νACA's Local Workshop on Hyper-Kamiokande Physics
Donostia International Physics Center,
San Sebastián, June 13-14, 2023

The Hyper-Kamiokande Project

A long-base-line neutrino experiment
A neutrino telescope
A nucleon decay experiment

L. Labarga, U.A.M.

Proyecto PID2021-124050NB-C31 financiado por MCIN/AEI /10.13039/501100011033 / FEDER, UE

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN

Testing mass production of Hyper-Kamiokande's high QE, high resolution PMT Hamamatsu R12860
June 5th, 2023

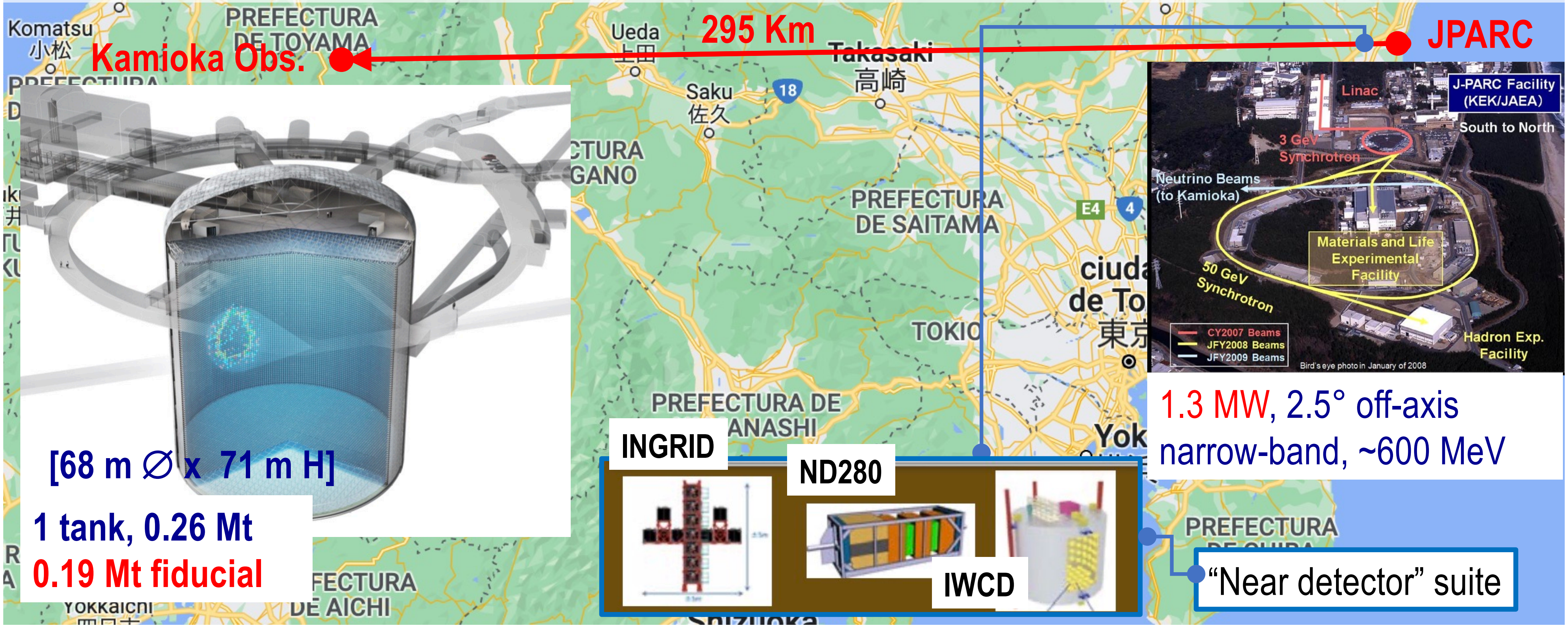
Mudanjiang
牡丹江市
Jixi
鸡西市
Spassk-Dalny
Спасск-Дальний
Ussuriysk
Уссурийск
Vladivostok
Владивосток
Yanbian
延边朝鲜
族自治州
Nakhodka
Находка
Asahikawa
旭川
Abashiri
網走
Shari
斜里町
Kitami
北見
Sapporo
札幌
Obihiro
帯広
Hakodate
函館
Sea of Japan
Sendai
仙台
Niigata
新潟
Tokyo
Japan
295 Km
Yokohama
横浜
Kyoto
京都
Himeji
姫路
Nagoya
名古屋
Osaka
大阪
Hiroshima
広島
Fukuoka
福岡
Nagasaki
長崎
Kumamoto
熊本
Kagoshima
鹿児島

- ✓ The world's largest detector for nucleon decay and neutrino experiments
- ✓ The world's most-intense neutrino beam
- ✓ New and upgraded near detectors to control systematics

8.4 x larger fiducial mass (**190 kiloton**), double-sensitivity photo-sensors than SK

J-PARC **ν** beam from 0.5 to **1.3 MW**

- uses Water-Cherenkov: unique technique to achieve huge amount of instrument matter
- maximizes available resources, experience & know-how → minimizes time, useless efforts, risks, delays, failure …

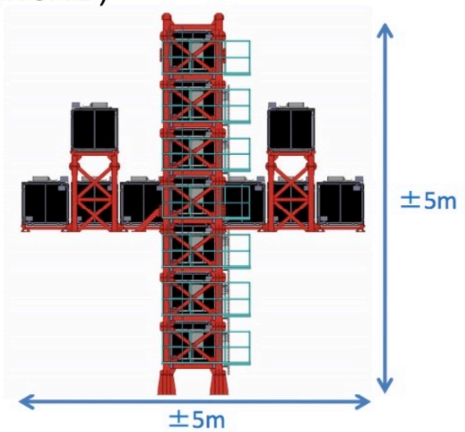


Neutrino detectors at J-PARC

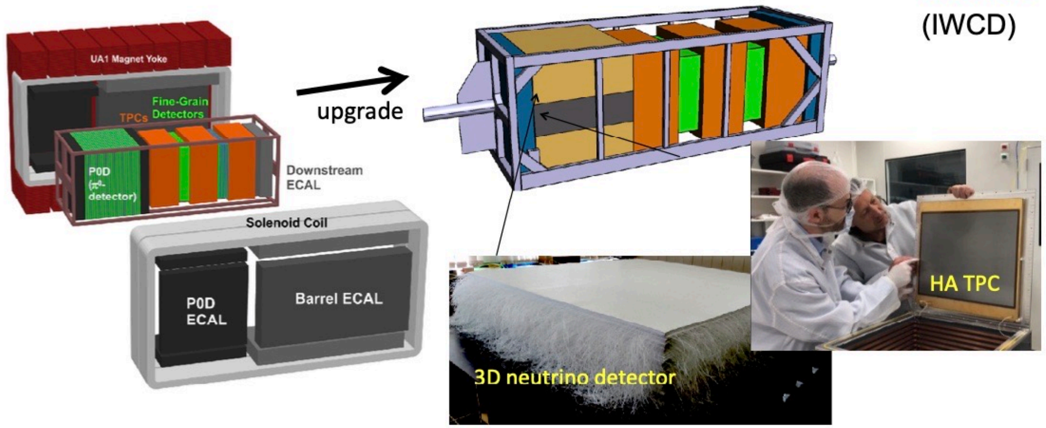
T. Nakaya @ US - J Symposium 20230522

Critical components to precisely understand J-PARC beam and neutrino interactions.

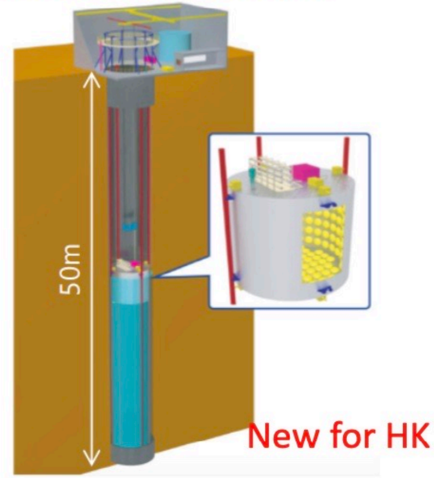
On-axis Detector
(INGRID)



Off-axis Magnetized Tracker
(ND280→Upgrade for T2K →Upgrade for HK)



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)

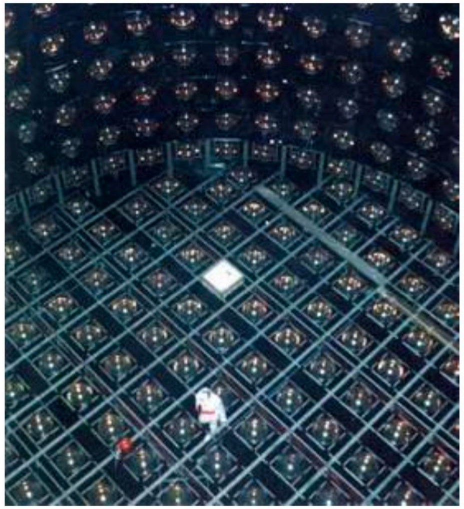


- On-axis detector: Measure beam direction and event rate
- Off-axis magnetized tracker: Measure primary (anti)neutrino interaction rates, spectrum and properties. Charge separation to measure wrong-sign background
  → Upgrade by T2K experiment and Intensive discussion for further upgrade in HK-era is on-going.
- Intermediate WC detector: H_2O target with off-axis angle spanning orientation.
  → Detector site investigation and conceptual facility design is on-going.

See T. Lux talk for the real stuff

Three Generations of Water Cherenkov Detector in Kamioka

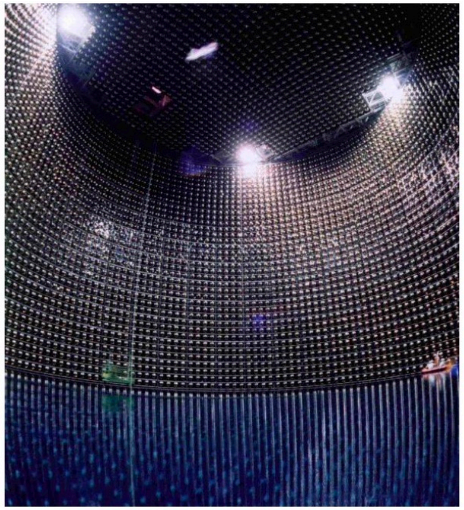
Yoichi Asaoka @ NNN22



Kamiokande
(1983-1996)

Birth of neutrino astrophysics

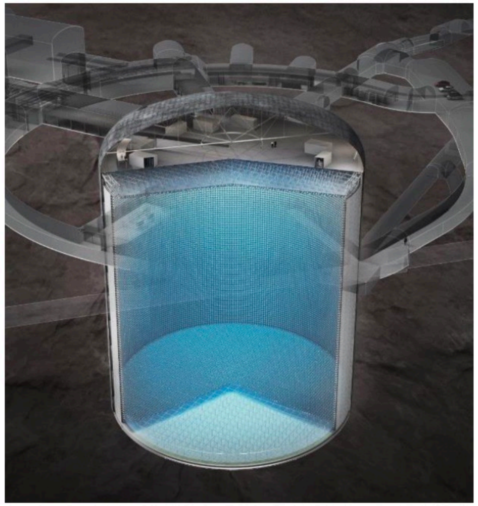
M_{tank} = 3kt, M_{eff} = ~1kt
#PMTs = 948



Super-Kamiokande
(1996 - ongoing)

Discovery of neutrino oscillations

M_{tank} = 50kt, M_{eff} = 22.5kt
#PMTs = 11,146



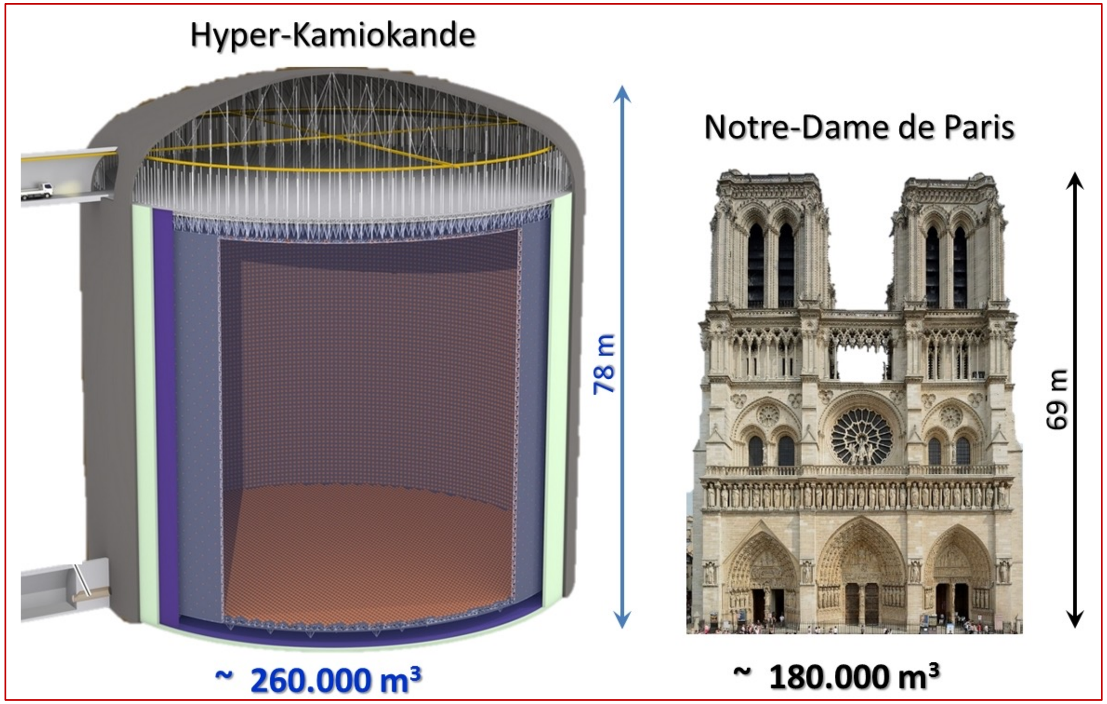
Hyper-Kamiokande
(start operation in 2027)

Explore new physics

M_{tank} = 260kt, M_{eff} = 188kt
#PMTs = 40,000

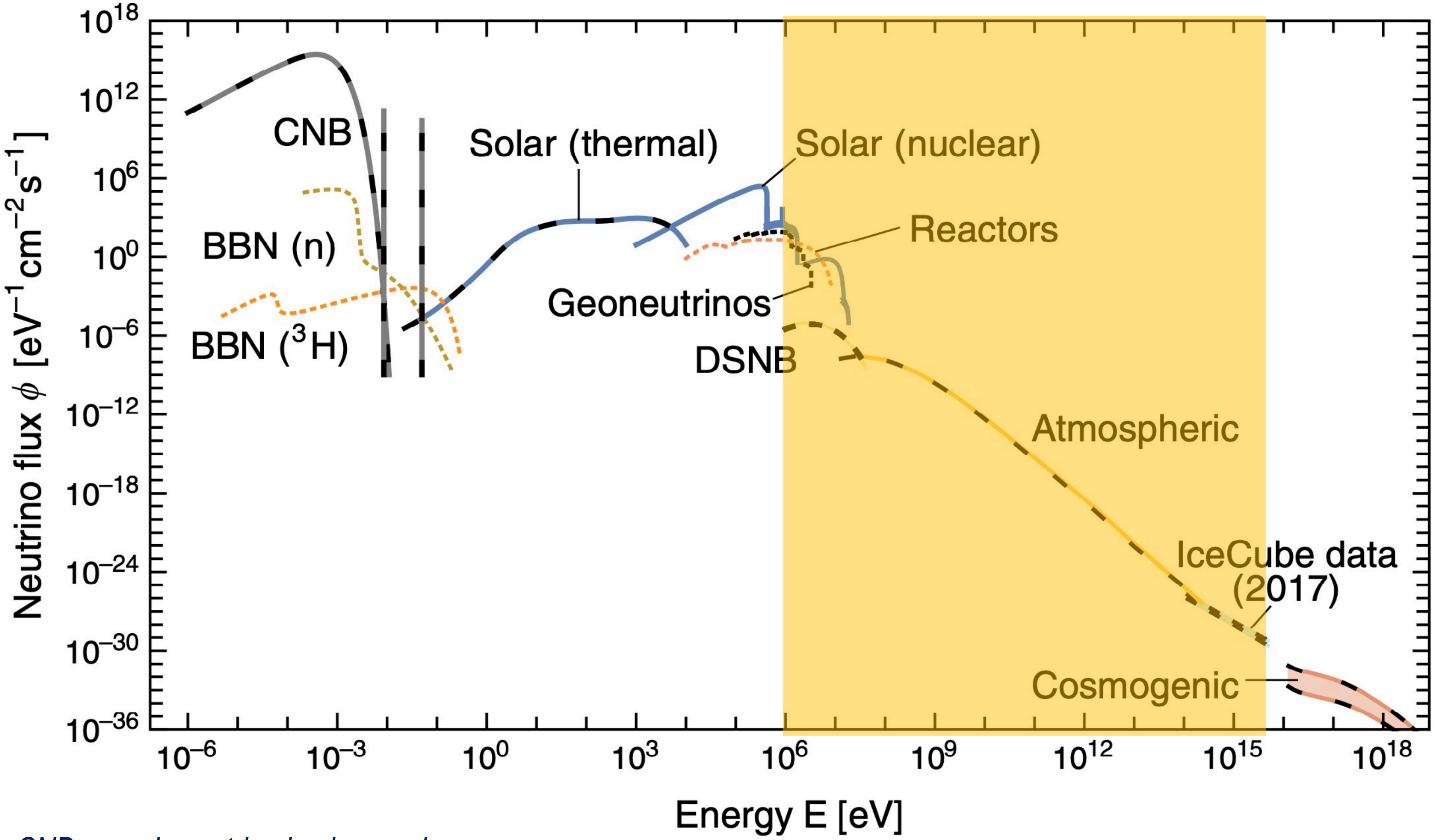
1. Area vs volume: effective scale up as long as water transparency allows.
2. Optimization of the detector configuration based on experience.

The 3 Kamiokande,s



neutrino spectrum at Earth: Sources and spectral components

E.Vitagliano, I. Tamborra. G. Raffelt; REVIEWS OF MODERN PHYSICS, VOLUME 92, OCTOBER–DECEMBER 2020



CNB: cosmic neutrino background
BBN: big-bang nucleosynthesis
DSNB: diffuse supernova neutrino background

spans almost 10 order of magnitude in E_ν

neutrino flux φ as a function of energy at Earth, integrated over directions and summed over flavors.

Solid lines are displayed for neutrinos, dashed or dotted lines are displayed for antineutrinos, and superimposed dashed and solid lines are displayed for sources of both ν and $\bar{\nu}$. The fluxes from BBN, Earth, and reactors encompass only antineutrinos and the Sun emits only neutrinos, whereas all other components include both.

The CNB is shown for a minimal mass spectrum of m_1= 0, m_2= 8.6, and m_3= 50 meV, producing a blackbody spectrum plus two monochromatic lines of nonrelativistic neutrinos with energies corresponding to m_2 & m_3. Line sources are in units of cm^{-2} s^{-1}.

HK officially started construction on 2020 and will start operations on 2027

The Hyper-Kamiokande project is a third generation within the Japanese Neutrino Program: a truly scientific success

- uses Water-Cherenkov: unique technique to achieve huge amount of instrument matter
- precise rec. of particle's energy, position, direction, type …
  - maximizes available resources → minimizes time, useless efforts …
  - maximizes experience & know-how → minimizes risks, delays, failure

$^{(2)}H_2O$-Cherenkov experimental technique // their origin: search for proton decay

In the Standard Model the proton is stable, however, given the physics-mathematics structure of the SM, the realistic theoretical approaches for its evolution, the current knowledge about the creation and development of the Universe...

This is one of the most important scientific concepts of Humanity.

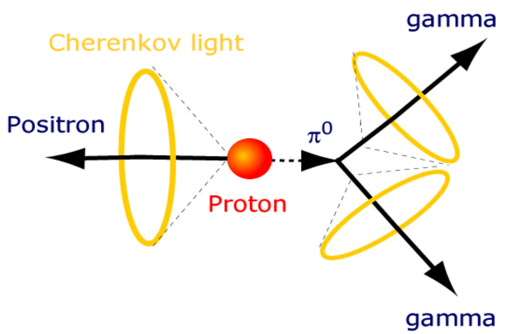
→ there is the "conviction" (however it is just intuition) of the non-stability of the proton

Triggered by the unambiguously prediction of a decaying proton decay in a SU(5) Grand Unification [*Georgi, Glashow, Physical Review Letters 32 (8): 438 1974*] experimental techniques aiming to observe huge amounts of protons were developed

Kamiokande was a pioneering experiment

✓ the $^{(2)}H_2O$-Cherenkov experiments allows to **instrument huge amounts of matter** (i.e of protons)

for instance: $p \rightarrow e^+\pi^0$



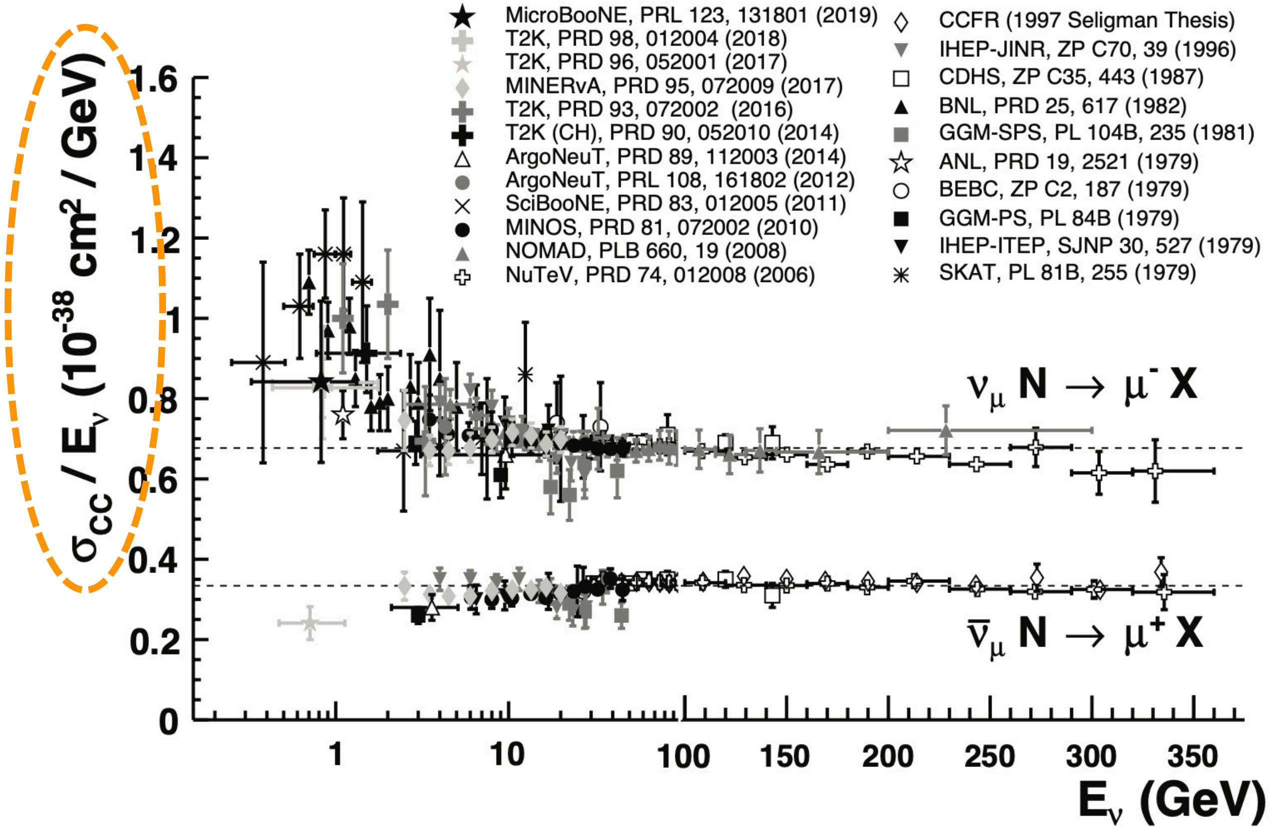
(Compton e⁻)

(Compton e⁻)

no candidate sofar ⇨ $\tau_p > 1.4 \times 10^{34}$ year

Super-Kamiokande, PHYSICAL REVIEW D 102, 112011 (2020)

But those huge amounts of instrumented matter also detect surrounding neutrinos; even though their **extremely low interaction cross section**, the extremely large amount of mass results in interactions that are detected (they are background for p-decay searches)



Measurements of per nucleon ν_μ and ν_μ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV.

