Supernova Neutrino Detection

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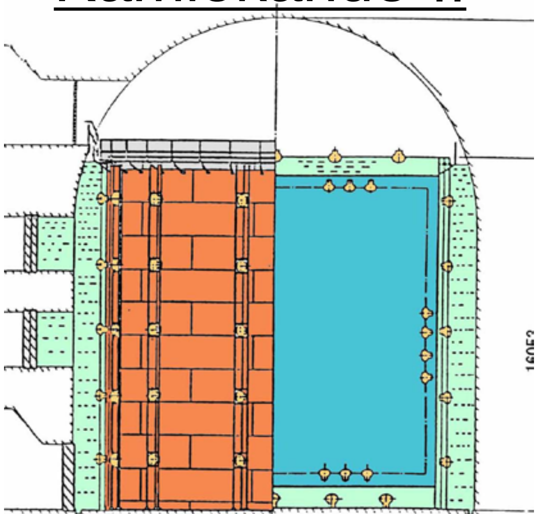
SN1987A

Contents

I will concentrate on burst neutrino detection by usual interactions.
CEvNS detection will be presented by Rafael Lang this afternoon.
Pre-supernova detection will be presented by Chinami Kato and Volodymyr Takhistov tomorrow, and presented by a poster by Koji Ishidoshiro yesterday.

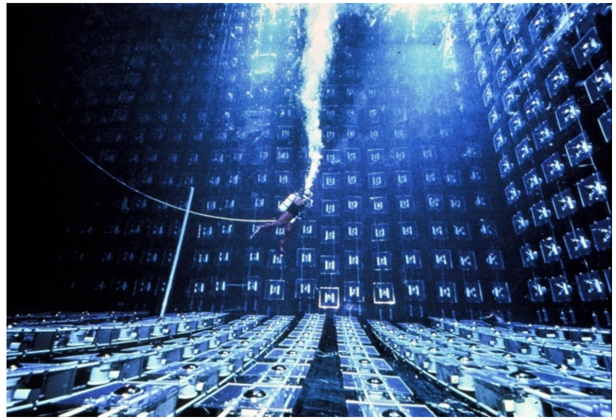
SN1987A: supernova at LMC(50kpc)

Kamiokande-II



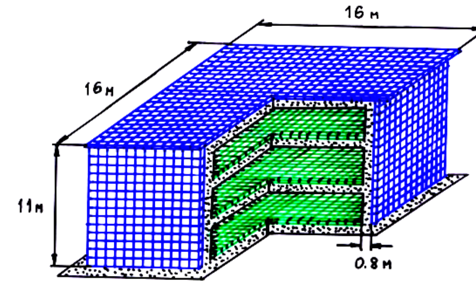
Kamioka mine, Japan
2140 ton fiducial
Water Cherenkov

IMB-3



Ohio state Morton mine, USA
~5000 ton Fiducial
Water Charenkov

BAKSAN



Baksan tunnel, Russia
330 ton in 3150 tanks
Liquid scintillator

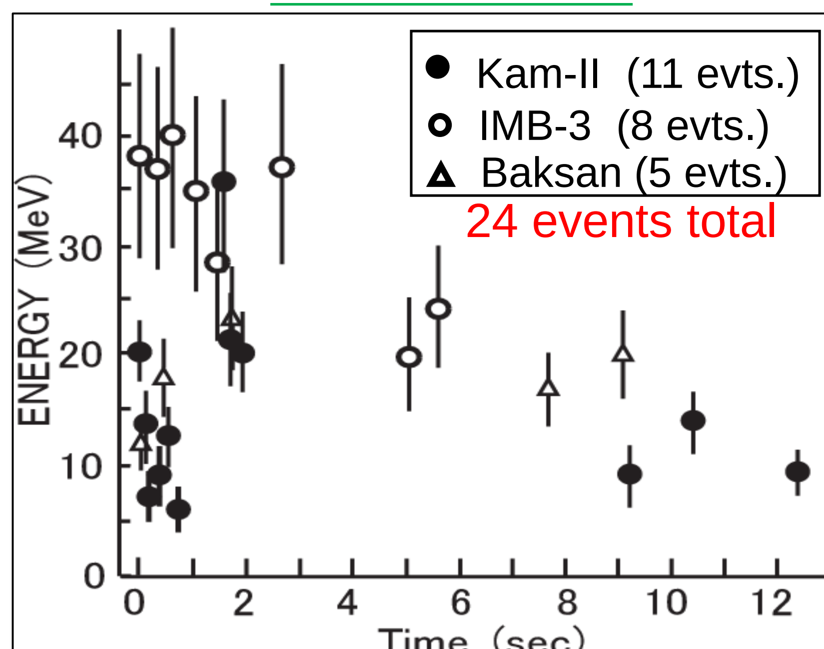
Total energy released by $\bar{\nu}_e$ was measured to be ~5x10^{52} erg.

The measured energy was consistent with core-collapse scenario.

Large error in neutrino mean energy.

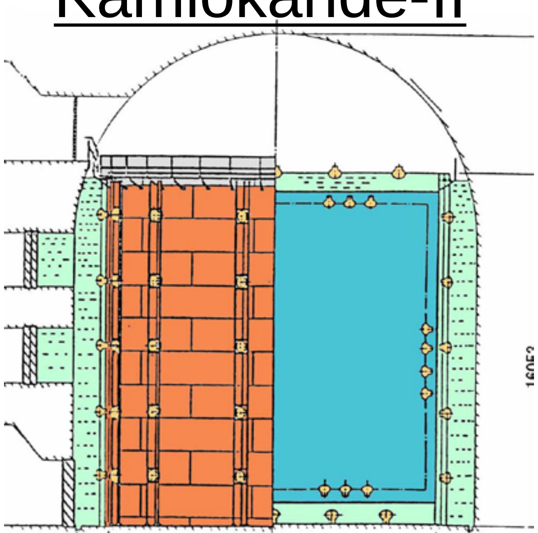
No detailed information of burst process was observed because of low statistics.

Observed events



SN1987A: supernova at LMC(50kpc)

Kamiokande-II



Kamioka mine, Japan
2140 ton fiducial
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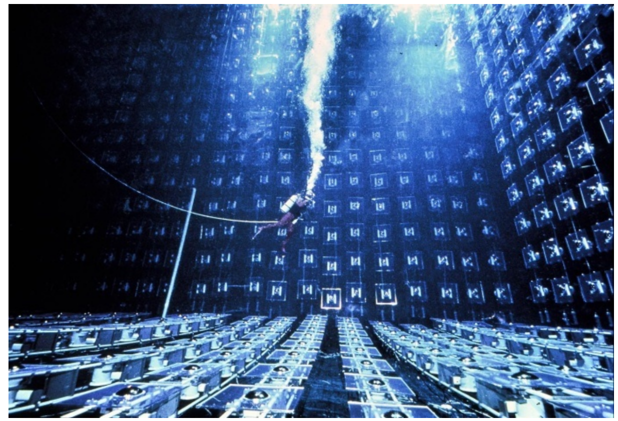

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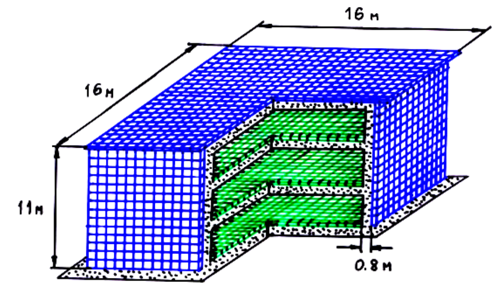
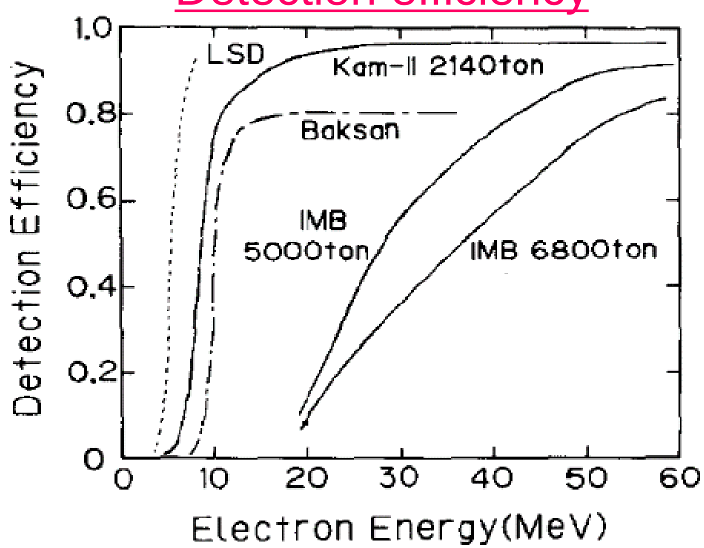


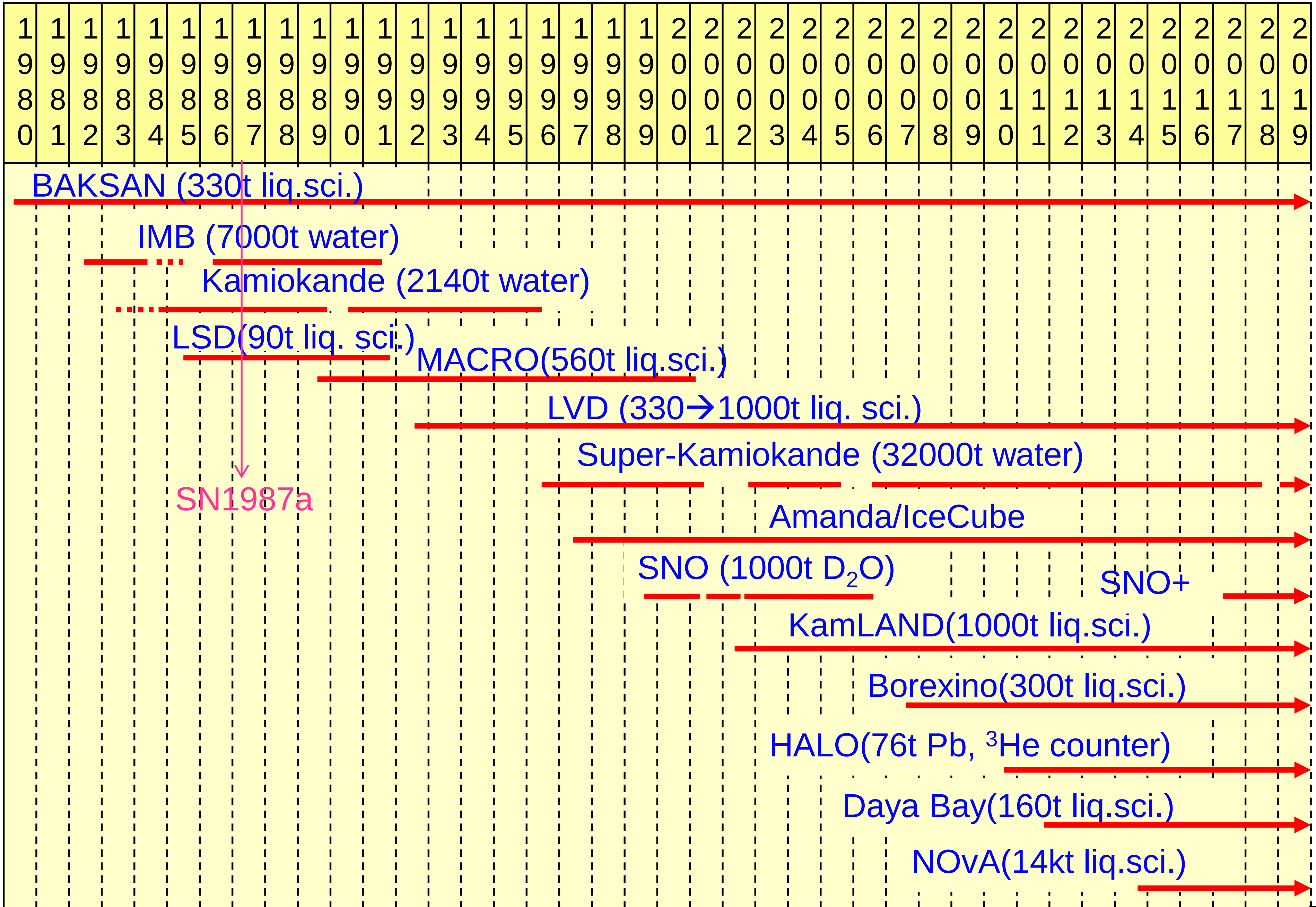
Baksan tunnel, Russia
330 ton in 3150 tanks
Liquid scintillator

Detection efficiency

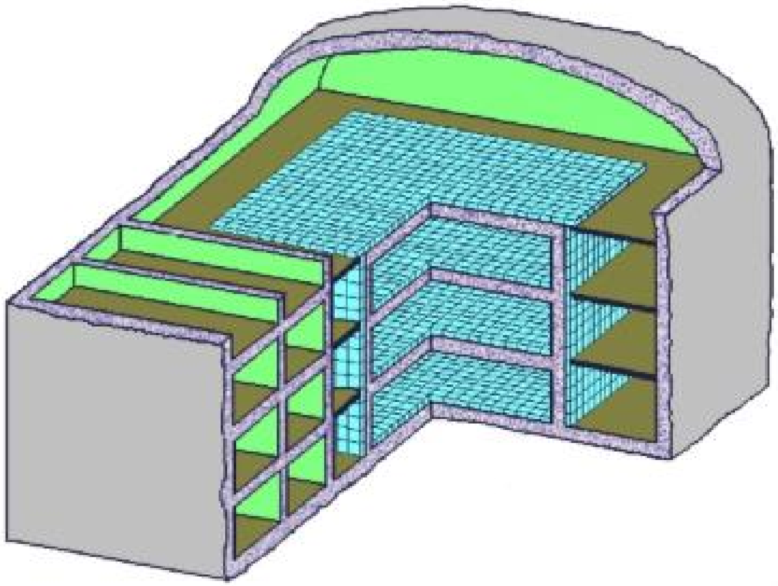


Energy threshold (at 50% eff.)
~8.5 MeV @ Kamiokande
~28 MeV @ IMB
~10 MeV @ Baksan

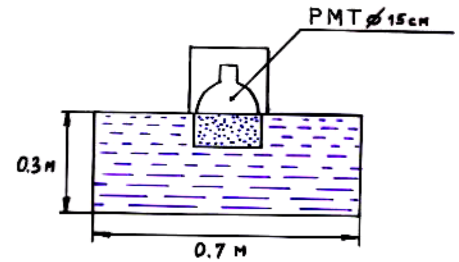
History of supernova detectors



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 33.02 years' observation time from June 1980 to December 2018. Upper limit of SN rate: < 7.0 /century (90% C.L.) (from V. Petkov, will be presented in TAUP2019).

