Supernova Neutrino Detection Overview

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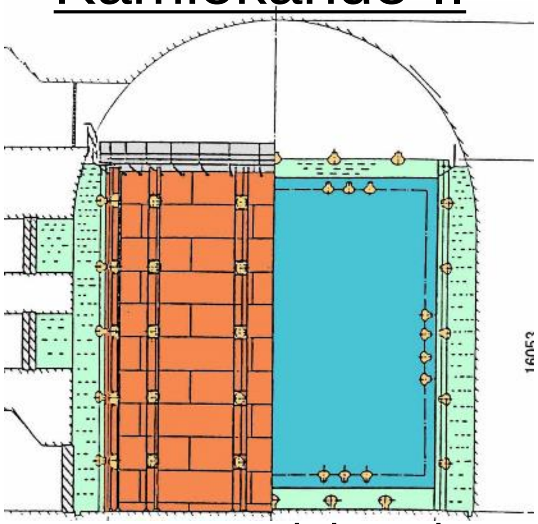
Contents

- What we have learned from SN1987A?
- Current supernova detectors in the world
- Supernova relic neutrinos

  (Diffuse Supernova Neutrino Background)
- Future large volume detectors

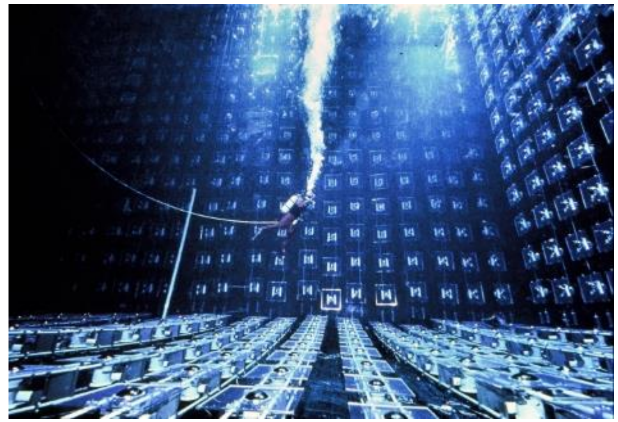
SN1987A: supernova at LMC(50kpc)

Kamiokande-II



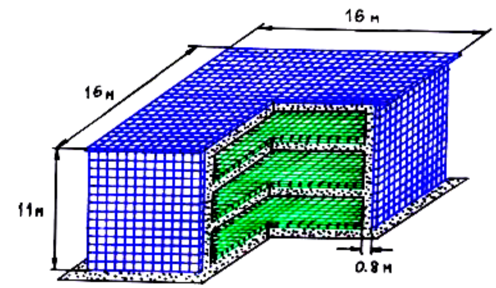
Japan Kamioka mine
2140ton fiducial
Water Cherenkov

IMB-3



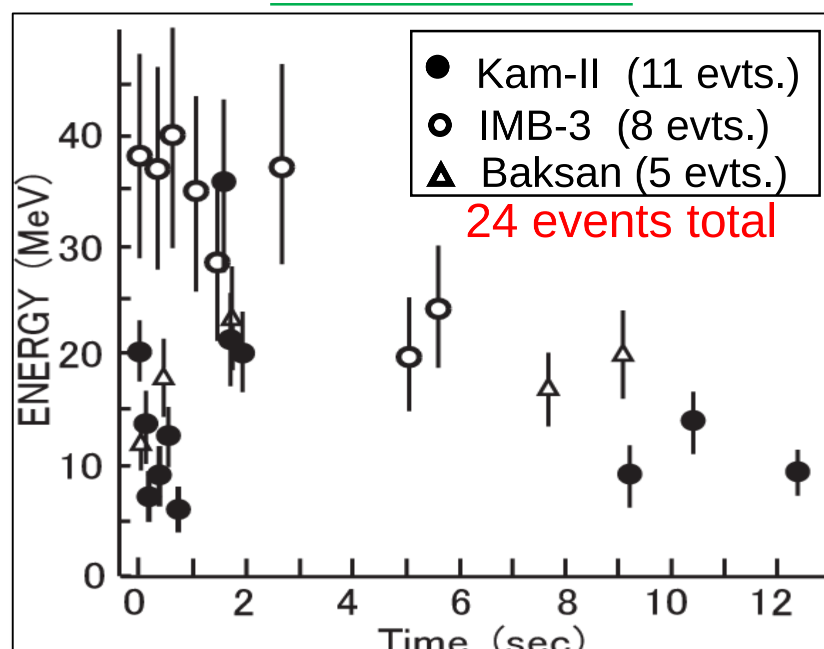
USA Ohio state Morton mine
～5000ton Fiducial
Water Charenkov

BAKSAN



Russia Baksan tunnel
330ton in 3150tanks
Liquid scintillator

Observed events



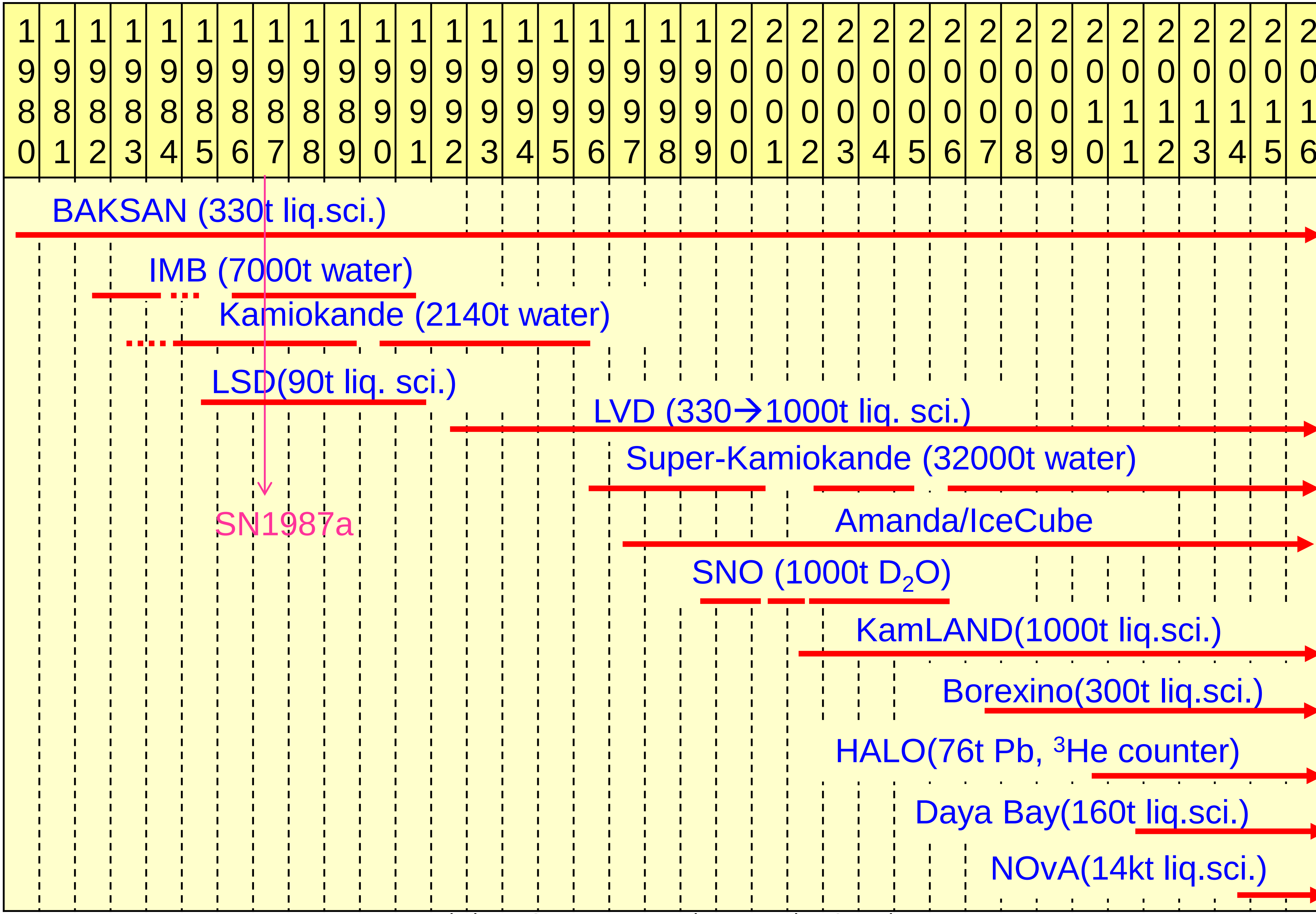
Total energy released by $\bar{\nu}_e$ was measured to be ~5x10^{52} erg.

The measured energy was consistent with core-collapse scenario.

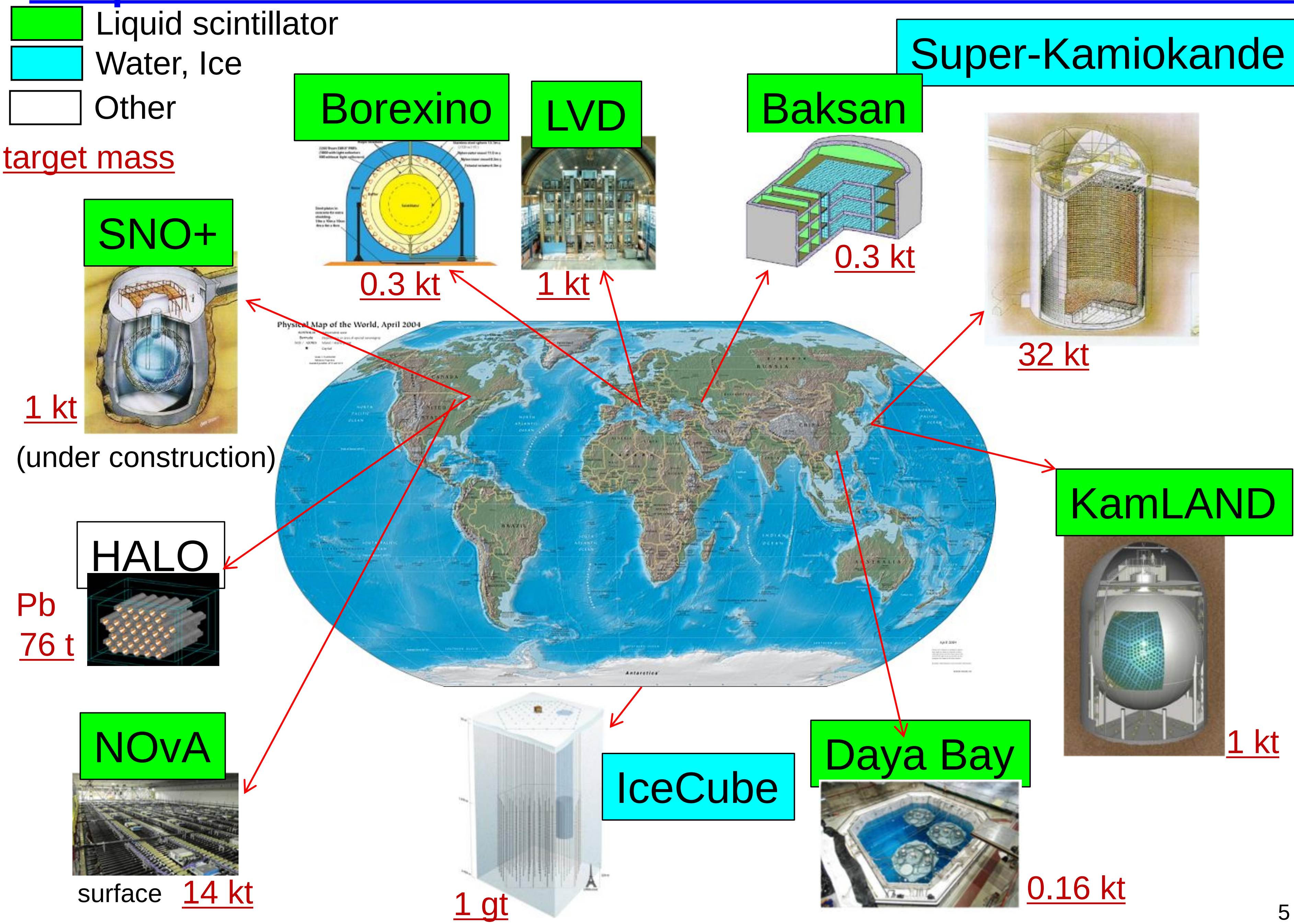
Large error in neutrino mean energy.

No detailed information of burst process was observed because of low statistics.

