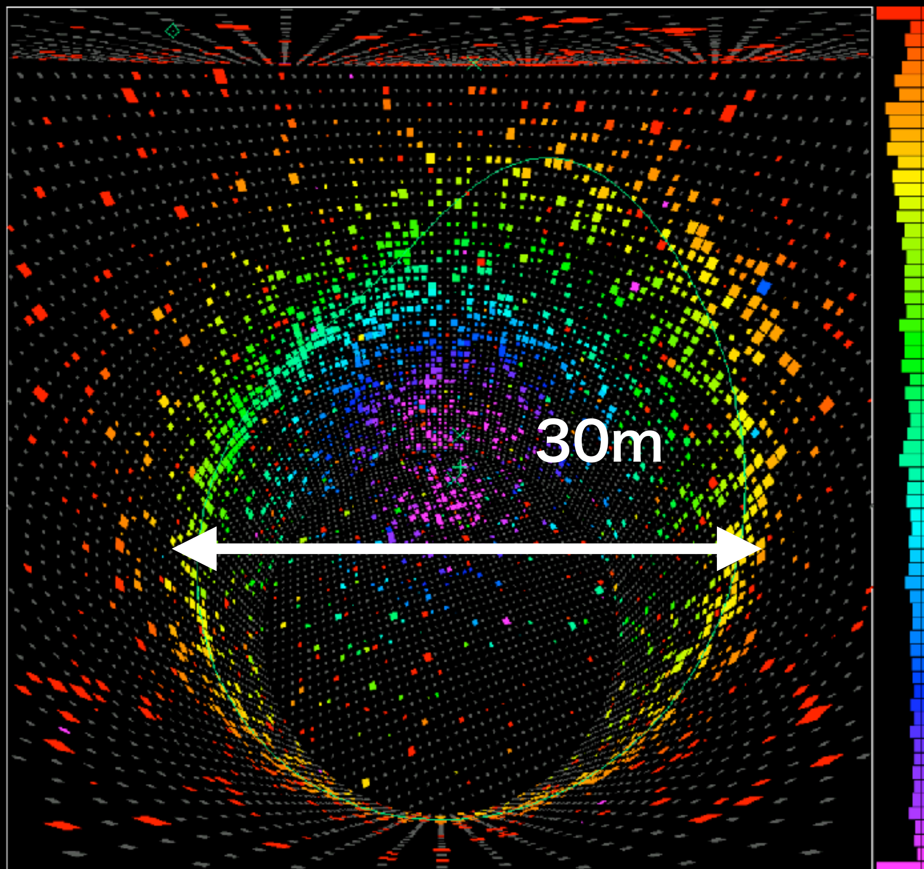


IFIRSE, ICISE Webinar 2020
August 20(Thus.)

Neutrino Physics in Japan with a gigantic detector, Super-Kamiokande

T. Nakaya (Kyoto Univ.)
on behalf of the Neutrino Group at ICISE

About us

Neutrino Group, IFIRSE, ICISE, Quy Nhon

Why neutrino physic now?

- Only palpable evidence beyond the Standard Model of elementary particles
- Guarantee the breakthroughs: CP violation, neutrino mass hierarchy and more
- International roadmap is clearly defined for at least 20 years

Why T2K experiment?

- Flagship in neutrino experiments
- Breakthrough prize in 2016
- Provide first hint on CP violation in the neutrino sector
- Extension proposed up to 2026 for CP violation measurement

Why joining us?

- Enjoy T2K physics with ~500 collaborators from 12 countries
- We are young, dynamic, ambitious, curiosity-driven
- Strong support from ICISE, Japan, International scientific committee

Wanna to enjoy neutrino physics, beach life in ICISE & Sakura in Japan?
Join US now!!!

ICISE July 17th 2017, MOU Signing. From right to left: Prof. Makota Miura (ICRR, Univ. of Tokyo), Prof. Atsumu Suzuki (Kobe Univ.), Prof. Yuichi Oyama (KEK/J-PARC), Prof. Tsuyoshi Nakaya (Kyoto Univ.), Jean T. T. Van (ICISE director), Prof. Nguyen T. H. Van (IFIRSE & IOP), Dr. Cao V. Son (KEK/J-PARC, IFIRSE affiliated)

Group photo July 2018

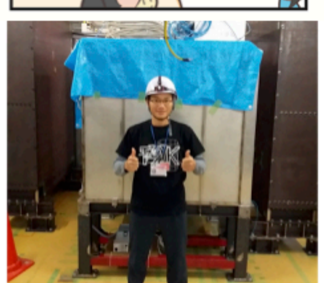
Visit: https://ifirse.icise.vn/nugroup/

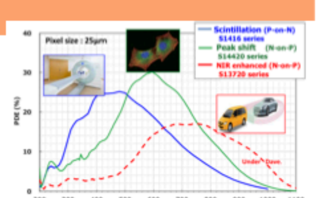
As T2K collaborator

- We officially joined T2K in Oct. 2017 as 12th country
- What do we involve: Neutrino event generator, Neutrino oscillation analysis and building T2K sub- Near detector
- In near future, we will seamlessly join Hyper-Kamiokande, next generation of neutrino experiment

Lab building at ICISE

- We have test bench for studying the Multi-pixel Photon Counter (MPPC) and scintillation materials for neutrino and dark matter detector
- A long-term project to build a real lab at ICISE





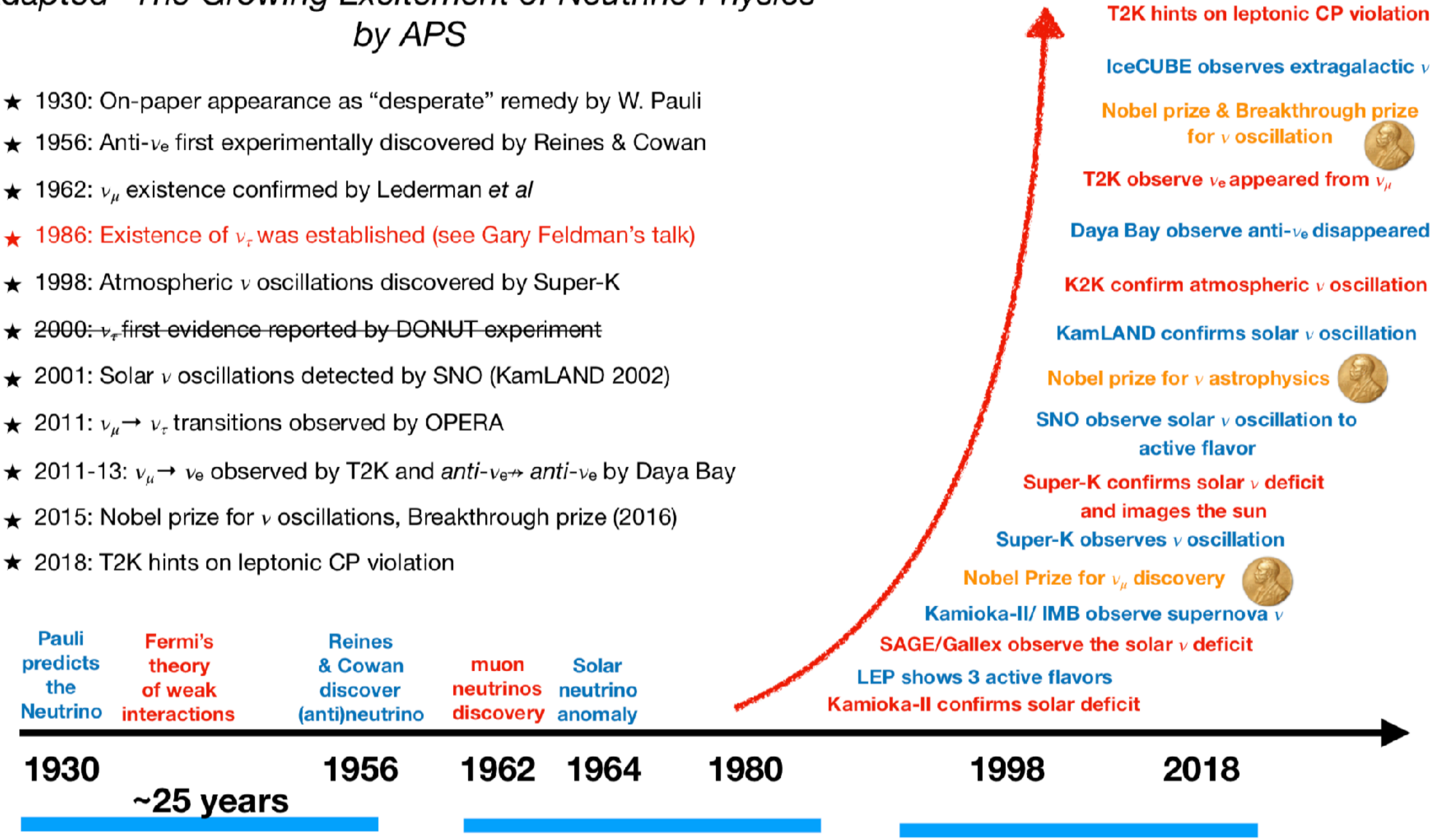
*We need you to build something much **bigger**!!!*

Contact: nhvan@ifirse.icise.vn cvson@ifirse.icise.vn

https://ifirse.icise.vn/nugroup/

Adapted "The Growing Excitement of Neutrino Physics " by APS

- ★ 1930: On-paper appearance as "desperate" remedy by W. Pauli
- ★ 1956: Anti-ν_e first experimentally discovered by Reines & Cowan
- ★ 1962: ν_μ existence confirmed by Lederman *et al*
- ★ 1986: Existence of ν_τ was established (see Gary Feldman's talk)
- ★ 1998: Atmospheric ν oscillations discovered by Super-K
- ★ ~~2000: ν_τ first evidence reported by DONUT experiment~~
- ★ 2001: Solar ν oscillations detected by SNO (KamLAND 2002)
- ★ 2011: $\nu_\mu \rightarrow \nu_\tau$ transitions observed by OPERA
- ★ 2011-13: $\nu_\mu \rightarrow \nu_e$ observed by T2K and *anti*-$\nu_e \nrightarrow$ *anti*-ν_e by Daya Bay
- ★ 2015: Nobel prize for ν oscillations, Breakthrough prize (2016)
- ★ 2018: T2K hints on leptonic CP violation



Nobel Prizes for neutrino research

1. In 1988, "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino", Leon M. Lederman, Melvin Schwartz and Jack Stecinberger shared the first Nobel Prize relating to neutrino research
2. In 1995, Frederick Reines was received the Nobel Prize for detecting the first neutrino in 1956
3. In 2002, Raymond Davis Jr. and Masotoshi Koshiba shared the Nobel Prize for detecting cosmic neutrinos
4. In 2015, Takaaki Kajita and Arthur B. Mc Donald have received the Nobel Prize for discovery of neutrino oscillation, showing that neutrinos have mass.

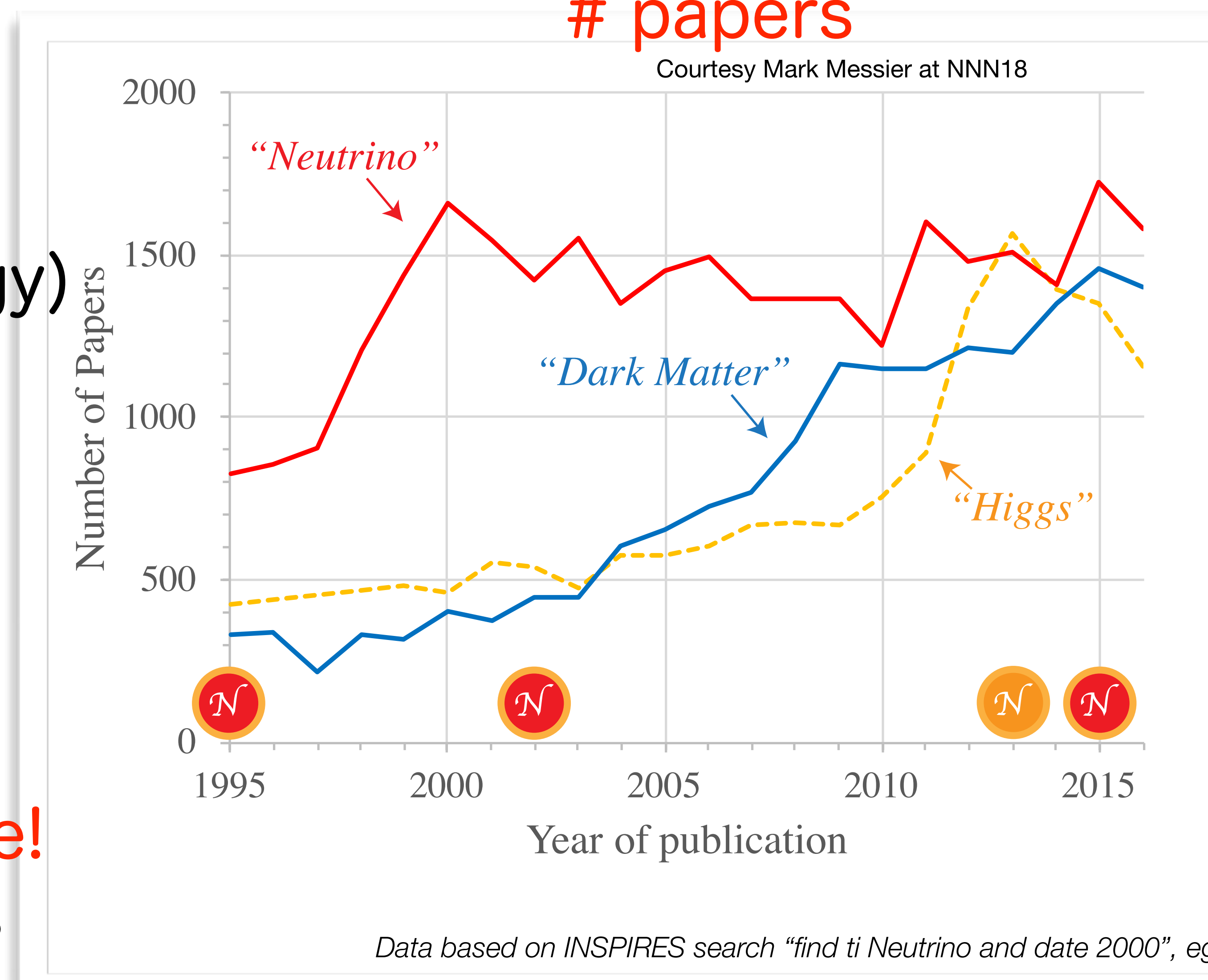
Introduction

Big problems in Particle Physics

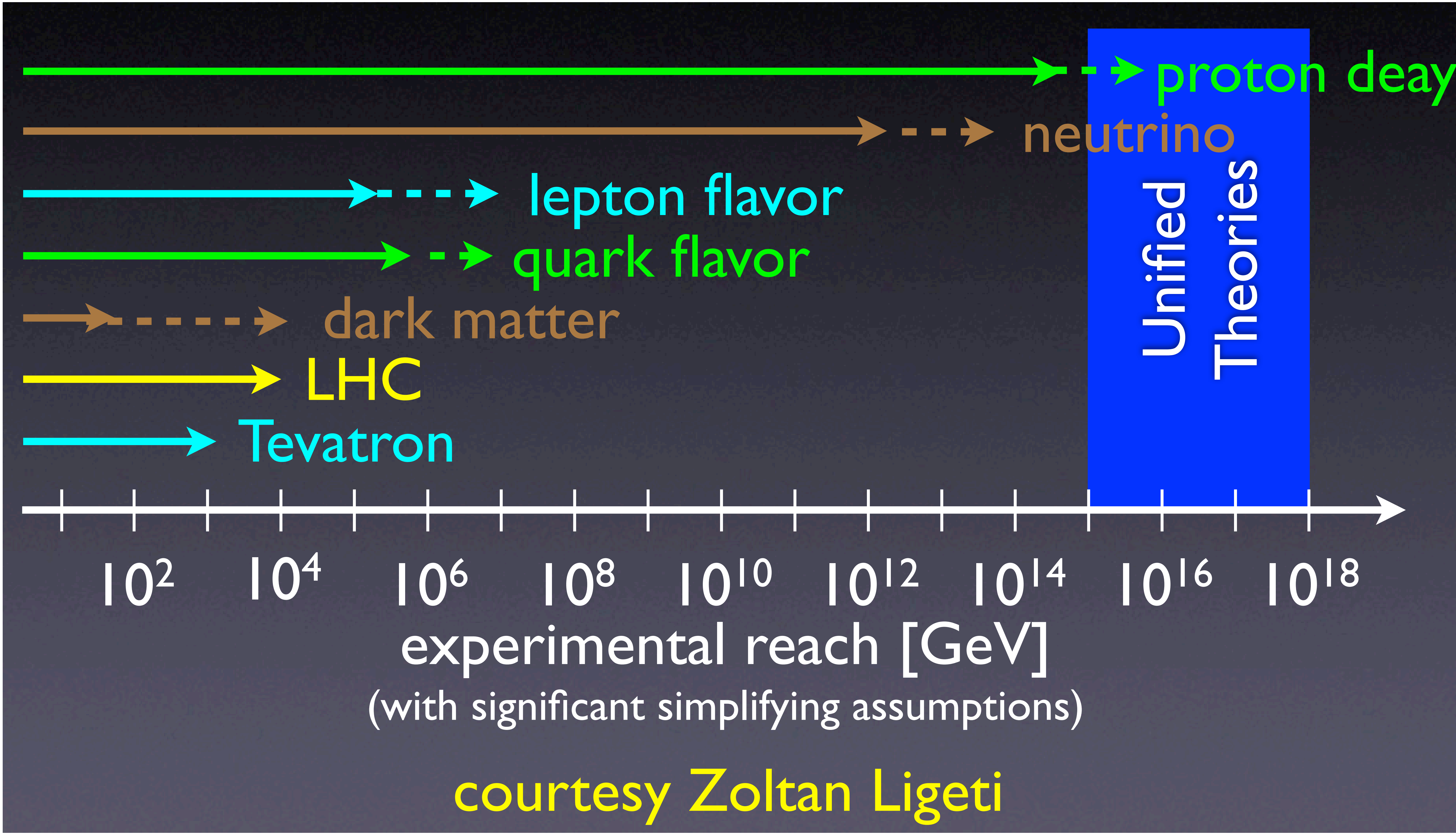
- Unification: Unification of forces [and particles]
- Origin of neutrino mass
- Family structure (3 families in quarks and leptons)
- Imbalance between matter and anti-matter (almost no anti-matters in our universe)
- Dark Matter
- Accelerating Universe (Dark Energy)
- Inflation

➡ Unknown the new energy scale!

papers



Explore New Physics



History of neutrinos in Japan

ν oscillation

ν astronomy

- Supernova ν
- Solar ν

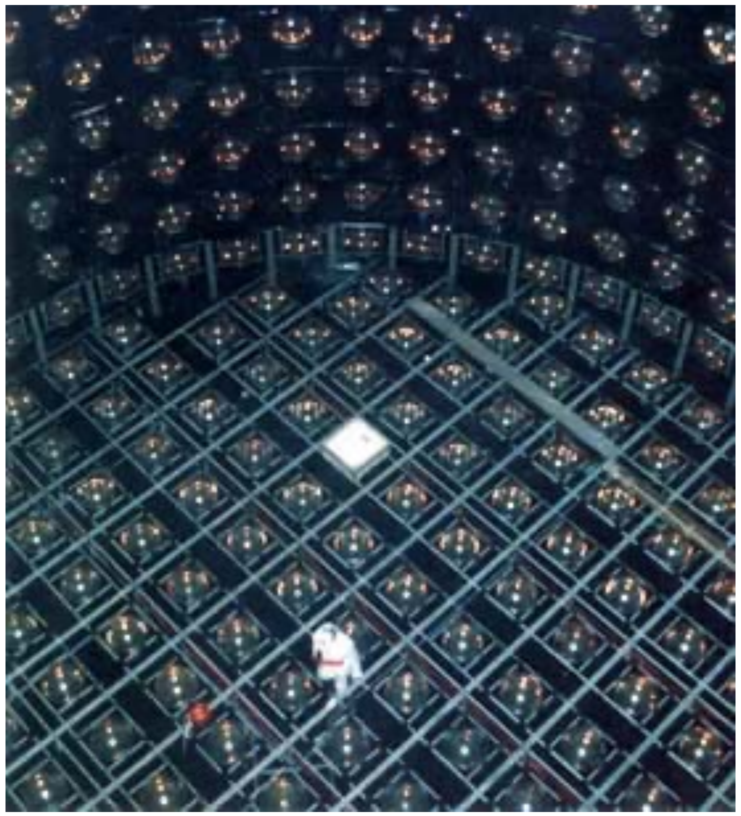
- Atmospheric ν
- Solar ν

- 6quarks

CP

- Atmospheric ν
- Accelerator ν

Kamioka
3rd generation water Cherenkov detectors

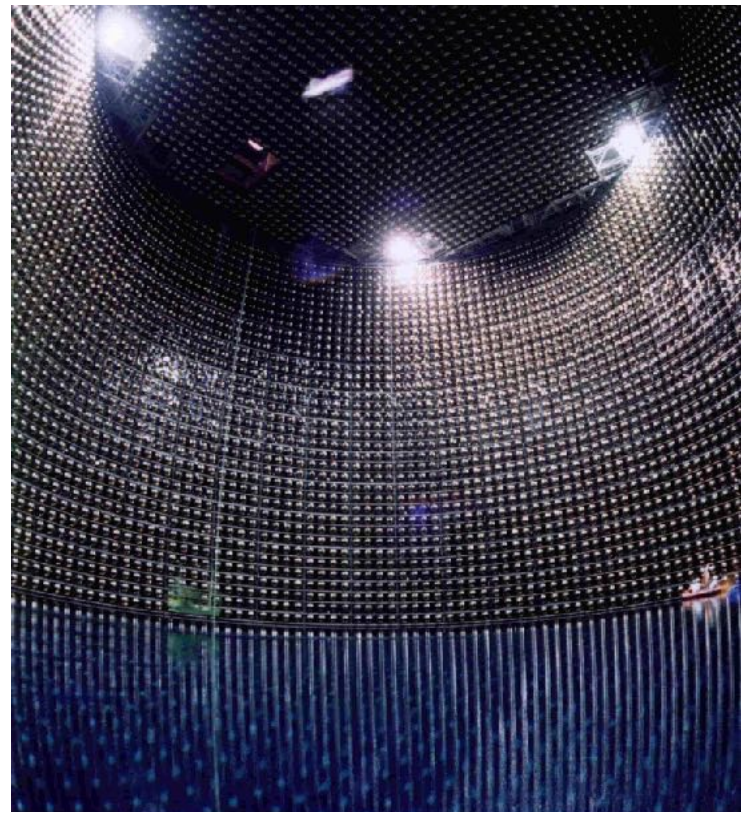


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino "anomaly"
- Supernova 1987A

Birth of neutrino astrophysics

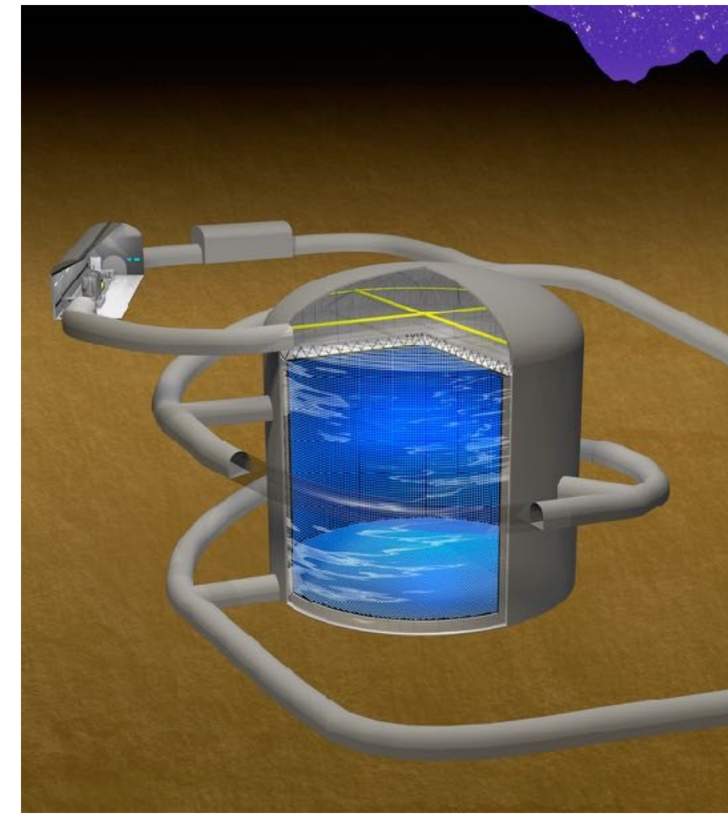


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - ➢ All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



Hyper-Kamiokande

(start operation in 2027)

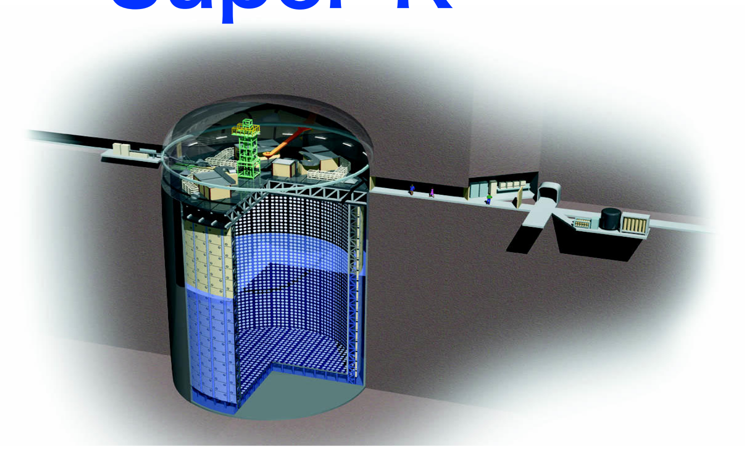
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

