スーパーカミオカンデにおける超新星ニュートリノの観測

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（岡山大学）

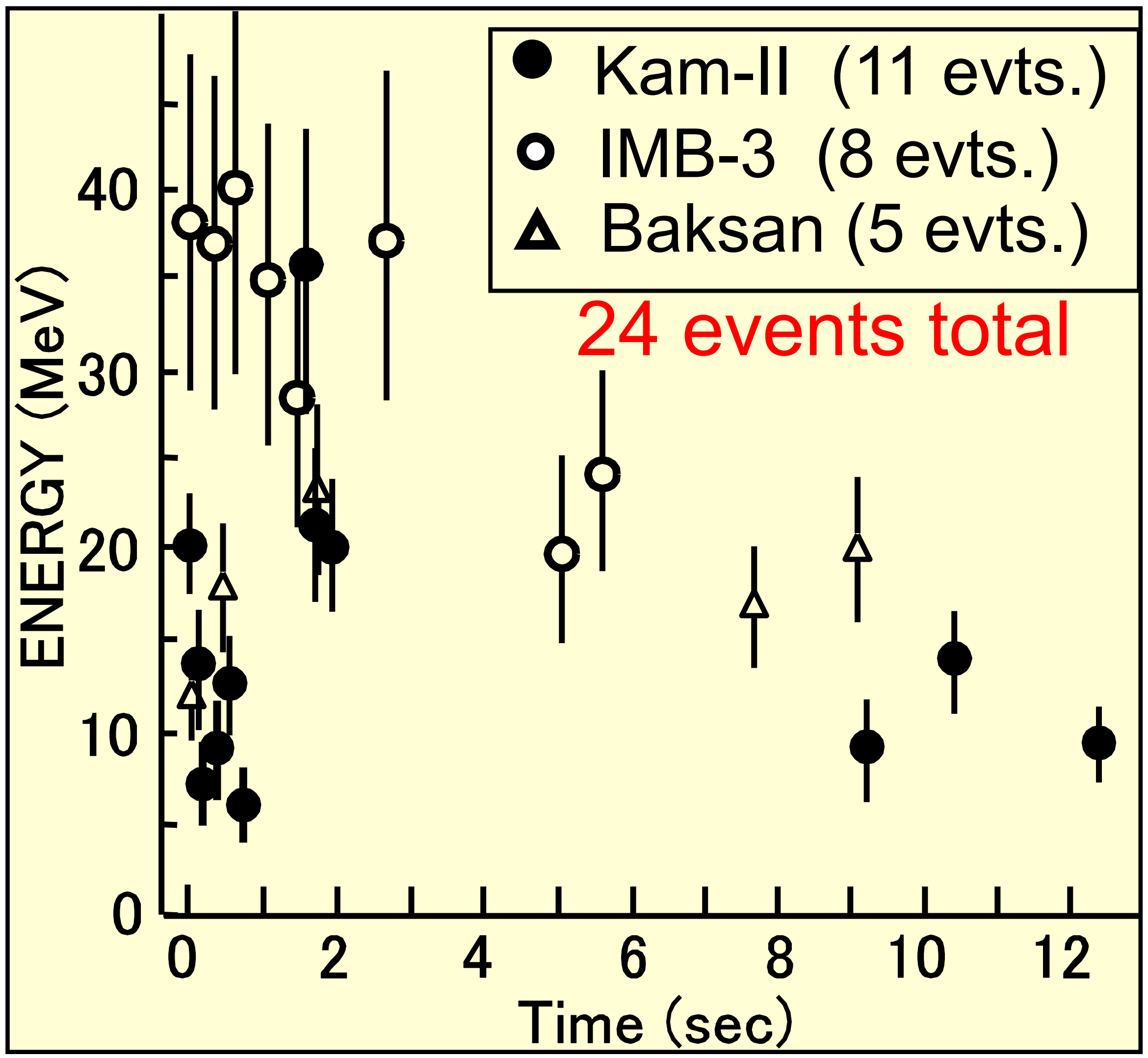
東北大学

2017年1月19日


Introduction

Review of the SN1987A in LMC

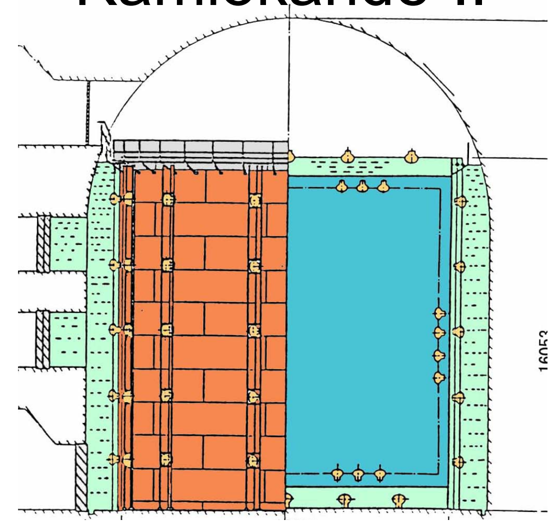
at 50 kpc, ν's seen ~2.5 hours before first light



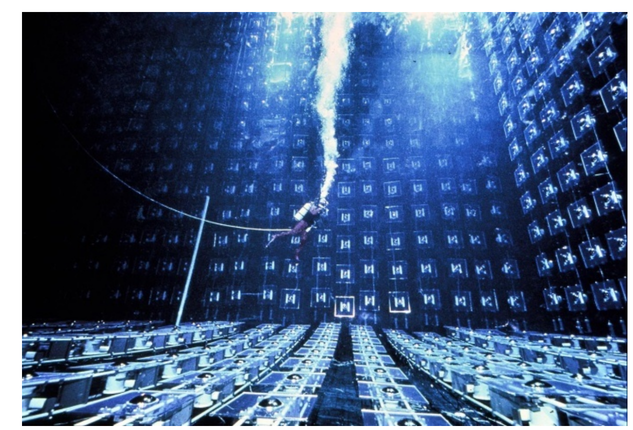
Most of them seems to $\overline{\nu_e}$ event

Water Cherenkov

Kamiokande-II



IMB-3

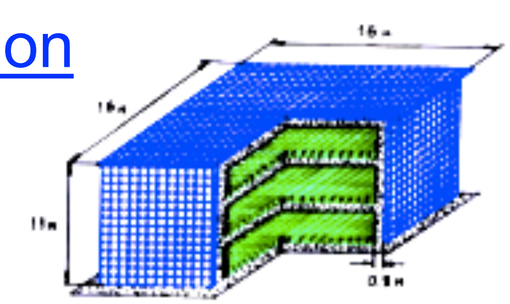


Strong directionality for ν_e event

Liquid Scintillator

Baksan

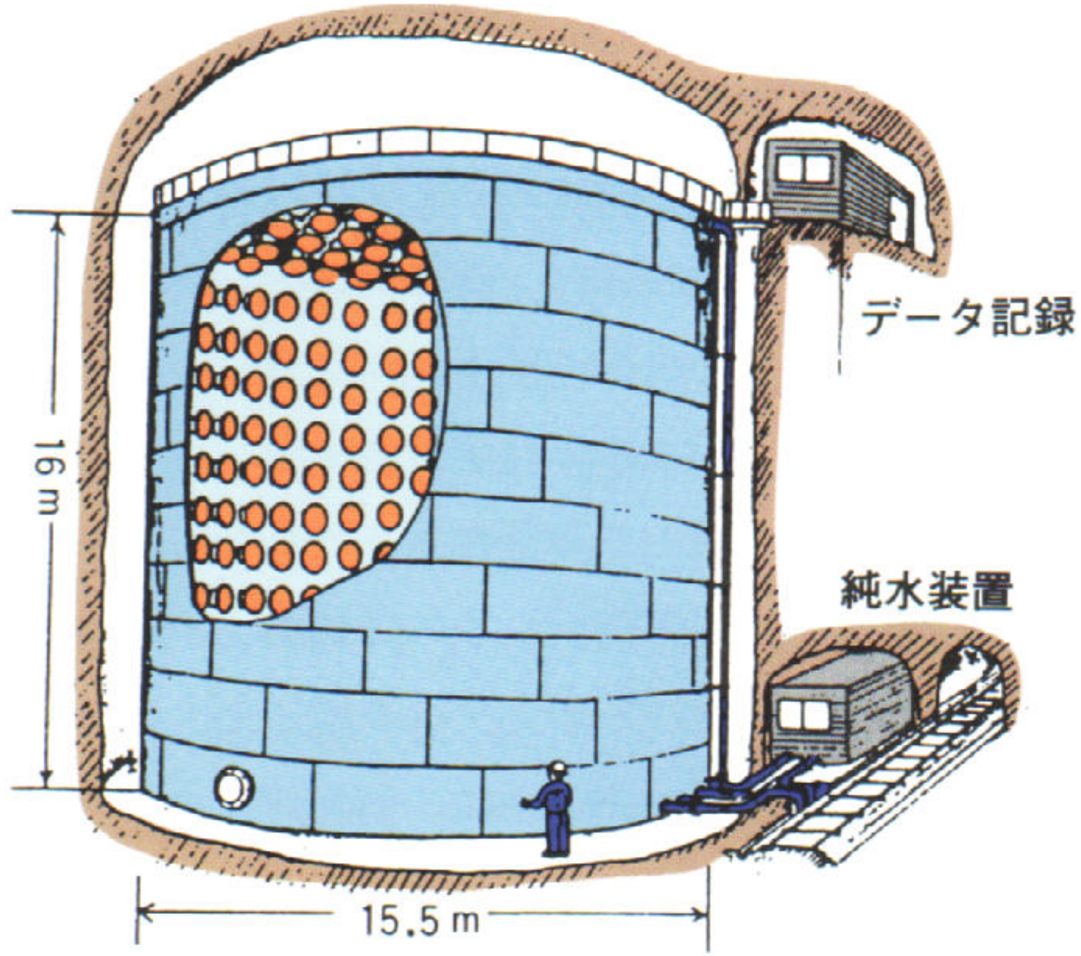
Good $\overline{\nu}_e$ event identification



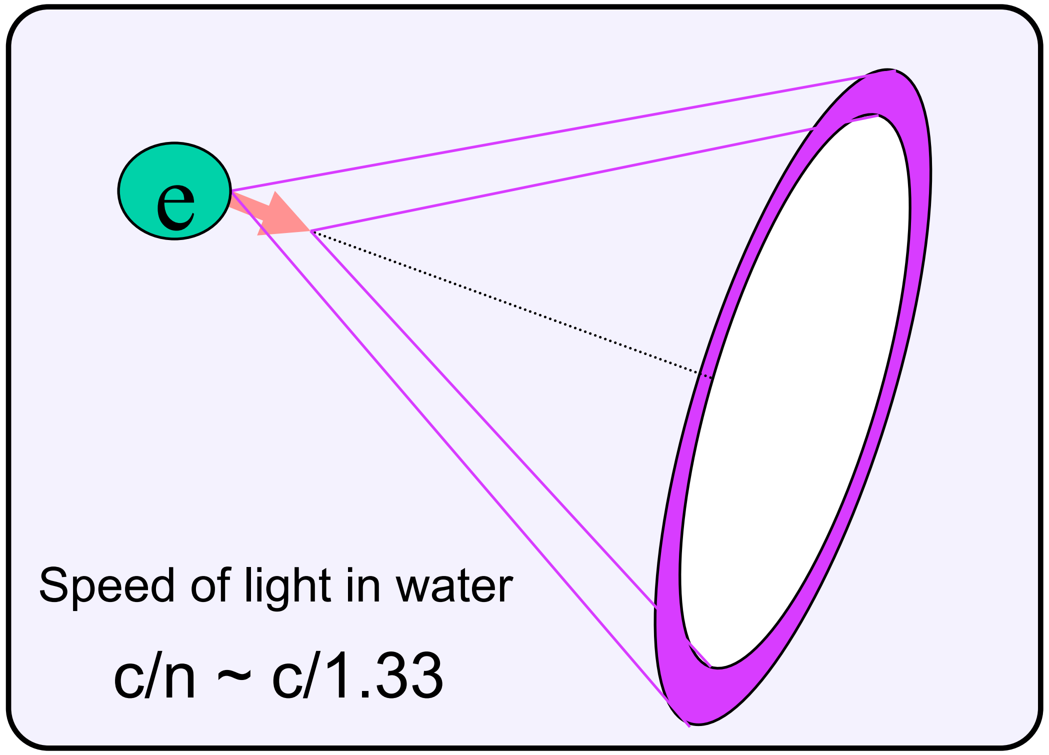
Water-Cherenkov detector

Kamiokande (1983-1995)

kamioka mine (2700mwe)

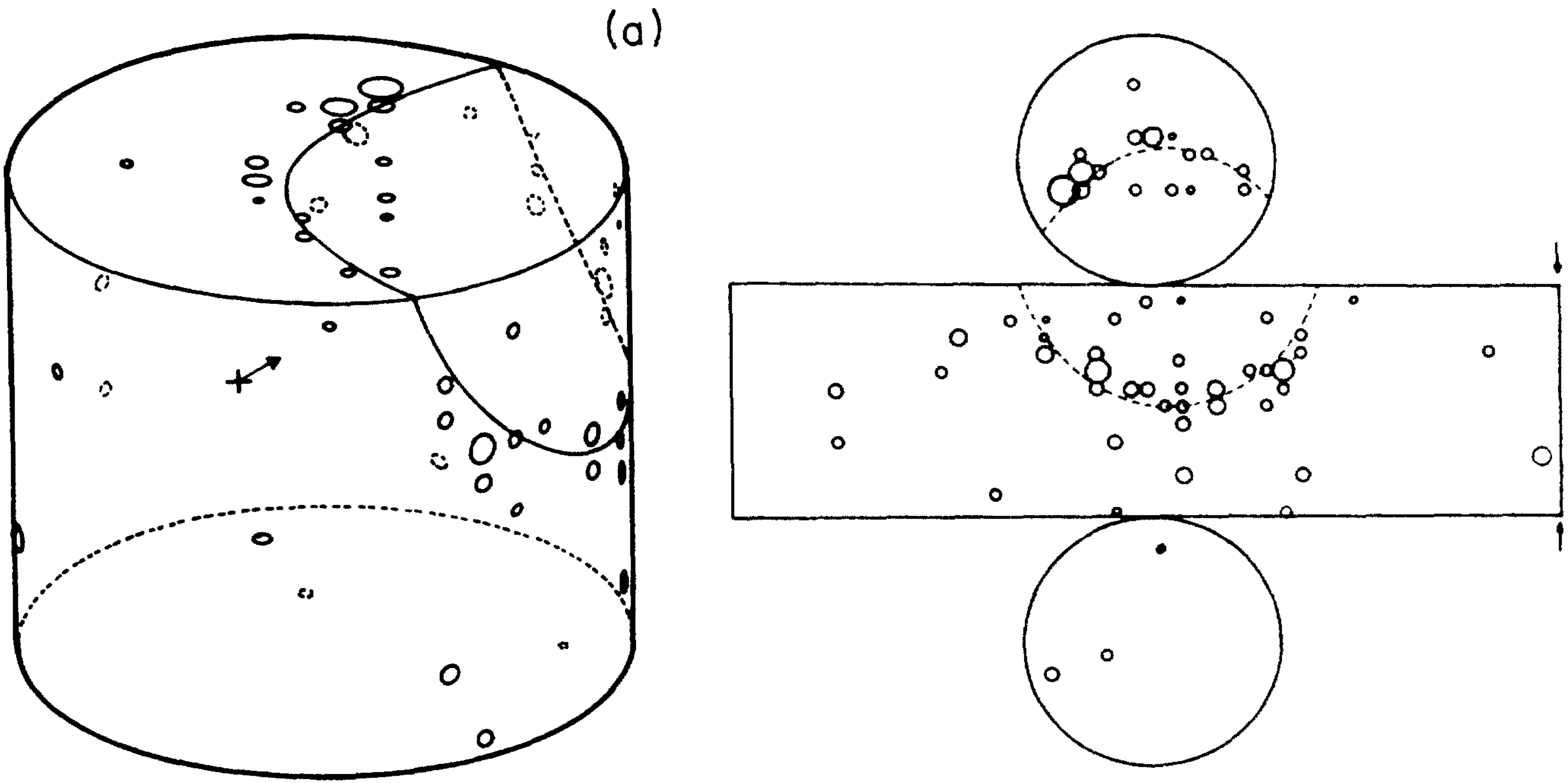


3000トン水タンク、約1000本の光電子増倍管



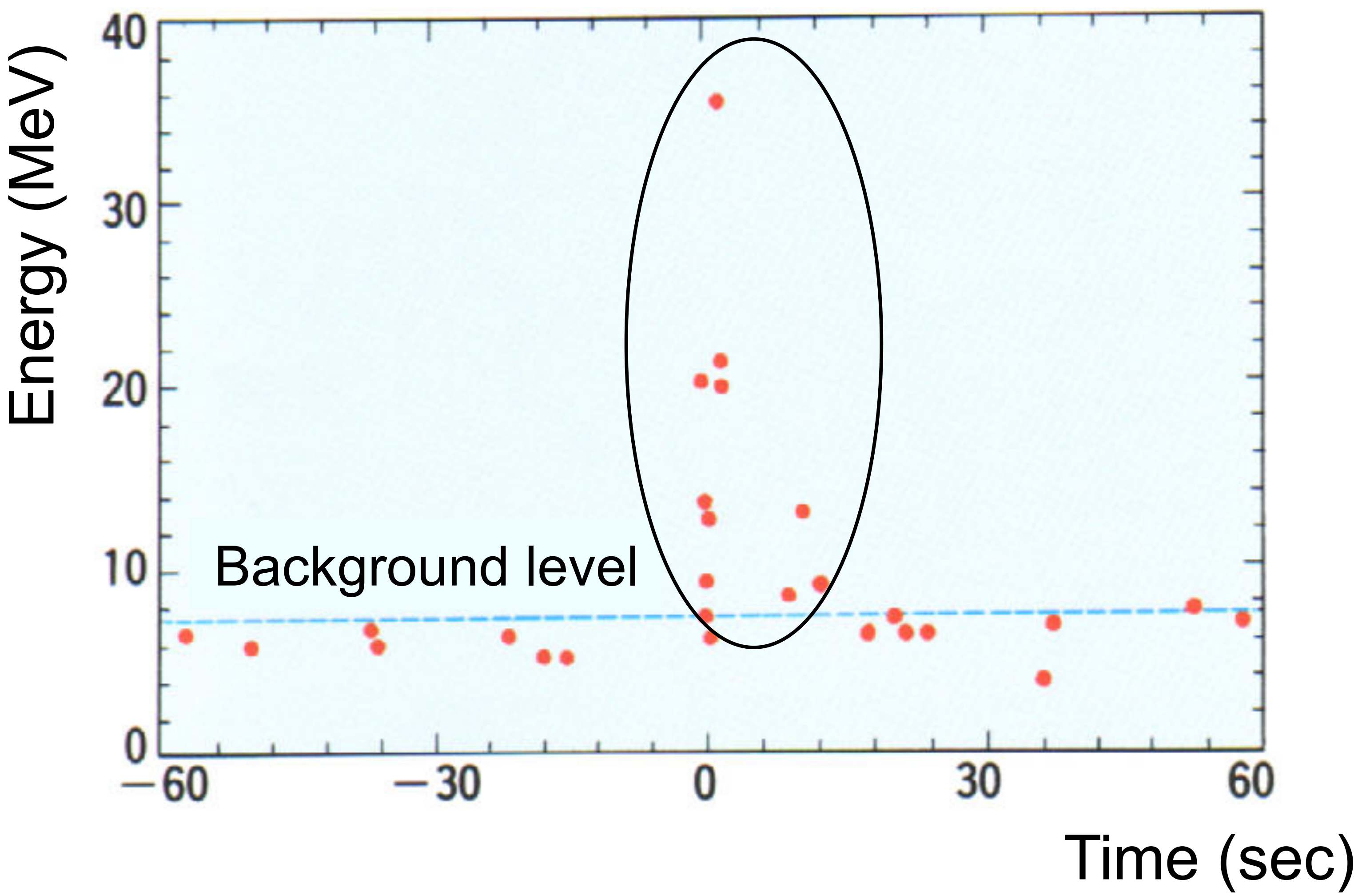
‘Event’ in Kamiokande

Energy, position, direction of each event are reconstructed using PMT-hit timing and pattern



SN1987A in Kamiokande

Time profile vs Energy



Realtime detector

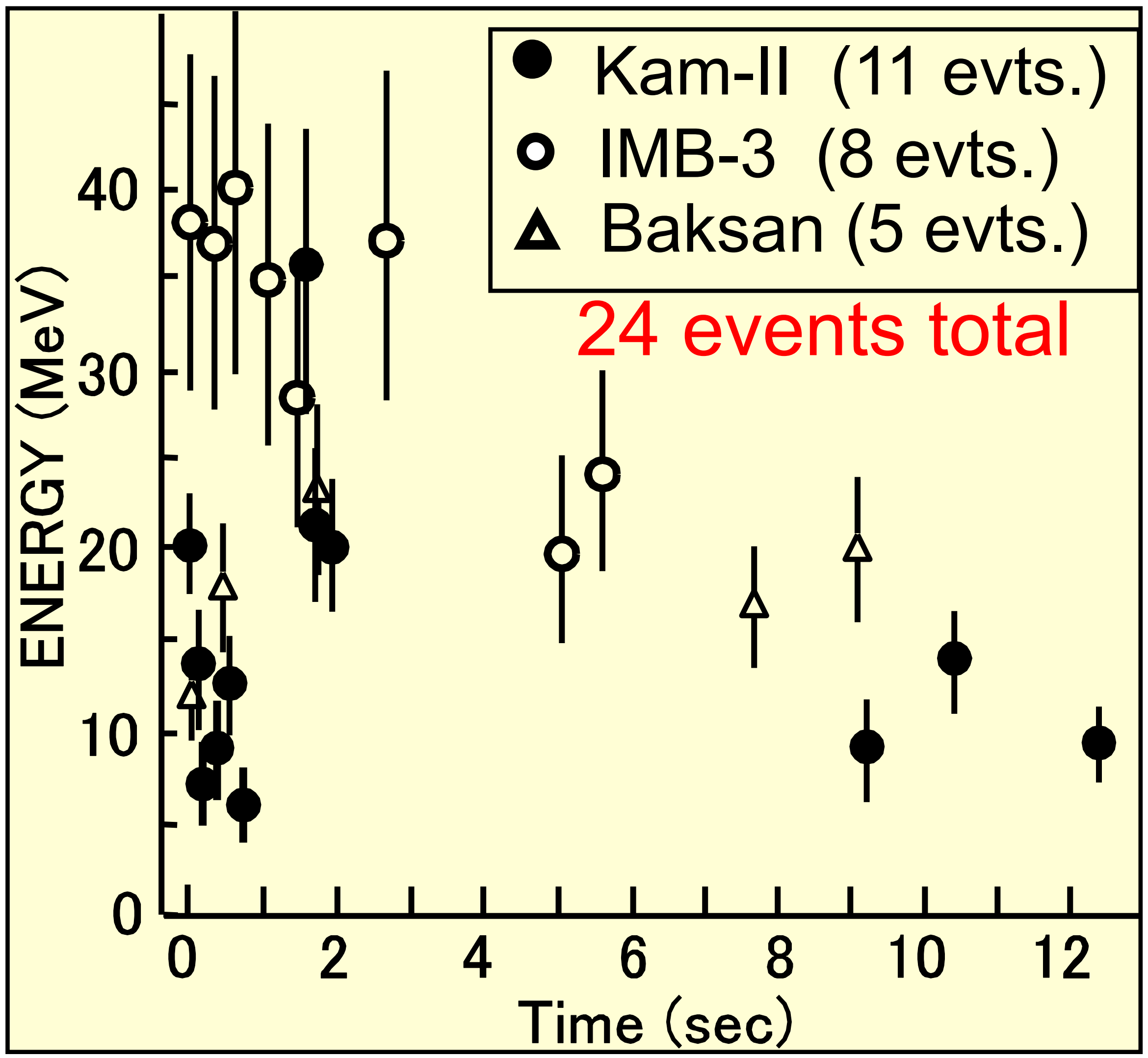
- Date : 23 Feb. 1987
- Time : 07:35:35 (UT)
- 11 events in 13 sec.

Energy is determined by the number of hit PMTs for which the residual time (T-Tof) is ± 15nsec

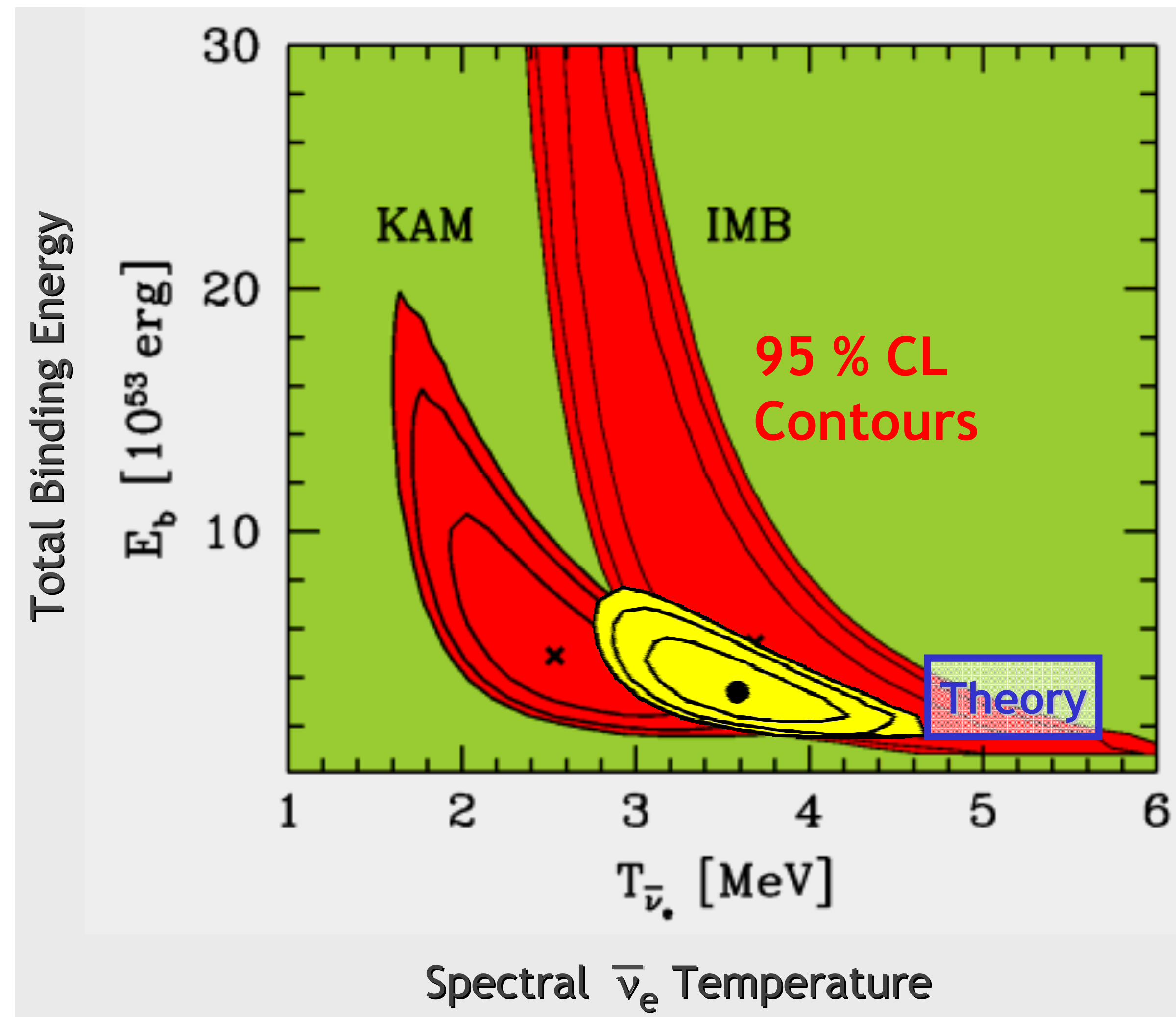
Trigger if 20 hits within 100 nsec ~ 7.5 MeV (@50% eff.)

