Results and prospects of underground physics research in Japan

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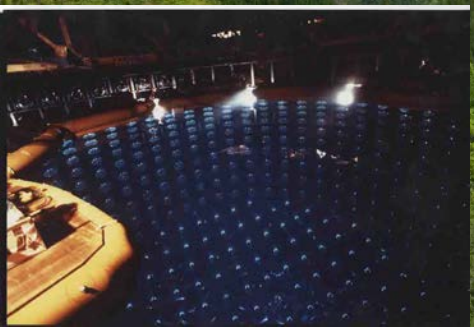

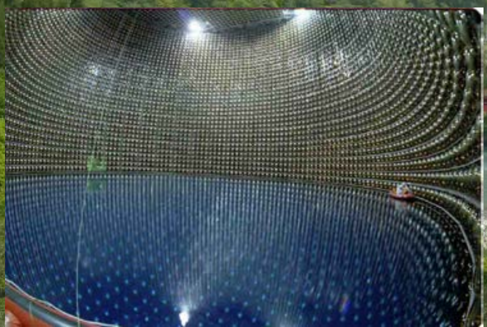

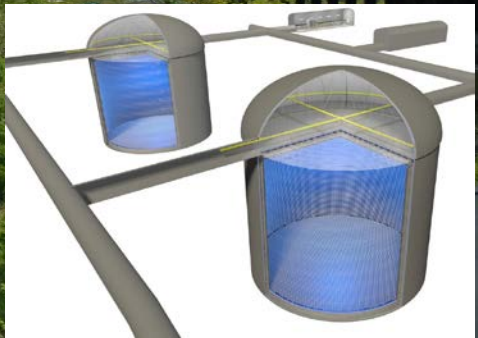

Congratulations for the 50th Anniversary of Baksan Neutrino Observatory

Photos taken during Baksan School 2001

30th Anniversary of SN1987A

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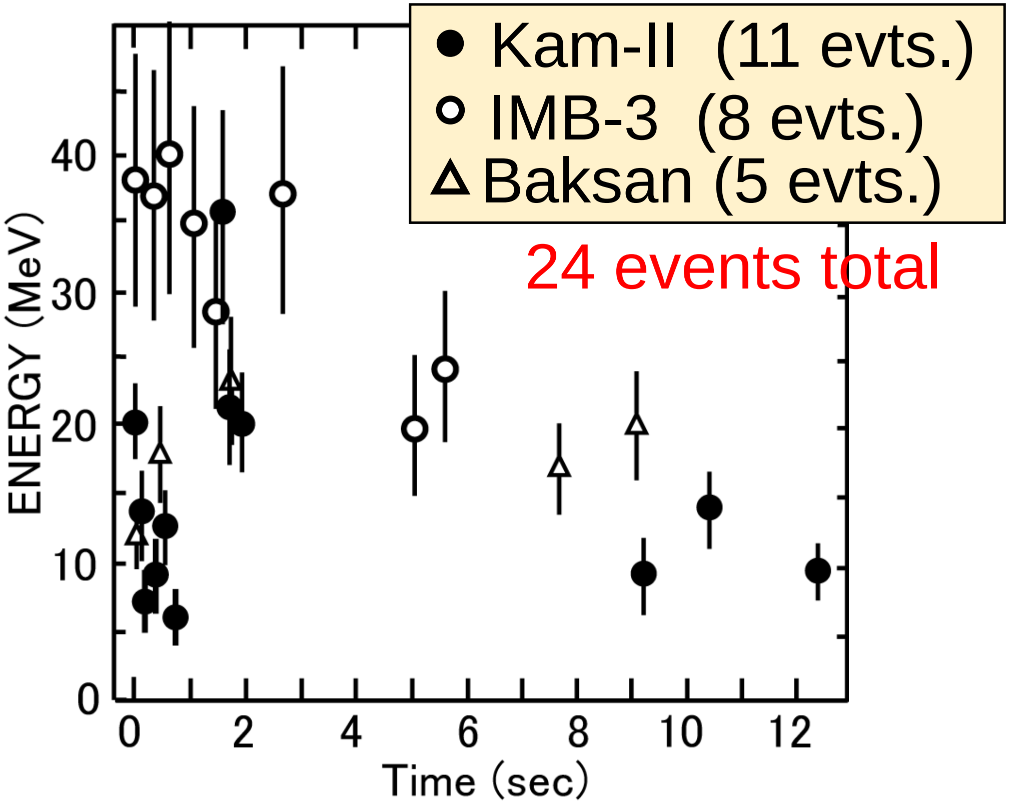
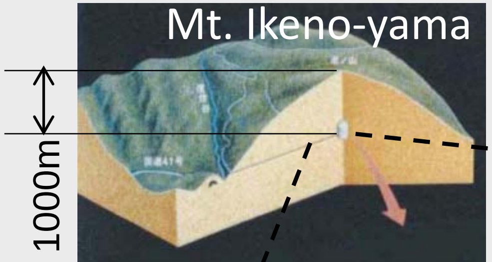


Kamiokande, IMB and Baksan detectors observed neutrinos from a supernova SN1987A at Large Magellanic Cloud on Feb.23rd, 1987.

Contents

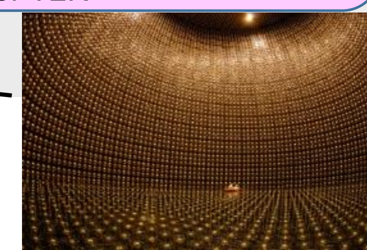
- What experiments are at Kamioka now
- Brief history of reserches at Kamioka
- Recent highlights from Kamioka
- Future

Kamioka underground (NOW)

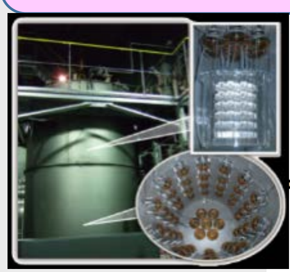


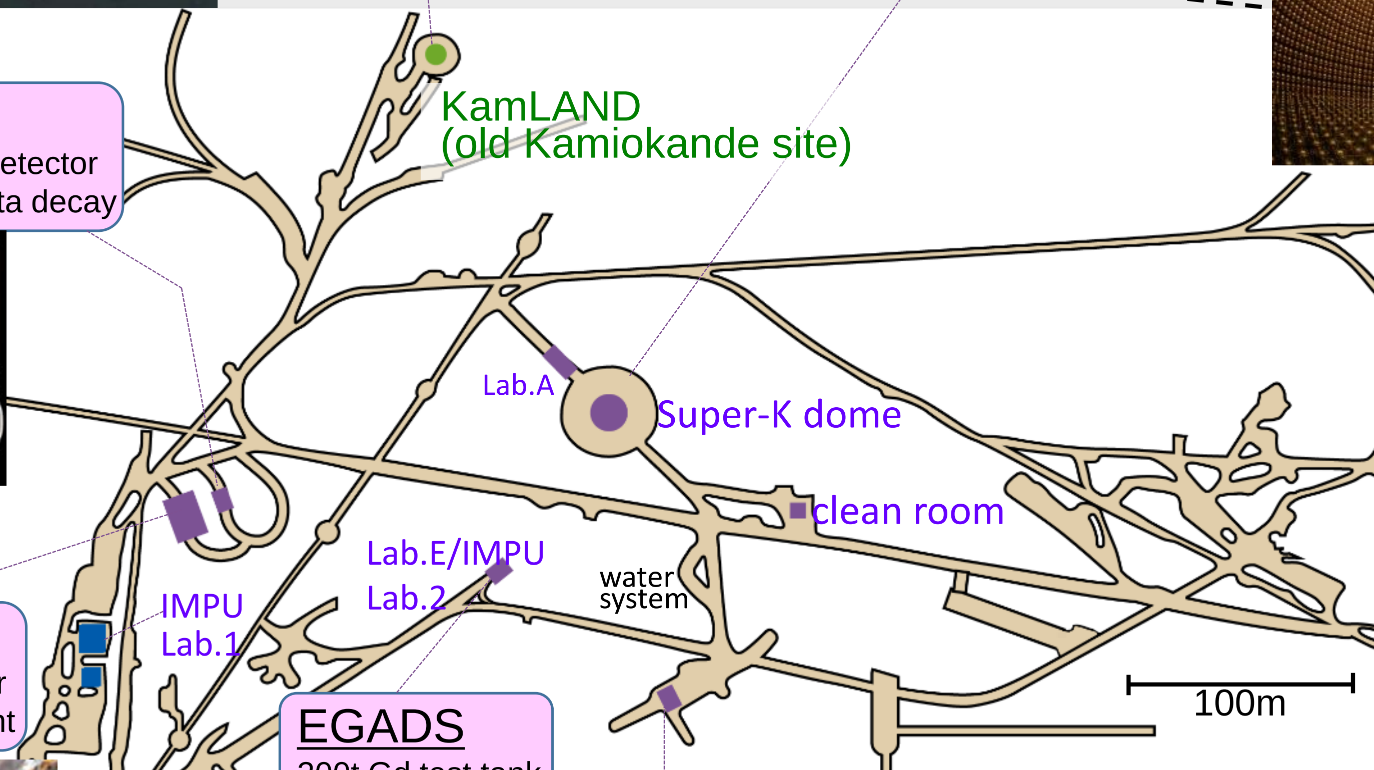
KamLAND (Tohoku Univ.)
1000ton liquid scintillator detector
Reactor, geo neutrinos
^{136}Xe double beta decay

Super-Kamiokande
50,000 ton water Cherenkov detector
Atmospheric, solar, supernova neutrinos
proton decay, indirect dark matter search
Far detector for T2K



CANDLES
CaF_2 scintillation detector
for ^{48}Ca double beta decay

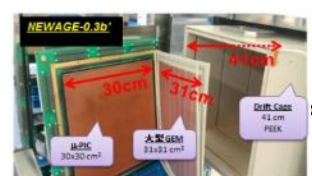




XMASS
Direct dark matter
search experiment

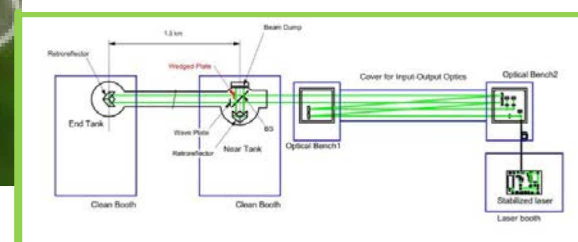
EGADS
200t Gd test tank

NEWAGE
Direction dark
matter experiment

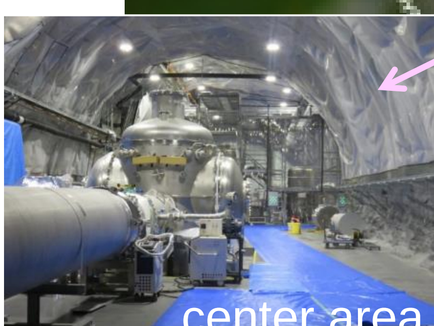


Kamioka underground experiments (NOW)

Laser strainmeter



1.5km Geophysics interferometer



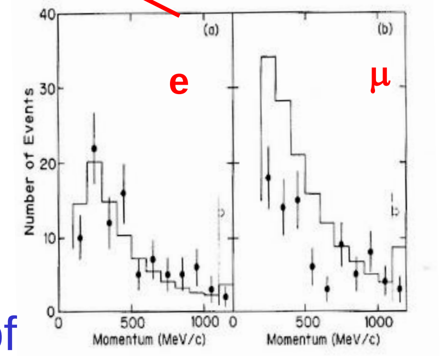
KAGRA
Gravitational-wave
Telescope
(under construction. Start in 2019)

Brief history of Kamioka underground

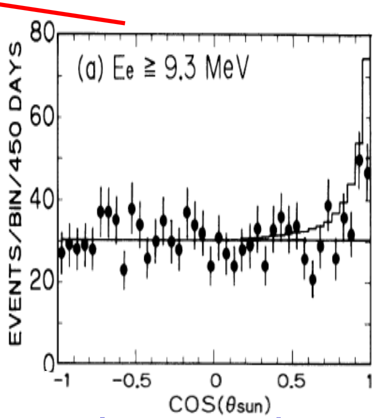
1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997

Kamiokande start (3,000t total vol.)