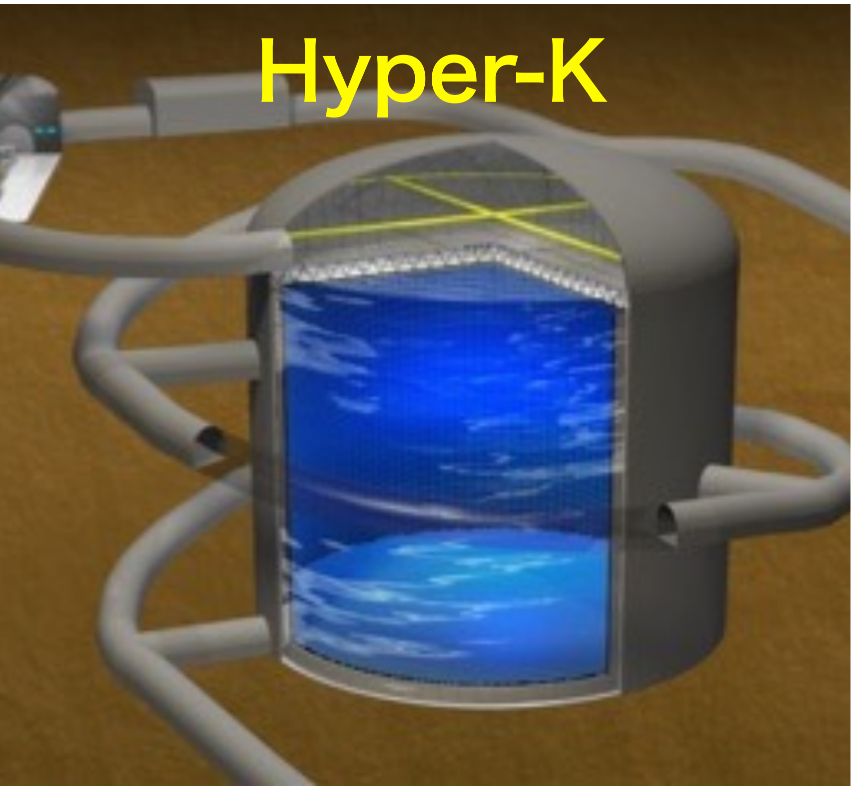
Neutrino Beams

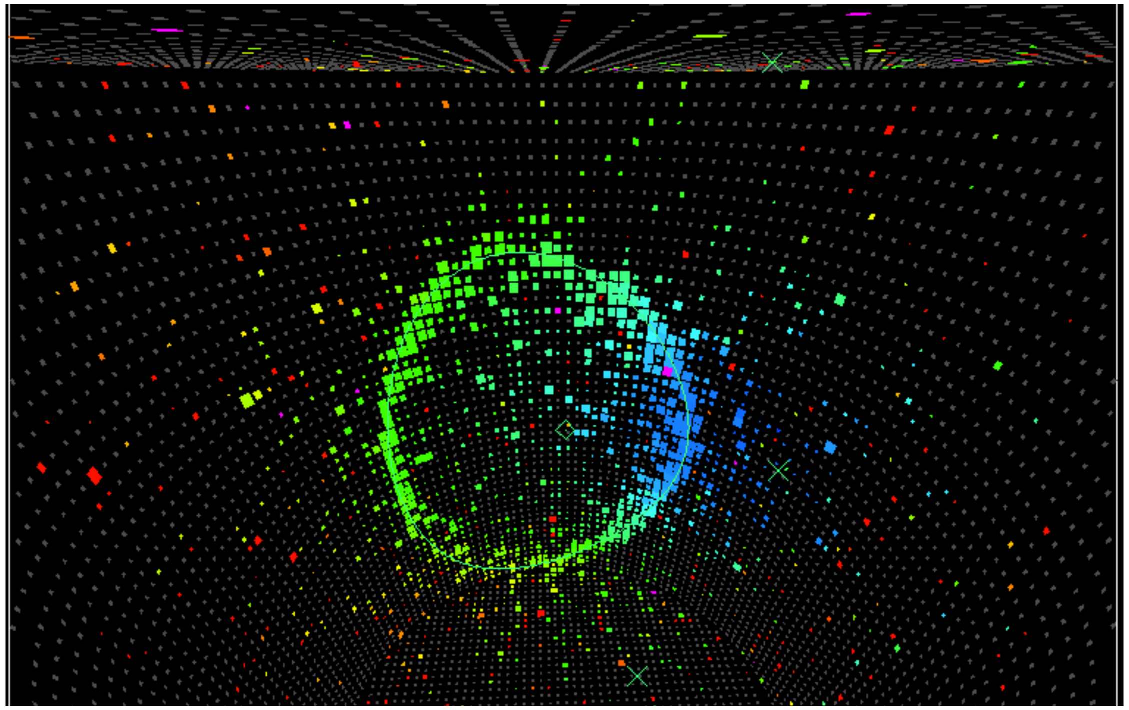
Gigantic detectors with the world-most intense neutrino beam

Super-K



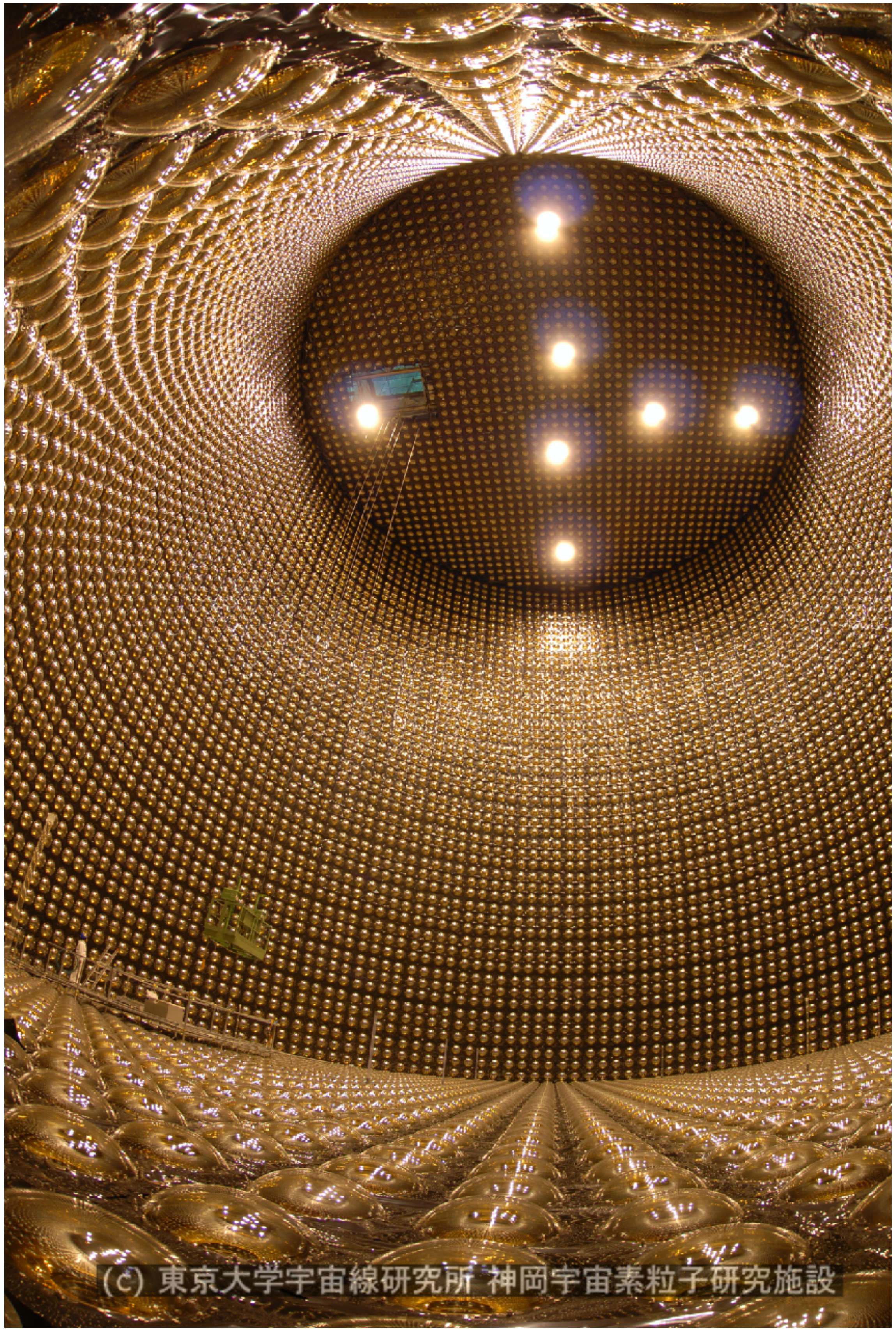
- 500 kW (today)
- ~1MW (2023)
- 1.3 MW (2026)



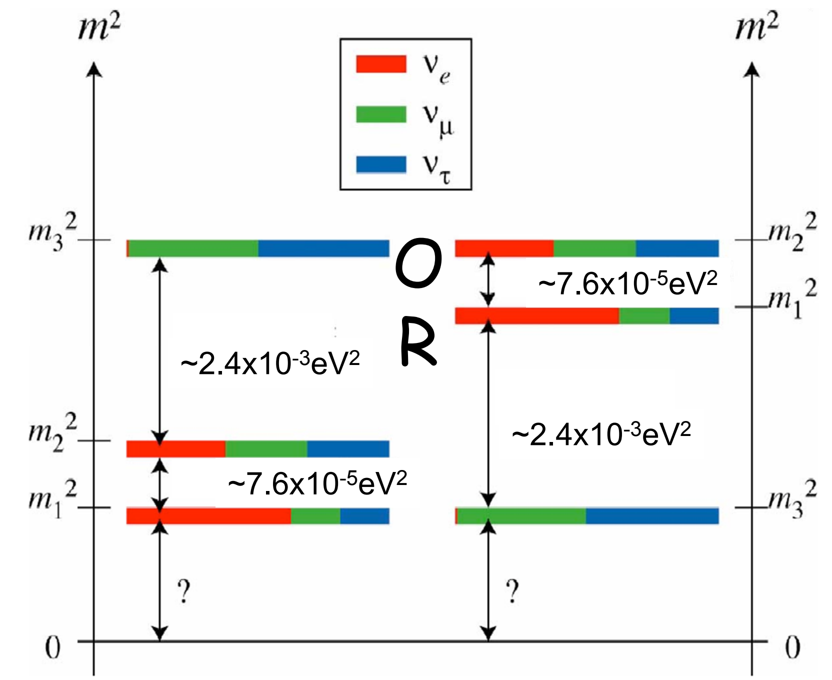


- 22.5 kton (Super-K, ~2027)
- 190 kton (Hyper-K, 2027~)

Super-Kamiokande



Neutrino Oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar, Reactor

Atmospheric, Accelerator

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
Accelerator

Accelerator
Reactor
Atmospheric

Solar
Reactor

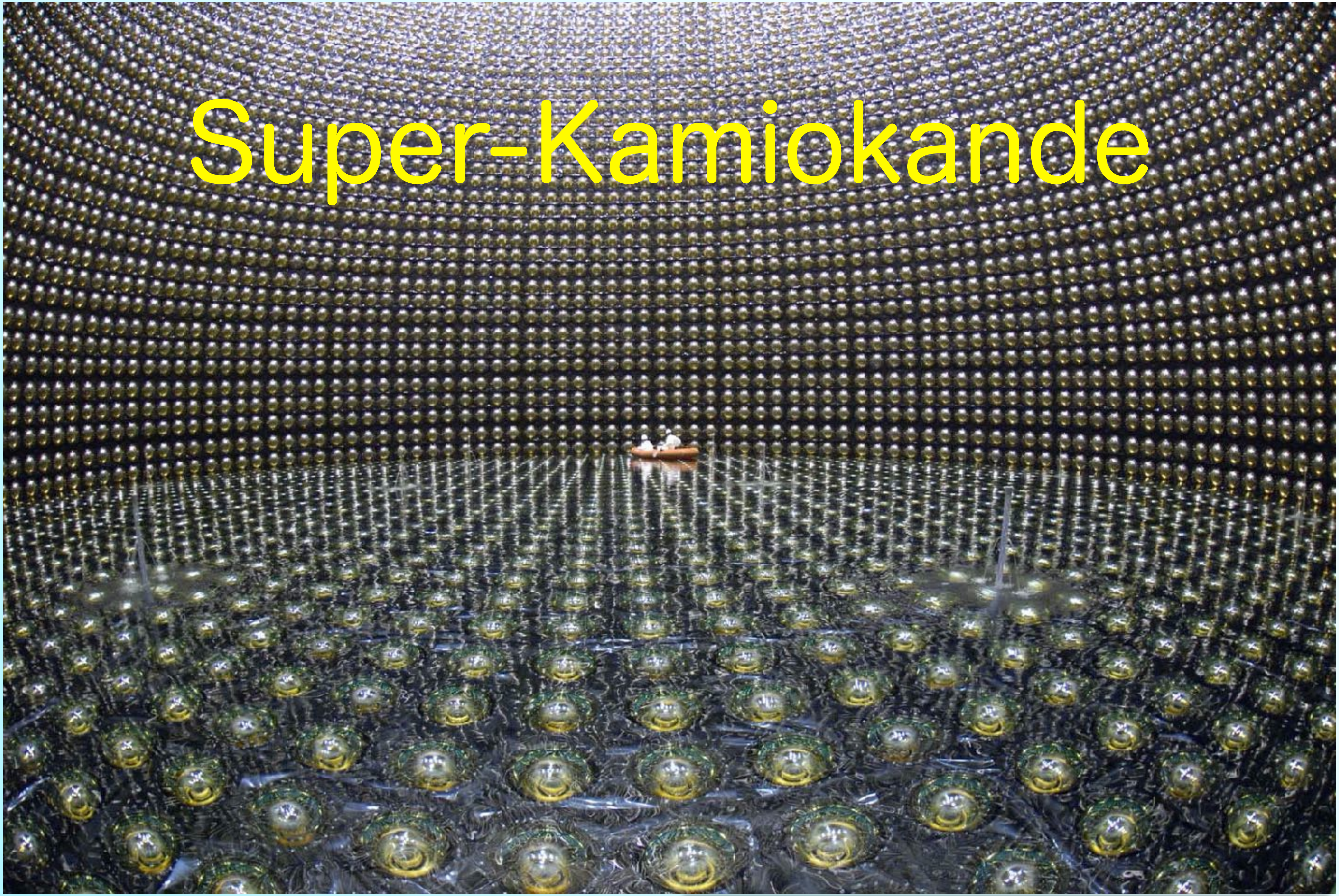
$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$\delta\sim -\pi/2$?

$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

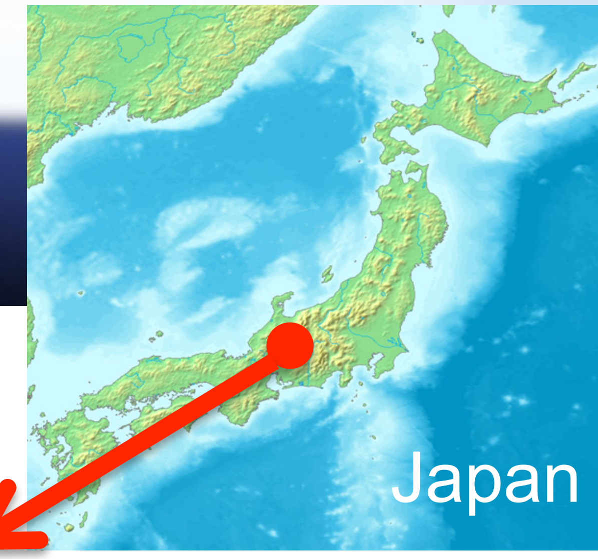
$\delta=60°$

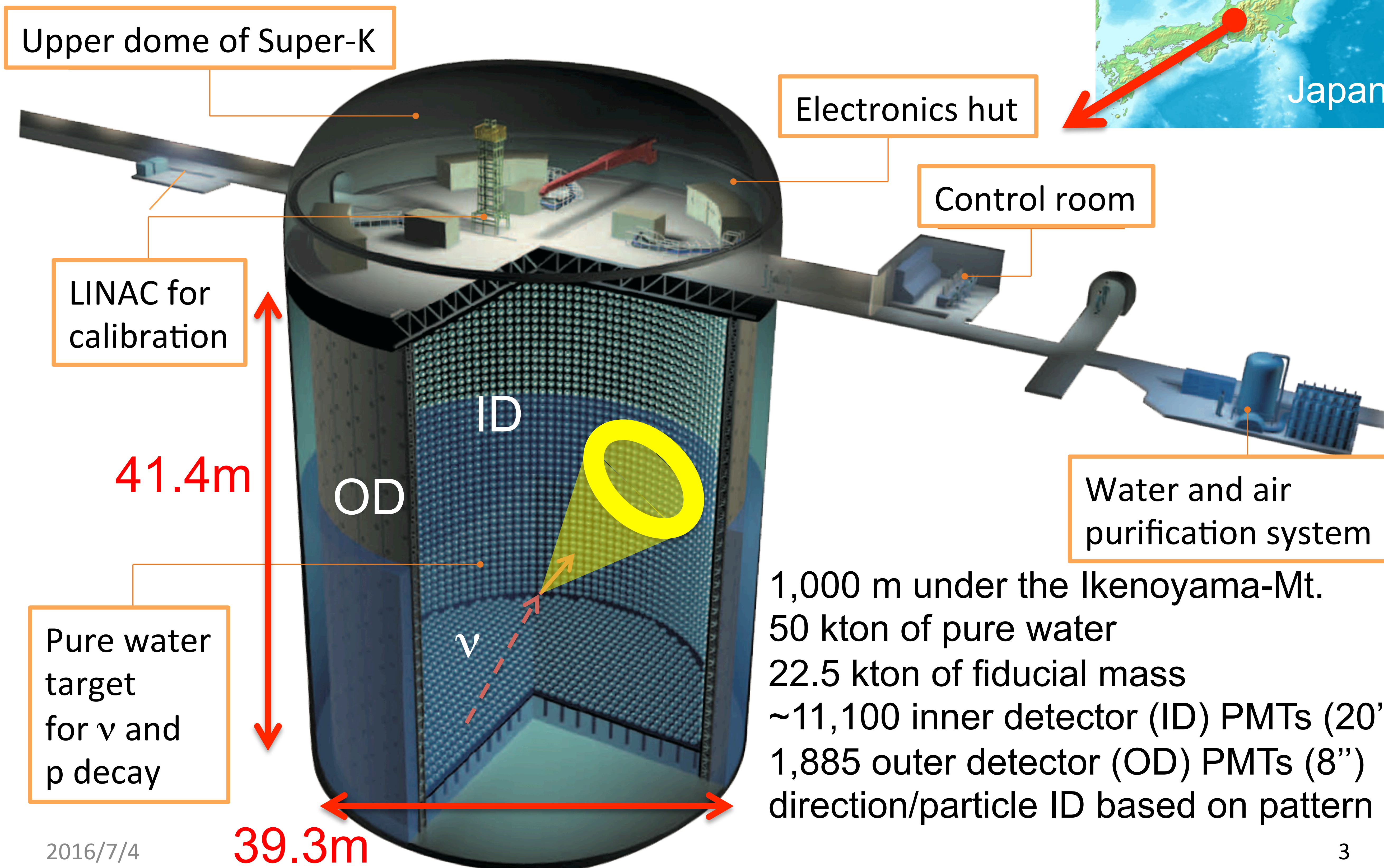
- Unknown in Neutrino oscillations
  - Mass Hierarchy： $m_1 < m_3$ or $m_1 < m_3$
  - CP violation： δ_{CP}



https://youtu.be/KJj2PusnkaQ

Super-Kamiokande detector





1,000 m under the Ikenoyama-Mt.
50 kton of pure water
22.5 kton of fiducial mass
~11,100 inner detector (ID) PMTs (20")
1,885 outer detector (OD) PMTs (8")
direction/particle ID based on pattern

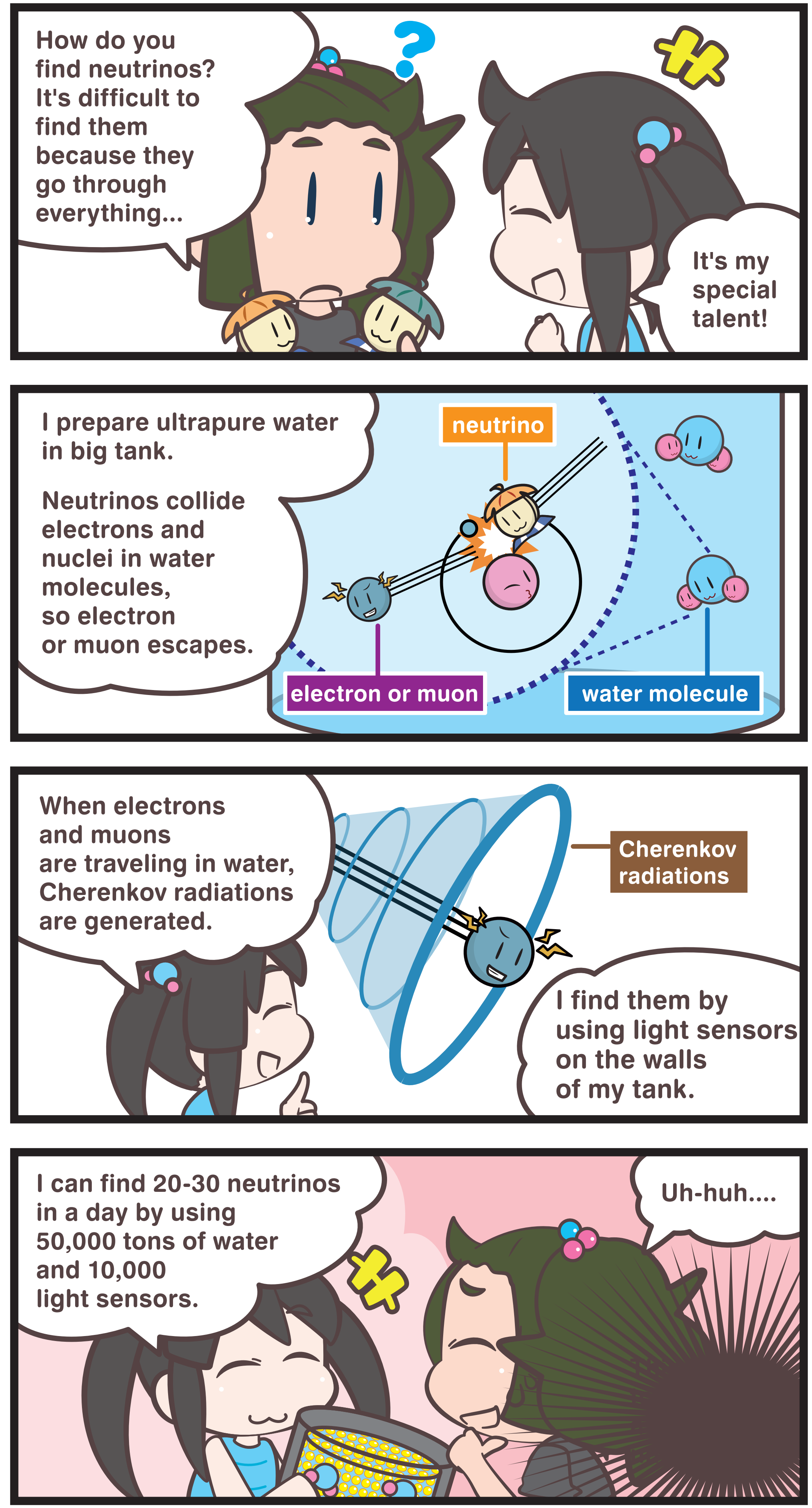
The Super-Kamiokande Collaboration

~190 collaborators from 49 institutes in 10 countries

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
Imperial College London, UK
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
Queen Mary University of London, 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
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
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

2

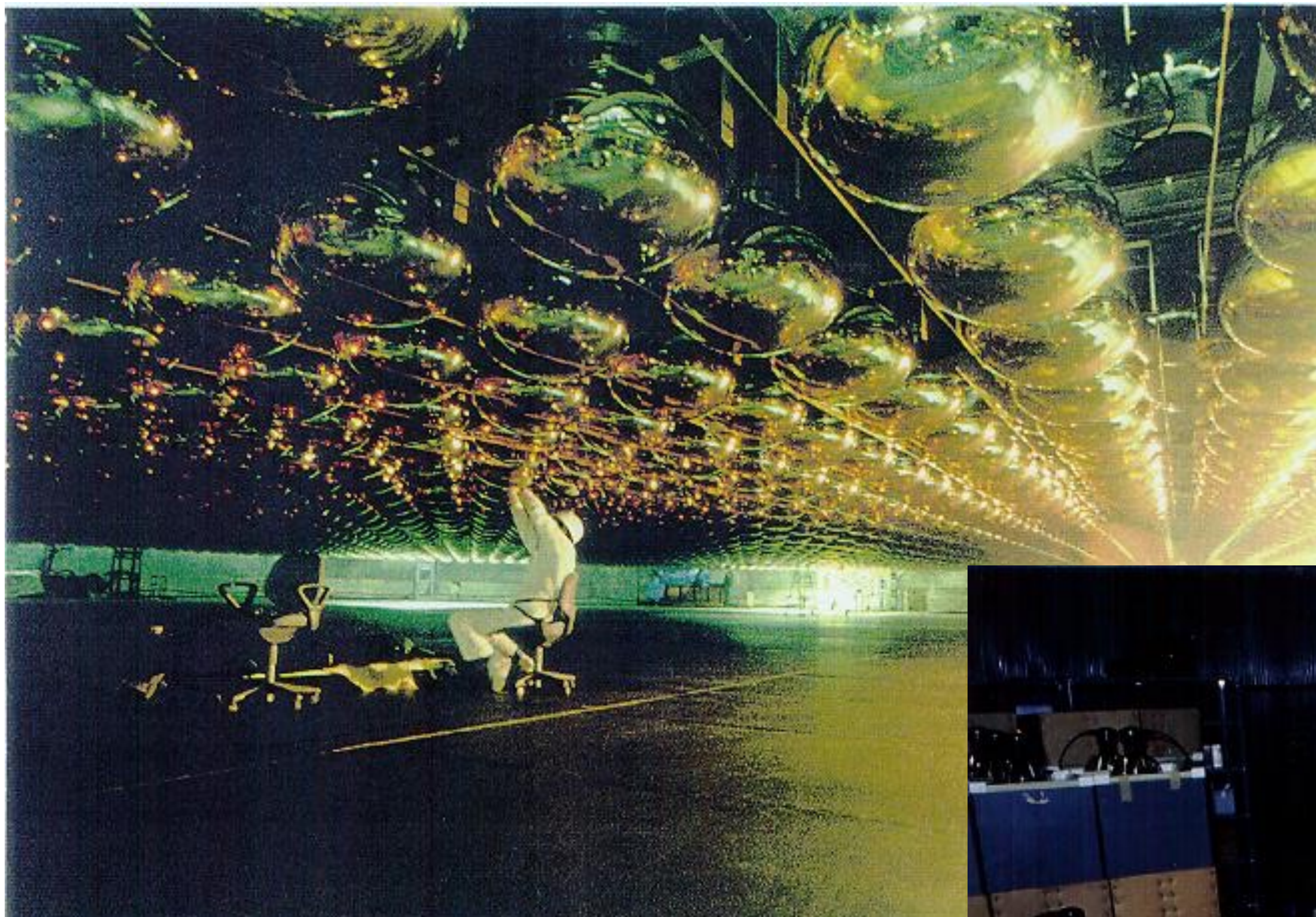
How to find neutrinos



Gigantic tank: It is filled with 50,000 tons of ultra-pure water. The bigger it is, the more neutrinos can be detected.

