HyperKamiokande: a next-generation long baseline neutrino experiment in Japan

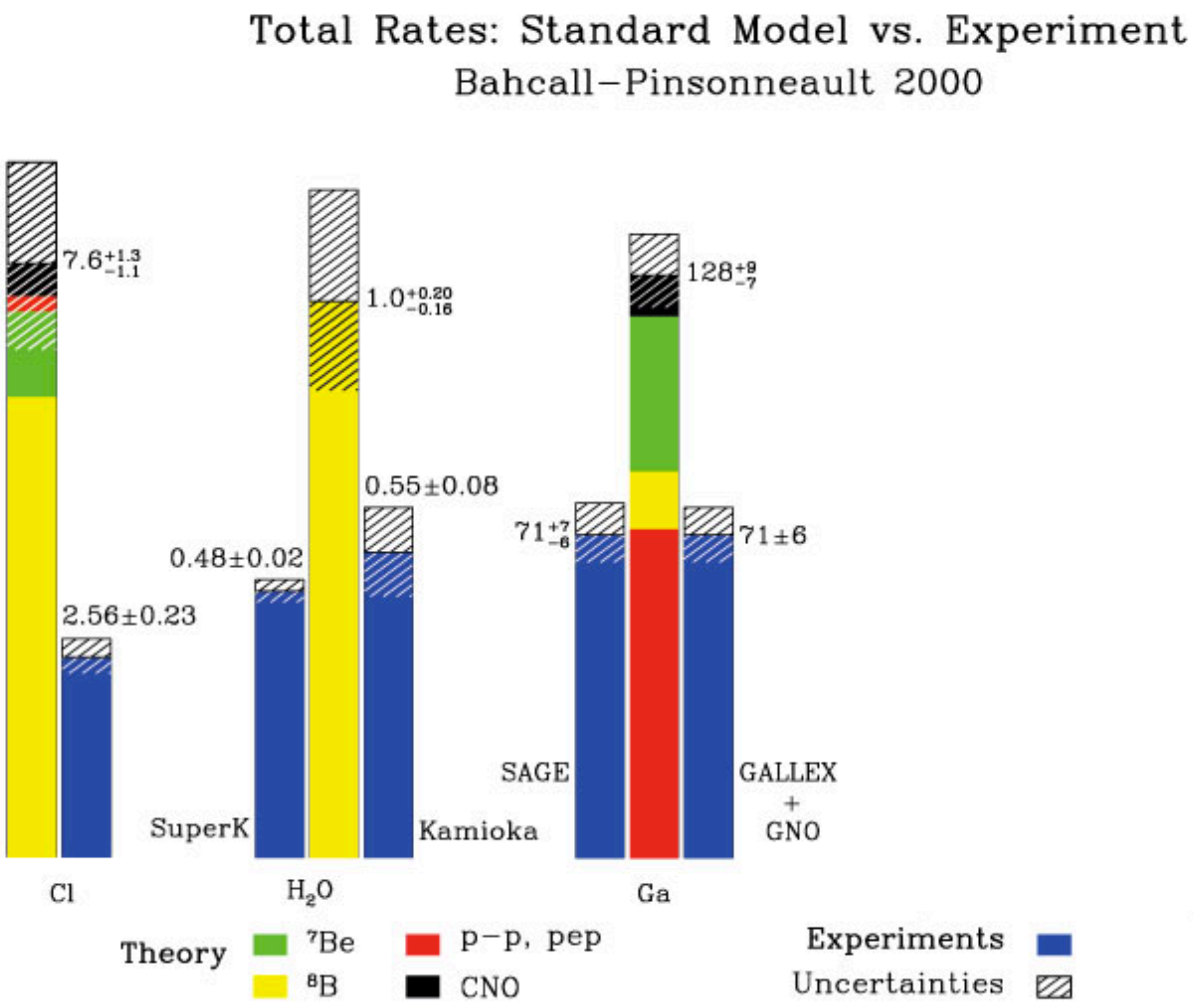
Lee Thompson
University of Sheffield

DESY Hamburg, 29th January 2019
DESY Zeuthen, 30th January 2019

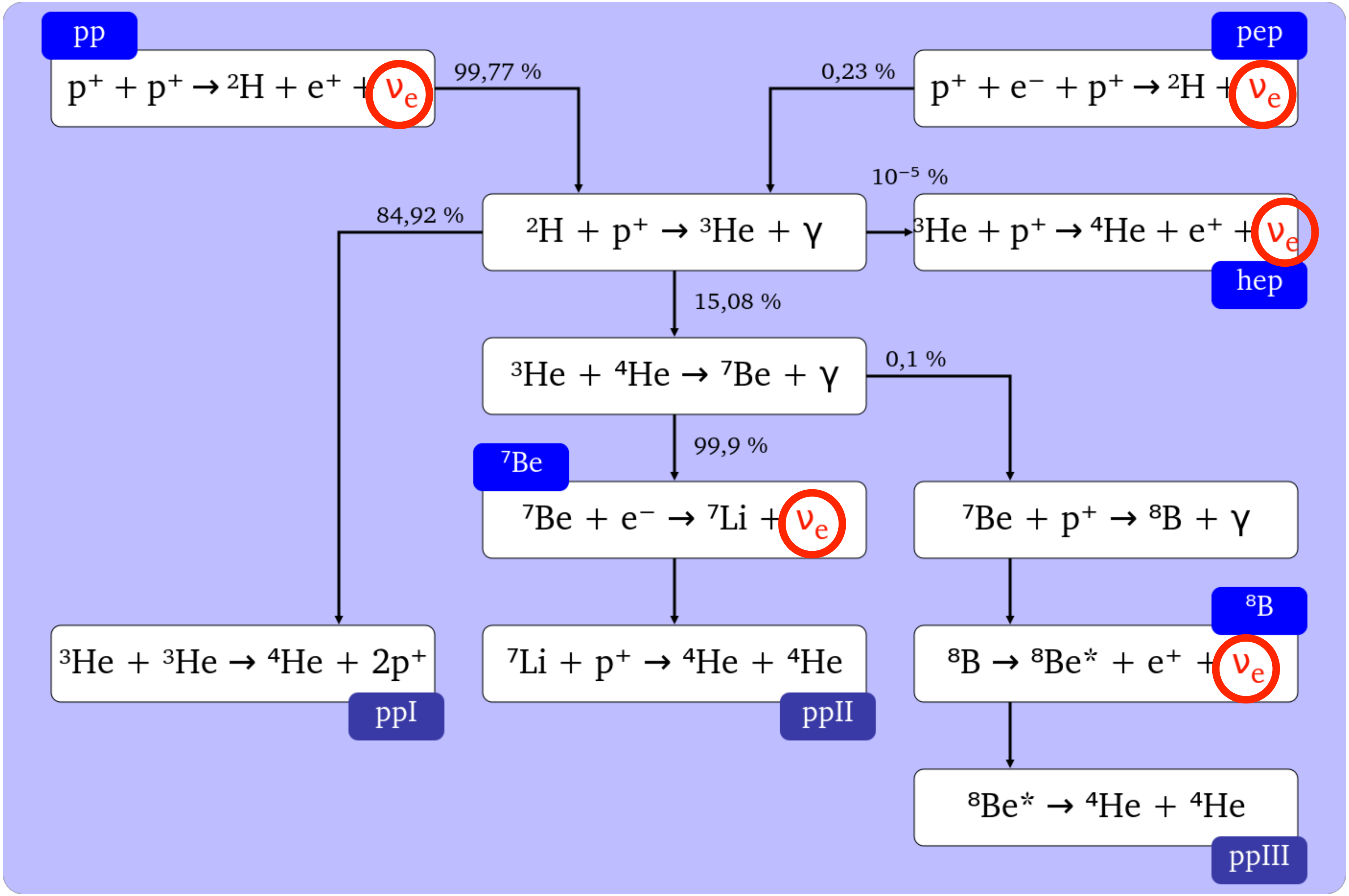
The University Of Sheffield.