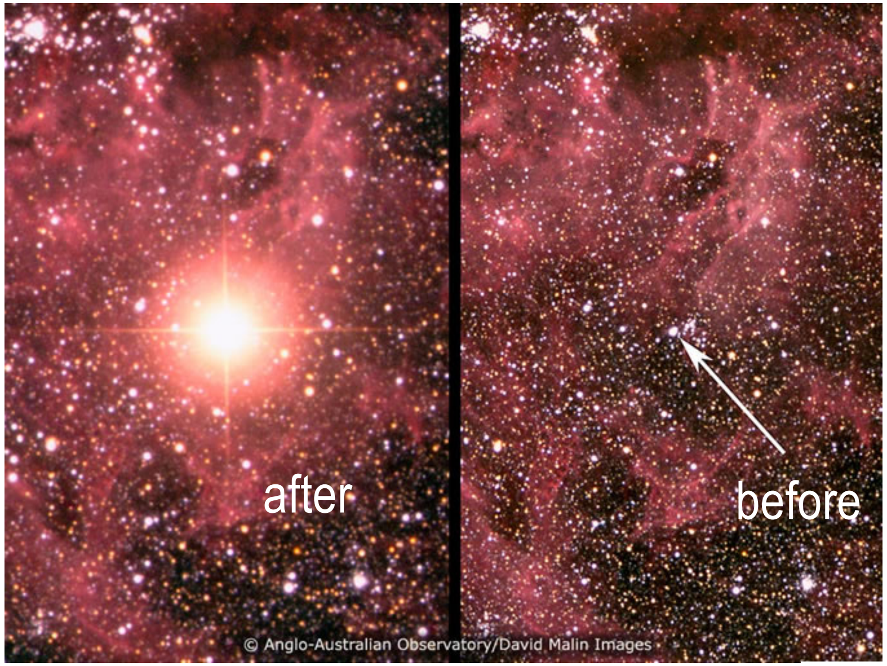
Improve Rn background with water purification, add an OD, improve timing of electronics

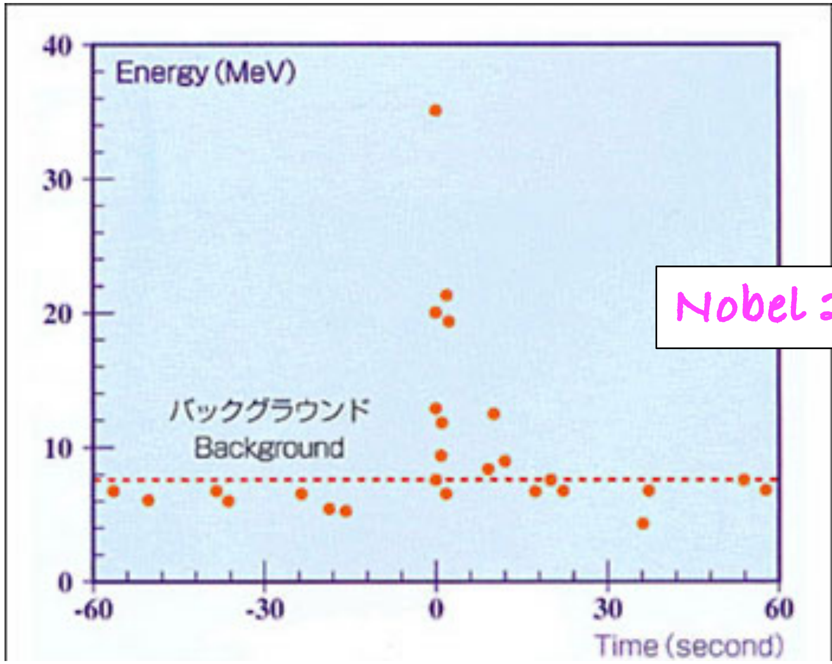
➔ Kamiokande II, a wonderful multipurpose proton decay and neutrino (also low energy) experiment

Nature itself came to guide us: made us discover that this type of detectors are **extraordinary** **neutrino telescopes**

Kamiokande; Phys. Rev. Lett. 58 (1987) 1490
IMB; Phys. Rev. Lett. 58 (1987) 1494

Supernova SN1987A @ Large Magellanic Cloud





Nobel 2002

flux and E spectrum of ν,s measured by Kamiokande II (precursor of SK) ((pre-precursor of HK))

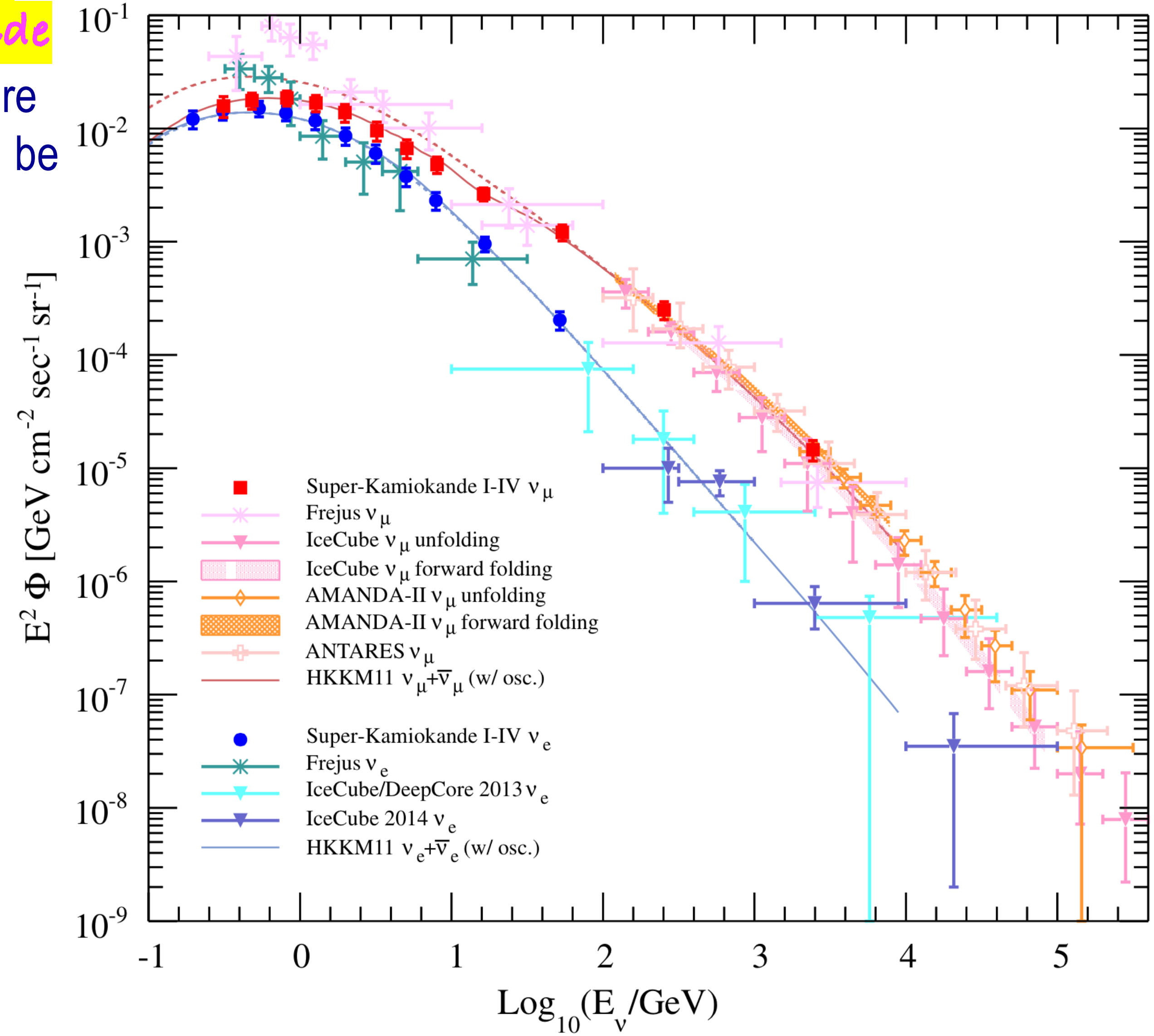
If more mass, and even better photosensors precise **fundamental neutrino physics** can be made

➔ Super-Kamiokande

The much larger mass of **Super-Kamiokande** allows many more reactions (events) to be produced and study

measurements of the atmospheric neutrino flux

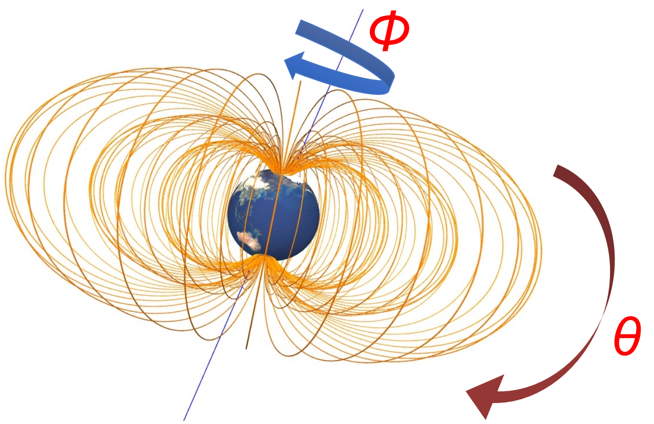
Super-Kamiokande; Phys. Rev. D 94, 052001 (2016)

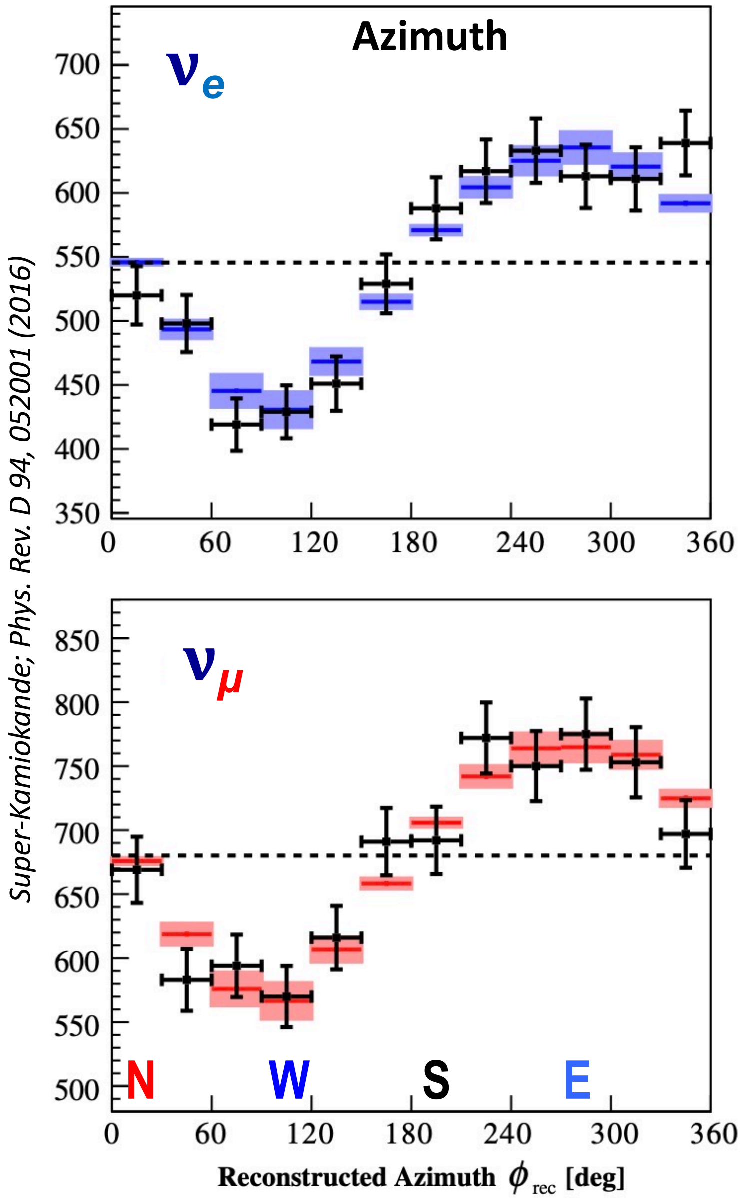


measured energy spectra of the atmospheric ν_e and ν_μ fluxes by SK, shown with measurements by other experiments, i.e., Frejus, AMANDA-II, IceCube and ANTARES.

Interlude
(this time for illustration purposes)

ν_e , ν_μ fluxes vs. incidence angle (azimuth): Φ symmetry does not totally hold because of earth magnetic field affecting the parent cosmic rays [E – W effect]



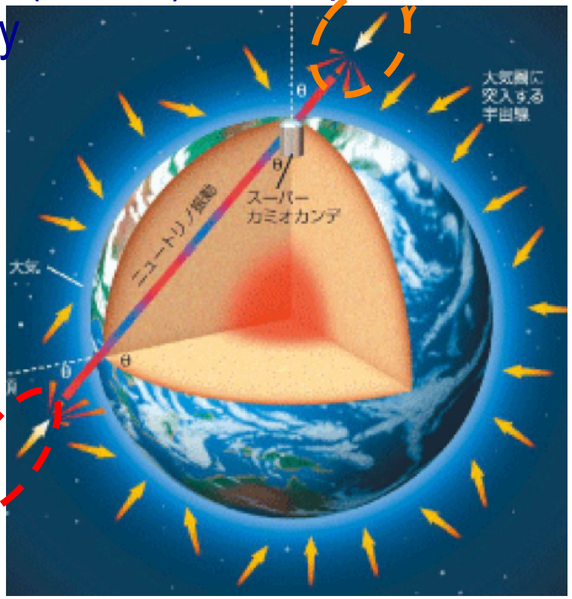


subselection of e-like and μ-like events, from the SK-I – SK-IV data (points with statistical error) and MC simulations (boxes with systematic error).

subselection is optimized for higest significance:
0.4 GeV< E(ν) < 3 GeV
| cos θ | < 0.6

→ Φ (azimuth) symmetry is as expected / well described

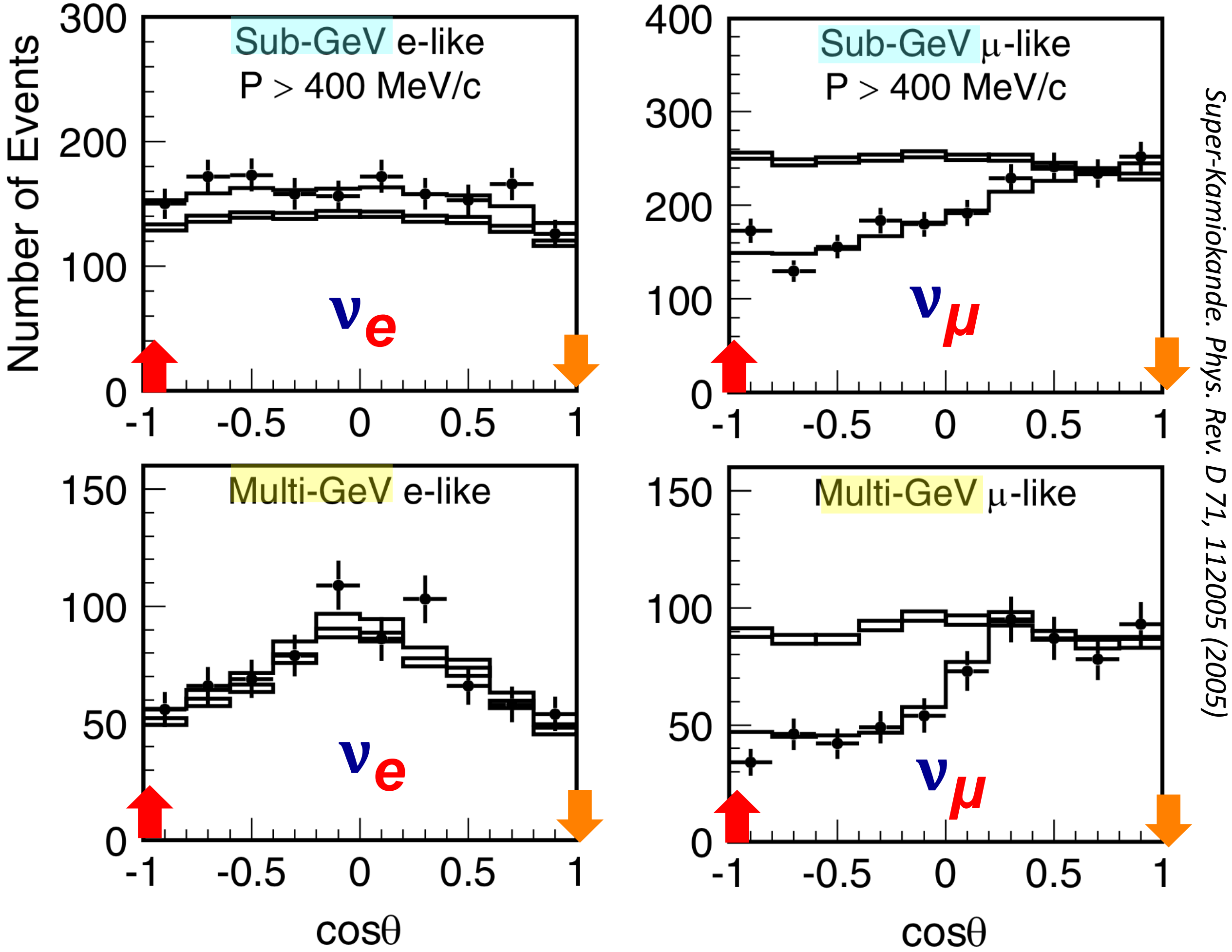
The much larger mass of Super-Kamiokande allows many more reactions (events) to be produced and study



upwards, travel ≈ 13000 km

downwards, travel ≈ 15 km

ν_e , ν_μ fluxes vs. energy and θ incidence angle (zenith)



measured ν_μ flux strongly dependent on travel distance → ν_μ oscillates (mainly to ν_τ) → **massive ν_X** ✓

Nobel 2015

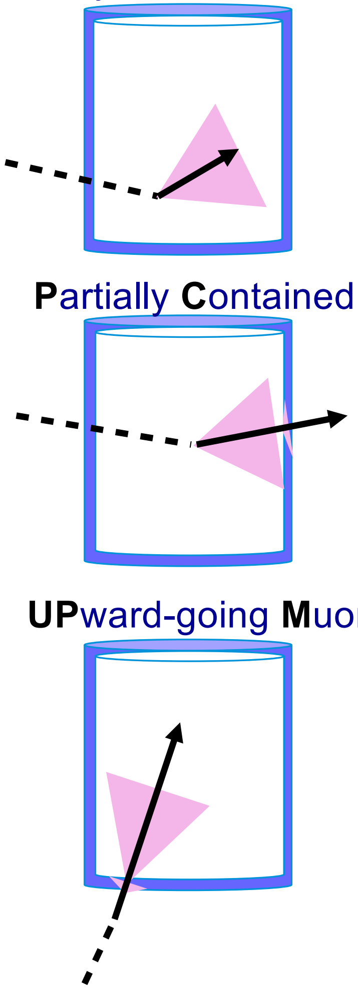
A full oscillation analysis:

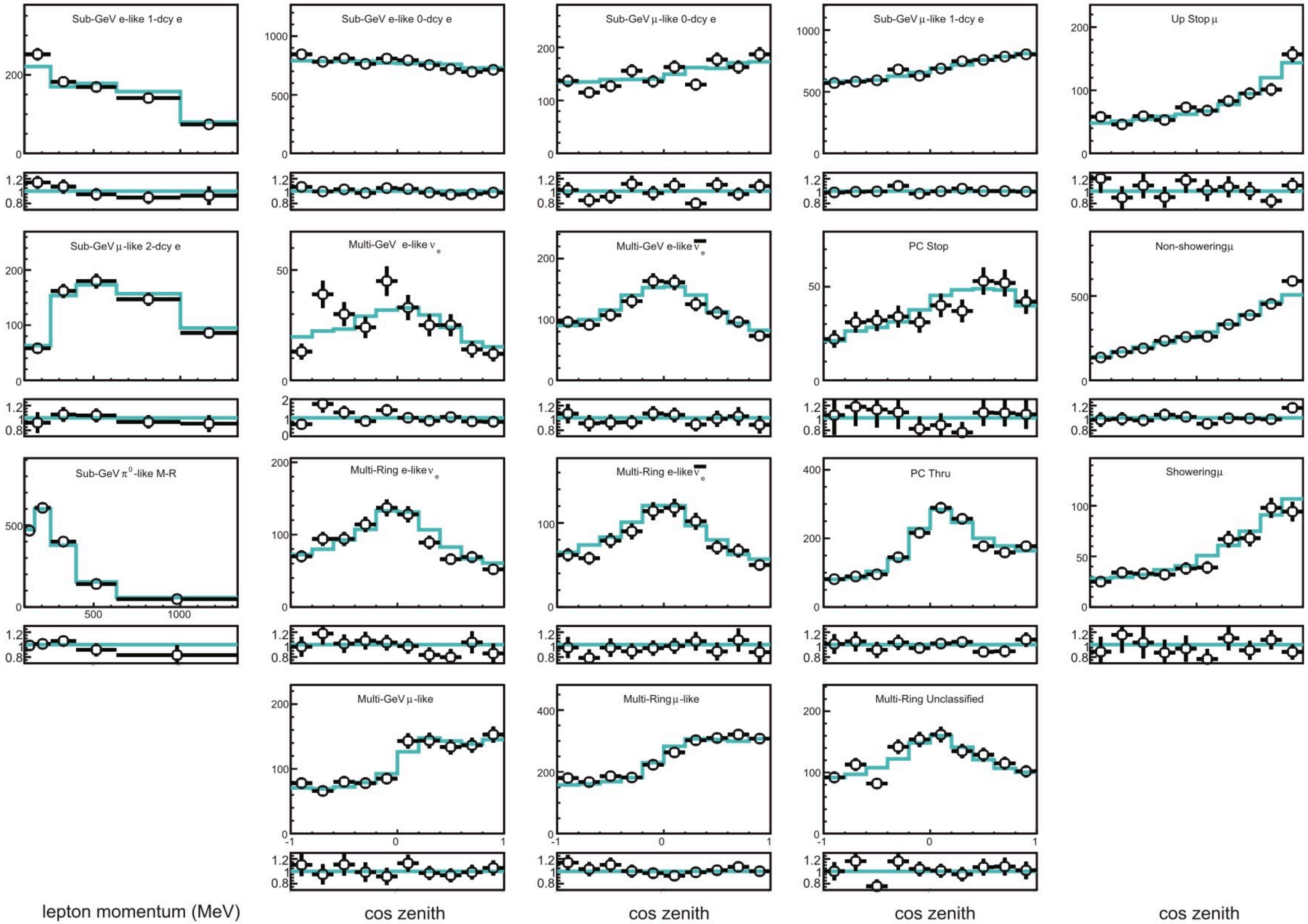
Super-Kamiokande, Prog. Theor. Exp. Phys. 2019, 053F01

Fully **C**ontained

Partially **C**ontained

UPward-going **M**uons





Huge statistics, extremely powerful data **if** systematics controlled to the same level of significance

Pontecorvo, B., J. Exp. Theor. Phys. 33, 549 (1957) [Sov. Phys. JETP 6, 429 (1958)]
Pontecorvo, B., J. Exp. Theor. Phys. 34, 247 (1958) [Sov. Phys. JETP 7, 172 (1958)]
Maki, Z., Nakagava, M. and Sakata, S., Prog. Theor. Phys. 28, 870 (1962)

interlude:

The Leptonic Mixing Matrix *(the PMNS matrix)*

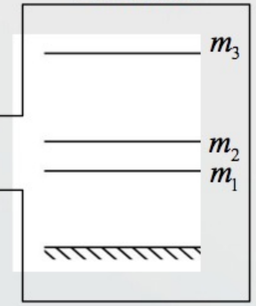
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Standard Model states