A lot of light sensors: Light sensors called photomultiplier tubes (PMTs). There are 11,129 sensors inside the tank.

Eyes of Super-Kamiokande



50cm PMT

10,000

by M. Nakahata@WIN2019

History of Discoveries at Super-K

1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019

SK Start

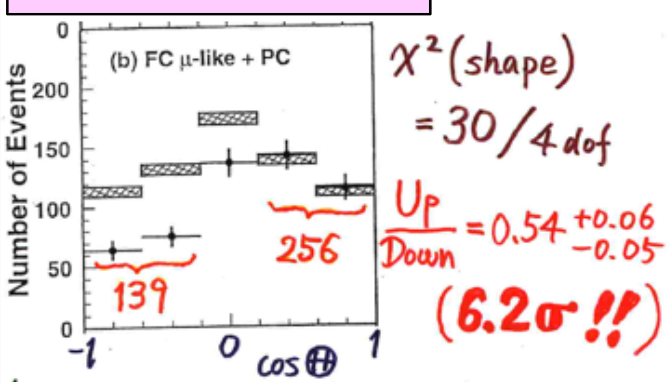
K2K start

T2K Start

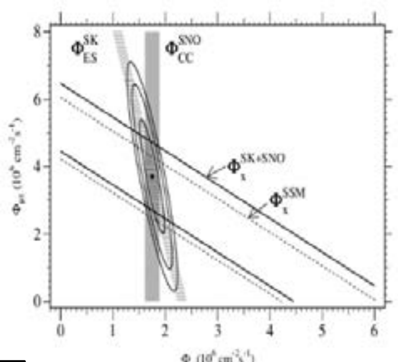
SK-Gd

Hope more discoveries

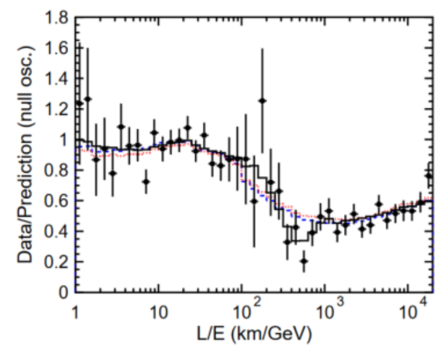
Discovery of atmospheric ν oscillation



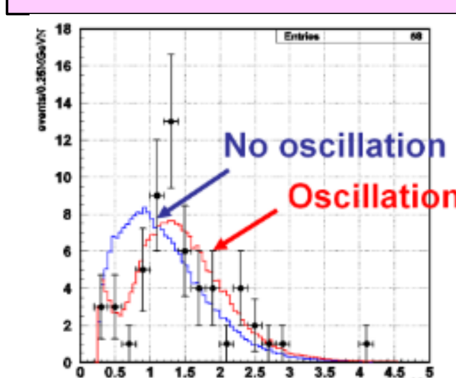
Discovery of solar ν oscillation



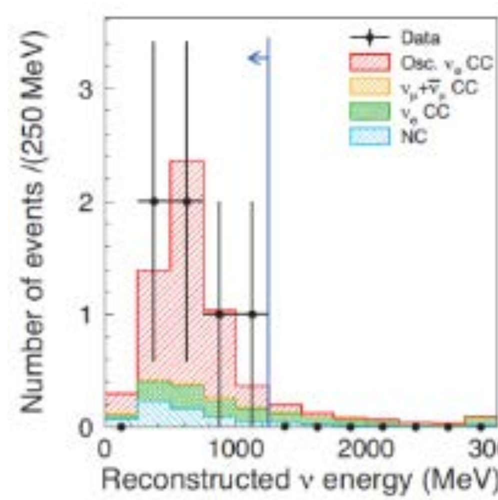
Discovery of oscillatory signature (atm.ν)



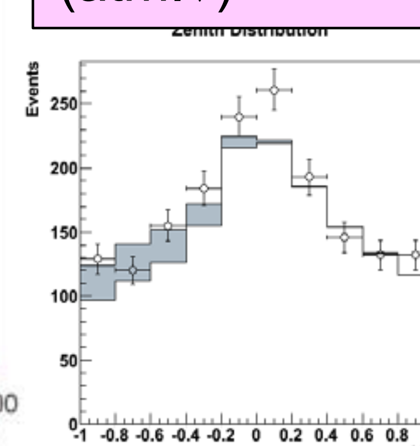
Discovery of ν oscillation by K2K



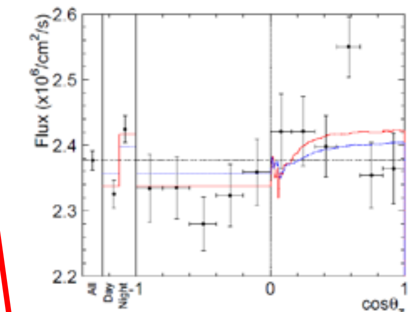
Discovery of ν_e appearance by T2K



Discovery of ν_τ appearance (atm.ν)



Discovery of day/night effect



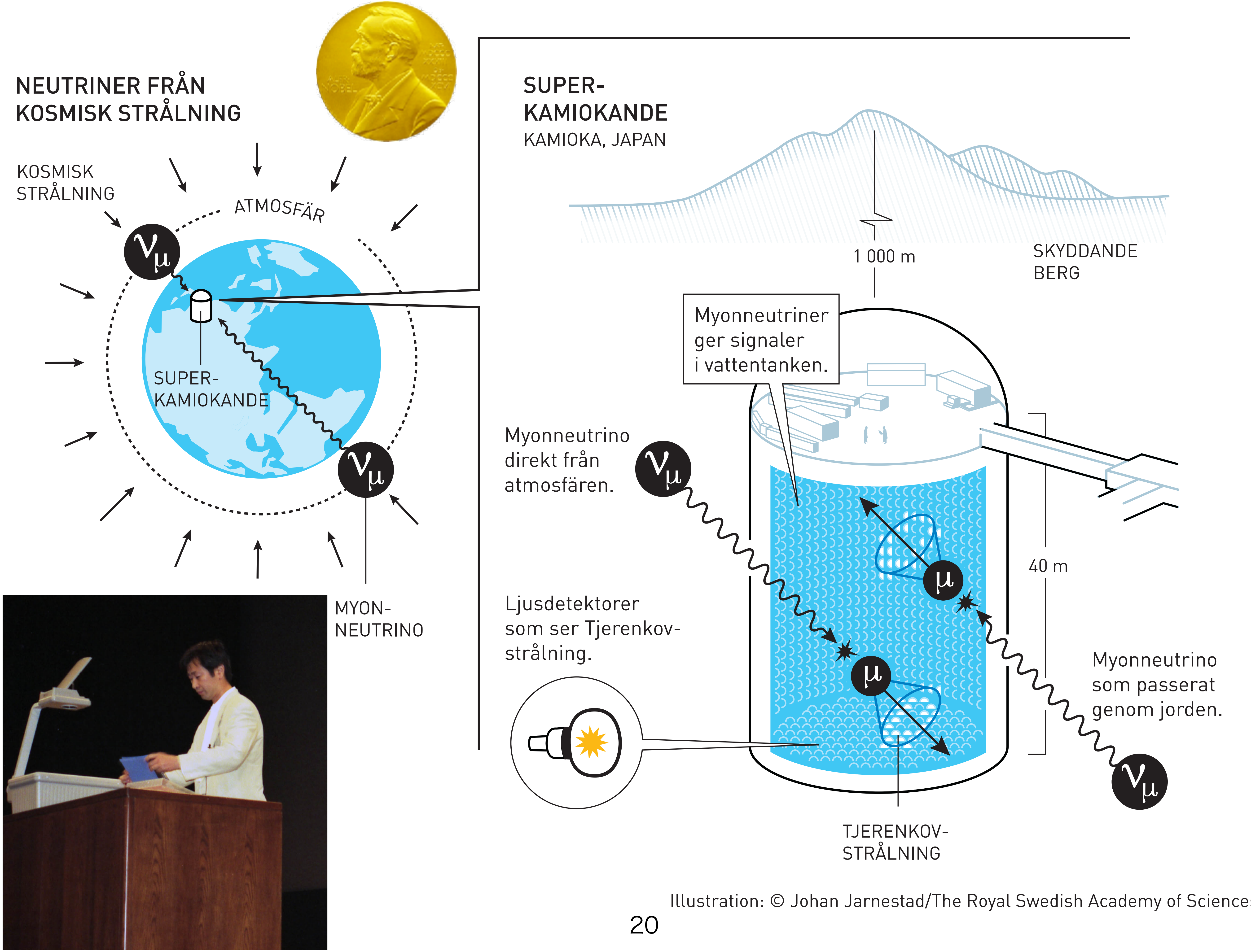
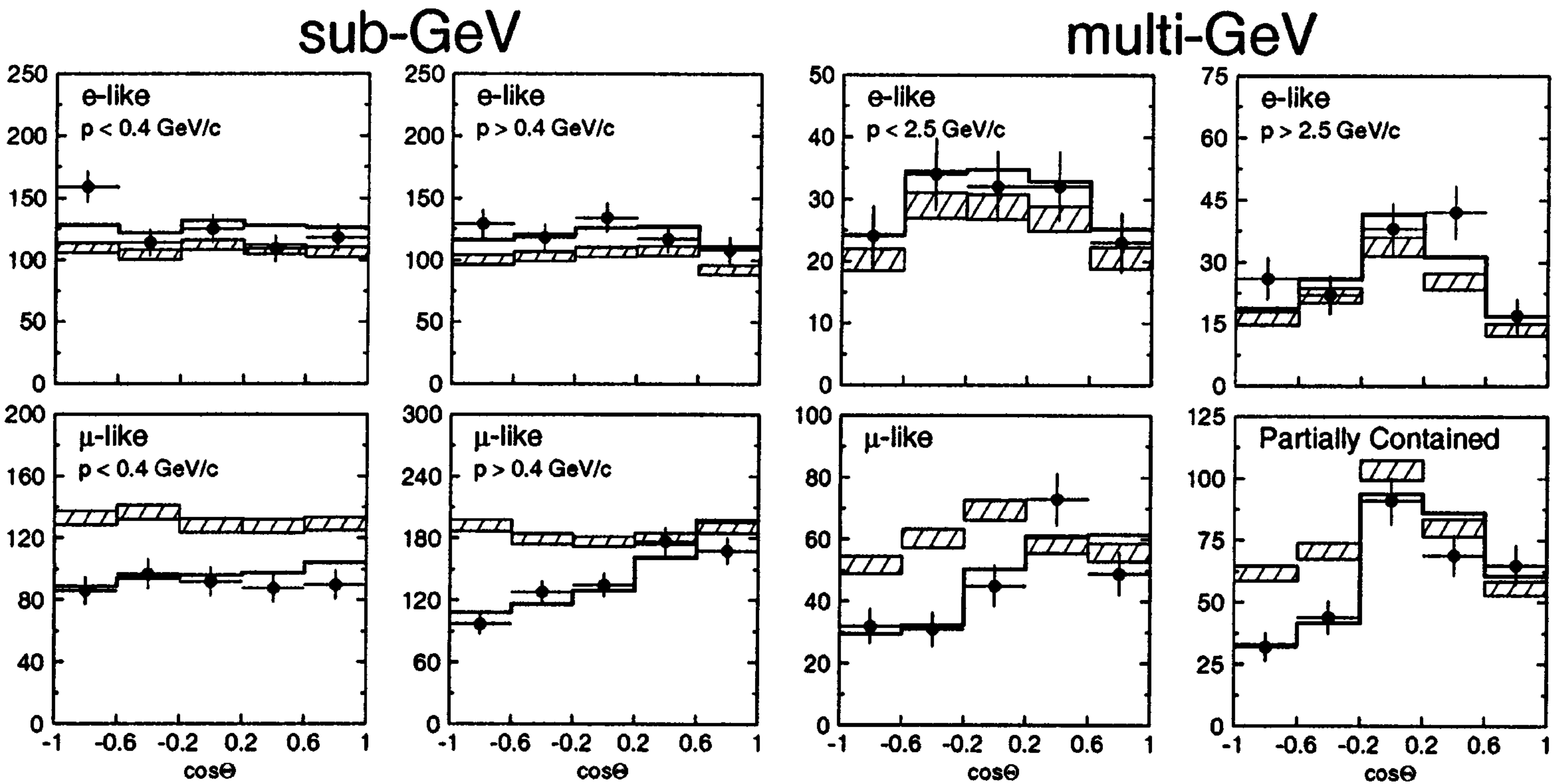


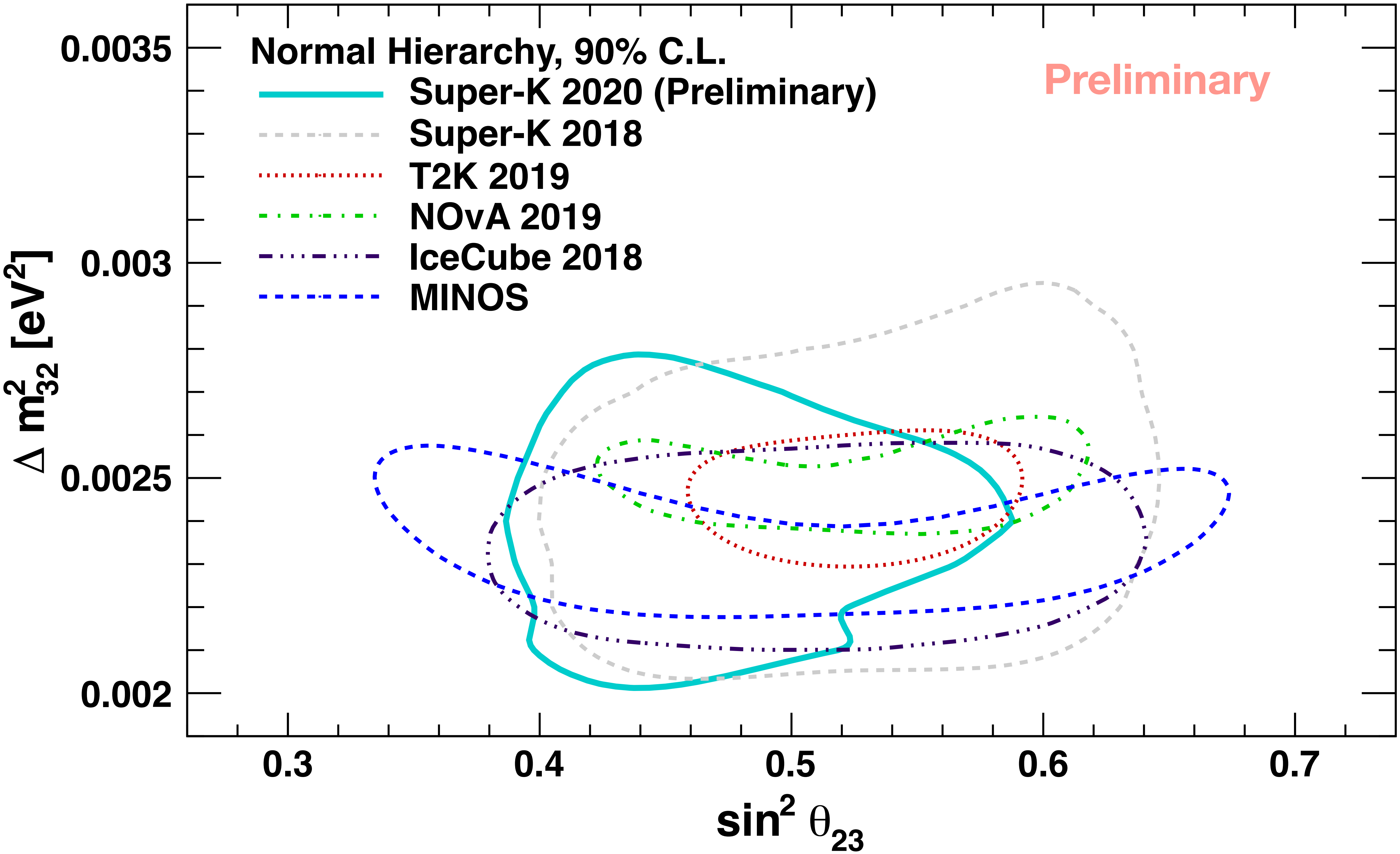
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Discovery of Neutrino Oscillation (1998)



Latest oscillation measurements (2020)

Δm^2_{32} vs $\sin^2\theta_{23}$ constraints



News in 2020

Super-Kamiokande Gadolinium Project (SK-Gd)

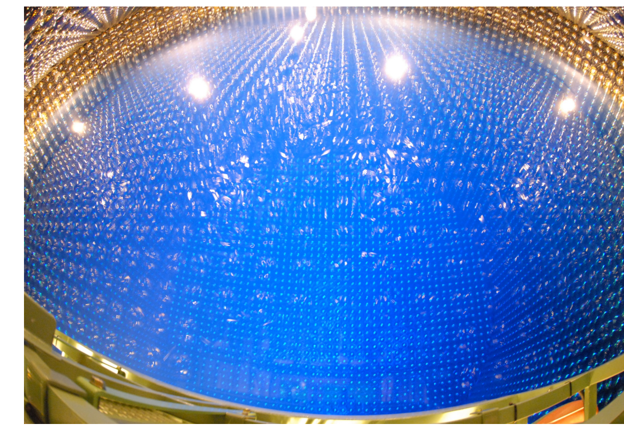
- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions

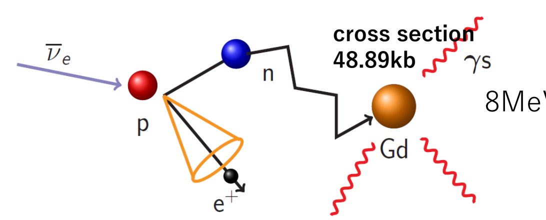
  J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110

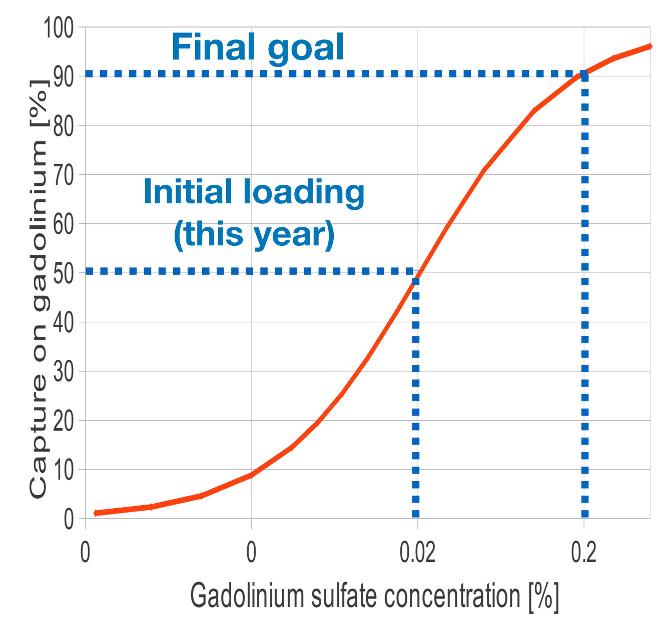
- Aiming for the **first observation of Diffuse Supernova Neutrino Backgrounds**
- Also aiming for:
  - Improving pointing accuracy for galactic supernova
  - Precursor of nearby supernova by Si-burning neutrinos
  - Reducing proton decay background
  - Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric neutrinos)
  - Reactor neutrino measurements
- As the first step, loading 0.02% of $Gd_2(SO_4)_3$ in 2020