Review of the SN1987A in LMC

SN neutrino temperature and energy



Most of them seems to $\overline{\nu_e}$ event

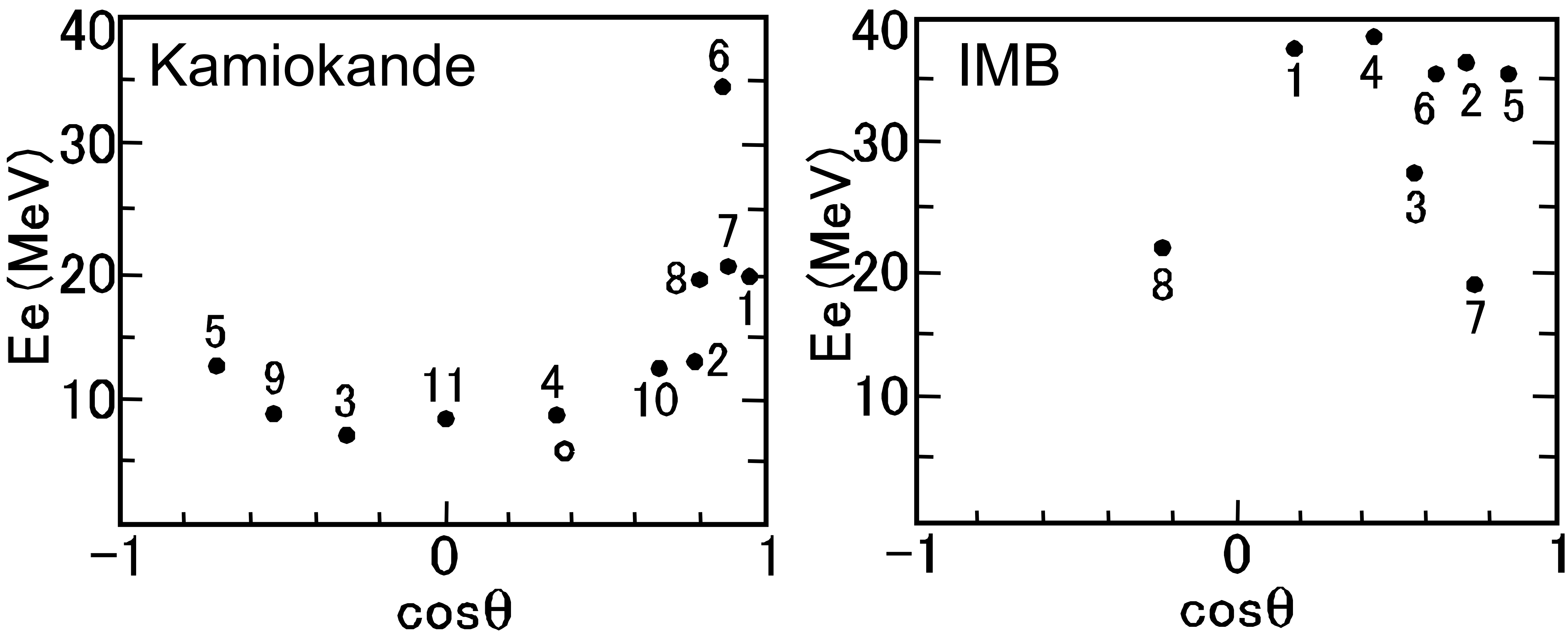


Jegerlehner, Neubig, Raffelt
PRD 54 (1996) 1194

Review of the SN1987A in LMC

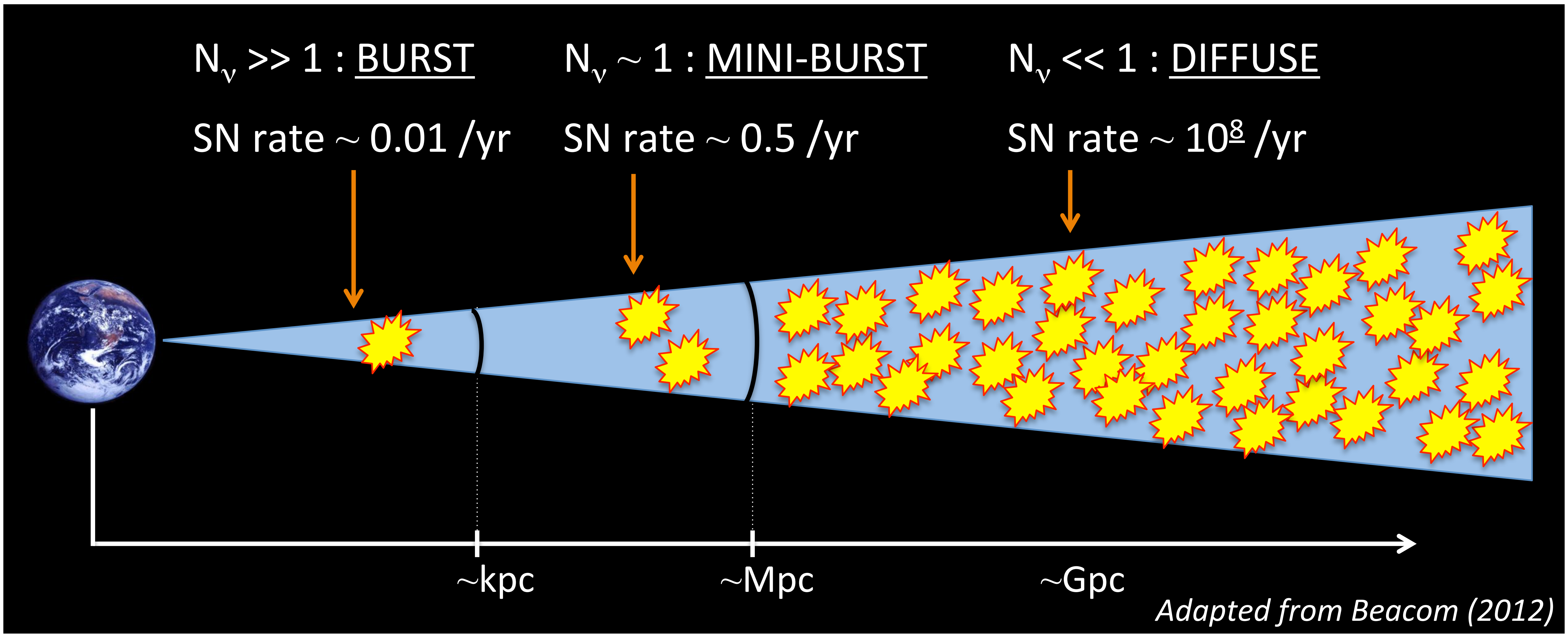
Angular distribution

ν_e event ?

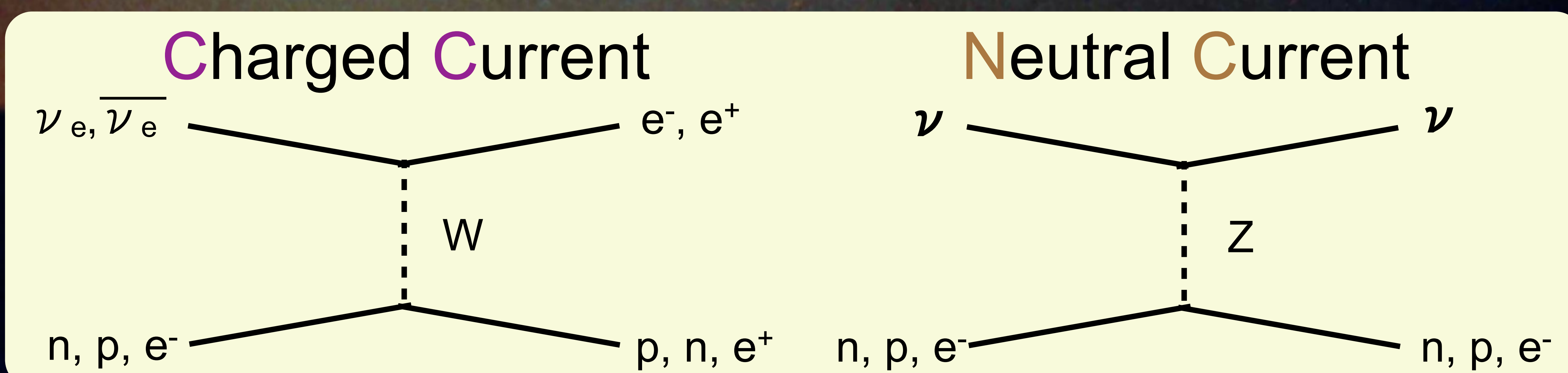


Hard to say anything...

Targets of Supernova neutrino



Neutrino interaction for supernova neutrino detection



Neutrino interaction for SN ν

Inverse beta decay

$\overline{\nu}_e + p \rightarrow e^+ + n$ (Charged Current interaction)

- ✓ Dominates for detectors with lots of free proton
  - Detect positron signal in water, scintillator, etc.
- ✓ $\overline{\nu}_e$ sensitive
- ✓ Obtain the neutrino energy from the positron energy
  - $E_e \sim E_\nu - (m_n - m_p)$, $E_\nu > 1.86\text{MeV}$
- ✓ Well known cross section
- ✓ Poor directionality
- ✓ Neutron tagging using delayed coincidence
  - $n + p \rightarrow d + \gamma$, $n + Gd \rightarrow Gd + \gamma$

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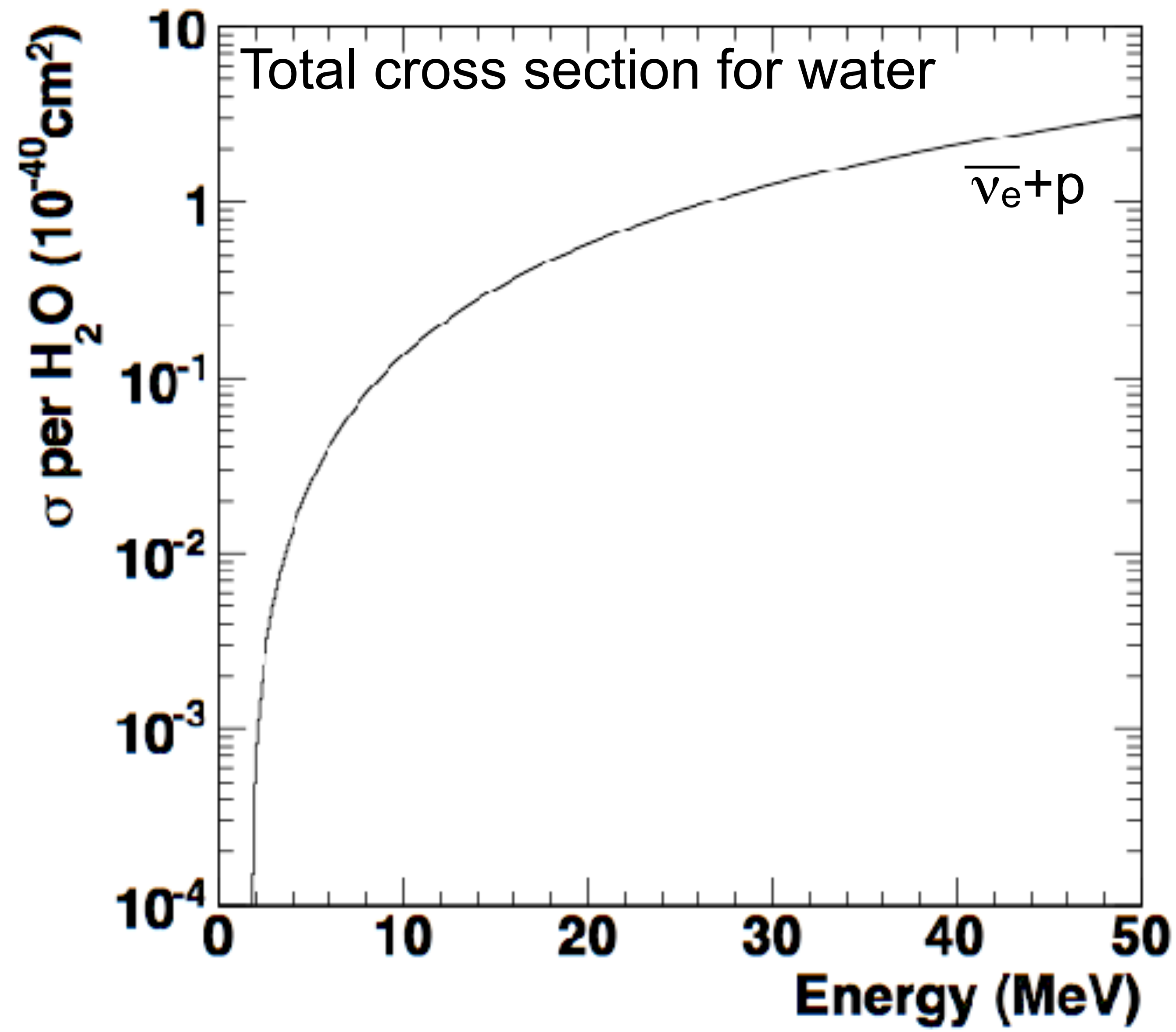
  - $n + p \rightarrow d + \gamma$, $n + Gd \rightarrow$ G

Strumia, Vissani
Phys. Lett. B564 (2003) 42



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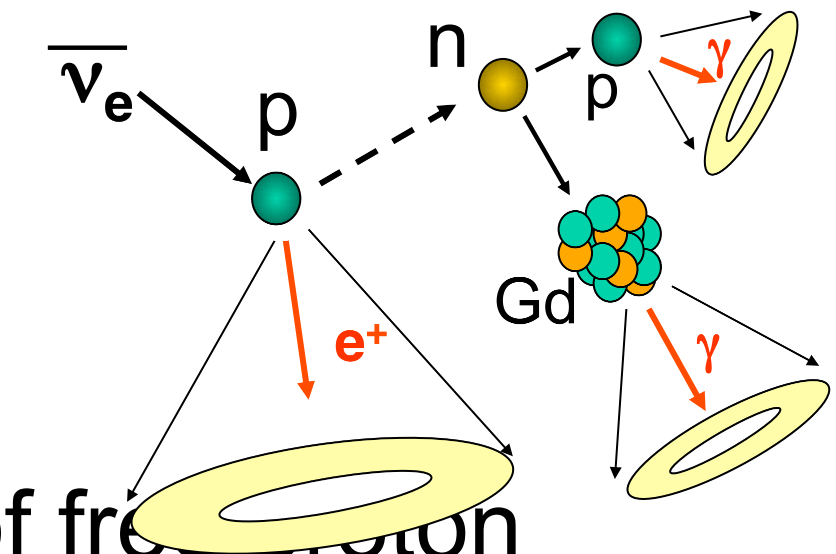

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Possible to enhance this signal if Gd loaded

Neutrino interaction for SN ν

Elastic scattering

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

(Both Charged Current and Neutral Current interaction)

✓ All neutrinos are sensitive

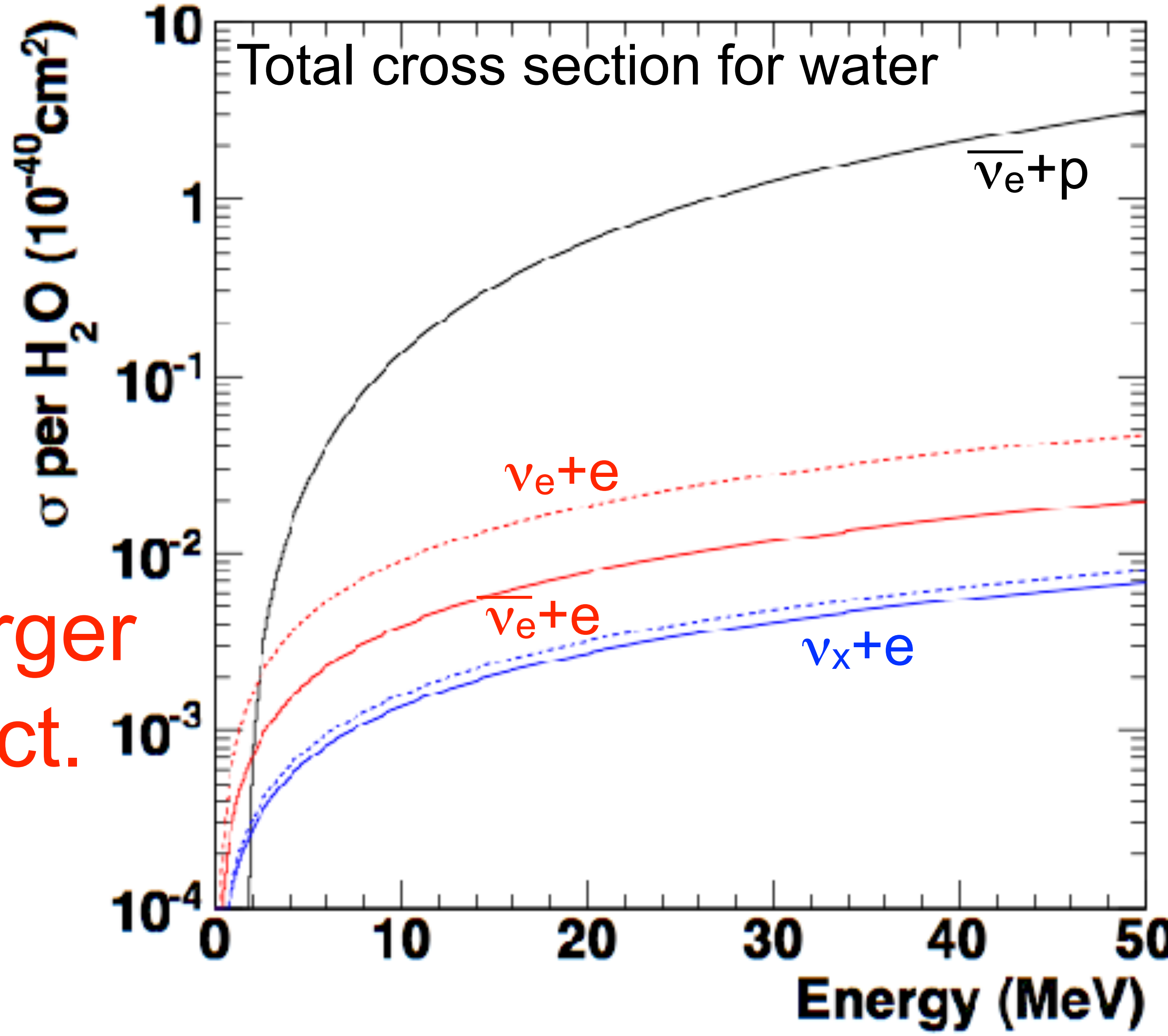
✓ The cross section for ν_e is larger than others because of CC effect.

✓ Well known cross section.

- few % of inverse beta decay

✓ Good directionality

✓ Measurable for only recoil electron energy, not neutrino energy



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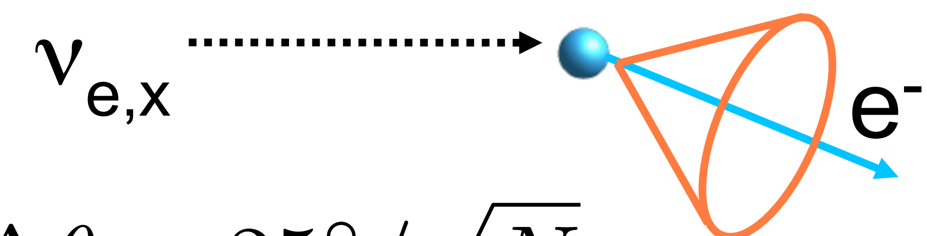
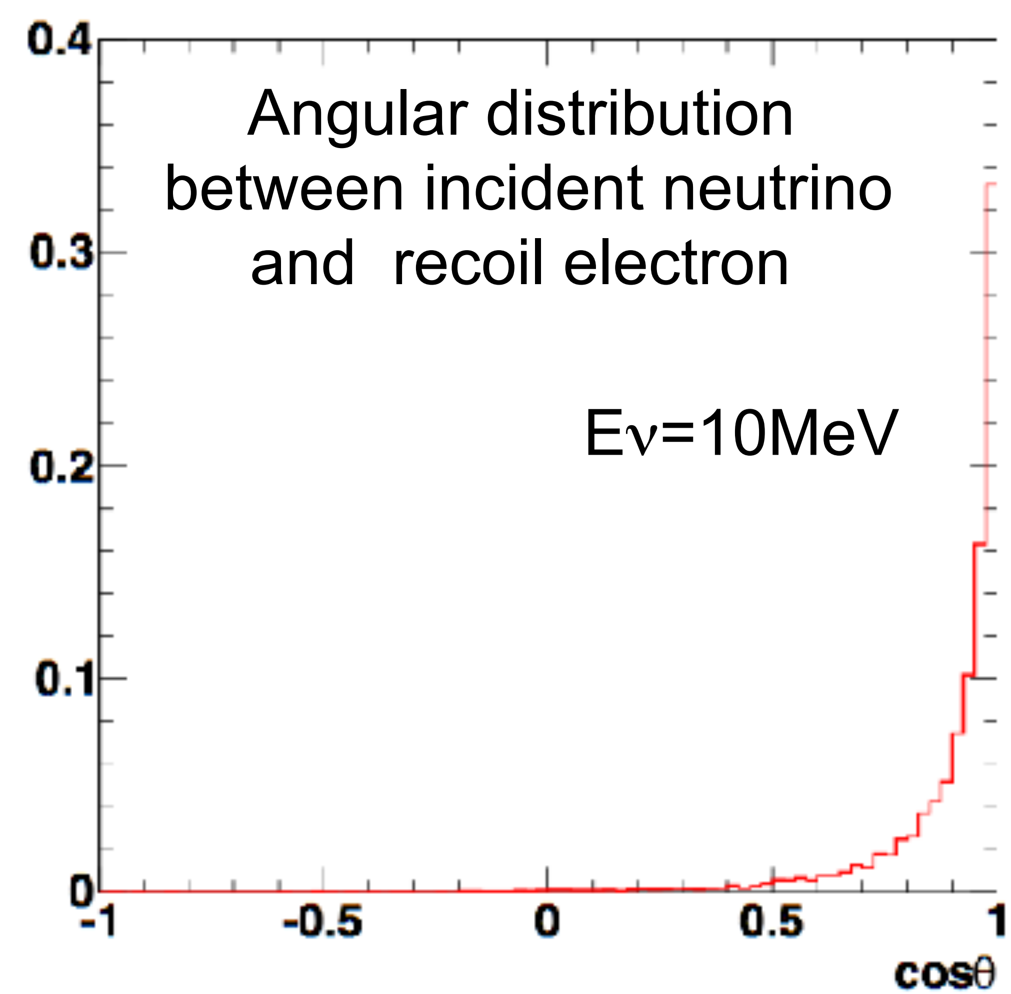
Water Cherenkov

