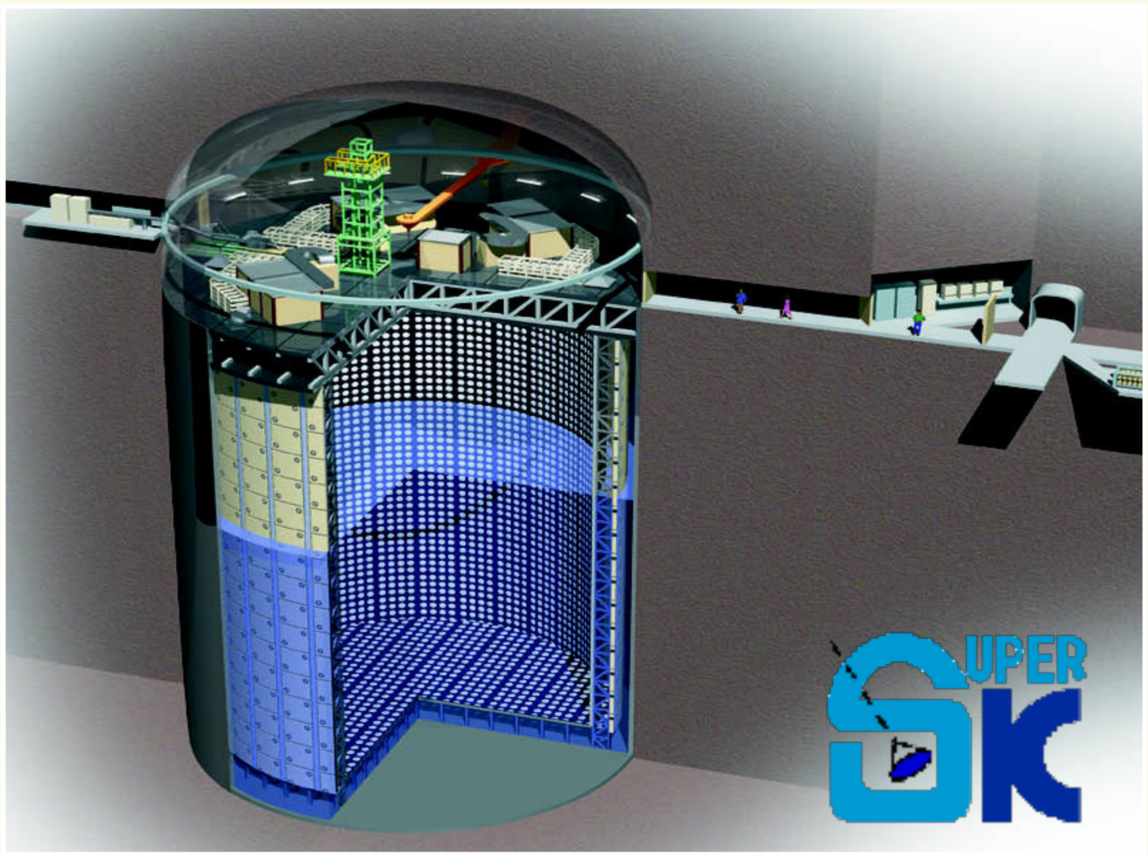
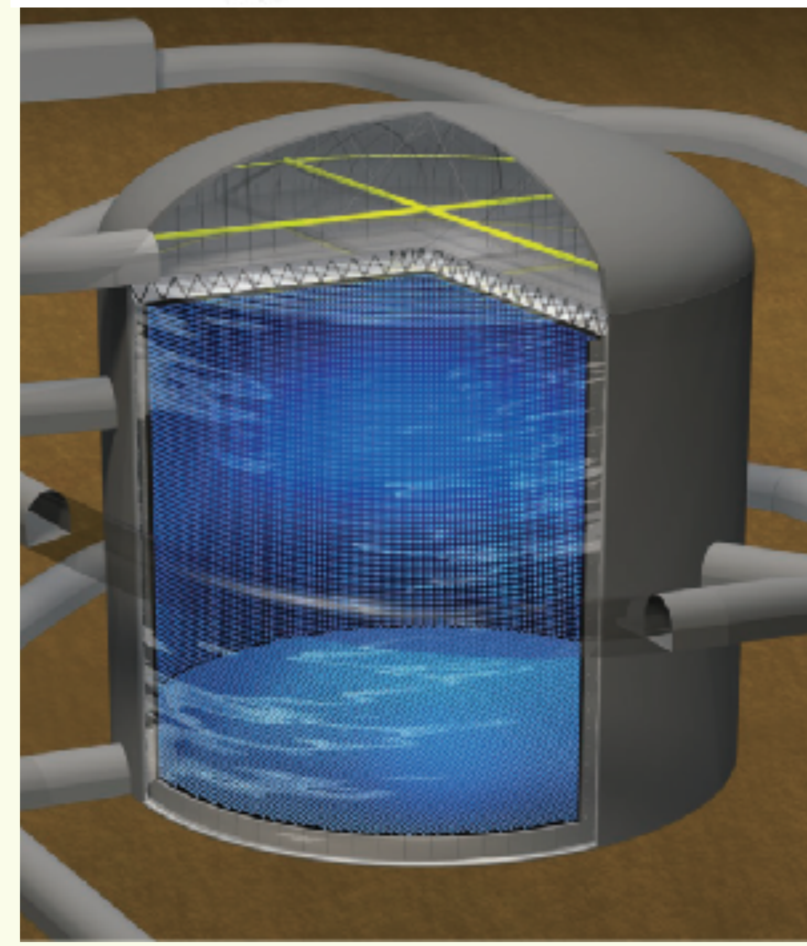
Highlights from ICRR ~~(ICCR)~~

(Institution for Cosmic Ray Research)



Hyper-Kamiokande

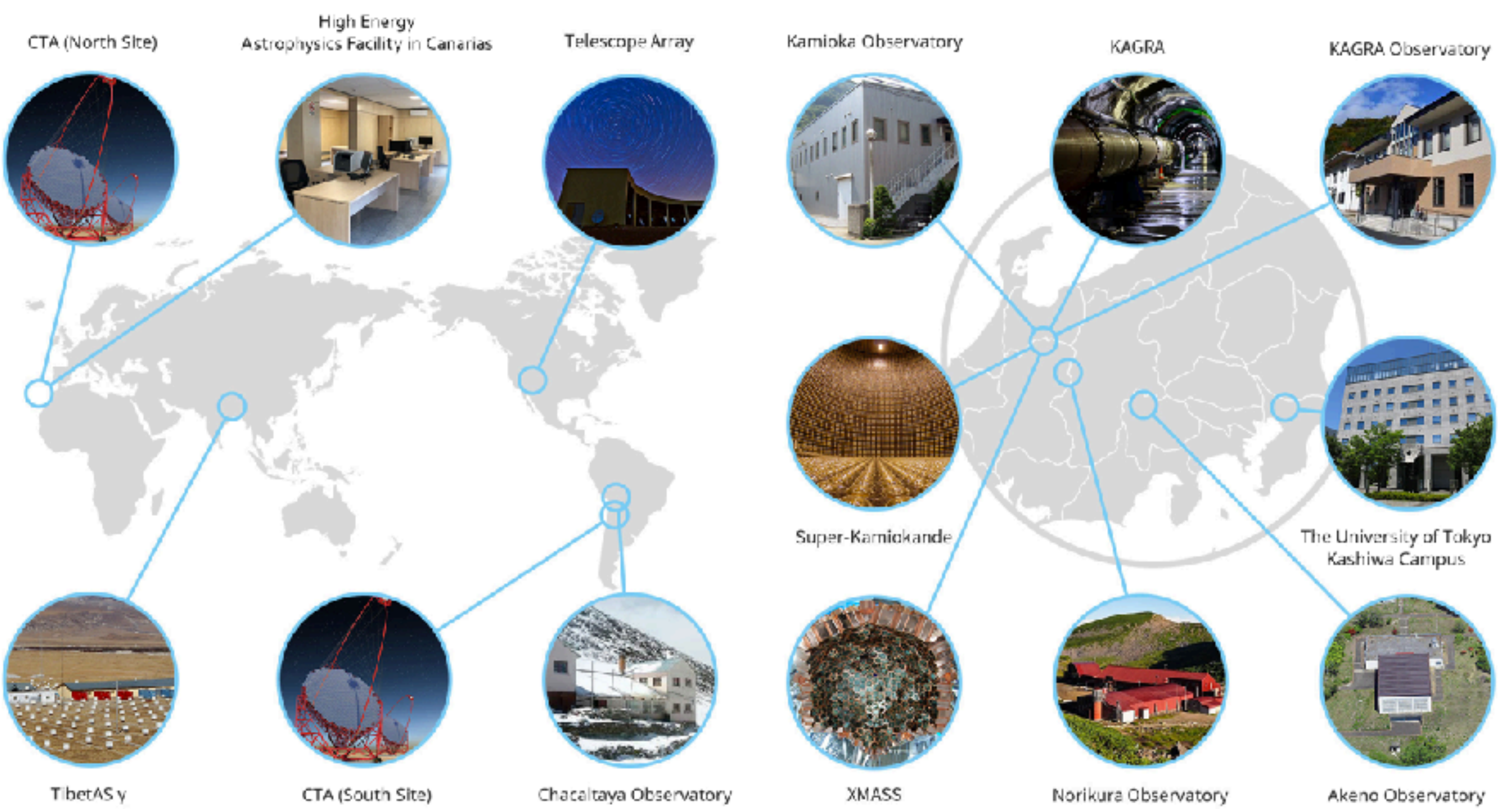


Yusuke Koshio
Okayama University

<<ETTORE MAJORANA>> Foundation and center for science culture
International school of subnuclear physics
58th Course: Gravity and Matter in the subnuclear world
16 June, 2022

What's ICRR?

Institution as an inter-university for various fundamental research on the universe and elementary particles using cosmic rays.



The director is changed

In April 2022

Prof. Kajita

Prof. Nakahata

Why I'm here?

Brief self introduction

- Join Kamioka group as a graduate student of ICRR, University of Tokyo. Got PhD in 1998, titled 'Study of Solar Neutrinos at Super-Kamiokande'
- Assistant professor in ICRR until 2013.
- Joined Borexino experiment 2009-2013, as visiting scientist of Gran Sasso Lab.
- Move to Okayama university in 2013, and continue Super-Kamiokande and Hyper-Kamiokande project.

Concentrate on neutrino physics in this talk

Brief introduction of Neutrino experiment in ICRR

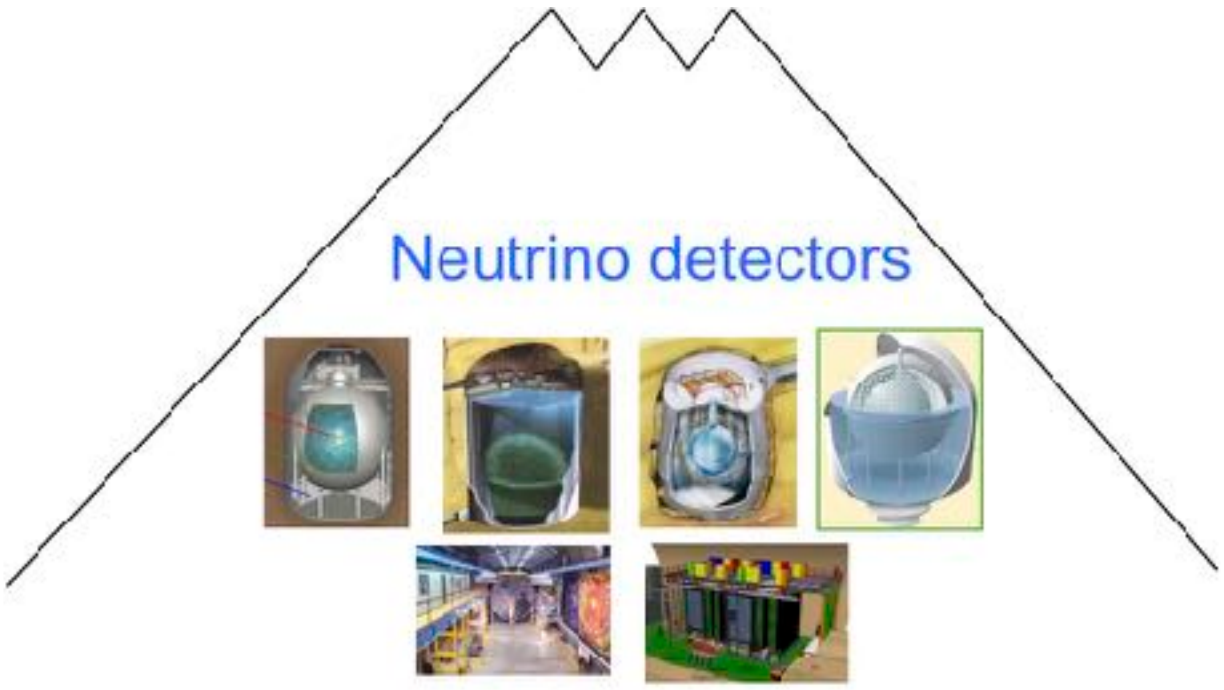
Neutrino experiment

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

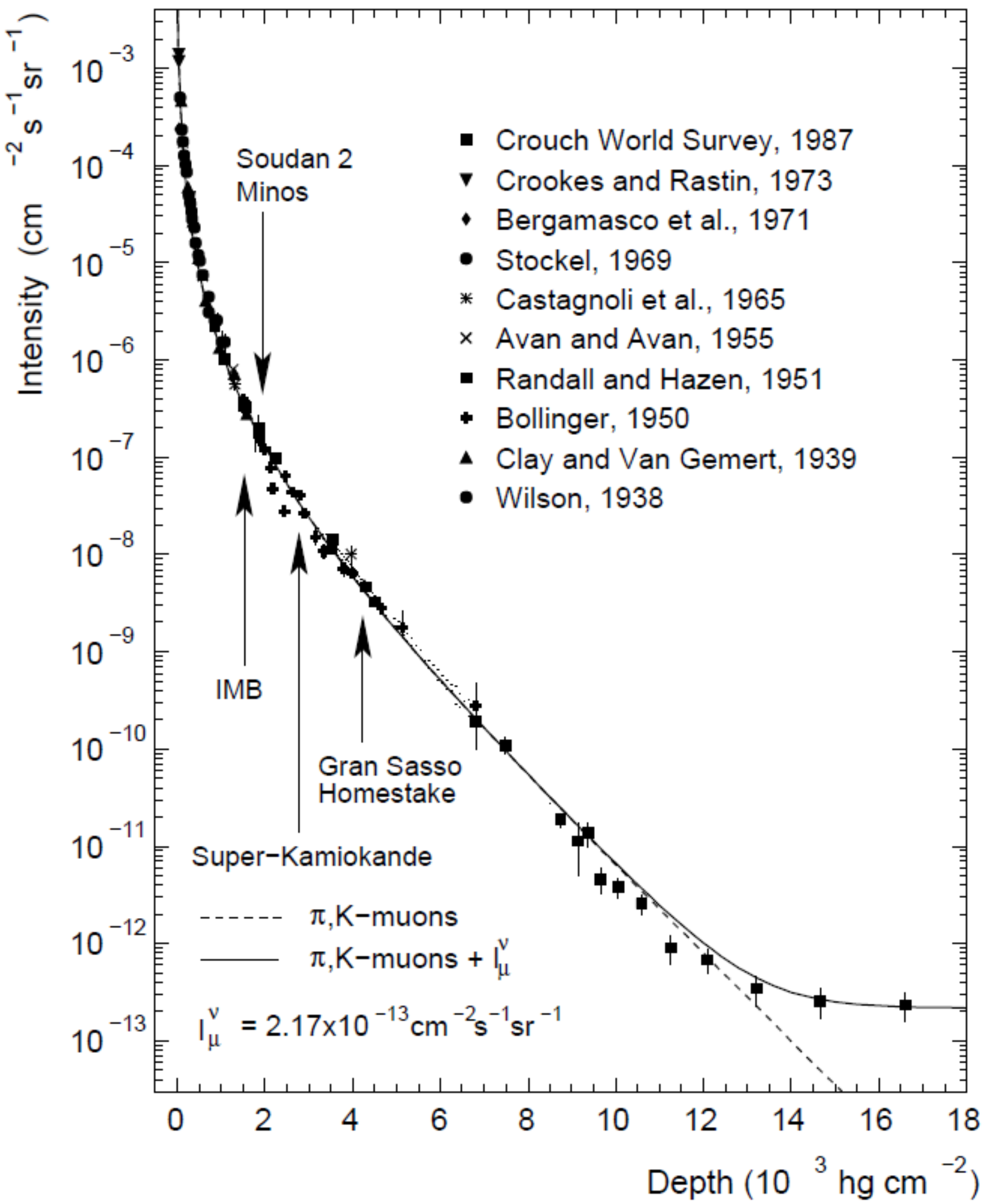
$$\sigma = \frac{G_F^2 s}{\pi}$$

$\sim(E_\nu[GeV])\times 10^{-38}cm^2$

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)

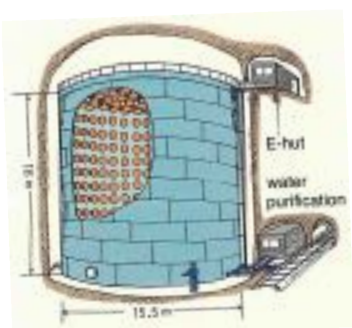


Deep underground in order to remove cosmic ray.

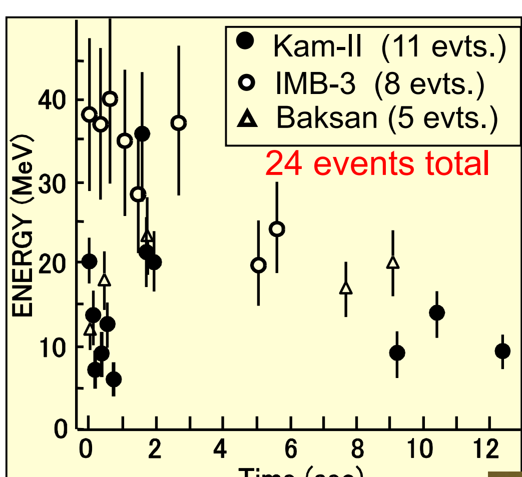


Three generations of "Kamiokande"

Kamiokande (1983-1995)

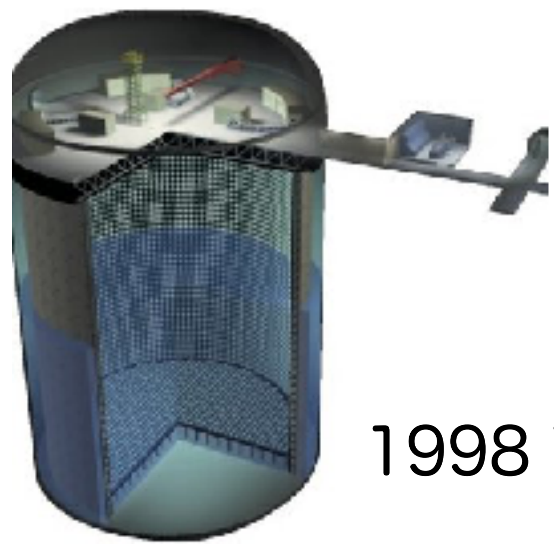


3kton
20% coverage
with 20' PMT



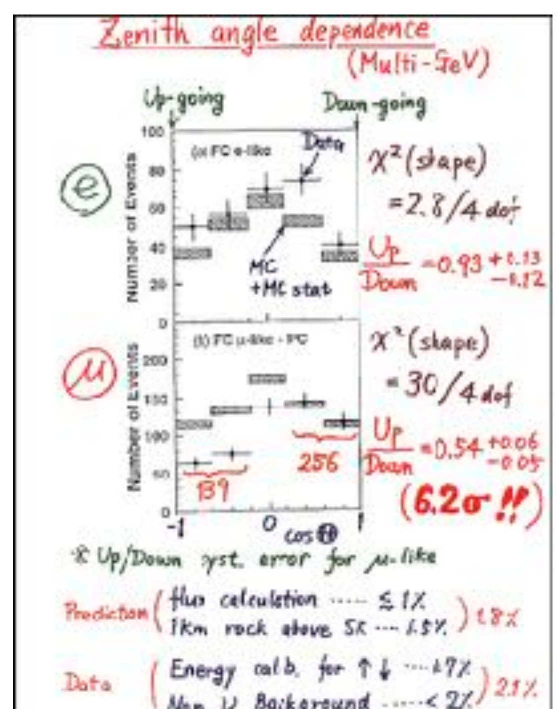
SN1987A

Super-Kamiokande (1996-)

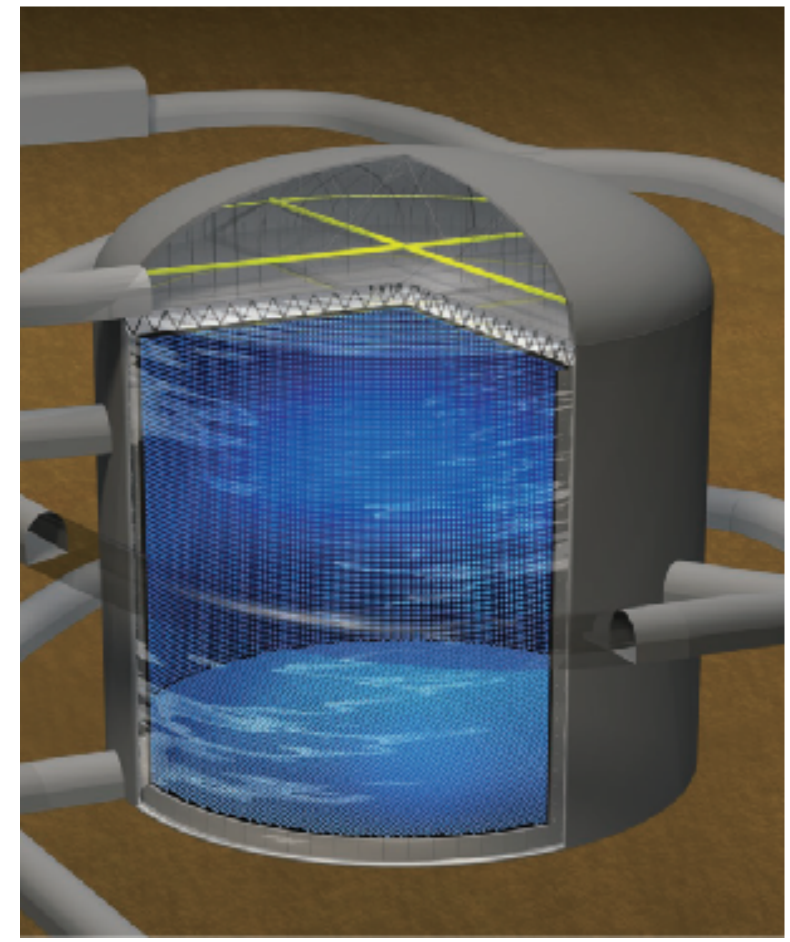


50k (22.5k) ton
40% coverage
with 20' PMT

1998 Takayama



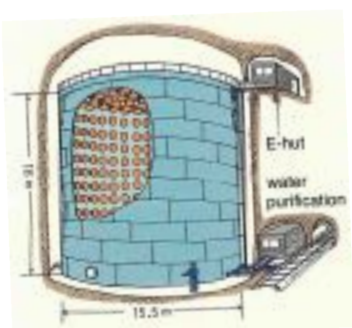
Hyper-Kamiokande (~2027-)



260k (190k) ton
20,000 high-QE 20' PMTs

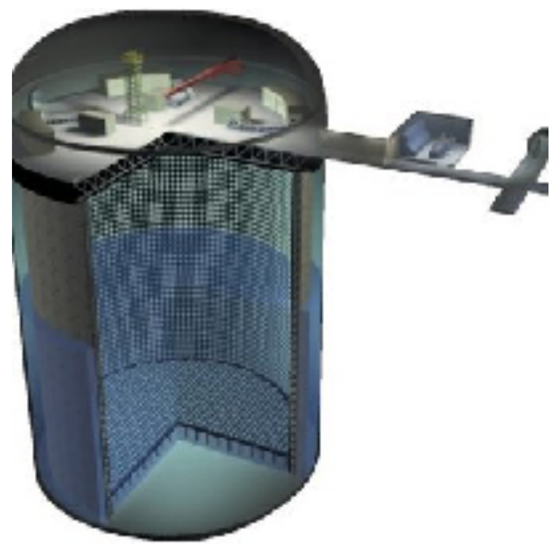
Three generations of "Kamiokande"

Kamiokande
(1983-1995)



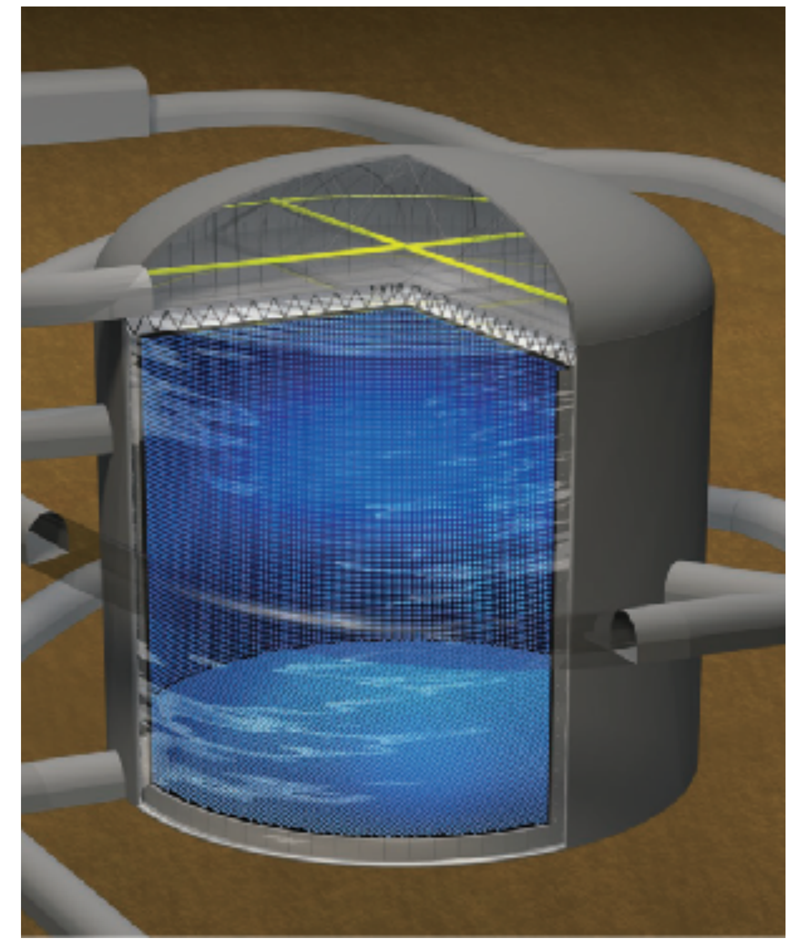
3kton
20% coverage
with 20' PMT

Super-Kamiokande
(1996-)