  ~50% n-capture on Gd

+

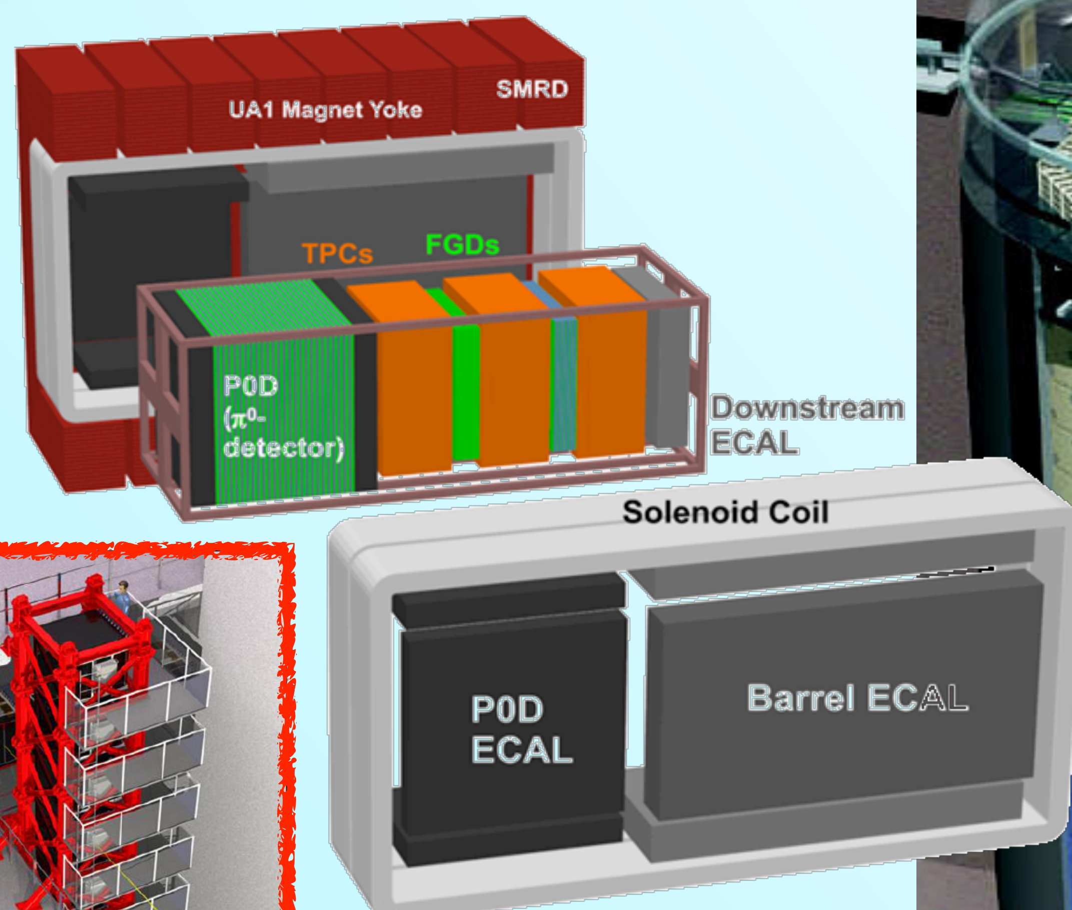


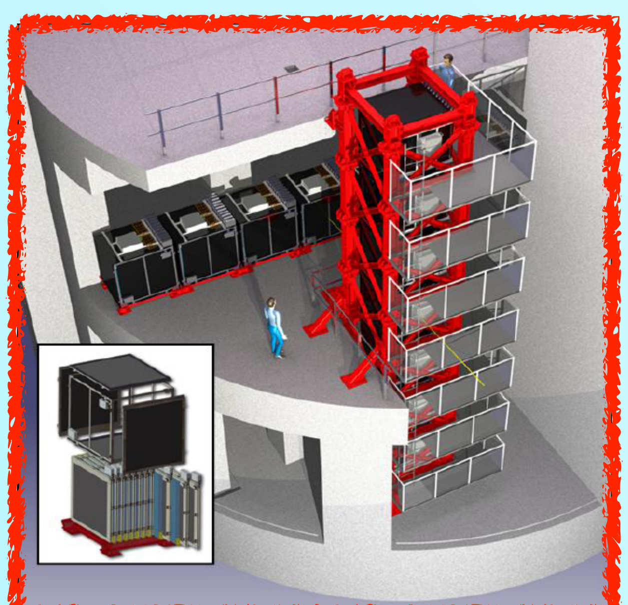


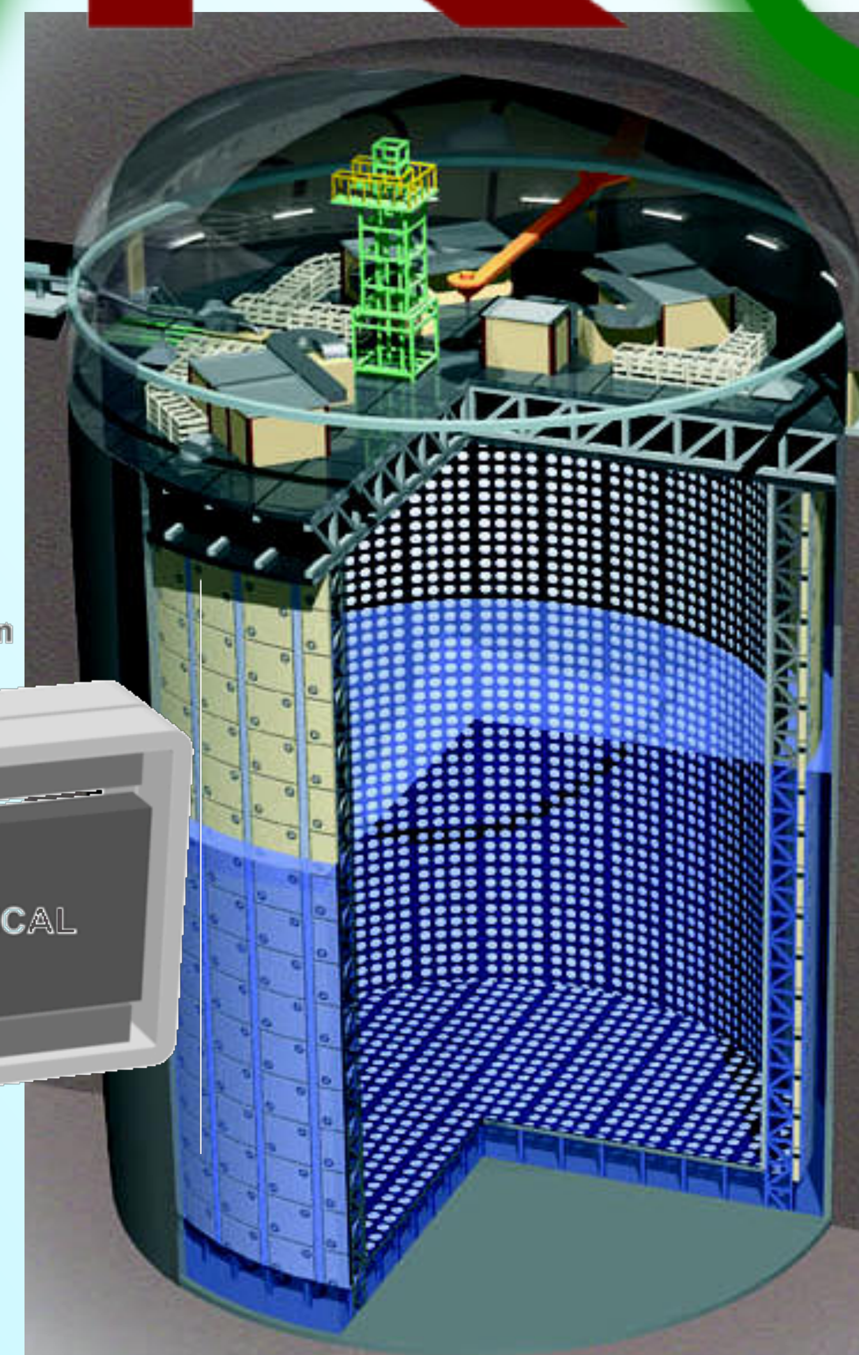


by Y. Nakajima@Neutrino2020

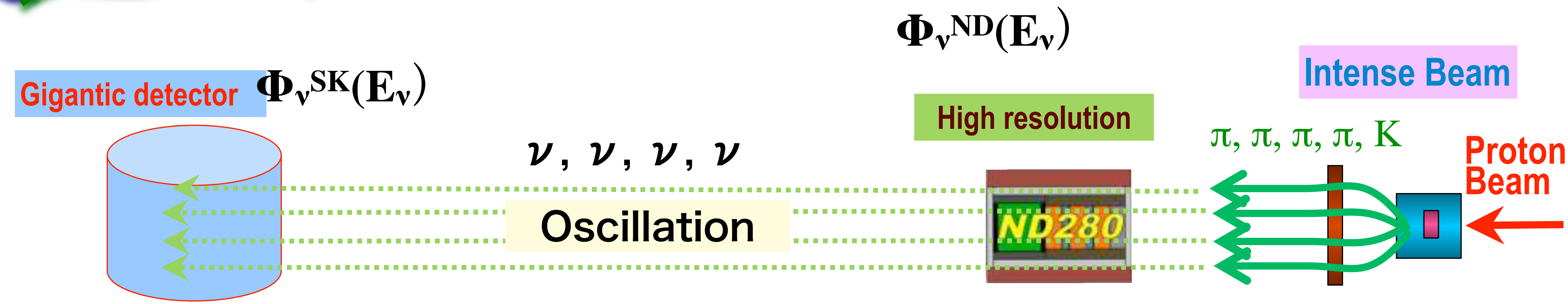
T2K

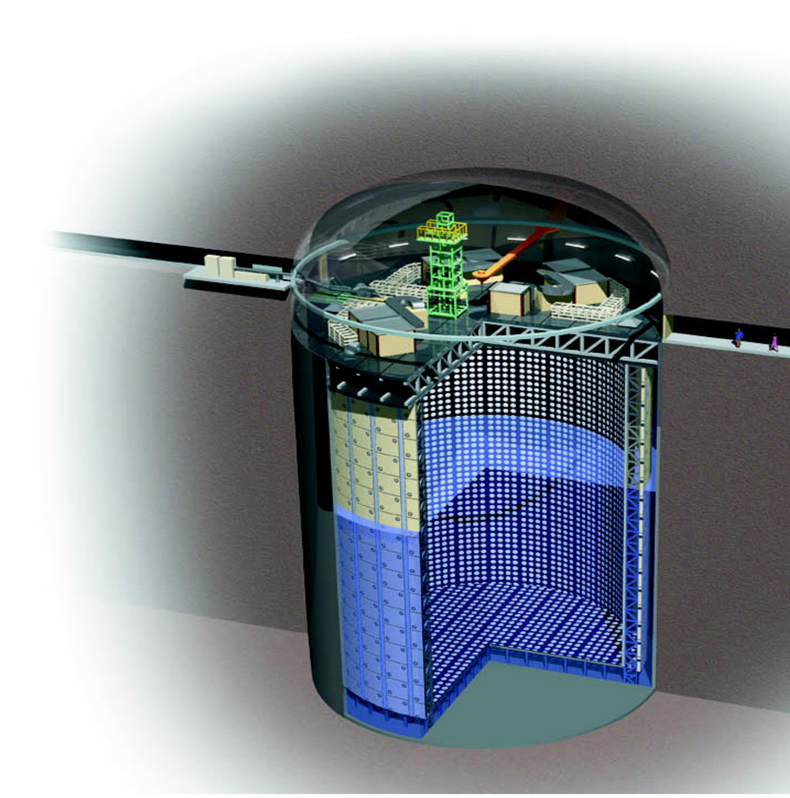

UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π0-
detector)
Downstream
ECAL
Solenoid Coil
P0D
ECAL
Barrel ECAL



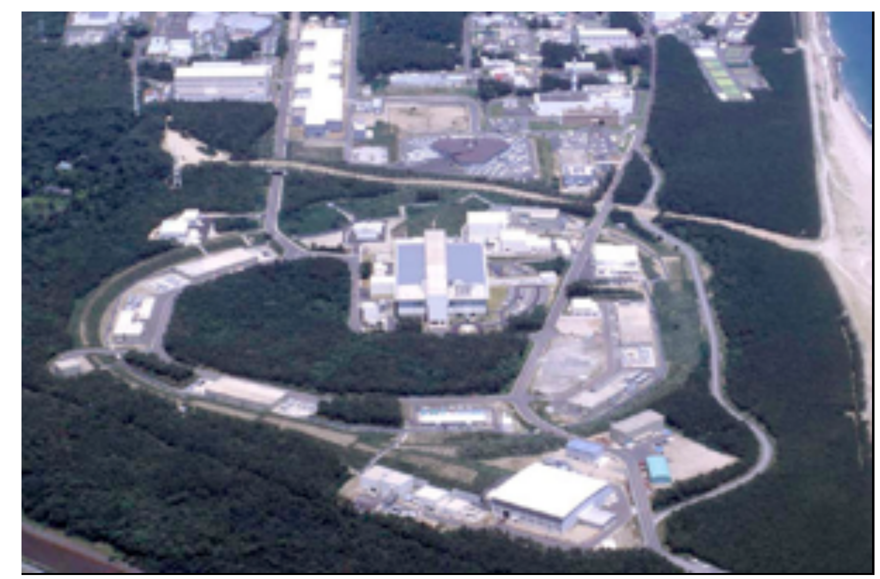


Accelerator Neutrino Experiments



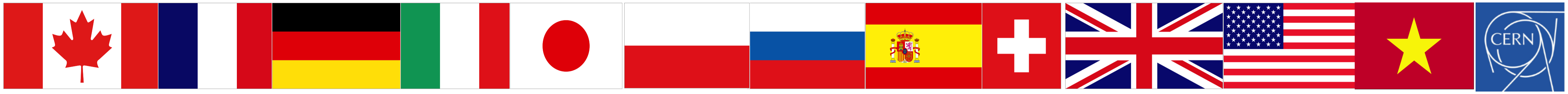


Credit: Super-K collaboration



Credit: J-PARC

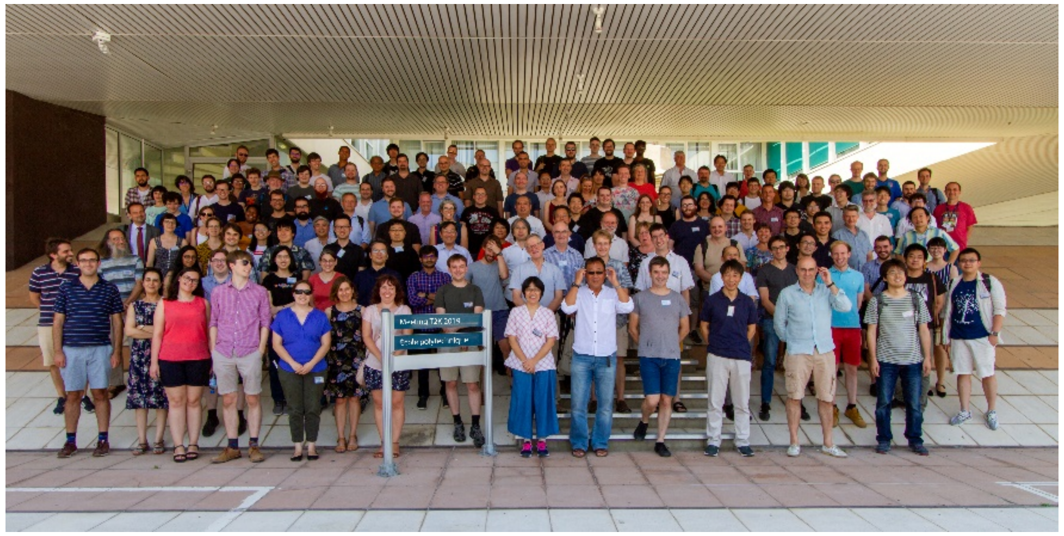
The T2K Collaboration (2020)



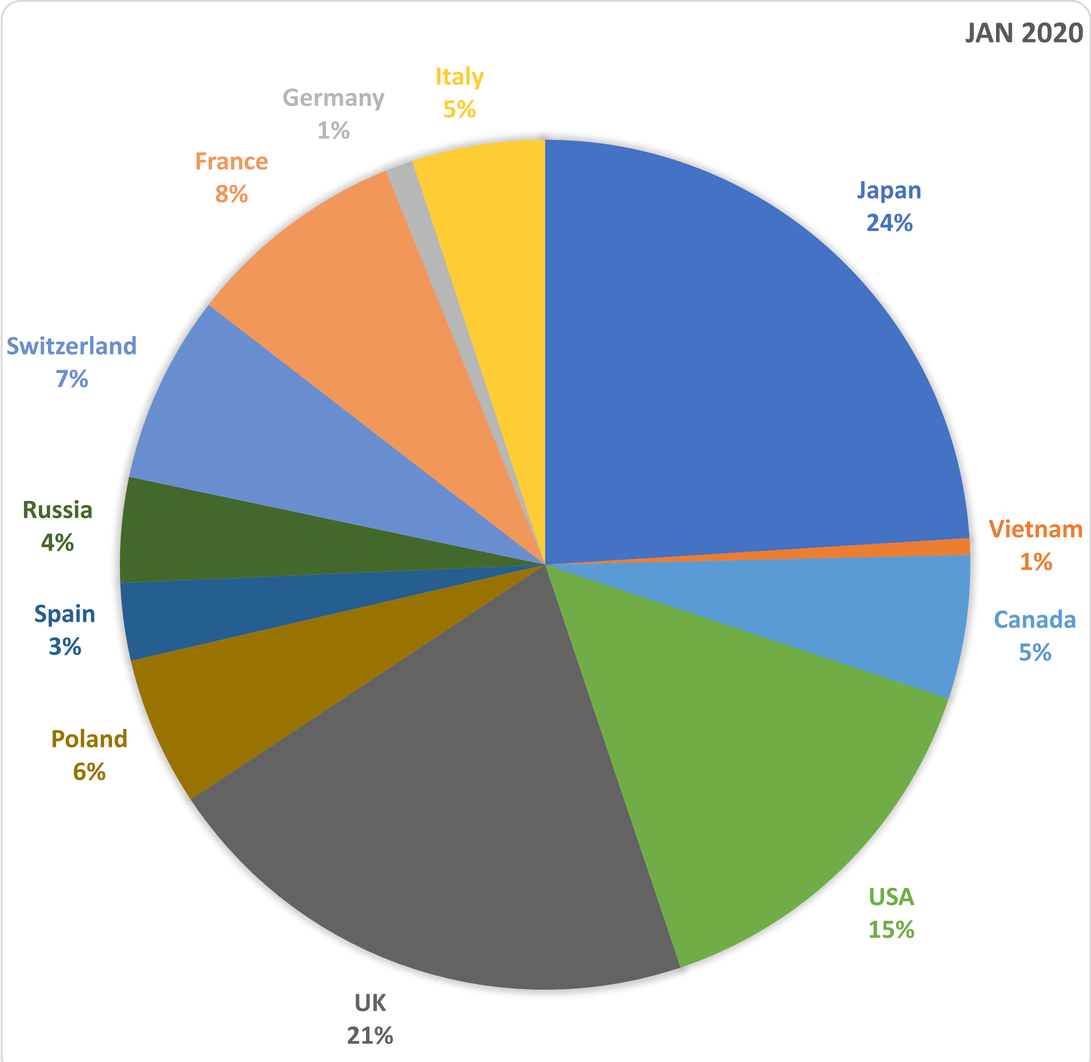
~500 members, 69 Institutes, 12 countries

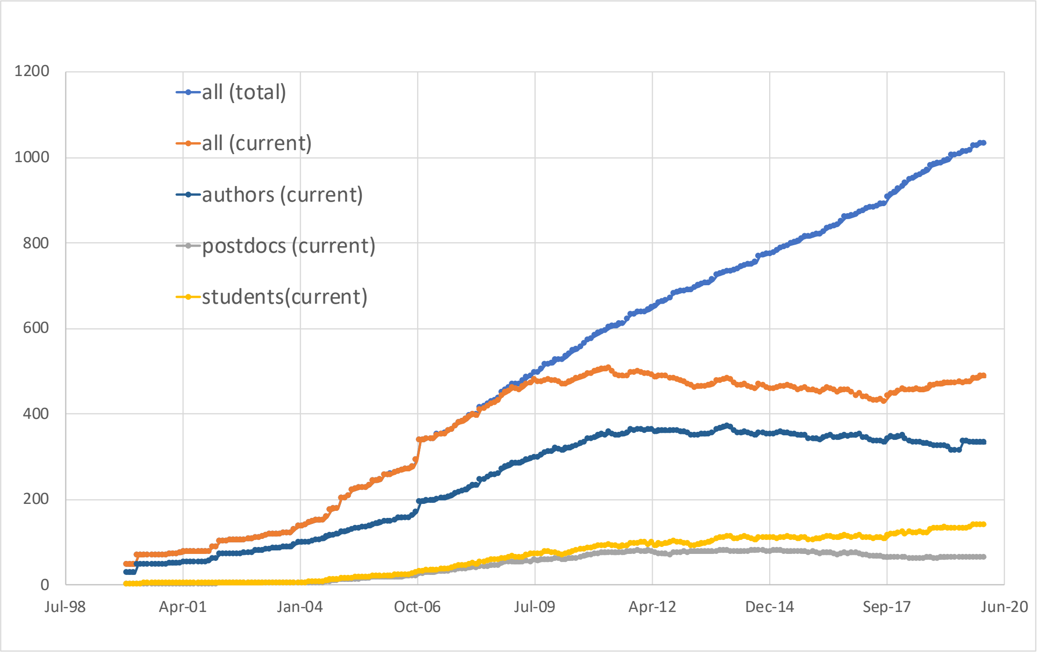
Asia	117
Japan	114
Vietnam	3

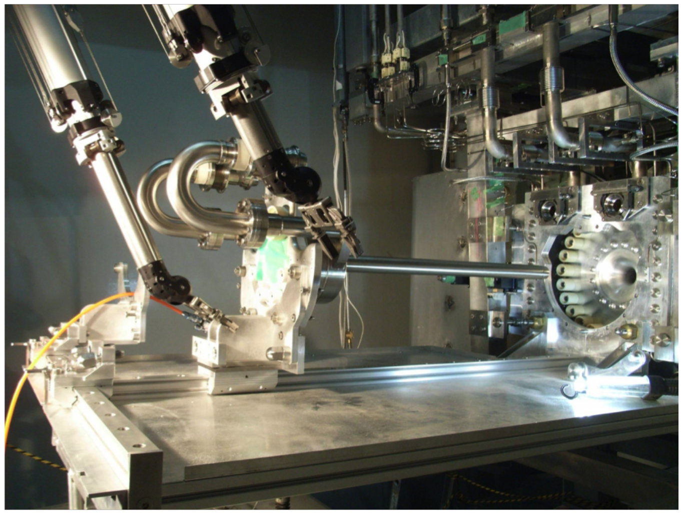
Americas	96
Canada	26
USA	70



Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99

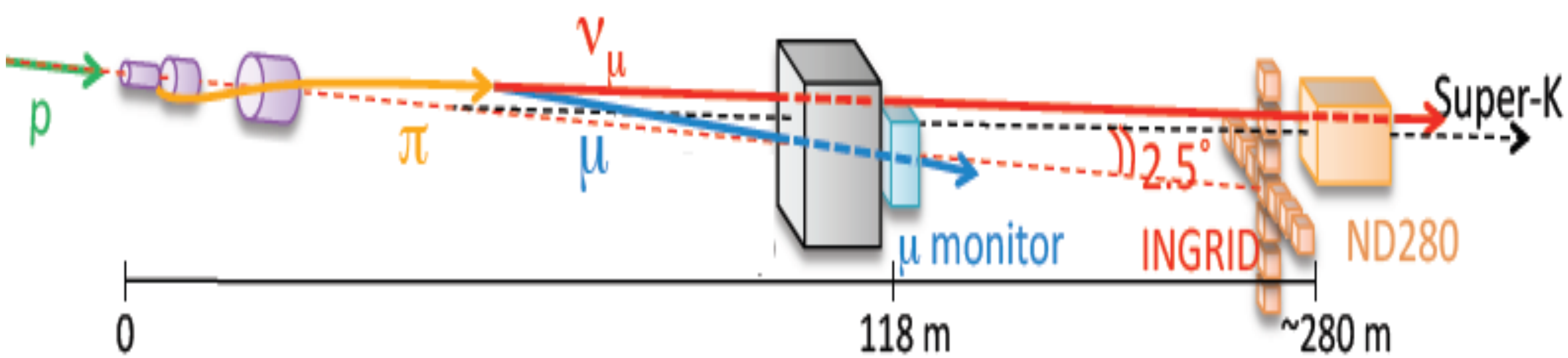


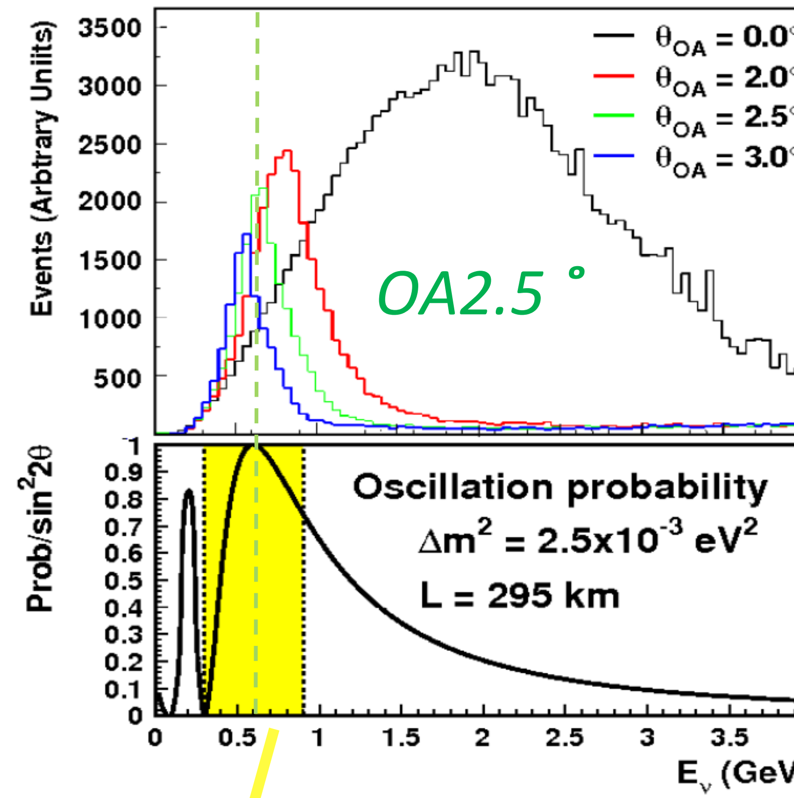




Target + remote handling system

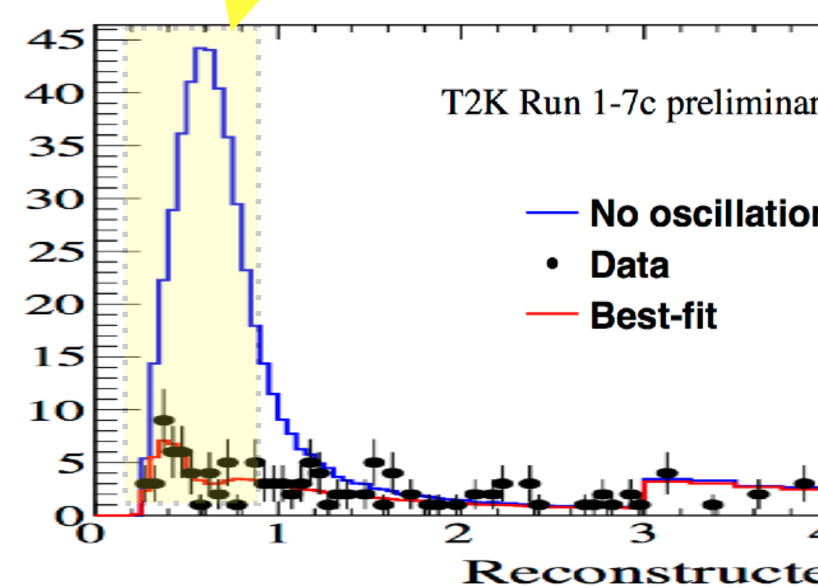
T2K ν beam





- 30 GeV **~2×10^14** protons extracted every 2.5 sec. Secondary π^+(and K^+) focused by three electromagnetic horns
- ν_μ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e in the beam come from K and μ decays

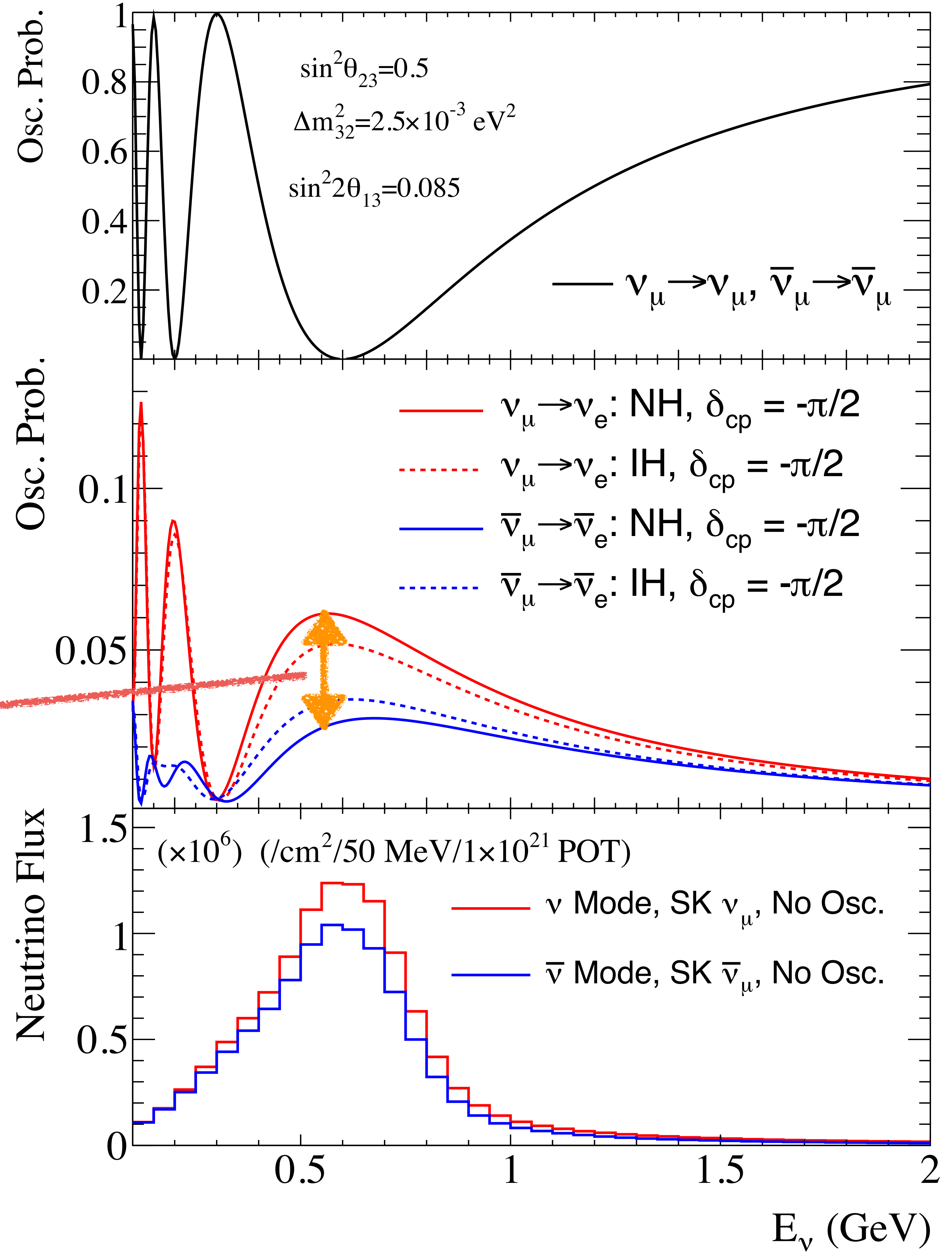
- **Off-axis (2.5 °) ν_μ beam**
  - Intense, low energy narrow-band
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - Small ν_e fraction (~1%)



