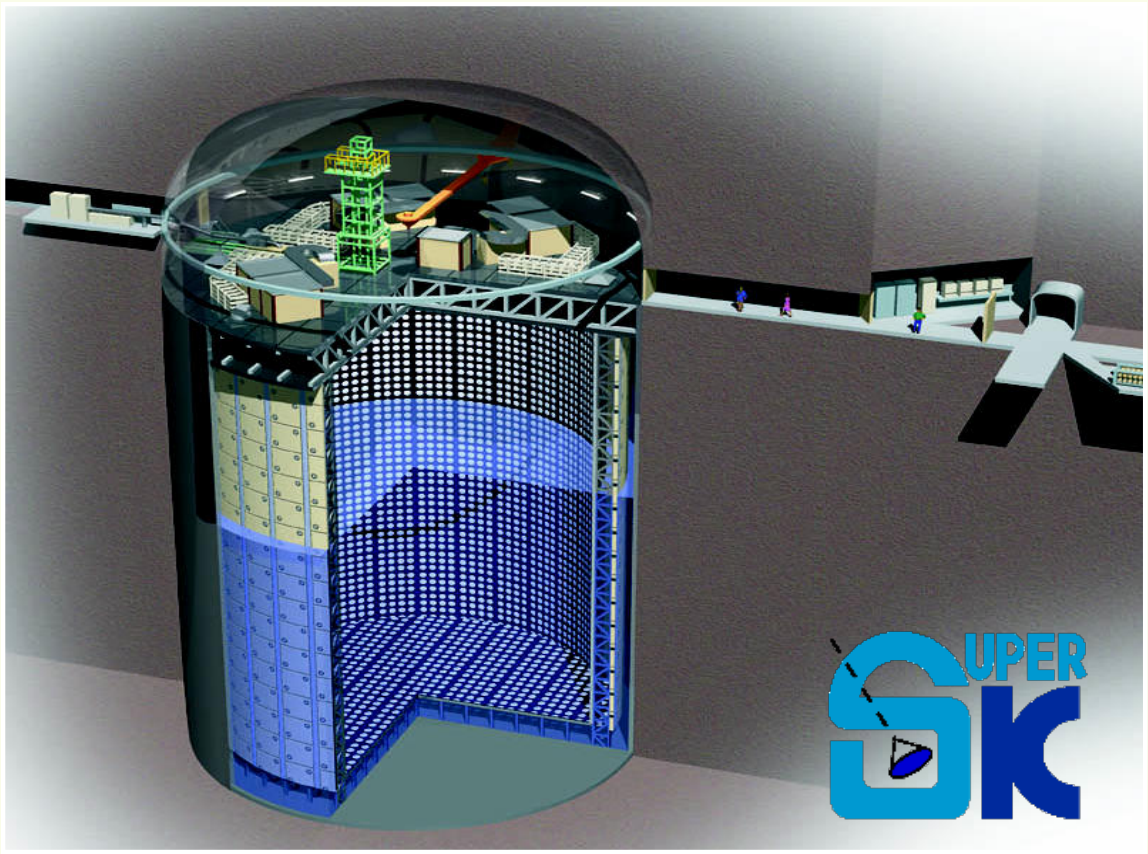
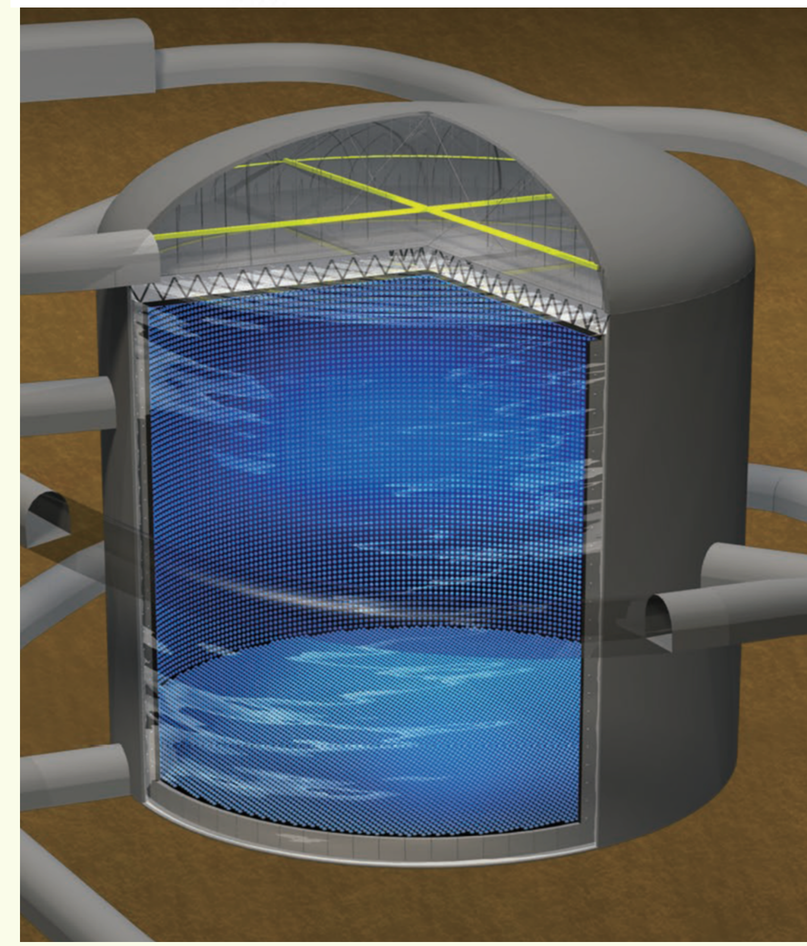
Neutrino physics in
Super-Kamiokande and Hyper-Kamiokande





Yusuke Koshio

Okayama University

5th Summer School on INtelligent signal processing for FrontIEr Research and Industry

16 May, 2019

Where is Okayama?

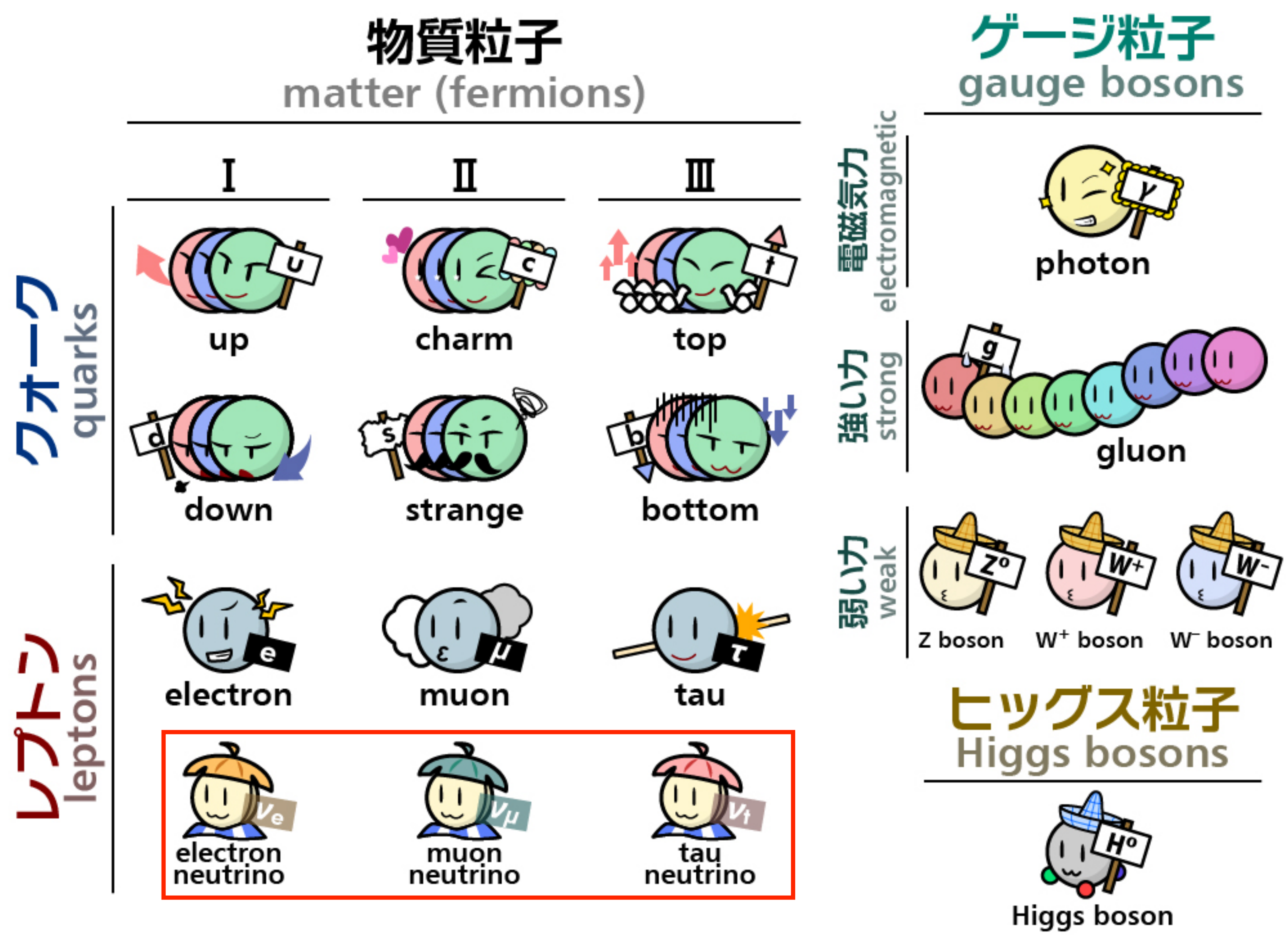
Okayama

Kamioka

Brief introduction of Neutrino physics

What's neutrino?

Elementary particles in the standard model
(http://higgstan.com)



Neutrinos:
- 3 flavors
- No electric charge
- Very small cross section with matter

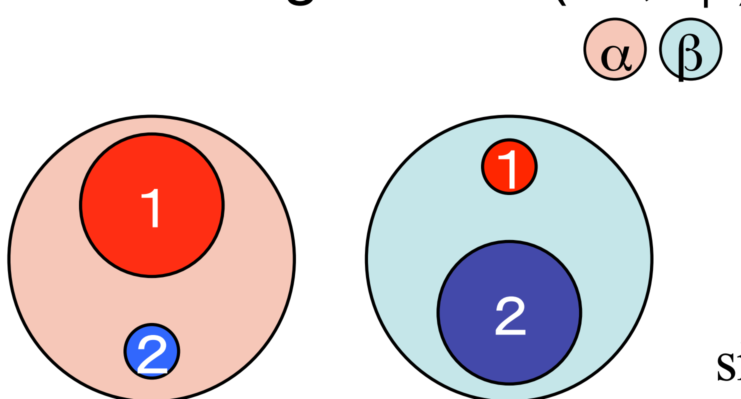
Purpose of the research:
- Reveal the mystery of its characteristics
- Research for astronomy and the earth, etc.

Neutrino oscillation

- ✓ Assume that neutrinos have different masses - Δm^2
- ✓ Assume that the mass eigenstate and flavor eigenstate is mixed - θ

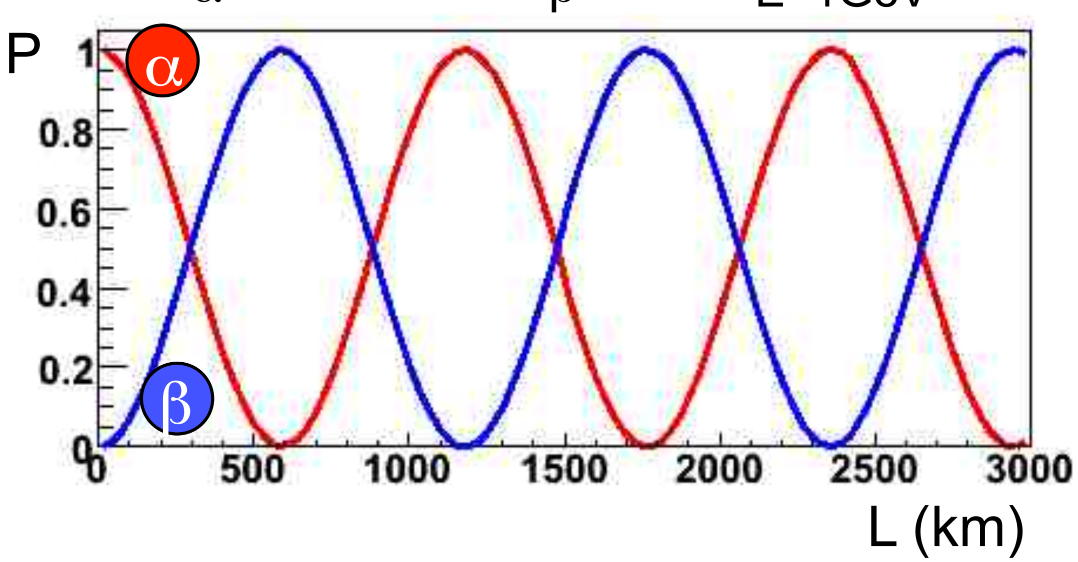
In the case of two neutrinos

A flavor eigenstate (ν_α , ν_β) is a mixture of mass eigenstate (ν_1 , ν_2)



ν_α ν_β

$\sin^2 2\theta = 1$
$\Delta m^2 = 2.1\times10^{-3}$
E=1GeV



How much of a mixture can be written as mixing angle θ in the following equation:

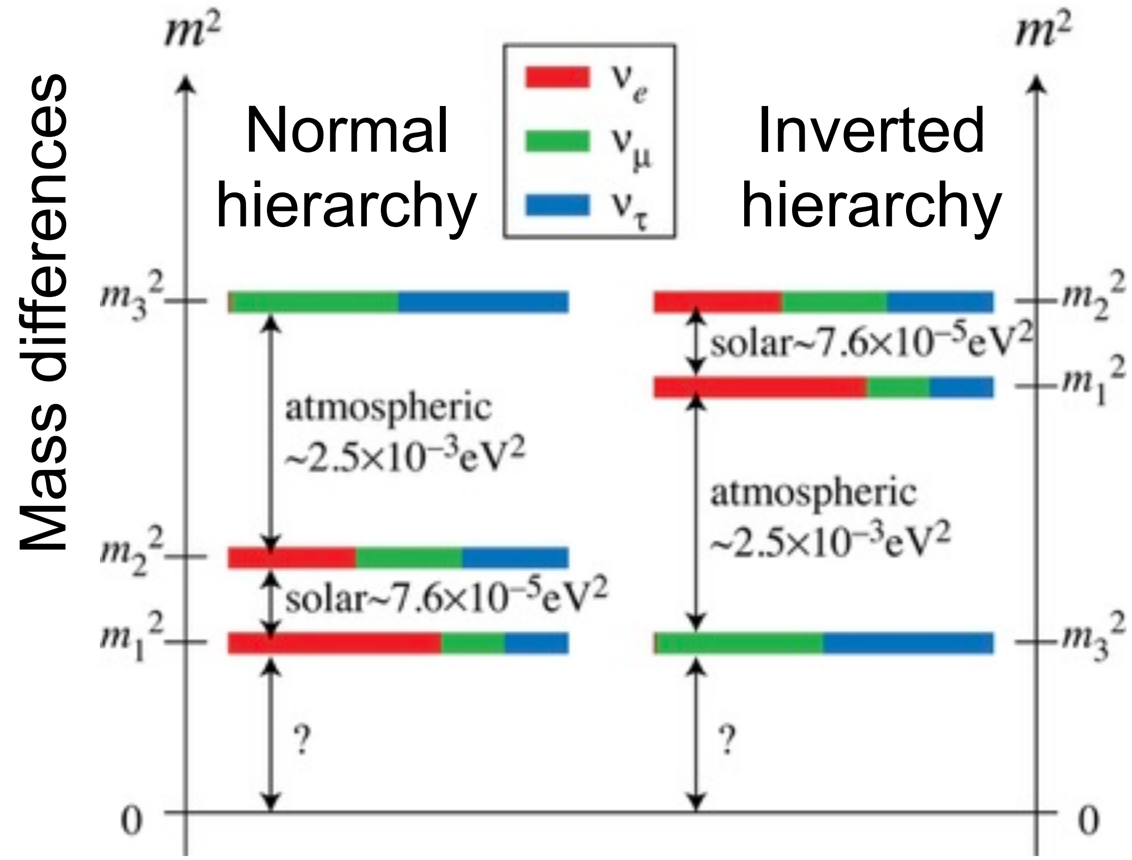
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

Neutrino oscillation

Three neutrinos scheme



Mixing matrix (Maki-Nakagawa-Sakata)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = V_{MNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$V_{MNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Atm. and Acc.	Reactor and Acc.	Solar and Reactor
$\theta_{23} \sim 45 \pm 5^\circ$	$\theta_{13} \sim 9^\circ$	$\theta_{12} \sim 34 \pm 3^\circ$
$\lvert\Delta m^2_{32}\rvert = 2.4 \times 10^{-3}\mathrm{eV}^2$		$\Delta m^2_{21} = +7.6 \times 10^{-5}\mathrm{eV}^2$

δ cp and Mass hierarchy of 2-3 are unknown

Atmospheric, Accelerator, Reactor

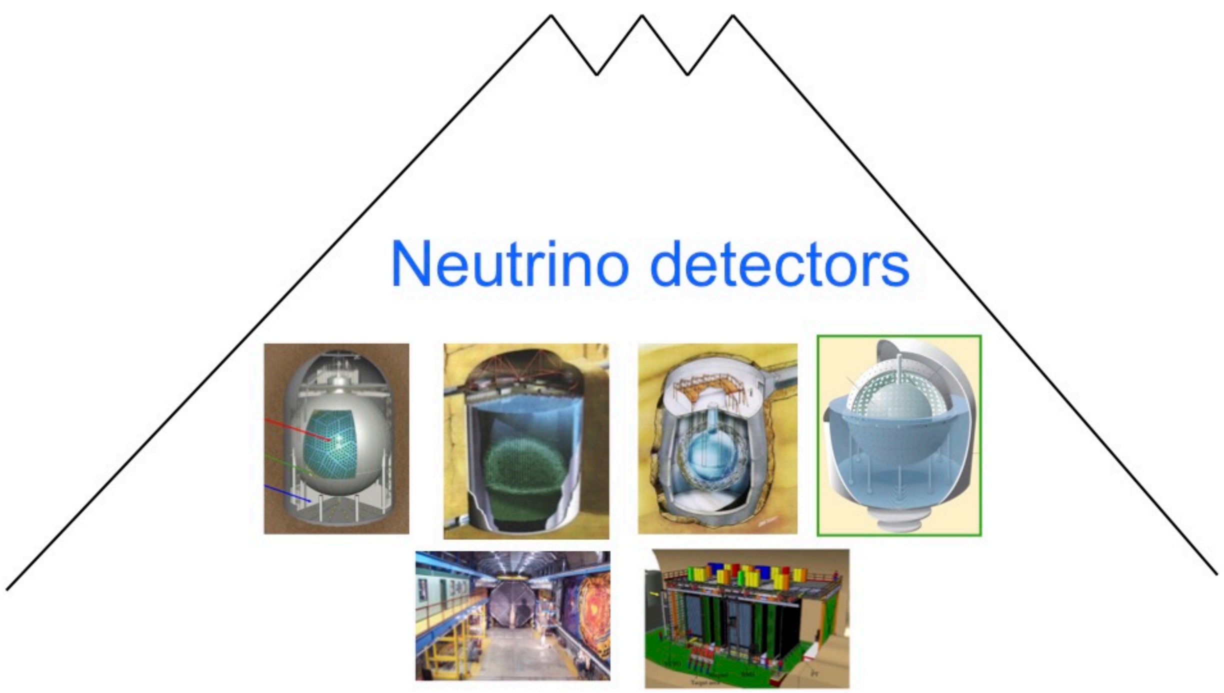
Neutrino experiment

Large size of detector is required, because the neutrino interaction with matter is very small cross section

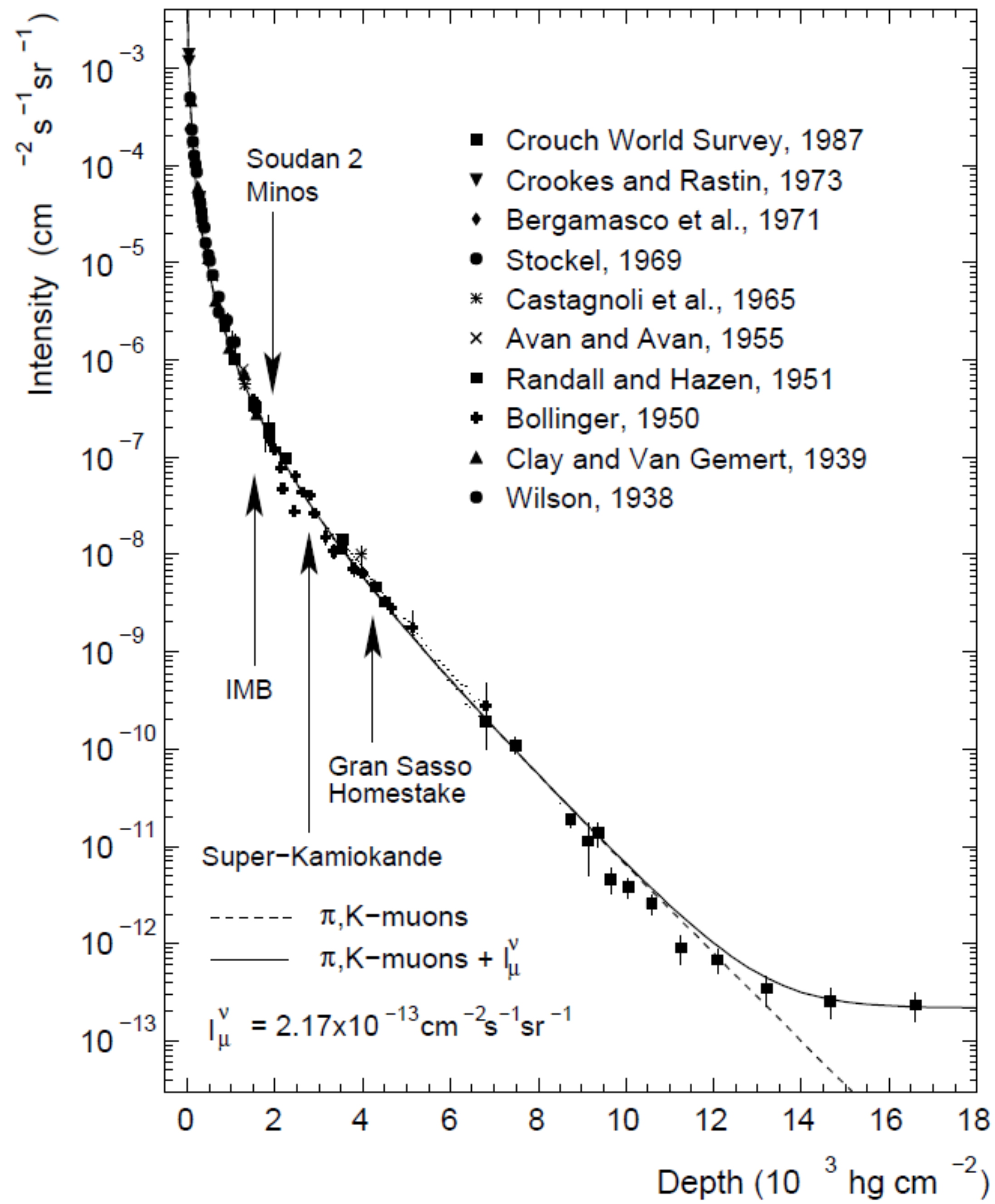
$$\sigma = \frac{G_F^2 s}{\pi}$$

$\sim (E_\nu[\mathrm{GeV}]) \times 10^{-41} \mathrm{cm}^2$

quite small cross section,
e.g. a neutrino with 10MeV interacts after transverse 3×10^{21} cm in the water.
(ref. 1 light year ~ 9.5×10^{17} cm)

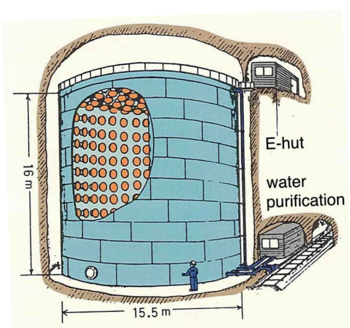


Deep underground in order to remove cosmic ray.

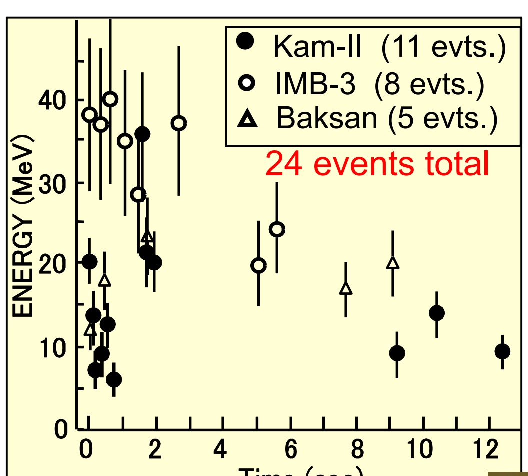


Three generations of “Kamiokande”

Kamiokande (1983-1995)

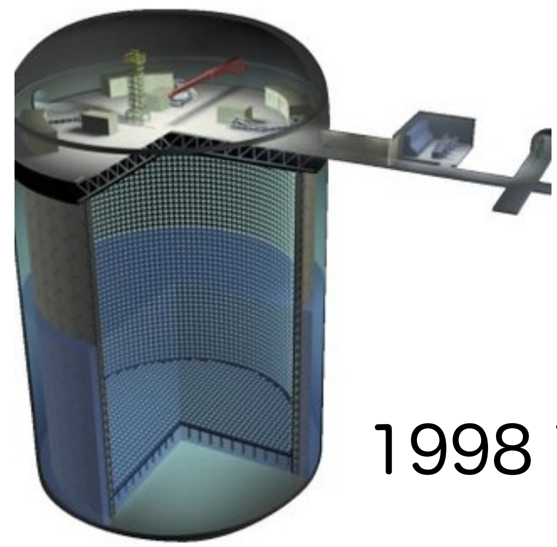


3kton
20% coverage
with 20’ PMT



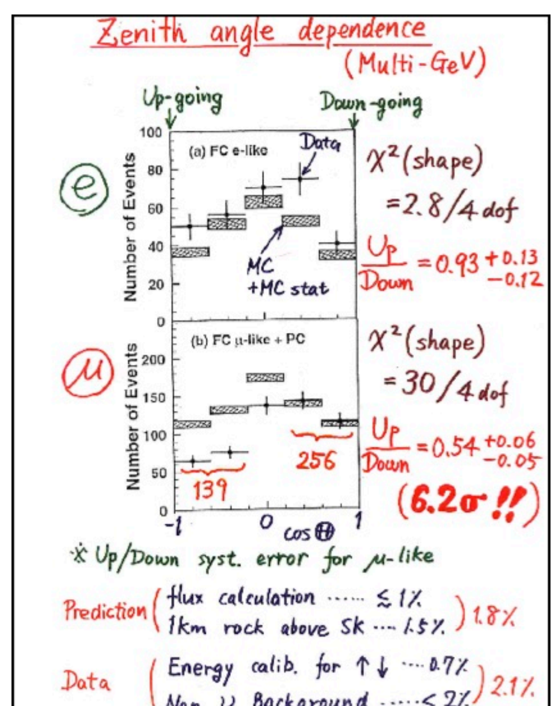
SN1987A

Super-Kamiokande (1996-)

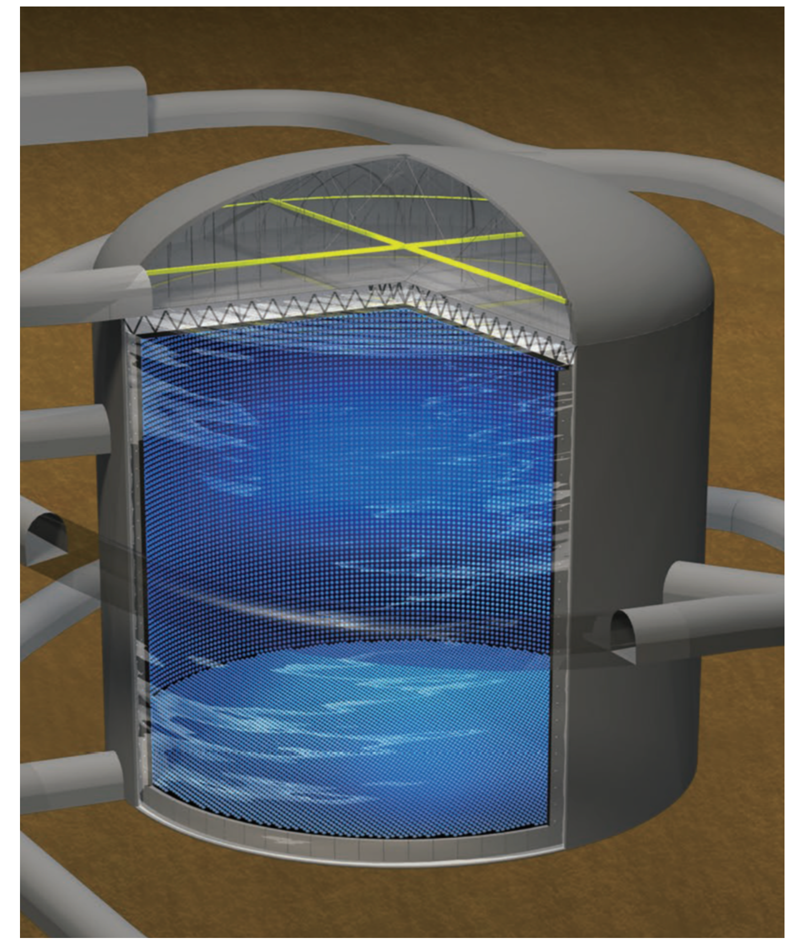


50k (22.5k) ton
40% coverage
with 20’ PMT

1998 Takayama



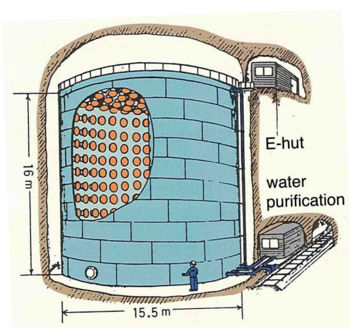
Hyper-Kamiokande (~2027-)



260k (190k) ton
40% coverage
with high-QE 20’ PMT

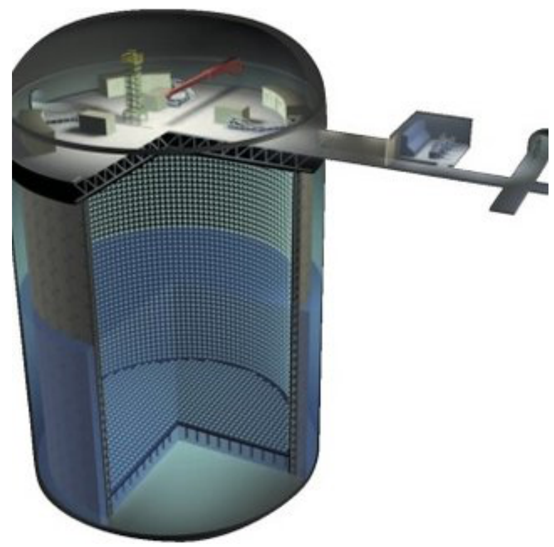
Three generations of "Kamiokande"