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

Hyper-Kamiokande (~2027-)

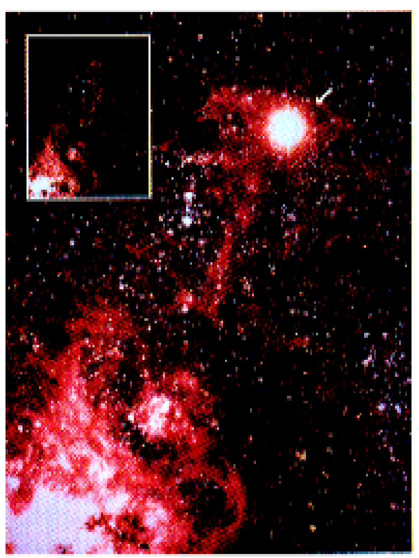


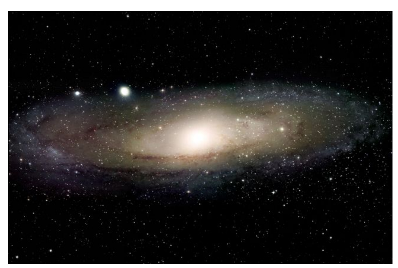
260k (190k) ton
20,000 high-QE 20' PMTs

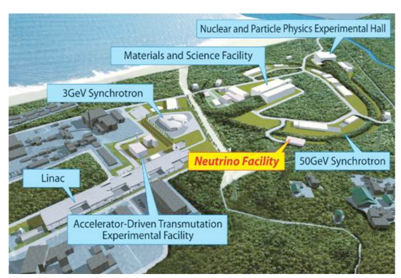
SuperK-Gd
(2020-)

Multi-purpose detector

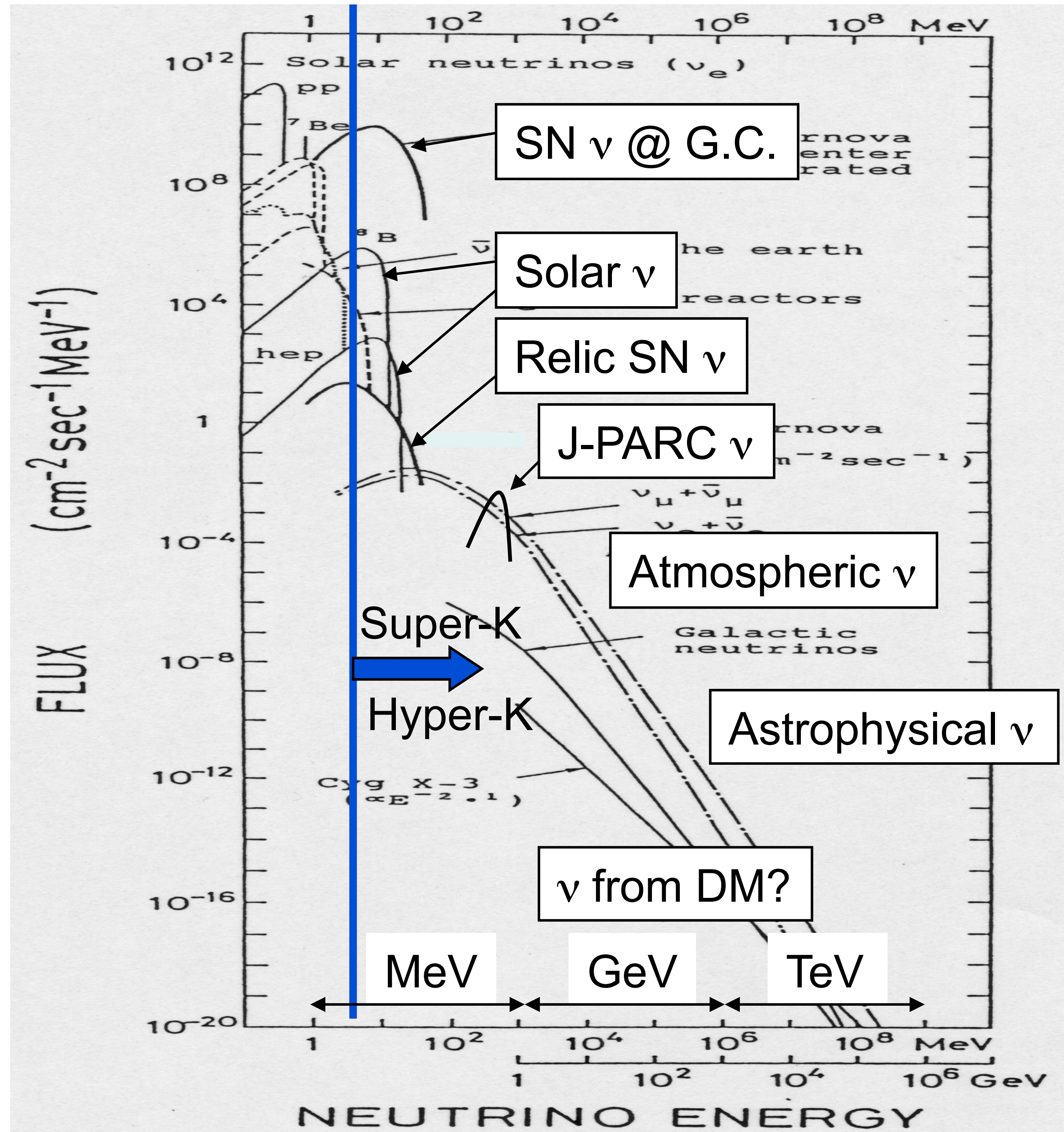
Broad scientific program
with wide energy range
(MeV~TeV)







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



Super-Kamiokande

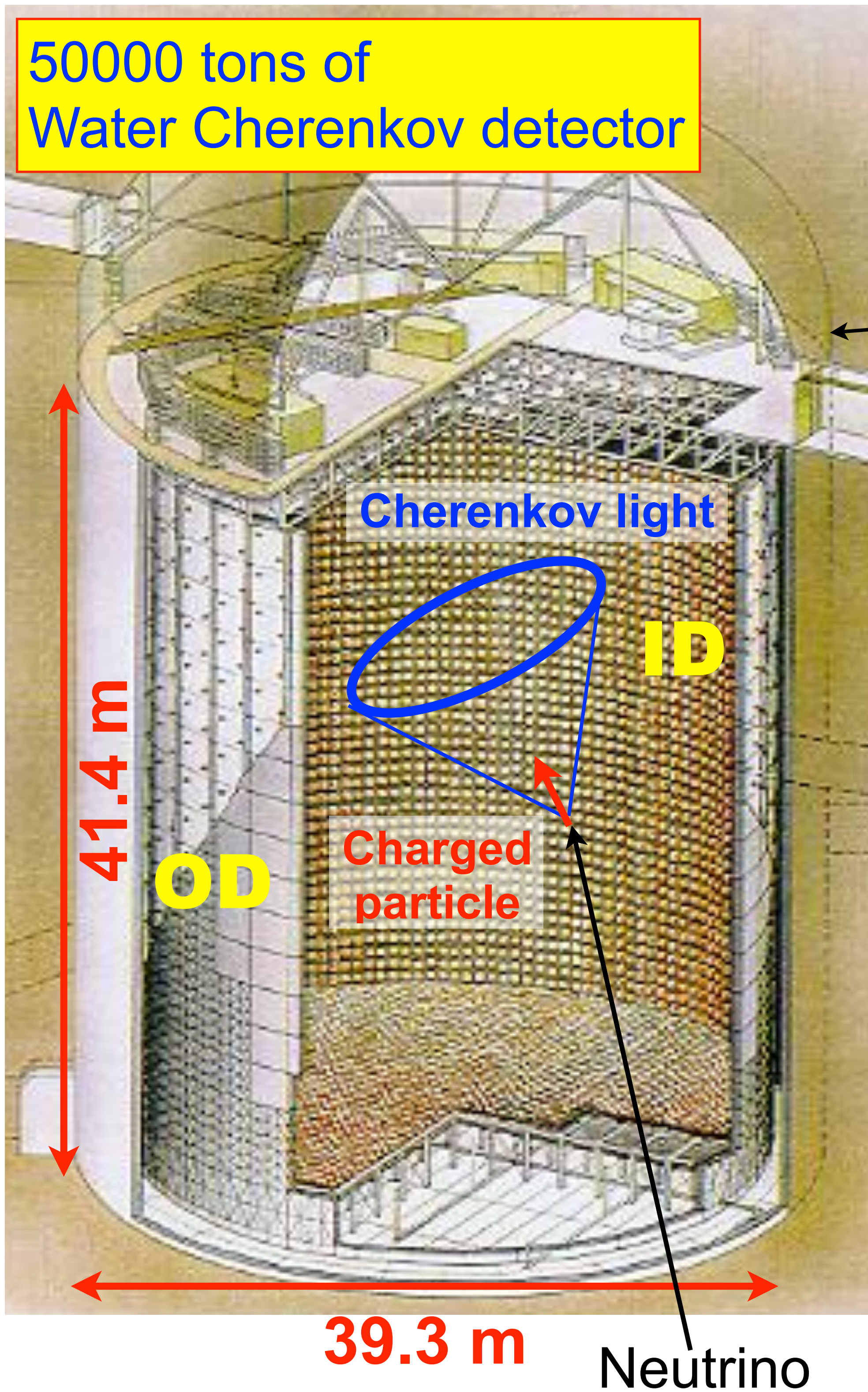
Super-Kamiokande collaboration

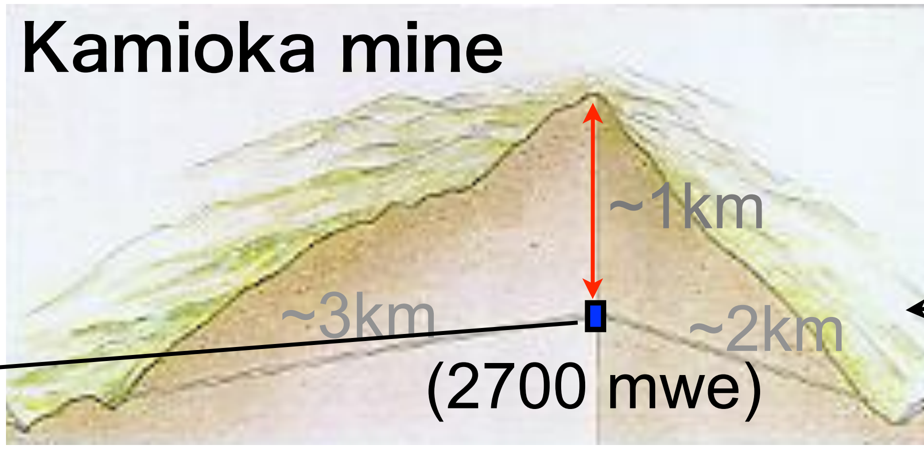
Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France

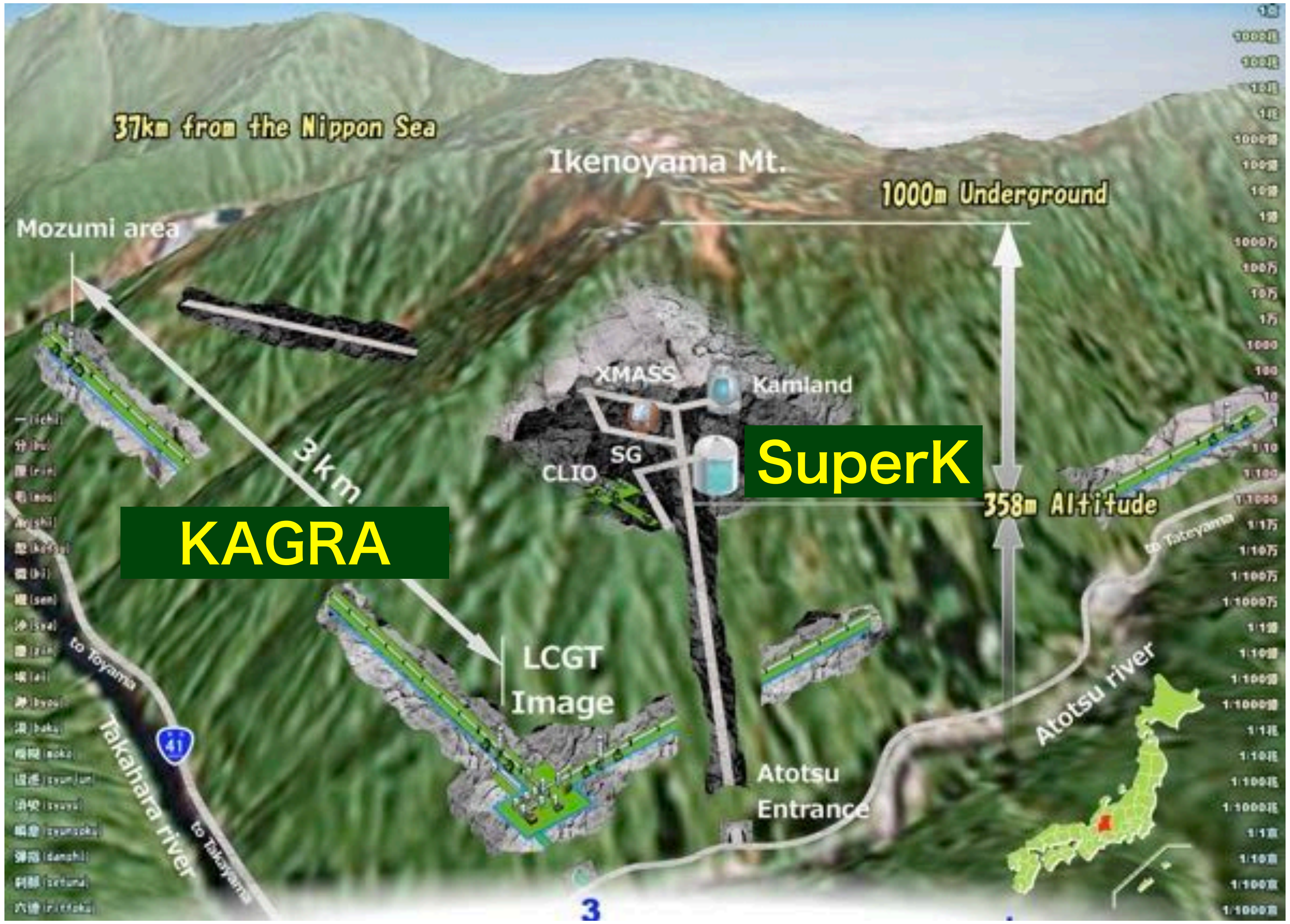
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK

Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

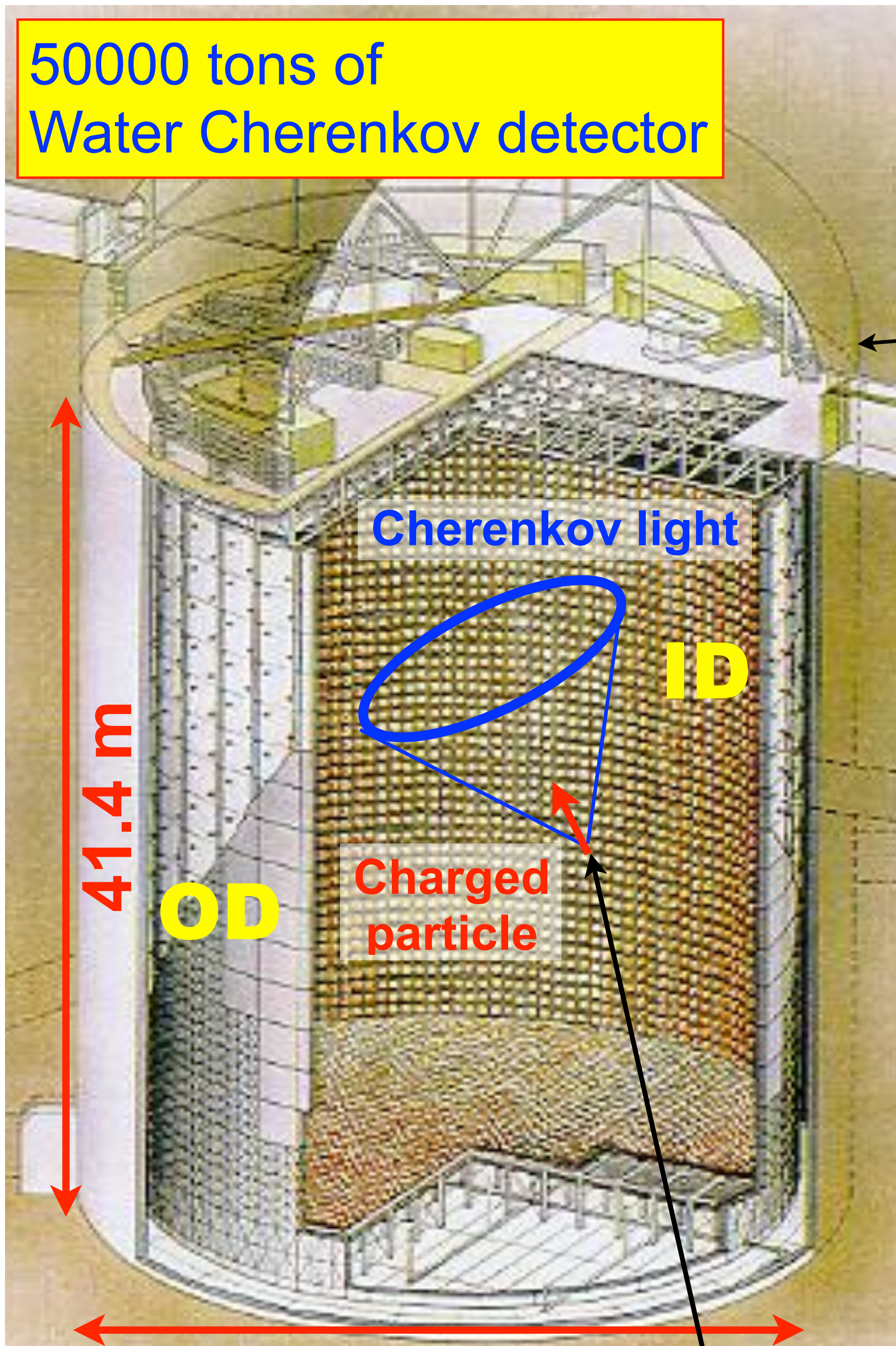
Super-Kamiokande detector

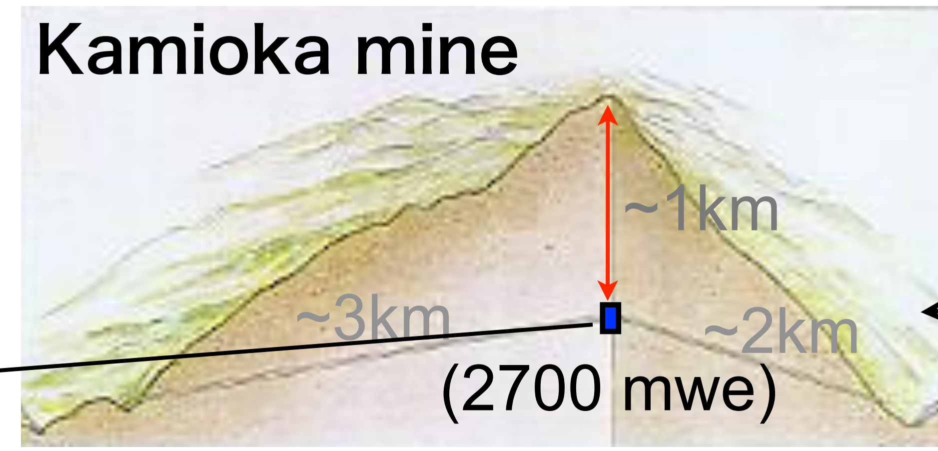






Super-Kamiokande detector





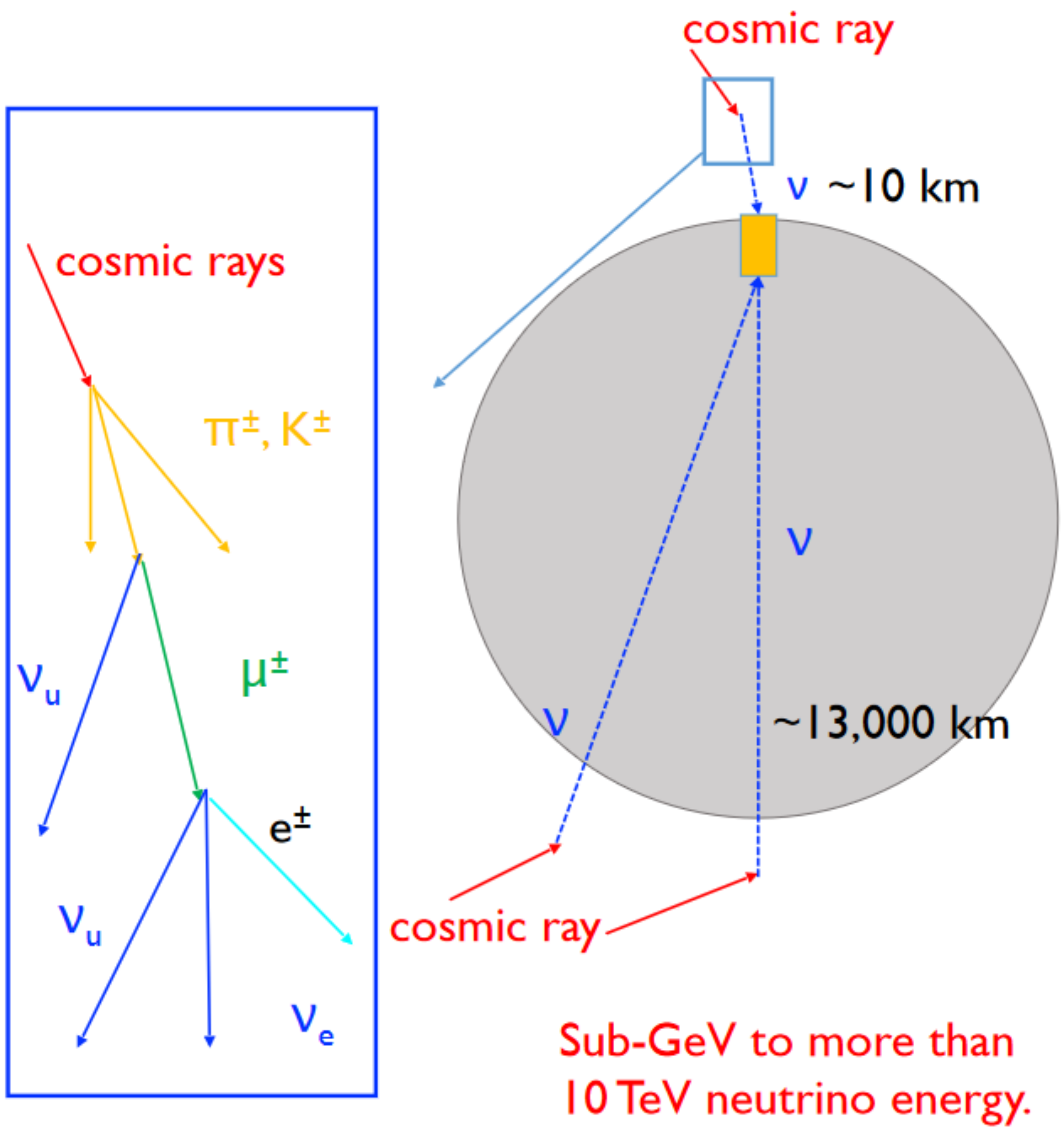
Phase	Period	# of PMTs (coverage)	Energy thr. (MeV)
SK-I	1996.4 ~ 2001.7	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	11129 (40%)	4.5
SK-IV	2008.9 ~ 2018.5		3.5
SK-V	2019.1 ~ 2020.8		(Kinetic energy)
SK-VI	**2020.8 ~ 2022.6**		On going
SK-VII	**2022.6 ~ just started!**		