T2K 2016 ν_μ disappearance

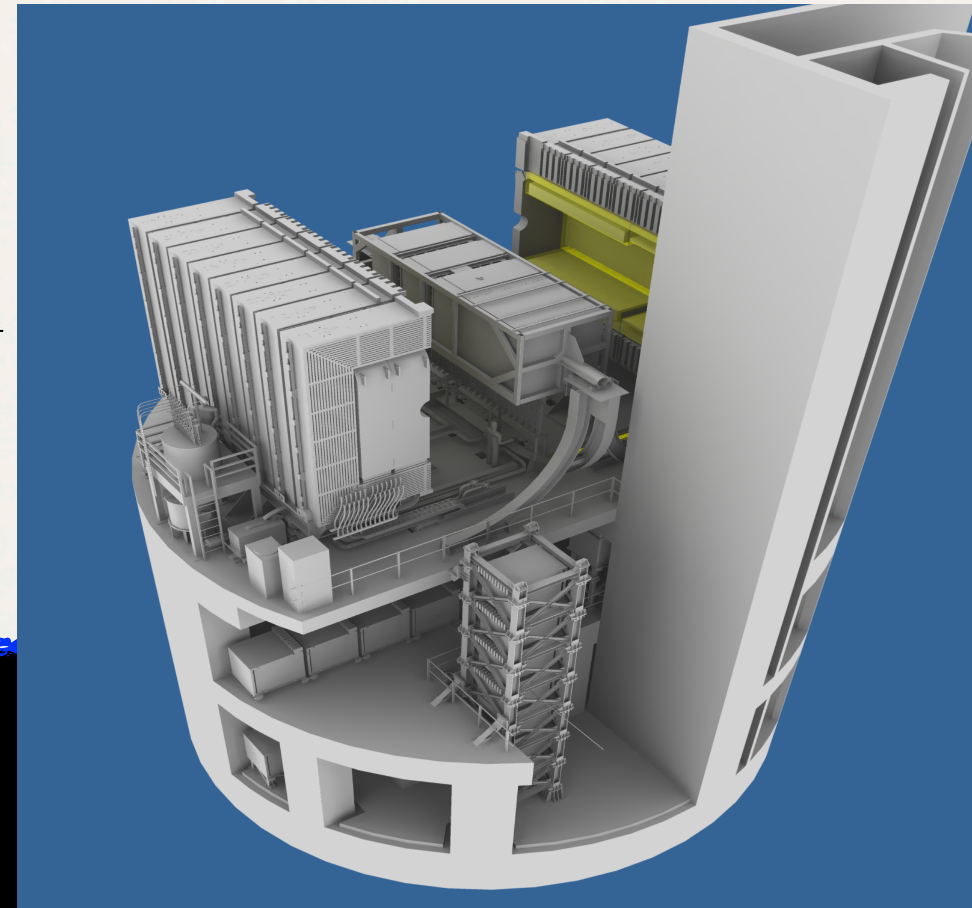
Neutrino oscillation measurements in T2K

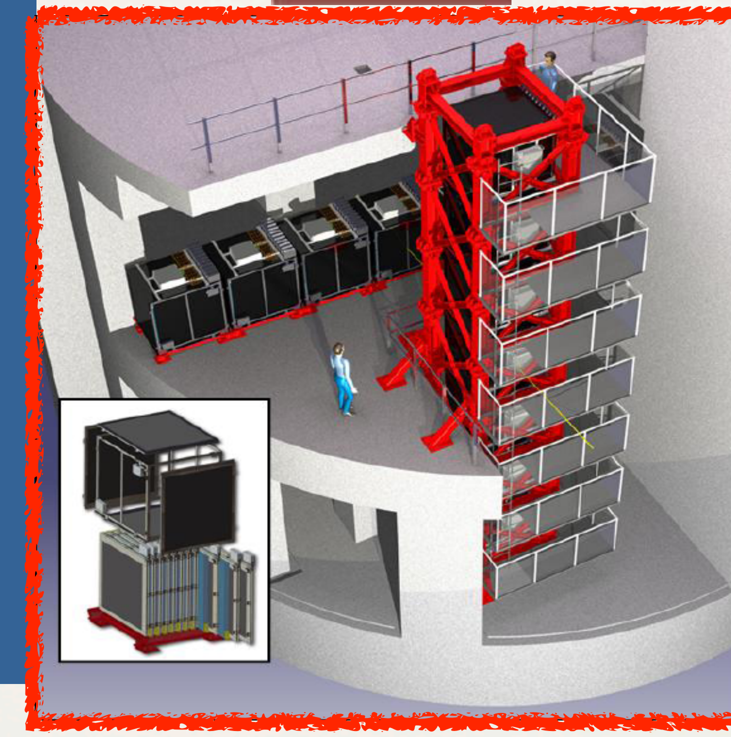
- ν_μ disappearance
  - $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$
- ν_e appearance
  - $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}, Δm^2_{31}
- CP violation by $\#\nu_e$
  - ~±20% in maximum

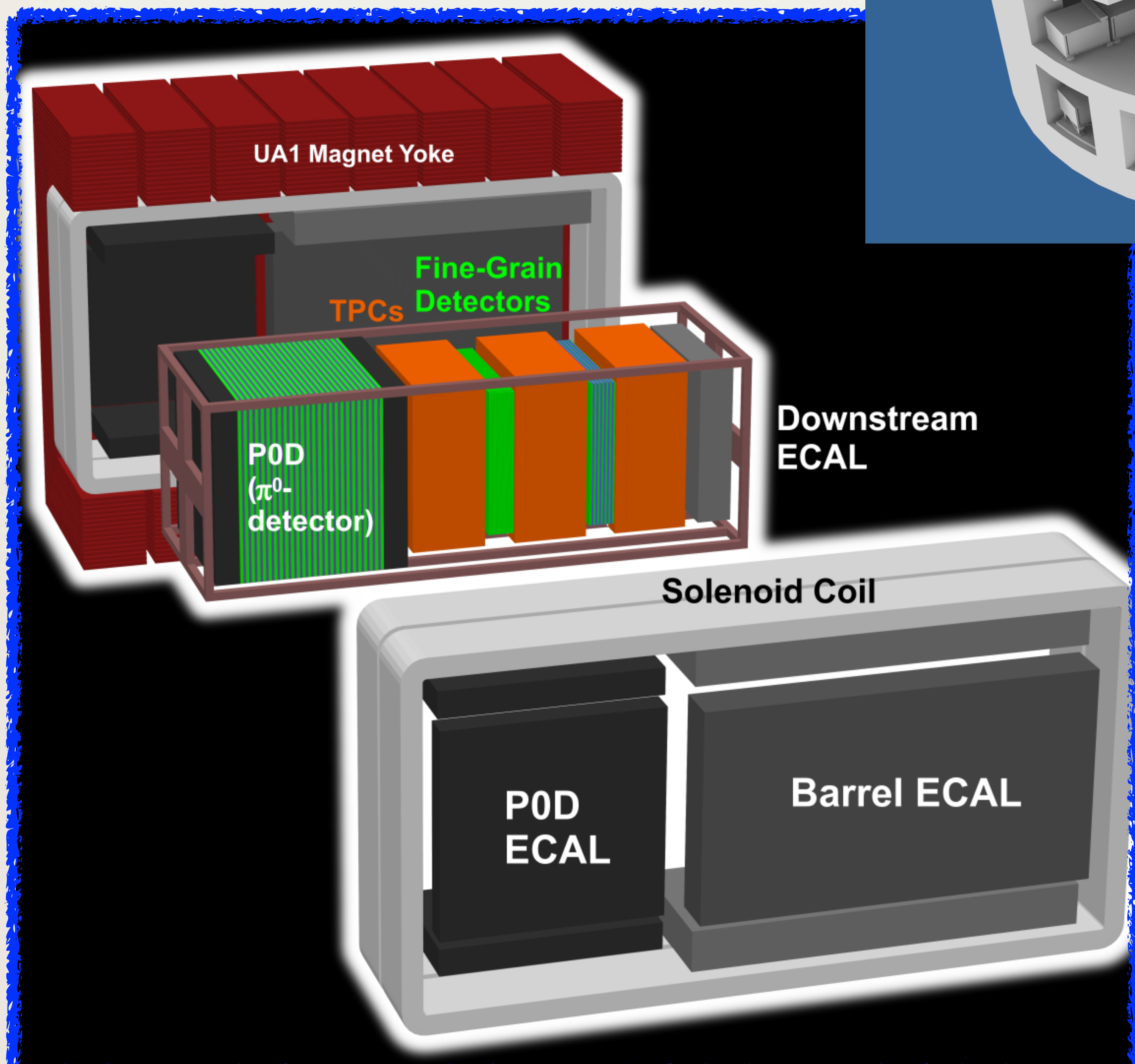


ND280

Near Detector @ 280m from the target



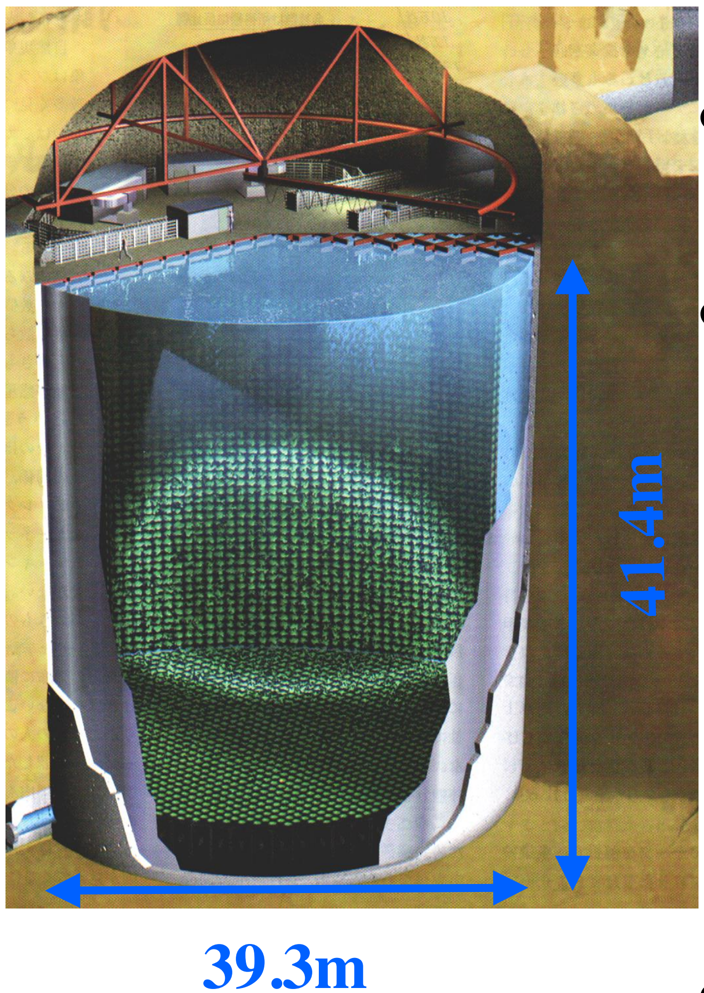




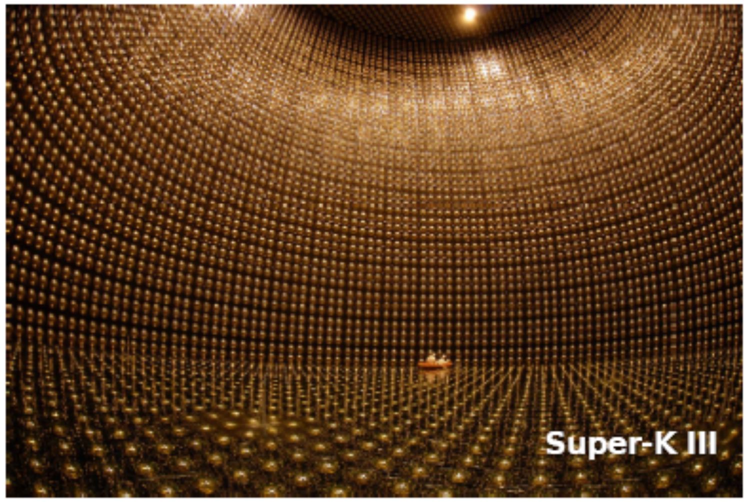
- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]

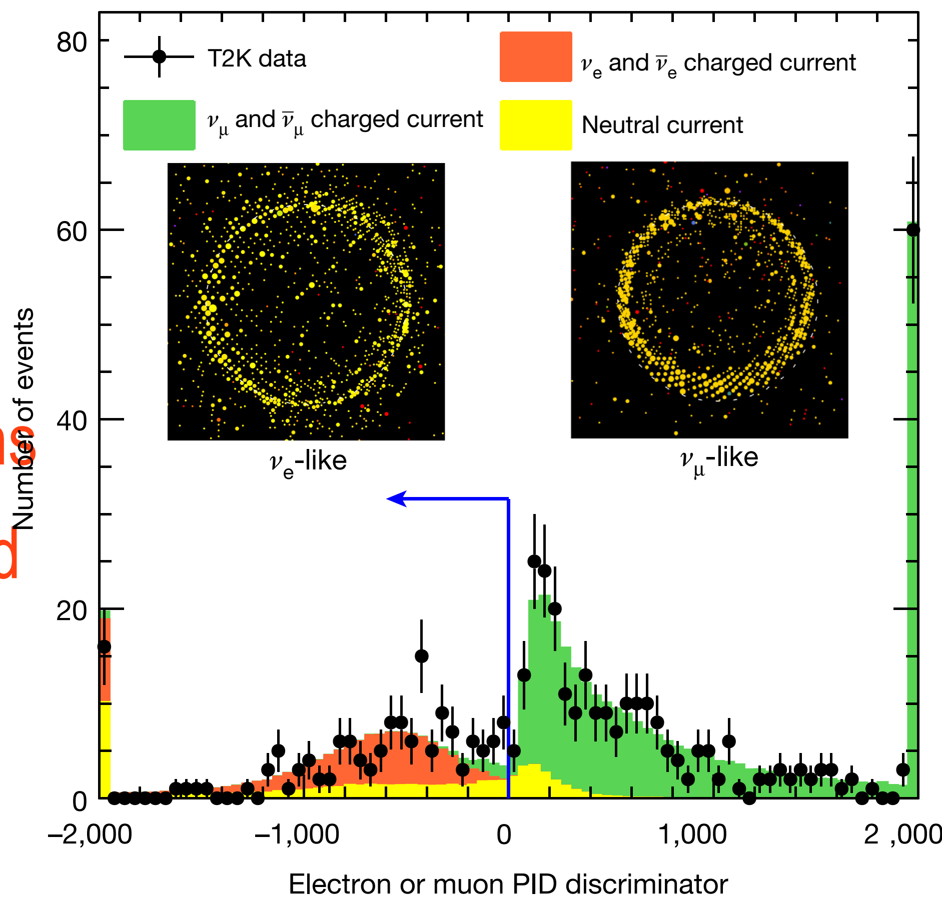
- **ND280** @ 2.5 degree off-axis
  - ✦ Normalization of Neutrino Flux
  - ✦ Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - **P0D:** π^0 Detector
    - **FGD+TPC:** Target + Particle tracking
    - **EM calorimeter**
    - **Side-Muon-Range Detector**

T2K-Far Detector: Super-Kamiokande



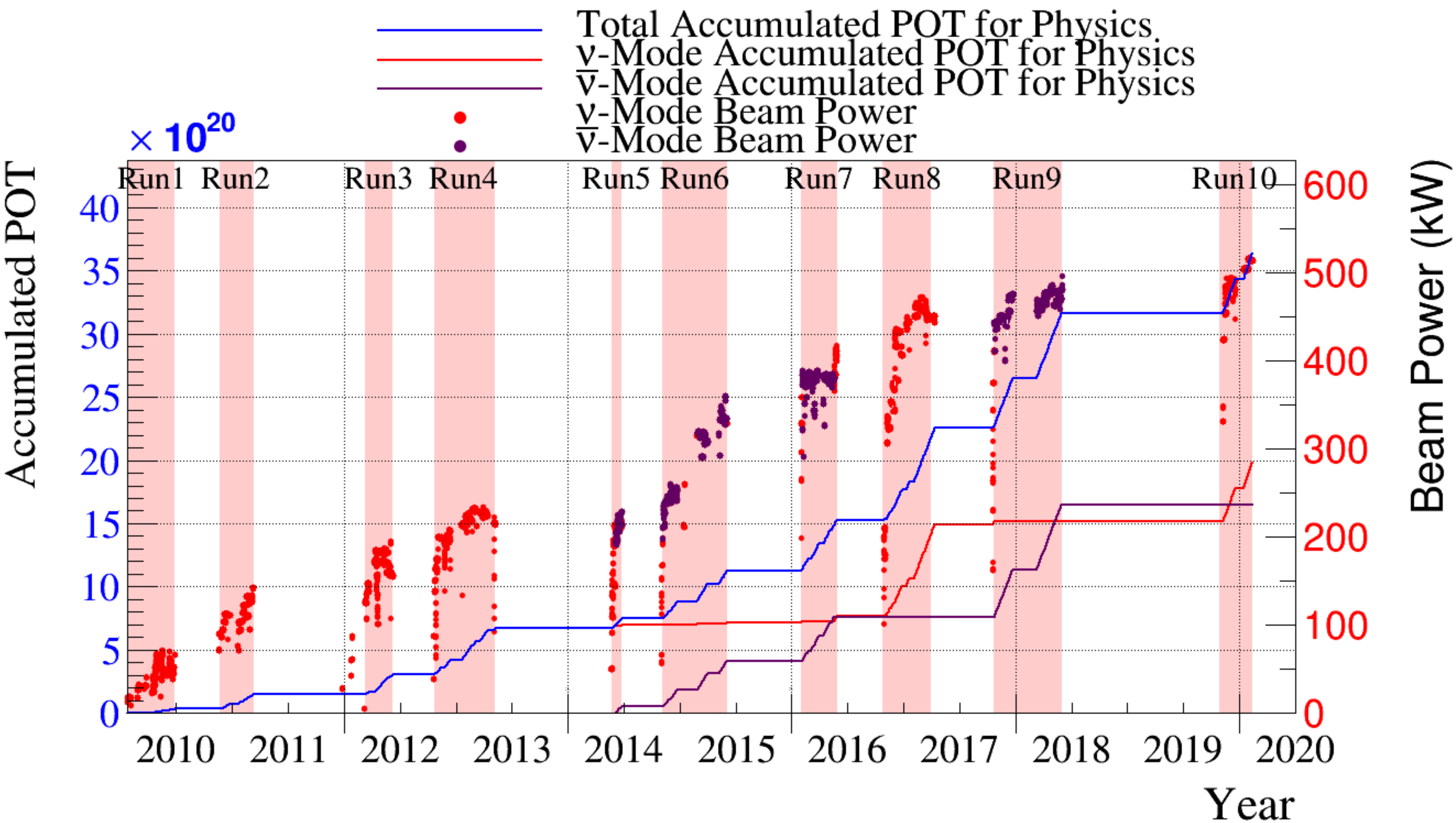
- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with >95% NC-$1\pi^0$ rejection
    - Inner tank (32 kton) :11,129 20inch PMT
    - Outer tank:1,885 8inch PMT
- Dead-time-less DAQ
- GPS timing information is recorded real-time at every accelerator spill
  - T2K recorded events: All interactions within a ±500μsec window centered on the the neutrino arrival time.





Data (proton beams) taken to date

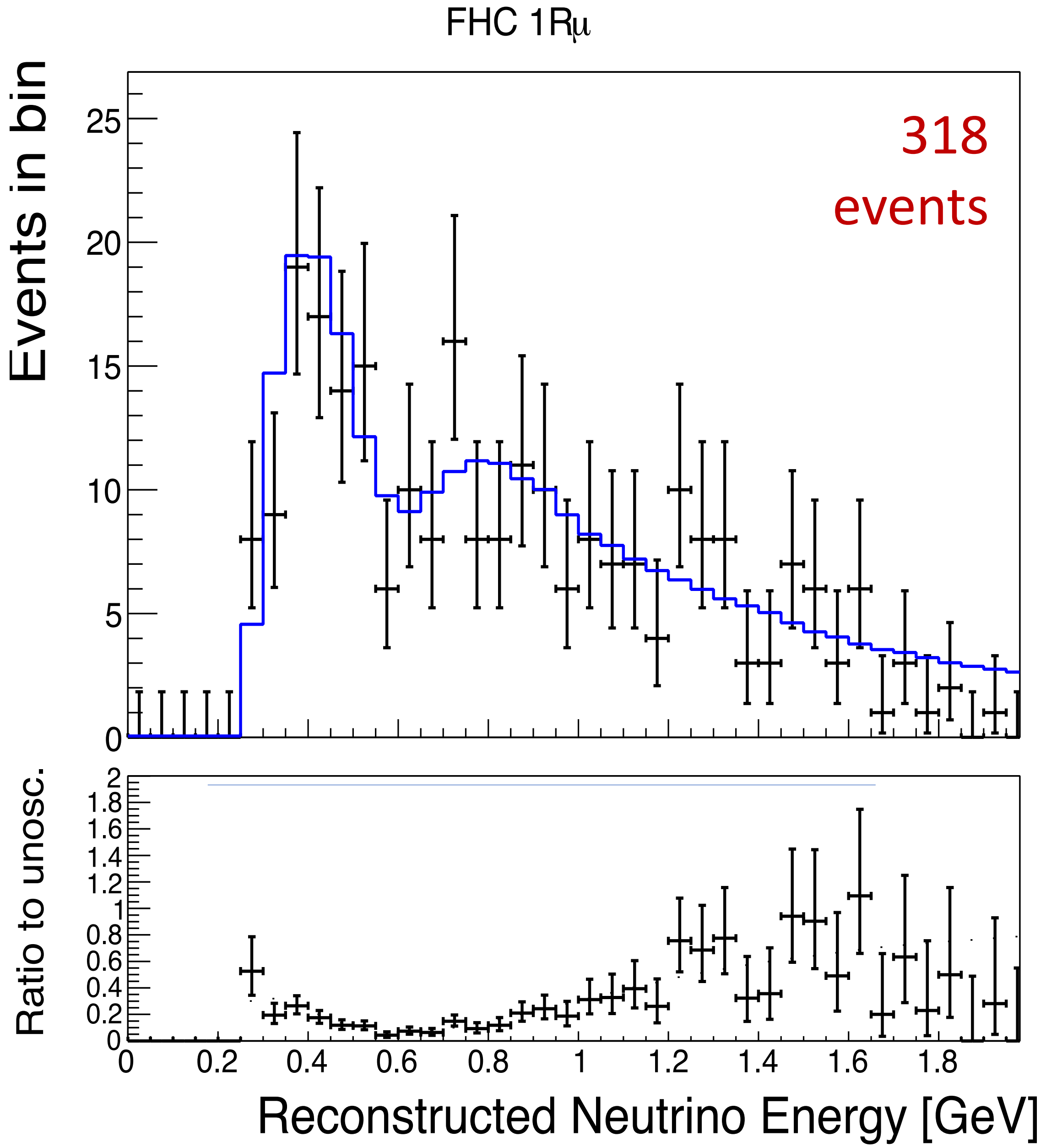
POT: Protons on Target



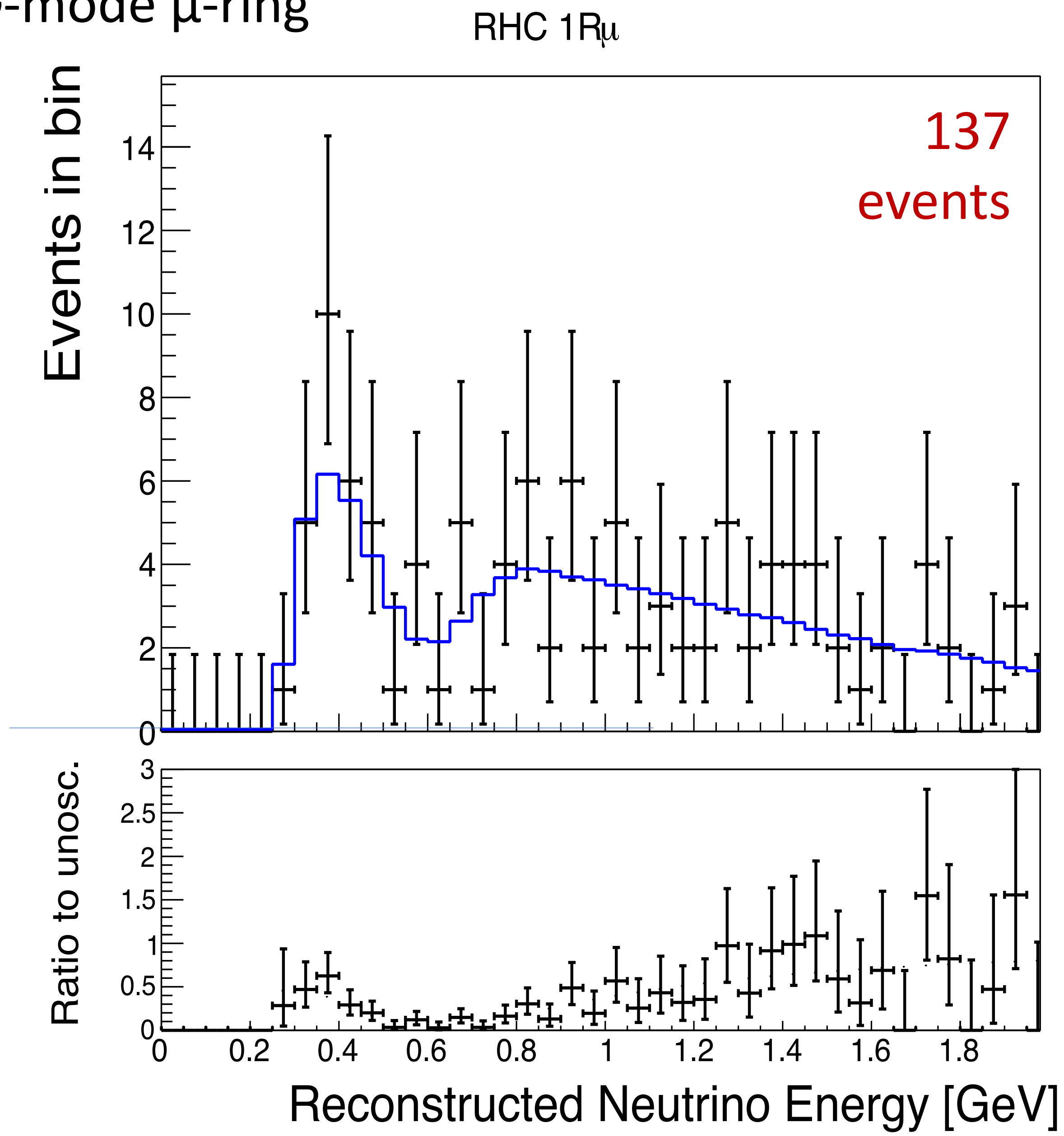
SK ν_μ (and anti-ν_μ) event samples

- Two samples with μ-like rings (one in ν-mode, one in $\bar{\nu}$-mode)