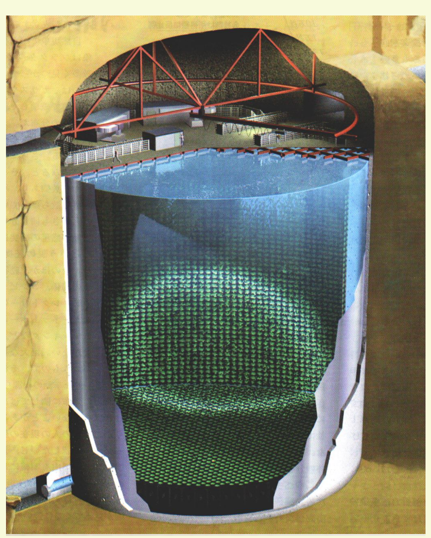


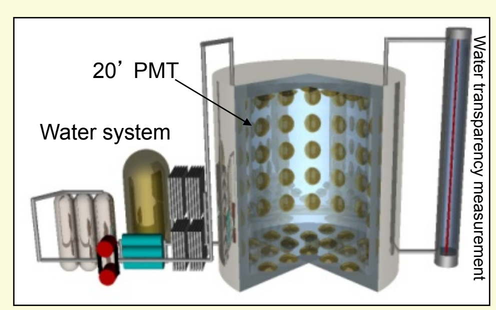
$$\Delta\theta \sim 25^\circ/\sqrt{N}$$

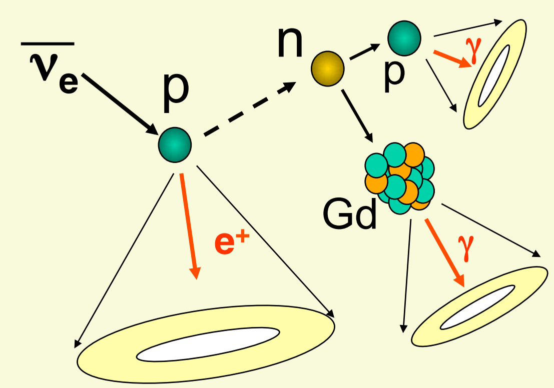


SN search at Super-Kamiokande

Super-K to SK-Gd



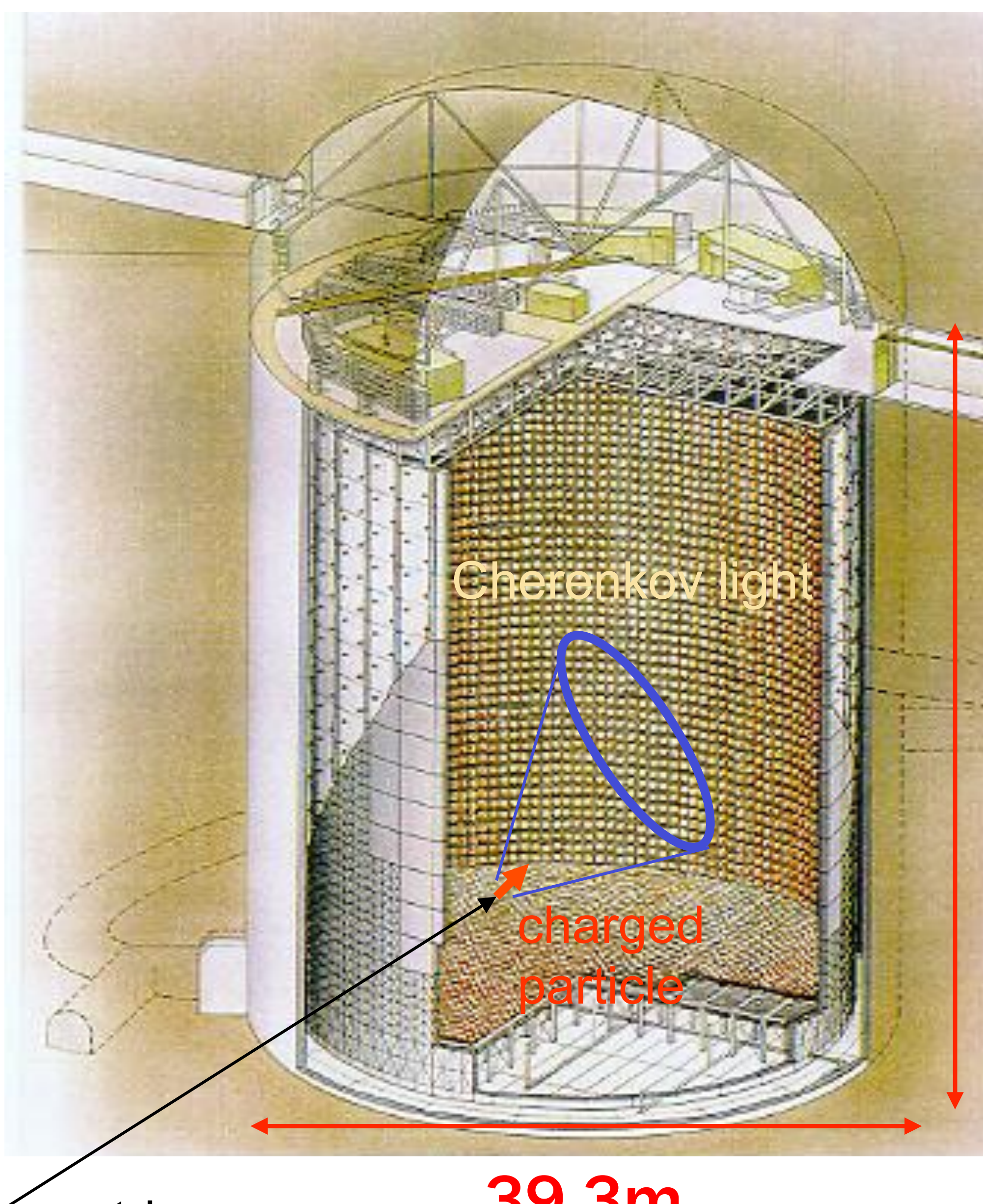




Kamioka underground detectors

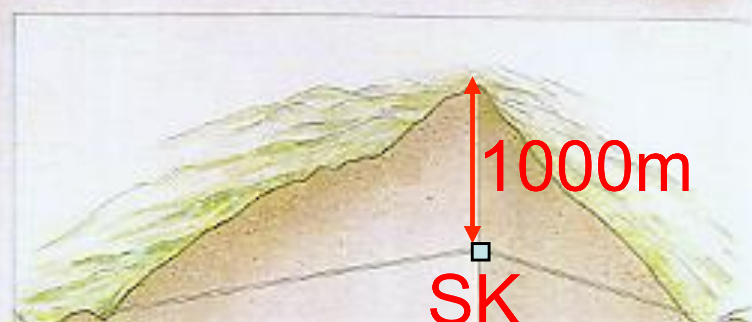
Super-Kamiokande

50kton Water Cherenkov detector

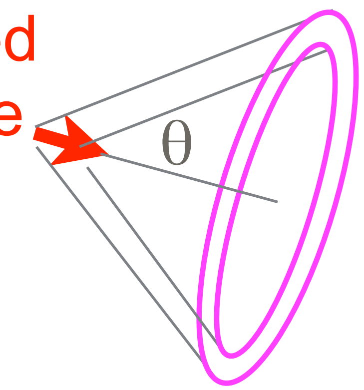


32kton fiducial volume for SN

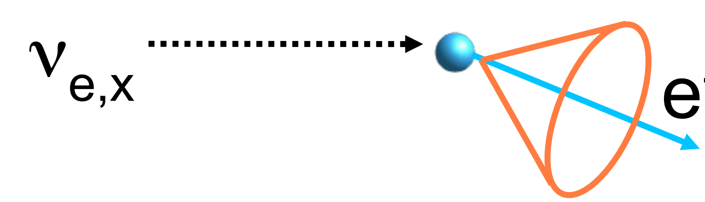
	20' PMT (inner)	photocathode coverage
SK-1	11,146	40%
SK-2	5,182	19%
SK-3	11,129	40%
SK-4	same as SK-3 with new electronics	



Placed inside the Kamioka mine
1000m underground

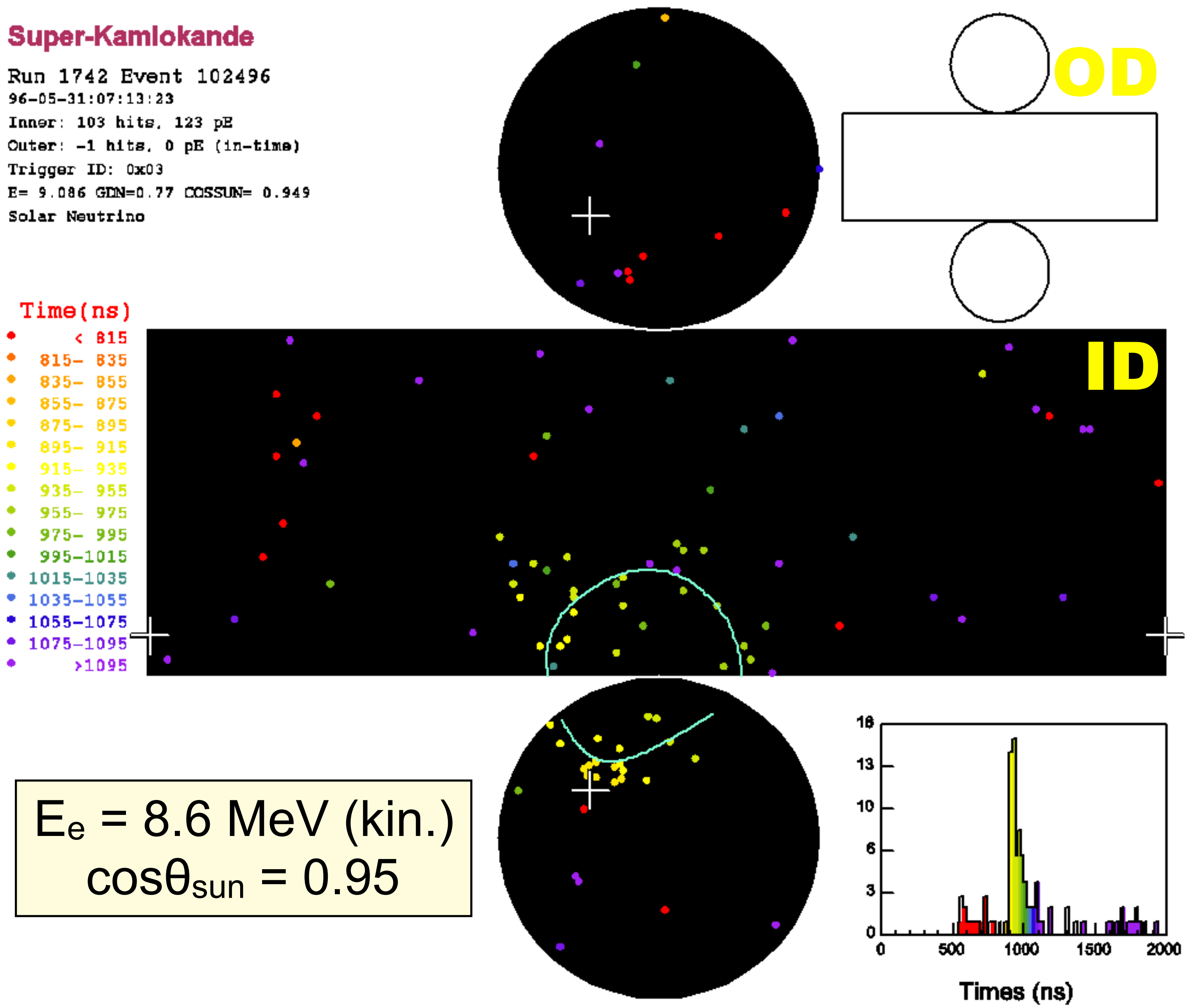


✓ Underground in Kamioka mine, (almost BG free)
✓ 3.5MeV energy threshold for recoil electron
✓ Dominant process is inverse beta decay
✓ Good directionality for νe elastic scattering



Super-Kamiokande

For supernova neutrinos (~MeV)



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

How to reconstruct?

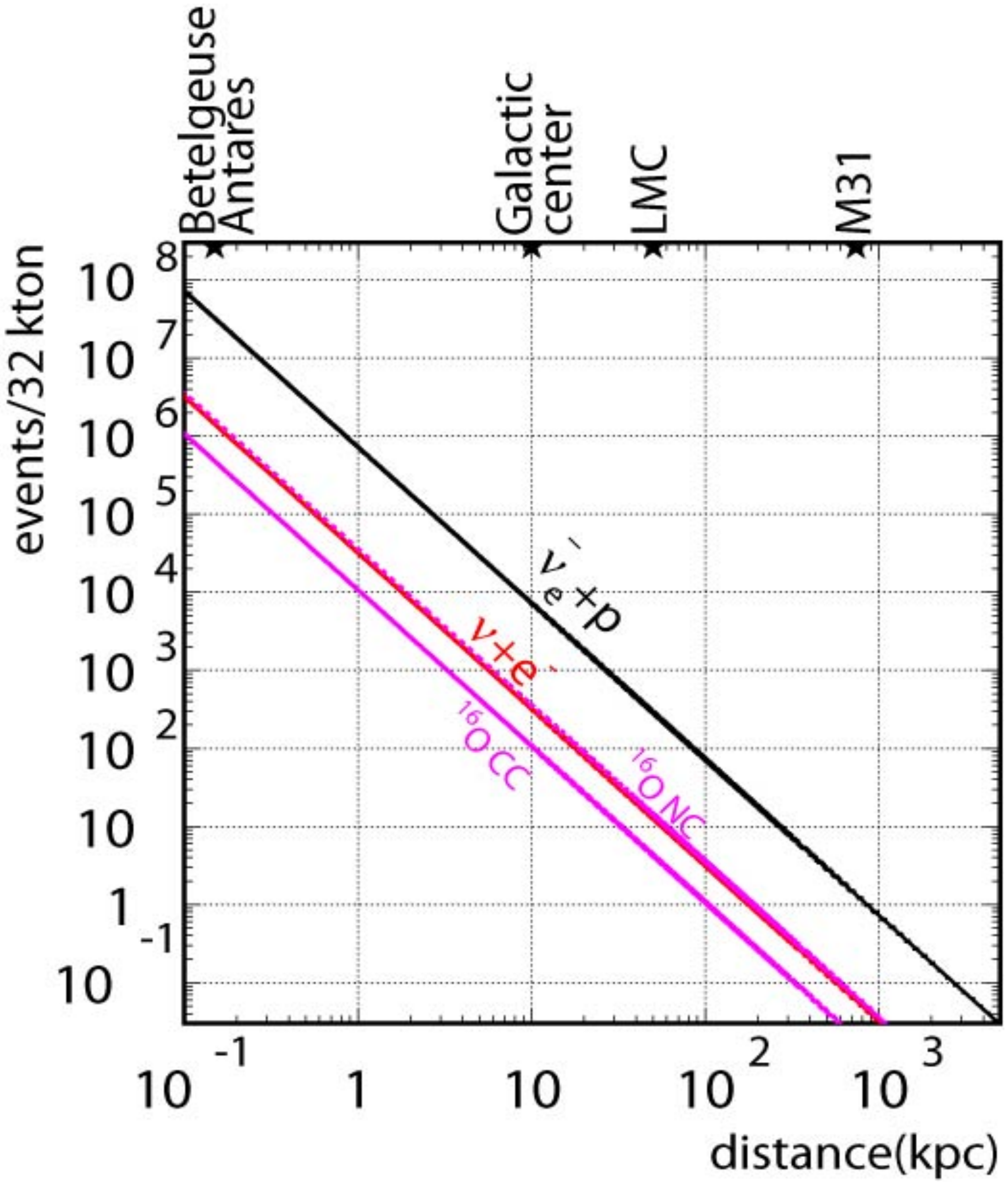
Detector performance

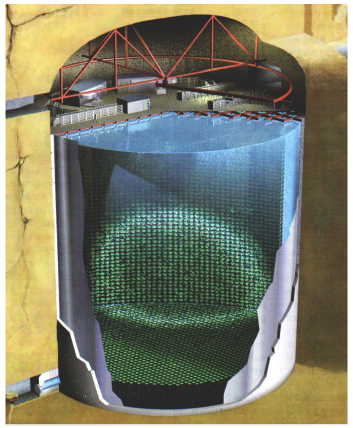
	Resolution@10MeV	Information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

~ 6 hits/MeV
well calibrated by LINAC / DT within 0.5% precision

Movie

Super-Kamiokande





Expected number of event

7.3k~10.2k ev (inverse beta decay)

320~380 ev (νe elastic scattering)

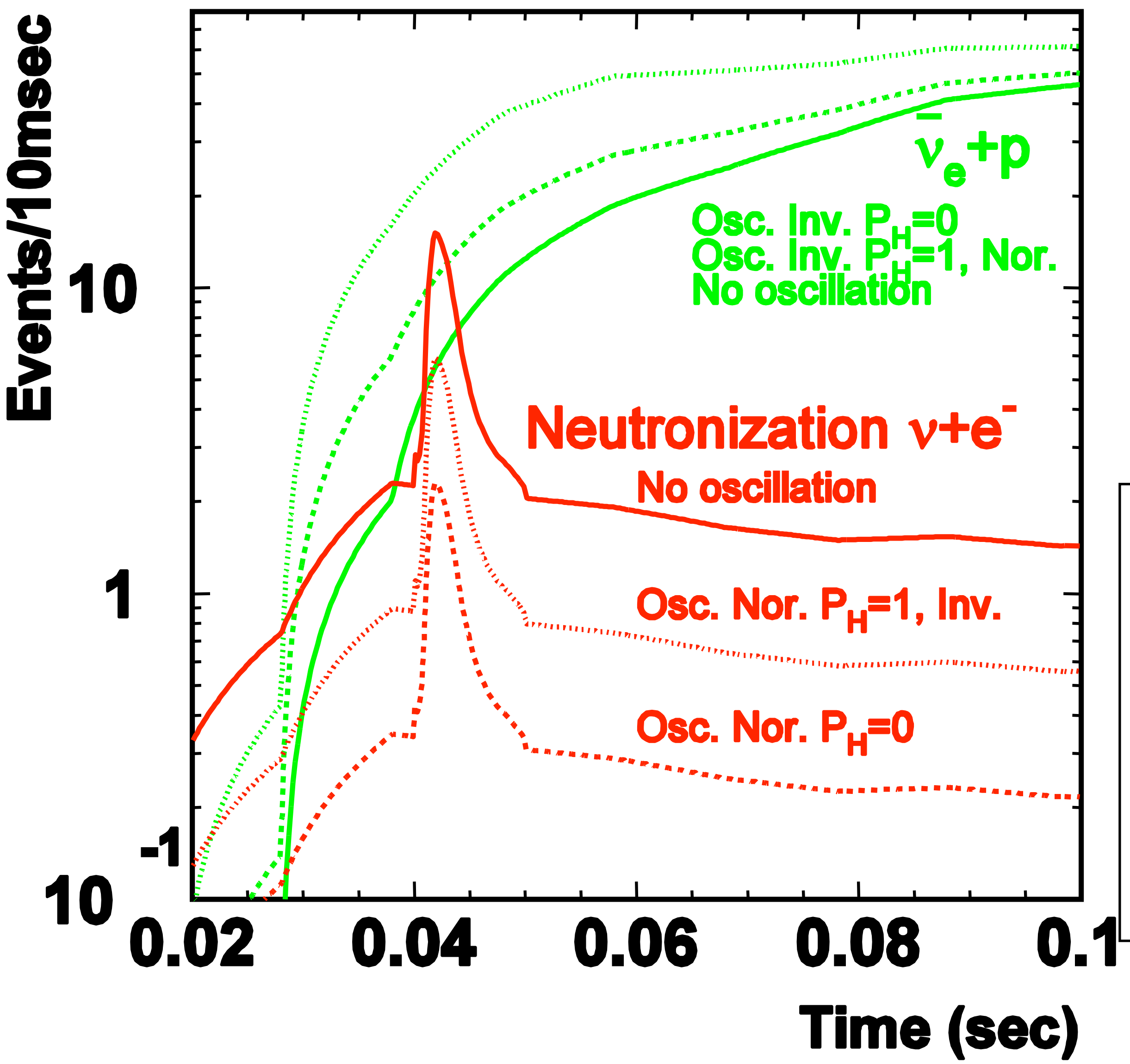
12~610 ev (ν_e CC)

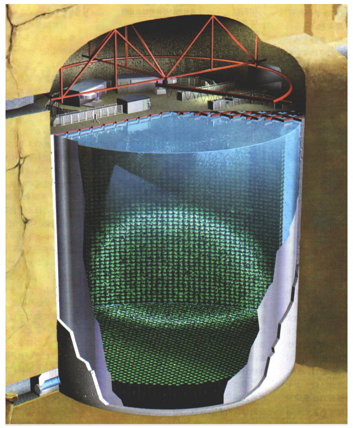
95~580 ev ($\bar{\nu}_e$ CC)

at 10kpc, 4.5MeV energy threshold

Livermore simulation
Totani, Sato, Dalhed, Wilson, ApJ. 496 (1998) 216

Super-Kamiokande





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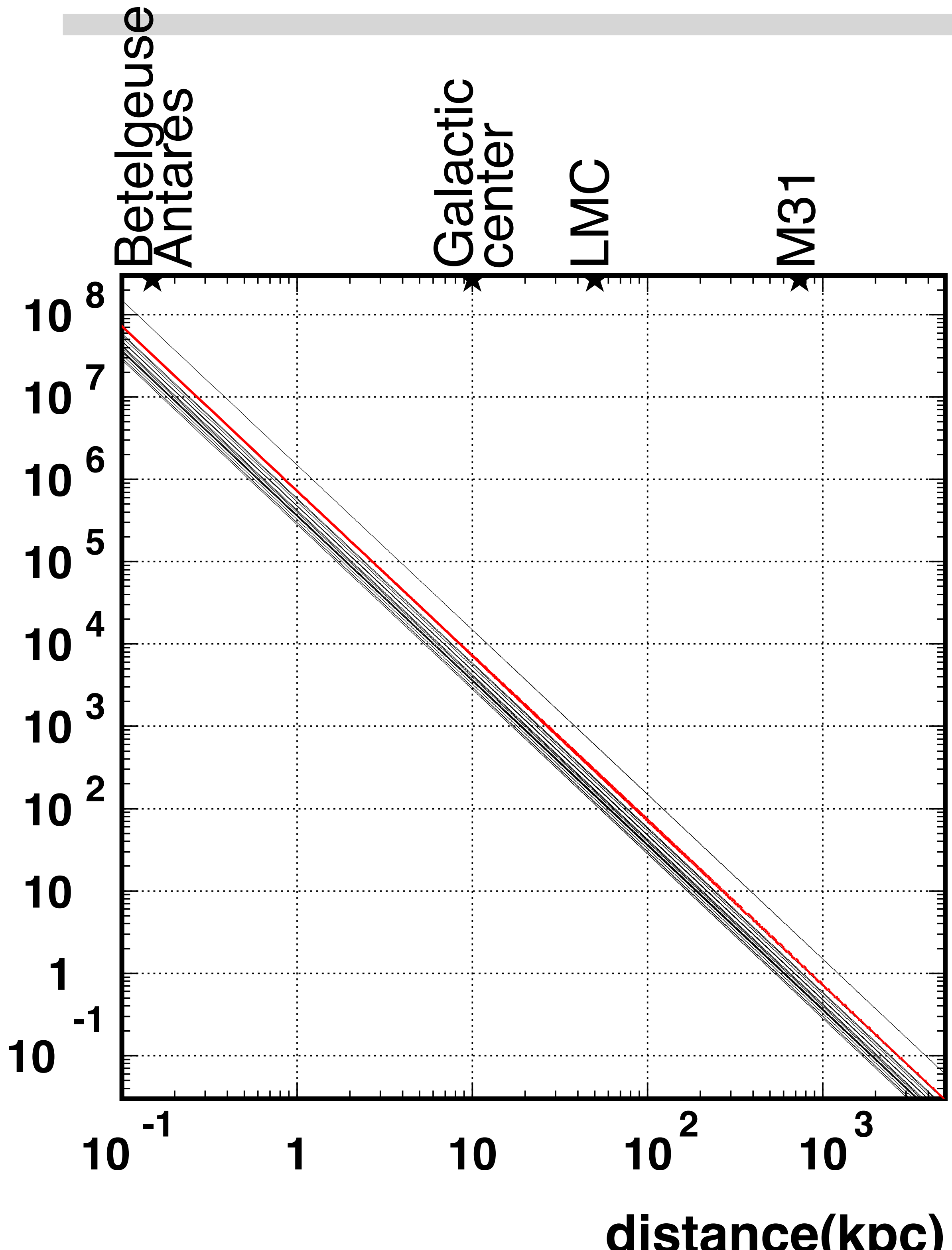
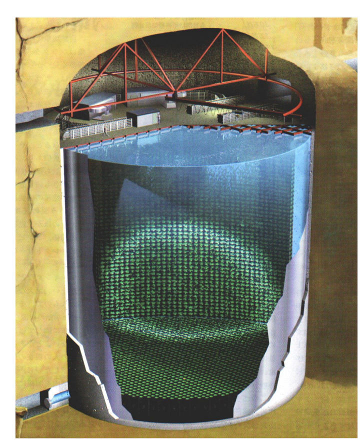


Nakazato et.al. ApJ.Suppl. 205 (2013) 2

http://asphwww.ph.noda.tus.ac.jp/snn/index.html

M_{init}	Z	Supernova models			BH models
		t_{revive}= 100ms	t_{revive}= 200ms	t_{revive}= 300ms	
13M_{solar}	0.02	258kB	257kB	256kB	---
20M_{solar}		258kB	257kB	257kB	
30M_{solar}		257kB	257kB	255kB	
50M_{solar}		257kB	256kB	256kB	
13M_{solar}	0.004	258kB	257kB	257kB	
20M_{solar}		258kB	257kB	256kB	
30M_{solar}		---			4.97MB (Shen)
					2.69MB (LS220)
50M_{solar}		259kB	258kB	257kB	---

at 10kpc, 4.5MeV energy threshold

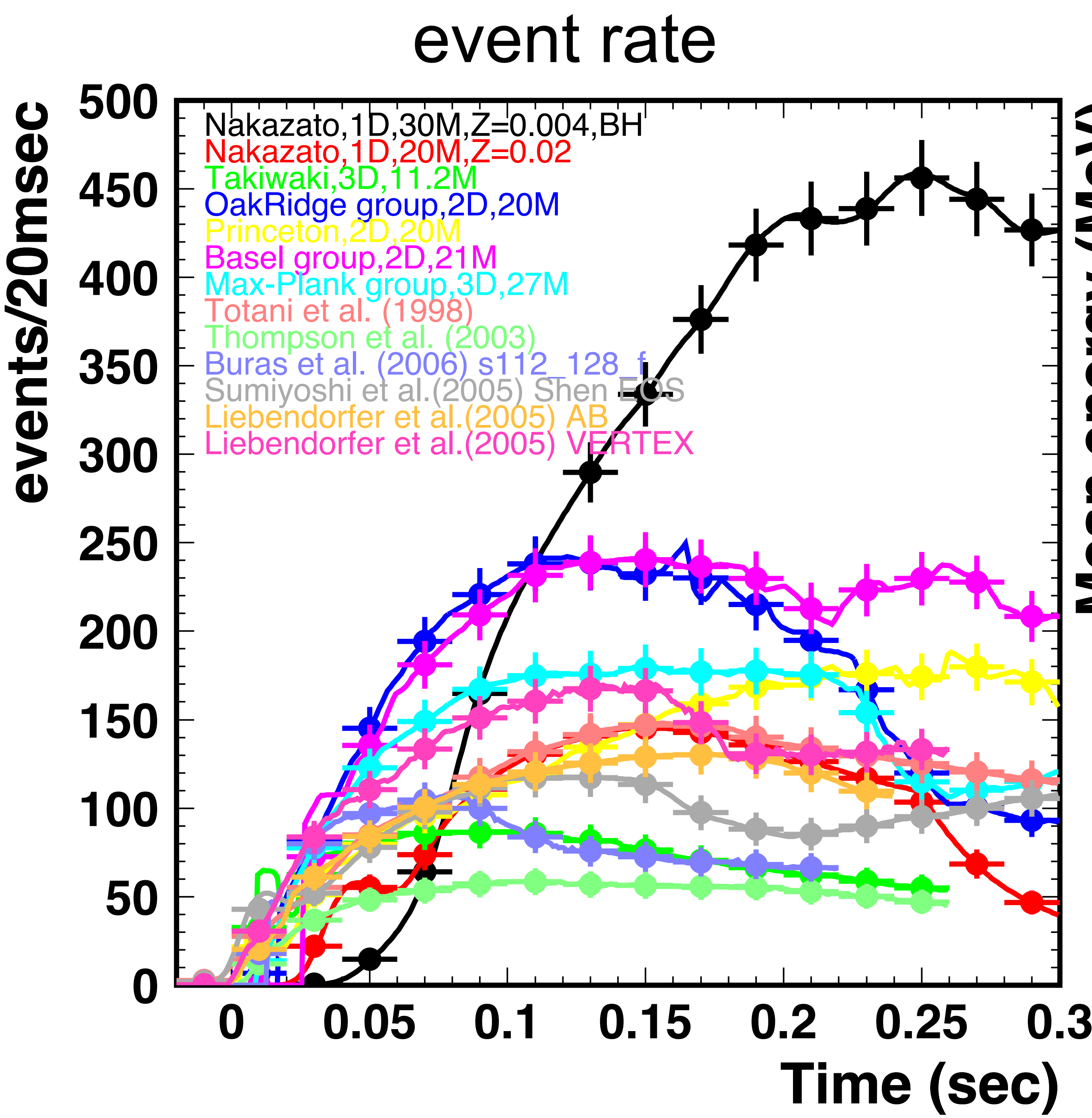


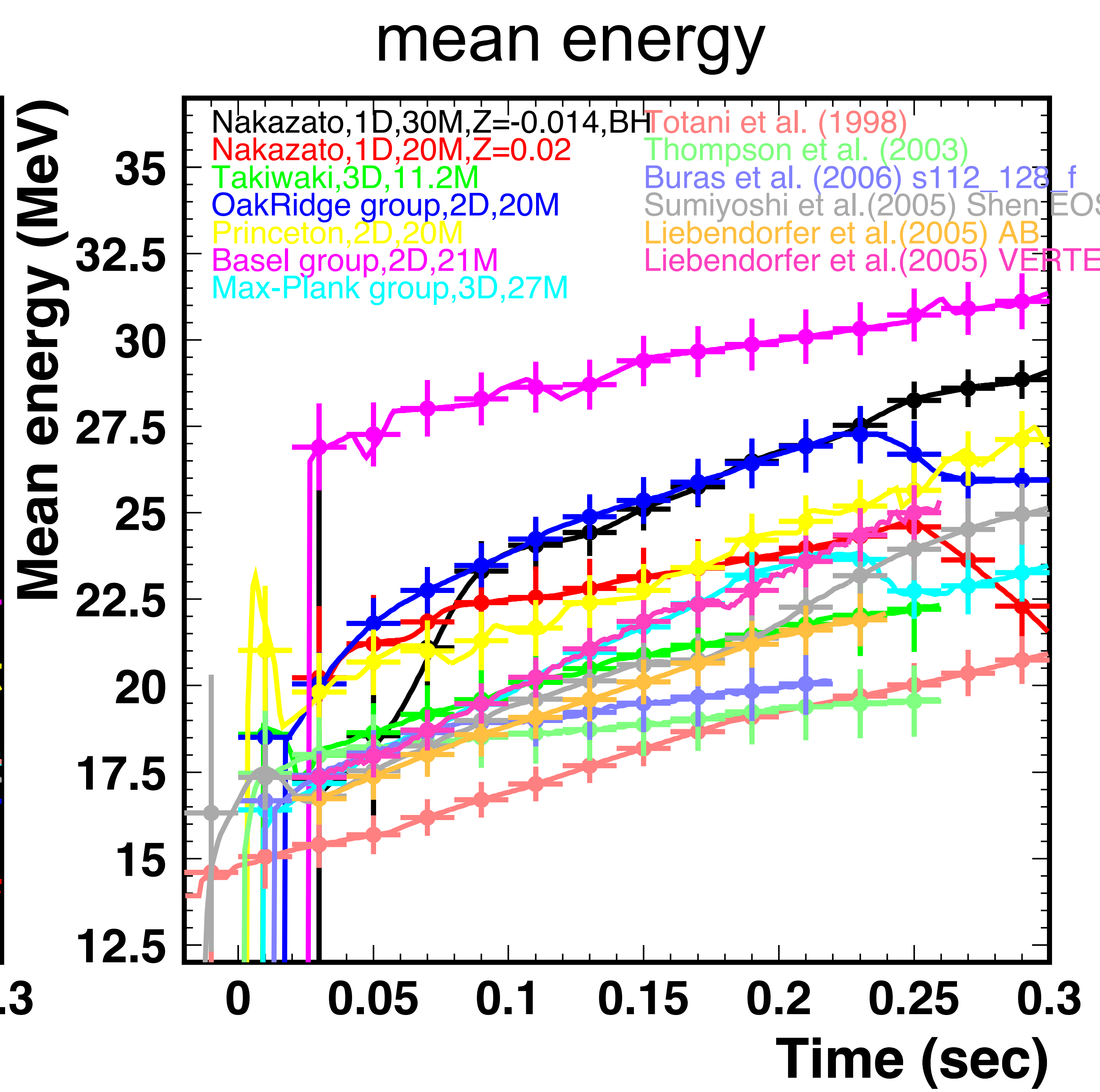
2.8k~15k ev

(inverse beta decay
7.3k for Livermore)

