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# Neutrino physics and astrophysics with water Cherenkov detectors

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# Outline

- *Early days*
- *Atmospheric neutrino oscillations*
- *Solar neutrino oscillations*
- *Long baseline oscillation studies*
- *Detecting relic supernova neutrinos*
- *Future water Cherenkov detector*
- *Summary*

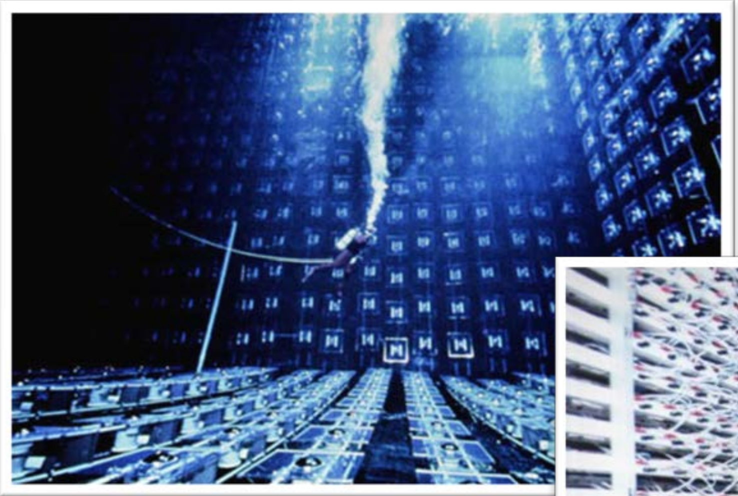
*(MeV to GeV neutrinos only)*

# *Early days*

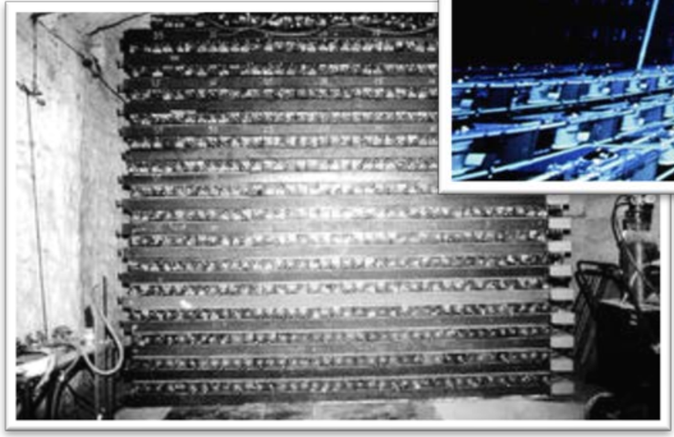
# Proton decay experiments (1980's)

- ✓ In the 1970's, Grand Unified Theories, predicted that protons should decay with the lifetime of about $10^{30}$ years.
- ✓ Several proton decay experiments began in the early 1980's.
- ✓ Two of them, IMB and Kamiokande, were water Cherenkov detectors.

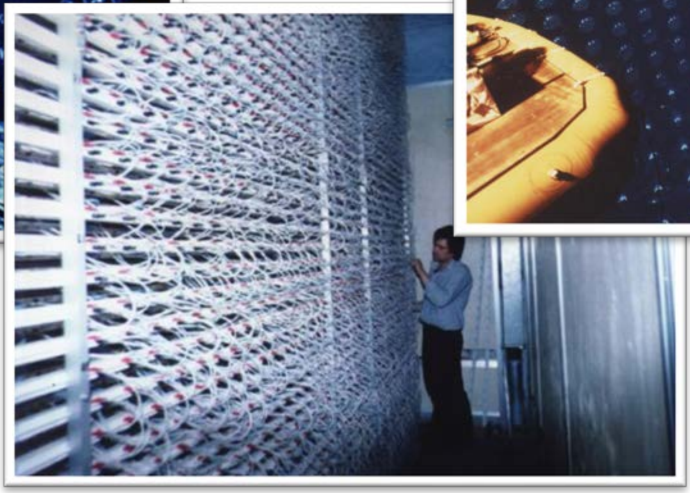
IMB (3300ton)



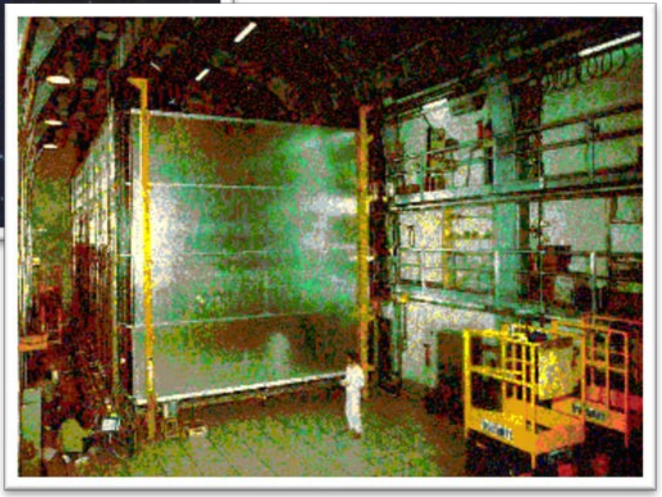
Kamiokande (1000ton)



KGF (100ton)



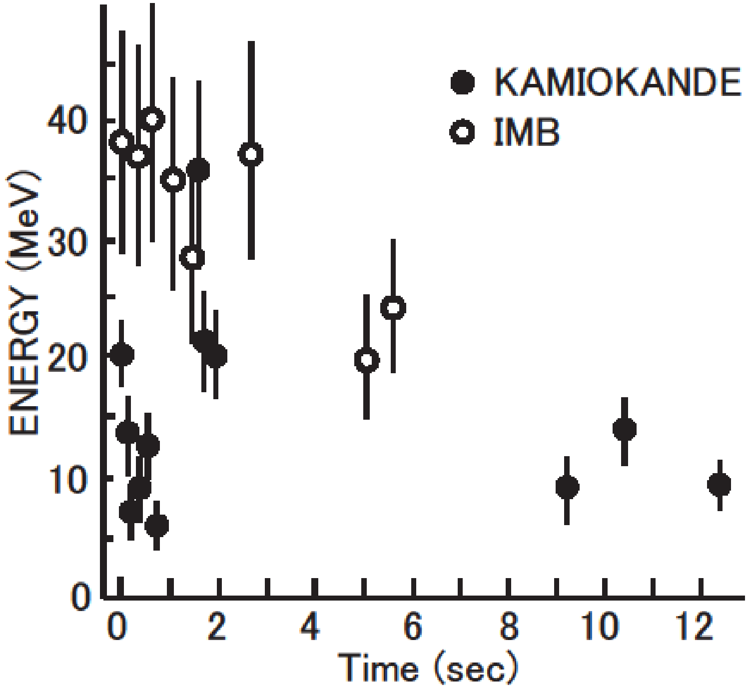
NUSEX (130ton)



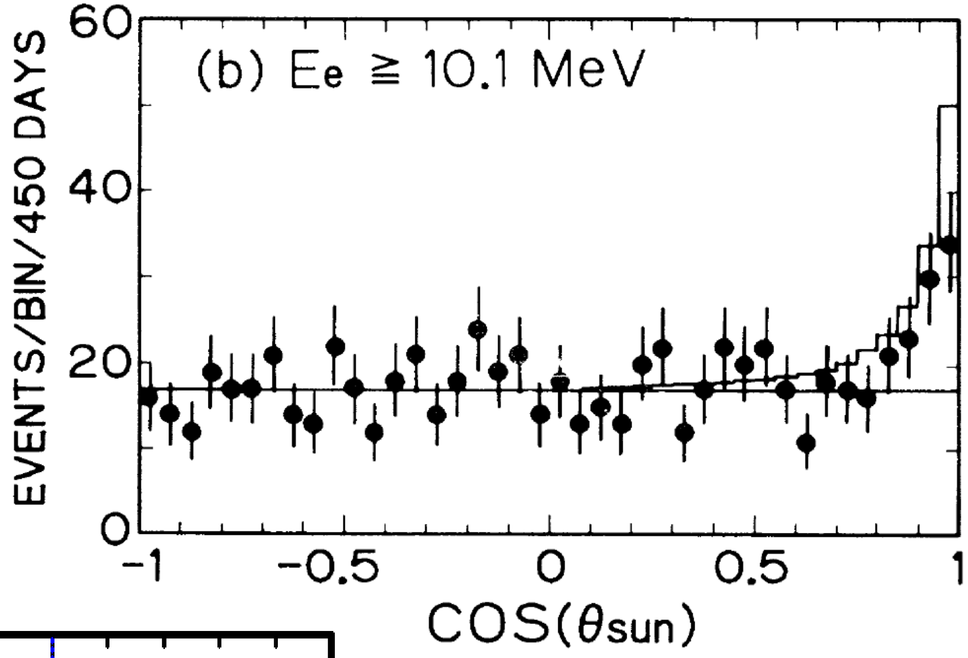
Frejus (700ton)

# Results from water Cherenkov detectors in the 1980's to 90's

## Detection of Supernova neutrinos (1987)

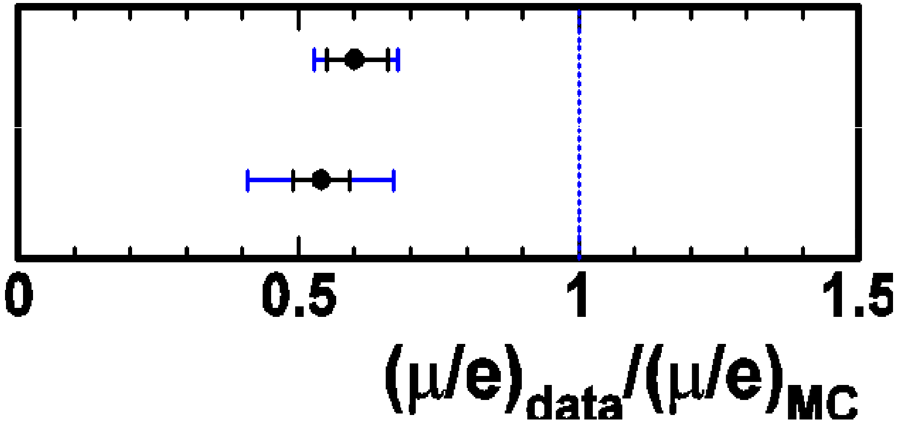



## Observation of solar neutrinos (Kamiokande)




Kamiokande (1988, 92, 94)

IMB (1991, 92)

