about 190 - 200 events.

N.H. +adiamacitc case: neutronization=~20ev., $\bar{\nu}_e$p = ~350 ev.(~35 for SN direction).

SASI Detection Perspective

I. Tamborra (TAUP2013)





Their 3D 27 M_{SUN} progenitor shows pronounced SASI.

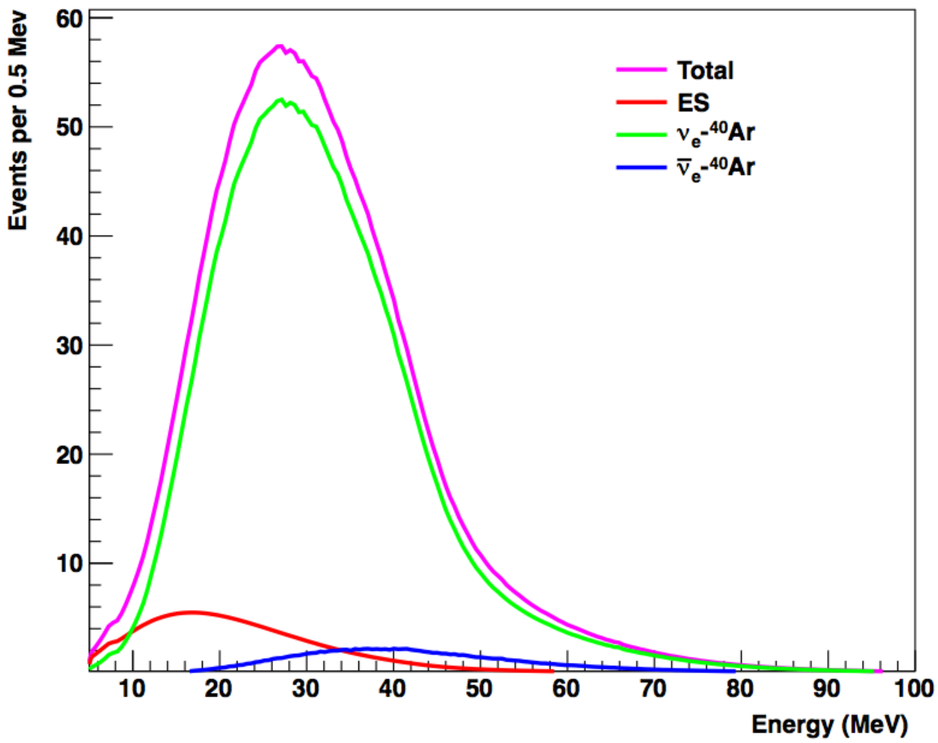
SASI sinusoidal modulation of the neutrino signal will be detectable by IceCube and Hyper-K.