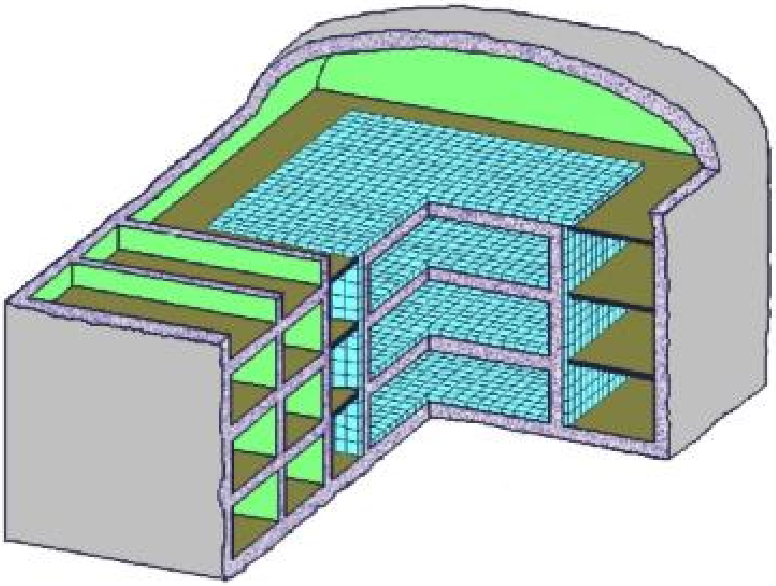
History of supernova detectors



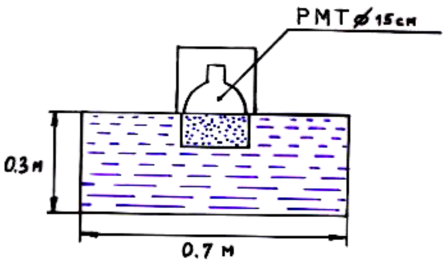
Supernova burst detectors in the world now



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 30.8 years' observation time from June 1980 to June 2016. Upper limit of SN rate: < 0.075 /yr (90% C.L.)
(from V. Petkov, Russian Cosmic Ray Conference, Dubna 2016)

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

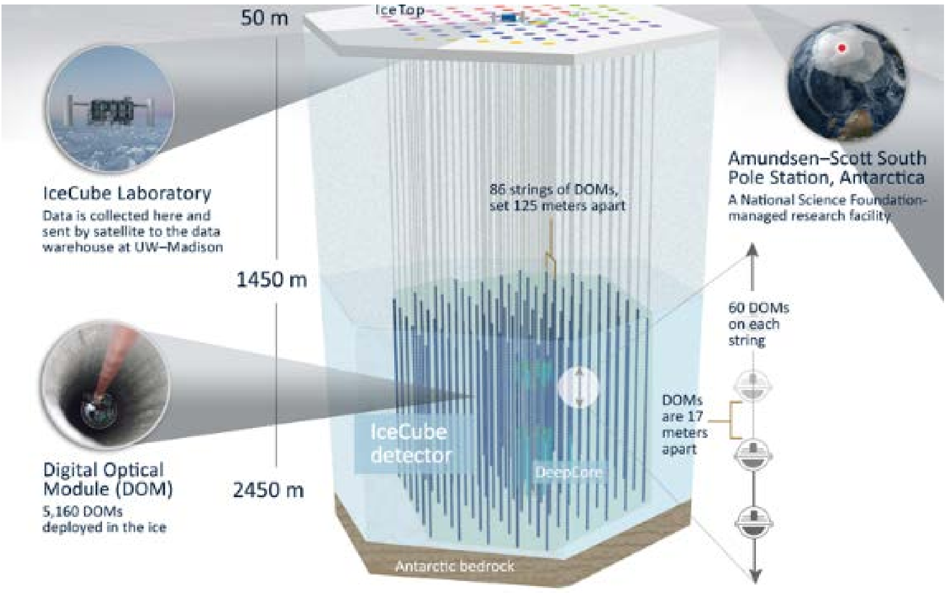
~300 $\bar{\nu}_e p \rightarrow e^+ n$ events expected for 10 kpc SN.

No candidate for 7843 days from 1992 to 2015.
Upper limit of SN rate: < 0.11 /yr (90% C.L.)

From W.Flugione

C.Vigorito et al., ICRC2015

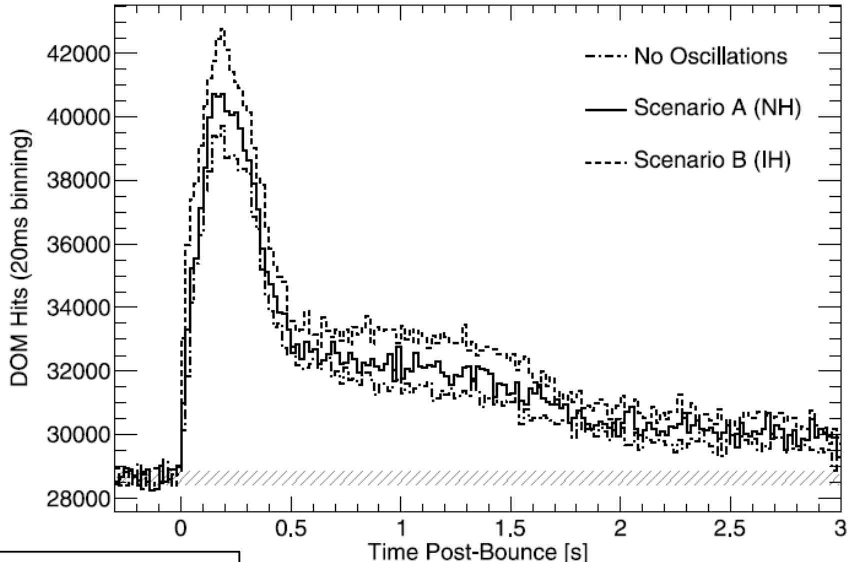
IceCube (South pole)

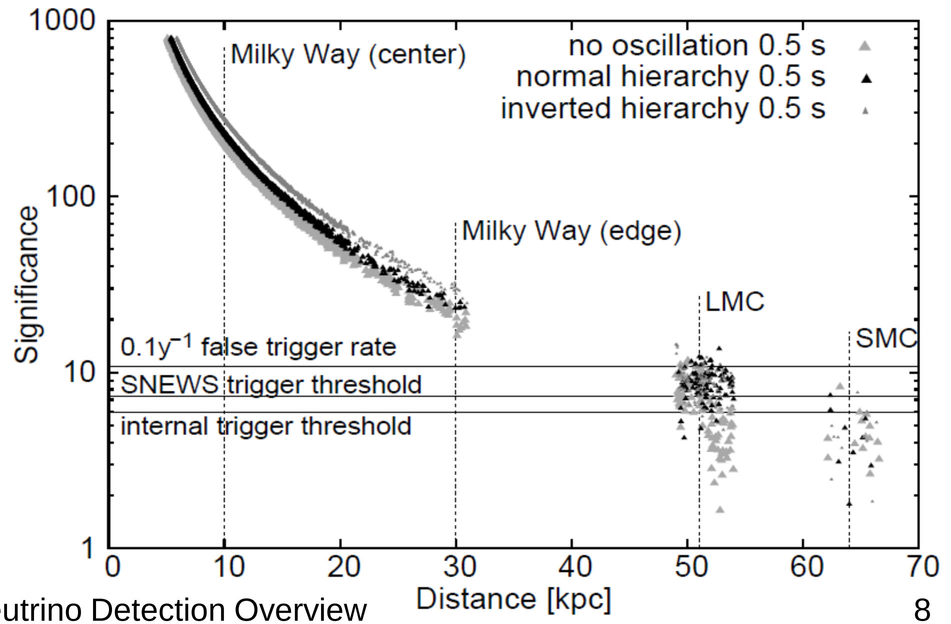


IceCube detector

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

Supernova neutrinos coherently increase single rates of PMTs.

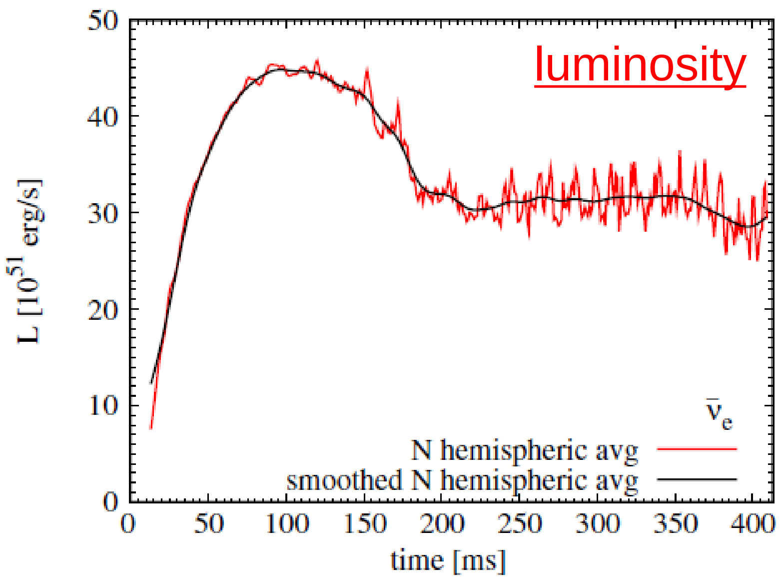


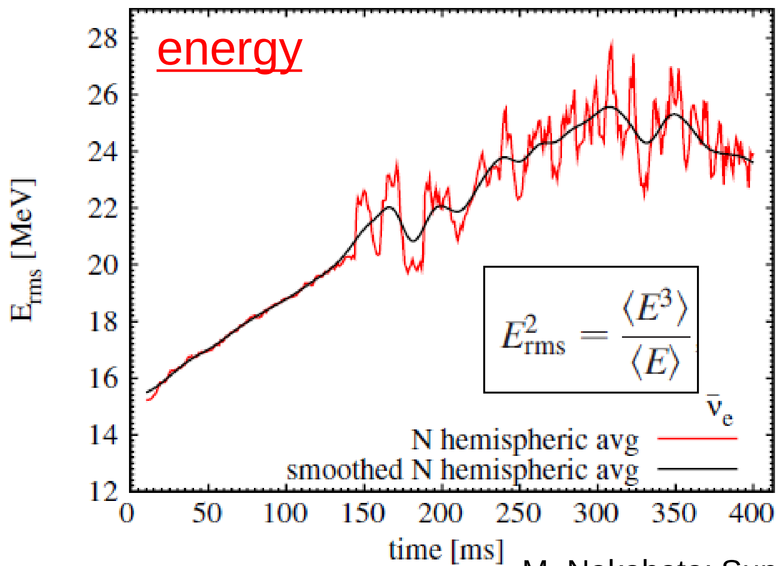


From L.Koepke

High frequency signal variation by SASI

SASI=standing accretion shock instability

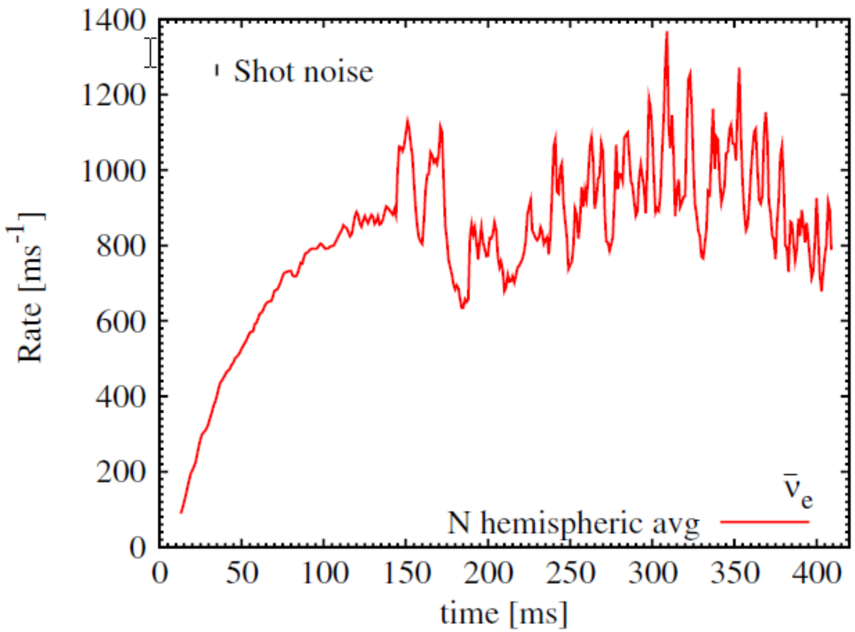




2-D(axially symmetric) simulation with PROMETHEUS-VERTEX code

Supernova at 10kpc

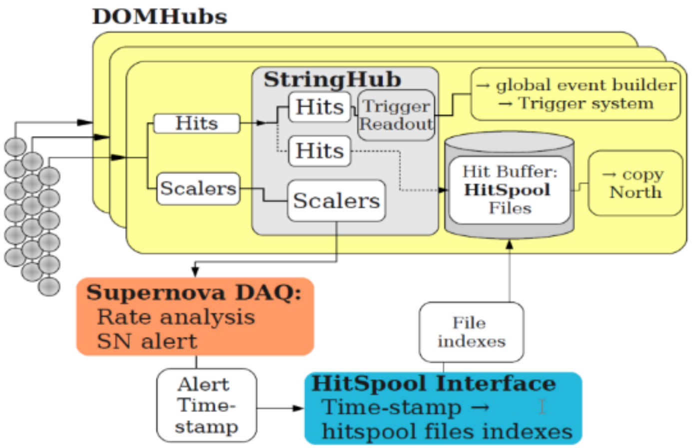
IceCube "event" rate



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

IceCube – HitSpooling and directional information

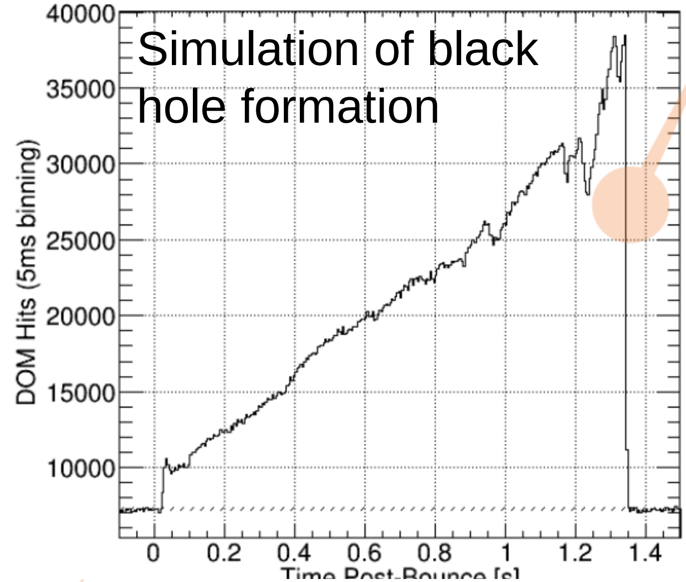
Improvement of Data Acquisition system in 2013



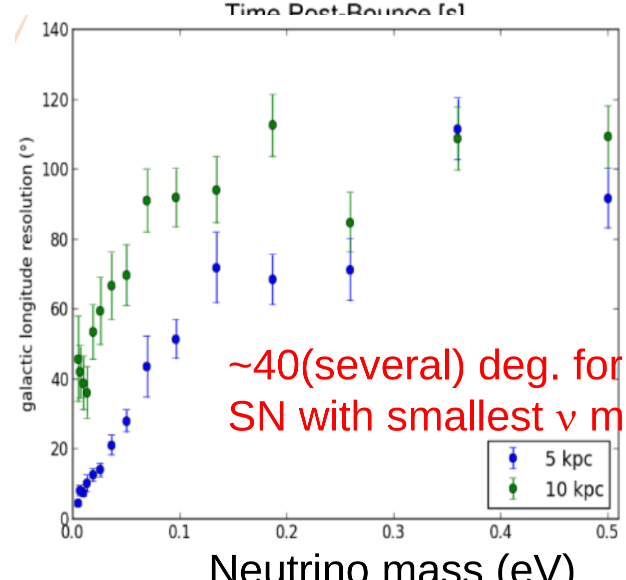
The newly installed HitSpool Interface enables

- Record all hit information in 90sec data around the burst with full data stream.
- Use correlation of hits of DOMs to estimate mean energy with a resolution of about 30% at 10 kpc.