Kamiokande
(1983-1995)



3kton
20% coverage
with 20' PMT

Super-Kamiokande
(1996-)



50k (22.5k) ton
40% coverage
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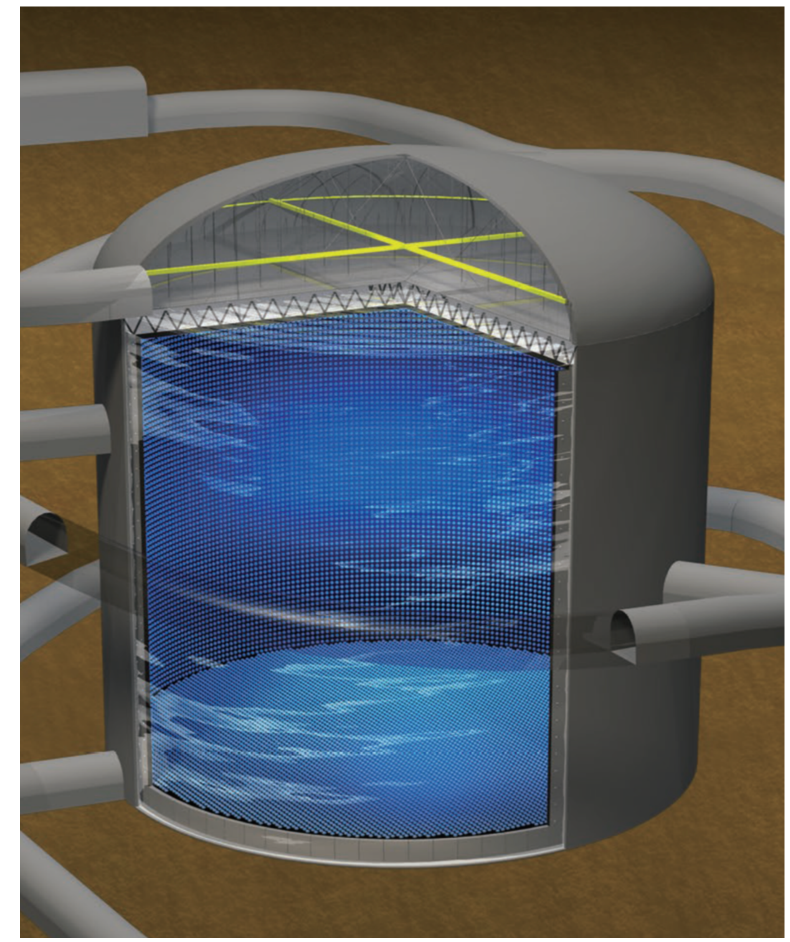
Hyper-Kamiokande (~2027-)

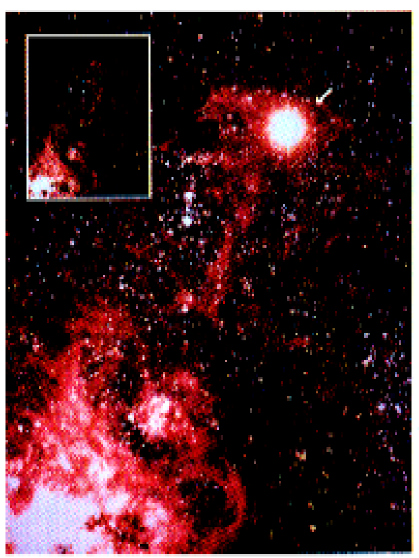


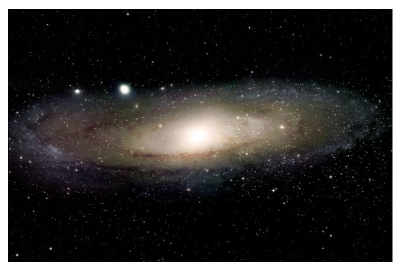
260k (190k) ton
40% coverage
with high-QE 20' PMT

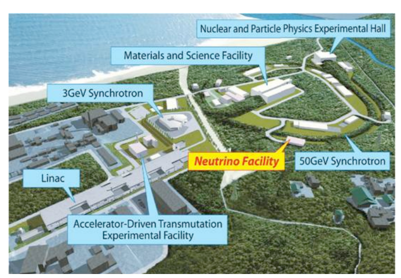
SuperK-Gd
(2019-)

Multi-purpose detector

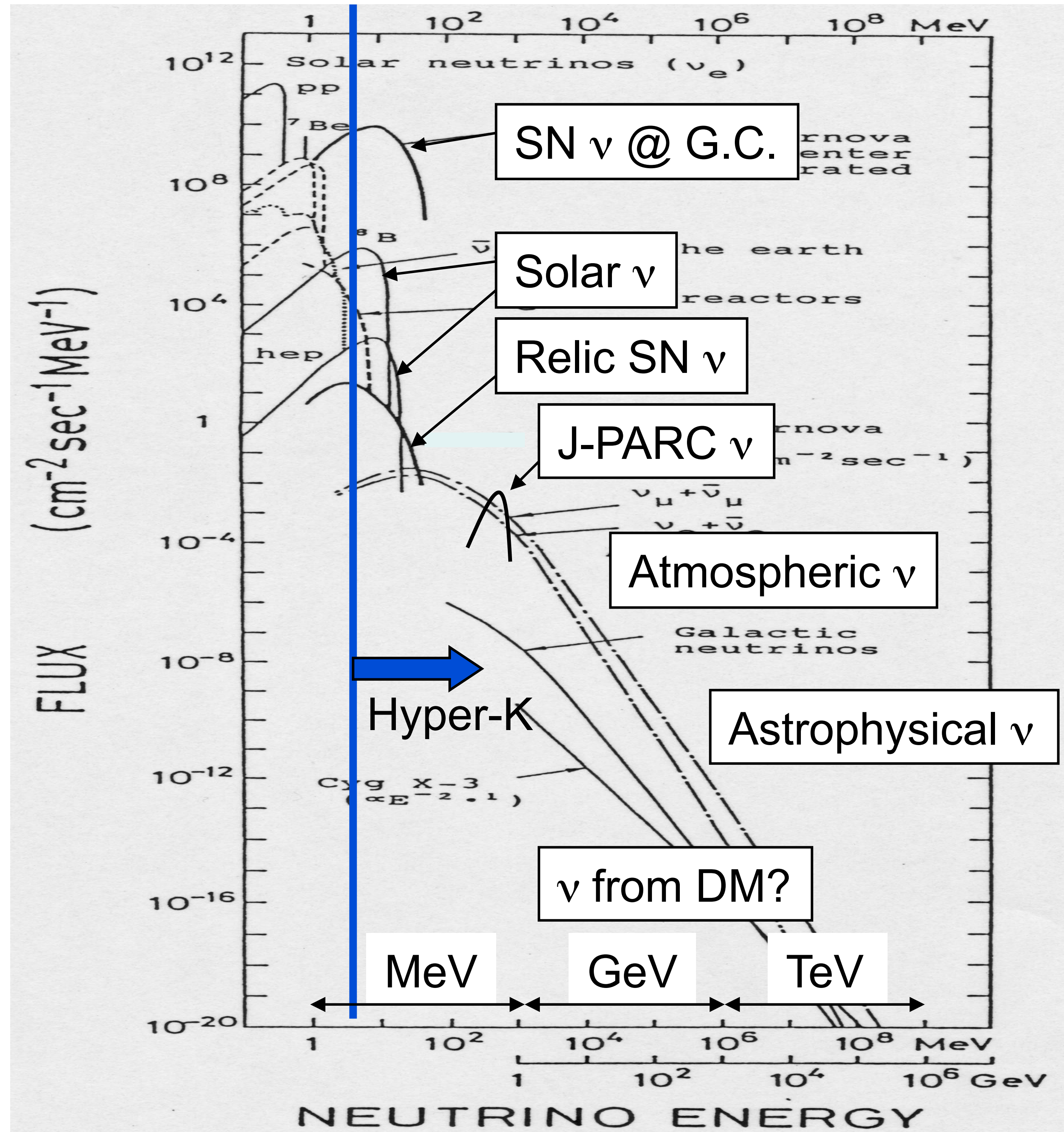
Broad scientific program
with wide energy range
(MeV~TeV)







Not only neutrinos
- Proton decay
- Dark matter search
- etc.



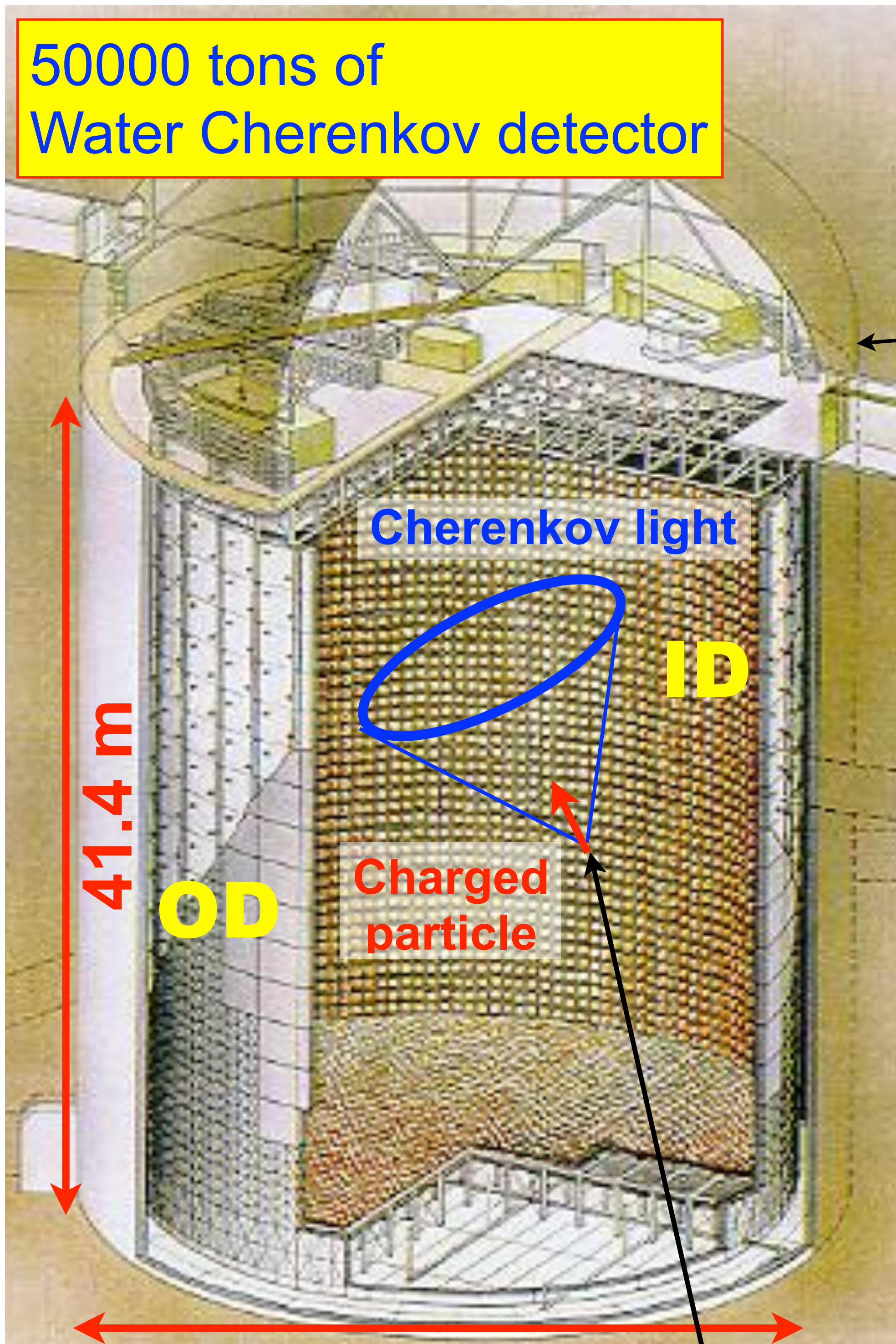
Super-Kamiokande

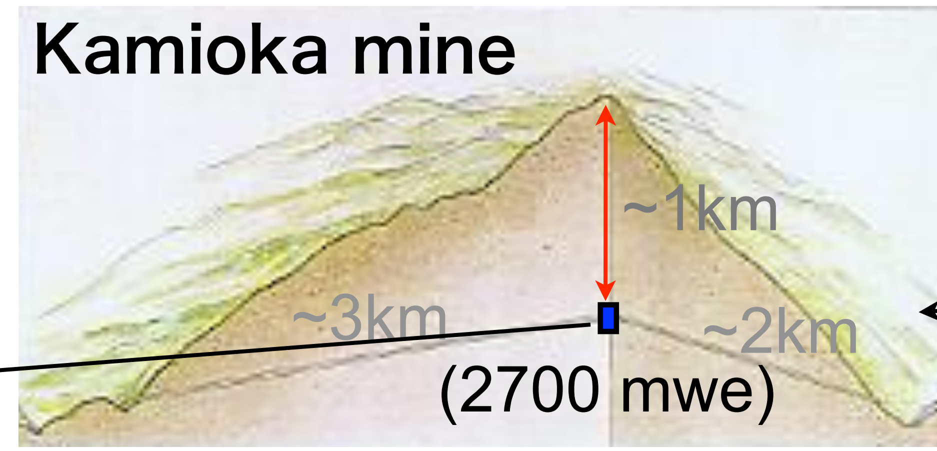
Super-Kamiokande collaboration

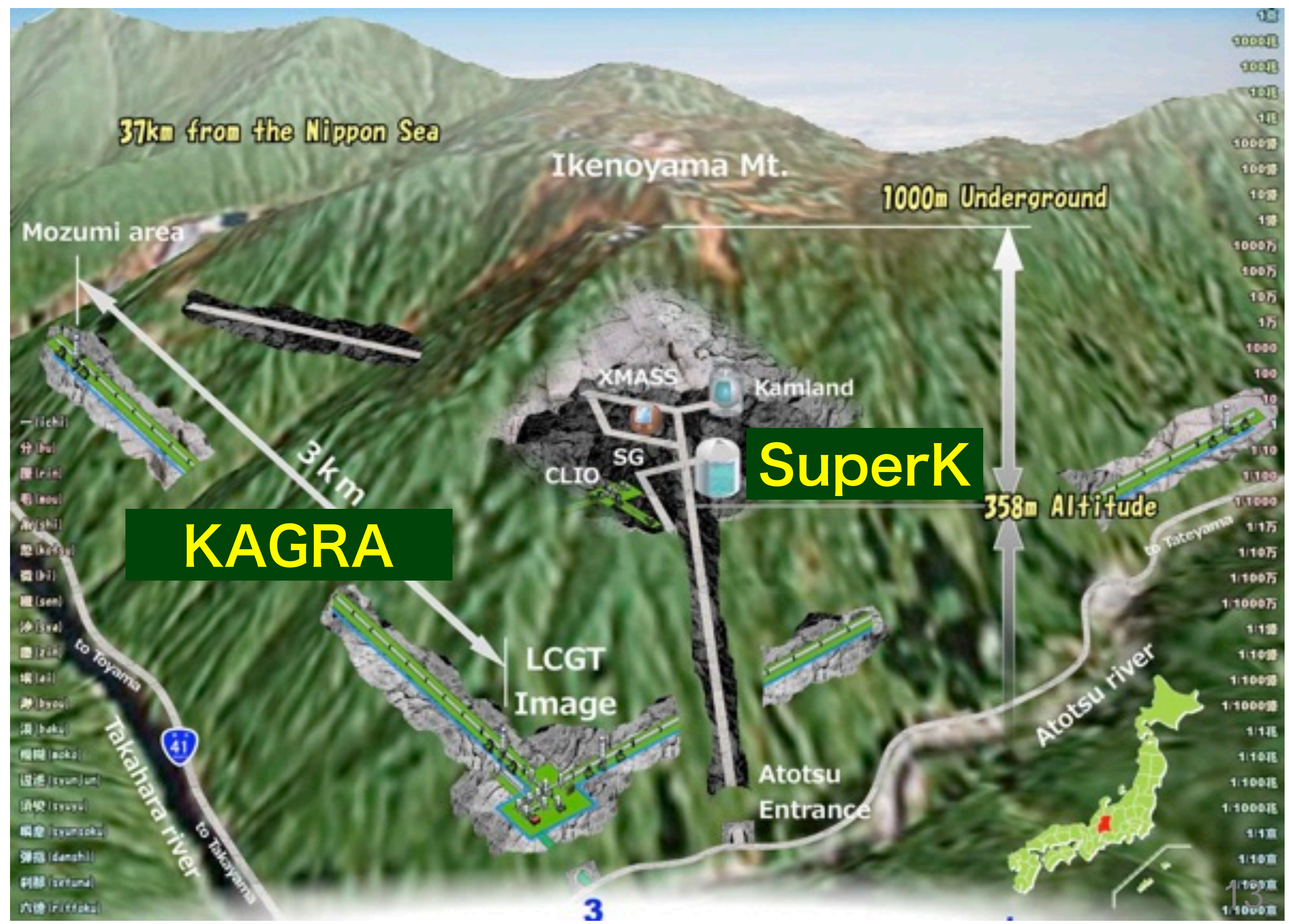
Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
NFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

178 collaborators
from 45 institutes
10 countries

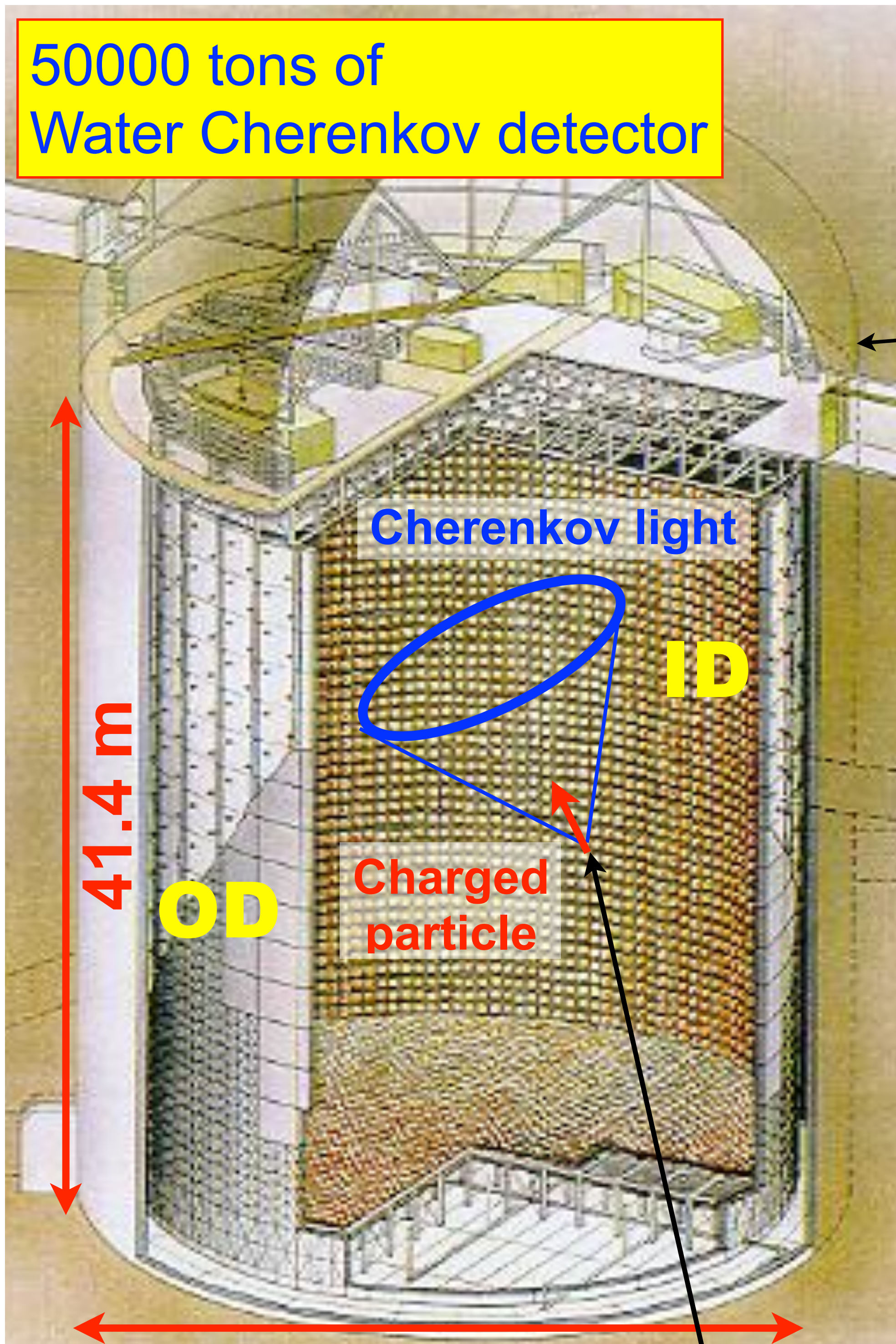
Super-Kamiokande

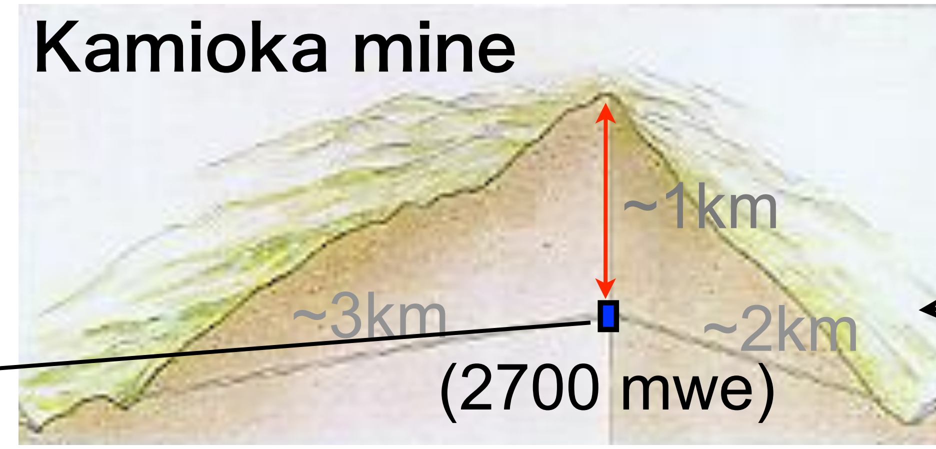






Super-Kamiokande



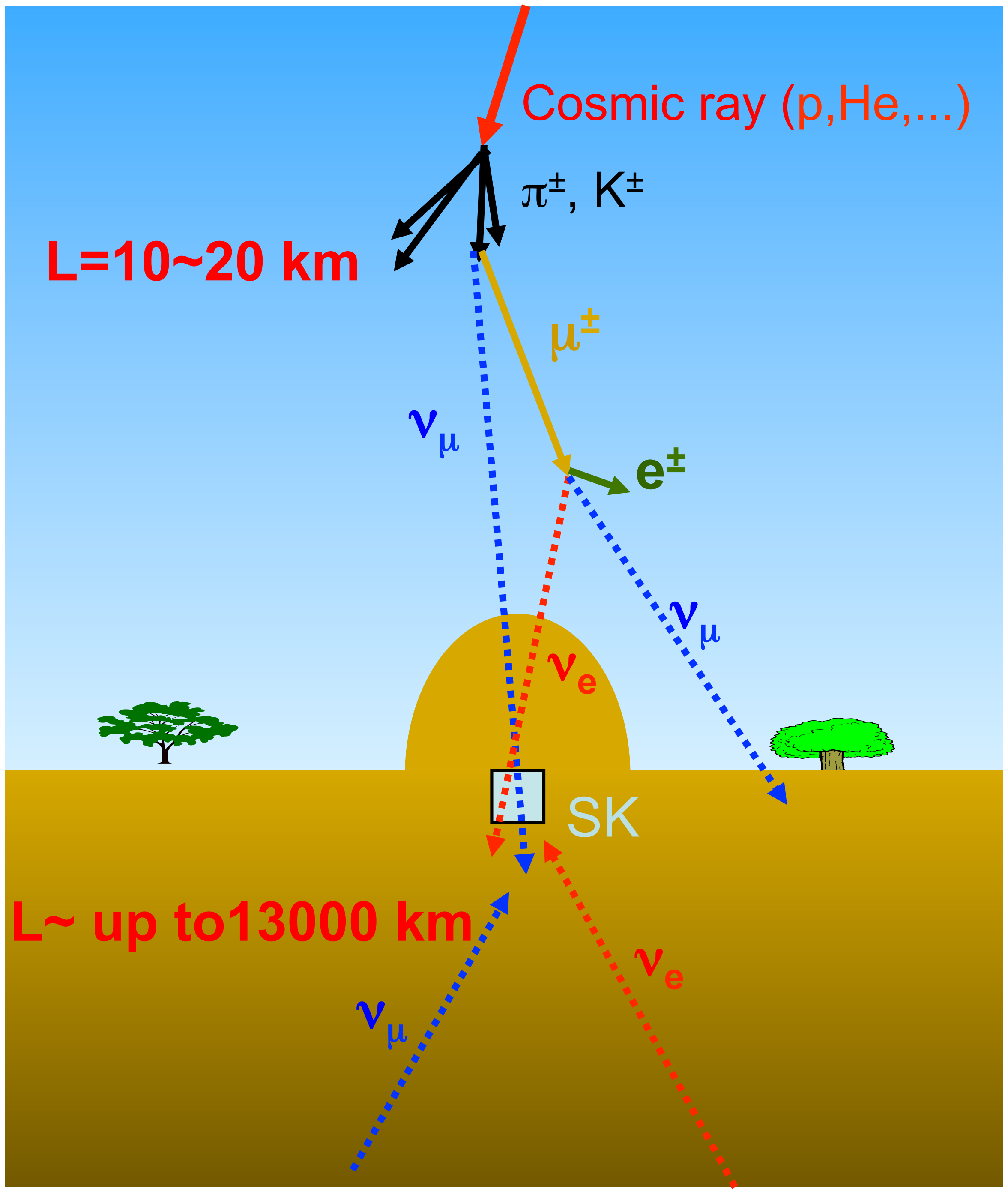


Phase	Period	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~ 2018.5	22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.9 (<4.5MeV)		3.5
SK-V	2019.1 ~	**just started!**		
			(coverage)	(Kin. energy)

Running and improvements over 20 years

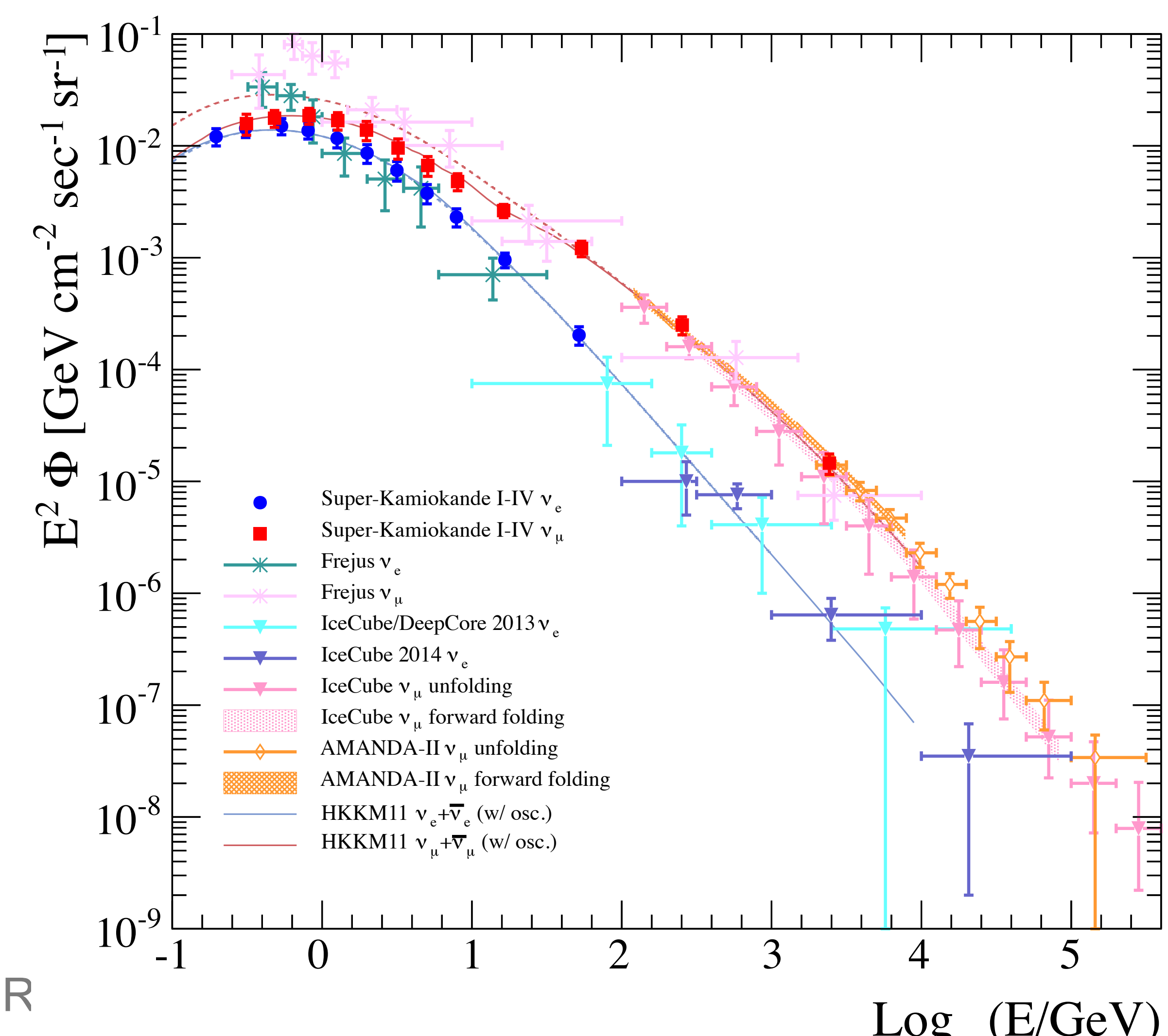
Atmospheric neutrino

Atmospheric neutrino

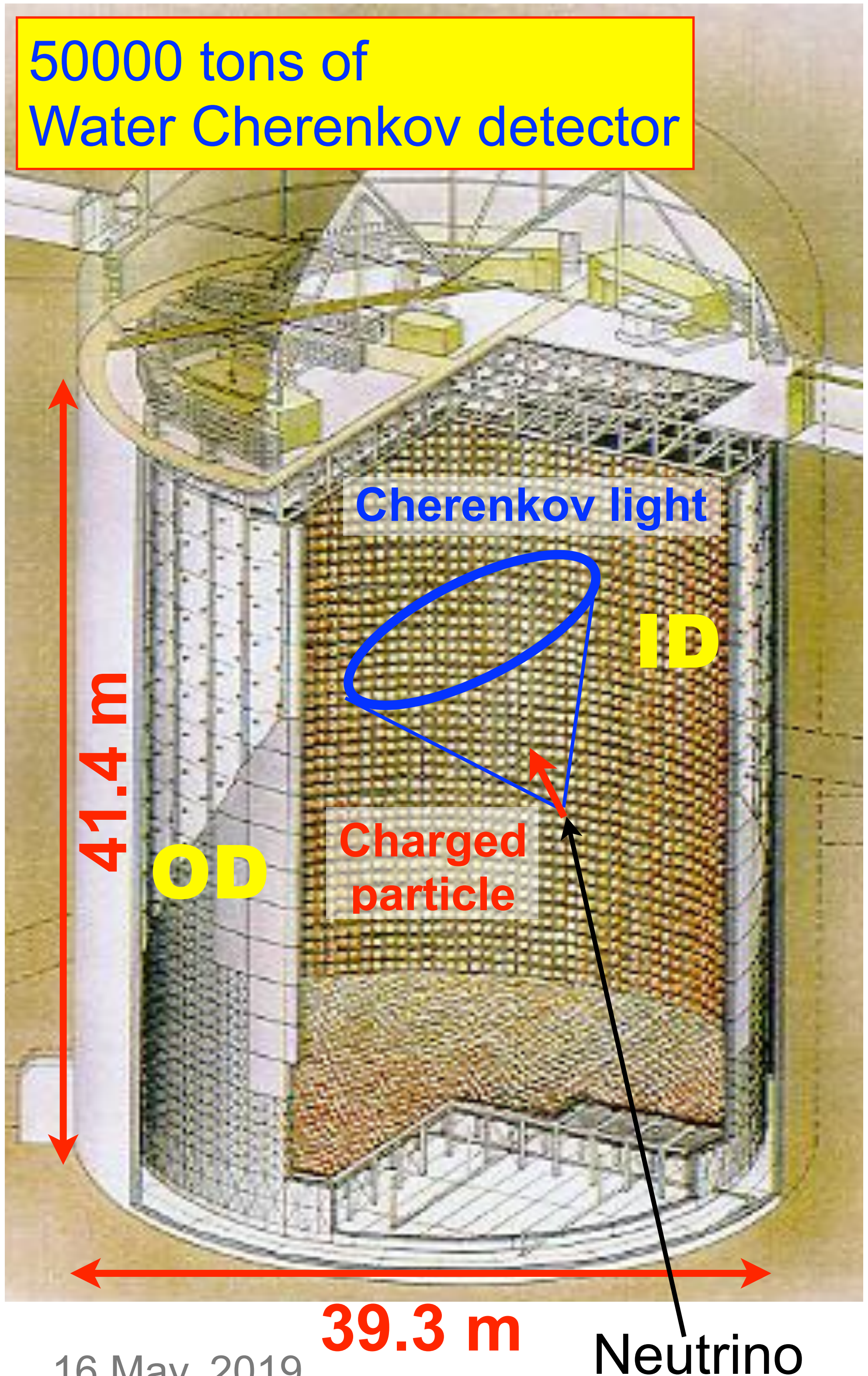


Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos.

