# Future of Super-Kamiokande and Hyper-Kamiokande

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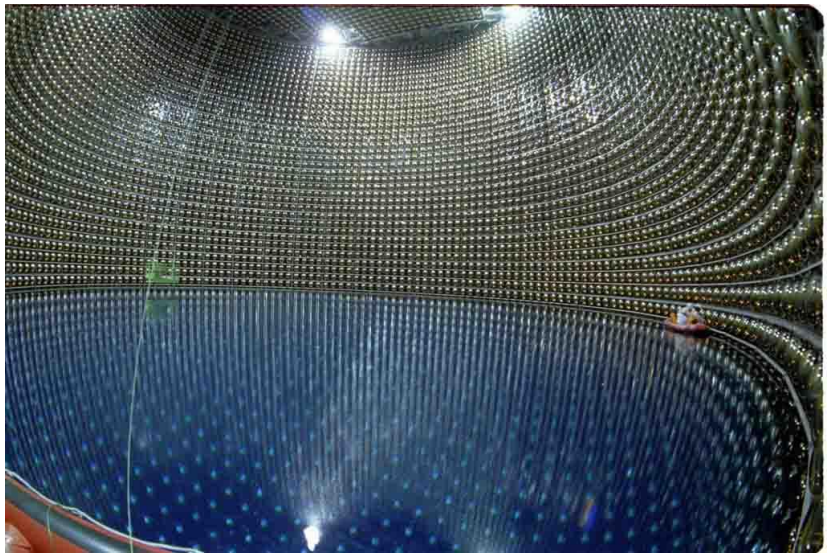
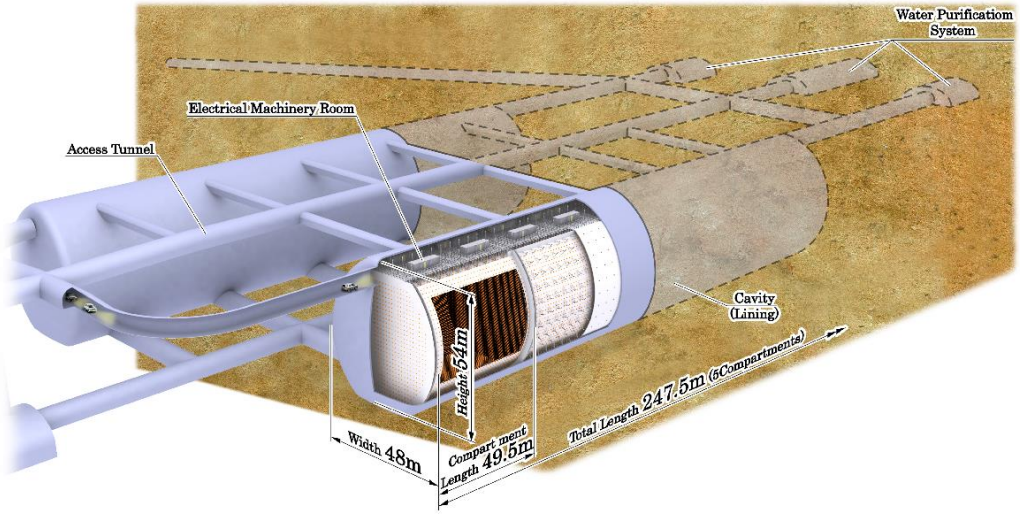
for Super-K collaboration and
Hyper-K working group





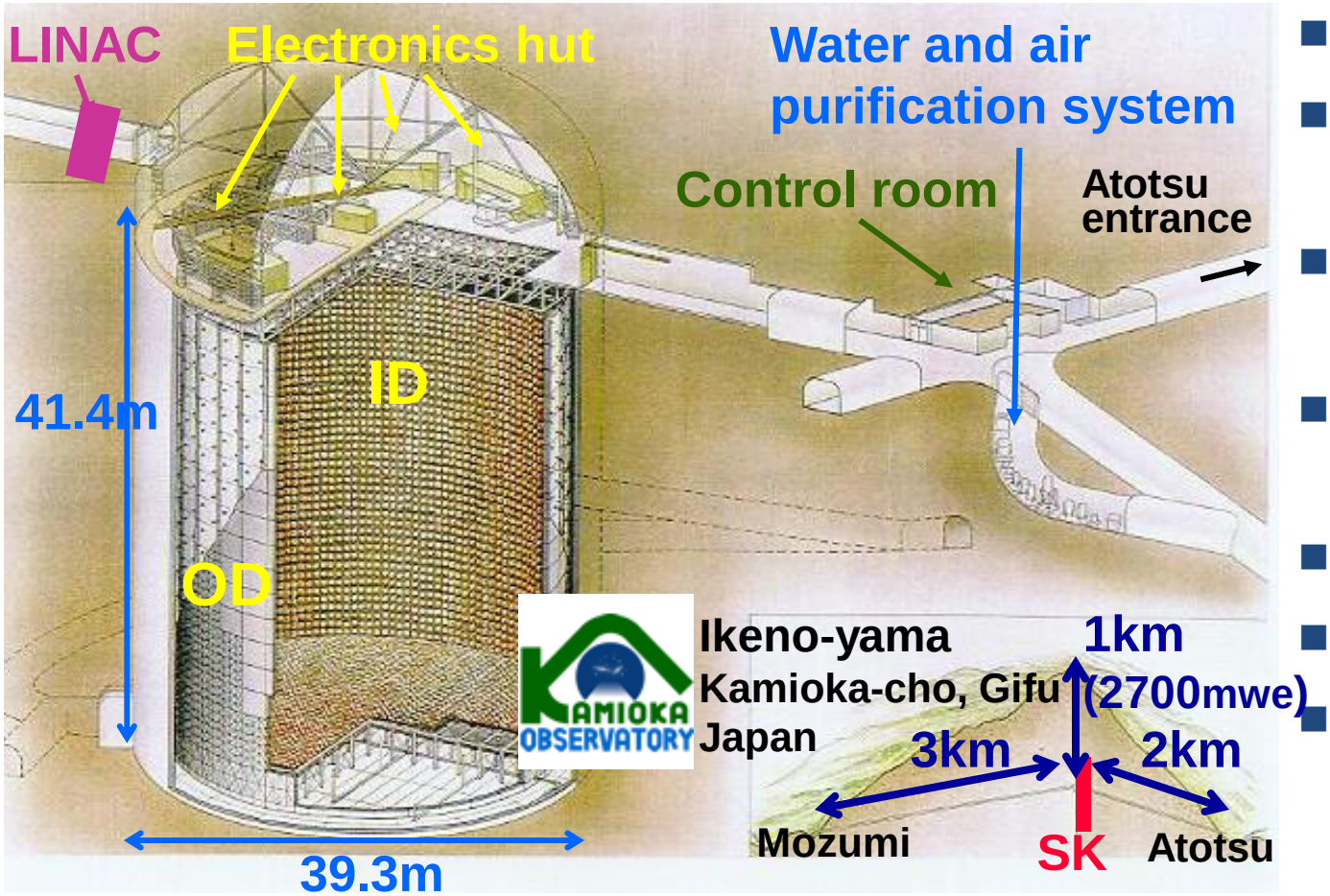



13th International Conference on Topics in Astroparticle and Underground Physics, September 12, 2013

# Contents

- What is Super-Kamiokande and what have been achieved
- Future of Super-Kamiokande
  - Summary of future sensitivity for various physics
  - R&D for GADZOOKS!
- Current and future of T2K
- Physics at Hyper-Kamiokande

# Super-Kamiokande detector

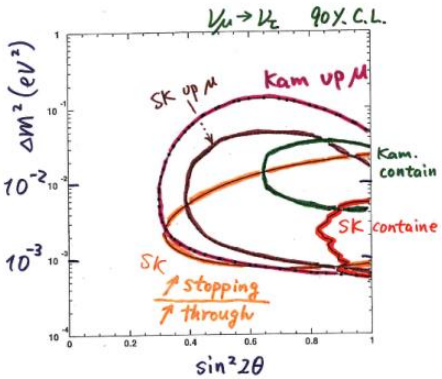



- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-IV is running
- Trigger efficiency
  >99%@4.0MeV$_{kin}$
  ~90%@3.5MeV$_{kin}$

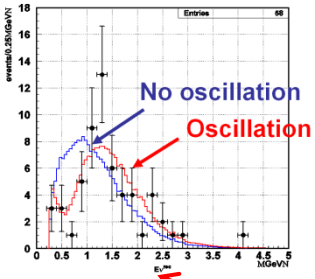
**Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)**
**Outer Detector (OD) PMT: 1885**

# Physics achievements with Super-K

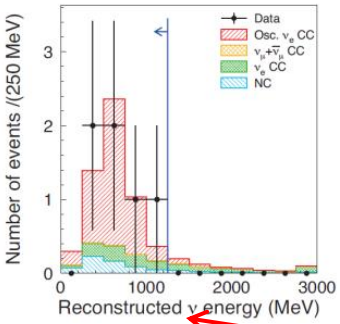
Atmospheric ν oscillations



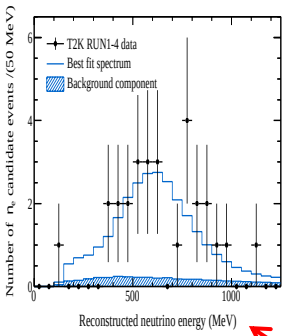

K2K confirmed atmospheric osc. by long baseline ν




θ13 by T2K (indication)