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

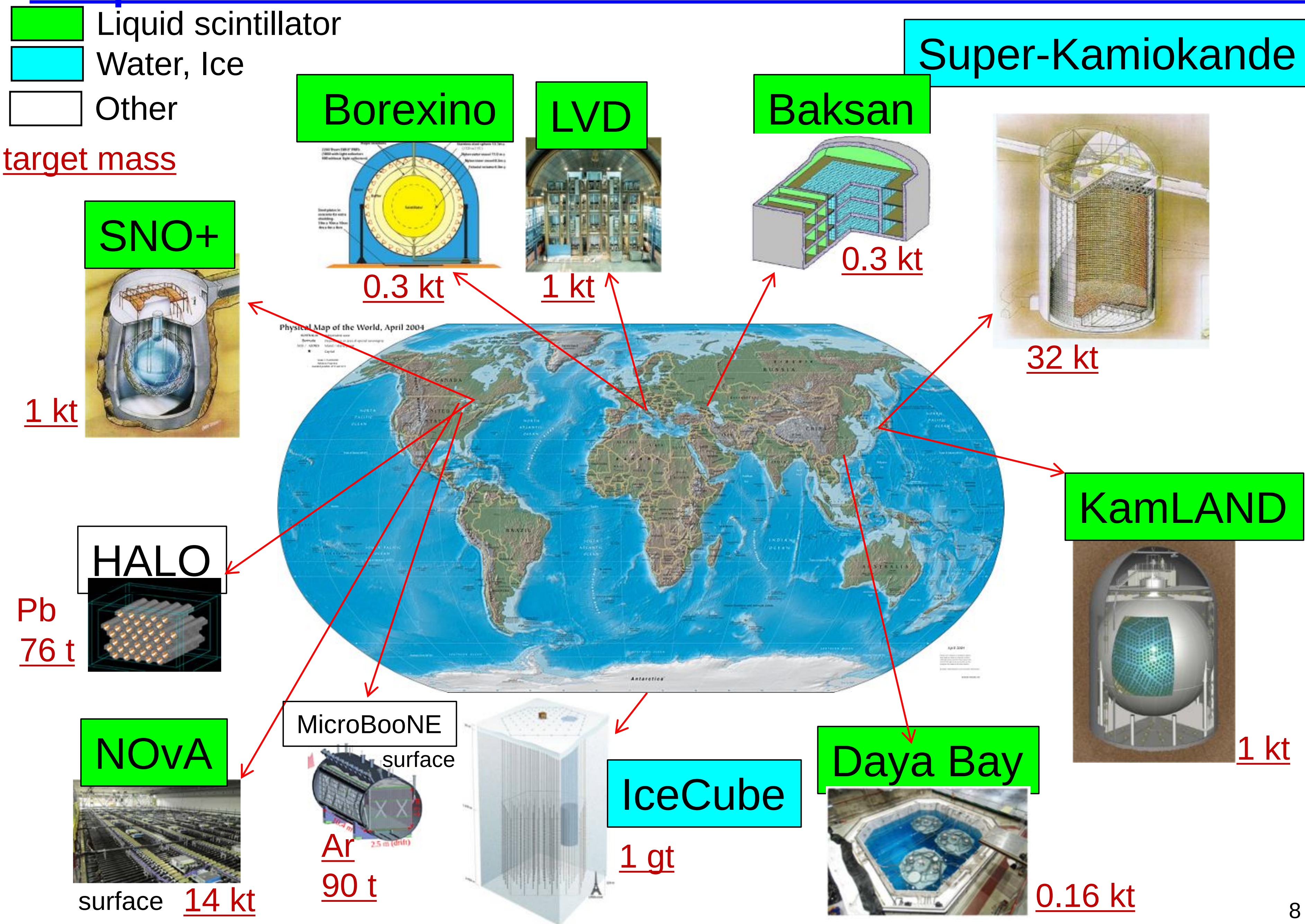
~300 $\bar{\nu}_e p \rightarrow e^+ n$ events expected for 10 kpc SN.

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

C.Vigorito et al., ICRC2017

From W.Flugione

Supernova burst detectors in the world now



Summary of supernova neutrino detectors

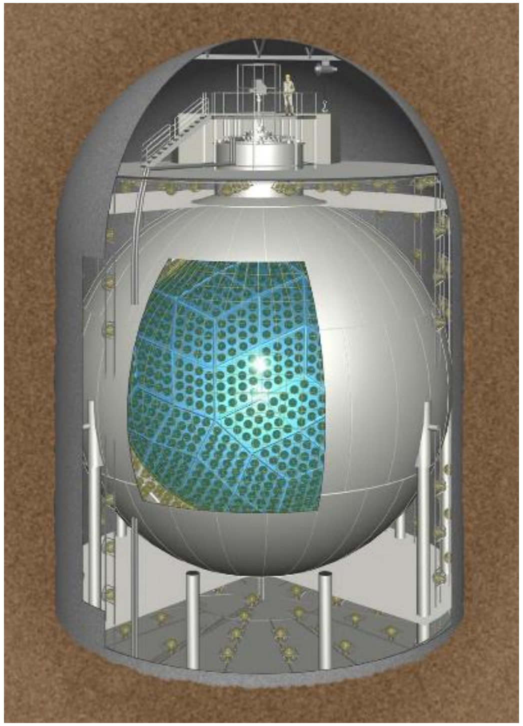
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK V)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOνA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	(Running)
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Future
IceCube Gen-2	Long string	South pole	(600)	(10^6)	Future

From K. Scholberg

plus reactor experiments, DM experiments...

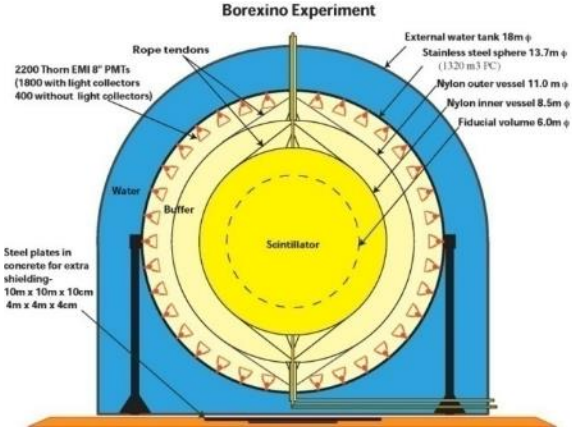
Single volume liquid scintillator detectors

KamLAND
(Kamioka, Japan)



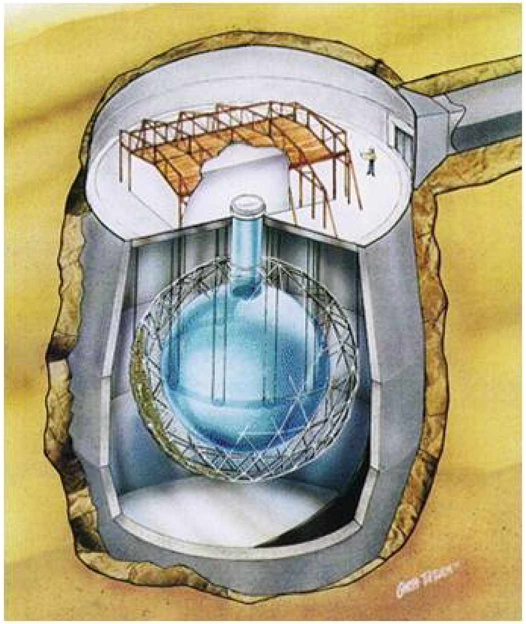
1000ton liq.sci.
Running since 2002.

Borexino
(Gran Sasso, Italy)



300ton liq.sci.
Running since 2007.

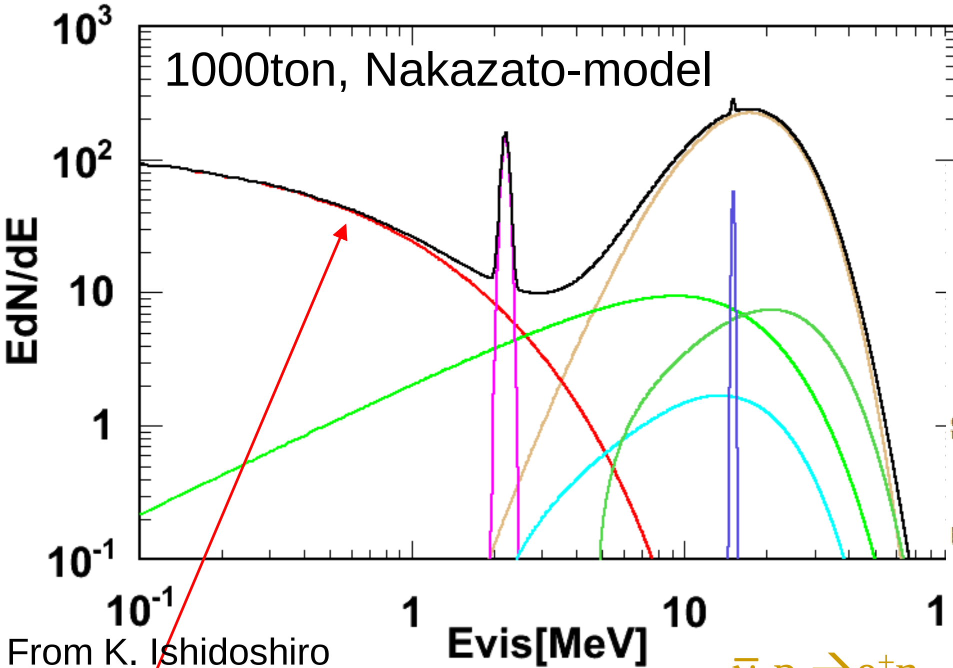
SNO+
(SNO Lab.,Canada)



1000ton liq.sci.
Under construction.

Energy spectrum expected at the liquid scintillation detectors

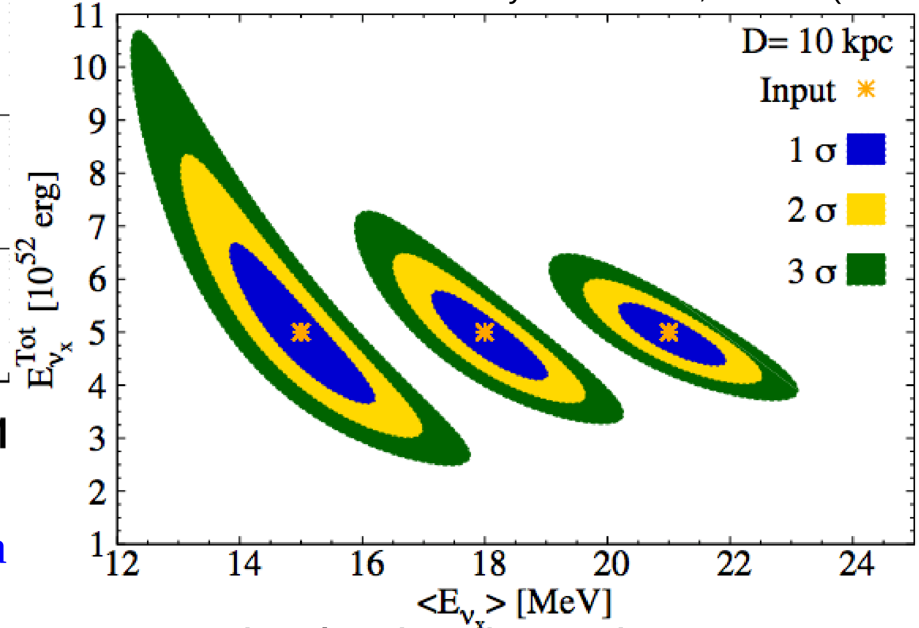
Expected energy spectrum (10kpc)



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)



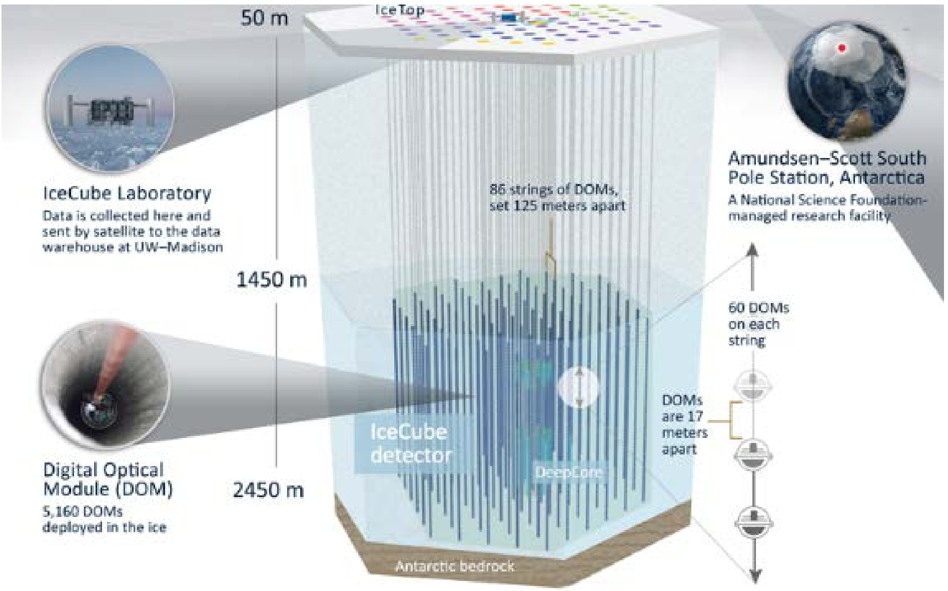
Determine luminosity and mean energy of ν_x

(ν_x : ν_μ , ν_τ at the source)

From K. Ishidoshiro

IceCube (South pole)