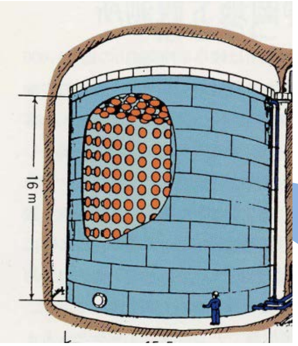



## Observation of atmospheric neutrino deficit

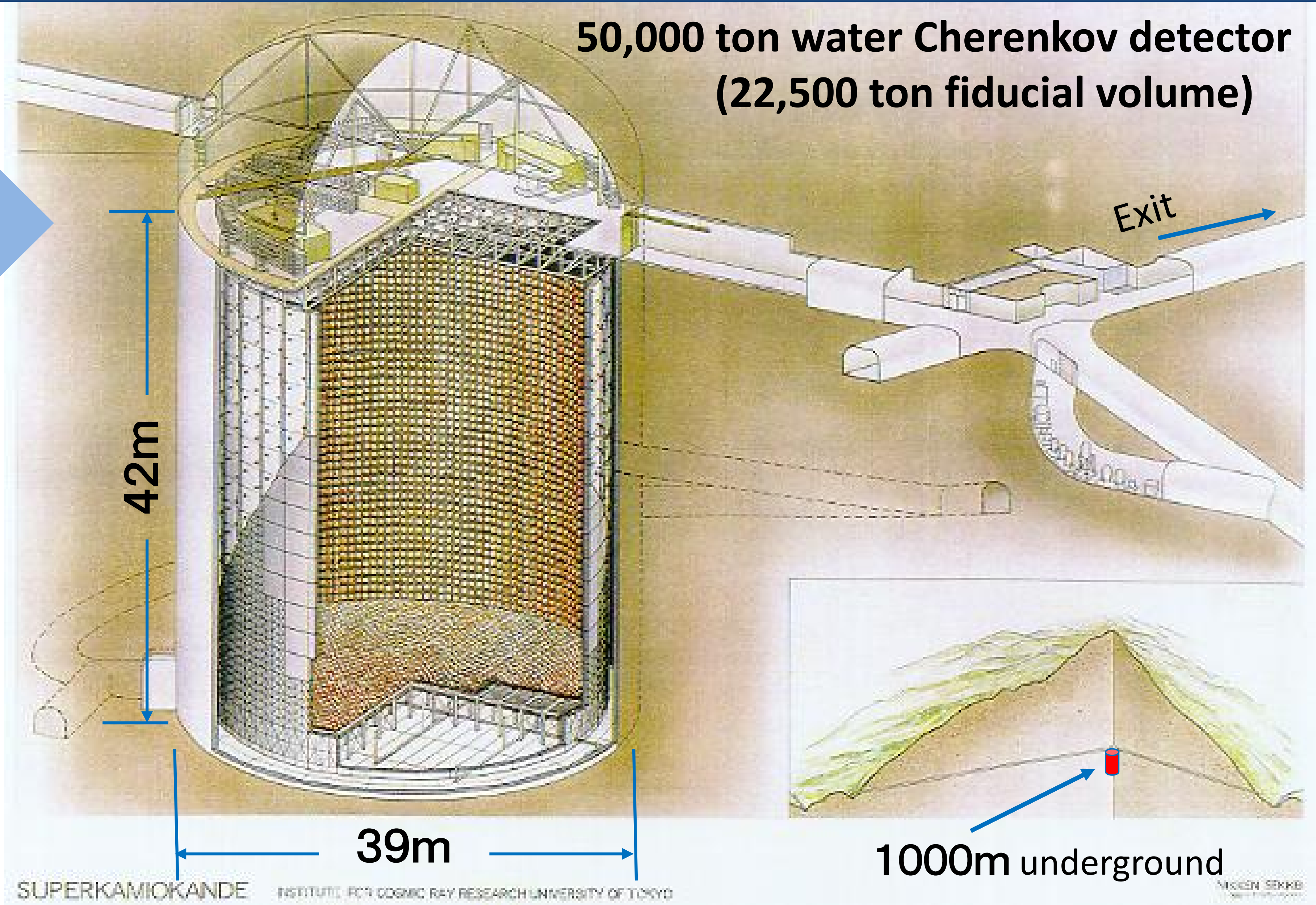
**Water Ch. are good for neutrino phys and astrophys.**