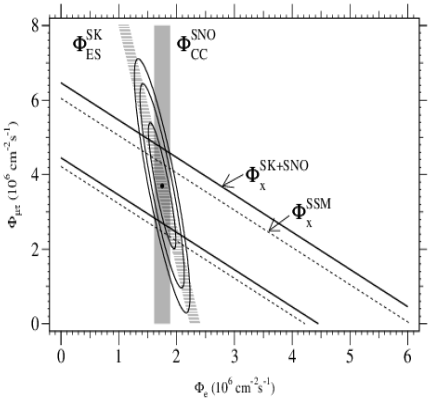



θ13 by T2K (observation)

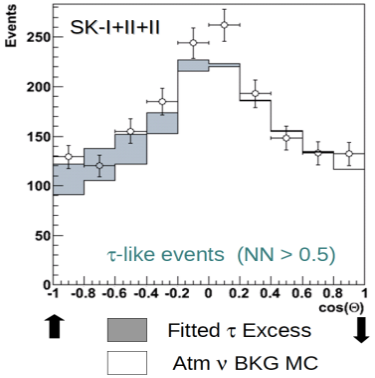



| 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

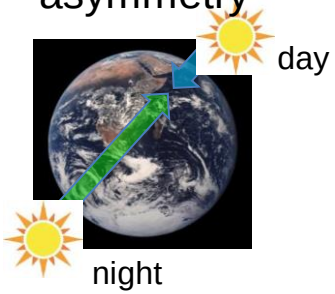
Solar ν oscillations




Tau-ν appearance in atmospheric ν




Solar day/night asymmetry




$A_{DN}$=-3.2±1.1±0.5 %

# Future prospects of Super-K

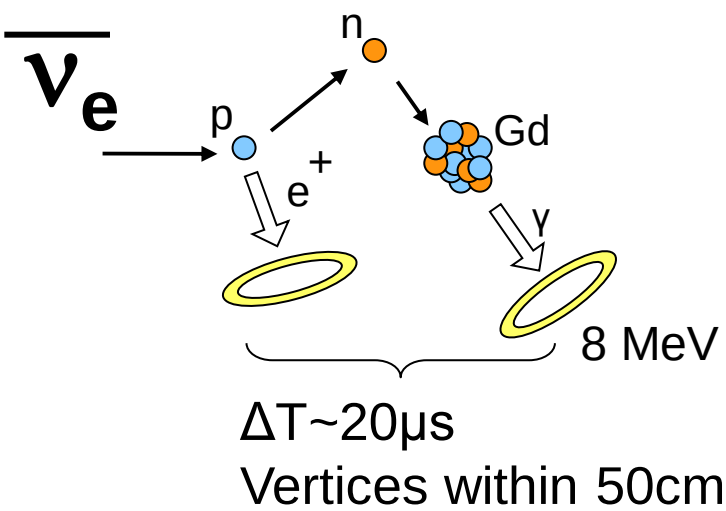
With ~10 more years' data

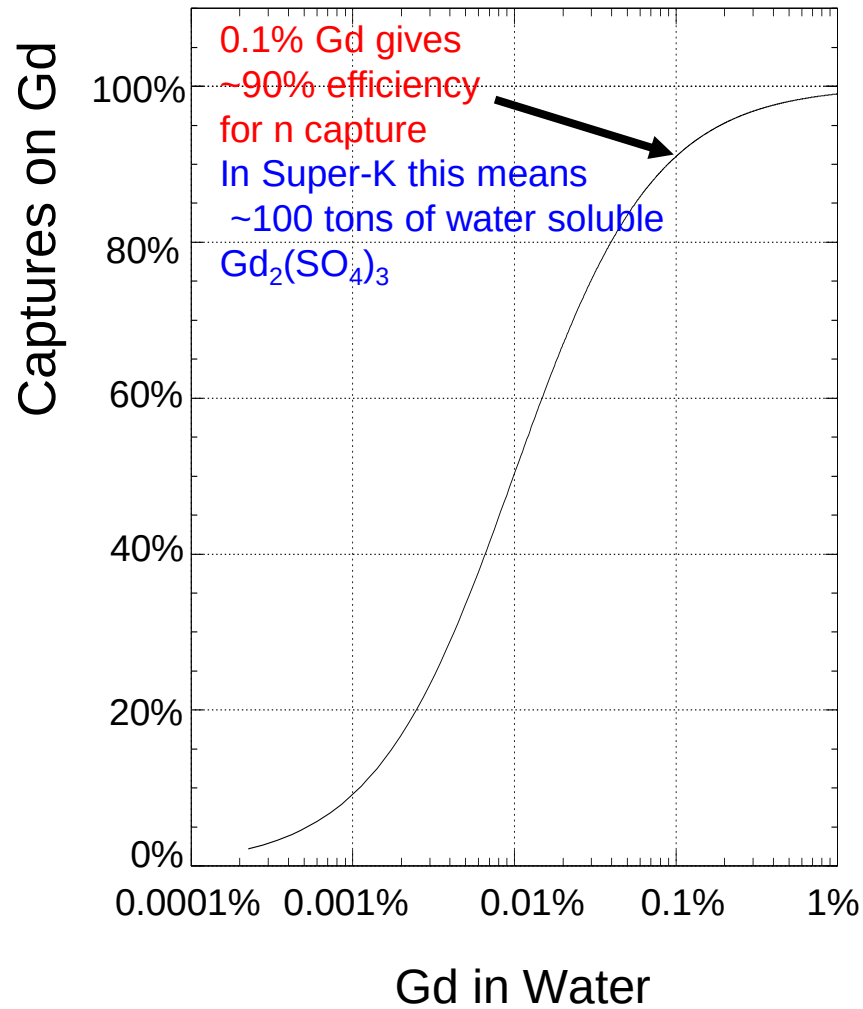
- Atmospheric neutrinos
  - Mass hierarchy (~2$\sigma$ level (for $\sin^2\theta_{23}$=0.6))
  - $\theta_{23}$ octant (2.1~2.6$\sigma$ level (for $\sin^2\theta_{23}$=0.4/0.6))
- Solar Neutrinos
  - Spectrum upturn expected from LMA (> 3$\sigma$ level)
- Supernova neutrinos
  - Observation of supernova relic neutrinos (SRN) (GADZOOKS! project: discussed later)
  - Galactic supernova ~8,000 events at 10kpc (if happens)
- Proton decay
  - Will reach ~2.4 x $10^{34}$ years for $p \rightarrow e^+\pi^0$, and ~9 x $10^{33}$ years for $p \rightarrow \bar{\nu}K^+$.
- Indirect dark matter search
  - High sensitivity for low mass WIMPs (~8x$10^{-41}$ $cm^2$(SD), ~2x$10^{-42}$ $cm^2$(SI) at 10 GeV for $\chi\chi \rightarrow \tau^+\tau^-$ channel)

# GADZOOKS! project

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

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




Physics targets:

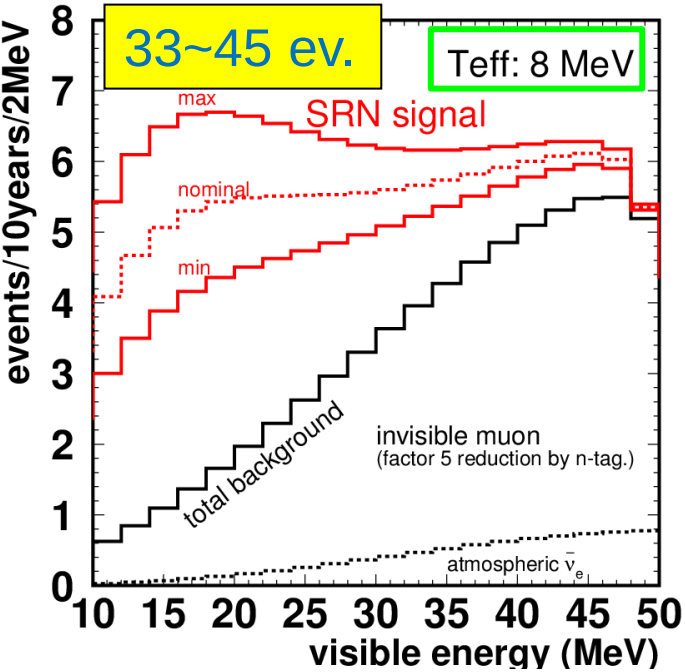
(1) Supernova relic neutrino (SRN)

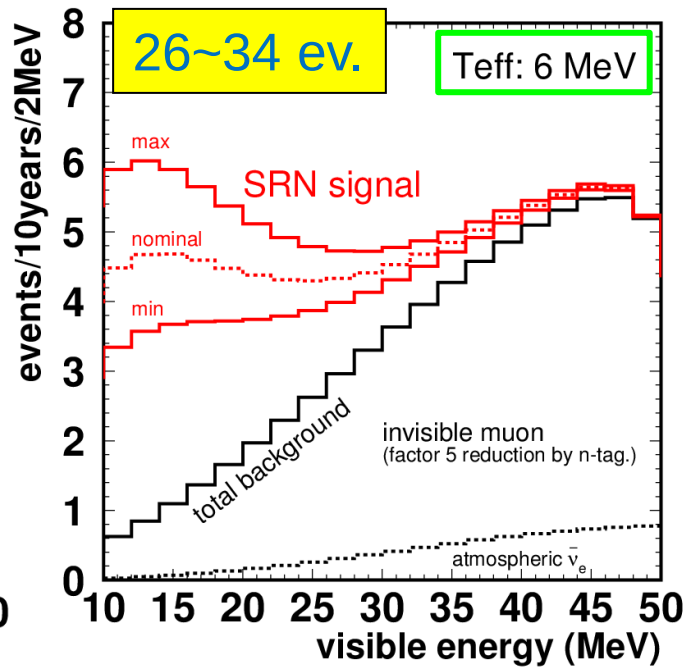
(2) Enhance directional signals for supernova burst