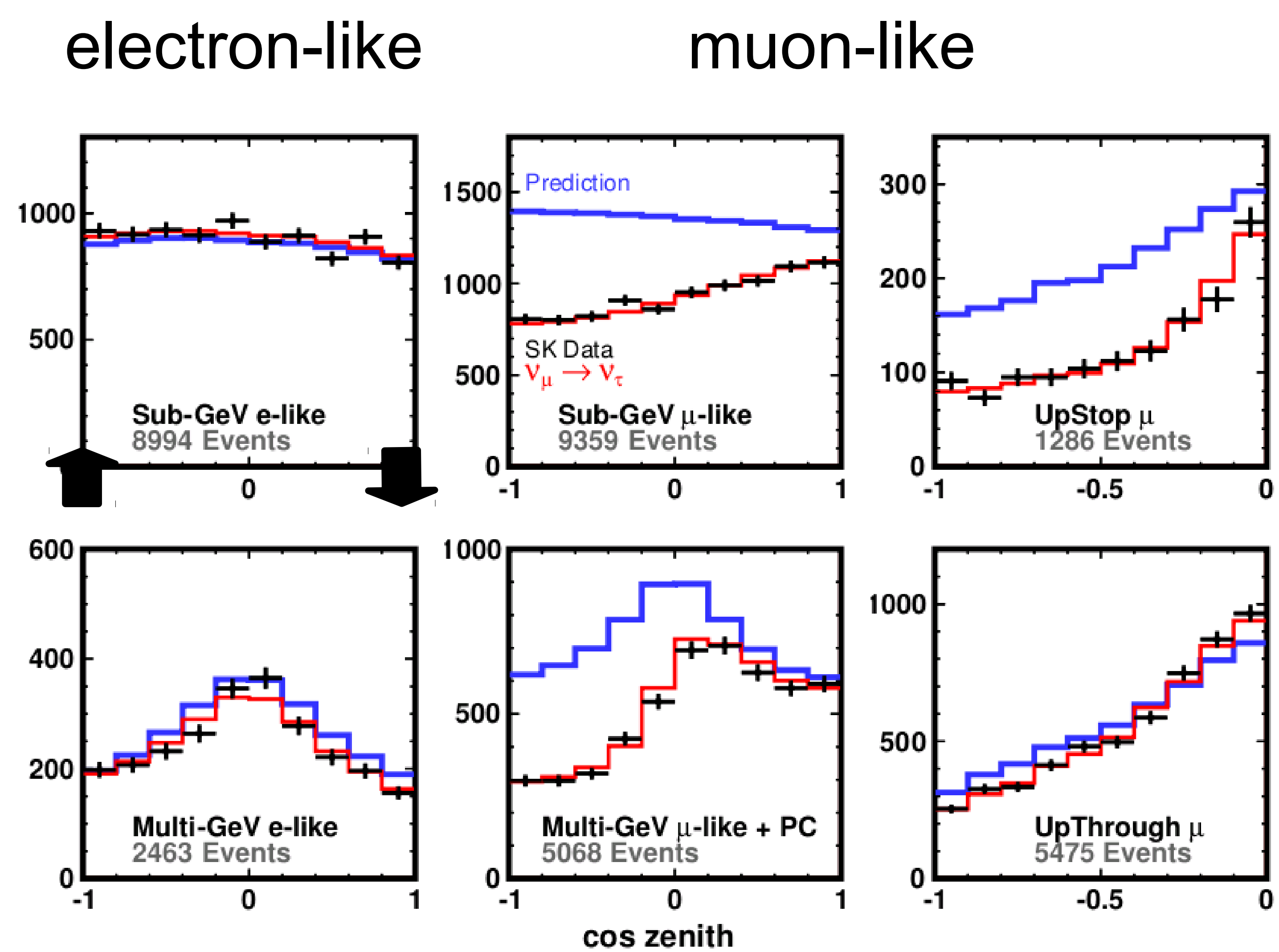
Running and improvements over 25 years

New phase with Gadolinium in SK, name SK-Gd

Atmospheric neutrino

Atmospheric neutrino oscillation

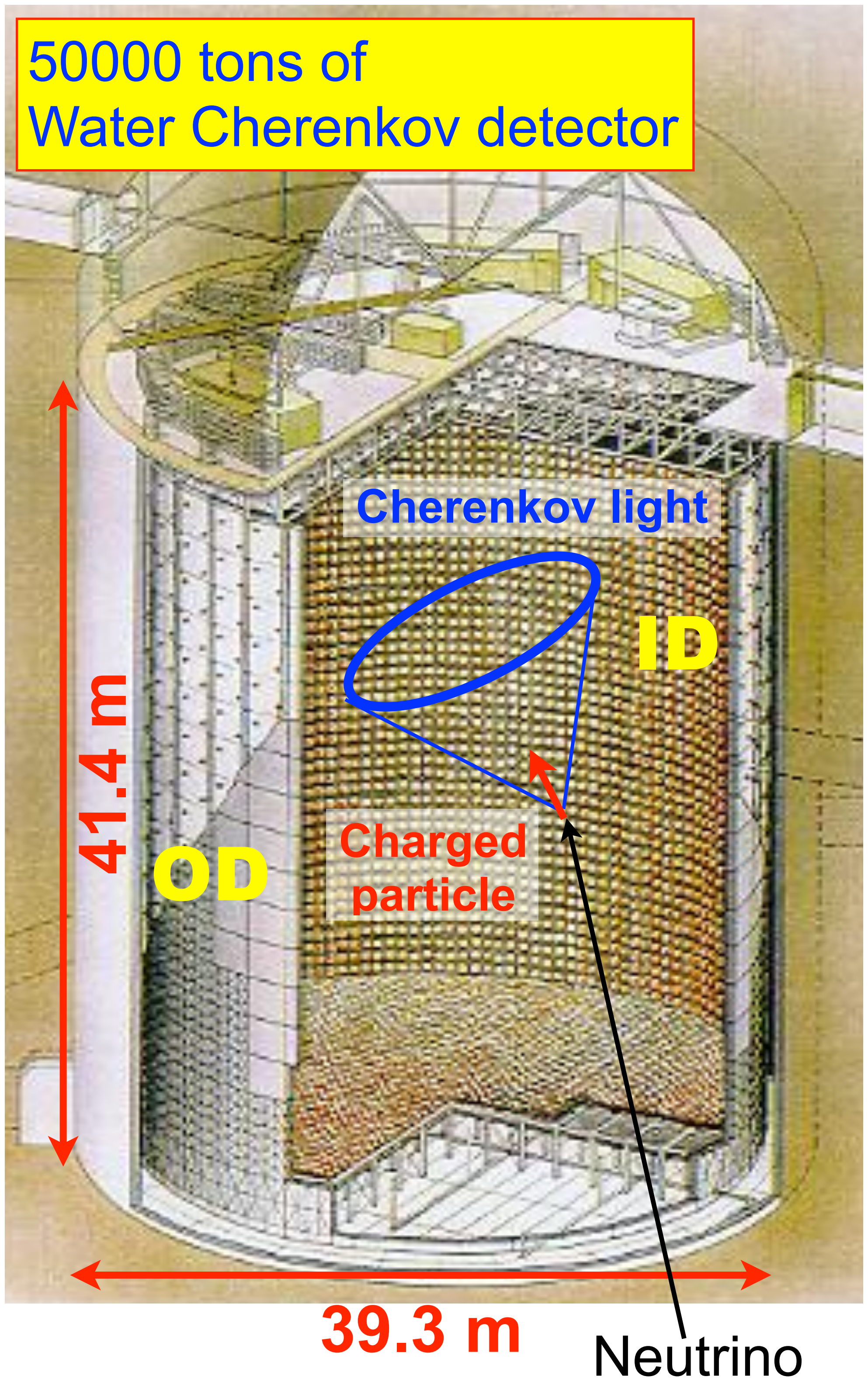




First evidence of neutrino oscillation in 1998

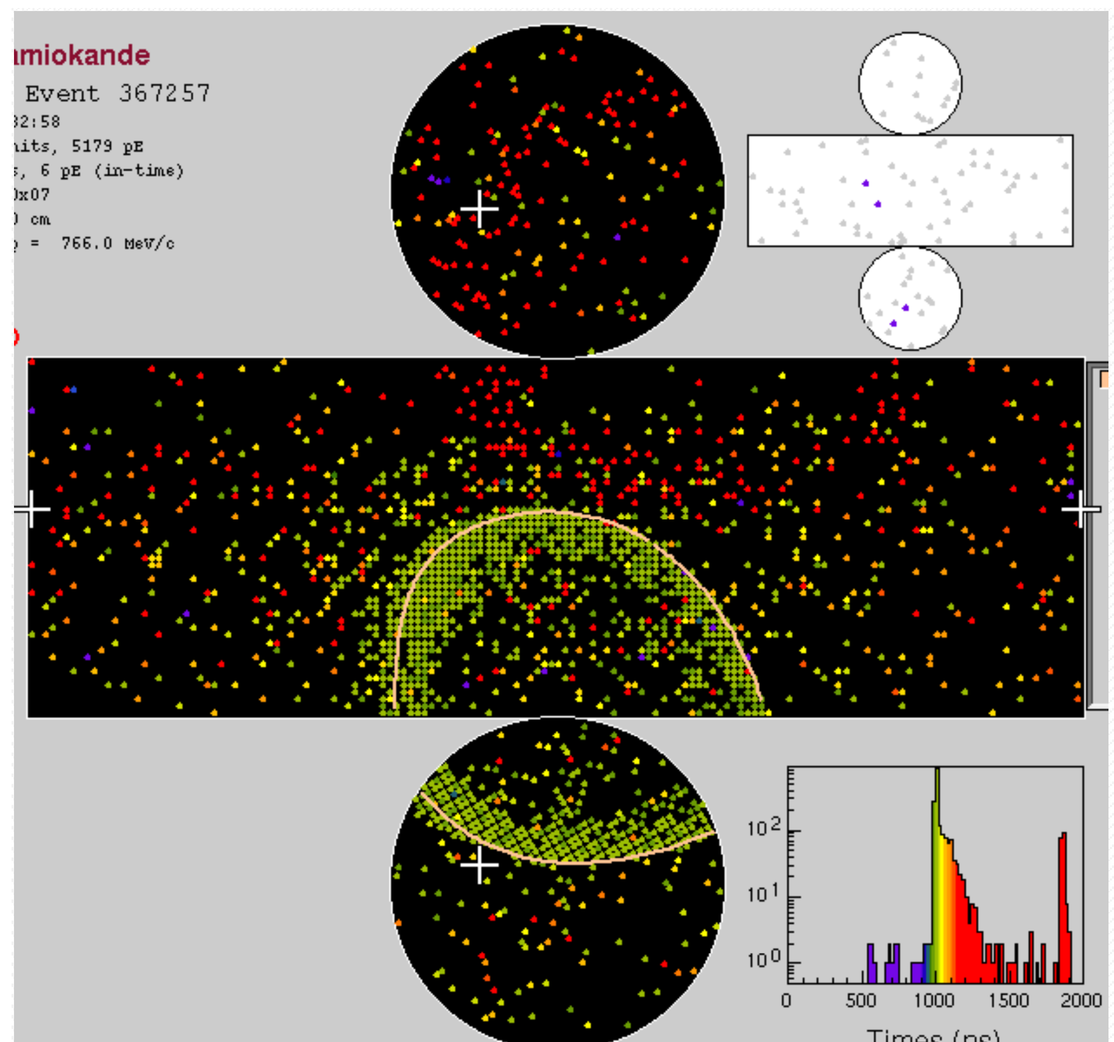
Super-Kamiokande

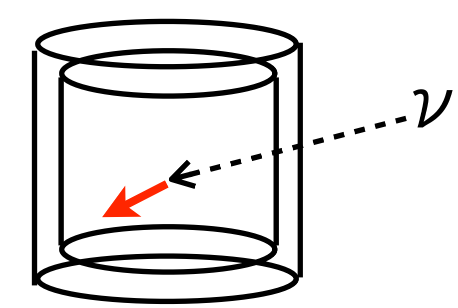
as an atmospheric neutrino detector



Neutrino interactions in SK

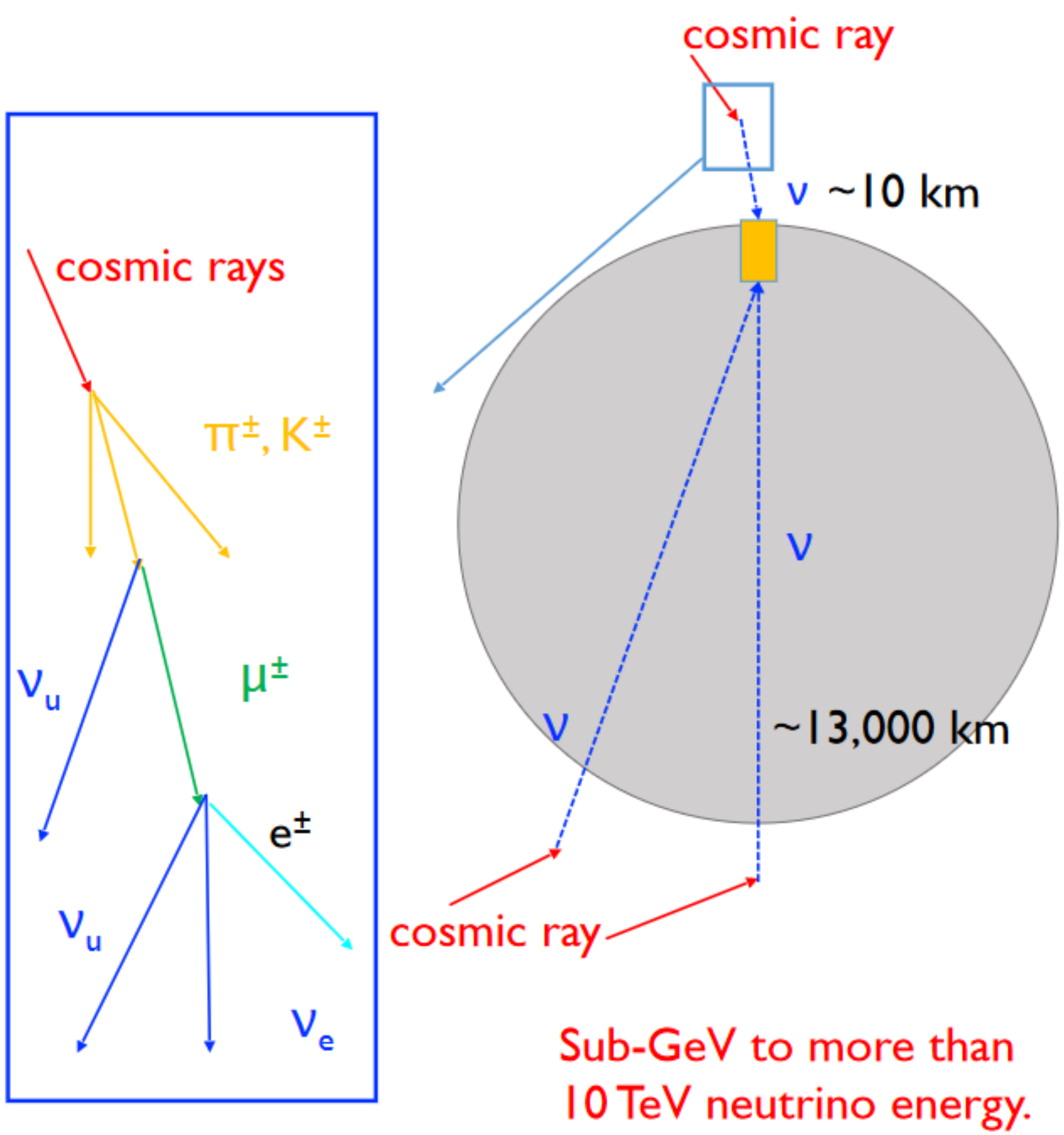
- (quasi-)elastic scattering : ν + N → l + N'
- single meson production : ν + N → l + N' + meson
- deep inelastic interaction : ν + N → l + N' + hadrons
- coherent pion production : ν + ^{16}O → l + ^{16}O + π





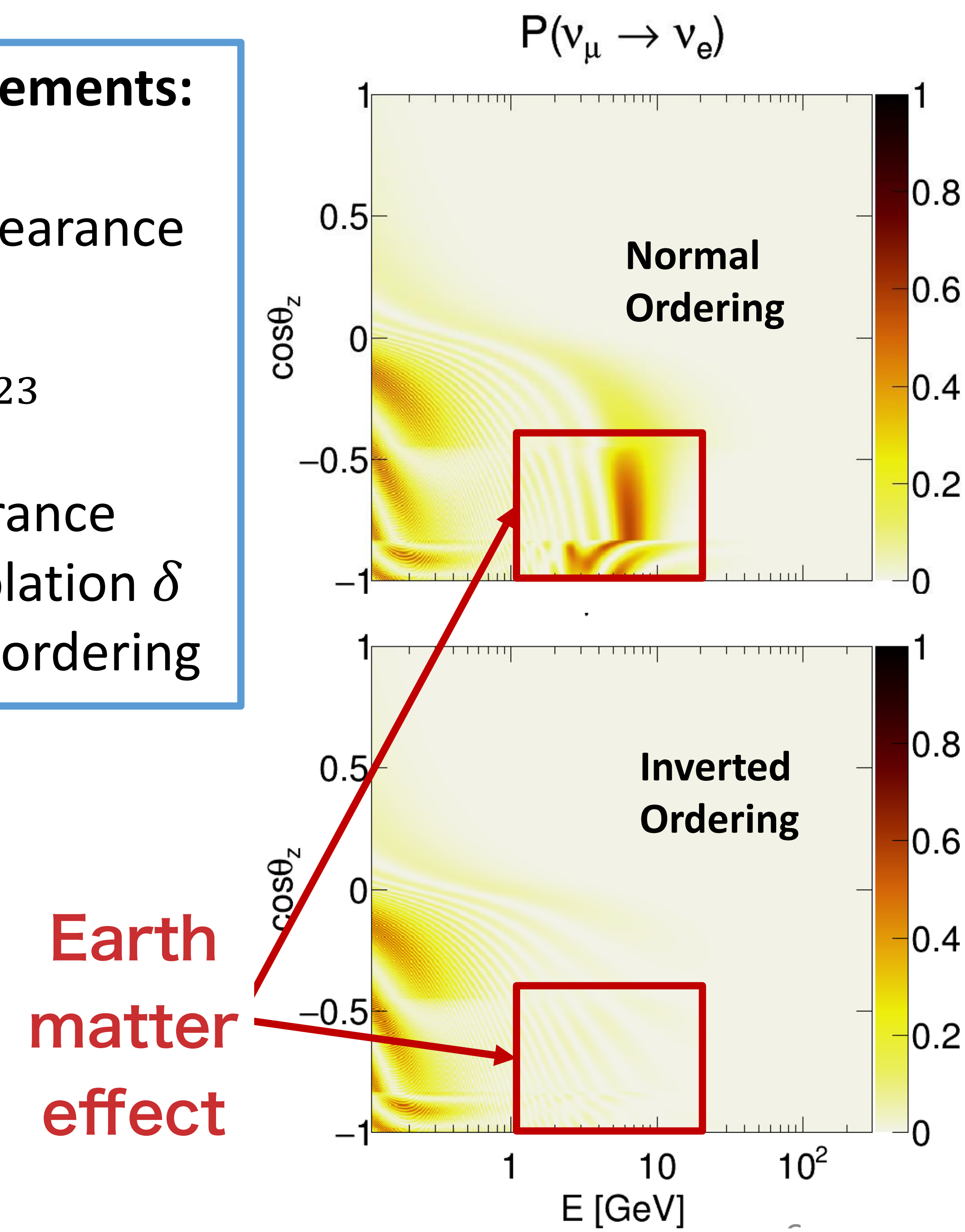
Muon
or
Electron

Atmospheric neutrino oscillation



Key measurements:

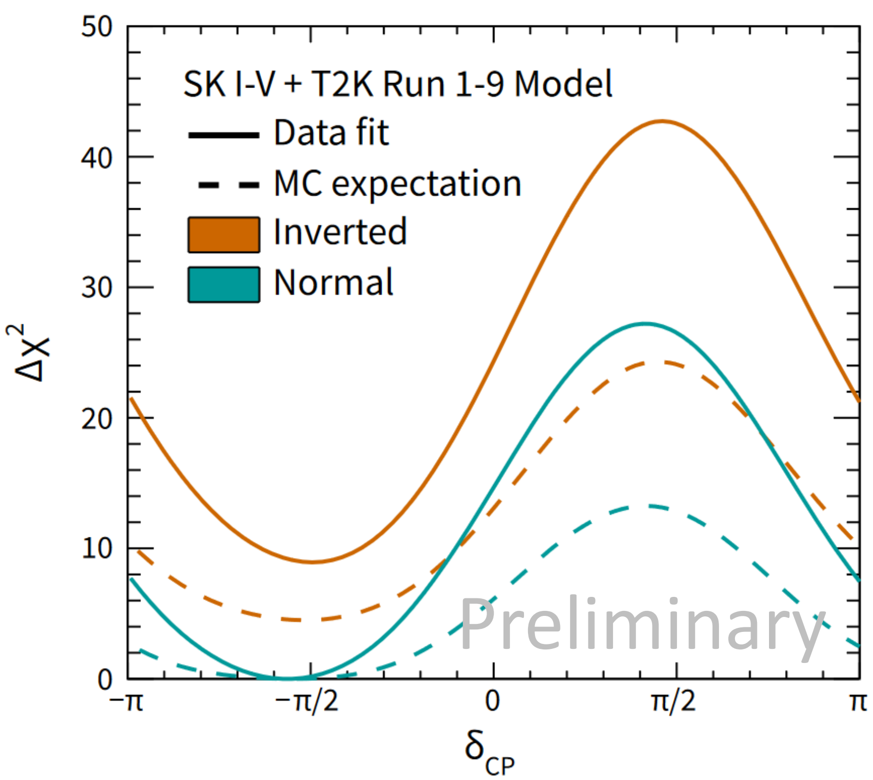
- ν_μ disappearance
  - Δm^2_{32}
  - $\sin^2\theta_{23}$
- ν_e appearance
  - CP violation δ
  - Mass-ordering

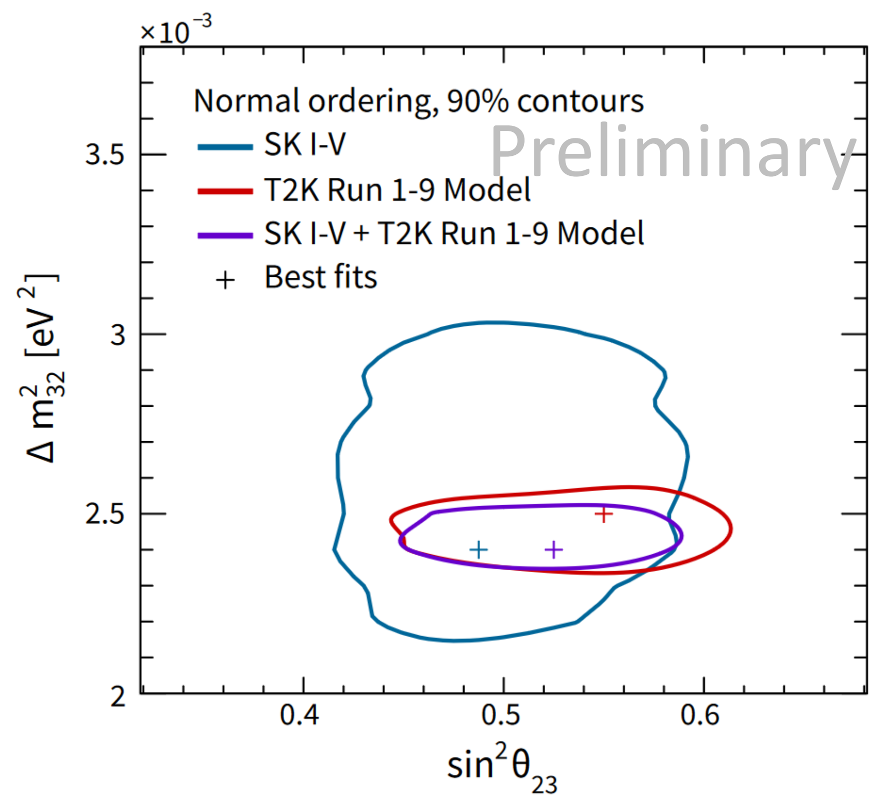


More precise measurements are required

Latest results

Neutrino oscillation parameters (SK atmospheric + T2K)





SK + external T2K constraints favor:

- maximal mixing
- $\delta_{CP} \approx -\frac{\pi}{2}$
- NO ($\Delta\chi^2 = 8.9$)

1020 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK+T2K NO	1086.33	4.54	0.53	2.4×10^{-3} eV^2
SK+T2K IO	1095.25	4.71	0.53	2.4×10^{-3} eV^2

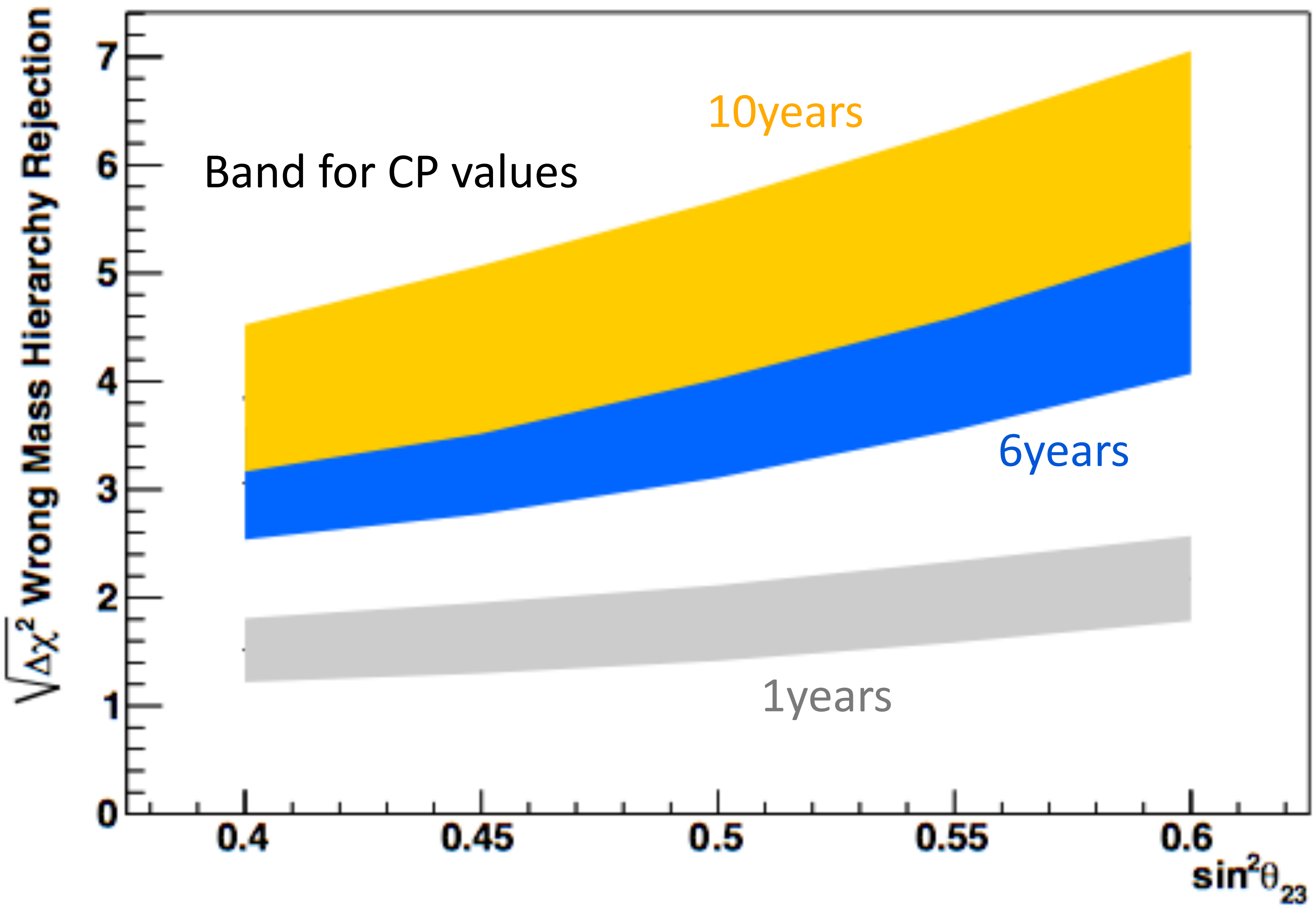
Preliminary

*Results from both experiments exceed sensitivity.