Hyper-Kamiokande

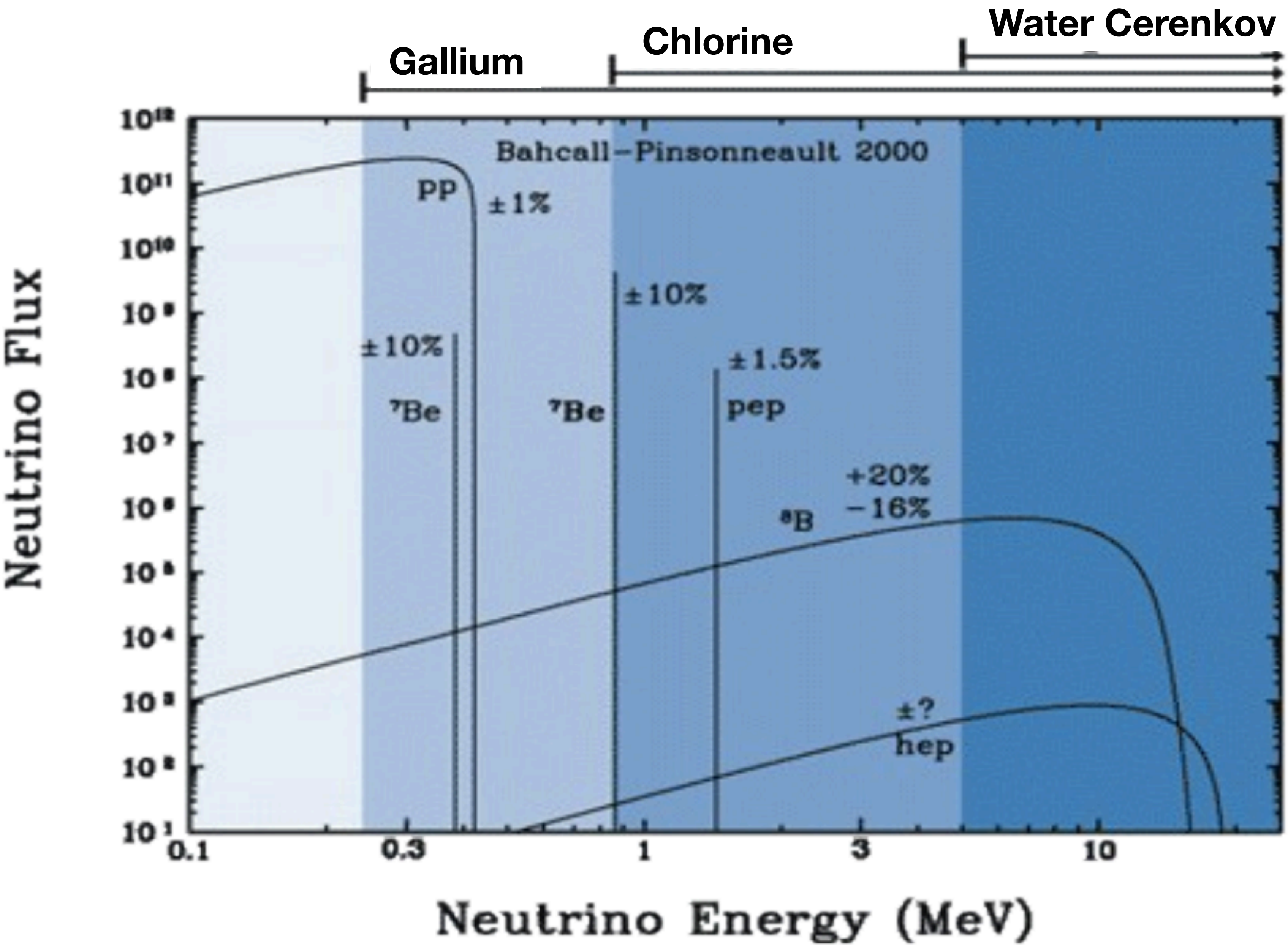
The solar neutrino deficit



Solar neutrino sources

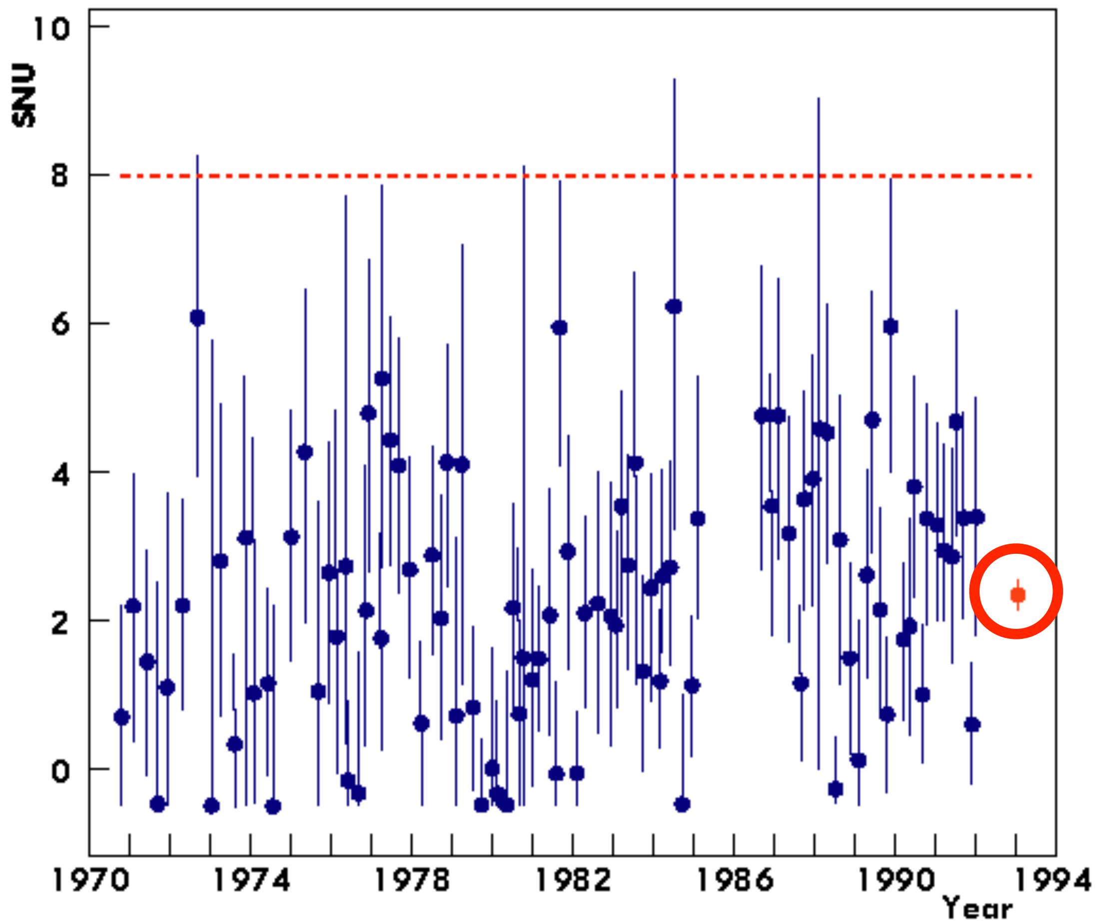


Solar neutrino spectra

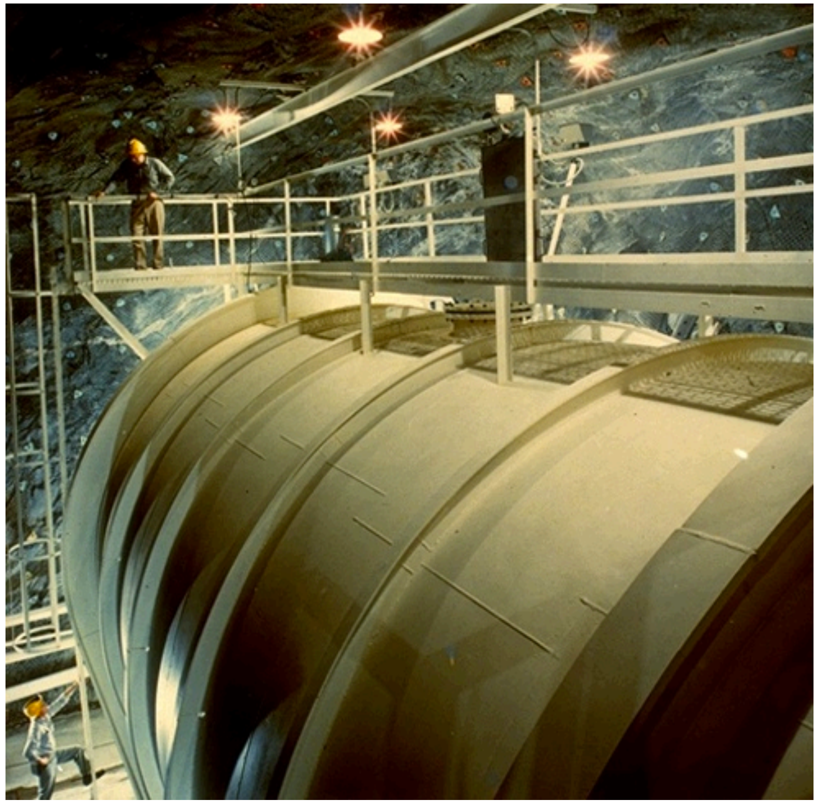


Homestake results

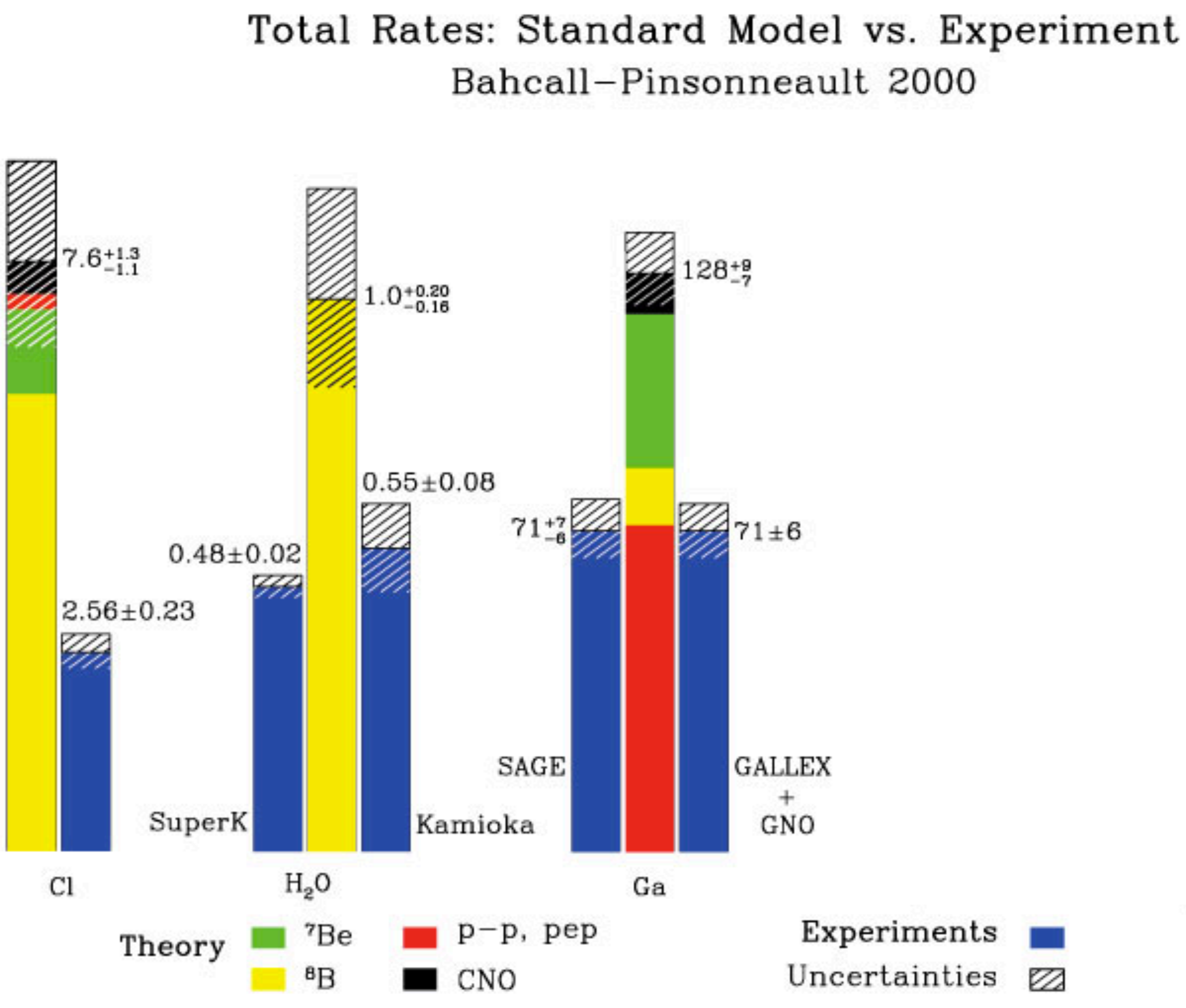
1 SNU = 10^{-36} captures /atom/second



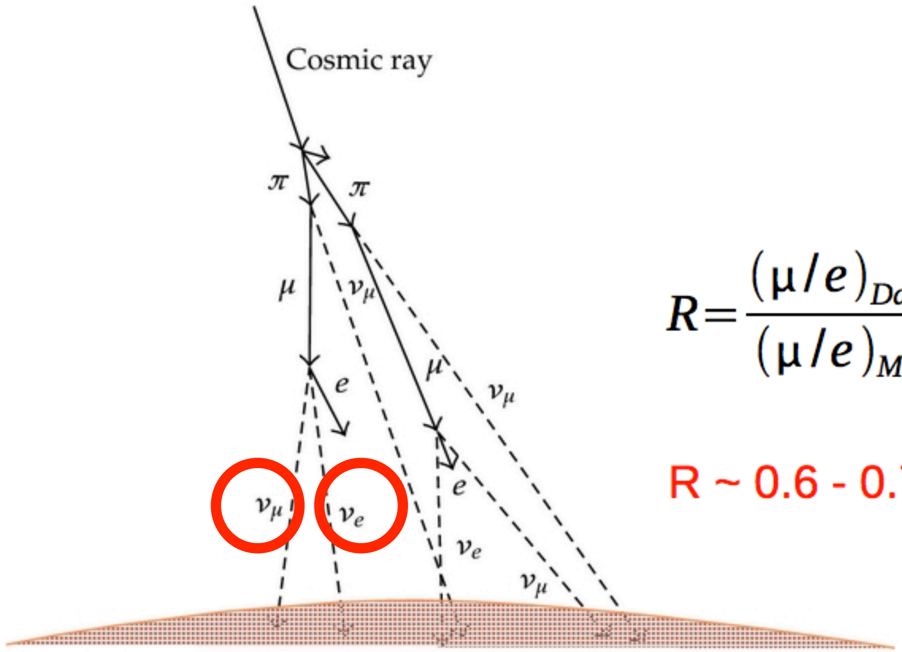
- Homestake: 100,000 US gallons (380 m^3) of perchlorethylene (dry cleaning fluid)
- $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$



The solar neutrino deficit

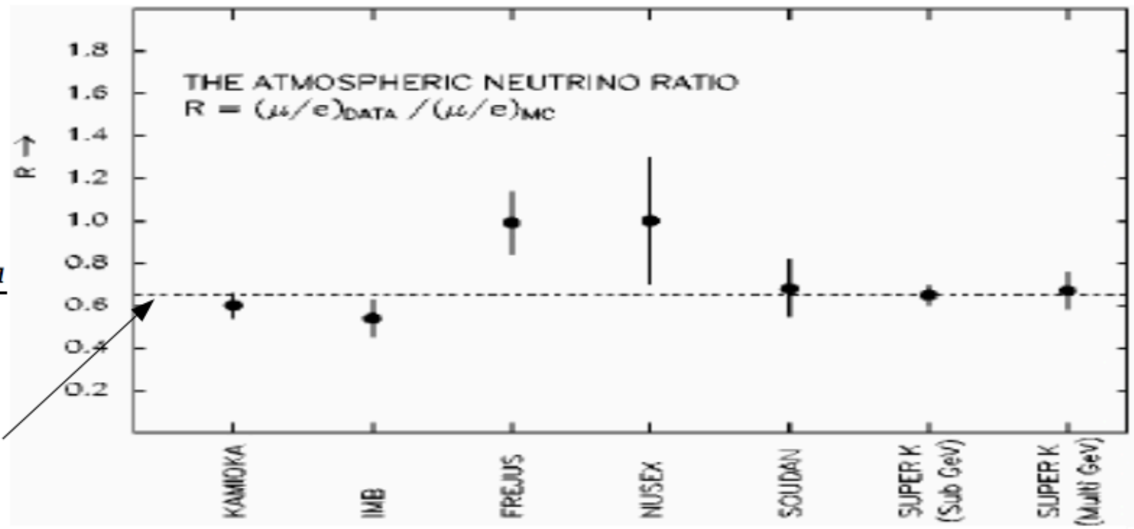


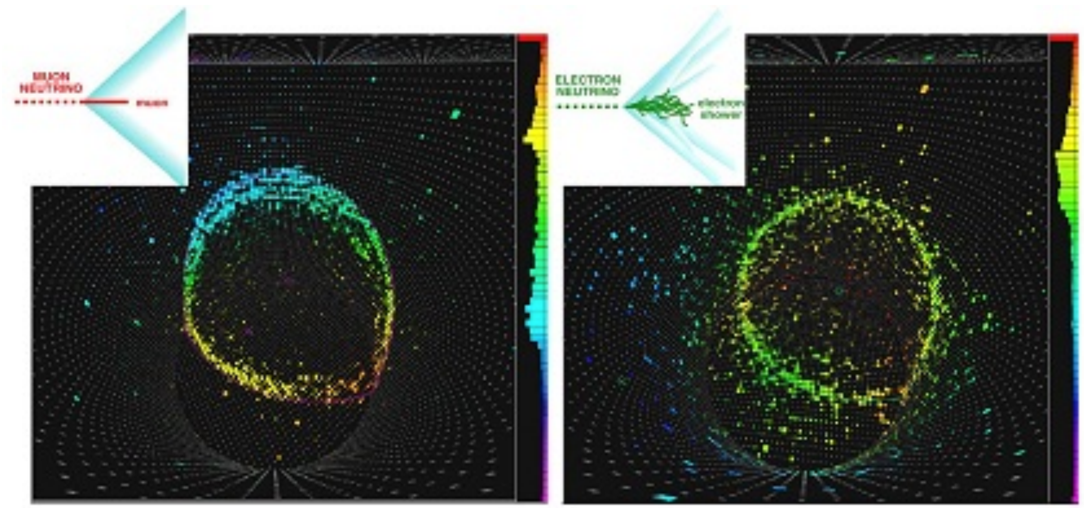
Atmospheric neutrino deficit



$$R = \frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$

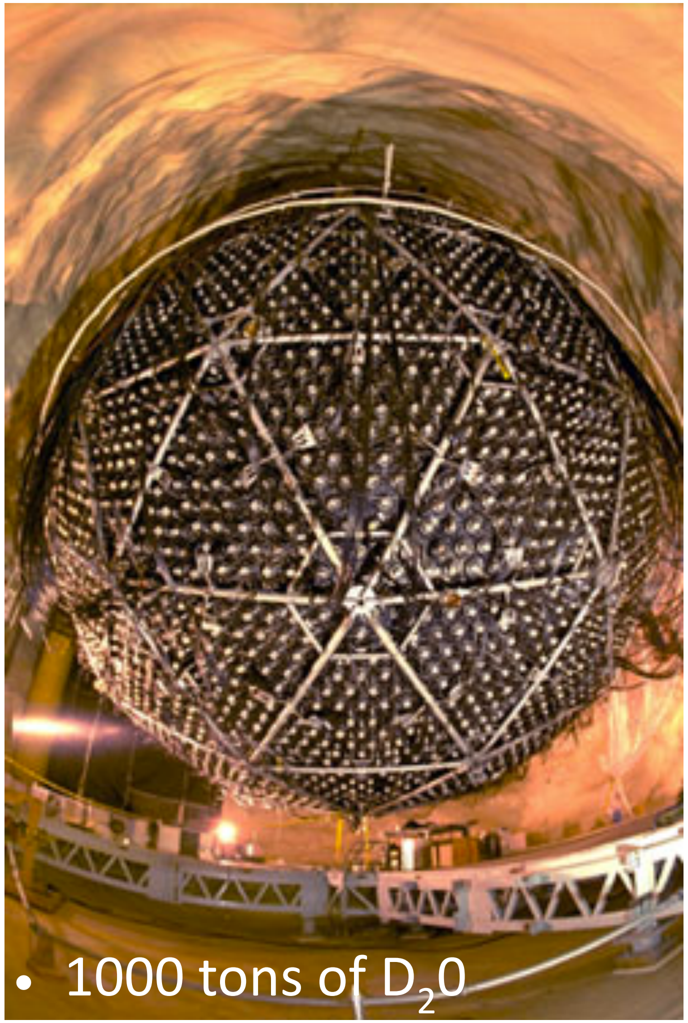
R ~ 0.6 - 0.7

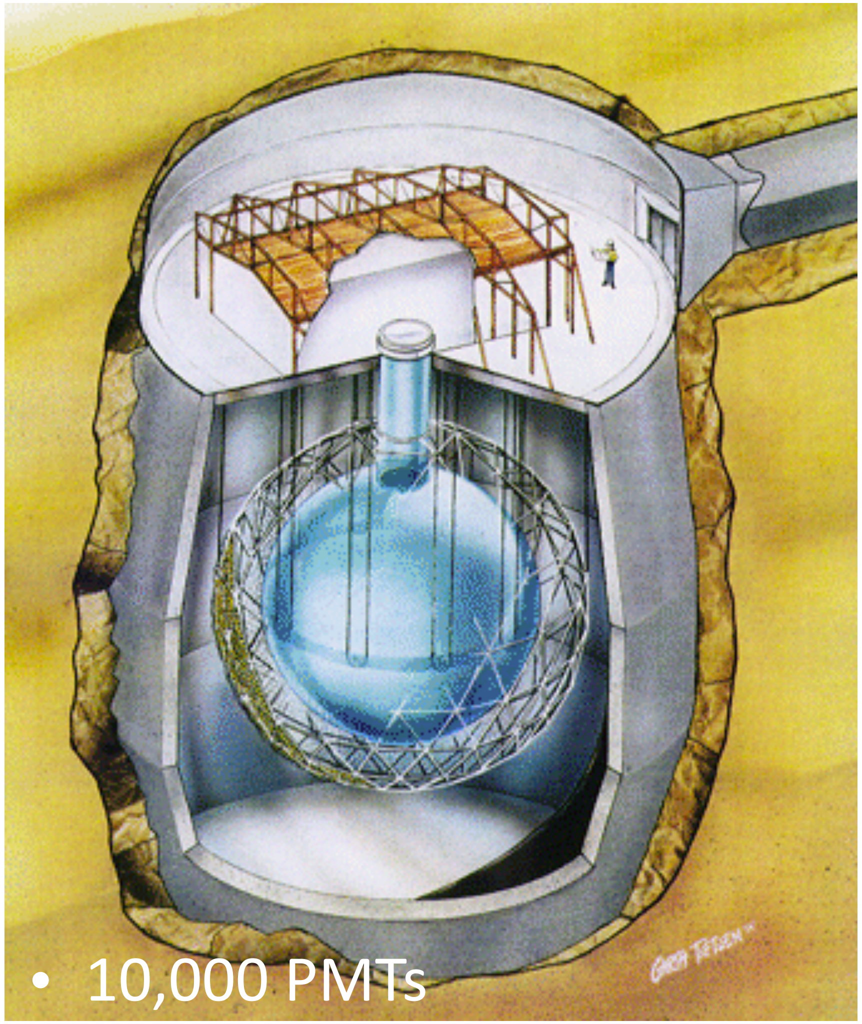




- Experiments such as SuperK were able to distinguish electrons and muons

Sudbury Neutrino Observatory





- 1000 tons of D_2O
- 6500 tons of H_2O
- 10,000 PMTs
- 2km underground

Sudbury Neutrino Observatory

CC $\nu_e + d \rightarrow p + p + e^-$

Produces Cherenkov Light Cone in D_2O

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

NC $\nu_x + d \rightarrow p + n + \nu_x$

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

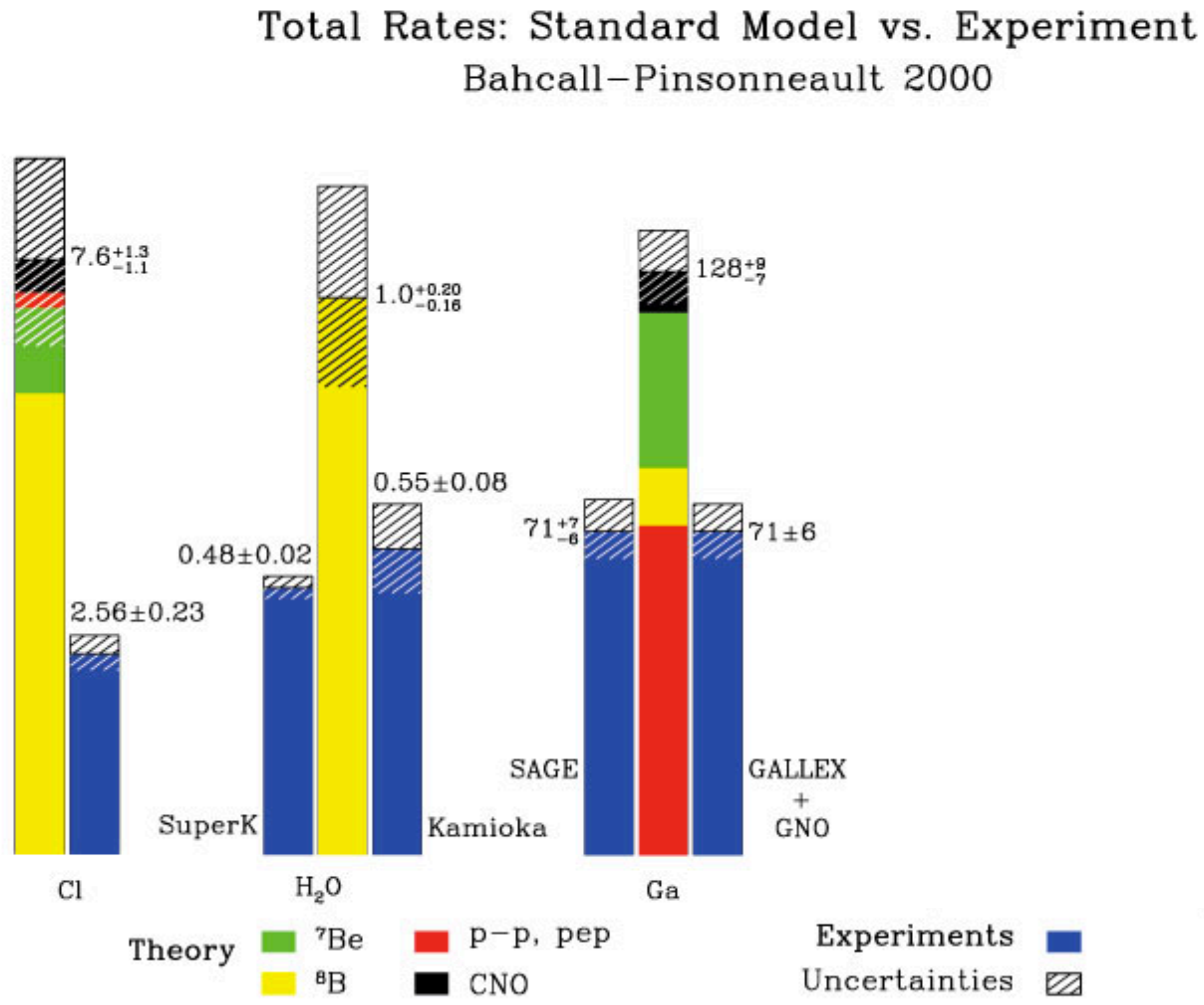
- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

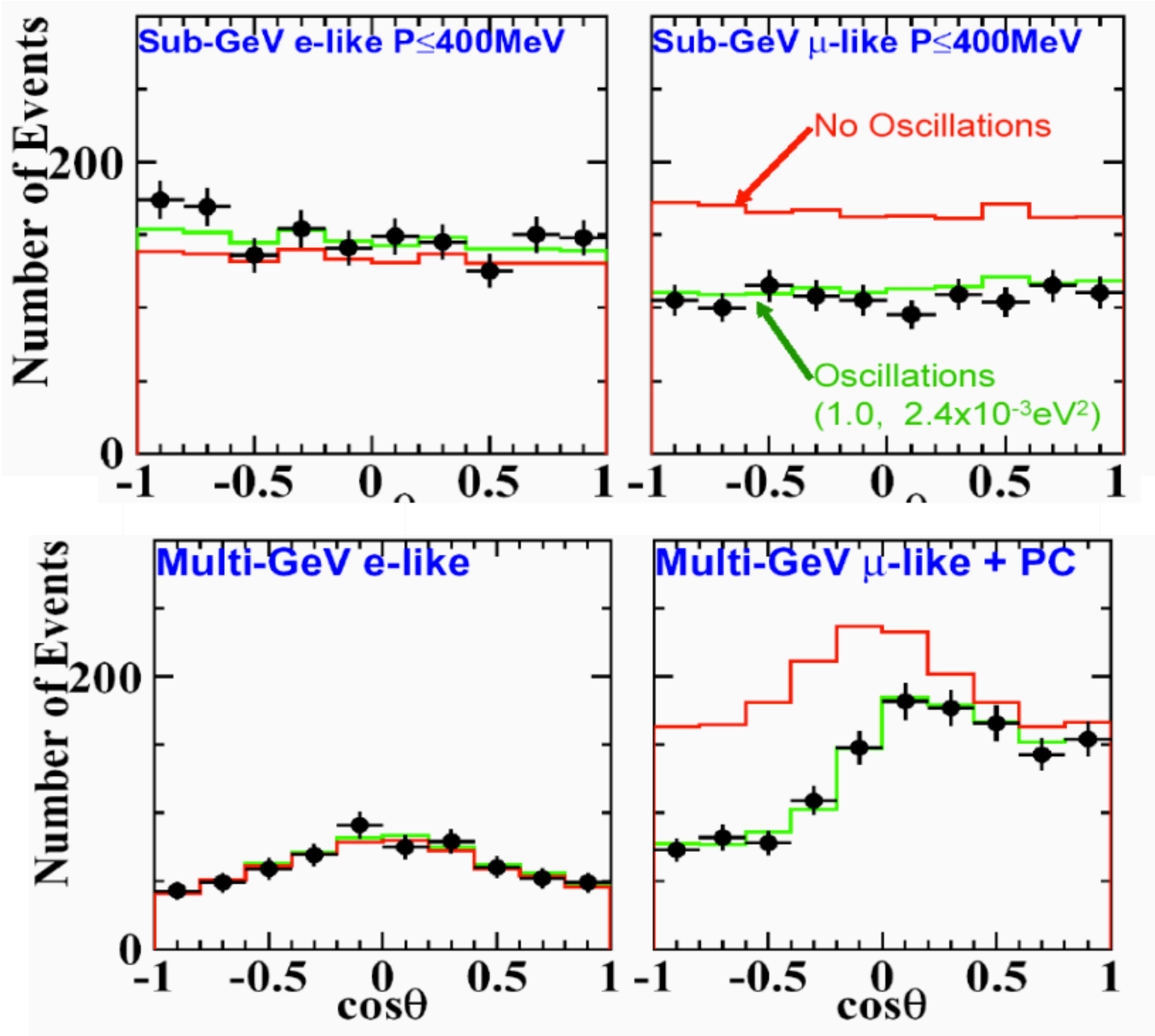
Produces Cherenkov Light Cone in D_2O

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

The solar neutrino ~~deficit~~



SuperKamiokande atmospheric data



- Re-interpretation of SK results assuming that some fraction of the CR ν_μ have oscillated to ν_τ (that SK is not sensitive to)