# *Atmospheric neutrino oscillations*

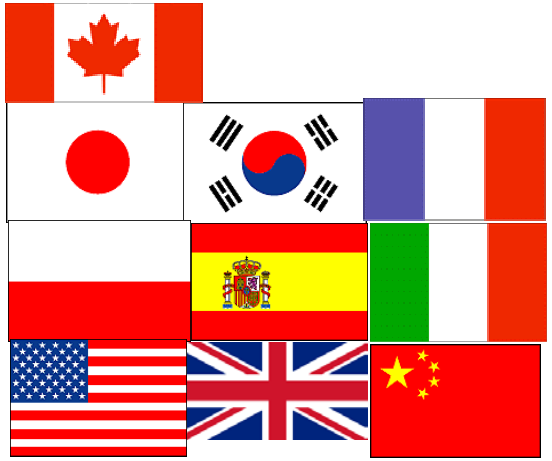
# Super-Kamiokande detector



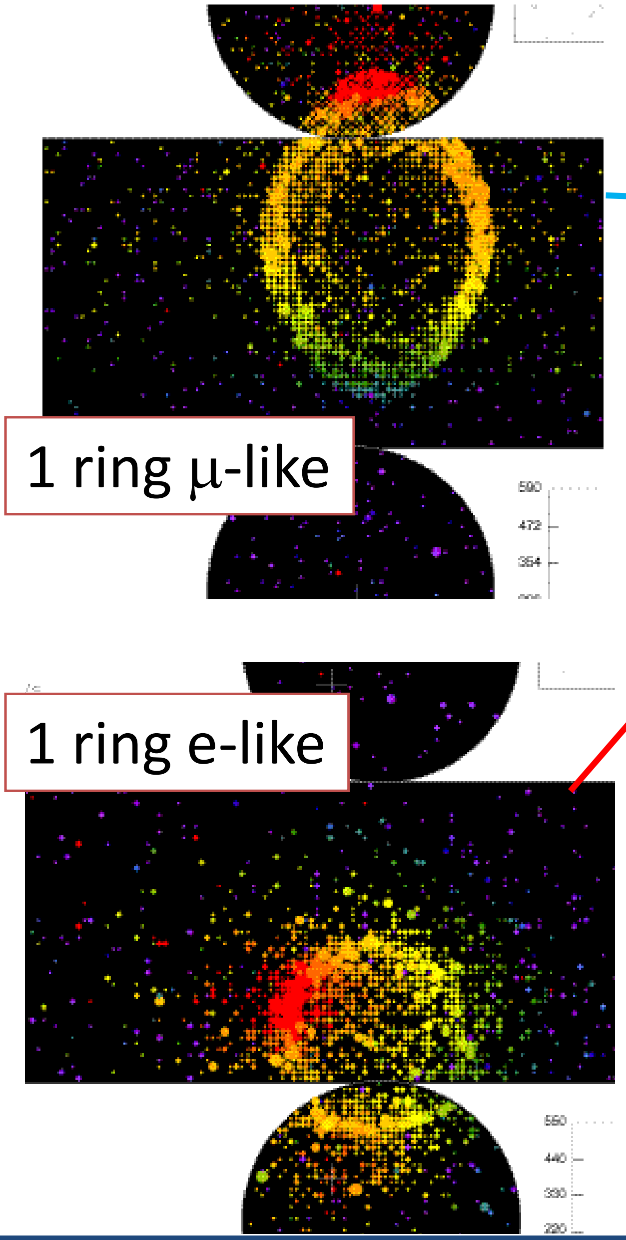
About 20 times larger mass

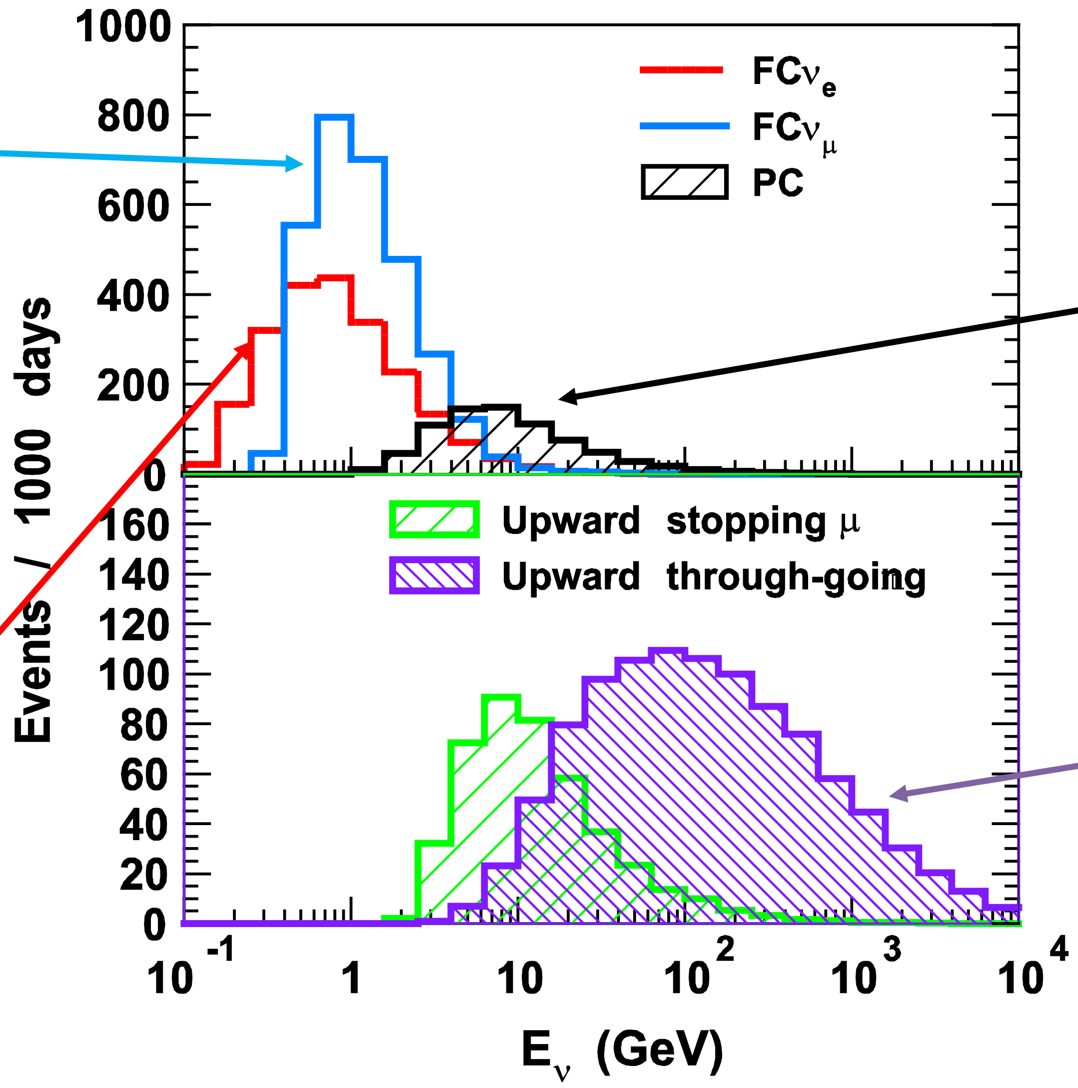


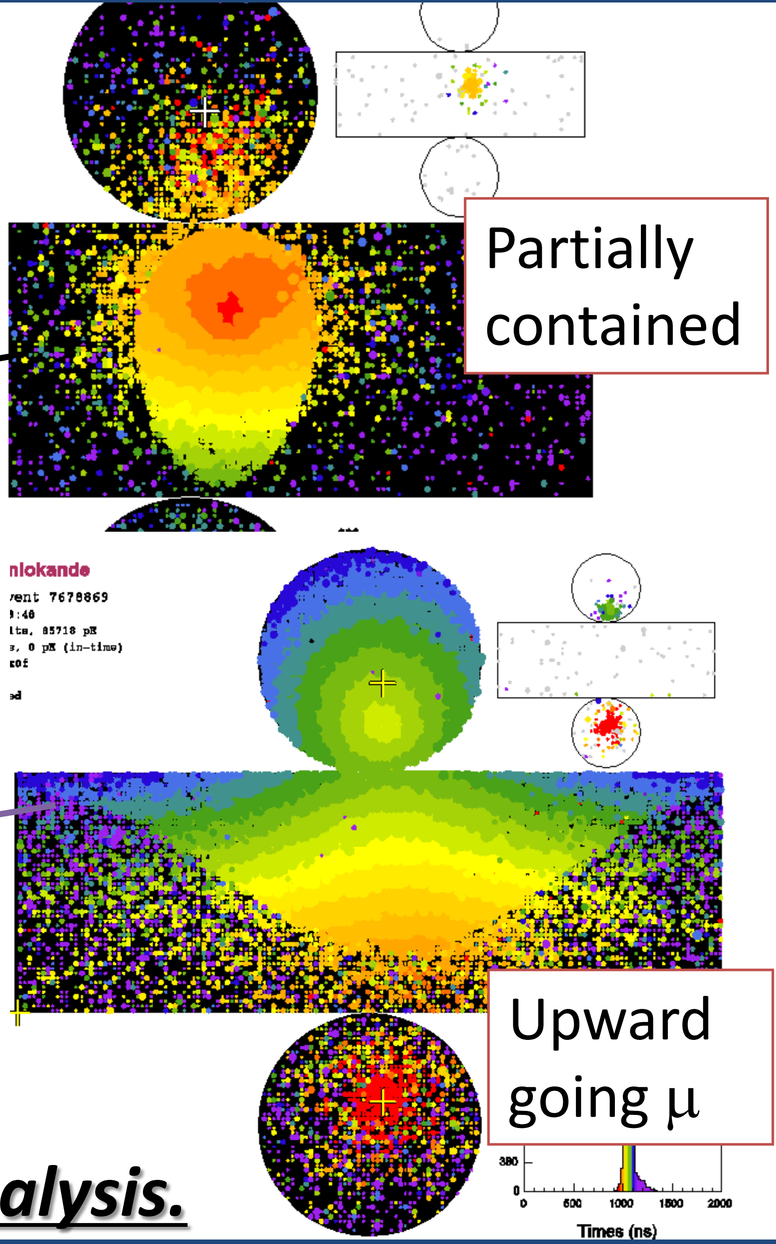

~160 collaborators



# Event type and neutrino energy



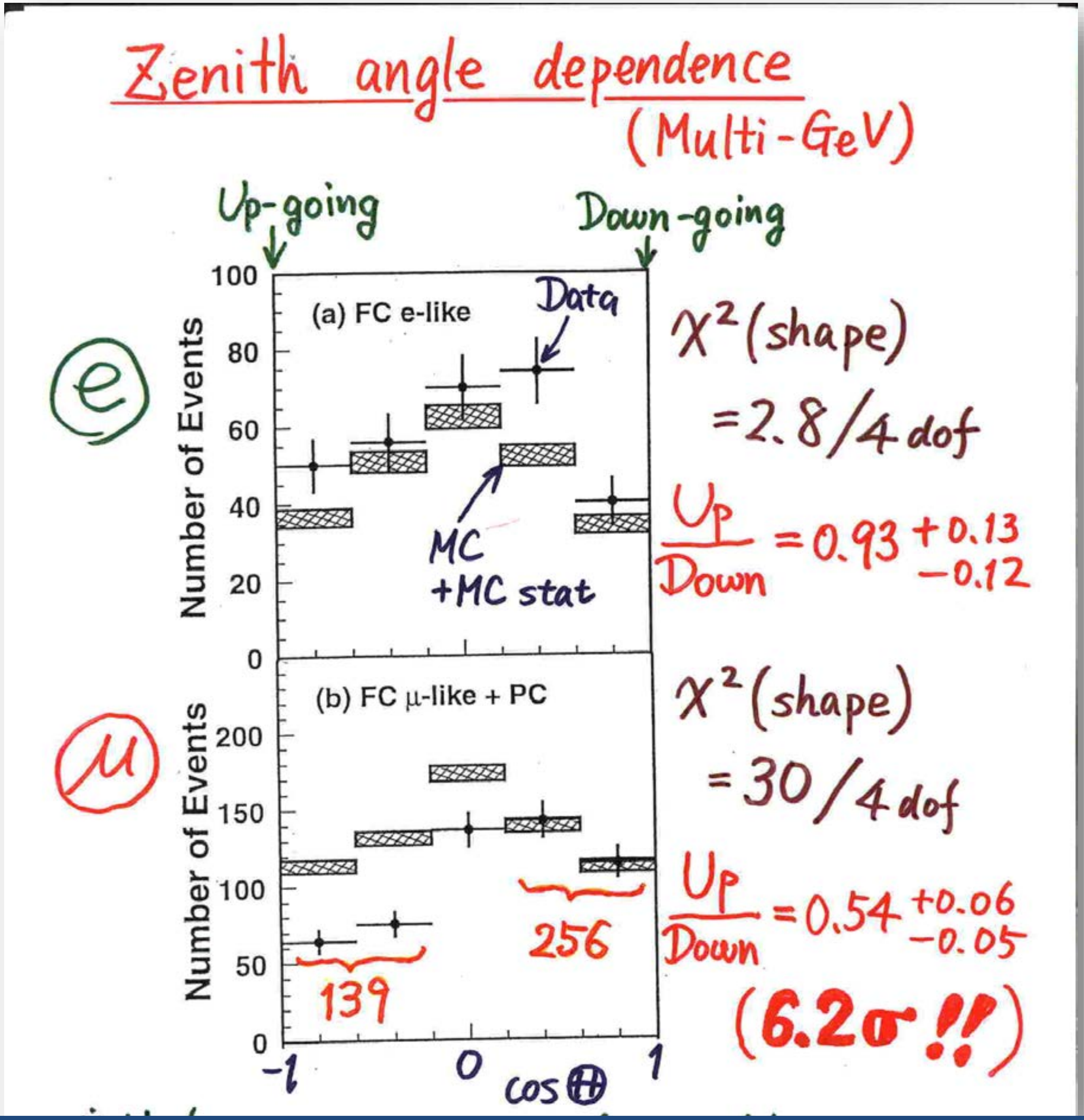



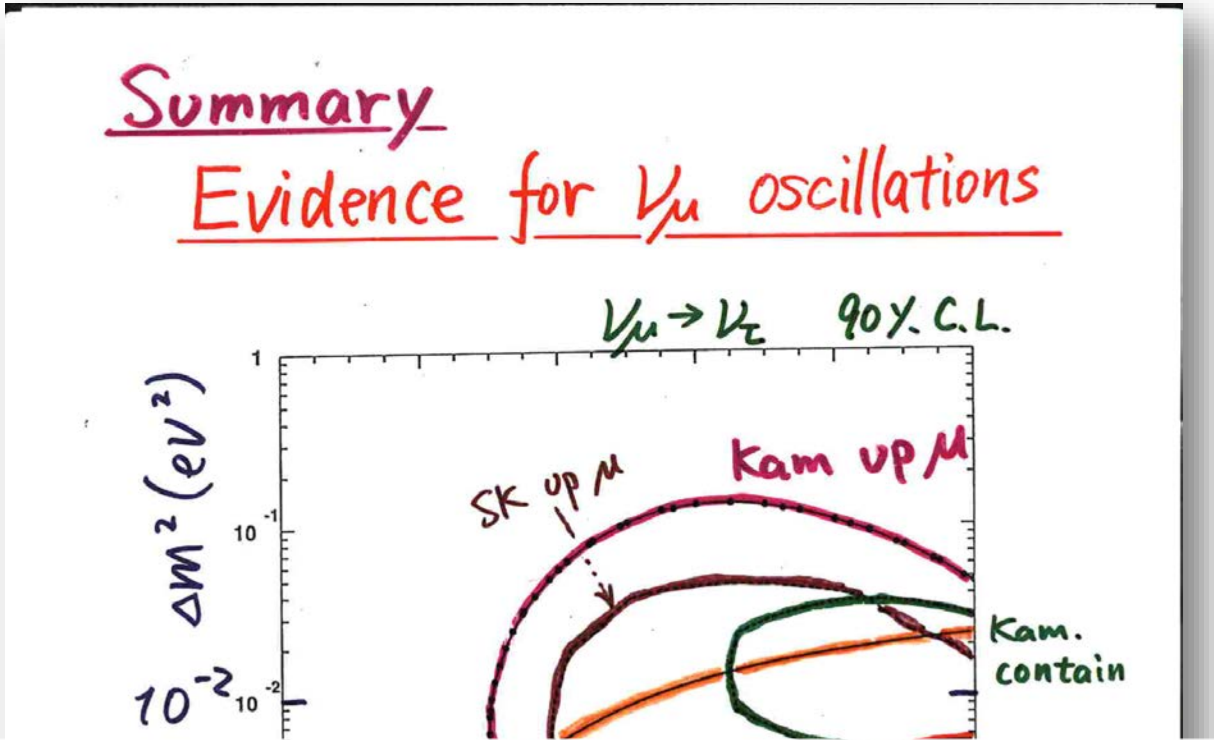




***<u>All these events are used in the analysis.</u>***

# Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Y. Fukuda et al., PRL 81 (1998) 1562



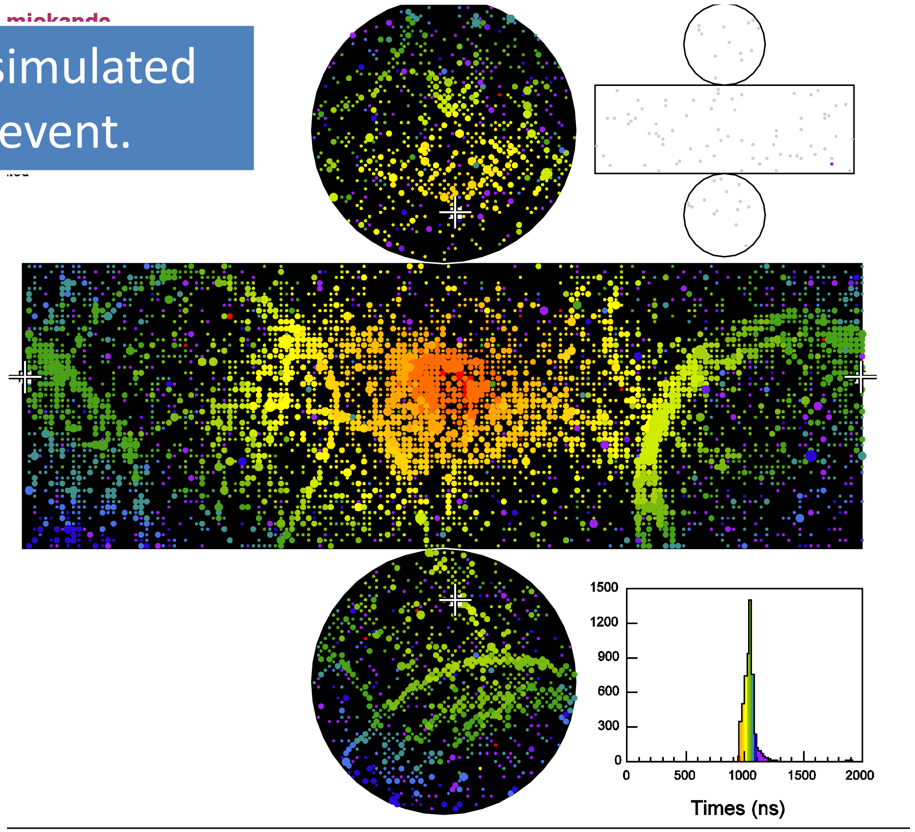




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

# Detecting tau neutrinos

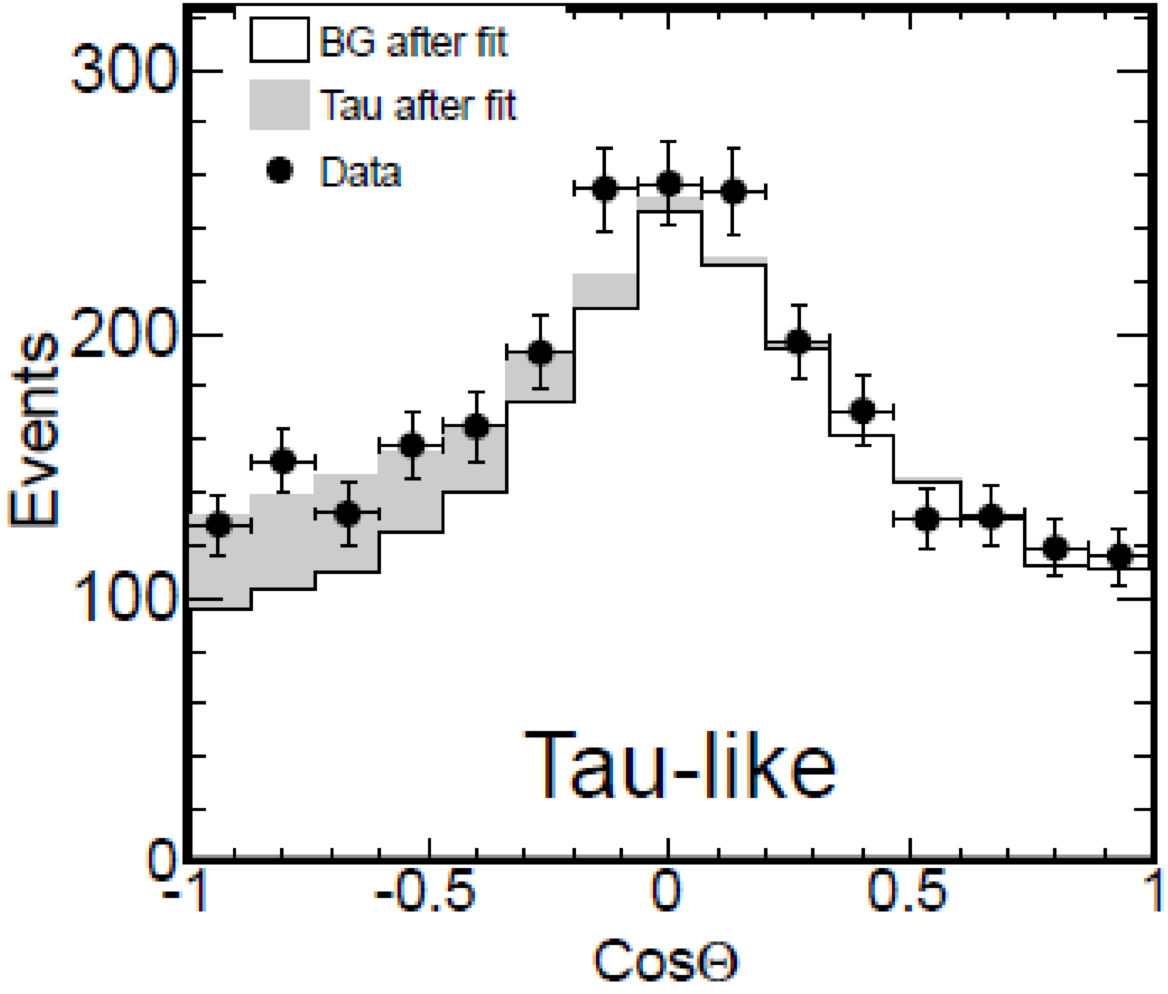
If the oscillations are between $\nu_\mu$ and $\nu_\tau$, one should be able to observe $\nu_\tau$'s.