If **Dirac Neutrinos**

Neutrino mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}$$

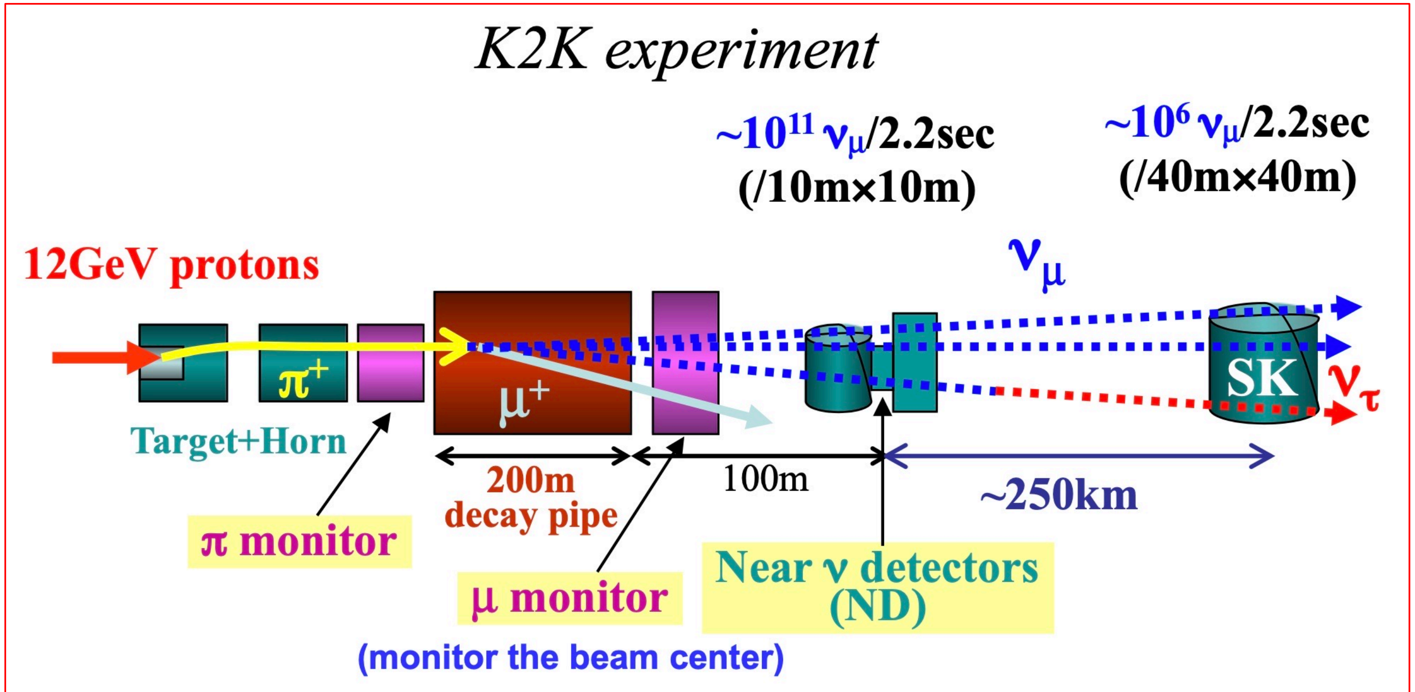
$s_{12} \equiv \sin\theta_{12}$; $c_{12} \equiv \cos\theta_{12}$ etc.; δ_{CP}: CP violation phase;

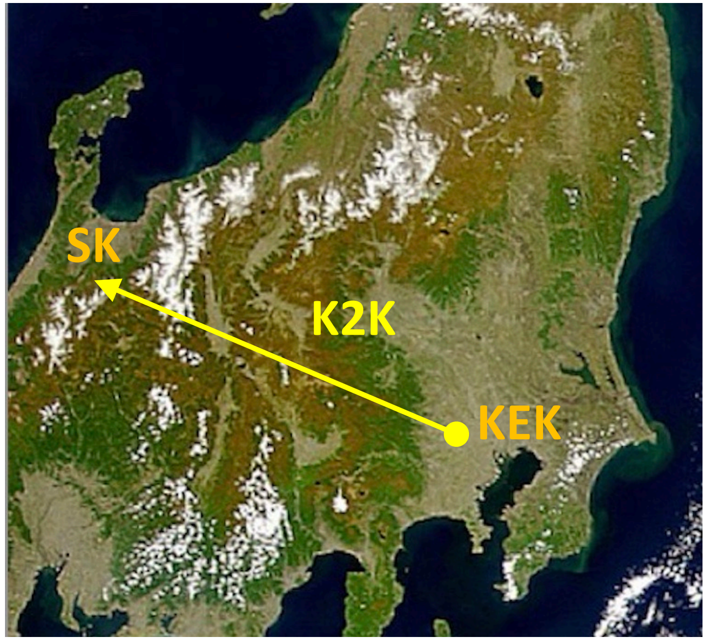
The whole process ought to be checked thoroughly / the birth of the Long-Base-Line ν beam experiments

K2K (from KEK-to-Kamioka)

Fully man-made ν oscillation experiment:

ν_μ disappearance in a ν_μ beam





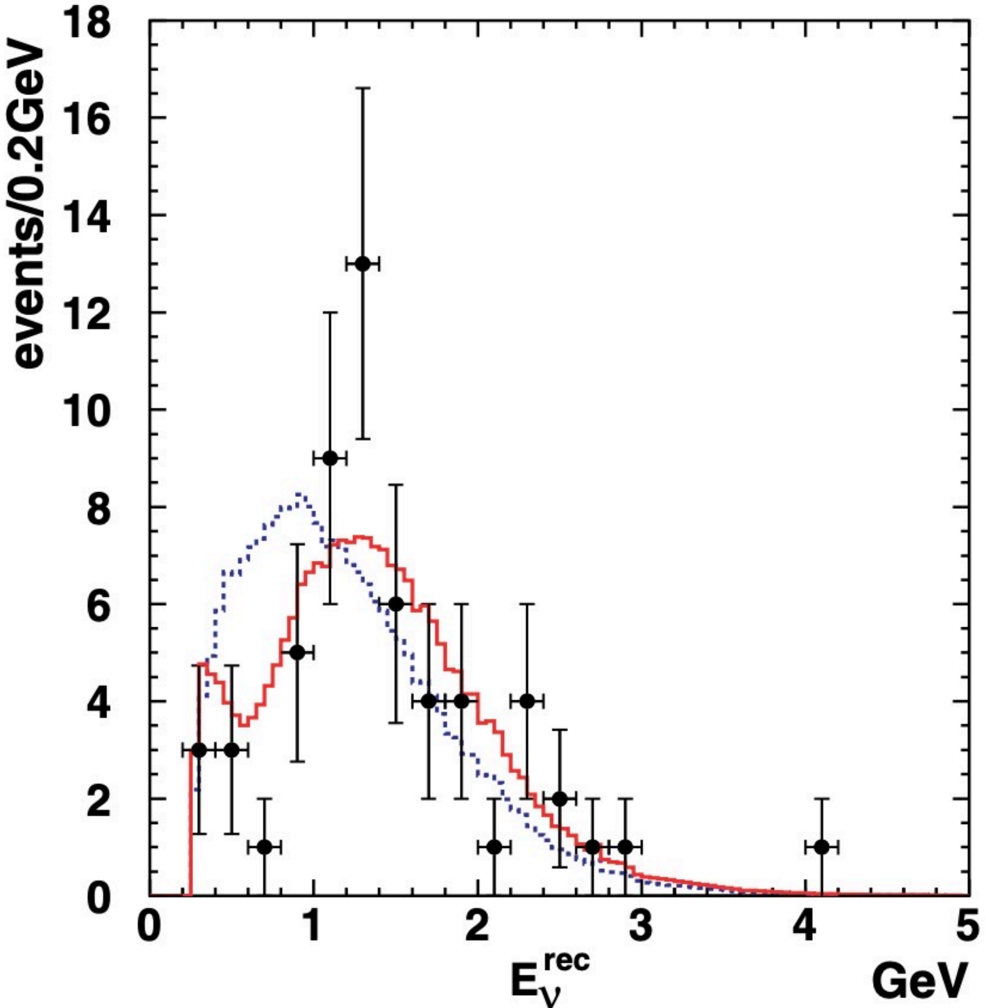
PRL 94, 081802 (2005)
PHYSICAL REVIEW D 74, 072003 (2006)

Abstract (PRD74,072003-2006)

We present measurements of ν_μ disappearance in K2K, the KEK to Kamioka long-baseline neutrino oscillation experiment. 112 beam-originated neutrino events are observed in the fiducial volume of Super-Kamiokande with an expectation of $158^{+9.2}_{-8.6}$ events without oscillation. A distortion of the energy spectrum is also seen in 58 single-ring μ-like events with reconstructed energies. The probability that the observations are explained by the expectation for no neutrino oscillation is 0.0015% (4.3 σ). In a 2-flavor oscillation scenario, the allowed Δm^2 region at $\sin^2 2\theta$= 1 is between 1.9 and 3.5 x 10^{-3} eV^2 at the 90% C.L. with a best-fit value of 2.8 x 10^{-3} eV^2

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2\ (\mathrm{eV}^2) L\ (\mathrm{km})}{E_\nu\ (\mathrm{GeV})}\right)$$

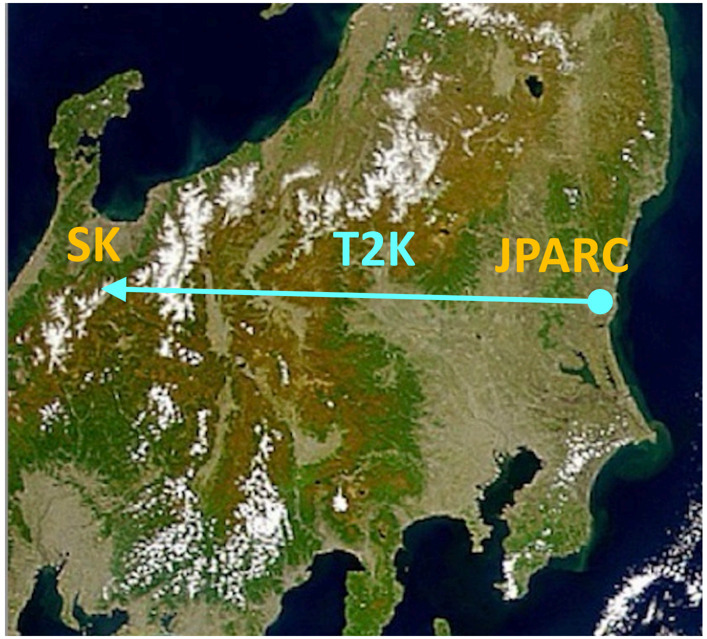
Success ! next is the whole PMNS matrix, … and to seeking for a door to CPV



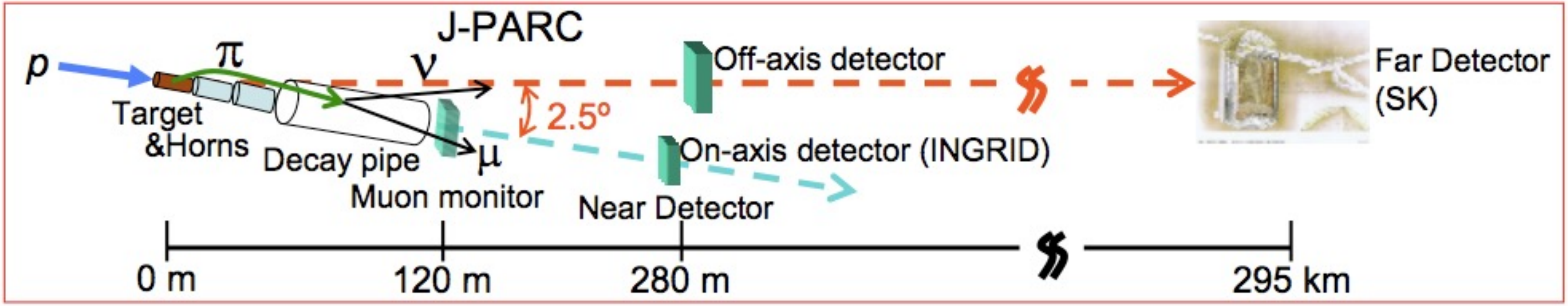
The reconstructed Eν distribution for the SK 1-ring μ-like sample. The solid line is the best fit spectrum and the dashed line is the expectation without oscillation.

T2K

Profit of the planned J-PARC nuclear laboratory (JAEA – KEK) to include a new powerful, custom, ν beam pointing to Kamioka



ν_μ and $\bar{\nu}_\mu$ **disappearance** in a ν_μ and $\bar{\nu}_\mu$ beams → θ_{23} , Δm^2_{23}
ν_e / $\bar{\nu}_e$ **appearance** in a ν_μ / $\bar{\nu}_\mu$ beam → θ_{13} , δ_{CP}



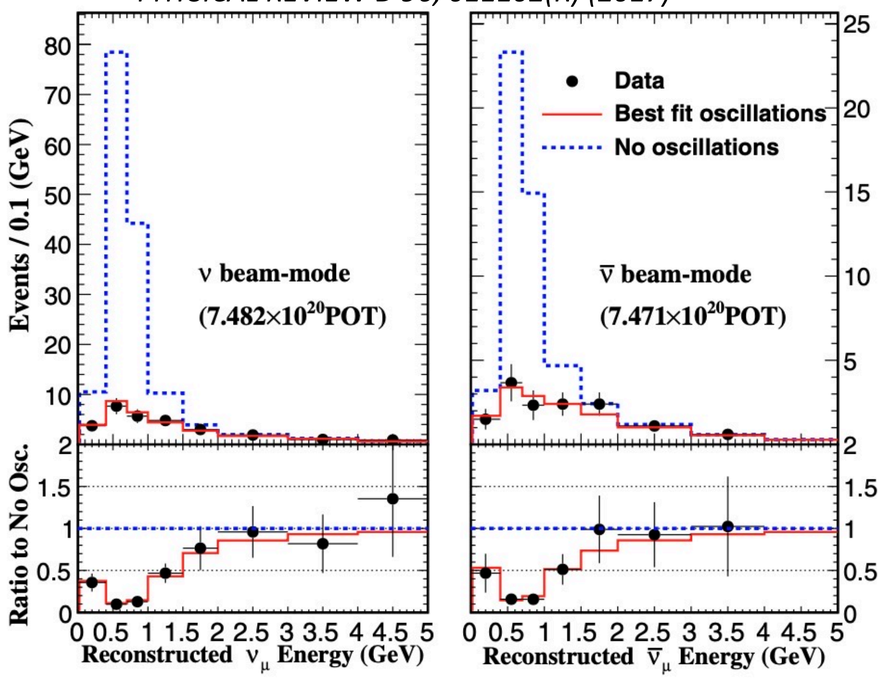
/ NoVa

2.5^o off-axis, almost pure ν_μ beam, E_ν peak tuned to oscil. max. ~0.7 GeV

T2K measurements of ν_μ and $\bar{\nu}_\mu$ disappearance

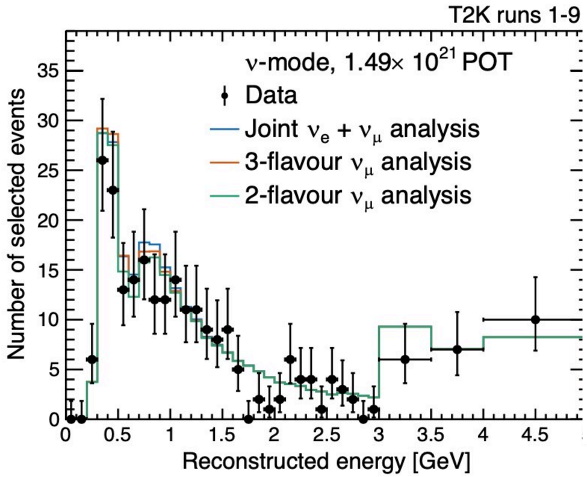
using 1.5×10^{21} POT

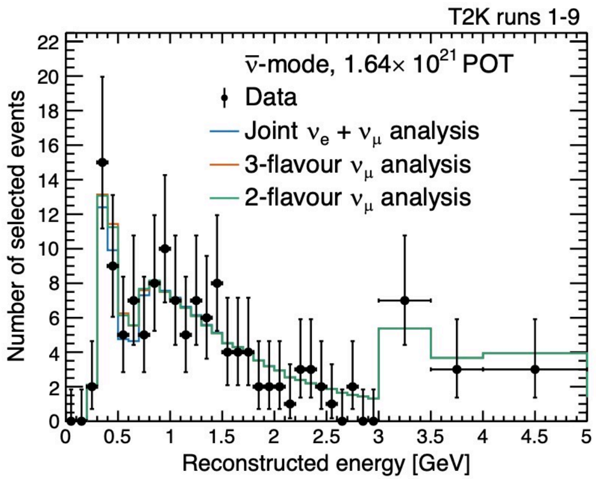
PHYSICAL REVIEW D 96, 011102(R) (2017)

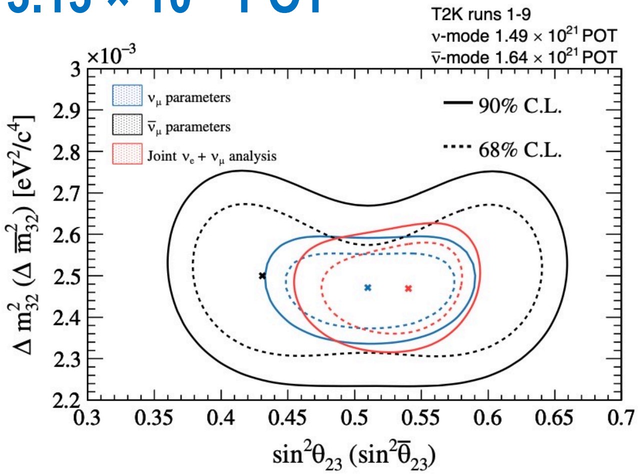


Reconstructed energy distribution of the 135 far detector $\boldsymbol{\nu_\mu}$-CCQE and 66 $\boldsymbol{\bar{\nu}_\mu}$ -CCQE candidate events, with predicted spectra for best-fit and no oscillation cases.

using 3.13×10^{21} POT







PHYSICAL REVIEW D 103, L011101 (2021)

electron neutrino appearance in a muon neutrino beam

PHYSICAL REVIEW D 88, 032002 (2013)

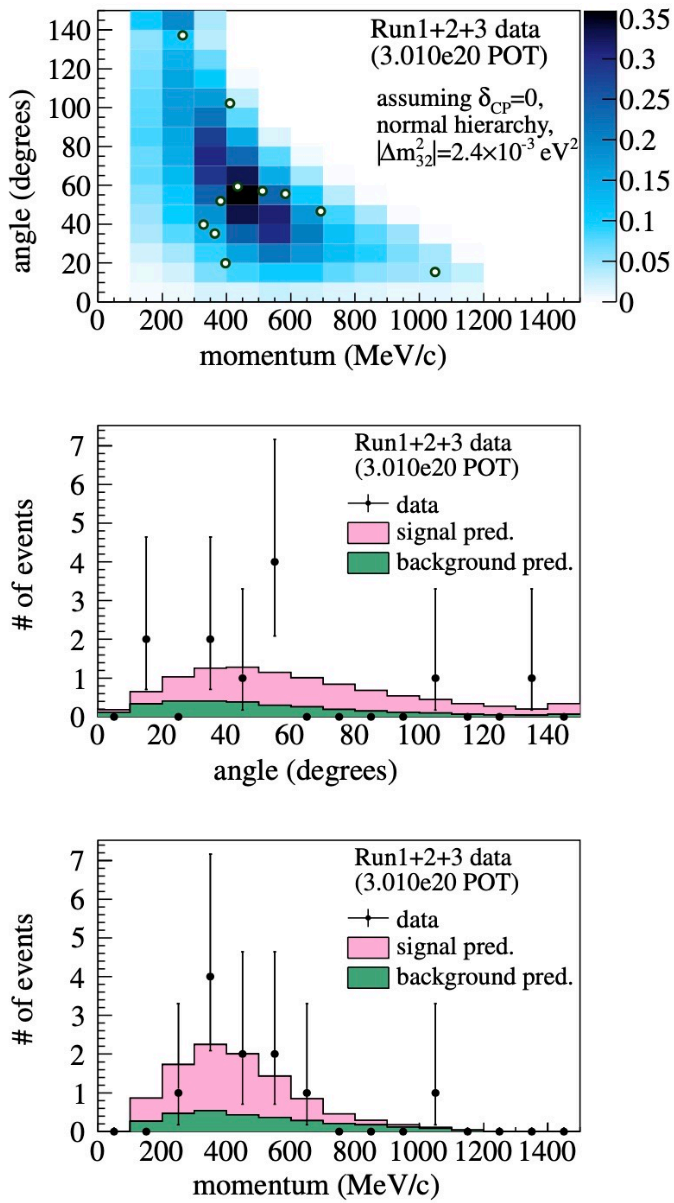


FIG. 35 (color online). The (p_e, θ_e) distribution of the ν_e events (dots) (top) overlaid with the prediction. The prediction includes the rate tuning determined from the fit to near detector information and a signal assuming the best-fit value of $\sin^2 2\theta_{13} = 0.088$. The angular distribution (middle) of the ν_e events in data overlaid with prediction, and the momentum distribution (bottom) with the same convention as above.

observed 11 candidate $\boldsymbol{\nu_e}$ events at the SK detector when 3.3 ± 0.4 (sys) background events are expected; the background-only hypothesis is rejected with a p value of 0.0009, equivalent to a 3.1 $\boldsymbol{\sigma}$ significance.

The excess of events at SK corresponds to a best-fit value of $\sin^2 2\theta_{13} = 0.088^{+0.049}_{-0.039}$ at 68% C.L., assuming $\boldsymbol{\delta}_{CP} = 0$, $\sin^2 2\theta_{23} = 1$ and normal hierarchy

Success ! The door for CPV has been found !

next is to search for CPV itself

Search for Electron Antineutrino Appearance in a Long-Baseline Muon Antineutrino Beam

PHYSICAL REVIEW LETTERS 124, 161802 (2020)

Electron antineutrino appearance is measured by the T2K experiment in an accelerator-produced antineutrino beam. It is observed 15 candidate electron antineutrino events with a background expectation of 9.3 events. Including information from the kinematic distribution of observed events, the hypothesis of no electron antineutrino appearance is dis-favored with a significance of 2.4 σ and no discrepancy between data and PMNS predictions is found.

Success ! **next** is to search for differences in electron neutrino/ Antineutrino appearance

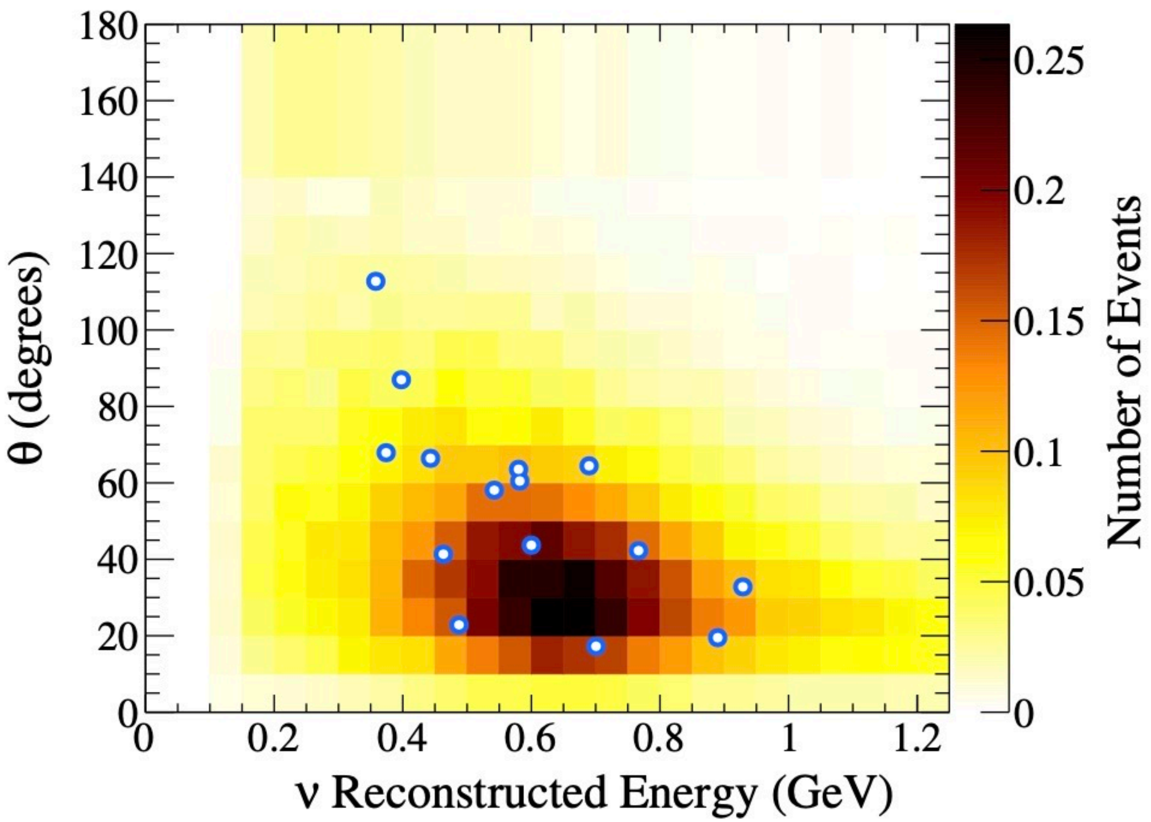
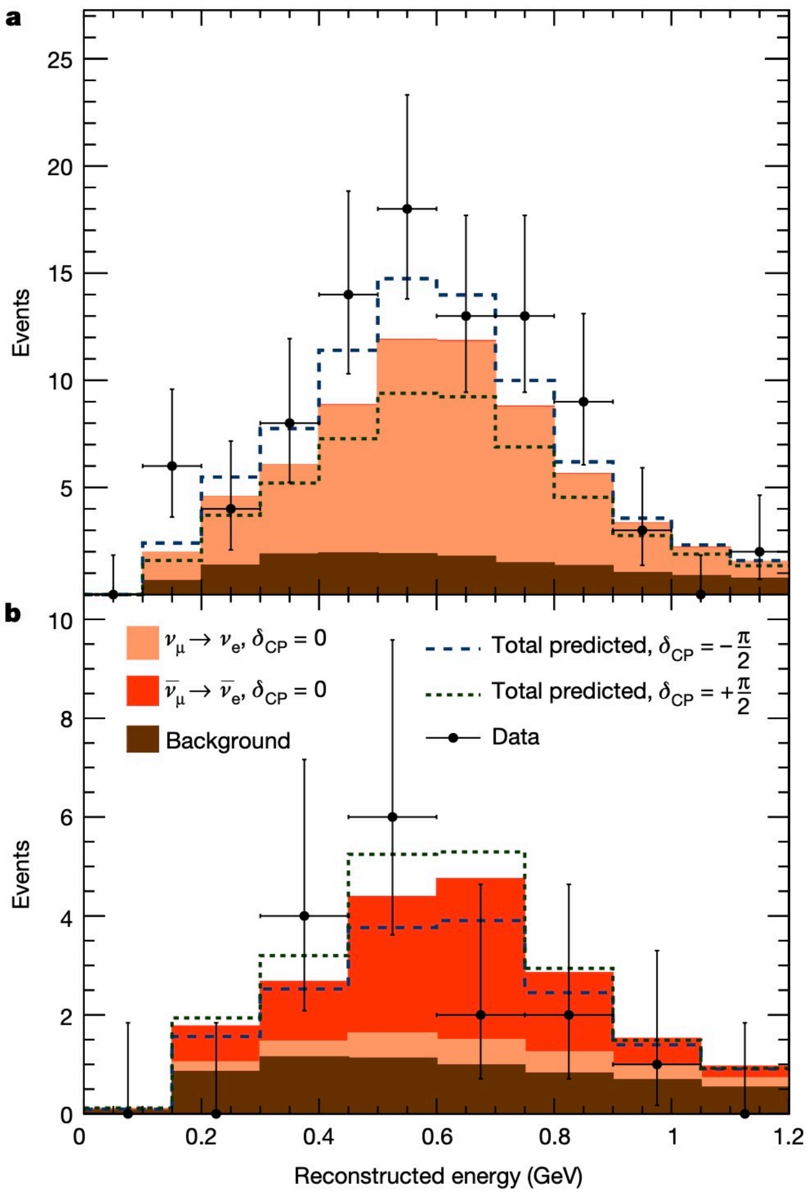


FIG. 1. Predicted $\bar{\nu}$ mode single-ring e-like spectrum (coloured histogram) compared against T2K data (white/blue points). The distribution is a function of both the reconstructed neutrino energy and the reconstructed angle between the outgoing lepton and the neutrino direction.