Super-Kamiokande

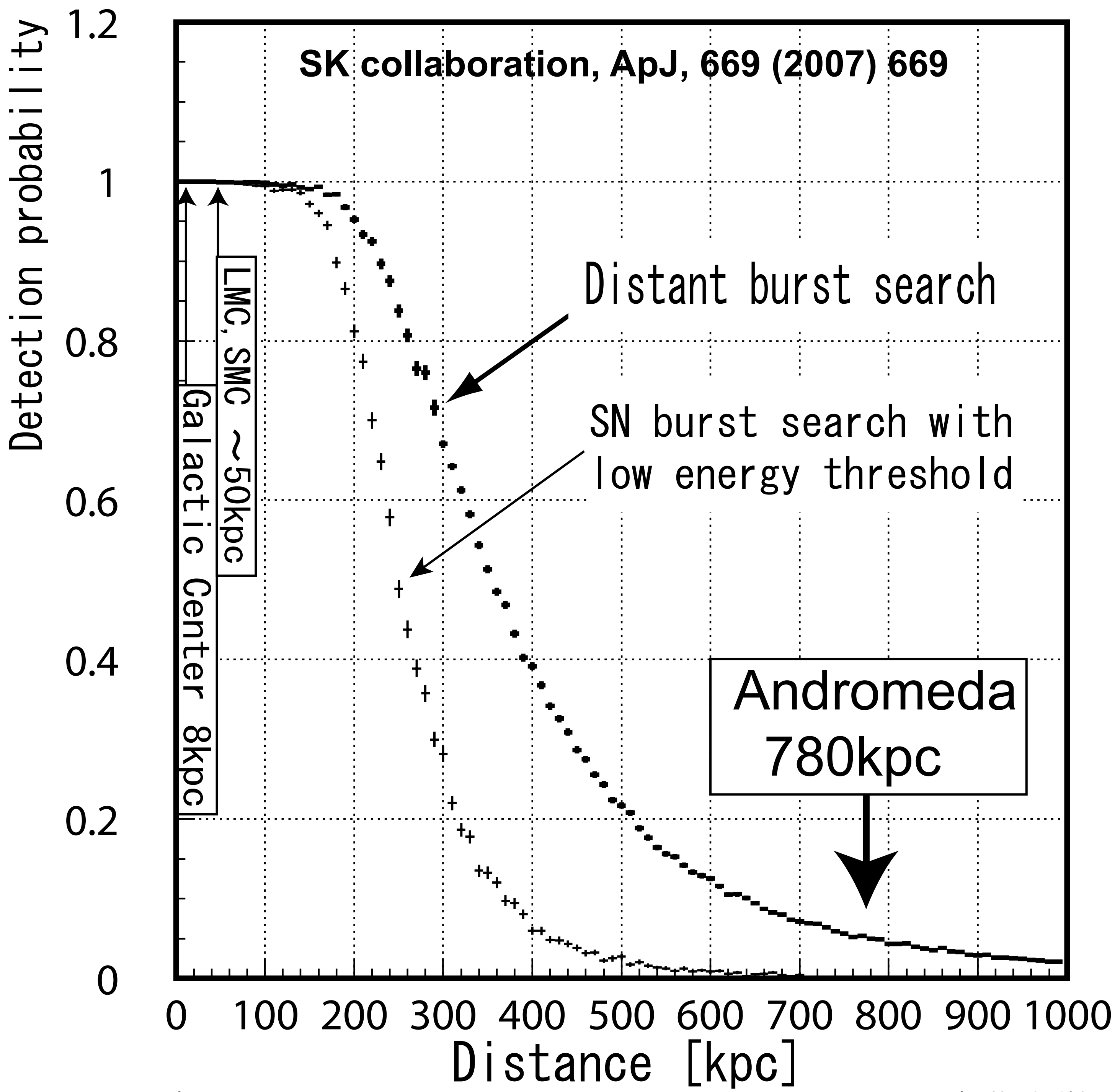
Time variation of $\overline{\nu_e}$+p at 10kpc





Super-Kamiokande

Detection probability as a function of distance

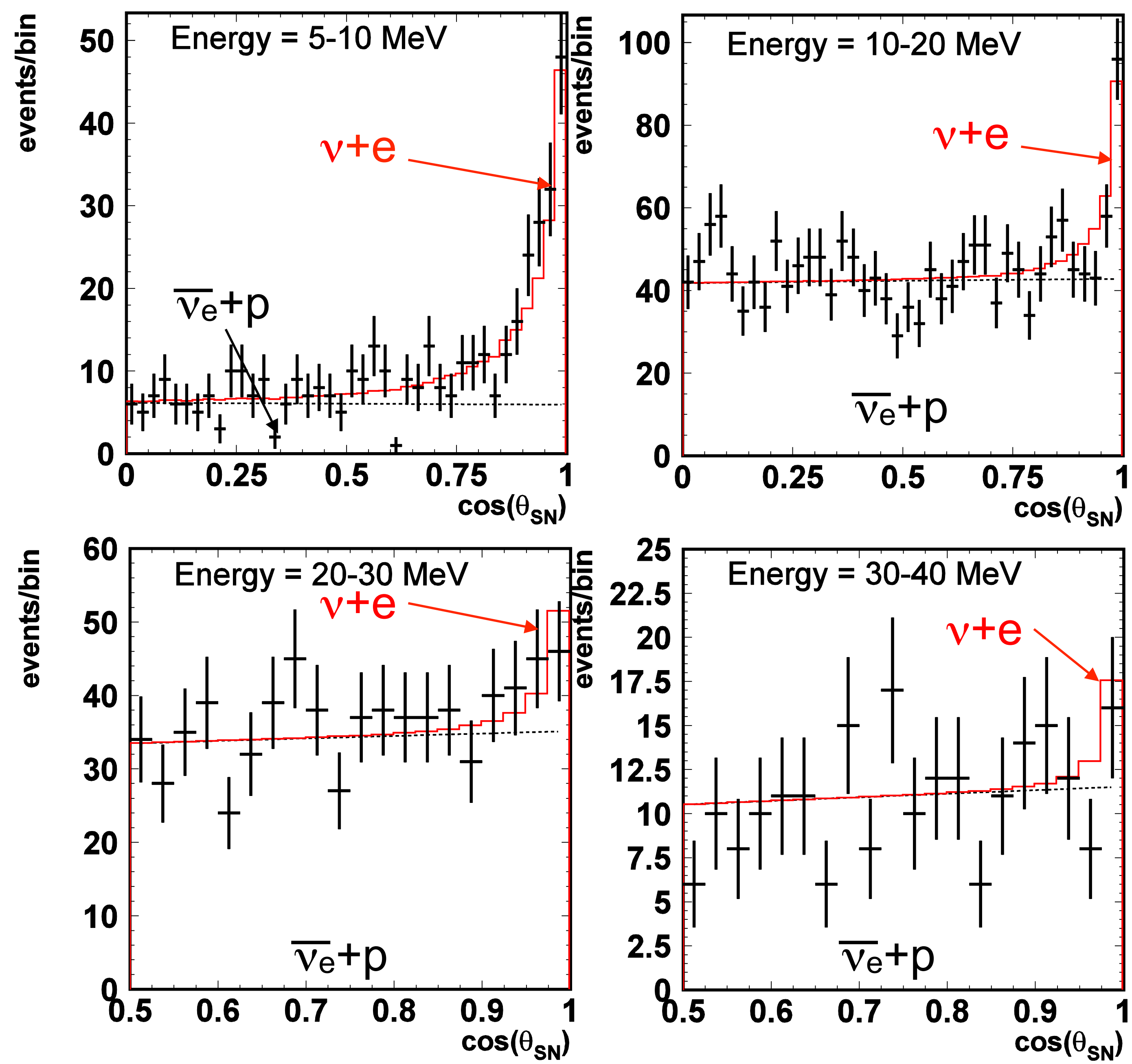


~350 kpc at 50% efficiency

Super-Kamiokande

✓ ν-e elastic scattering has good directionality.
✓ Direction of supernova can be determined with an accuracy of ~5 degree.
✓ Spectrum of νe events can be statistically extracted using the direction to supernova.
✓ If Gd loaded, it will be more accurate since ν_e signal can be separated. (later)

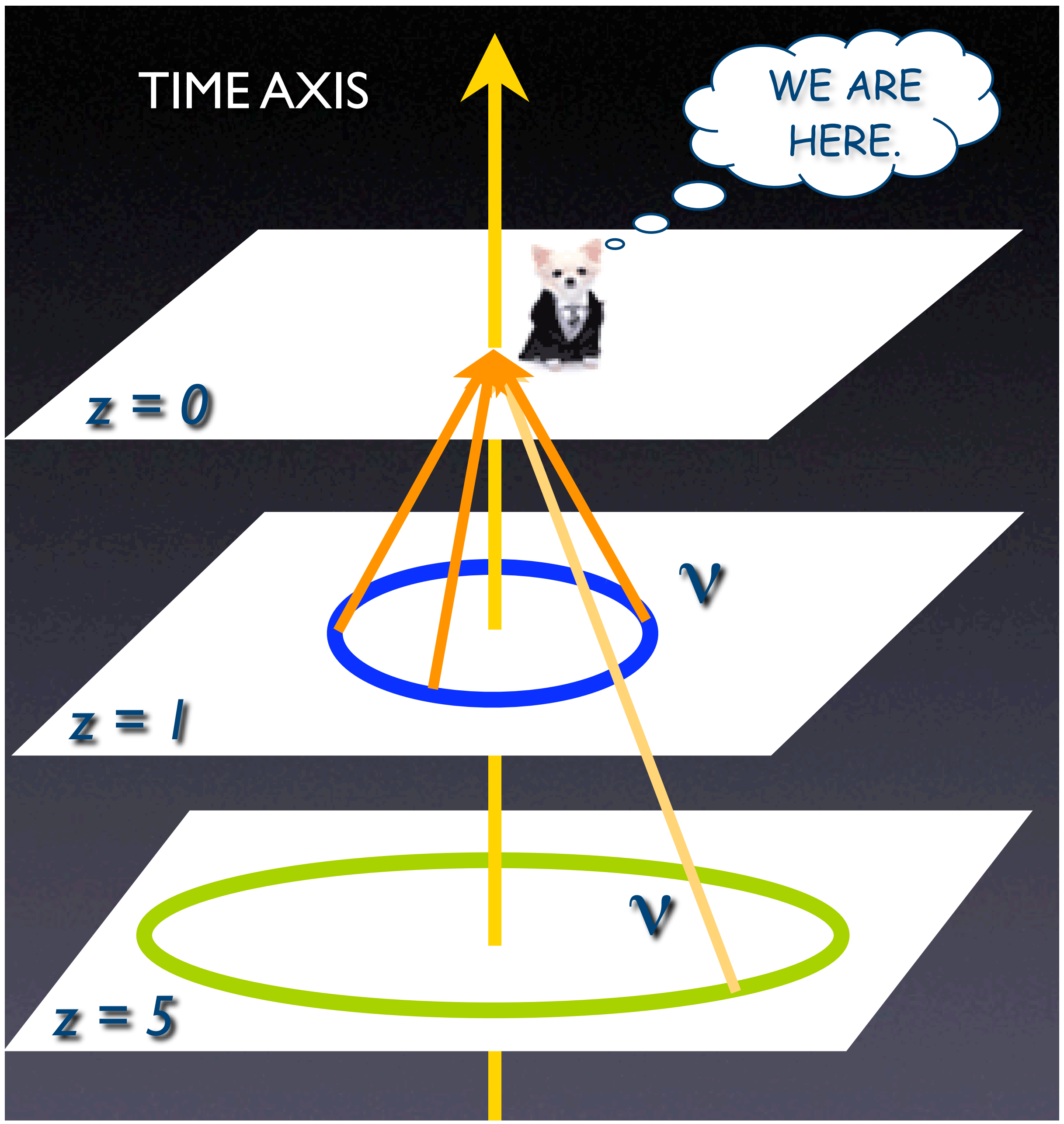
Simulation of angular distribution

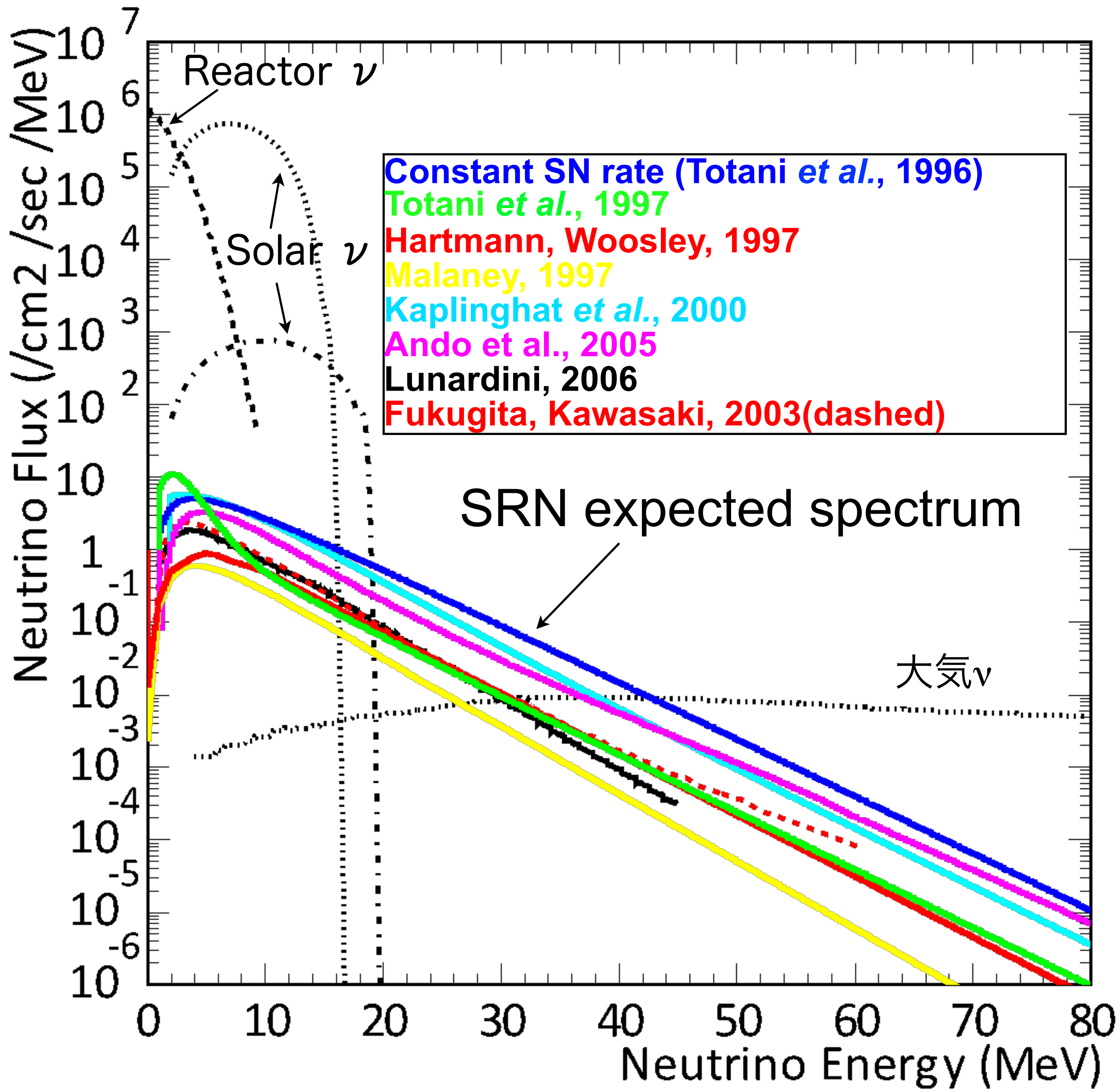


Diffuse Supernova Neutrino Background (Supernova Relic Neutrino)

Neutrinos emitted from past supernovae

S.Ando

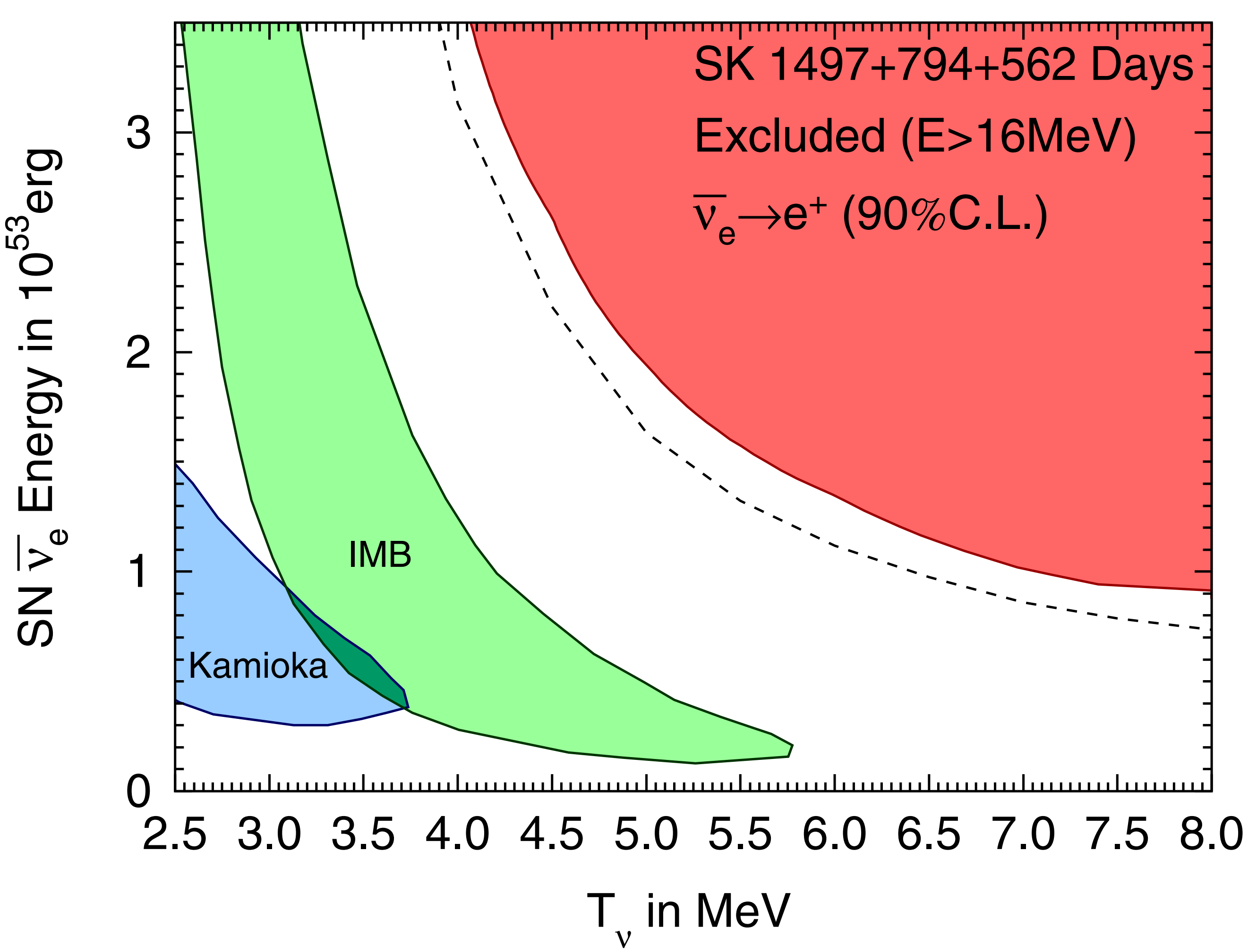


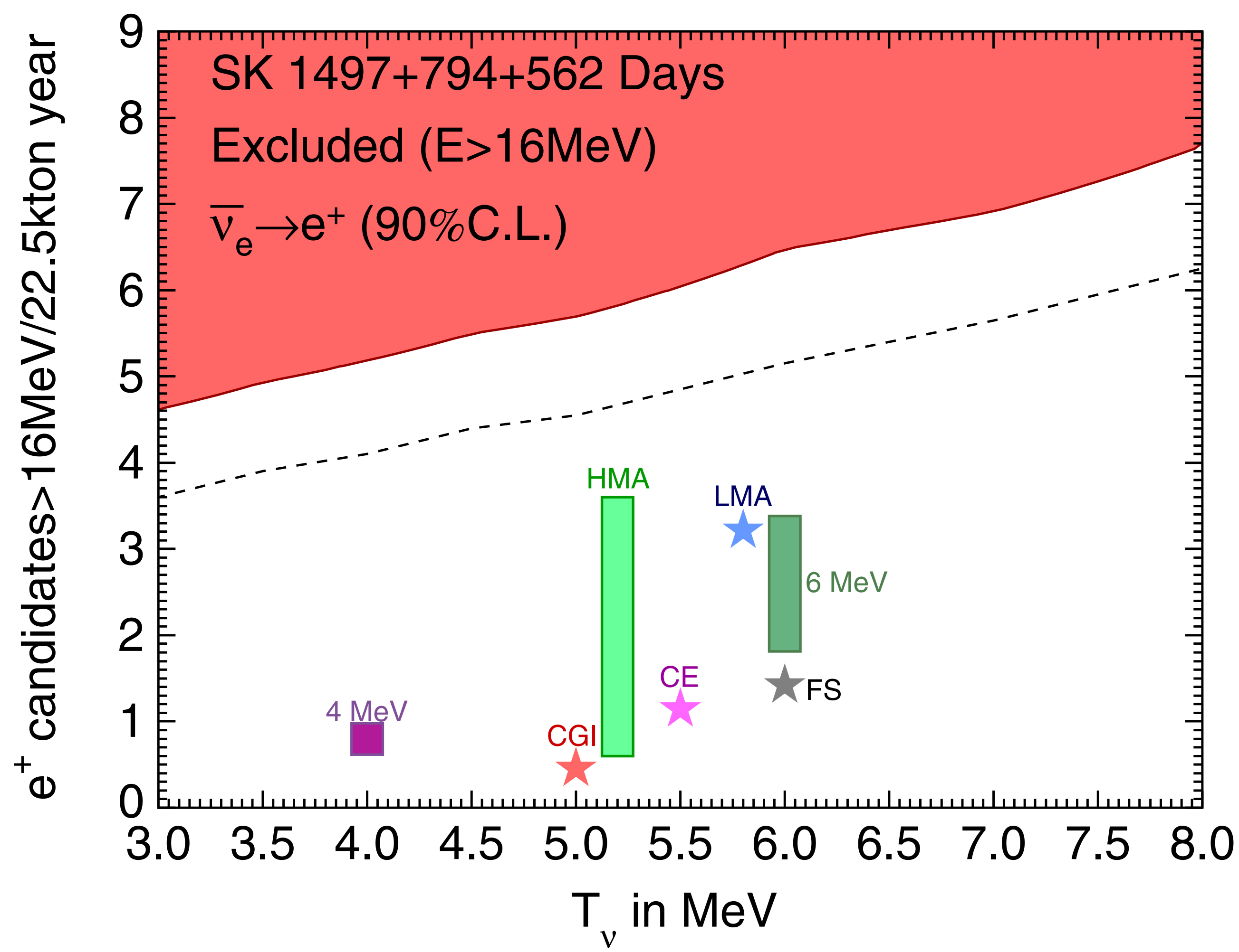


SRN in Super-K

Current Super-K w/o neutron tagging

SK collaboration, Phys. Rev. D 85, 052007 (2012)