✓Primary cosmic rays isotropic about Earth
✓ν's travel 10-10,000km before detection
✓Both neutrinos and antineutrinos in the flux



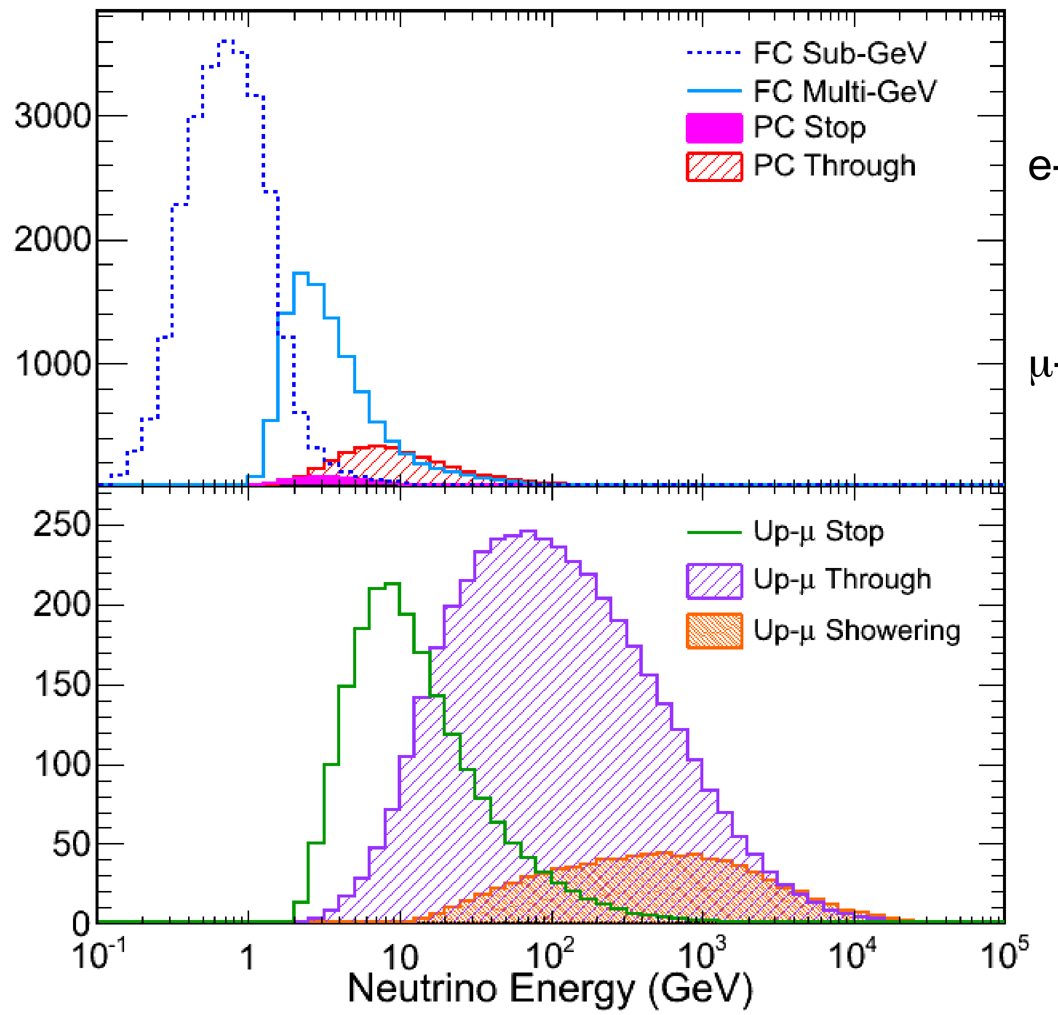
Super-Kamiokande
as an atmospheric neutrino detector



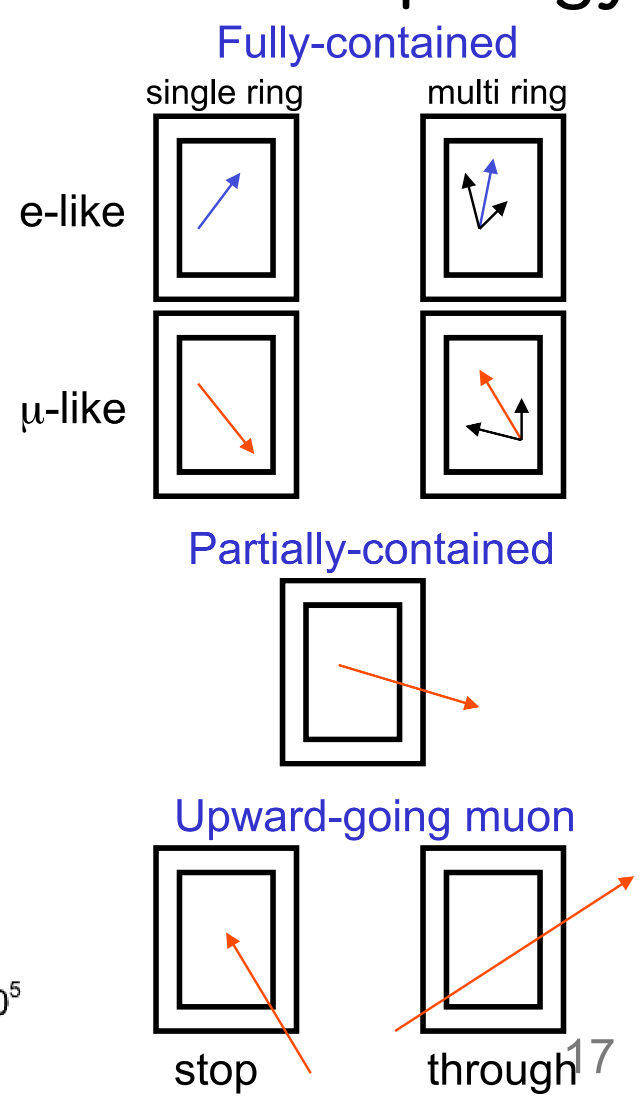
Neutrino interactions in SK

- (quasi-)elastic scattering : ν + N → l + N'
- single meson production : ν + N → l + N' + meson
- deep inelastic interaction : ν + N → l + N' + hadrons
- coherent pion production : ν + ^{16}O → l + ^{16}O + π