A simulated $\nu_\tau$ event.




It is not possible for Super-K to identify $\nu_\tau$ events by an event by event bases. ➔ Statistical analysis knowing that $\nu_\tau$'s are upward-going only.

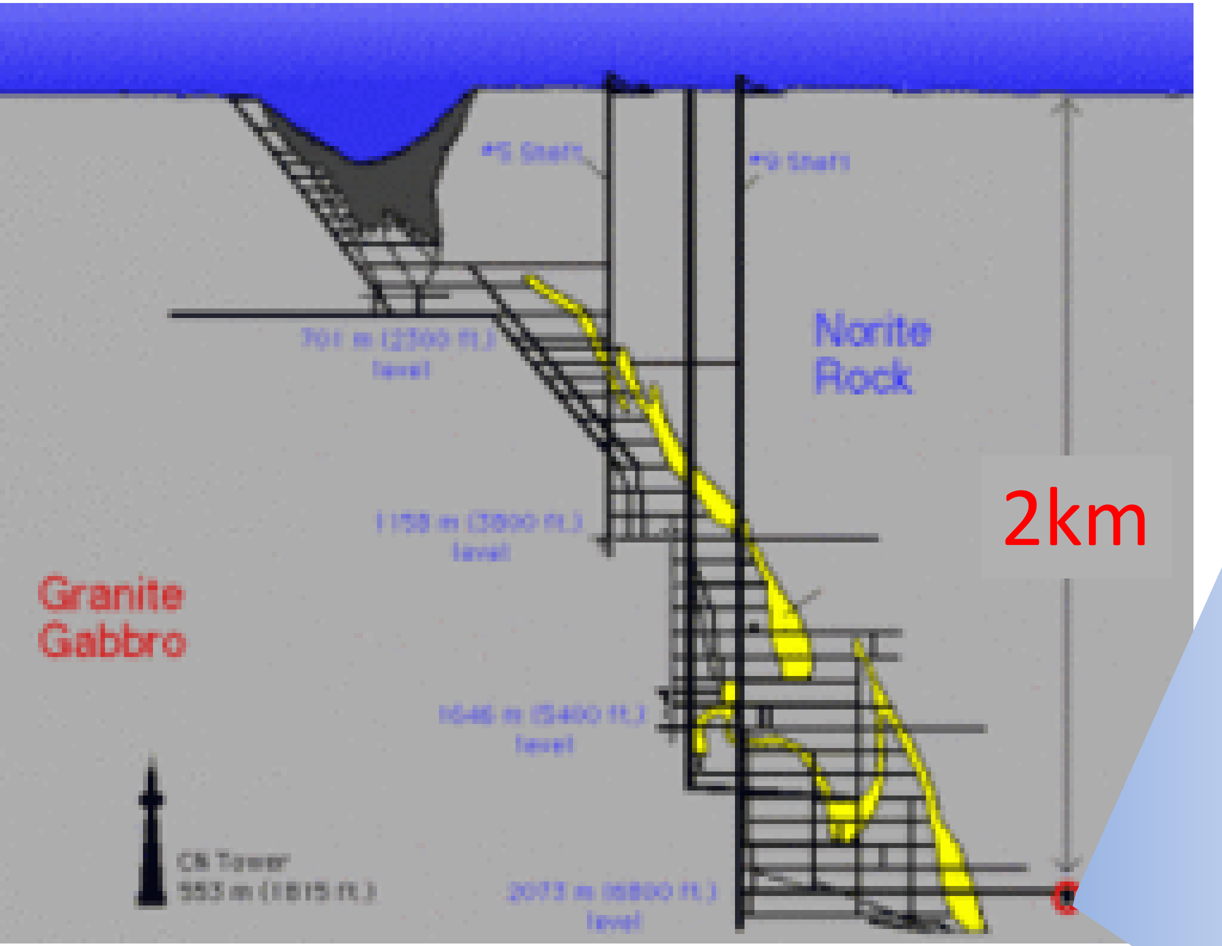
Super-K, PRD98 (2018) 052006

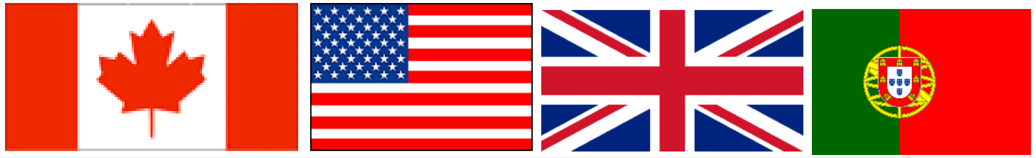


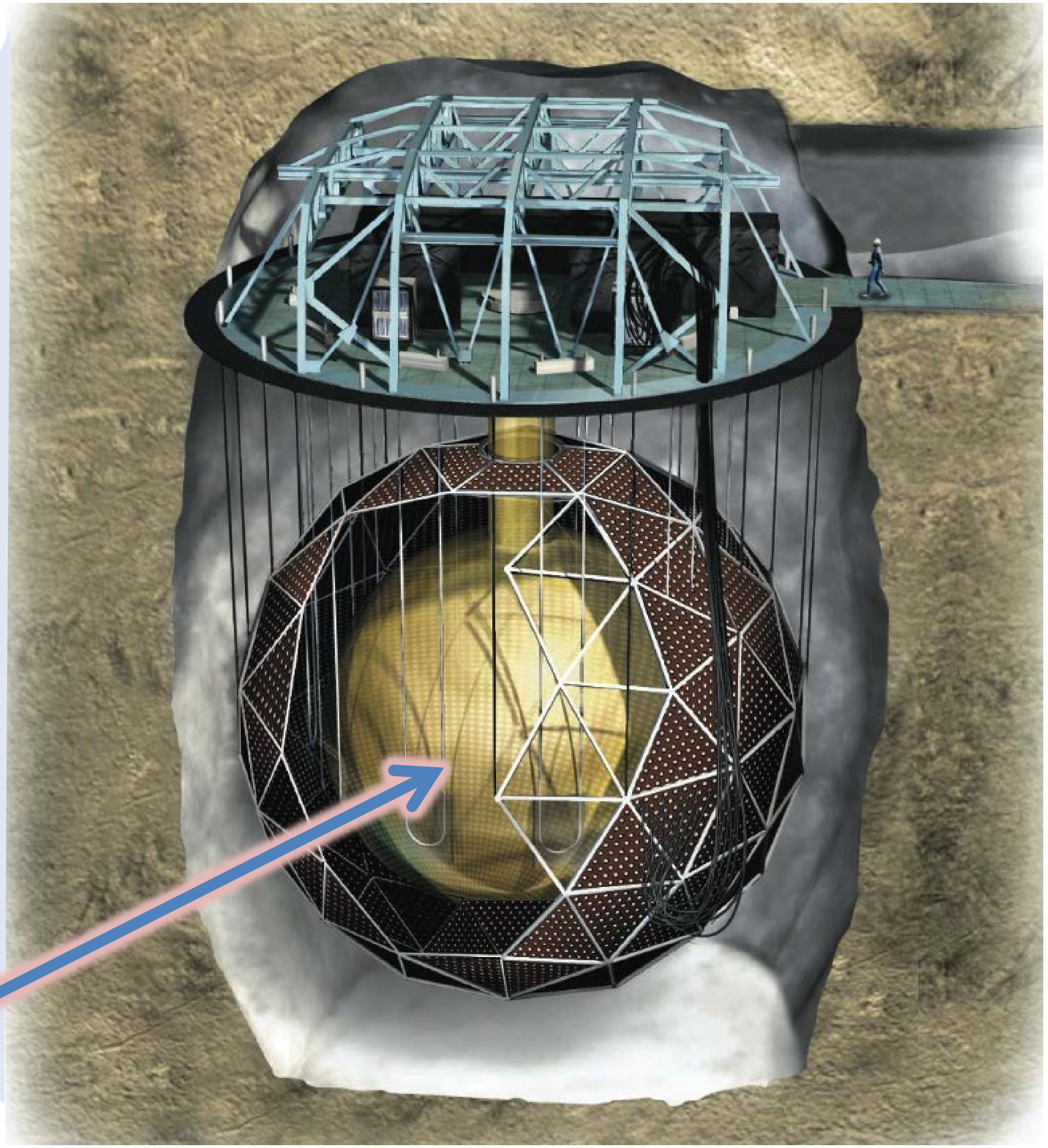

$\tau$-appearance at 4.6$\sigma$ (consistent with OPERA)

# *Solar neutrino oscillations*

# SNO (Heavy water Cherenkov detector)

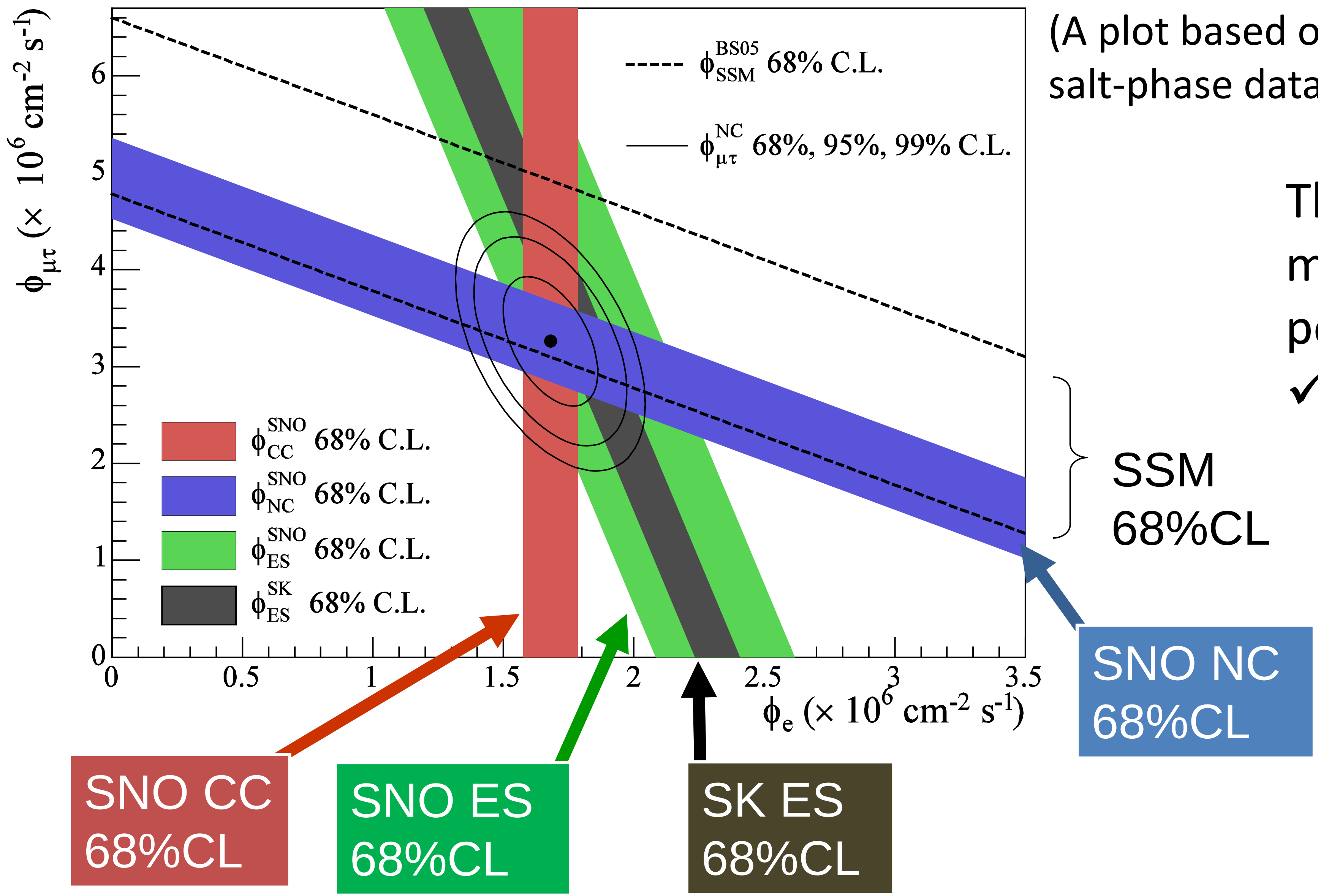




1000 ton of heavy water

# Evidence for solar neutrino oscillations




(A plot based on the salt-phase data)

SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

Three (or four) different measurements intersect at a point.