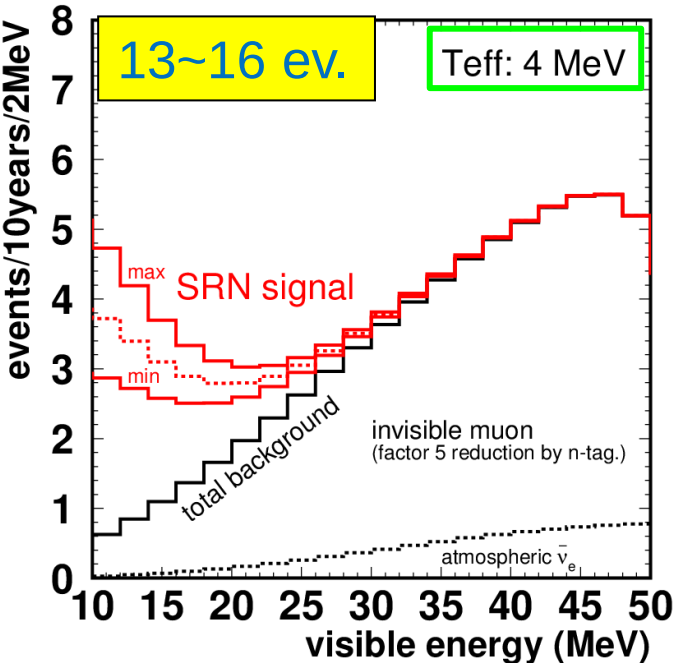
(3) Reactor neutrinos

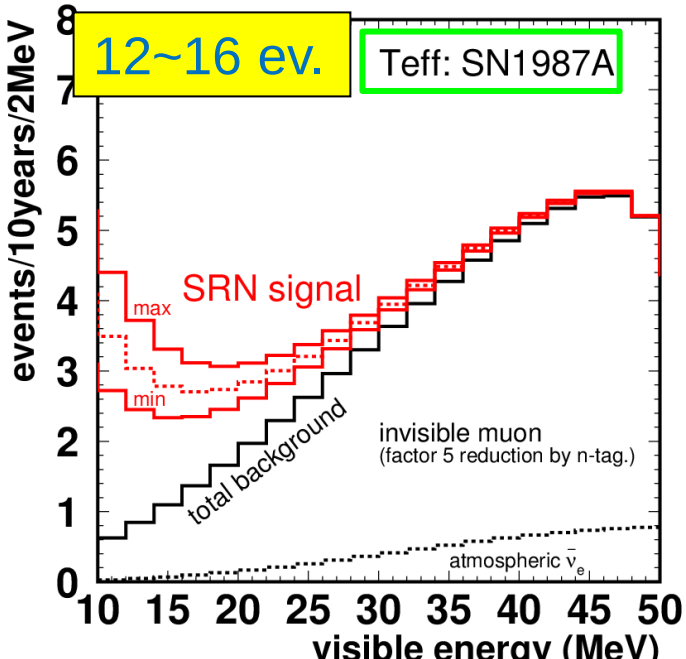
(4) Proton decay background ID

# SRN: Expected signal and background




Expect number of events in 10 years in $E_{total}$ =10-30 MeV

Assuming

Capture efficiency of 90% and Gd gamma detection efficiency of 74%.

Invisible muon B.G. is 35% of the SK-IV invisible muon BG.

Min/nominal/Max are due to uncertainties in astronomy.

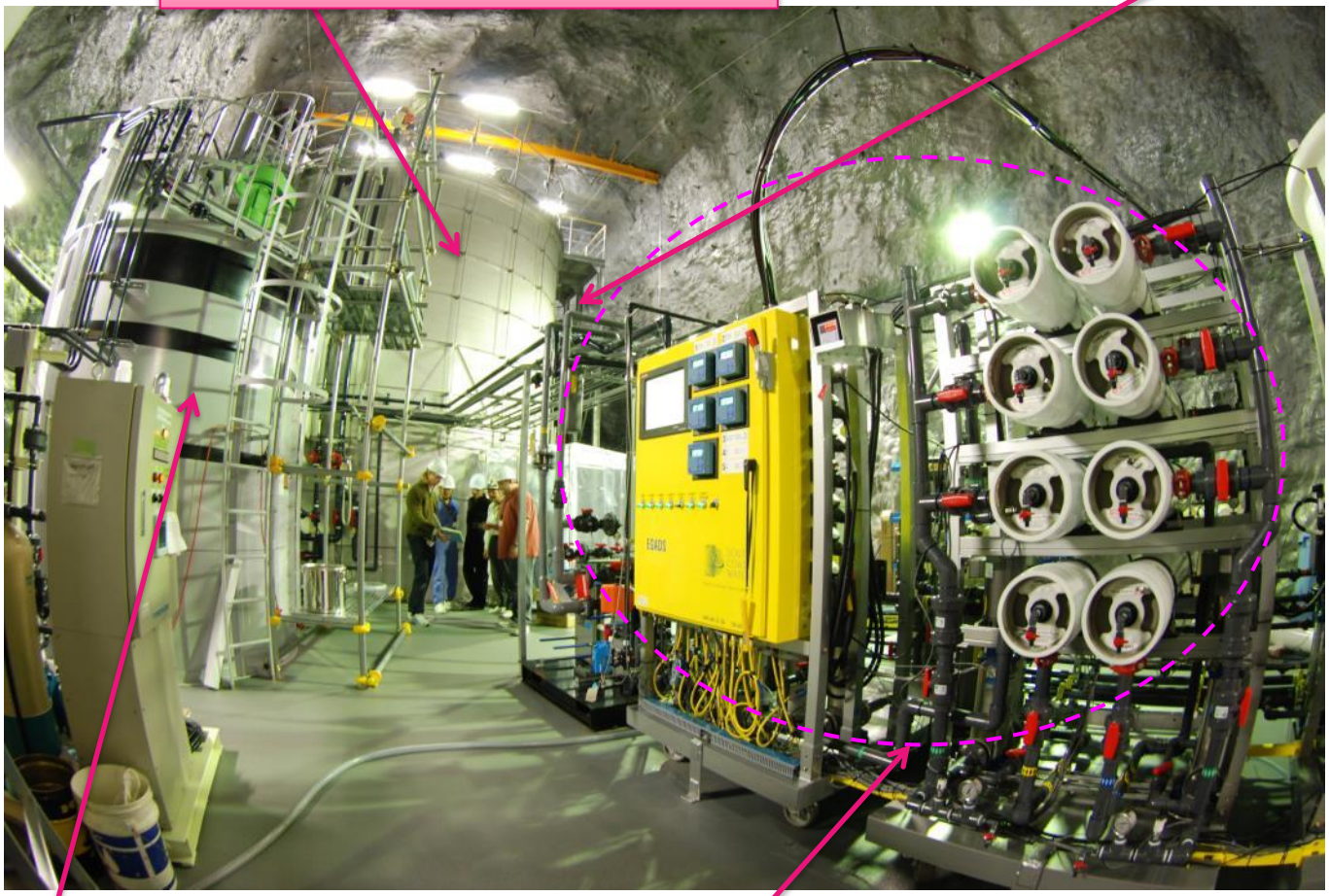
Background: ~18 ev.

SRN flux from Horiuchi et al. PRD, 79, 083013 (2009)

