Hyper Kamiokande

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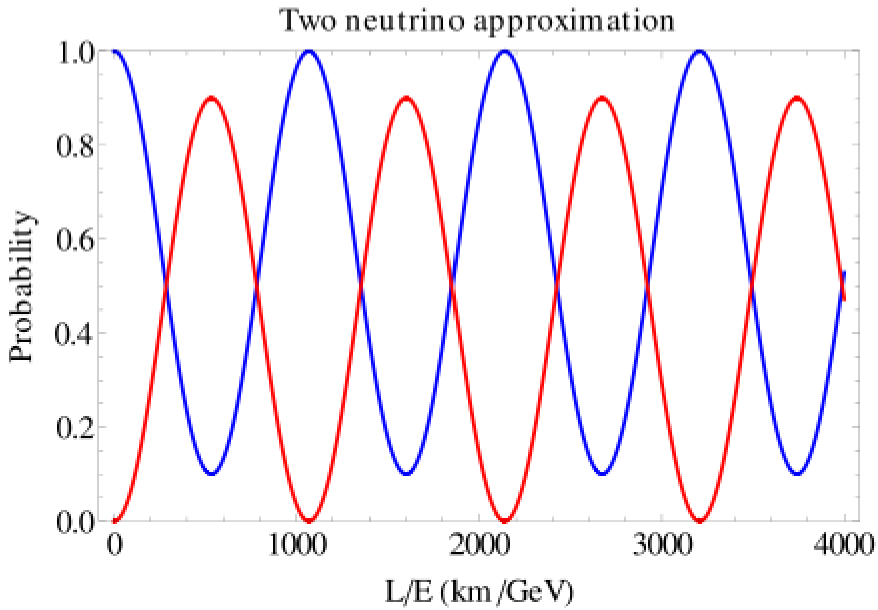
Neutrino Oscillations

New physics, beyond the standard model

Evidence for
- Neutrino mass
  - Scale much smaller than other fermions
- Neutrino mixing
  - Angles much larger than quark sector

New place for CP violation to be found.

Simple model of neutrino mixing still needs testing



$$p(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2 \frac{1.27\Delta m^2 L}{E}$$

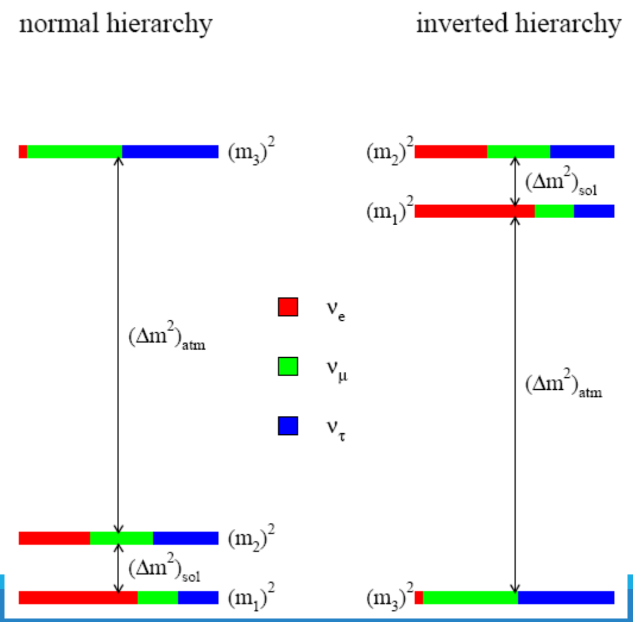
Neutrino Physics

Neutrino mixing is characterised by the PMNS matrix.

$$\mathbf{U}_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Fundamental parameters of nature just like CKM

Open questions
- Mass Hierarchy.
- CP Violating Phase δ
- Octant of θ_{23}, is it maximal?
- Absolute Mass Scale
- Dirac or Majorana
- Sterile states



Neutrino Oscillations from ν_μ to ν_e

$$p(\nu_\mu \rightarrow \nu_e) = \boxed{4c_{13}^2 s_{13}^2\, s_{23}^2 sin^2\Phi_{13}}$$

$$\boxed{+8c_{13}^2 s_{12} s_{13}\, s_{23}(c_{12}c_{13}cos\delta - s_{12}s_{13}\, s_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}}$$

$$\boxed{-8c_{13}^2 c_{12}\, c_{23}\, s_{12}s_{13}\, s_{23}\sin\delta\, \sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}}$$

$$\boxed{+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2\, c_{12}c_{23}\, s_{12}s_{13}\, s_{23}cos\delta)\, sin^2\Phi_{12}}$$

$$\boxed{-8c_{13}^2 s_{13}^2\, s_{23}^2(1 - 2s_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}}$$

$$\Phi_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

$$a = 2\sqrt{2}G_F n_e E$$

Leading order term – T2K θ_{13} measurement

CP Even term - CP Odd term

Solar term

Matter term

Key to measurement

To determine PMNS parameters and mass differences we can exploit the different terms in this formula

Experimental observables

- Distance L - easy, we know this exactly in long baseline experiments
- Neutrino flavour – moderate, detector must distinguish muons and electrons
- Neutrino Energy E – Difficult, we do not observe the neutrino directly.
- Rate – Difficult, we must know the neutrino cross section well. Cross sections are small, large masses and high power beams required.