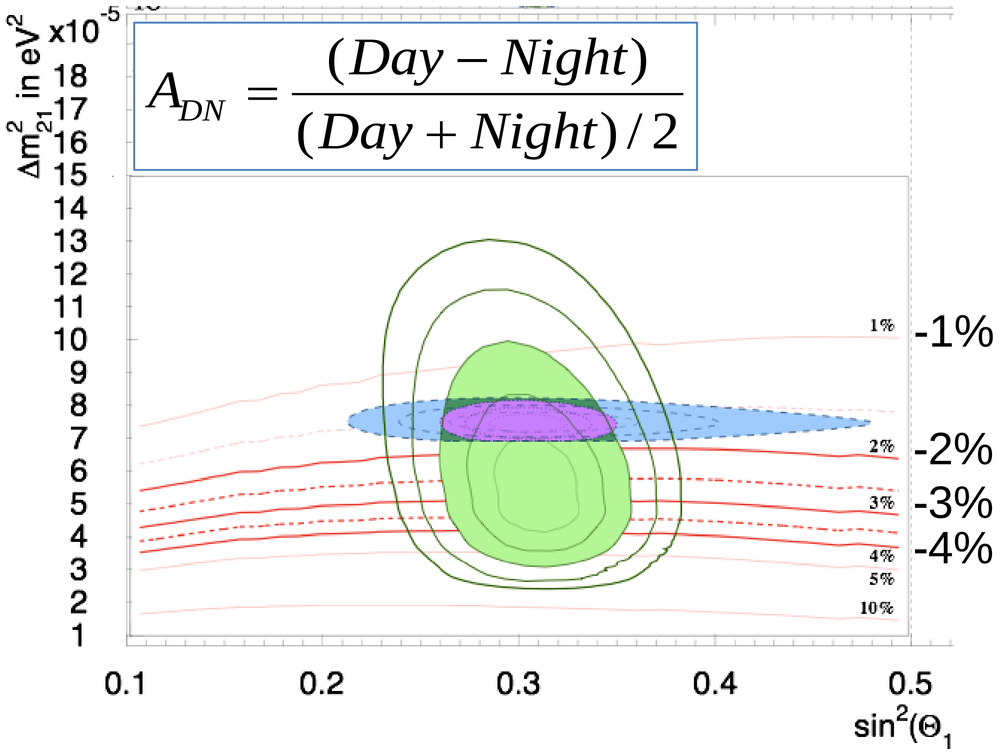
✓ *Evidence for ($\nu_\mu$+$\nu_\tau$) flux*

# *Further studies of solar neutrino osci. with Super-K*

## *Day-Night effect*

Super-K, PRD94, 052010 (2016)

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



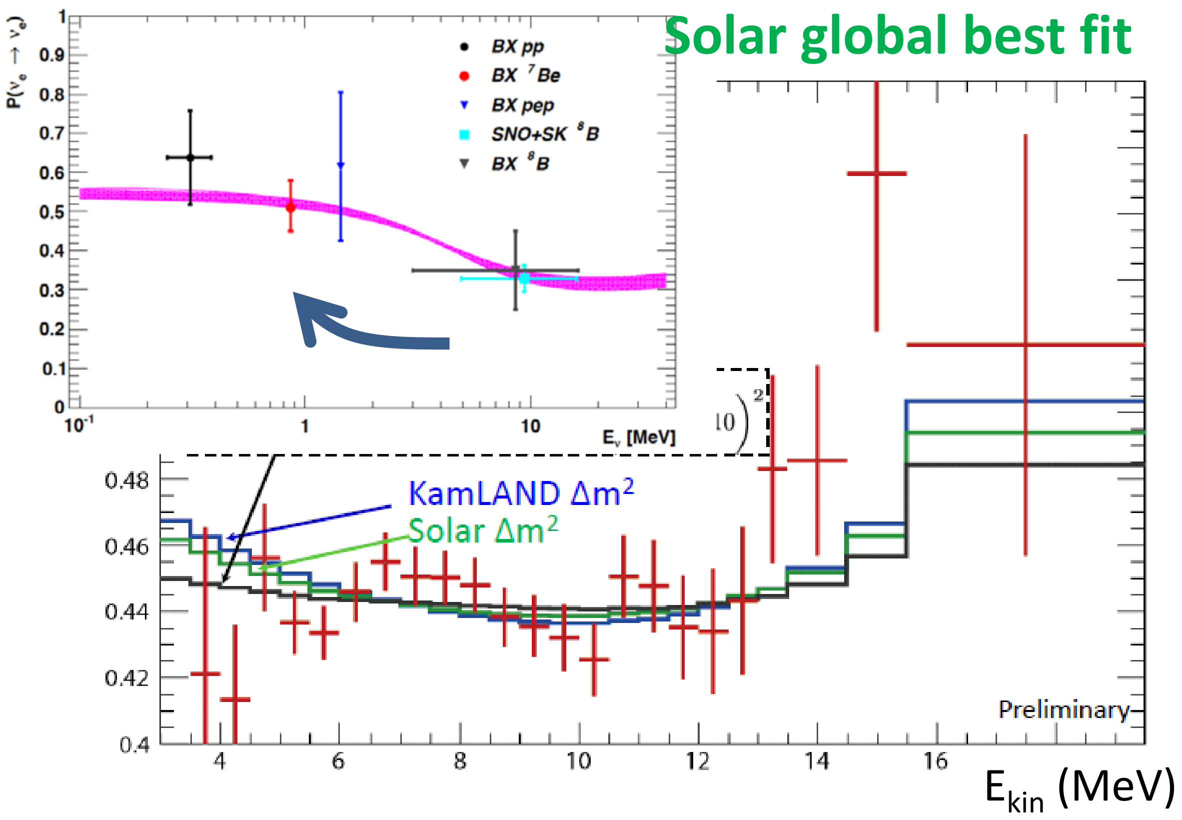

| | $A_{DN}^{fit}$ (%) |
|---|---|
| **SK-I~IV, 4499 days** | **-3.3+/-1.0+/-0.5** |
| **Non-zero significance** | **2.9 σ** |

## *Spectrum upturn*

(Super-K, Neutrino 2018)

**Solar+KamLAND best fit**

**Solar global best fit**




| **Solar best fit** | **Consistent within 1.5σ** |
|---|---|
| Solar+KamLAND best fit | Marginally within ~2σ |

*Interesting. But we need more data.*

# *Long baseline oscillation studies*

# Water Ch. contribution to LBL oscillation experiments

(Sorry, not “astroparticle physics”)

***K2K experiment (1999 – 2004)***


Confirmation of neutrino oscillation with accelerator beam.

***T2K experiment (2010 -)***

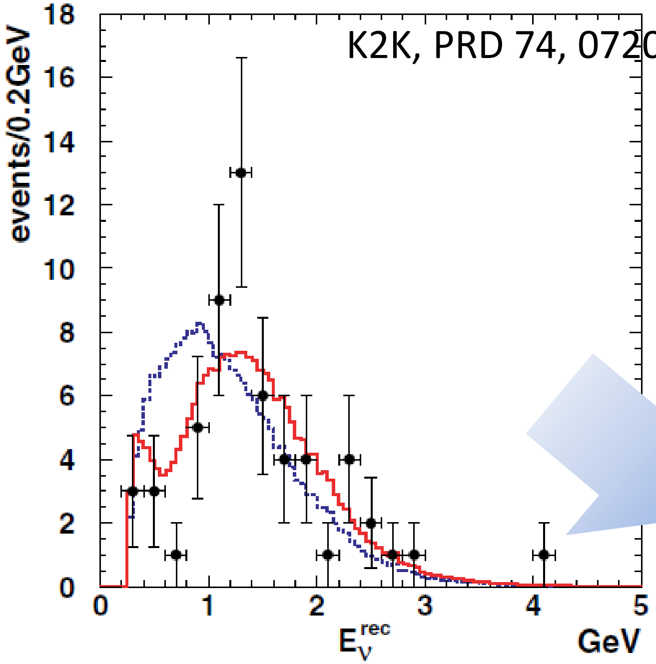
Electron neutrino appearance (evidence for 3 flavor oscillation effect).


(Of course, there are other important long baseline experiments: MINOS, OPERA, NOvA. )

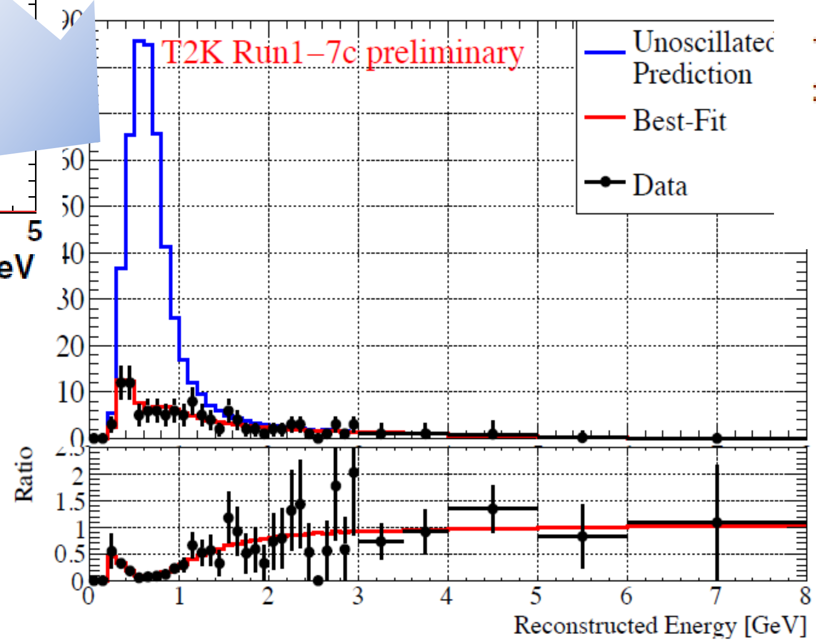
# Some highlights from LBL experiments with water Ch.