Possible directional information in case of black hole formation



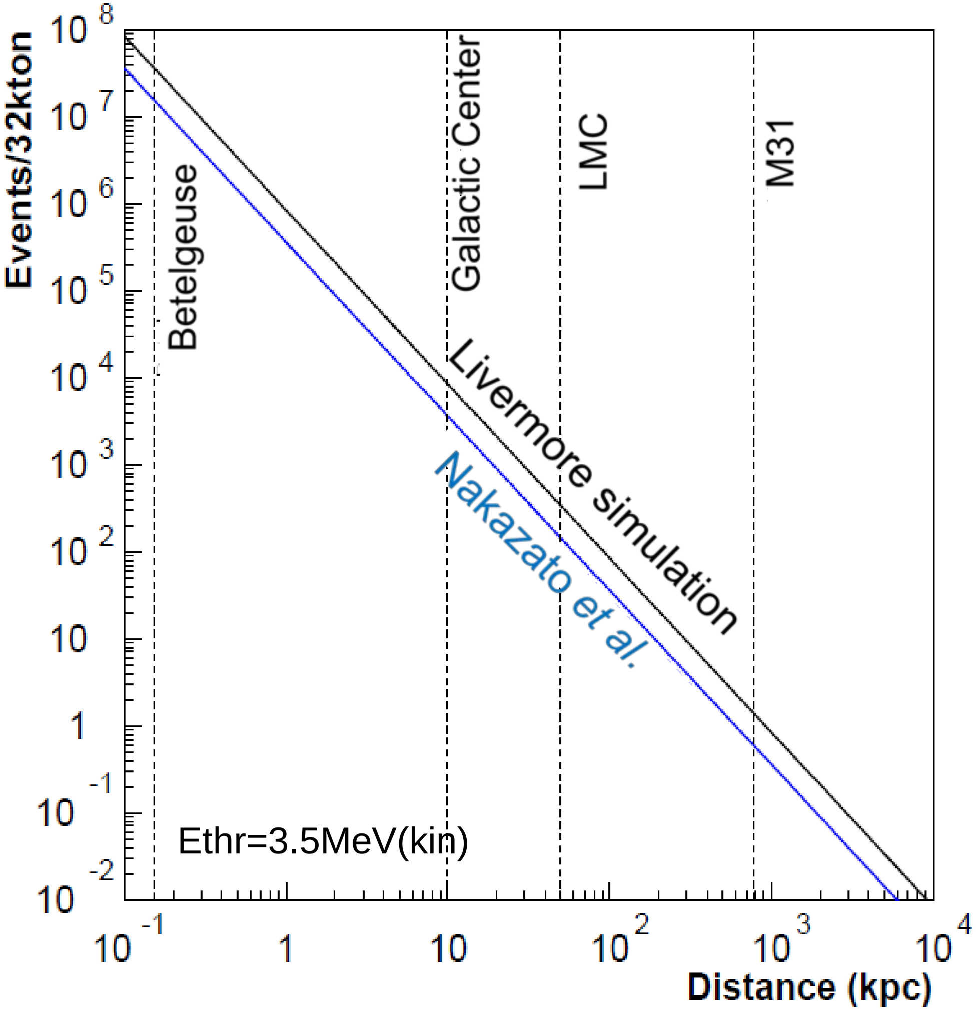
Abrupt rate change



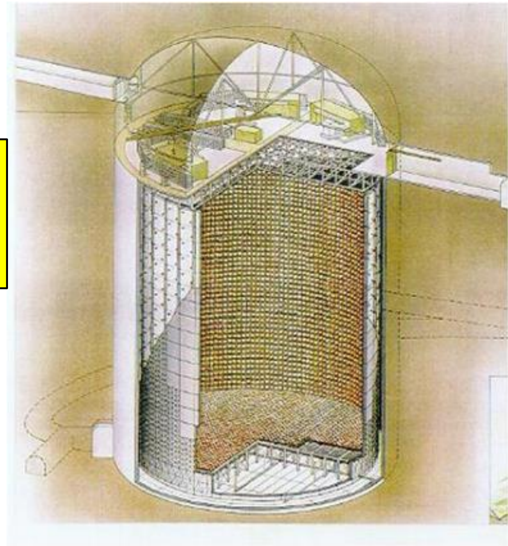
~40(several) deg. for 10 (5) kpc SN with smallest ν mass

Super-K: Number of events

Number of events vs. distance



32kton water Cherenkov



For each interaction

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

Directional information

Supernova at 10 kpc

32kton SK volume

4.5MeV(kin) threshold

No oscillation case.

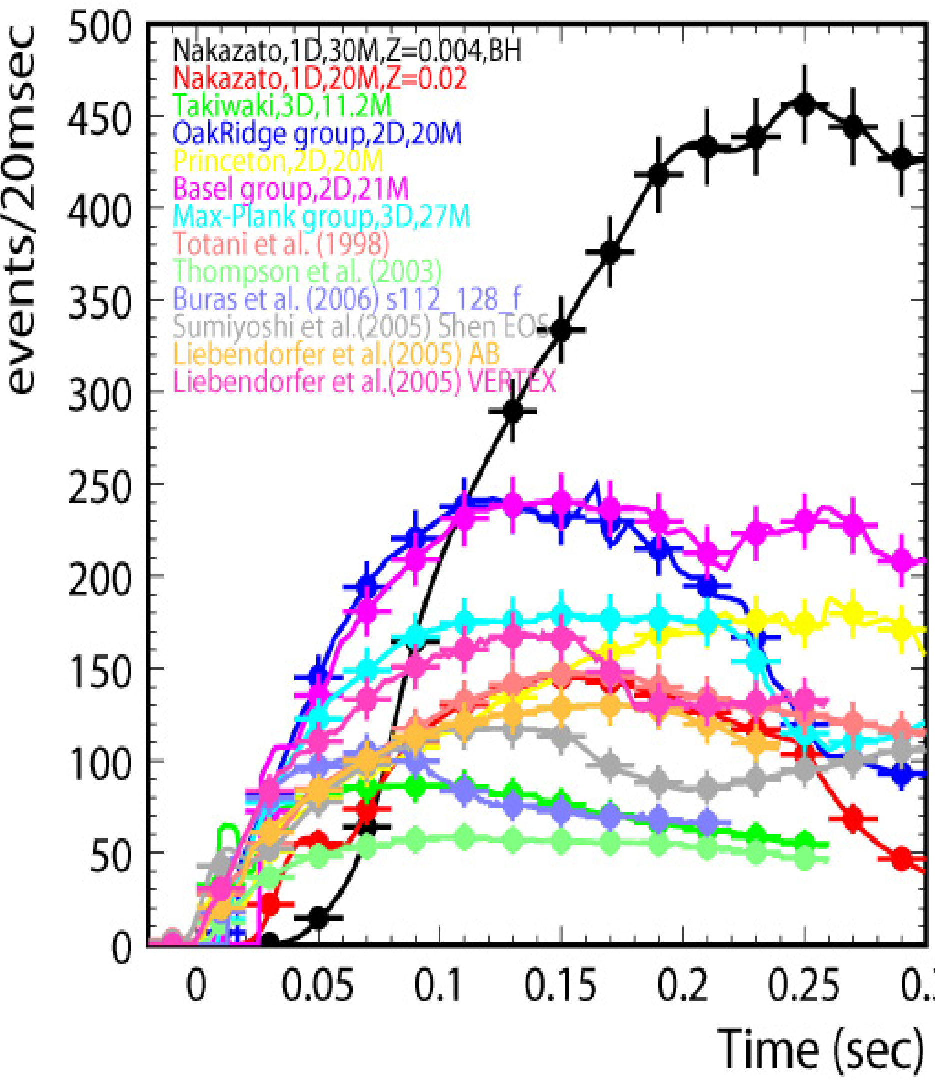
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

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)

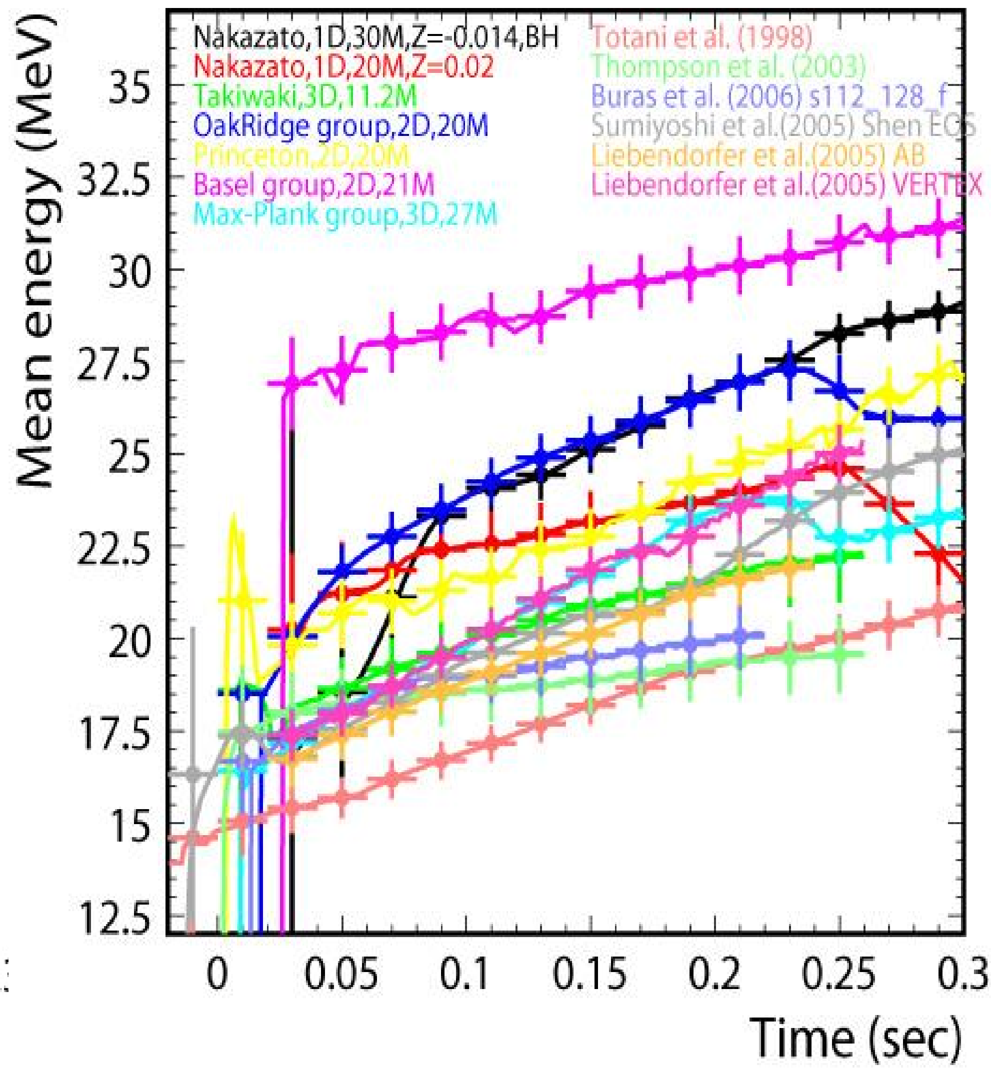
Sensitivity of Super-K for the model discrimination

For 10kpc supernova

Time variation of event rate



Time variation of mean energy



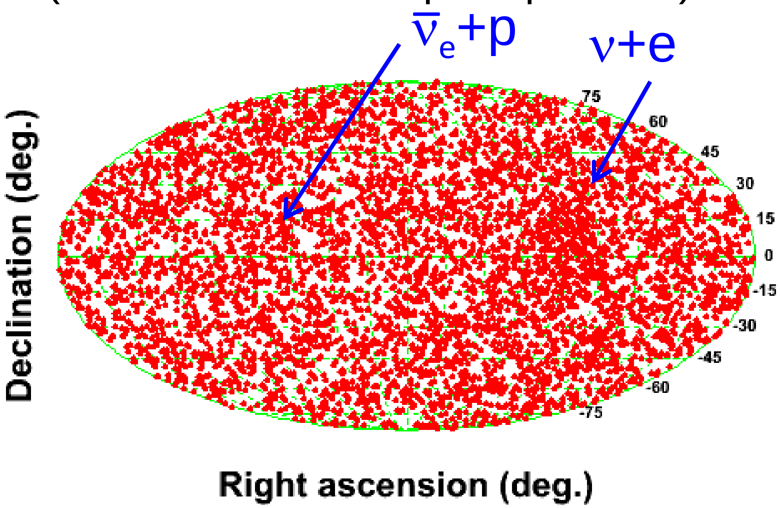
High statistics enough to discriminate models