$\sin^2\theta_{13} = 0.0220 \pm 0.0007$

Sensitivity in Hyper-Kamiokande

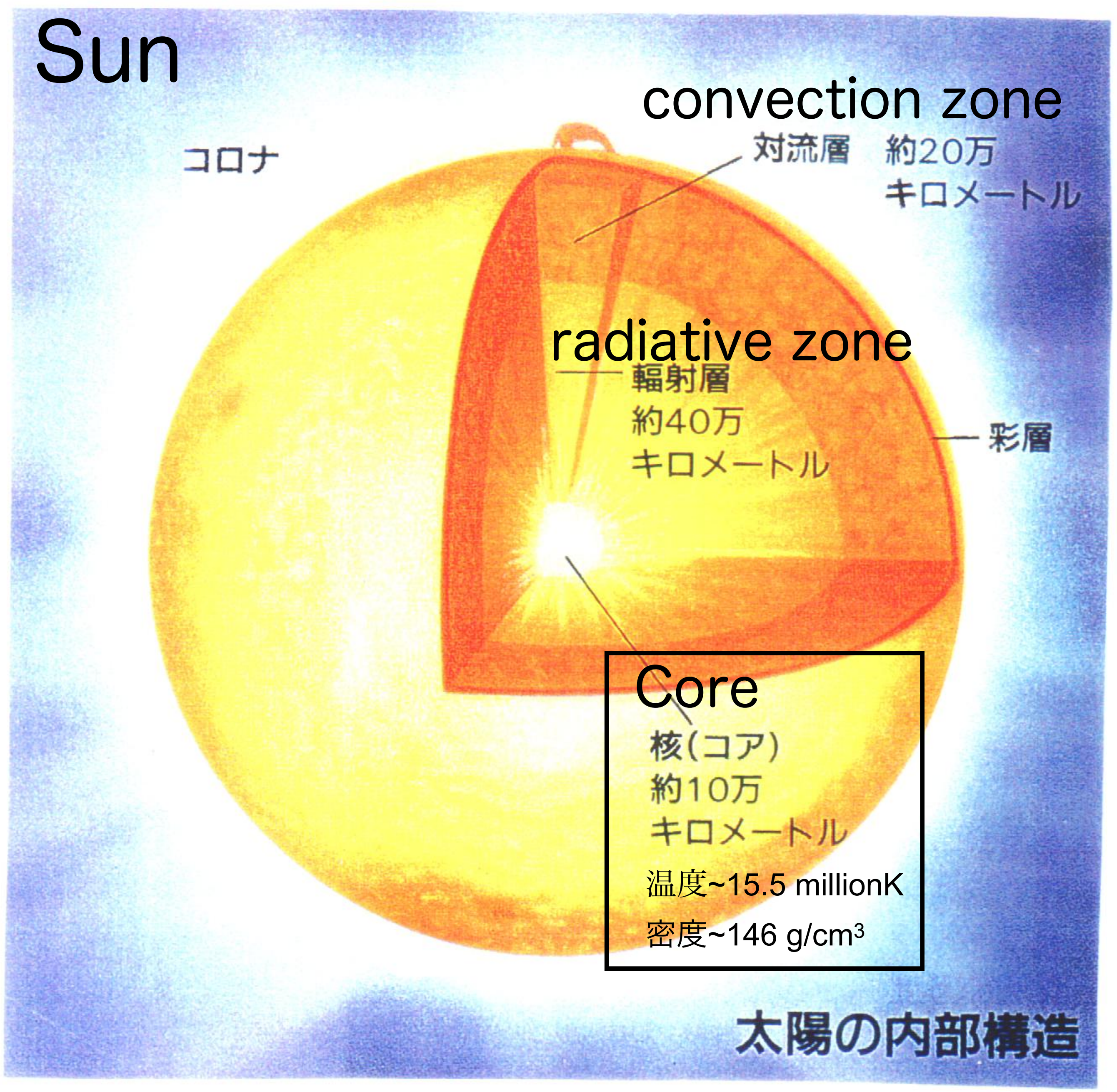
Mass ordering



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

Solar neutrino

Solar neutrinos



Nuclear fusion reaction deep inside the Sun

$4p \rightarrow {}^{2}He + 2e^{+} + 2\nu_e$ + thermal energy

($\sim 6.6\times10^{10}$ neutrinos/sec/cm^2)

This reaction is actually realized through pp-chain / CNO cycle.

Feature/Purpose of measurement

- Measurement of the current status in the center of the Sun.
- Study of
  - the mechanism of energy generation in the Sun
  - the property of neutrinos

Super-Kamiokande

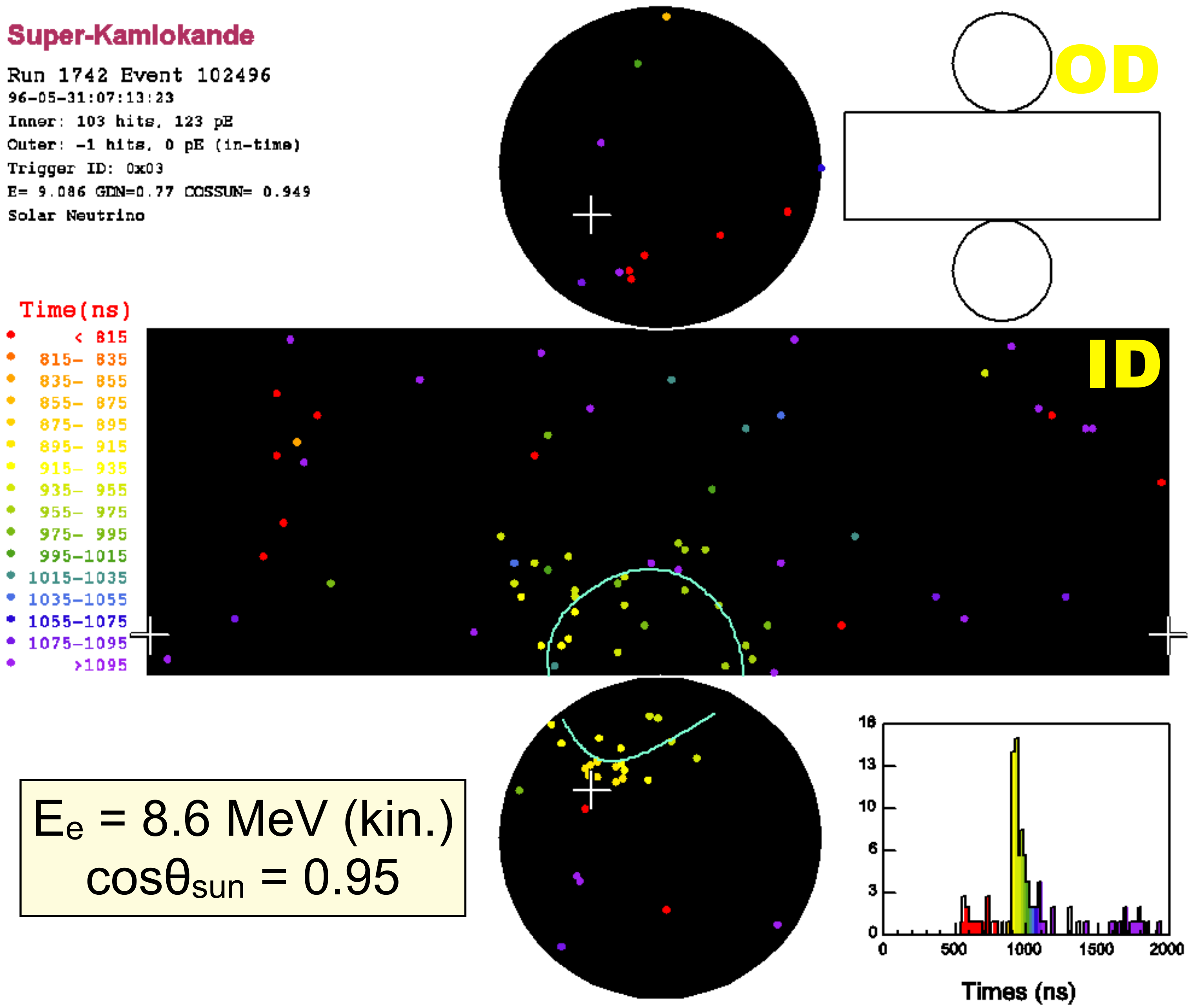
as a solar neutrino detector

Typical event

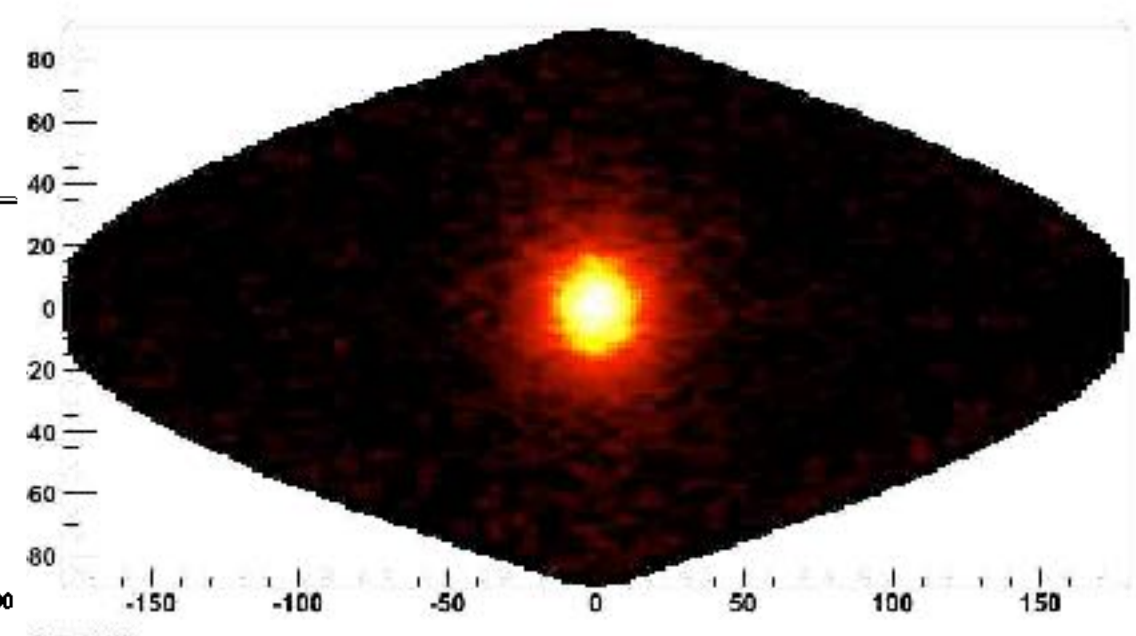
neutrino-electron elastic scattering

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

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



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



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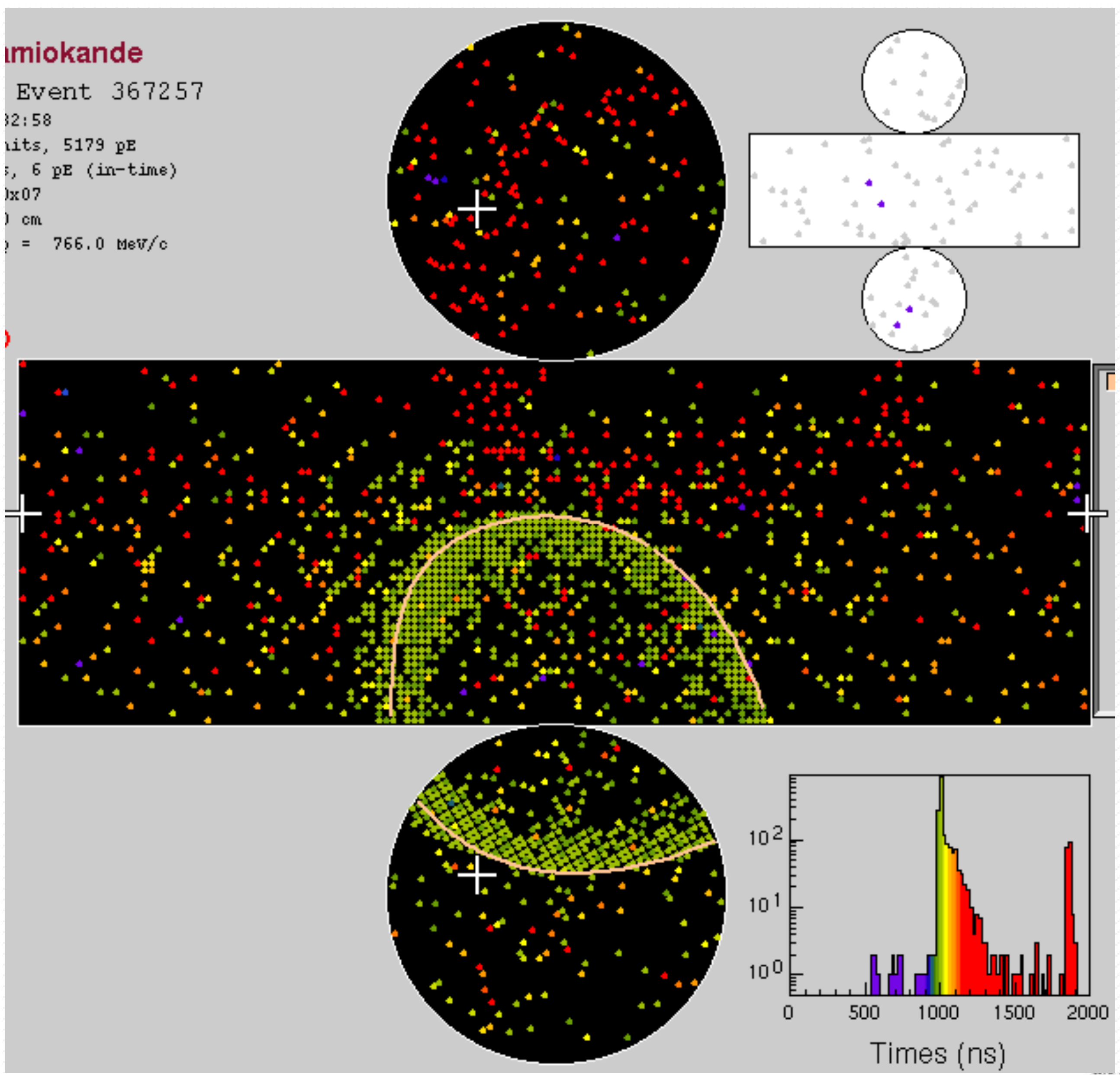

neutrino-electron elastic scattering

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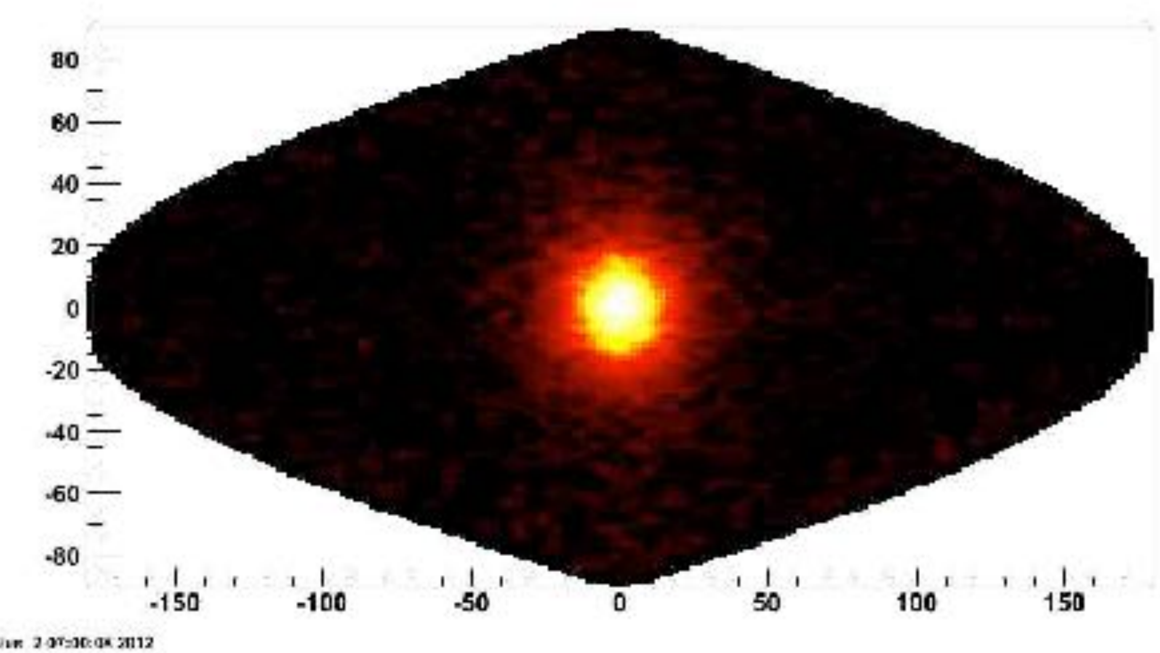
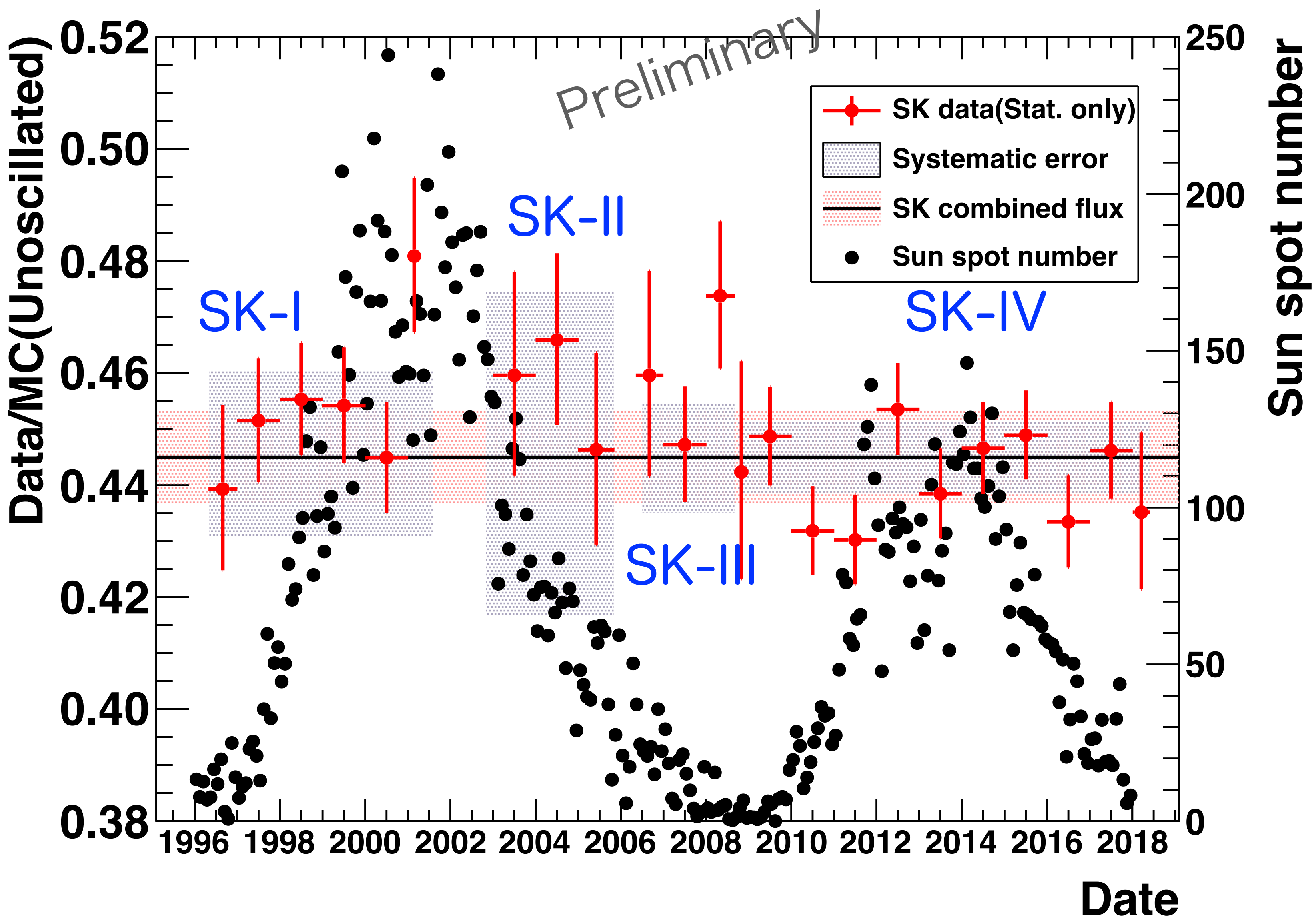


Yearly solar neutrino flux



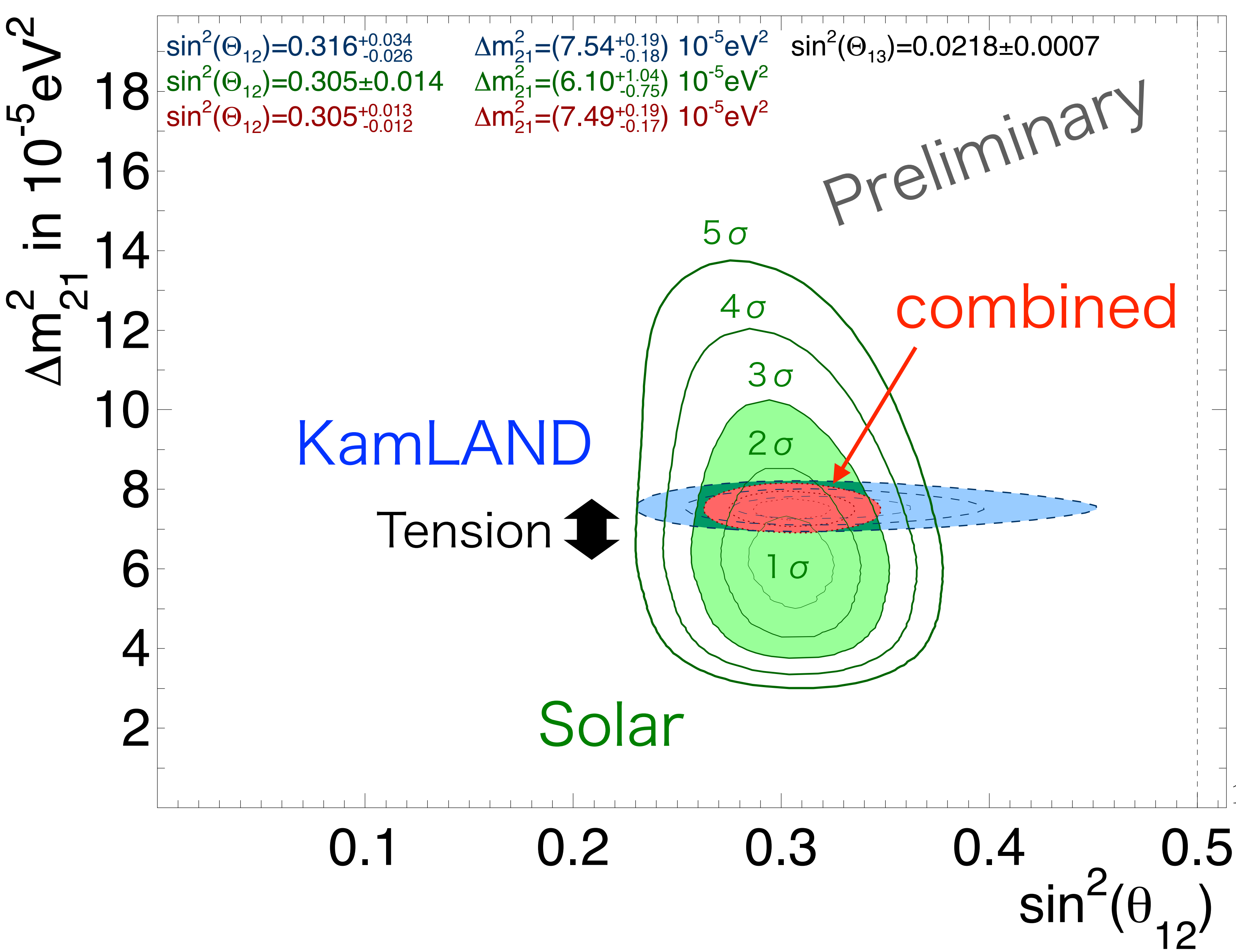
^{8}B flux vs sun spot

No correlation with 11 years solar activity is observed

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

Solar neutrino oscillation

~1.5σ tension between solar global and KamLAND in Δm^2_{21}

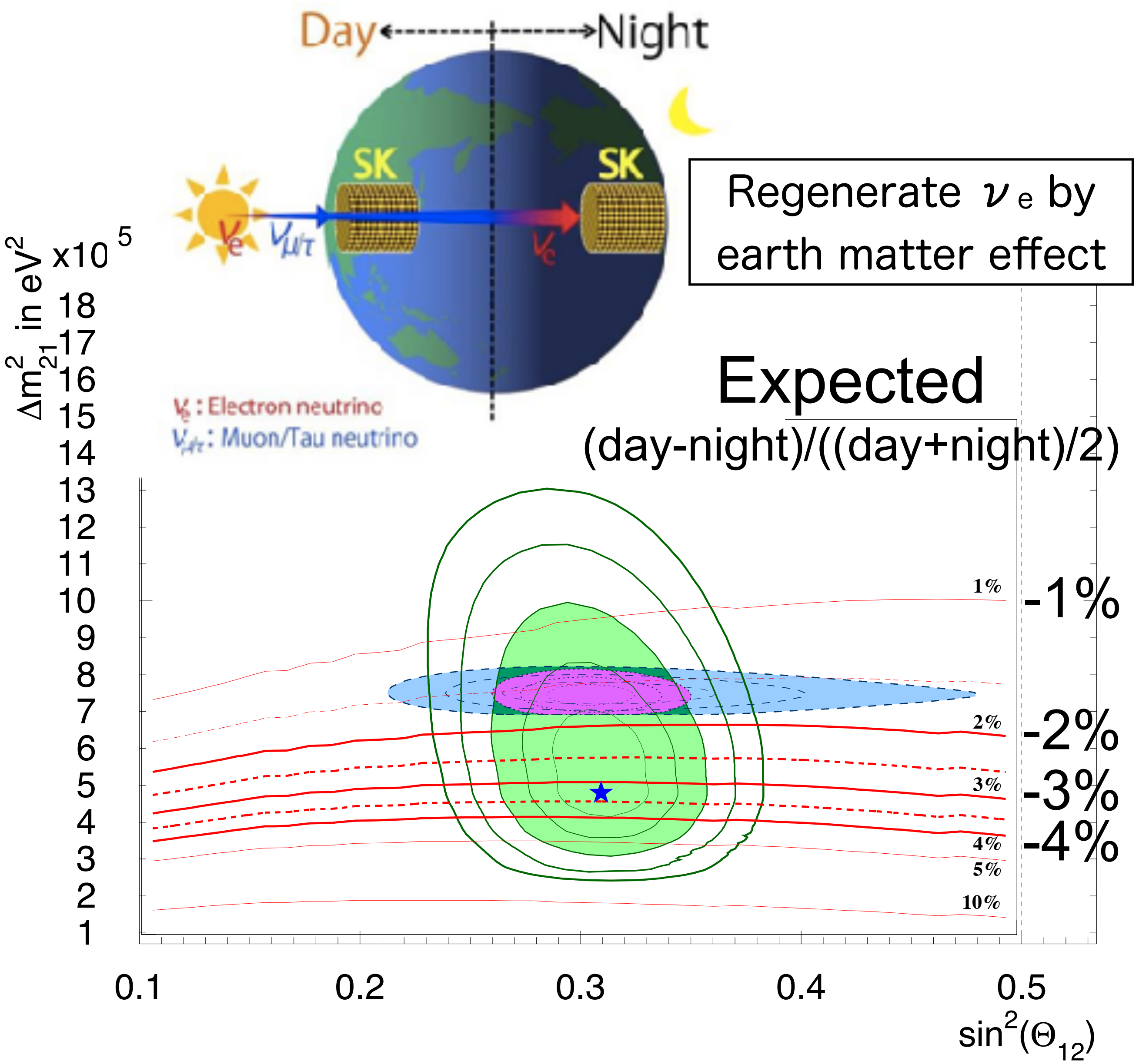


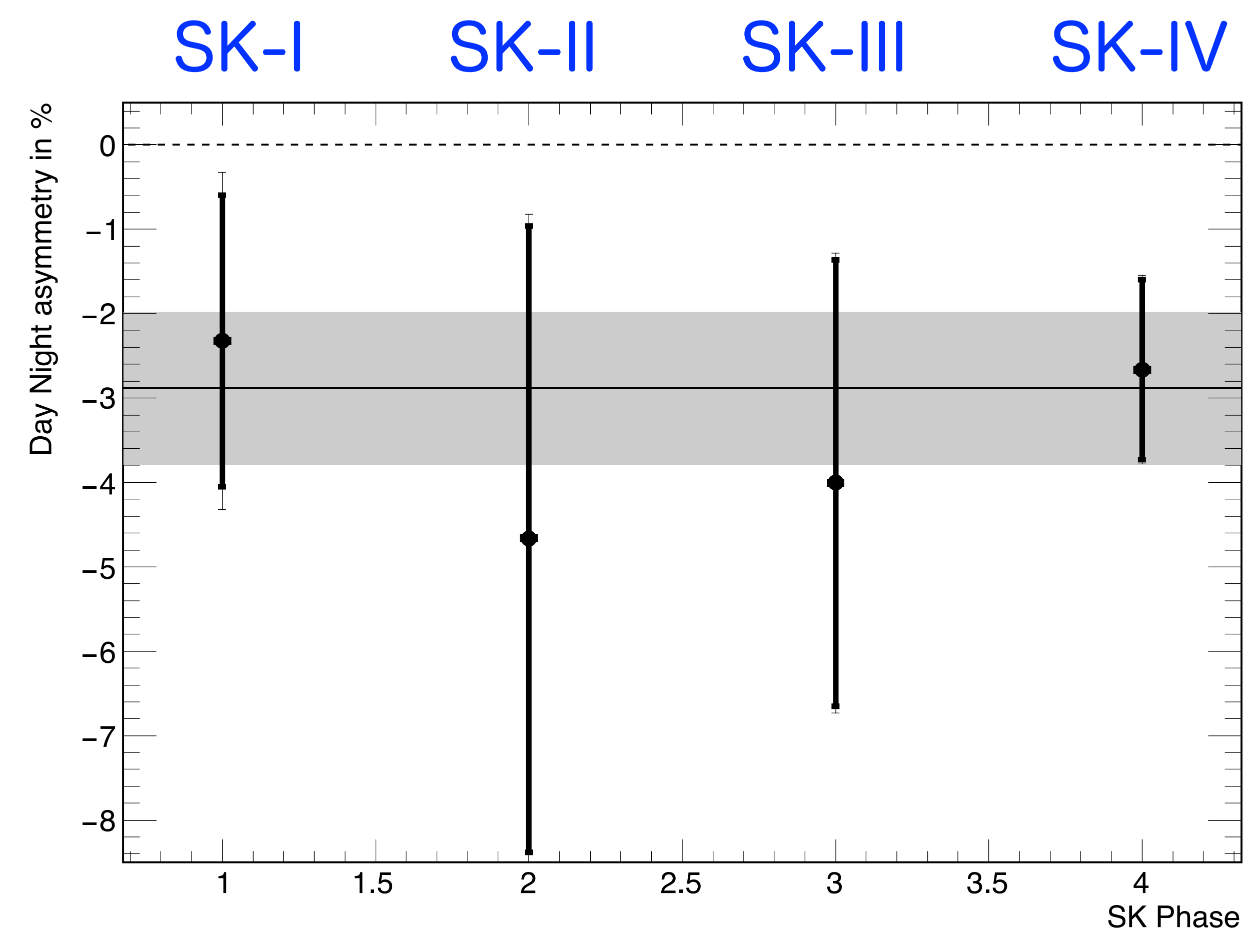
$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.305 \pm 0.014$$
$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75}$$
$$\sin^2\theta_{12} = 0.305^{+0.013}_{-0.012}$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