parent neutrino spectra

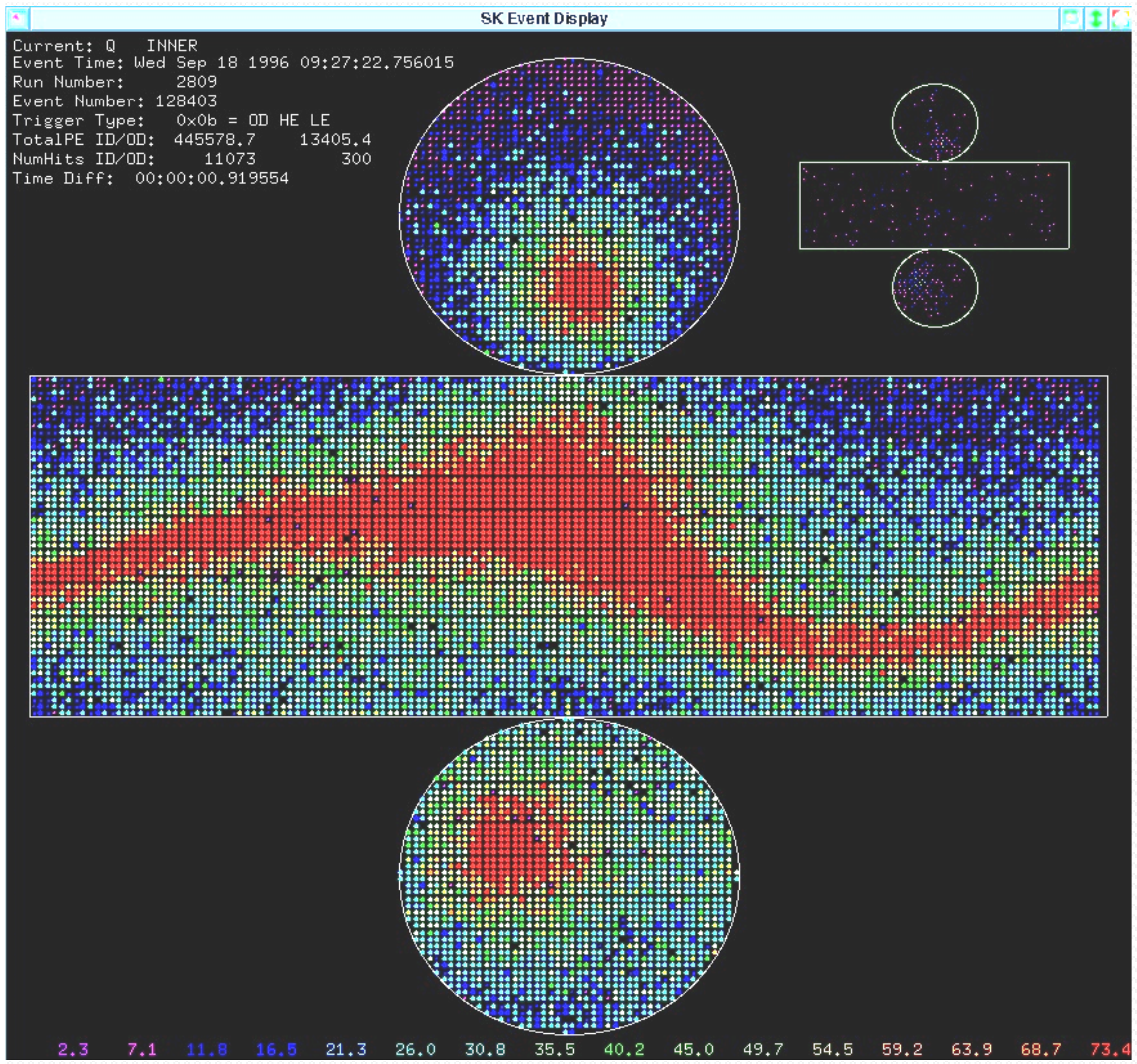


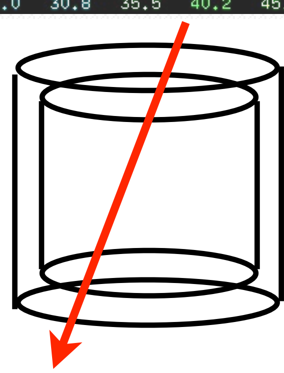
Event topology



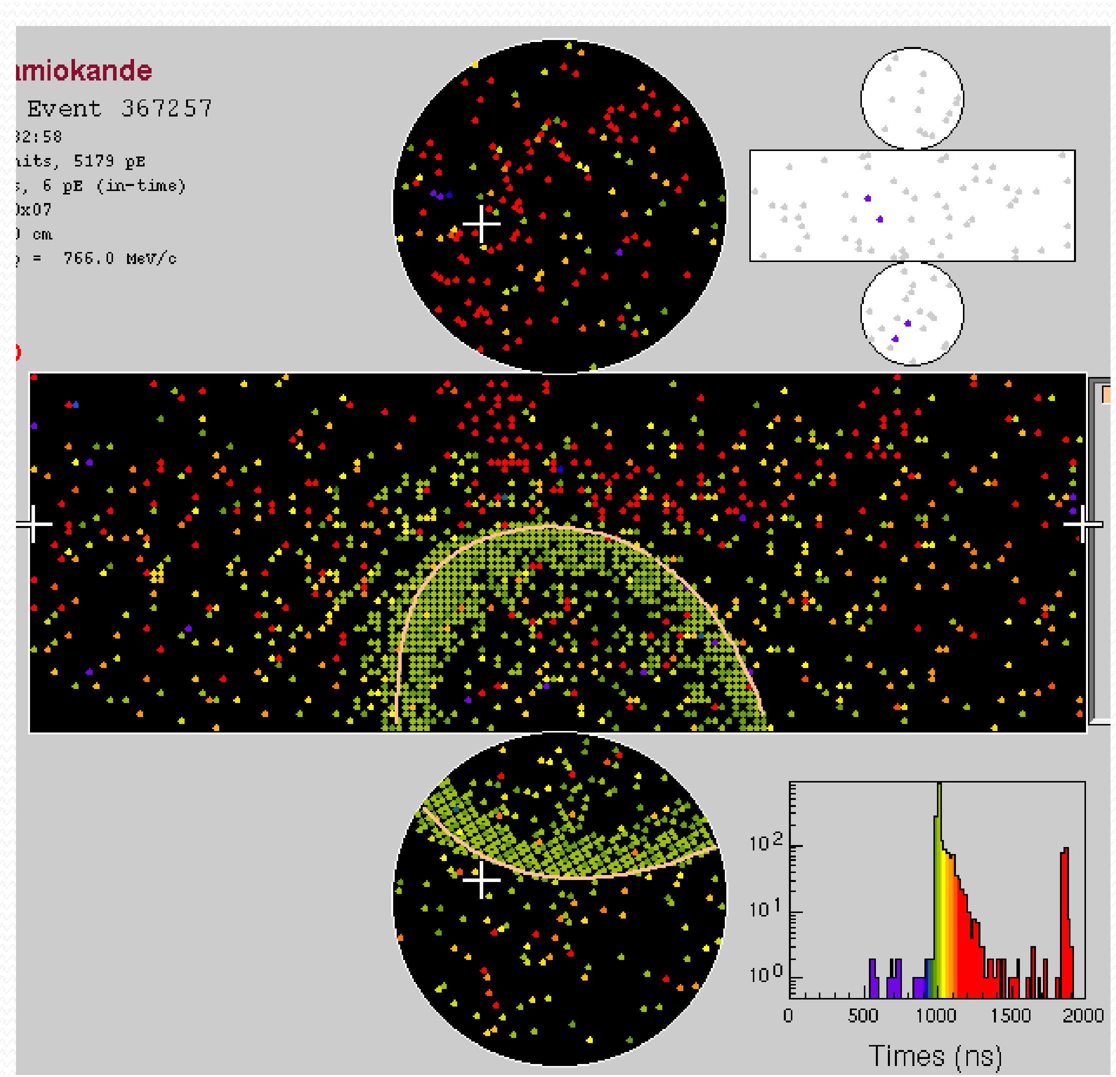
Super-Kamiokande

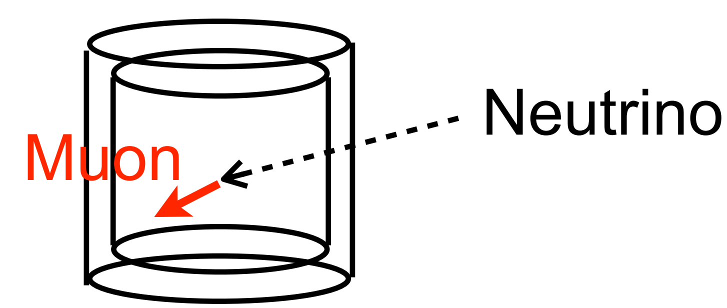
Cosmic ray muon





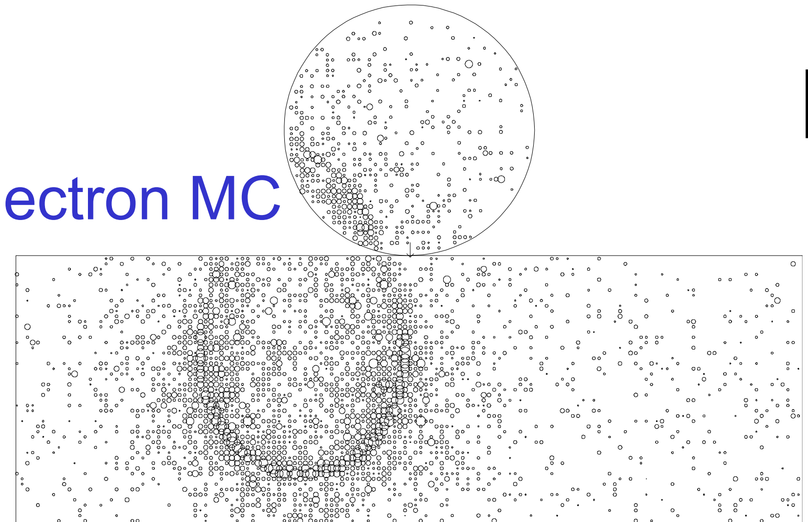
Neutrino signal



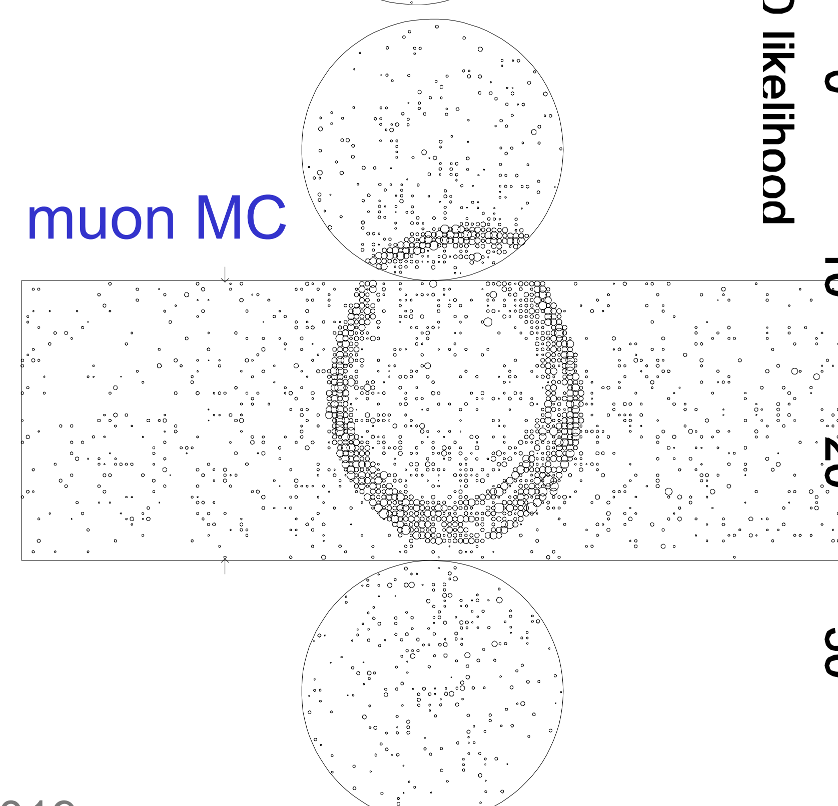


Atmospheric neutrino in SK

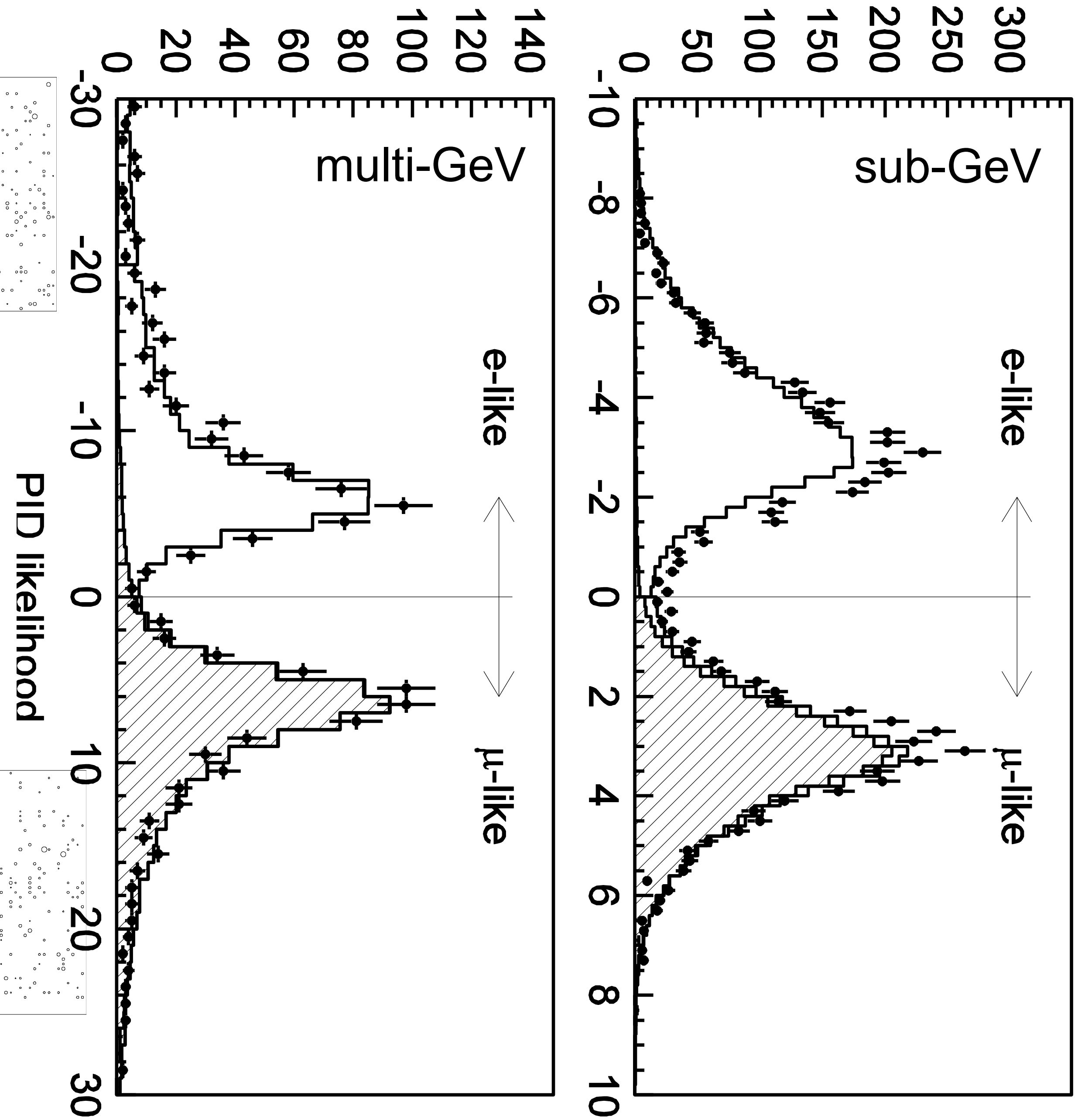
electron MC



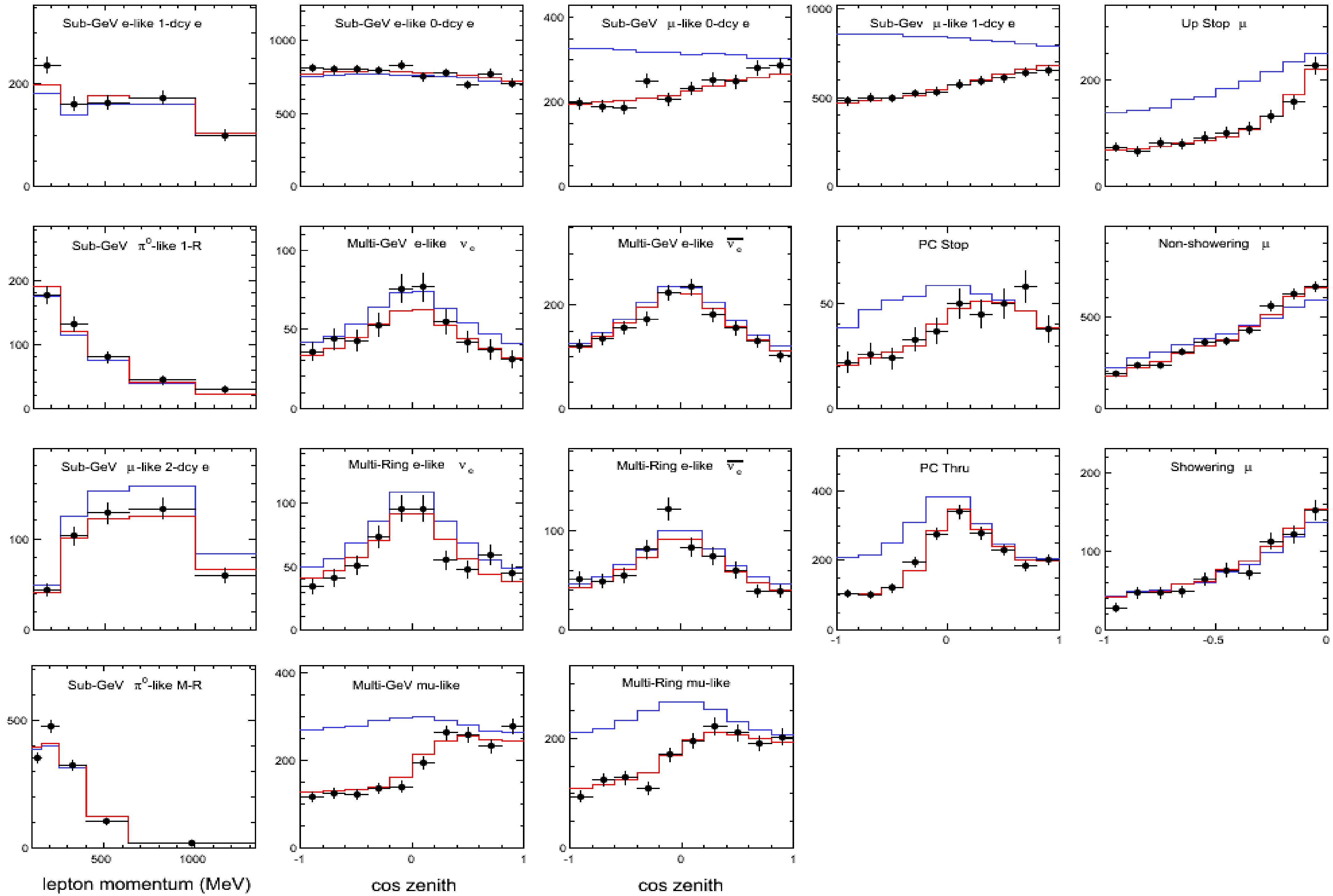
muon MC



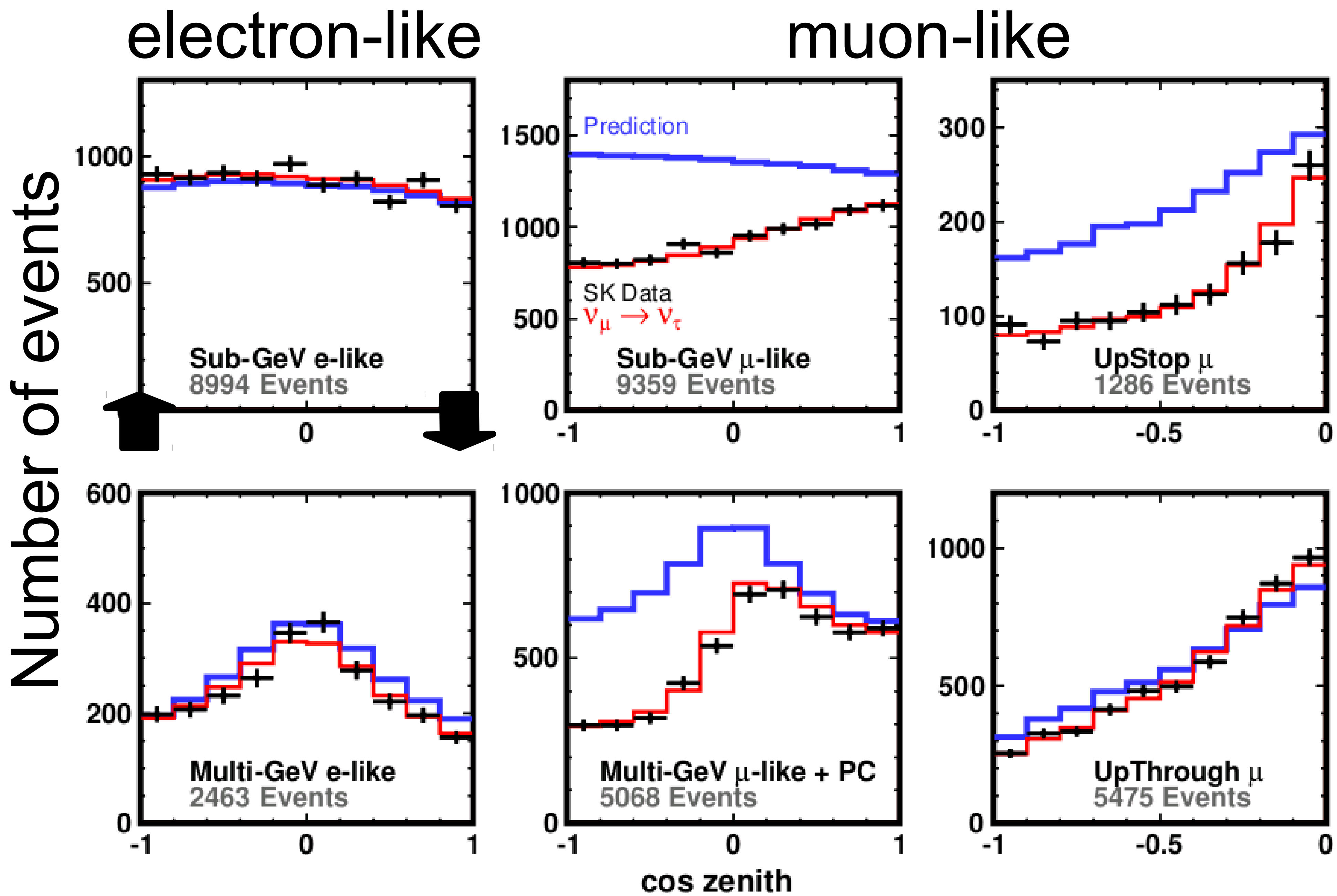
How to identify electron and muon



Atmospheric neutrino in SK

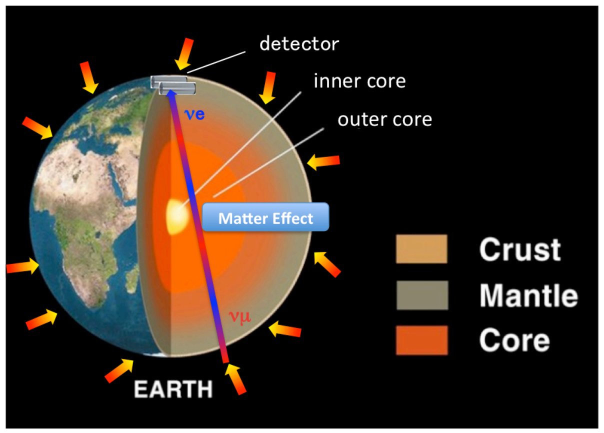


Atmospheric neutrino in SK



First evidence of neutrino oscillation in 1998

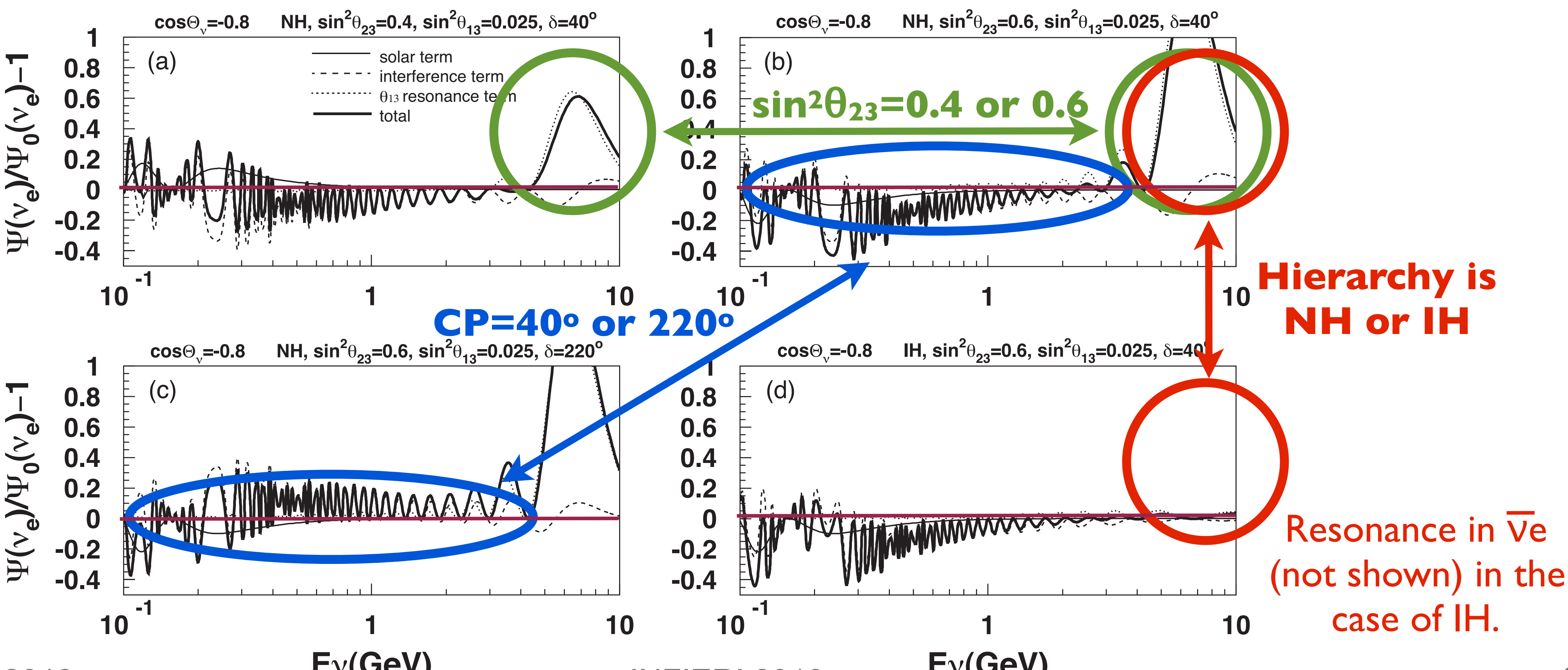
Neutrino oscillation in future



Consider all the sub-leading effects (Δm^2_{21}, matter)

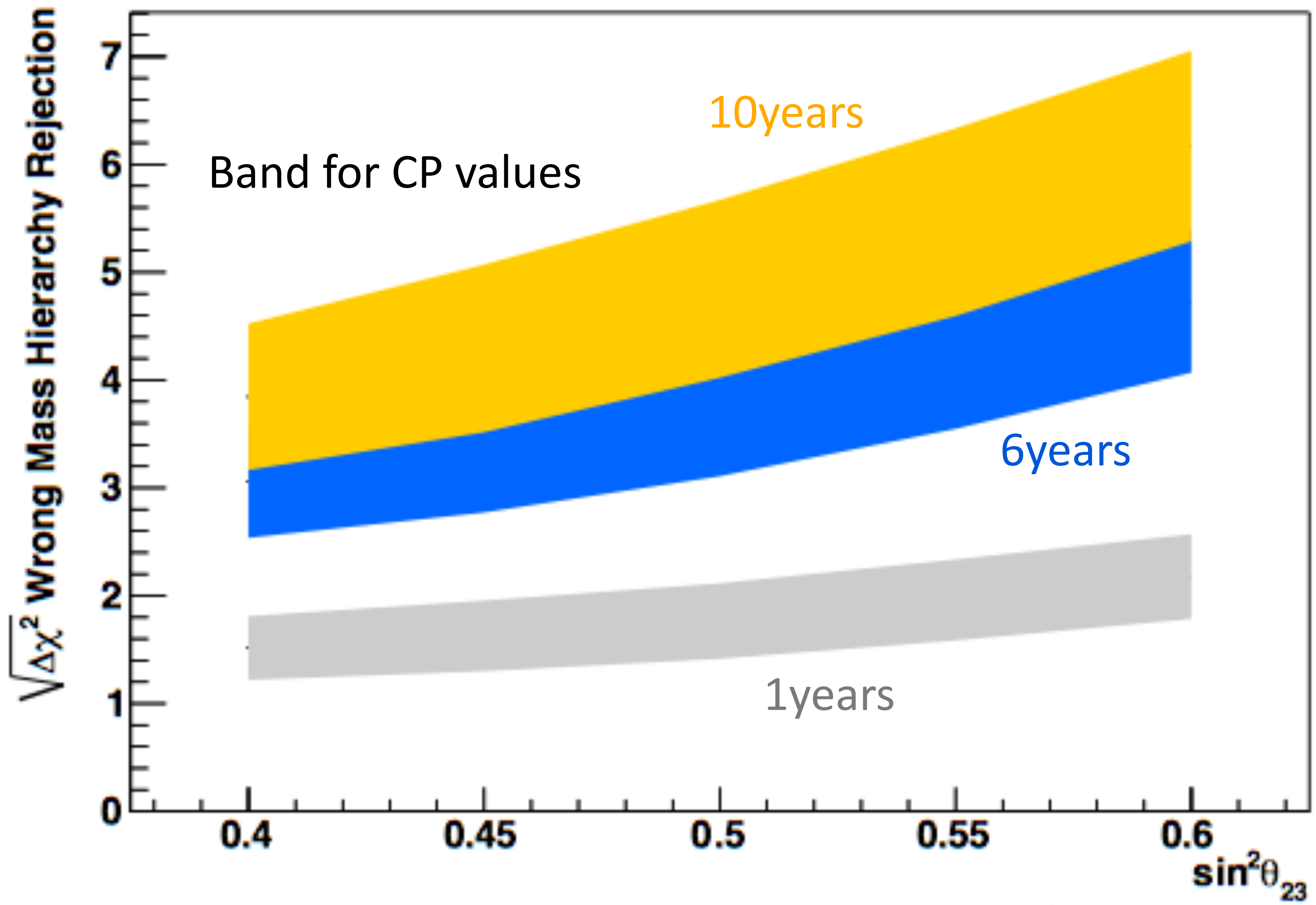
- Mass hierarchy : resonance in multi-GeV ν_e or $\overline{\nu}_e$
- Octant θ_{23} : magnitude of the resonance
- δ_{CP} : interference btw two Δm^2 driven oscillation

Fractional change of upward ν_e flux ($\cos\theta_{zenith}$ = -0.8)



Sensitivity in Hyper-Kamiokande

Mass hierarchy



Determination possible by ~5 years ($\sin^2\theta_{23}$=0.5)

Solar neutrino

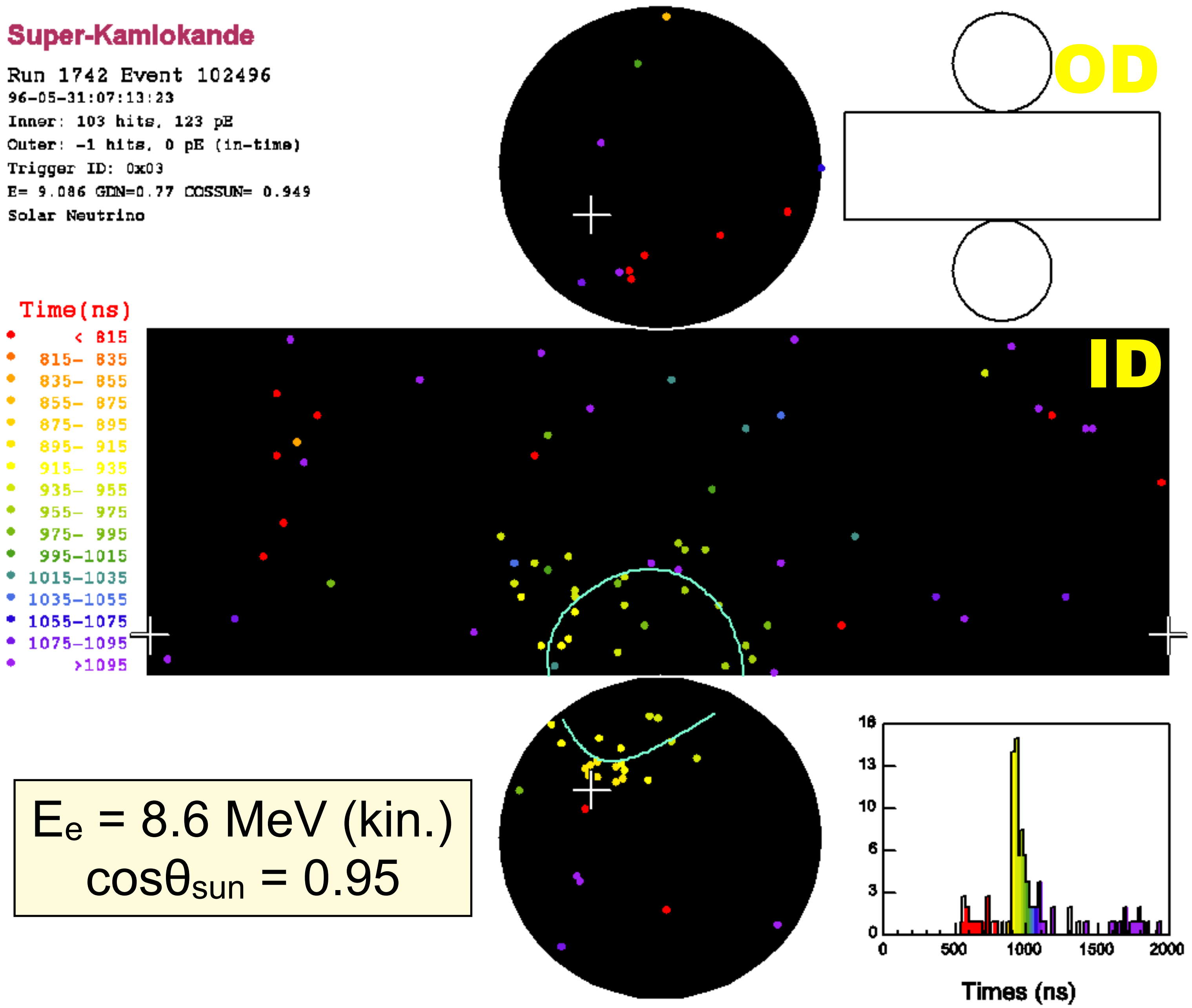
Super-Kamiokande

as a solar neutrino detector

neutrino-electron elastic scattering

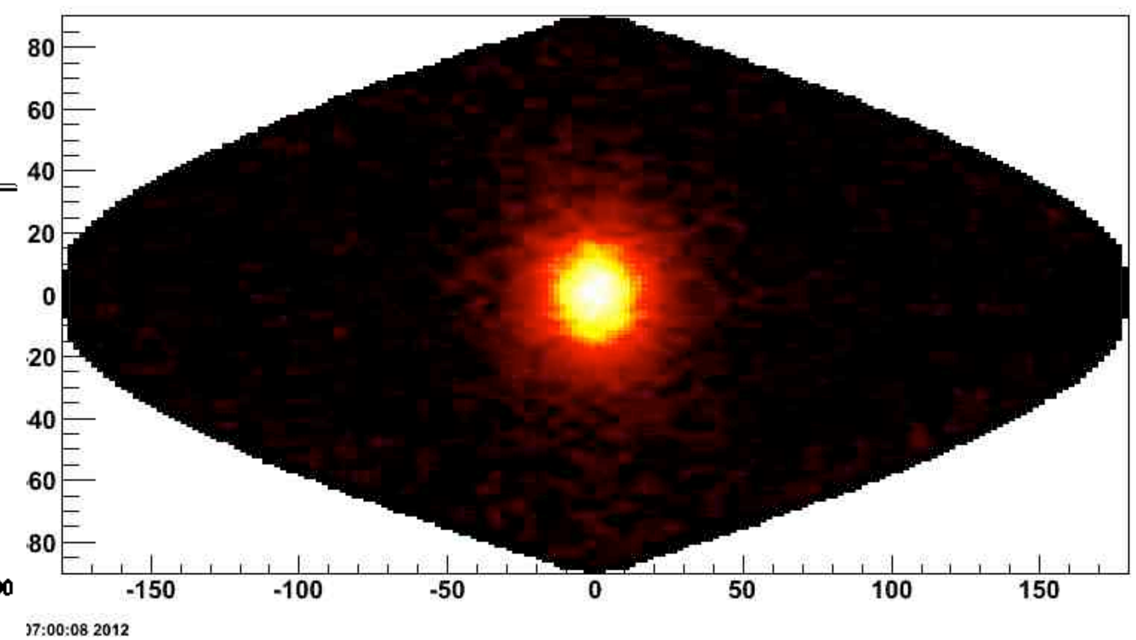
$$\nu + e^- \rightarrow \nu + e^-$$

Typical event



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

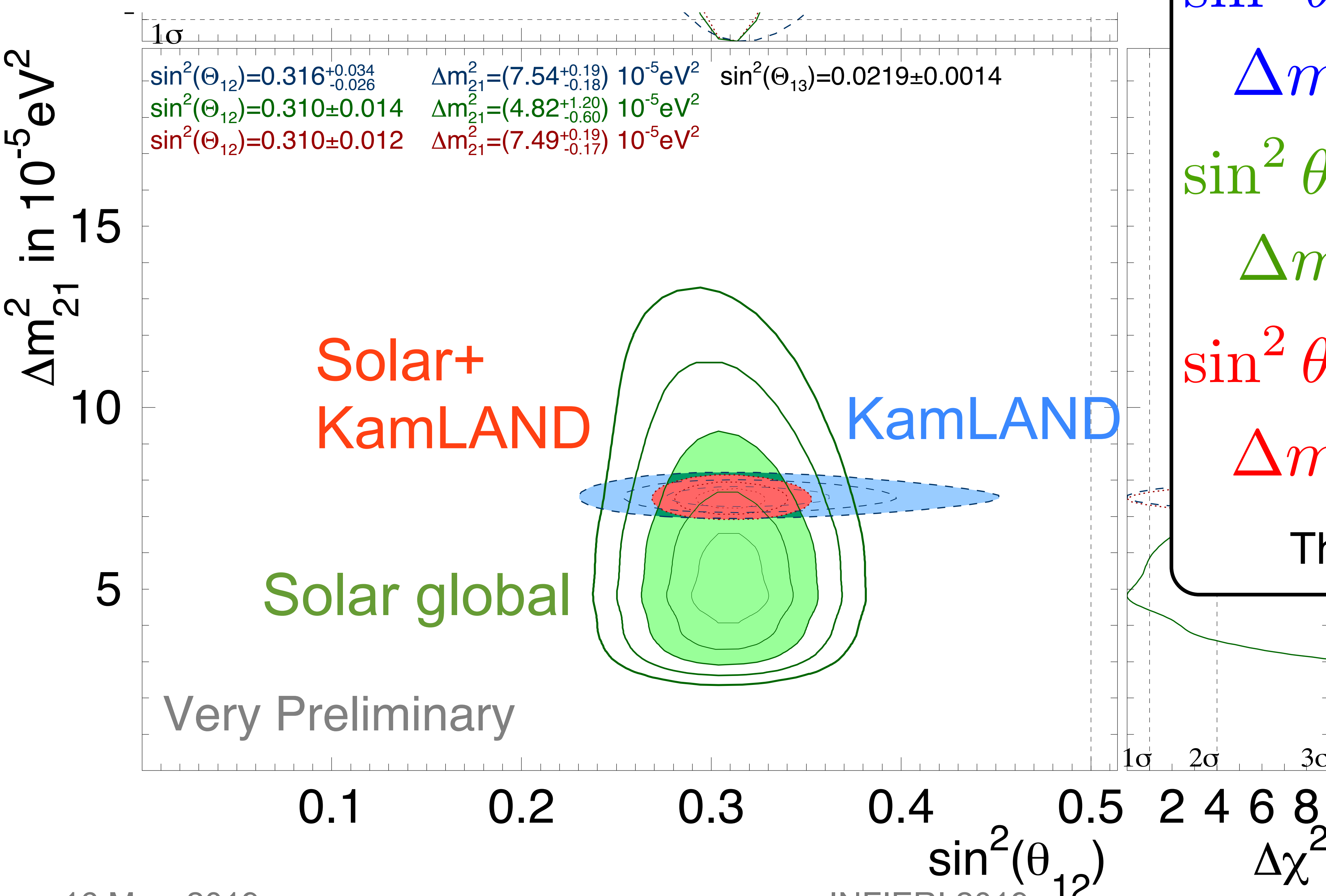
- ✓ Find solar direction
- ✓ Realtime measurements
  - day-night flux differences
  - seasonal variation
- ✓ Energy spectrum



Preliminary

Neutrino oscillation

~2σ tension between solar global and KamLAND in Δm^2_{21}



$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$

$$\sin^2\theta_{12} = 0.310 \pm 0.014$$
$$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60}$$

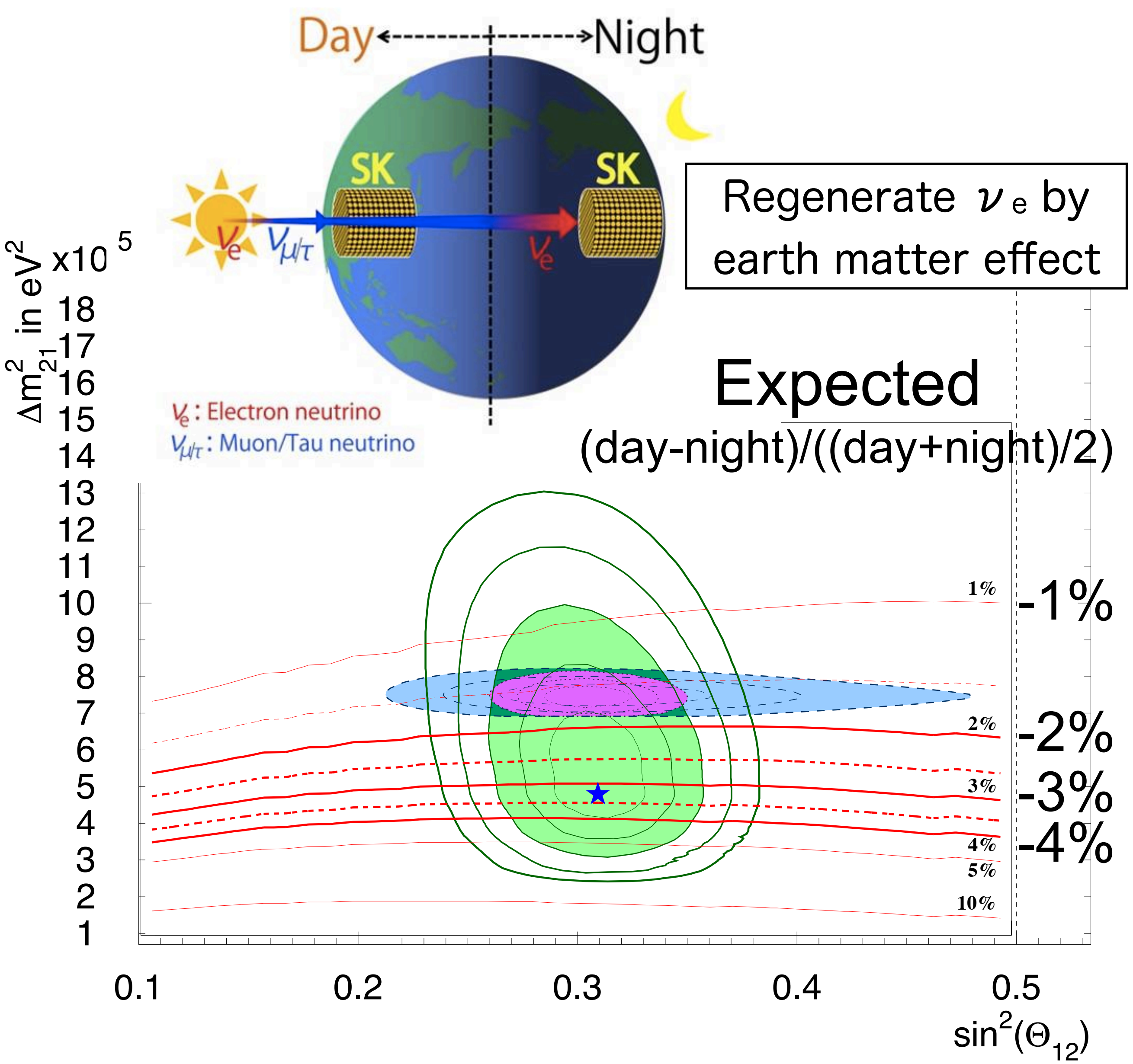
$$\sin^2\theta_{12} = 0.310 \pm 0.012$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

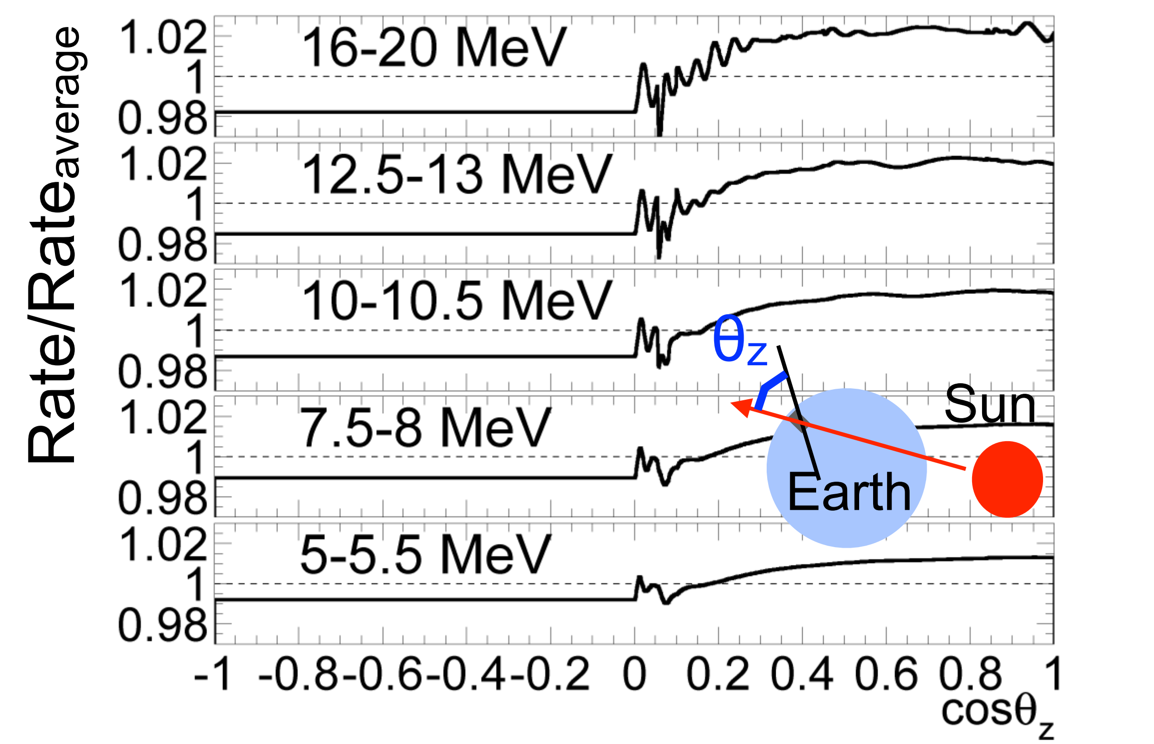
$\sin^2\theta_{13} = 0.0219 \pm 0.0014$

M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857

Day/Night solar neutrino flux asymmetry



expected time variation as a function of $\cos\theta_z$



PRL112, 091805 (2014)

Day/Night Amplitude is fitted to

-3.3±1.0±0.5%

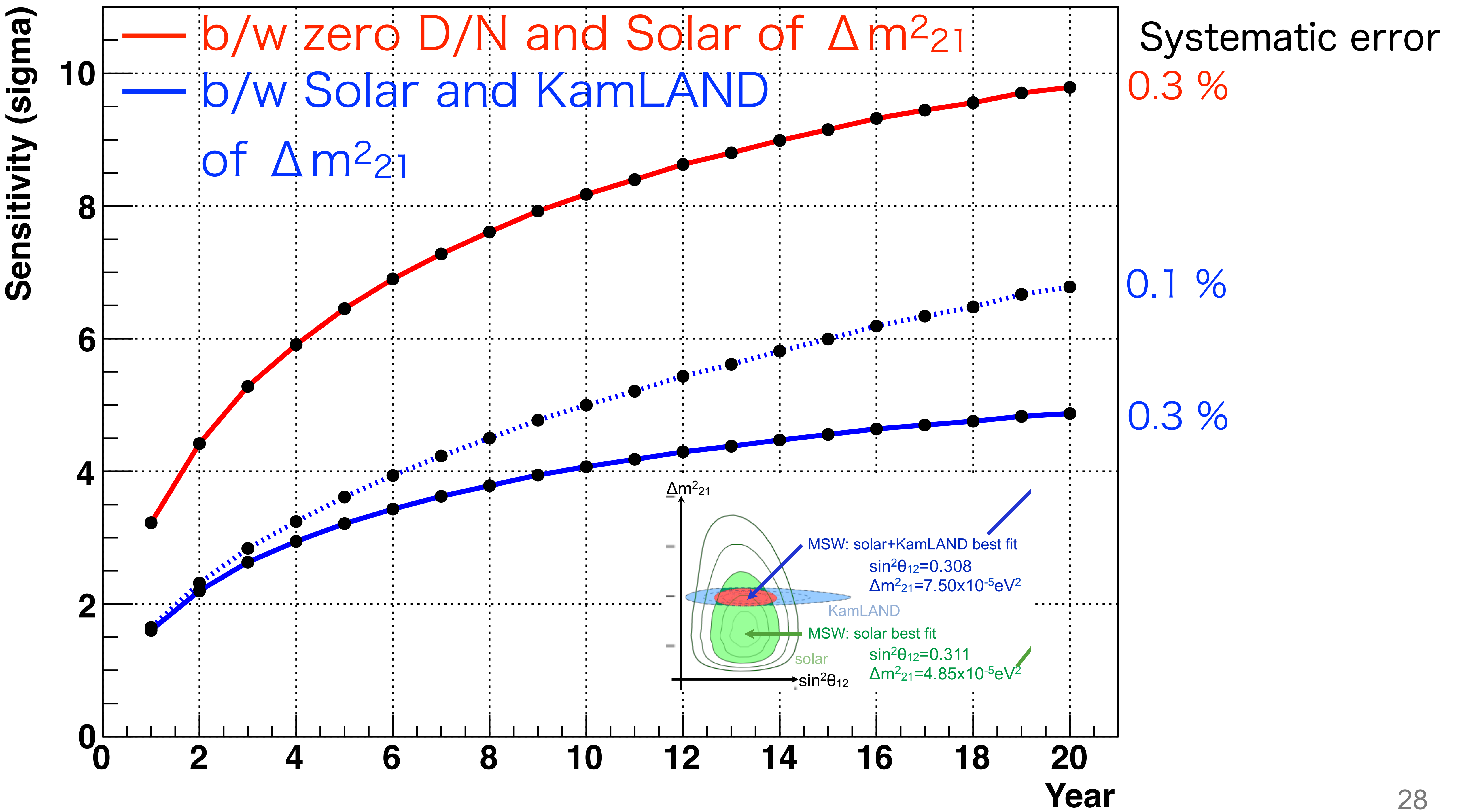
Non-zero significance is

2.9σ

in SK-I to IV (4499 days)