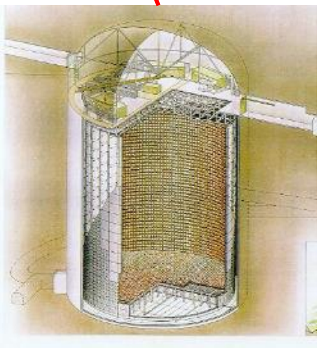
Observation of neutrinos from SN1987A



Atmospheric anomaly

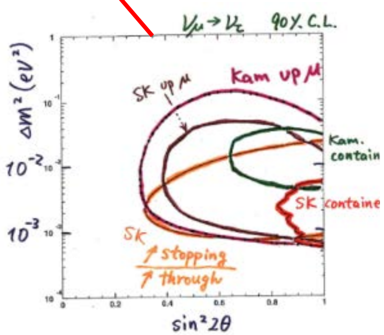


Solar neutrino problem (by Kamiokande)

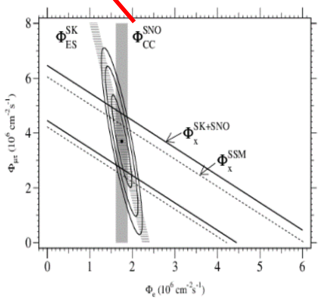


Super-K start (50,000 total vol.)

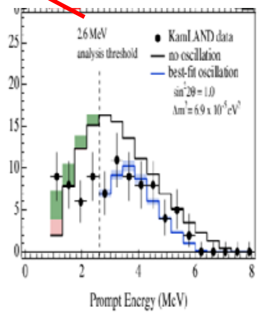
1998	1999	2000	2001	2002	2003	2004	……	…..	2011	2012	2013	2014	2015	2016



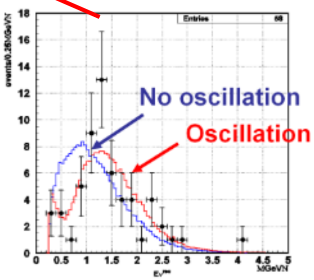
Discovery of atmospheric ν oscillation



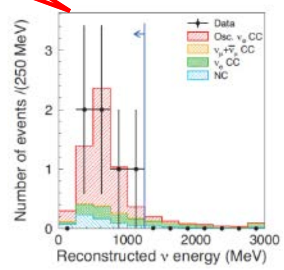
Discovery of solar ν osc. (SK vs. SNO CC)



Discovery of reactor ν osc. （KamLAND）



K2K confirmed ν osc. by artificial neutrinos



Discovery of finite θ13 by T2K

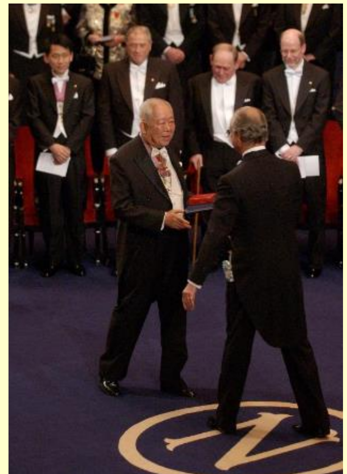
Brief history of Kamioka underground

1983	1984	1985	1986	1987	19		91	1992	1993	1994	1995	1996	1997

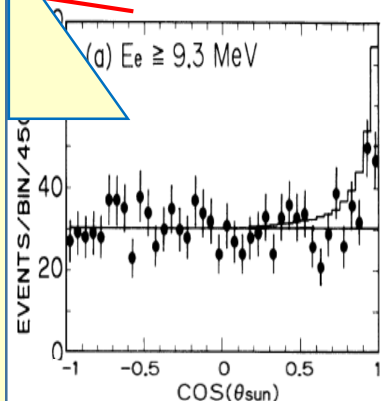
Kamiokande start (3,000t total vol.)

Observation of neutrinos from SN1987A

Koshiba's Nobel Prize in 2002



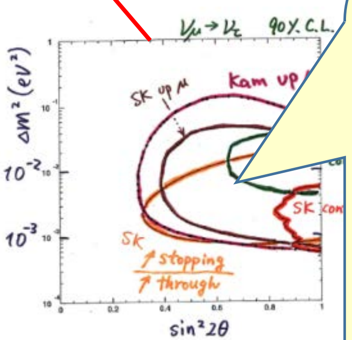
a



Solar neutrino problem (by Kamiokande)

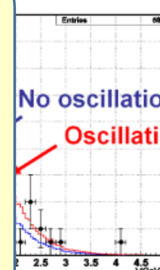
Super-K start (50,000 total vol.)

1998	1999	2000	2001	2002	2003	2004	……	…..	2011	2012	2013	2014	2015	2016

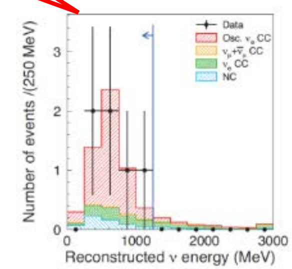


Discovery of atmospheric ν oscillation

Kajita's Nobel Prize in 2015



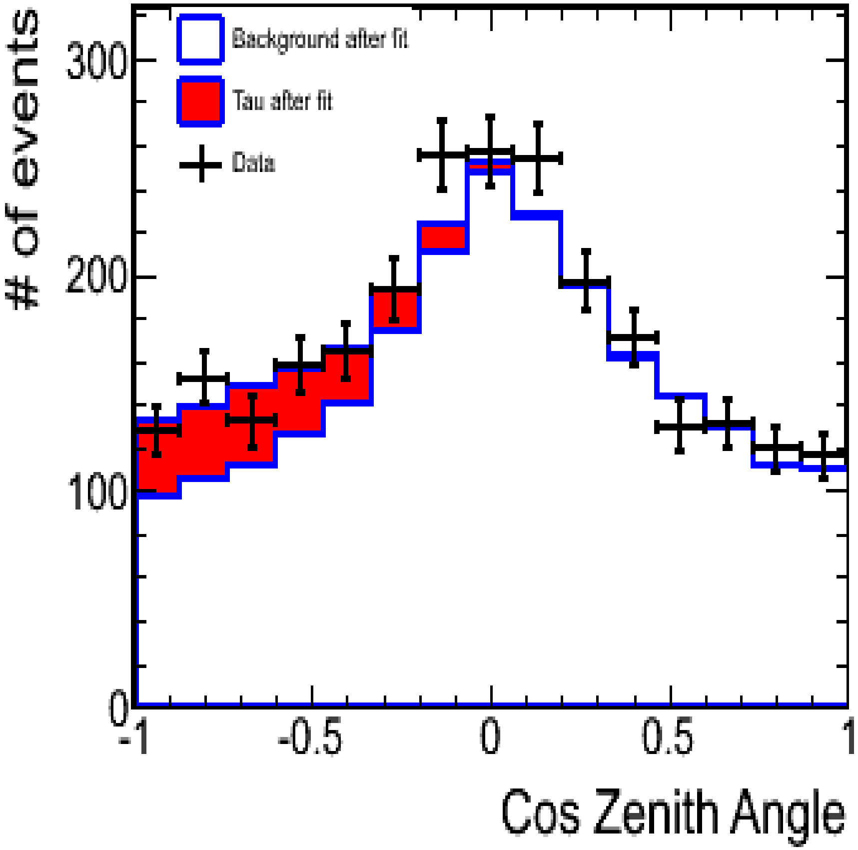
confirmed ν by artificial
trinos

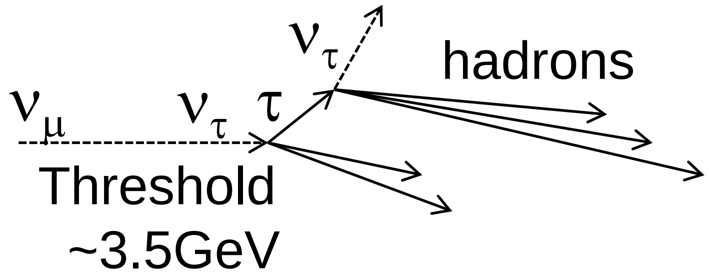


Discovery of finite θ13 by T2K

Recent Highlights from Kamioka
(SK, T2K, KamLAND)

SK atmospheric ν: ν_τ appearance



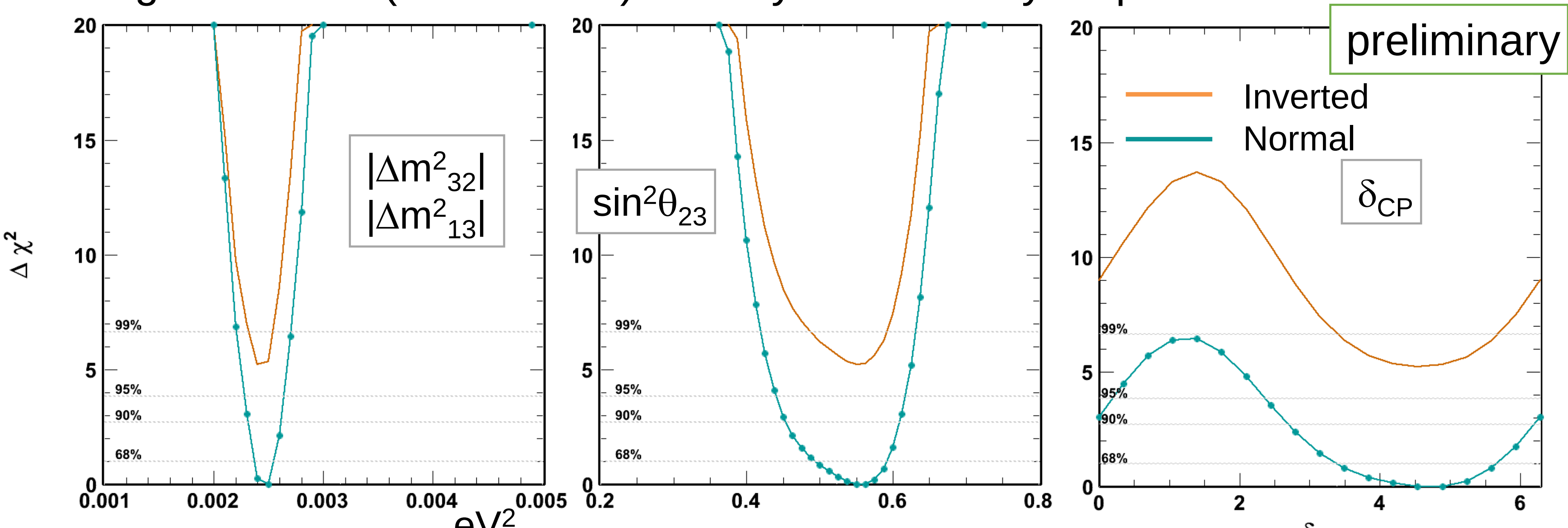


- Search for events consistent with hadronic decay of τ lepton
  - Multi-ring e-like events with visible energy above 1.3GeV.
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced: **upward-going**

Observed # / Expected #
=1.47+/-0.32
(4.6σ from 0)
assuming NH

SK atmospheric ν analysis (with T2K constraint)

Using all SK data(SK-I/II/III/IV). Totally 0.33 Mton･yr exposure.



Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	$2.5\text{x}10^{-3}$
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	$2.4\text{x}10^{-3}$

- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$

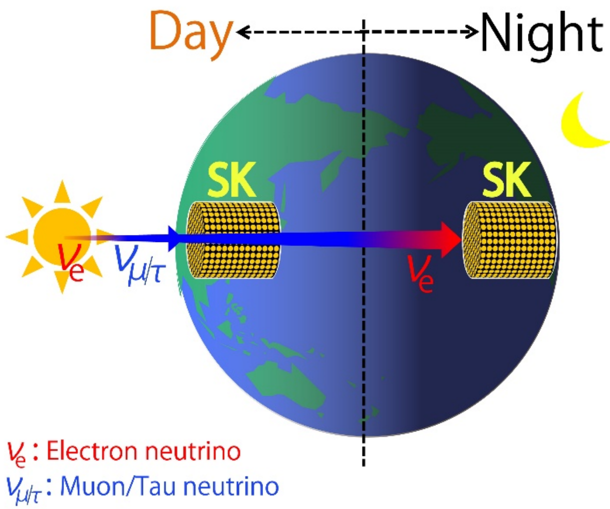
  (-3.8 (-3.1) expected for SK best(combined) oscillation parameters)

- With toy MC studies,

  P($\Delta\chi2 < -5.2$) for IH is 2.4%, while that for NH is 43.3% (for $\sin^2\theta_{23}$=0.6)

SK solar ν: day/night effect

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

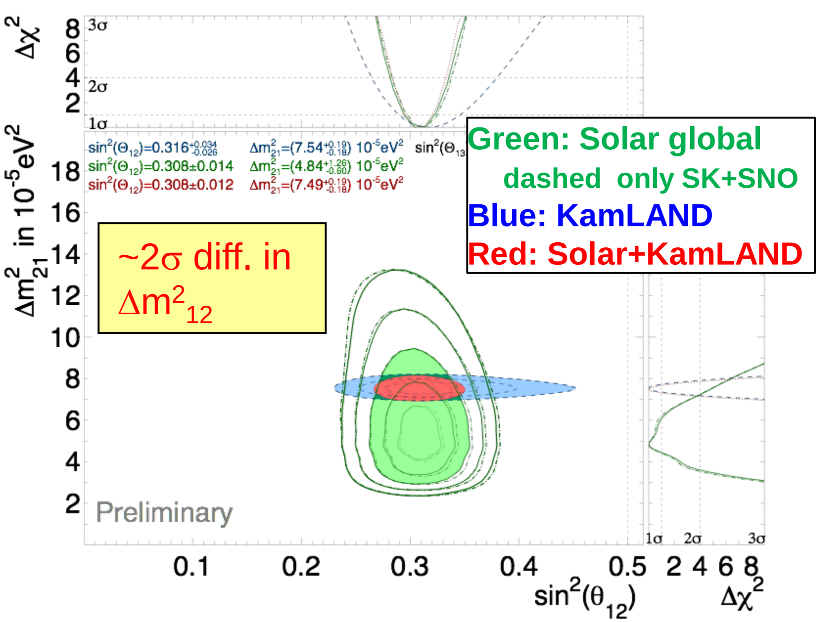


	D/N asymmetry (A_{DN})
	Δm^2_{21}=4.84x10^{-5} eV^2
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	-3.3±1.0±0.5%
non-zero significance	3.0σ

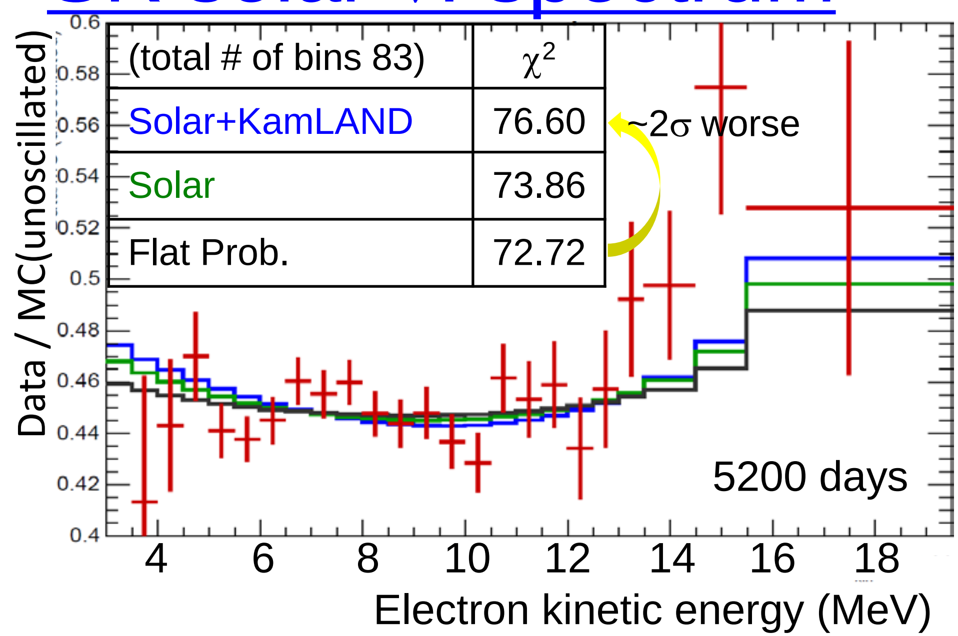
4499 days

Direct indication of matter effect.

Solar global analysis

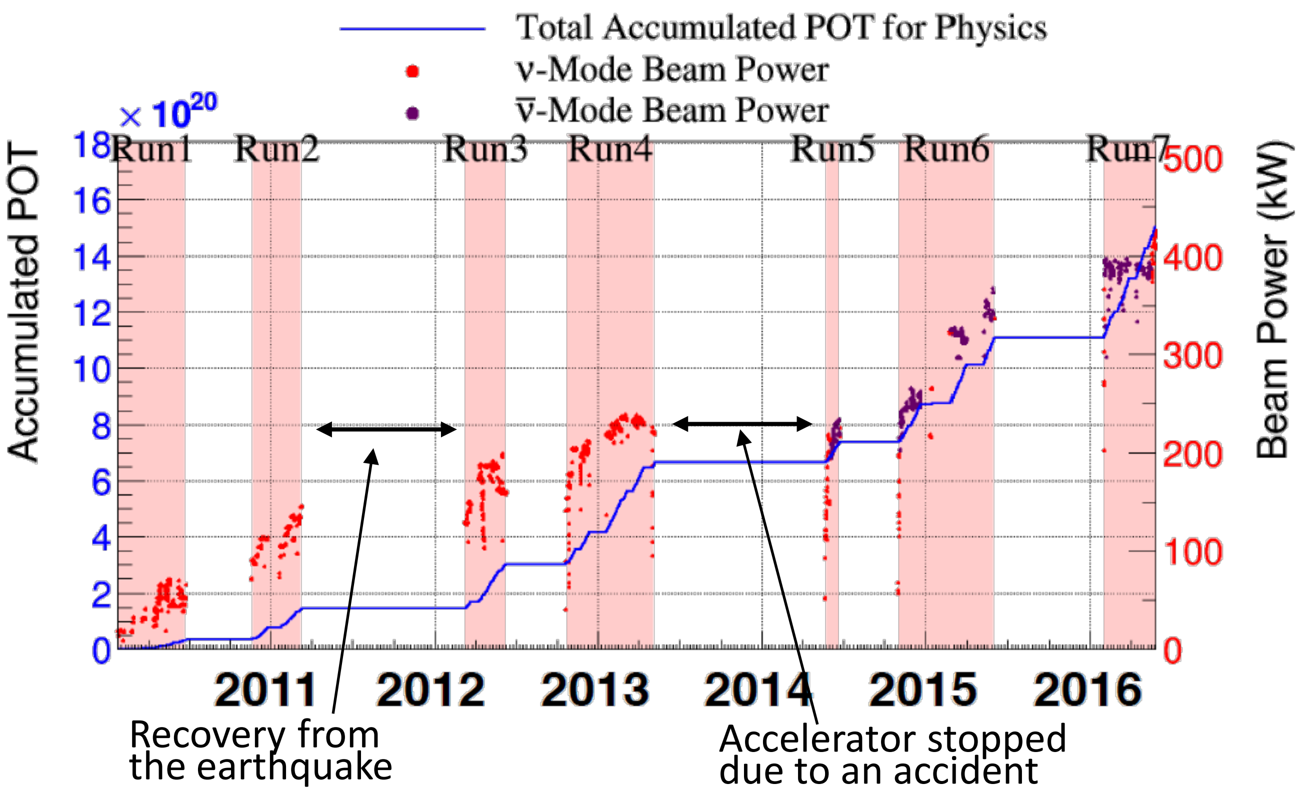


SK solar ν: spectrum



Results from T2K

- ν_e appearance for the study of θ_{13} and δCP
- ν_μ disappearance for the study of θ_{23} & Δm^2_{23}



Until May 2016

15 x 10^{20} POT

(~20% of the planned total)