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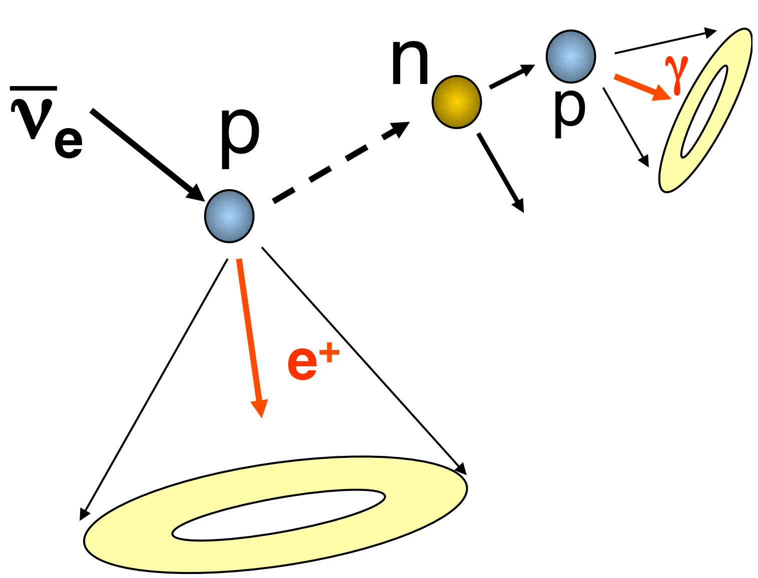
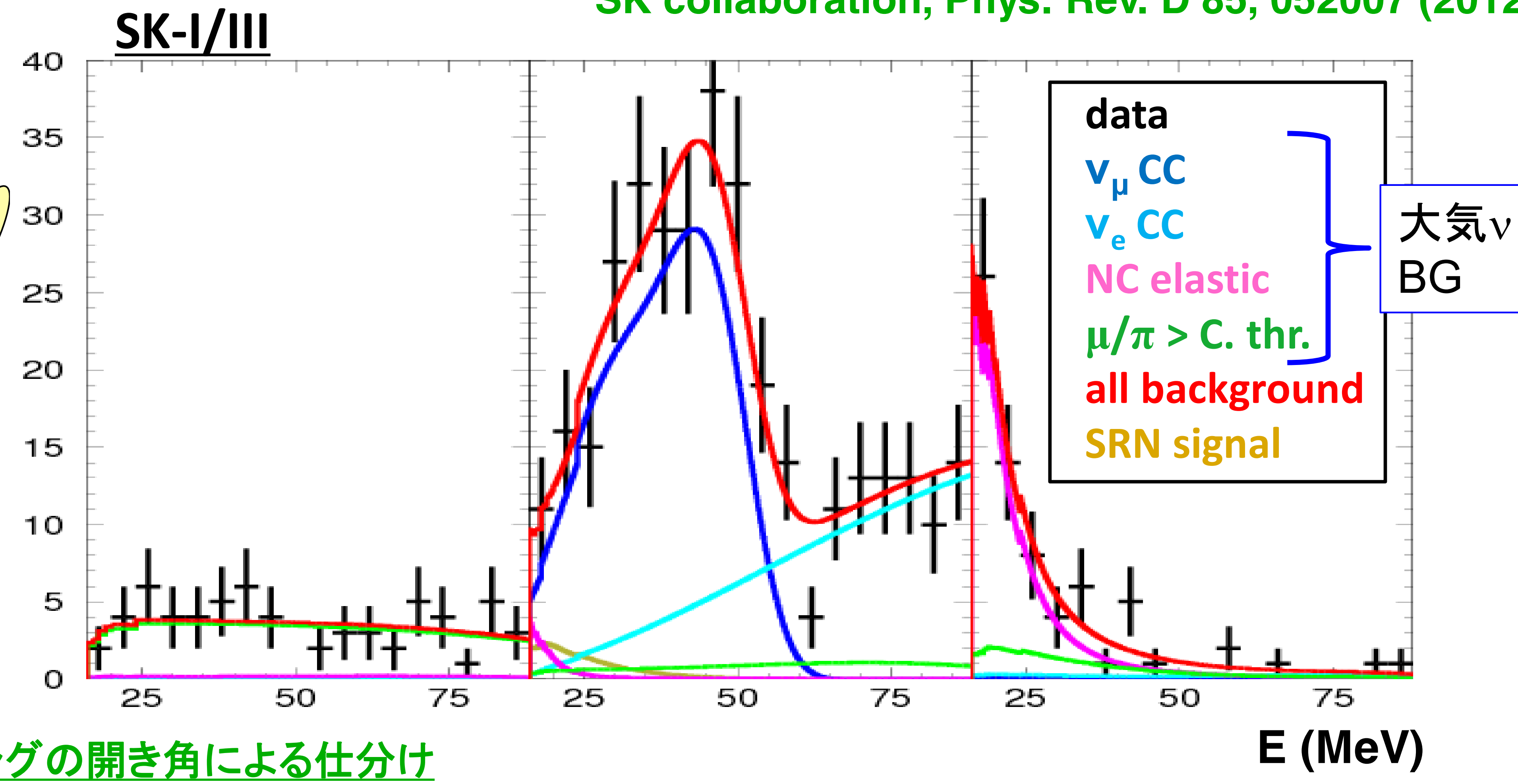


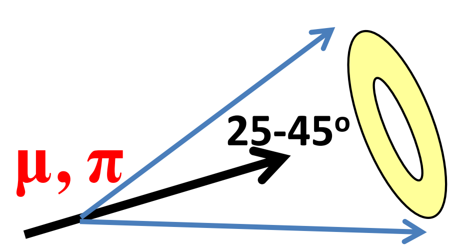
Only this signal

SK collaboration, Phys. Rev. D 85, 052007 (2012)

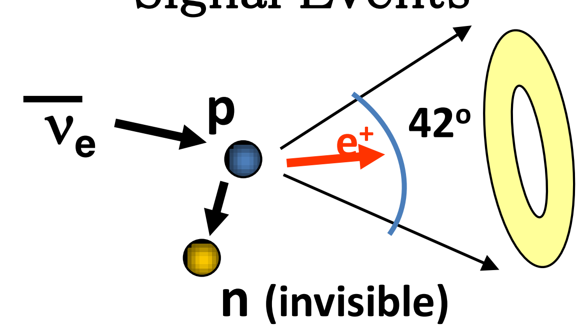


リングの開き角による仕分け

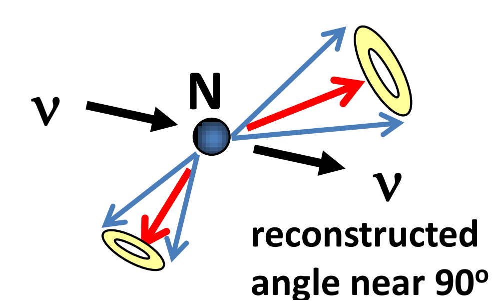
Low angle events



Signal Events



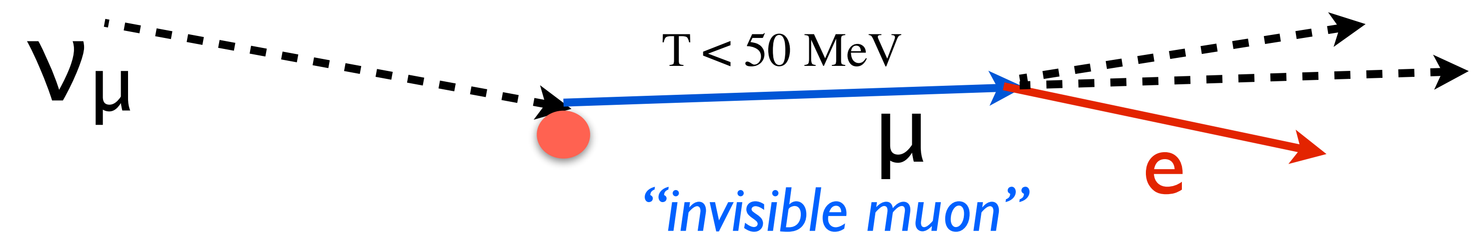
Isotropic Events



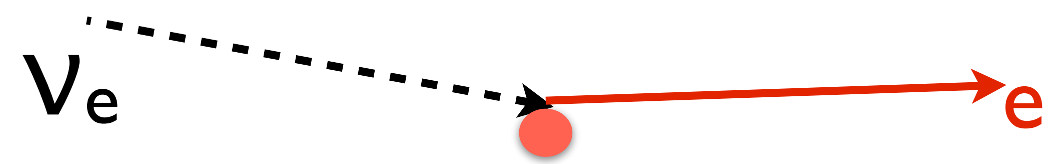
SRN in Super-K

Background

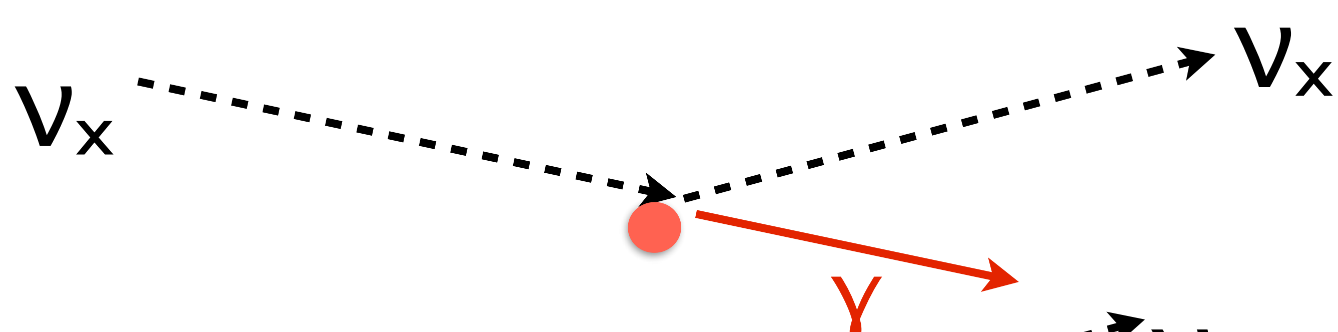
Decay electron
"atm. muon neutrinos"



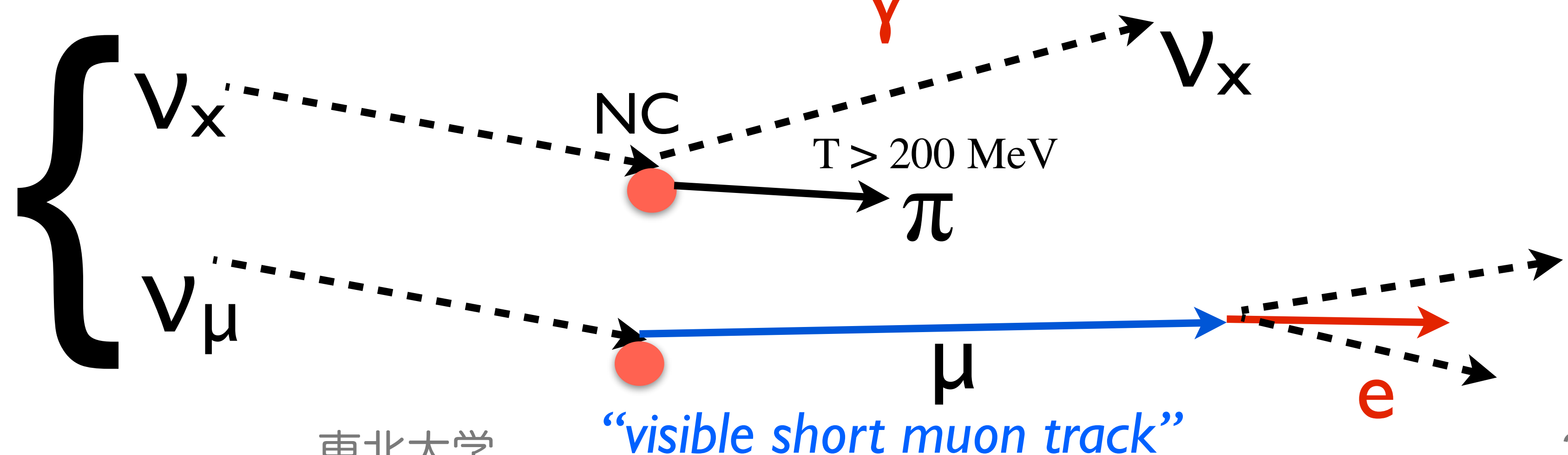
ν_e CC
"atm. electron neutrinos"



NC Elastic
"atmospheric"



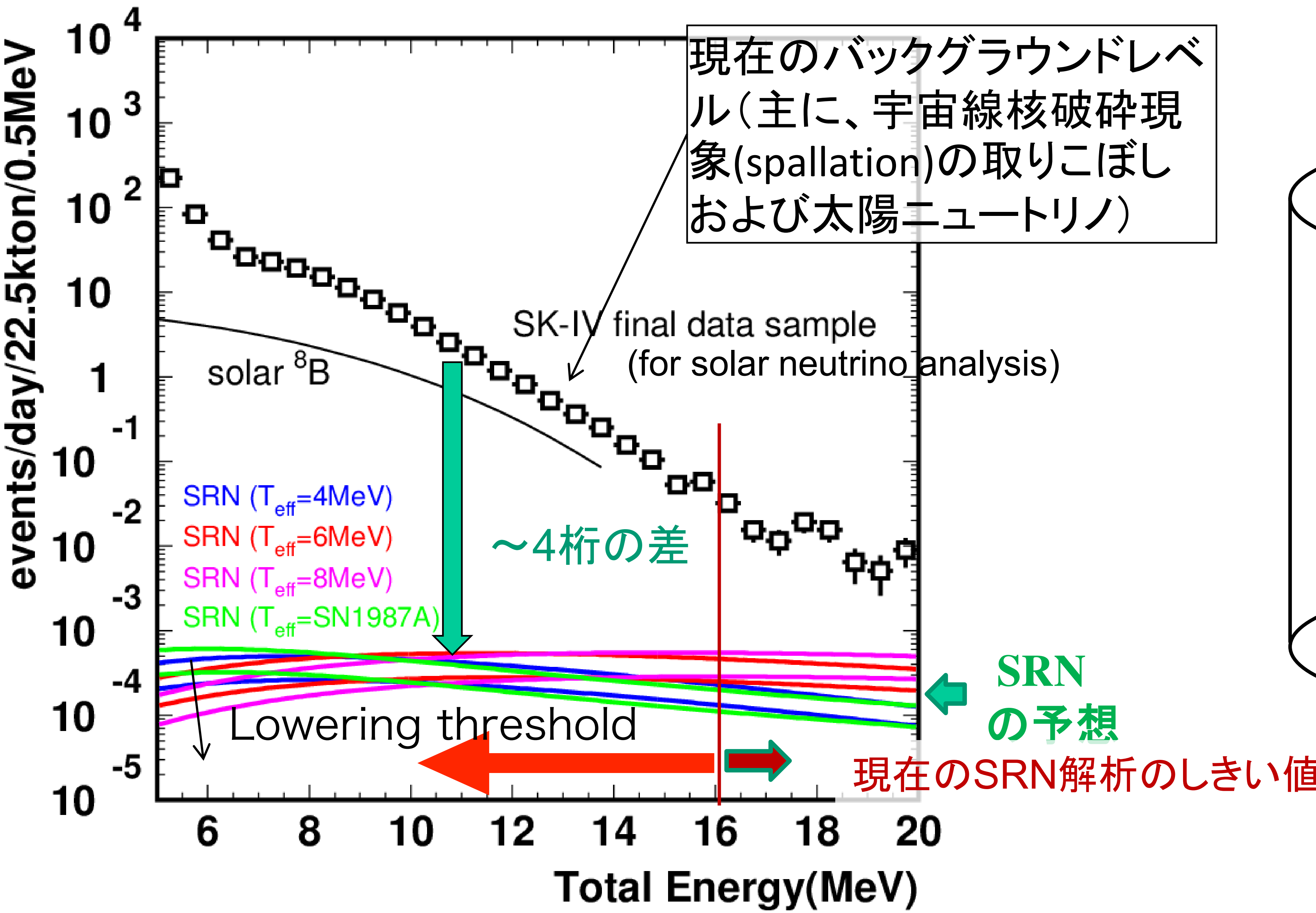
μ/π
"μ/π production from atm. neutrinos"

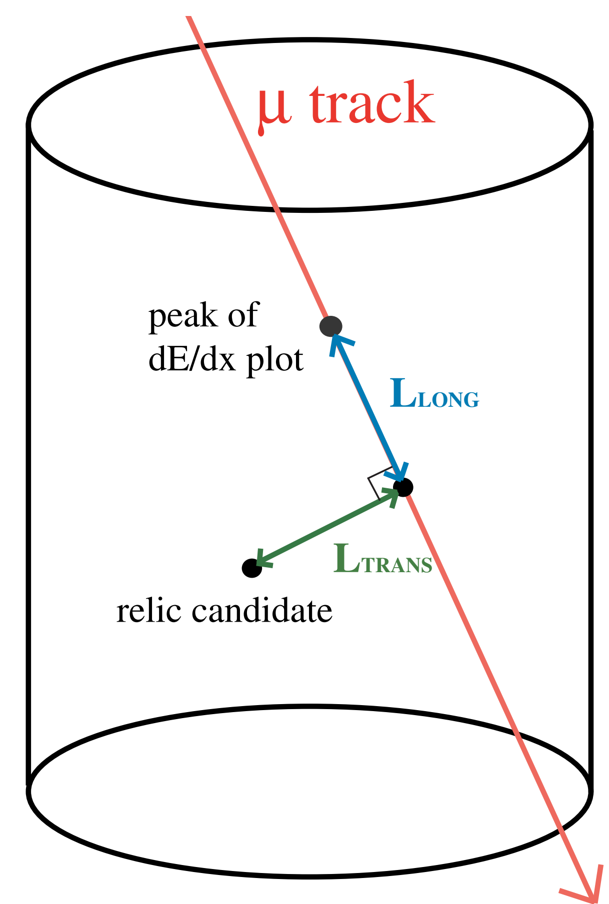


SRN in Super-K

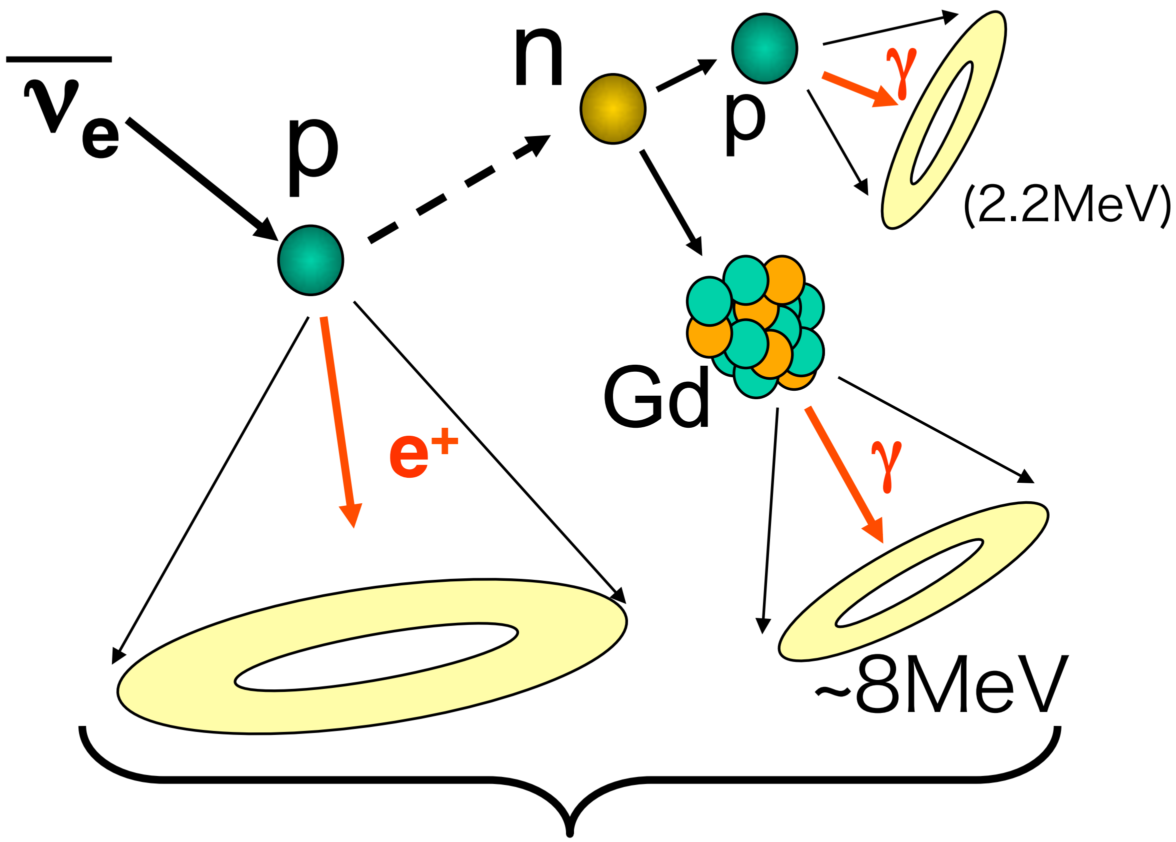
Background

For solar / SN neutrinos (~MeV)





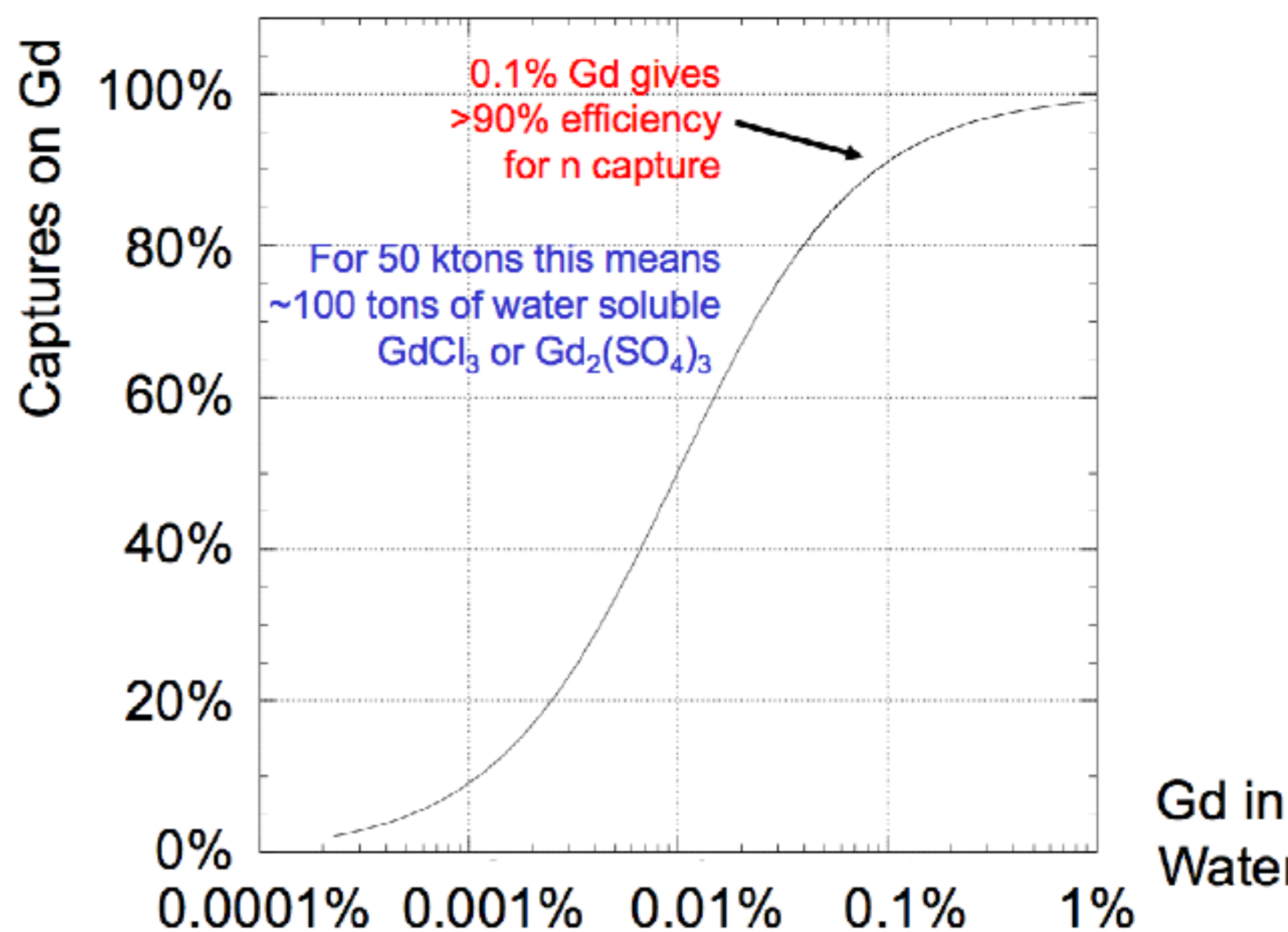
SRN in upgraded Super-K



•Delayed coincidence
- Suppress B.G. drastically for $\overline{\nu}_e$ signal
- ΔT~20μsec
- Vertices within ~50cm

GADZOOKS!

Dissolve Gadolinium into Super-K
J.Beacom and M.Vagins,
Phys.Rev.Lett.93 **(2004)** 171101



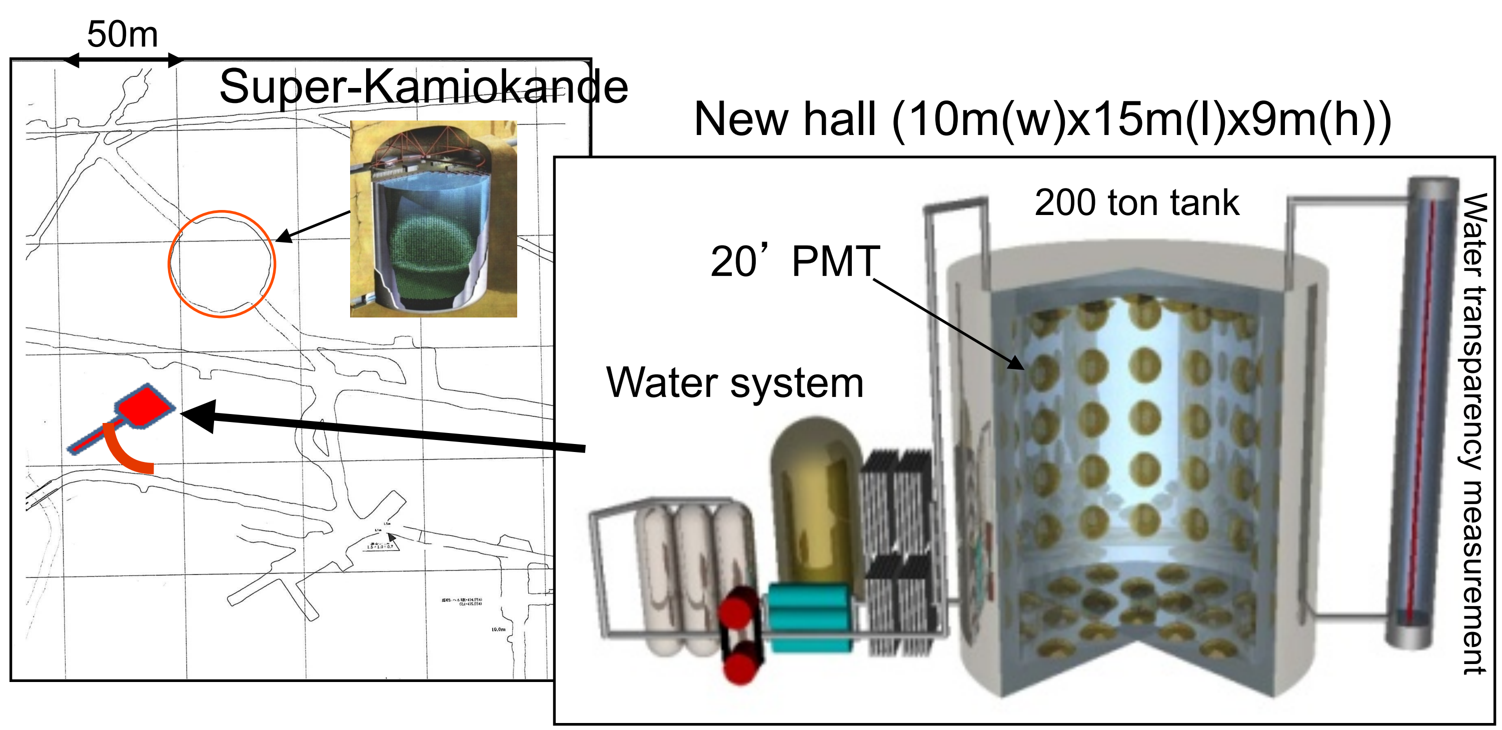
Proposed in 2004,
but not so easy..

EGADS as R&D

(Evaluating Gadolinium's Action on Detector Systems)

Purpose
✓Water transparency
✓How to purify
✓How to introduce and remove
✓Effect on detector
✓Effect from environment neutrons
✓etc.