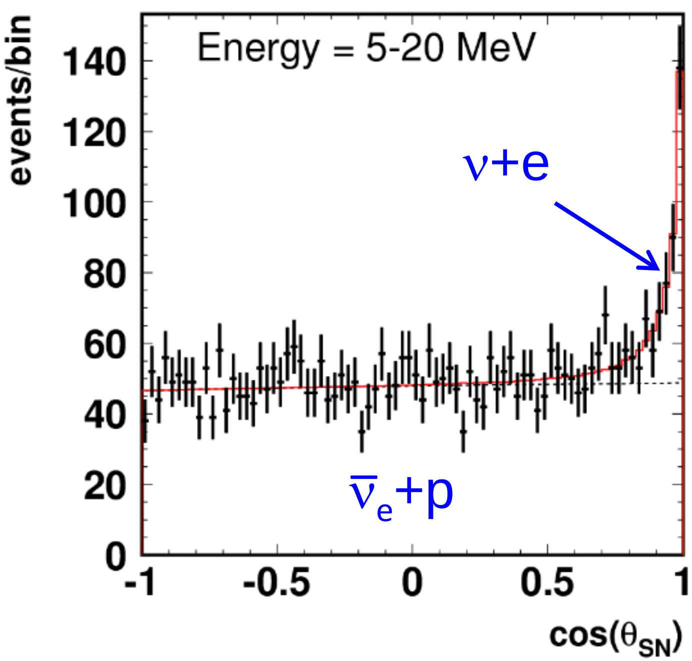
Cooperation: H. Suzuki

Super-K: directional information

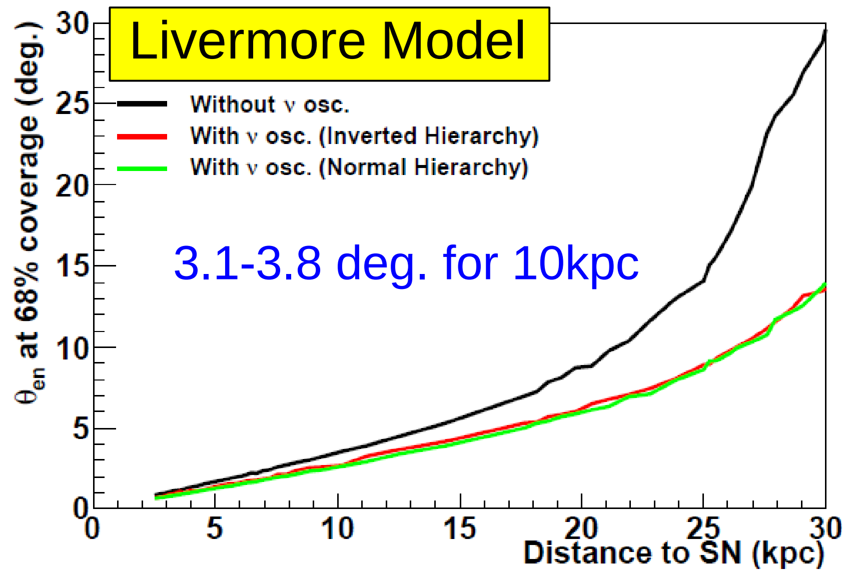
Reconstructed direction

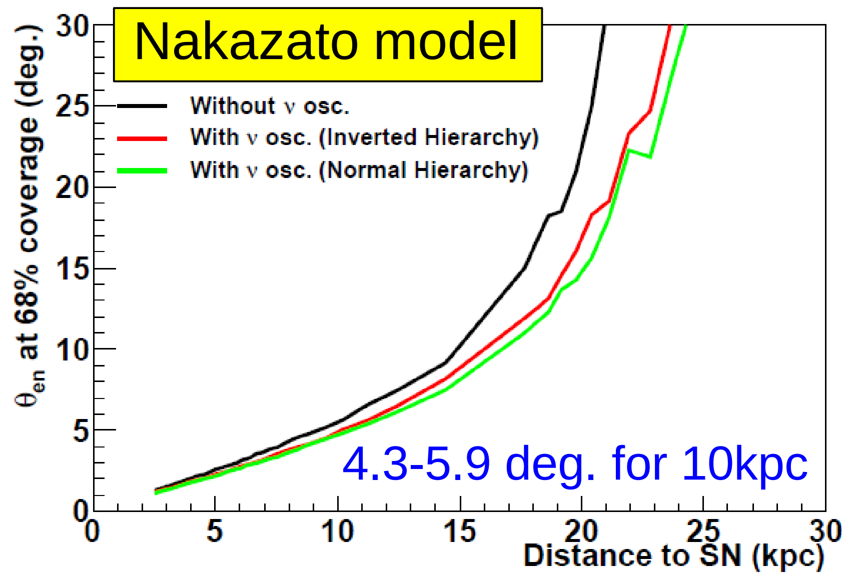
(Simulation of a 10kpc supernova)





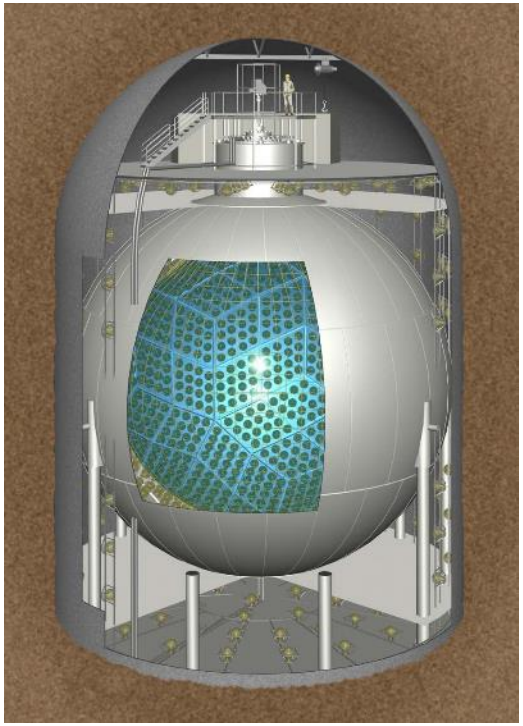
Distance vs. pointing accuracy





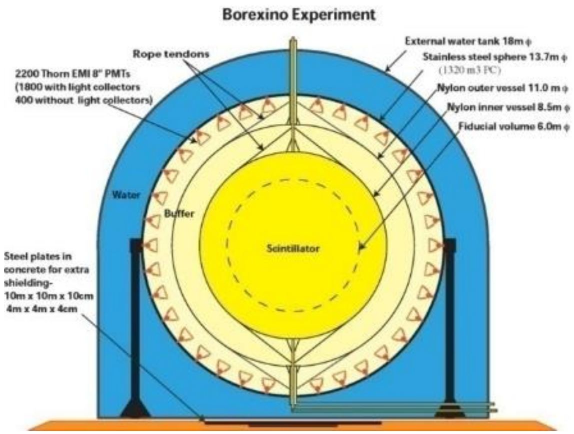
Single volume liquid scintillator detectors

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



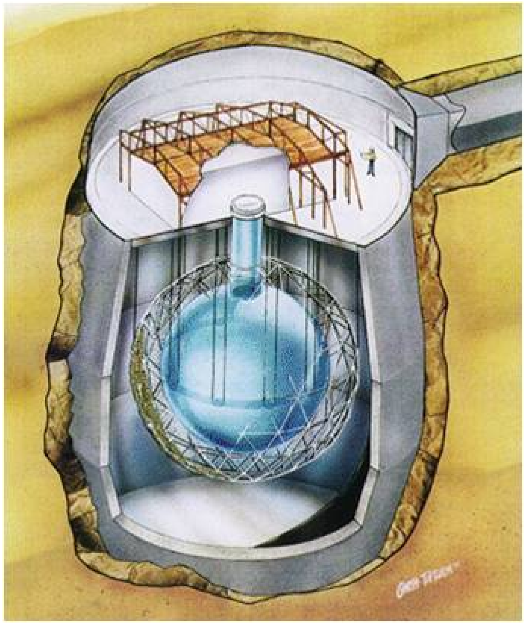
1000ton liq.sci.

Running since 2002.



300ton liq.sci.

Running since 2007.

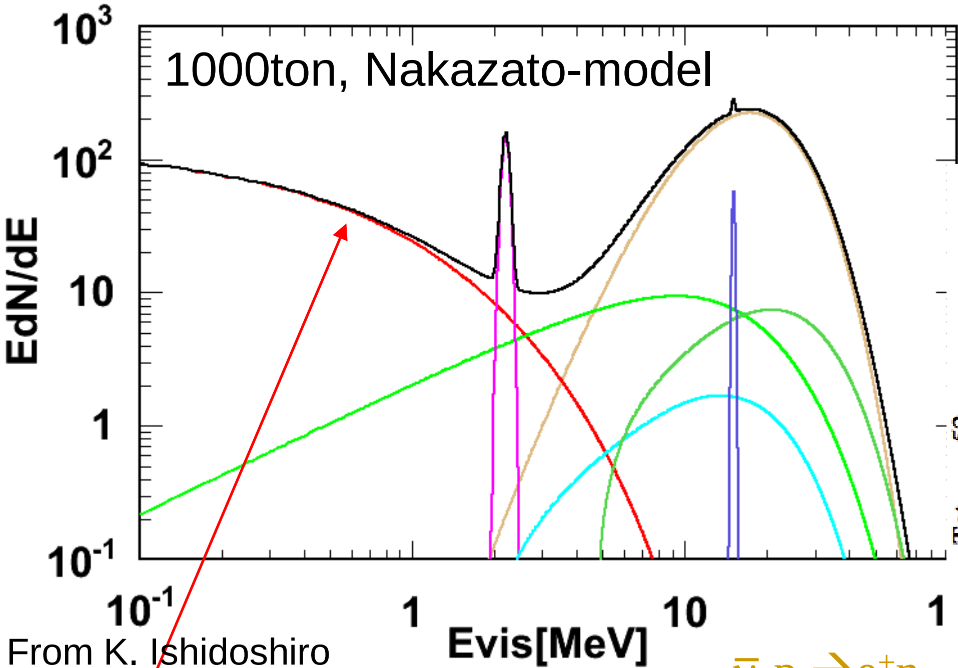


1000ton liq.sci.

Under construction.

Energy spectrum expected at the liquid scintillation detectors

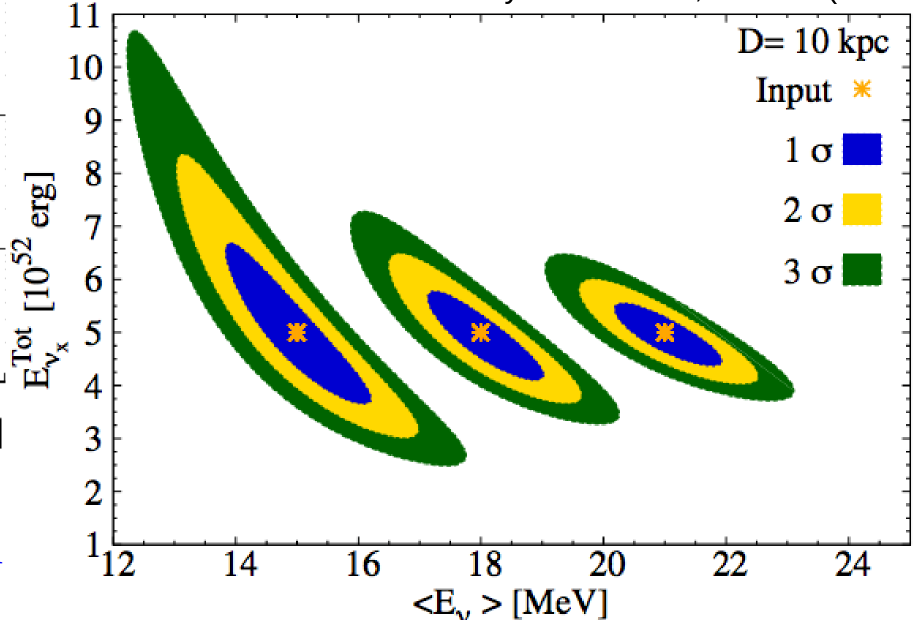
Expected energy spectrum (10kpc)



From K. Ishidoshiro

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

Phys. Rev. D 86, 125001 (2012)



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

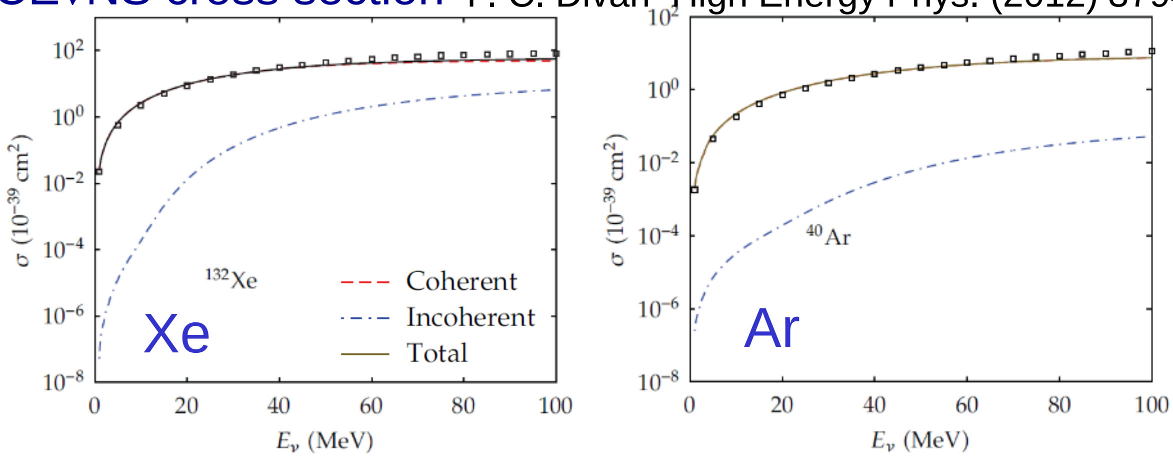
Determine luminosity and mean energy of ν_x

(ν_x : ν_μ , ν_τ at the source)

Supernova signals by Dark Matter detectors

Coherent elastic neutrino-nucleus scattering

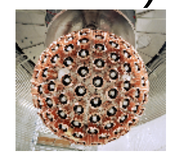
CEνNS cross section P. C. Divari High Energy Phys. (2012) 379460



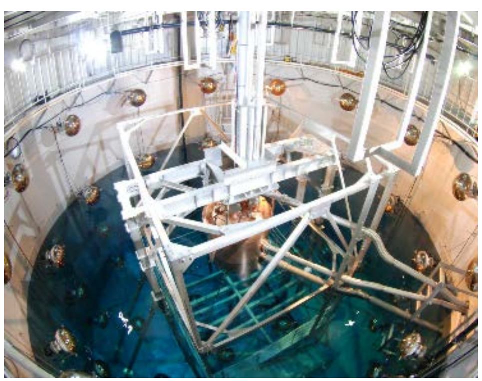
LUX(Xe0.37ton)

XENON1T
(Xe 1ton)