I.Tamborra et al., arXiv:1307.7936

Expected signal in Liquid Ar

For 34 kton Liq. Ar   SN @ 10 kpc

Interactions, as a function of neutrino energy

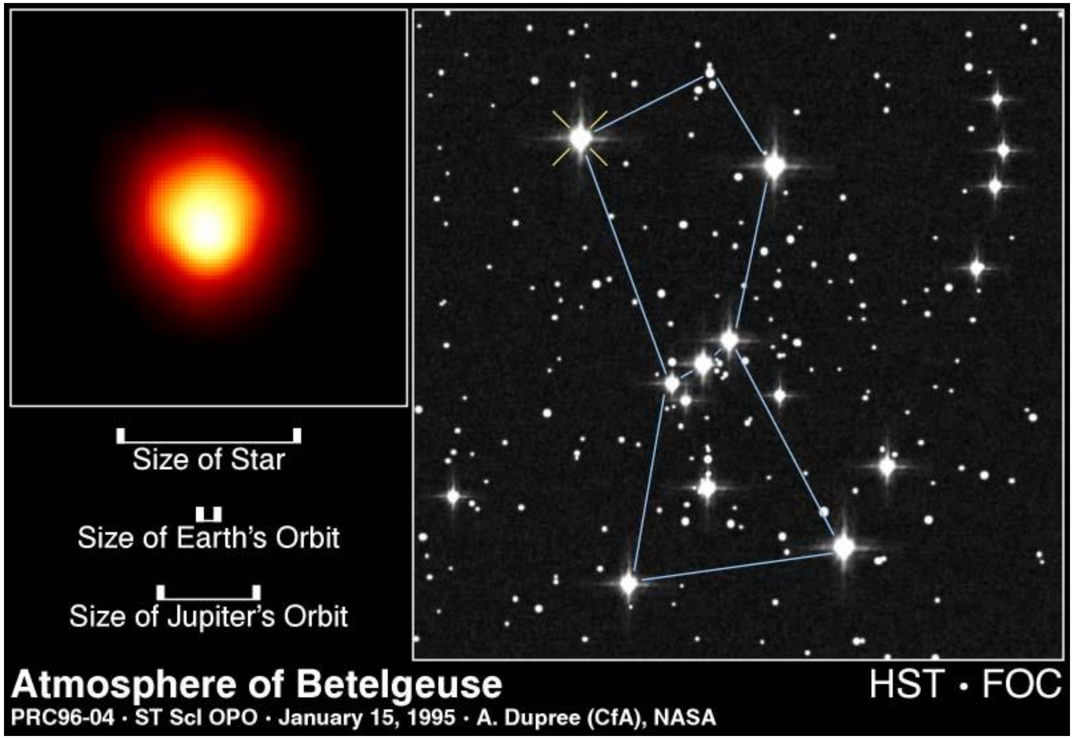


Channel	No of events (observed), GKVM, 34 kton	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

Dominated by ν_e

From K. Scholberg

If Betelgeuse explodes…



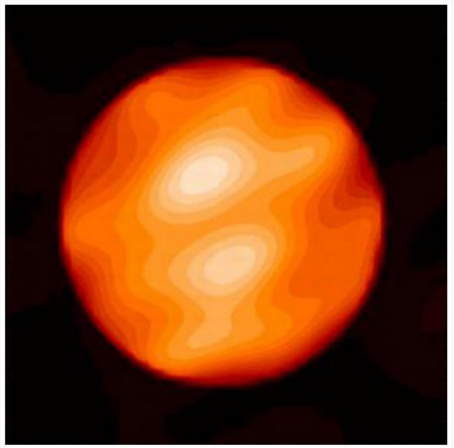


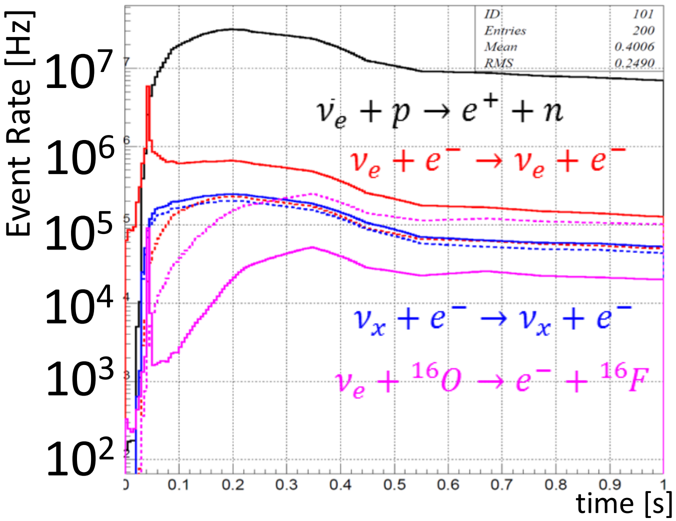
Image credits: © 2010 Haubois / Perrin (LESIA, Paris Observatory)

Betelgeuse shrank by 15% in 15 years. (cf. *ApJ* **697**, L127)