R&D for Gd test experiment



Now working well

EGADS as R&D

200 ton tank

UDEAL

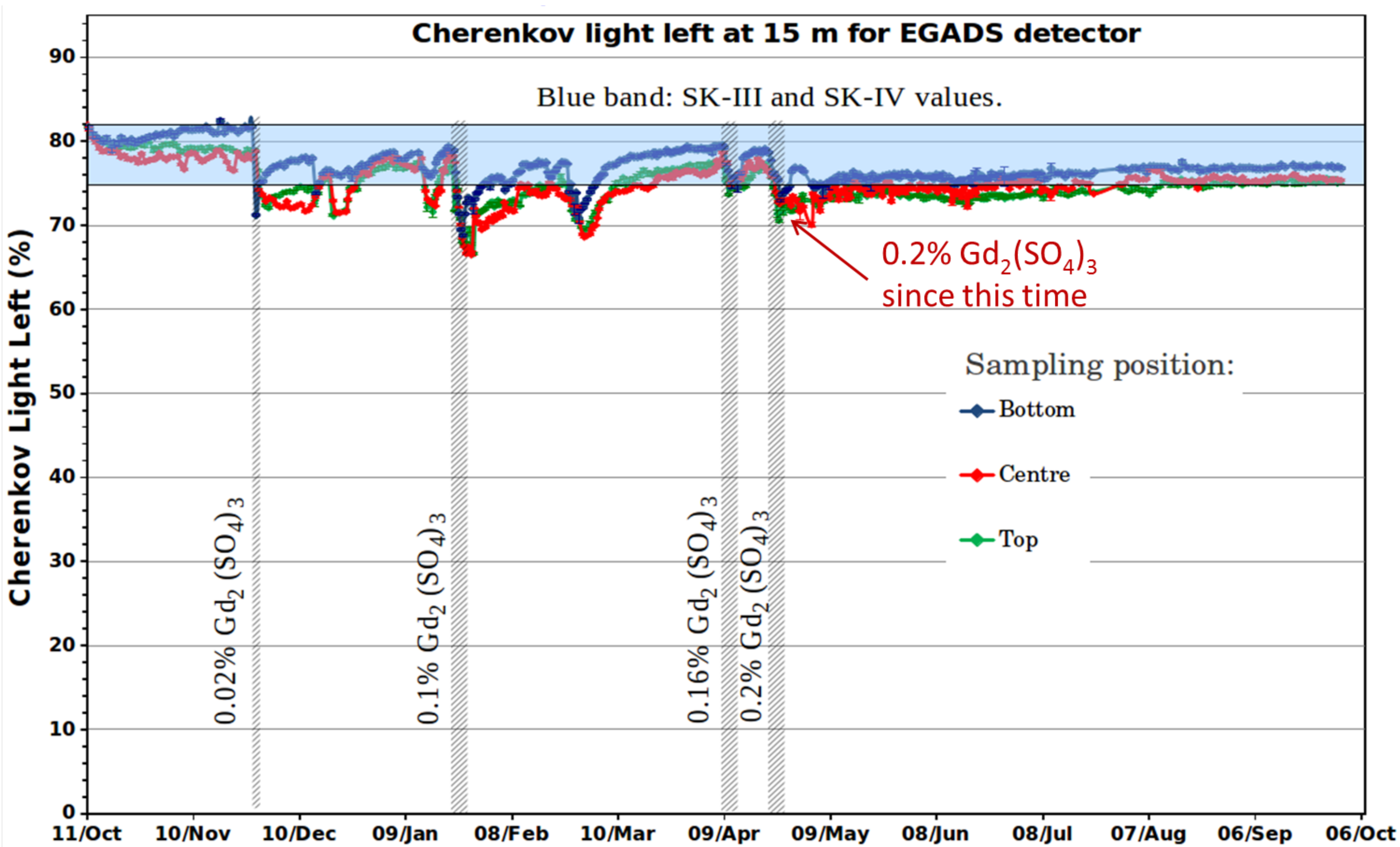
water transparency measurement

15 ton buffer tank

Control panel of circulation system

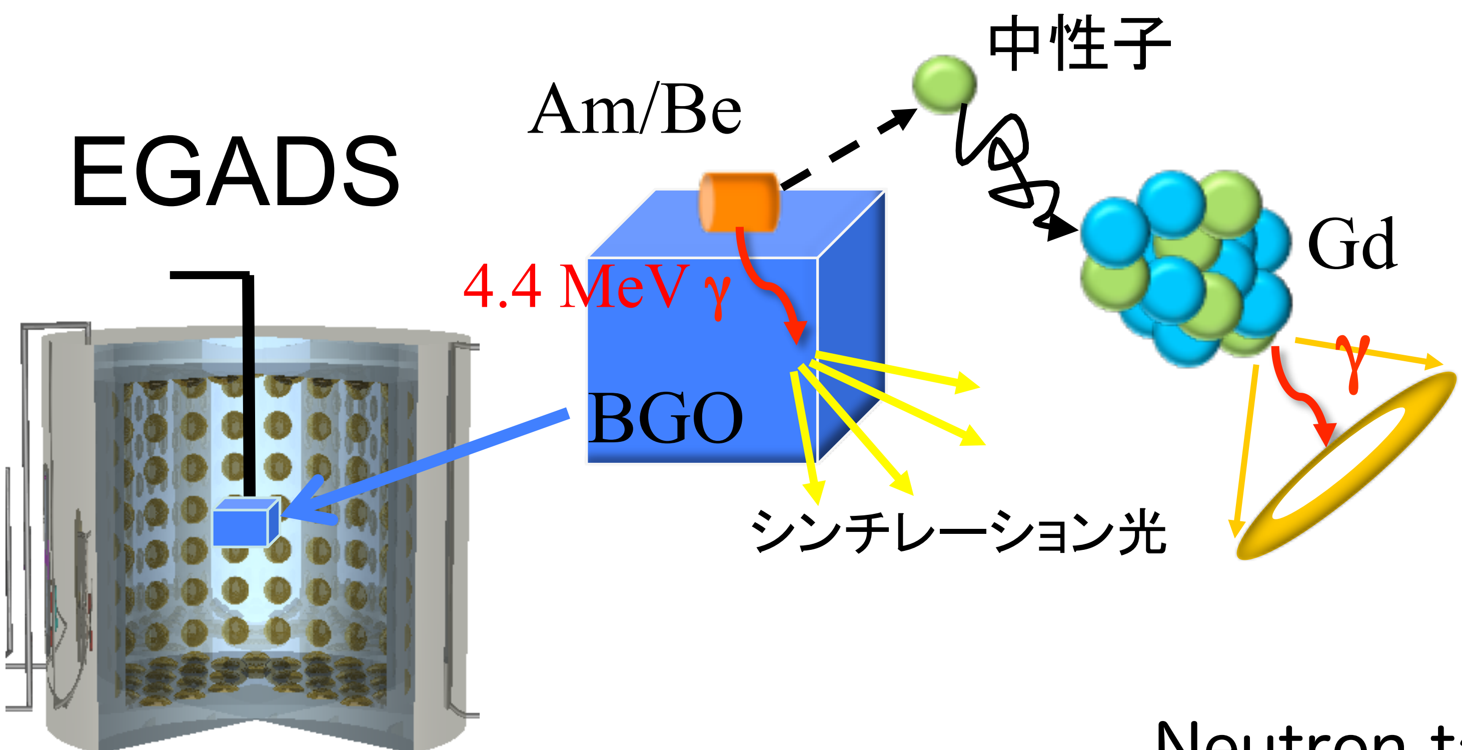
Filter

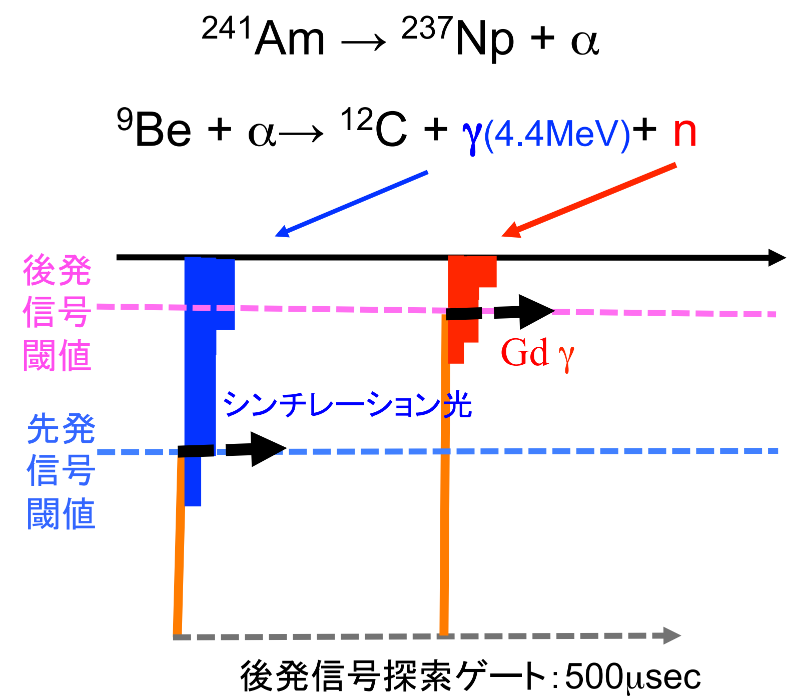
EGADS as R&D



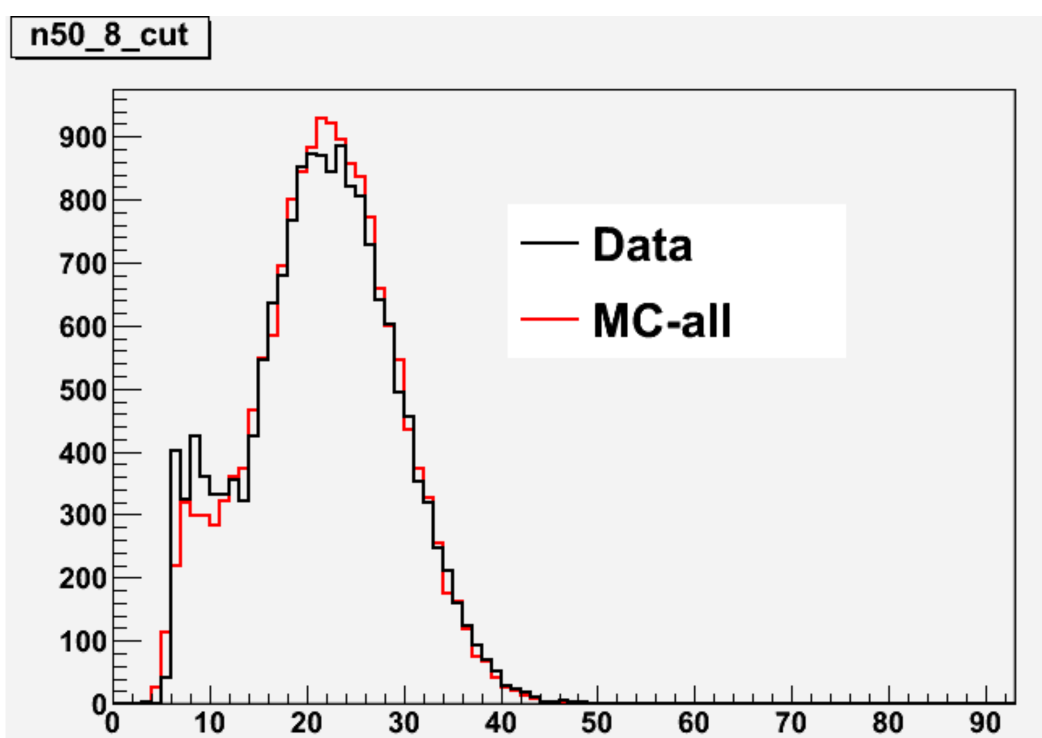
Very stable and continuous data taking

Neutron tagging





Neutron tagging with delayed coincidence



Neutron capture time

	2178±44ppm	1055±21ppm	225±5ppm
Data	29.89±0.33	51.48±0.52	130.1±1.7
MC	30.03±0.77	53.45±1.19	126.2±2.0

Neutron capture efficiency

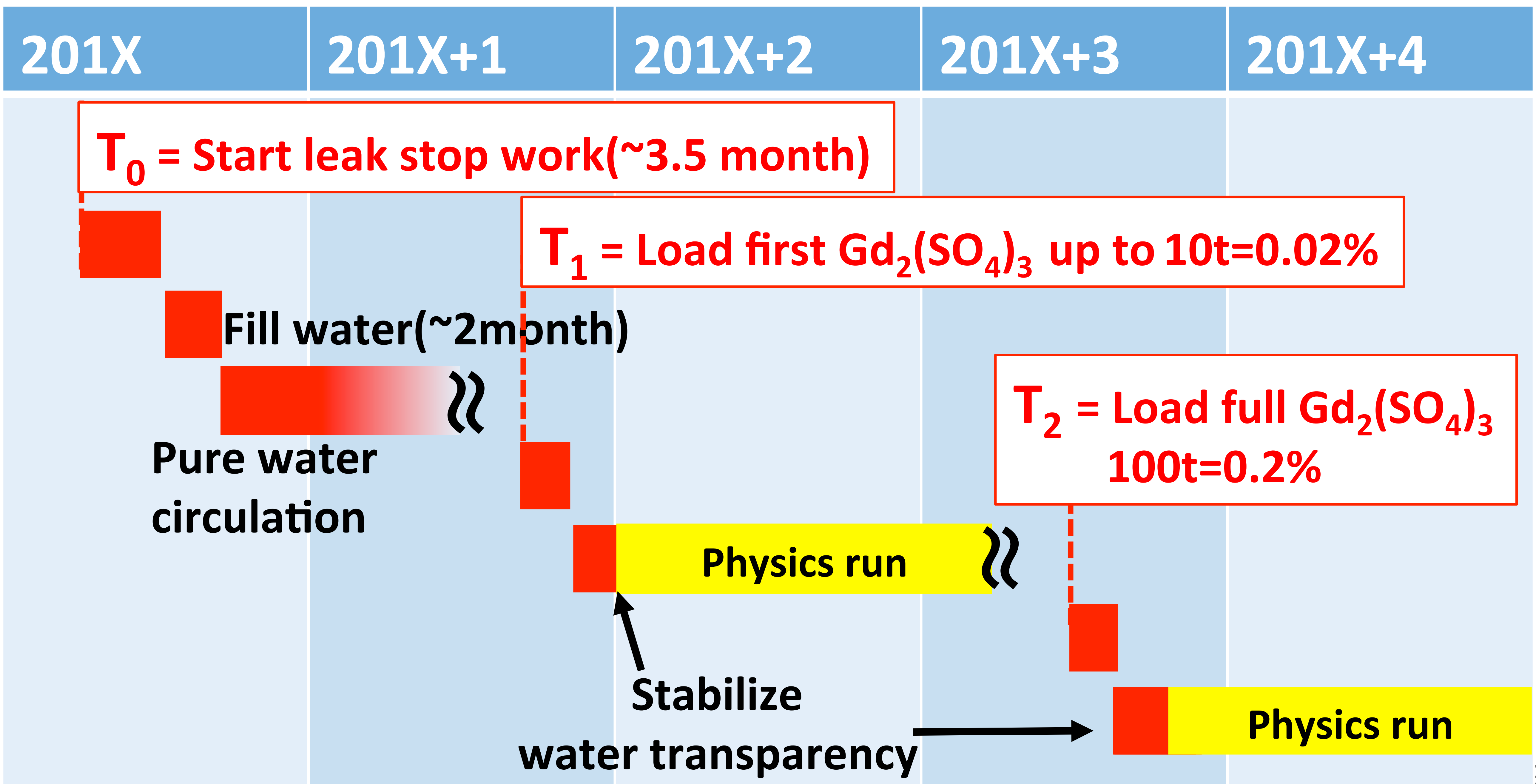
Data	MC
84.36± 1.79%	84.51±0.33%

Approved by the
Super-K collaboration
in 2015

‘Super-K Gd’ or ‘SK Gd’

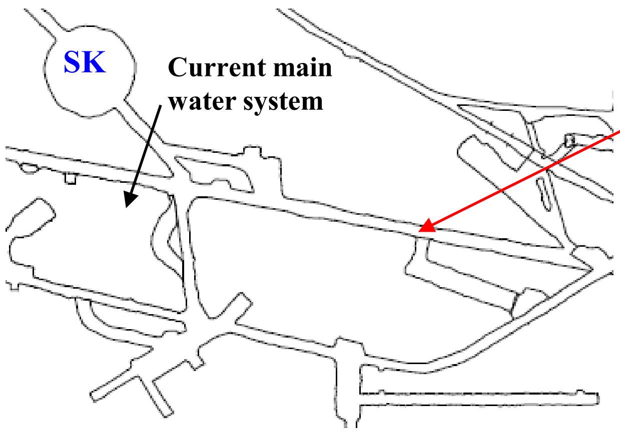
Time line

Given the current anticipated schedules, the expected time of the refurbishment is 2018.

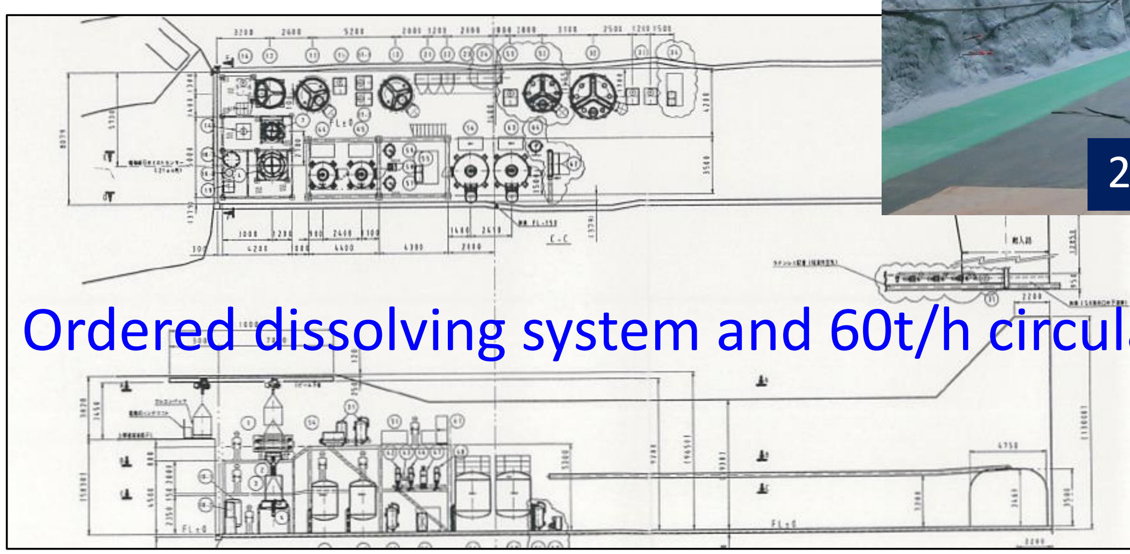


Remaining work toward SK-Gd

New water purification system



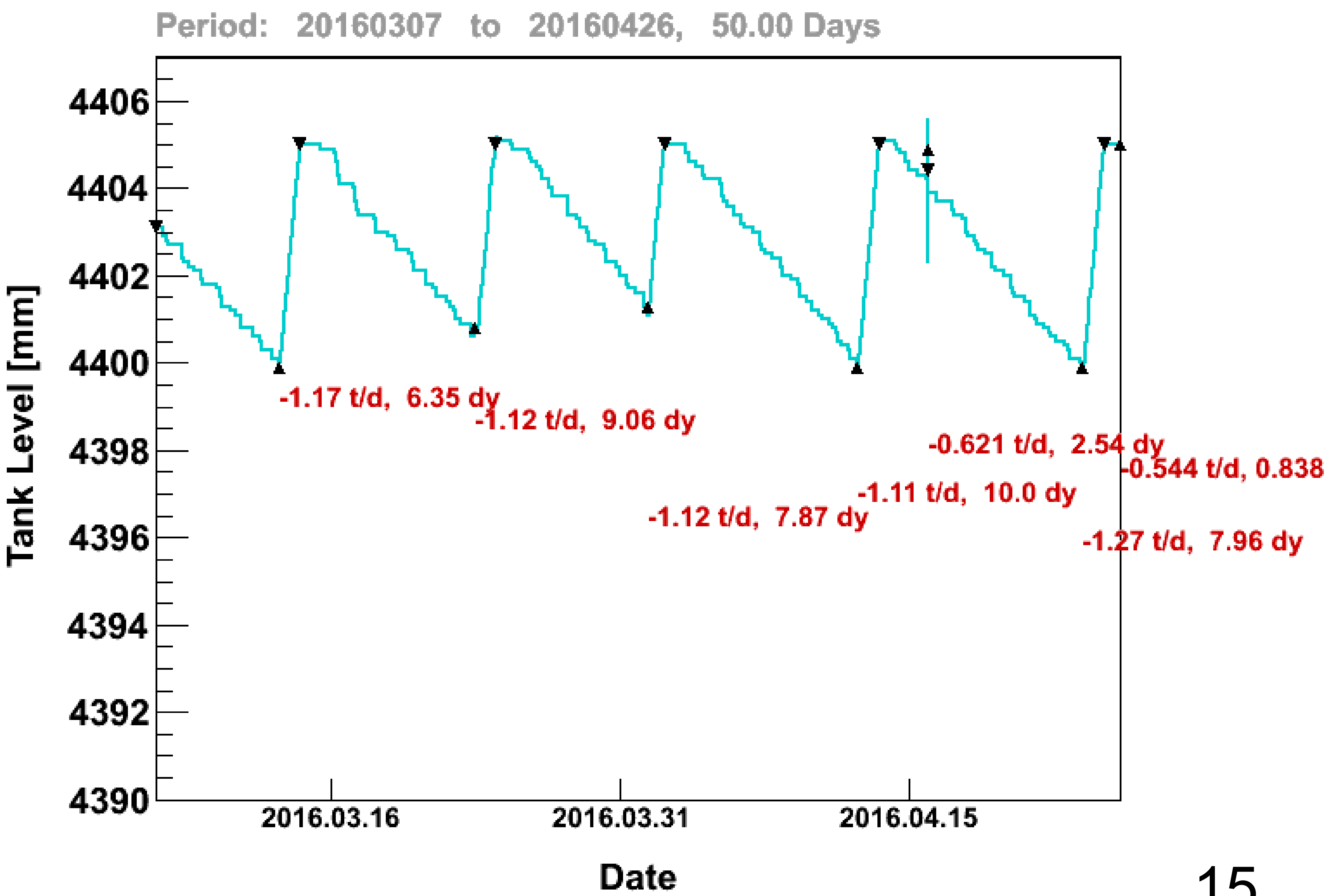
system room



Ordered dissolving system and 60t/h circulation system

This will be i

Leak fixing


Period: 20160307 to 20160426, 50.00 Days
Tank Level [mm]
4406
4404
4402
4400
4398
4396
4394
4392
4390
-1.17 t/d, 6.35 dy
-1.12 t/d, 9.06 dy
-0.621 t/d, 2.54 dy
-0.544 t/d, 0.838
-1.11 t/d, 10.0 dy
-1.12 t/d, 7.87 dy
-1.27 t/d, 7.96 dy
2016.03.16
2016.03.31
2016.04.15
Date

Leak fixing

Cover all the welded places with sealing materials

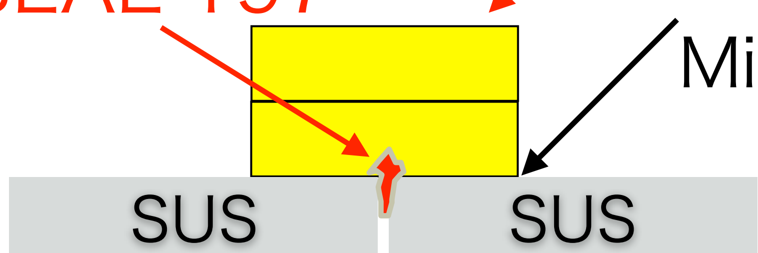
Cover with two materials.
One is BIO-SEAL 197 (epoxy resin) which sneak into small gaps, the other is 'Material' (poly-urea) which allows more displacement.