Neutrino mode

7.57x10^{20} POT

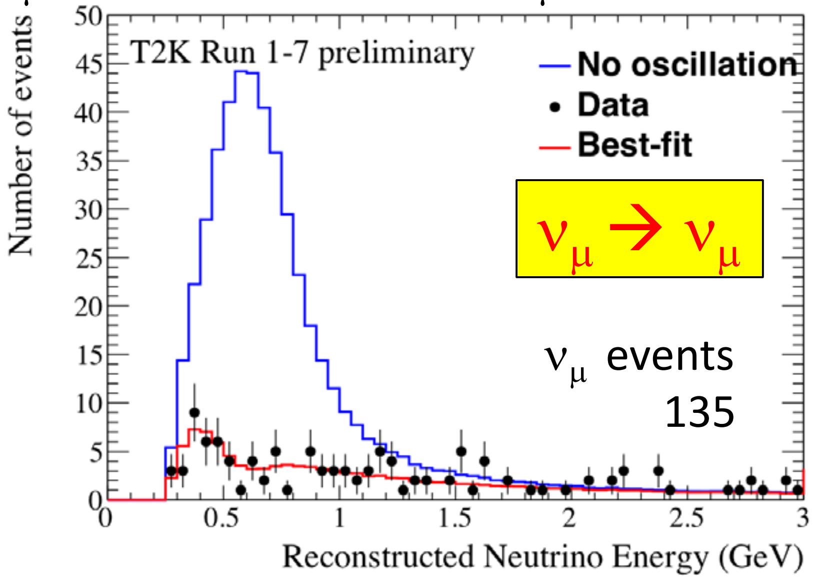
Anti-Neutrino mode

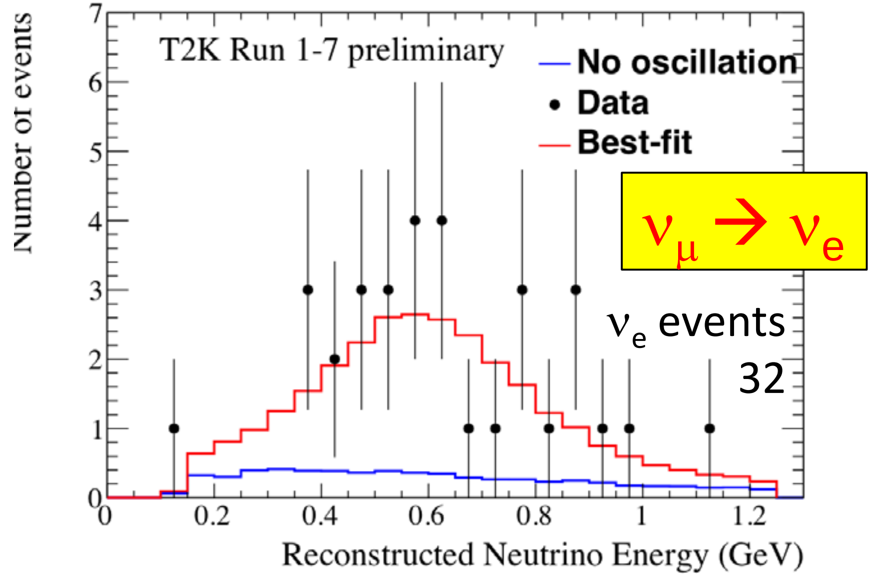
7.53x10^{20} POT

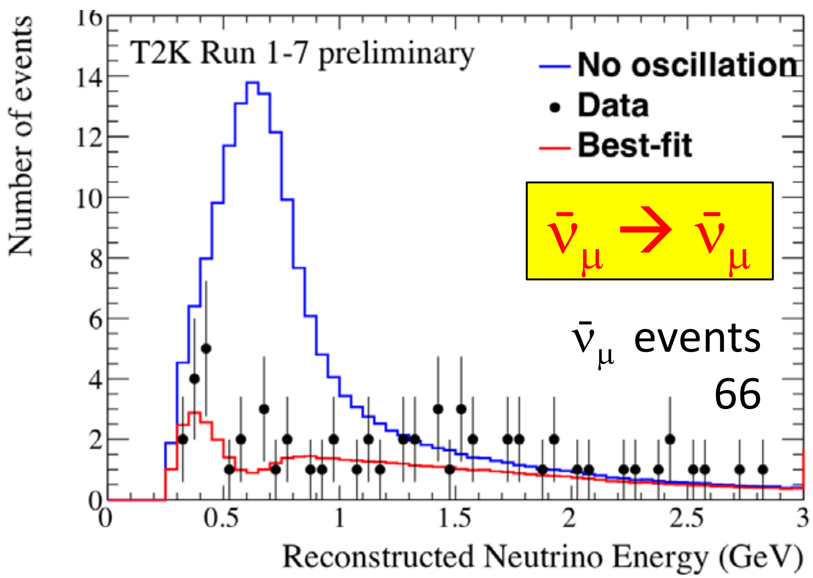
(POT: Proton On Target)

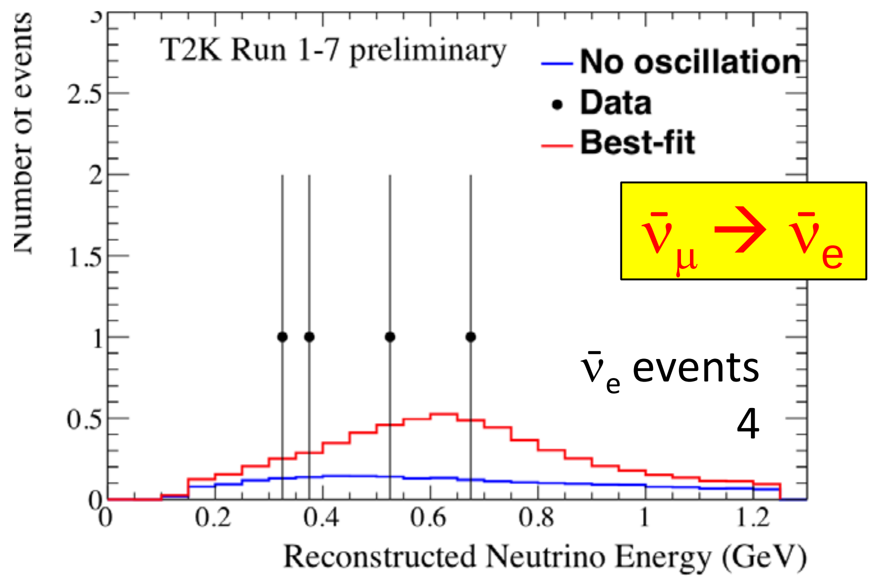
T2K: ν_μ disappearance and ν_e appearance data

ν_μ 7.57x10^{20} POT, $\bar{\nu}_\mu$ 7.53x10^{20} POT data





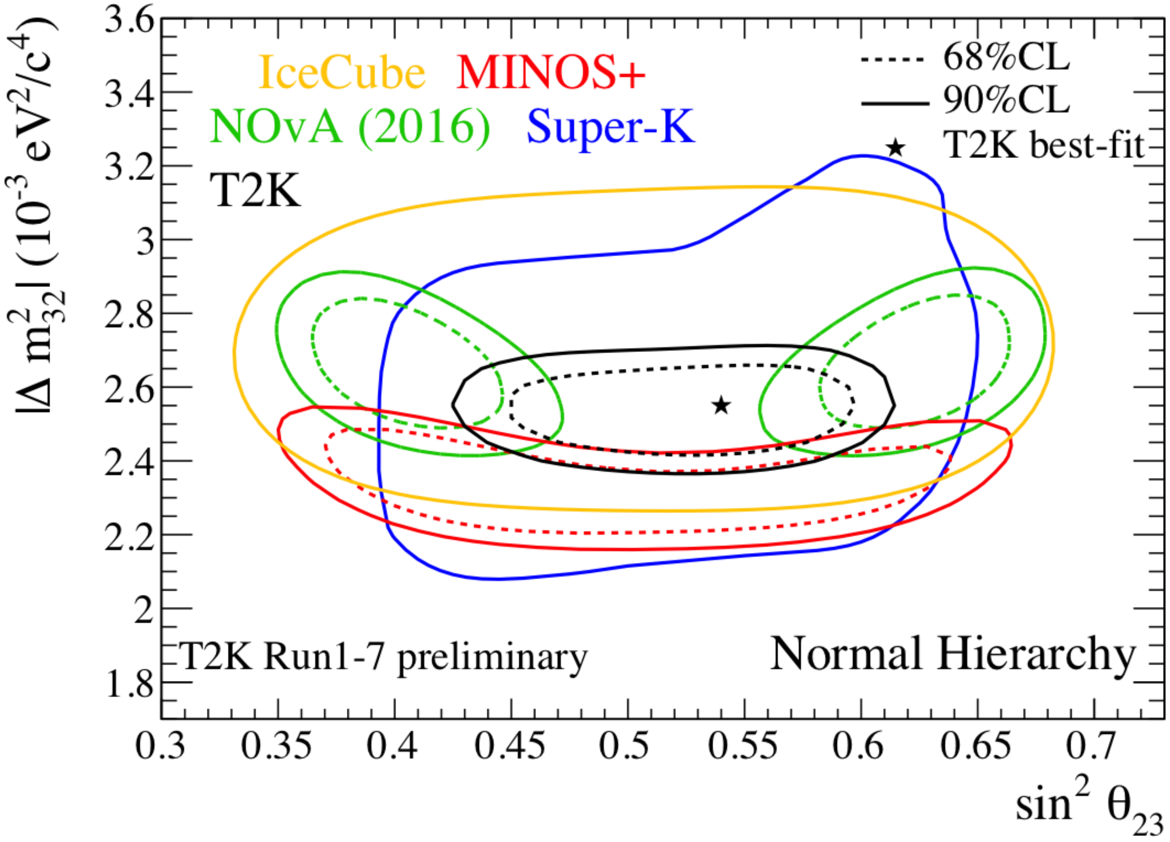




T2K: results from $\nu_\mu + \bar{\nu}_\mu$ disappearance

ν_μ 7.57x10^{20} POT, $\bar{\nu}_\mu$ 7.53x10^{20} POT data

Oscillation parameters of $\sin^2\theta_{23}$ and Δm^2_{32} compared with others



Best fit values:

$(\sin^2(\theta_{23}), |\Delta m^2_{32}|)$=

$(0.550, 2.54 \times 10^{-3}(eV^2))$

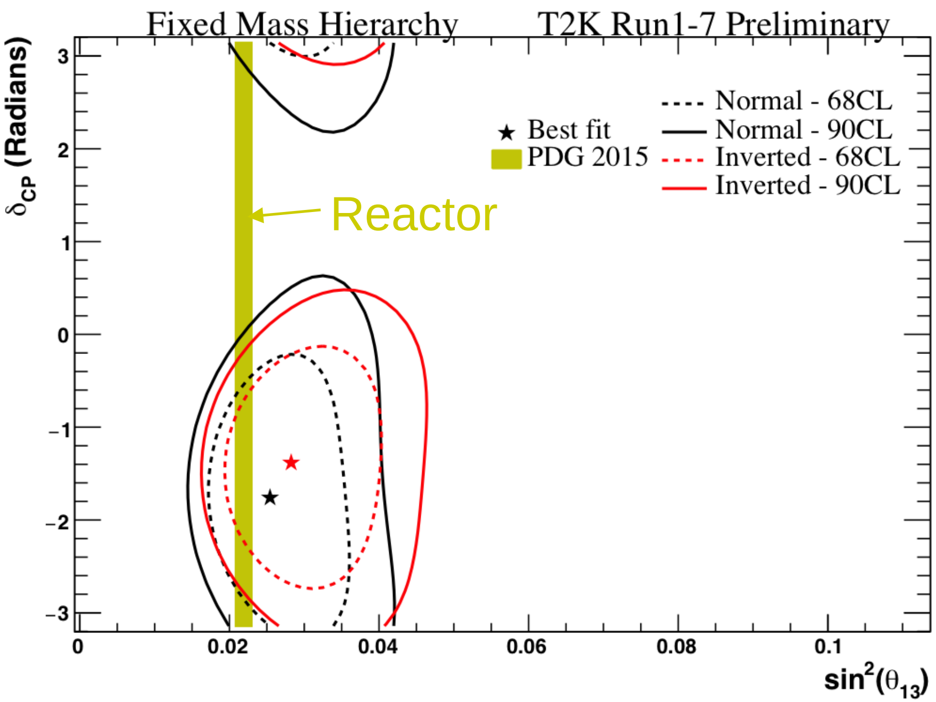
Assuming normal hierarchy

T2K has given the most precise measurement. T2K favors maximal mixing ($\sin^2\theta_{23}$=0.5) but NOvA disfavors. Need more data to conclude.