# EGADS

Evaluating Gadolinium's Action on Detector Systems

200 $m^3$ tank with 240 PMTs

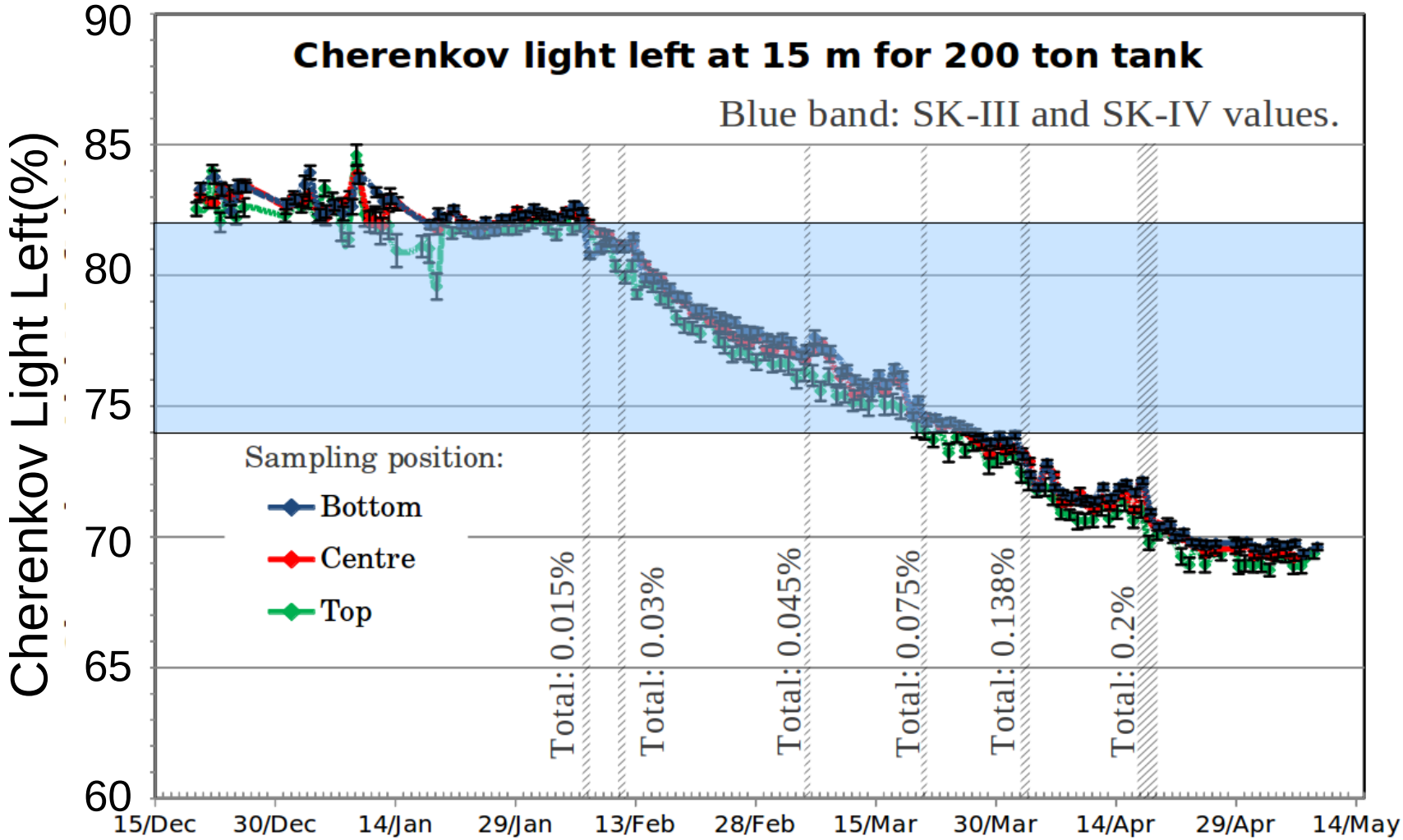


15$m^3$ tank to dissolve Gd

Gd water circulation system (purify water with Gd)

Transparency measurement (UDEAL)

# Transparency of Gd-loaded water (before mounting PMTs)




The light left at 15 m in the 200m$^3$ tank (stainless steel) was ~69% for 0.2% $Gd_2(SO_4)_3$ , which corresponds to ~84% of pure water.

# 240 PMTs were mounted in the 200 $m^3$ tank in this summer.

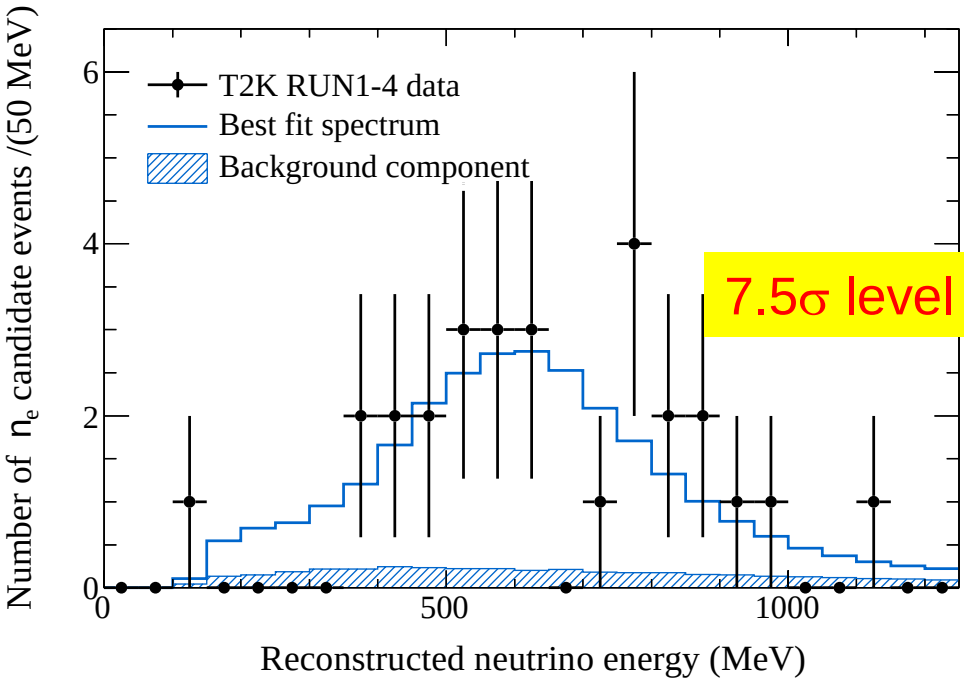
Pure water circulation was started.
Gd-loaded test is expected start soon.

# Latest result from T2K on $\nu_e$ appearance(Run 1+2+3+4)

Data of $6.39 \times 10^{20}$ POT (protons on target)
[it is only 8% of designed POT of T2K.]

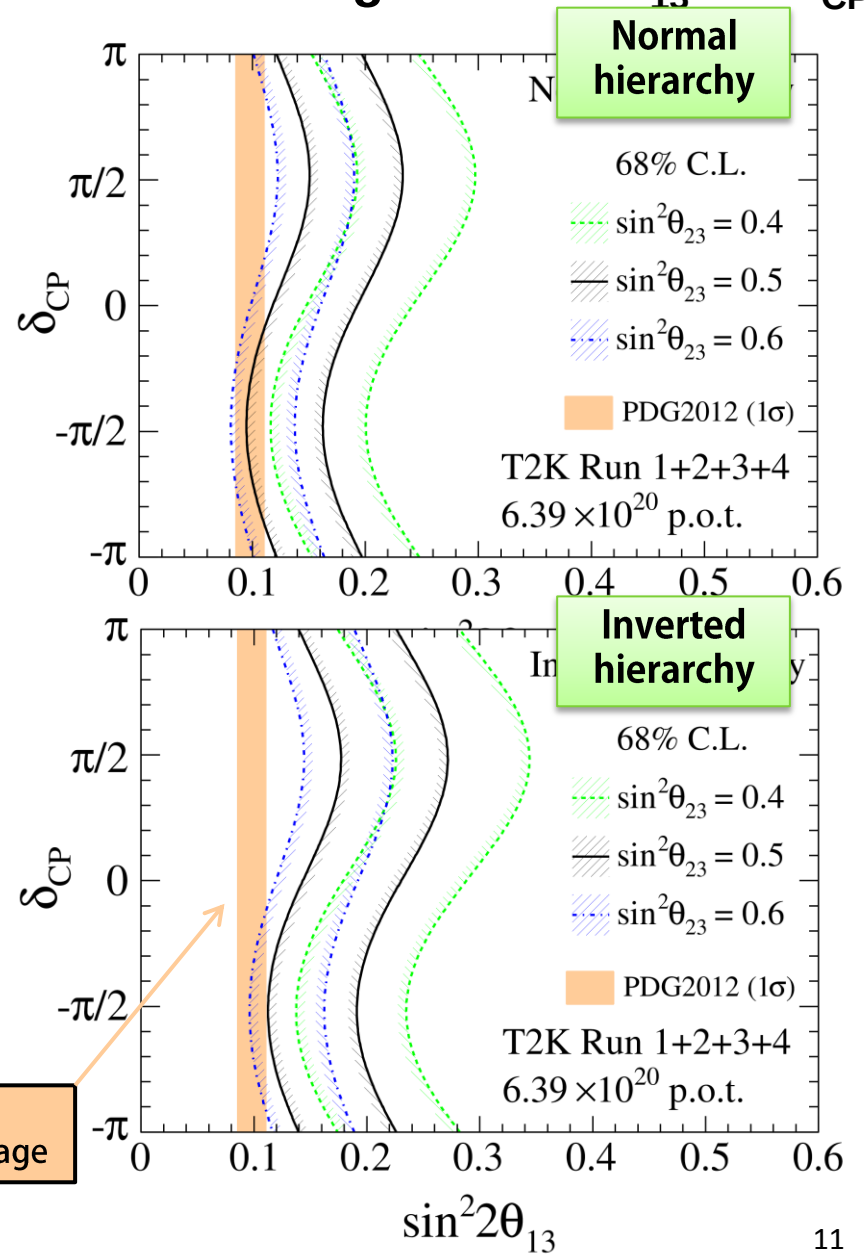
**28 electron neutrinos observed.**

Expected number of background
$4.64 \pm 0.52$ (syst.) for $\sin^2(2\theta_{13})=0$




**7.5σ level**

**Allowed range of $\sin^2 2\theta_{13}$ for $\delta_{CP}$**




PDG2012
reactor average

# T2K full sensitivity (Expected 90% C.L. allowed region)

(with $7.8 \times 10^{21}$ POT)