Nature | Vol580 | 16April2020 | 339

Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$
$$\mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \rightarrow \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

Observed ν_e and ν_e candidate events at SK. **a**, **b**, The reconstructed ν energy spectra for the SK samples containing e-like events in neutrino-mode (a) or antineutrino-mode (b) beam running. **c**, The predicted number of events for $\delta_{CP} = -\pi/2$ and the measured number of events in the three electron-like samples at SK. NO is assumed, and $\sin 2\theta_{23}$ and Δm^2_{32} are at their best-fit values. $\sin^2\theta_{13}$, $\sin^2\theta_{12}$ and Δm^2_{21} take the values indicated by external world average meas.

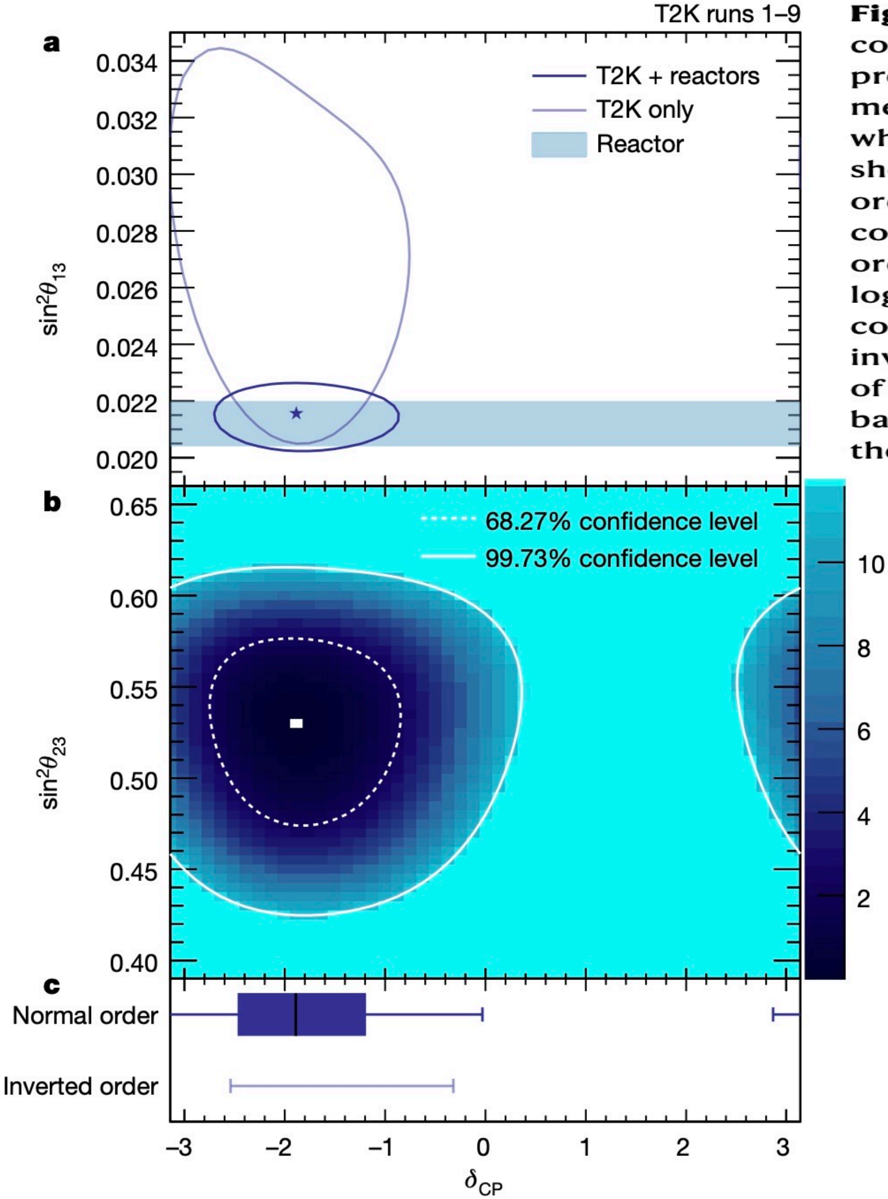


Fig. 4 | Constraints on PMNS oscillation parameters. a, Two-dimensional confidence intervals at the 68.27% confidence level for δ_{CP} versus $\sin^2\theta_{13}$ in the preferred normal ordering. The intervals labelled T2K only indicate the measurement obtained without using the external constraint on $\sin^2\theta_{13}$, whereas the T2K + reactor intervals do use the external constraint. The star shows the best-fit point of the T2K + reactors fit in the preferred normal mass ordering. **b**, Two-dimensional confidence intervals at the 68.27% and 99.73% confidence level for δ_{CP} versus $\sin^2\theta_{23}$ from the T2K + reactors fit in the normal ordering, with the colour scale representing the value of negative two times the logarithm of the likelihood for each parameter value. **c**, One-dimensional confidence intervals on δ_{CP} from the T2K + reactors fit in both the normal and inverted orderings. The vertical line in the shaded box shows the best-fit value of δ_{CP}, the shaded box itself shows the 68.27% confidence interval, and the error bar shows the 99.73% confidence interval. We note that there are no values in the inverted ordering inside the 68.27% interval.

The 3σ confidence interval for δ_{CP}, which is cyclic and repeats every 2π, is [−3.41, −0.03] for the so-called normal mass ordering and [−2.54, −0.32] for the inverted mass ordering. *Our results indicate CP violation in leptons and our method enables sensitive searches for matter– antimatter asymmetry in neutrino oscillations using accelerator-produced neutrino beams*.

Success ! CPV seems to occur !

next is to confirm and measure it precisely

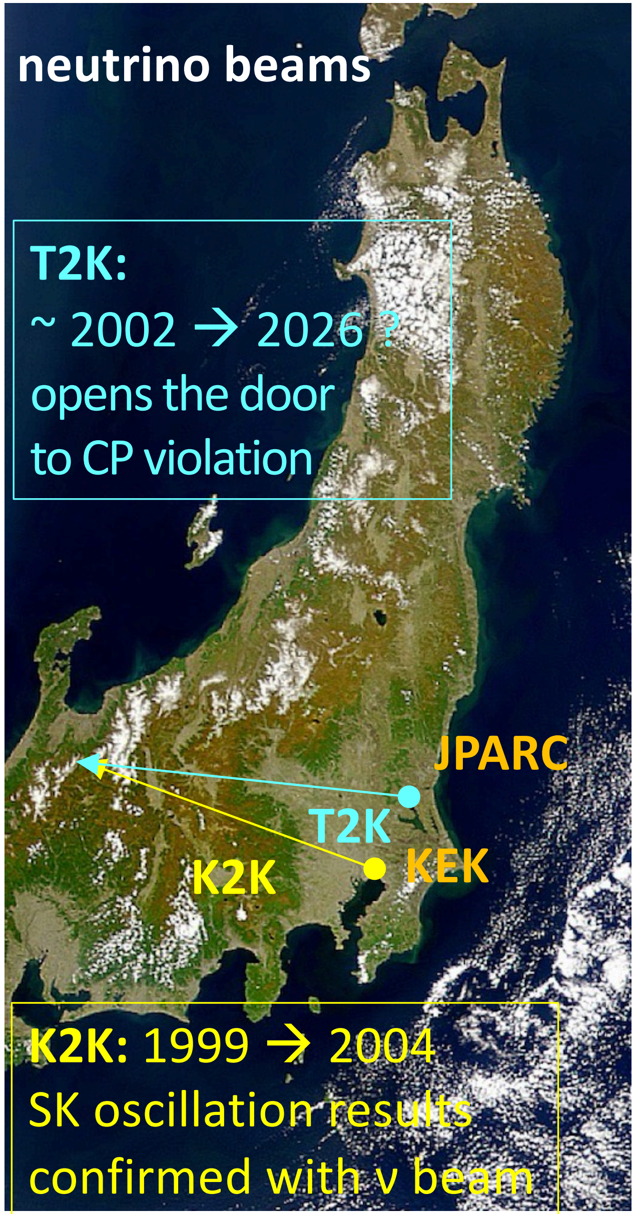
The Japanese Neutrino Program

Kamiokande, ~ 1983 → 1996

- search for proton decay
- first **ν** astronomy, SN1987A

Super-Kamiokande, **KEK**, **T2K** ~1996 →

- **ν**s are massive,
- Solar **ν**s
- What's going on with proton decay
- SN relic neutrino discovery ?
- **The road to CPV is opened**



With the *Super-Kamiokande's* very large mass, and with **JPARC T2K's** powerful **ν beam**,
we are approaching a realistic exploration of **leptonic CP violation*** !

To achieve it we "only" need

- A more powerful beam,
- a better understanding of it
- and more massive detector

➔ i.e. the *Hyper-Kamiokande* project; it provides the above by starting / upgrading / improving the current / running experimental setup / suite

extremely difficult / expensive if started from scratch ! (f.i. DUNE)

(*) CP violation in neutrino oscillations would generically ensure a non vanishing baryon asymmetry through leptogenesis

Fukugita, Yanagida; Phys. Lett. B174, 45 (1986)
Pascoli, Petcov, Riotto; Phys. Rev. D75, 083511 (2007)
Pascoli, Petcov, Riotto; Nucl. Phys. B774 (2007) 1

See P. Casado's talk for the expectations

The Japanese Neutrino Program

Kamiokande, ~ 1983 → 1996
- search for proton decay
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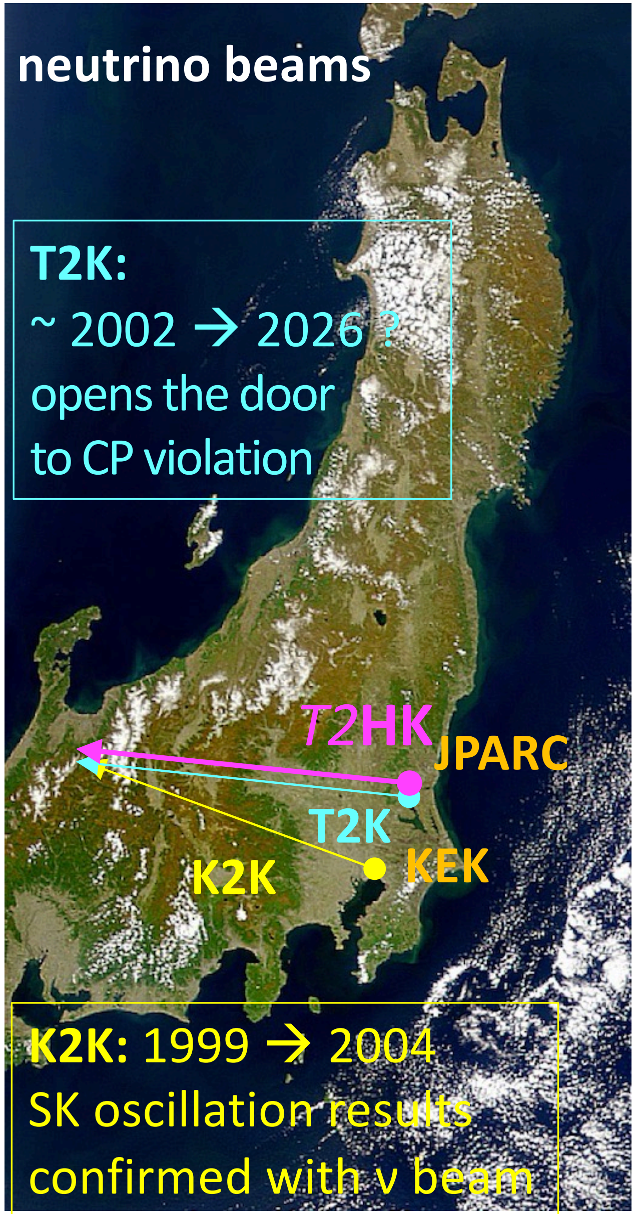
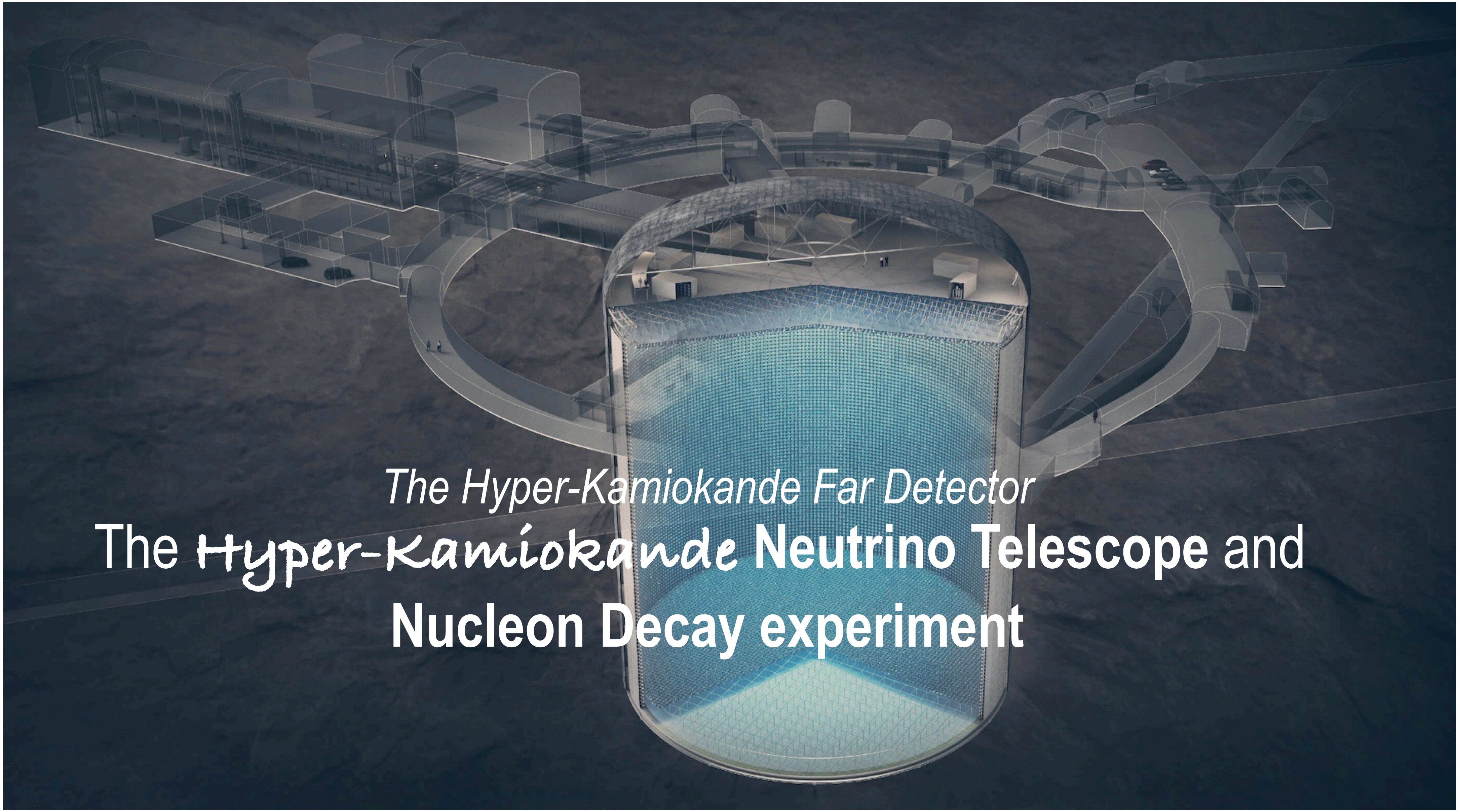
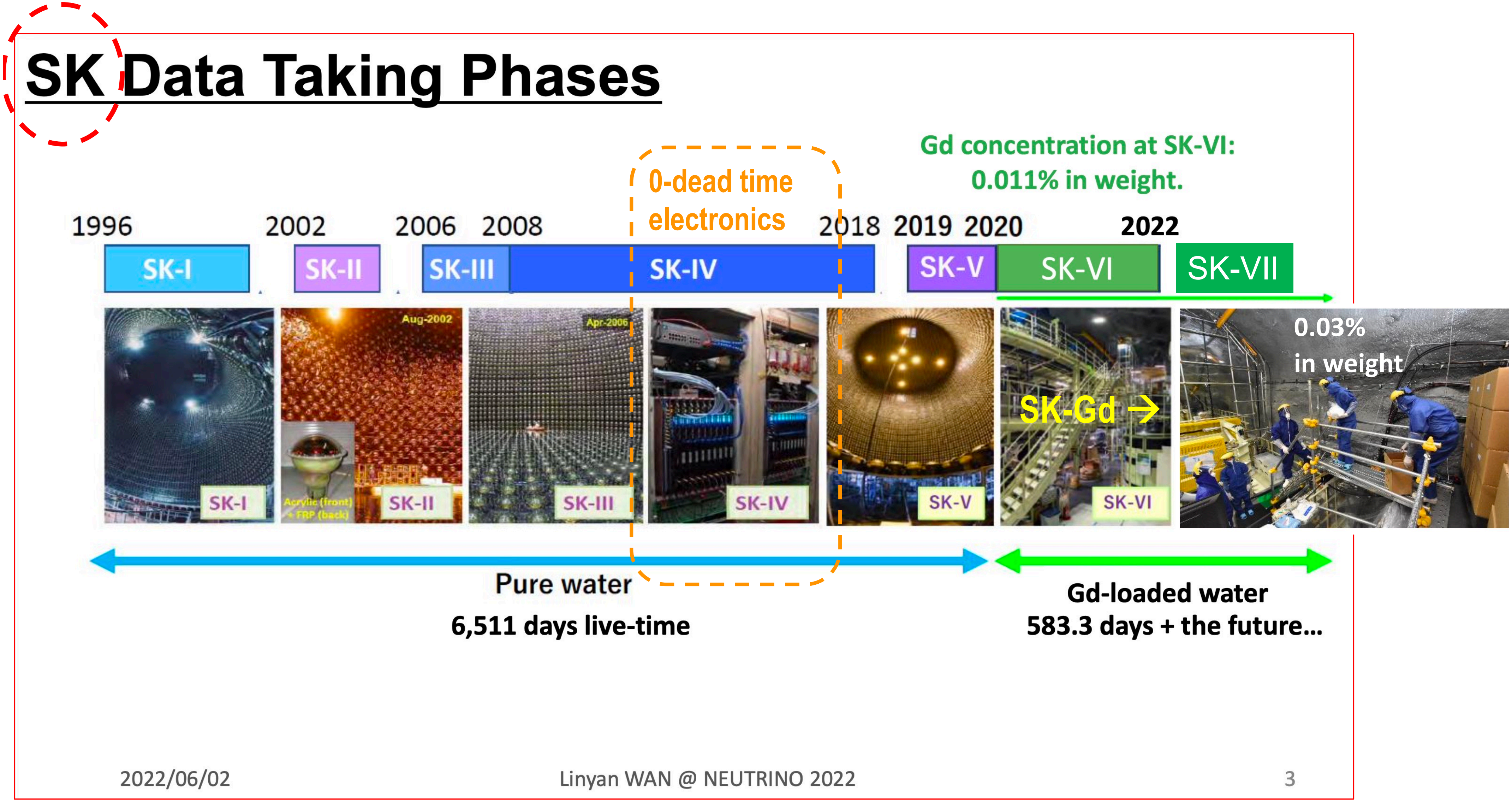
Super-Kamiokande, **KEK**, **T2K** ~1996 →
- **ν**s are massive,
- Solar **ν**s
- What's going on with proton decay
- SN relic neutrino discovery ?
- **The road to CPV is opened**

next: Hyper-Kamiokande, ~ 2027 →
- Origin of **ν** mass, matter anti-matter asymmetry
- **ν** astrophysics and cosmology:
  Supernovae physics, DSNB energy flux, other sources
- proton decay, Grand Unification




The Hyper-Kamiokande Far Detector
The Hyper-Kamiokande Neutrino Telescope and
Nucleon Decay experiment

Much larger mass and beam power do matter, but also a steady improvement of the technology



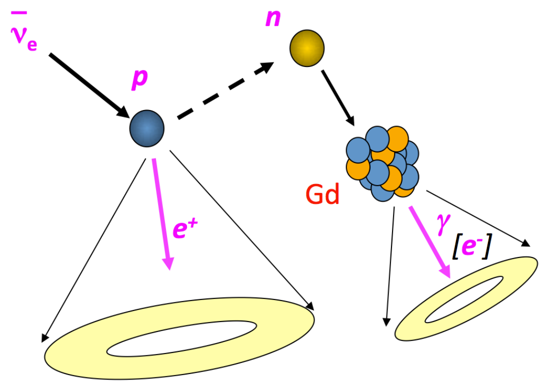
Neutron tagging in water-cherenkov detectors

SuperK-Gd !

- Pure WC detectors lack of the ability to distinguish the charge of the measured particle
  → Very little information about the particle/antiparticle nature of the incoming neutrino
- Also / due-in-part-to lack of capacity of directly measuring neutrals, neutrons in particular
- A **new break-through by Super-Kamiokande** is to upgrade the detector to be able to identify neutrons with a high efficiency and purity (> 70%): dissolve Gd [$Gd_2(SO_4)_3$] in its water

  Gd: largest **n** absorption cross section in nature + emission of an 8 MeV cascade of **γ**s that is detected by SK

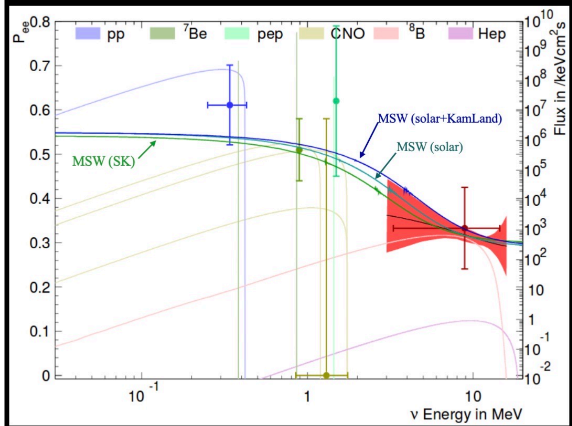
One illustration of its impact: the probably most important outcome reaction is inverse **β** process



1. *e^+ is detected*
2. *n wanders around for ~12μs until thermalises*
3. *~ 20μs [50cm] until **Gd**-capture*
4. *8 MeV γ,s cascade*
5. *e^- are Compton-scat. off the γ and detected*
6. *$\bar{\nu}_e$ is identified from coincidence [e^+, delayed e^-]*

Very low ν energy detection: SK's Wide Intelligent Trigger

Motivation



- Study neutrino oscillations by looking at the survival probabilities of solar neutrinos.