$\sin^2\theta_{13}=0.0219\pm0.0014$

Day/Night flux asymmetry





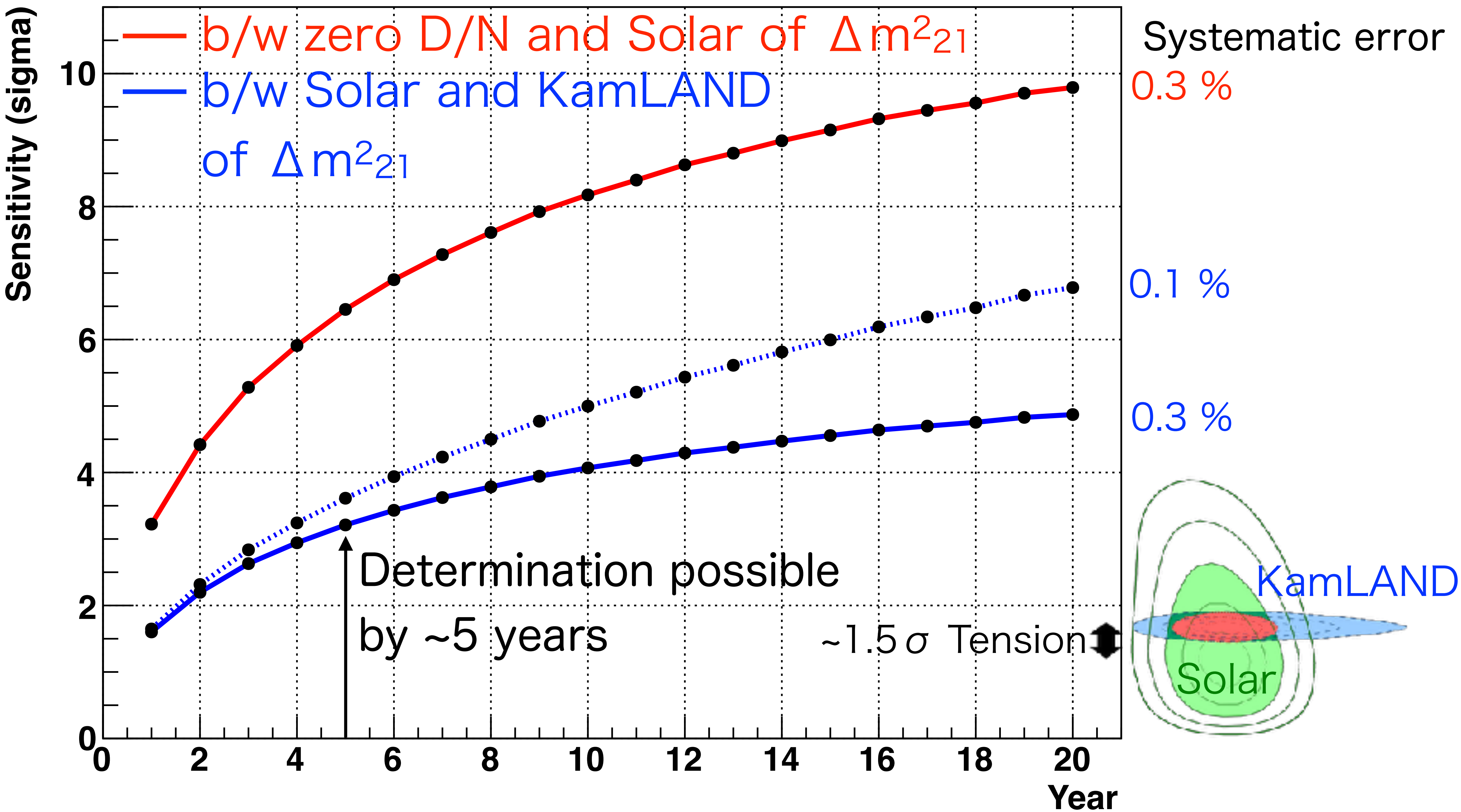
Significance of D/N asymmetry:

3.2σ for Solar Best fit

3.1σ for Global Best fit

Sensitivity in Hyper-Kamiokande

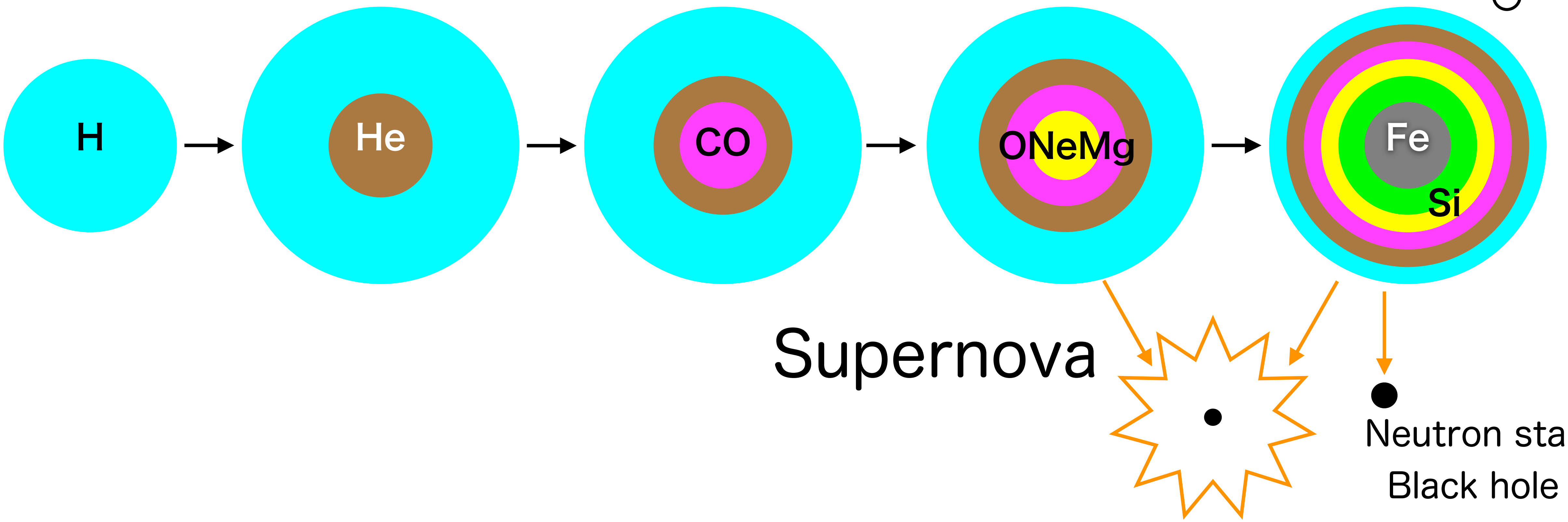
Day/Night flux asymmetry



Toward the next decade

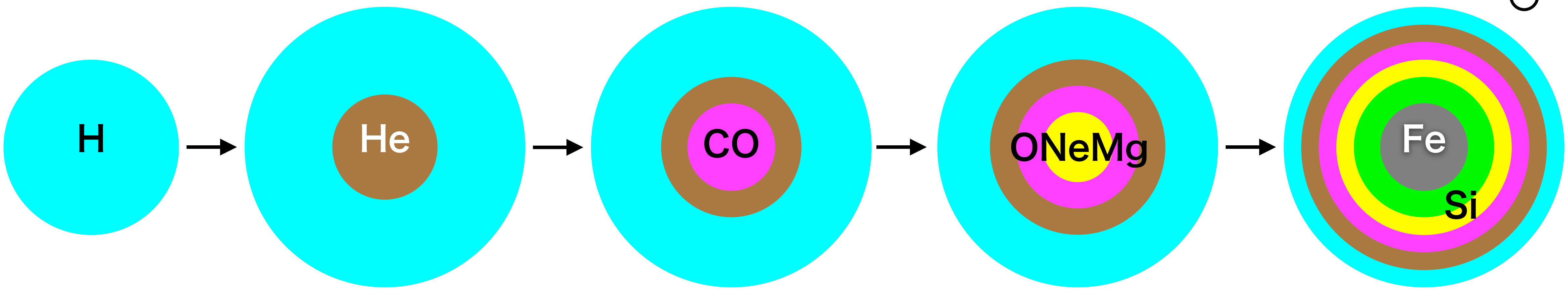
Supernova

Main sequence star evolution process $M > 10M_{\odot}$

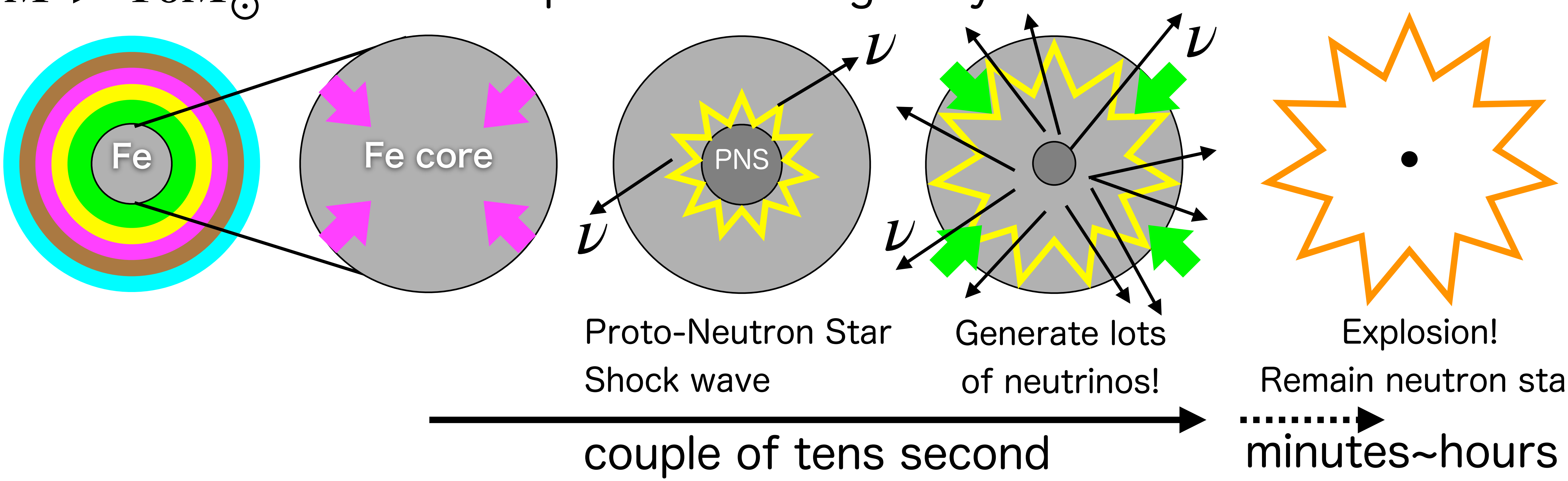


Supernova neutrinos

Main sequence star evolution process $M > 10M_\odot$



$M > 10M_\odot$ → Core collapse due to its gravity

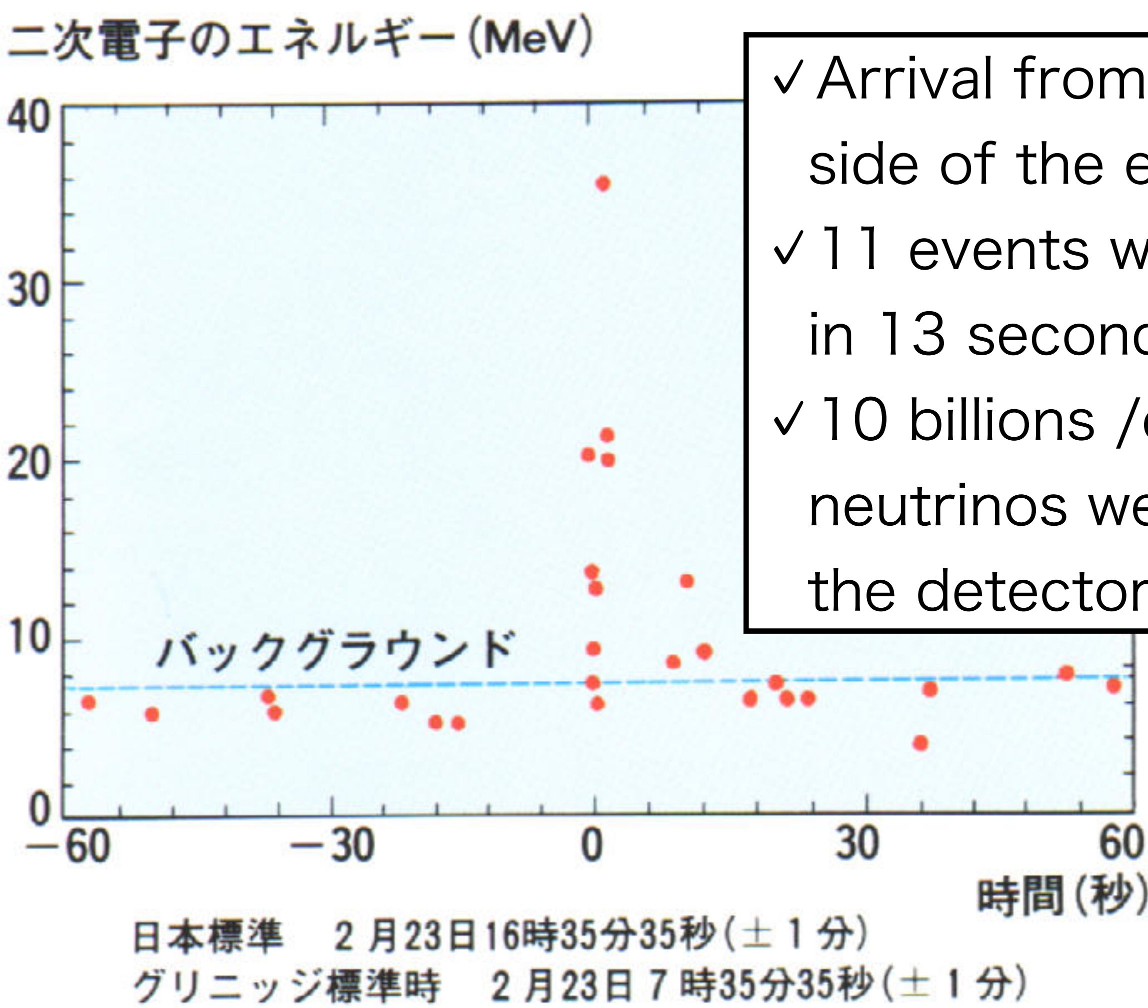


35 years since SN1987A

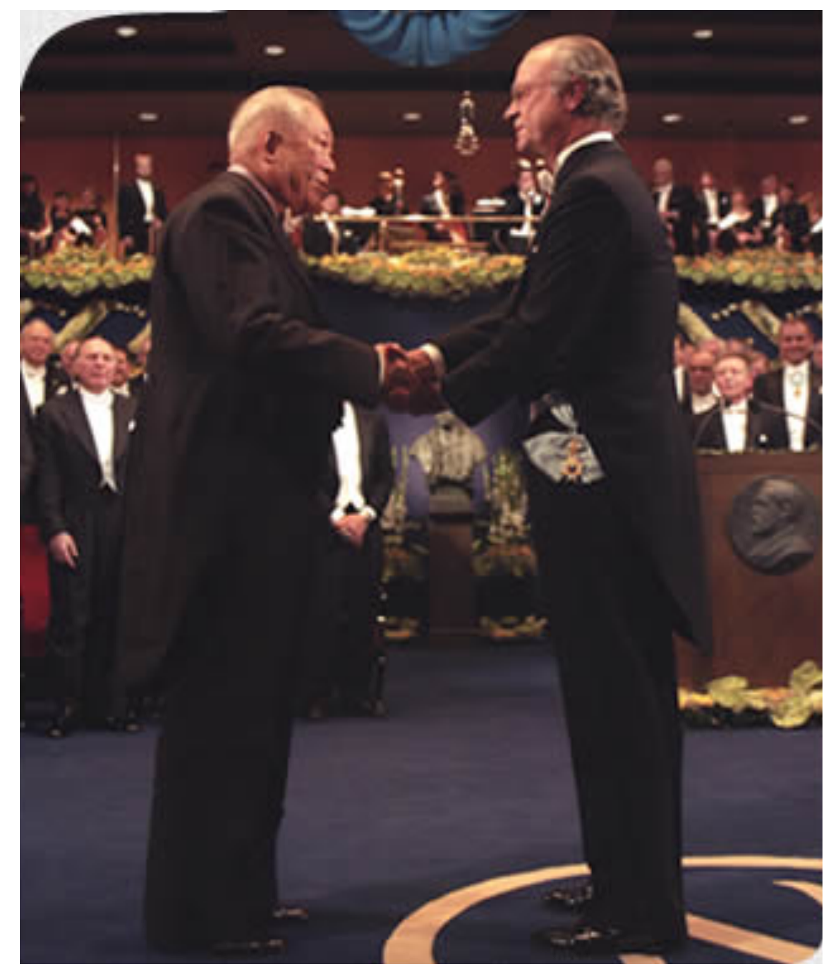
Large Magellanic cloud ~50kpc

First observation by Kamiokande

Prof. Koshiba
Nobel prize in 2002



- ✓ Arrival from opposite side of the earth
- ✓ 11 events were observed in 13 second.
- ✓ 10 billions /cm2 neutrinos went through the detector.

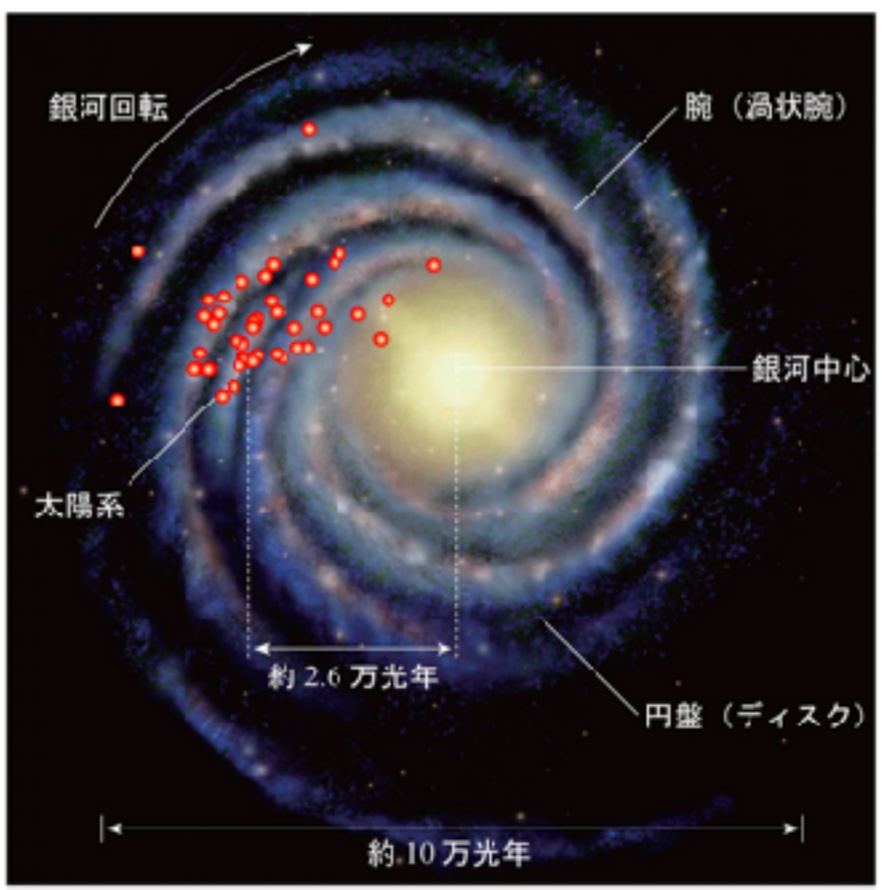


No Supernova neutrino detection since then..

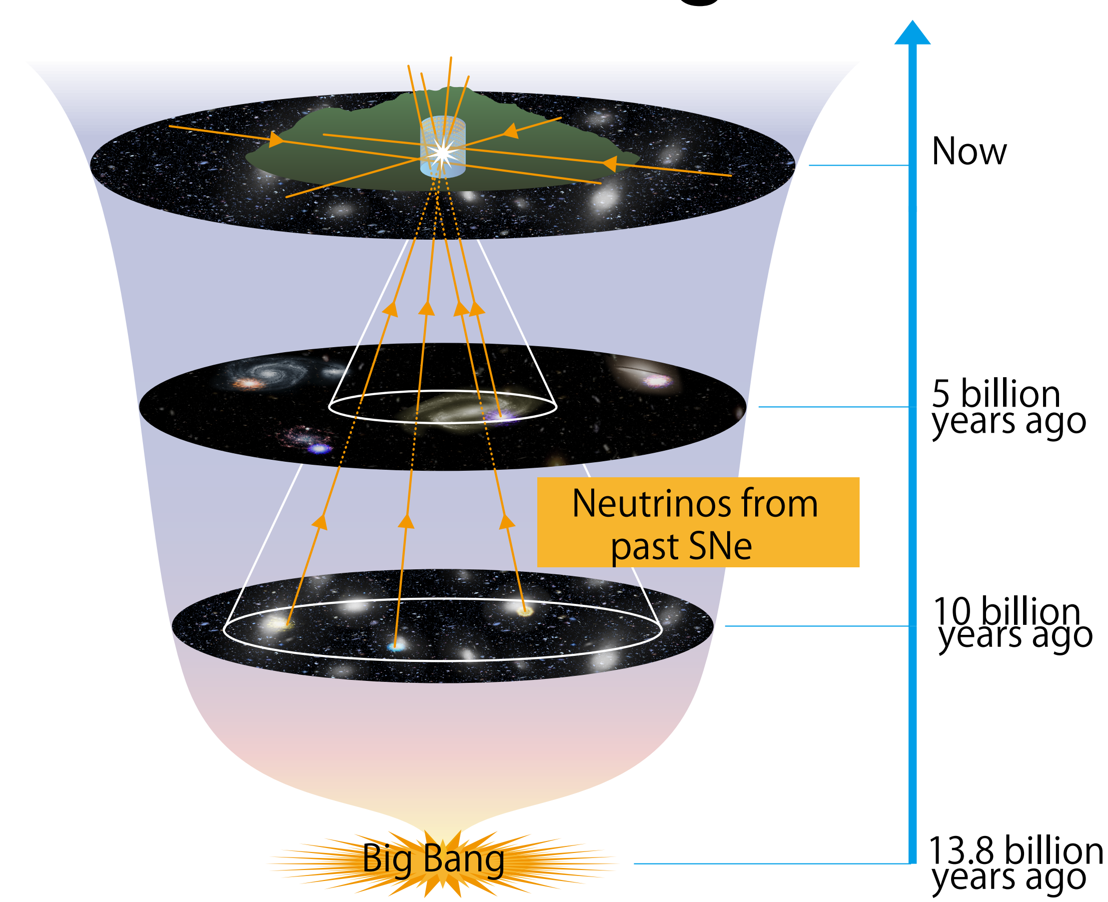
No chance for Supernova neutrino detection for next hundred’s years?