## $\nu_\mu$ disappearance

K2K, PRD 74, 072003 (2006)

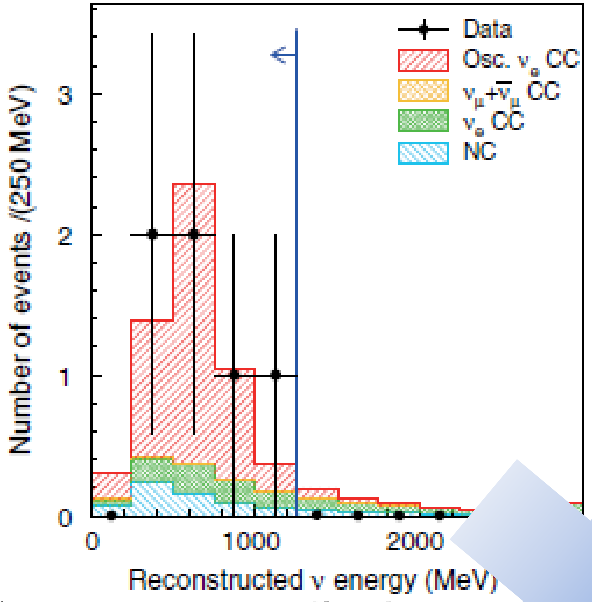



T2K, PRL 112 (2014) 181801
T2K@ICHEP 2016

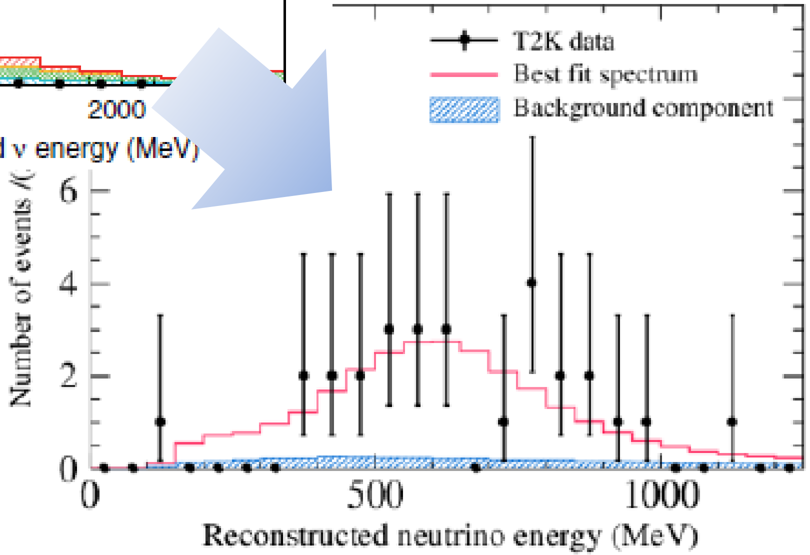



## $\nu_e$ appearance

T2K, PRL 107 (2011) 041801



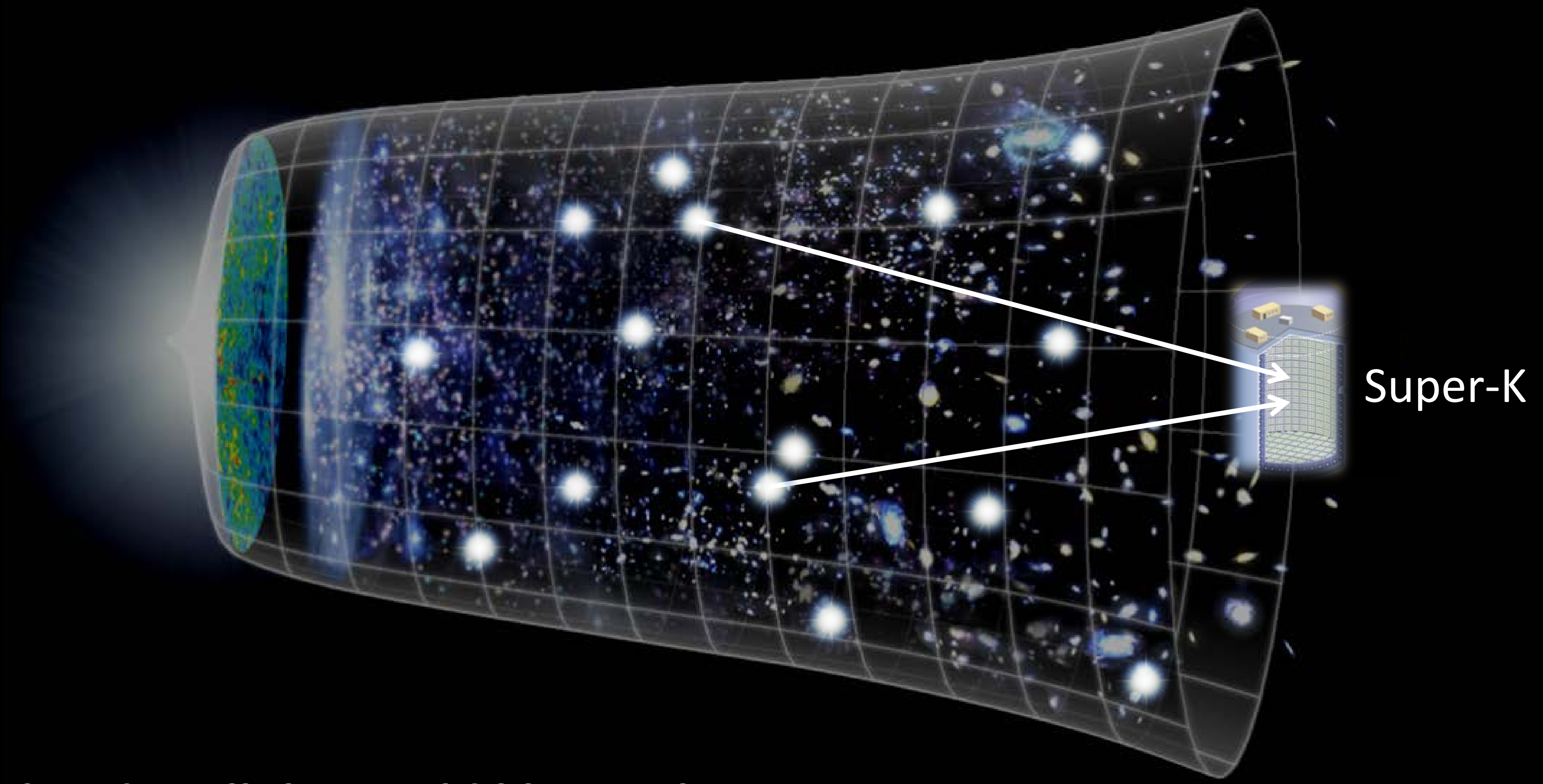

T2K, neutrino 2016




**_Water Ch. detector is proven to be a very good far detector in LBL experiments!_**

# *Detecting relic supernova neutrinos*

# *Supernova relic neutrinos*



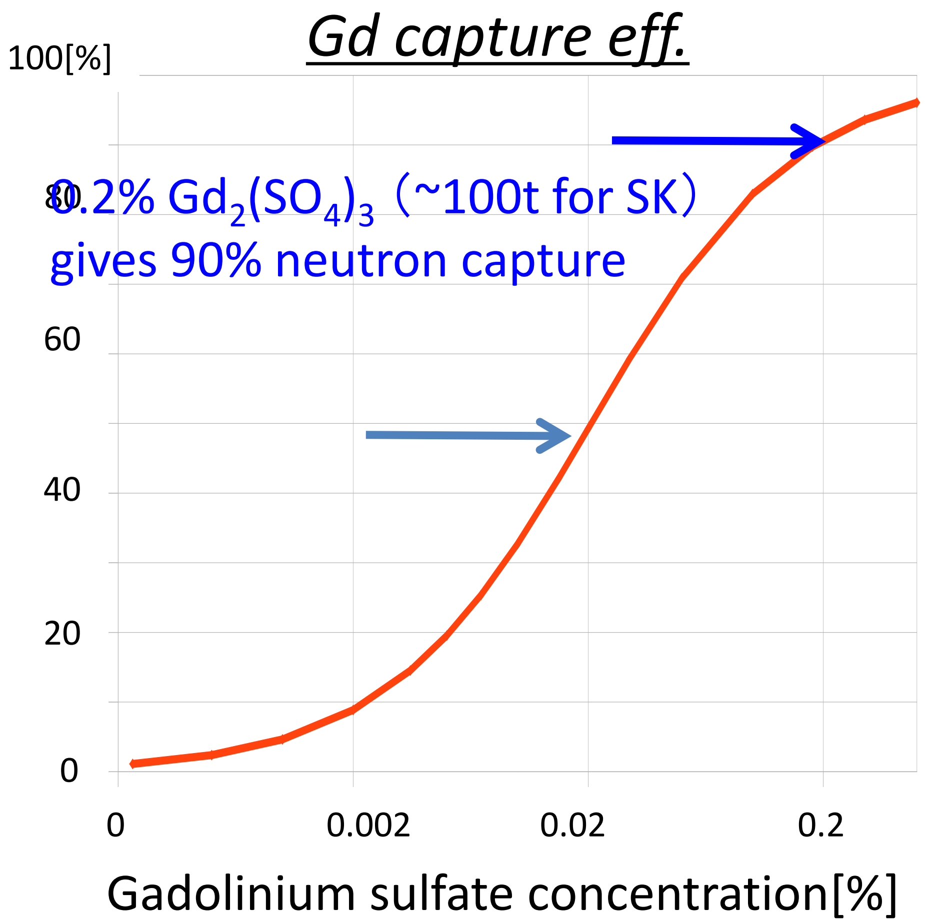

***Super-Kamiokande collab. would like to observe neutrinos produced by the Supernova explosion in the past Universe!***

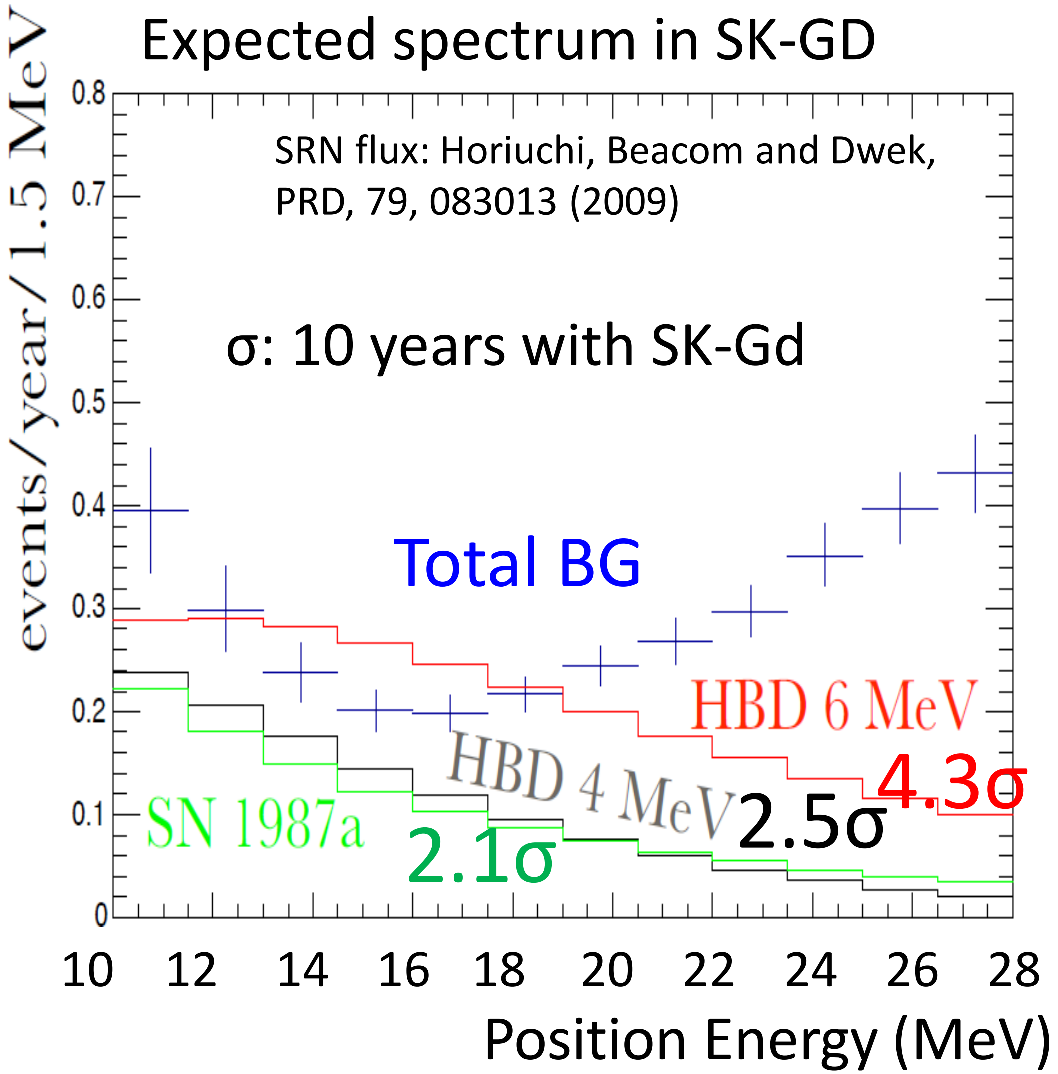
Credit: NASA/WMAP Science Team

# Detecting Supernova relic neutrinos

$\bar{\nu}_e + p \rightarrow e^+ + n$ ,
$n + Gd \rightarrow Gd + \gamma$'s (total E of $\gamma$'s ~8MeV)