For $\delta_{CP}$=-90°
$\sin^2 2\theta_{23}$=1.0
Normal Hierarchy

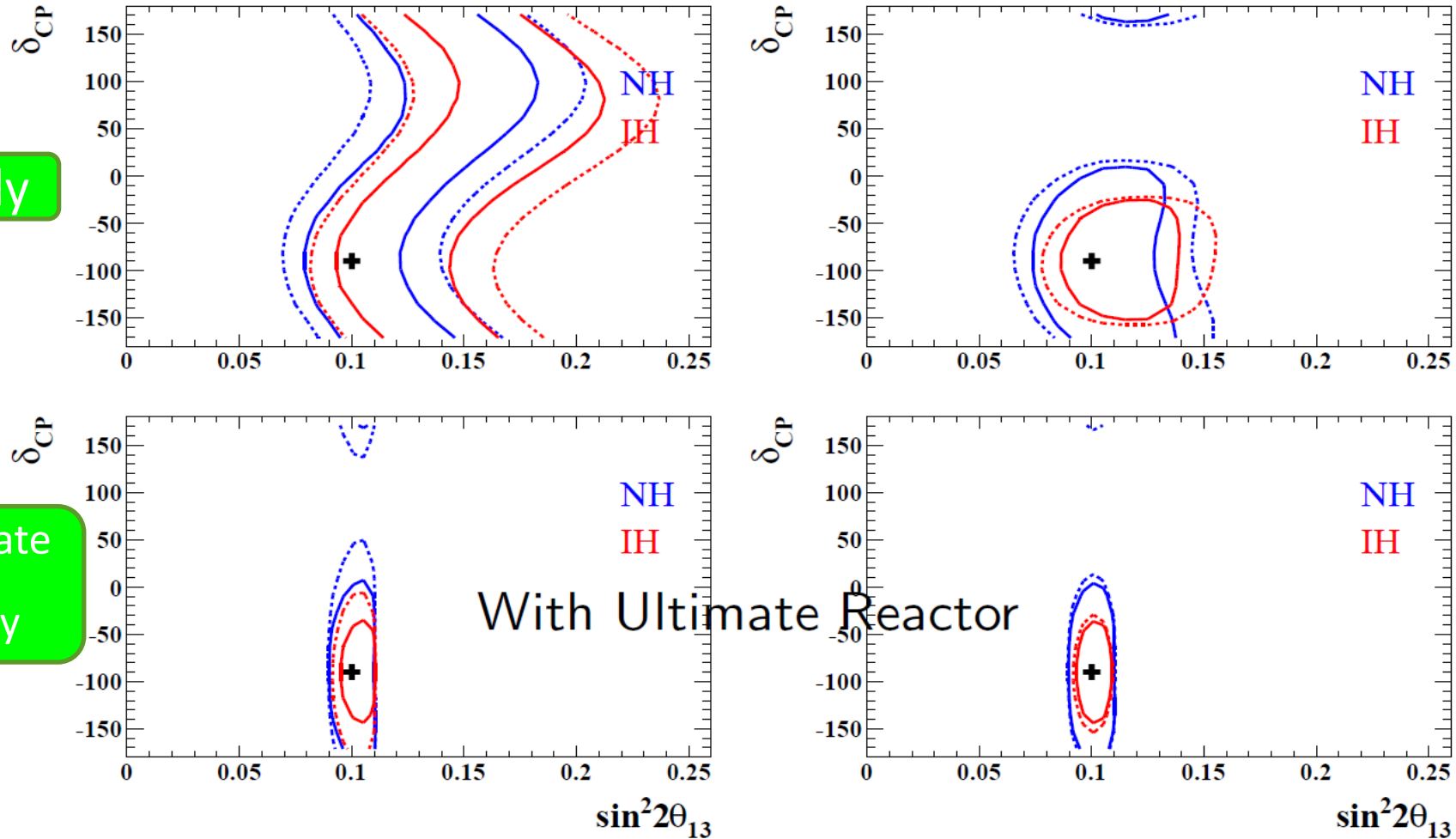
Allowed region assuming NH or IH
Solid : w/o systematic error
Dashed : w/ current systematic error

Running fraction

ν mode:anti-ν mode = 100%:0% 50%:50%

T2K only

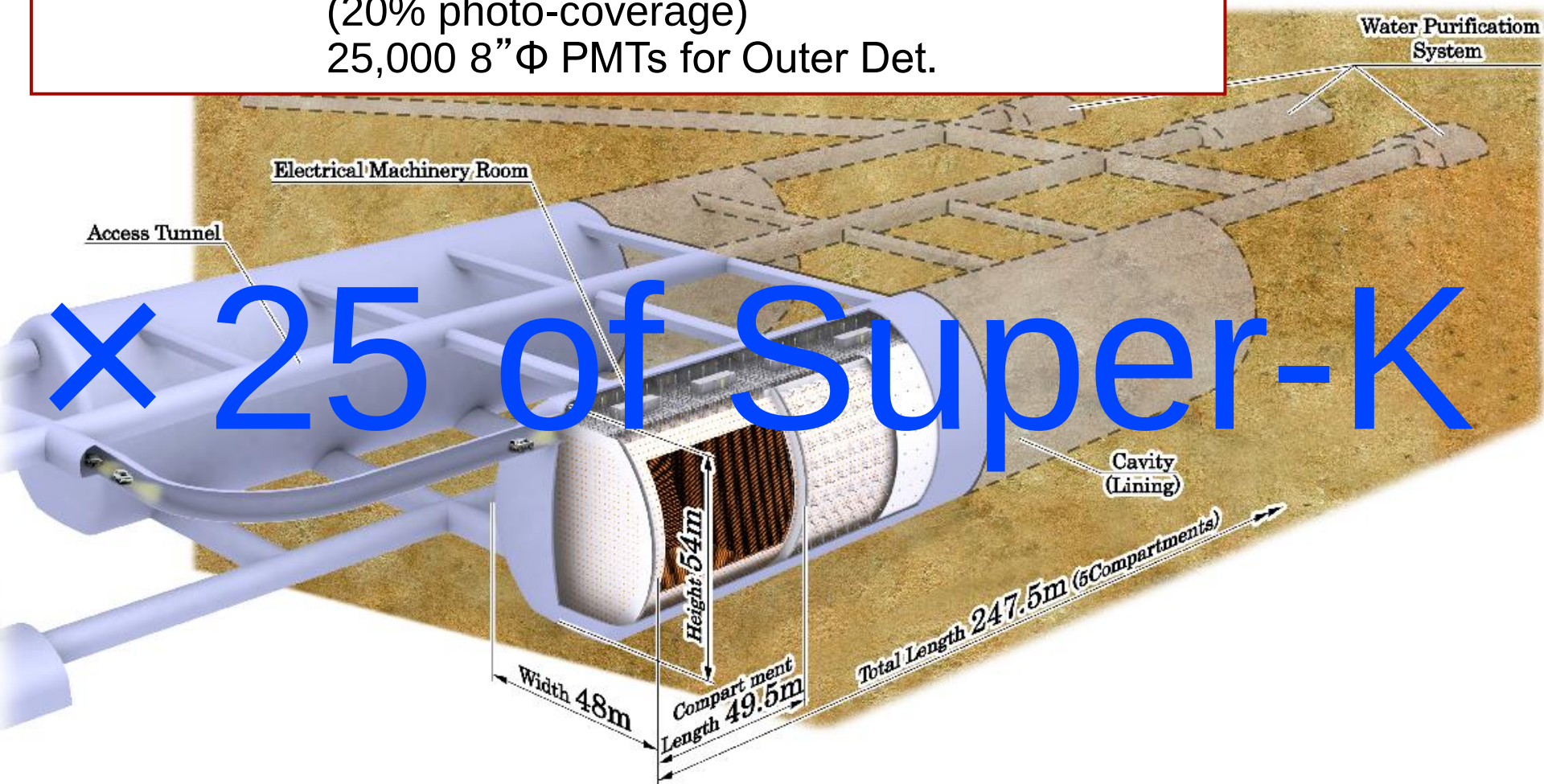
w/ ultimate reactor sensitivity




With Ultimate Reactor

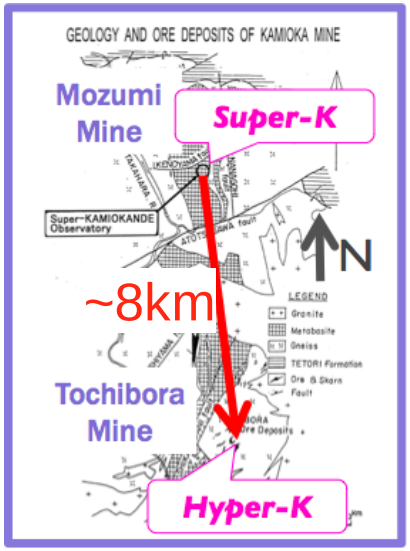
# Hyper-Kamiokande Detector

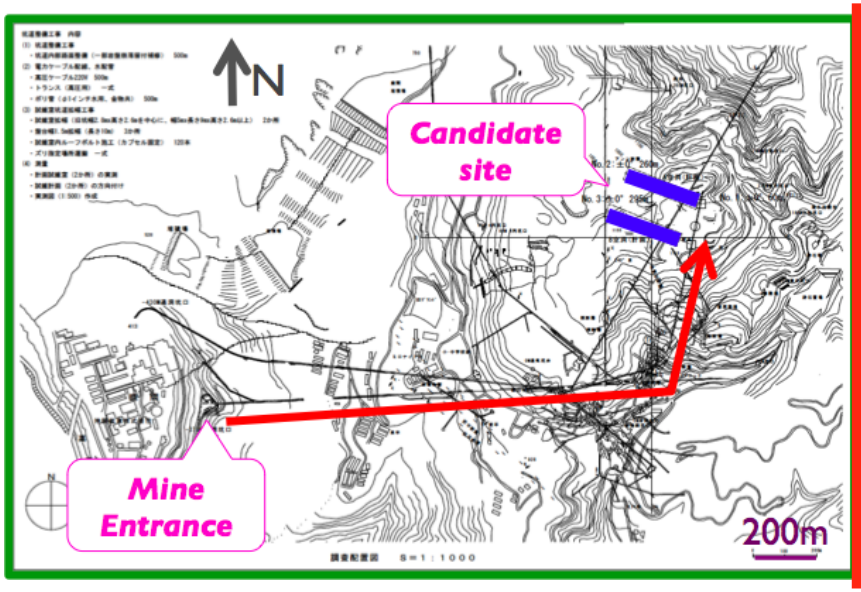
| | |
|---|---|
| Total Volume | 0.99 Megaton |
| Inner Volume | 0.74 Mton |
| Fiducial Volume | 0.56 Mton (0.056 Mton × 10 compartments) |
| Outer Volume | 0.2 Megaton |
| Photo-sensors | 99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det. |