We believe, yes!

Galactic Supernova burst (a few per century)



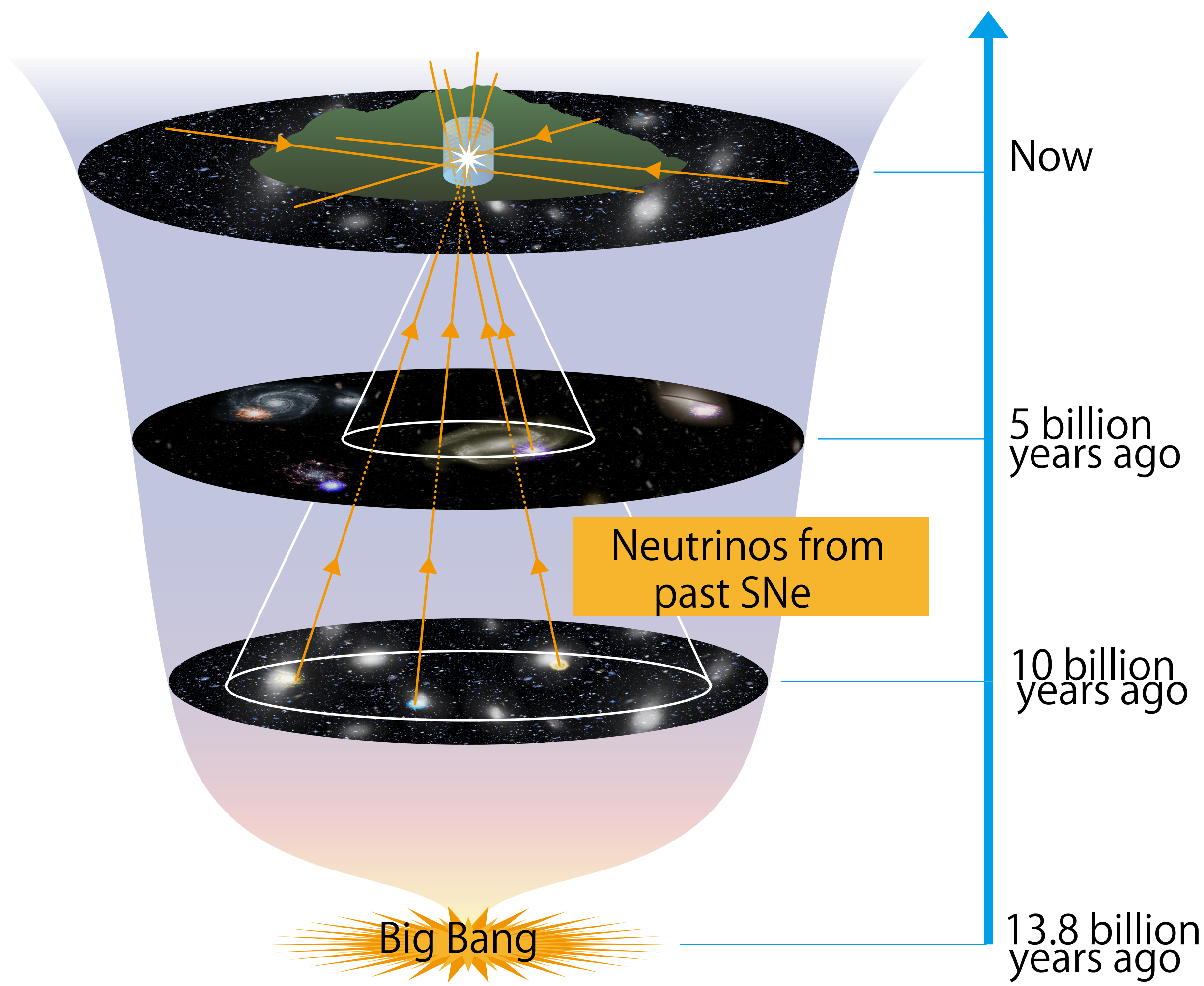
Diffuse Supernova Neutrino Background

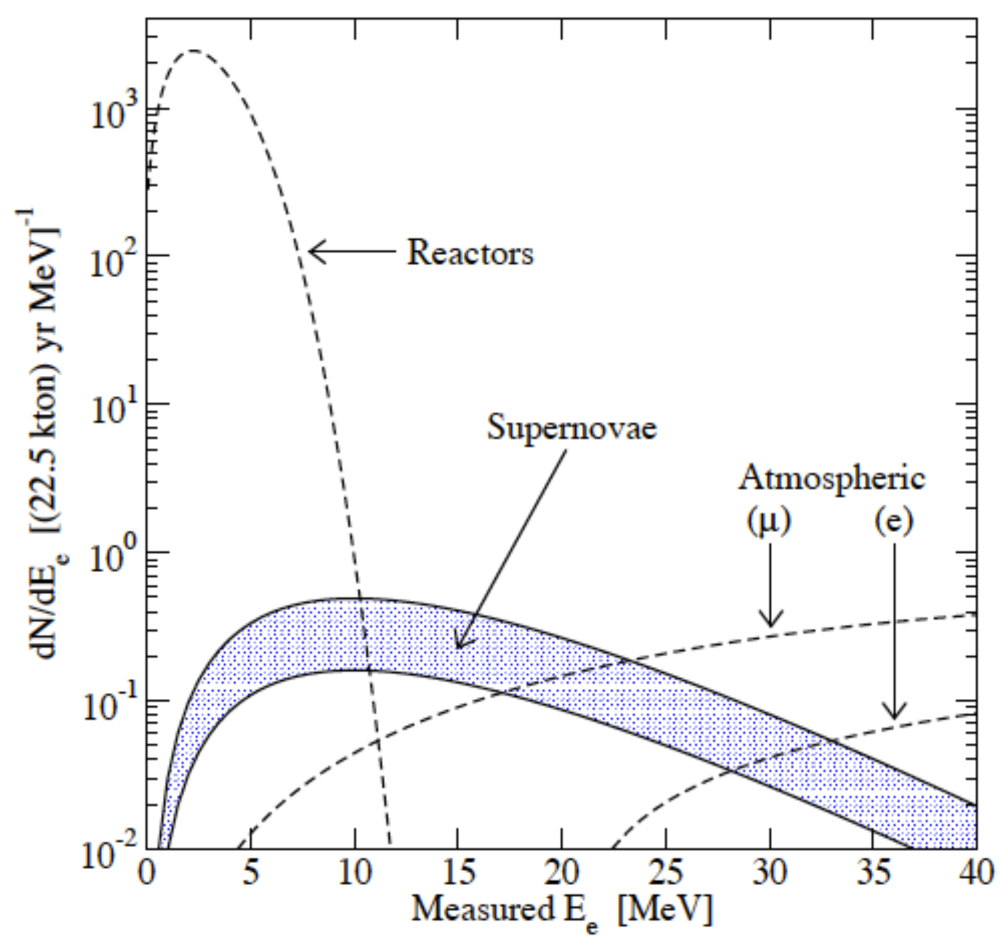


Super-K Gd / SK-Gd

For the first observation of DSNB

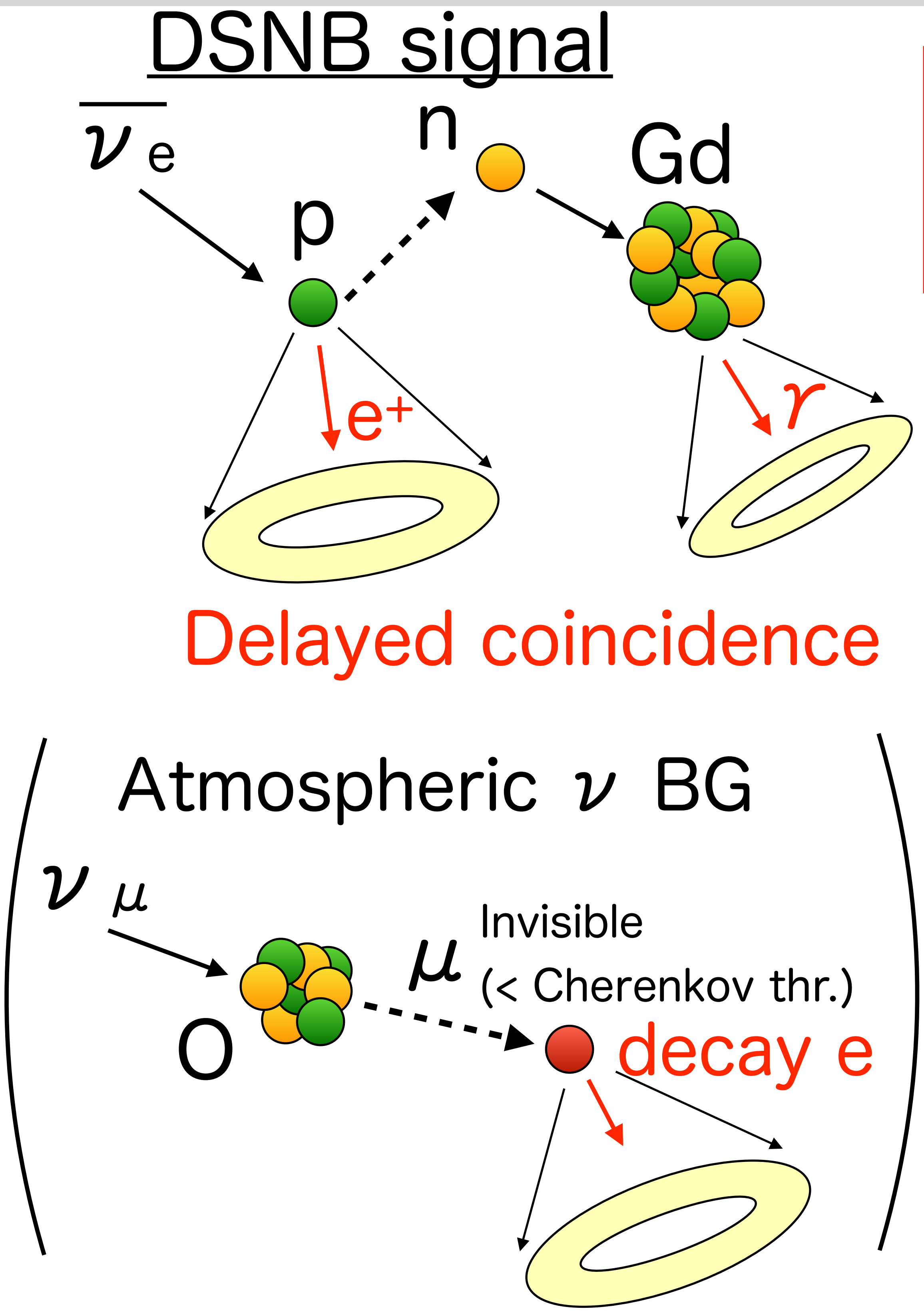
(Diffuse Supernova Neutrino Background)





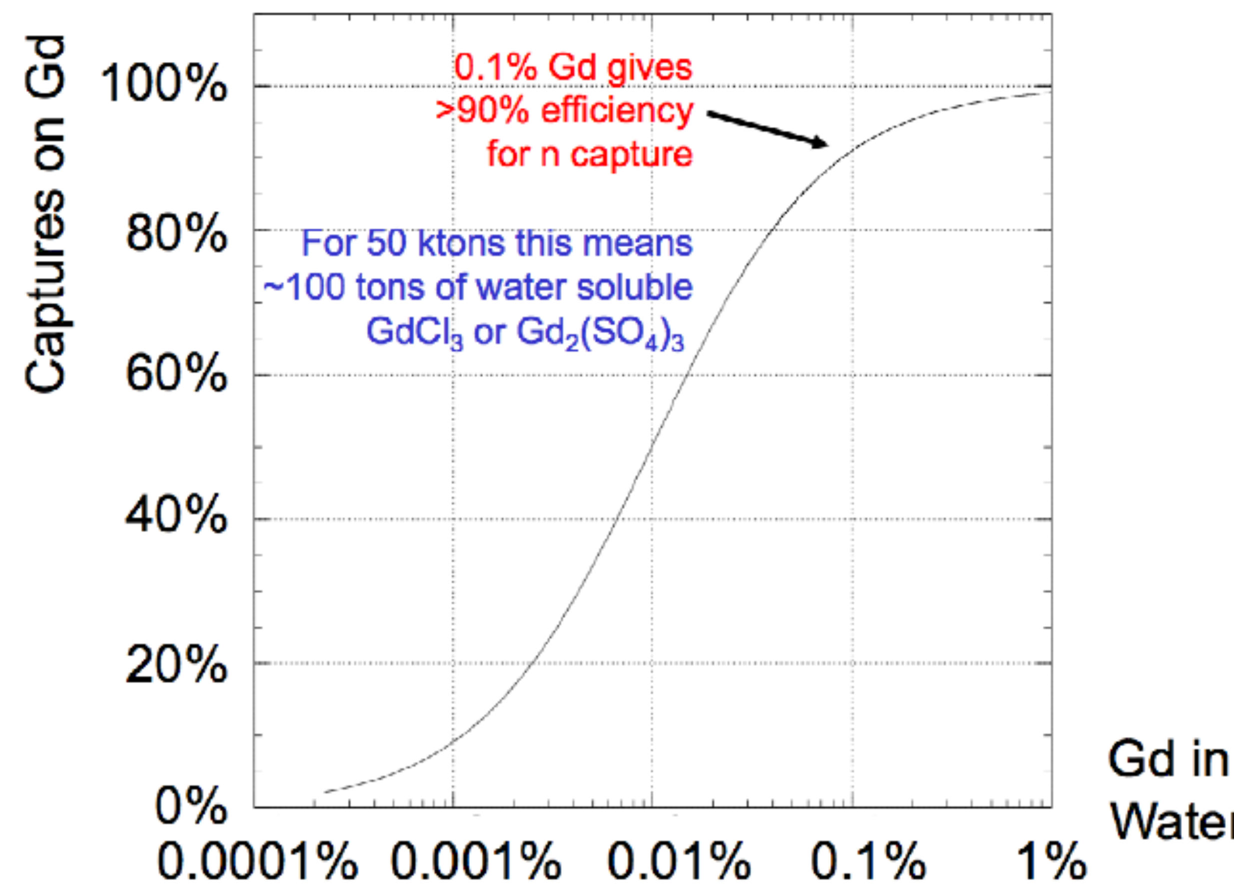
How to reduce atmospheric neutrino BG?

Super-K Gd / SK-Gd



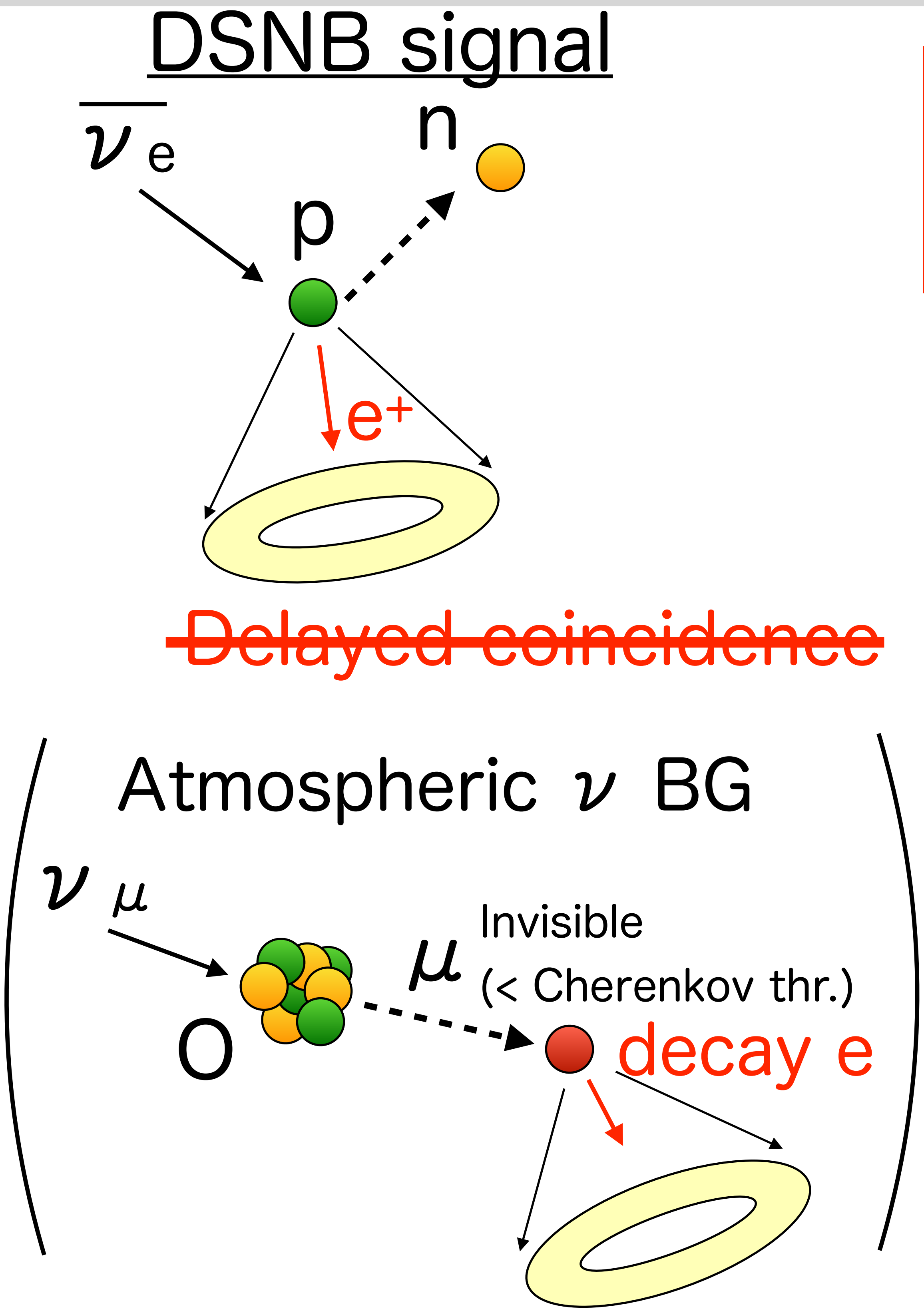
Dissolve Gadolinium into Super-K

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 Gd / SK-Gd



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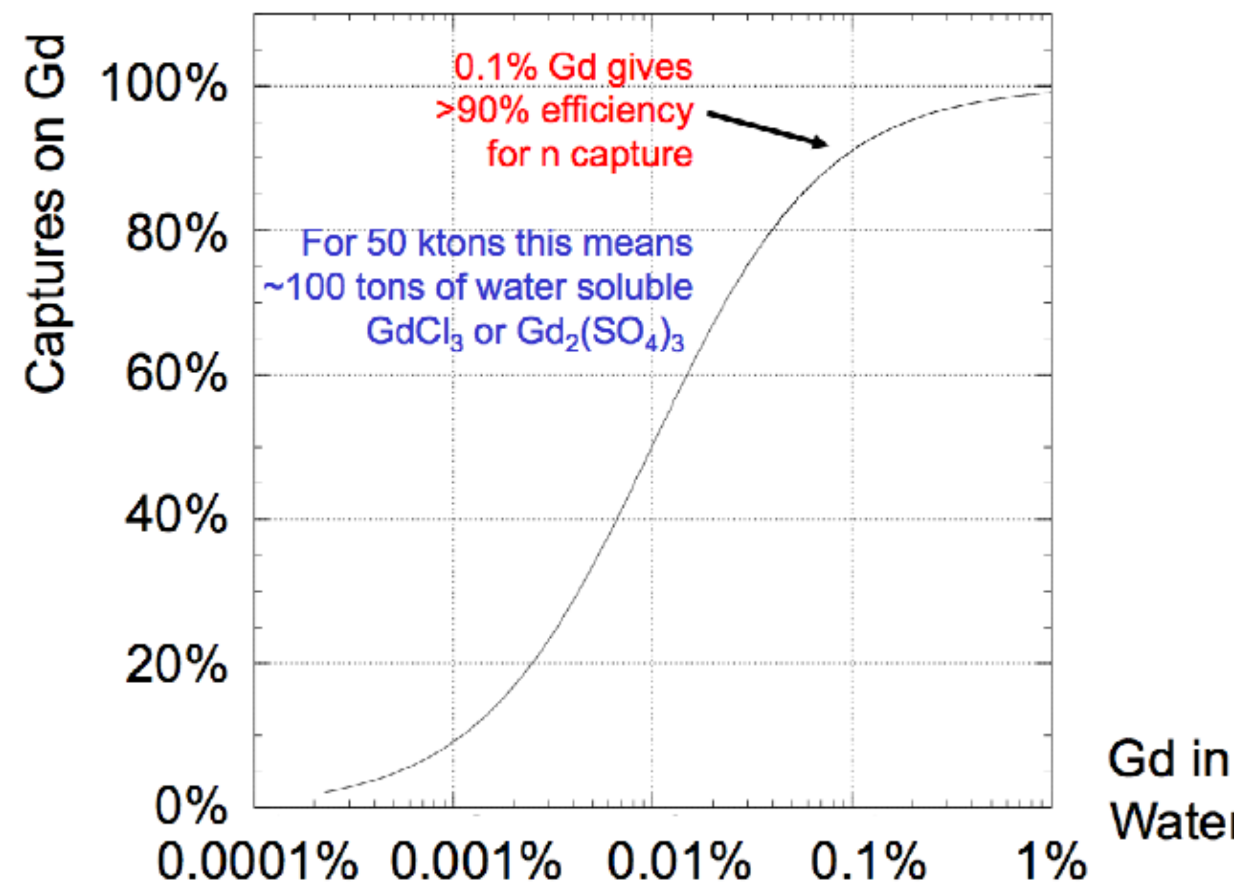

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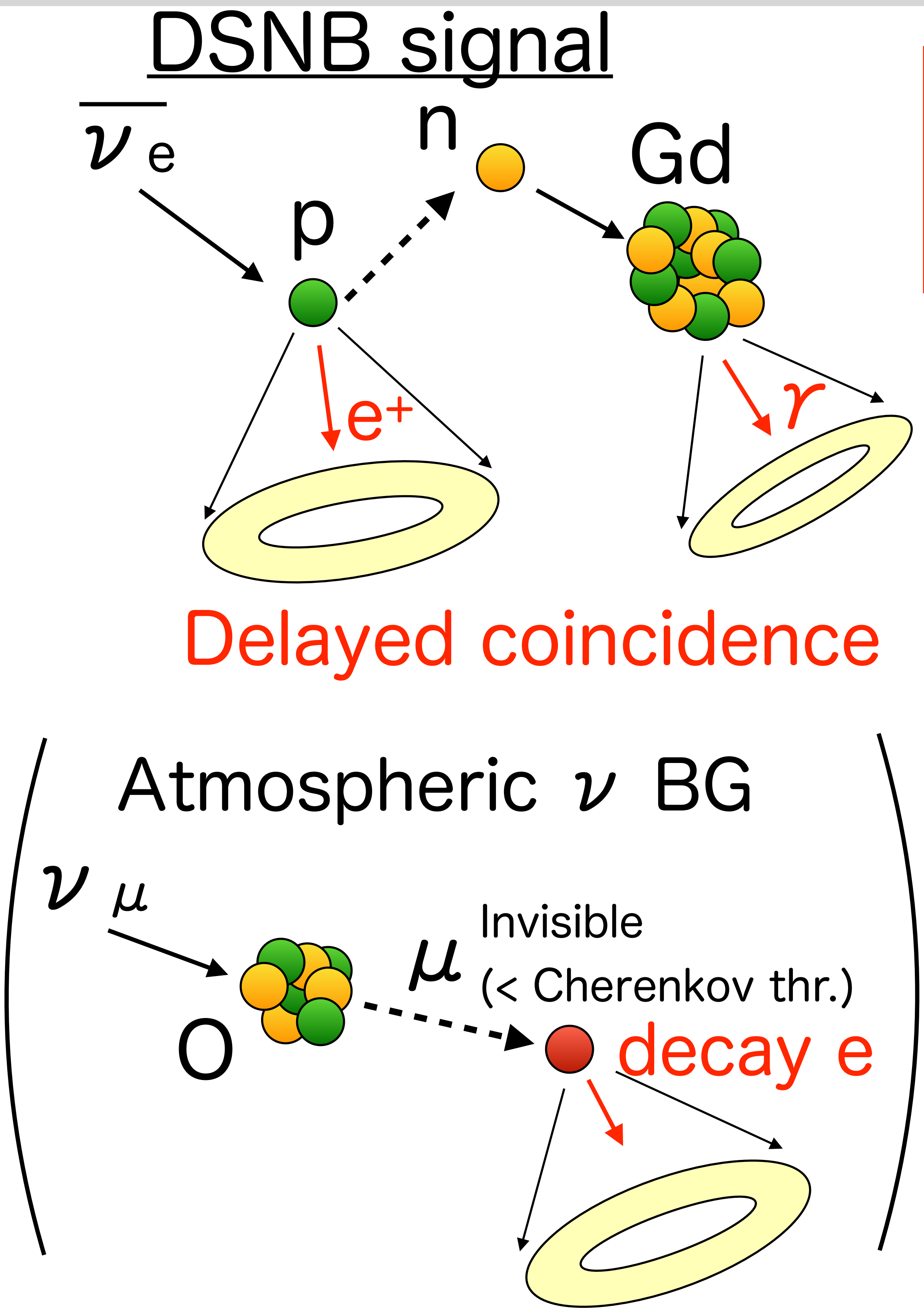