ν-mode μ-ring

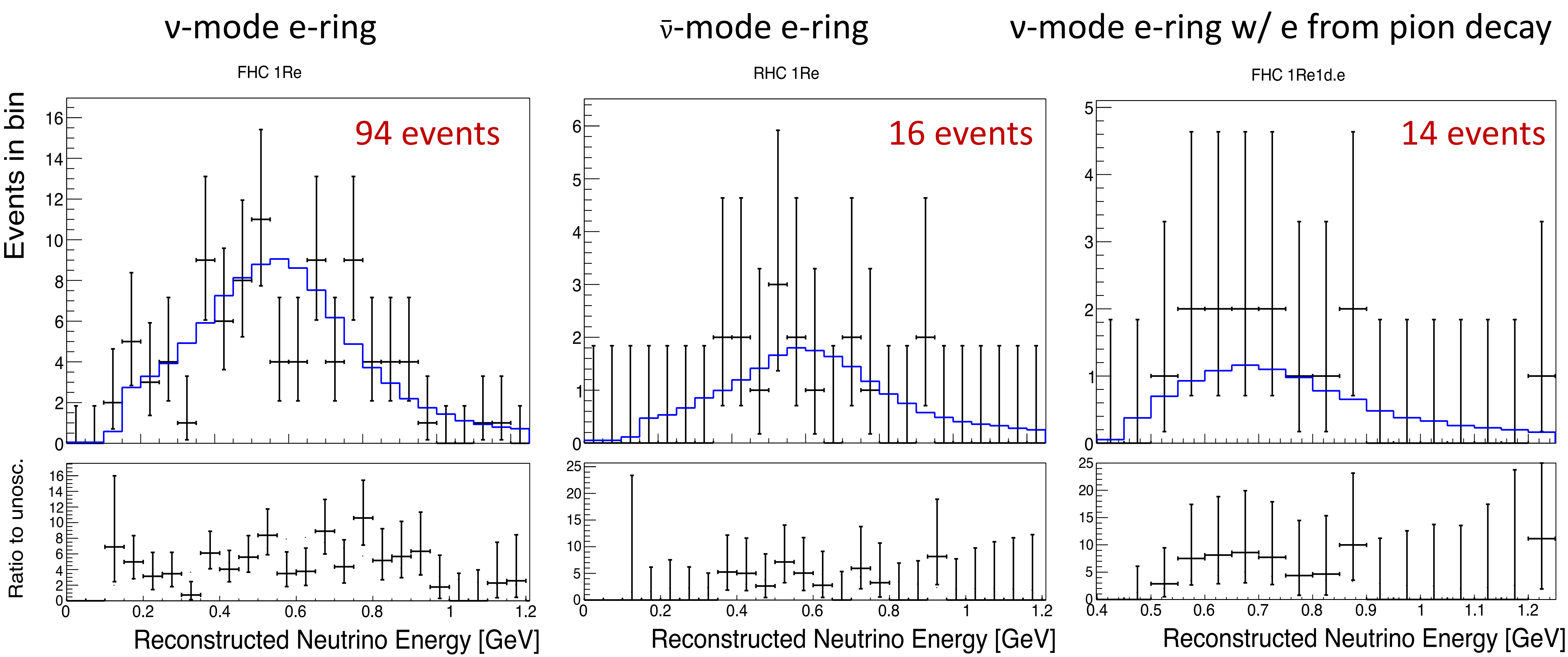


ν̄-mode μ-ring



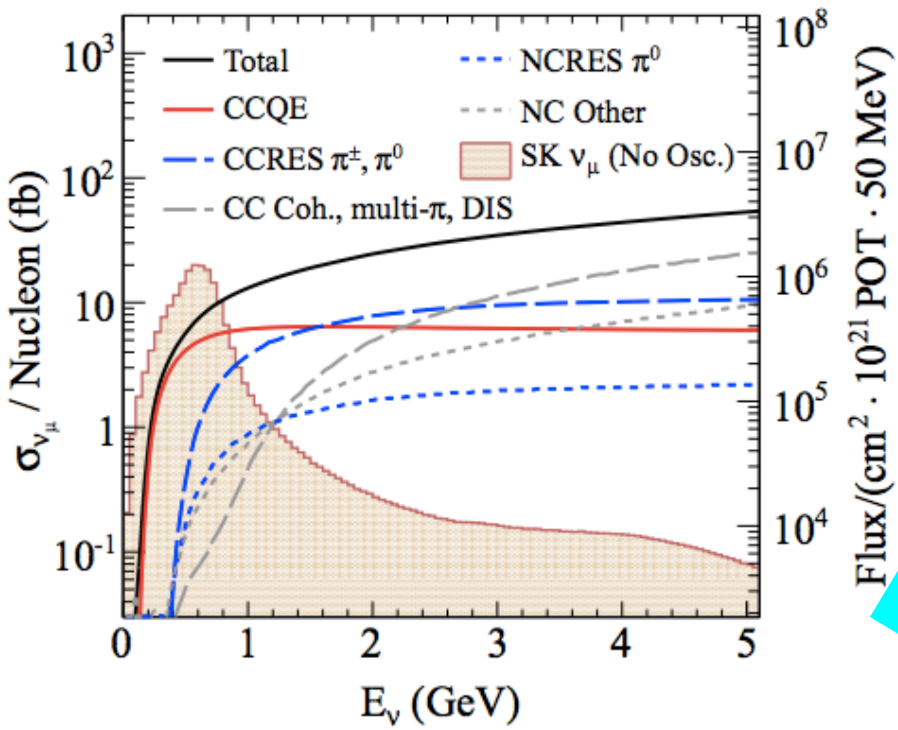
SK ν_e (and anti-ν_e) event samples

- Three samples with e-like rings
  - Two with e-ring only in ν-mode and $\bar{\nu}$-mode targeting CC0π events
  - One with Michel electron from π decay targeting CC1π events