THE NOBEL PRIZE

The Nobel Prize in Physics 2015

Takaaki Kajita
Arthur B. McDonald

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The Nobel Prize in Physics 2015

Takaaki Kajita

Prize share: 1/2

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

www.nobelprize.org

Neutrino oscillations

- The neutrino weak eigenstates and mass eigenstates are not the same (are not 'aligned')
- The neutrino propagates in the mass eigenstate but interacts in the weak eigenstate
- NB this can <u>only</u> happen if neutrinos have mass
- "Beyond Standard Model" physics
- The Pontecorvo-Maki-Nakagama-Sakata (PMNS) mixing matrix relates the weak and mass eigenstates

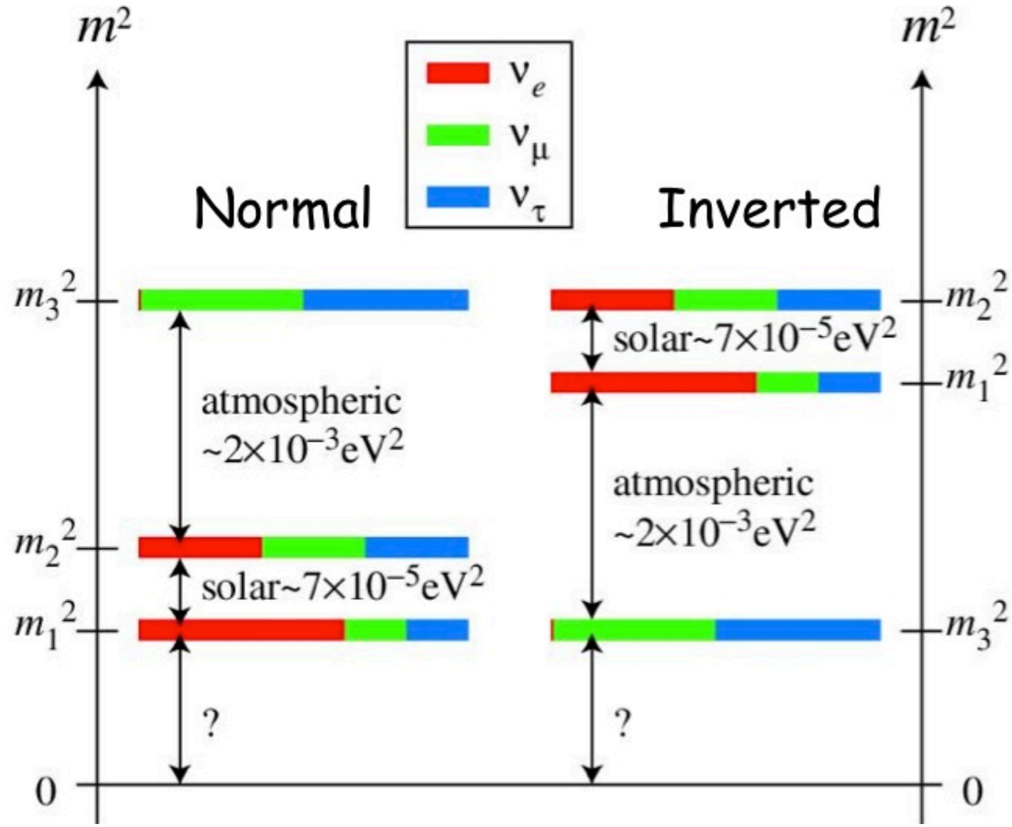
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Generally the PMNS (U above) is written in terms of 3 mixing angles θ_{12}, θ_{13}, θ_{23} and a complex phase δ (s=sin, c=cos):

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

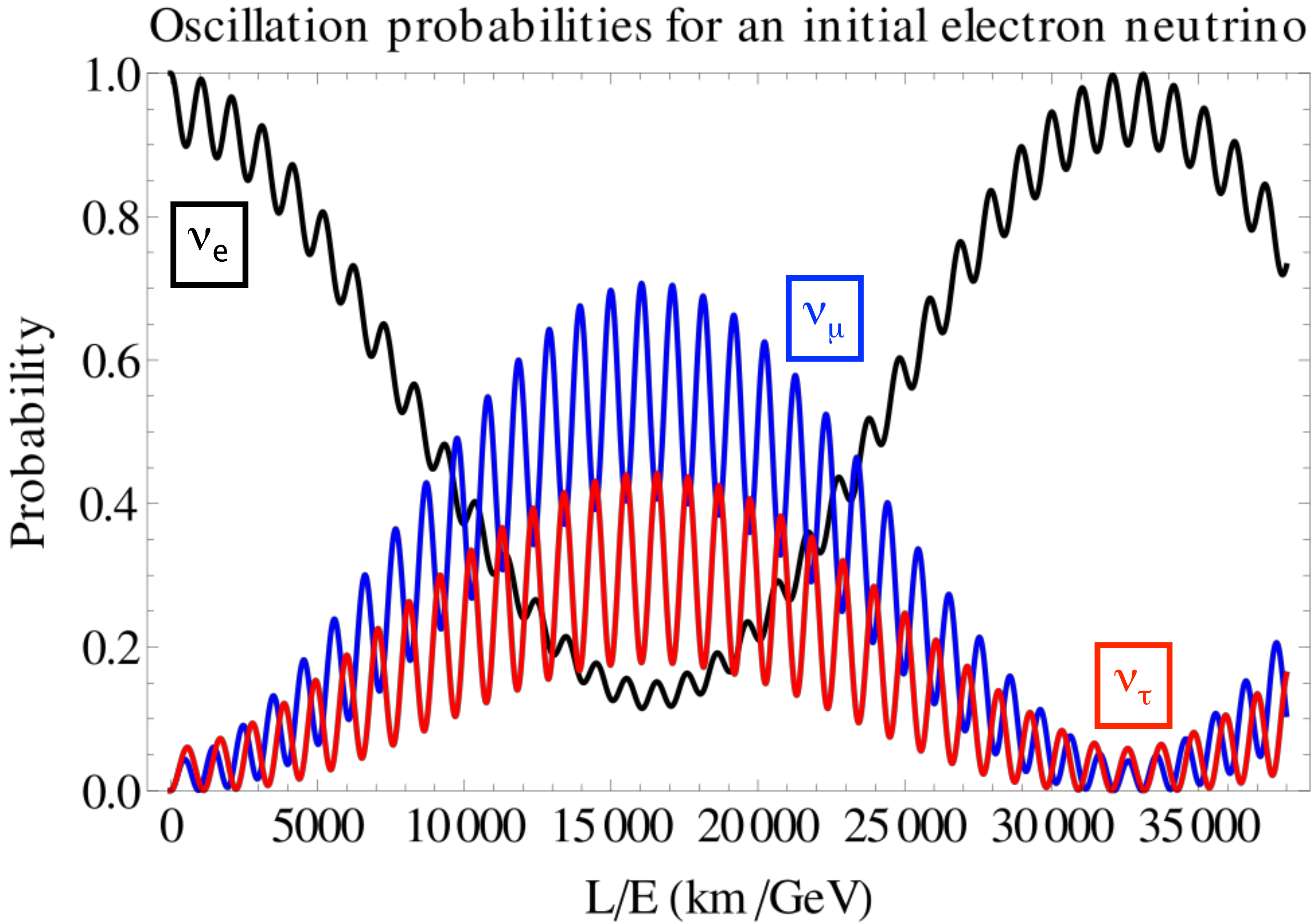
Mass hierarchy and flavour content

$$P(\nu_\alpha \rightarrow \nu_\beta)_{(\alpha \neq \beta)} = -4 \left(\underbrace{U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 2}}_{C_{12}} \sin^2\left(1.27 \frac{\Delta m_{12}^2 L}{E}\right) + \underbrace{U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 3}}_{C_{13}} \sin^2\left(1.27 \frac{\Delta m_{13}^2 L}{E}\right) + \underbrace{U_{\alpha 2} U_{\beta 2} U_{\alpha 2} U_{\beta 3}}_{C_{23}} \sin^2\left(1.27 \frac{\Delta m_{23}^2 L}{E}\right) \right)$$



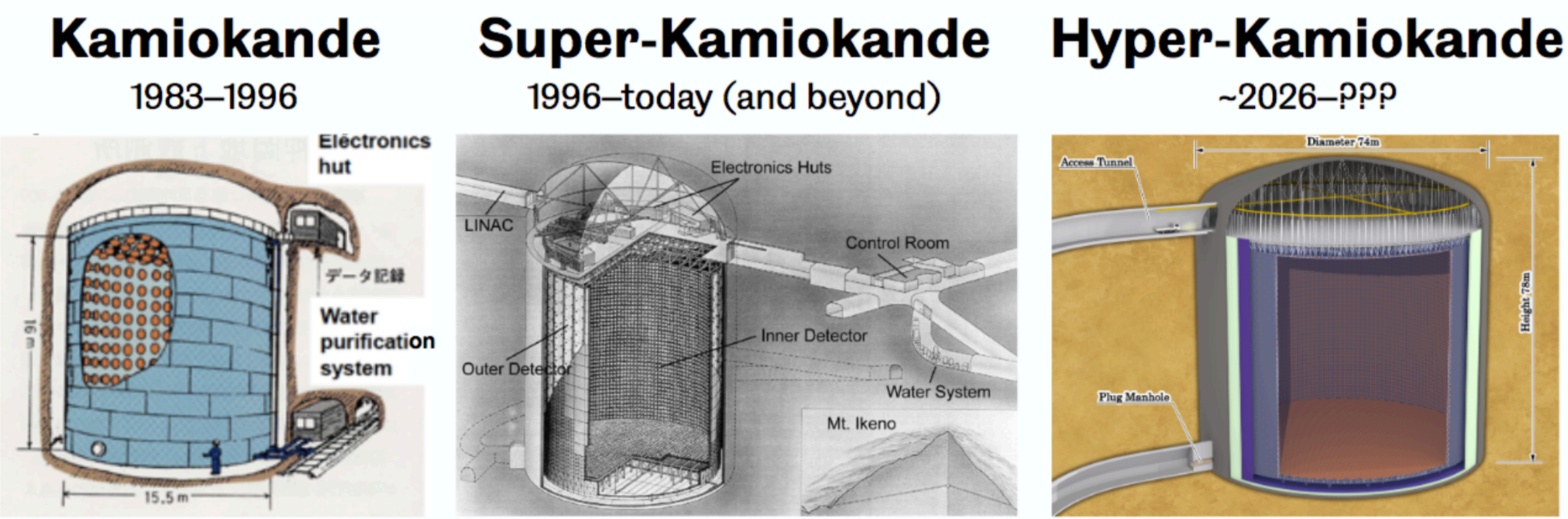
- Oscillation probabilities contain terms which include mass squared differences
- However, the sign of Δm_{13}^2 isn't known leading to 2 mass ordering possibilities
- Note also P(L,E)

Neutrino oscillations

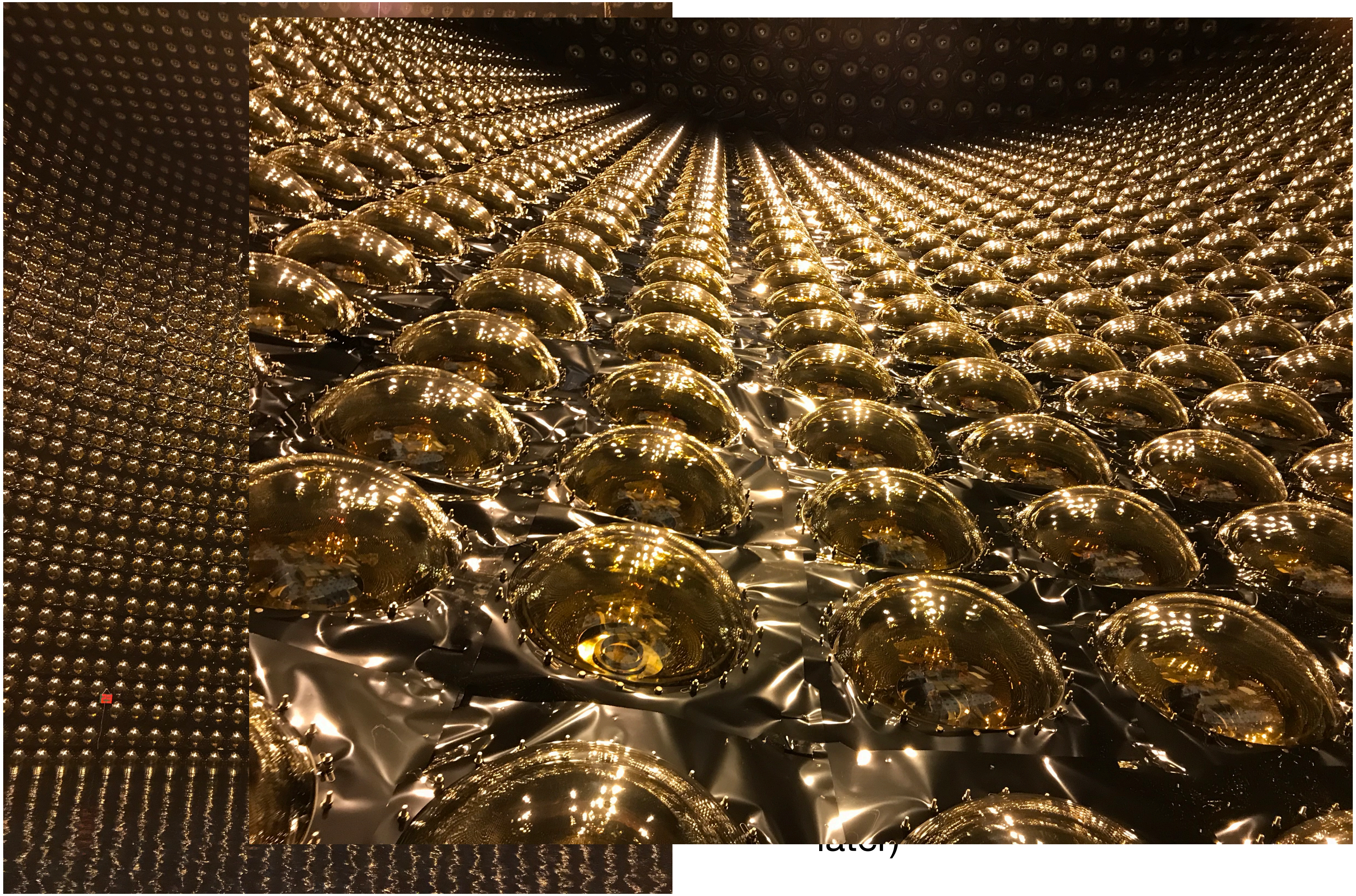


HyperKamiokande detector

- A next generation Water Cerenkov neutrino detector building on expertise and know-how from the successful, Nobel Prize winning, Kamiokande and Super-Kamiokande projects

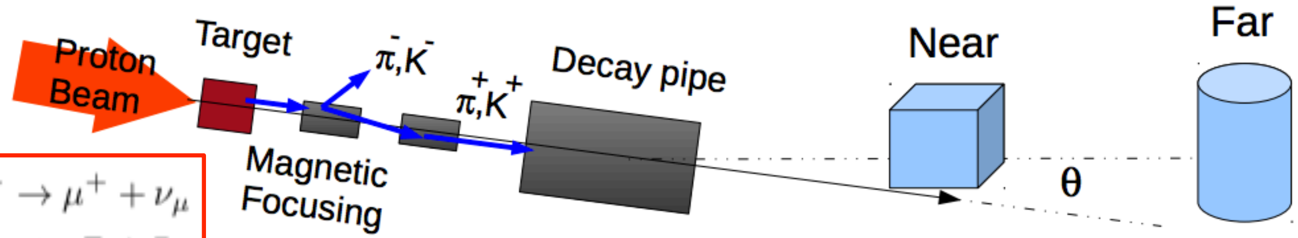


SuperKamiokande Detector



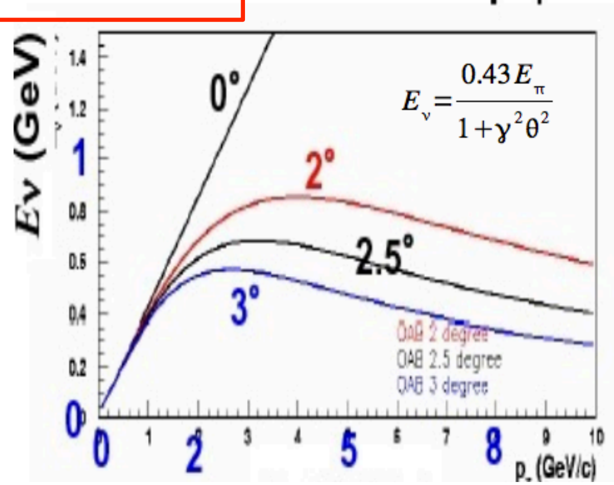
lator)

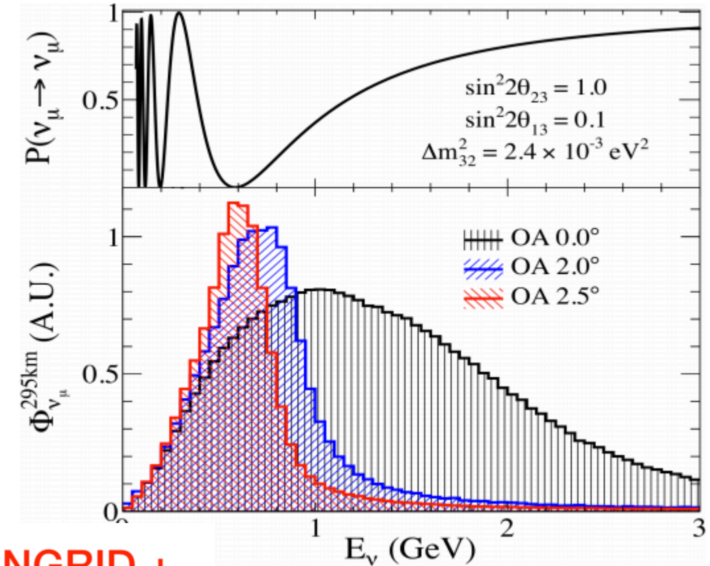
T2K - long-baseline neutrino physics

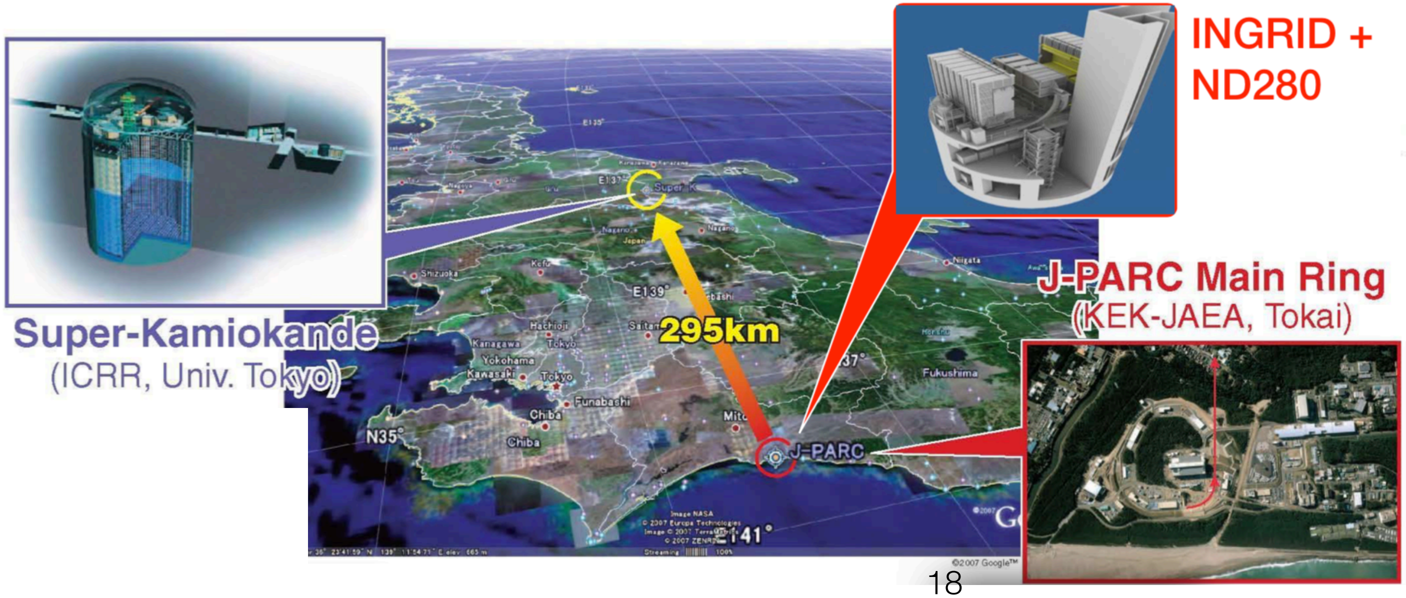


- First ever off-axis (anti-)neutrino beam
- Beam energy is tuned to oscillation maximum