It may explode tomorrow or 500,000 years from now.
(from Nomoto-san)

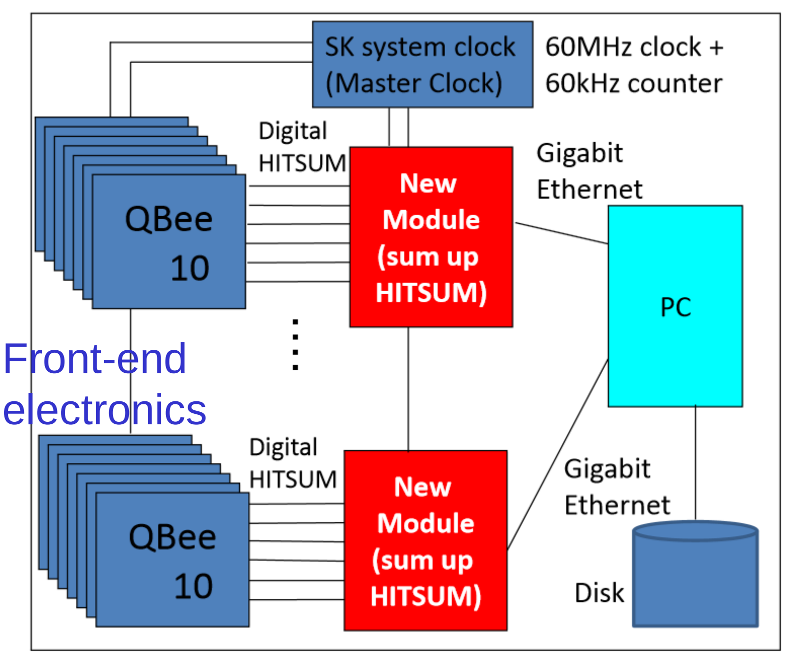
It is only ~640 light-years (0.2kpc) from us.

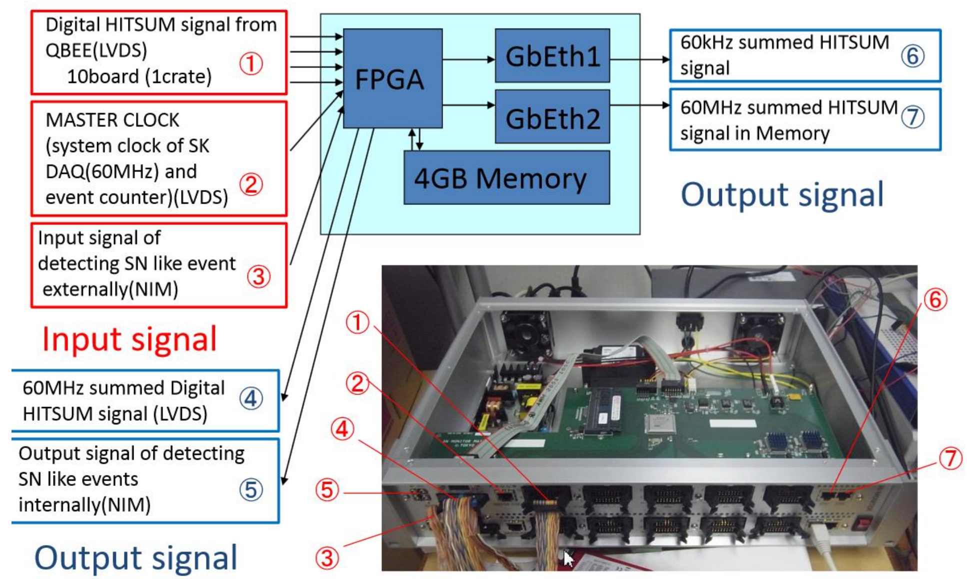
New electronics for Betelgeuse at Super-K