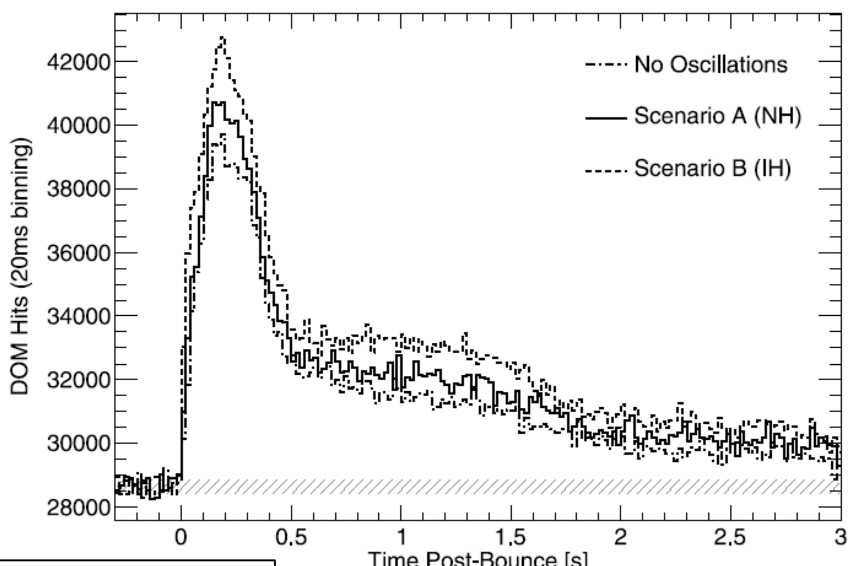
M.G. Aartsen *et al* 2017 *JINST* **12** P03012



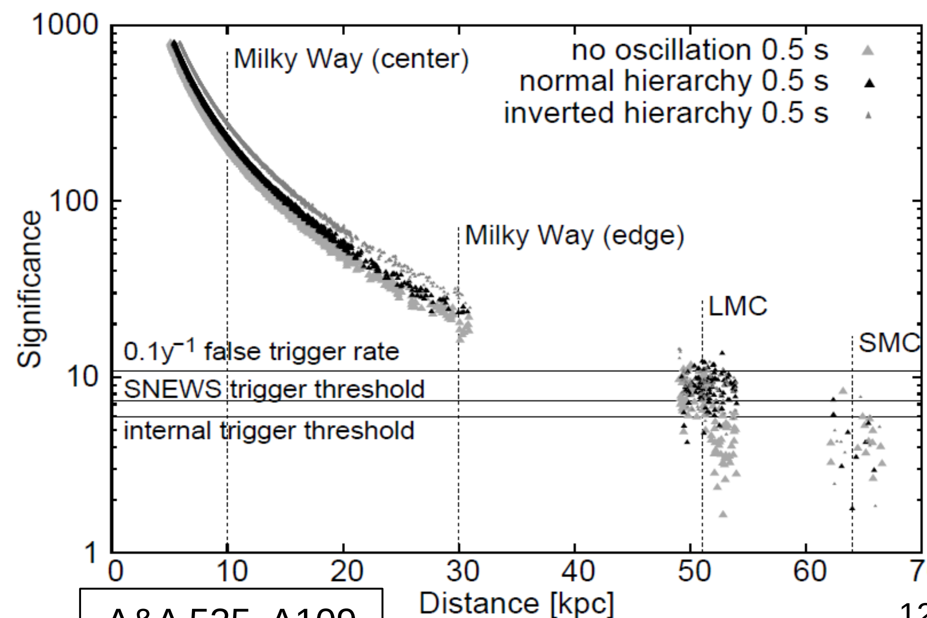
IceCube detector

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

Supernova neutrinos coherently increase single rates of PMTs.



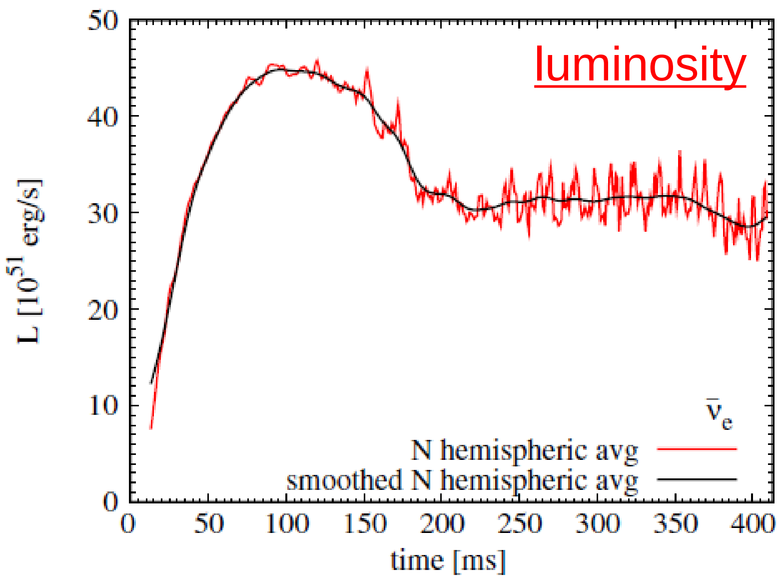
A&A 535, A109

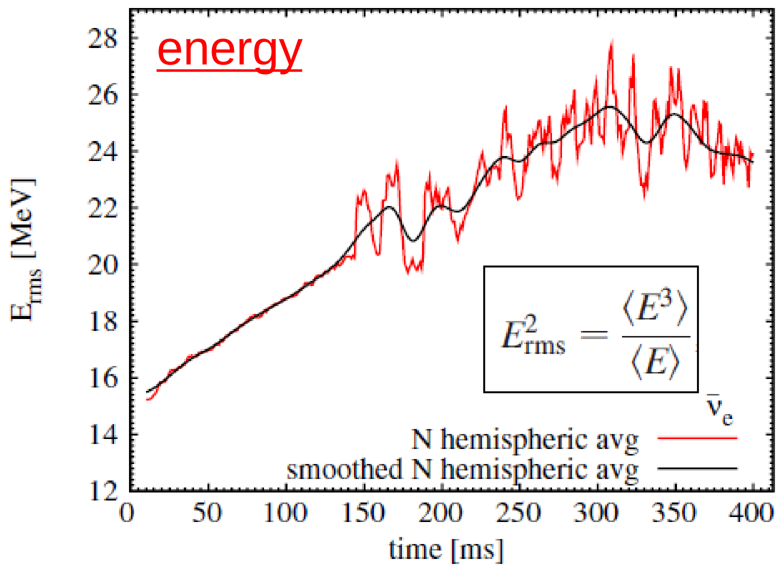


A&A 535, A109

High frequency signal variation by SASI

SASI=standing accretion shock instability

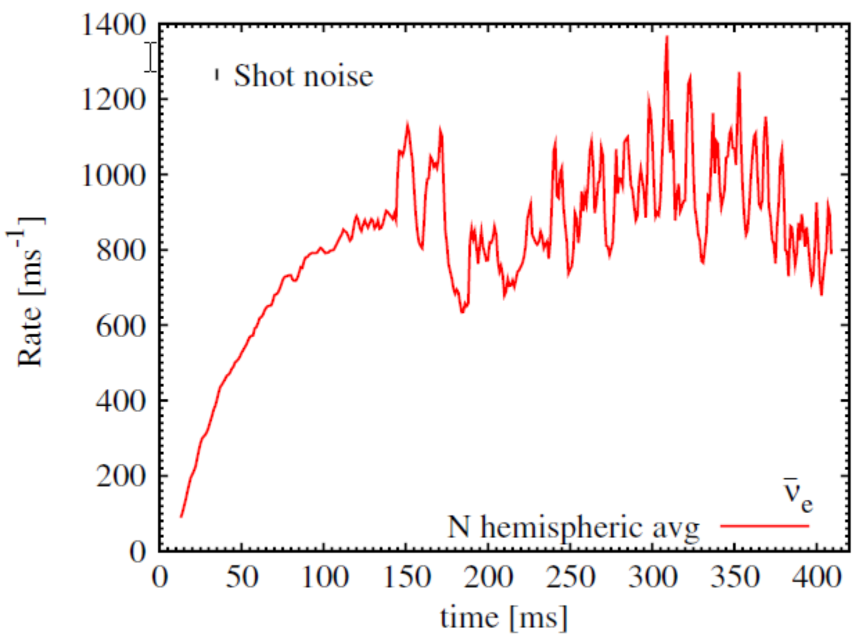




2-D(axially symmetric) simulation with PROMETHEUS-VERTEX code

Supernova at 10kpc

IceCube "event" rate

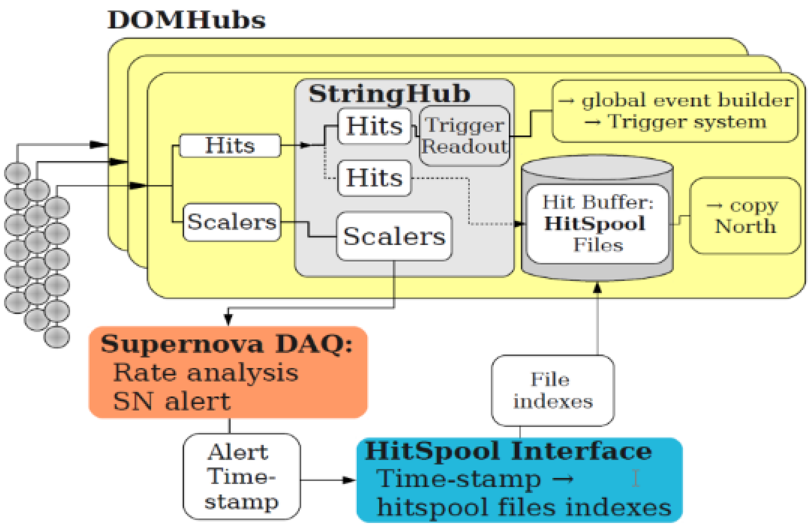


T.Lund et al., Phys. Rev. D82, 063007(2010).

IceCube – HitSpooling and directional information

HitSpool Interface

(installed in 2013)

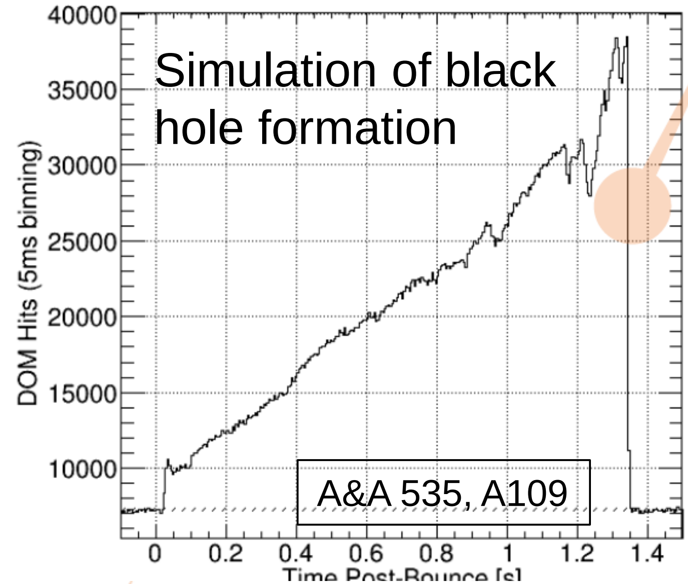


The HitSpool Interface enables

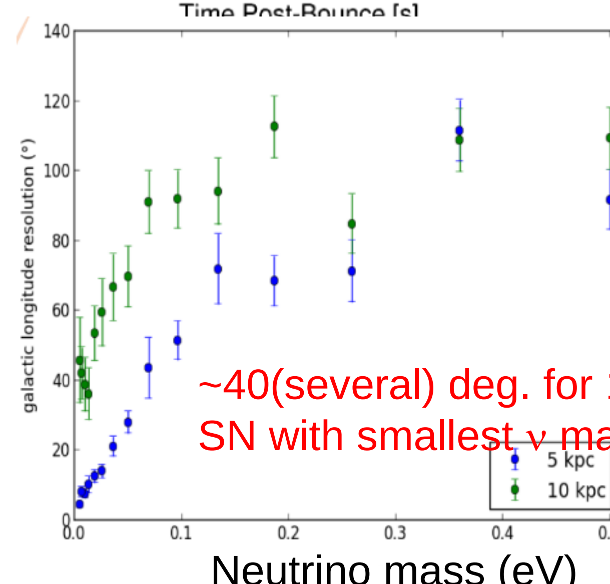
- Record all hit information in 90sec data around the burst with full data stream.
- Use correlation of hits of DOMs to estimate mean energy with a resolution of about 30% at 10 kpc.