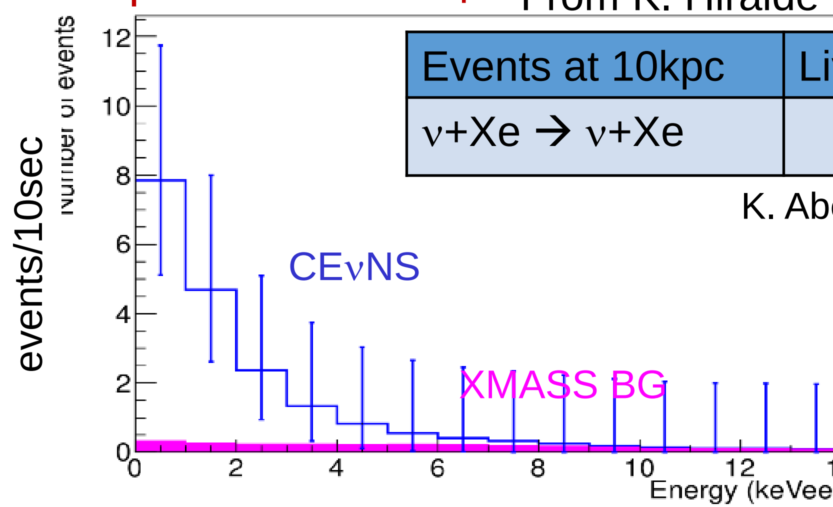
DEAP3600
(Ar 3.6ton)



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



Supernova at 10 kpc From K. Hiraide

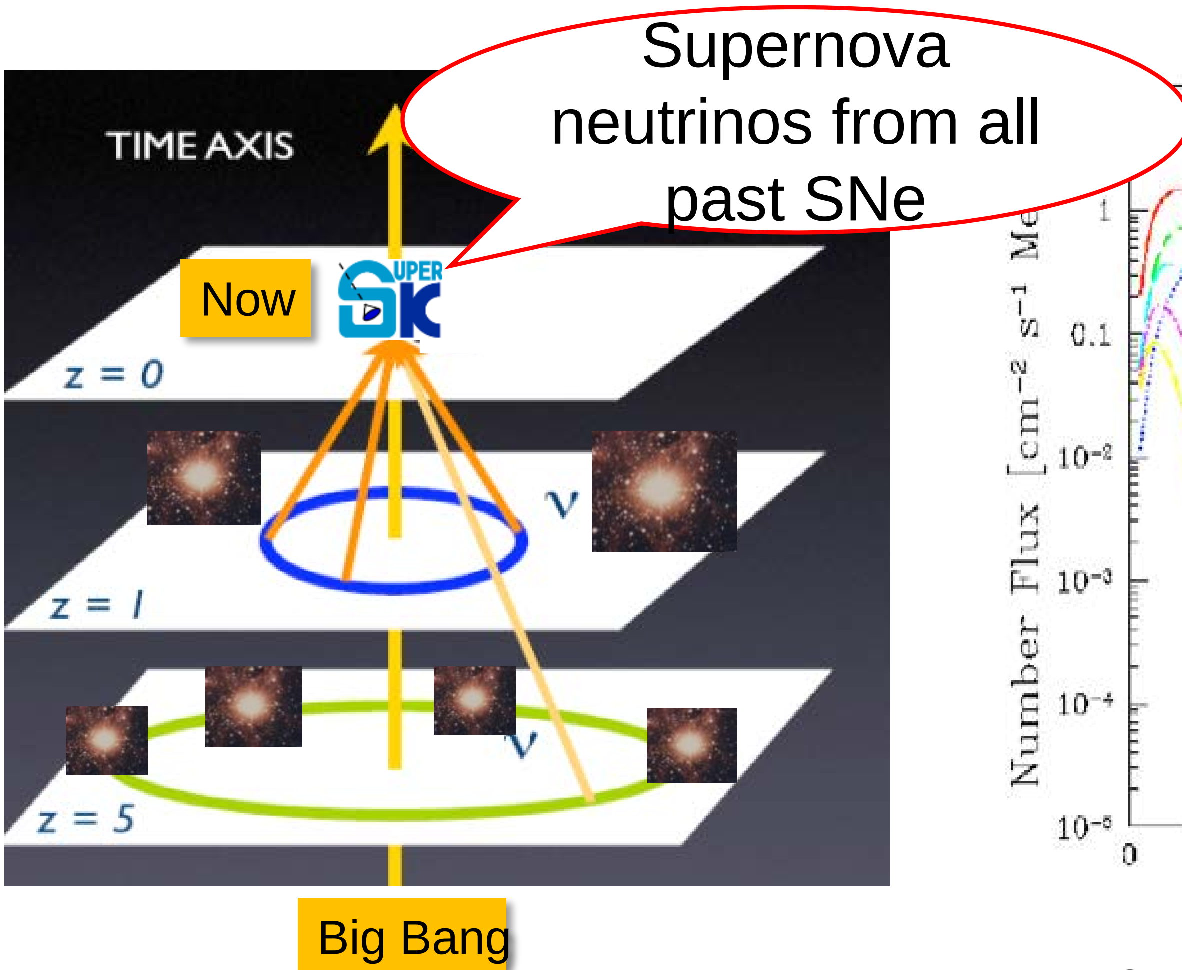


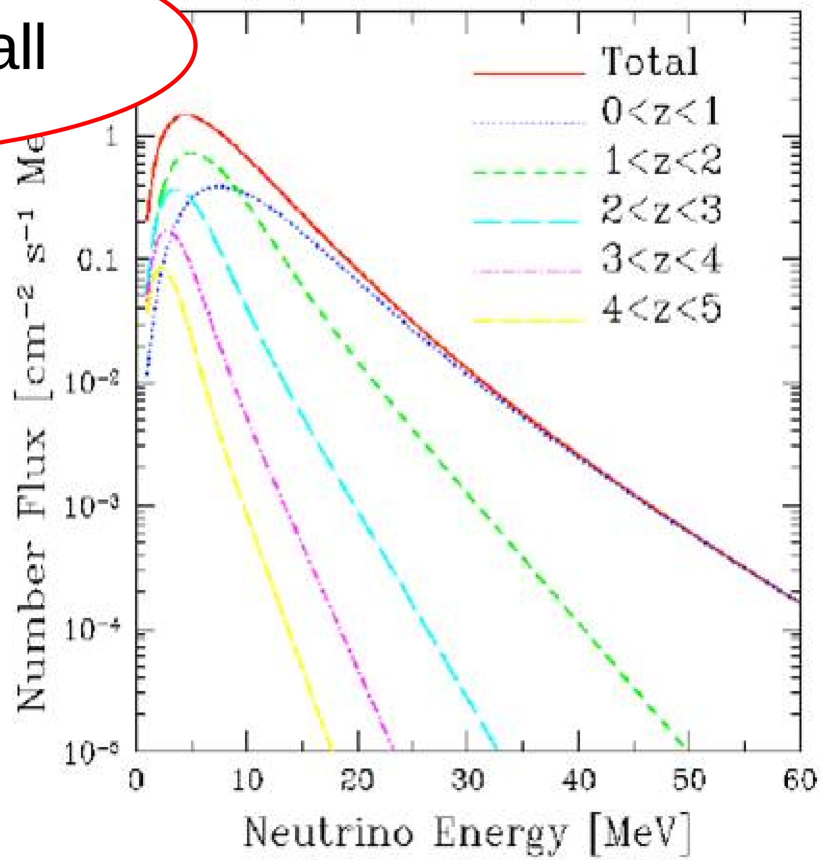
Events at 10kpc	Livermore	Nakazato
ν+Xe → ν+Xe	15	3.5 ~ 21

K. Abe et al., arXiv:1604.01218

Supernova Relic Neutrinos

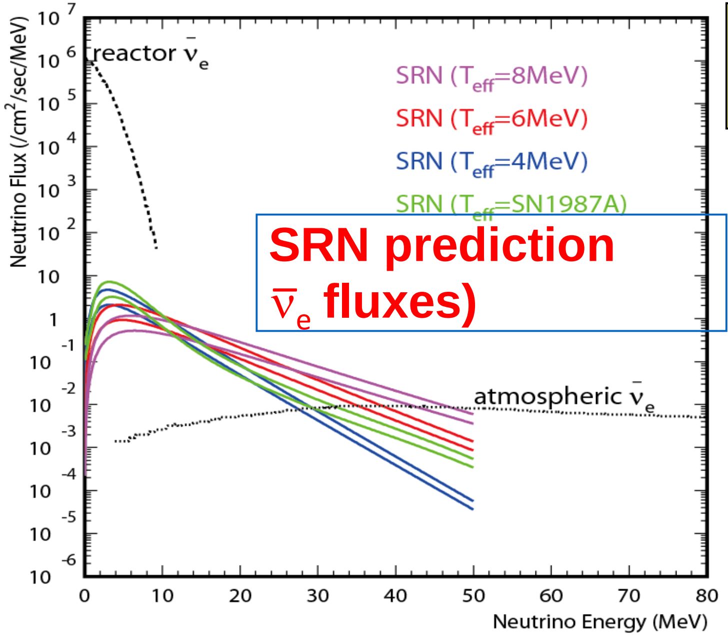
10^{10} stars/galaxy $\times 10^{10}$ galaxy $\times$ 0.3%(massive star->SN) ~$O(10^{17})$SNe



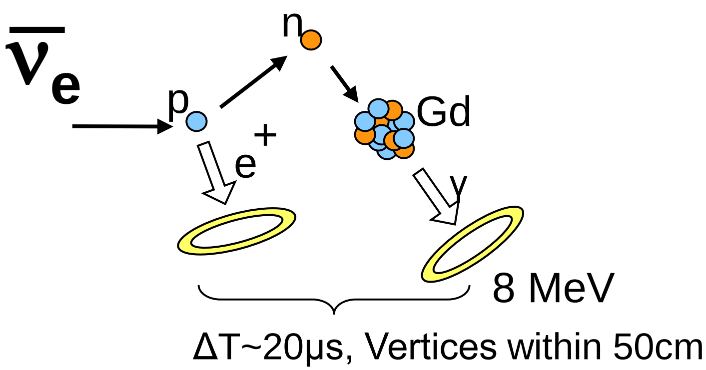


S.Ando, Astrophys.J. 607, 20(2004)

SK-Gd project for Supernova Relic Neutrino



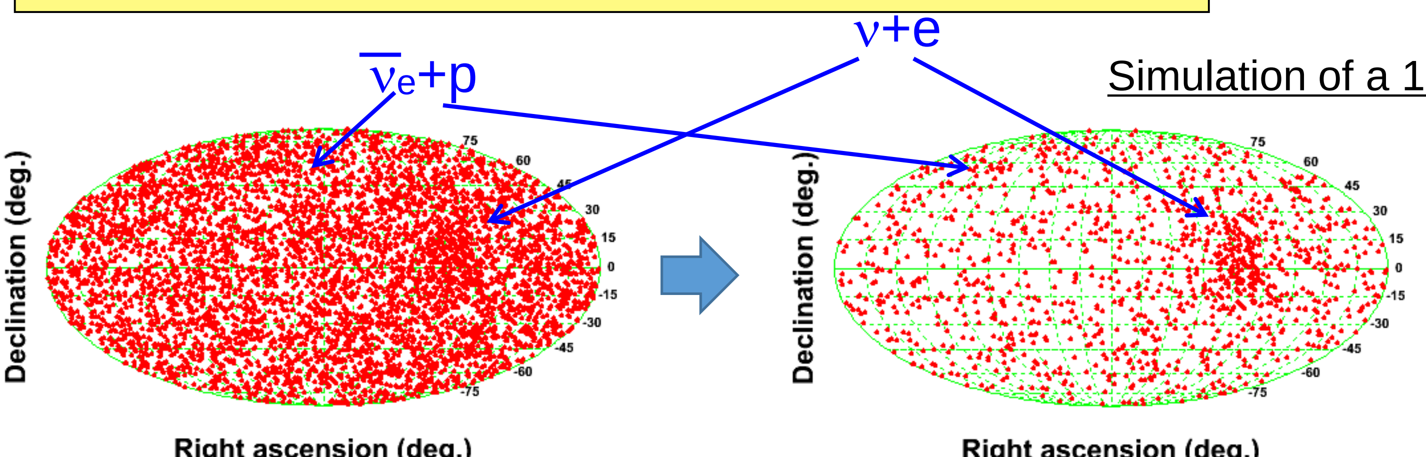
Open widow for SRN at 10-30MeV
Expected rate 1.3 -6.7 events/year/22.5kt(10-30MeV)