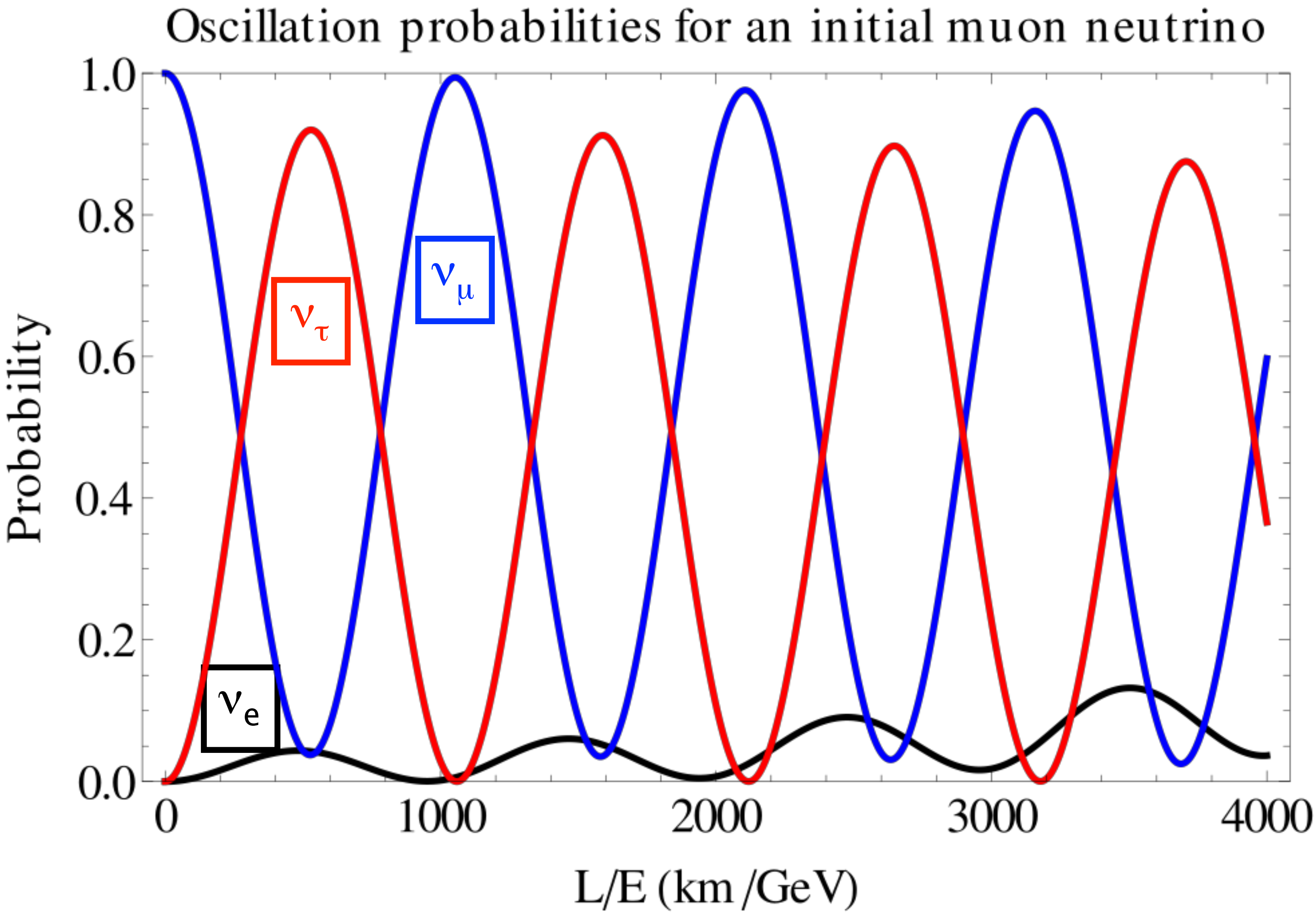
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$





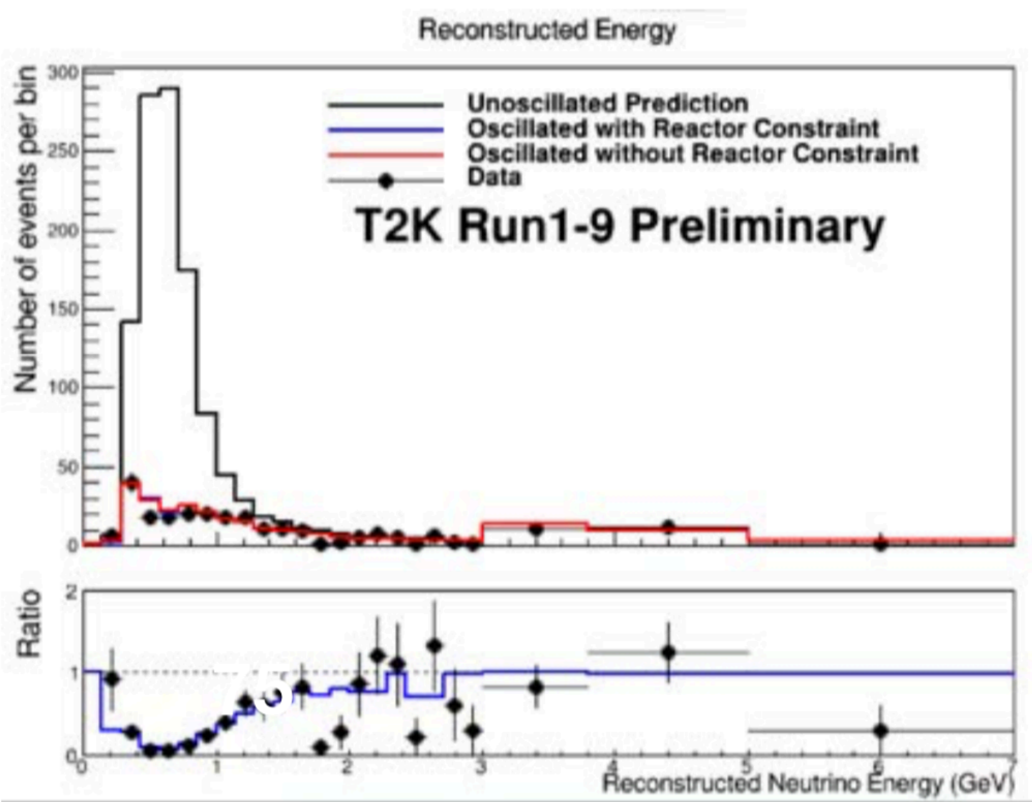


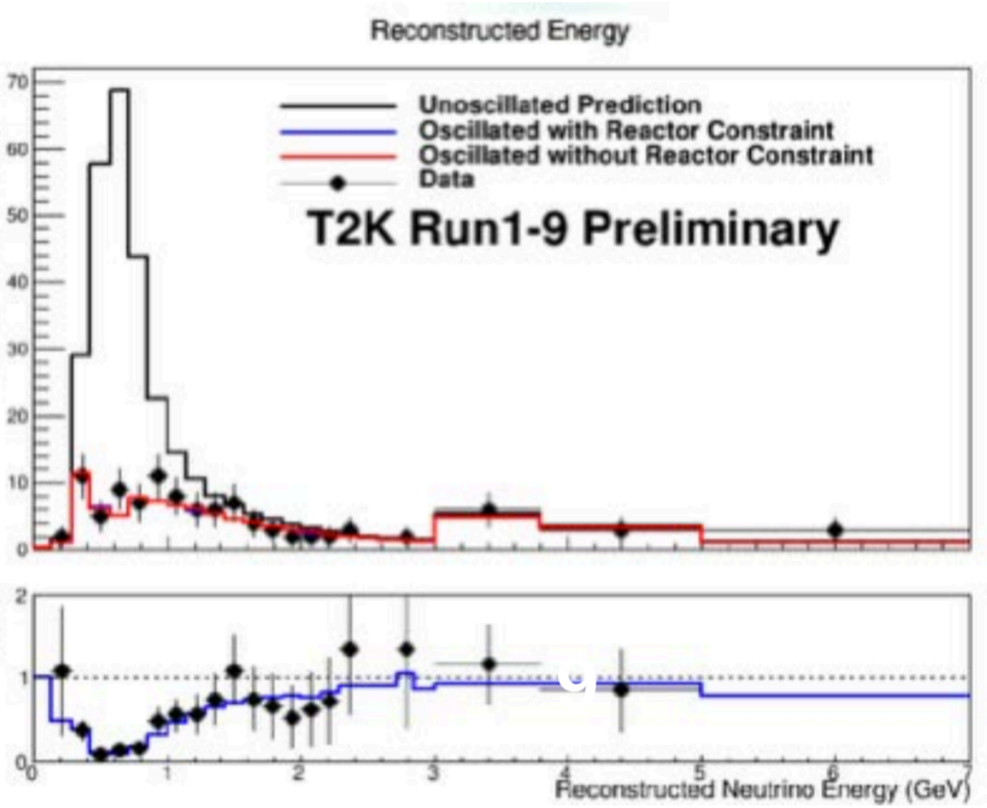
Neutrino oscillations



T2K event rates

$\nu_\mu \to \nu_\mu$ $\qquad$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$



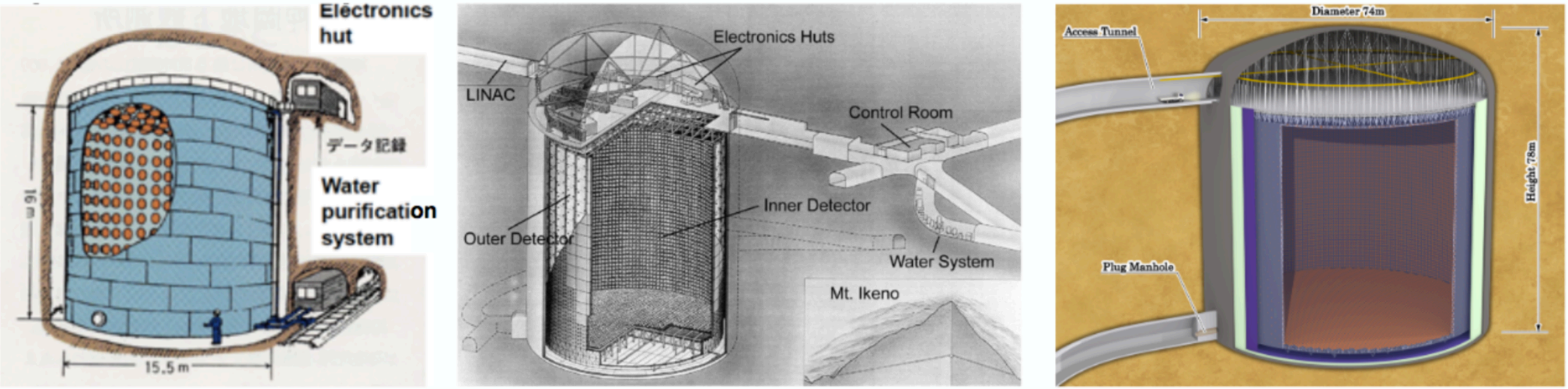


$243\ \nu_\mu - \mathrm{CC}$ events $\qquad$ $102\ \bar{\nu}_\mu - \mathrm{CC}$ events

HyperK detector

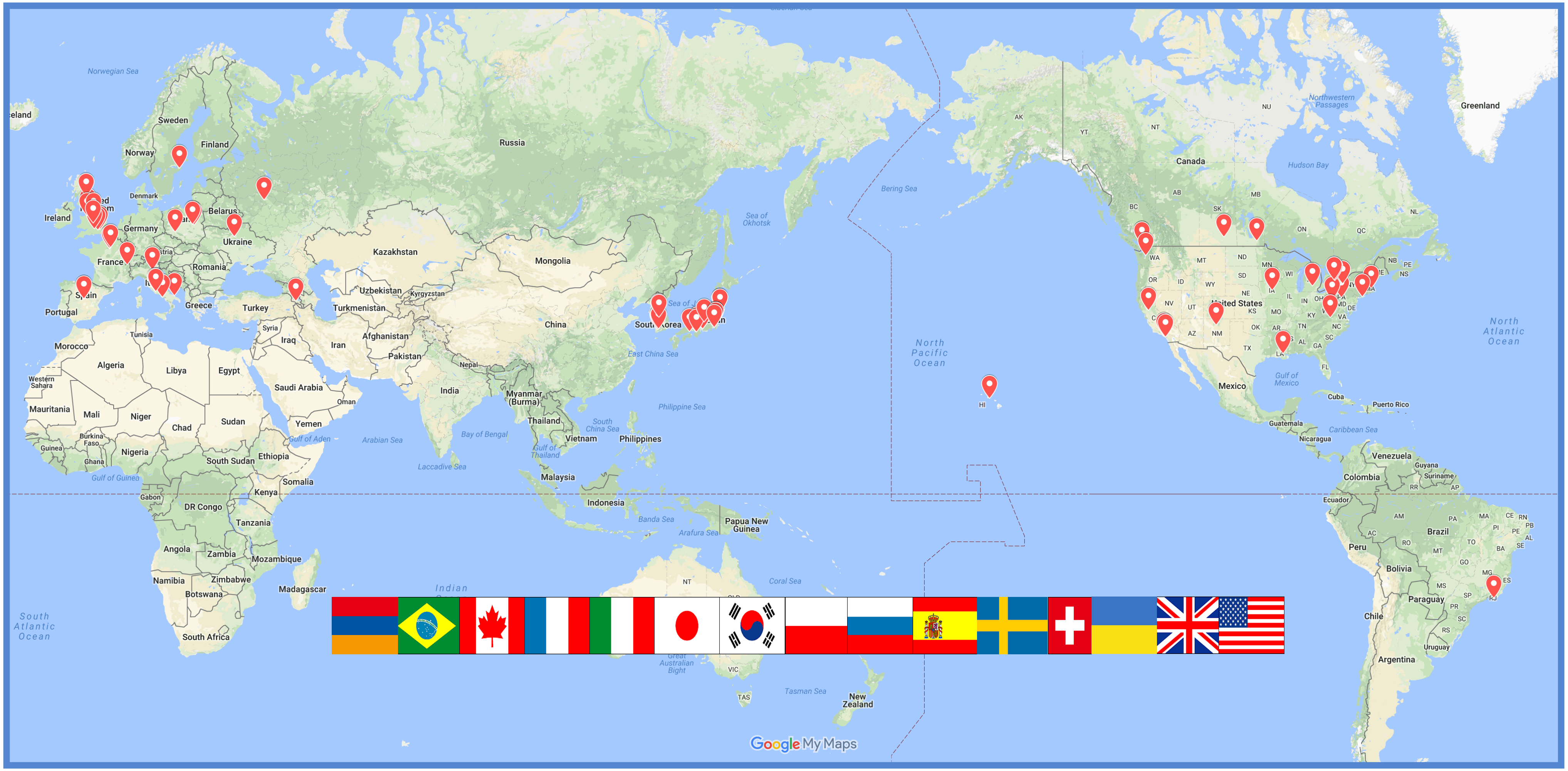
- A next generation Water Cerenkov neutrino detector building on expertise and know-how from the successful, Nobel Prize winning, Kamiokande and Super-Kamiokande projects

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983–1996	1996–today (and beyond)	~2026–???



	Super-K	Hyper-K (1st Tank)
Site	Mozumi	Tochibora
ID PMTs	11,129	40,000
Photo-coverage	40%	40% (x2 1PE efficiency)
Mass (Fiducial Mass)	50kton (22.5kton)	260kton (187kton)

HyperK proto-collaboration



- **Currently ~300 physicists from 76 institutes across 15 countries**

Recent funding (good) news

HYPER-KAMIOKANDE EXPERIMENT TO BEGIN CONSTRUCTION IN APRIL 2020

Posted on SEPTEMBER 19, 2018 5:01 PM by ADMIN

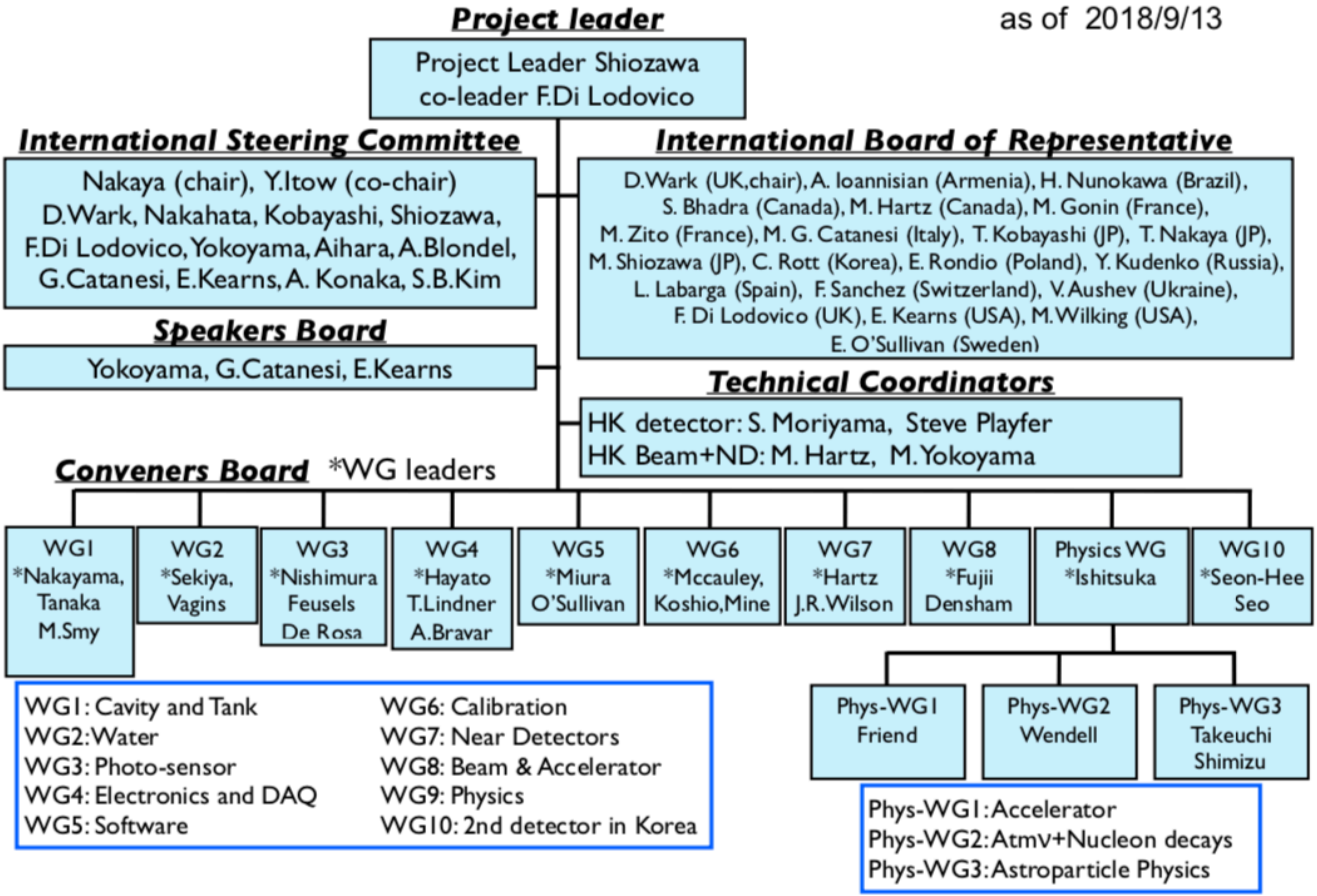
Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.