2013 ICRC Proceeding by V. Baum

Possible directional information in case of black hole formation



Abrupt rate change

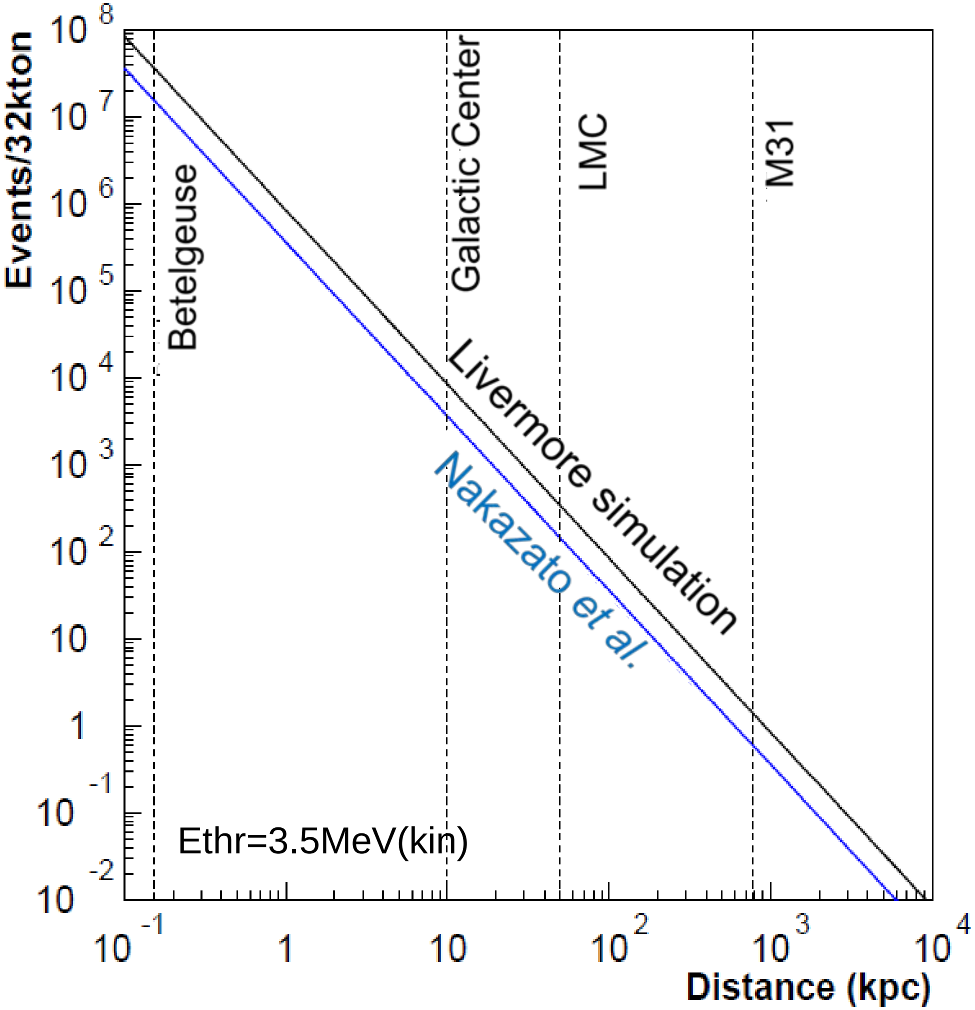


~40(several) deg. for 10 (5) kpc SN with smallest ν mass

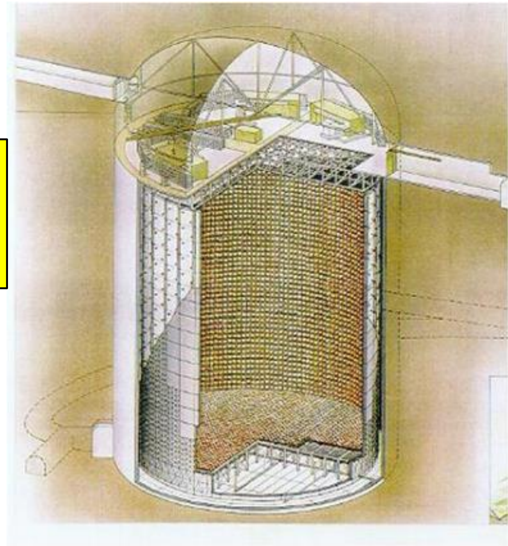
B. Eberhardt's Ph.D. thesis

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.

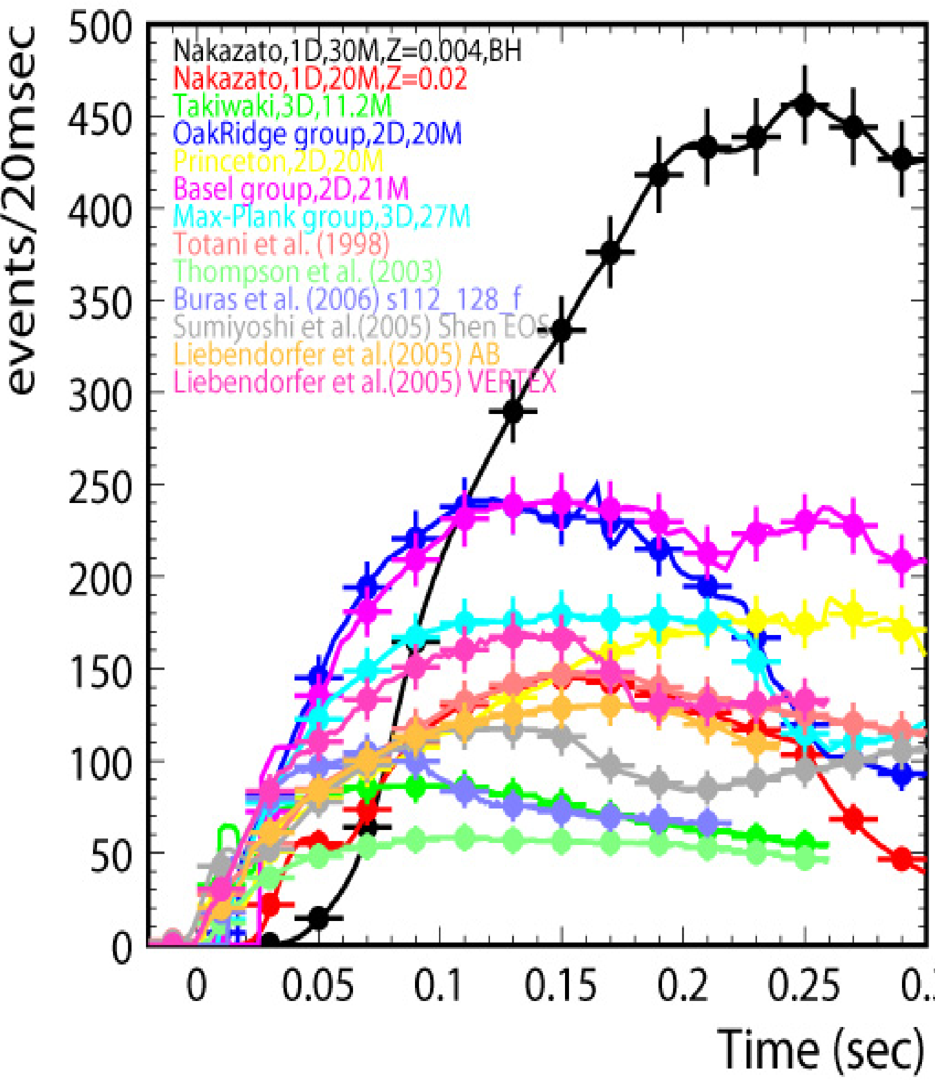
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

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)

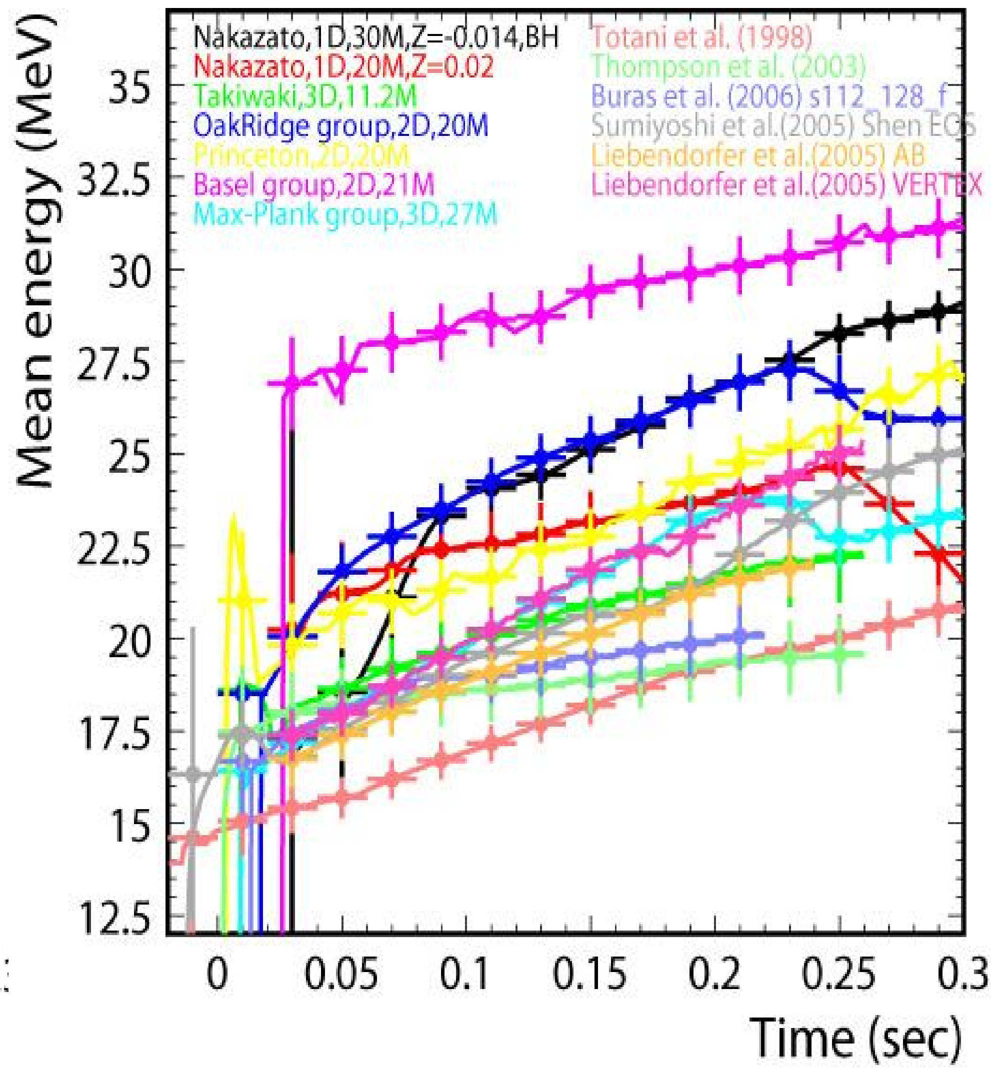
Sensitivity of Super-K for the model discrimination

For 10kpc supernova

Time variation of event rate



Time variation of mean energy



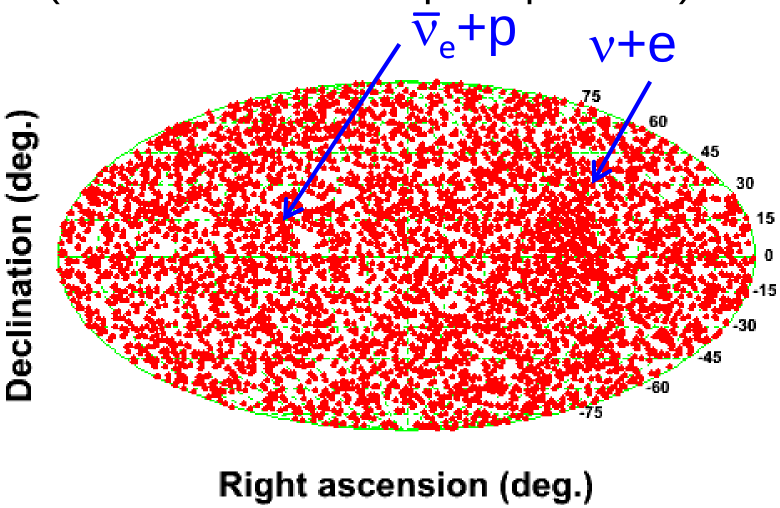
High statistics enough to discriminate models

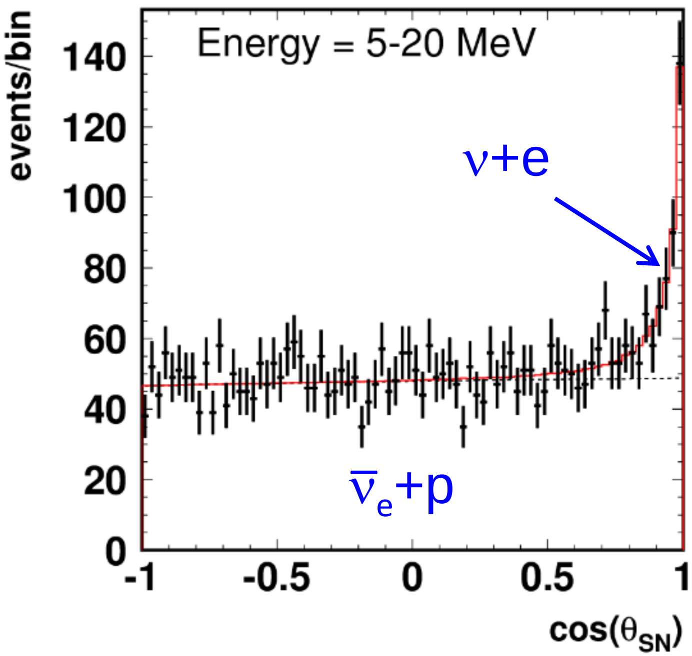
Cooperation: H. Suzuki

Super-K: directional information

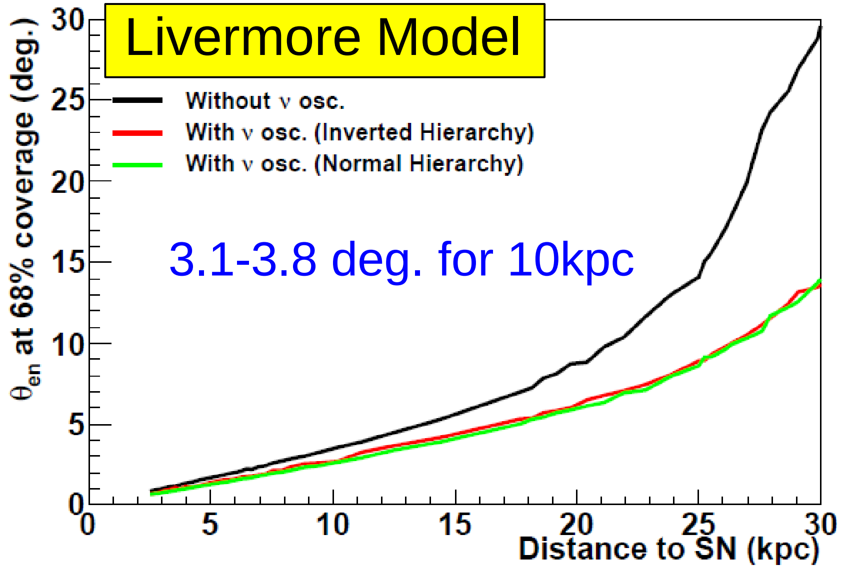
Reconstructed direction

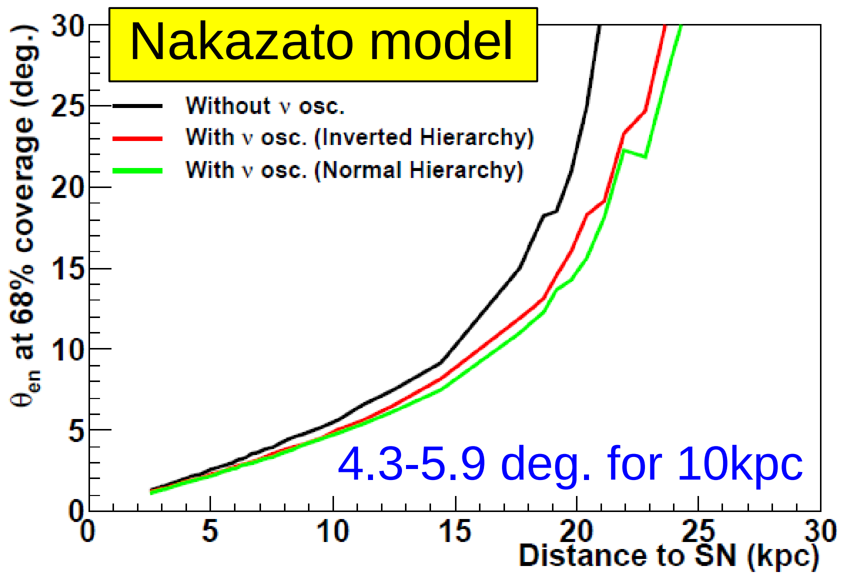
(Simulation of a 10kpc supernova)