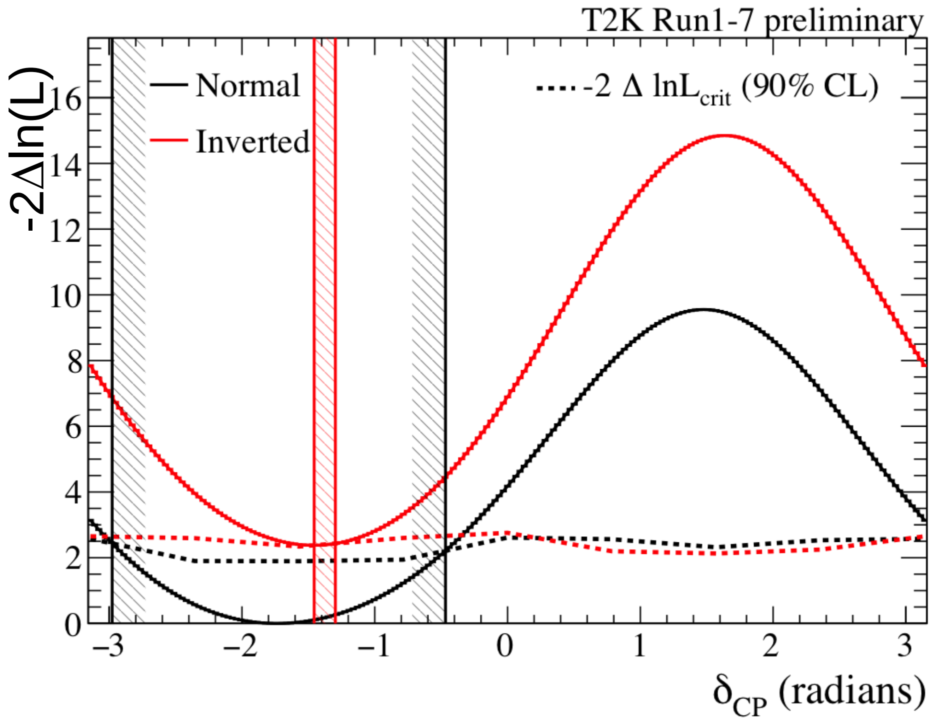
T2K: Results on $\sin^2\theta_{13}$ and δCP

arXiv:1701.00432 [hep-ex]

$\sin^2\theta_{13}$ vs. δCP



δCP (constrained with reactor θ_{13})

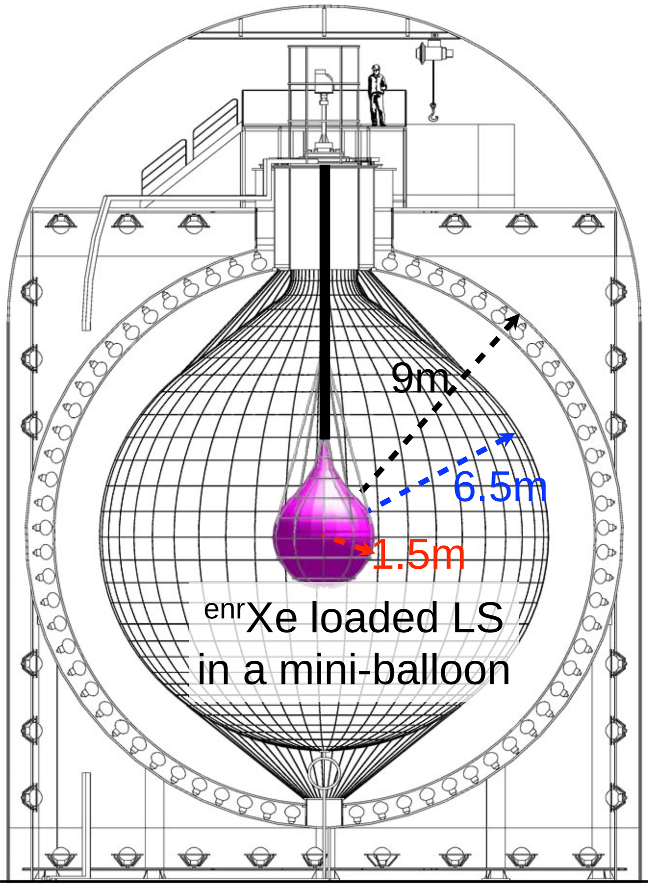


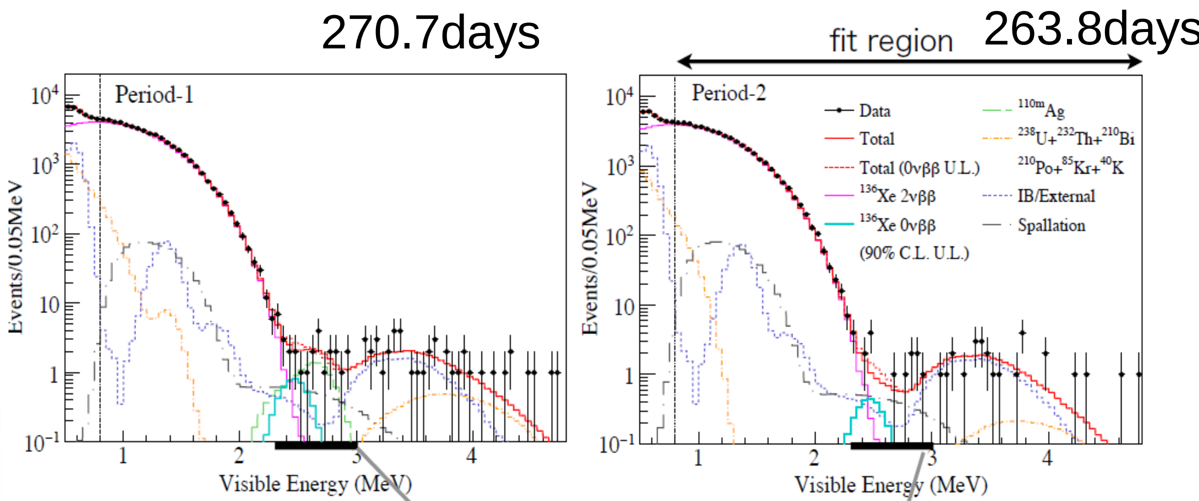
The best fit points lie near the maximally CP violating value δ_{CP}=-0.5π.
The CP conserving values (δ_{CP}=0 and δ_{CP}= π) lying outside of the T2K 90% confidence level interval.

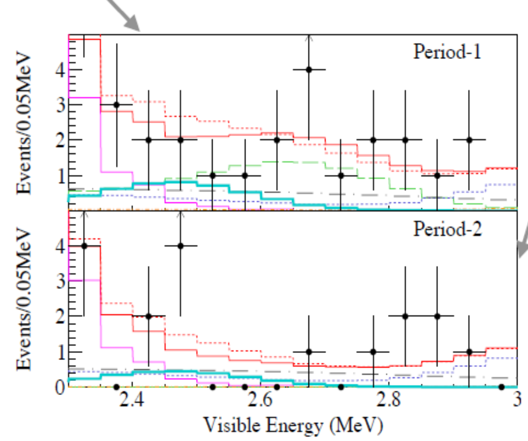
KamLAND-Zen

World best 0νββ experiment at present

Zero Neutrino double beta decay search





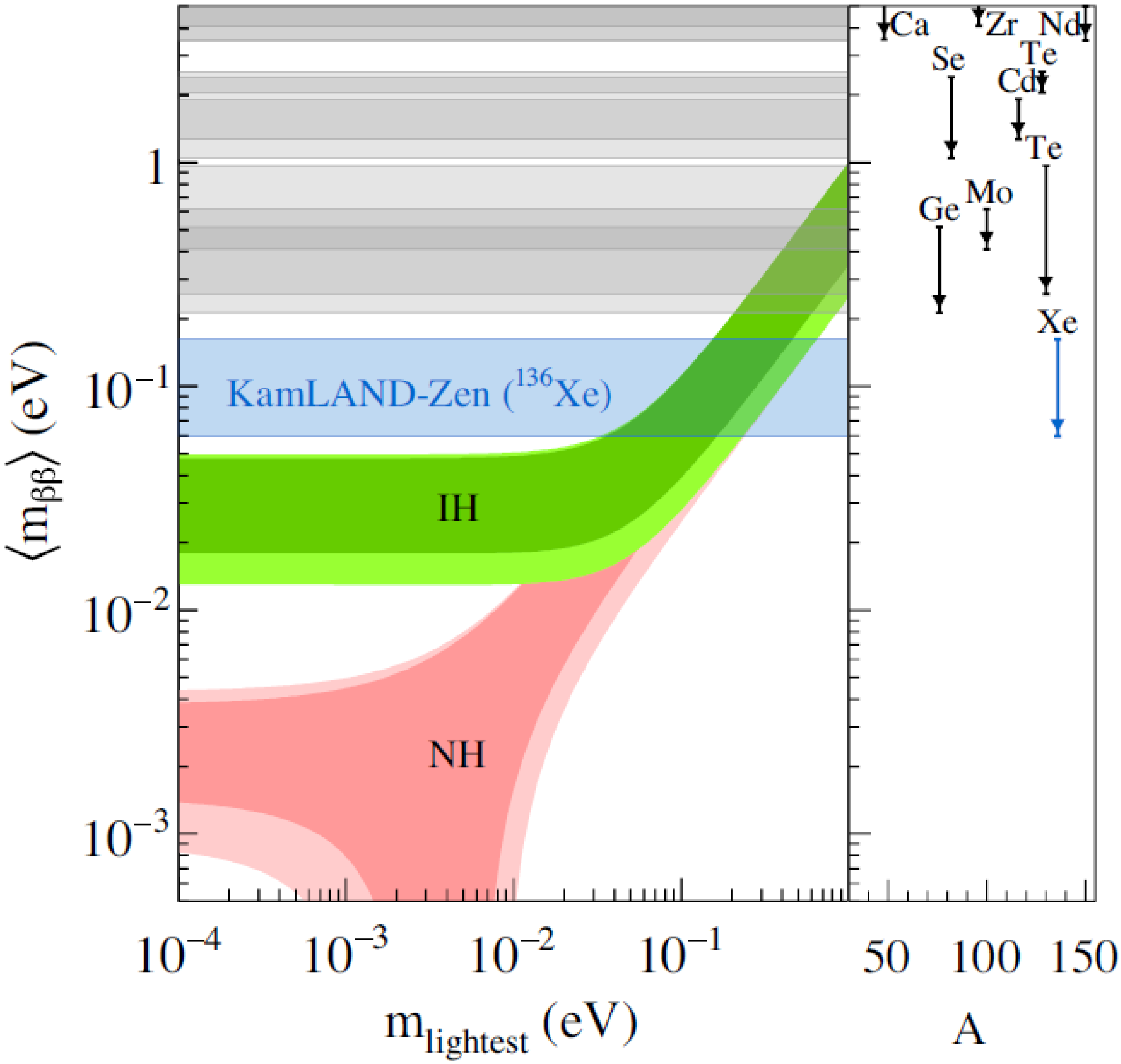


380kg 90% enriched ^{136}Xe for phase-II (2013/12/11-2015/10/27)

No significant excess of 0νββ

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \mathrm{yr}$$

KamLAND-Zen result on $<m_{\beta\beta}>$



$$\langle m_{\beta\beta}\rangle < (61 - 165)\,\mathrm{meV}$$

It also provides upper limit of $m_{lightest}$ at 180-480 meV.