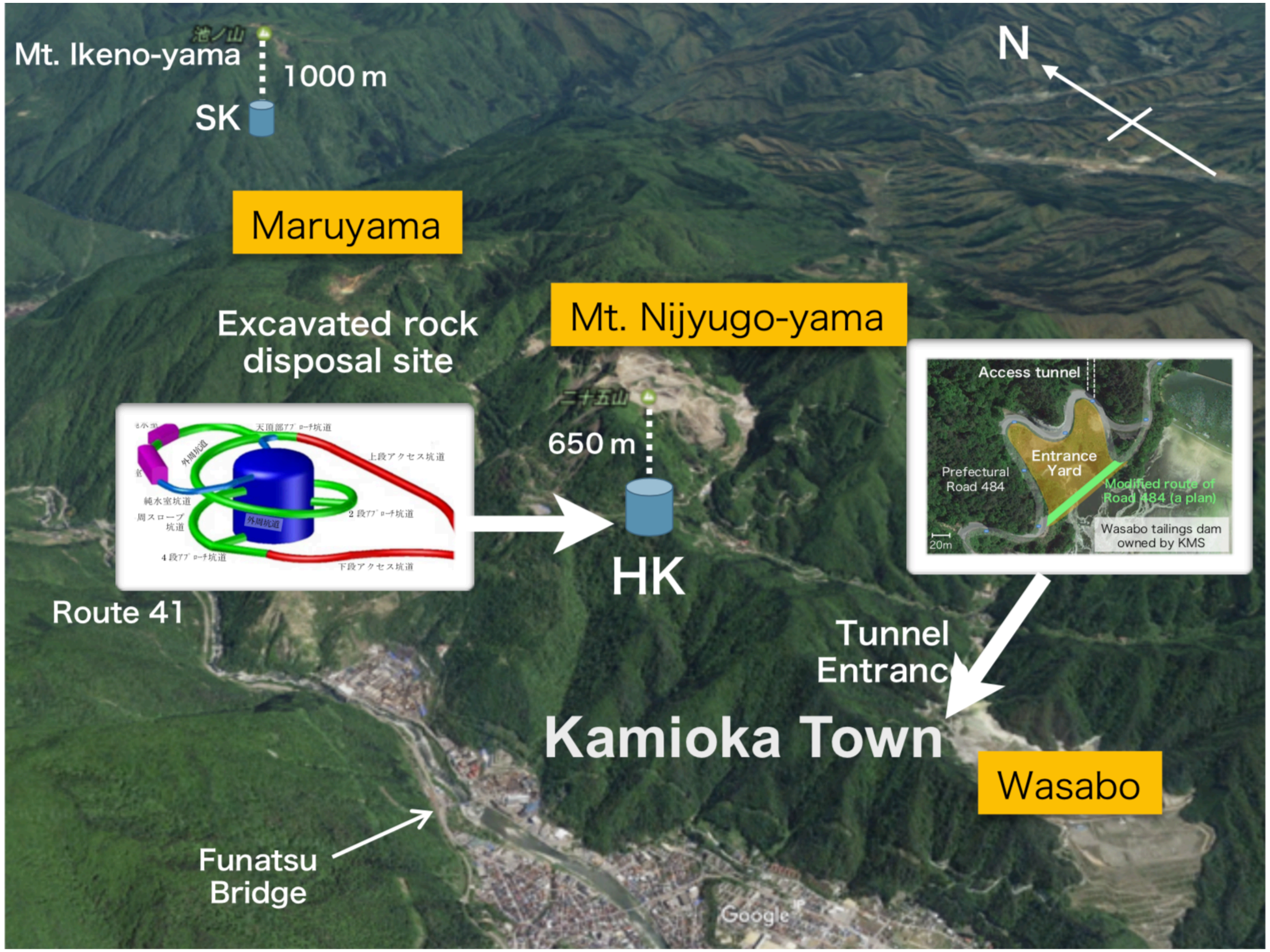
The Hyper-Kamiokande proto-collaboration welcomes this exciting endorsement of the project and the boost it will give to increasing even further the international contributions and participation in the experiment. Introducing the statement, Professor Takaaki Kajita, Director of the Institute for Cosmic Ray Research at the University of Tokyo and 2015 Nobel Laureate in Physics, pointed out that the Japanese funding agency MEXT has included seed funding for Hyper-Kamiokande in its JFY 2019 budget request. He illustrated with many examples that it is standard in Japan for large projects to begin with a year of seed funding, and said that in any case the University of Tokyo commitment meant that Hyper-Kamiokande construction will begin in April 2020.

The Hyper-Kamiokande Proto-Collaboration will now work to finalize designs, and is very open to more international partners to join in this far-reaching new experiment.

HyperK proto-collaboration structure



Detector Location



- HyperK detector location is 8km south of SuperK site
- 295km from J-PARC and 2.5 deg. off-axis beam (same as SuperK)
- Narrow band energy peak is at 600 MeV (same as SuperK)

Near detectors and beam (T2HK)

More Power at MR → 750 kW → 1.3 MW

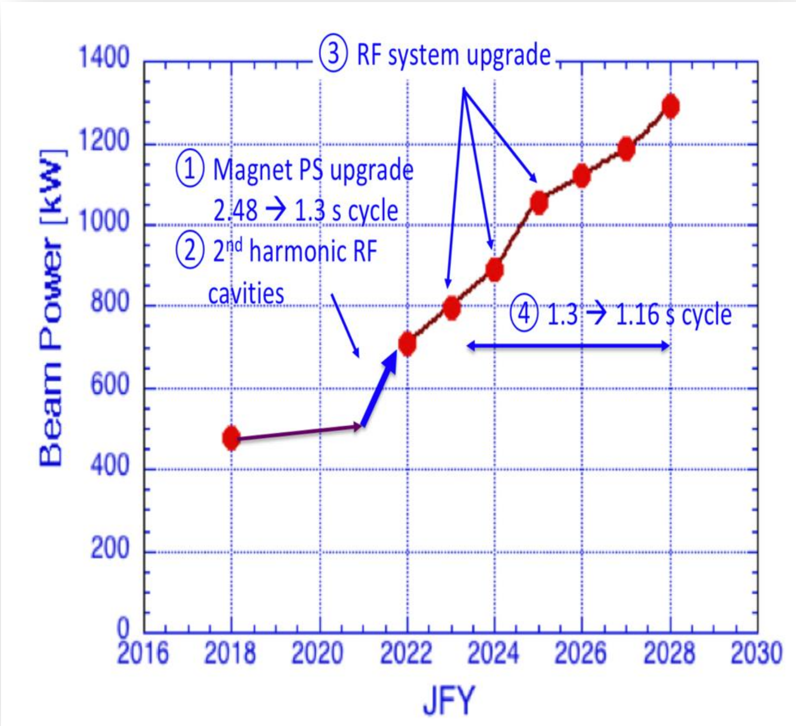
More Rapid Cycle:

2.48 s → 1.32 s → 1.16 s

- Main Power Supply to be renewed
- High gradient RF Cavity
- Improve Collimator
- Rapid cycle pulse magnet for injection/extraction

More Protons / Pulse :

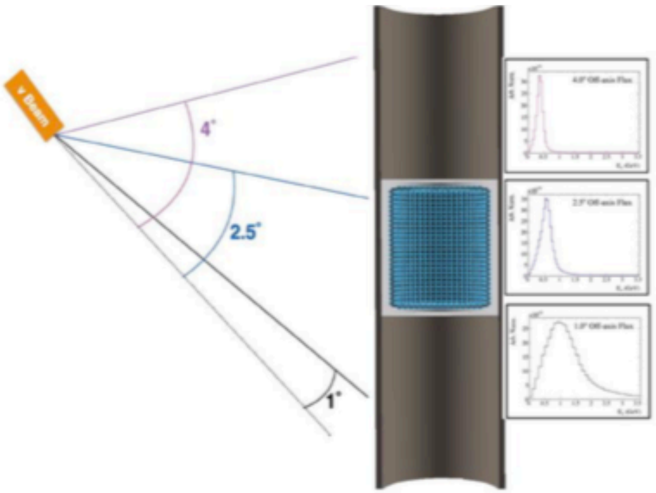
- Improve RF Power
- More RF Systems
- Stabilize the beam with feedback



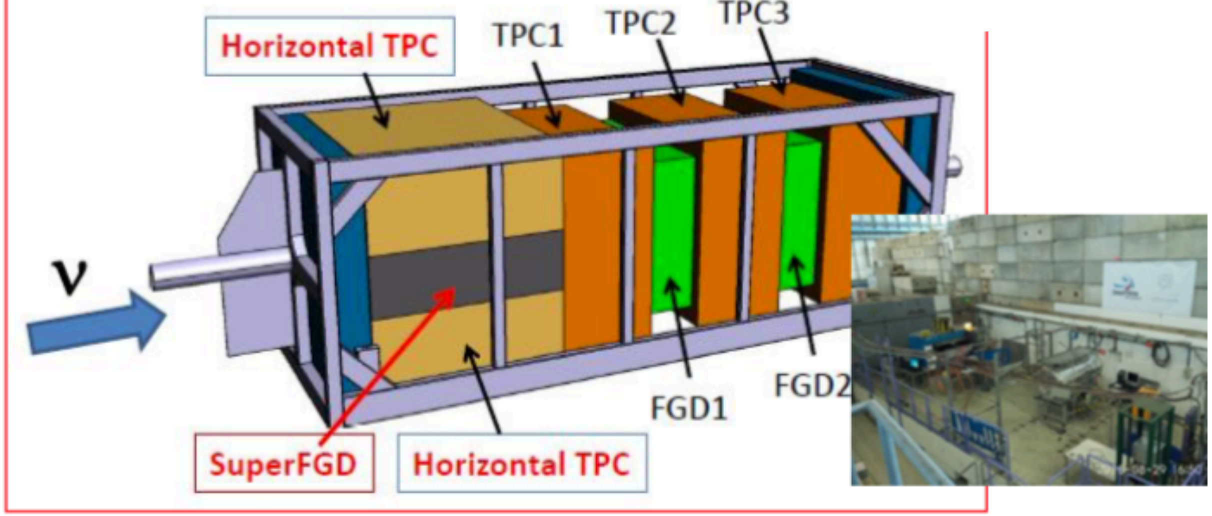
- J-PARC 30 GeV neutrino beam creates a narrow-band neutrino beam with peak enemy 600 MeV
- Neutrino beam be upgraded from 485kW (2018 operation) to 1.3MW via improvements to beam power and number of protons per pulse

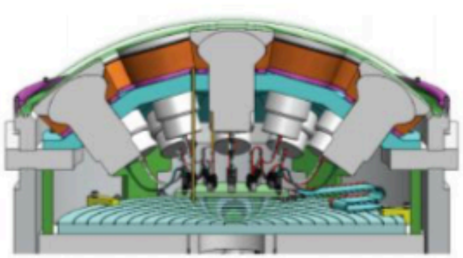
Near detectors and beam (T2HK)

arXiv:1412.3086



arXiv:1609.04111

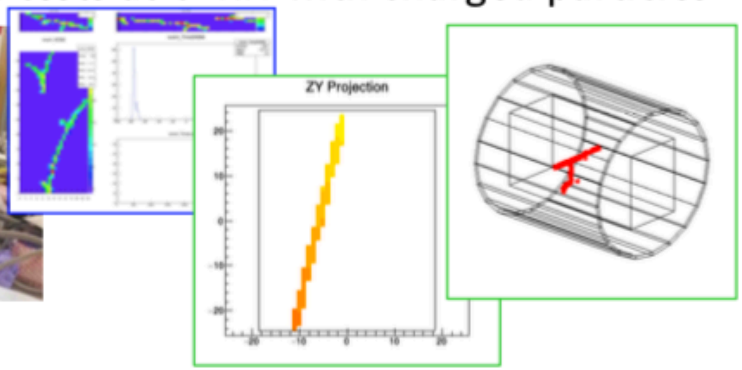




Multi-PMT

SFGD prototype

Beam tests at CERN with charged particles



TPC prototype

- Upgrades to the near detectors are also planned
- Current T2K ND280 detector to be upgraded with new TPCs, super-FGD and TOF system
- New moveable water Cerenkov detector for beam profiling

Inner detector PMT R&D

HyperK inner detector photosensor requirements:

- Large aperture
- High quantum efficiency
- Wide dynamic range (1-1000pe)
- Low dark rate (<4 kHz for 20" PMTs)
- Waterproof
- High pressure tolerance (>8 atm)

Requirements	Value	Conditions
Quantum efficiency (QE)	30%	Minimum at 400nm
Collection efficiency (CE)	85%	Minimum at 400nm
Detection efficiency	26%	QE $\times$ CE
Timing resolution	5.2ns	FWHM for 1PE
Charge resolution	50%	Maximum σ/mean for 1PE
Signal window	200ns	Contains 95% of integrated charge
Dynamic range	2 photons/cm^2	Maximum flux per unit area
Gain	10^7	Typical
Afterpulse rate	5%	Maximum for 1PE
Dark count rate	2Hz/cm^2	Typical
Rate tolerance	10MHz	1PE rate for 10% change of gain
Magnetic field tolerance	100mG	Maximum for 10% change of gain
Life time	20years	Less than 10% dead PMTs
Pressure rating	0.8MPa	Minimum static load in water

The full inner detector surface area comprises ~40,000 70cm x 70cm square "cells"

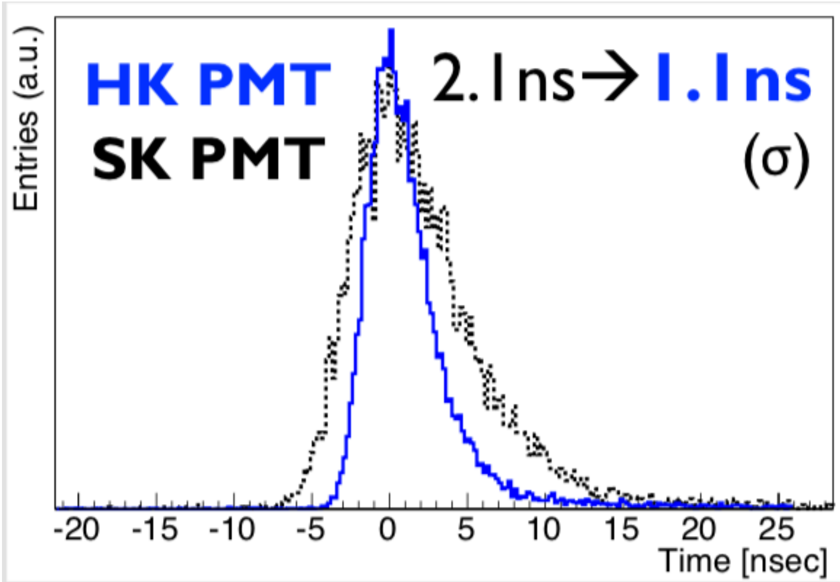
If all cells are instrumented with 20" PMTs then this corresponds to 40% photo coverage

Inner detector PMT R&D

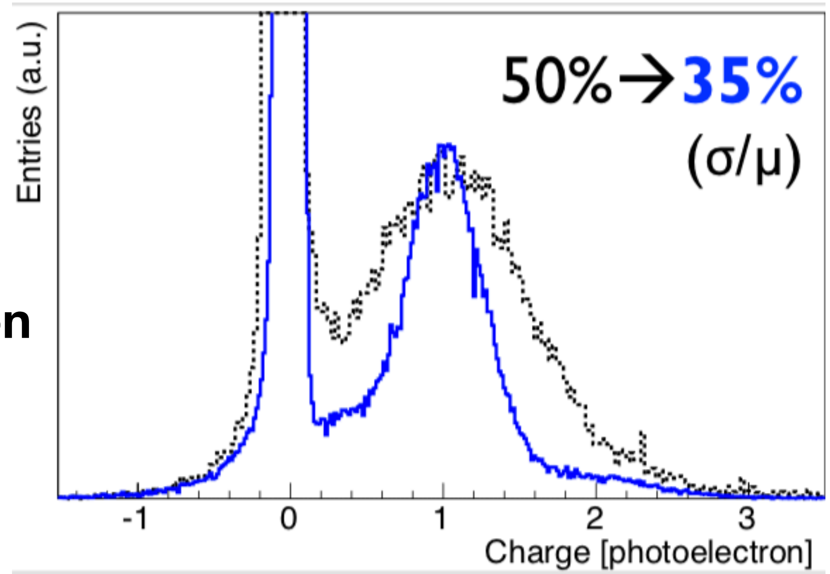
20” PMTs: Primary candidate: **Hamamatsu R12860**

- Developed by Hamamatsu for HyperK
- “Box and line” design
- High quantum efficiency
- Improved dynodes
- Initial tests demonstrate:
  - x2 single photon detection efficiency
  - x2 improvement in timing resolution
  - x2 hydrostatic pressure tolerance (c.f. SK)

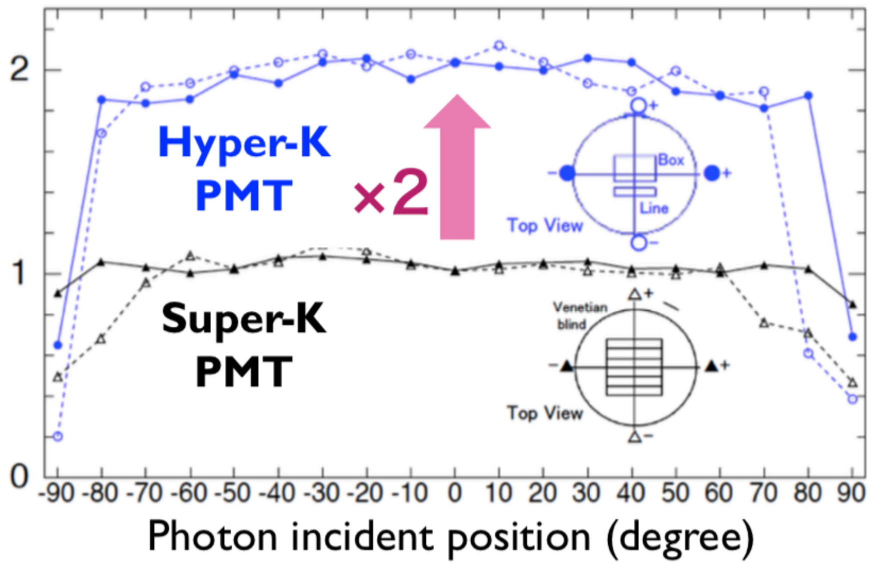
Single photoelectron timing



Charge separation



Single photon detection efficiency

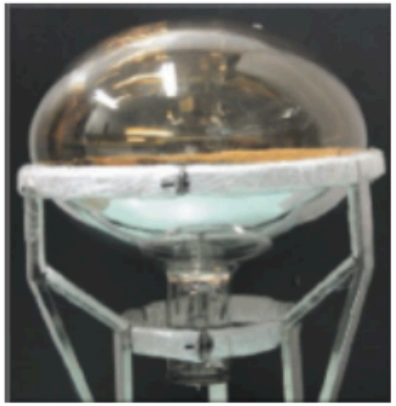


Inner/outer detector PMT R&D

Inner-Det.