- Transition between vacuum and matter-dominated oscillations around 3 MeV.

^{8}B neutrinos are well suited for this analysis and SuperK studies them.

→ To fill the gap at the transition energy we need to push towards lower energies

Summary

- To study neutrino oscillations we need to lower the energy threshold at SuperK.

- SuperK front-end electronics are capable of reading out every single hit.

- Traditional strategy has been to save events above a given hit threshold.

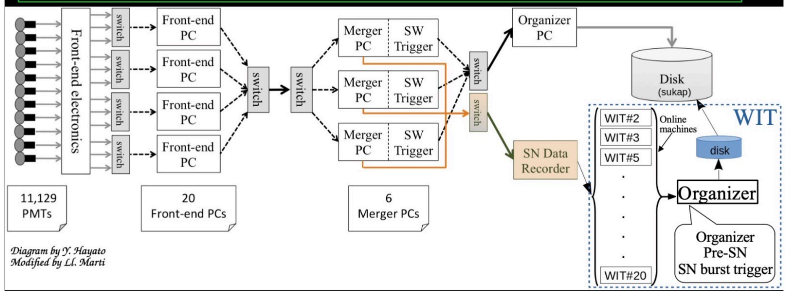
- WIT attempts to do a better job by selecting good hits and looking for a good event vertex within the detector fiducial volume.

WIT System Summary

Computer cluster running parallel software trigger:

Online machines: WIT#[2-20]
Receive 23 ms data blocks
+
Event reconstruction

Organizer
Sorts the data blocks

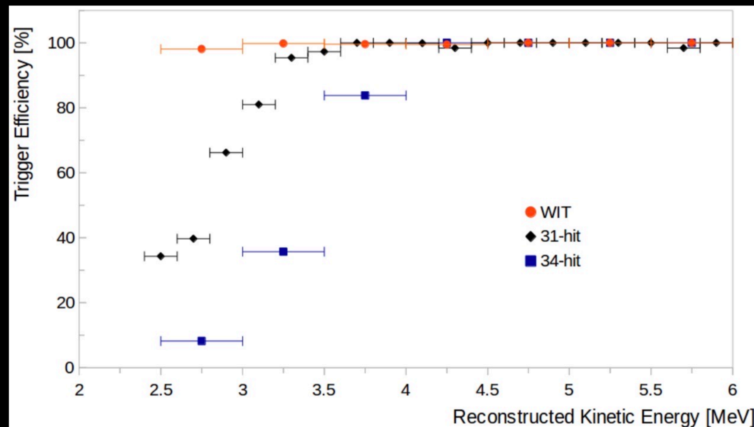


WIT hosts:
- Triggers low energy events (electrons of E_{kin} > 2.5 MeV).
- Online pre-supernova alarm.
- Online SN burst trigger and SN-triggered raw data saving system.

Ll Marti,
SK's U.C.I., IPMU, YNU groups

Efficiency

- Throughout the history of SuperK several hit-thresholds have been used. The two last ones being 34 and 31 (current)



Very good efficiency down to 2.5 MeV !!

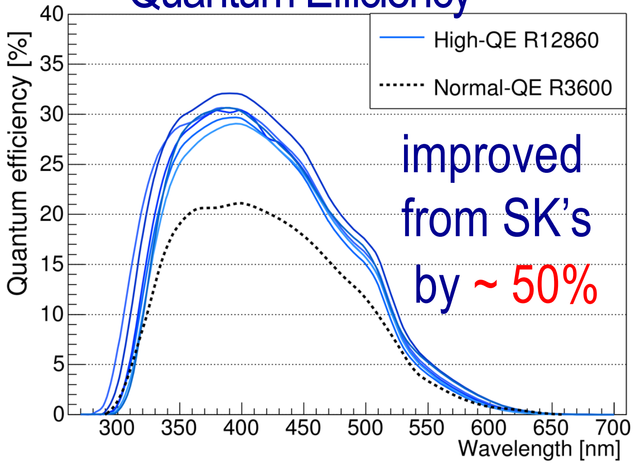
double-sensitivity photo-sensors for Hyper-Kamiokande

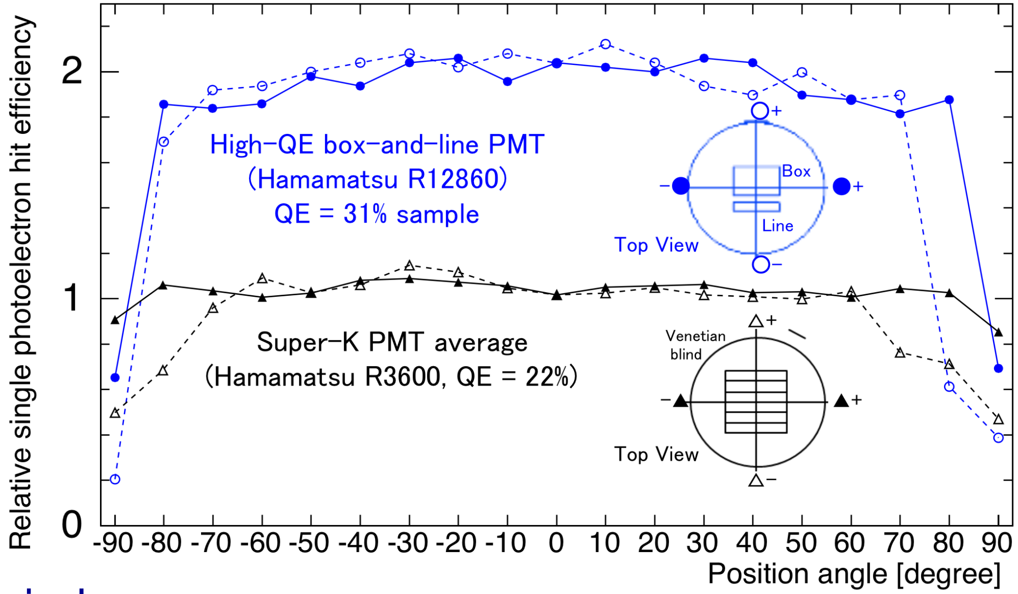
HK's high-QE Box&Line PMT Hamamatsu R12860

vs. SK-PMT Hamamatsu R3600

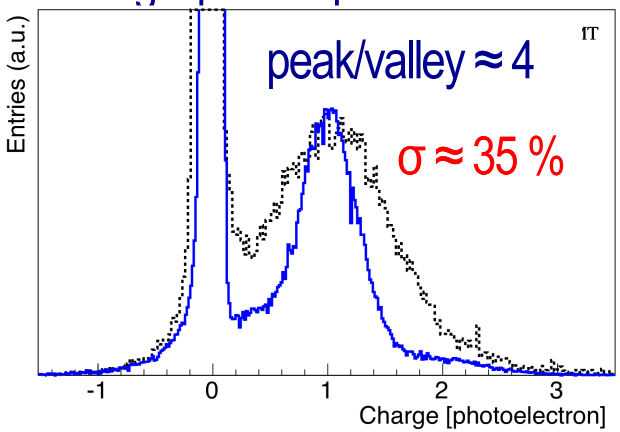
relative single photoelectron det. efficiency [Quantum, Collection, and Cut efficiencies]

Quantum Efficiency

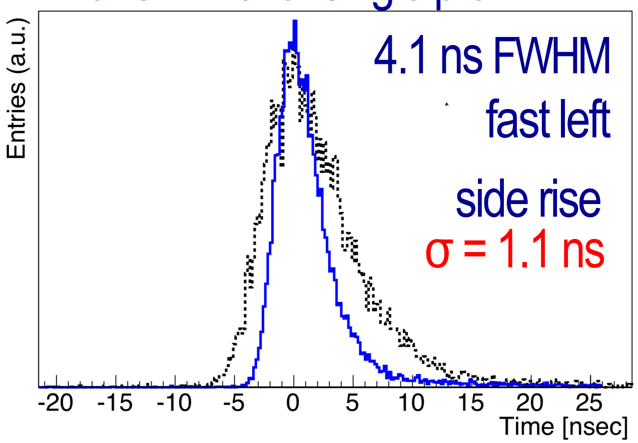




single p.e. w/ pedestal



transit time for single p.e.



2 x better efficiency, timing resolution, charge resolutions →

- enhance solar $\boldsymbol{\nu}_s$,
- signature $\boldsymbol{n}$ ($\boldsymbol{p}$, $\boldsymbol{d}$) $\boldsymbol{\gamma}$
- p → $\boldsymbol{\nu}$K$^+$
- ….

Hyper-Kamiokande

What about **nucleon decay**?

- SU(5) **nd** was the physics-to-search behind the invention of the H_2O-Cherenkov exp. technique
- it was Kamiokande's primary goal but failed, it was/is one of SK's primary goals but failed (?).

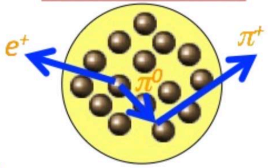
What is going on with the Grand Unification hypothesis ?

WORLD-LEADING PROTON DECAY SEARCHES

	material	Fiducial Mass (kton)
Super-K	Water	22
Hyper-K	Water	190
Dune	Argon	40
JUNO	Liq. Scinti	20

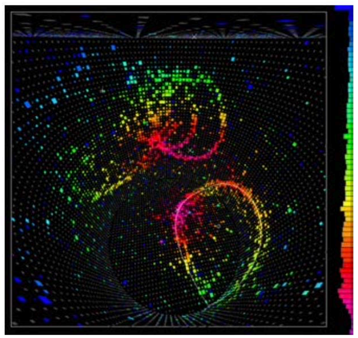
- **High mass (190kton for HK)**
  - To advance **$p \to e^+\pi^0$(>10^{35} years), νK^+(>3×10^{34} years),** and others beyond Super-K
- **Free-p (^{1}H) available**
  - No Fermi motion, nuclear effect
  - High efficiency & good S/N separation
- **Excellent & well-proven detector performance**
  - Good ring-imaging capability at sub-GeV
  - Excellent particle ID (e or μ) capability > 99% (single-ring)
  - Energy resolution ~3%

$p \to e^+\pi^0$ in ^{16}O



Free proton→$e^+\pi^0$

- No Fermi motion
- No π's re-scattering

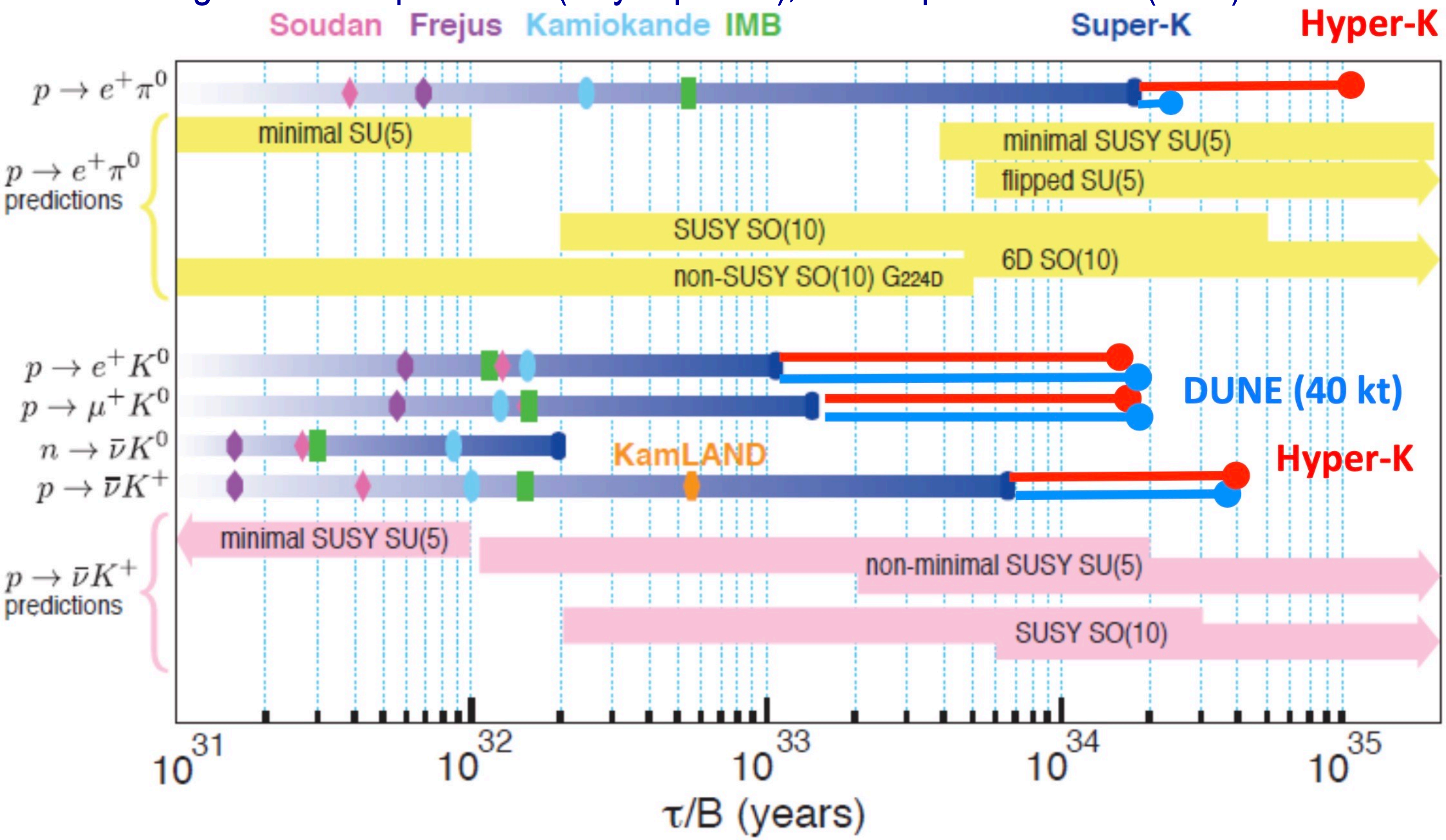


Hyper-K

M. Shiozawa @ 7th HKFF 20230607

4

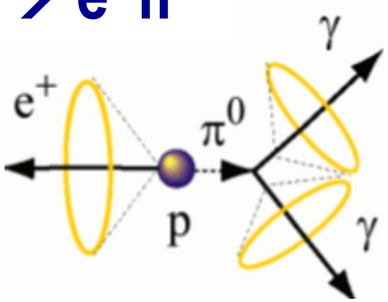
status & next generation expectations (10 y exposure), most important modes (2017):

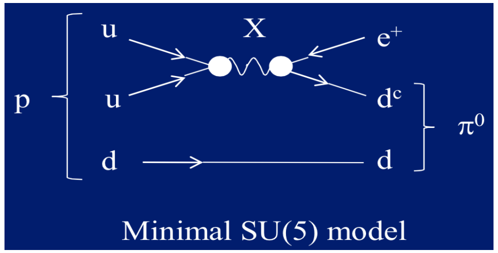


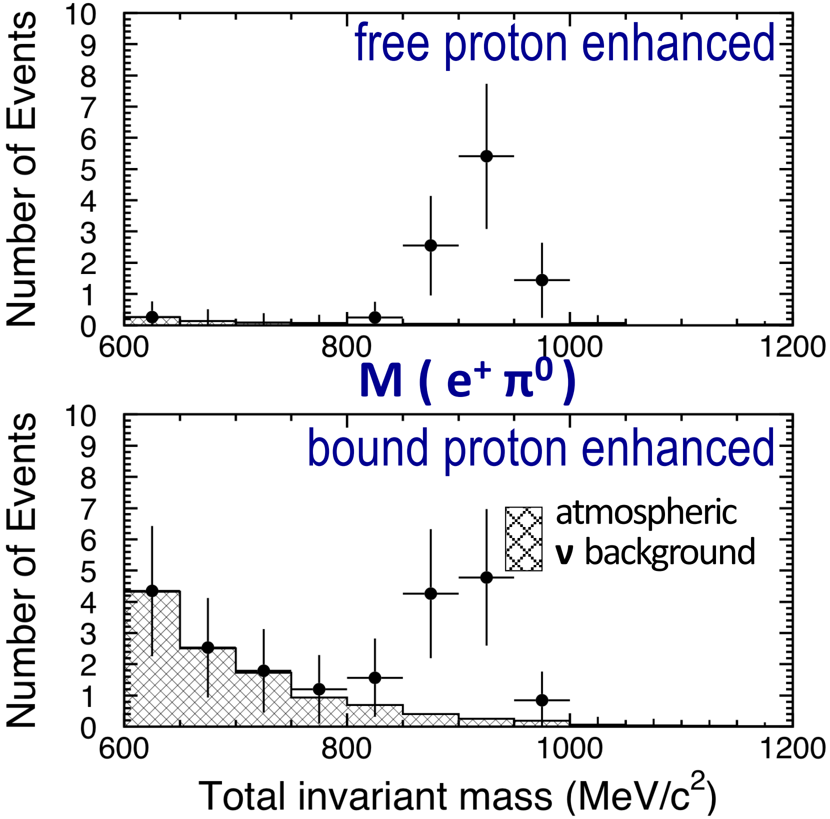
HK design emphasizes $p \to e^+\pi^0$, $p \to \nu K^+$ while keeping sensitivity to many other

A primary goal of the very massive **Hyper-Kamiokande**: shed key light on **nucleon decay**
(at least improve life-time limits by more than one order of magnitude)

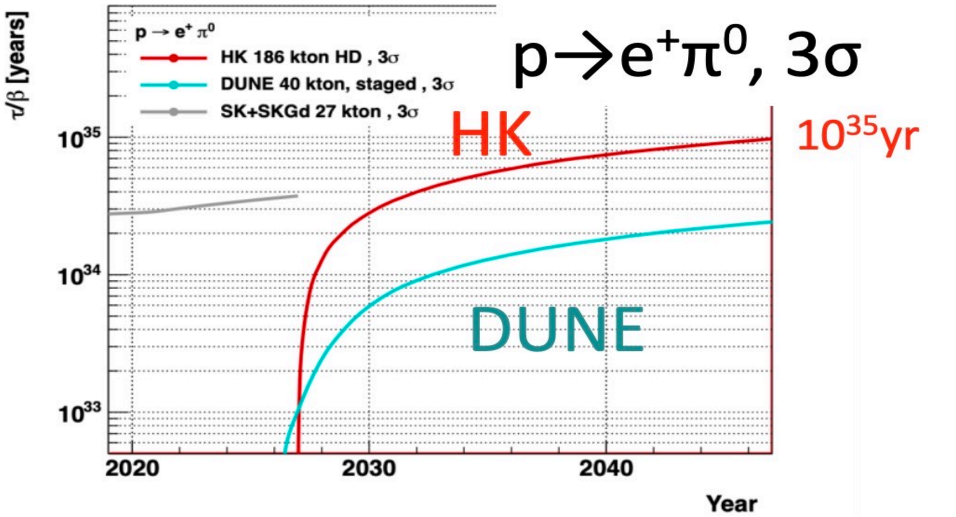
$p \rightarrow e^+\pi^0$

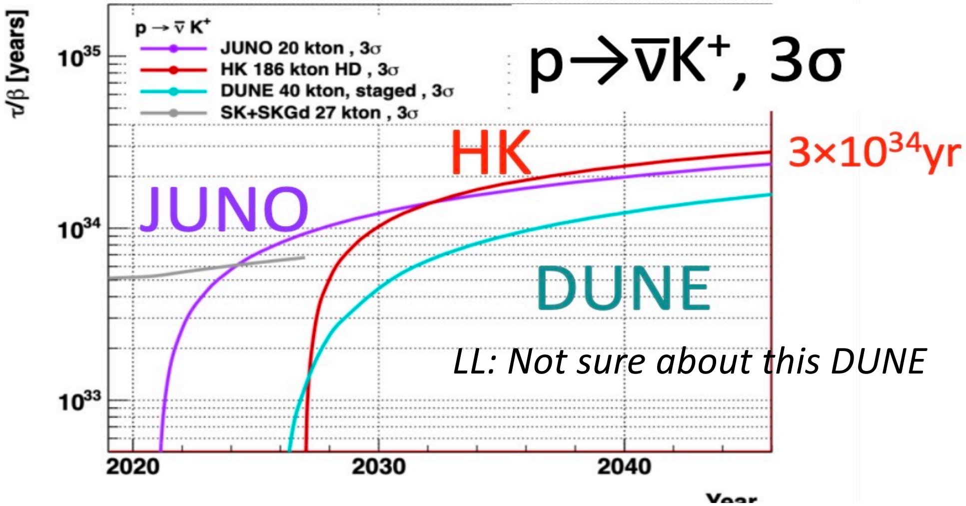






Proton decay: 3σ discovery potential





ν,s from the next Galactic Supernova

an extraordinary physics laboratory by itself

~10^5 events if SN at 10 Kpc

- unravel the explosion mechanism,
- probe the properties of the nascent neutron star,
- study neutrino interaction / oscillations that occur at extreme conditions
- understand the origin of many heavy elements, and
- look for signs of physics beyond the Standard Model
- …

M. Nakahata; Solar and Supernova Neutrinos at Super-Kamiokande, *UAM seminar 20121114*

Standard scenario of the core-collapse supernova

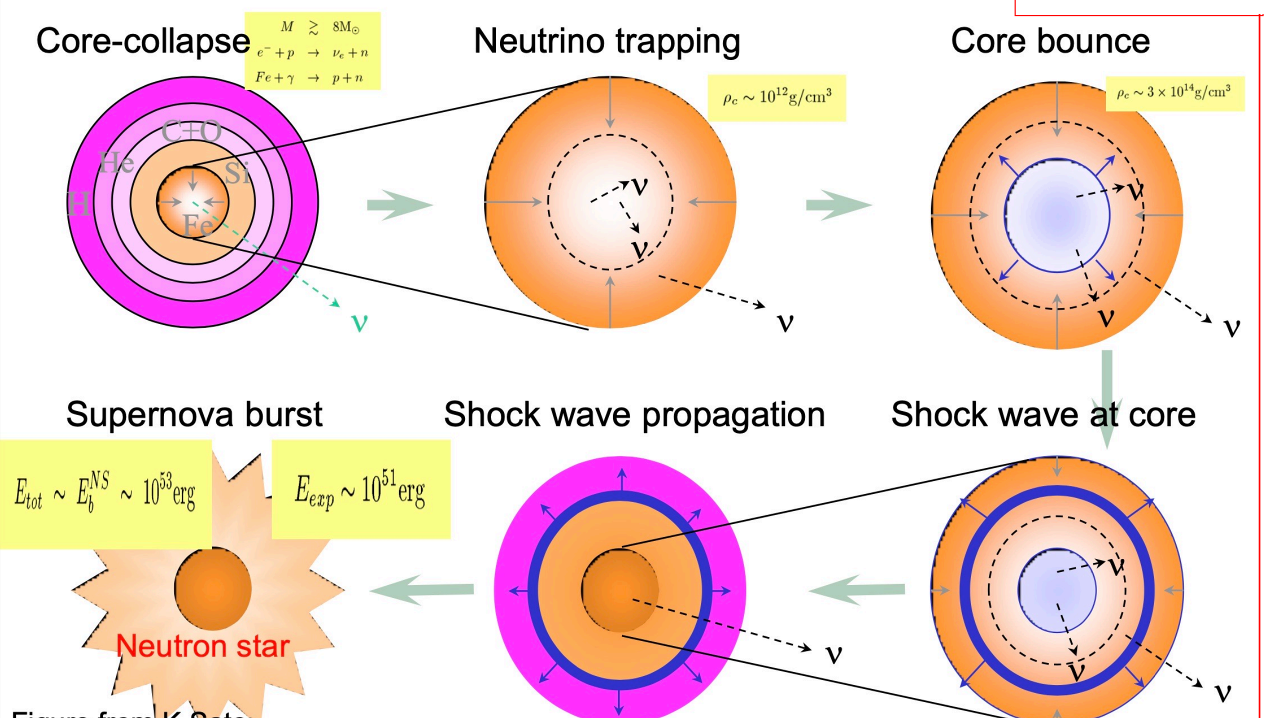
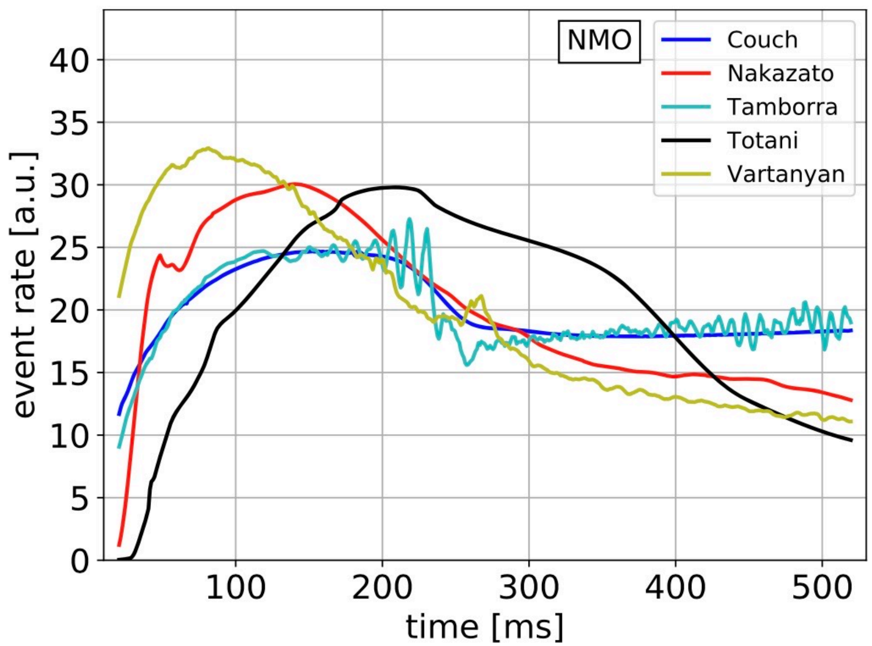