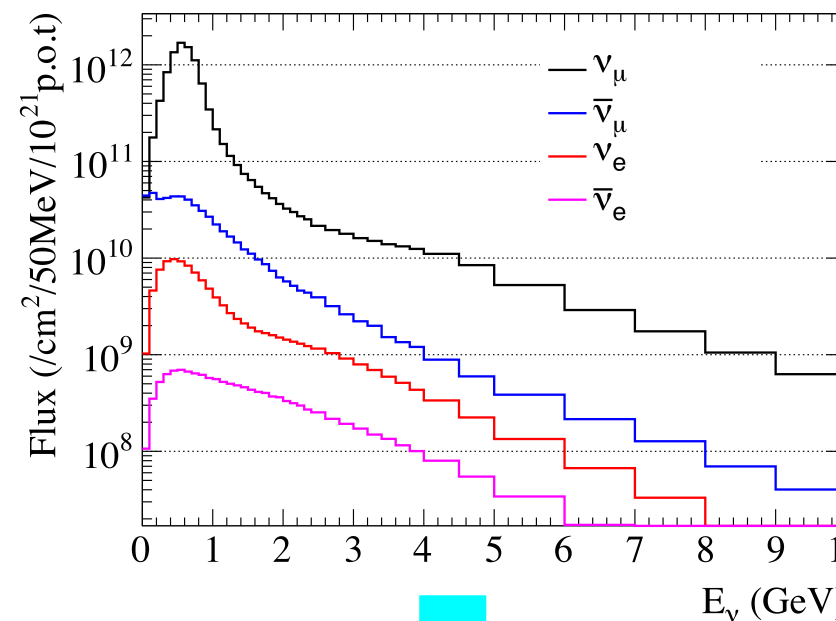


Oscillation Analysis

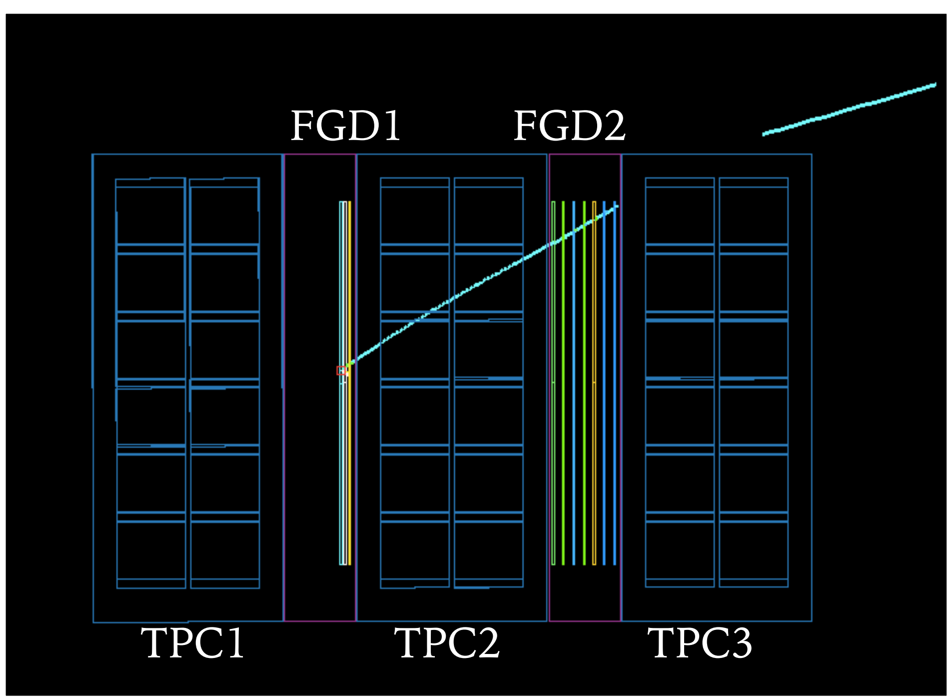
Neutrino Interactions



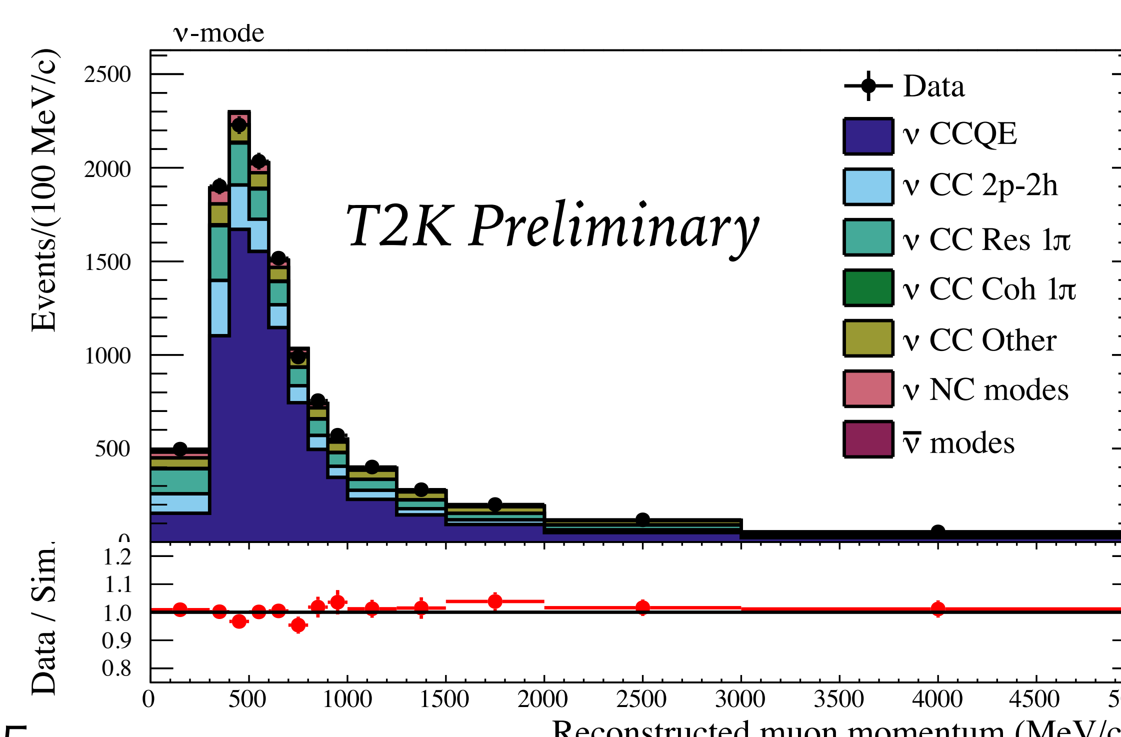
Neutrino Beam Flux



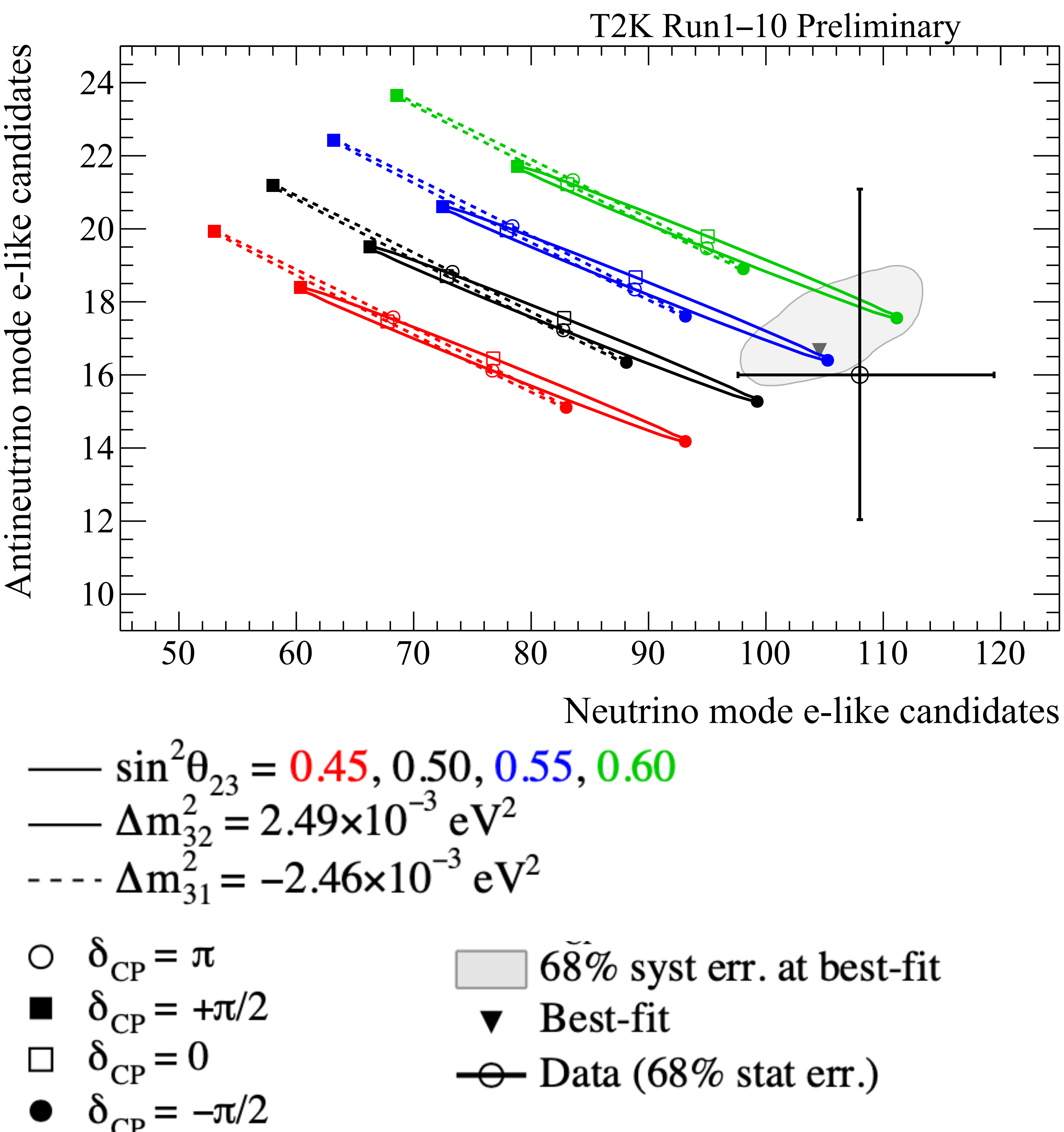
Measurements in ND280

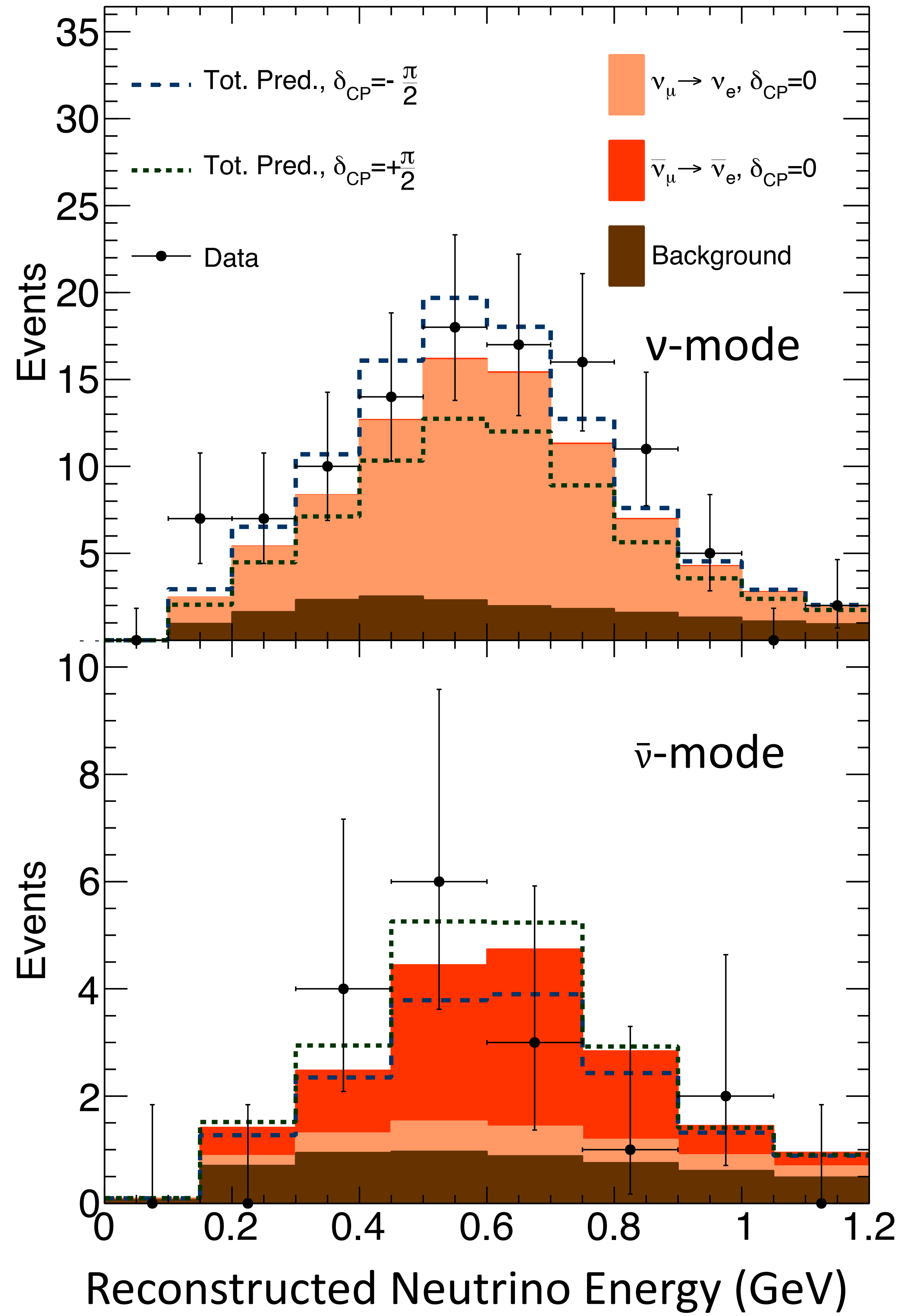


Constraints on flux and Interaction models



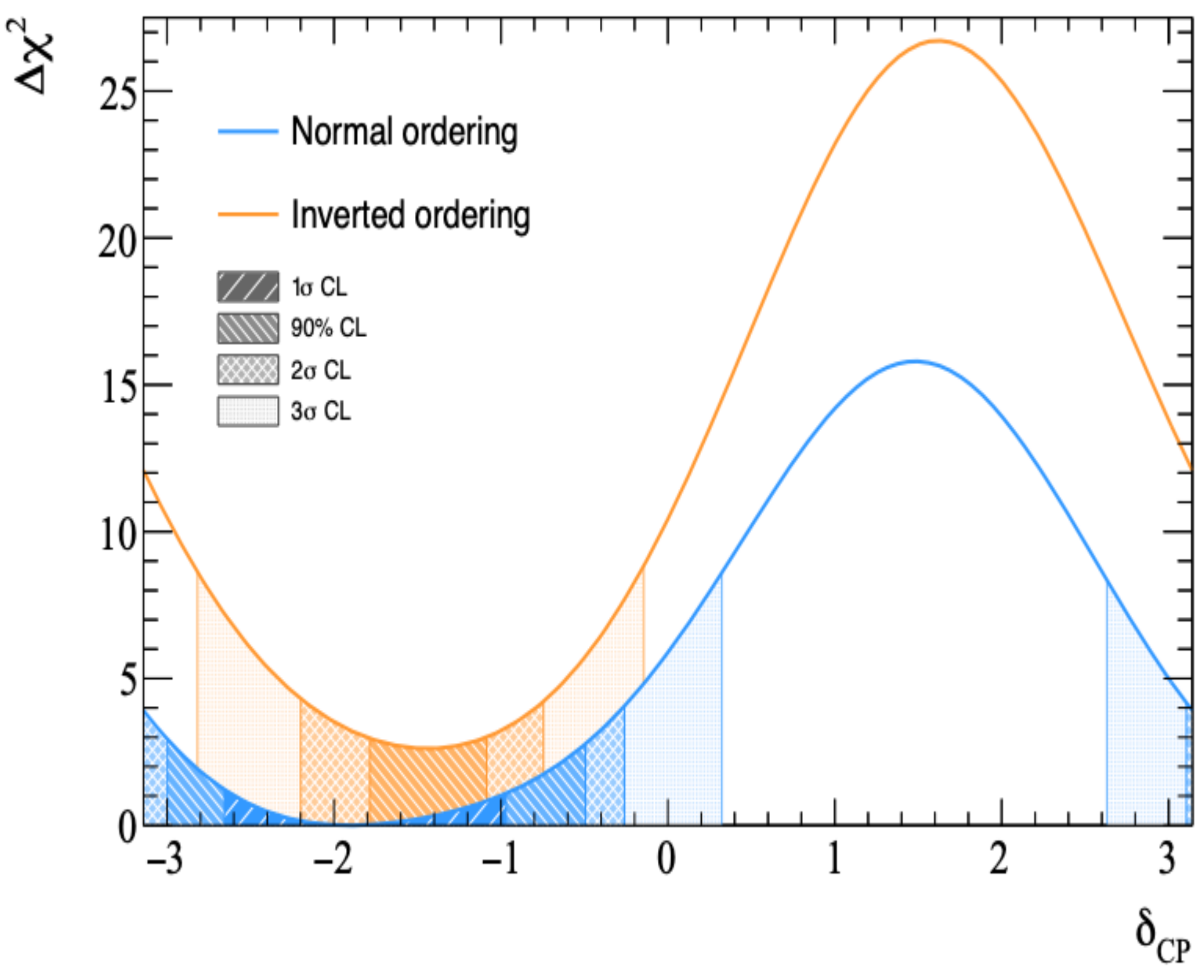
Oscillation Measurements in SK

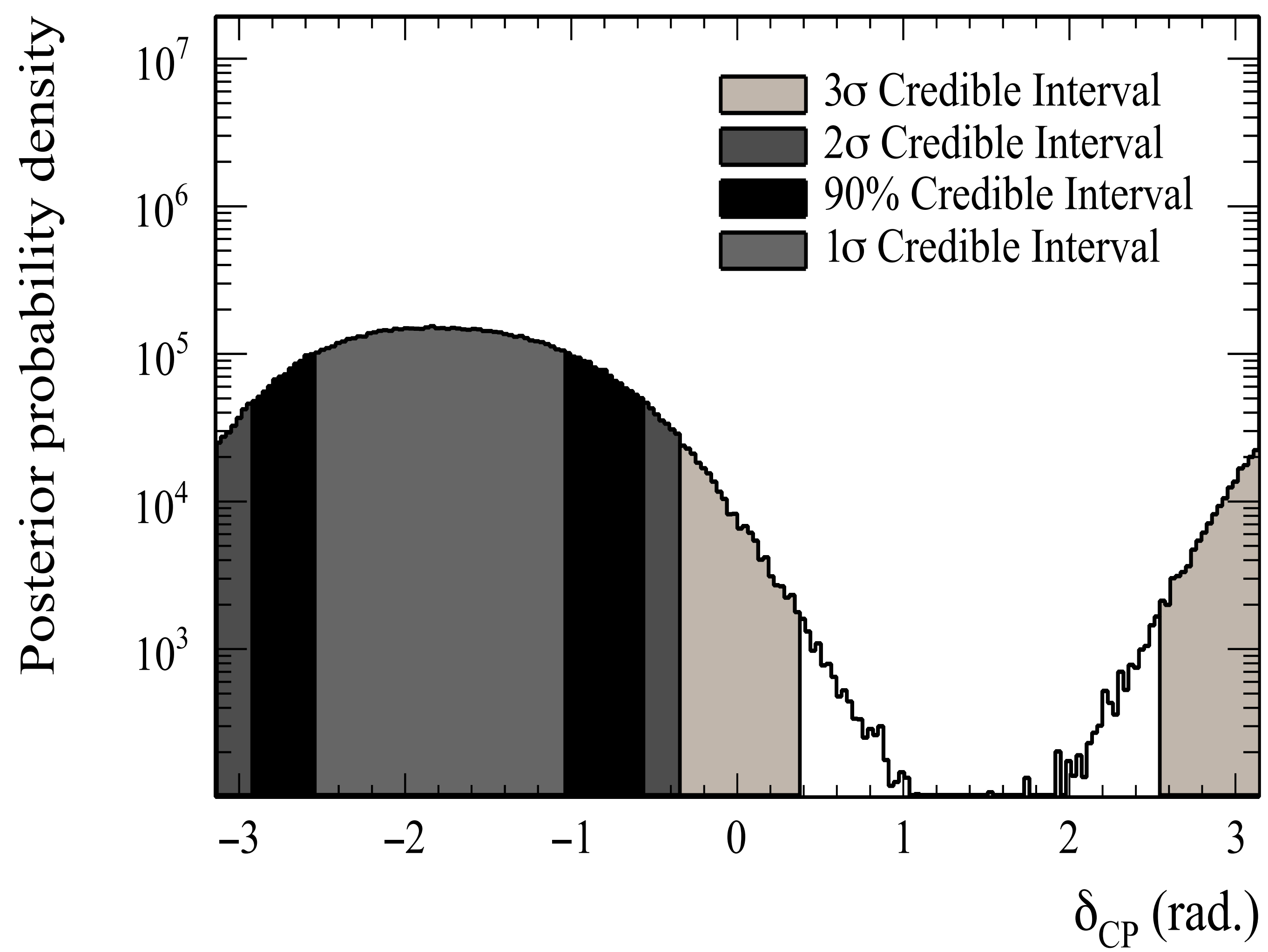




1D δ_{CP}

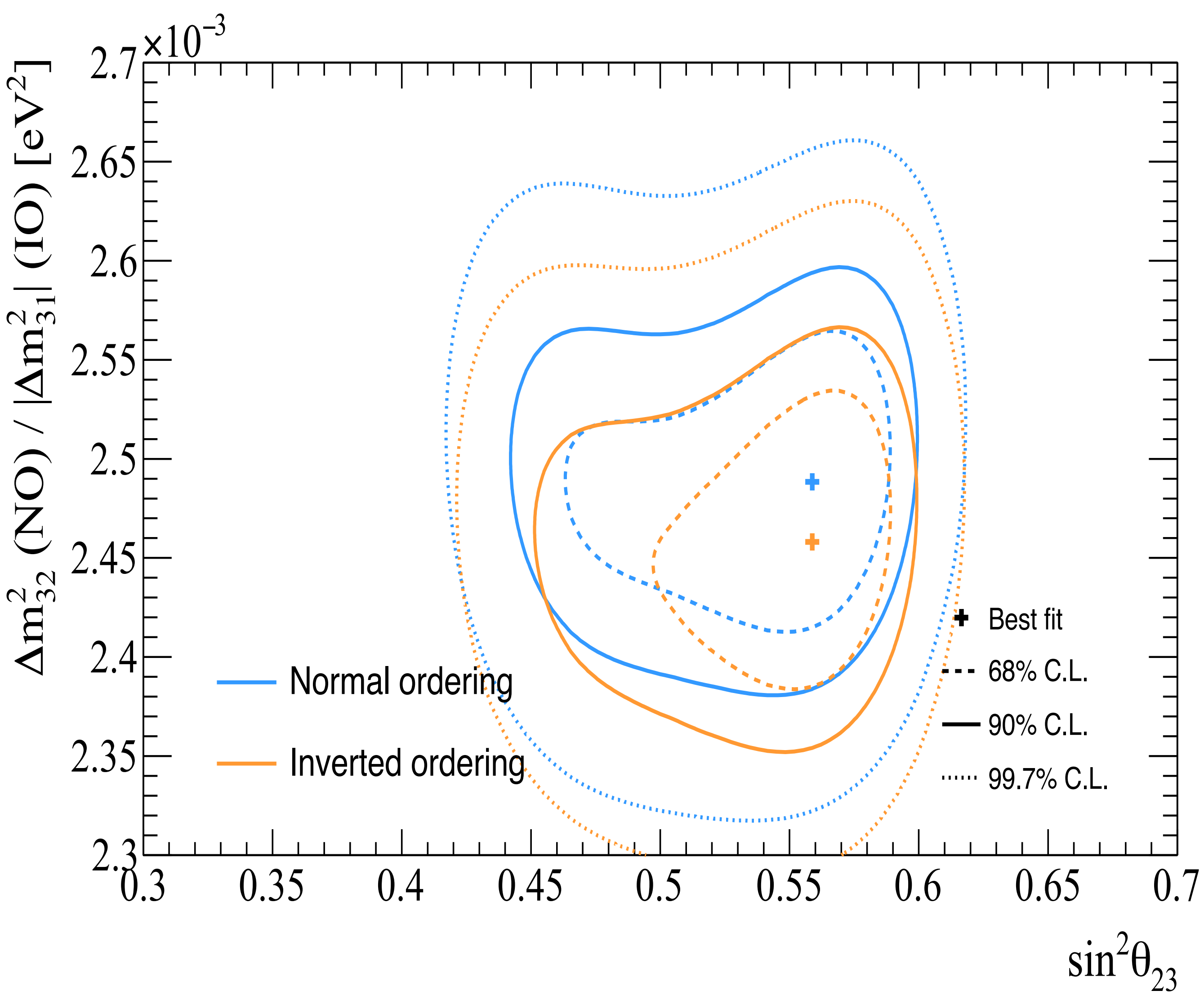
- 35% of values excluded at 3σ marginalized across hierarchies
- CP conserving values $(0,\pi)$ excluded at 90% but π not quite at 2σ





θ_{23} and Δm_{32}^2

- Data shows preference for normal hierarchy and upper octant



Posterior probability

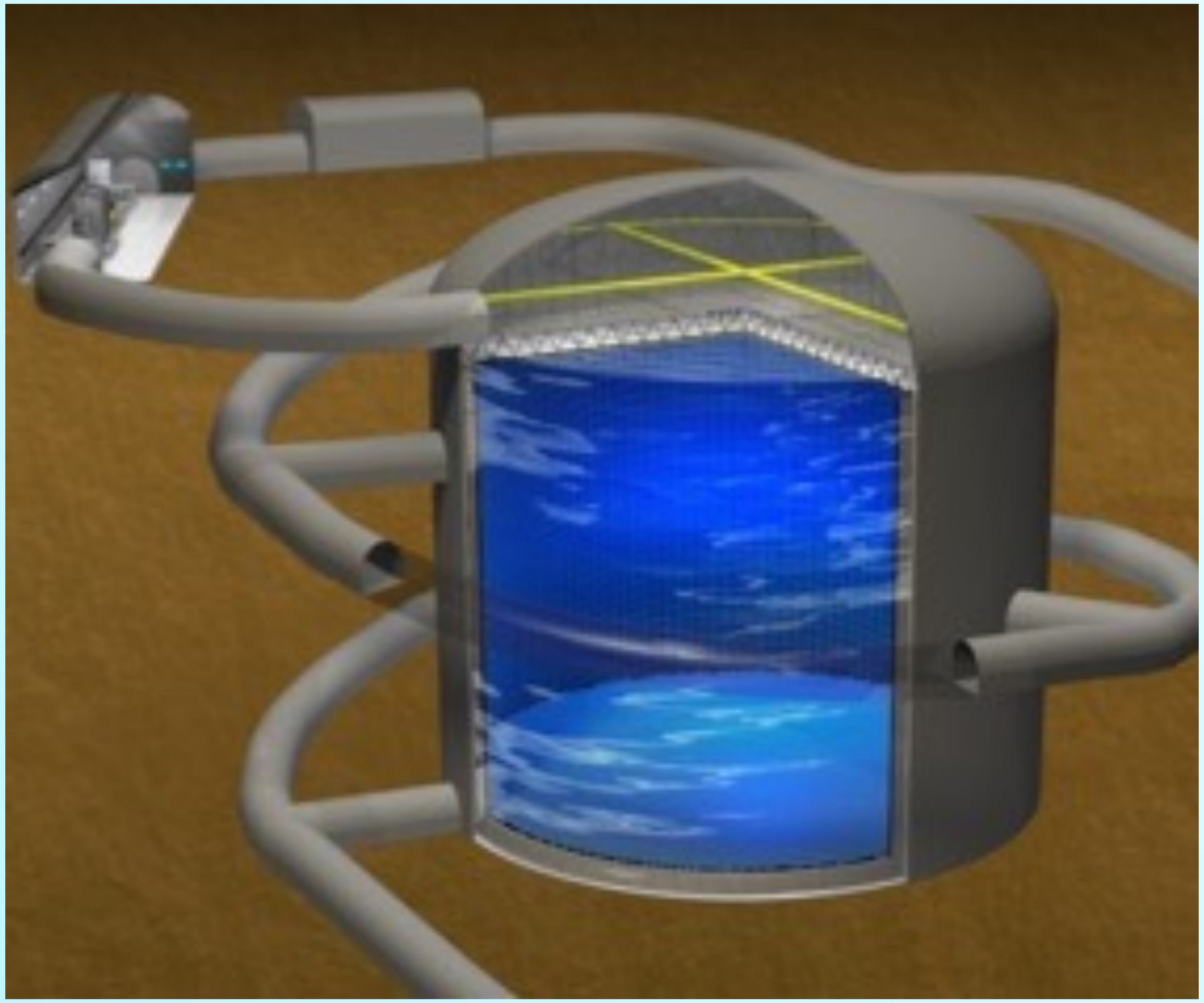
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	−2.596 – −2.452 & 2.368 – 2.592

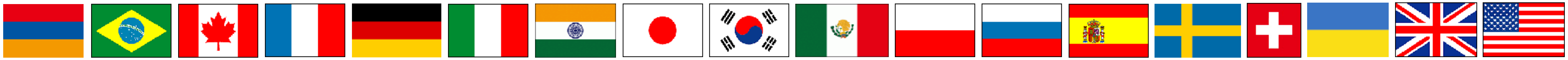

The international journal of science / 16 April 2020
nature
THE MIRROR CRACK'D
An indication of matter–antimatter symmetry violation in neutrinos

Hyper-Kamiokande

(now under construction, and operation in 2027)

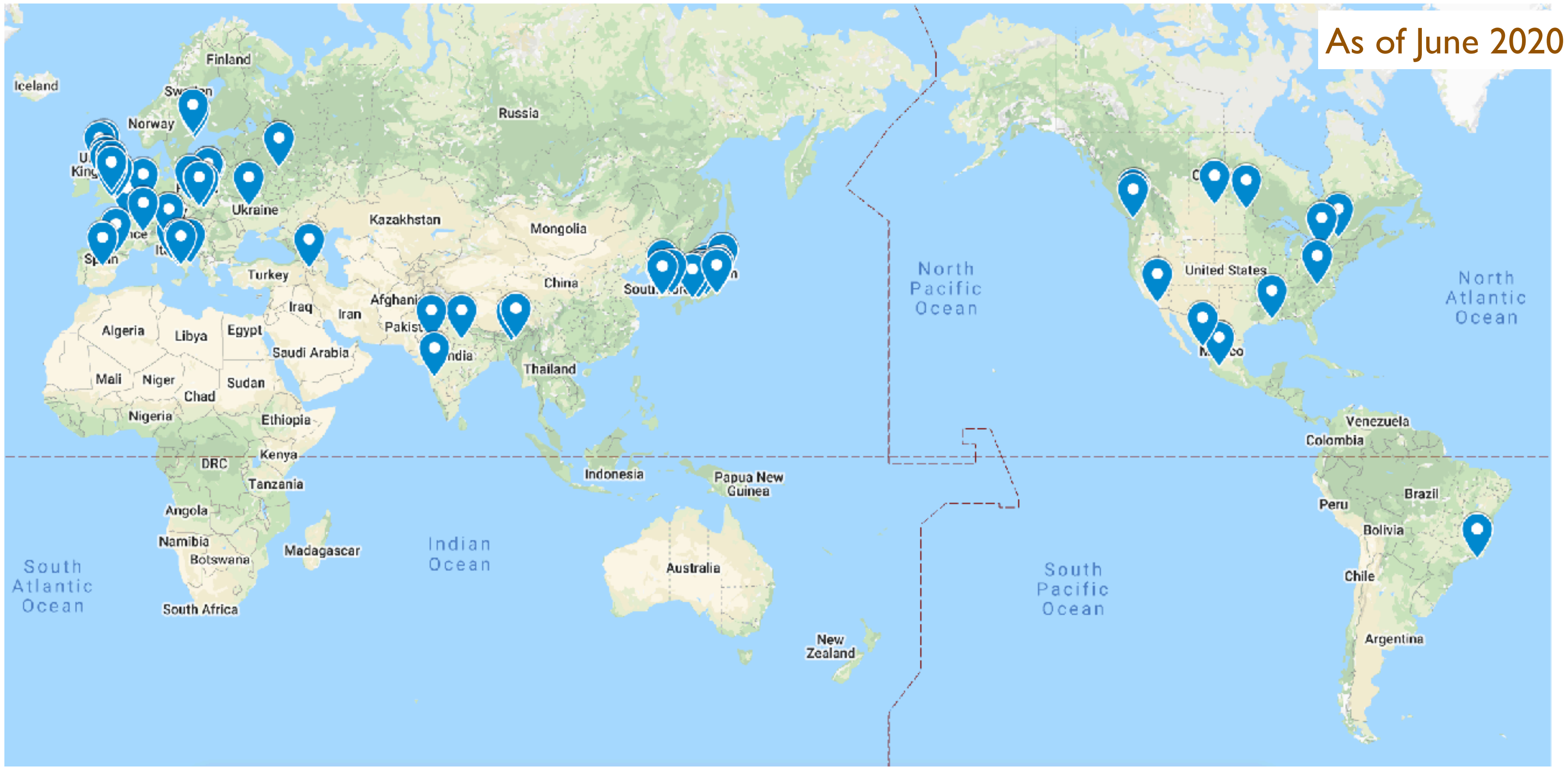


Hyper-Kamiokande Proto-Collaboration

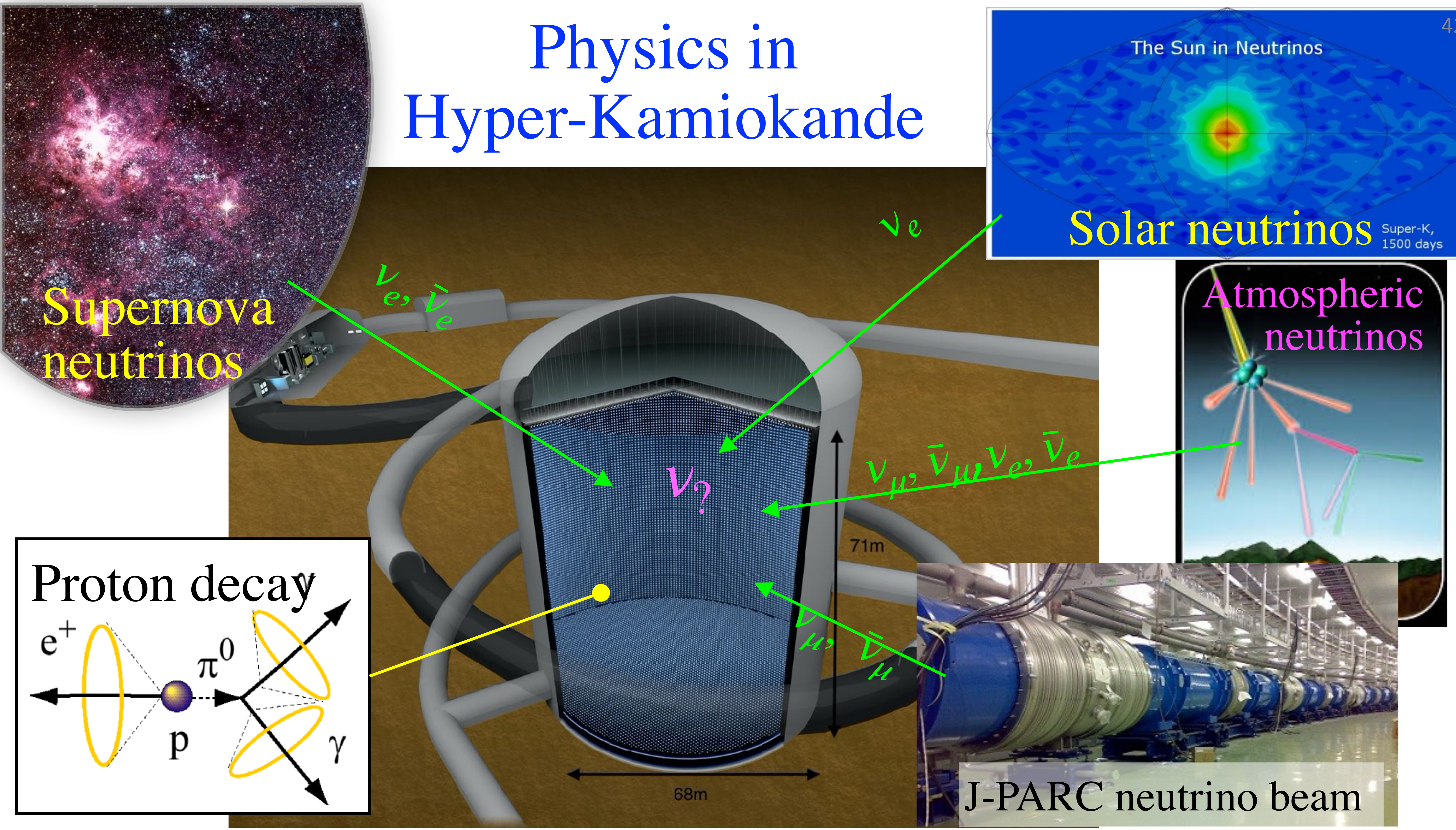


18 countries, 82 institutes, ~390 people

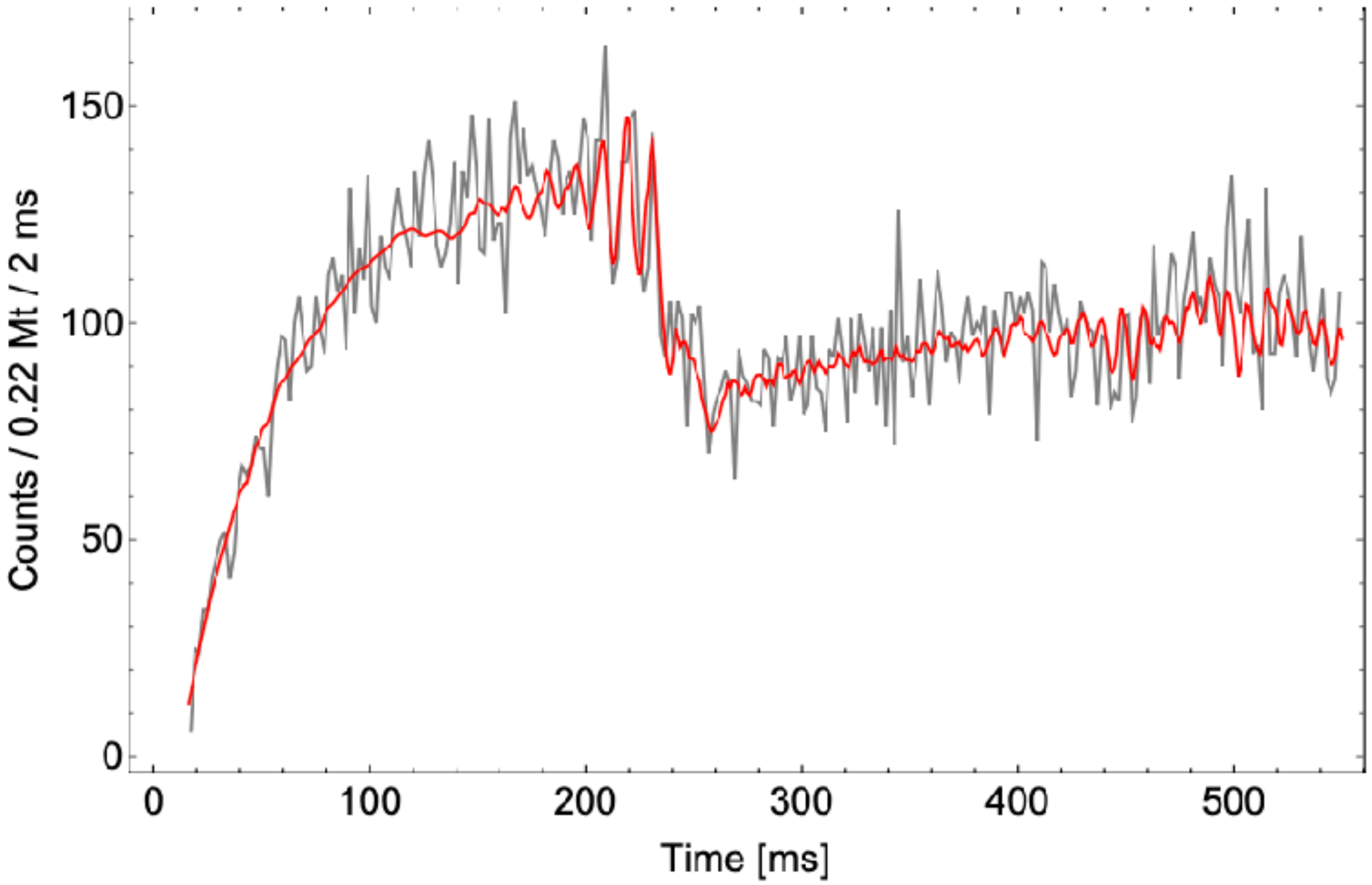
Hyper-Kamiokande



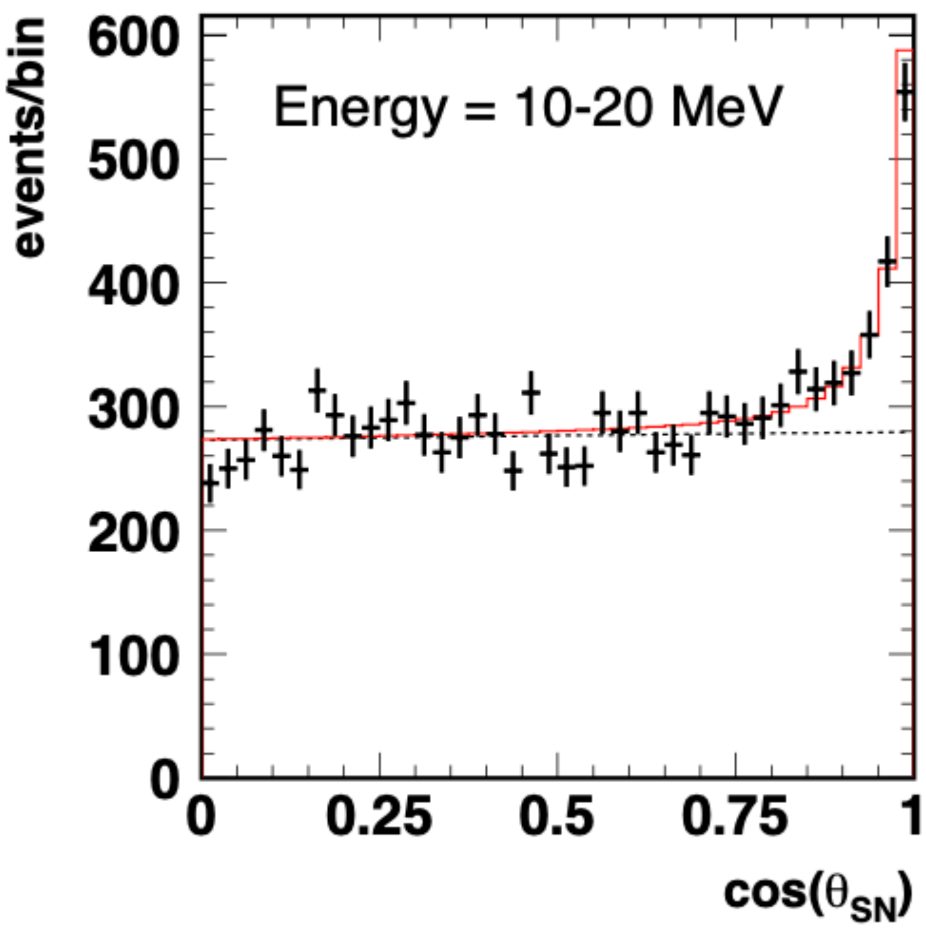
Physics in Hyper-Kamiokande



Neutrino astrophysics -Supernova -

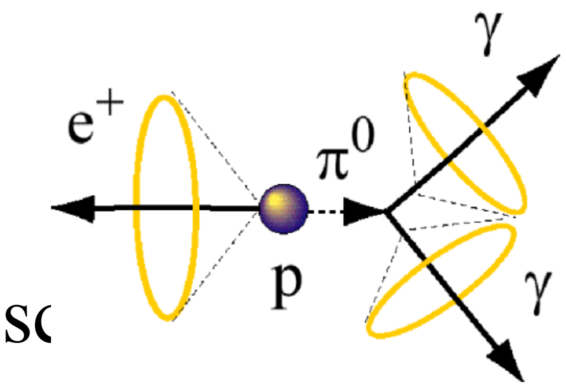


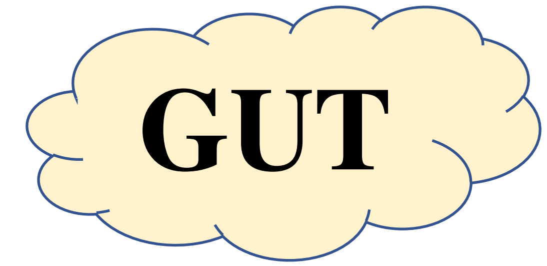
Modulation induced by SASI
statistical fluctuation in HK