Need to wait several hours to the next step

BIO-SEAL 197

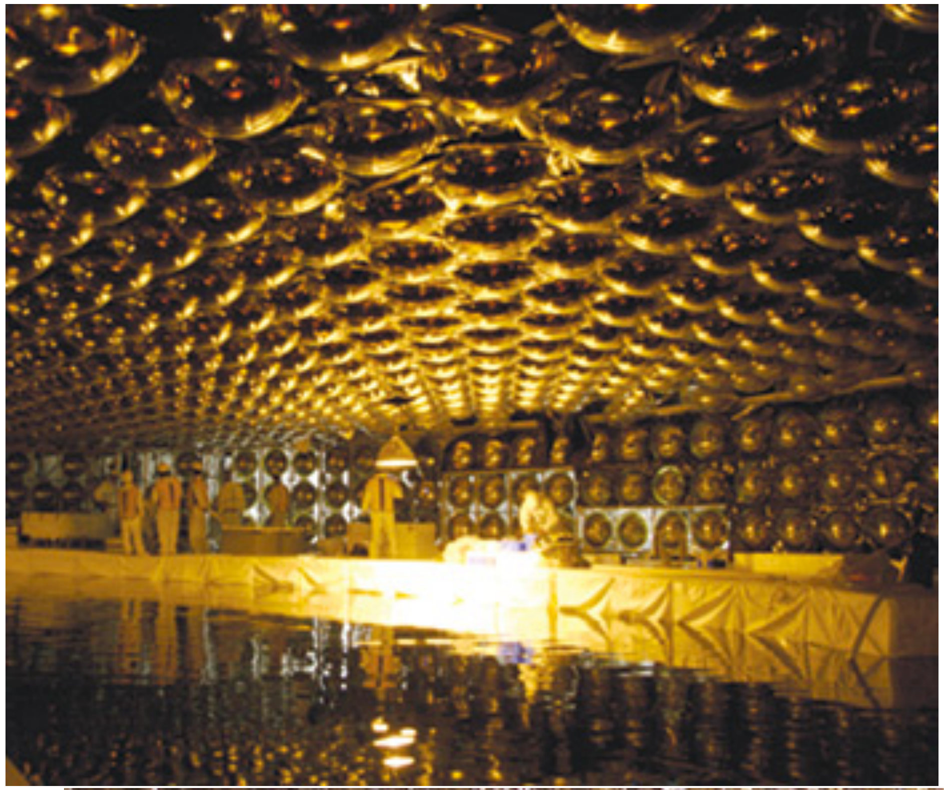
'Material' (two layers)

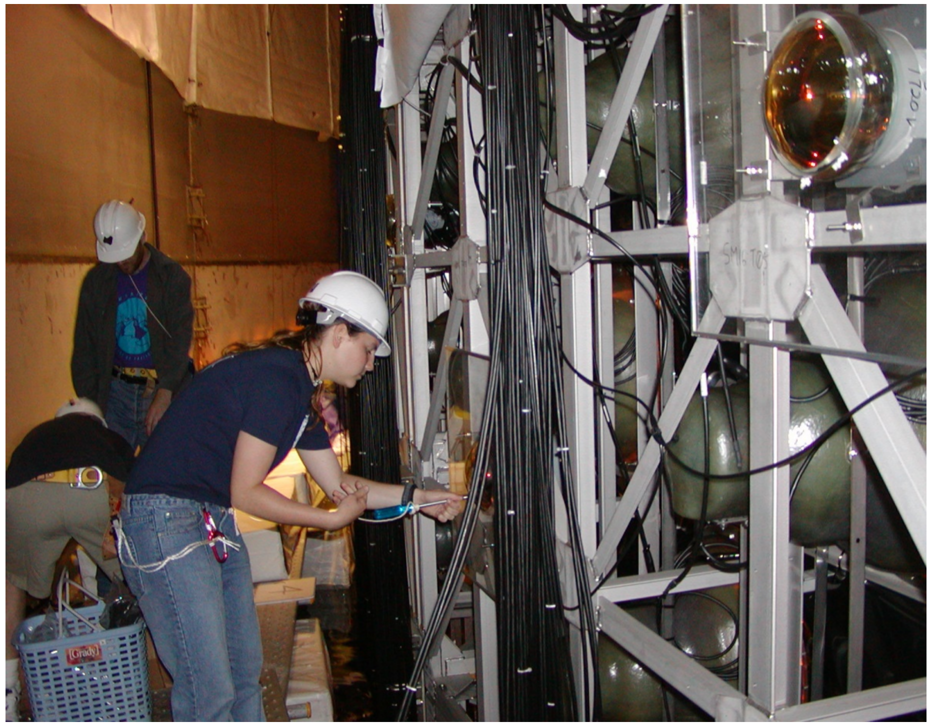
Primer between MineGuard and SUS

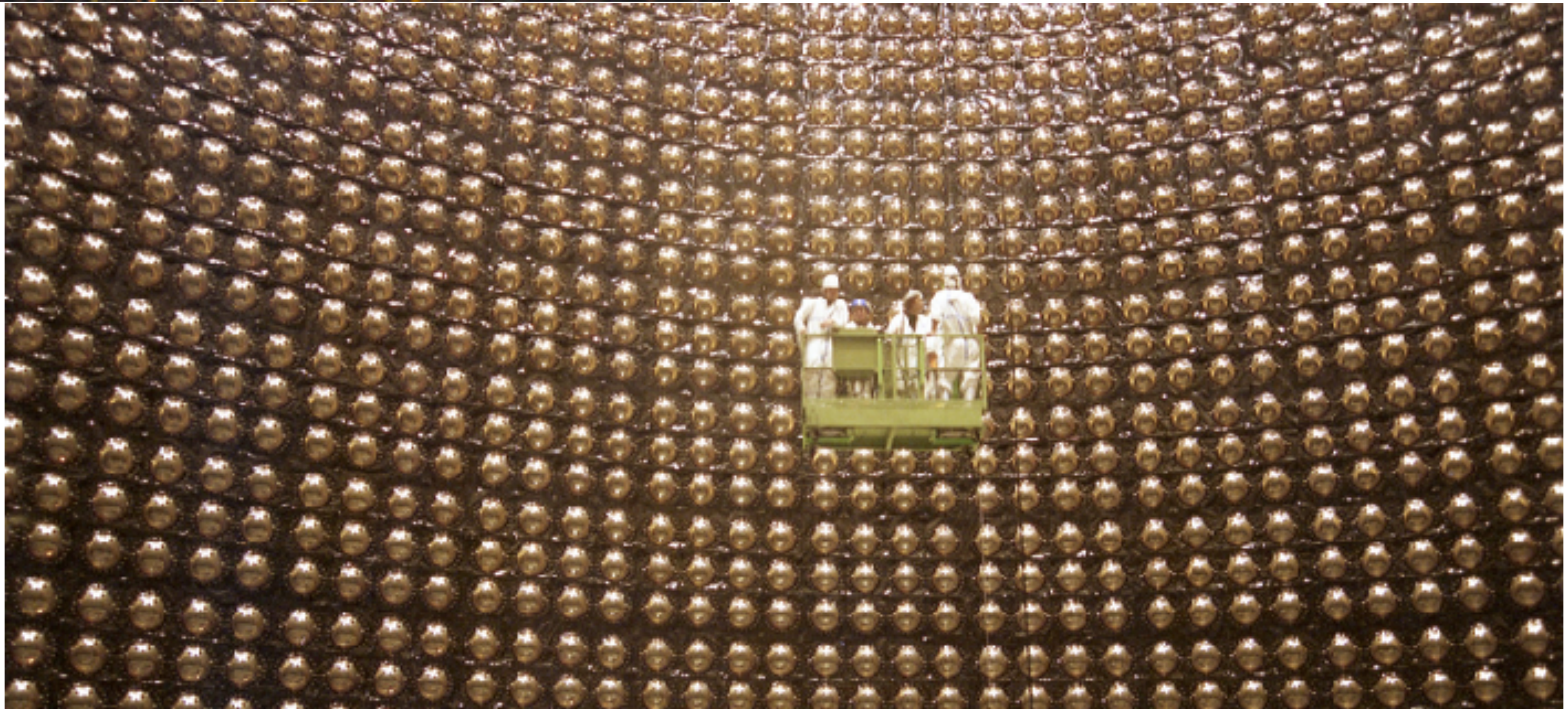


Backer as a bank to keep the coating region

Working inside the Super-K







Reduction of RI background

Intrinsic radioisotopes in $Gd_2(SO_4)_3$ could add low energy background in ^8B solar ν region of spectrum

- BG reduction ➔ Purification of 100 tons of $Gd_2(SO_4)_3$

Typical $Gd_2(SO_4)_3$ on the market

Chain	Main sub-chain isotope	Radioactive concentration (*mBq/kg*)
^{238}U	^{238}U	50
	^{226}Ra	5
^{232}Th	^{228}Ra	10
	^{228}Th	100
^{235}U	^{235}U	32
	^{227}Ac/ ^{227}Th	300

For DSNB

Expected signal ~5 events/year/FV

- ^{238}U Spontaneous Fission:

~ 5.5 [$\gamma(E\gamma>10.5\ MeV)$ + 1n] / year / FV

1 order reduction

For solar neutrino

Current BG ~200 events/day/FV

- U (n) ~320events/day/ FV

1 order reduction

- Th/Ra (β,γ) ~3×10^5 events/day/ FV

3 orders reduction

Achievements

U/Th measured by as well as ICP-MS

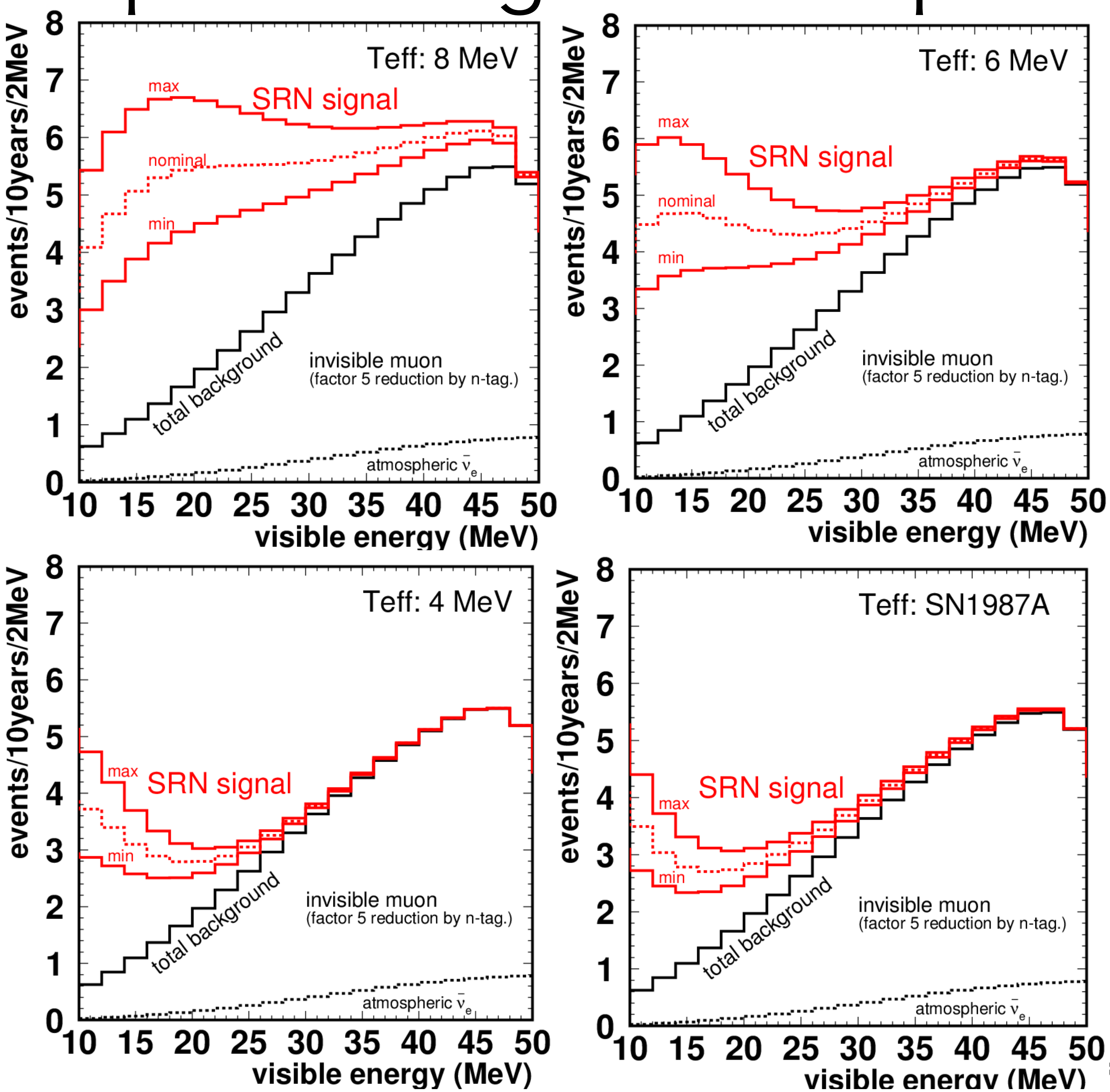
試料	U [g(U)/g] (×10^{-9}) ICP-MS (Ge検出器)	Th [g(Th)/g] (×10^{-9}) ICP-MS (Ge検出器)
A	0.26±0.01 (<2.02)	0.19±0.01 (<0.22)
B	0.25±0.03 (<1.18)	0.05±0.02 (<0.12)
C	0.19±0.04 (<4.78)	0.06±0.02 (<0.34)
D	0.26±0.03 (<0.71)	0.06±0.02 (<1.45)

Typical : 4x10^{-9}
Goal : < 0.4x10^{-9}
Achieved!

Typical : 25x10^{-9}
Goal : < 0.02x10^{-9}
~1/3 more for goal

Physics expectation in SK-Gd

Expected signal of Supernova Relic Neutrinos



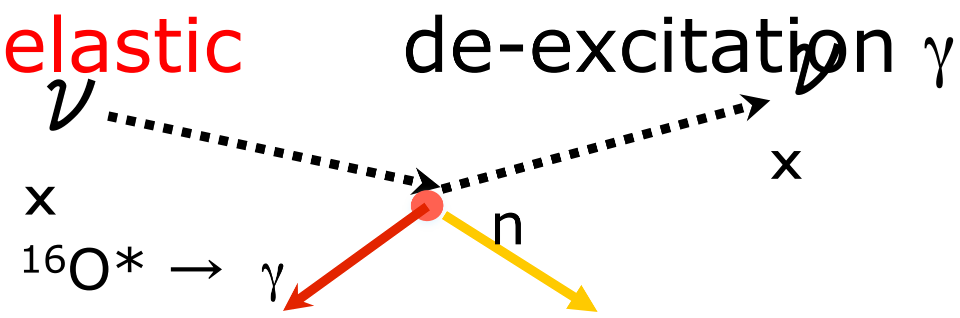
Assumption:
- 90% neutron capture efficiency
- 74% Gd γ detection efficiency
- Invisible muon B.G. is 35% of ones in the SK-IV

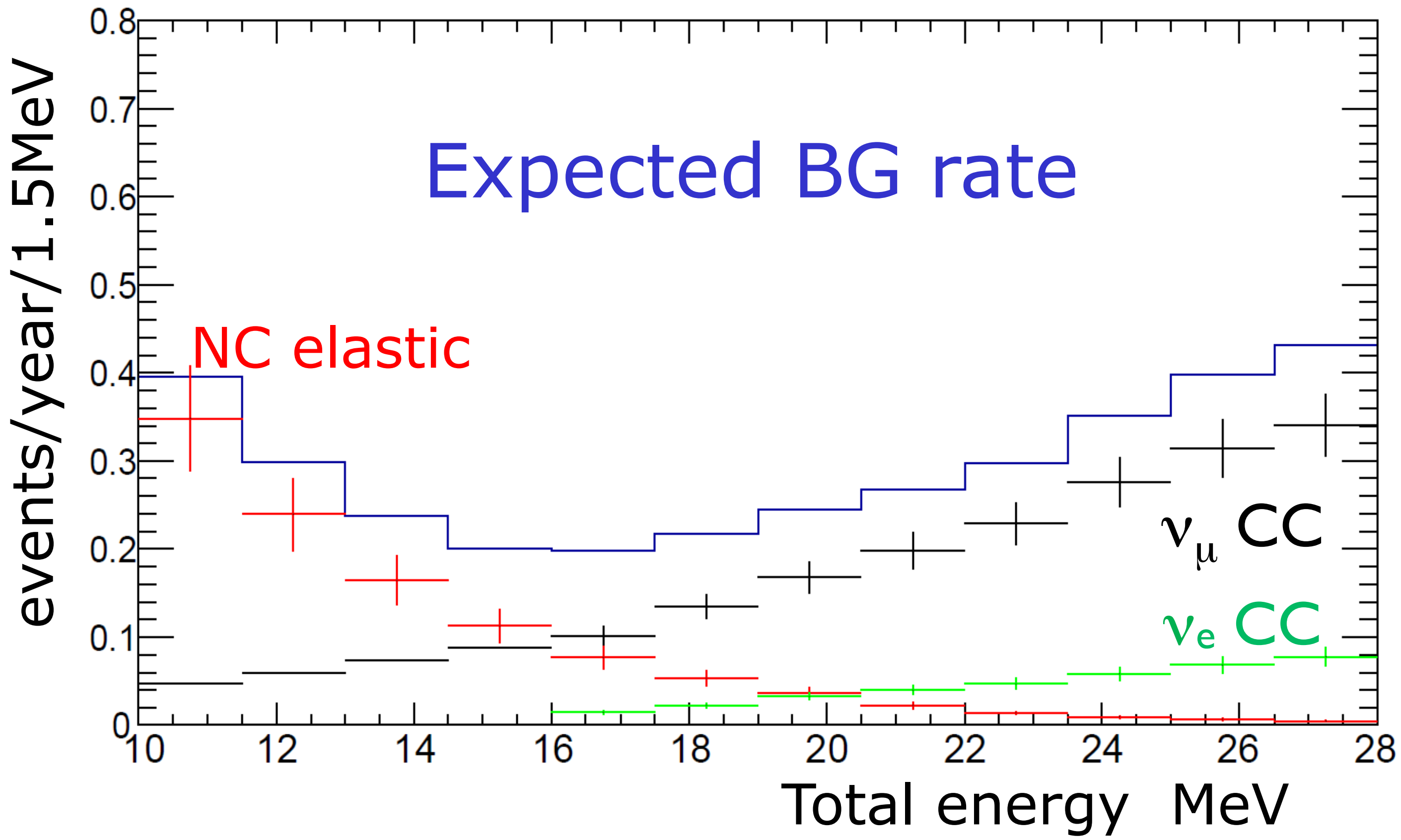
10~45 SRN events in 10 years data taking (E_{vis}=10-30MeV)

Physics expectation in SK-Gd

Background originated from atmospheric ν

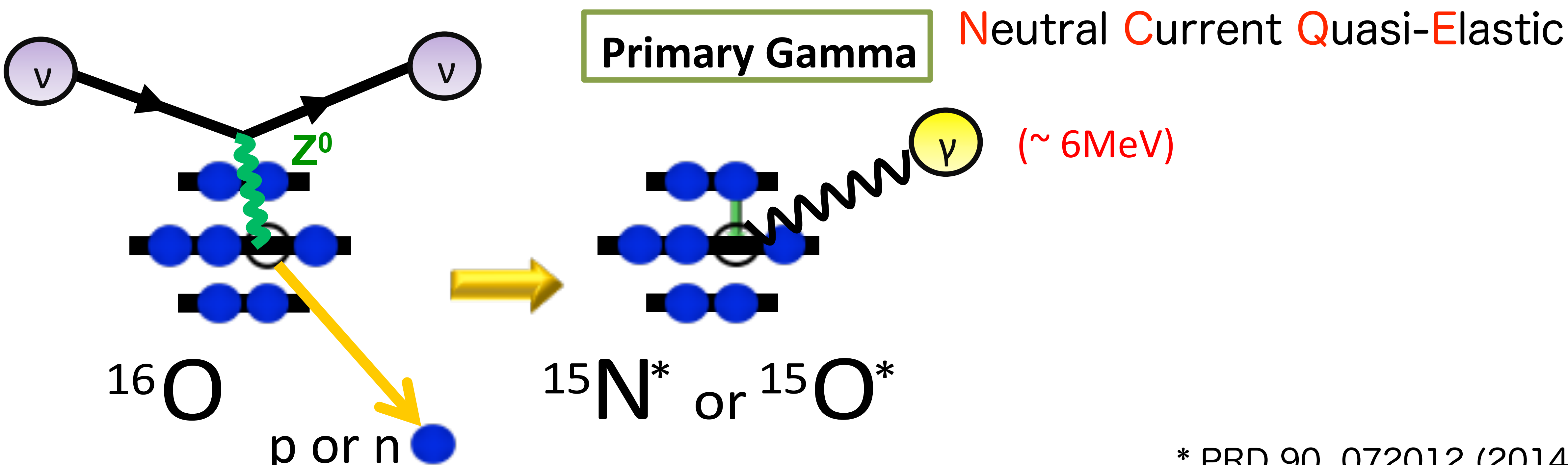
- NC





Background related

De-excitation gamma ray after NCQE interaction

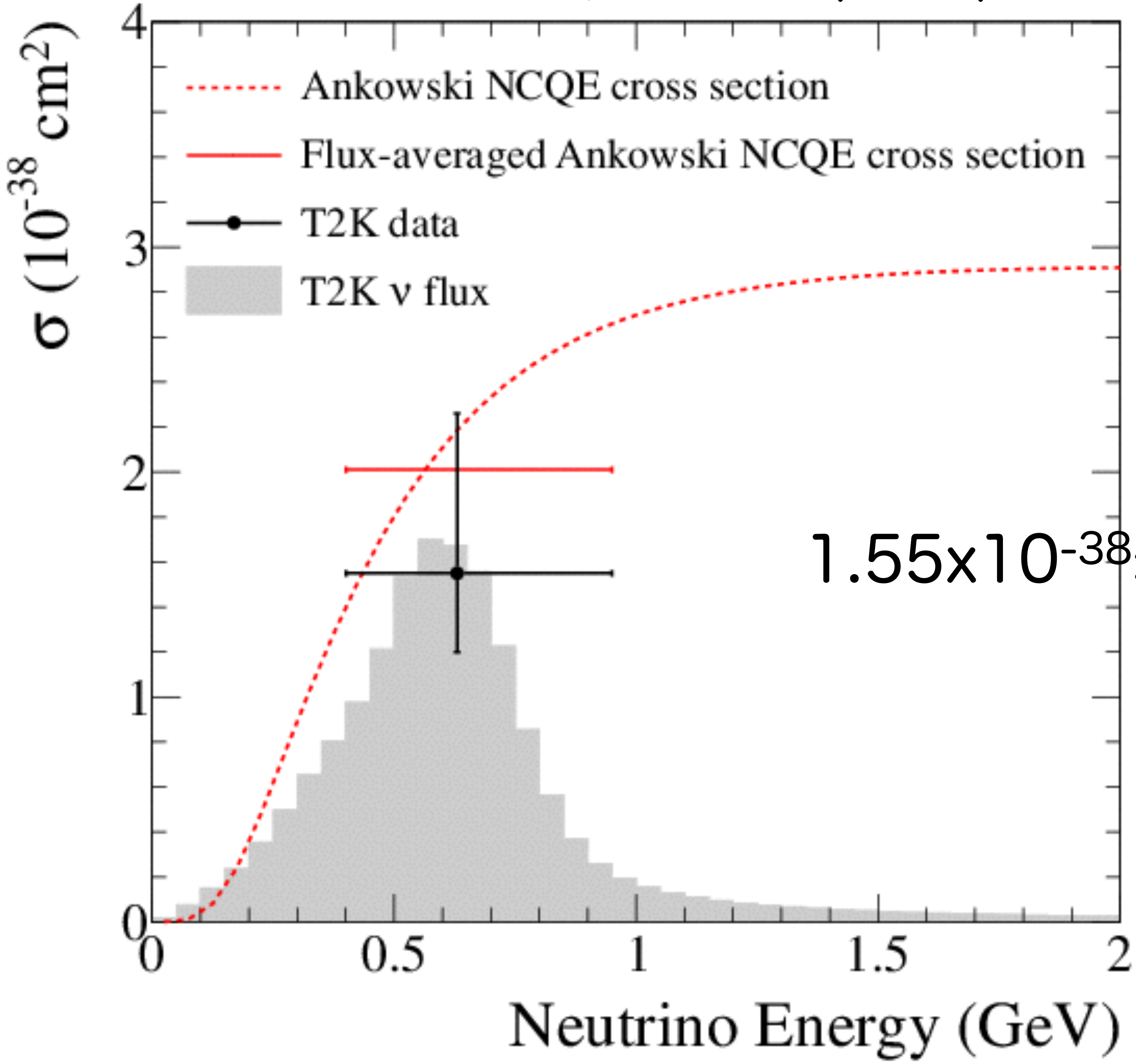


* PRD 90, 072012 (2014)

- Never had been observed yet. T2K measured it*.
- One of signal from supernova neutrinos in Super-K.
- Same interaction from atmospheric neutrinos is one of main B.G. for supernova relic neutrinos in SK-Gd.
- Search for sterile neutrinos, low-mass dark matter.

NCQE cross section in T2K

PRD 90, 072012 (2014)



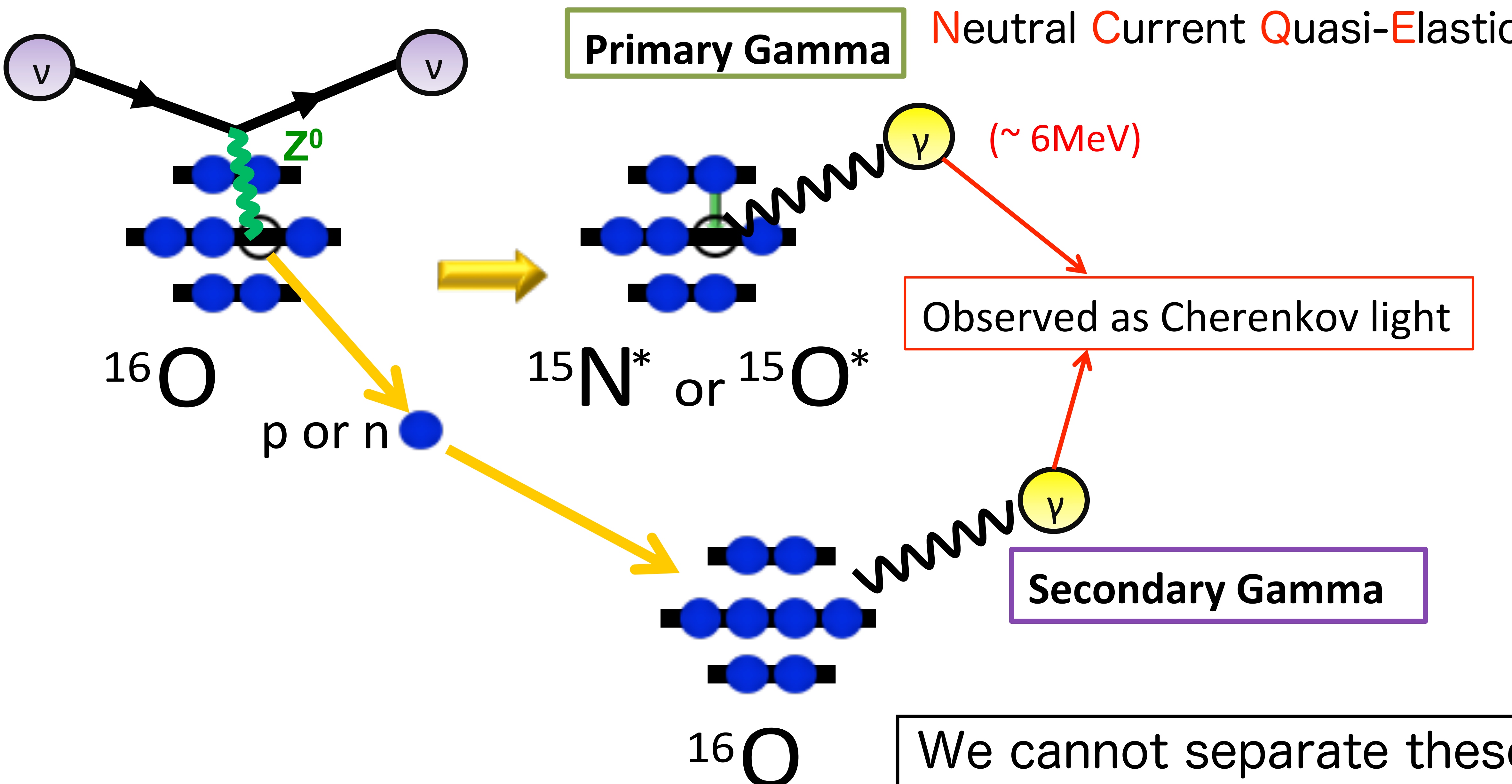
First observation by T2K

$1.55\times10^{-38}\pm0.395(\text{stat.})\,^{+0.65}_{-0.33}\,(\text{sys.})\ \text{cm}^2$