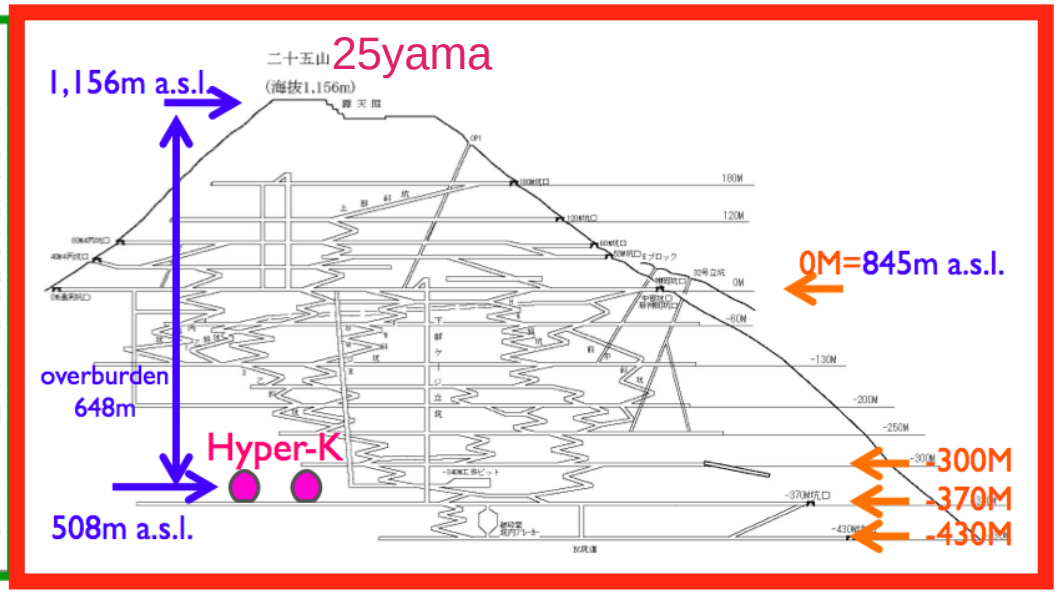


# Hyper-Kamiokande candidate site

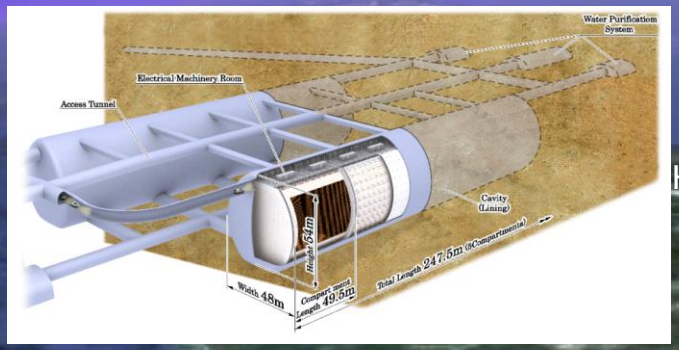
- 8km south from Super-K
  - same T2K beam off-axis angle (2.5 degree)
  - same baseline length (295km)
- 2.6km horizontal drive from entrance
- under the peak of Nijuugo-yama
  - 648m of rock or 1,750 m.w.e. overburden
- 13,000 $m^3$/day or 1megaton/80days natural water