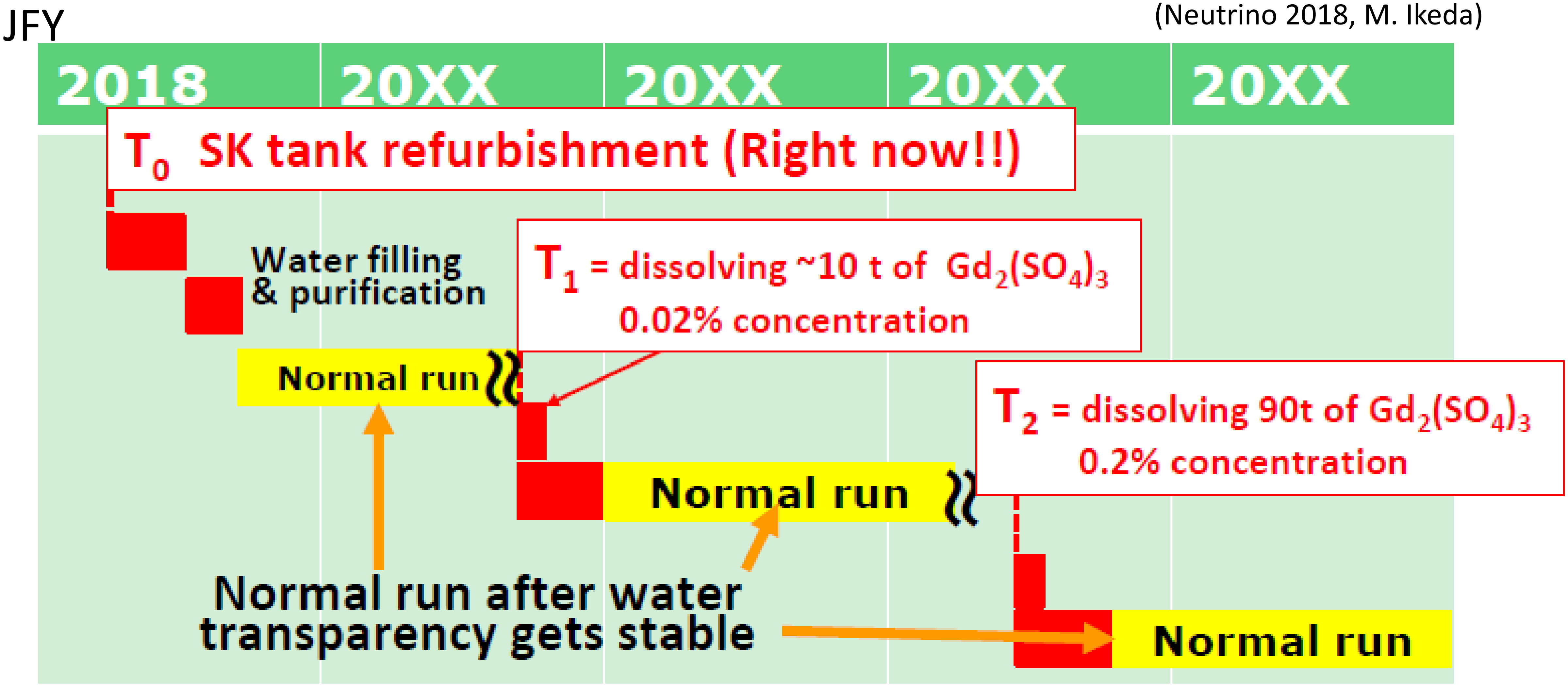
(M. Ikeda, neutrino 2018)



# Schedule of SK-Gd

(Neutrino 2018, M. Ikeda)

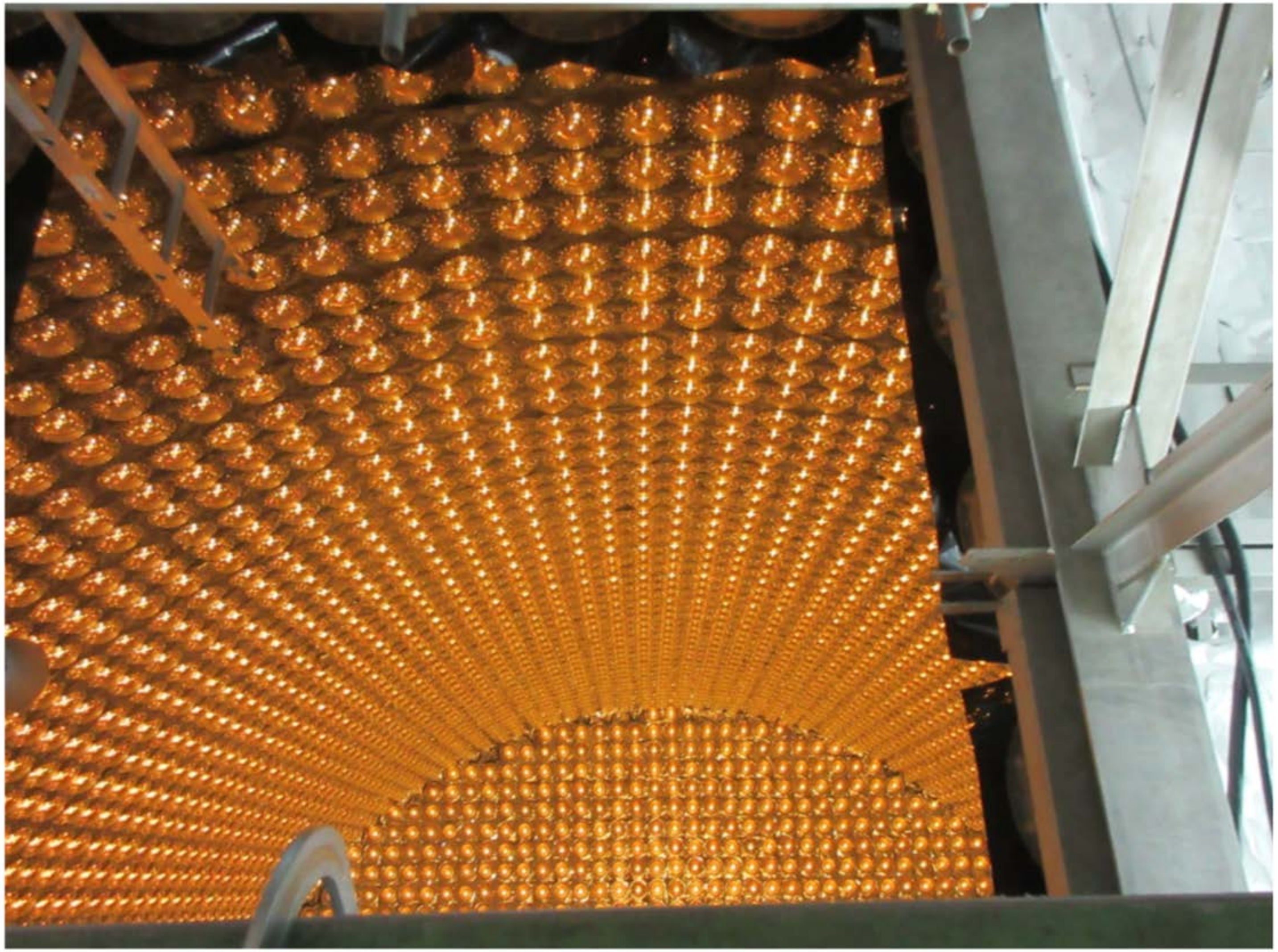



Probably, Gd (0,02%) in Super-K will be in late 2019.

# Super-Kamiokande 2018

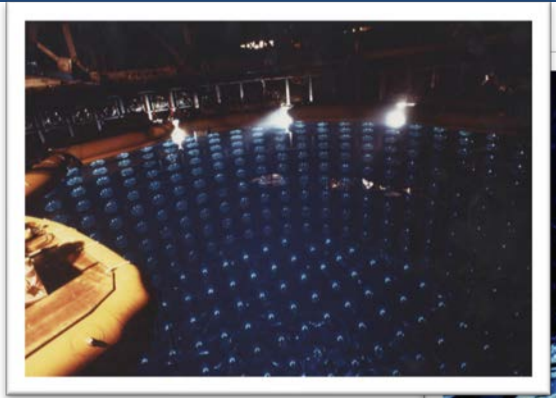
July 2018

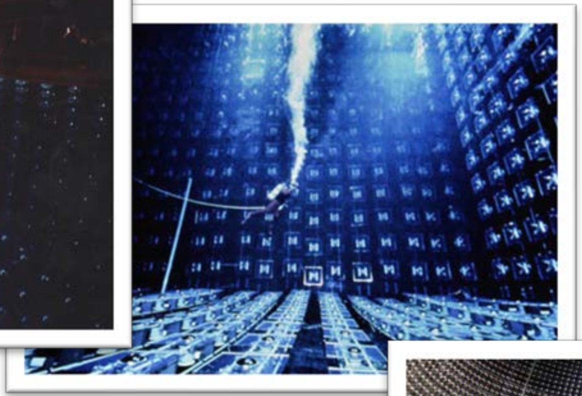
End of Aug., 2018



# *Future water Cherenkov detector*

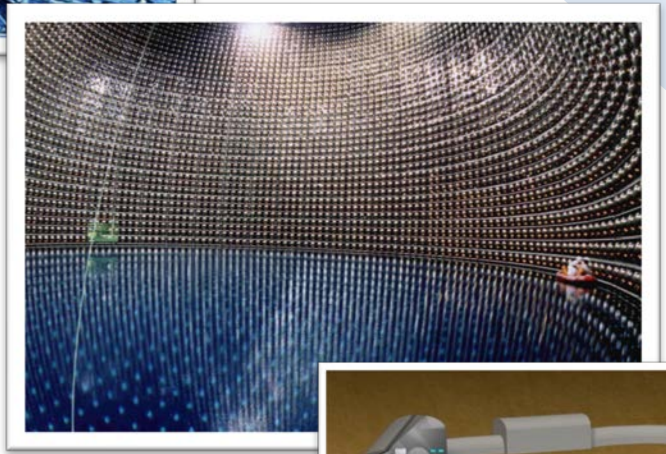
# *Hyper-K as a natural extension of (light) water Ch. detectors*





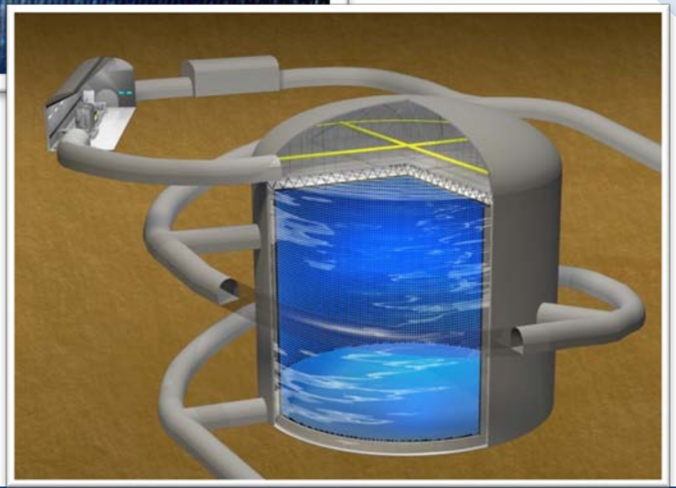
*Kamiokande & IMB*

- *Neutrinos from SN1987A*
- *Atmospheric neutrino deficit*
- *Solar neutrino (Kam)*