MCP-PMT

Ongoing R&D to improve timing, reduce dark rate, water-proofing, cover etc

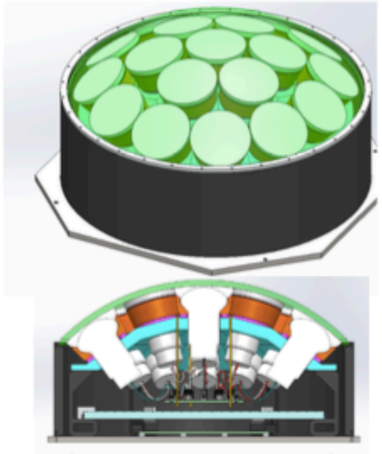


φ50cm

Inner-Det.

Multi-PMT module

Many R&D are needed on module/ assembly, acrylic vessel, electronics, simulation&reconstruction etc



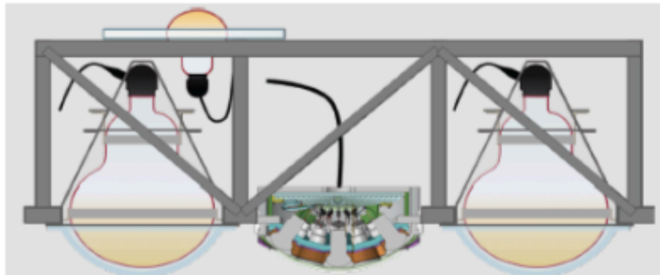
φ50cm

Outer-Det.

Outer-detector system

Open for photo-sensor type, density, light-concentrator, deployment method

Potential design of OD PMT w/ wavelength shifter plate

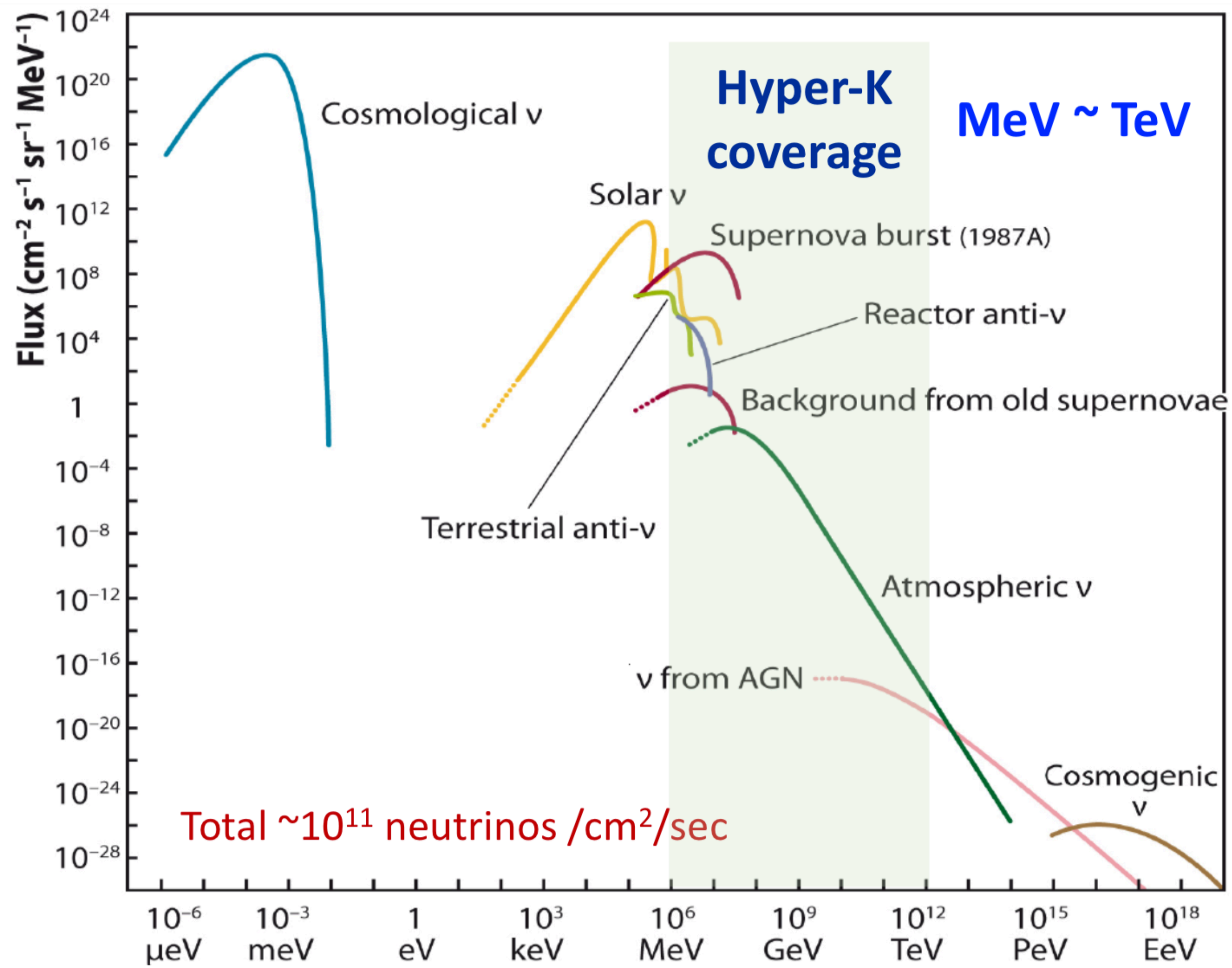


Potential combination of 50cm PMTs and multi-PMT modules

Different options under consideration including

- Multi-PMTs à la KM3NeT DOMs (finer granularity, improved timing, etc.)
- Wavelength-shifting plates (lower cost per unit area, timing?)
- Hybrid 20”/3.5” PMT system for inner detector

Physics programme



- Sensitivity to a wide range of neutrino energies opens up a broad physics programme

Physics programme

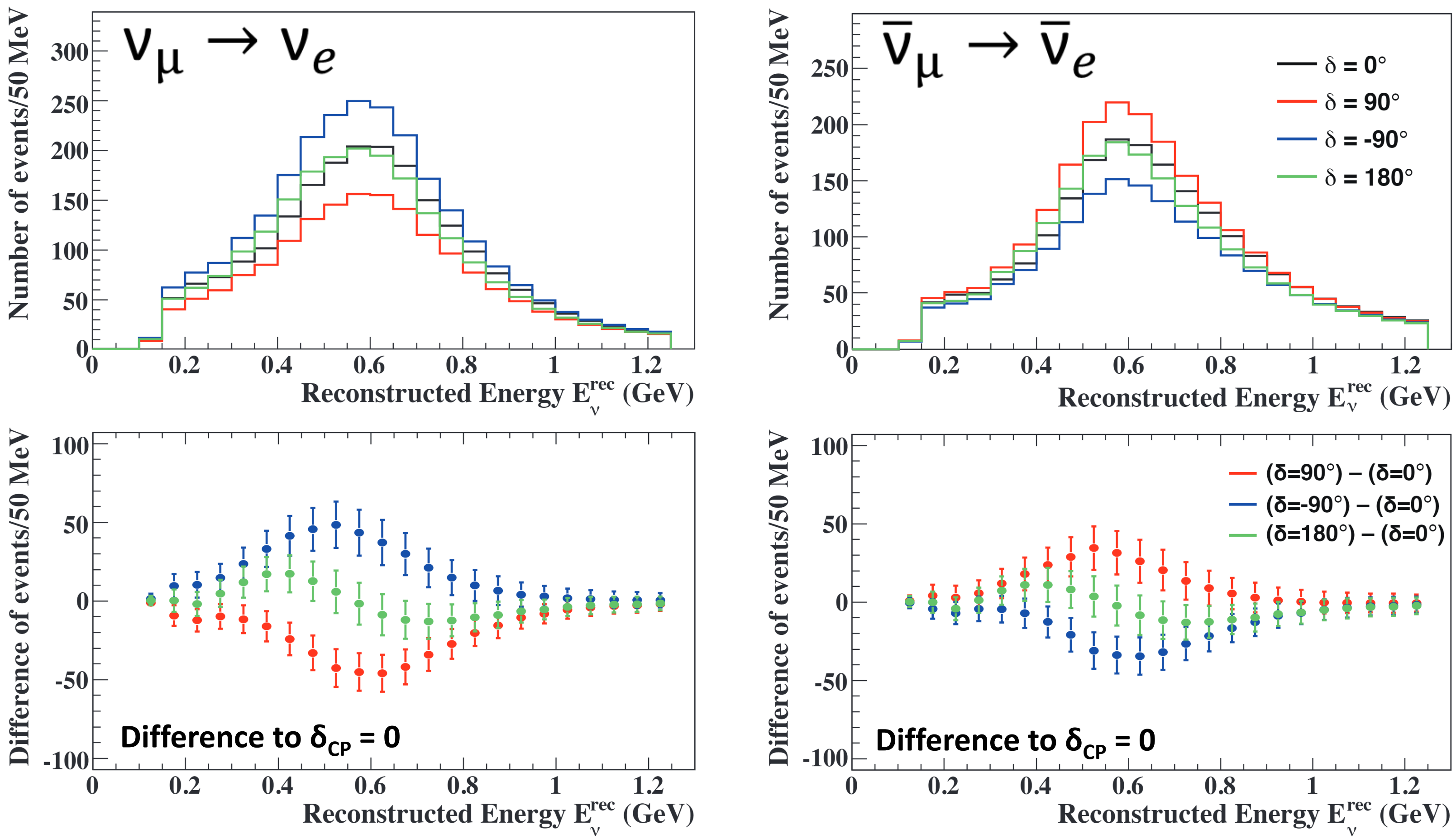
By studying a combination of accelerator, atmospheric and solar neutrinos HyperK will address key questions including:

- Precision measurements of the neutrino mixing matrix parameters
- search for CP violation and the measurement of δ_{CP}
- neutrino mass hierarchy
- θ_{23} octant determination
- (Solar and atmospheric neutrinos)
- Supernova detection
- Supernova relic neutrinos
- Proton decay searches

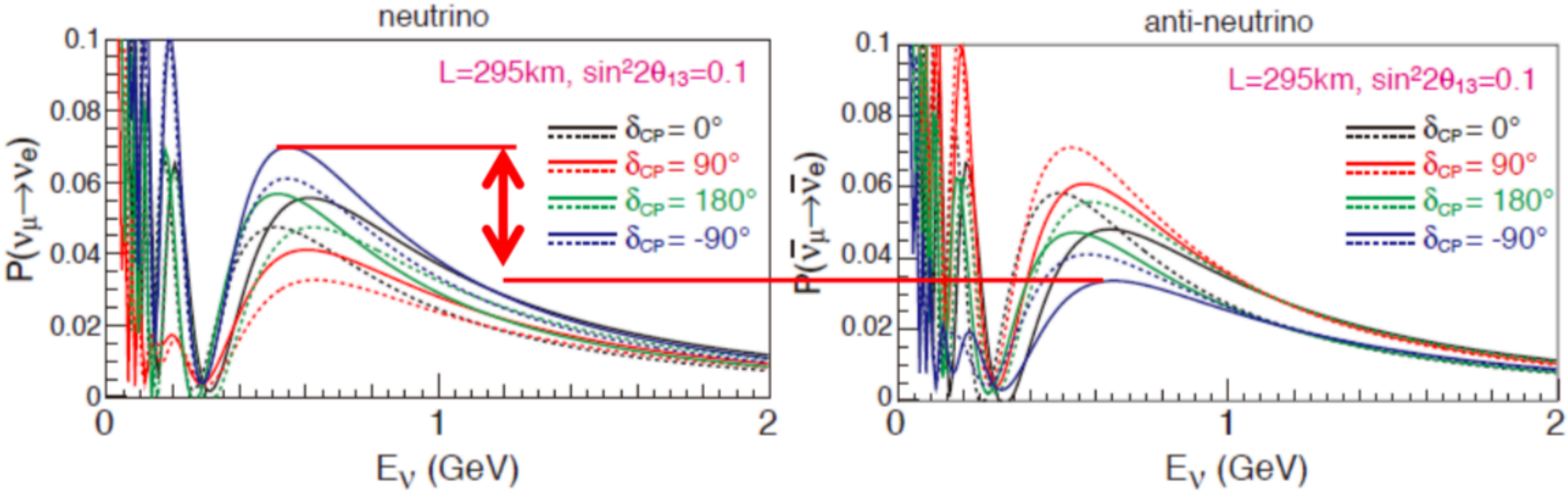
Event rates

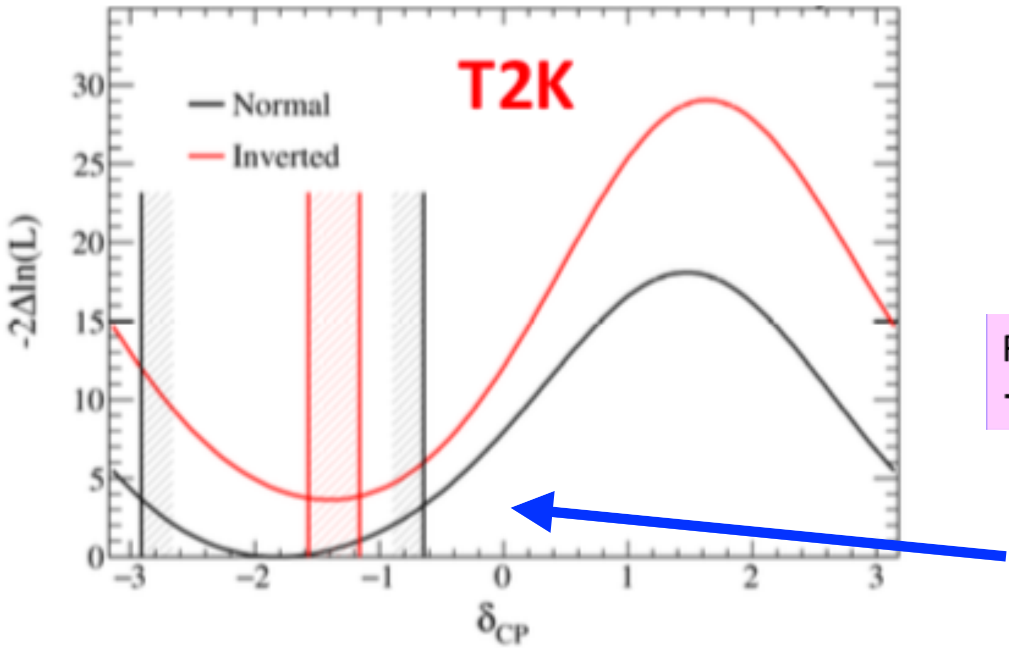
		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

Assumes:
Normal Hierarchy
$\sin^2\theta_{13} = 0$
10 years running
(1.3MW x 10^8 s)
$\nu : \bar{\nu}$ = 1:3



Search for CP violation



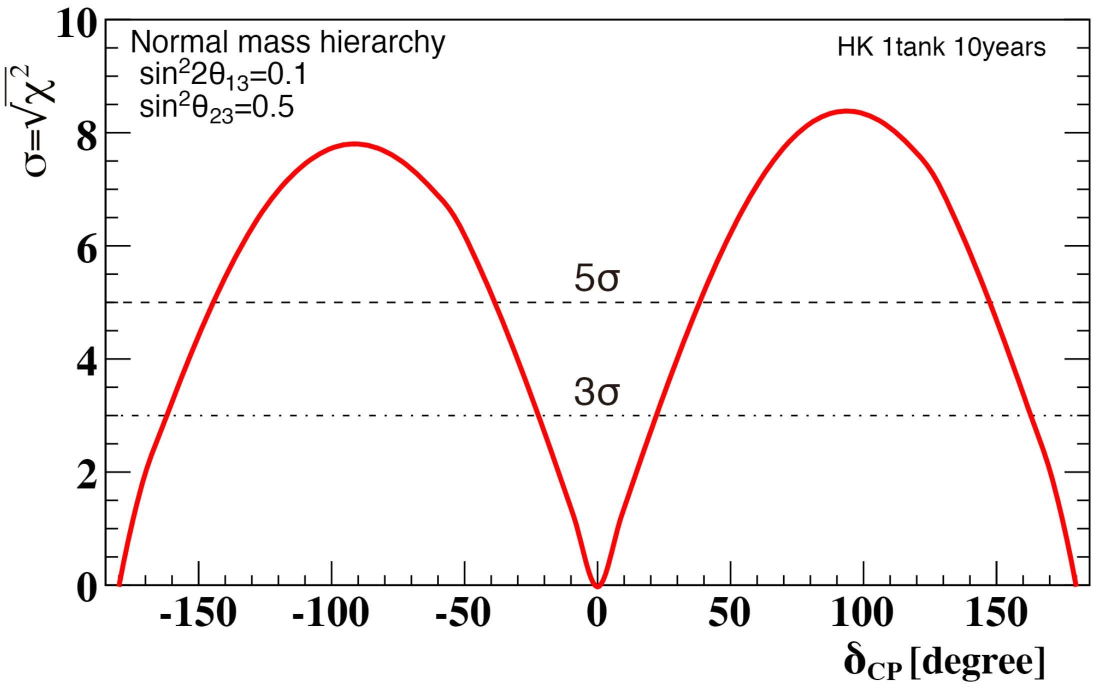


$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})}$$

For $\delta = -\pi/2$
→ CP violation effect $A_{CP} \sim 28\%$, matter effect ~8%