A. Gando et al., PRL 117,082503(2016)

Future

How to measure CP phase δ

Long baseline accelerator: ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2{}_{31}L(km)}{E_\nu(GeV)}\right)$$ Leading term

Sub-leading

$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPC

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPV

$$+4S_{12}^2 C_{13}^2(C_{12}^2C_{23}^2 + S_{12}^2S_{23}^2S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Delta_{21}$$ "solar"

$$-8C_{13}^2S_{13}^2S_{23}^2\frac{aL}{4E_\nu}(1-2S_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$

matter

$$+8C_{13}^2S_{13}^2S_{23}^2\frac{a}{\Delta m_{31}^2}(1-2S_{13}^2)\sin^2\Delta_{31}$$

$S_{ij} \equiv \sin\theta_{ij}, C_{ij} \equiv \cos\theta_{ij}$

$\Delta_{ij} \equiv \Delta m_{ij}^2 L / E_\nu$

$a = 2\sqrt{2}G_F.n_eE_\nu$

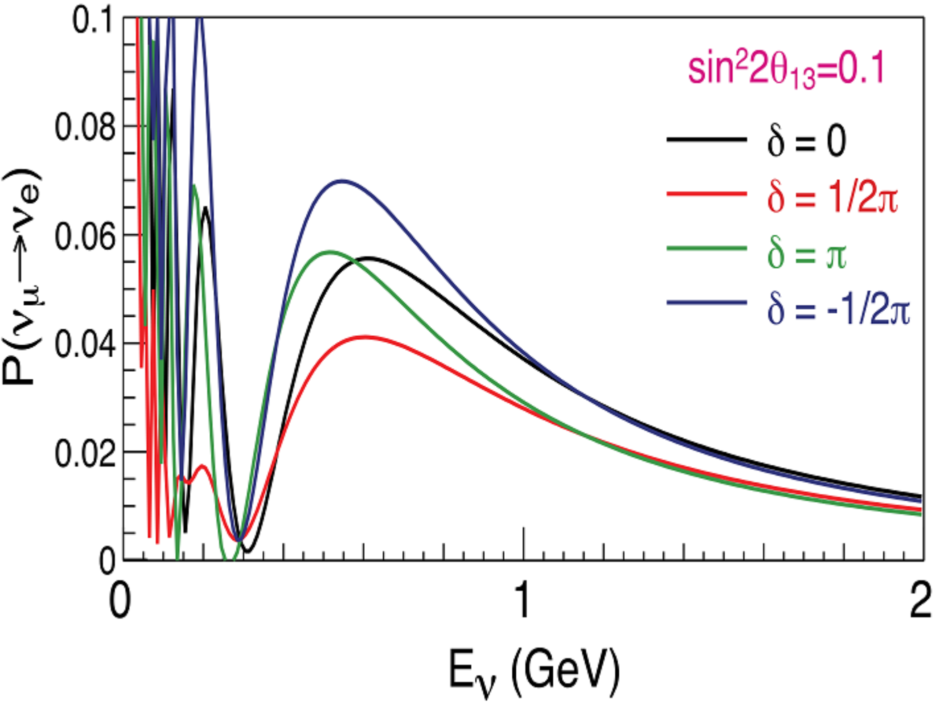
for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ δ → -δ and a → -a

Compare $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for CP phase measurement

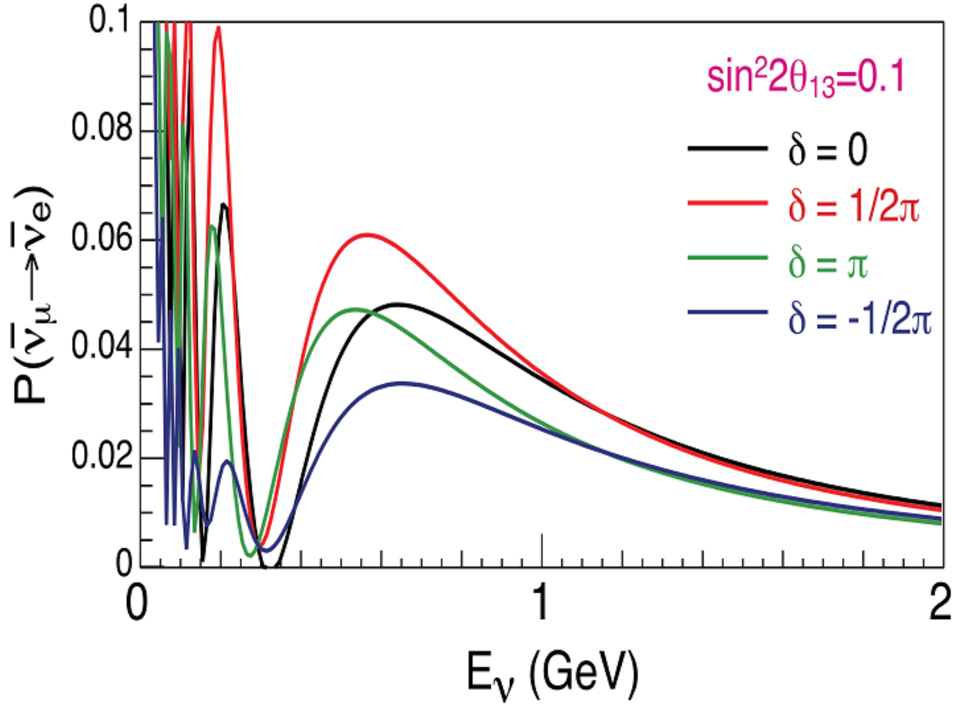
$\nu_\mu \rightarrow \nu_e$ probability (L=295km)

Normal hierarchy

Neutrino case



Anti-neutrino case

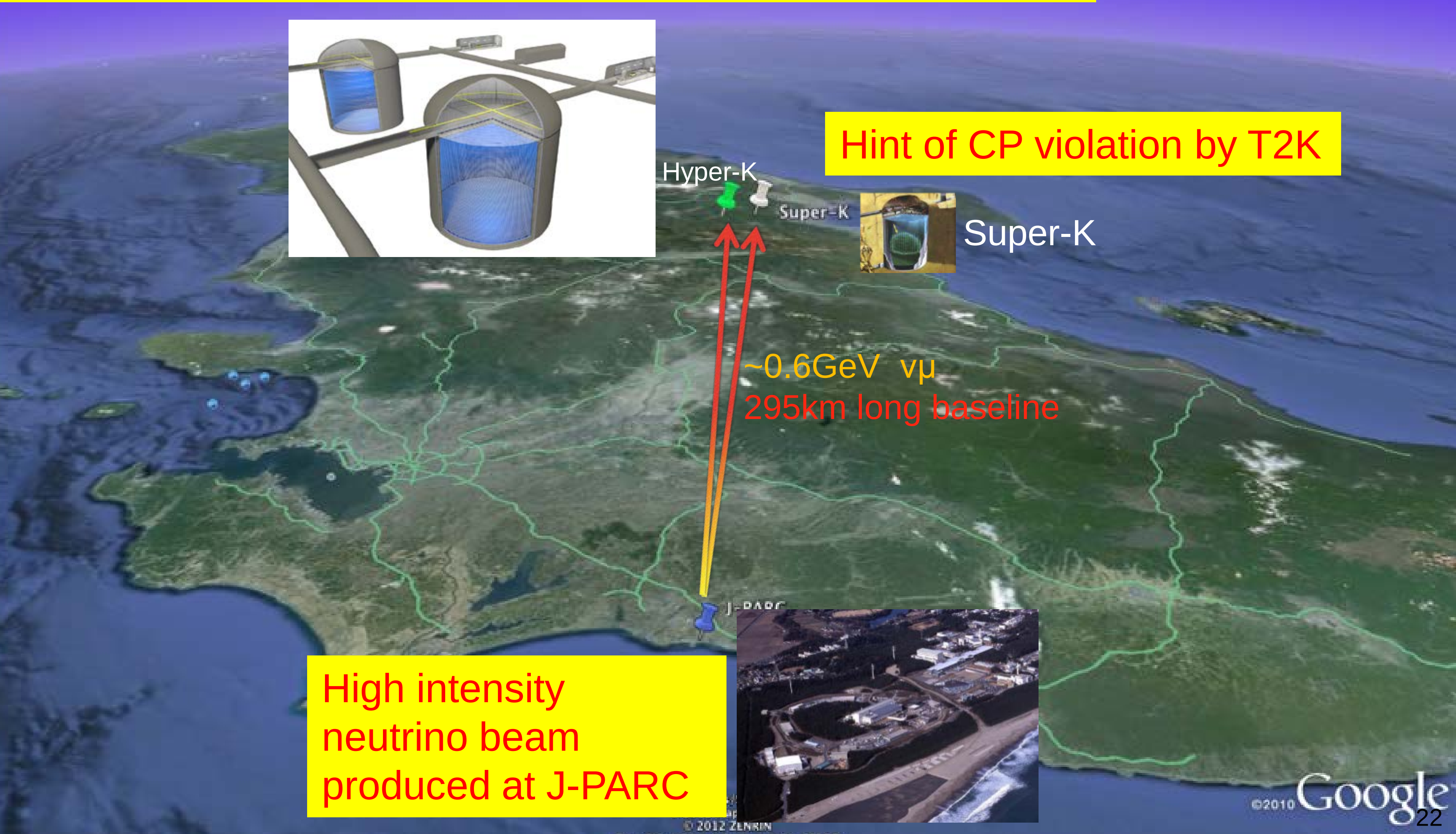


- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - As large as ~25% from nominal
- It is sensitive also to exotic (non-PMNS) CP violation cases.