- If Betelgeuse explodes,
  - #events@SK: > 30M / 10s
  - Max. event rate: > 30MHz
- Current DAQ
  - Handles up to 6M events/10s
  - Records only first 20%
    - Bottleneck: disk access speed

Data flow to the new electronics





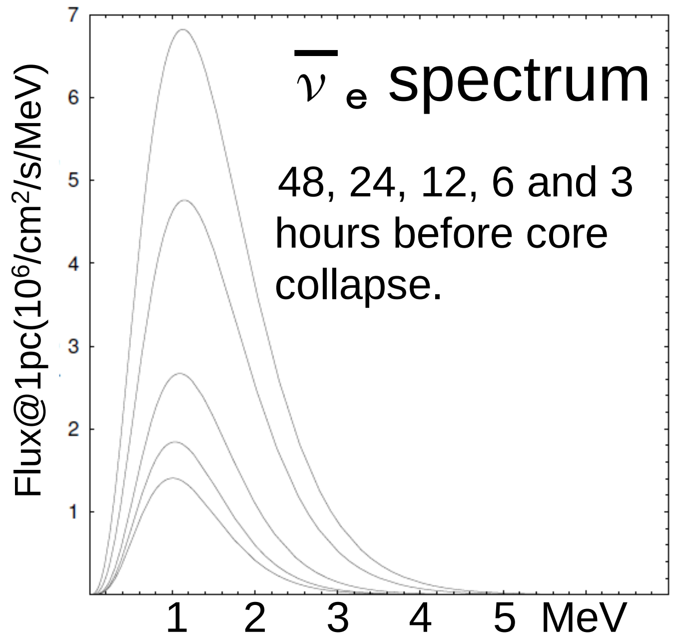
The new electronics will record sum of PMT hits with 60kHz continuously, and 60MHz data for ~1 minute around the burst.

Thermal Neutrinos during Si burning phase

A.Odrzywolek, M.Misiaszek, M.Kutschera, AIP Conf. Proc. 944, 109(2007)

Neutrino-cooled stage of the 15 x M_{sun} star

Evolutionary stage	Average neutrino luminosity [erg/s]	Duration of a stage	Total energy radiated as neutrinos [ergs]
C	3.8×10^{38}	22000 years	2.6×10^{50}
Ne	1.8×10^{41}	32 years	1.8×10^{50}
O	8.4×10^{42}	3.7 years	9.7×10^{50}
Si	2.6×10^{44}	16 days	3.6×10^{50}
Si-shell	2.2×10^{45}	12.7 hours	1.0×10^{50}
Pre-collapse	8.4×10^{45}	1 hour	0.3×10^{50}



This means only neutron signals in $\bar{\nu}_e$+p interactions.

In case of Betelgeuse

Detector	Target mass	Min. $\bar{\nu}_e$ energy	Events 48-24 hours before collapse	Events 24-0 hours before collapse	Events 3-0 hours before collapse
Super-K	32 kt	5 MeV	0.6	173	158
GADZOOKS!	22.5 kt	3.8(1.8) MeV	9 (204)	442 (1883)	345 (1130)
Borexino	0.3 kt	2 MeV	2	22	13
KamLAND	1 kt	2 MeV	11	108	65

In this paper, distance is assumed to be 0.13kpc. So, the numbers must be reduced to 50%.

Neutrinos during the Si-burning phase can be used for precursor of core collapse.

Conclusions

- Supernova burst neutrinos
  - Many detectors in the world with various types of signals.
  - ~8,000 events expected at Super-K for 10kpc SN.
  - High precision time profile by Icecube.
  - ~5 deg. accuracy in direction of supernova by Super-K neutron-electron scattering events.
  - Onset time with ~2 msec resolution by Super-K and IceCube.
- Supernova relic Neutrinos
  - R&D for GADZOOKS! project is ongoing.
- Nearby (Betelgeuse) supernova
  - New electronics at Super-K.
  - KamLAND and Super-K(GADZOOKS!) can get precursor using Si-burning neutrinos.