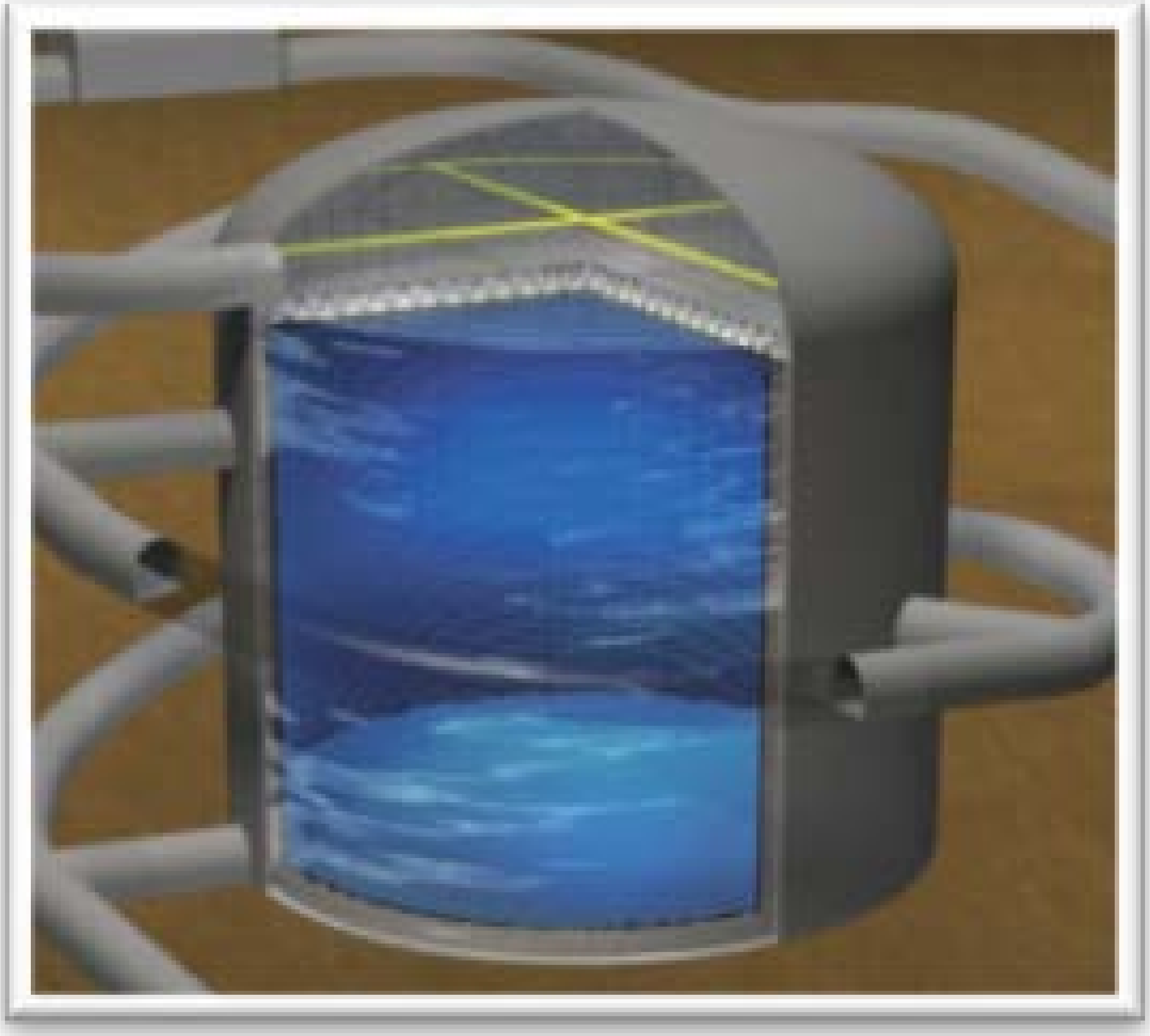
*Super-K*

- *Atmospheric neutrino oscillation*
- *Solar neutrino oscillation with SNO*
- *Far detector for K2K and T2K*



*Hyper-K*

# Hyper-K



Hyper-K detector will be used to study:

- ✓ Neutrino oscillations with J-PARC neutrino beam(1.3MW beam),
- ✓ atmospheric neutrino oscillations,
- ✓ solar neutrino oscillations
- ✓ Proton decays
- ✓ Supernova neutrino burst (multi-messenger astronomy!)
- ✓ Past supernova neutrinos
- ✓ ….

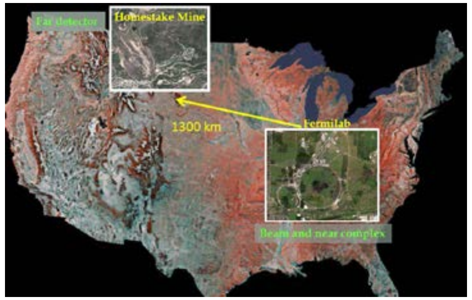
◆Φ 74 meters and H 60 meters.

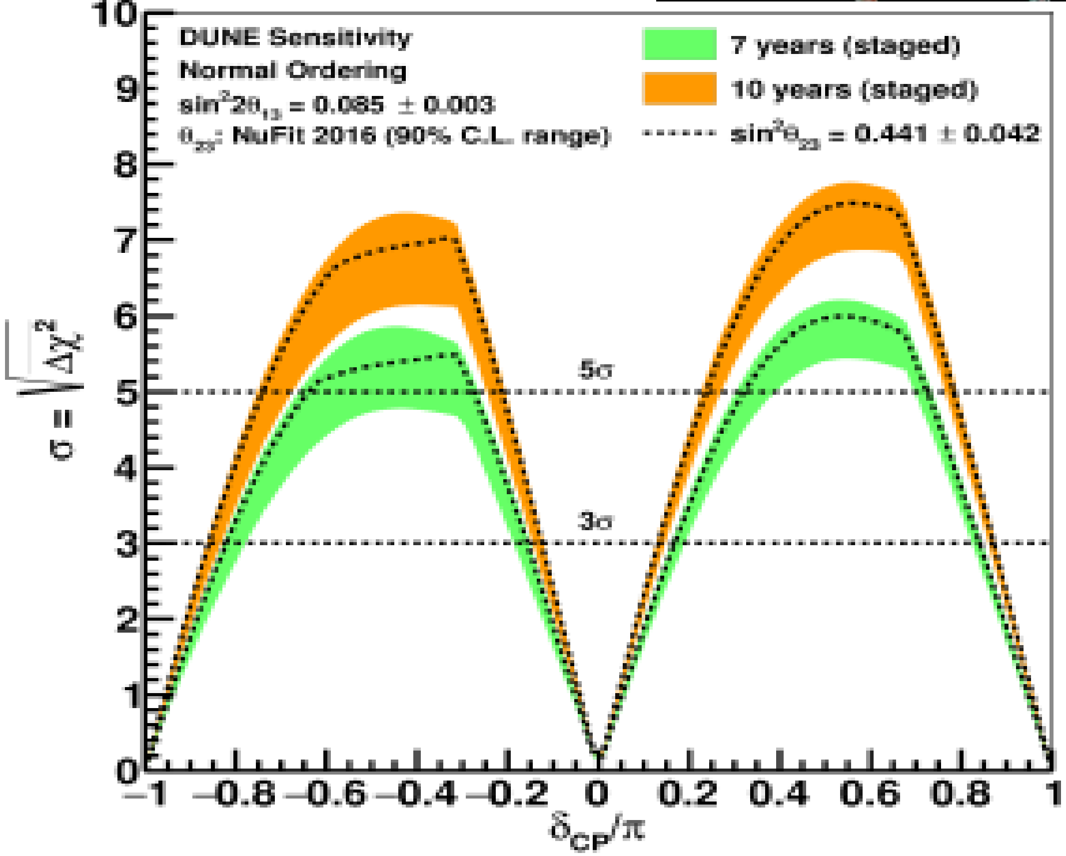
◆The total and fiducial volumes are 0.26 and 0.19 M tons, respectively.

# Sensitivities

## *DUNE*

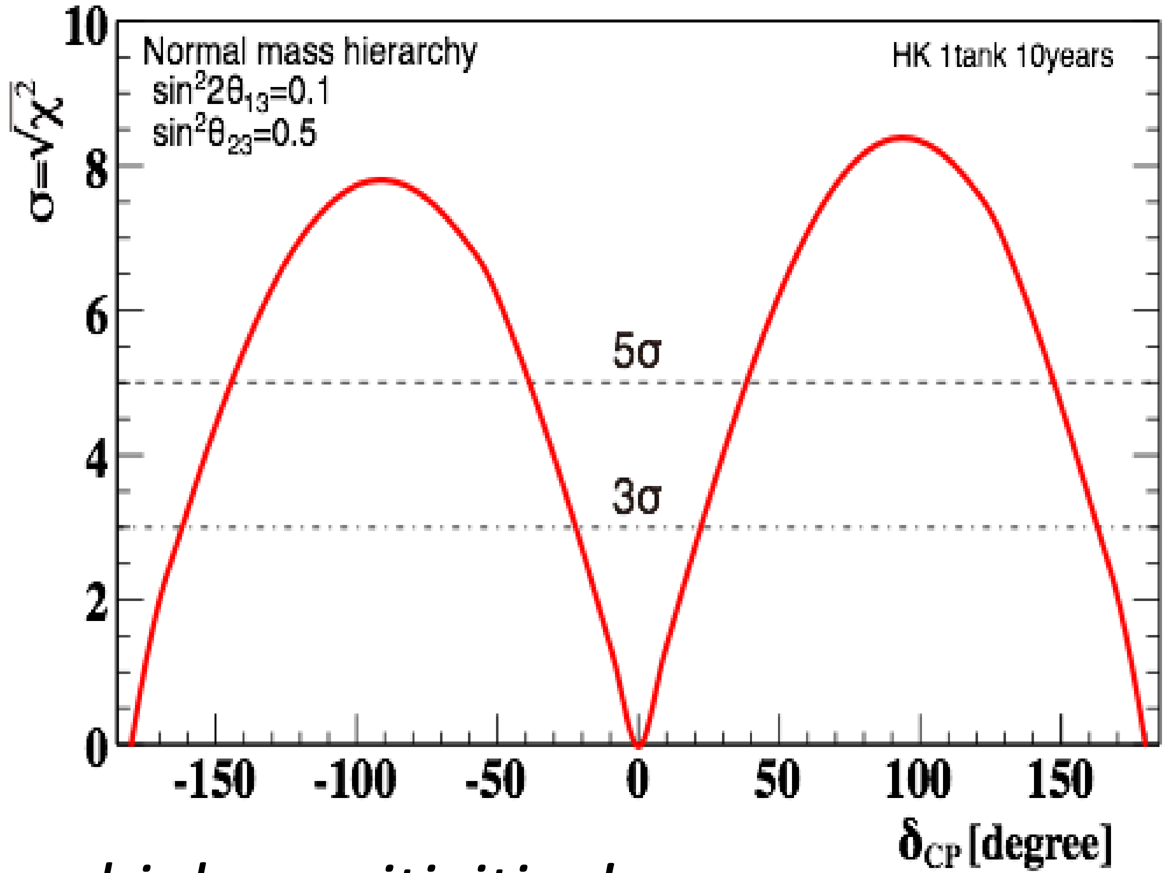
(Nu2018, E. Worcester)




## *Hyper-K*

(Nu2018, M. Shiozawa)


➔ *Both experiments have very high sensitivities!*

# *Status of Hyper-K*

- ✓ Hyper-K has been selected as one of the 7 large scientific projects in the Roadmap of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017.
- ✓ Since then, we have been discussing intensively with MEXT.
- ✓ At the end of Aug. 2018, MEXT has decided to request the budget to Ministry of Finance for “funding for feasibility study” which is equivalent to “seed funding” in some other countries. This funding is usually for 1 year (or 2 years).
- ✓ Then, the President of the Univ. of Tokyo, in recognition of both the project's importance and value both nationally and internationally, pledged to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020.

***Hyper-K construction will begin in April 2020!***

***You are most welcome to work together in Hyper-K!***

# Summary

- Water Cherenkov detectors have been playing very important roles for neutrino physics and astrophysics:
  - Kamiokande
  - IMB
  - Super-Kamiokande
  - SNO
- We would like to continue contributing to neutrino physics and astrophysics with the next generation water Cherenkov detector, Hyper-Kamiokande.