Distance vs. pointing accuracy

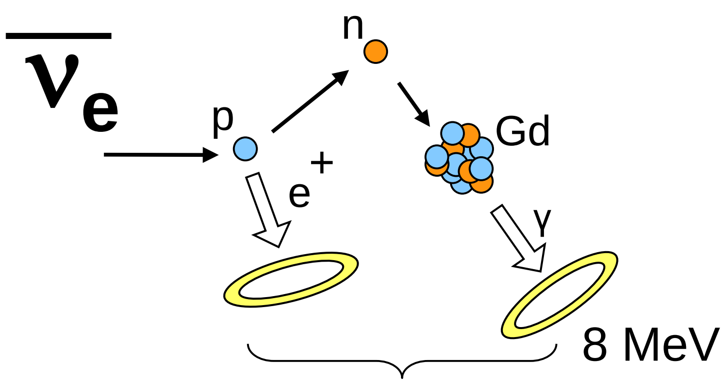




Gadolinium project at Super-K: SK-Gd

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

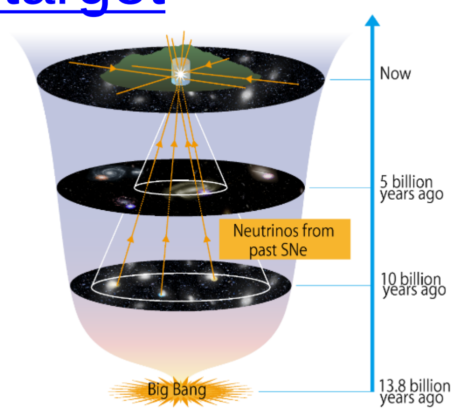
Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

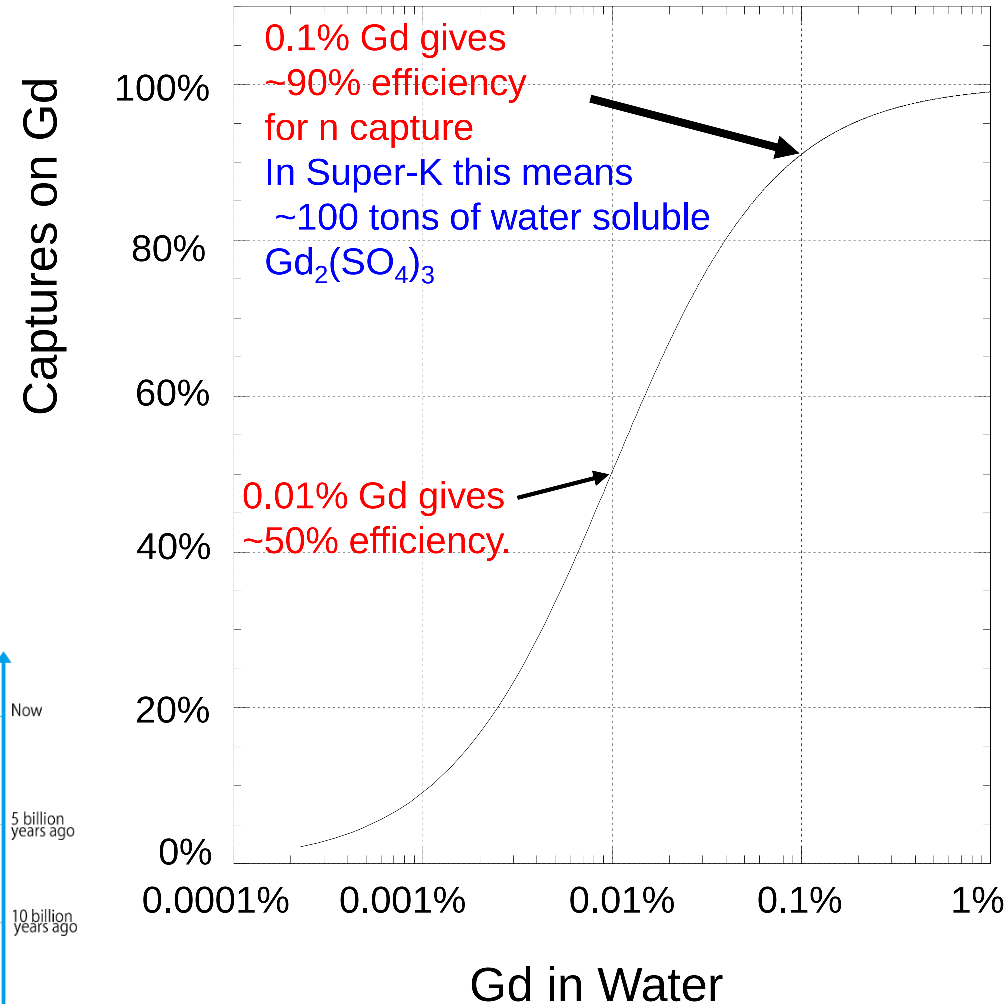


ΔT~30μs
Vertices within 50cm

Main physics target

Observation of Supernova Relic Neutrinos.



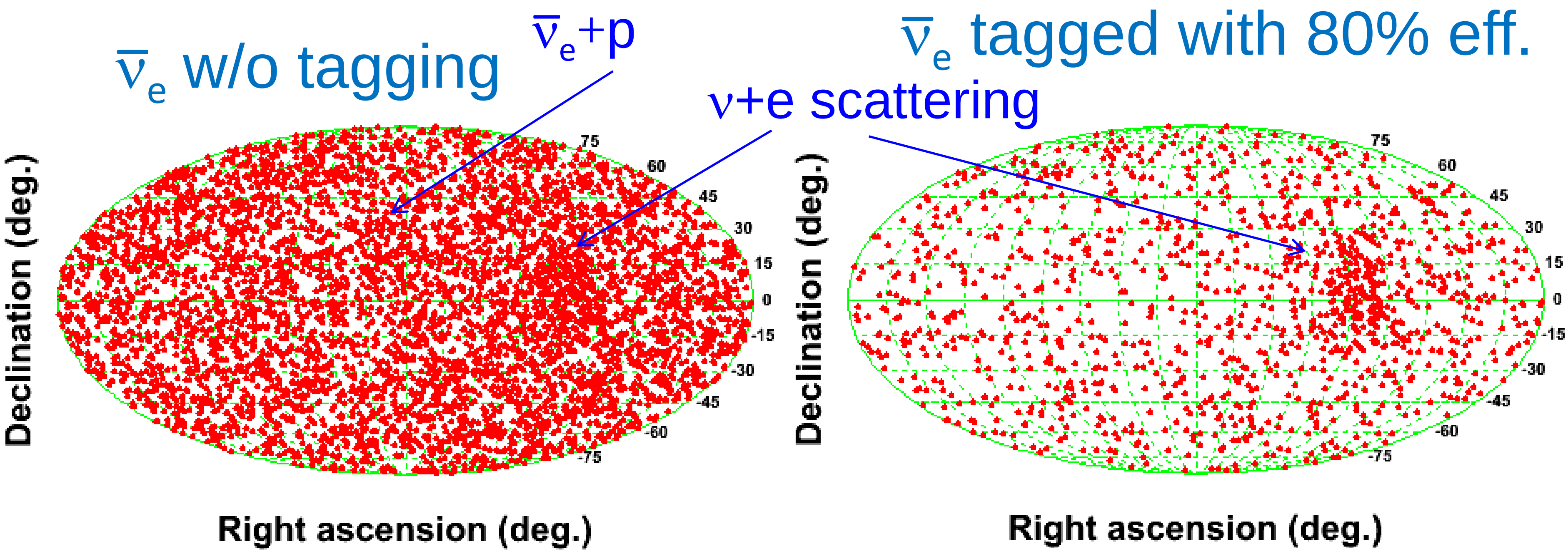


Plan to start 0.01%Gd phase in early 2020.

In case of Galactic supernova

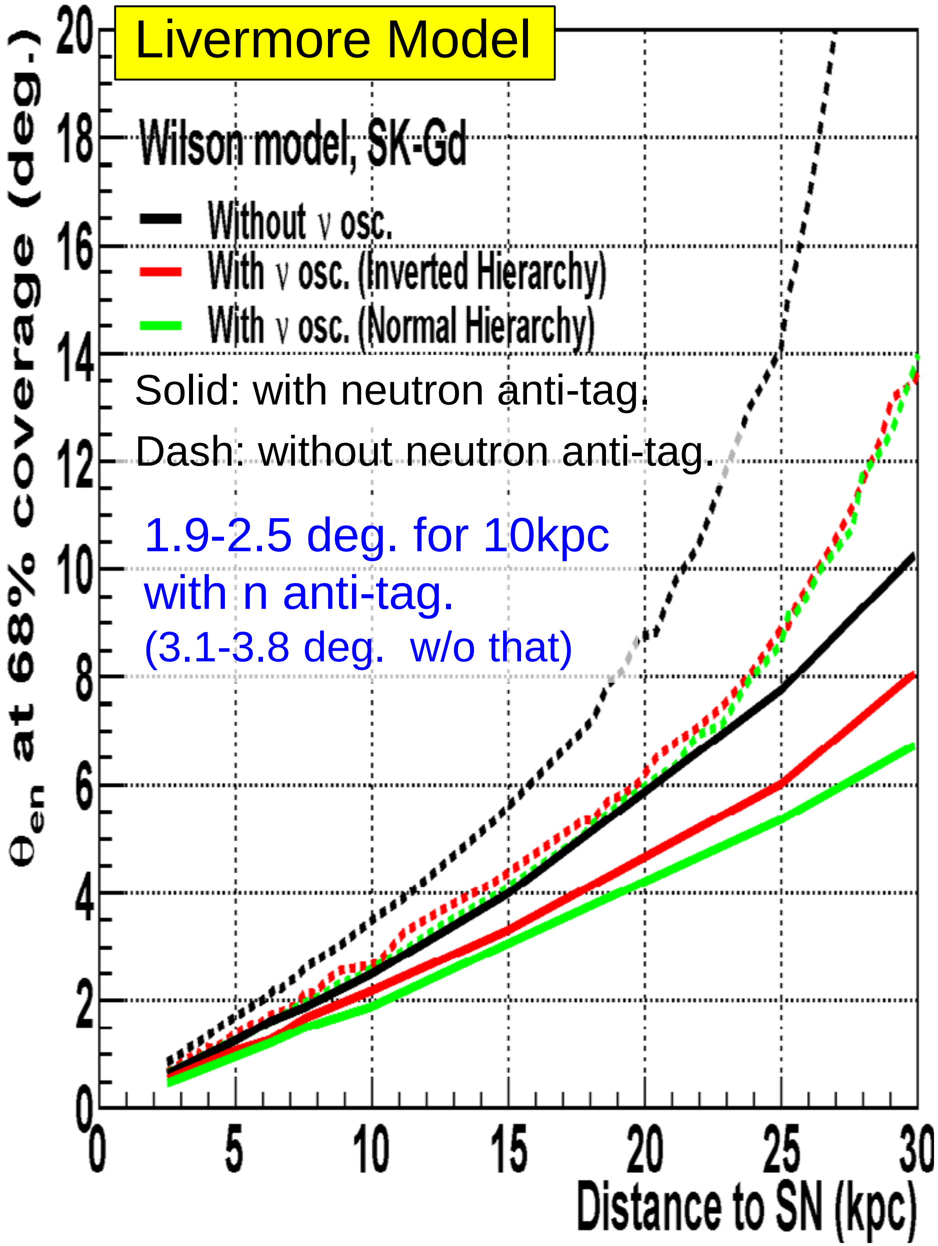
Improve pointing accuracy

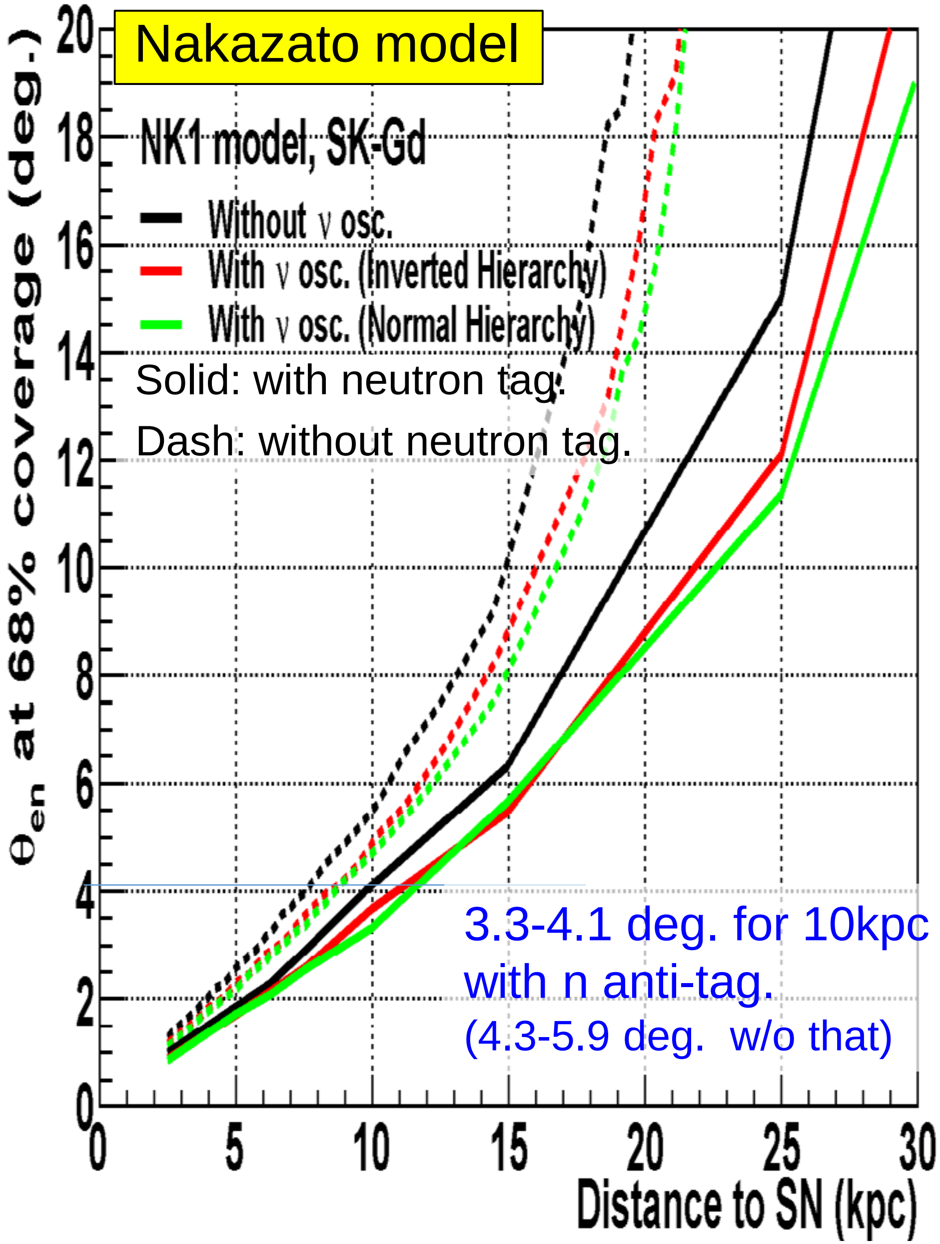
(10kpc SN simulation)