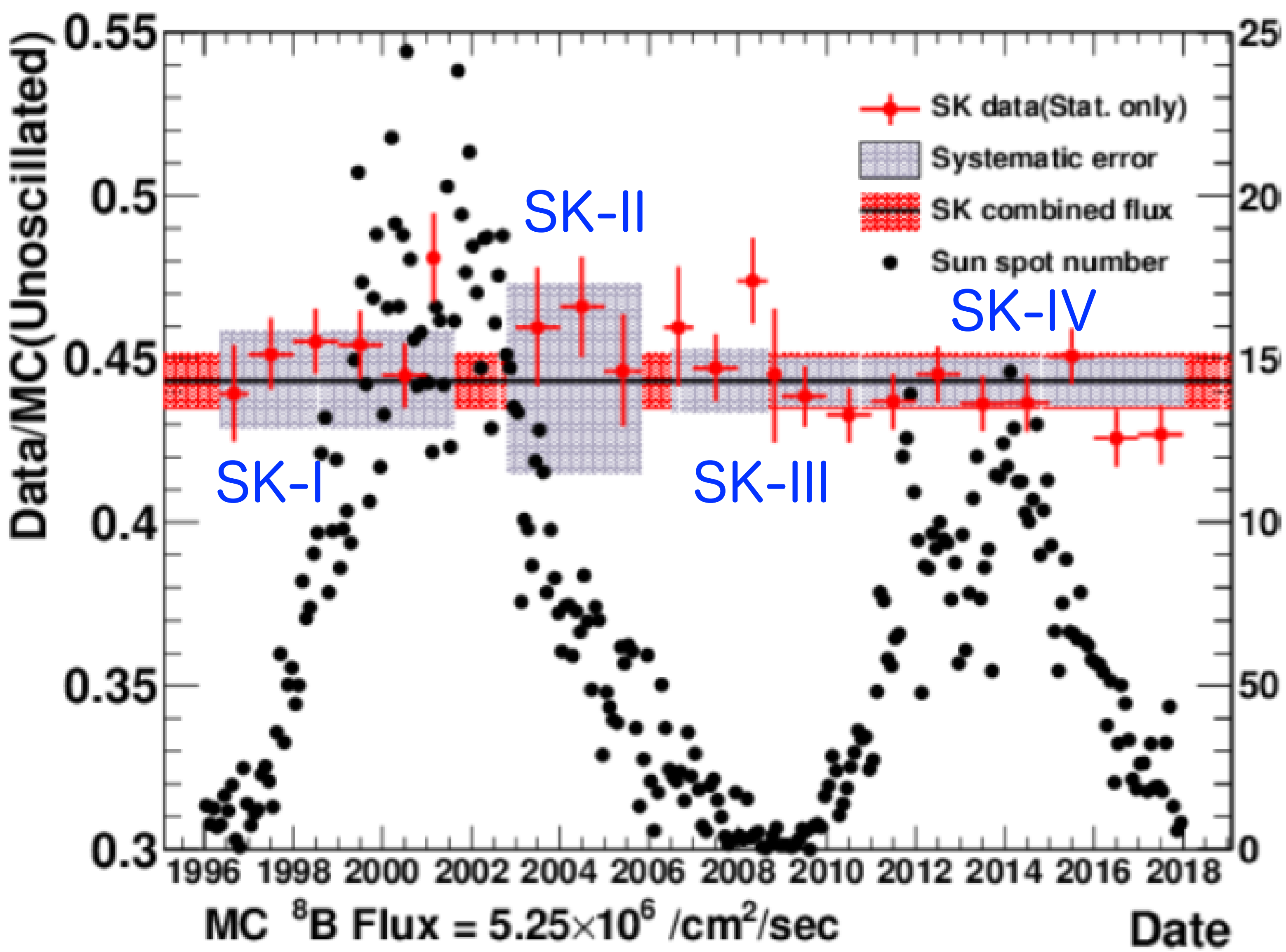
Sensitivity in Hyper-Kamiokande

Day/Night flux asymmetry



Preliminary

Yearly solar neutrino flux



M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857

^{8}B flux vs sun spot

No correlation with 11 years solar activity is observed

χ^2=21.57/21 (dof)
Prob. = 41.4%

Sun spot number : http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

Solar neutrino rate measurement in SK is fully consistent with a constant solar neutrino flux emitted by the Sun

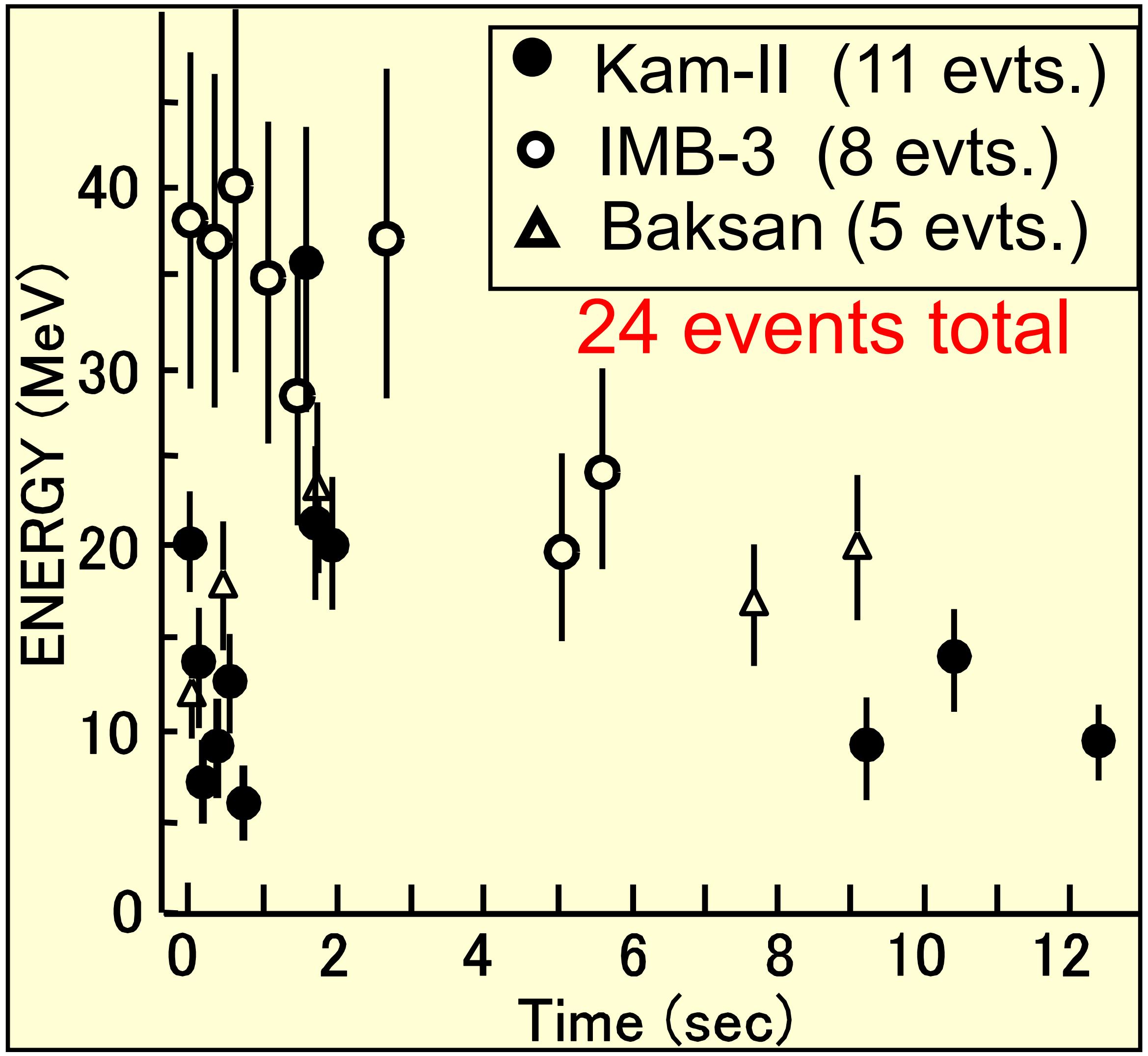
Toward the next decade

30 years anniversary of SN1987A

(2017)

Workshop at Koshiba hall in U.of.Tokyo
on February 12-13, 2017

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

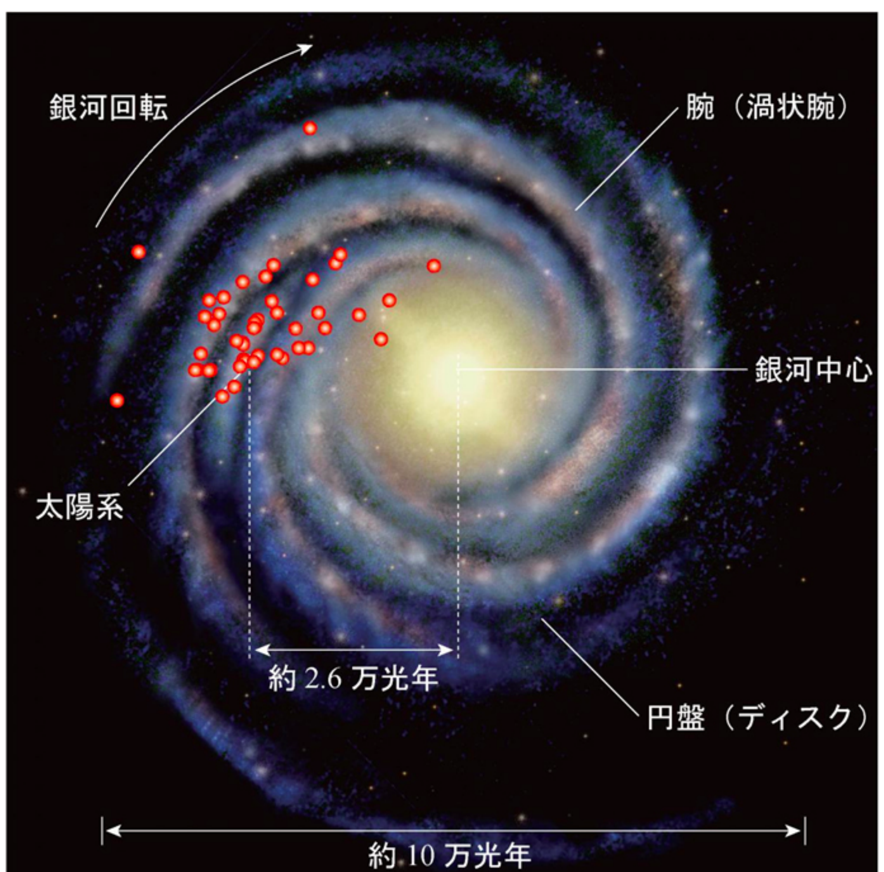


No Supernova neutrino detection since then..

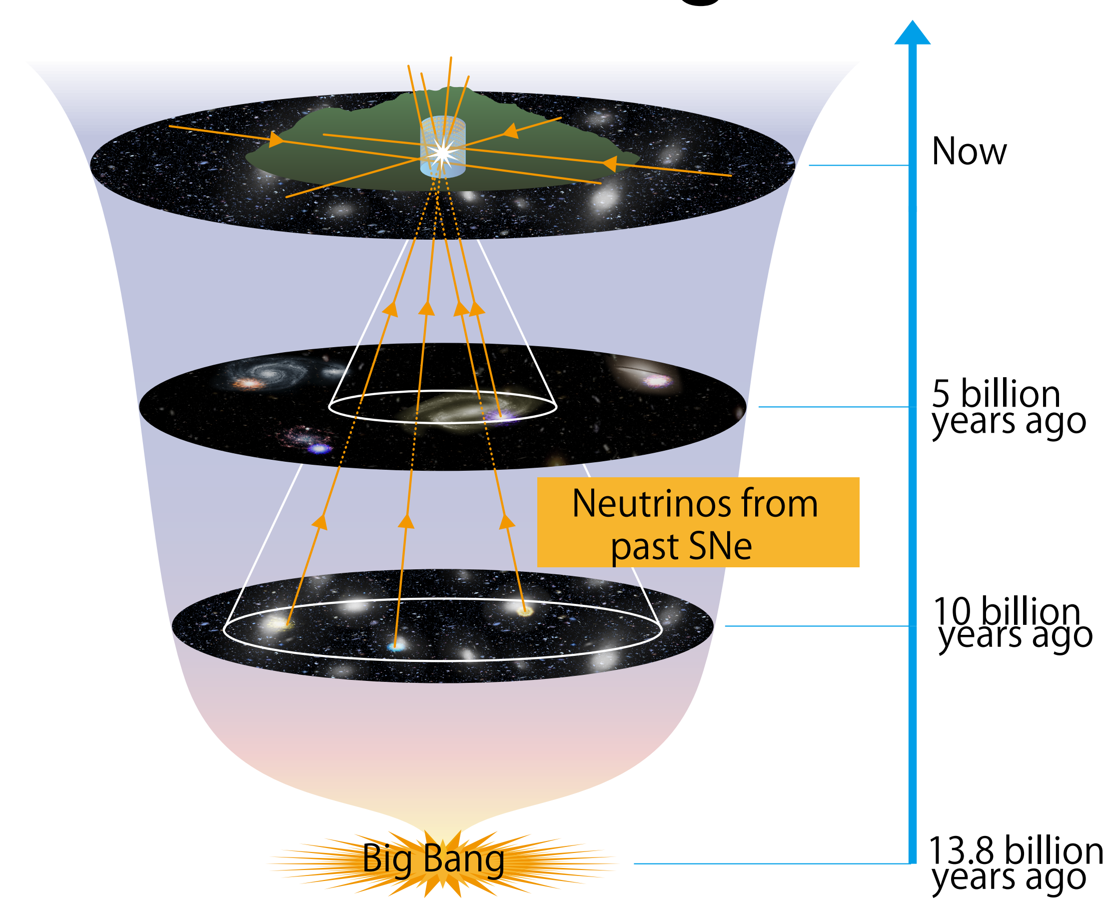
No chance for Supernova neutrino detection for next hundred's years?

We believe, yes!

Galactic Supernova burst (a few per century)

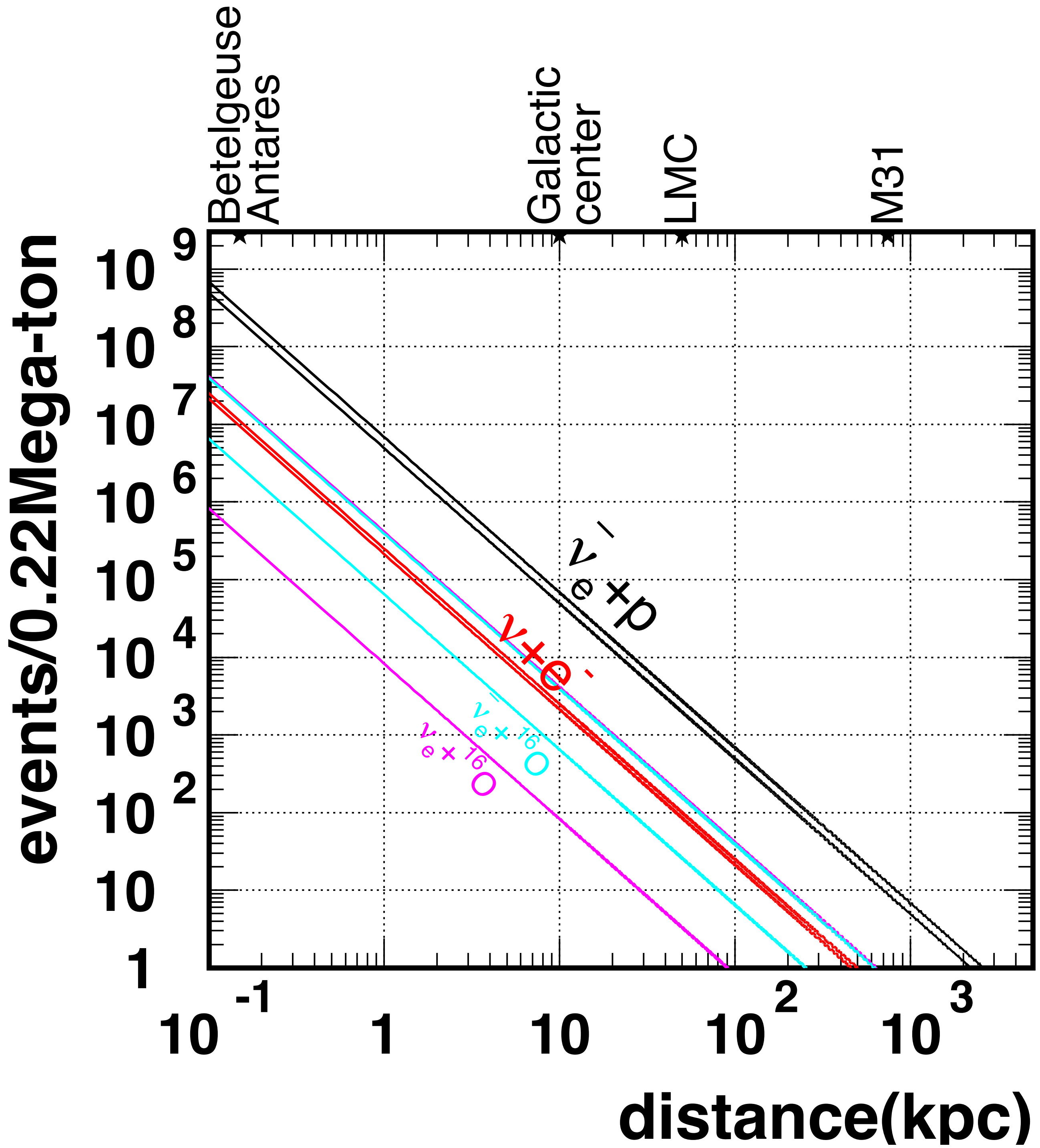


Diffuse Supernova Neutrino Background



Supernova burst

expected number of events in Hyper-Kamiokande



arXiv : 1805.04163

Expected number of event

49k~68k ev (IBD)
2.1k~2.5k ev (νe ES)
(6~40 for neutronization)
80~4100 ev (ν_e CC)
650~3900 ev ($\bar{\nu}_e$ CC)

at 10kpc

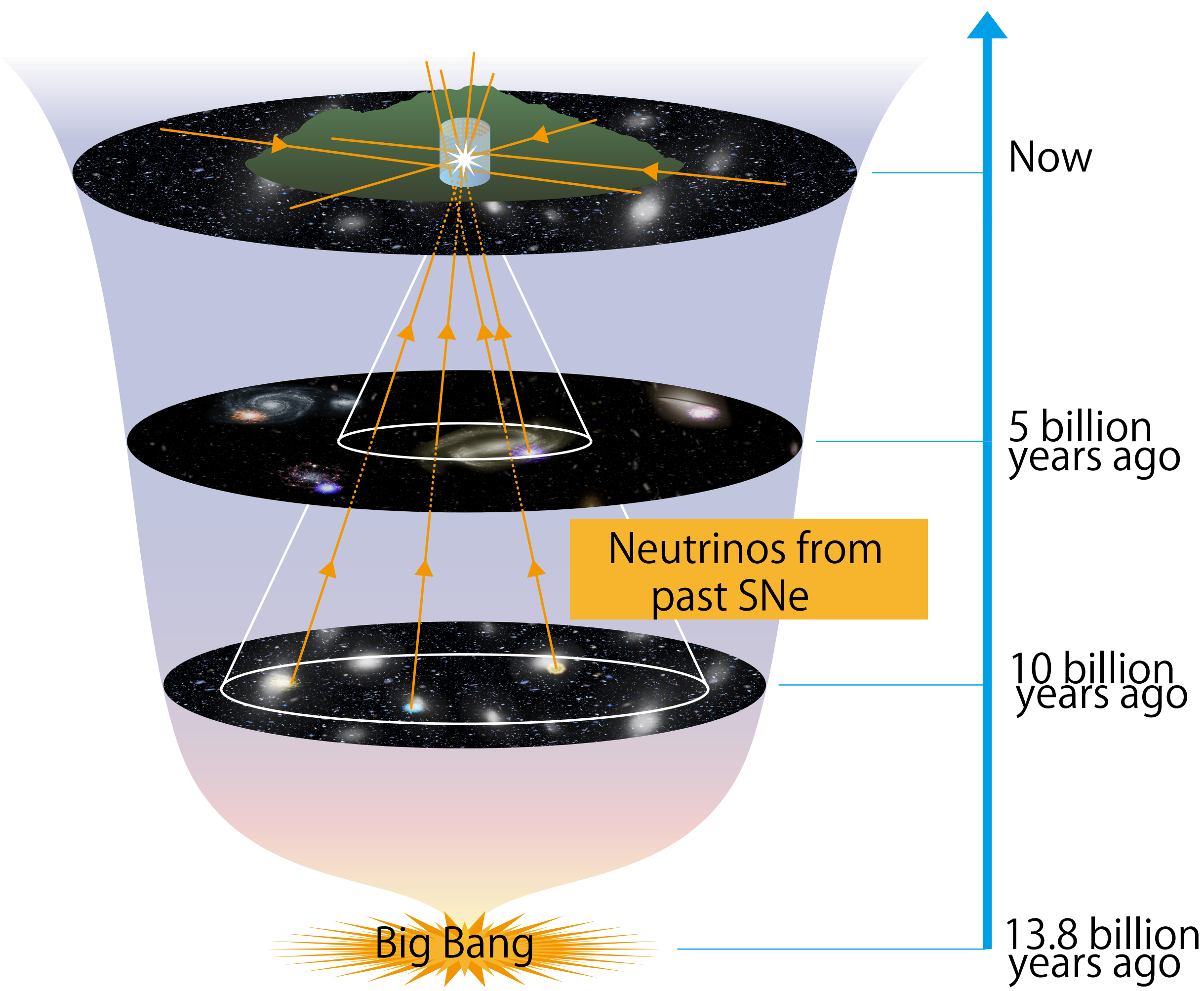
Livermore simulation

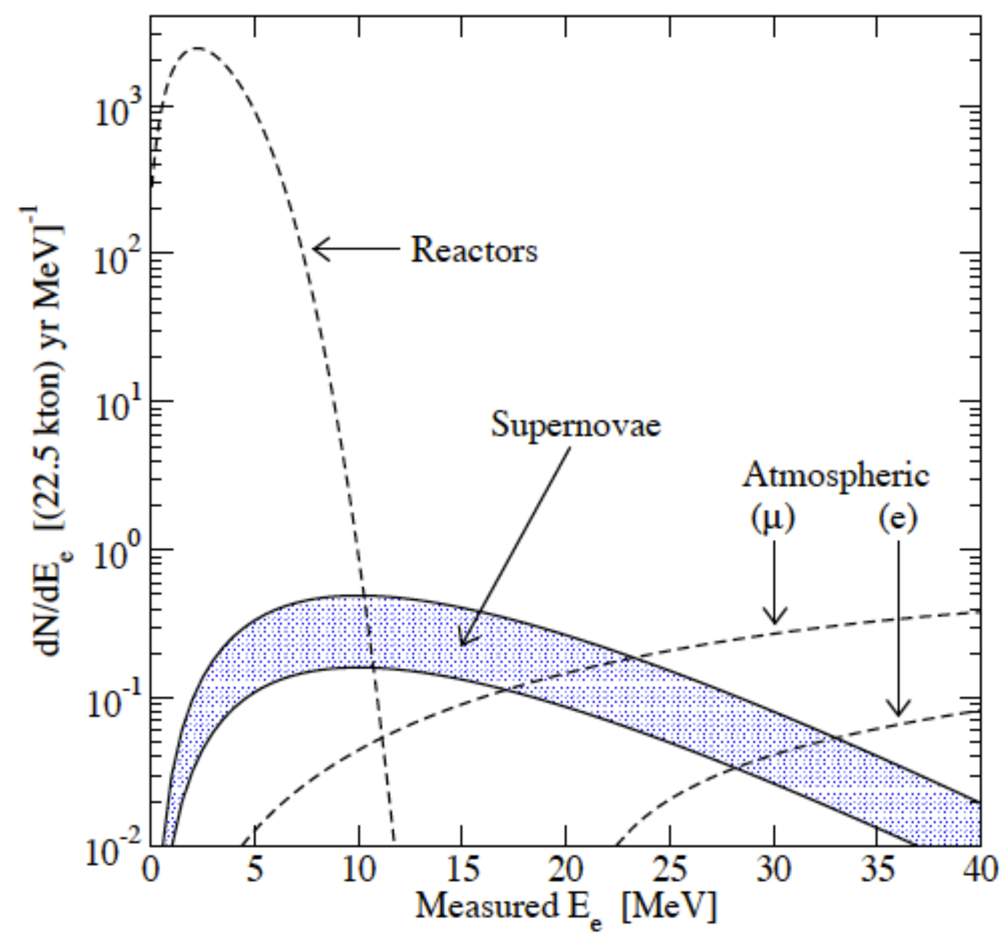
Totani, Sato, Dalhed, Wilson, ApJ. 496 (1998) 216

Super-K Gd

For the first observation of DSNB

(Diffuse Supernova Neutrino Background)

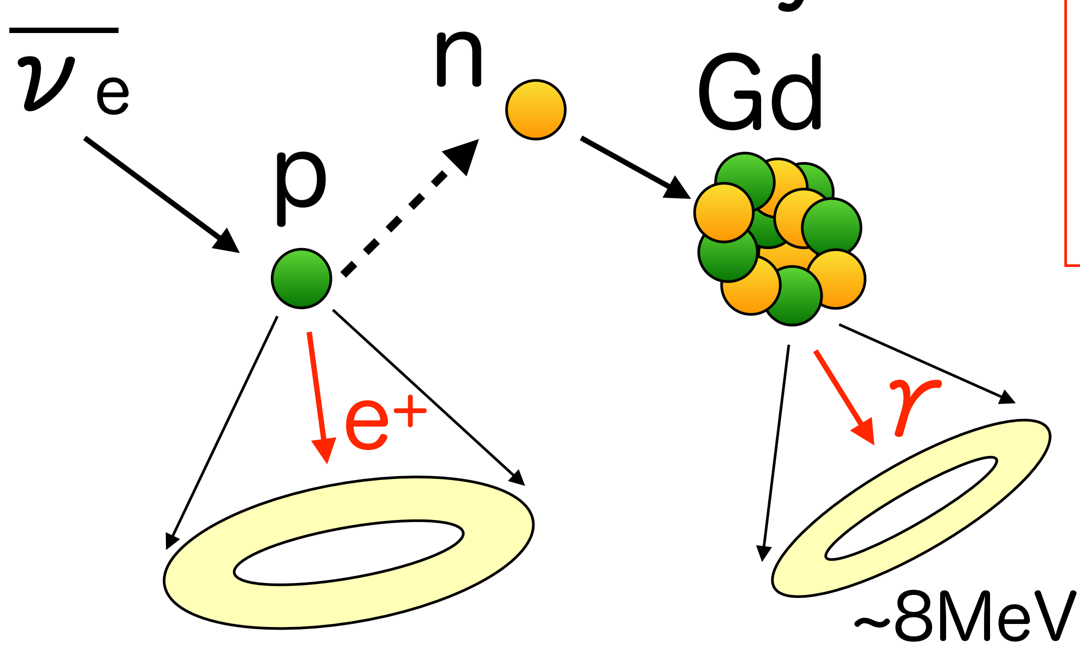




How to reduce atmospheric neutrino BG?

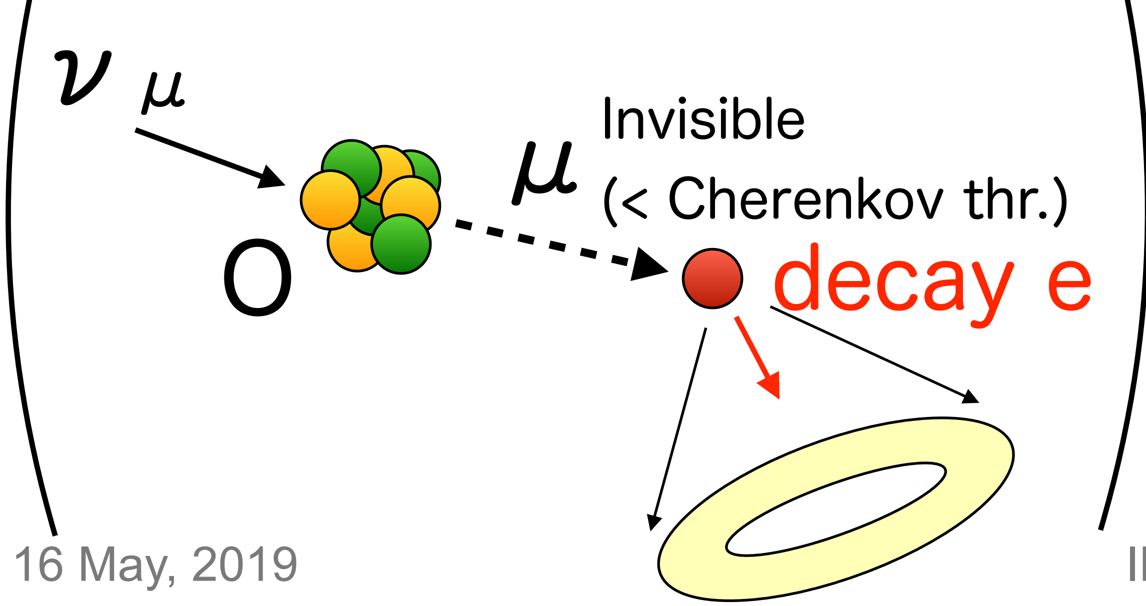
Super-K Gd

Inverse beta decay

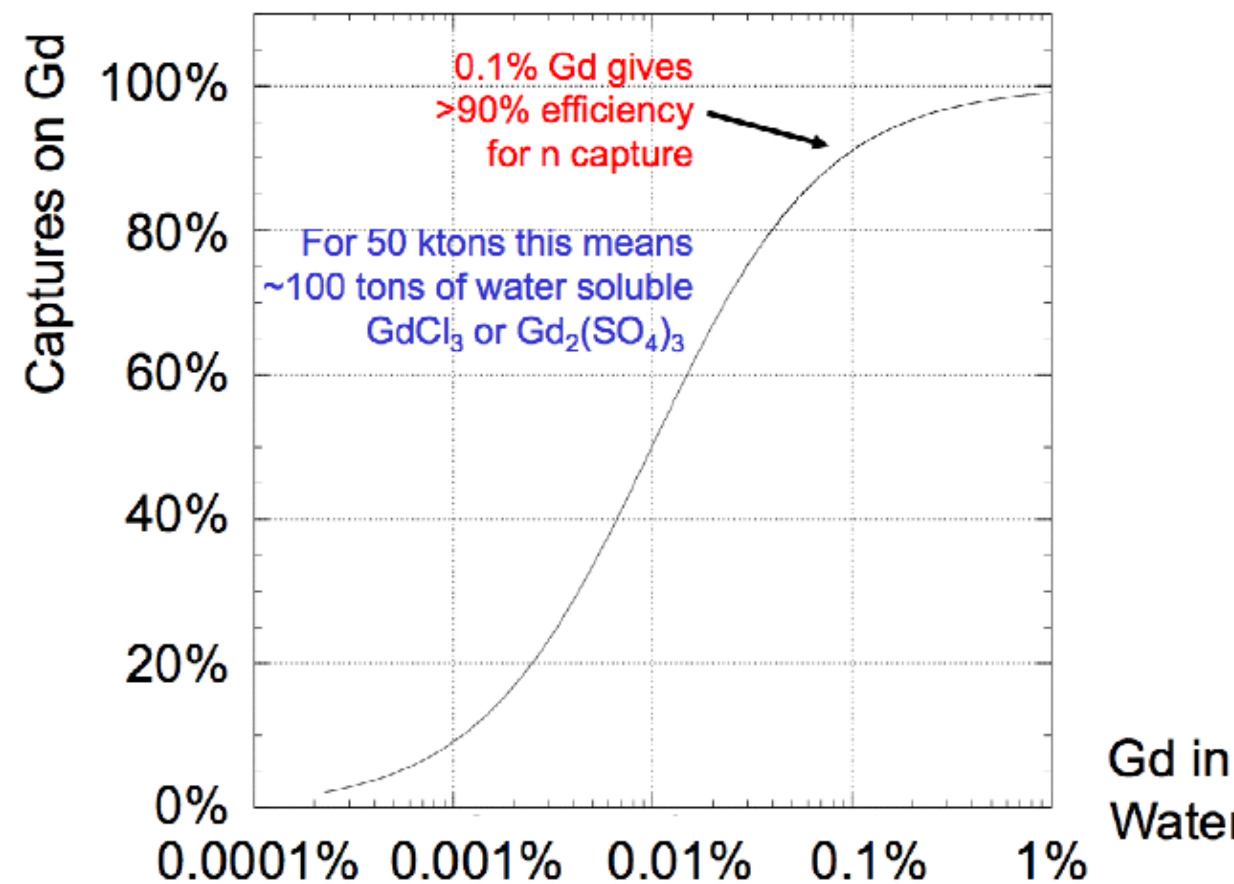


Delayed coincidence

Atmospheric ν BG



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

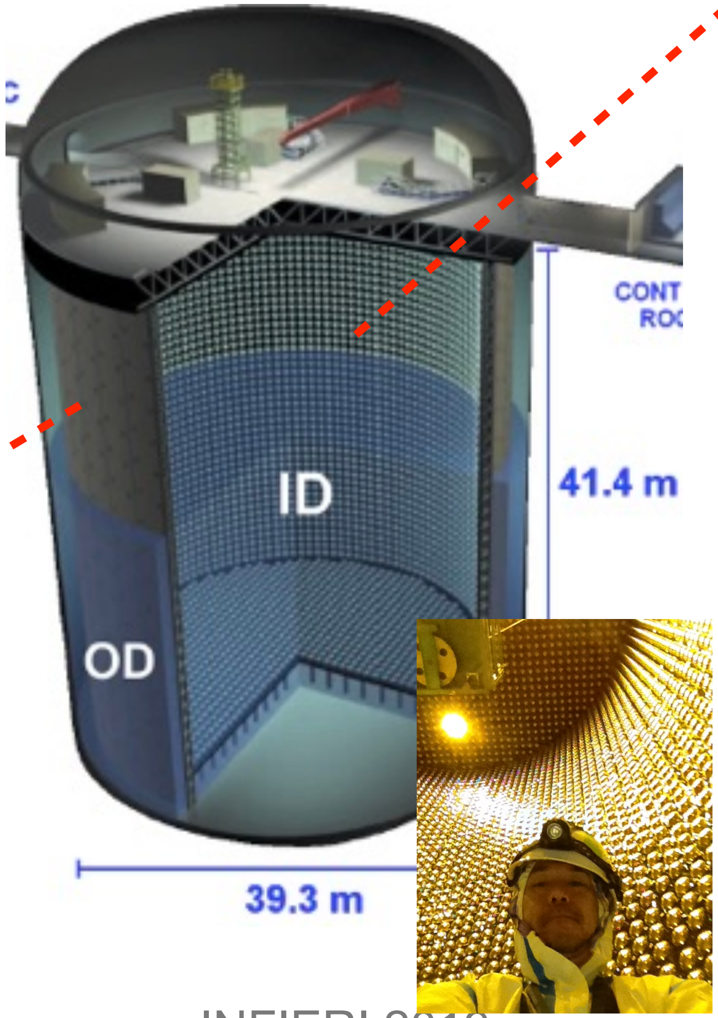


~90% of neutrons are tagged in 0.2% $Gd_2(SO_4)_3$ (0.1% Gd)