Figure from K.Sato

Hyper-Kamiokande; The Astrophysical Journal, 916:15, 2021



Expectations for measuring Supernova with Hyper-Kamiokande

Hyper-Kamiokande; The Astrophysical Journal, 916:15 (17pp), 2021

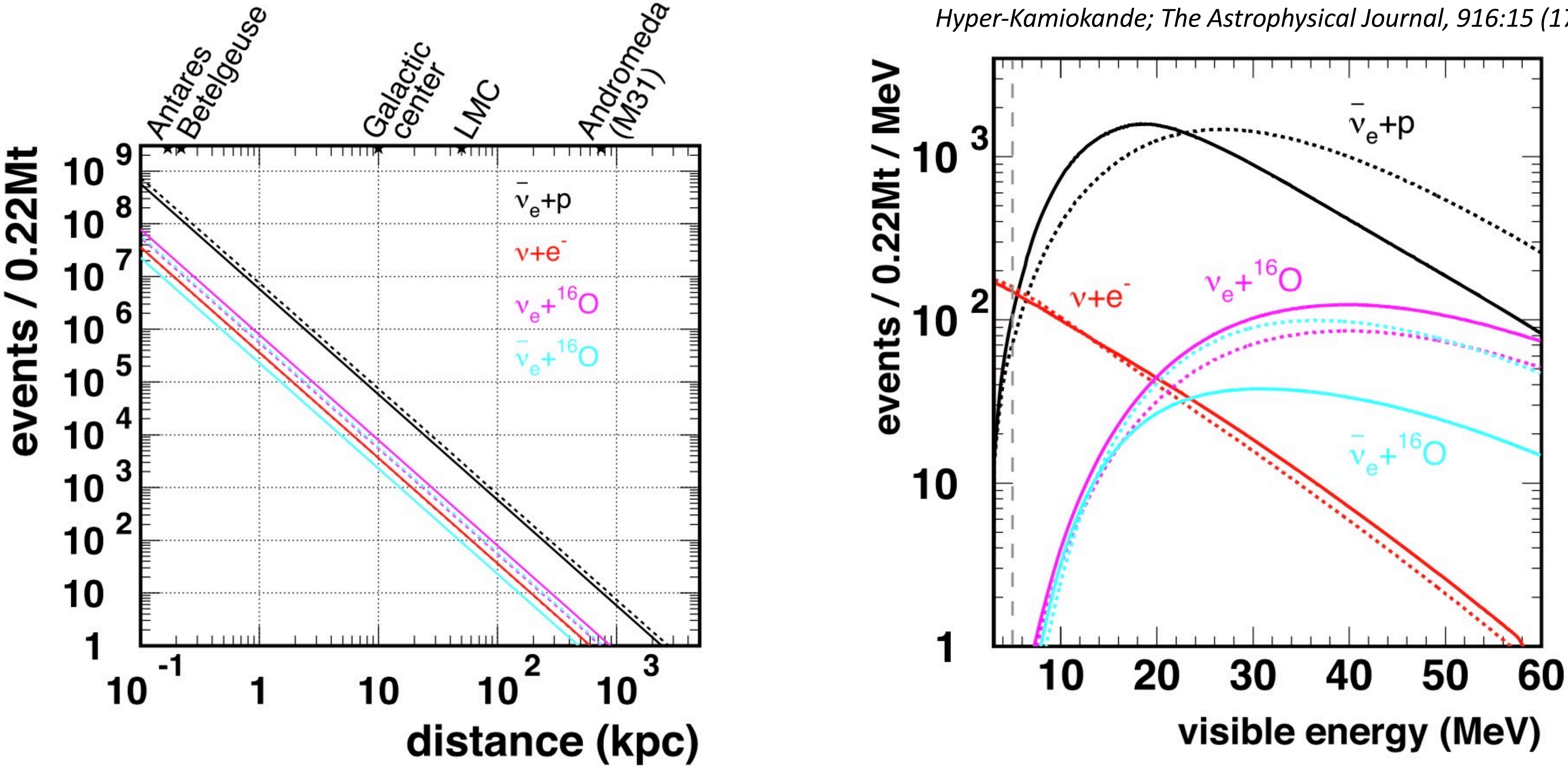
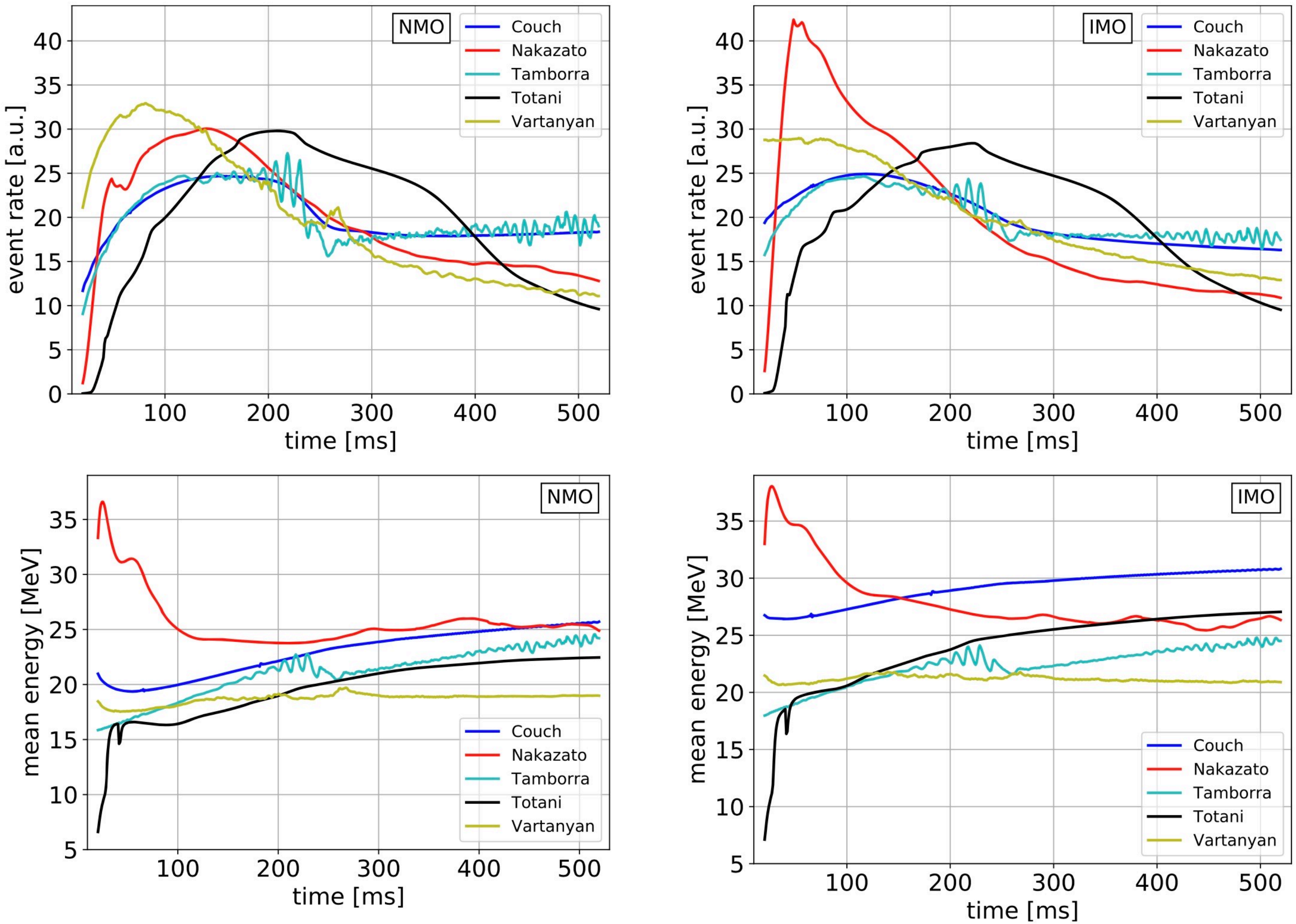


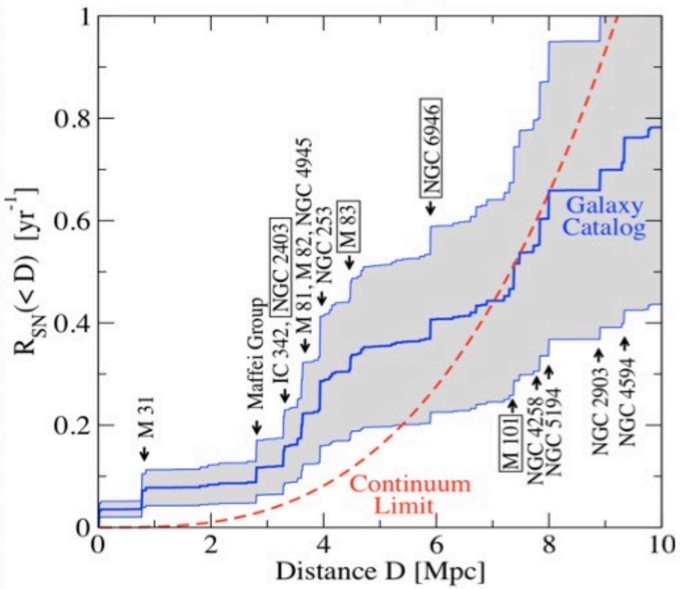
Figure 2. Left: expected number of events as a function of supernova distance. Right: true energy spectra of prompt events in the full inner detector for a supernova at 10 kpc; for reference, the energy threshold used in this analysis (see Section 3.4) is indicated by a dashed gray line. Both panels assume the supernova model by Totani et al. (1998). Solid (dashed) lines correspond to normal (inverted) mass ordering, while different colors correspond to the interaction channels inverse beta decay (black), νe-scattering (red), $\nu_e + {}^{16}$O CC (purple), and $\bar{\nu}_e + {}^{16}$O CC (light blue).

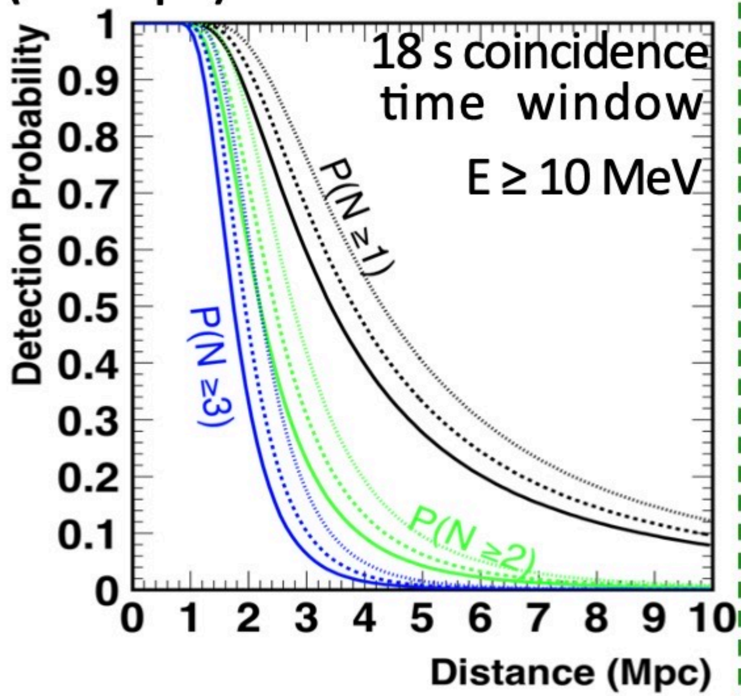
Supernova Model Discrimination with Hyper-Kamiokande



Hyper-Kamiokande; The Astrophysical Journal, 916:15 (17pp), 2021

SN in **nearby Galaxies** (> 1Mpc)

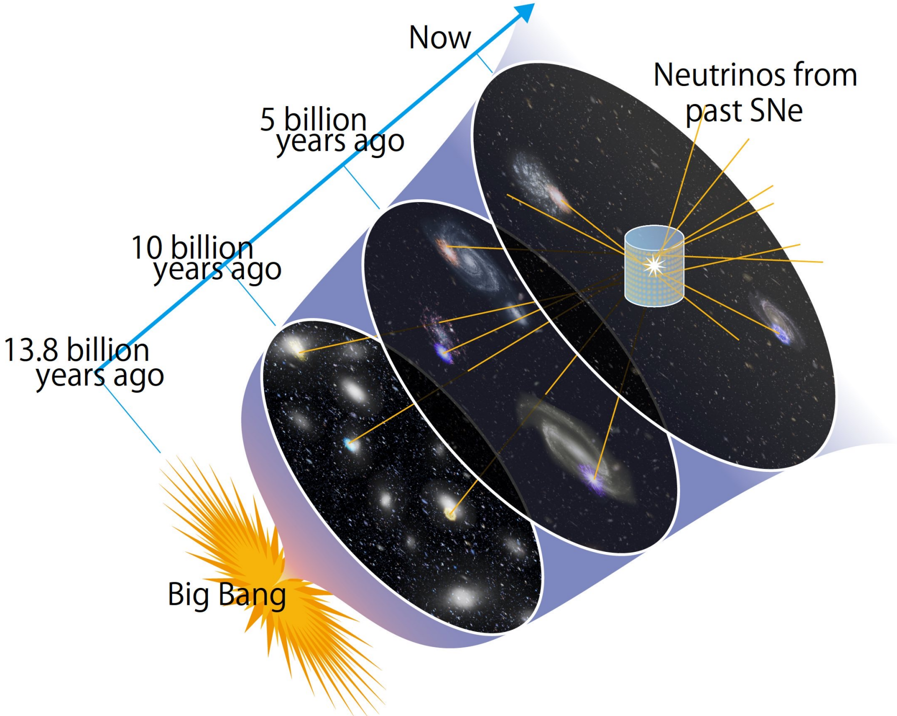




- large volume of HK: ≈ 2-20 SN events in 20y
- reference energy spectrum, without varying red-shift effects. for DSNB E spectrum
- prove strange supernovae, eg. dim supernovae

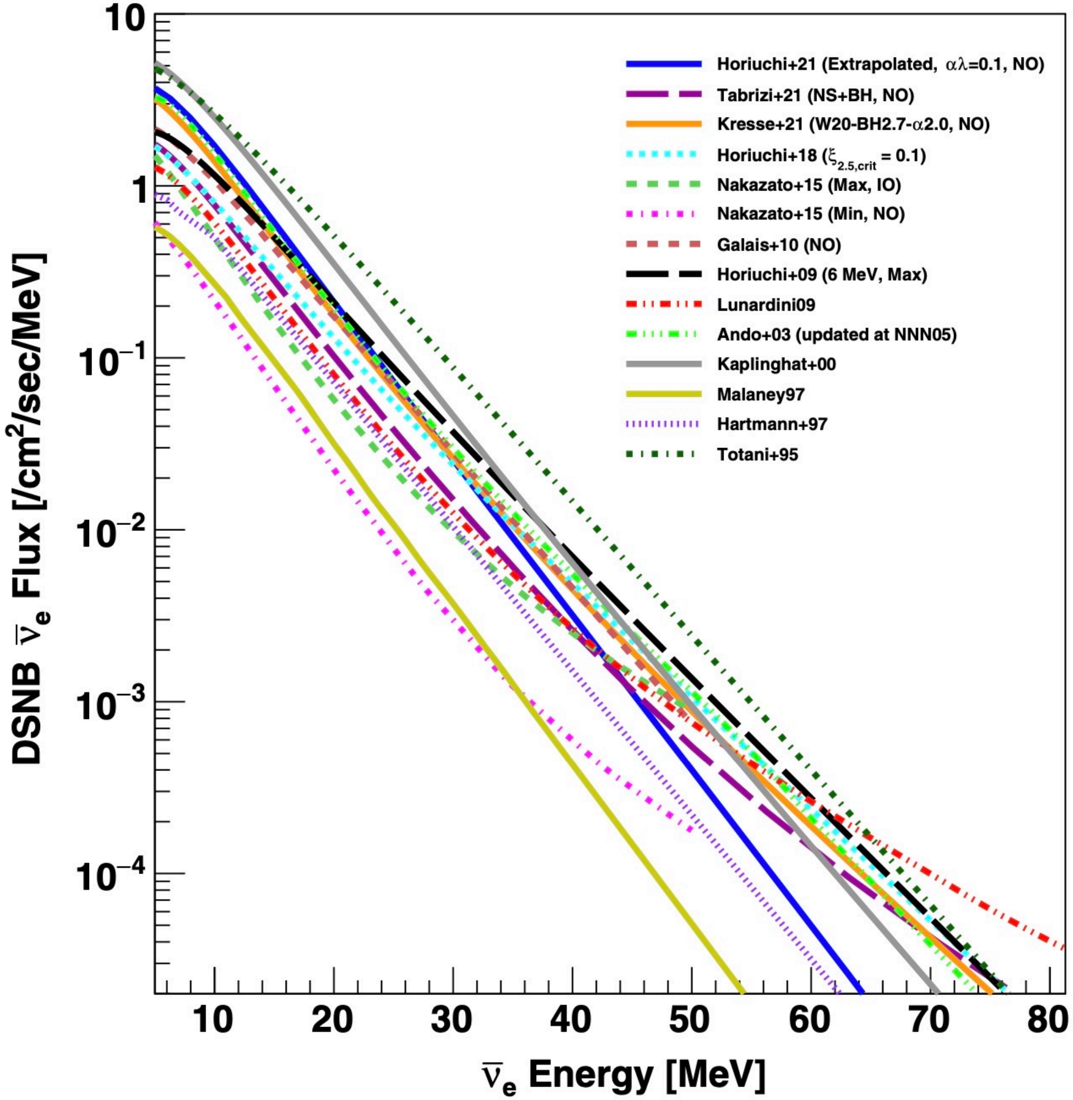
Diffuse Supernova Neutrino Background (DSNB)

Super-Kamiokande Coll. PHYSICAL REVIEW D 104, 122002 (2021)



$$\Phi(E_\nu) = \frac{c}{H_0} \int \sum_s R_{\mathrm{SN}}(z, s) \sum_{\nu_i, \bar{\nu}_i} F_i(E_\nu(1+z), s) \times \frac{dz}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}},$$

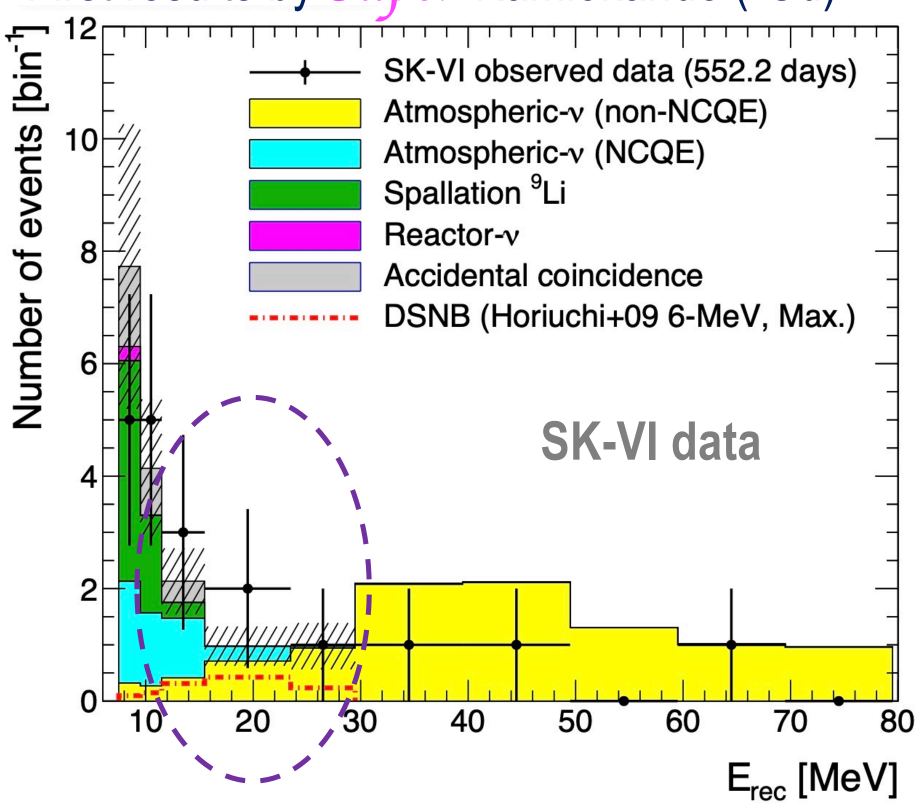
H_0: Hubble constant, z: redshift, $R_{SN}(z,s)$: redshift-dependent SN rate, F_i: SN neutrino emission spectrum for a given flavor I, index s: the different possible classes of SN associated with specific neutrino emission spectra. Last factor accounts for the Universe expansion; Ω_M / Ω_Λ : dark matter / energy contributions to the energy density of the Universe



Diffuse Supernova Neutrino Background (DSNB)

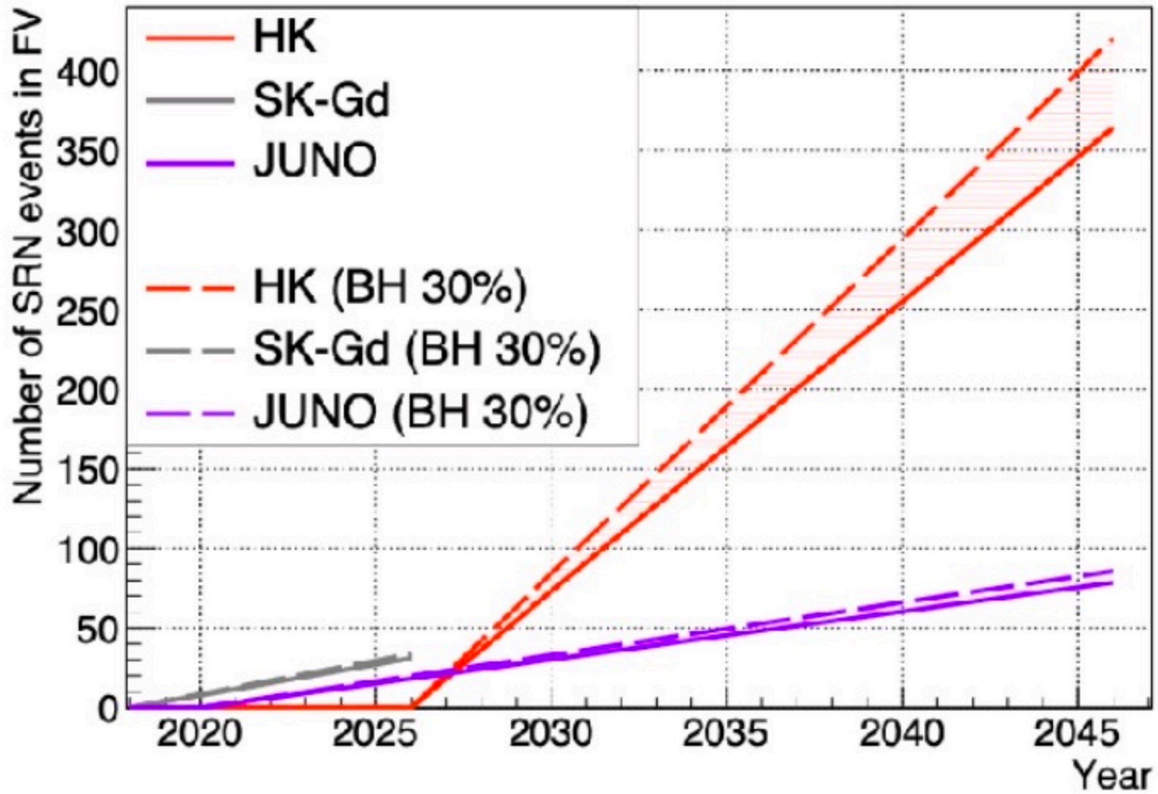
The ~10x Hyper-Kamiokande larger mass allows many more reactions (events) to be produced / studied

First results by Super-Kamiokande (-Gd)