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

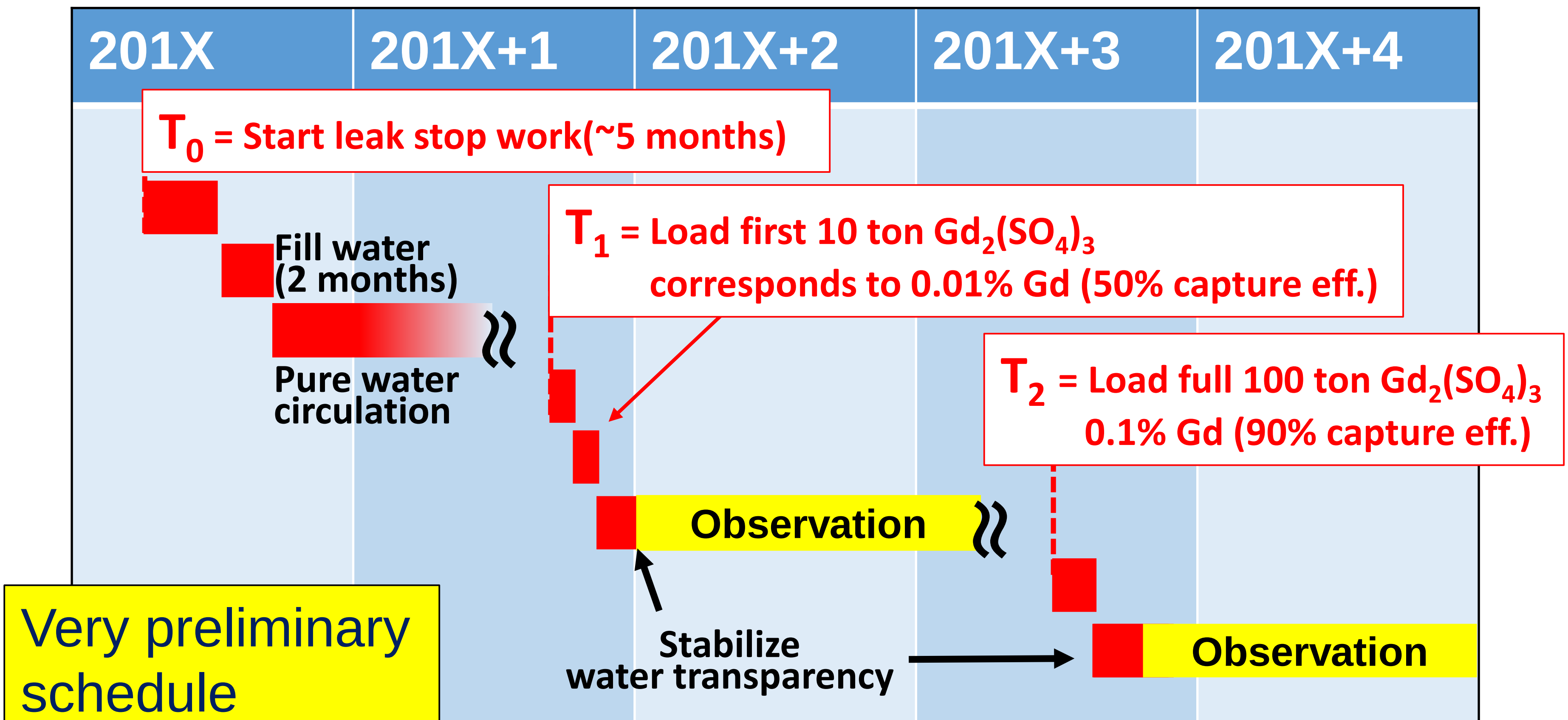
Simulation of a 10kpc supernova



Approval of the SK-Gd project and its schedule

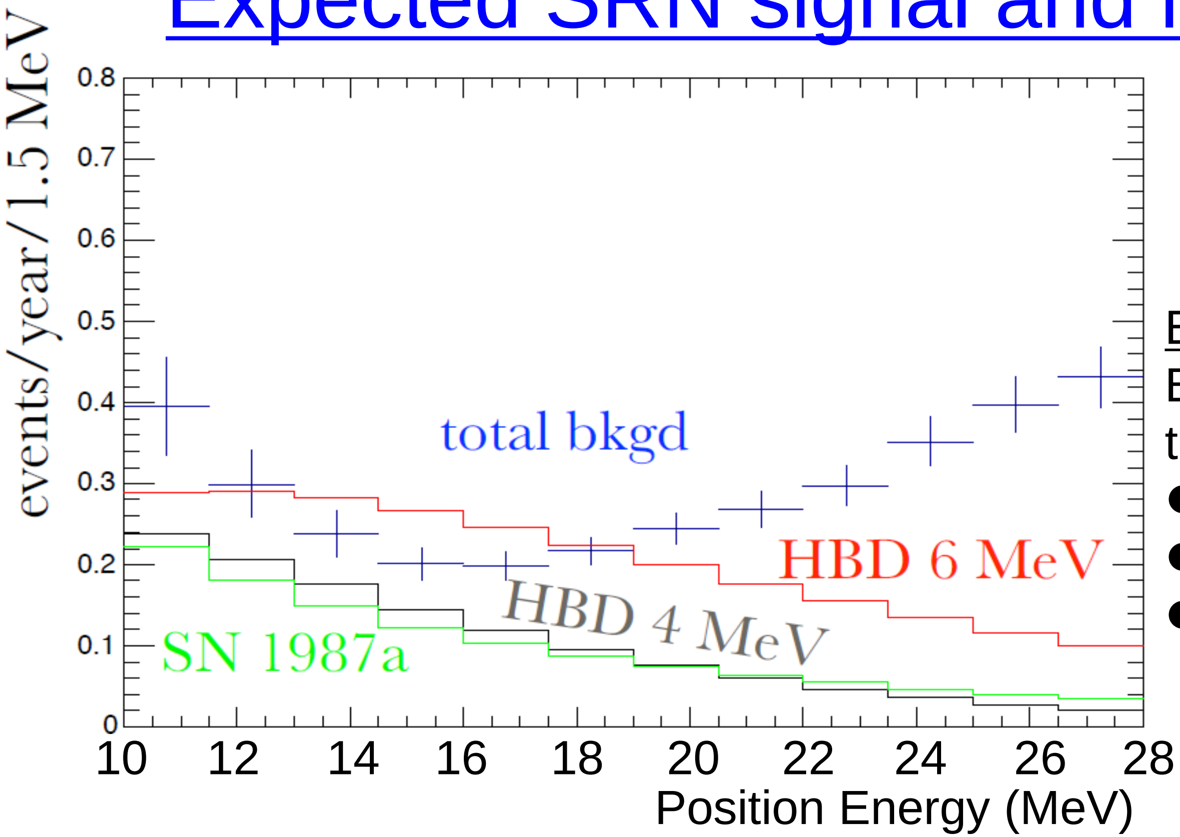
On June 27, 2015, the Super-Kamiokande collaboration approved the SK-Gd project which will enhance neutrino detectability by dissolving gadolinium in the Super-K water.

T2K and SK will jointly develop a protocol to make the decision about when to trigger the SK-Gd project, taking into account the needs of both experiments, including preparation for the refurbishment of the SK tank and readiness of the SK-Gd project, and the T2K schedule including the J-PARC MR power upgrade. Given the currently anticipated schedules, the expected time of the refurbishment is 2018.



Expected SRN signal and its significance

preliminary



SRN flux from
Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)

BG assumption

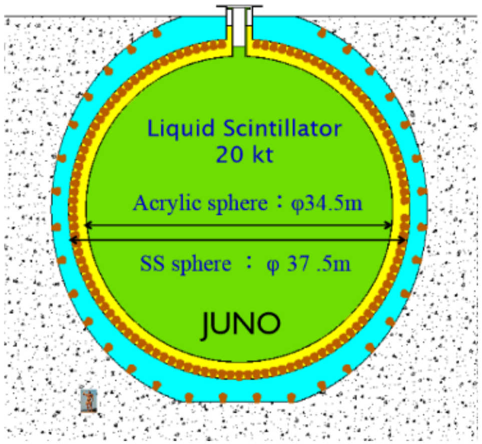
BG can be reduced by neutron tagging as follows

- ν_μ CC BG 1/4
- ν_e CC BG 2/3
- NC elastic BG 1/3（require only one neutron)

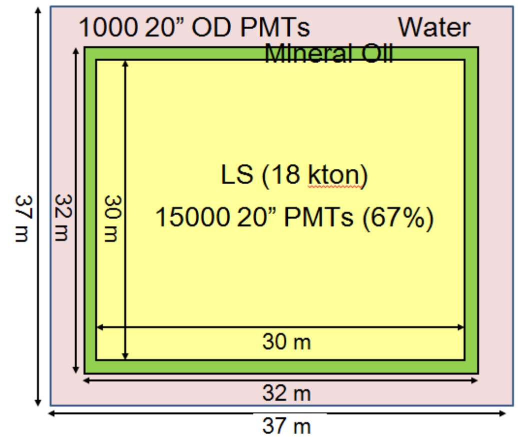
Model	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	Significance (2 energy bin)
HBD 8MeV	11.3	19.9	31.2	5.3 σ
HBD 6MeV	11.3	13.5	24.8	4.3 σ
HBD 4MeV	7.7	4.8	12.5	2.5 σ
HBD SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

Future Large Volume Detectors

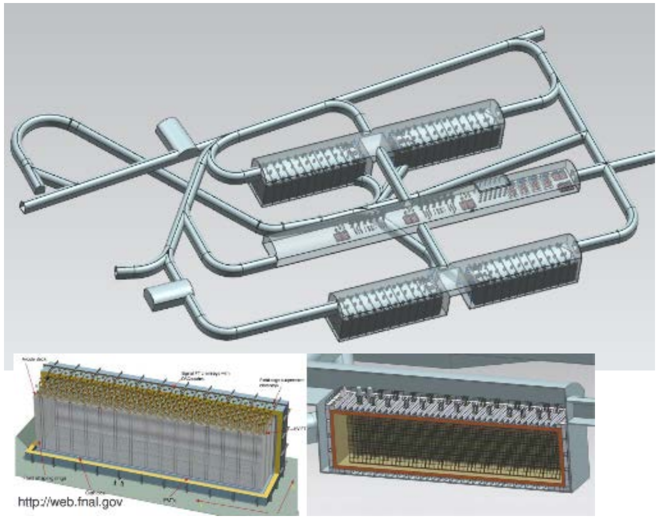
JUNO(China)
(20kton Liq. Sci.)



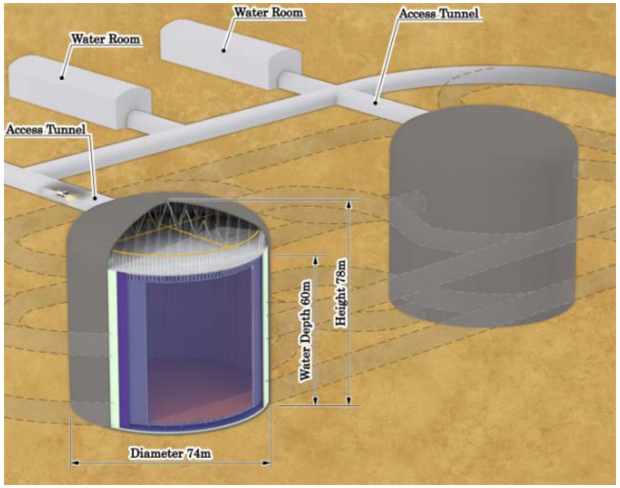
RENO-50(Korea)
(18kton Liq. Sci.)



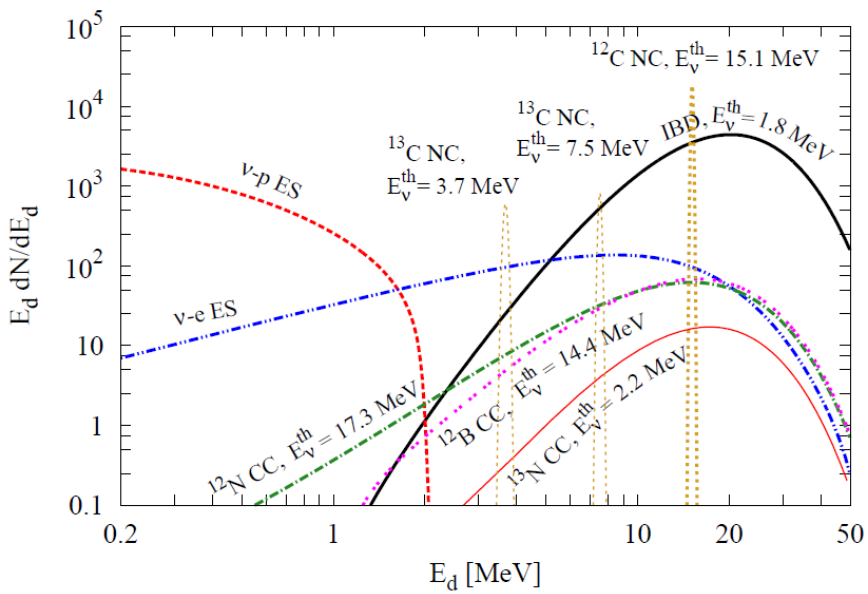
DUNE/LBNF (US)
(40 kton Liq. Ar detector)



Hyper-Kamiokande
(440 kton Water Cherenkov)



Expected signal at JUNO



1) IBD events dominate at the high energy range
2) nu-p ES channel dominates at low energies
3) coincidence events vs. singles events
4) e. vs. p discrimination: Pulse shape discrimination

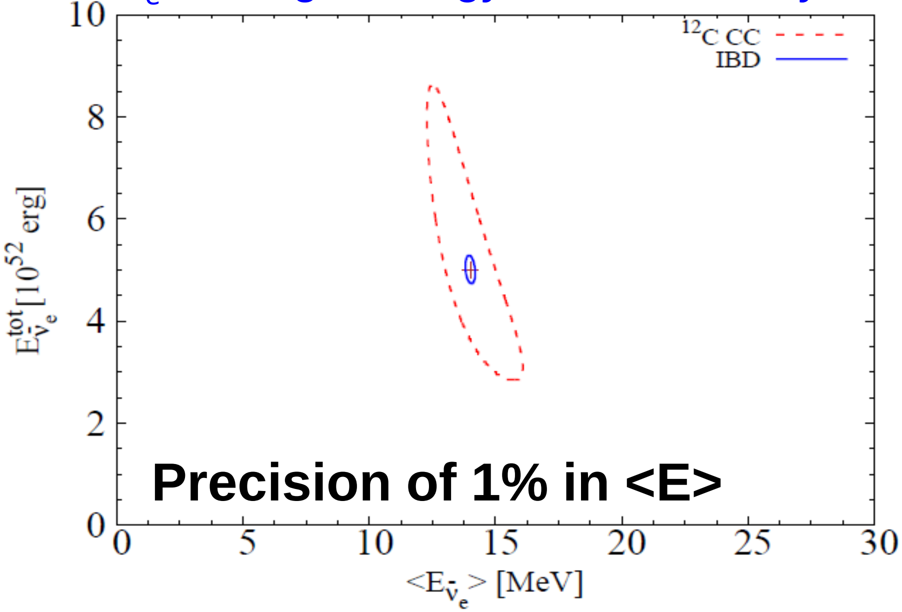
Expected number of events for a SN @ 10 kpc

Channel	Type		Number of SN Neutrino Events at JUNO		
			No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		314	316	316
		ν_e	157	159	158
		$\overline{\nu}_e$	61	61	62
		ν_x	96	96	96
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC		43	134	106
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC		86	98	126
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226
$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}$	CC		19	29	26
$\nu + {}^{13}\mathrm{C} \to \nu + {}^{13}\mathrm{C}^*$	NC	$3/2^-(5/2^-)$	23(15)	23(15)	23(15)
		ν_e	3(1)	4(3)	4(2)
		$\overline{\nu}_e$	3(2)	4(2)	4(3)
		ν_x	17(12)	15(10)	15(10)