Super-K tank refurbishment

- Stop water leak (~3ton/day)
- Change bad PMTs
- Install new water pipe for better water control
- Cleaning

Change bad PMTs

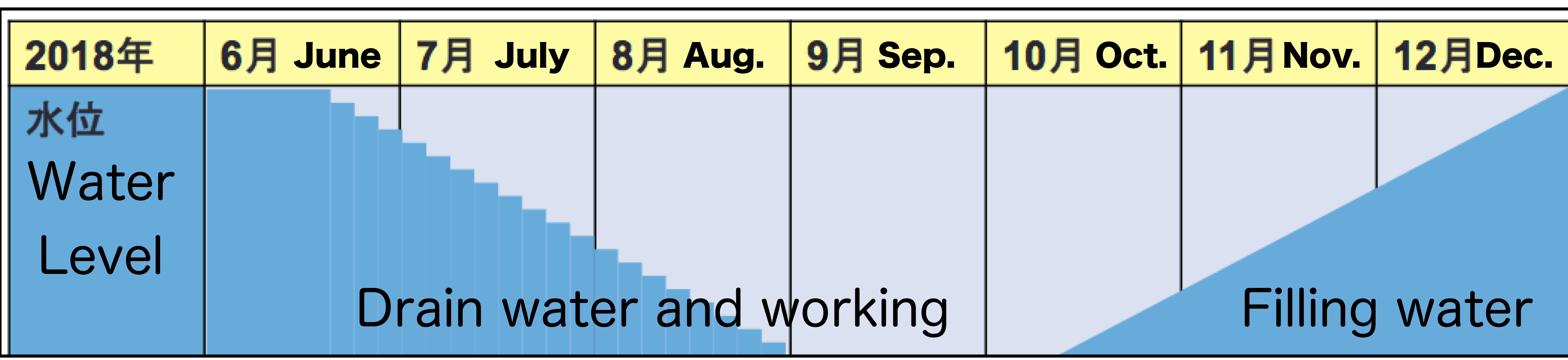


Seal whole welding lines

Install new water pipe

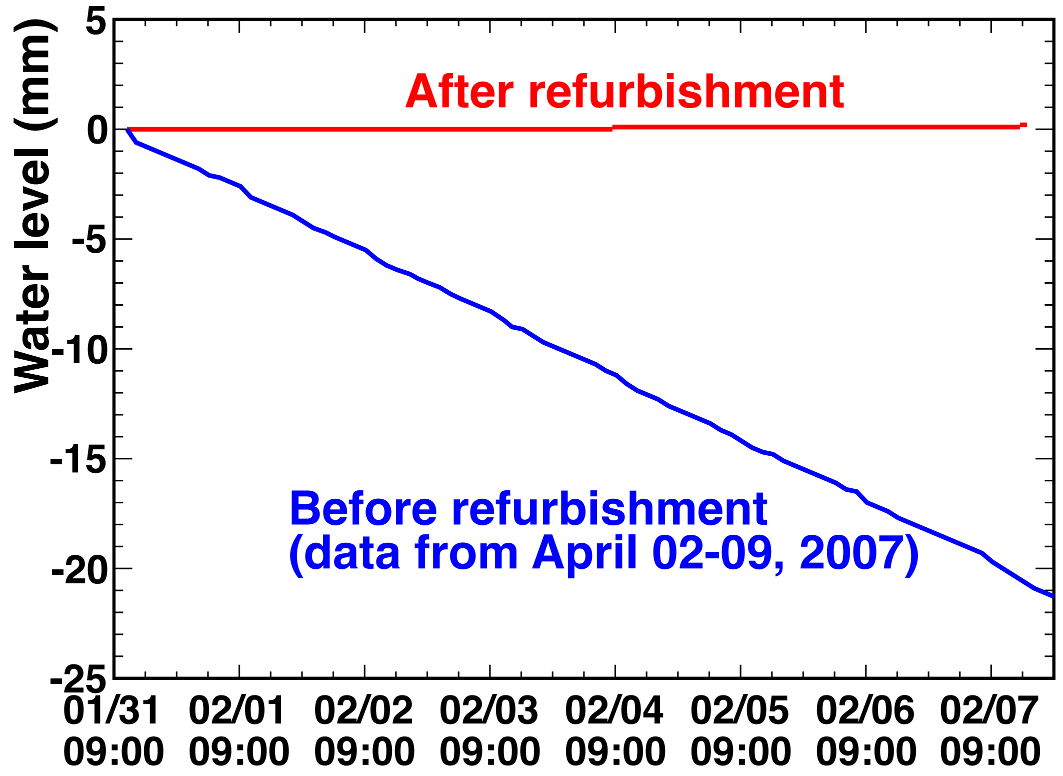
Super-K tank refurbishment

- Start on 31st May, 2018, work on barrel part draining water. After complete draining in the end of August, working on bottom part.
- Start filling water in the middle of October, 2018.
- After complete filling water on 29th January, 2019, resume the data taking as SK-V.



Water leakage from SK tank

After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31st January to 15:52 on 7th February, 2019. (7 days 4 hours 22 minutes in total)

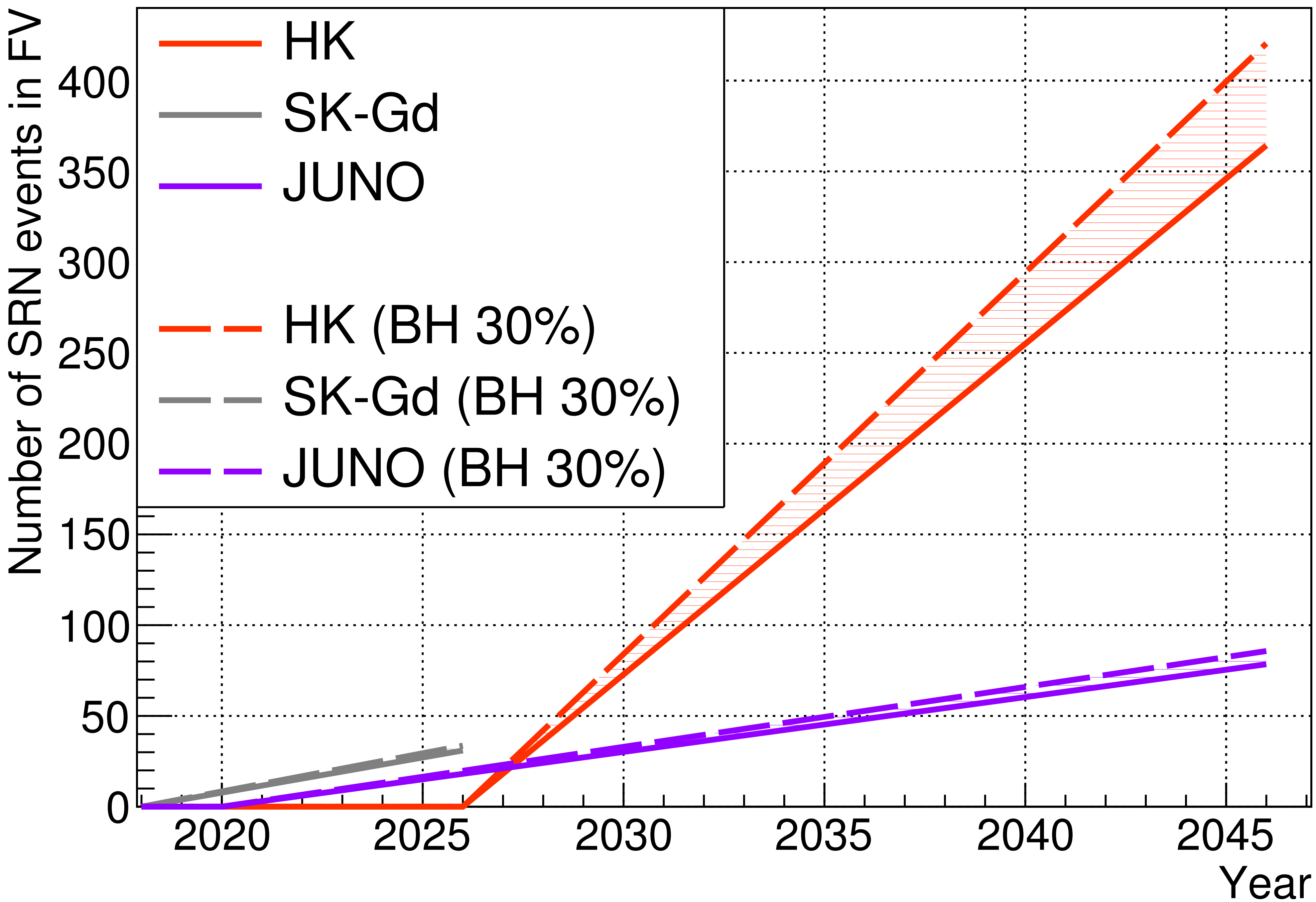


- Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- This is less than 1/200th of the leak rate observed before the tank refurbishment.

Diffuse Supernova Neutrino Background

expected number of events

(detection efficiency is not considered)



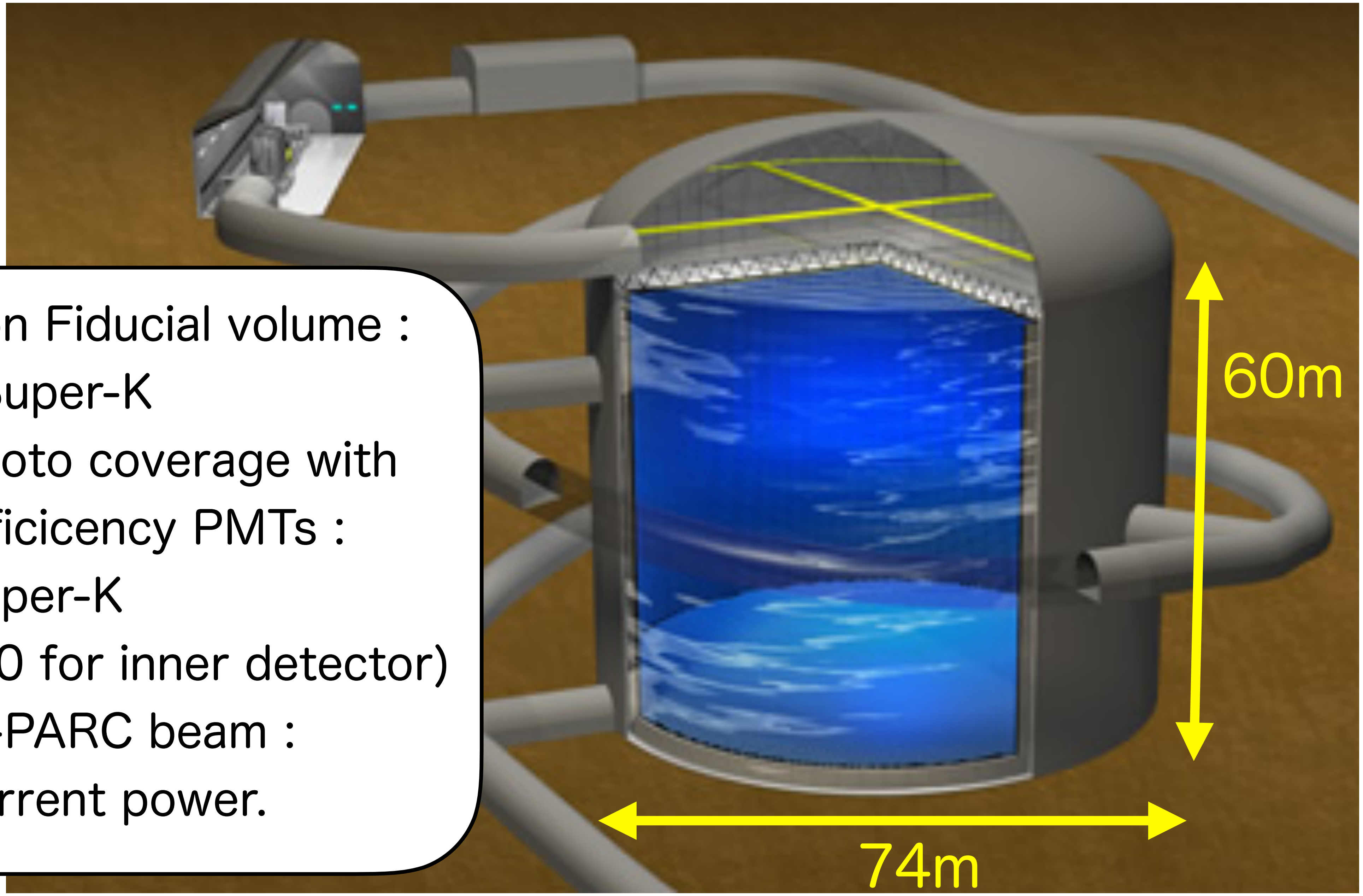
Hyper-Kamiokande

Hyper-Kamiokande

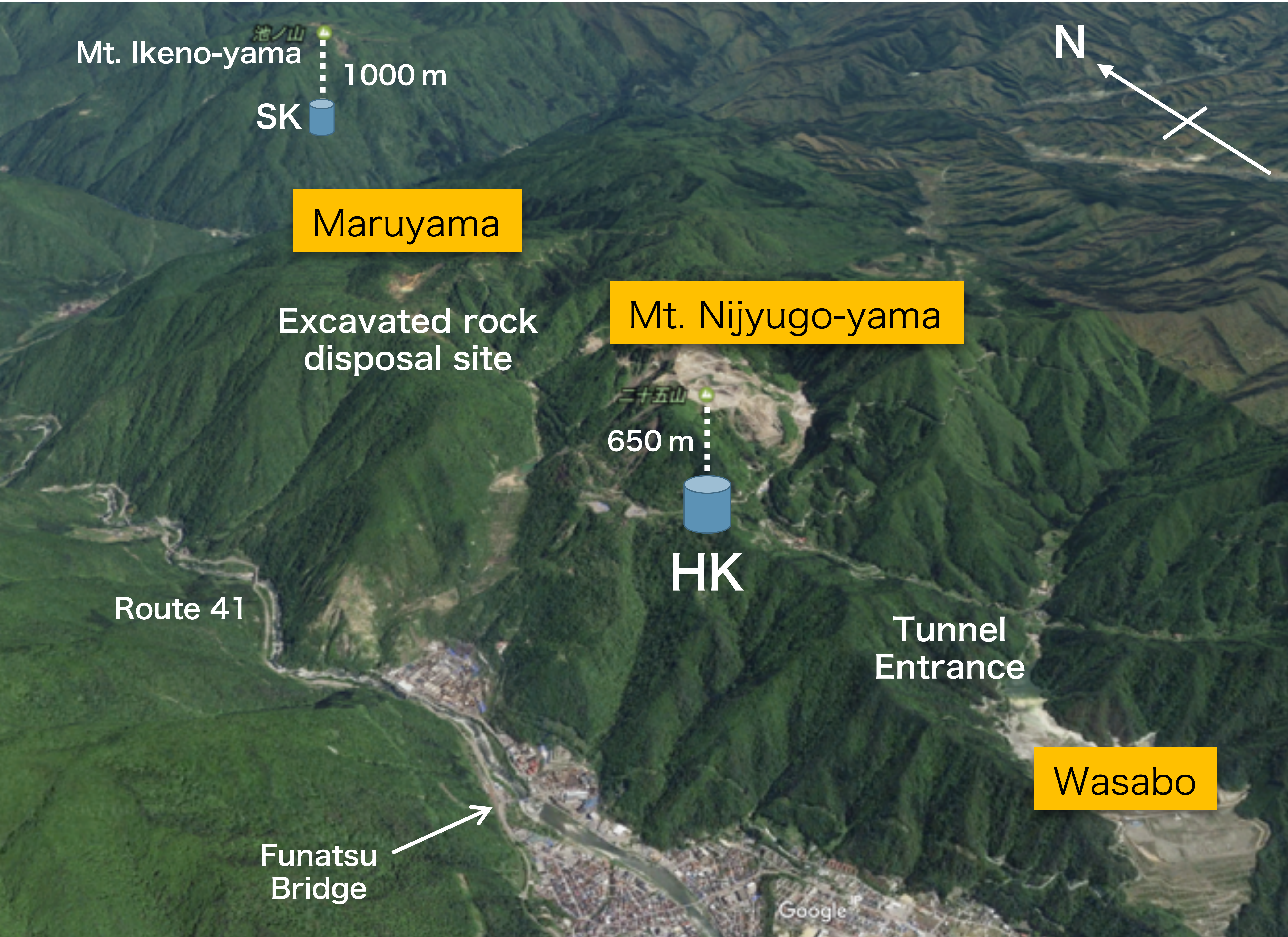
(See also “Hyper-Kamiokande Design Report”, arXiv : 1805.04163)

Next generation of large water Cherenkov detector

(~2027 -)



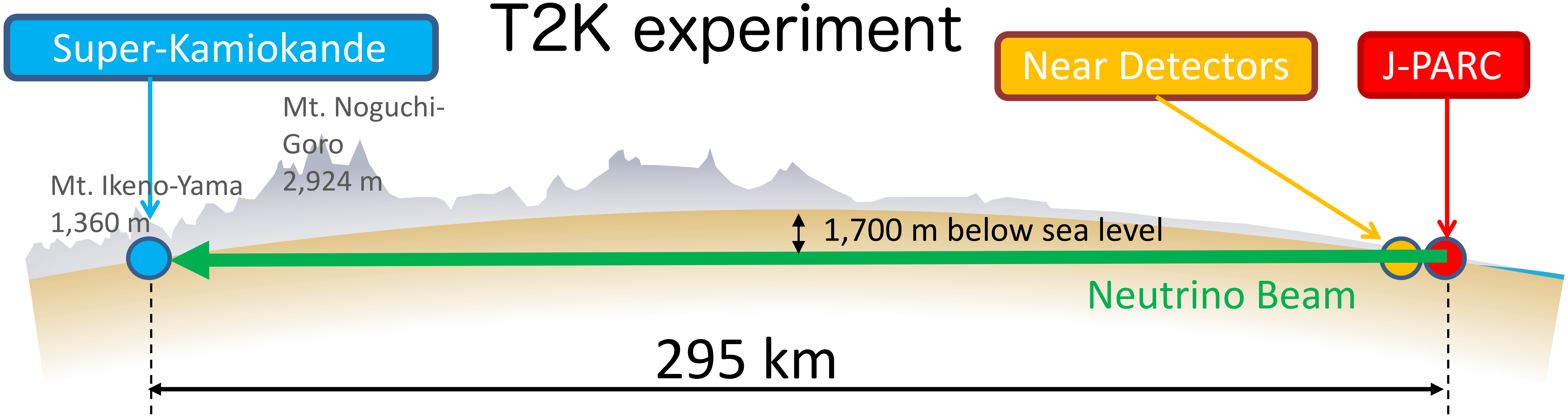
- 190kton Fiducial volume : ~10 x Super-K
- 40% photo coverage with high-efficicency PMTs : ~2 x Super-K (~40000 for inner detector)
- >MW J-PARC beam : ~3 x current power.

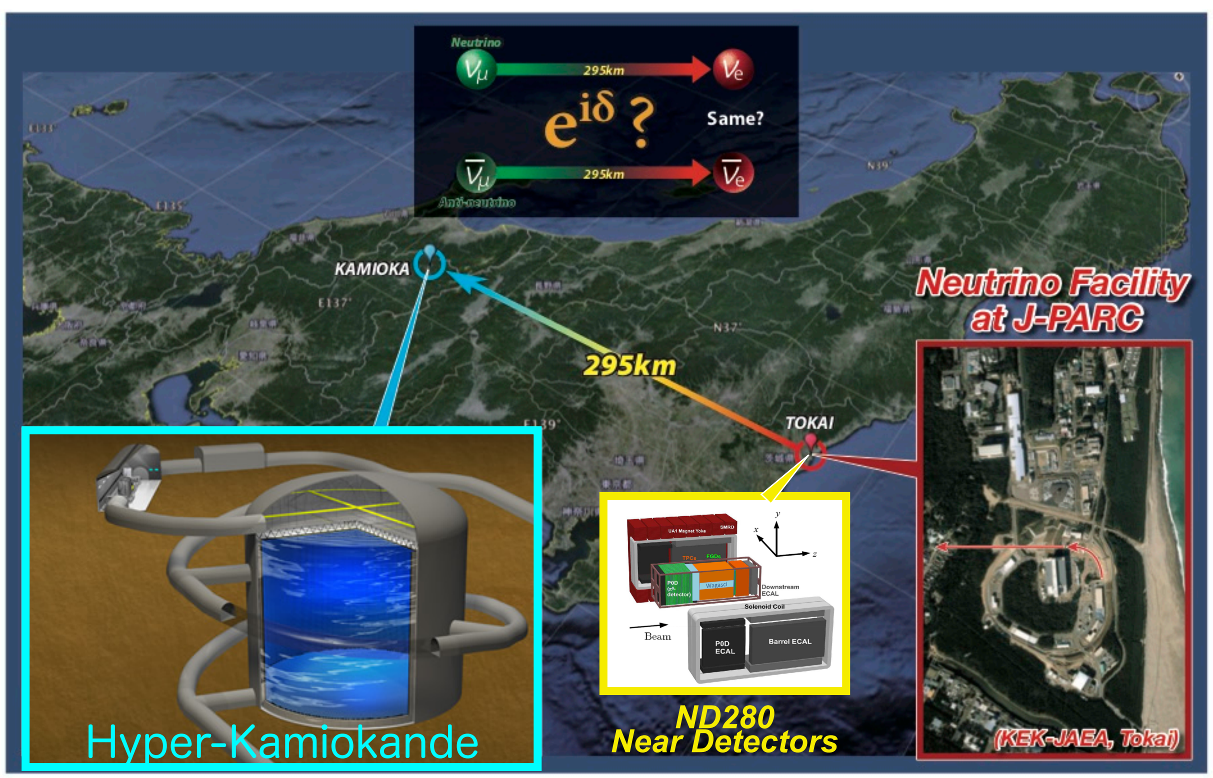


池ノ山
Mt. Ikeno-yama
1000 m
SK
N
Maruyama
Excavated rock
disposal site
Mt. Nijyugo-yama
二十五山
650 m
HK
Route 41
Tunnel
Entrance
Wasabo
Funatsu
Bridge
Google

Accelerator neutrino

Neutrino beam from J-PARC





Same beamline as T2K

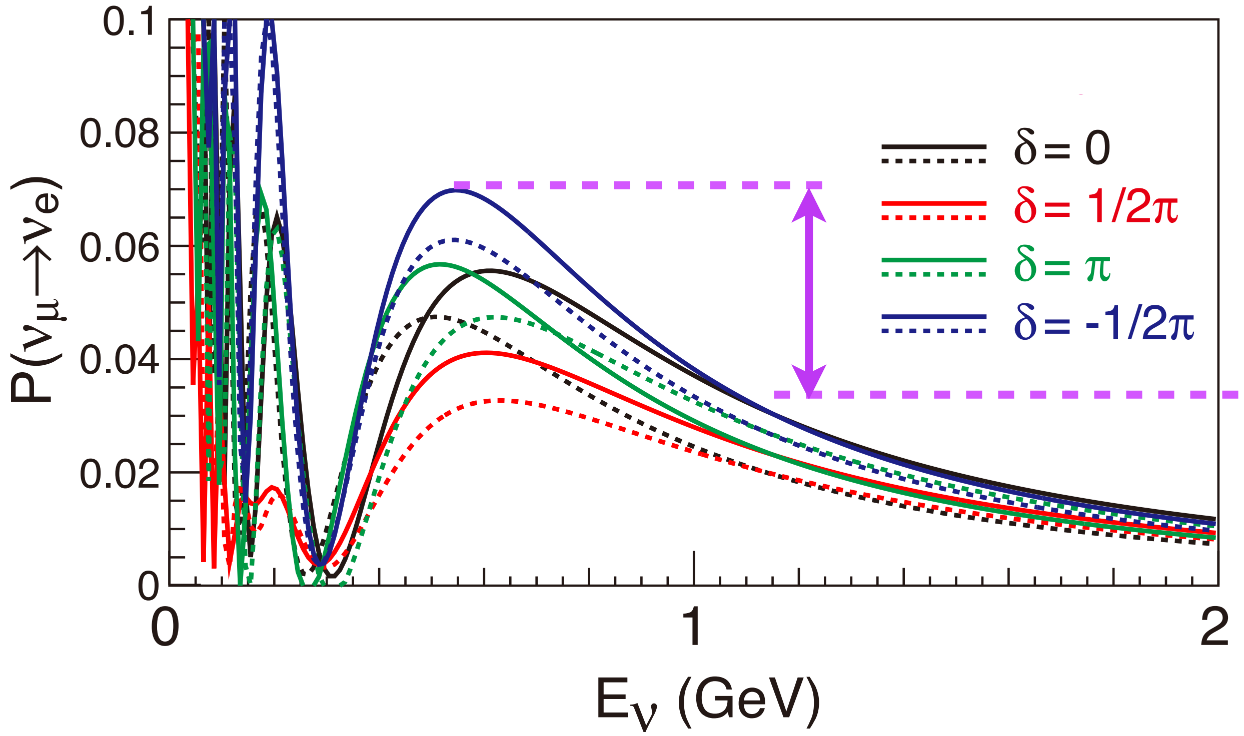
30GeV, 485kW in 2018

>1.3MW by upgrade

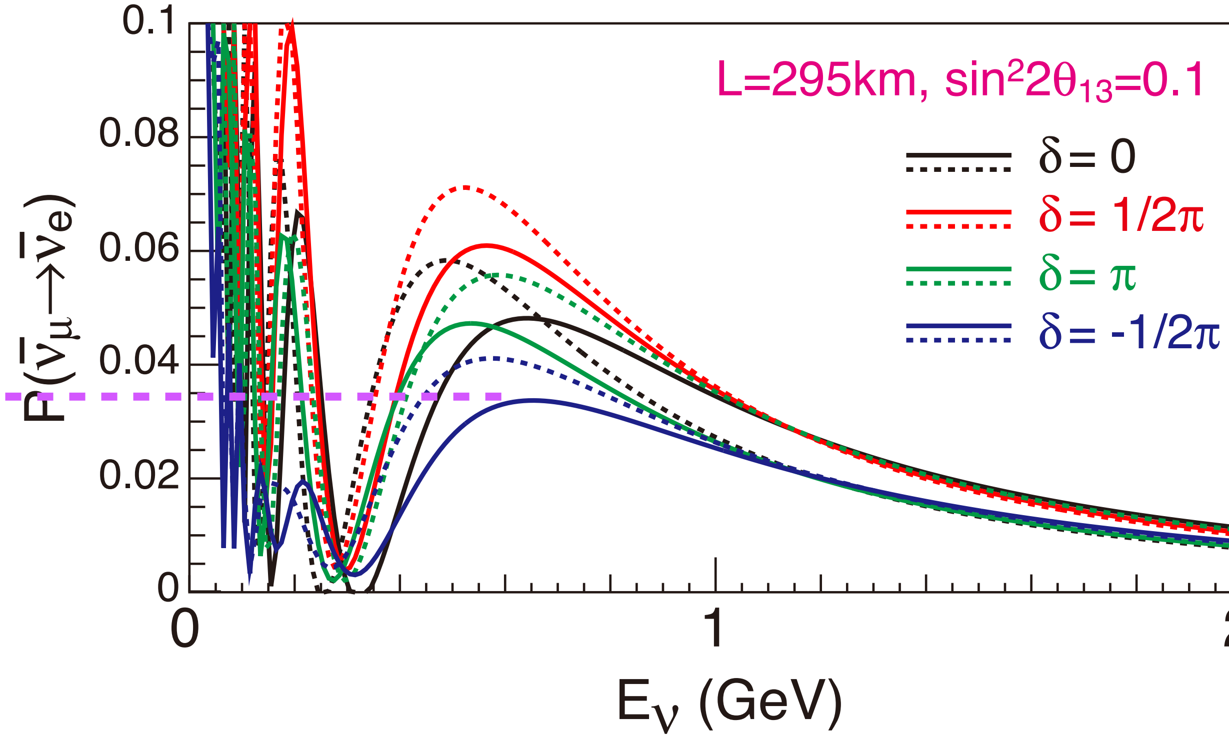
Reduce rep. cycle with new power supplies

Search for CP violation

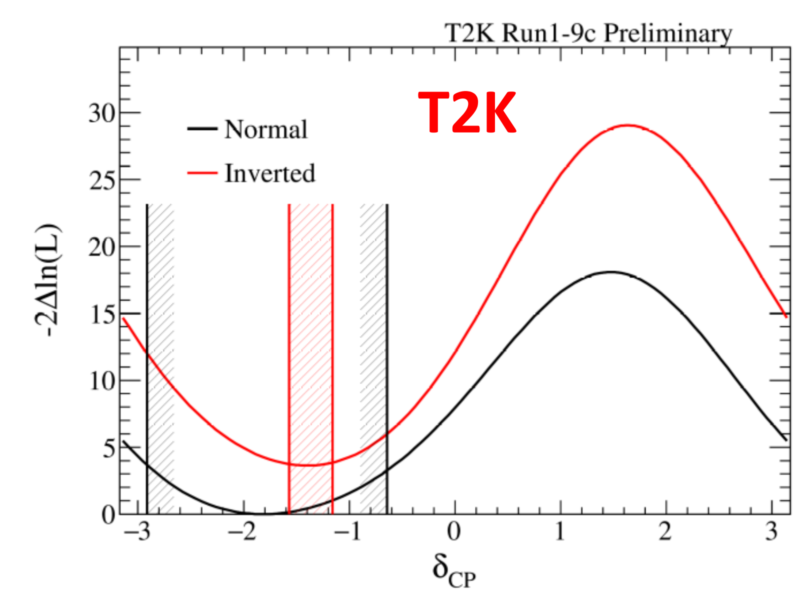
Neutrino



Anti-Neutrino



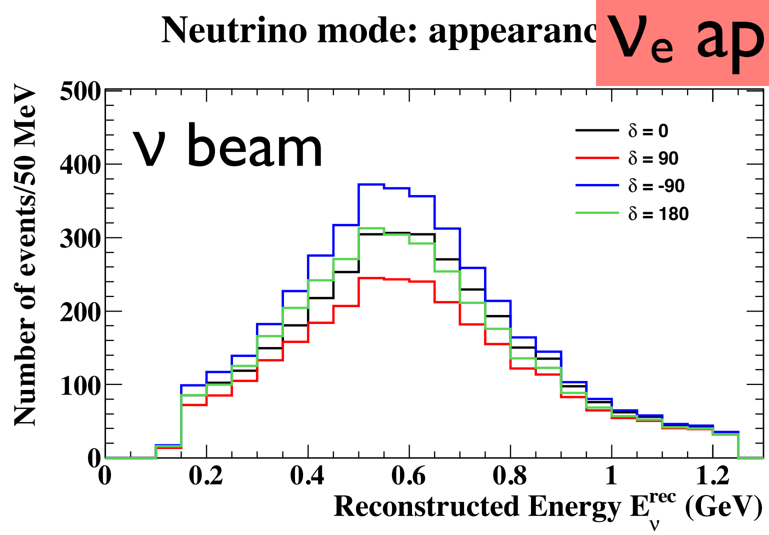
- Hint on maximal CP violation, however, need more statistics, O(1000), for definite measurement,
  cf. current T2K : 89 ν_e and 7 ν_e
- Control of systematics is crucial,
  - Neutrino beam, interaction and detector.
  - Assigned 6-7% in current T2K.