If $\bar{\nu}_e$ can be tagged and subtracted from the plot, directional events (ν+e scattering events) can be enhanced and pointing accuracy can be improved.

SK-Gd: Pointing accuracy with neutron information

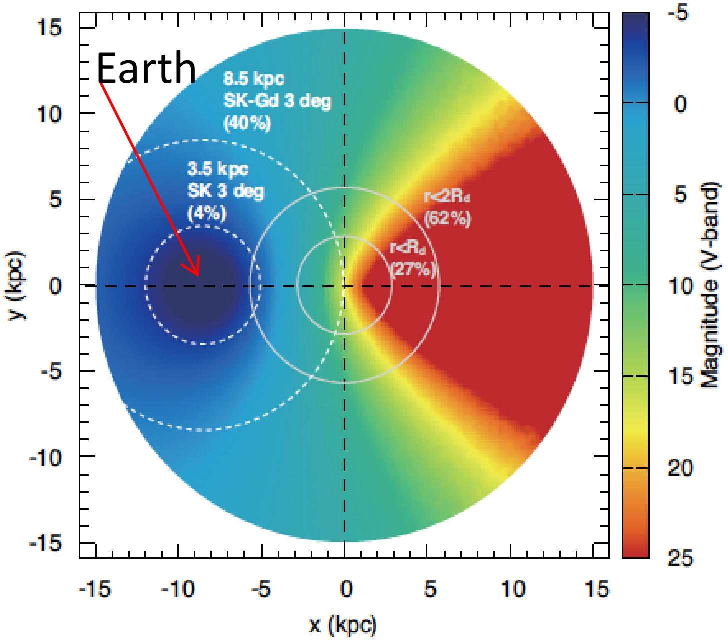




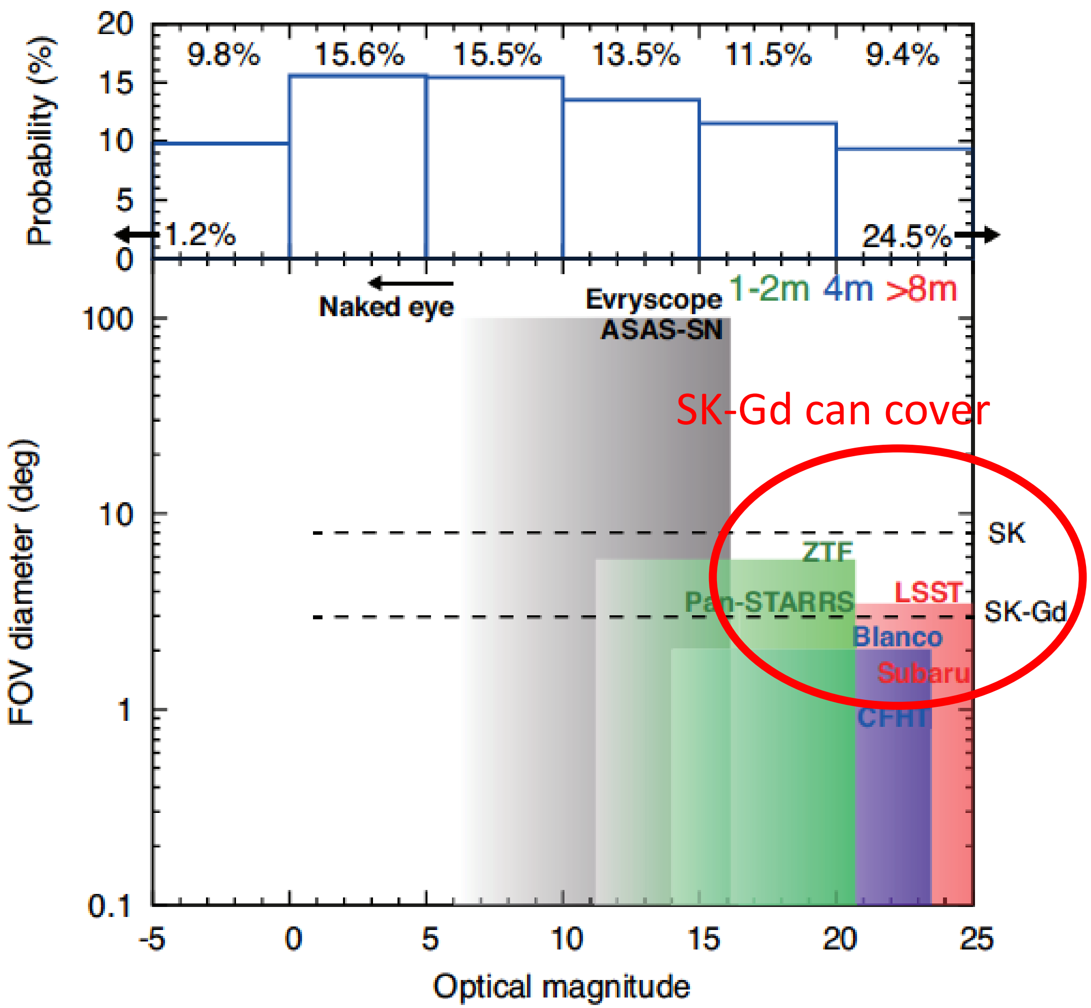
Pointing accuracy can be improved by neutron anti-tagging.

Electromagnetic follow up

Optical magnitude

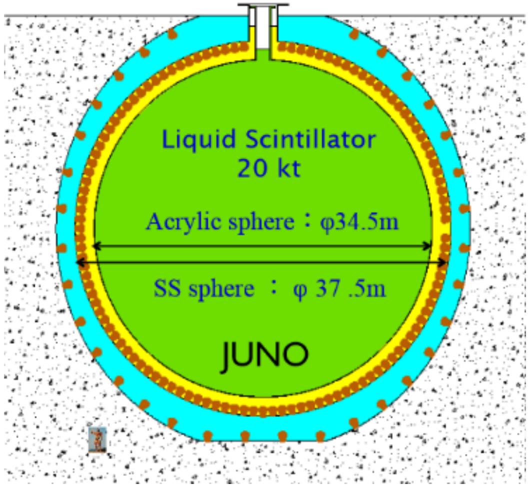


Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, Kotake,MNRAS 461 (3): 3296-3313,
http://arxiv.org/abs/1602.03028



Future Large Volume Detectors

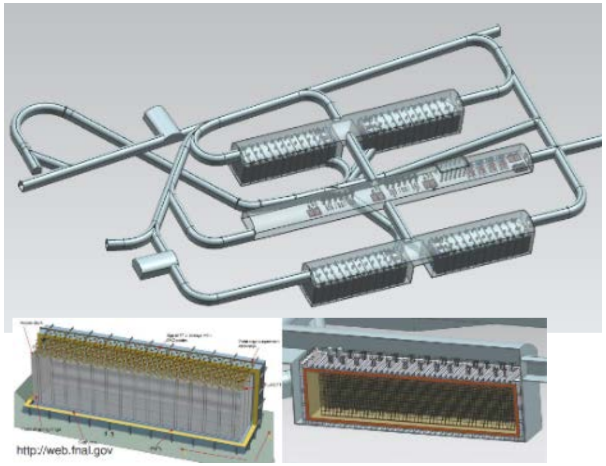
JUNO(China)
(20kton Liq. Sci.)



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

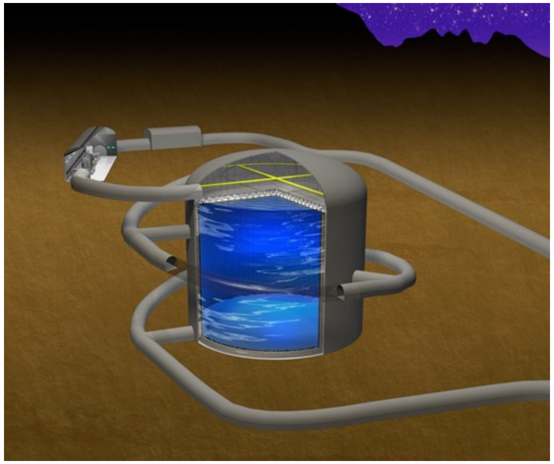
DUNE/LBNF (US)
(40 kton Liq. Ar)



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

~3000 ν_e events for 10kpc SN.

Hyper-Kamiokande
(220 kton Water)

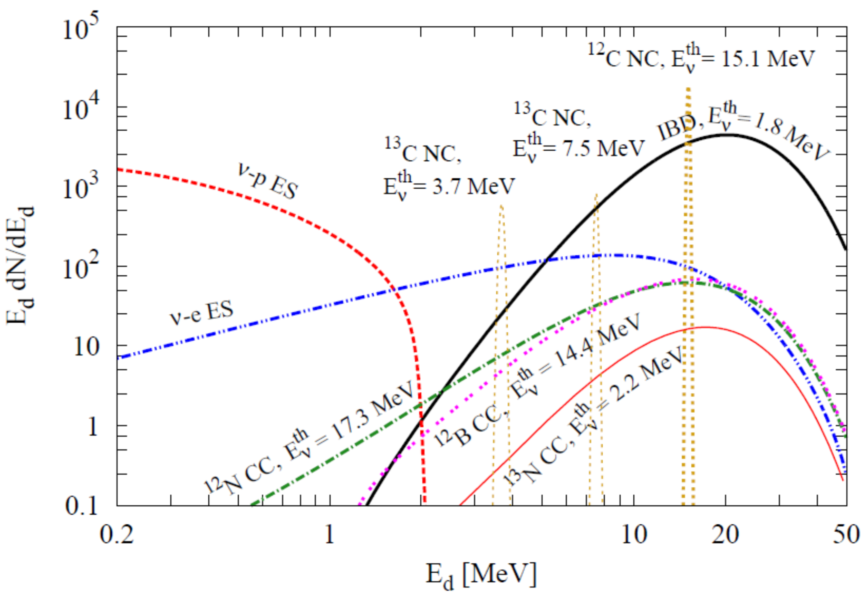


50k~80k $\bar{\nu}_e p$ events for 10 kpc supernova. Precise measurement of time variation.

1~2 deg. pointing accuracy.

Detection of supernova neutrinos at nearby galaxies.

JUNO: Expected signals



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

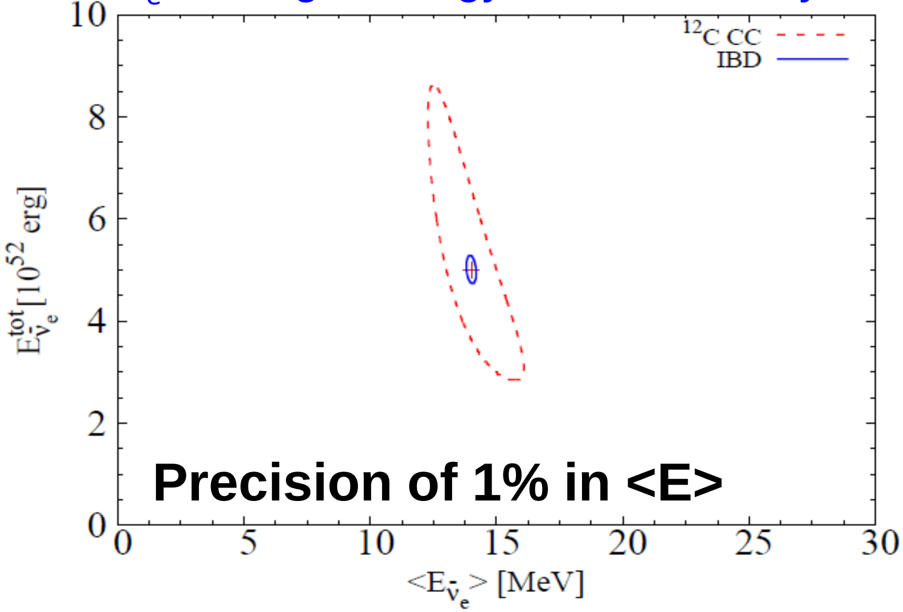
Expected number of events for a SN @ 10 kpc

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
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC		43	134	106
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC		86	98	126
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226
$\nu_e + {}^{13}C \to e^- + {}^{13}N$	CC		19	29	26
$\nu + {}^{13}C \to \nu + {}^{13}C^*$	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)