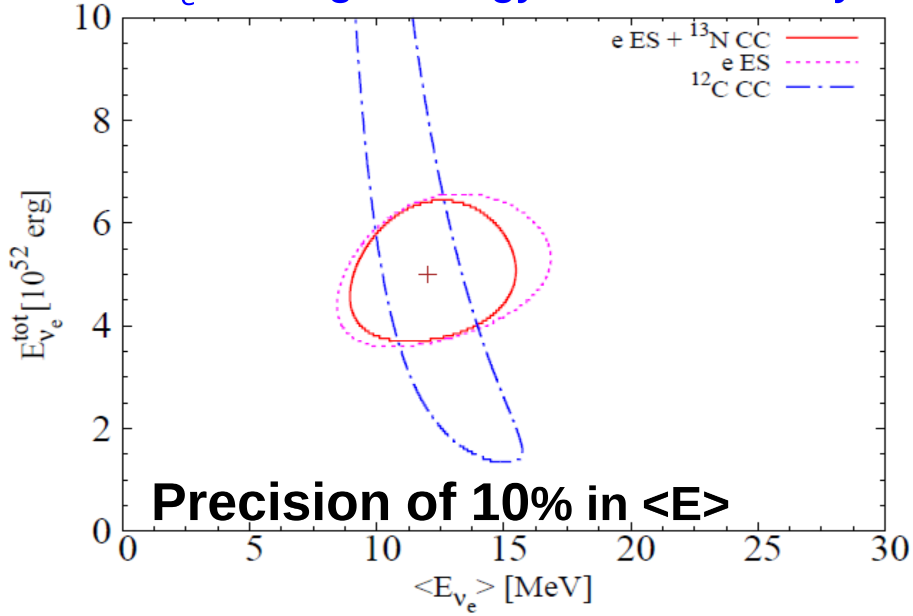
Lu, YFL, Zhou, PRD 2016

Sensitivity of JUNO

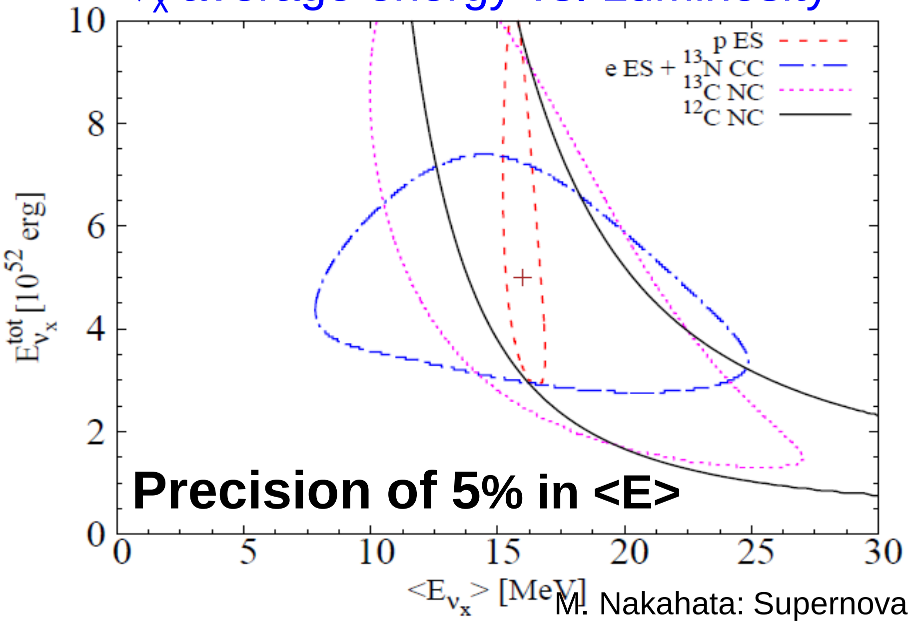
$\bar{\nu}_e$ average energy vs. Luminosity



ν_e average energy vs. Luminosity



ν_x average energy vs. Luminosity

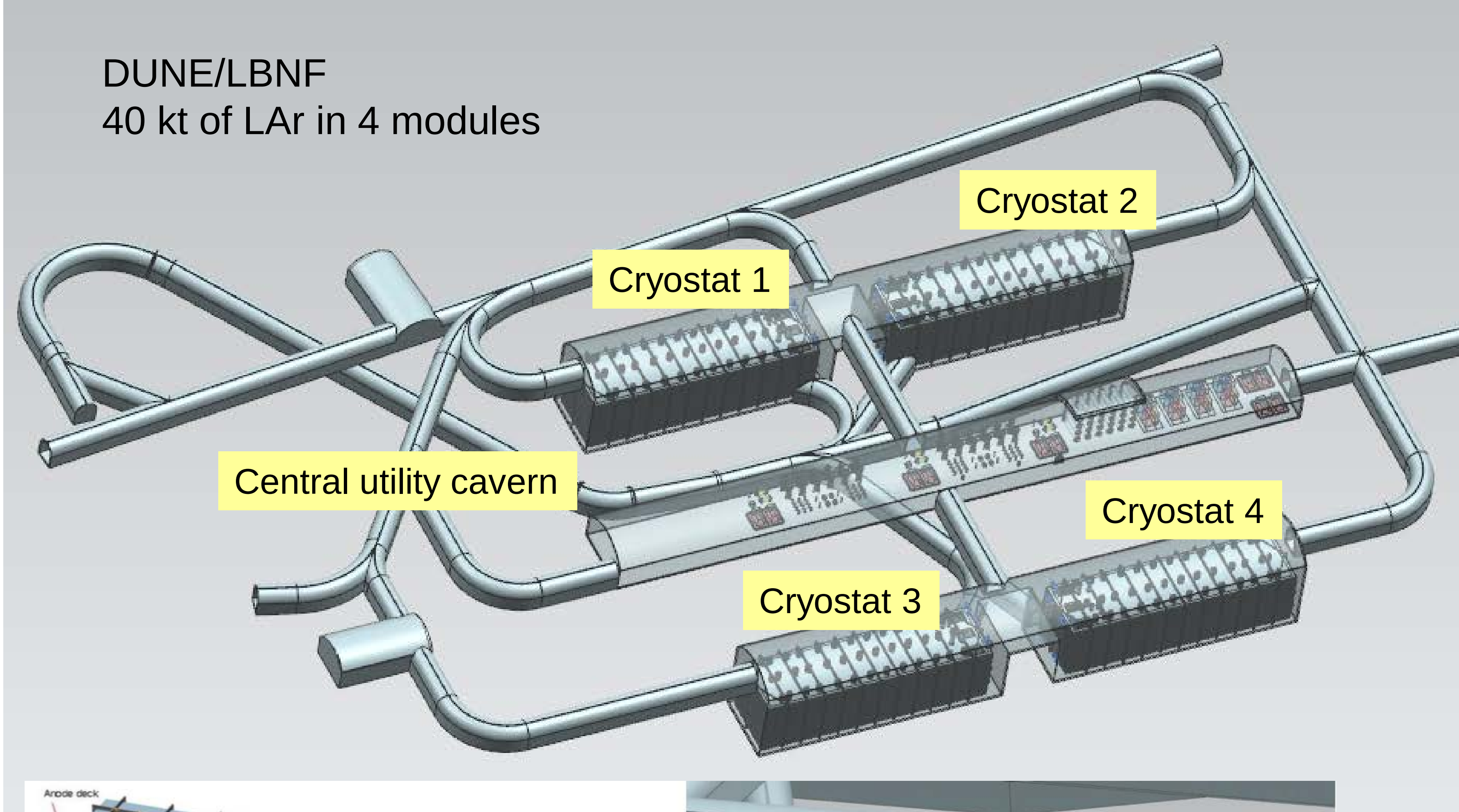


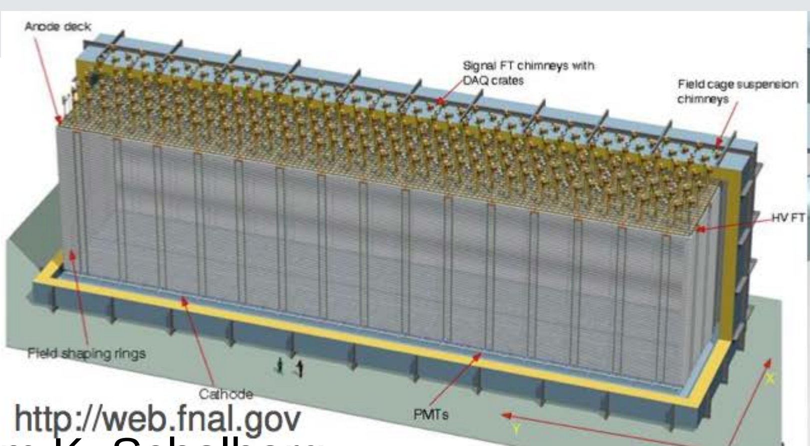
Lu, YFL, Zhou, arXiv:1605.07803
(Phys. Rev. D 94, 023006 (2016))

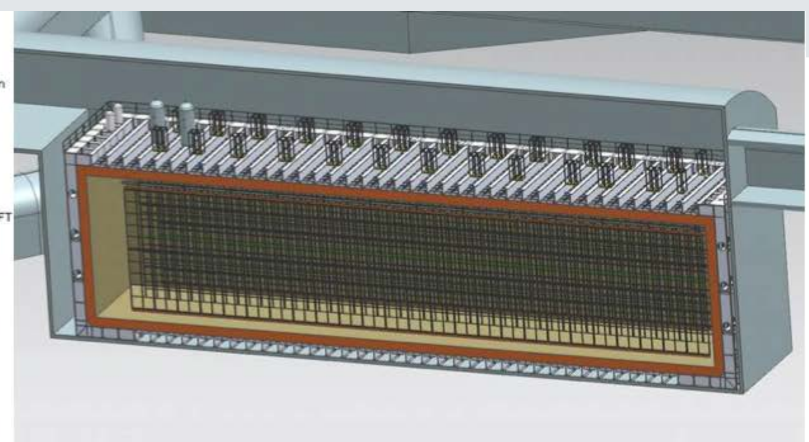
Plots are for no ν oscillation.

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

DUNE/LBNF
40 kt of LAr in 4 modules







From K. Scholberg

Low energy neutrino interactions in argon

Charged-current absorption

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

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Not much information in literature

Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

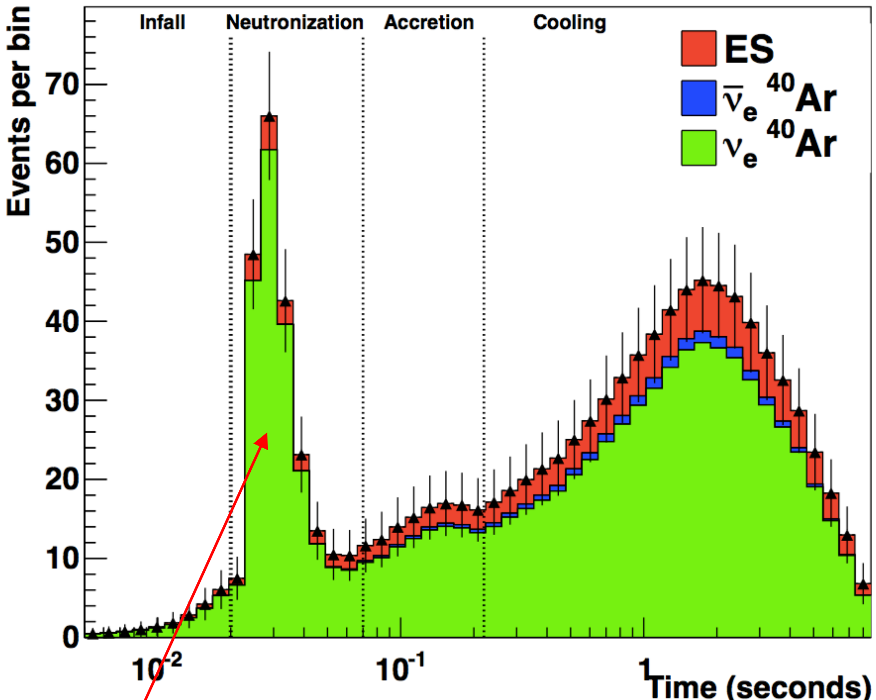
Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

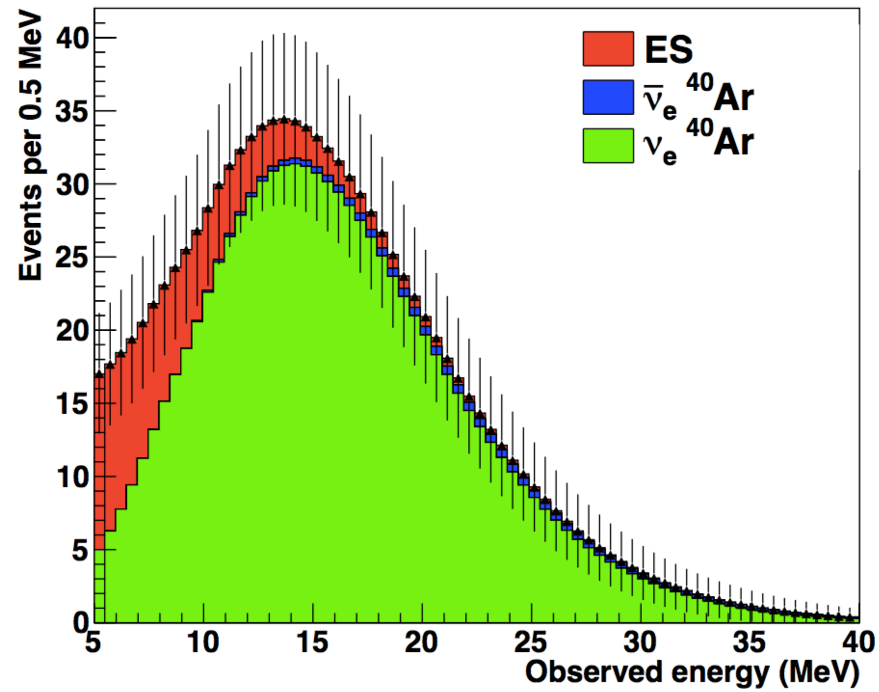
From K. Scholberg

Expected signal at DUNE (Liq. Ar)

Flavor composition
as a function of time



Energy spectra
integrated over time



For 40 kton @ 10 kpc, Garching model (no oscillations)

~180 events from neutronization burst (no oscillation case).
~0 for normal hierarchy and
~60 for inverted hierarchy oscillations.