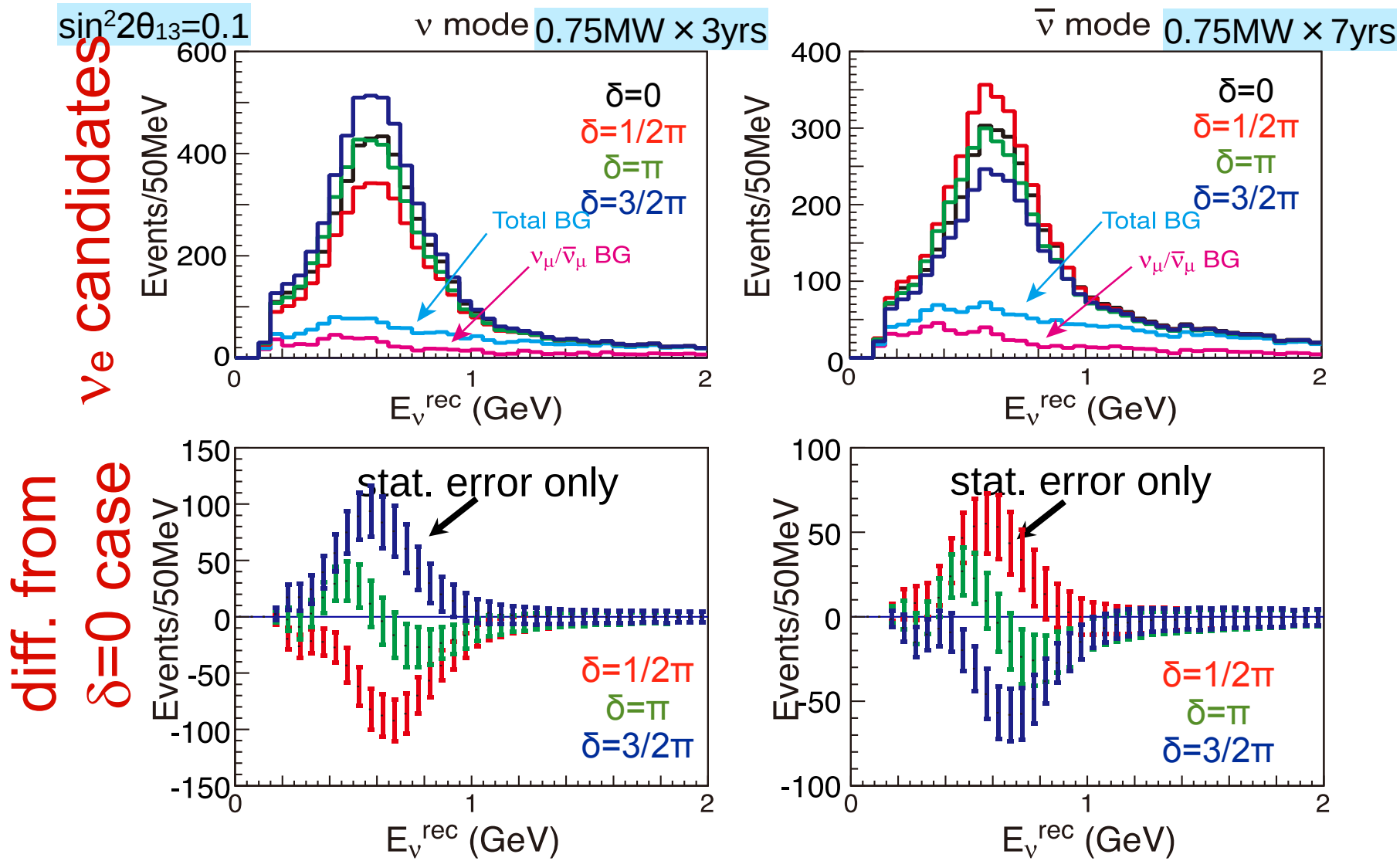



# Neutrino beam from J-PARC



# Expected $\nu_e$ CC candidates



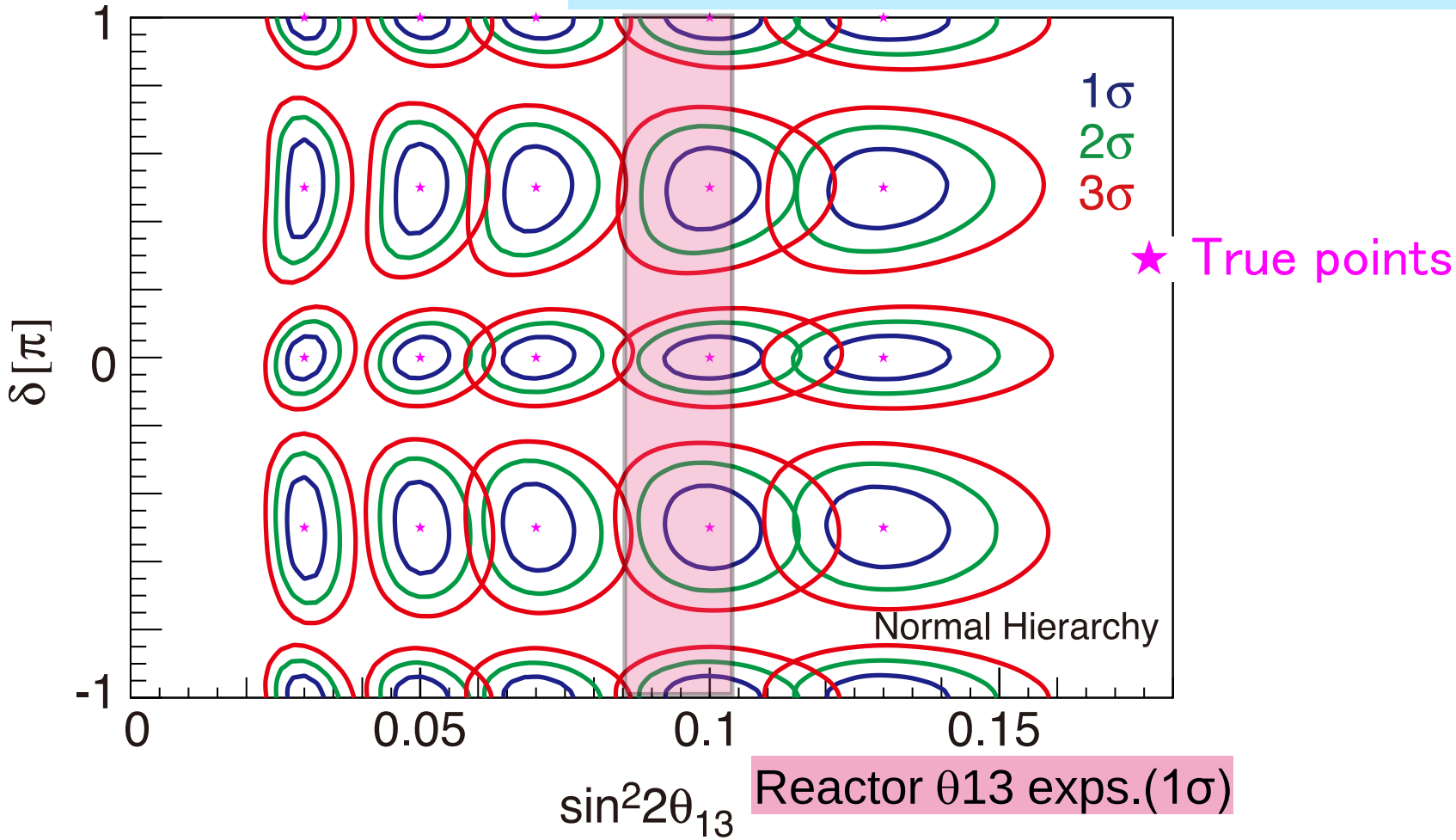

Numbers and shape for CP measurement

# Expected Contours

7.5MW・years

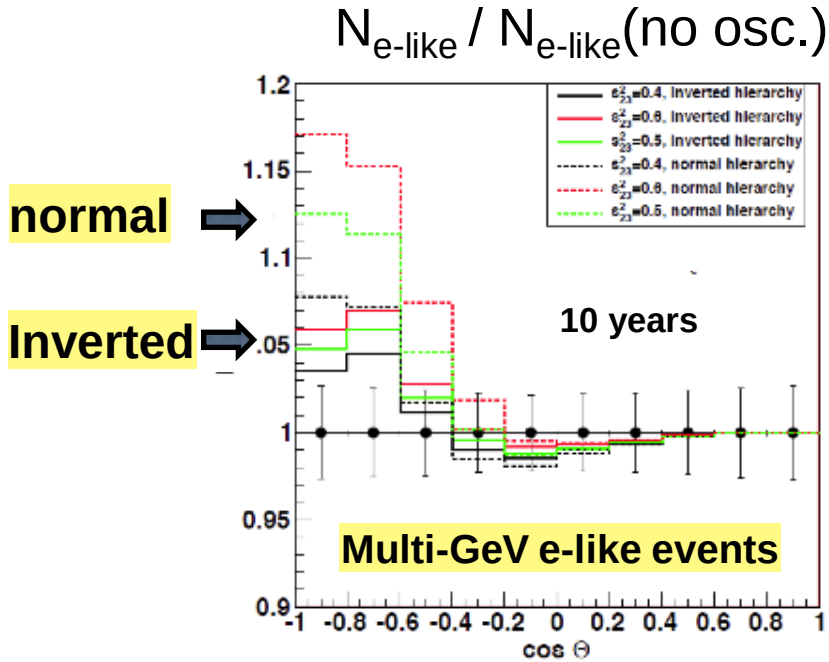
Normal mass hierarchy (known)

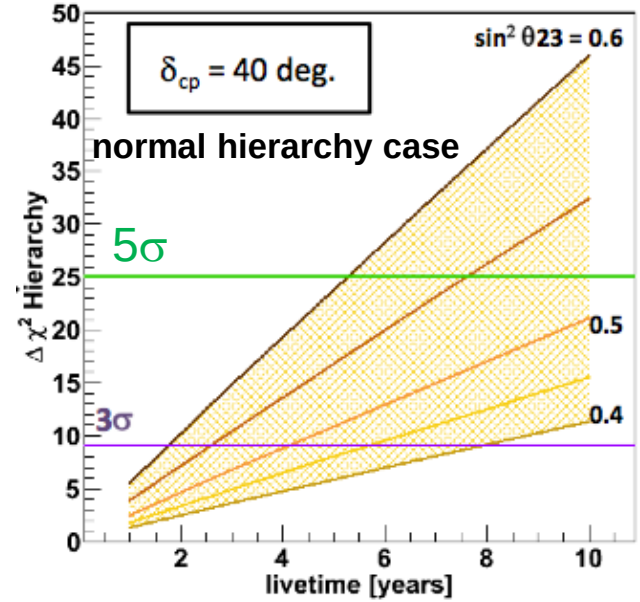
5% systematics on signal, $\nu_\mu$ BG, $\nu_e$ BG, $\nu/\bar{\nu}$




- Good sensitivity for CP δ measurement

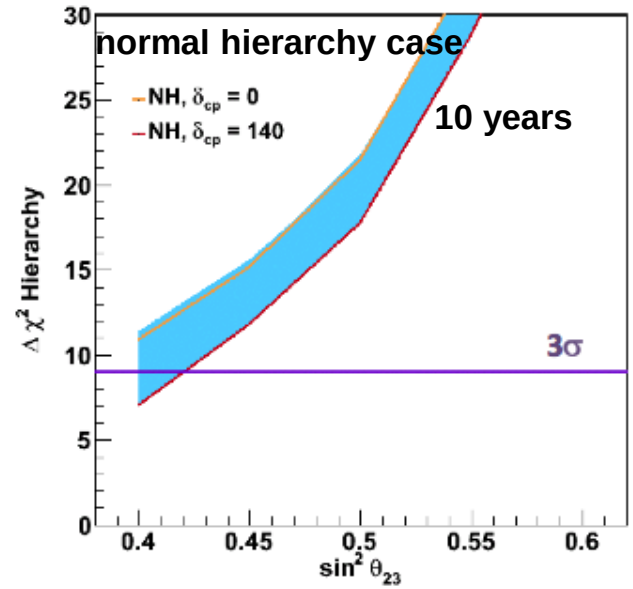
# Mass Hierarchy Sensitivity by atmospheric neutrino



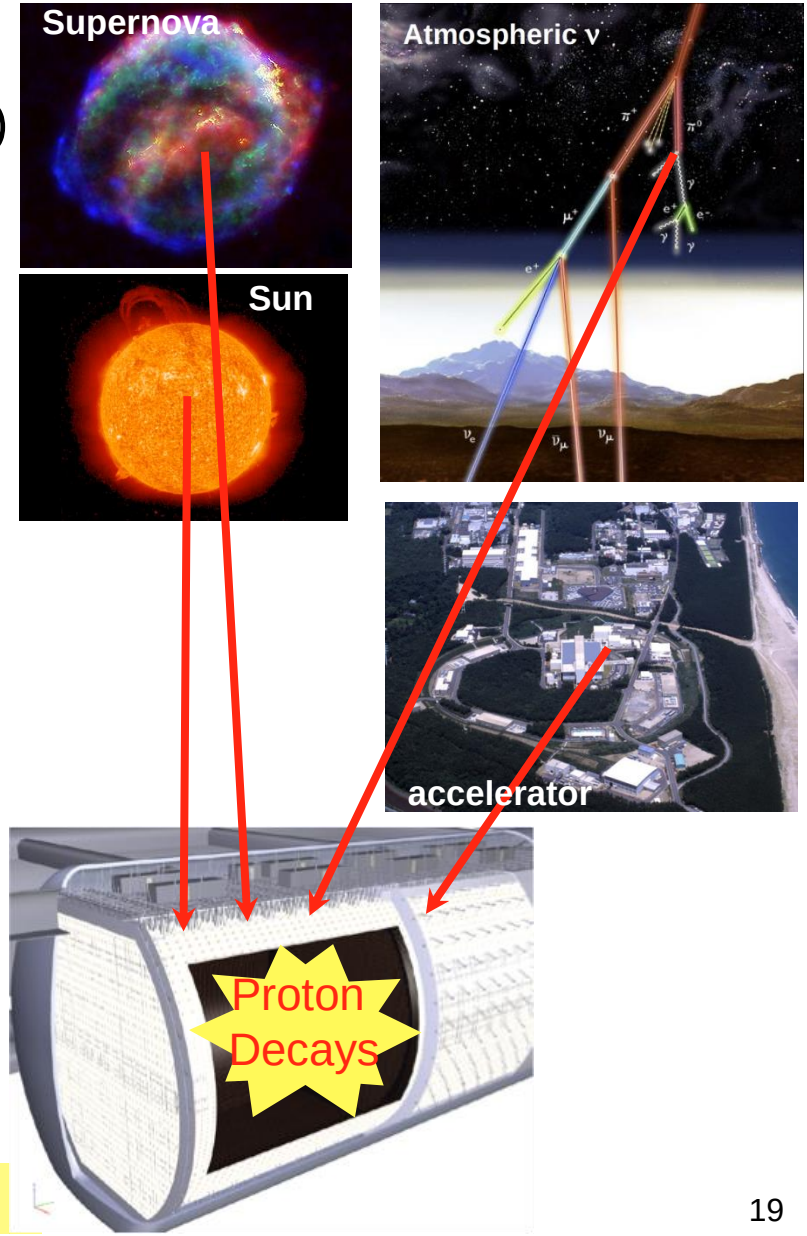

Sensitivity depends on $\theta_{23}$, δ and mass hierarch (a little).