Hint of maximal CP violation at $\delta_{CP} \sim -\pi/2$ from T2K

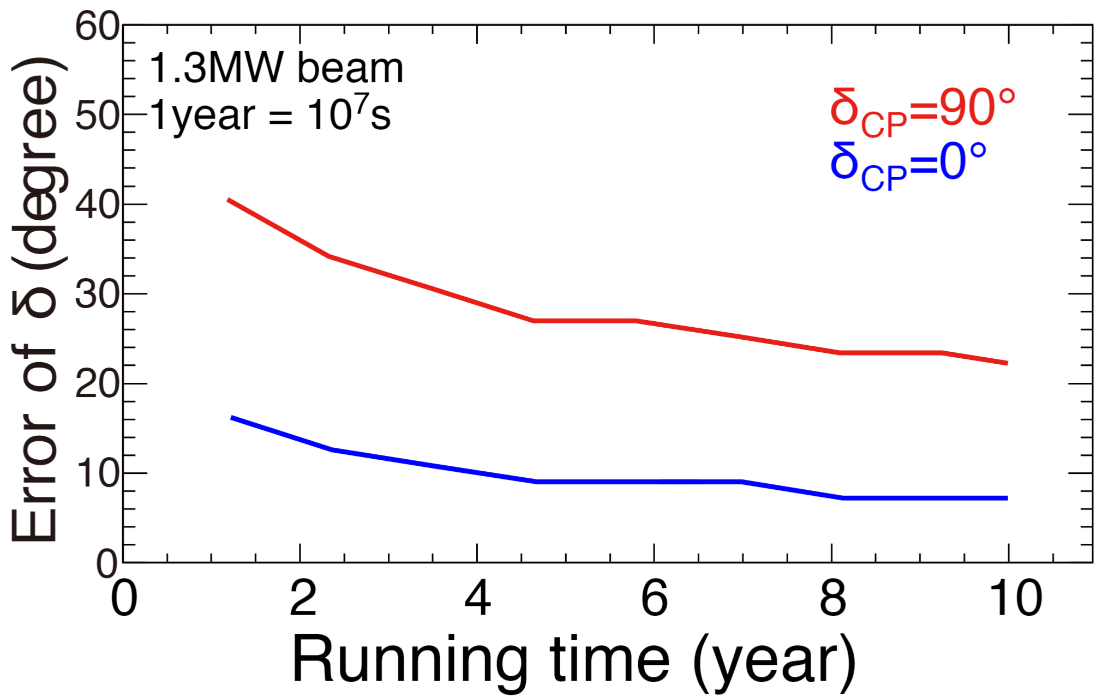
Sensitivity to CP violation



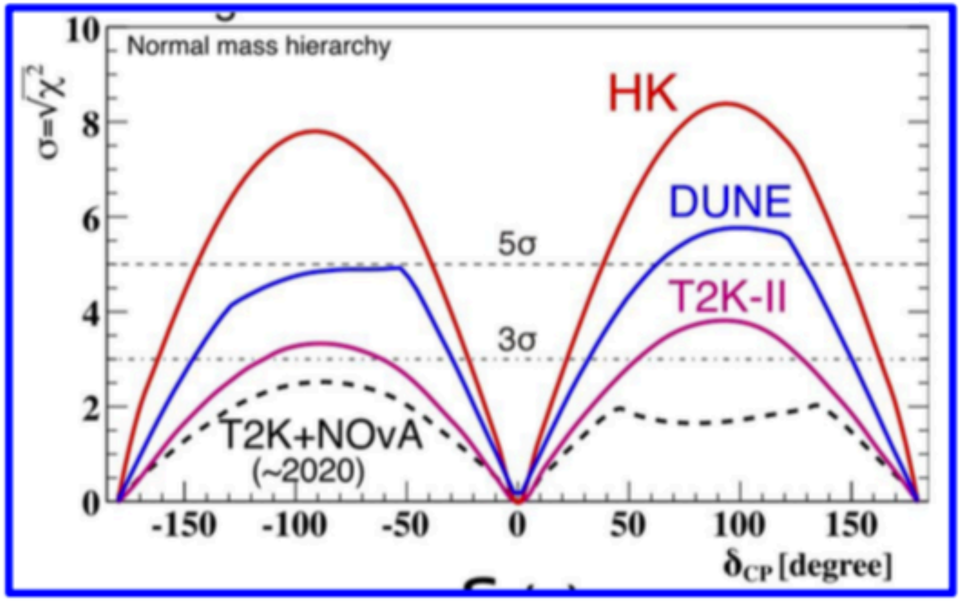
5σ observation of CP Violation for 58% of δ_{CP} parameter space

Precision of δ_{CP} measurement:

~ 22° for $\delta_{CP} = \pm 90°$
~ 7° for $\delta_{CP} = 0°$



CP significance comparison

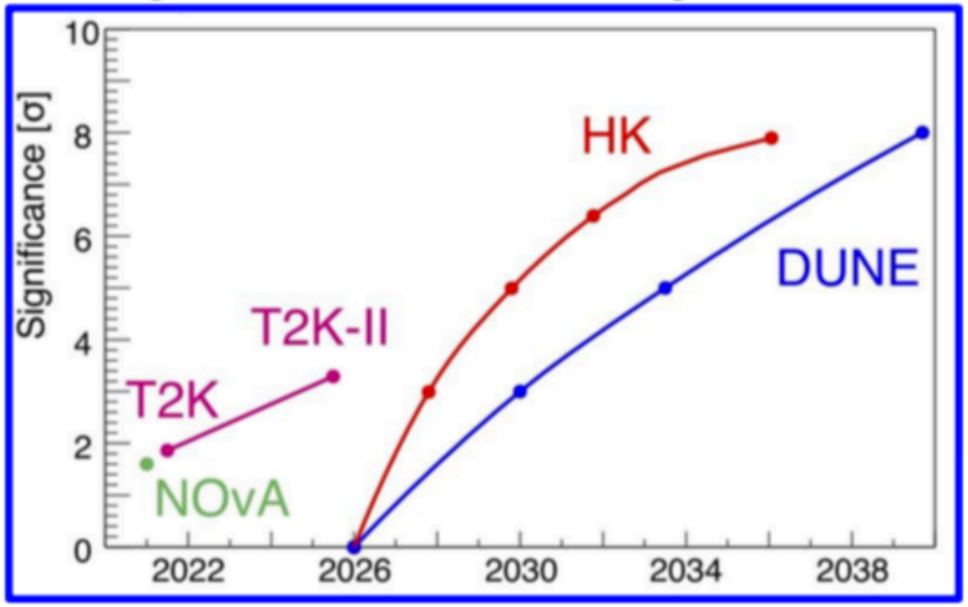


arXiv:1805.04163

Hyper-K
- Single tank
- Normal hierarchy
- Systematics 3-4%

  $\nu:\bar{\nu}=1:3$
- CPV (δ = -90 deg, 5σ) 1.3MW x 4 years

Significance for δ=-90 deg



arXiv:1807.10334

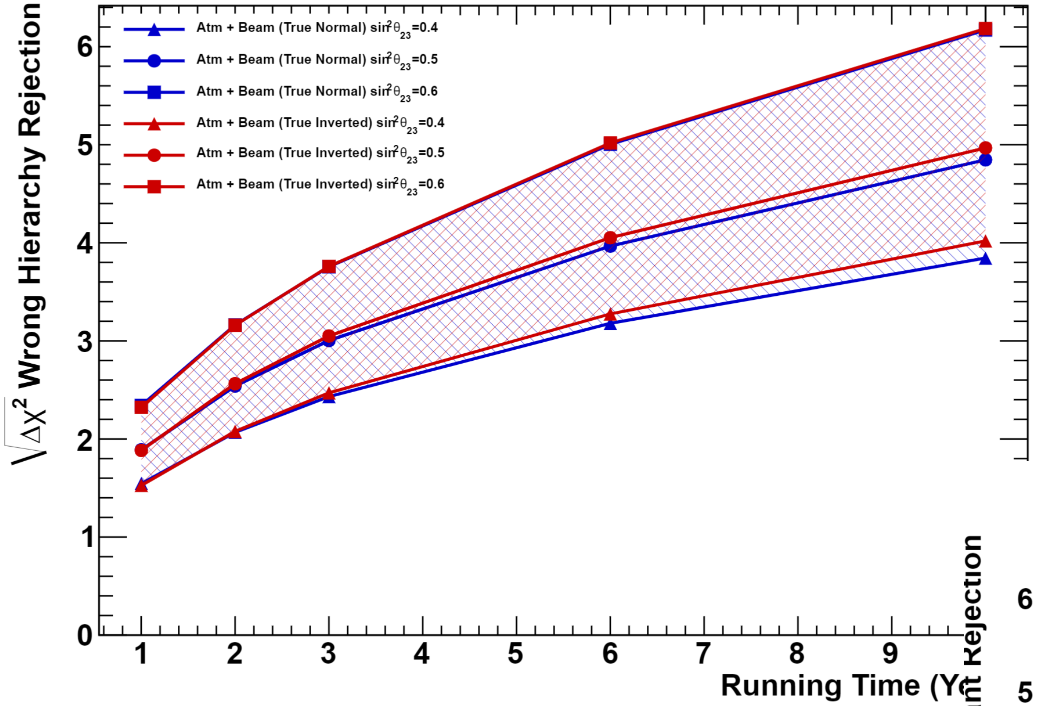
DUNE
- Staging plan
- Normal hierarchy

  $\nu:\bar{\nu}=50\%:50\%$
- CPV (δ = -90 deg, 5σ) 253 kt·MW·year

  → 6.5 years

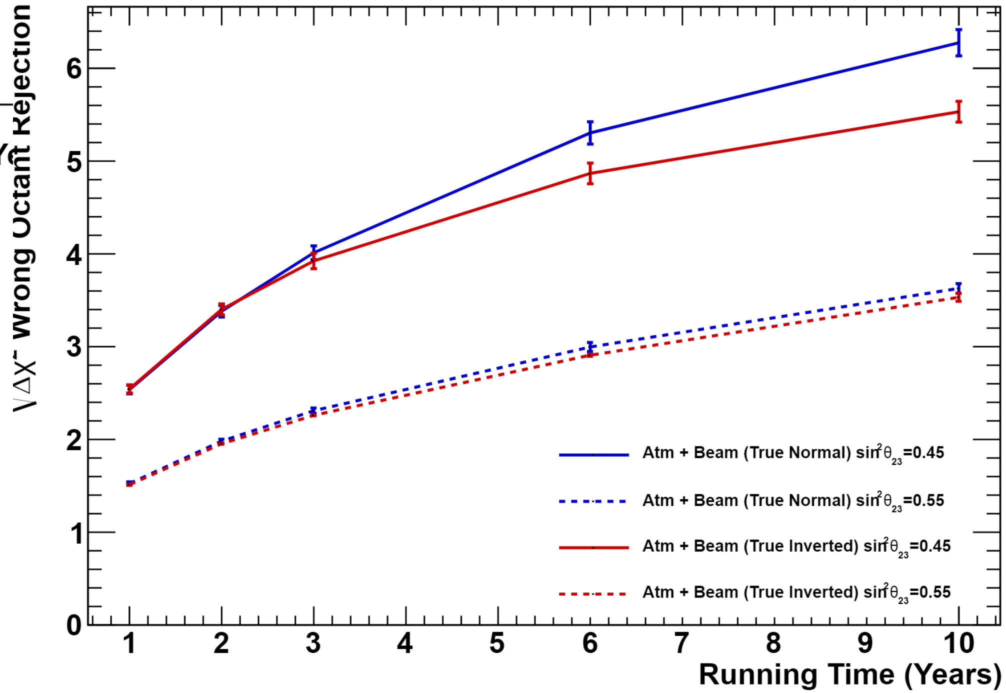
Mass hierarchy and θ_{23} octant sensitivity

Based on joint analysis combining data from 1 HK tank and atmospheric neutrino samples



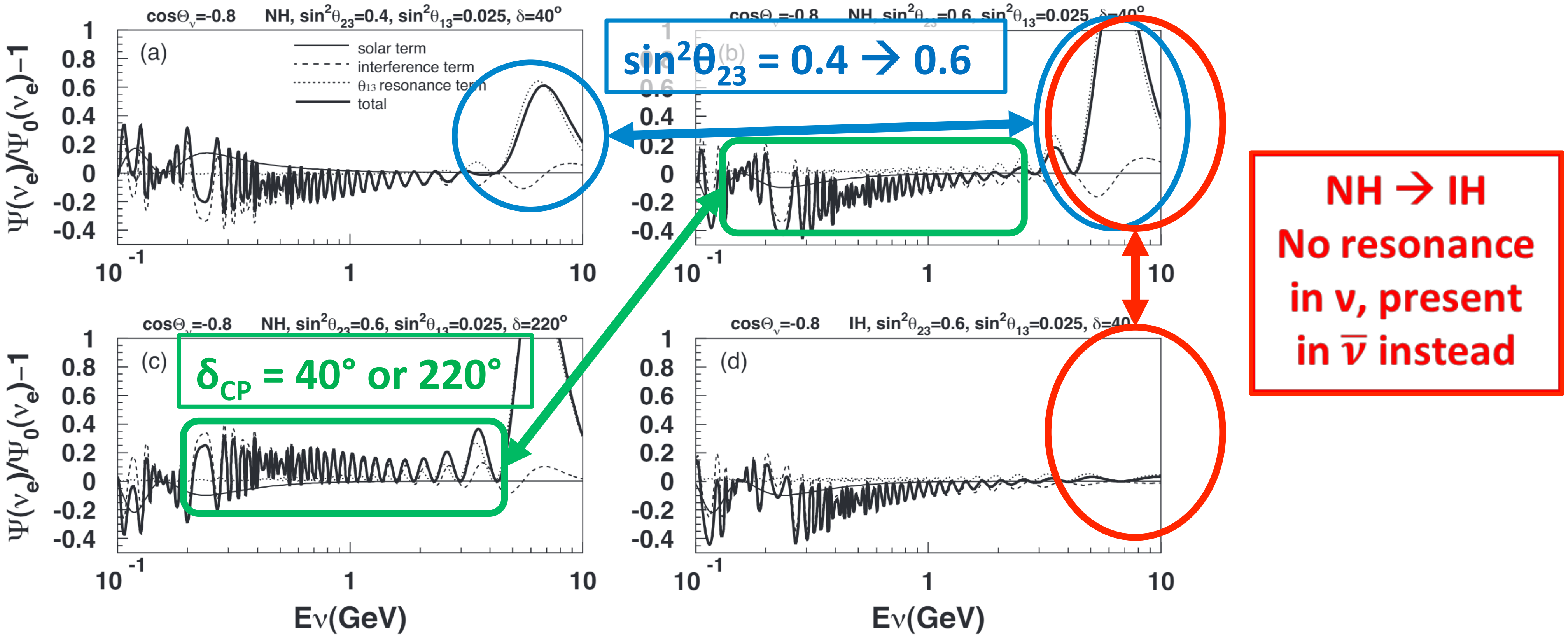
Mass hierarchy determination at 3σ for all possible values of θ_{23}

Octant determination at 3σ for $|\theta_{23} - 45°| \geq 2.3$

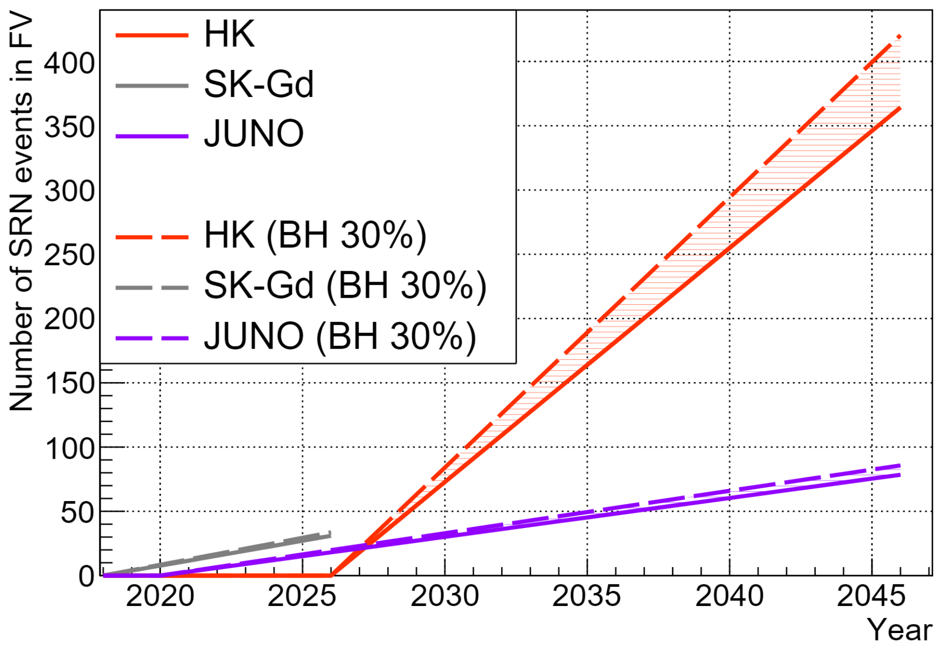


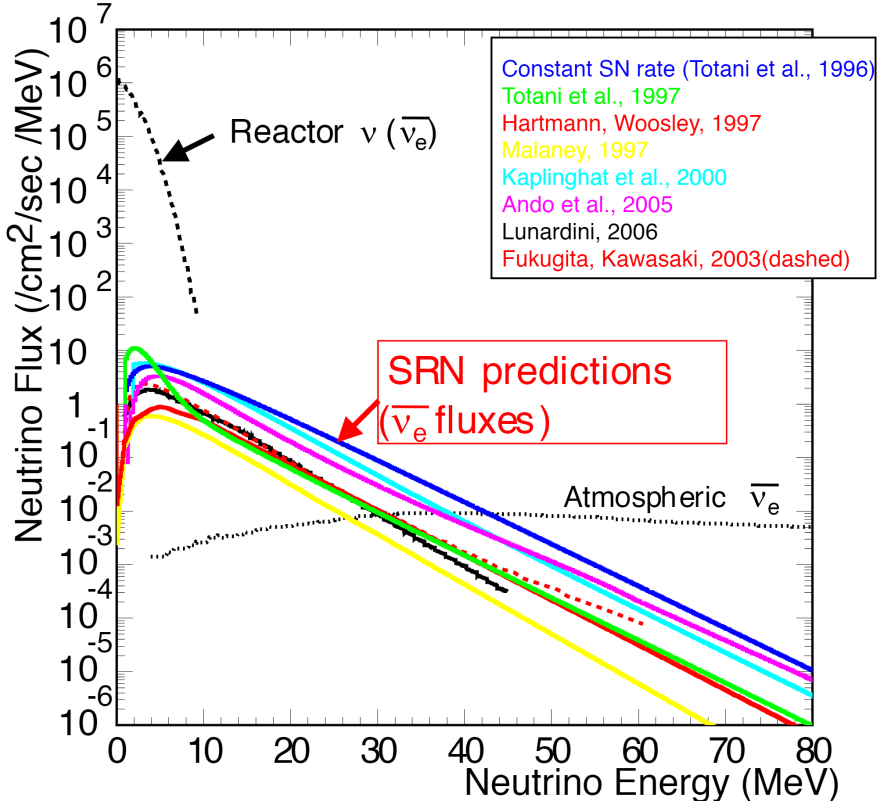
Atmospheric neutrinos

- Earth matter effects modify the energy spectrum of the electron (anti-)neutrinos as they pass through the Earth's core
- These matter effects are sensitive to **mass hierarchy**, **δ_{CP}**, and **θ_{23} octant**



Supernova Relic Neutrinos





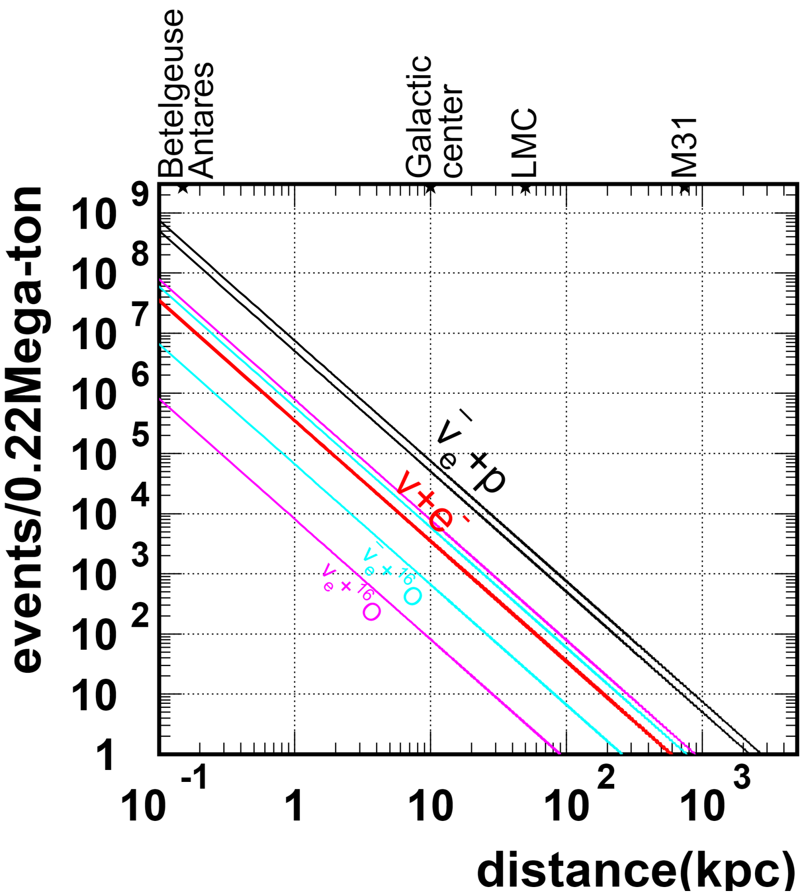
- By loading SuperK with Gd the improved neutron capture efficiency will facilitate SRN detection