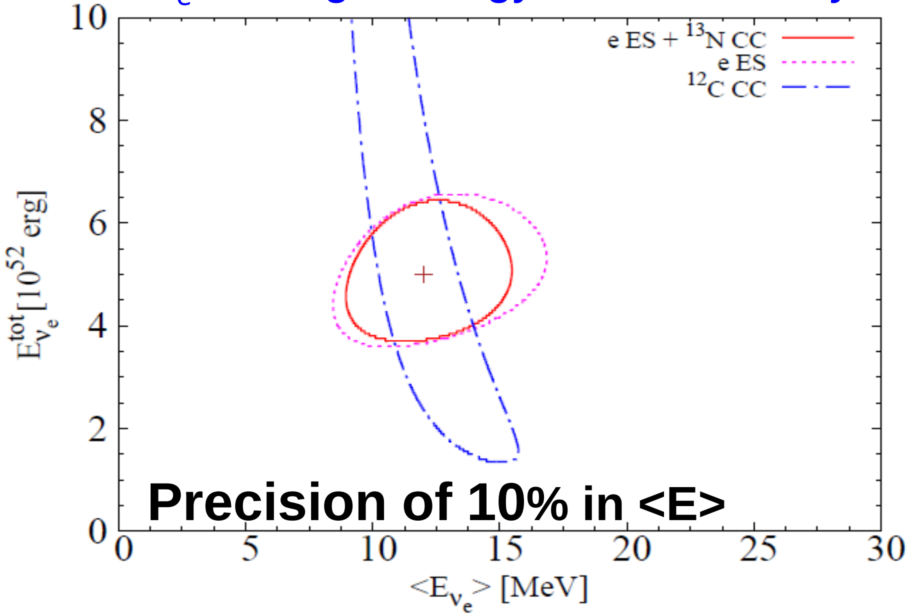
Lu, YFL, Zhou, PRD 2016

JUNO: Sensitivity for each neutrino flavor

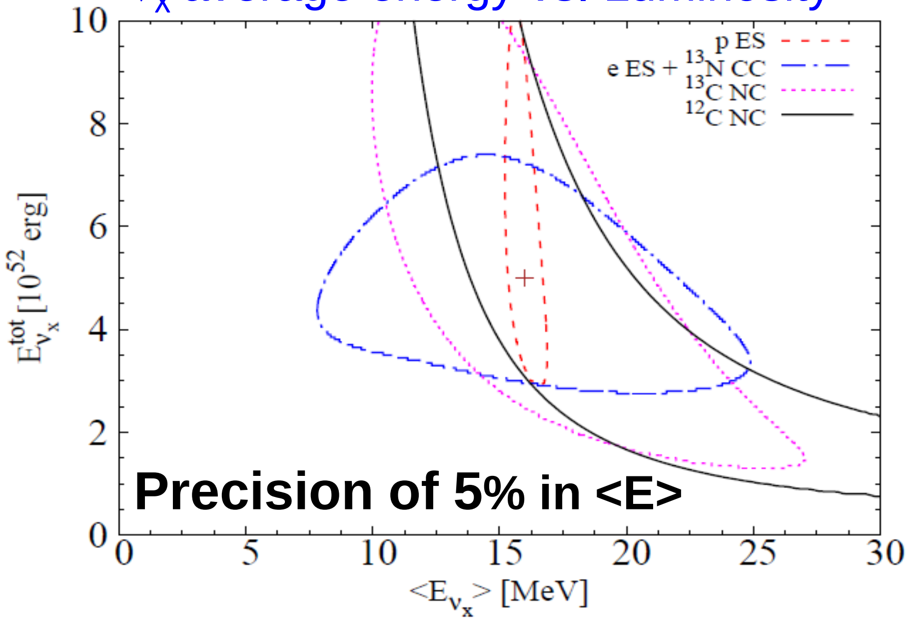
$\bar{\nu}_e$ average energy vs. Luminosity



ν_e average energy vs. Luminosity



ν_X average energy vs. Luminosity



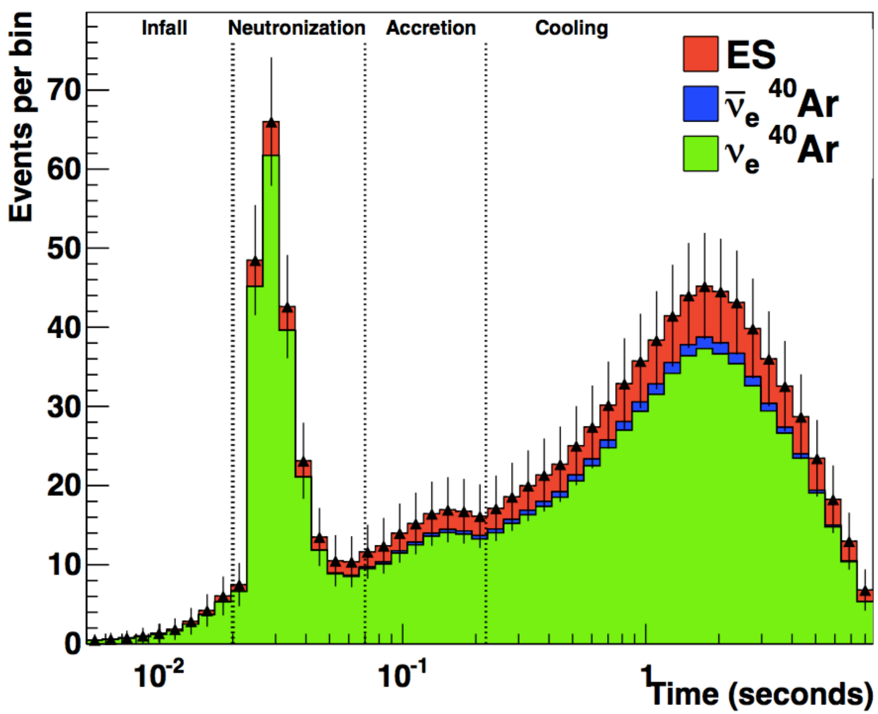
Lu, YFL, Zhou, arXiv:1605.07803
(Phys. Rev. D 94, 023006 (2016))

Plots are for no ν oscillation.

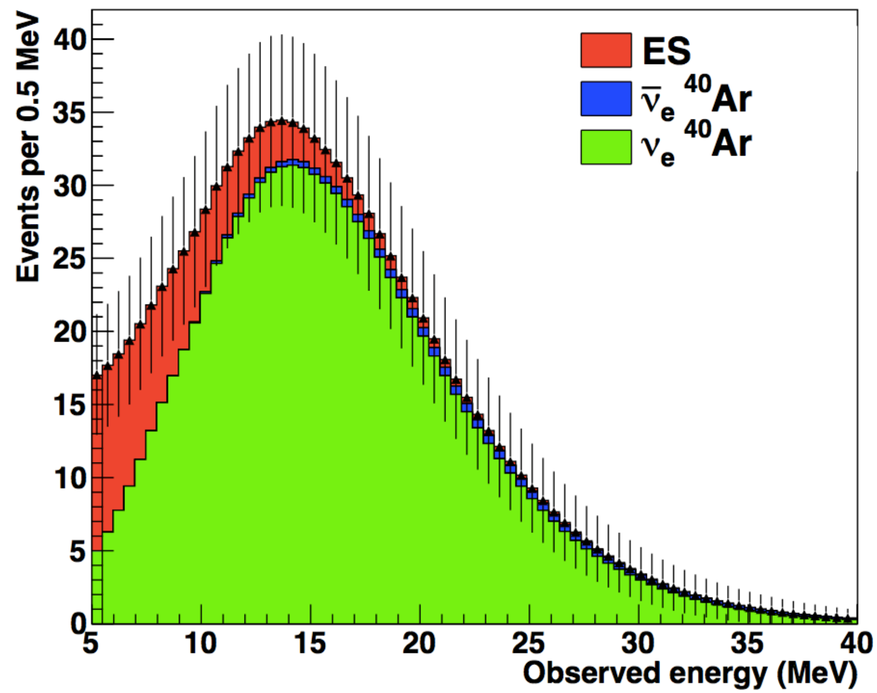
Precise measurement of average energy and luminosity for all neutrino flavors.

DUNE: Expected time profile and spectrum

Flavor composition
as a function of time



Energy spectra
integrated over time

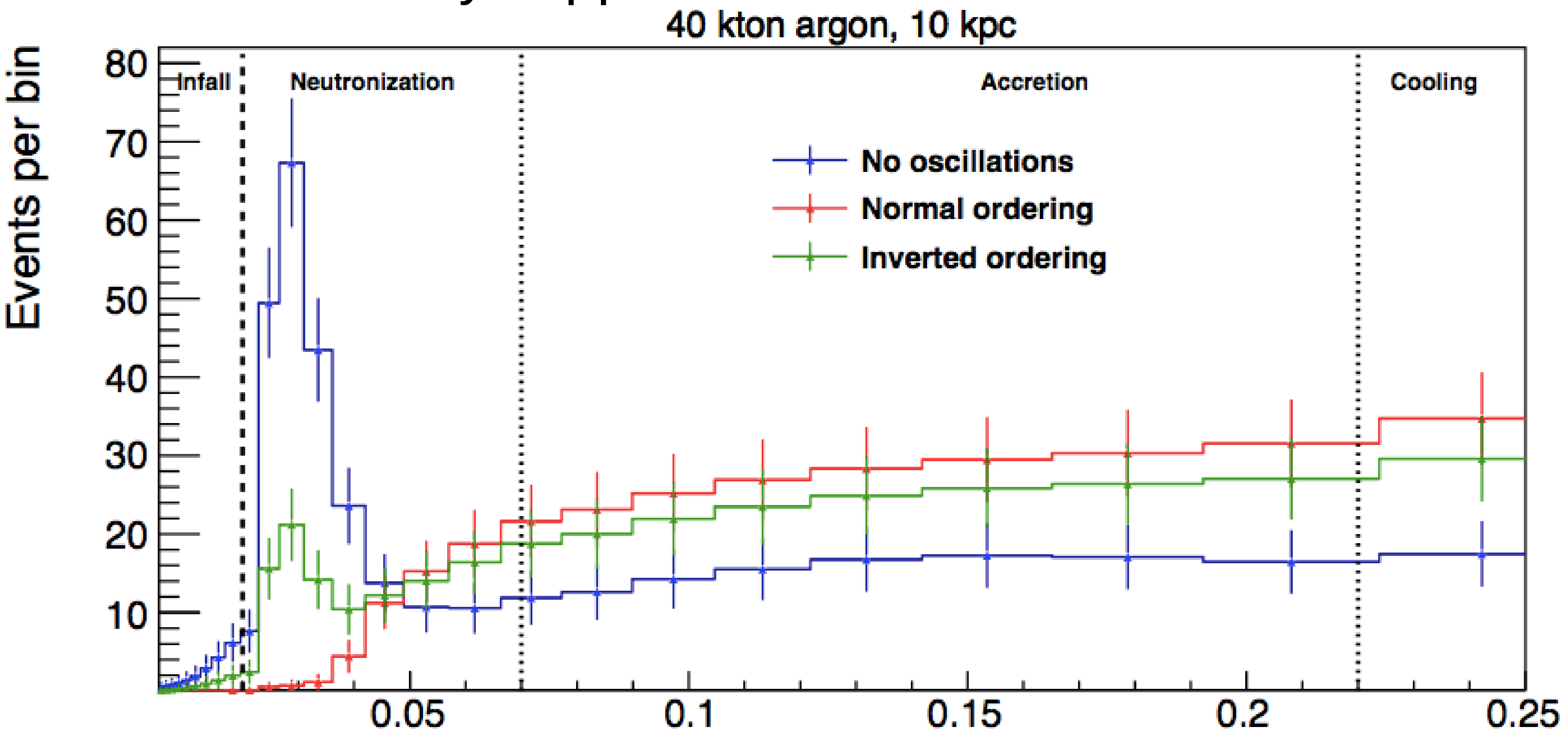


For 40 kton @ 10 kpc,
Garching model
(no oscillations)

From K. Scholberg

DUNE: effect of neutrino oscillations

Note that the neutronization burst gets substantially suppressed with flavor transitions



Simple MSW assumption (assume OK at early times)

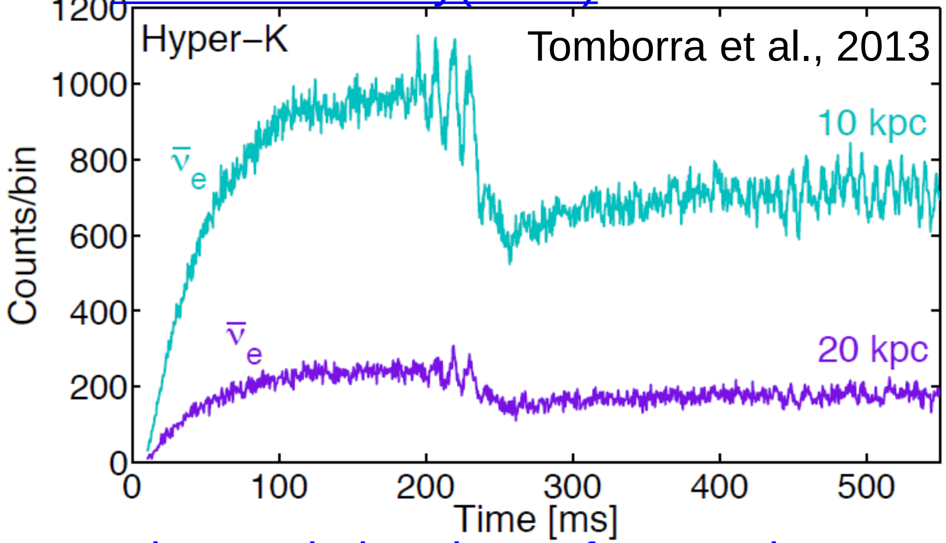
NMO: $F_{\nu_e} = F^0_{\nu_x}$

IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$

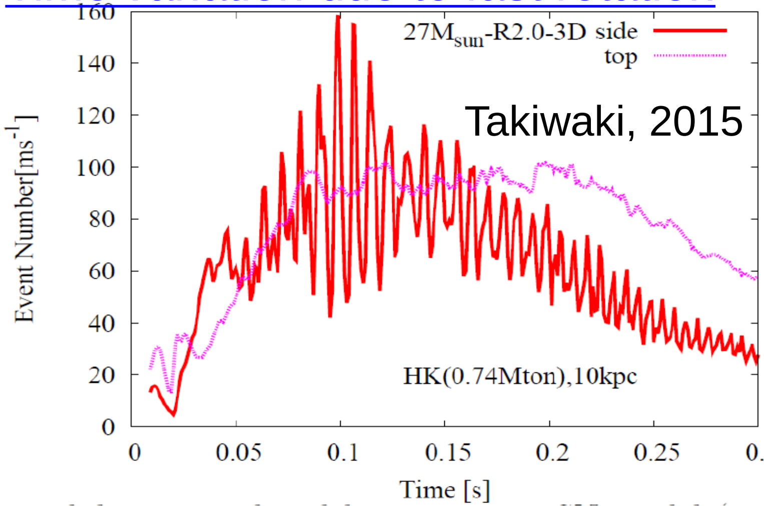
From K. Scholberg

Hyper-K: high statistics measurement

Time variation due to Standing Accretion Shock Instability(SASI)