3σ mass hierarchy determination for $\sin^2\theta_{23}$>0.42 (0.43) in the case of normal (inverted) hierarchy.



# Hyper-K is a Multi-purpose Detector

- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac $\delta$)
  - $\nu$ mass hierarchy determination($\Delta m^2_{32}$>0 or <0)
  - $\theta_{23}$ octant determination ($\theta_{23}<\pi/4$ or $>\pi/4$)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years
- Neutrinos from astrophysical objects
  - 200 $\nu$'s / day from Sun
    - possible time variation, day/night matter effect.
  - 250,000 (50) $\nu$'s from Supernova @Galactic-center (Andromeda)
  - ~800 $\nu$'s / 10 years (>10MeV) SN relic $\nu$
  - WIMP $\nu$, solar flare $\nu$, etc

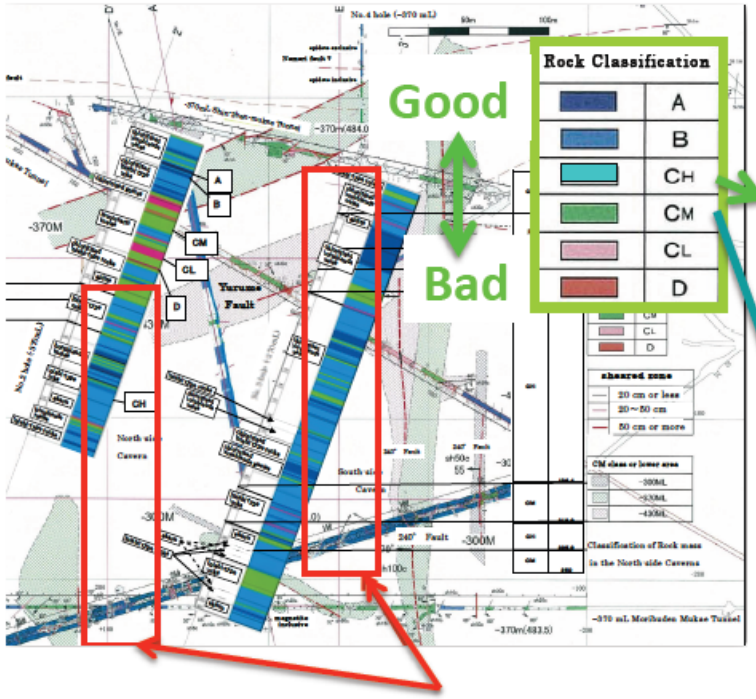



Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

# Cavern stability analysis

- Candidate site
  - 8km south from Super-K
  - 648m of rock overburden (1,750 m.w.e)

**Rock mass characterization**

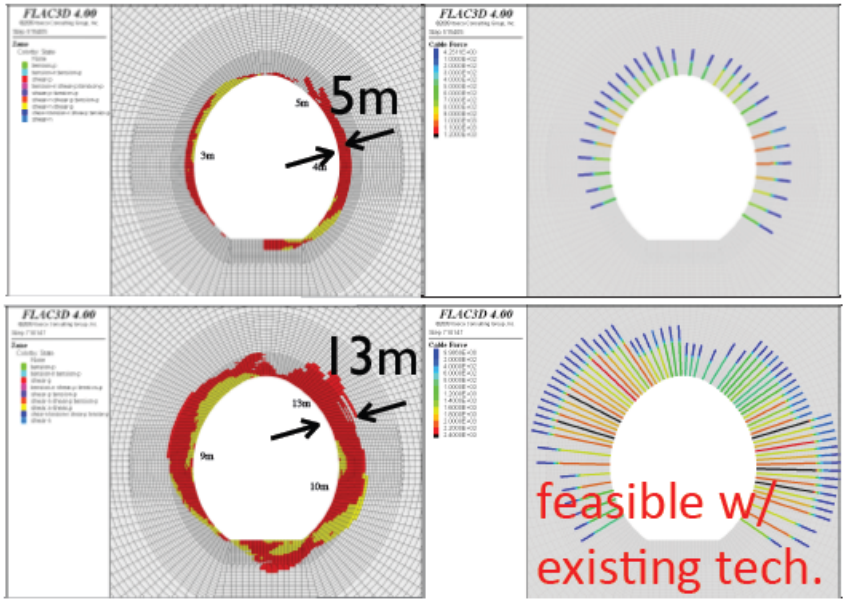



CH class

CM class

**Required Pre-Stressed (PS) anchors**

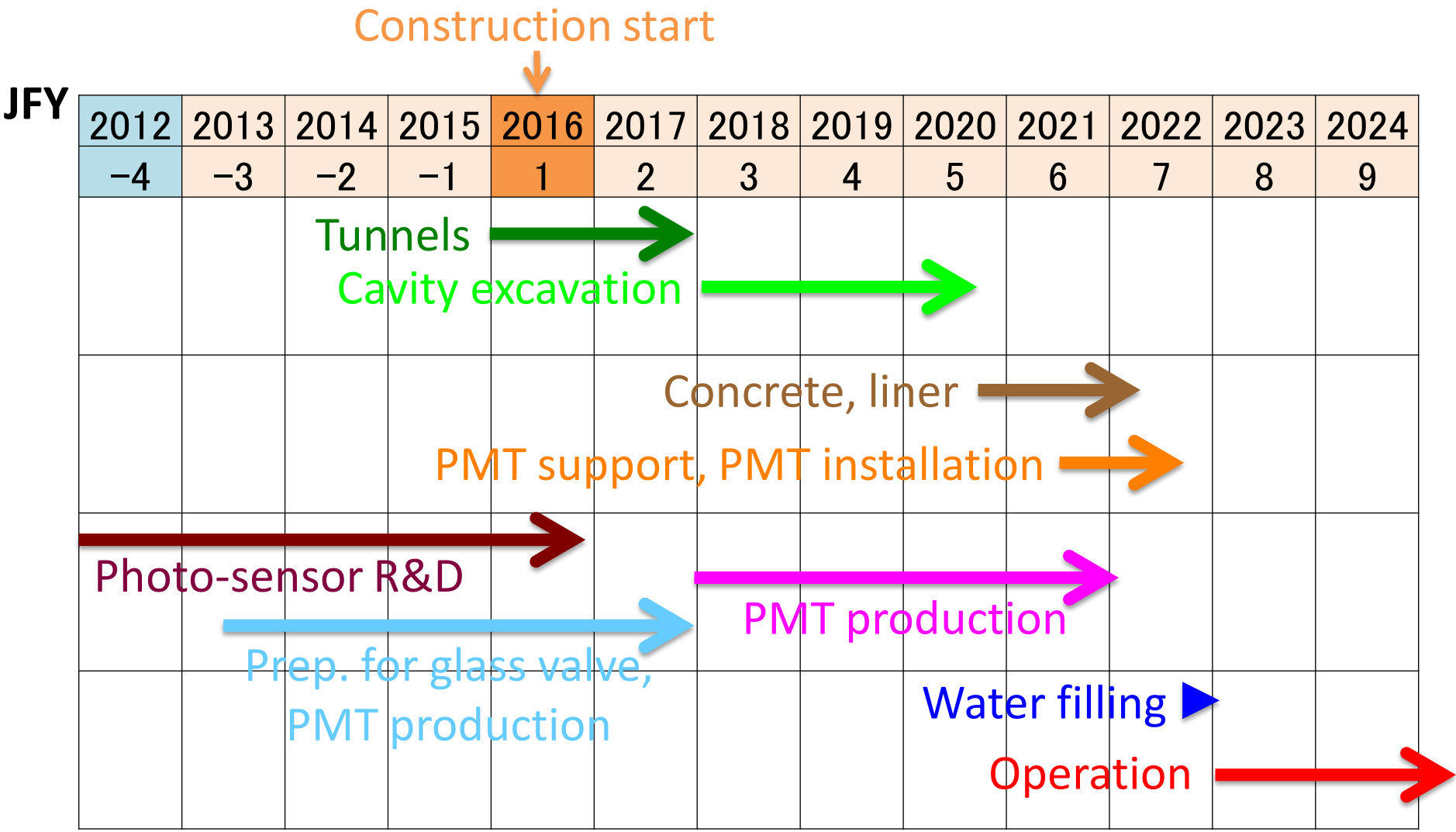
Plasticity region depth PS-anchor tension




For all rock mass classes (B, CH, CM), HK caverns can be constructed.

# Schedule

assuming budget being approved from JPY2016



# Summary

- Still many fruitful physics at Super-K.
- R&D project for GADZOOKS! (EGADS) is going well.
- T2K observed $\theta 13$, and has future prospects to discuss $\delta$CP.
- The Hyper-K detector has a high sensitivity for $\delta$CP measurement and mass hierarchy.
- Hyper-K is a multiple purpose detector which investigate (discover) also nucleon decays and astrophysical neutrinos.