Neutrino oscillation vs. anti-neutrino oscillation

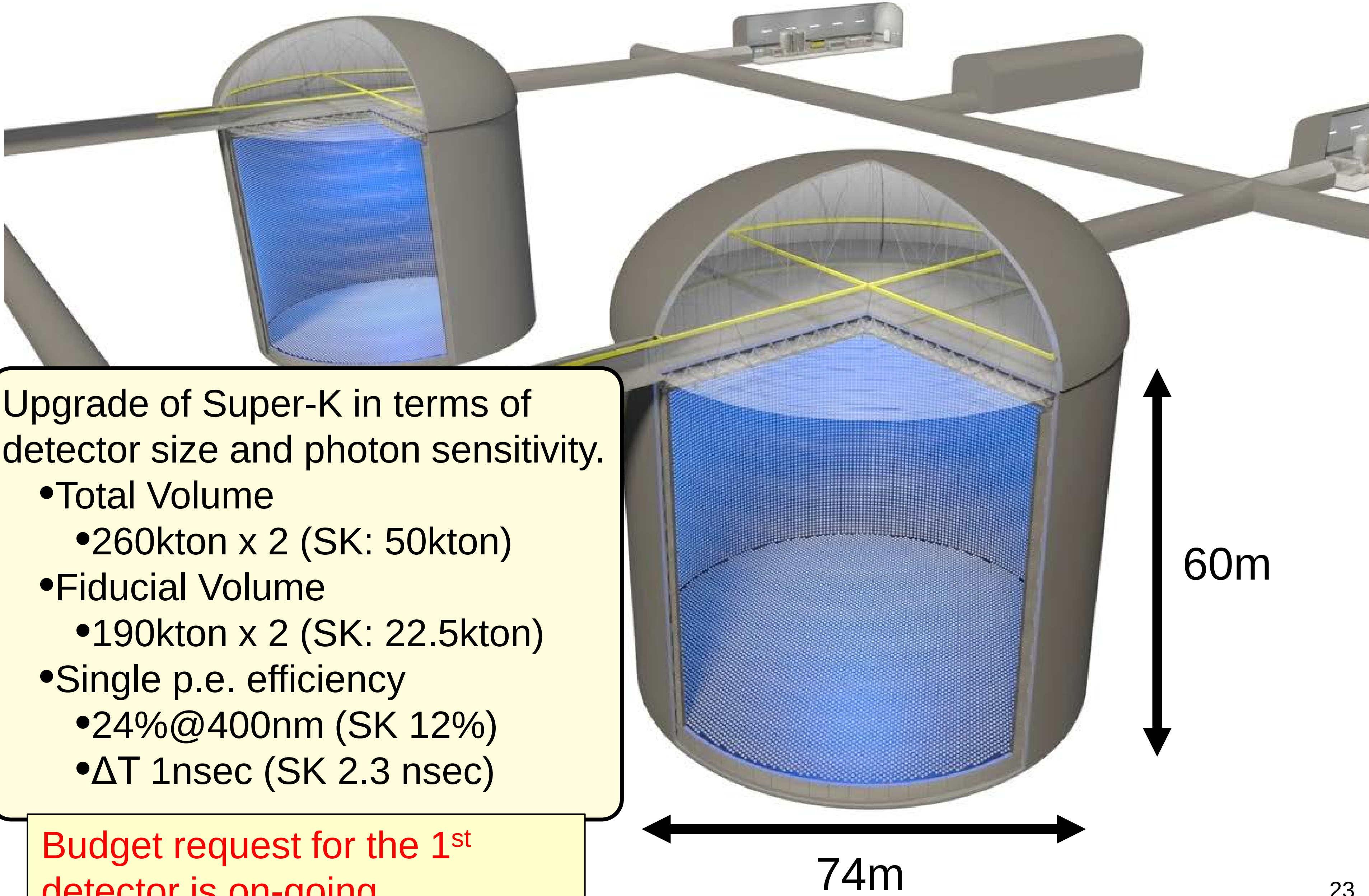
Evidence and precise measurement by Hyper-Kamiokande

Hint of CP violation by T2K



High intensity
neutrino beam
produced at J-PARC

Hyper-Kamiokande

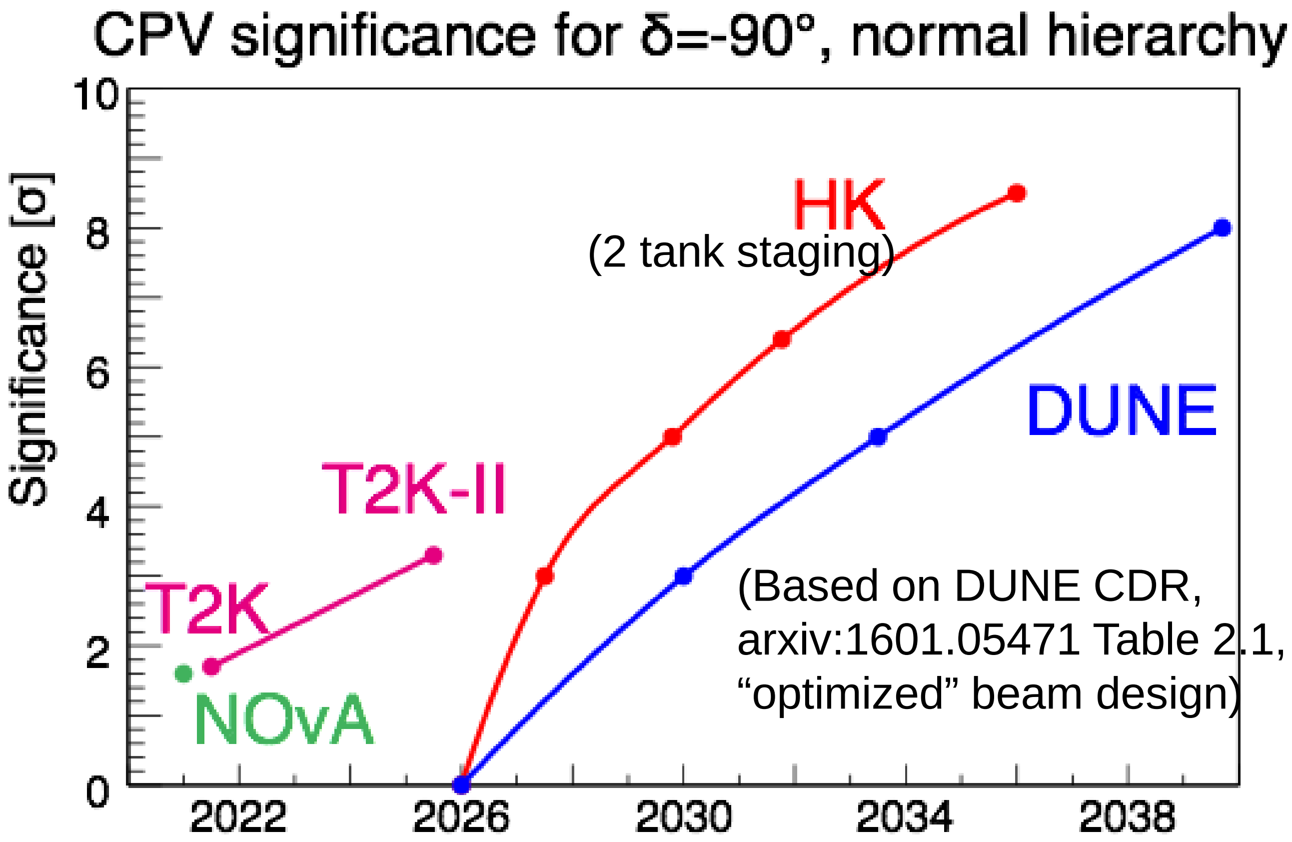


Upgrade of Super-K in terms of detector size and photon sensitivity.

- Total Volume
  - 260kton x 2 (SK: 50kton)
- Fiducial Volume
  - 190kton x 2 (SK: 22.5kton)
- Single p.e. efficiency
  - 24%@400nm (SK 12%)
  - ΔT 1nsec (SK 2.3 nsec)

Budget request for the 1st detector is on-going.

Towards leptonic CP asymmetry



Strategy of Japan-based program

~3σ indication with T2K→T2K-II,

>5σ discovery and measurement with HK

A Multi-purpose Experiment

Comprehensive study of ν oscillation

- CPV
- Mass hierarchy with beam+atmosph. ν
- θ_{23} octant
- Test of exotic scenarios

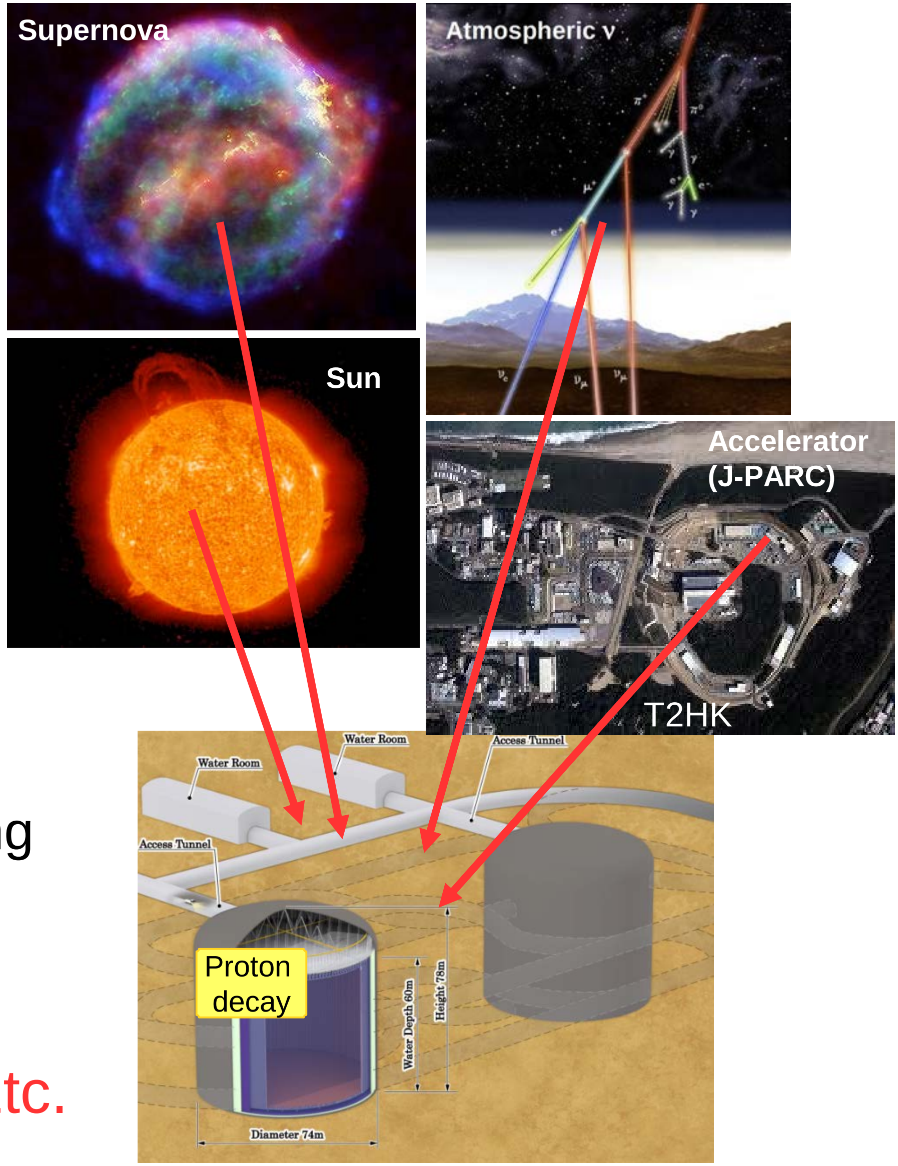
Nucleon decay discovery potential

- All visible modes including p → $e^+ \pi^0$ and p→$\bar{\nu}K^+$ can be advanced beyond SK.
- Reaching 10^{35}yrs sensitivity