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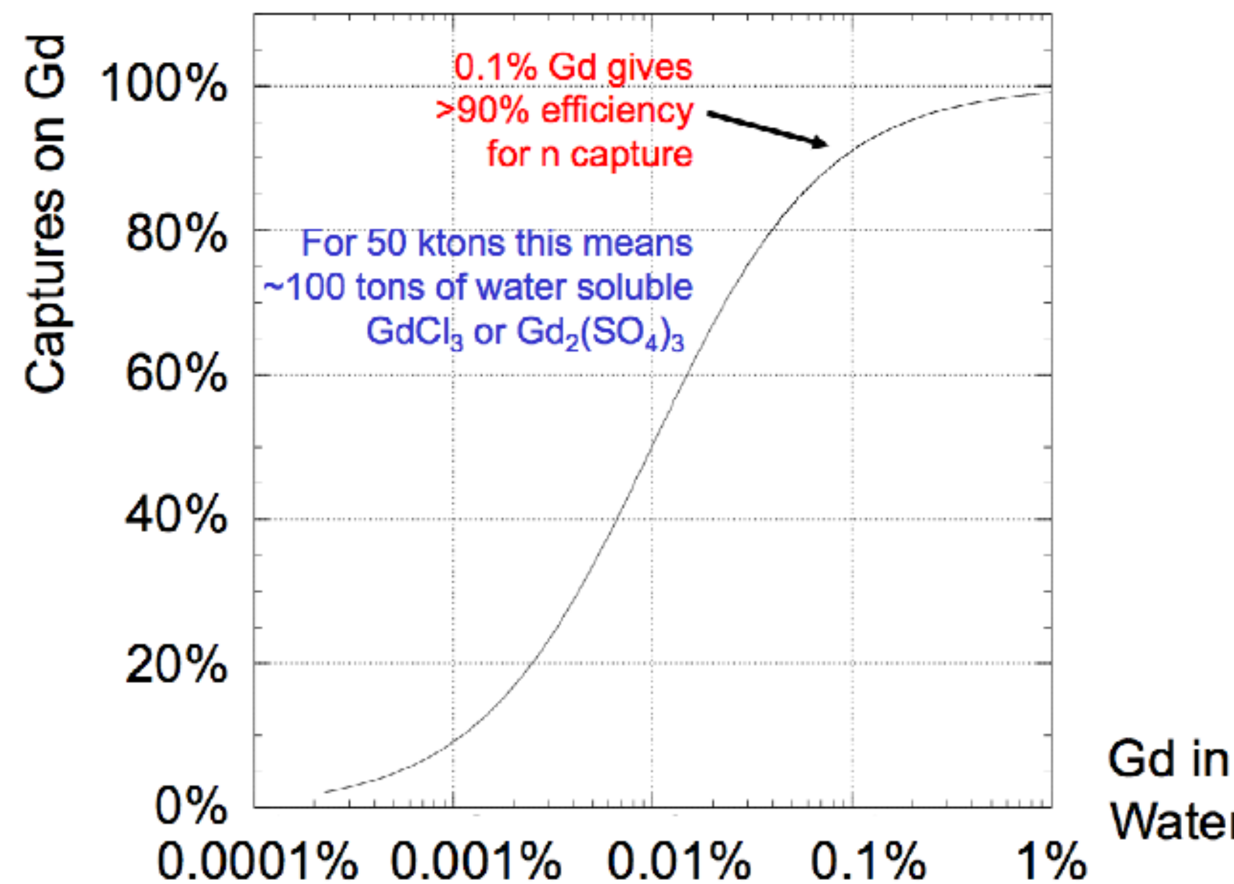

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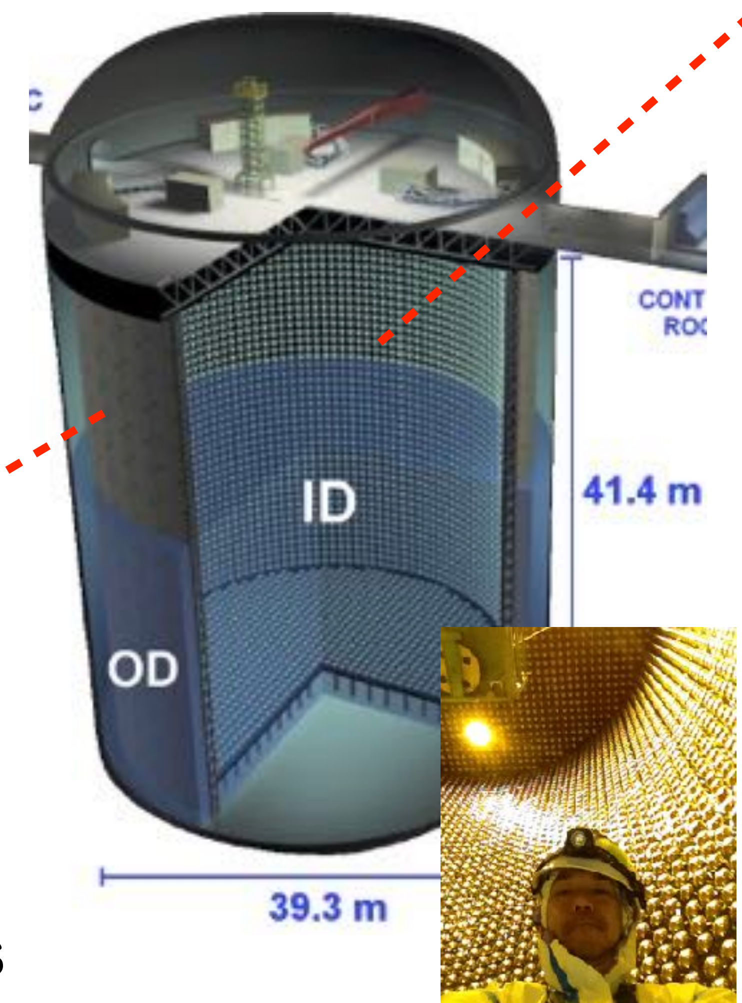
Super-K tank refurbishment

(2018.6 ~ 12)

- Stop water leak (~1ton/day)
- Change bad PMTs
- Install new water pipe for better water control
- Cleaning

Change bad PMTs

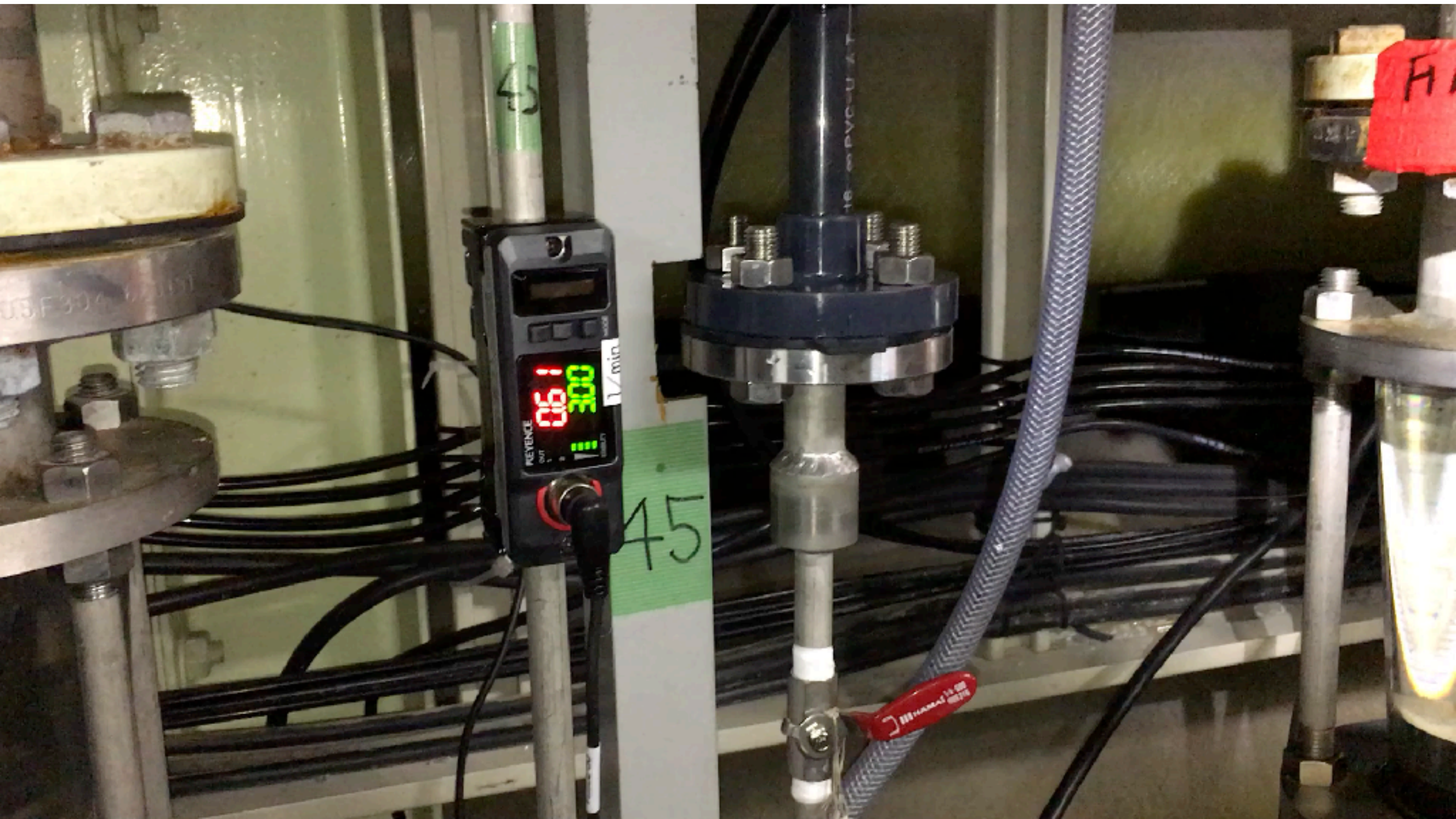


Seal whole welding lines

Install new water pipe

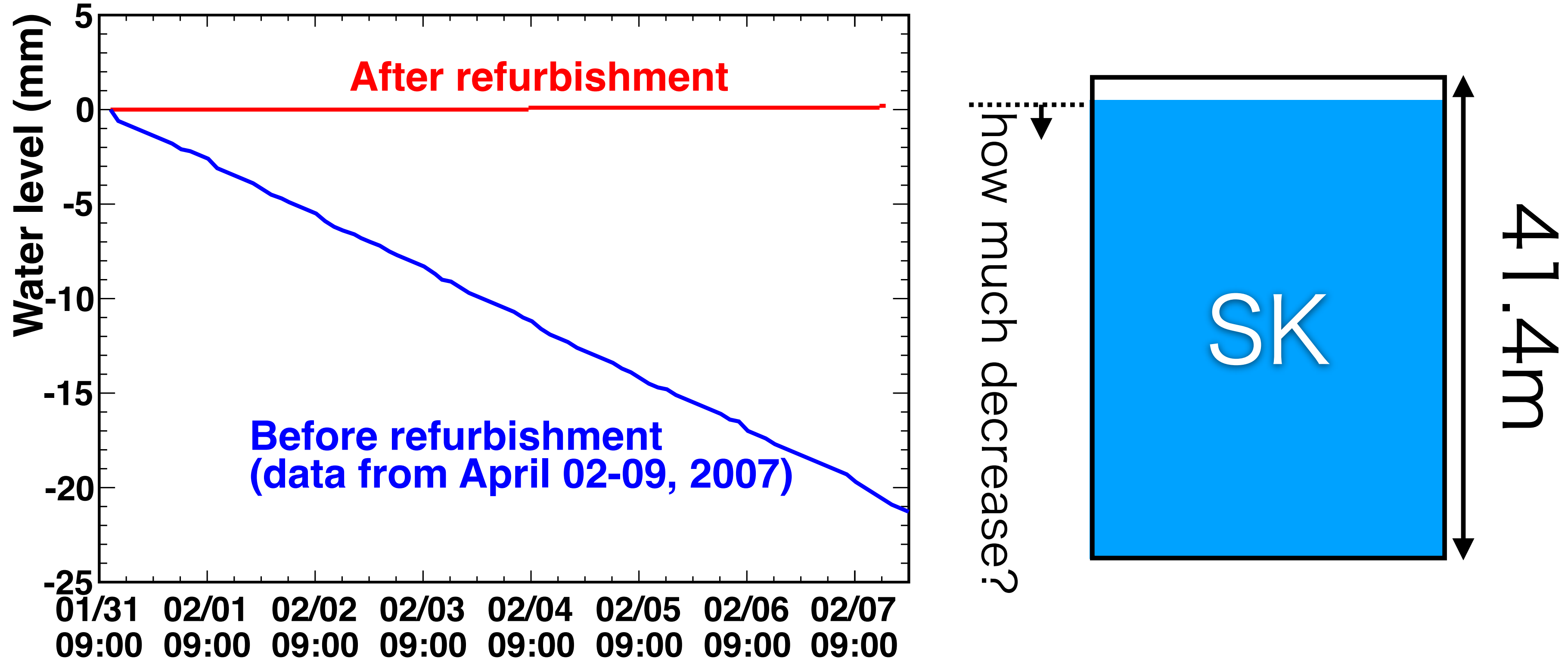
Water leakage in SK

How about ~1ton/day



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.

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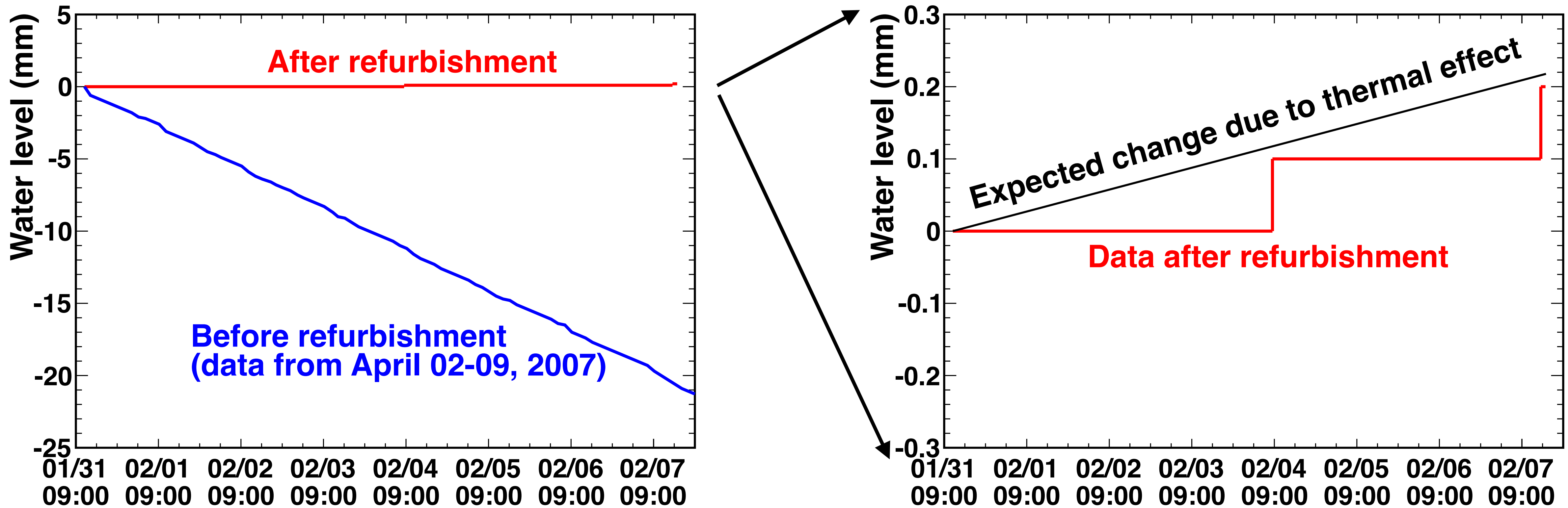

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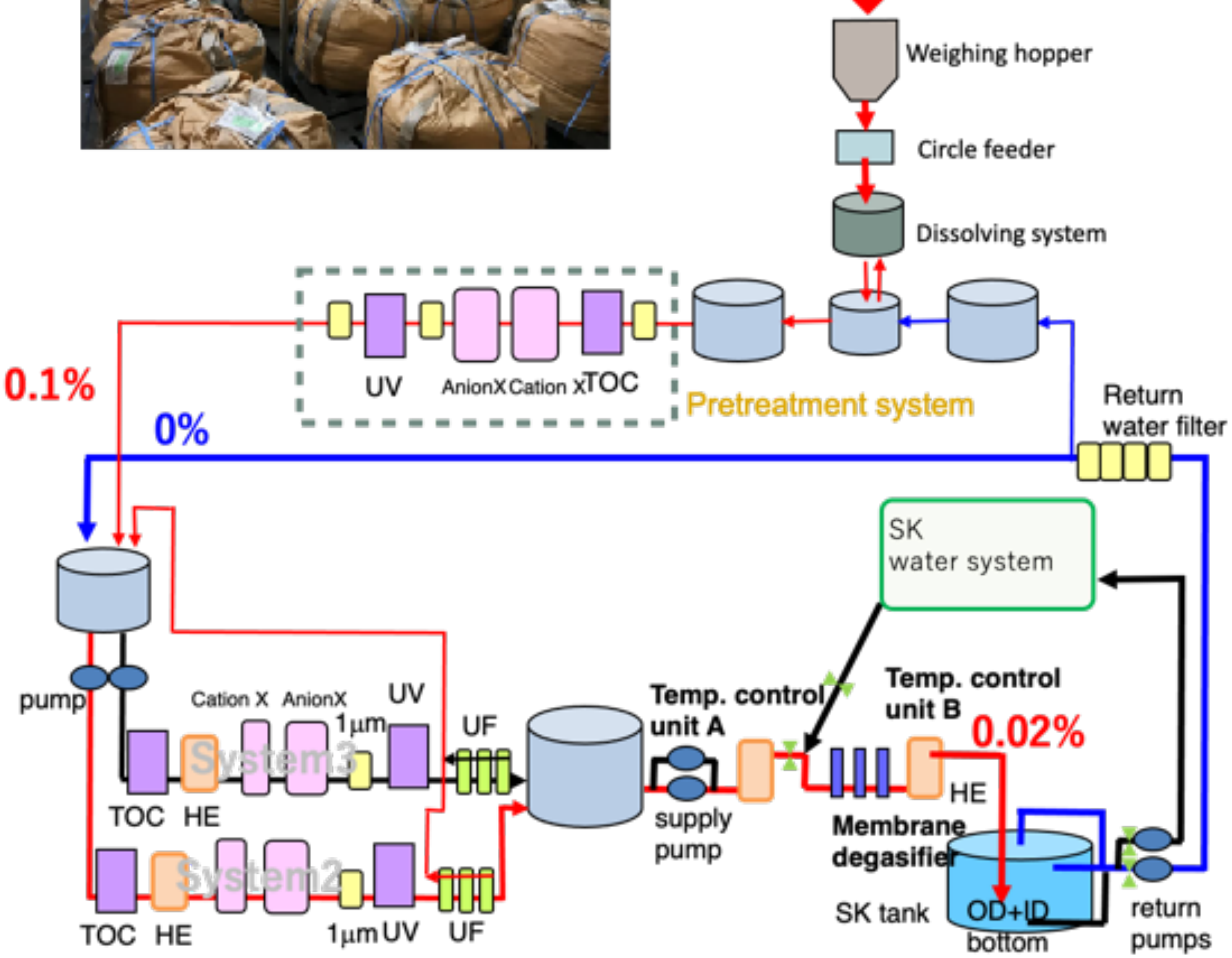
Gadolinium loading (2020)

13 tons of Gadolinium sulfate

Water purification system



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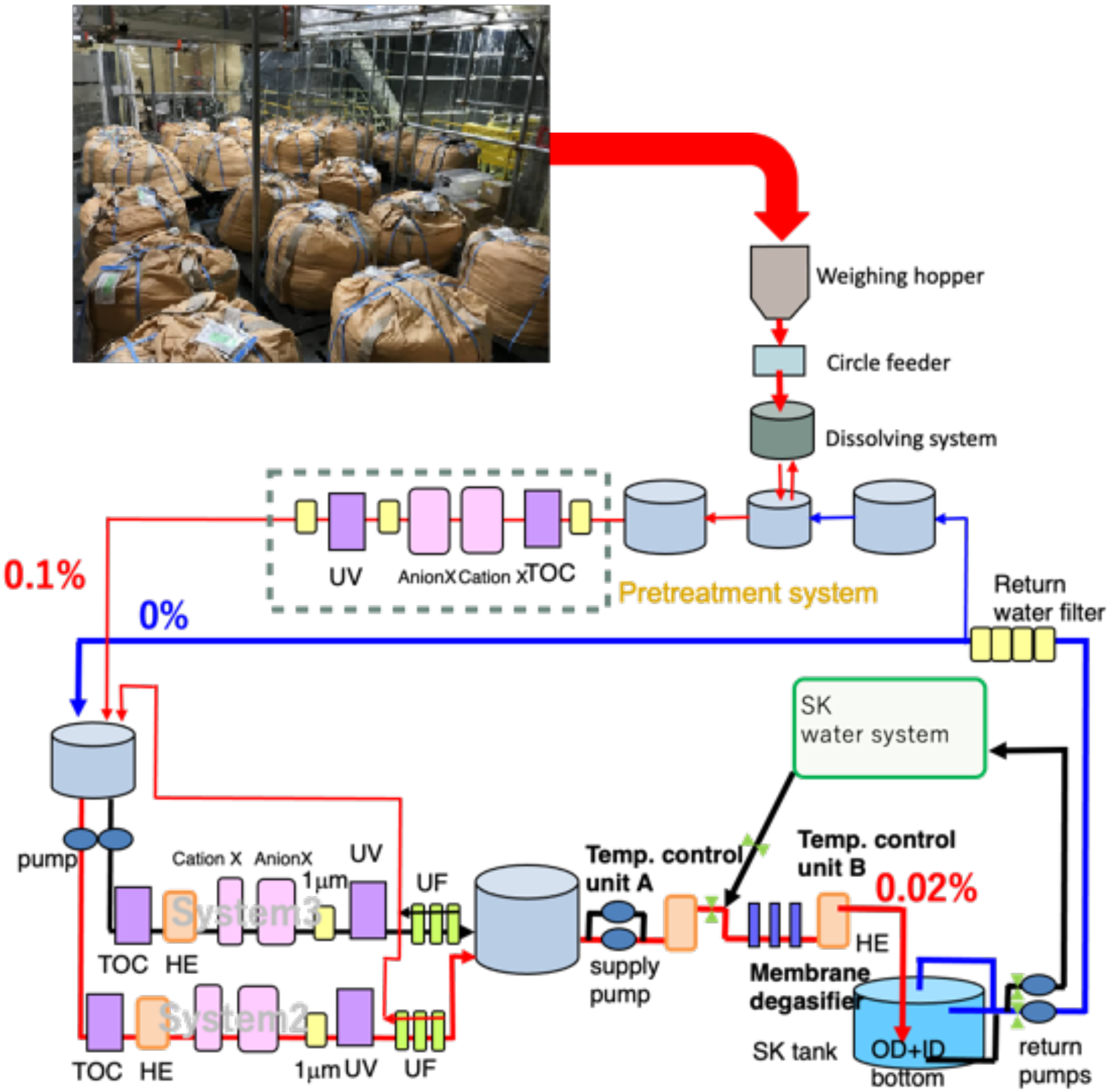