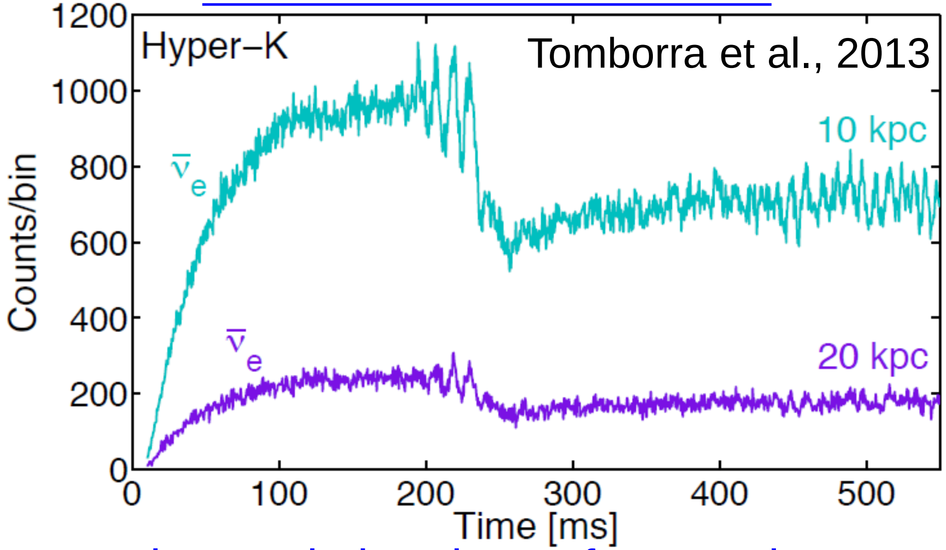
~4000 events for 10kpc SN
Dominated by ν_e

Figures From K. Scholberg

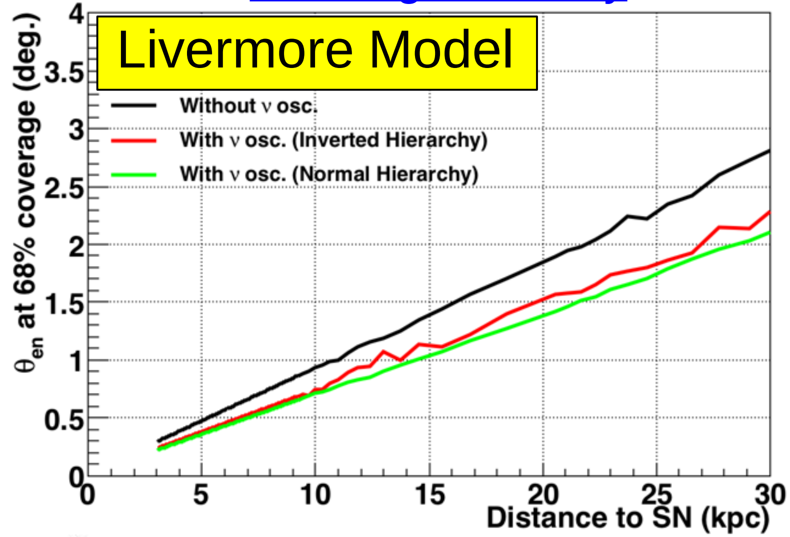
Hyper-K: high statistics measurement

100,000~140,000 $\bar{\nu}_e p$ events, 4,200~5,000 ν+e events for 10 kpc supernova

Time variation due to SASI

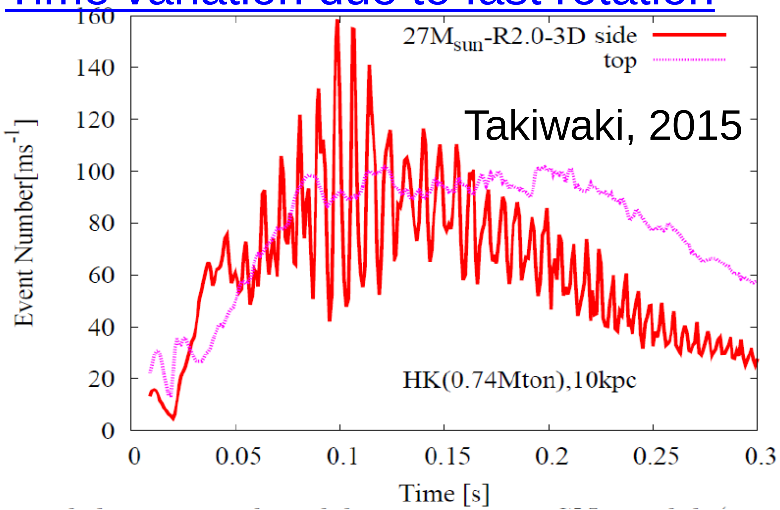


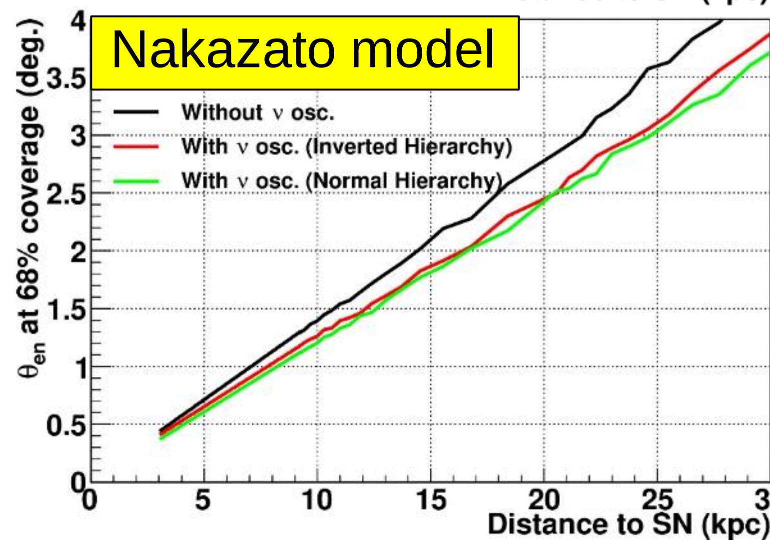
Pointing accuracy



4.9
3.9
3.7
at 50kpc

Time variation due to fast rotation



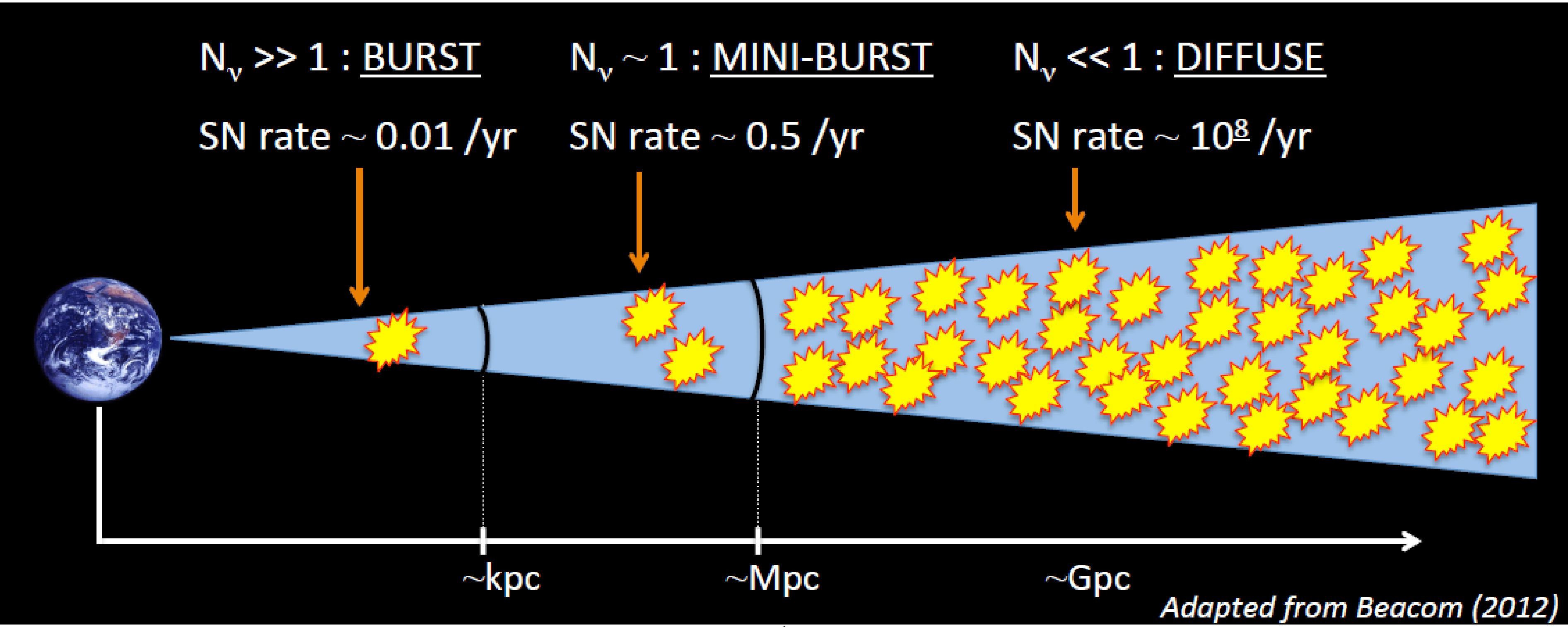


8.3
7.4
6.8
at 50kpc

Quite high rate to study fine time structure

~1 deg. accuracy for 10 kpc SN.
4~8 deg. even for LMC (50kpc).

Supernovae and distance scale



From S. Horiuchi

Galactic（＋LMC）supernova bursts

Large number of events are expected for a single SN, but burst is rare is low (once per 30-50 years).

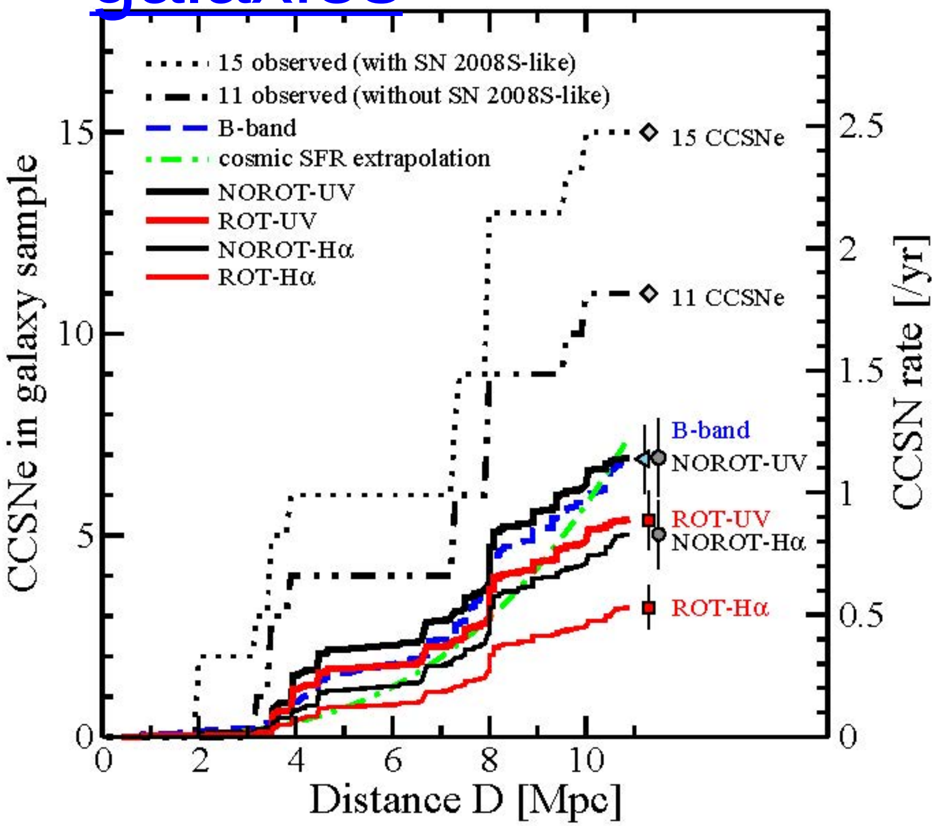
Nearby galaxy supernova

~1 neutrino events per burst at Hyper-K. Burst rate of once per a few years. Give information of spectrum w/o red shift.

Relic supernova

Many bursts contribute to the diffuse spectrum. Give spectrum with red shift.

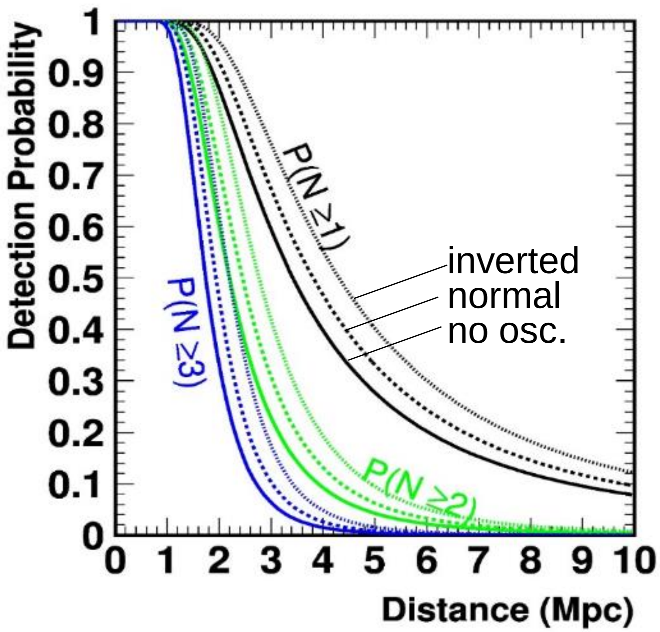
Hyper-K: supernova neutrino from nearby galaxies



Horiuchi, Beacom, Bothwell, and Thompson, J. 769 (2013) 113

Supernova rate based on observed supernovae from 2000 to 2011 (w/ and w/o SN2008S-like dim supernova), and expectation from UV observation.

Detection probability at Hyper-K



Expected number of supernovae
15.6~20.3 SNe/20years (15 CCSNe)
9.0~12.6 SNe/20years (11 CCSNe)
3.7~5.3 SNe/20years (ROT-UV)

Conditions:

- Livermore simulation
- At least one event with 10MeV threshold
- # range for no osc., N.H. and I.H.
- Not include M31, i.e. > 1Mpc

Conclusions

- From SN1987A, we learned that basic principle of supernova explosion is OK but more data are necessary to understand detailed mechanism.
- Many detectors in the world are waiting for next supernova.
- SK-Gd project will search for supernova relic neutrinos.
- Future large volume detectors will give information of many aspects of supernova neutrinos.