Super-Kamiokande Coll. ArXiv:2305.05135; accepted by ApJL

Expectations for Hyper-Kamiokande



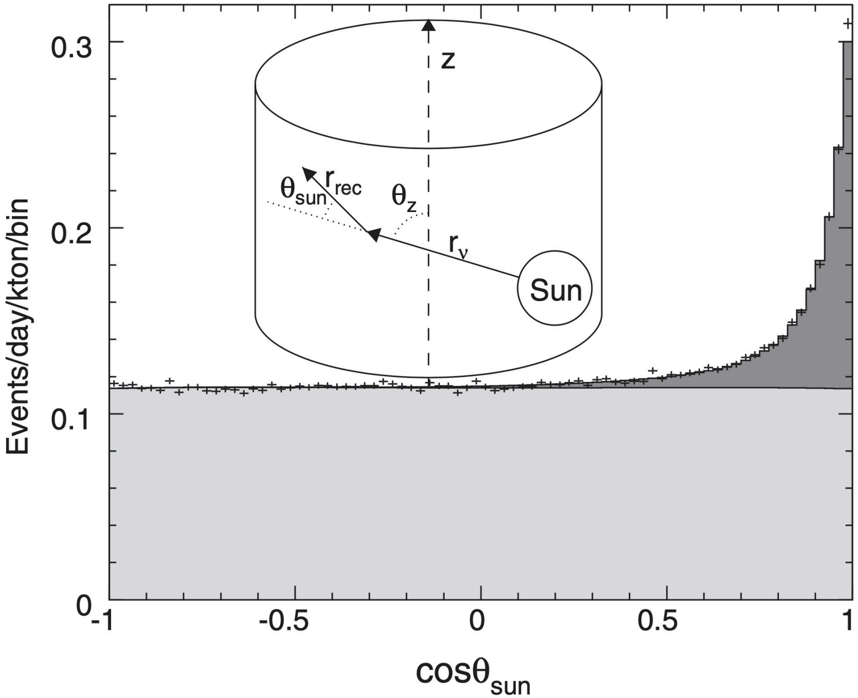
Several hundred event: enough to start getting deep insight from the measured energy flux

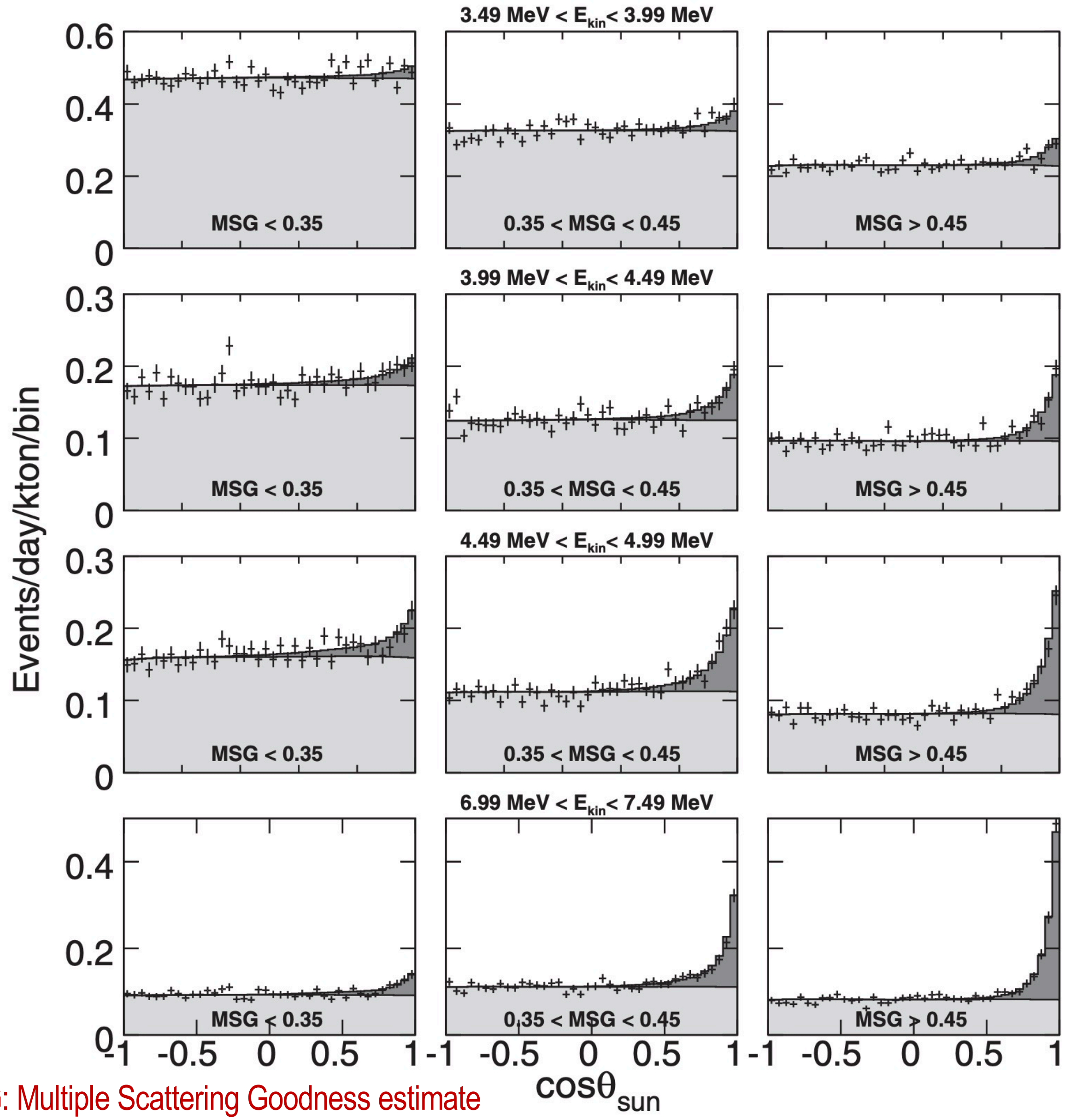
Solar Neutrinos

Published Super-Kamiokande IV Solar ν,s

Super-Kamiokande; PRD 94, 052010 (2016)

signal extracted from directional correlation of recoiling e^- with incident ν at ν - e^- scattering





MSG: Multiple Scattering Goodness estimate

Solar Neutrinos

Super-Kamiokande; PRD 94, 052010 (2016)

^{8}B solar ν flux by Super-Kamiokande

input: νe^- elastic cross-section

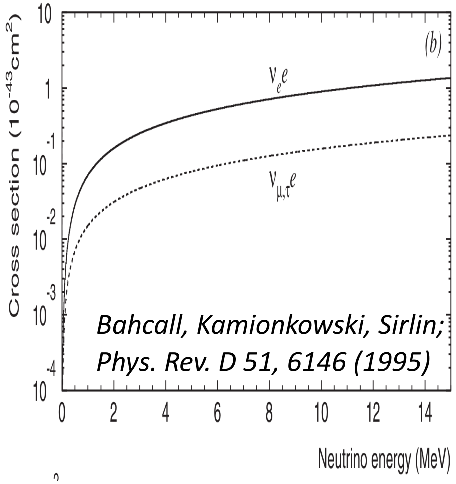


TABLE VI. SK measured solar neutrino flux by phase.

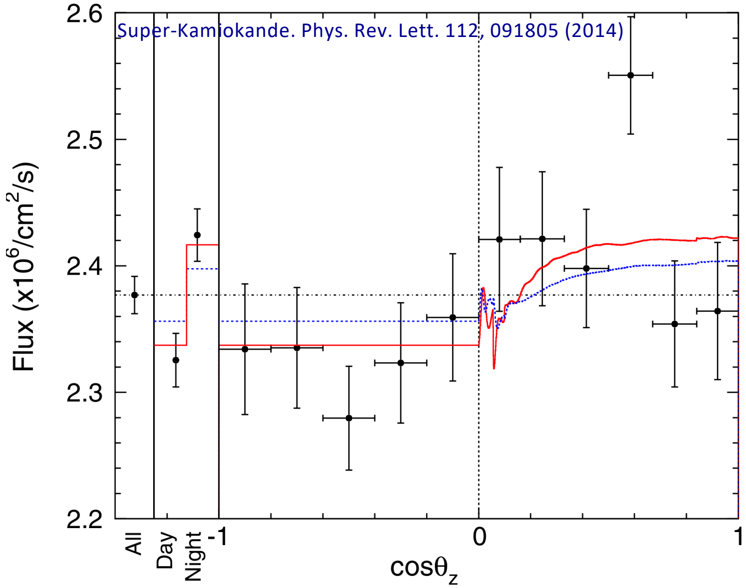
	Flux ($\times 10^6/(\mathrm{cm}^2\ \mathrm{sec})$)
SK-I	$2.380 \pm 0.024^{+0.084}_{-0.076}$
SK-II	$2.41 \pm 0.05^{+0.16}_{-0.15}$
SK-III	$2.404 \pm 0.039 \pm 0.053$
SK-IV	$2.308 \pm 0.020^{+0.039}_{-0.040}$
Combined	$2.345 \pm 0.014 \pm 0.036$

expected SSM:

$5.79 \cdot 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Bahcall, Pinsonneault; PRL 92, 121302 (2004)

First Indication of Terrestrial Matter Effects on Solar ν Oscillation



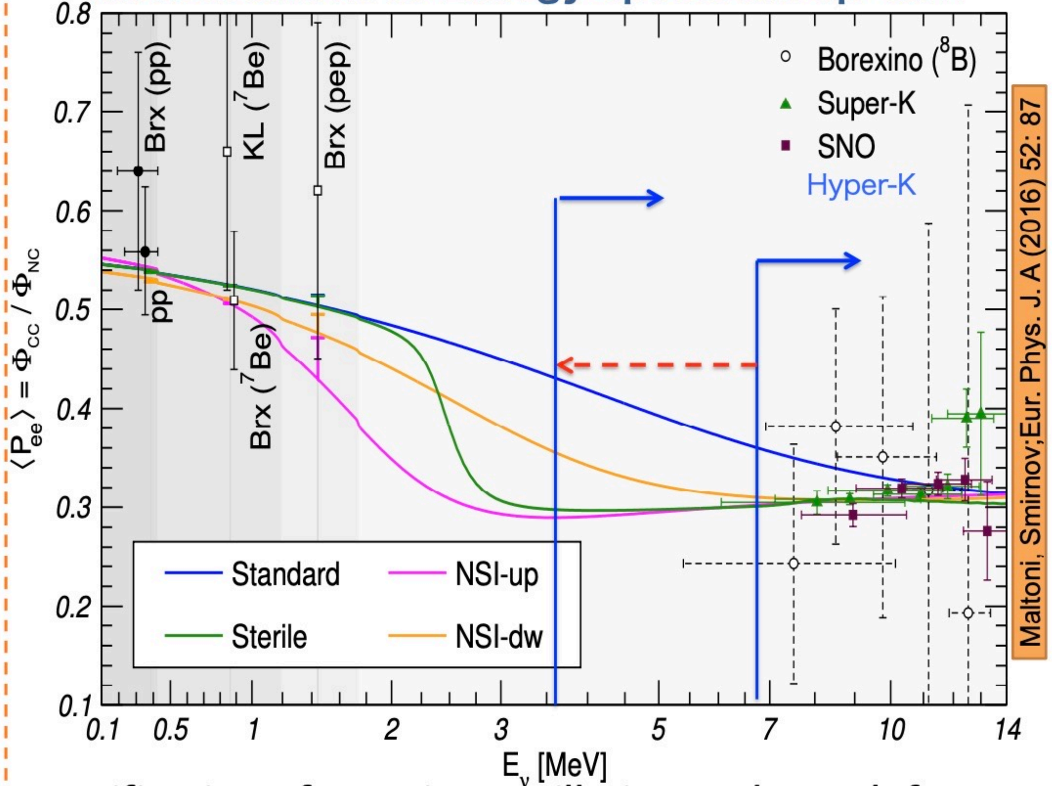
← Thorough study with Hyper-Kamiokande

E_{recoil} > 4.5 MeV in SK-I, -III, -IV

> 7 MeV in SK-II

Thorough study with Hyper-Kamiokande, but very large background: need *W.I.T.* or similar

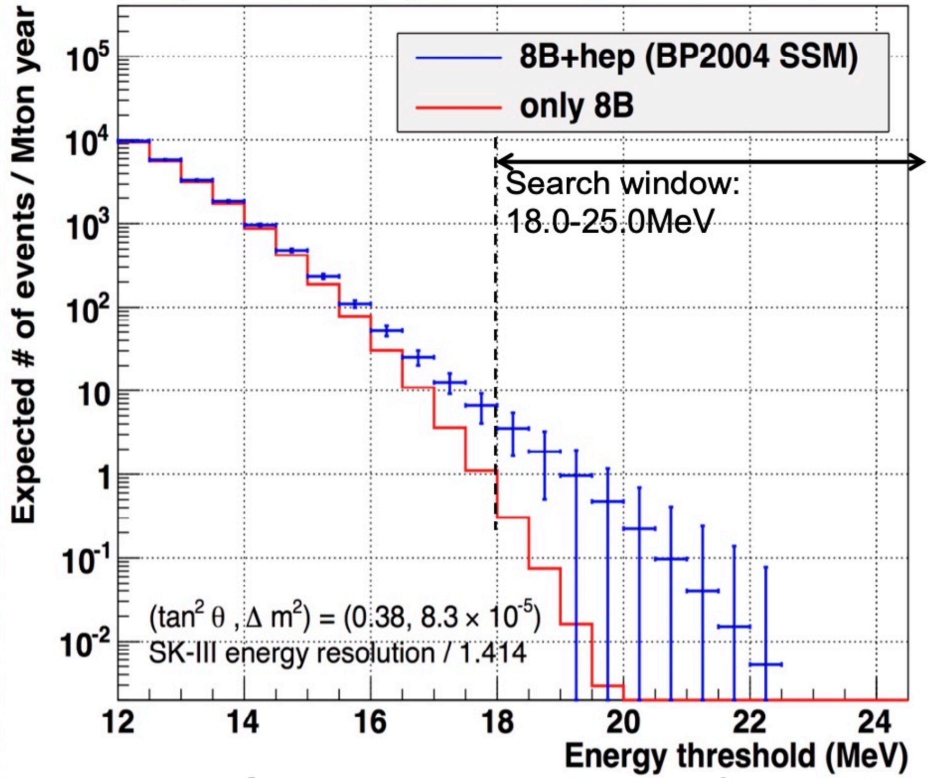
Measurement of Energy spectrum up-turn



- Verification of neutrino oscillation and search for BSM physics → Non-standard interactions, sterile ν ...
- separable w/ up-turn from w/o up-turn with ~5σ (3.5MeV threshold, staging 10y)

Thorough study with Hyper-Kamiokande, little but hopefully enough statistics

ν hep: discovery and measurement

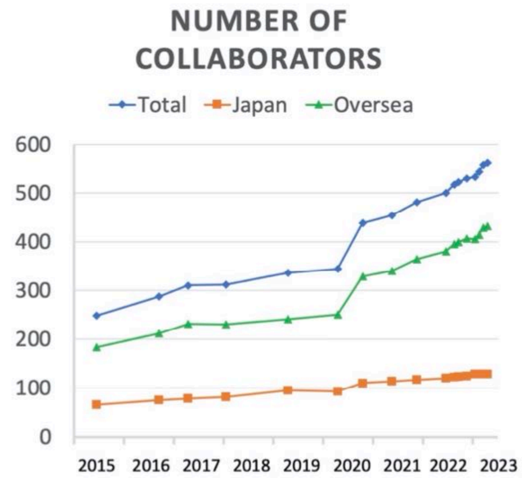


- neutrino from He+p reaction at the sun
- verification of SSM
- very small fraction; yet undiscovered.
- expected (10y): 8.5 ev (+BG 0.7ev.)

Hyper-Kamiokande collaboration

Univ. of Tokyo and KEK host the project

- ~560 people from 21 countries, 101 institutions
    - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN



First face-to-face meeting after project approval

Hyper-Kamiokande collaboration

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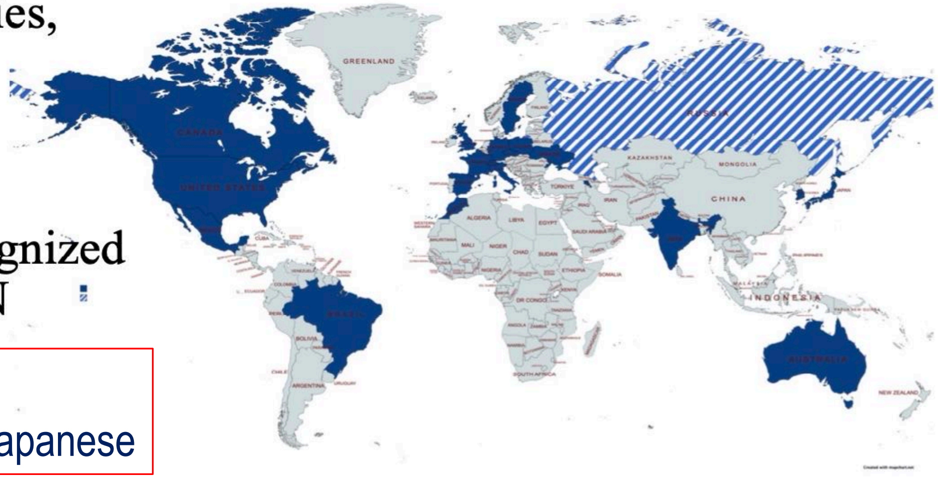
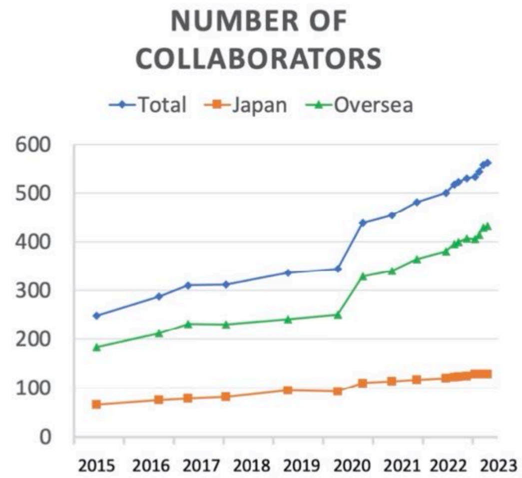




Funding:
~ 85% Japanese / ~ 15% non-Japanese

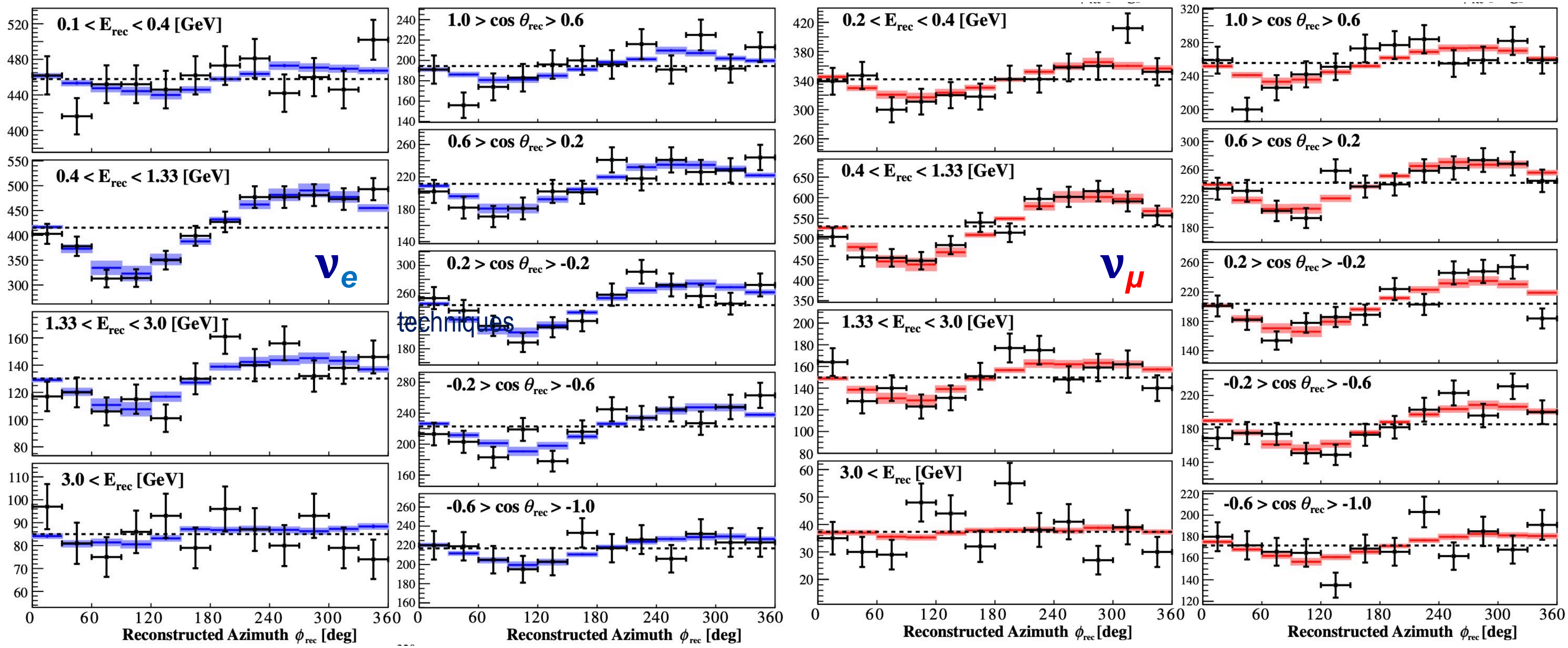
First face-to-face meeting after project approval

Additional materials (randomly chosen)

ν_e , ν_μ fluxes: full azimuth [Φ] and zenith [θ] space

Super-Kamiokande; Phys. Rev. D 94, 052001 (2016)

Predicted neutrino flux by: *Honda, Kajita, Kasahara, Midorikawa, PRD 83, 123001 (2011)*

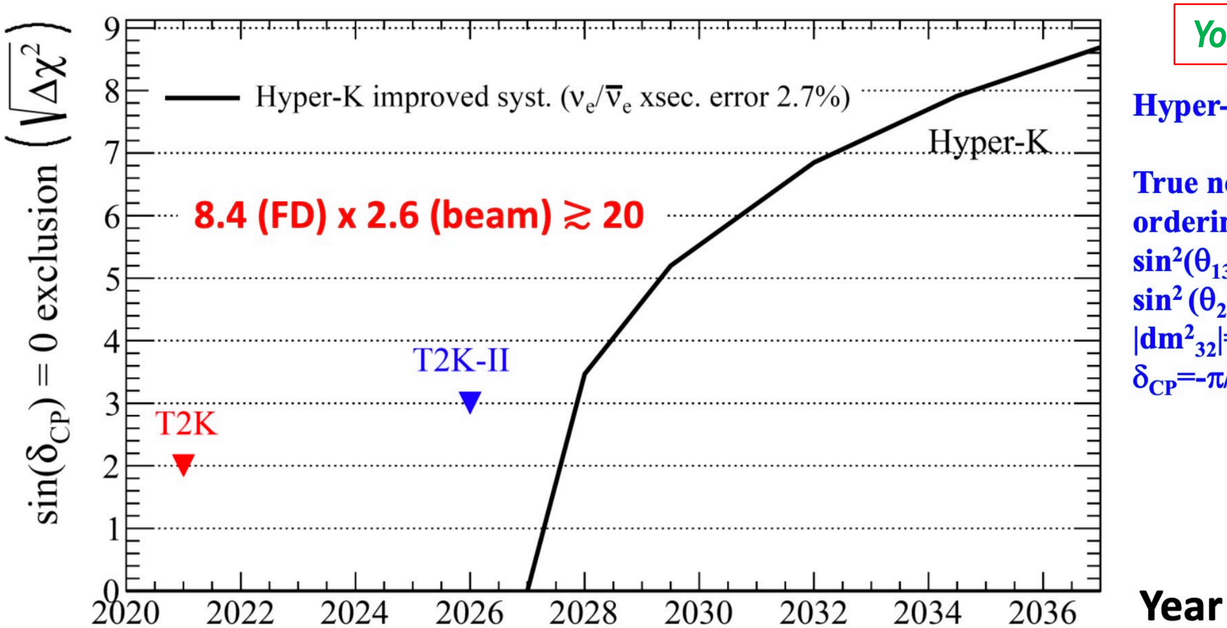


SKI – SKIV data (points with statistical error) & MC simulations (boxes with systematic error)

Huge statistics, extremely powerful data if systematics controlled to the same level of significance