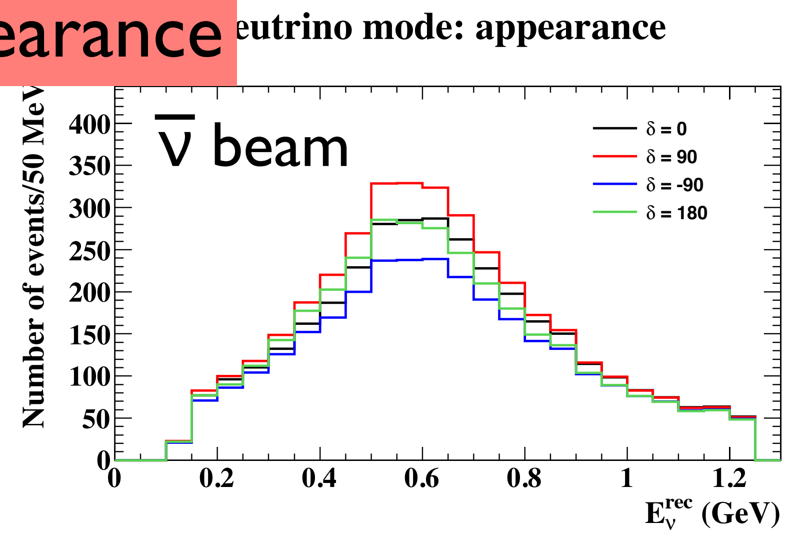


Expected events at HK

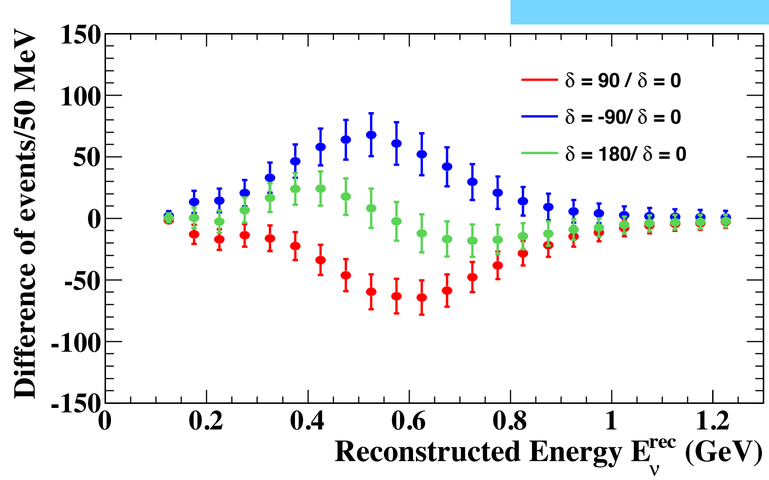
10 years (10yrs×1.3MW×10^7s), ν : νbar = 2.5yrs : 7.5yrs

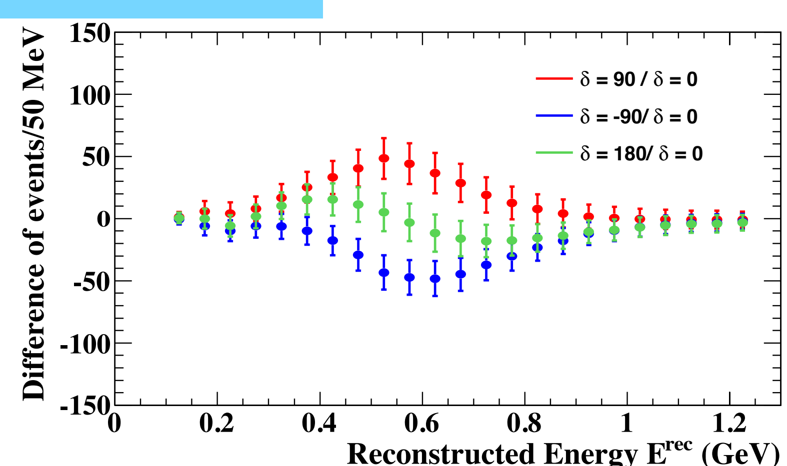
ν_e appearance



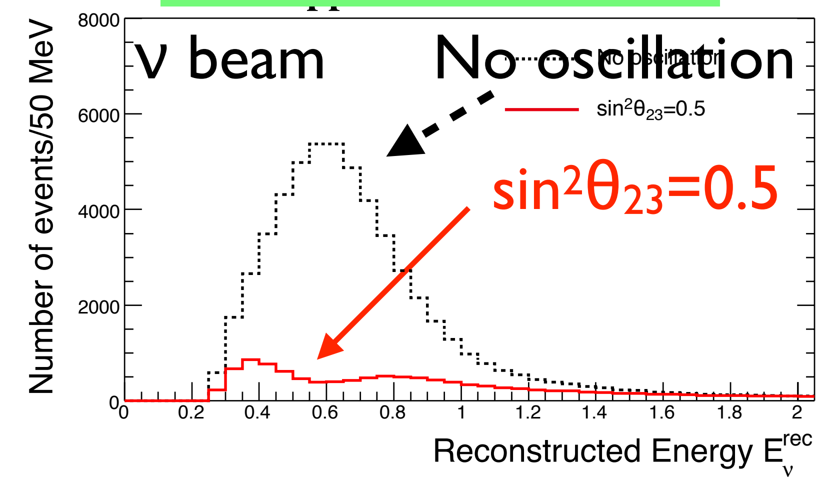


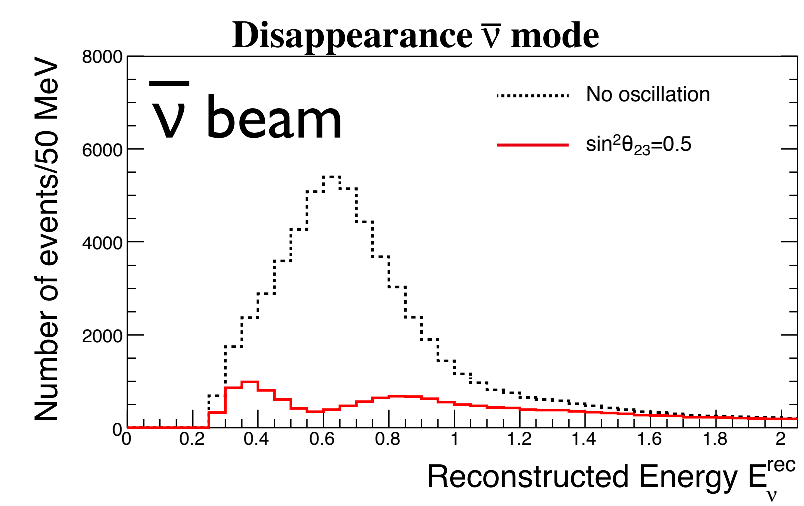
Difference from δ_{CP}=0





ν_μ disappearance





for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν beam	1,643	15	7	159	134
$\bar{\nu}$ beam	1,183	206	4	317	196

	$\nu_\mu+\bar{\nu}_\mu$ CCQE	ν_μCC nonQE	Others
ν beam	6,391	3175	515
$\bar{\nu}$ beam	8,798	4315	614

Status of the project

International organization

- International Hyper-Kamiokande proto-collaboration
  - 15 countries, 73 institutes, ~300 members, ~75% from abroad
- 2 host institutes: UTokyo/ICRR and KEK/IPNS
- UTokyo launched an institute for HK construction: Next-generation Neutrino Science Organization (NNSO)
- External review by Advisory Committee

Hyper-K meeting@Madrid, March 2018

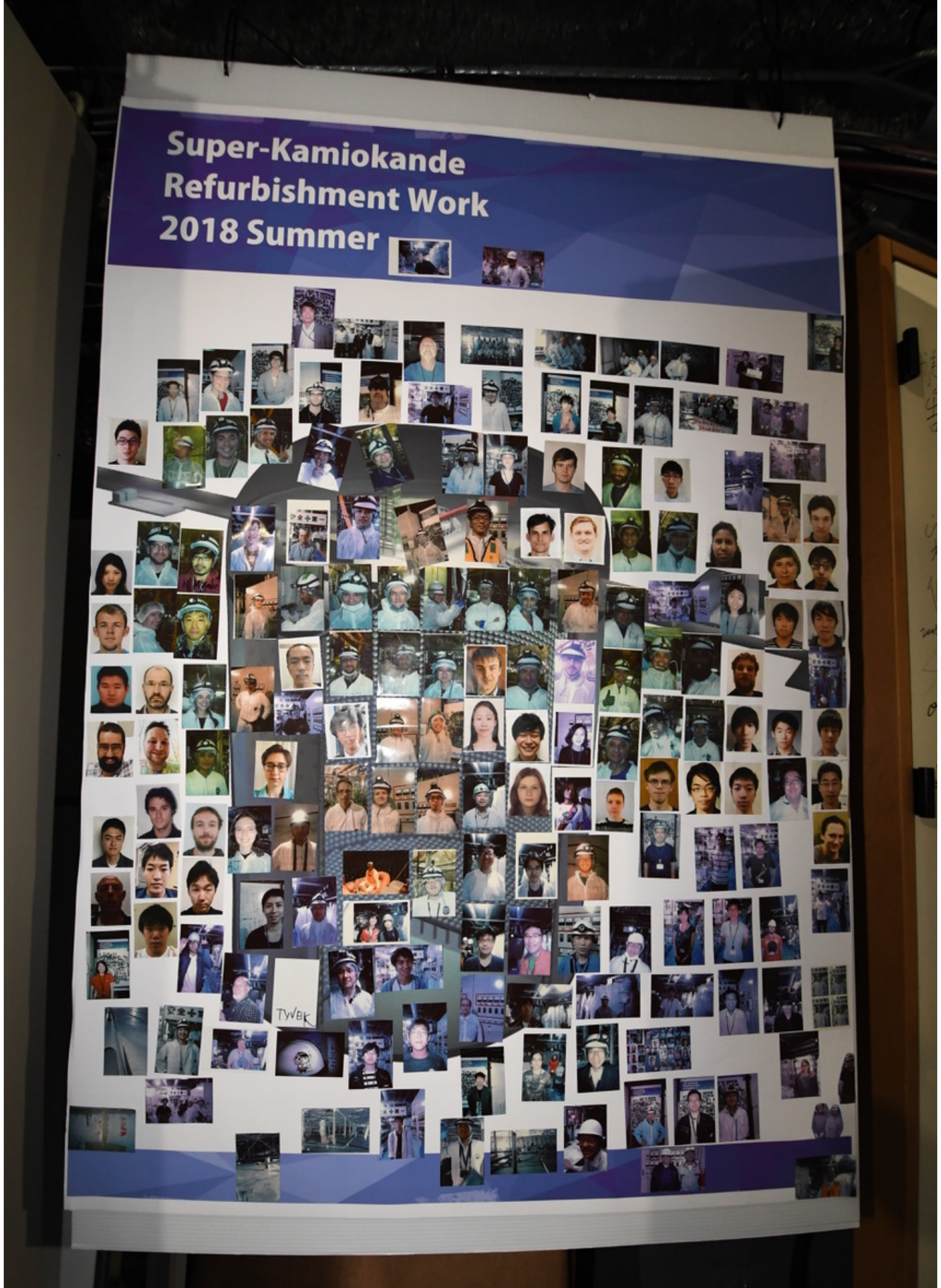
Inaugural Symposium@Kashiwanoha, January 2015

NNSO Inaugural Ceremony@Kamioka, October 2017

Research for Neutrinos

One of the hottest field in the particle physics and astrophysics. There are still remaining mysteries, and we are making the best effort to solve them.

Stay tuned!



Thank you for your attention!

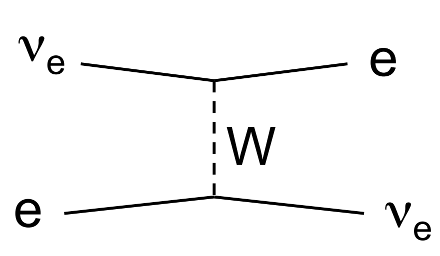
backup

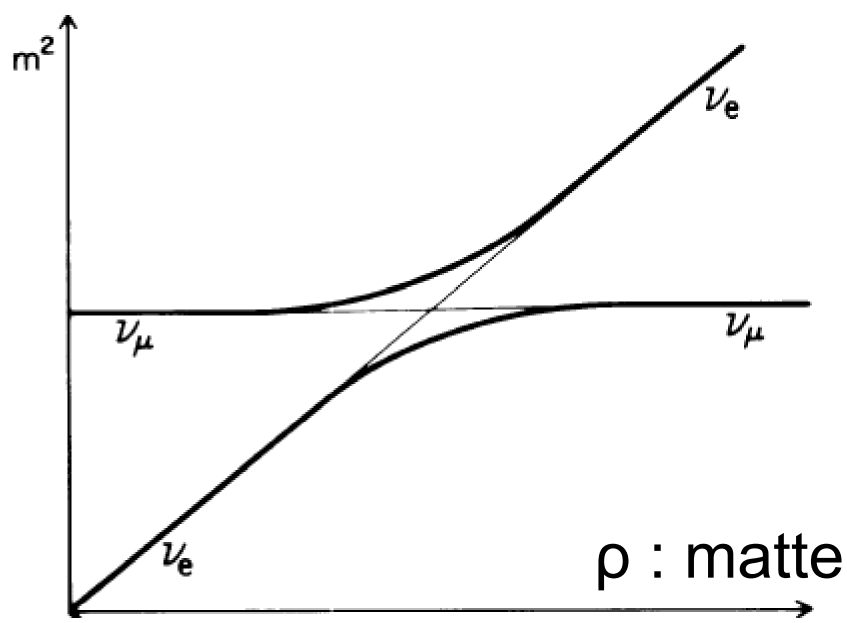
Neutrino oscillation -MSW effect-

Even if the mixing angle is small, neutrino oscillation can be enhanced by traveling through matter, especially high density like the core of the sun.

Additional potential ($V_e = \sqrt{2} G_F n_e$) should be applied only for ν_e because of the charged current.

$$i \frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + V_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}$$



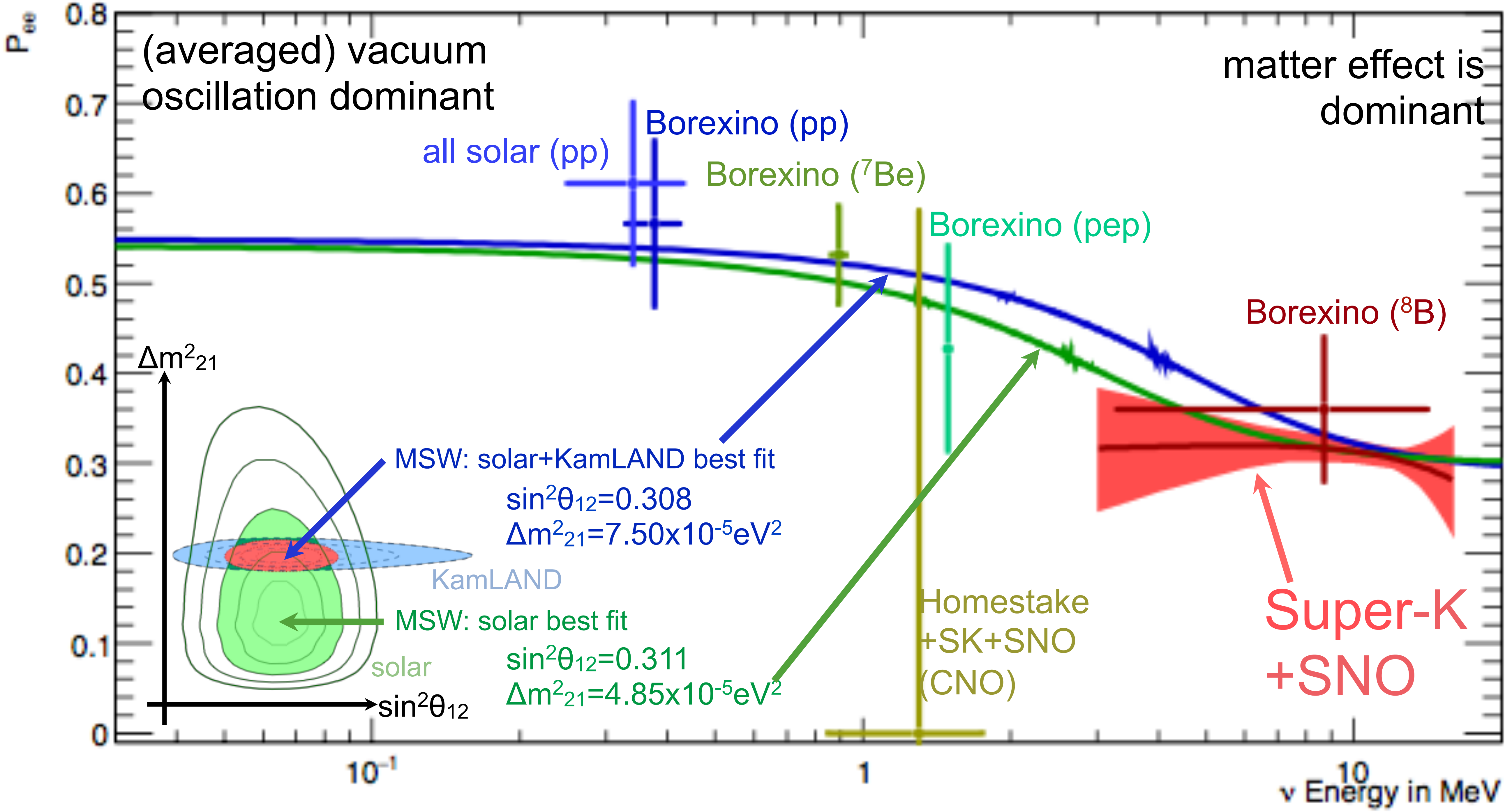


Preliminary

Survival probabilities

M. Ikeda, Neutrino 2018

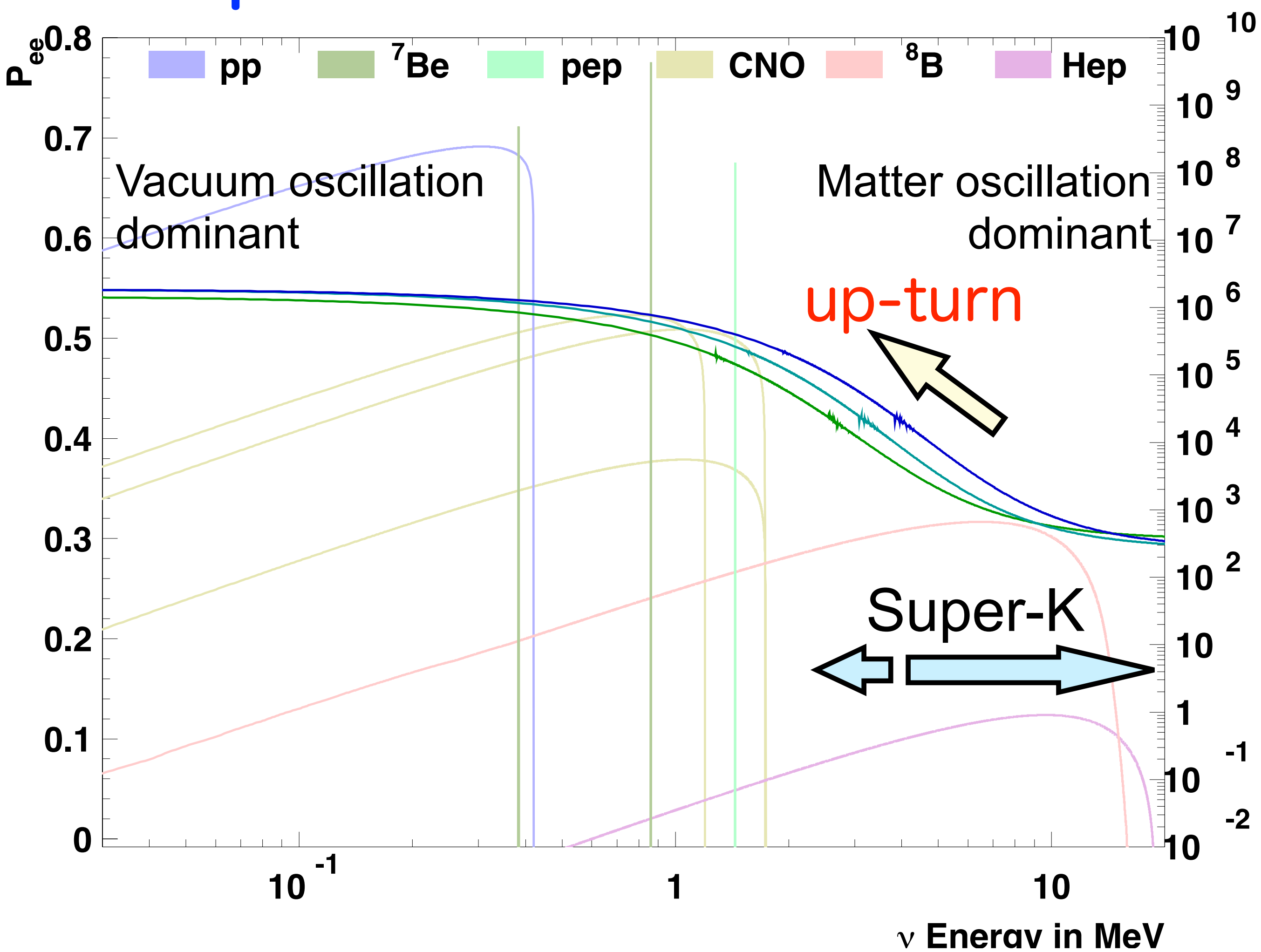
DOI: 10.5281/zenodo.1286857



Motivation of the measurement

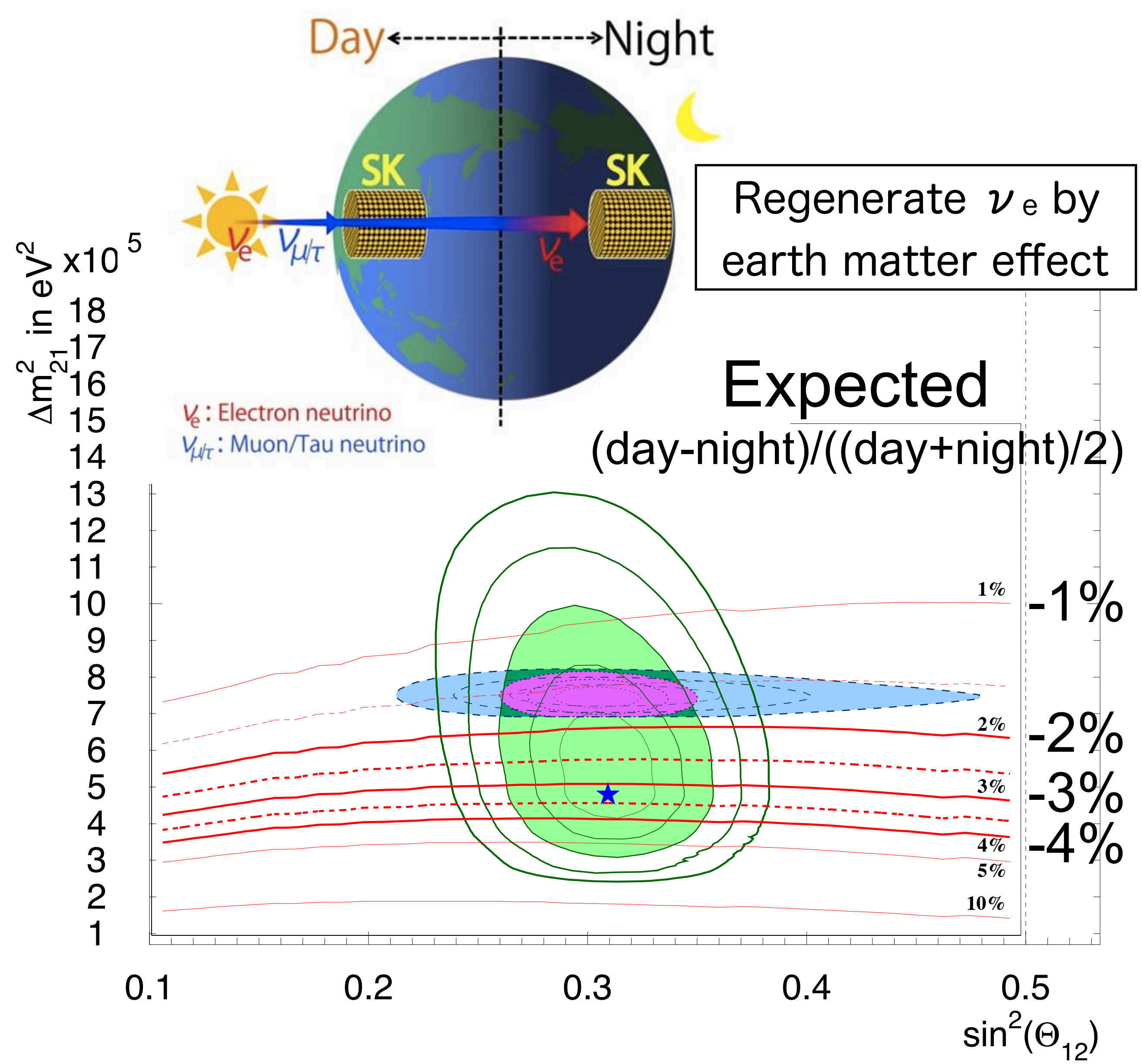
See the neutrino oscillation MSW effect directly

Spectrum distortion



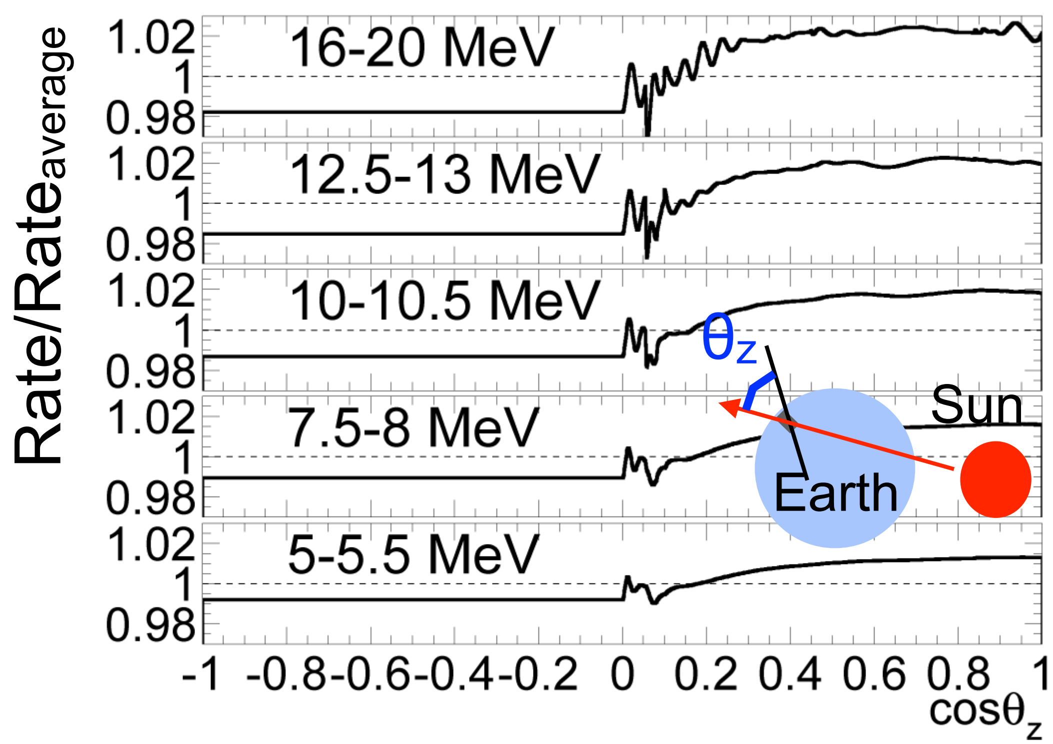
Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