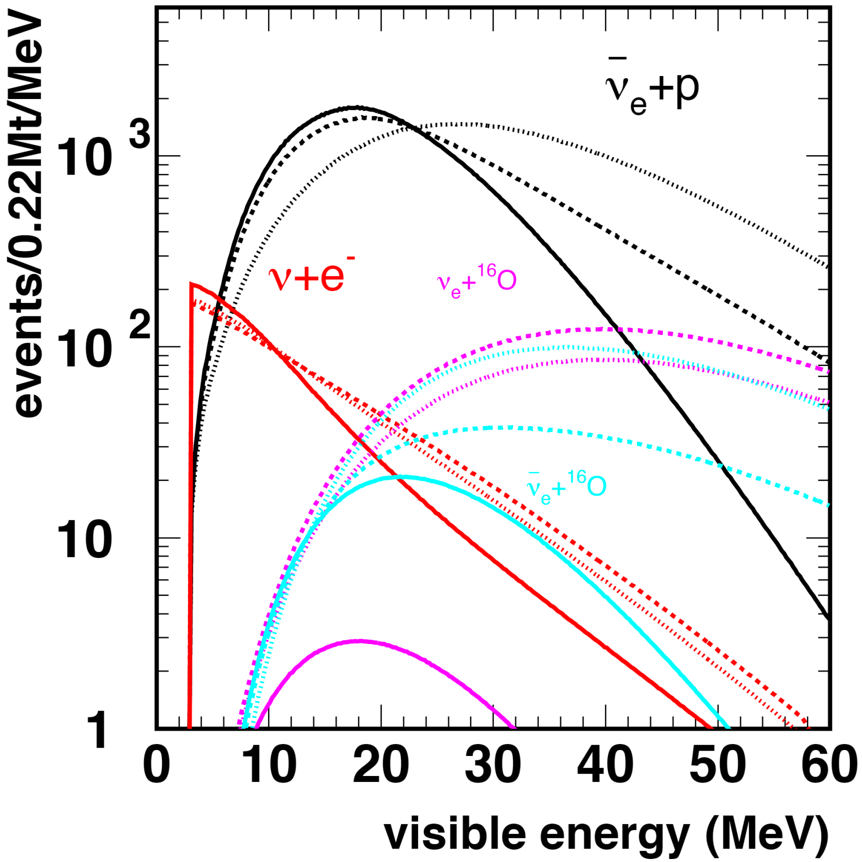
- HyperK will collect enough events to measure the spectrum

- Allows insights into star formation history, heavy elements and black hole formation

Supernova neutrinos

- Expected neutrino event rates for supernova:
  - Galactic centre: 50k-80k
  - LMC: 2k-3k
  - M31: ~10



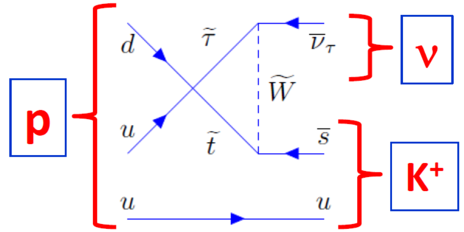


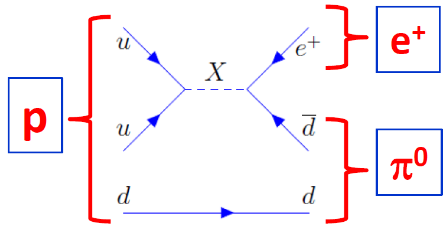
- Will enable, e.g. underlying astrophysics, e.g. Standing Accretion Shock Instabilities - (SASI) behind the SN to be probed

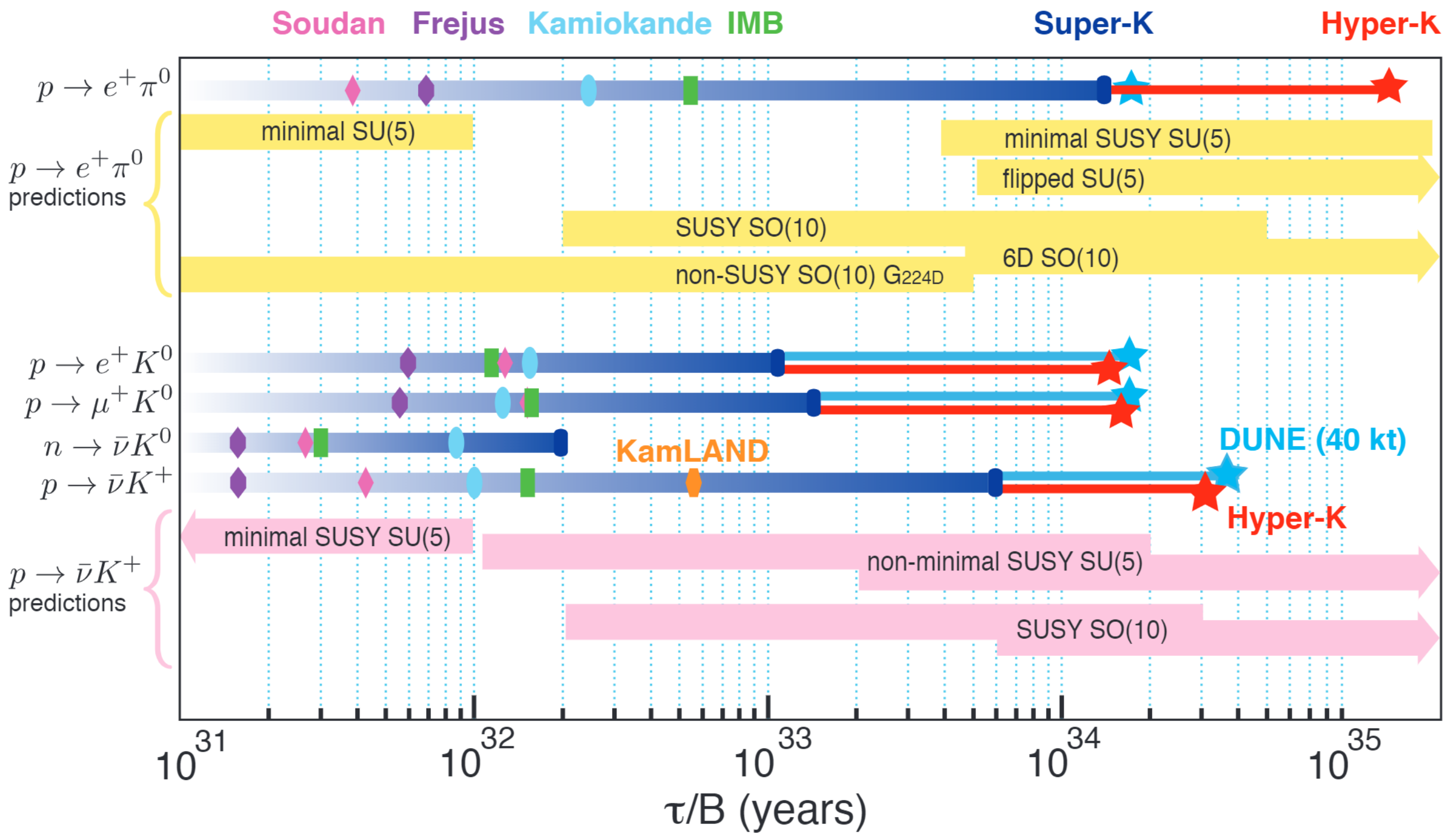
see, e.g. https://arxiv.org/pdf/1610.00559.pdf

Proton decay

- Proton decay is a fundamental prediction of GUT theories, e.g.:
    - Supersymmetric GUT theories
    - X boson-mediated GUT theories



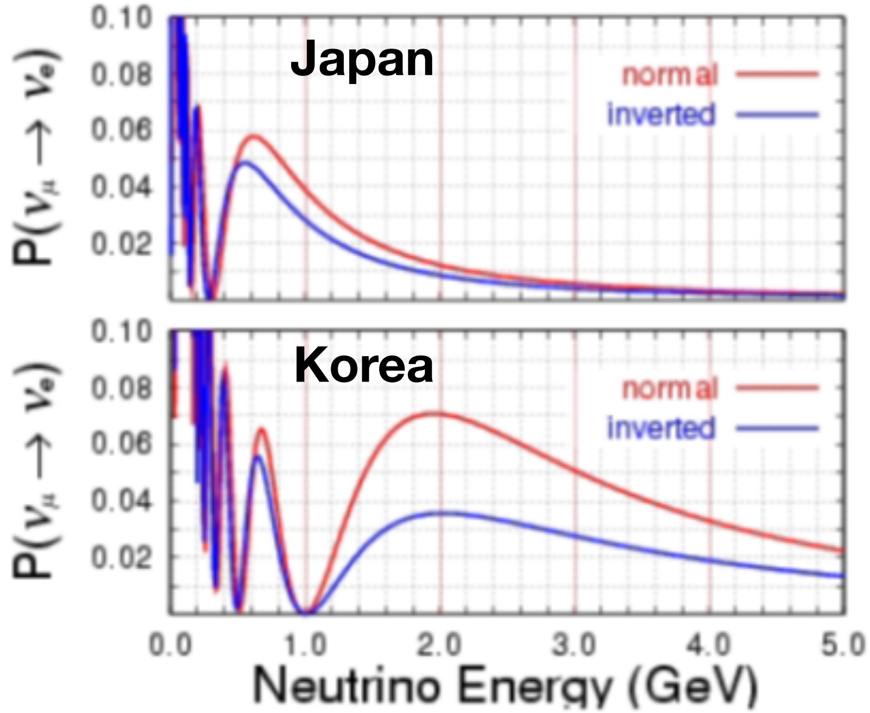


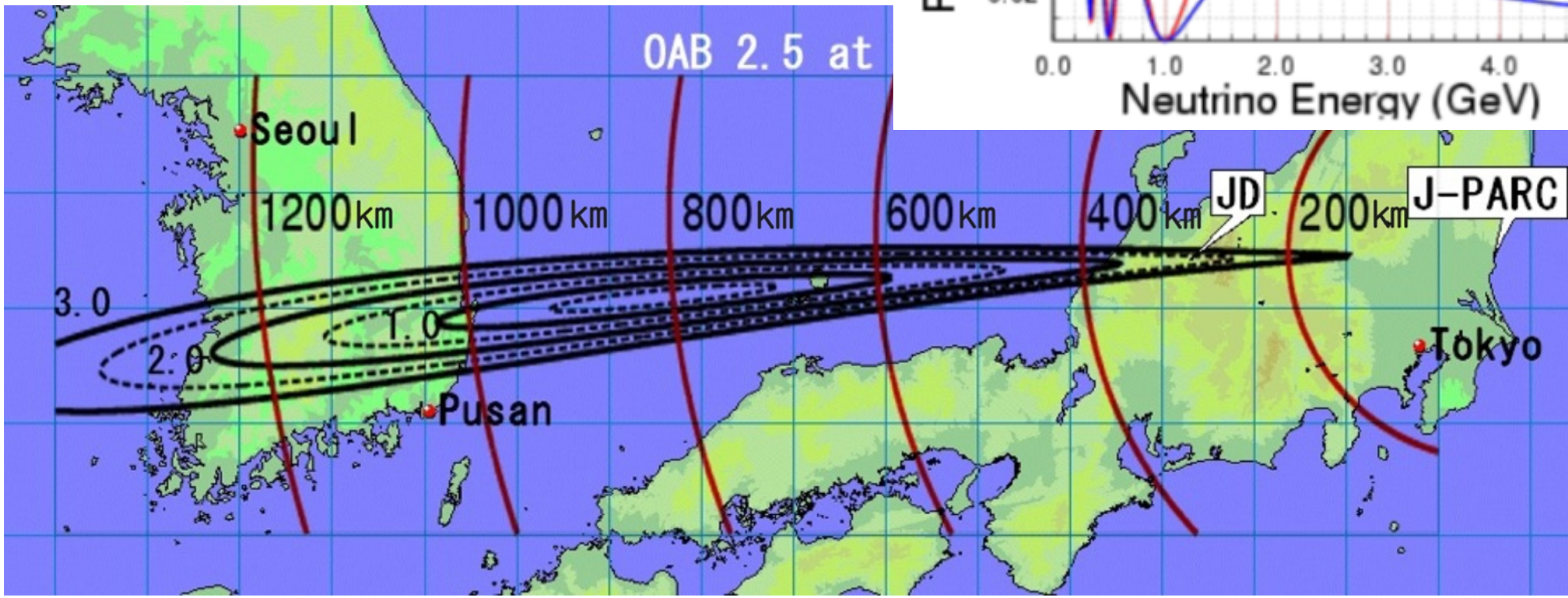


- HyperK will extend the search for proton decay to ~10^{35} years, which covers many more theoretical models than present

A second detector in Korea (T2HKK)

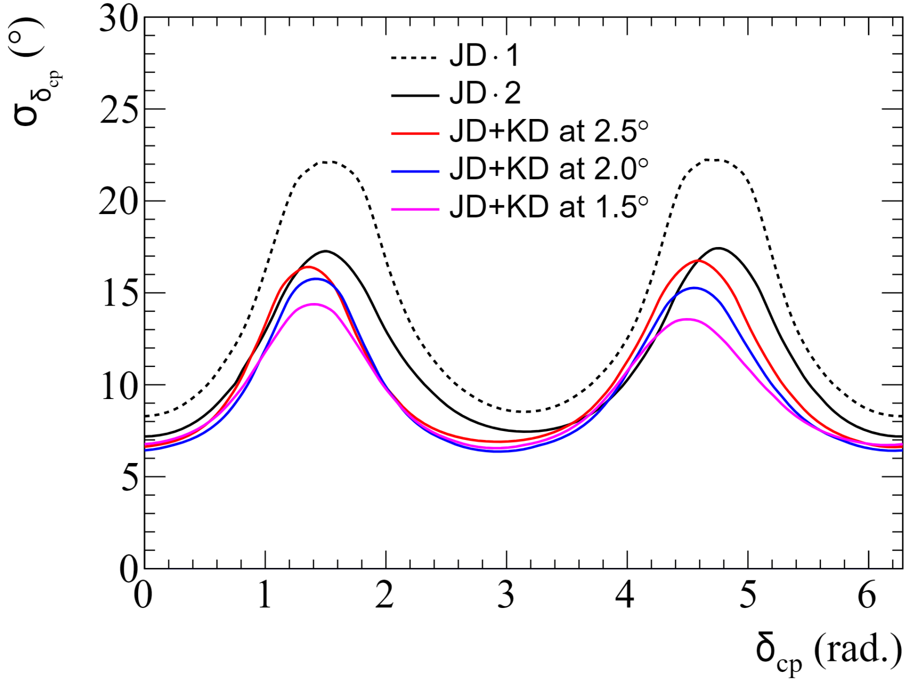
- HyperK plans to add a second, identical tank
- South Korea would be an suitable location for this tank
  - Enables the second oscillation maximum to be studied
  - Improves sensitivities for all HyperK studies

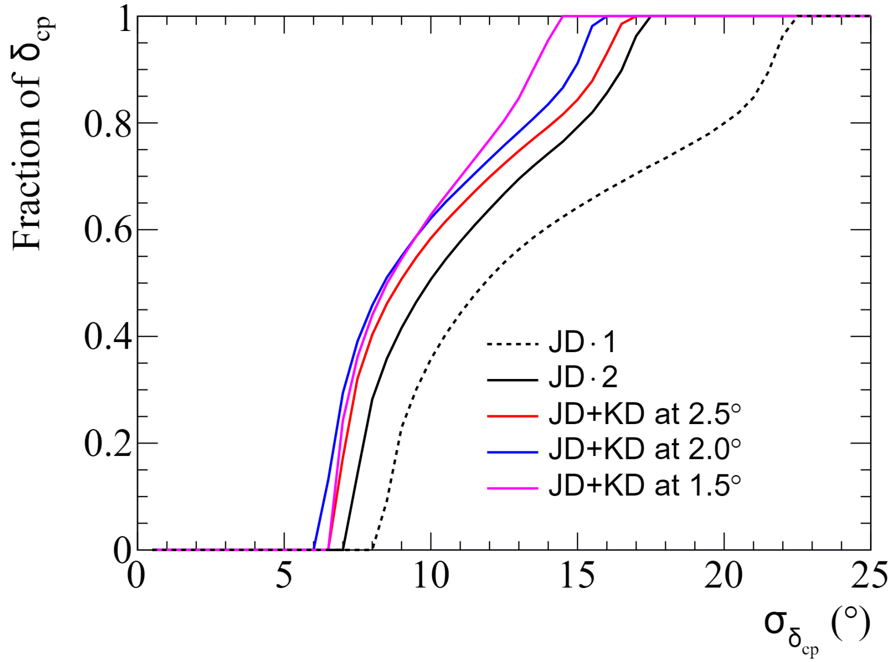




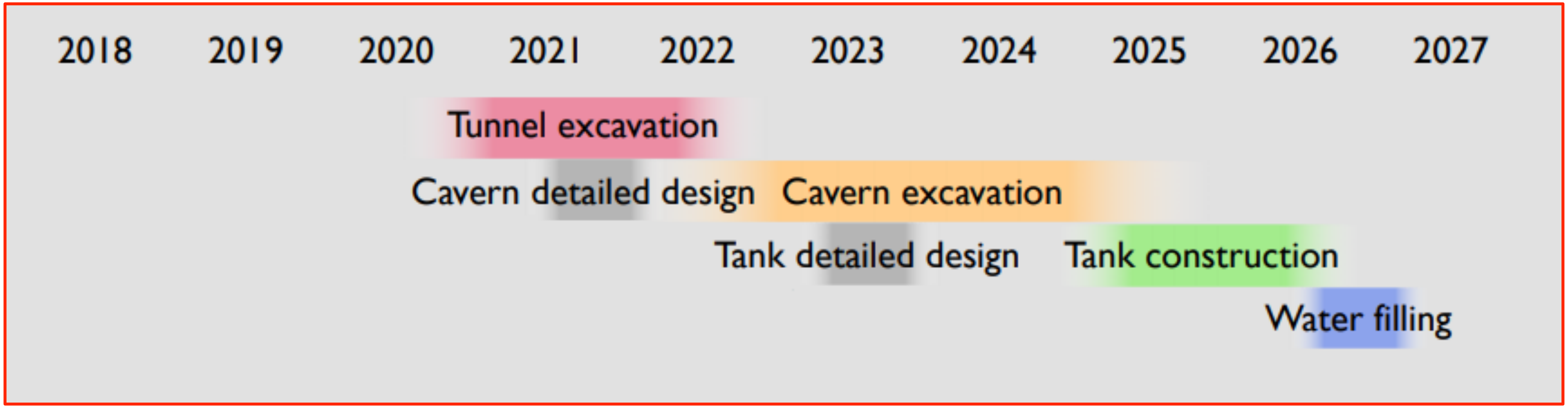
A second detector in Korea (T2HKK)

- Locating the second detector in South Korea results in improved sensitivities compared with 2 HyperK tanks in Japan
- For example:
  - The uncertainty on δ_{CP} is up to 3° smaller with a 2nd tank in Korea
  - There is also an increase in sensitivity to the neutrino mass hierarchy due to increased matter effects over the longer baseline





HyperK timeline



- Excavation will begin in 2020
- Operations are expected to commence in 2027

Summary

- HyperK is a next generation water Cerenkov detector that will be built in Japan
- It will observe (anti-)neutrinos from the J-PARC beam as well as atmospheric, solar and (possibly!) supernova neutrinos
- With a 187 kton fiducial volume HyperK will enjoy a broad, rich and exciting physics programme including neutrino oscillation, CP violation, mass hierarchy, supernova physics, etc.
- Operations are expected to commence in 2027, new collaborators are welcome in many areas of detector construction and operations (recent discussions in Mainz and Munich), HK spokesperson visiting Europe in 2019