Lepton CPV: Sensitivity and Measurement Capability

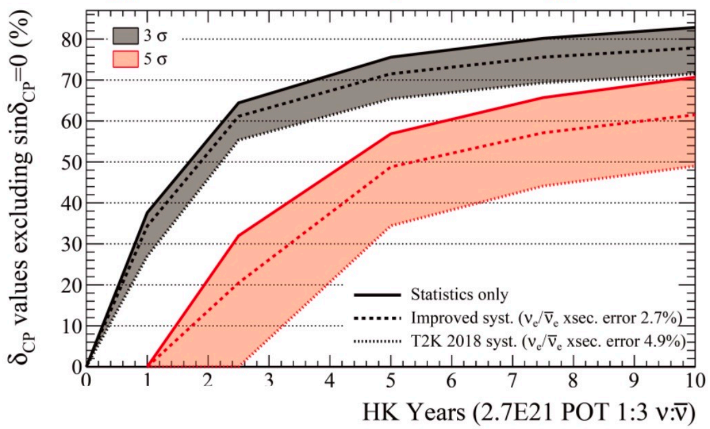
Yoichi Asaoka @ NNN22



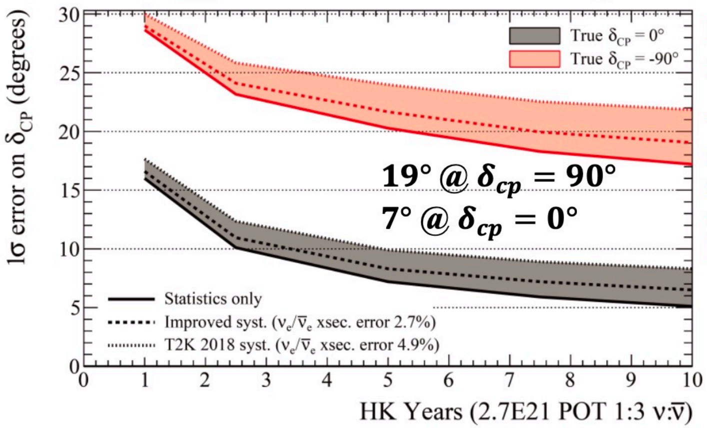
Hyper-K preliminary

True normal ordering (known)
$\sin^2(\theta_{13})$=0.0218
$\sin^2(\theta_{23})$=0.528
$|dm^2_{32}|$=2.509e-3 eV^2/c^4
δ_{CP}=-π/2

δ_{CP} fraction to reject $\sin\delta_{CP} = 0$



δ_{CP} measurement accuracy



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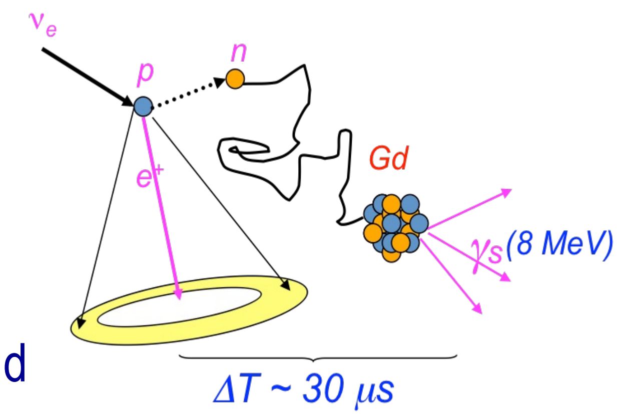
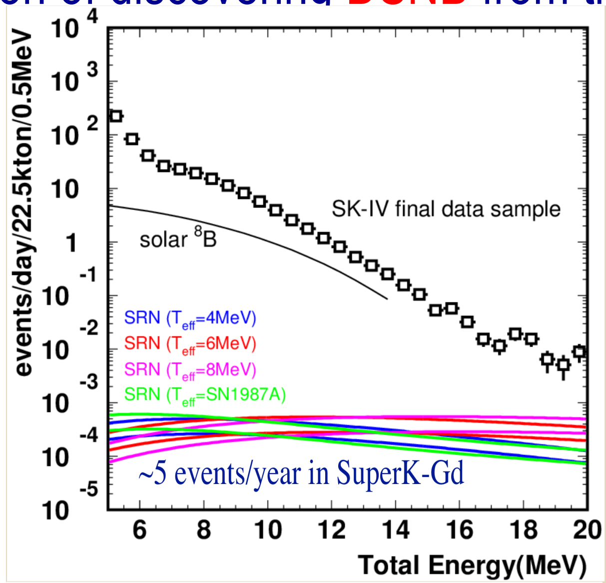
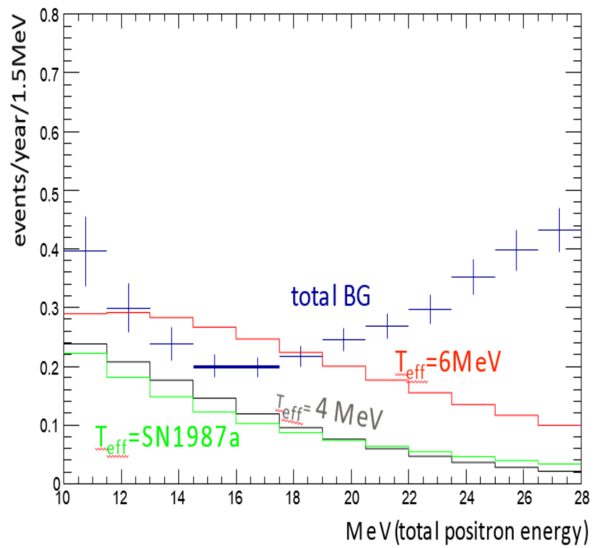
Neutron tagging in water-cherenkov detectors

➔ **anti-neutrino tagging at inverse β reaction**



- be in position of discovering DSNB from the very much reduced background

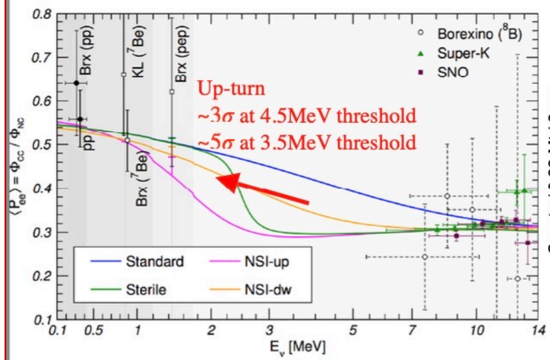




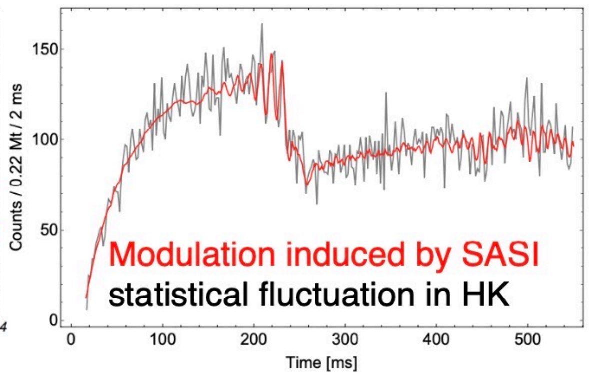
- improve pointing accuracy for Supernova
- Supernova early warning from Si burning νs
- high precision solar- νs elements from reactor νs (if available)

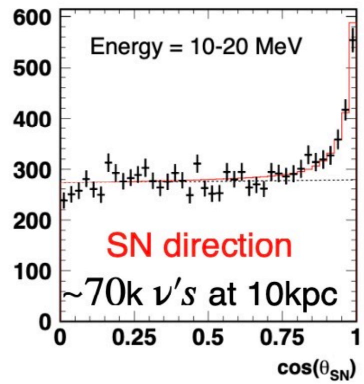
Neutrino Astrophysics

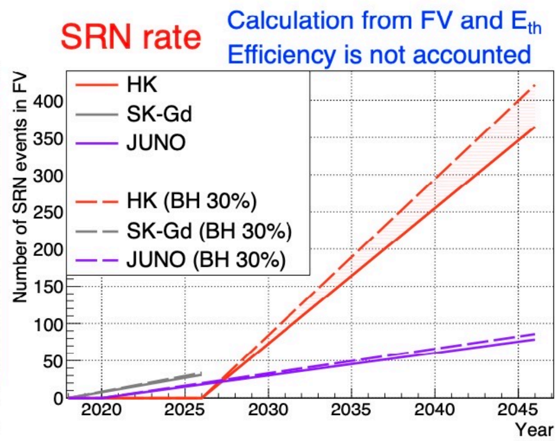
- Observation of a few~10MeV neutrinos with time, energy and direction information
  - Unique role in multi-messenger observation
- Solar neutrinos: up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- Supernova burst neutrinos: explosion mechanism, BH/NS formation, alert with ~1° pointing
- Supernova Relic Neutrinos (SRN): stellar collapse, nucleosynthesis and history of the universe



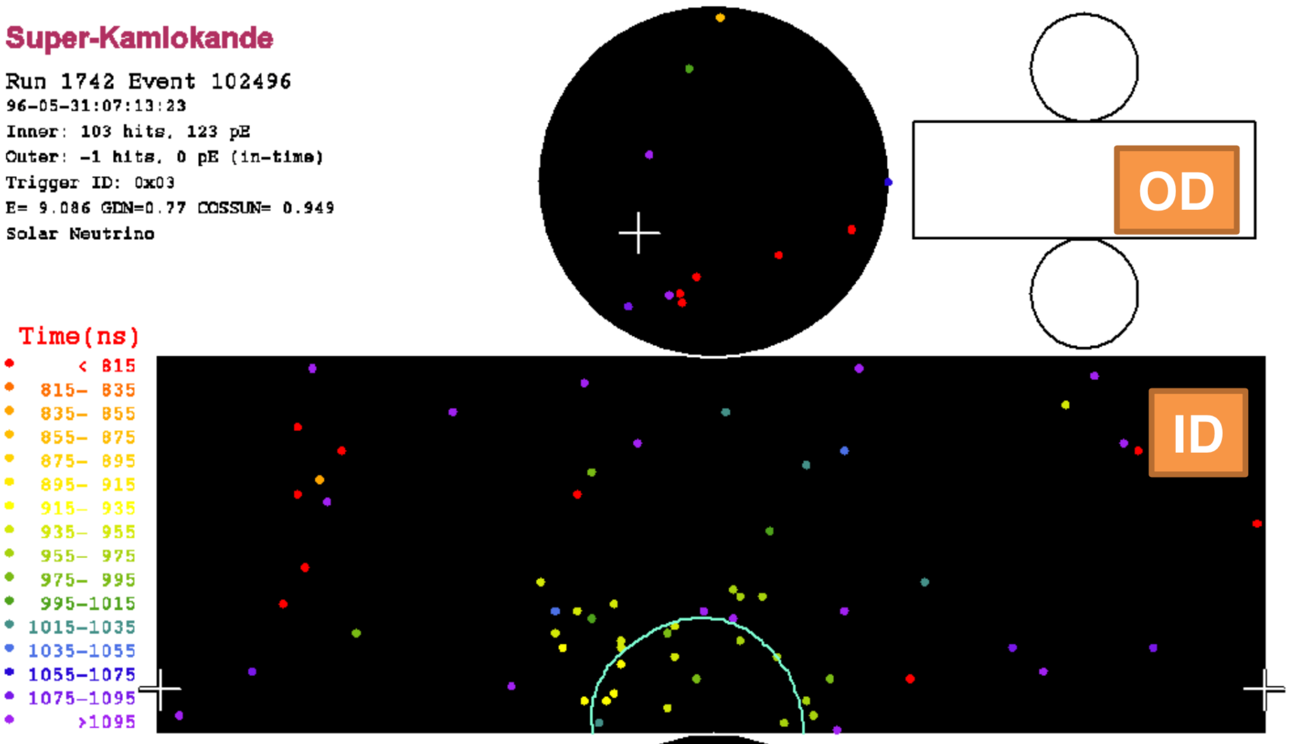
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)





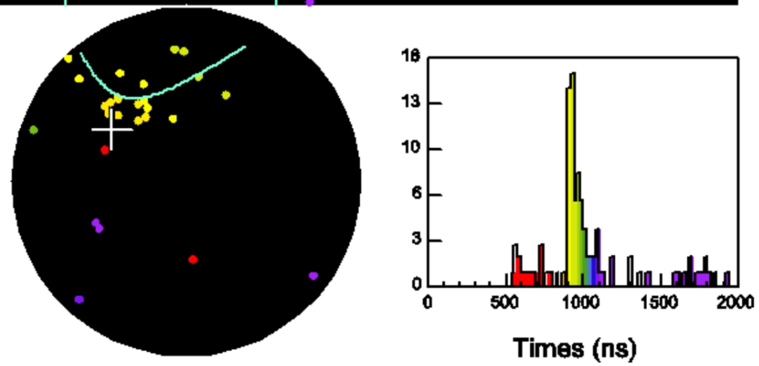


Solar ν,s reconstruction by Super-Kamiokande



(color: time)

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95



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

Elastic scattering (ES) reaction is used for solar neutrinos

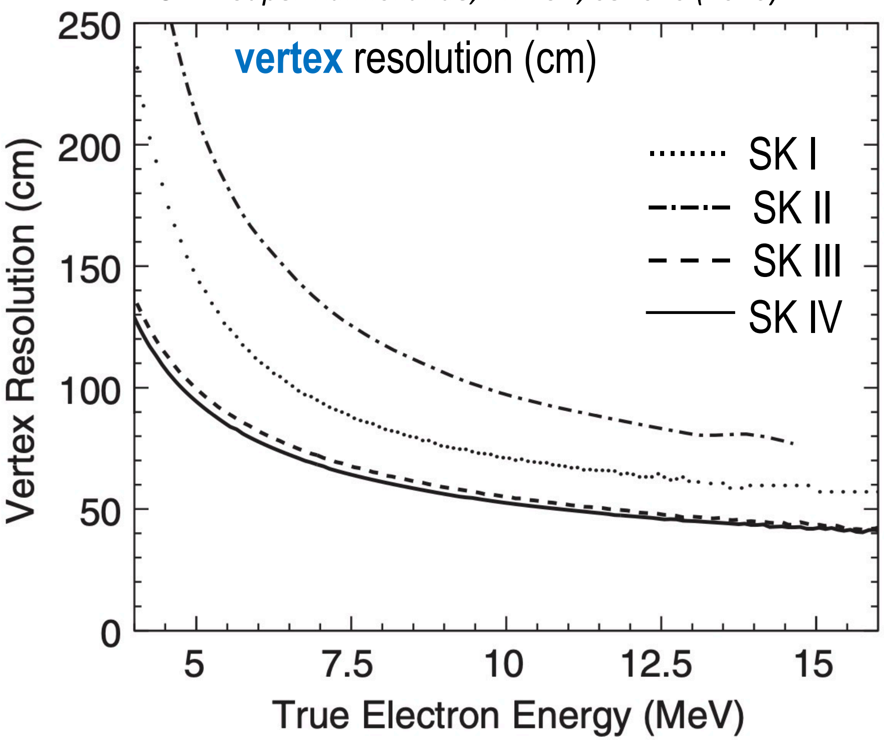
- **Timing information**
  ⇨ **vertex position**
- **Ring pattern**
  ⇨ **direction**
- **Number of hit PMTs**
  ⇨ **energy**

~6hit / MeV (SK-I, III, IV)

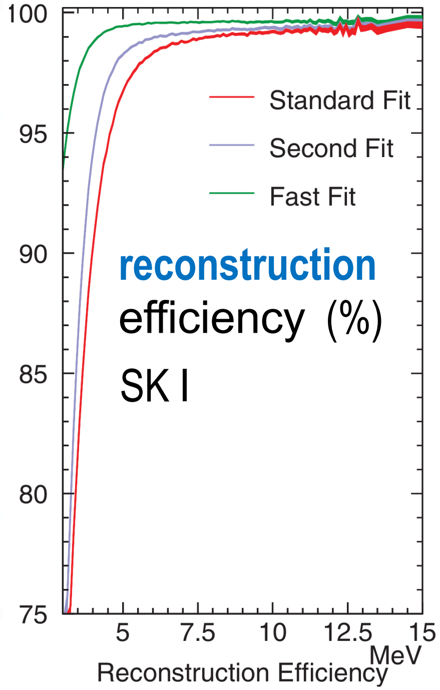
Solar ν,s reconstruction by Super-Kamiokande

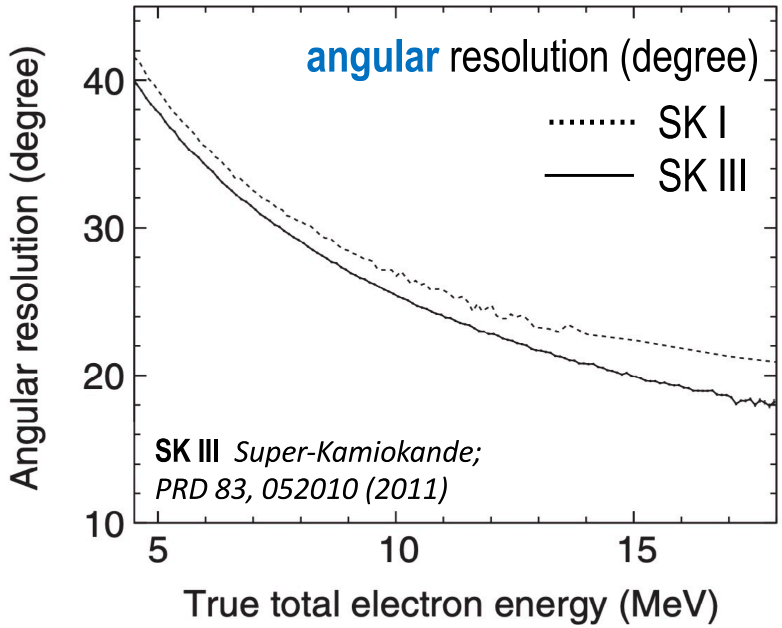
$$\nu + e \longrightarrow \nu + e$$

SK IV *Super-Kamiokande; PRD 94, 052010 (2016)*

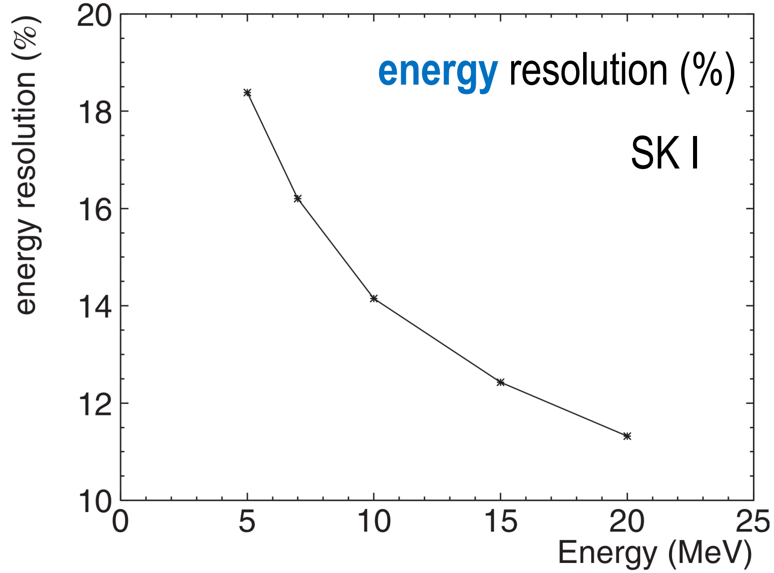


SK I *Super-Kamiokande; Phys. Rev. D 73, 112001 (2006)*



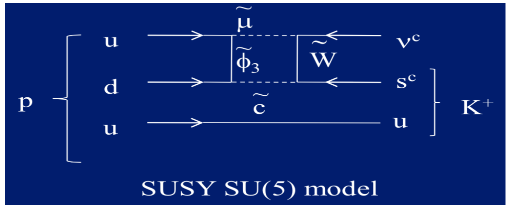


SK III *Super-Kamiokande; PRD 83, 052010 (2011)*



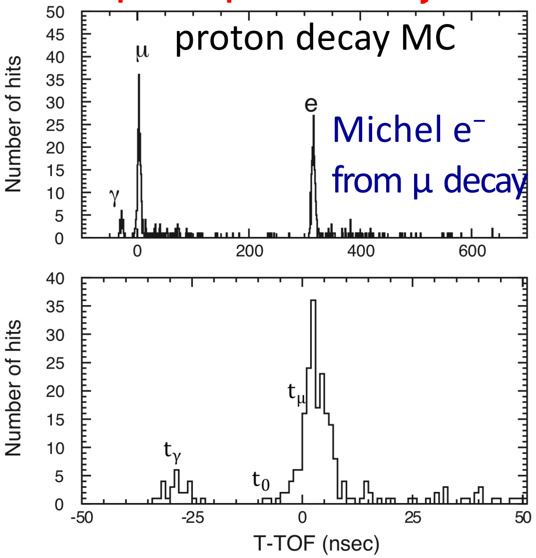
$p \to \bar{\nu} K^+$

- feature of super-symmetric GUTs

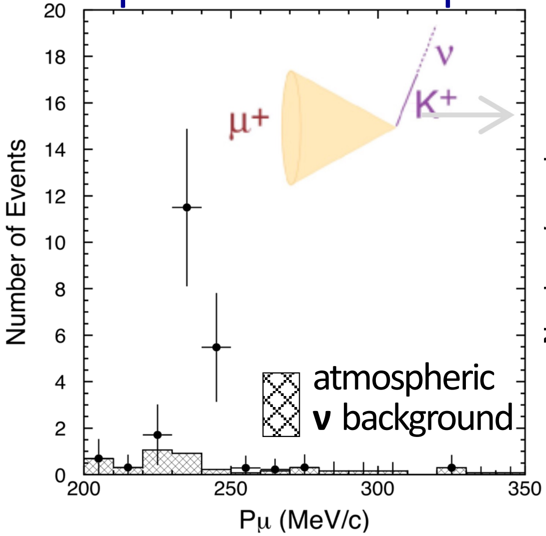


- rather interesting but difficult to reconstruct
- at decay $p(K^+)$= 340 MeV, K^+ ch-light threshold: 749 MeV → reconstruct K^+ from its decay products $K^+ \to \nu \mu^+$ *(64%)*, $K^+ \to \pi^+\pi^0$ *(21%)*
- 2-body decays → monochromatic particles: $p(\mu^+)$= 236 MeV,
  $p(\pi^+)= p(\pi^0)$= 205 MeV
- $\tau(K^+) \approx$ 12ns → possible to observe prompt 6 MeVγ from ^{16}O de-excitation

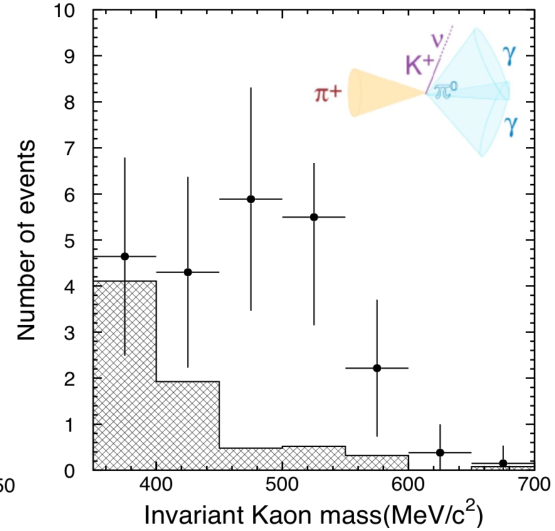
prompt 6 MeVγ



μ^+ from $K^+ \to \nu \mu^+$



$\pi^+\pi^0$ search

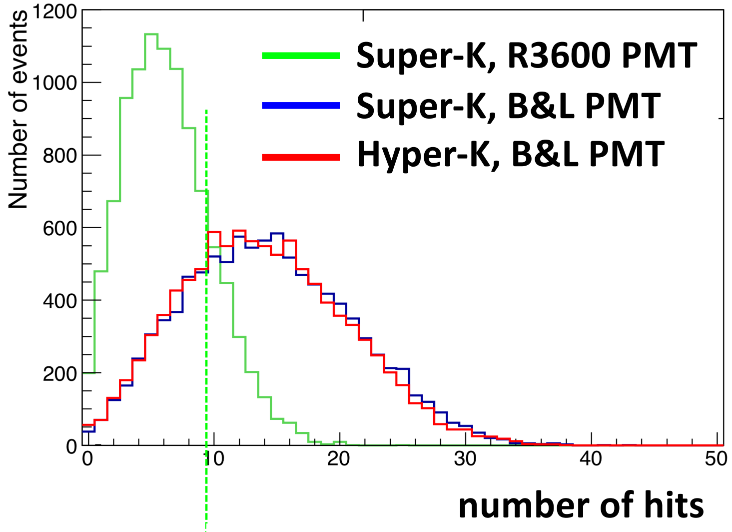


used τ_p= 6.6 • 10^{33} (SK limit), 10 years exposure

$p \rightarrow e^+\pi^0$ some of the benefits from increased photon yield

- neutron tagging (veto):
  - p decay: **no** neutrons // atmospheric ν background: **yes** neutrons
  - neutrons at (pure) water: 2.2 MeV γ from n (p, d) γ

8 MeV γ cascade if Gd capture



→ SK criterion:

≈ 18% tagging efficiency

→ much better expected for Hyper-Kamiokande

discovery potential (3 σ)