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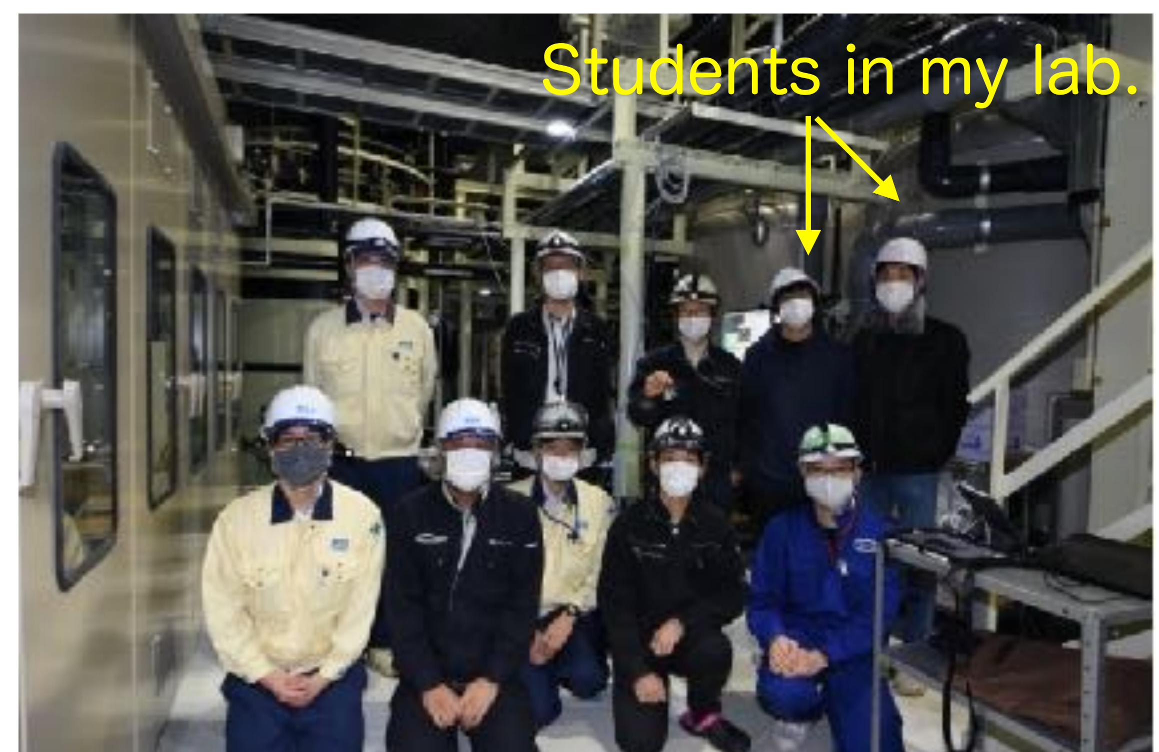
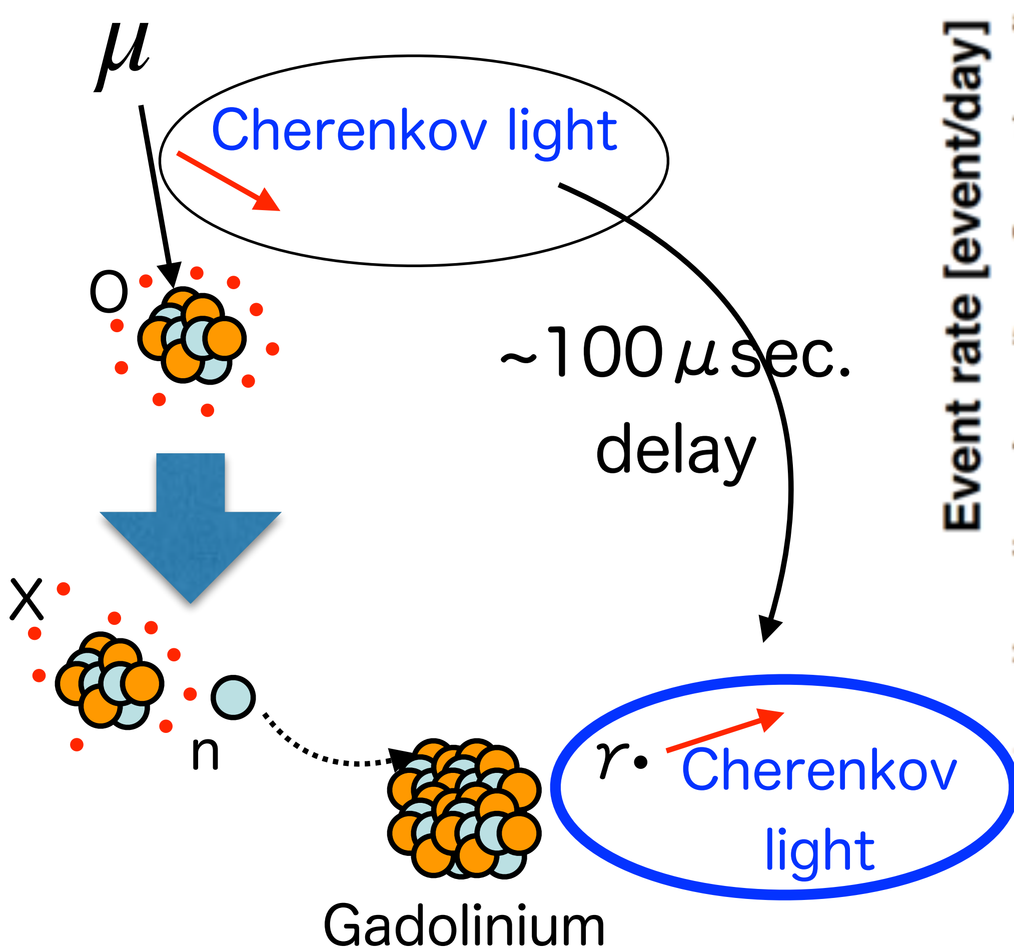
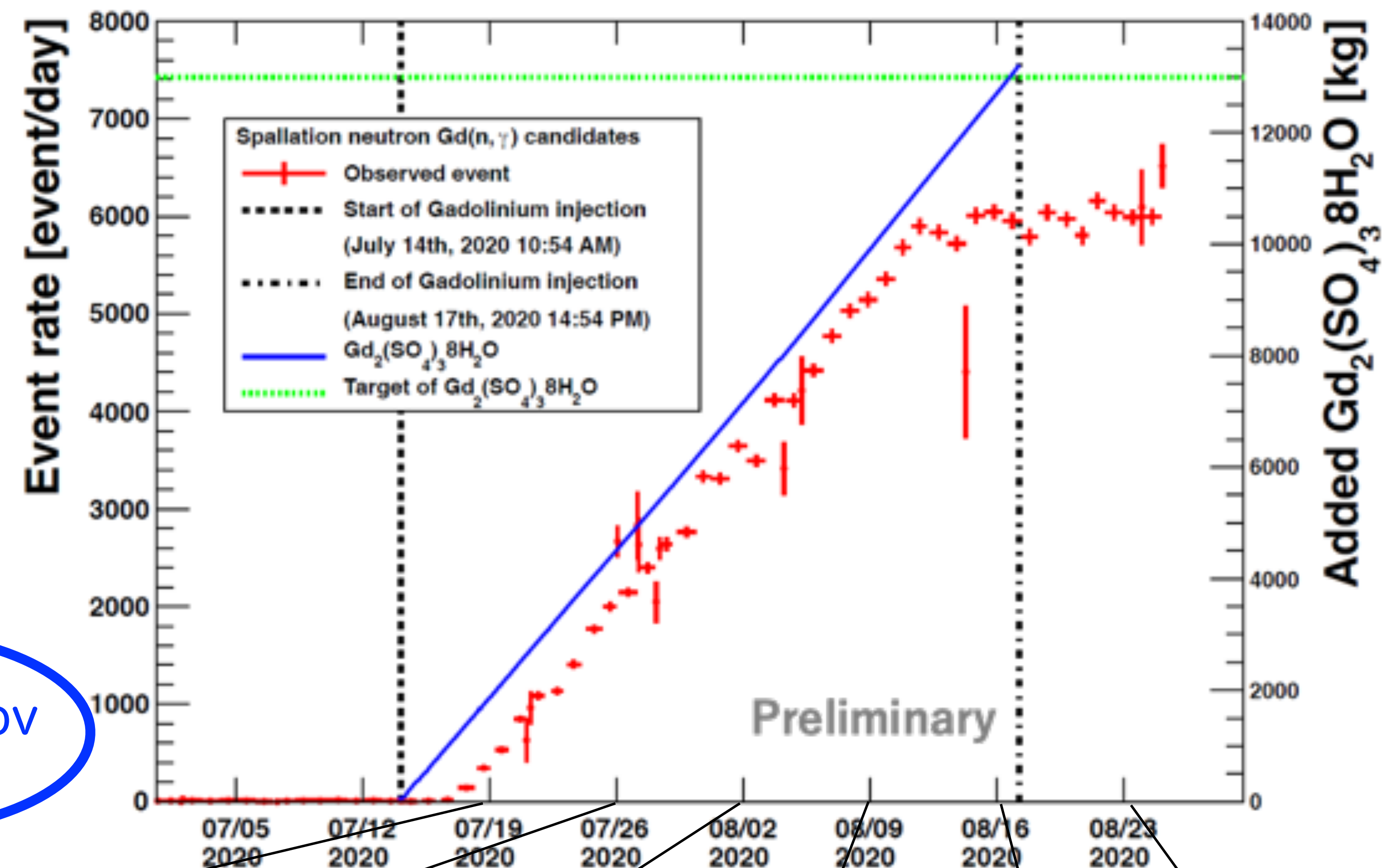
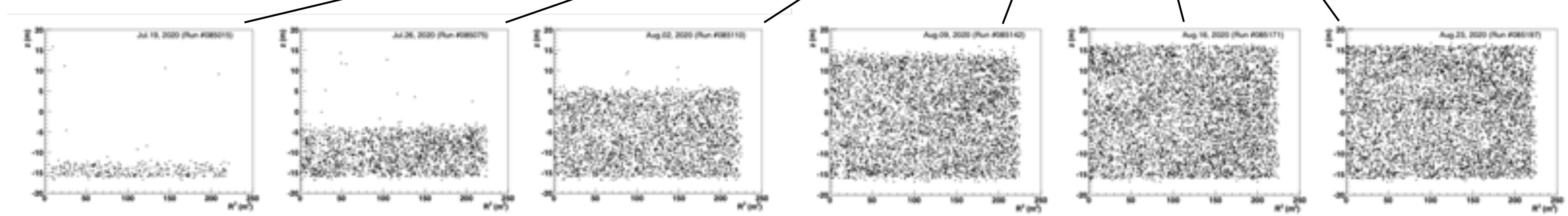


Gadolinium loading (2020)

Confirm that the neutron signal was increased
as Gd loading using cosmic ray muon data







What's next?

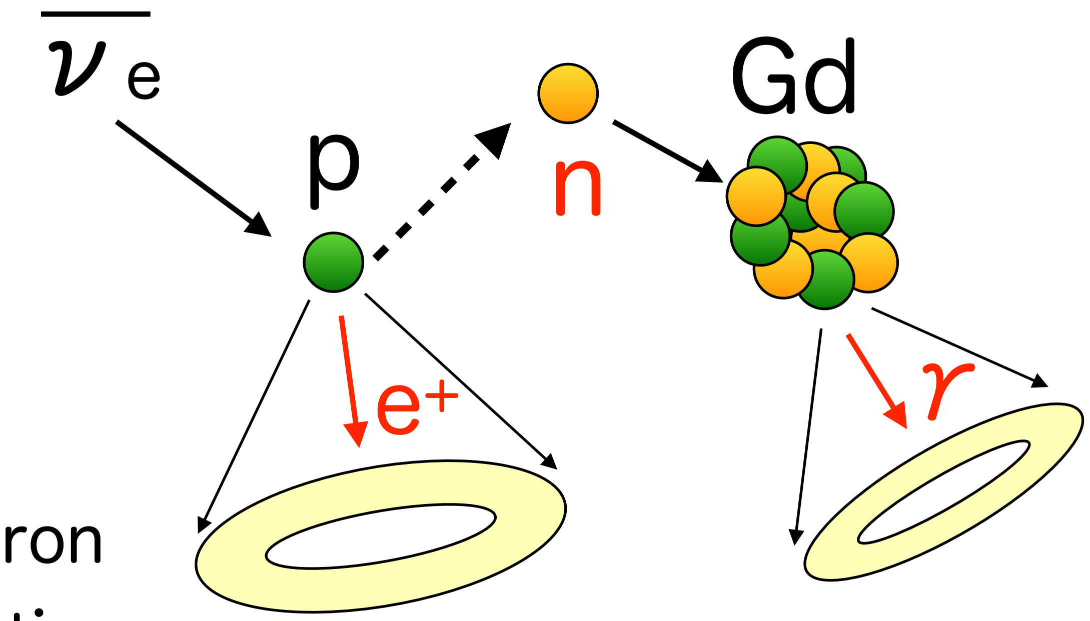
(just now)

Additional Gadolinium loading

June 1st, 2022, the next phase of SK operations (SK-VII) began.

At 10:26 a.m. JST, the continuous loading of another 26 tons of Gadolinium sulfate was started. The will bring the Gd concentration to 0.03% within July.

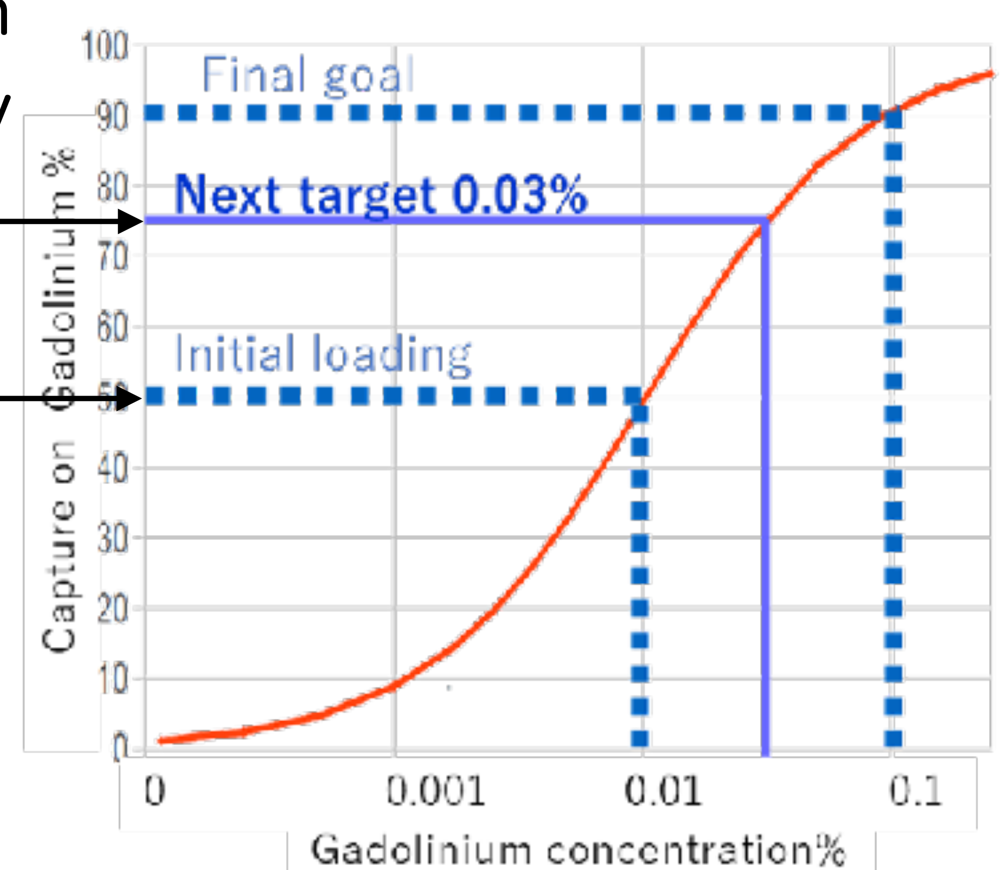
DSNB signal



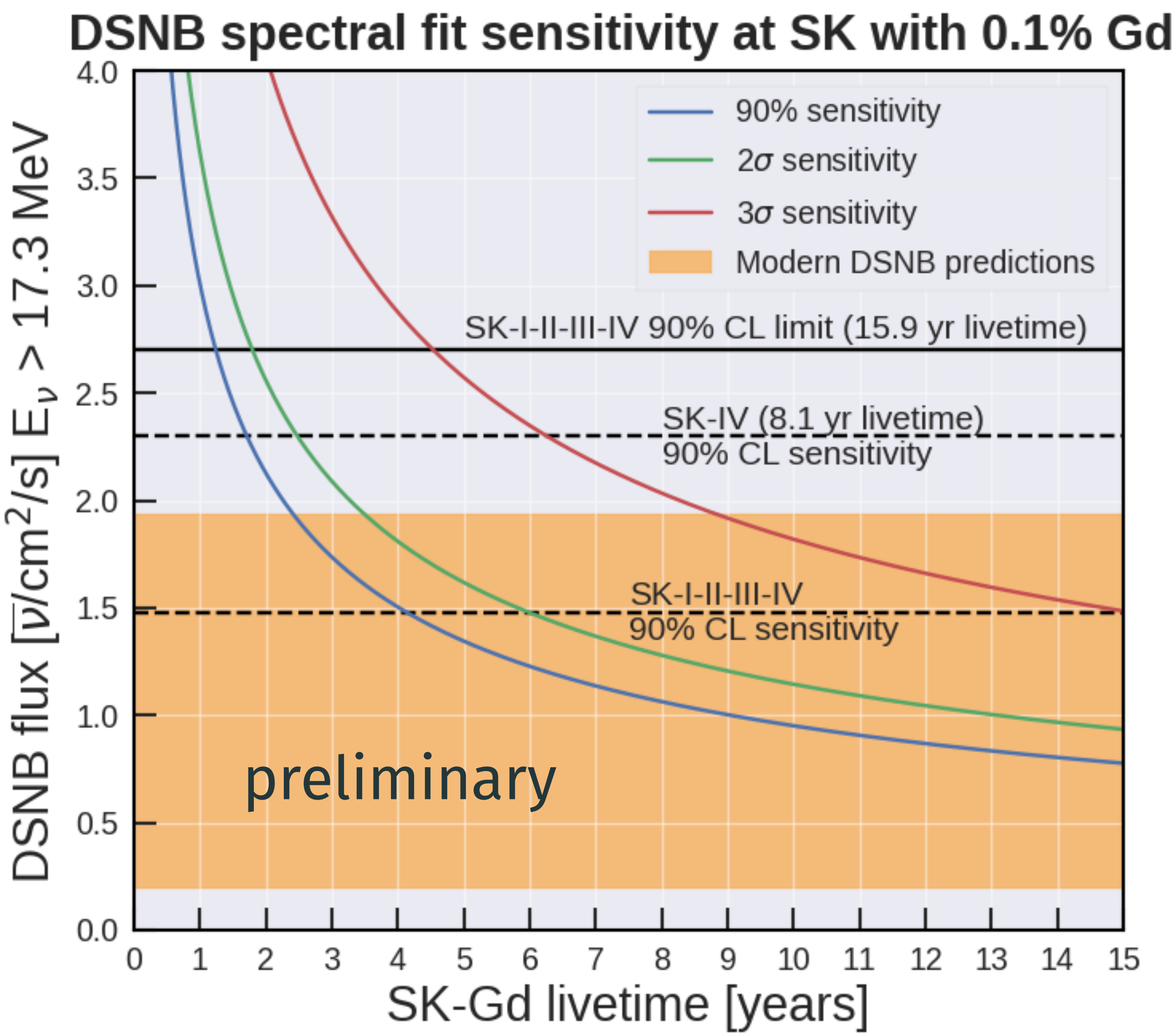
Neutron detection efficiency

75%

50%



Sensitivity of DSNB discovery



Expect 99.7% C.L. discovery at 10 years operation with the same condition

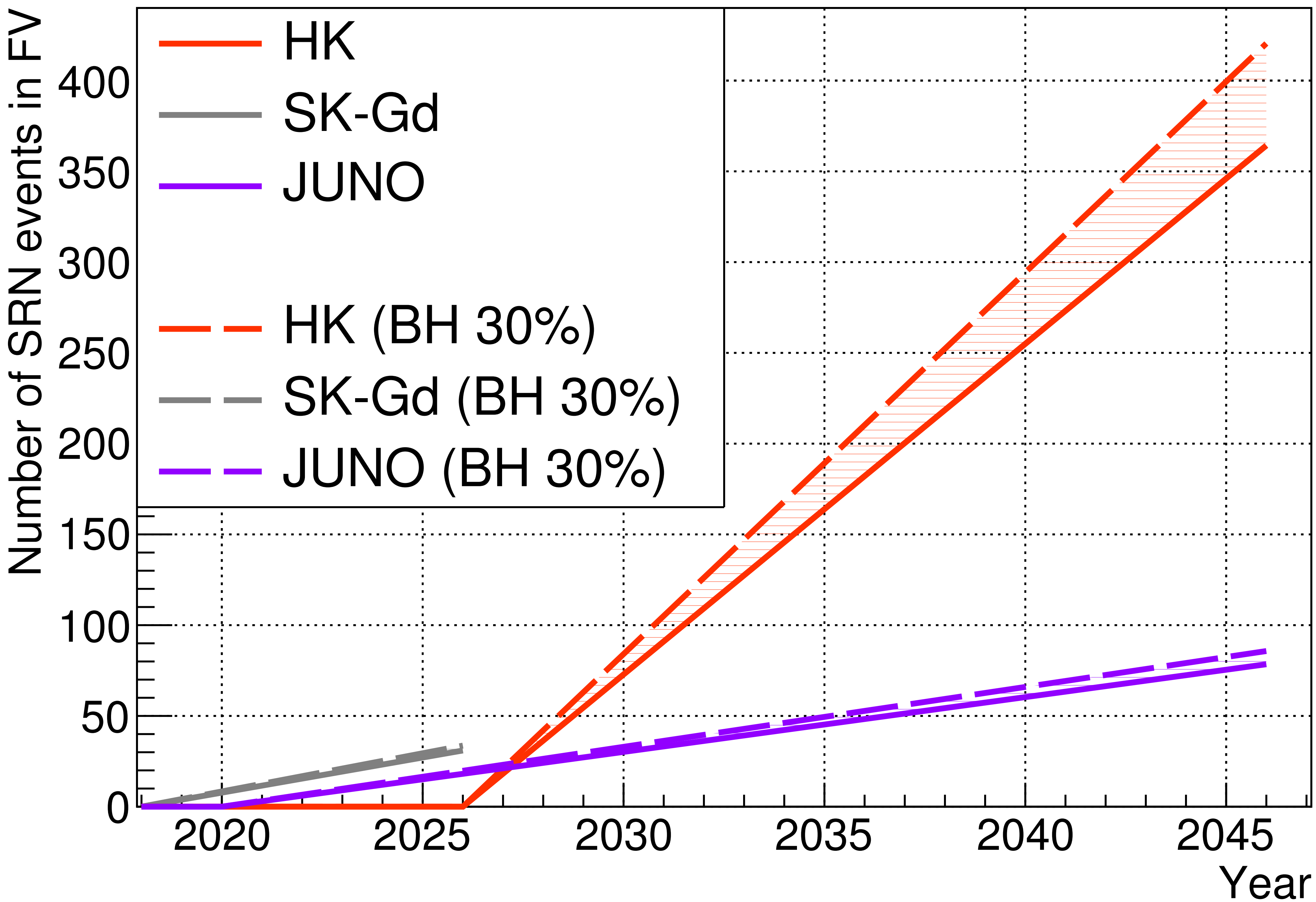
⬇

Effort of background reduction to increase the sensitivity, and hope to discover as soon as possible

Diffuse Supernova Neutrino Background

expected number of events

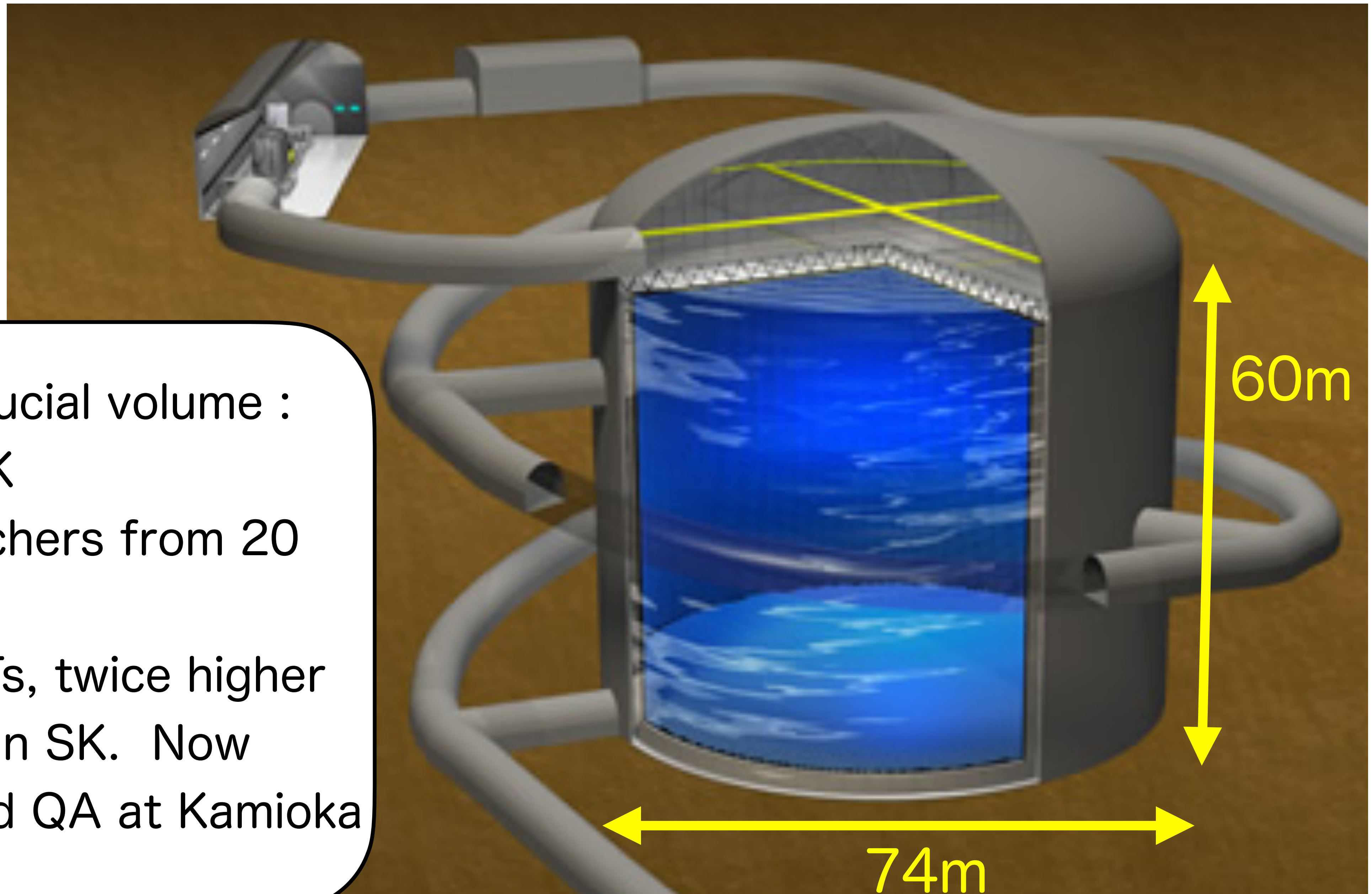
(detection efficiency is not considered)



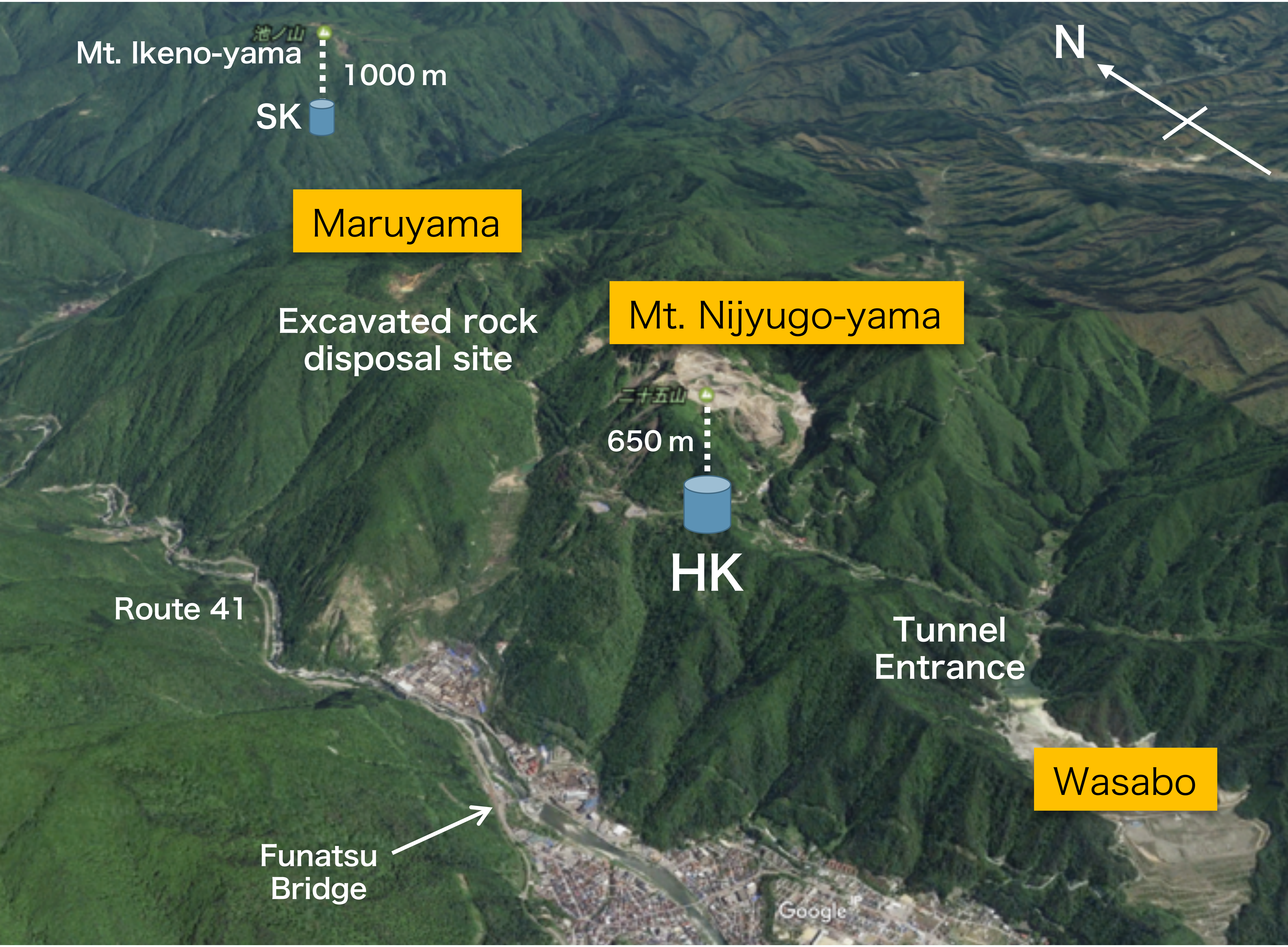
Hyper-Kamiokande

Hyper-Kamiokande

Next generation of large water Cherenkov detector (2027 -)



- 188 kton Fiducial volume : 8.4 x Super-K
- ~500 researchers from 20 countries
- ~20000 PMTs, twice higher efficiency than SK. Now delivering and QA at Kamioka



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

Project status and plan

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027

MoU signed, May 2020

Ground-breaking, May 2021

Access tunnel complete, Feb 2022

Approach and peripheral tunnels, Summer 2022

Operation starts!

Cavern Excavation

Tank construction

PMT installation

Water filling

PMT production

Thank you for your attention!

Stay tuned from ICRR