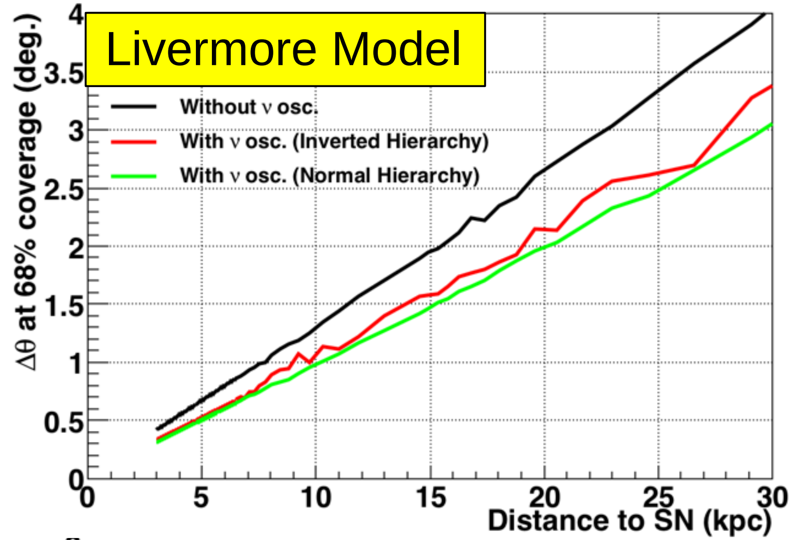


Time variation due to fast rotation

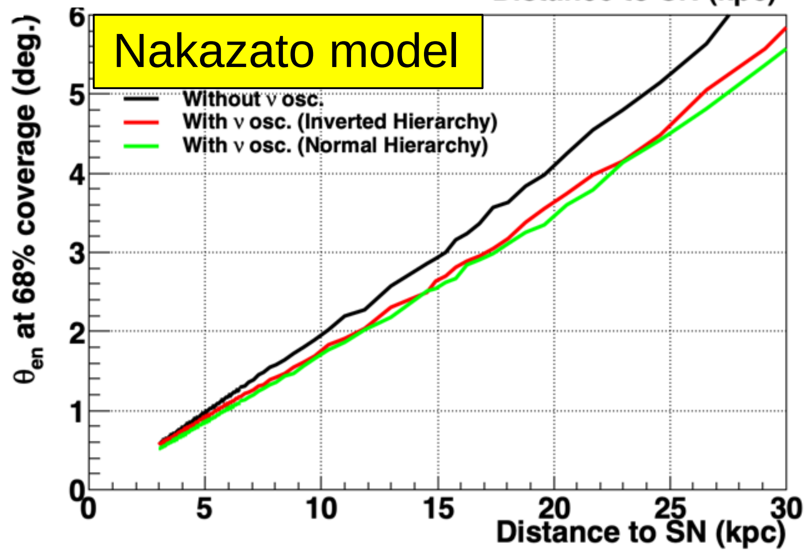


Quite high rate to study fine time structure

Pointing accuracy



8.2
5.8
5.7
at 50kpc

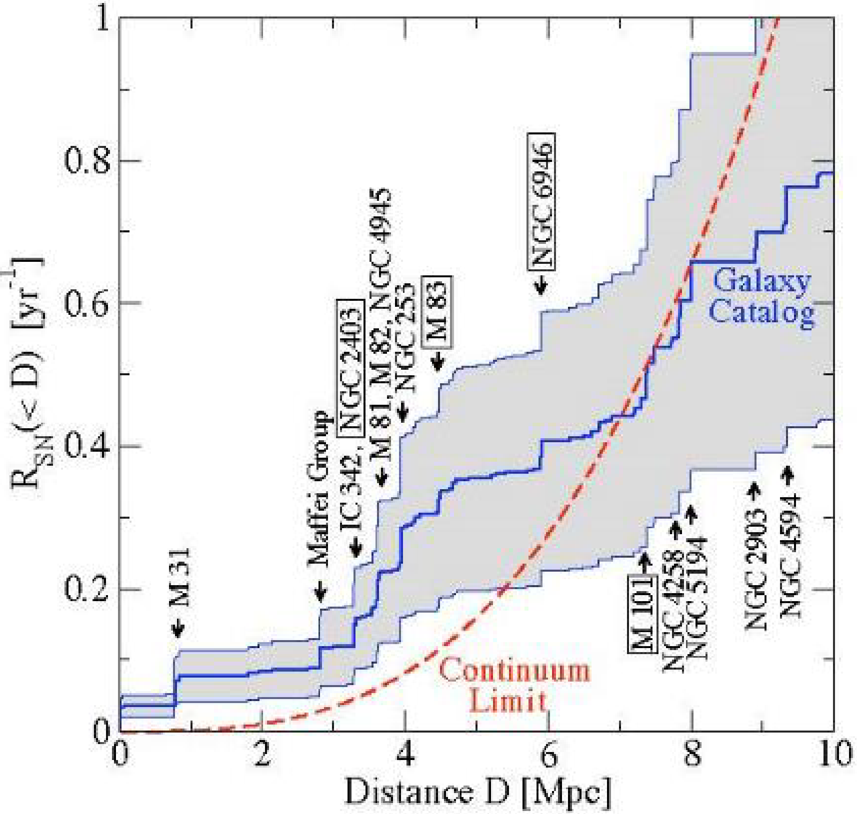


19
15
14
at 50kpc

1~2 deg. accuracy for 10 kpc SN.
6~15 deg. even for LMC (50kpc).

Supernova rate in nearby galaxies

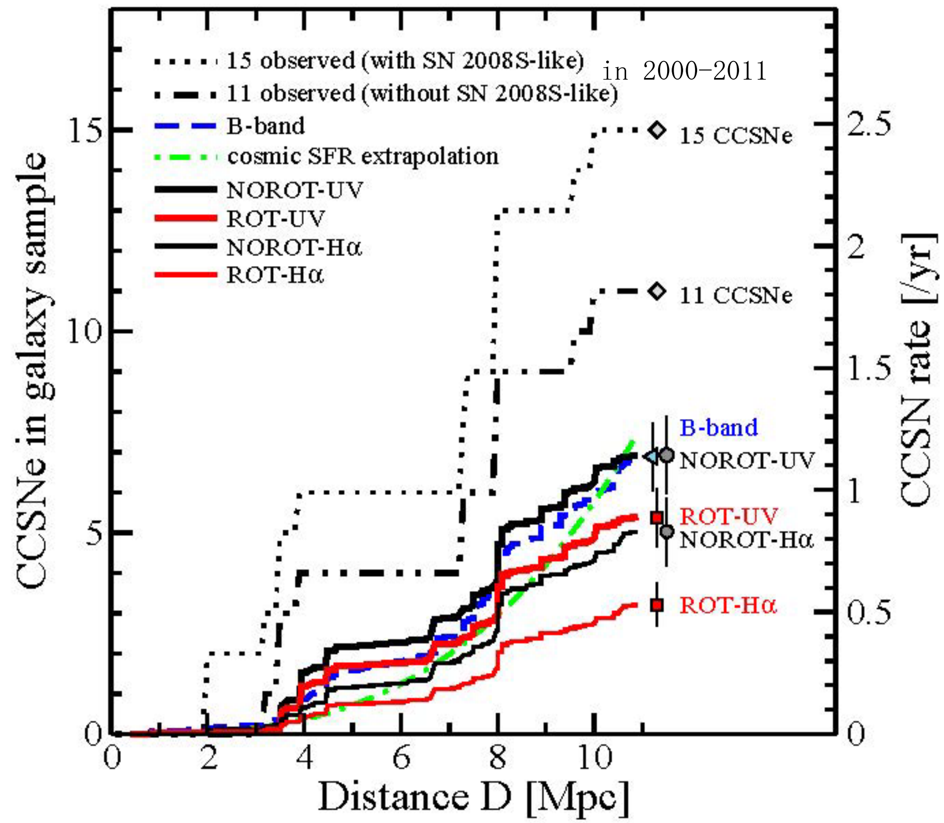
Cumulative rate (yr^{-1})



Ando, Beacom, Yuksel, Phys. Rev. Lett. 95, 171101 (2005)

Estimated supernova rate within 10Mpc

~14 SNe/20y



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

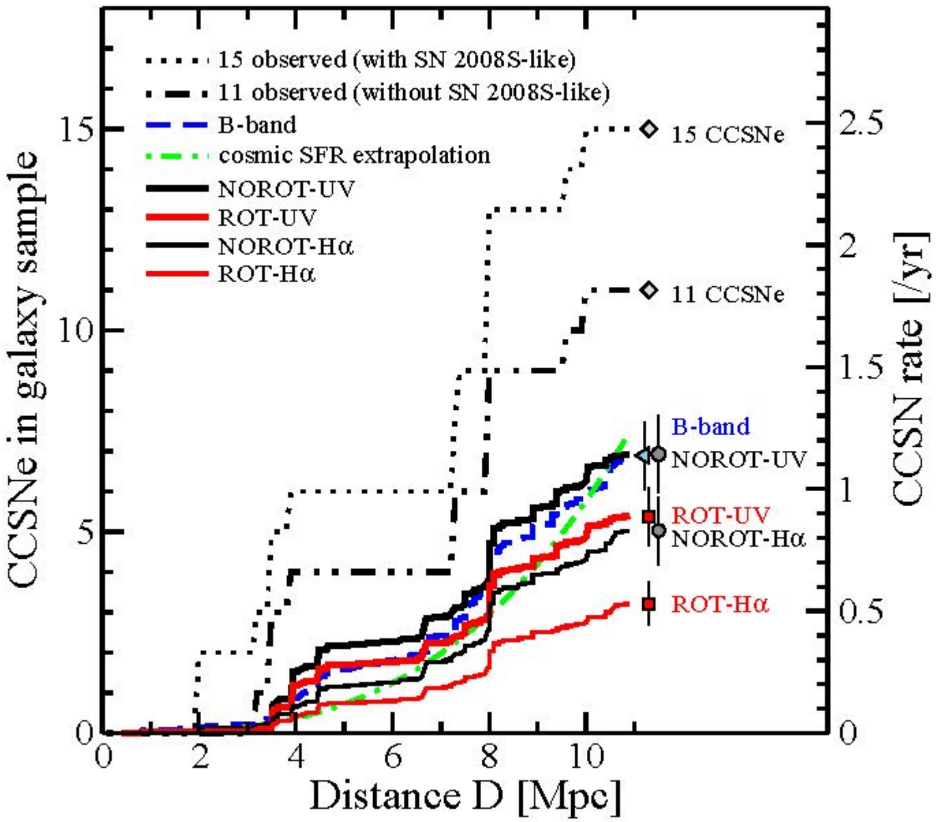
Estimated supernova rate:

"15CCSNe": ~50 SNe/20y

"11CCSNe": ~36 SNe/20y

UV obs.: ~18 SNe/20y

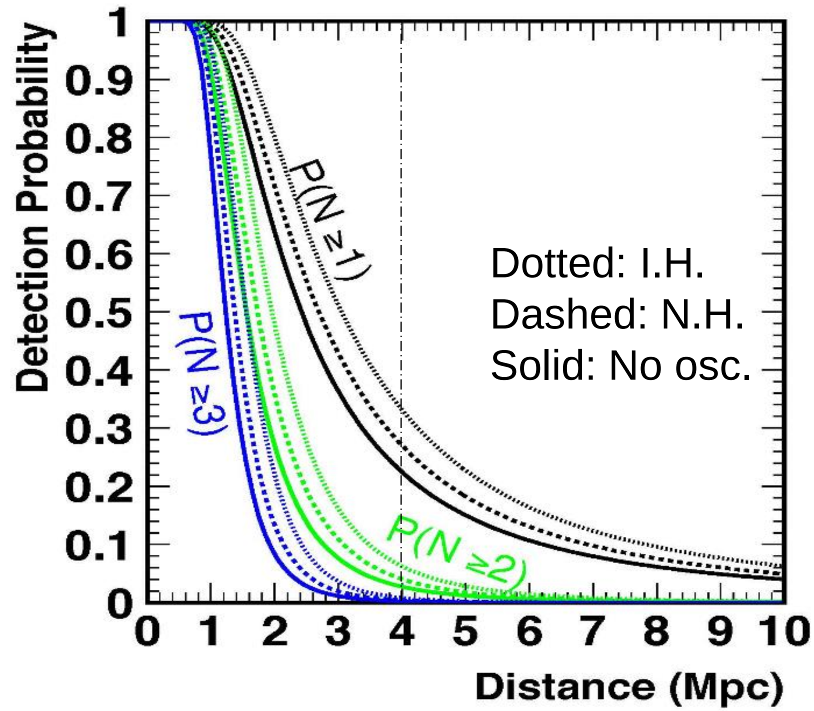
Hyper-K: supernova neutrino from nearby galaxies



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 SNe

10~14 SNe/20years (15 CCSNe)

5~ 8 SNe/20years (11 CCSNe)

2~ 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 are not included

Conclusions

- Many detectors in the world are waiting for next supernova.
- Large number of neutrino events are expected at various detectors.
  - Various interaction modes are detected in liquid scintillation detectors.
  - Study of fine time structure by IceCube.
  - Good pointing accuracy by Super-K and will be improved by SK-Gd.
- Future large volume detectors will give detailed information.
  - Precise energy measurement of all neutrino types by JUNO.
  - ν_e measurement by DUNE.
  - 1~2 deg. level pointing accuracy and nearby galaxy SN by Hyker-K.