SN direction
~70k $\nu's$ at 10kpc

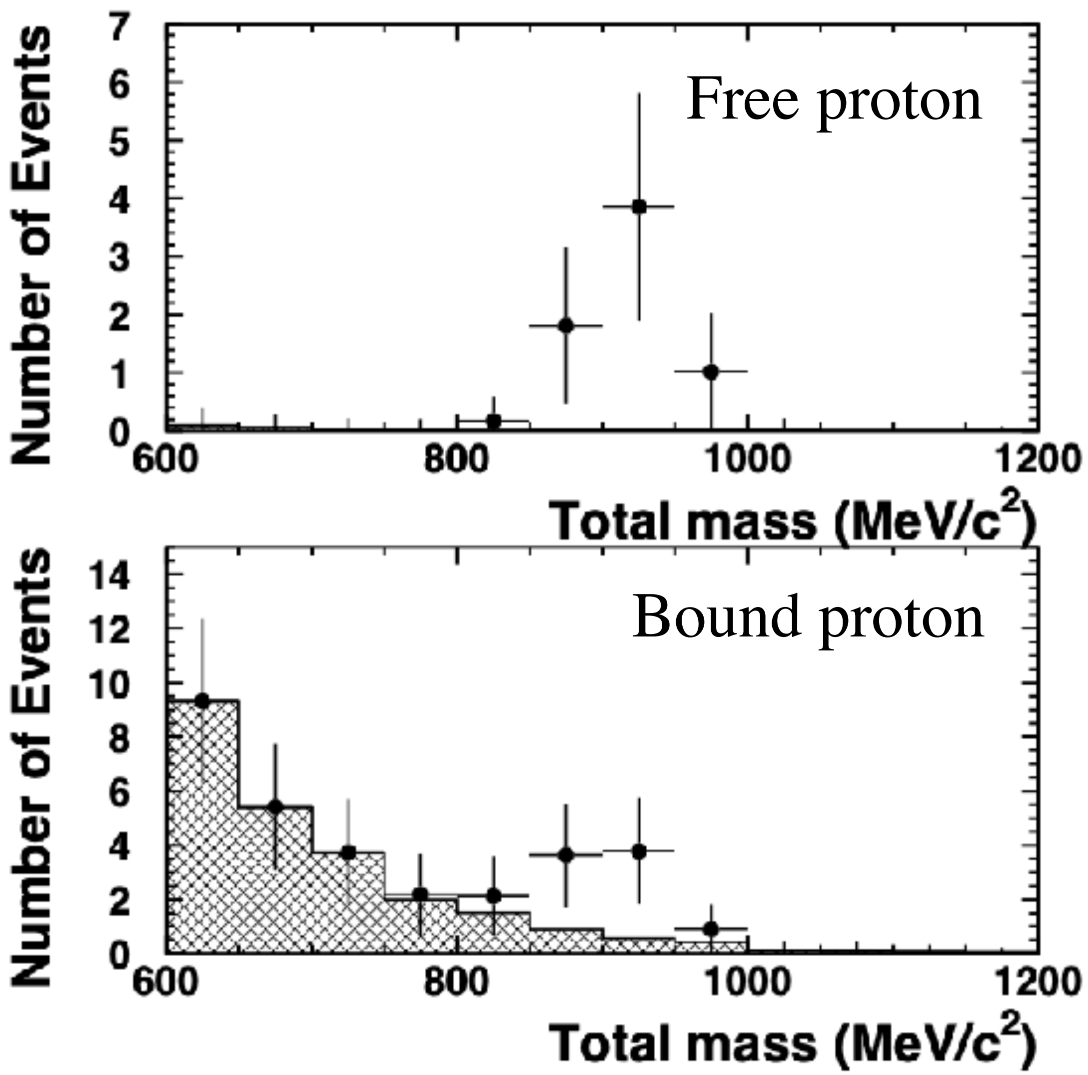
Proton decay search

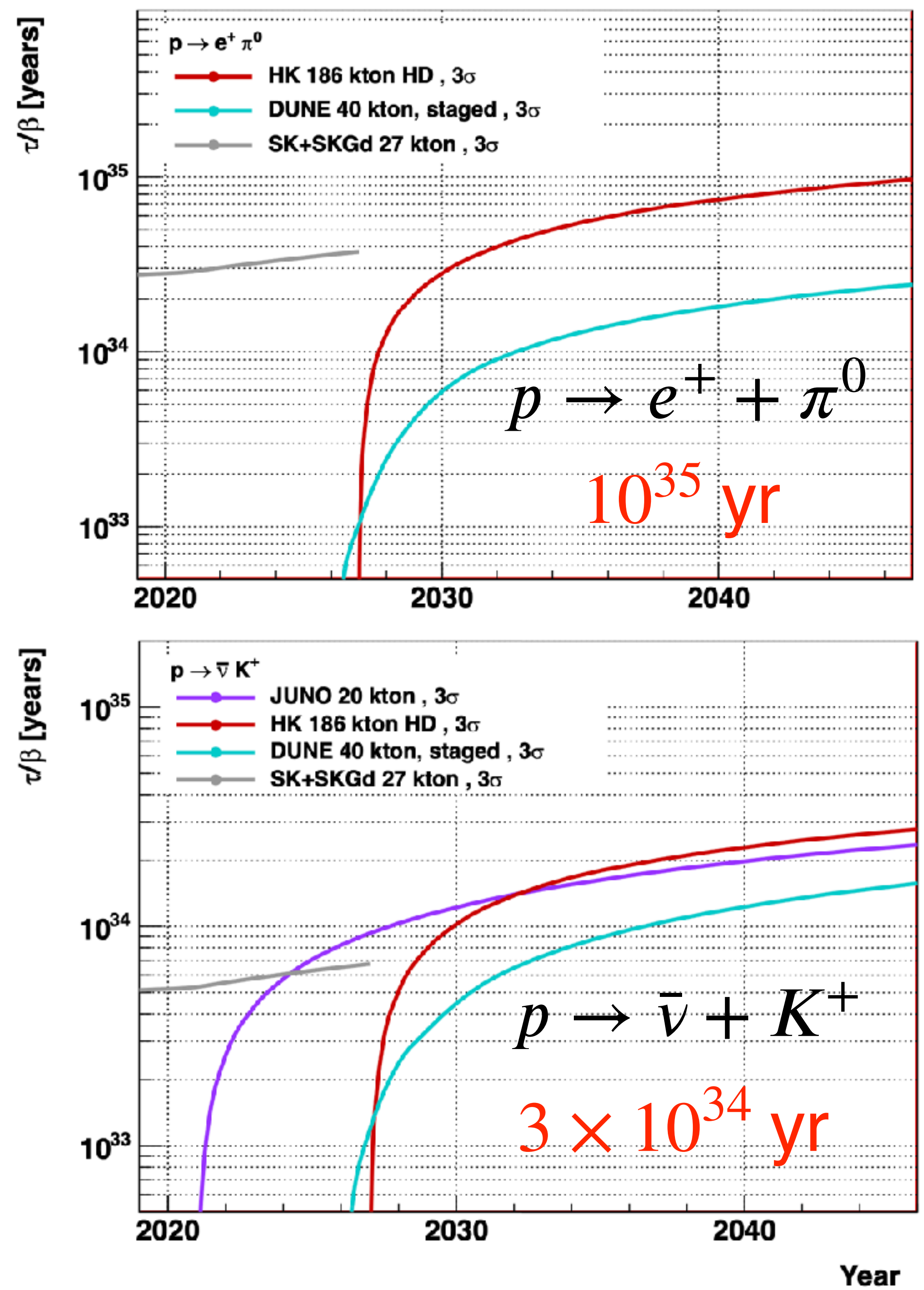




- One possible approach to reach GUT energy sc
- Extend proton decay search by one order of magnitude beyond the current limits

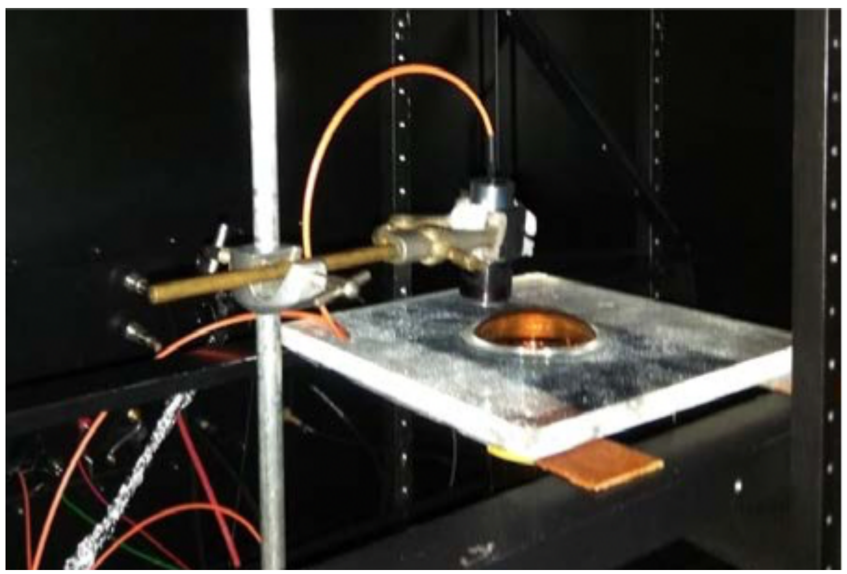
After 10 years of HK
if $\tau = 1.7 \times 10^{34}$ years ⋯





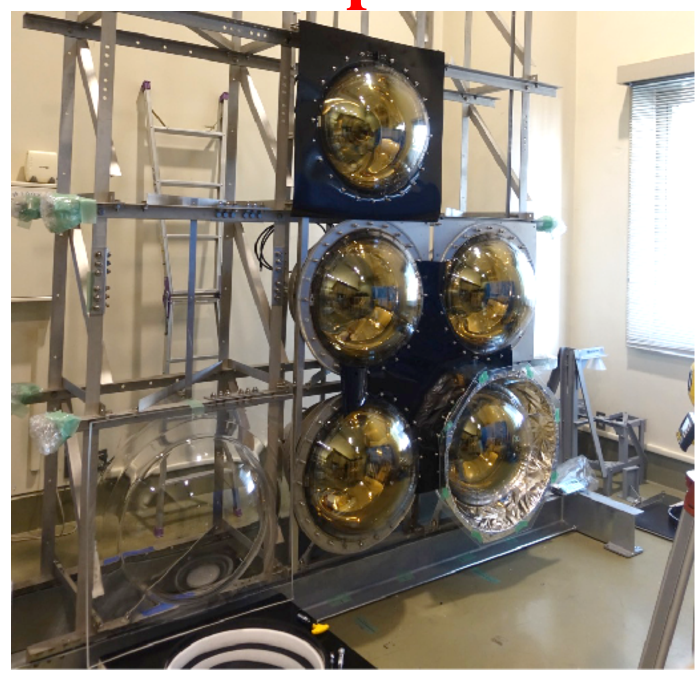
Detector R&D for Hyper-Kamiokande

Outer detector:
PMT + WLS plate (UK)



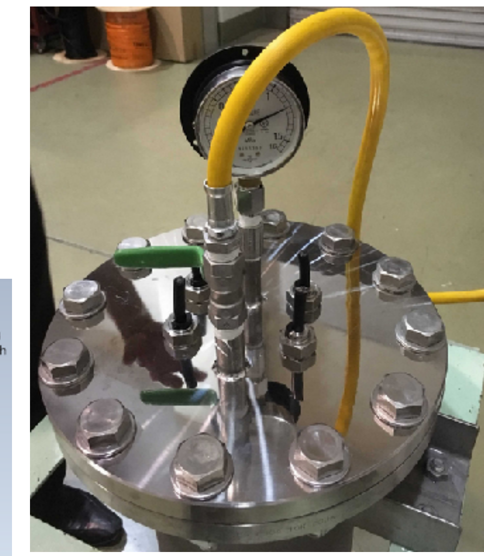
3-inch water proof PMT

ID mockup at ICRR

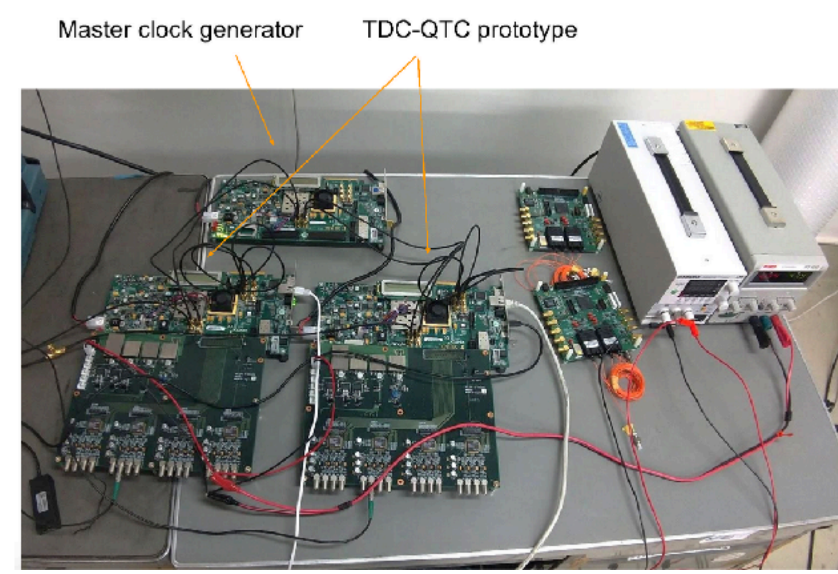


PMT cover
in Spain

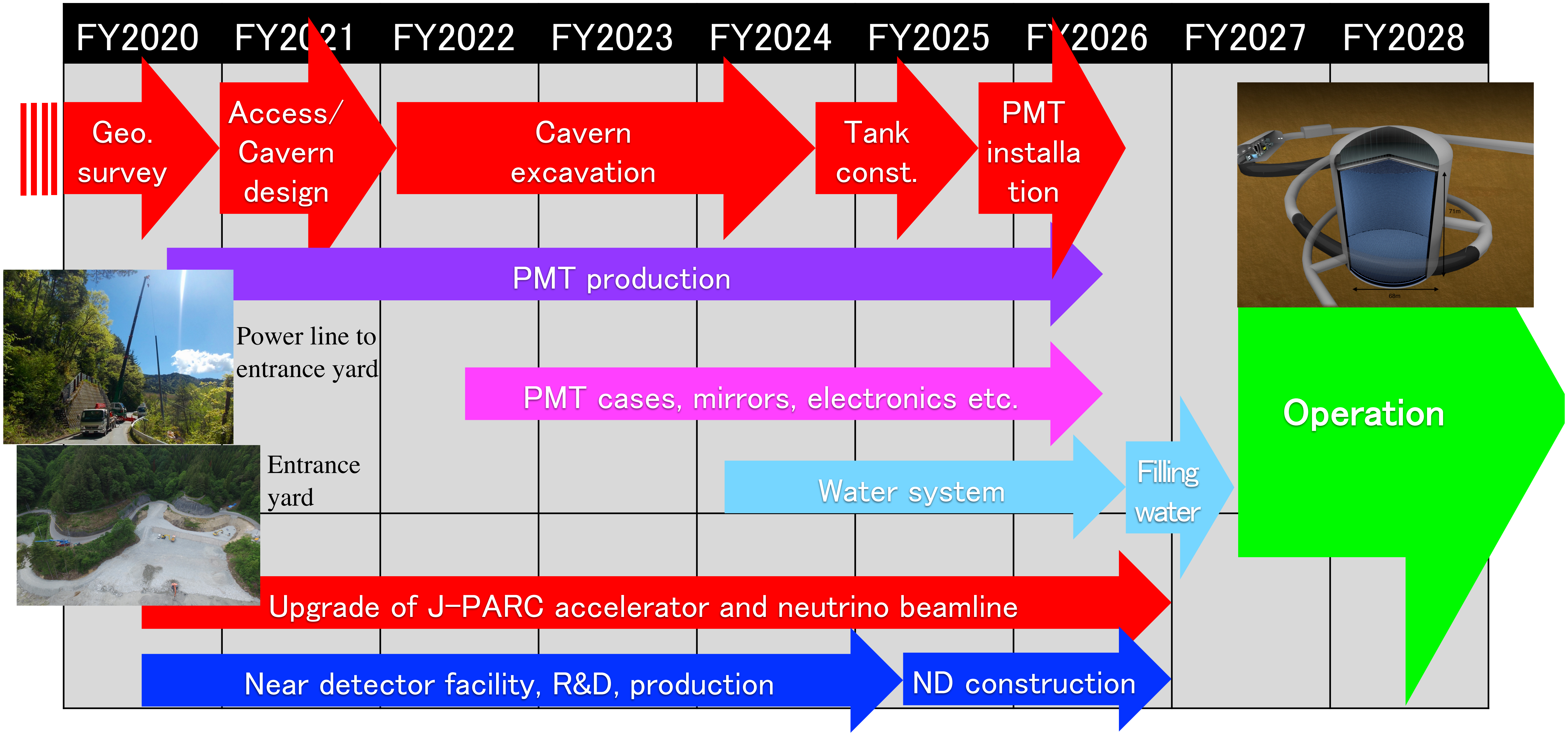
Underwater electronics:
Case design and feedthrough



Sync and clock system
test bench at TokyoTech



Hyper-Kamiokande schedule

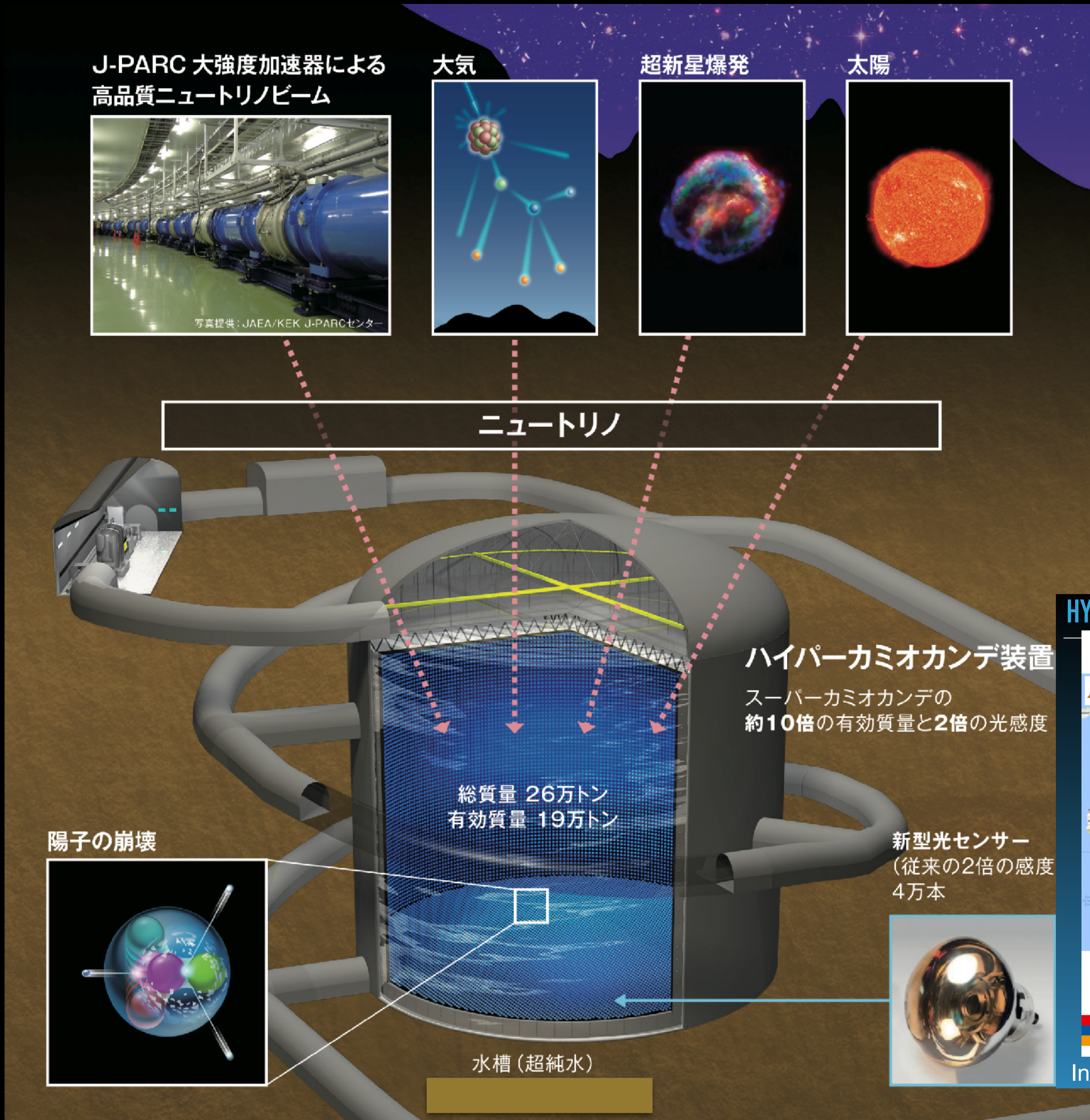


Summary

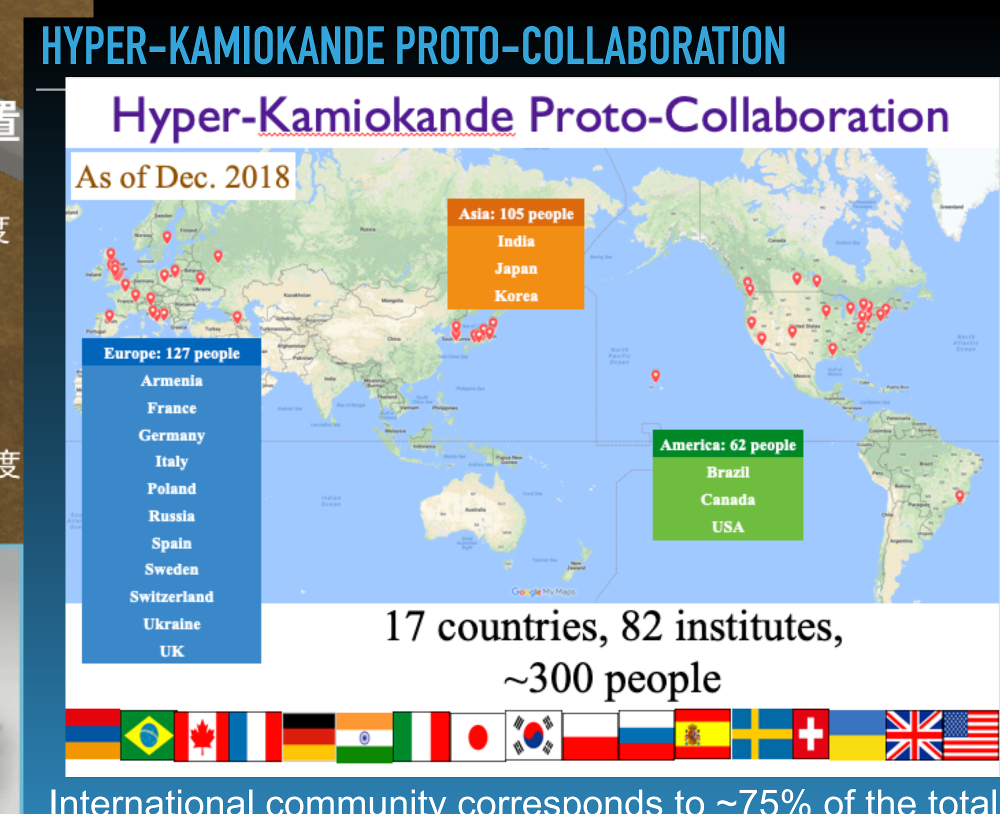
- Challenging and Interesting problems in particle physics
- Growing excitements of neutrino physics
- We have a tradition of neutrino physics in Japan.
  - Two Nobel prizes in neutrino physics
  - On-going activities with Super-Kamiokande
  - Future projects with Hyper-Kamiokande
- The neutrino group at ICISE in Vietnam is launched in good collaboration with Japanese physicists.

https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

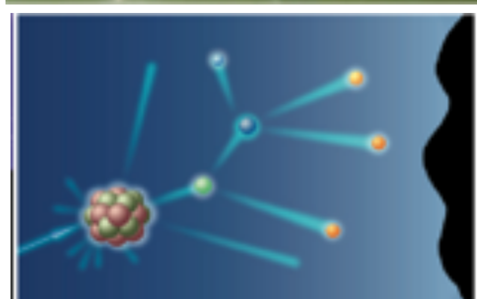
ハイパーカミオカンデ

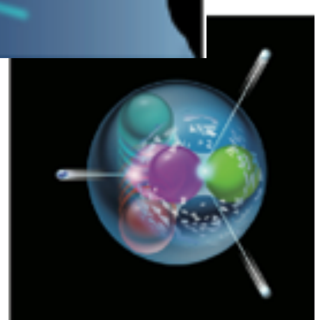


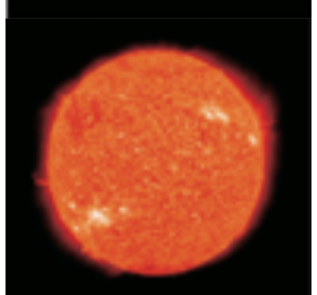
- ☆ 73m(高さ)×70m（直径）
- ☆ 総質量：237 kton
- ☆ 有効質量：197 kton
  (~8× Super-K)
- ☆ 光電面領域：40%
- ☆ 40,000 50cm ID PMTs
- ☆ 15,000 7.5cm OD PMTs

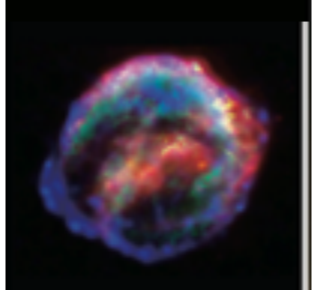


多彩な物理









加速器 (1.3MW×10years)	δ 精度	7°-22°
	CPの破れ (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ 精度 (for 0.5)	±0.017
大気(+加速器) (10 years)	質量階層性	>3.8σ
	八分円決定(3σ)	$\lvert\theta_{23}-45°\rvert>2°$
陽子崩壊 (20 years)	$e^+\pi^0$ (3σ)	1×10^{35}
	$\bar{\nu}K$ (3σ)	3×10^{34}
太陽 (10 years)	昼夜効果 (from 0/from KL)	8σ/4σ
	アップターン	>3σ
超新星	バースト (10kpc)	54k-90k
	背景	70ν's / 10 years