Systematic error is comparable to statistic error

NCQE cross section in T2K

De-excitation gamma ray after NCQE interaction

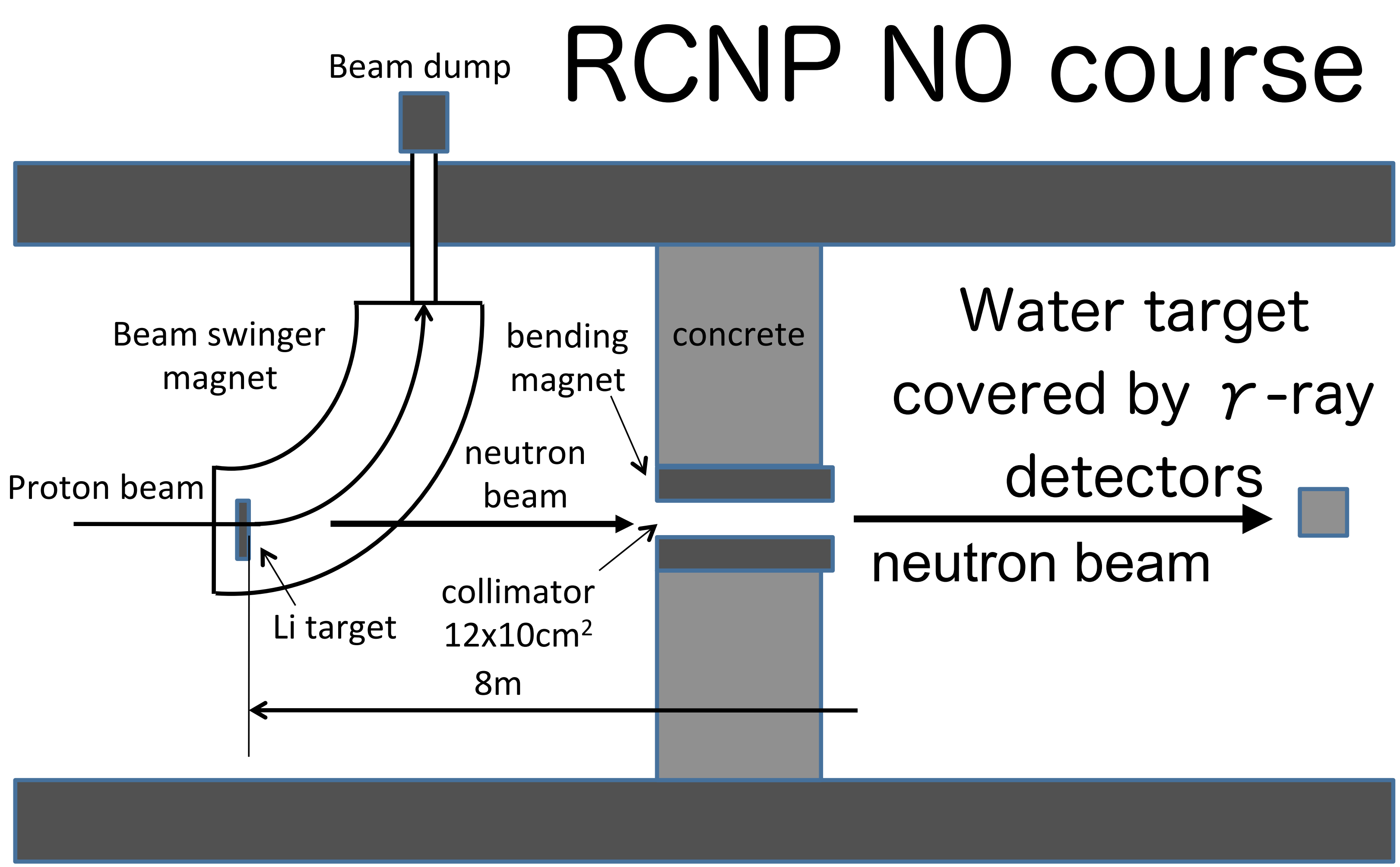


We cannot separate these two gammas by analysis

Neutron beam experiment in RCNP

Measure the **energy** and **multiplicity** of γ-rays from neutron interaction for water target

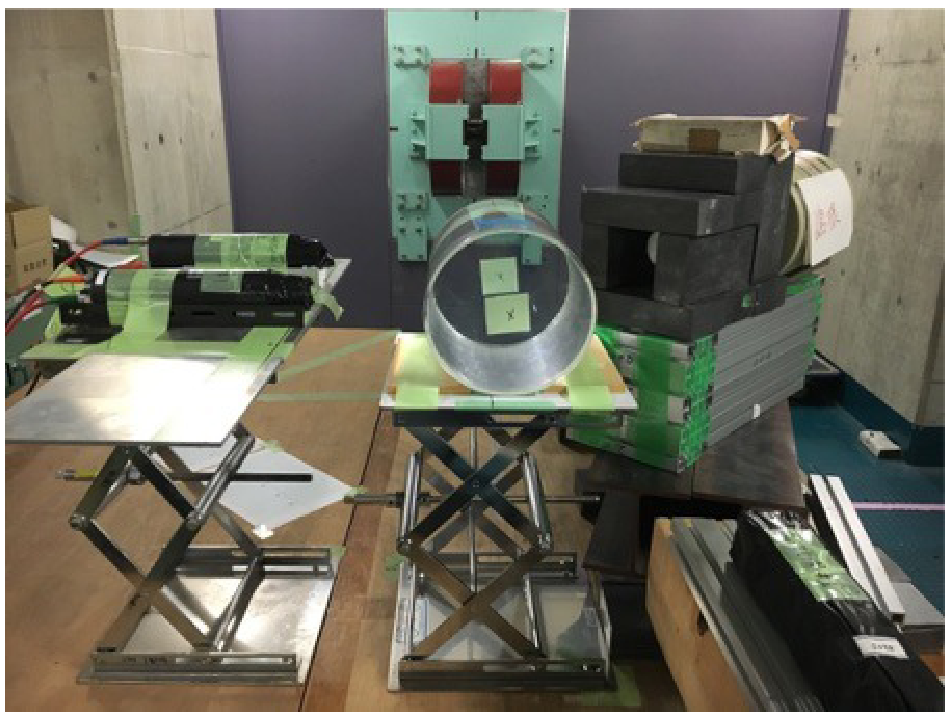
照射体系(0°　)

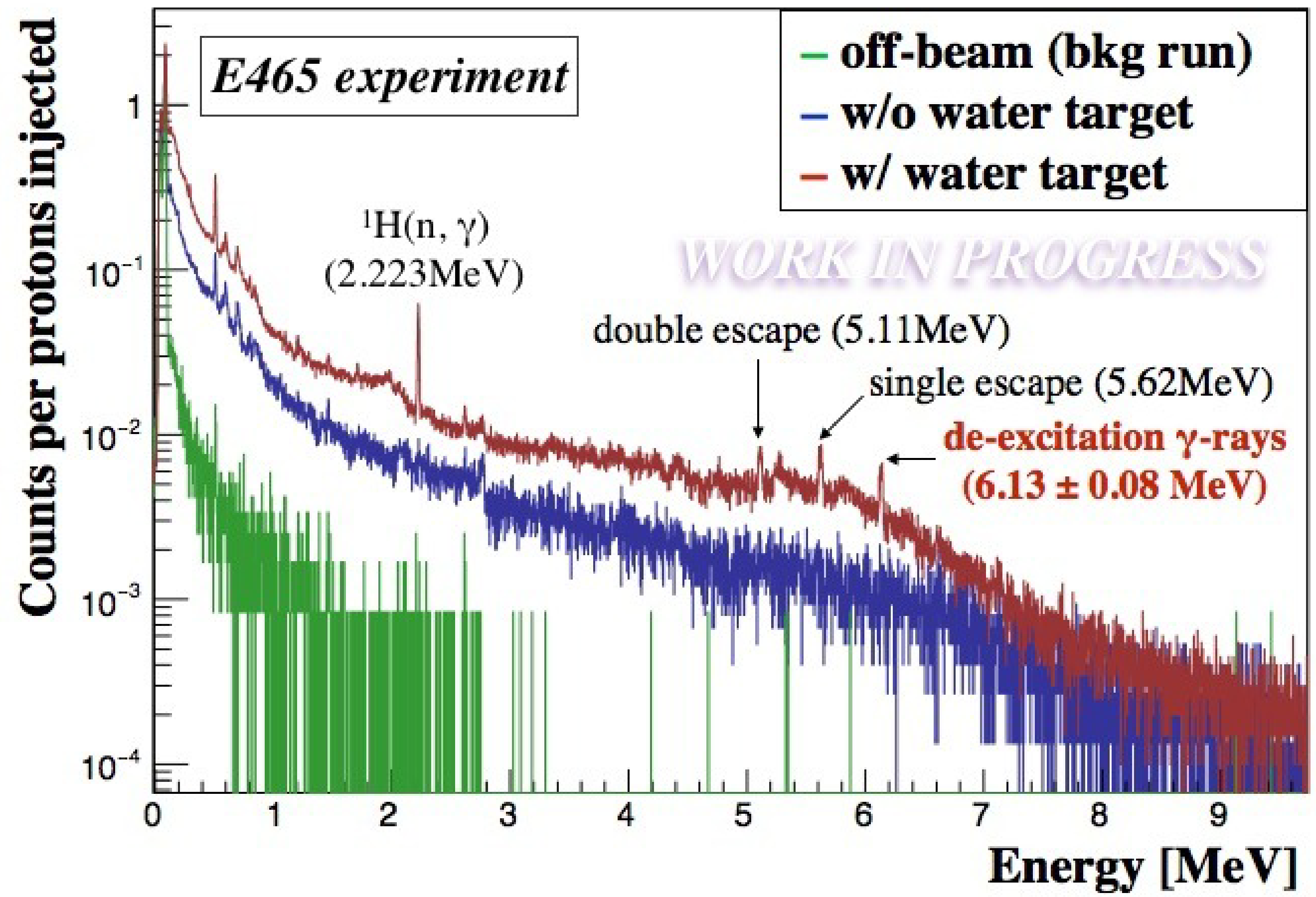


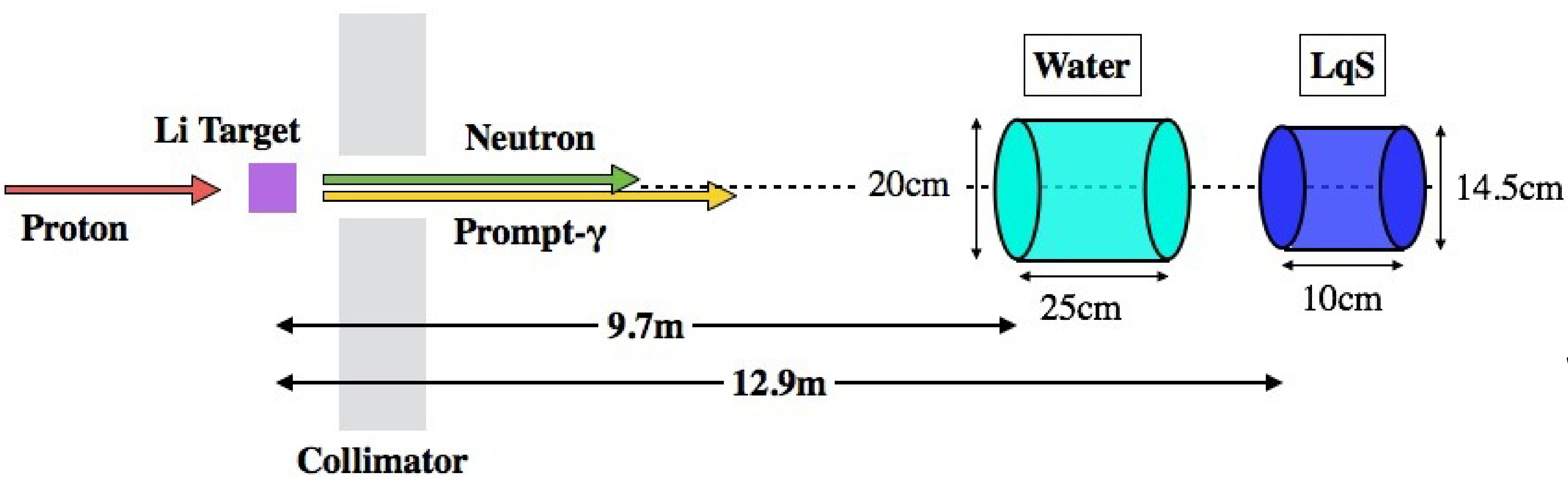
- ✓ Monochromatic and various neutron energies are available. It agrees with the neutron energy in T2K experiment.
- ✓ Good BG separation using ToF information.
- ✓ Big tunnel, facilitate the detector setting.

Neutron beam experiment in RCNP

Pilot experiments were successful





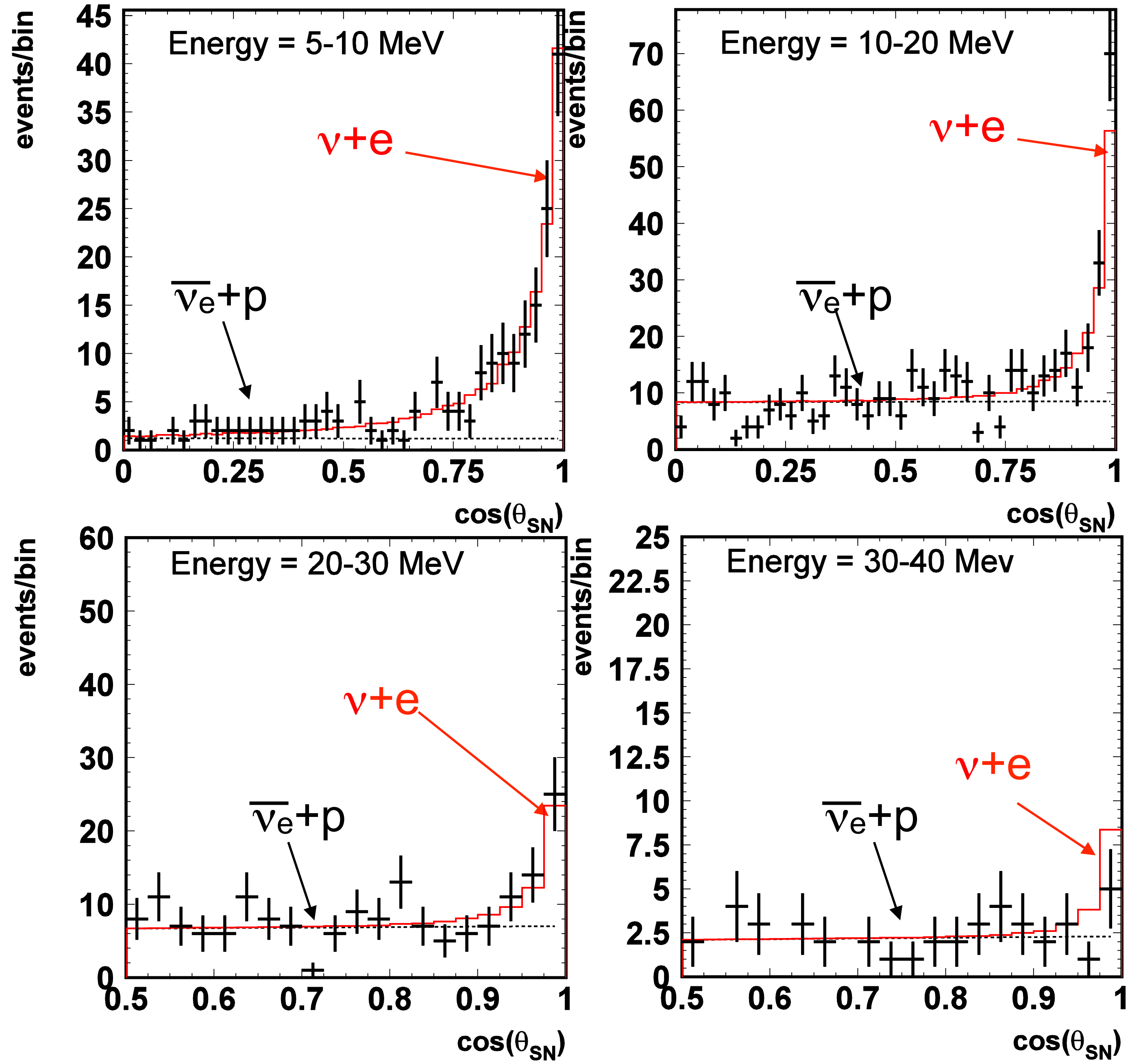


Stay tune!

Physics expectation in SK-Gd

For Supernova burst neutrinos

- ✓ ν-e elastic scattering has good directionality.
- ✓ Direction of supernova can be determined with an accuracy of 4~5 degree.
- ✓ Spectrum of ν_e events can be statistically extracted using the direction to supernova.
- ✓ If Gd loaded, it will be more accurate since ν_e signal can be separated.
- ✓ Sensitive to Si burning, 800~2000 ev/day at 200pc



Physics expectation in SK-Gd

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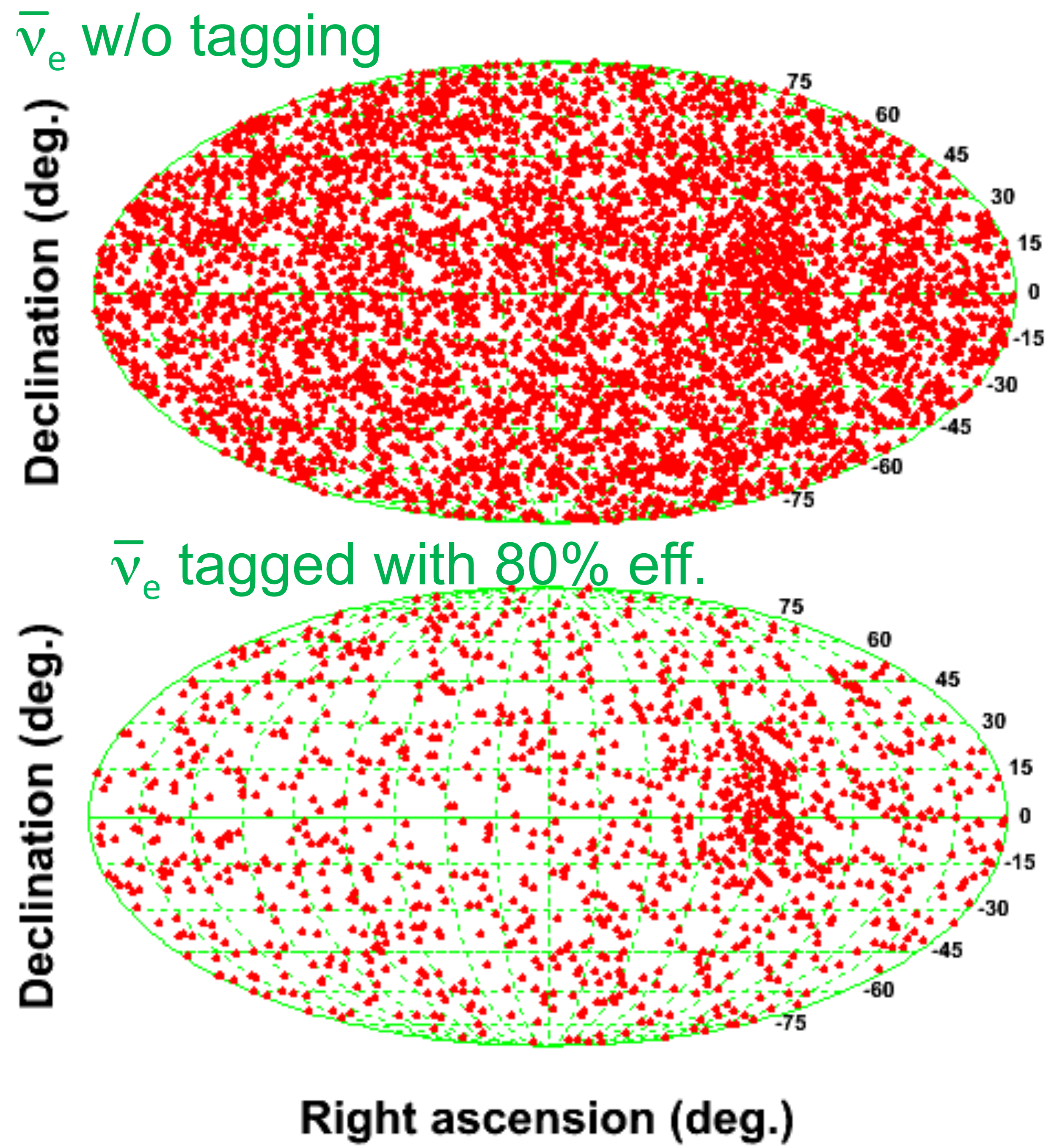
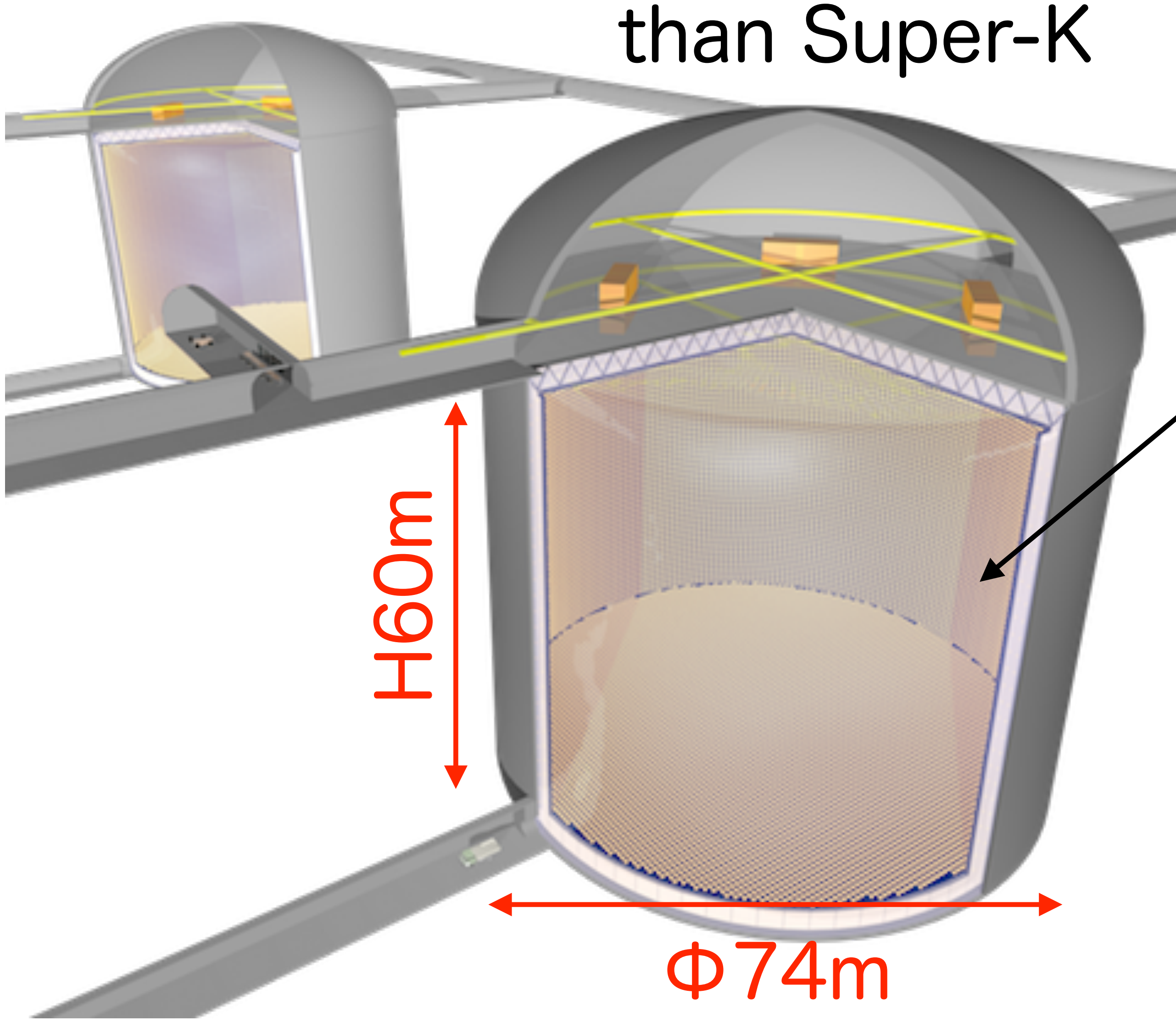


In future

Hyper-Kamiokande

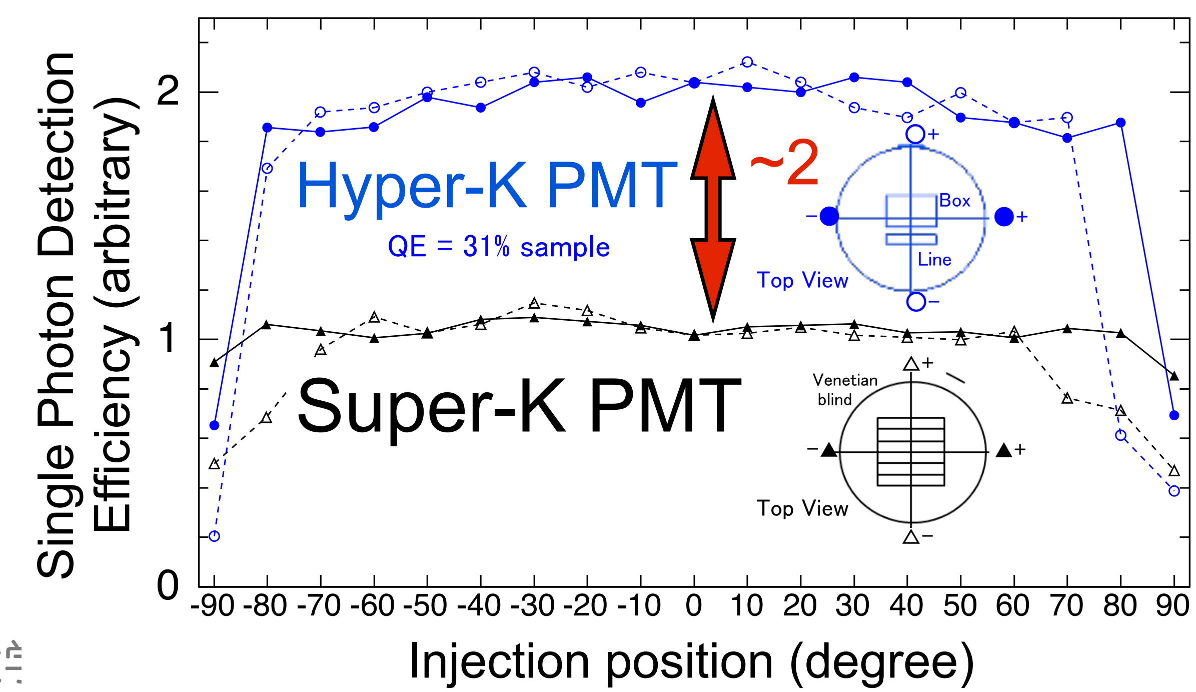
2 tanks x
with staging

~10 times larger volume
than Super-K



~40000 PMT / tank

New photo-censer which has
twice sensitivity than Super-K



Supernova at Hyper-Kamiokande

http://www-sk.icrr.u-tokyo.ac.jp/indico/conferenceDisplay.py?confId=2935

www-sk.icrr.u-tokyo.ac.jp/indico/conferenceDisplay.py?confId=2935

More | Asia/Tokyo | English | Logged in as users, S. | Logout

Workshop on Supernova at Hyper-Kamiokande

12-13 February 2017 *Koshiba hall, University of Tokyo*
Asia/Tokyo timezone

- **Overview**
- Scientific Programme
- Timetable
- Registration
  - Registration Form
- Invited speakers

Support

30 years from SN1987A and the future

Hyper-Kamiokande represents the next generation of large water Cherenkov detectors. It is to be a multi-purpose detector, whose capabilities shall include the precision study of neutrino oscillations; proton decay searches; and the observation of astro-particle neutrinos, such as supernova neutrinos, solar neutrinos, and high energy astro neutrinos. Due to Hyper-Kamiokande's unprecedented reach in all of these areas, it will provide a wealth of possibilities for new discoveries and deepen our understanding of nature.

In this workshop, we will discuss the supernova neutrino research that will be conducted by Hyper-Kamiokande and several other near-future detectors, as well as Hyper-Kamiokande's potential for studying the other types of astro-particle neutrinos.

Since February 2017 marks the 30th anniversary of SN1987A, we are also planning several memorial lectures commemorating the historic supernova neutrino observations made in 1987.

We are looking forward to seeing you at the workshop.

Thank you very much,
LOC of the workshop (Y.Koshio, I.Shimizu, Y.Suwa, Y.Takeuchi, M.Yokoyama)

Dates: from 12 February 2017 08:00 to 13 February 2017 11:00

Summary

Let's go supernova!

Thanks