Day/Night asymmetry

expected time variation as a function of $\cos\theta_z$



PRD94, 052010 (2016)

Day/Night Amplitude is fitted to

−3.3±1.0±0.5%

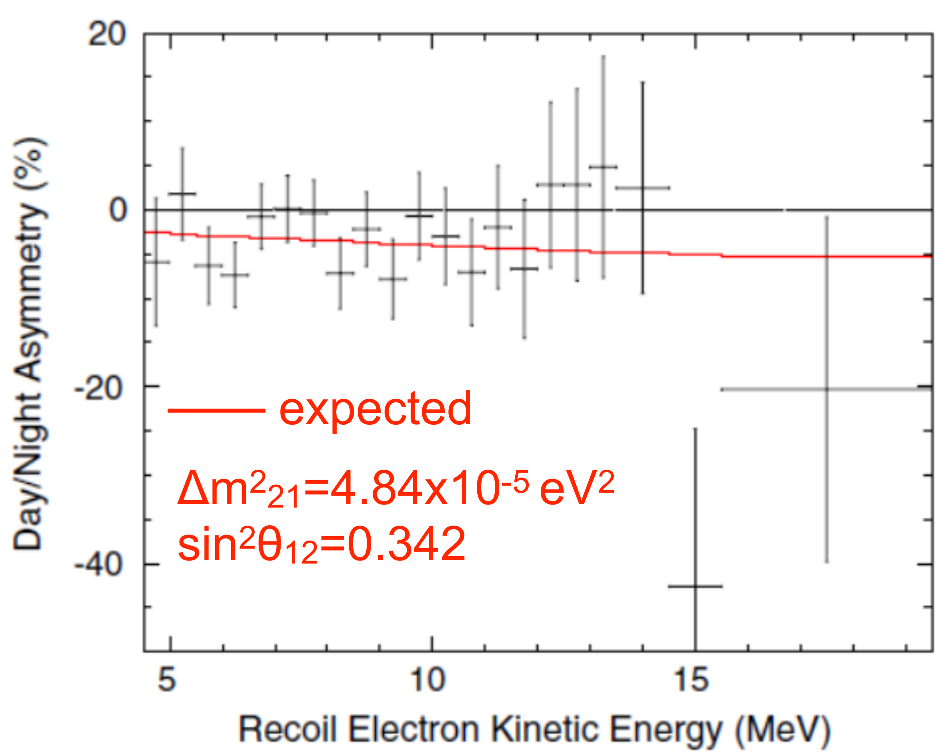
$\Delta m^2_{21}=4.84\times10^{-5}\ eV^2$
$\sin^2\theta_{12}=0.311$
$\sin^2\theta_{13}=0.025$

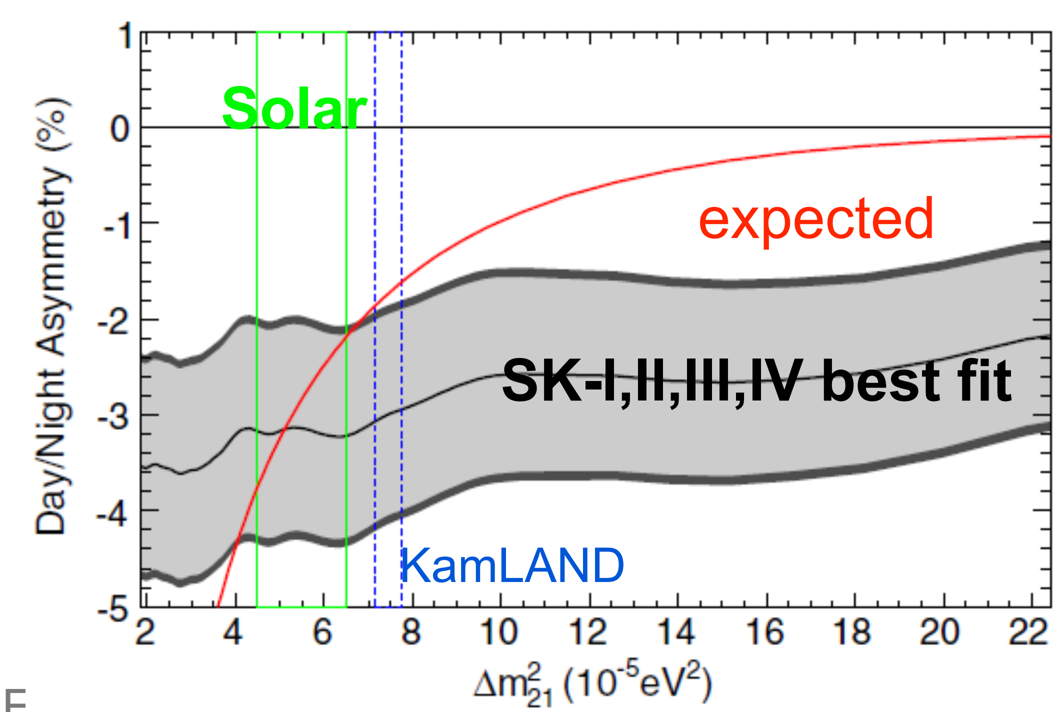
Non-zero significance is

2.9 σ

in SK-I to IV (4499 days)

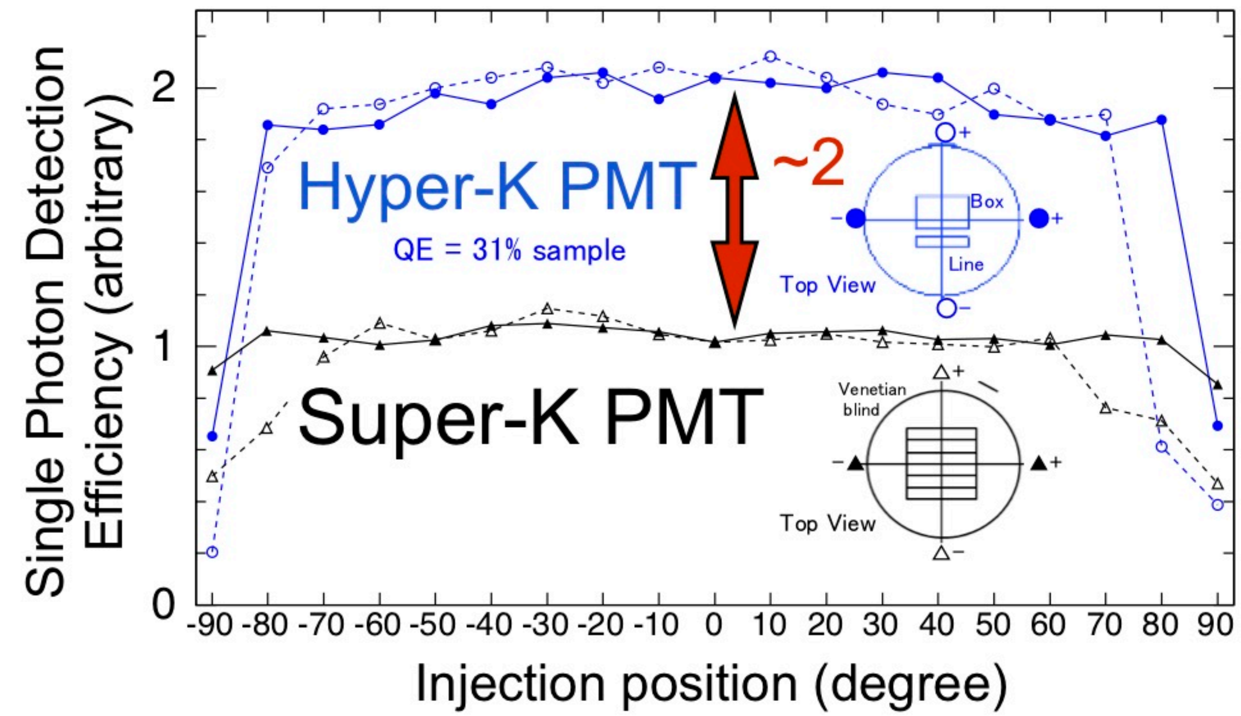
PRL112, 091805 (2014)



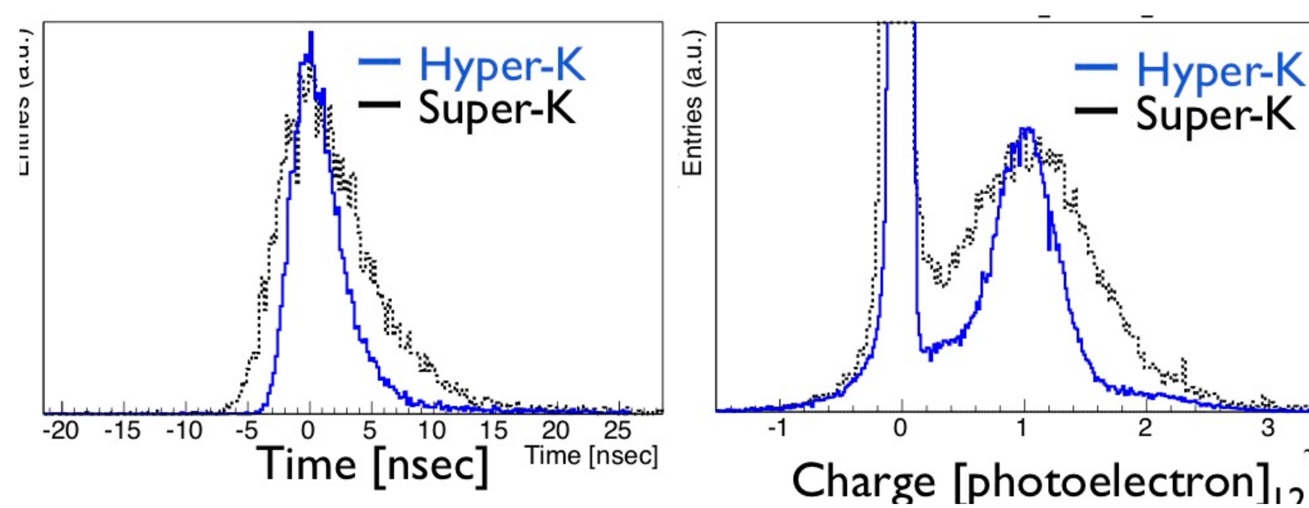


New developed photo-sensor

- Sensitivity:
  2 x SK
- Time resolution:
  1/2 x SK
- Pressure:
  2 x SK



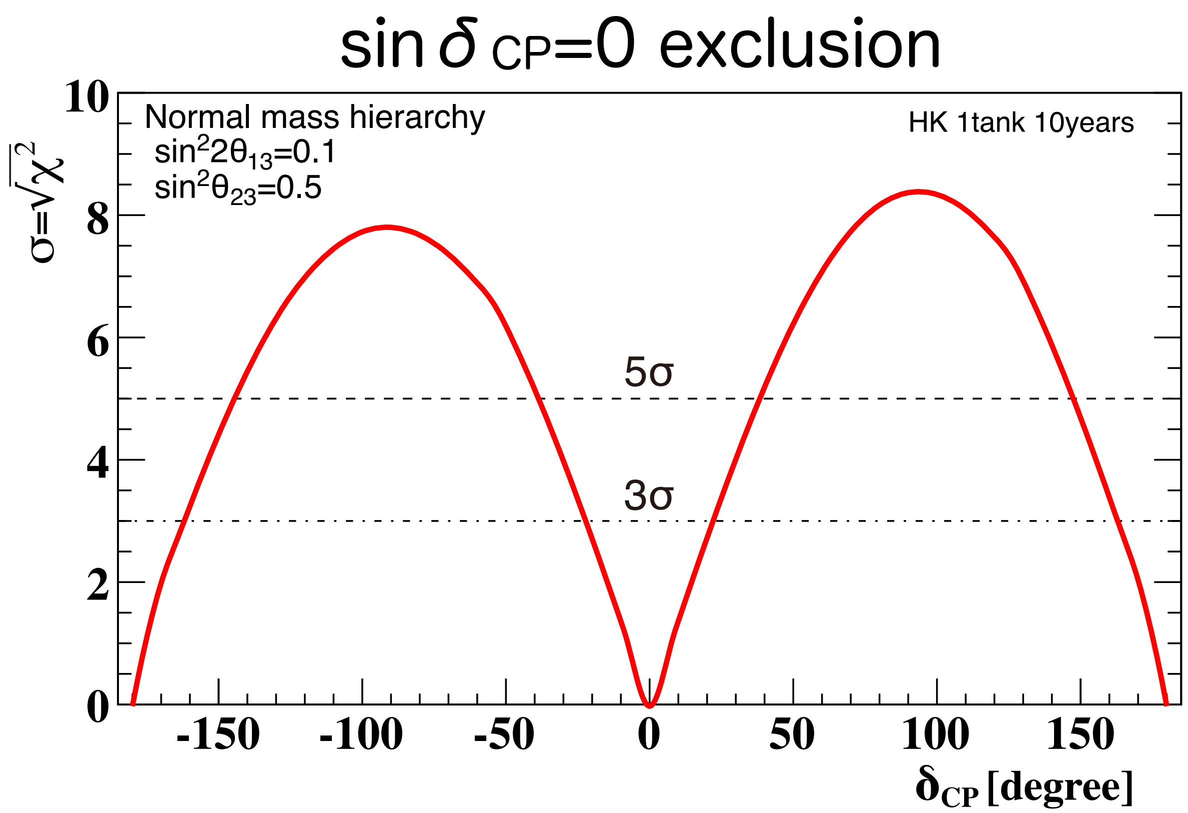
~140 new PMTs have been installed in SK this summer. Performance will be checked with Cherenkov light for years.

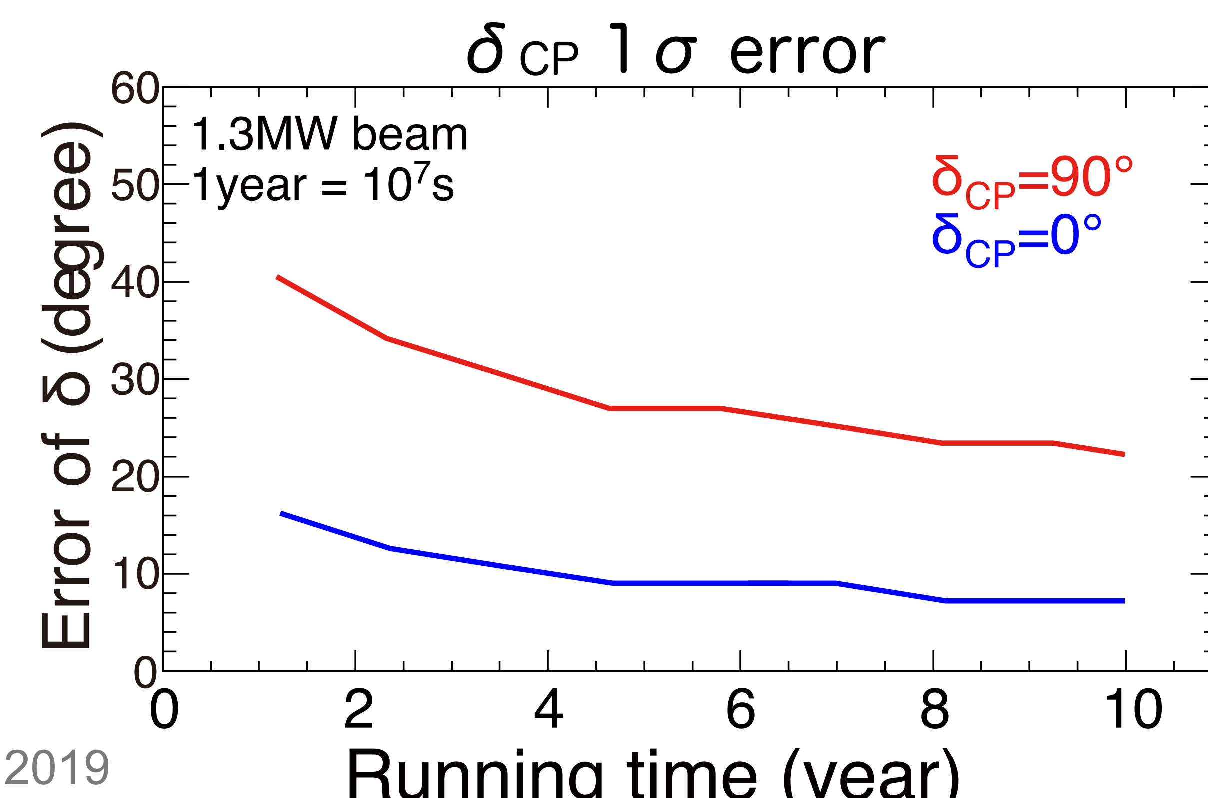


Continuous effort for improvements, e.g. noise reduction, cover design, light concentrator, etc.

CP violation sensitivity

- Exclusion of sin δ CP=0
  - 8σ (6σ) for δ=-90° (±45°)
  - 76% (58%) coverage of parameter space for CPV discovery w/ >3σ (>5σ)
- δ CP precision measurement
  - 22° for δ=±90°
  - 7° for δ=0° or 180°
- Enhanced further by combination with atmospheric ν





Toward construction start

- MEXT (Ministry of Science in Japan) lists the Hyper-K in its Roadmap2017 as a priority big project
- UTokyo is making all efforts to get funded with strong leadership of the president Gonokami.
  - Hyper-K is requested to MEXT as a top priority project
  - UTokyo launched "Next-Generation Neutrino Science Organization" to host Hyper-K
- Seed funding has been allocated within MEXT budget request for JFY2019
  - It usually led to full funding in the following year, as it was the case for the Super-Kamiokande

Statement of the president of UTokyo

September 12th, 2018

https://www.u-tokyo.ac.jp/focus/ja/articles/z0208_00006.html

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020.

September 12th, 2018

Concerning the Start of Hyper-Kamiokande

Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

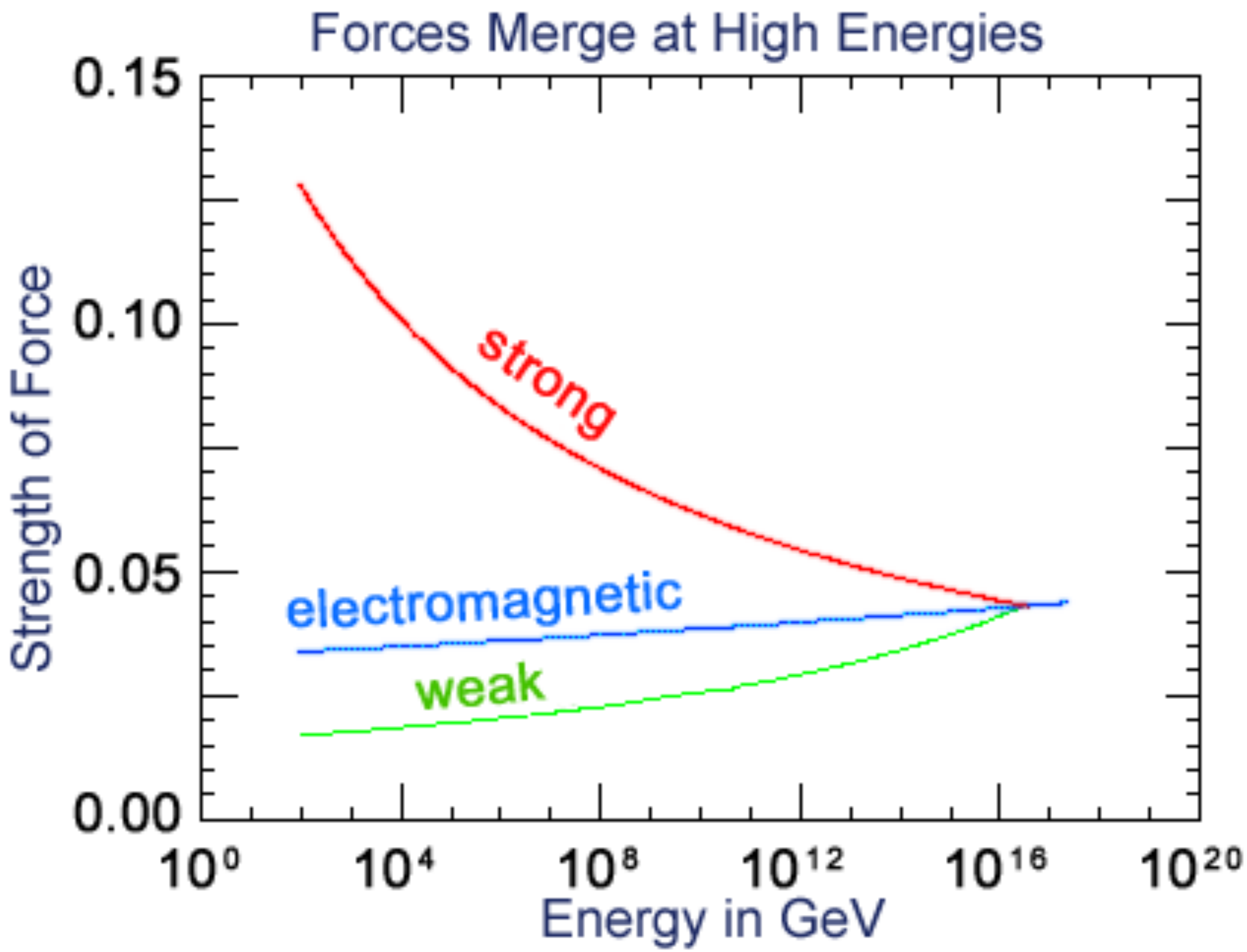
The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

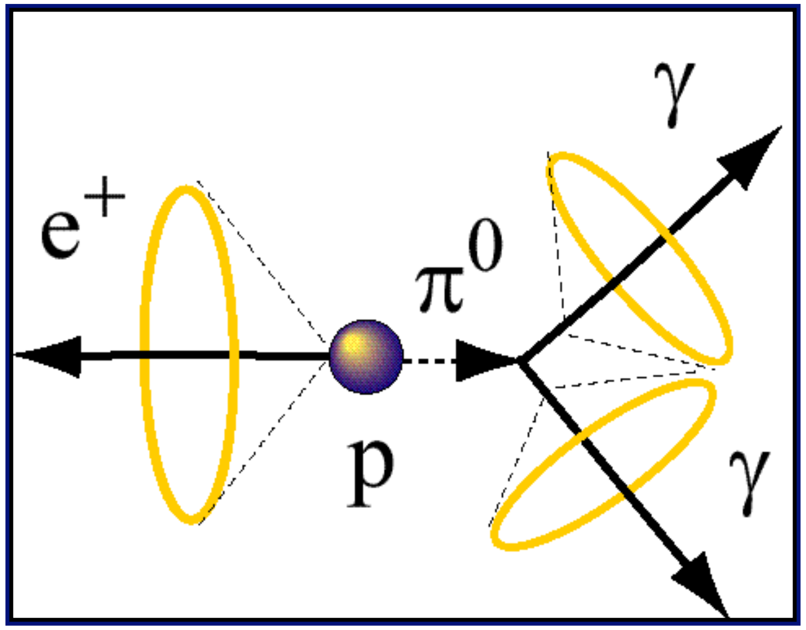
Makoto Gonokami

Makoto Gonokami
President, The University of Tokyo

Nucleon decay

Motivation

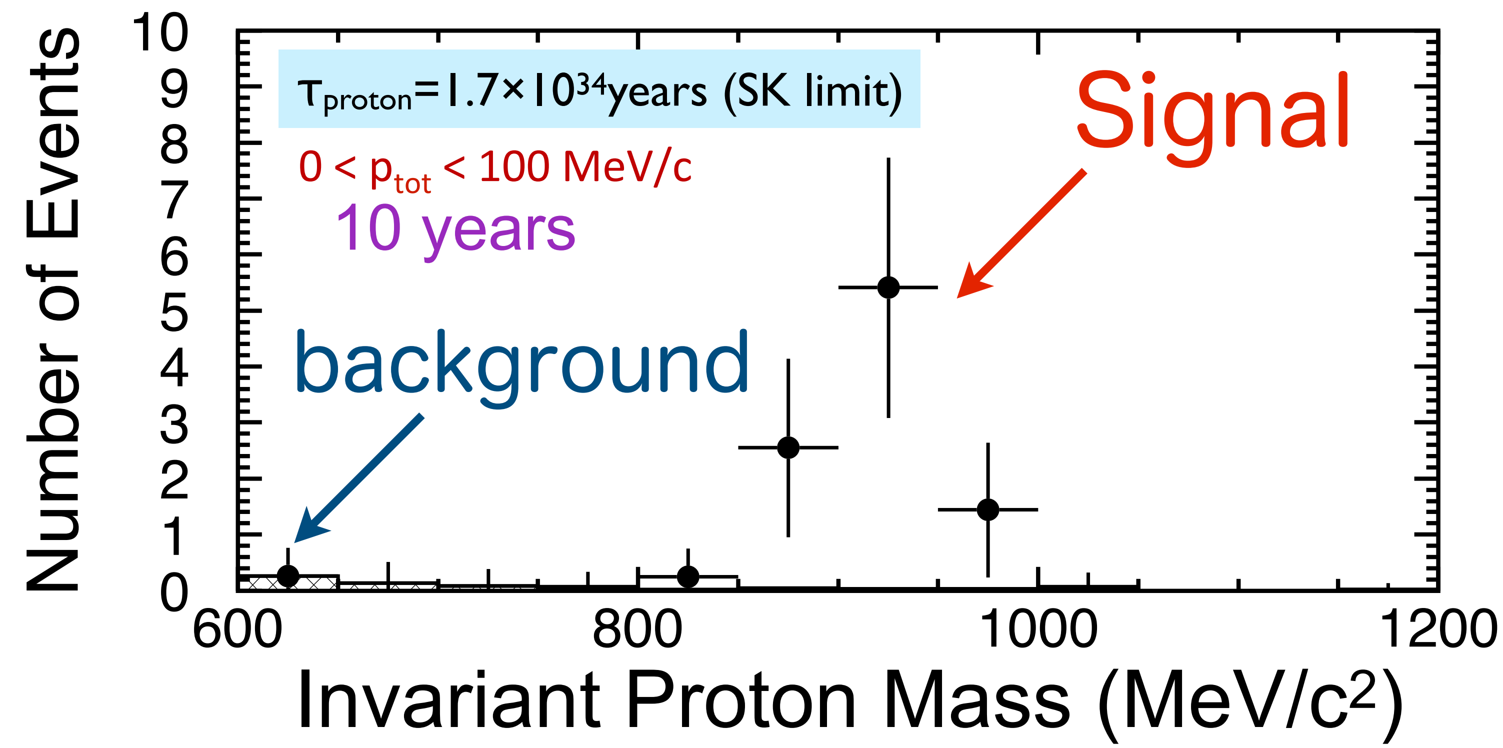




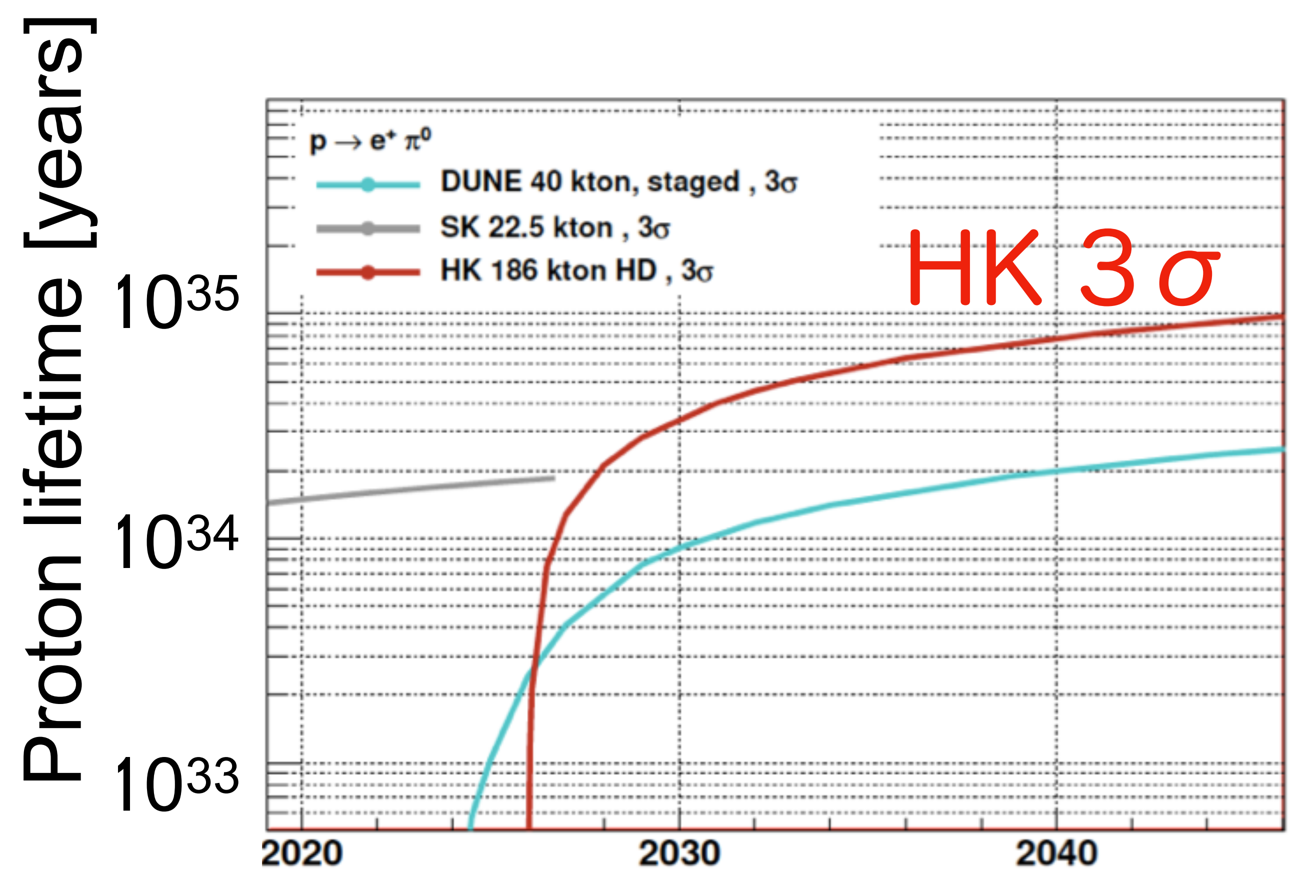
Only possible to directly prove the grand unification

p -> $e^+\pi^0$ discovery potential

- Look at an invariant proton mass
- Possible BG free search (0.06 BG/Mton year)
- Discovery potential reach to 10^{35} years



p_{tot}<100MeV/c		100<p_{tot}<250MeV/c	
Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
18.7	0.06	19.4	0.62



p -> νK^+ discovery potential

- K is invisible, so it is identified by daughter particles;
  - Monochromatic muon (236 MeV/c) for K->$\mu\nu$
  - K->$\pi^+\pi^0$
- Possible BG free search (0.06 BG/Mton year)
- Discovery potential reach to > 3 x10^{34} years

prompt-γ & $K^+\to\mu^+\nu$		$K^+\to\pi^+\pi^0$	
Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
12.7	0.9	10.8	0.7