Unique Astrophysics

- Precision measurement of solar ν
- High statistics Supernova ν with pointing capability and energy info.
- Supernova relic ν (non-burst $\bar{\nu}$) observation is also possible

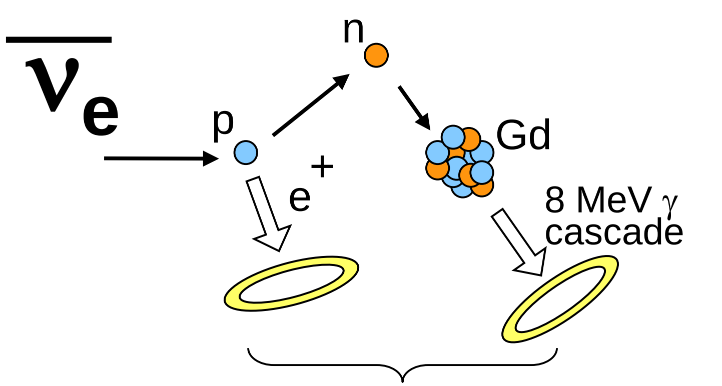
Earth core's chemical composition Etc.



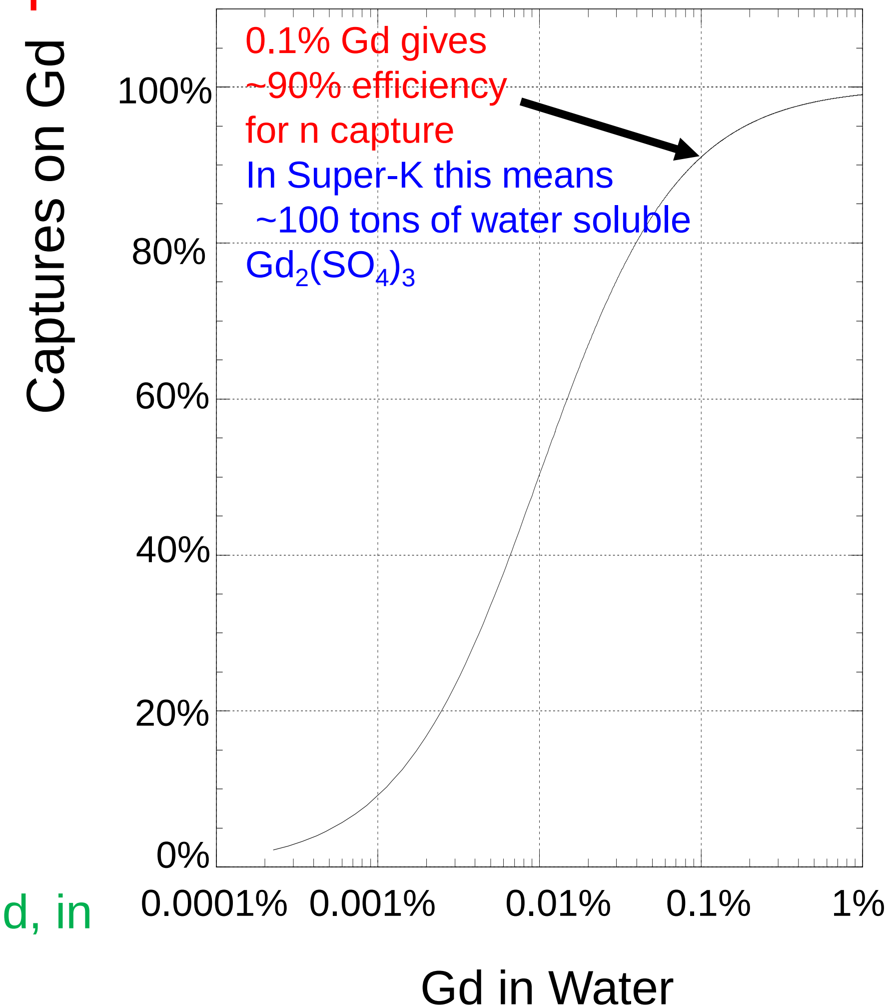
SK-Gd project

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

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



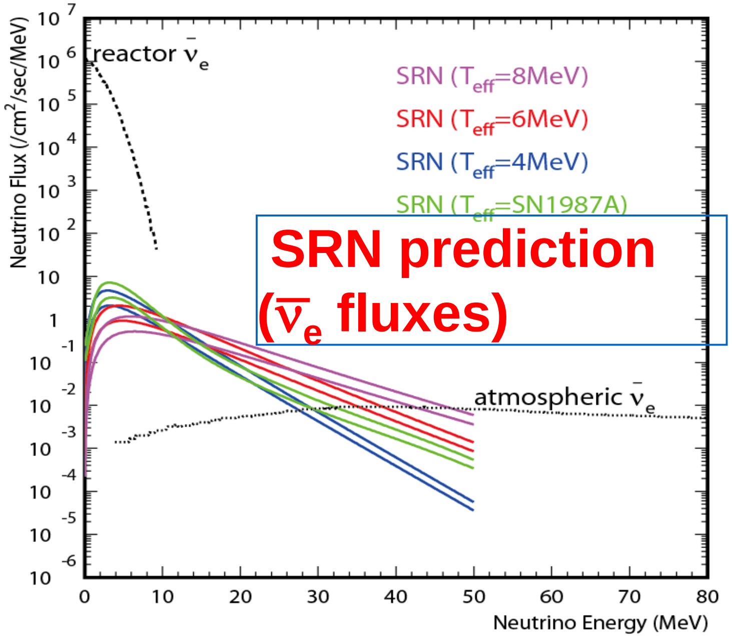
ΔT~30μs
Vertices within 50cm



SK-Gd schedule plan

- Open the tank in 2018 and fix water leak
- Load 10 tons of $Gd_2(SO_4)_3$, i.e. 0.01% Gd, in 2019 for the first step.
- Plan to increase to 0.1% Gd after analyzing 0.01% Gd data for one or a few years.

Physics with SK-Gd



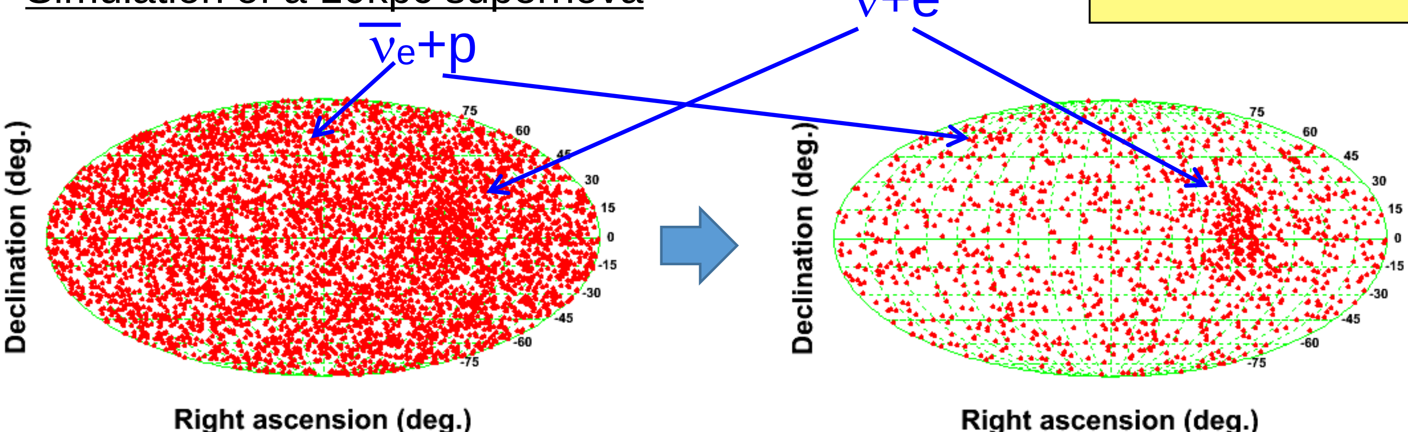
Supernova Relic Neutrinos (SRN)

- Open widow for SRN at 10-30MeV
- Expected event rate 1.3 -6.7 events/year/22.5kt(10-30MeV)
- Study supernova rate from the beginning of universe and averaged energy of $\bar{\nu}_e$.

- Discriminate proton decay (essentially no neutron) and atmospheric neutrino background(with neutrons).
- Neutrino/anti-neutrino identification.
- Precise measurement of θ_{12} and Δm^2_{21} by reactor neutrinos.

Improve pointing accuracy for supernova bursts, e.g. 4~5°→ 3°(90%C.L.) for 10kpc

Simulation of a 10kpc supernova



Future of KamLAND-Zen

- Immediate next step is the750 kg enriched ^{136}Xe run called KamLAND-Zen 800.

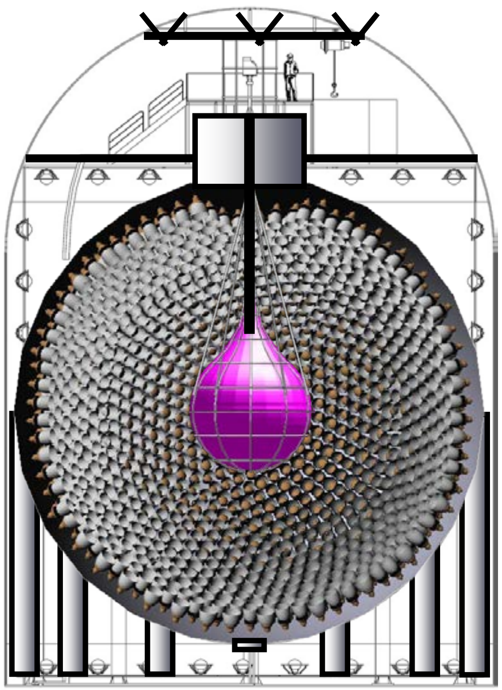
More future plan

Higher energy resolution for reducing 2ν BG ⇨ KamLAND2-Zen

Winston cone light collection ×1.8

high q.e. PMT light collection ×1.9
17"φ→20"φ ε=22→30+%

New LAB LS light collection ×1.4
(better transparency)



1000+ kg xenon

Expected σ(2.6MeV)= 4% → ~2%

Target sensitivity of $m_{\beta\beta}$ of 20 meV

Conclusions

- More than 30 years have passed since we started experiments at Kamioka.
- Neutrino oscillations have been established in the last 30 years and Japanese projects have been contributed for them.
- There are still many important unknowns in neutrino physics.
- Japanese future projects will continue to investigate nature of neutrinos and to proceed neutrino astronomy.