Detector must be tuned energy regime of interest to provide performance required for discovery.

Neutrino Interactions

To reconstruct neutrino energy, the type of neutrino interaction is crucial.

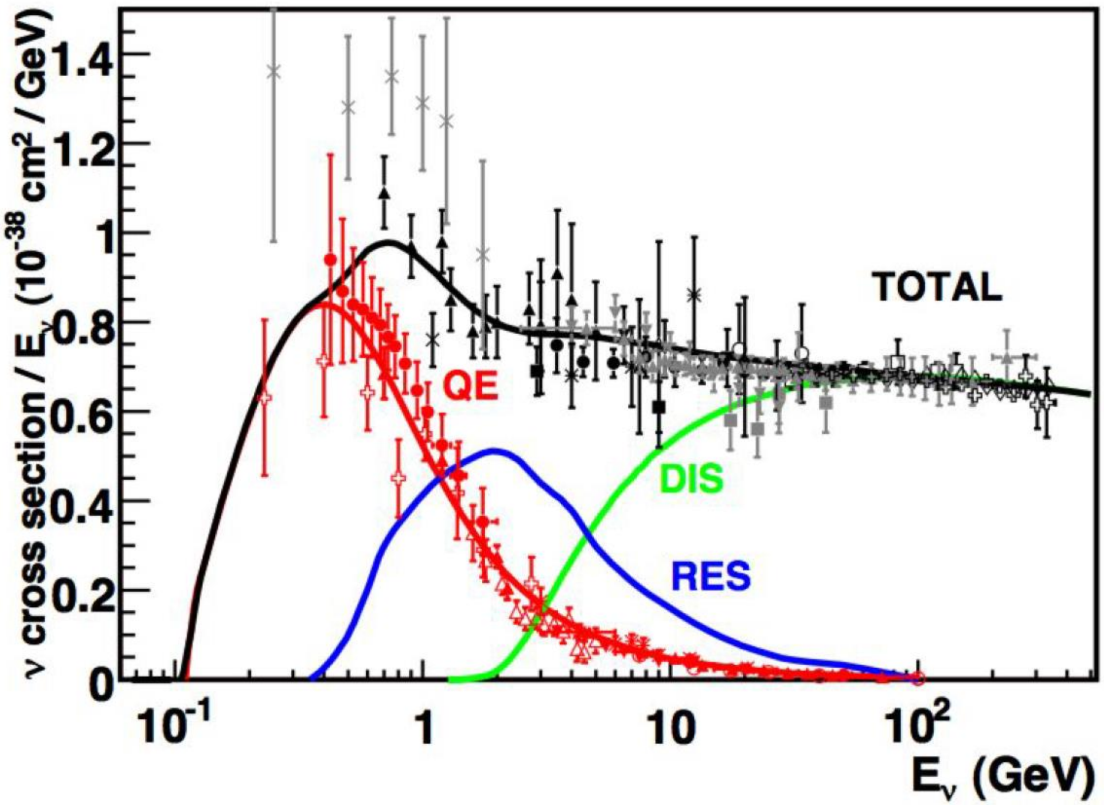
- It varies dramatically as energy rises past 1 GeV.

< 1 GeV Quasi-Elastic interactions

- Reconstruct neutrino energy from lepton kinematics
- Systematics due to incomplete nuclear models (e.g. 2p2h)

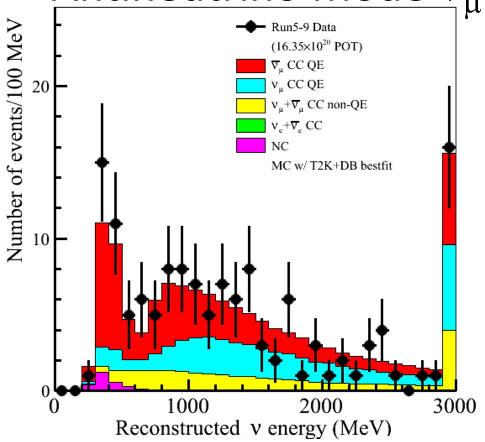
> 1 GeV Resonance -> DIS

- Multi particle final states
- Need to reconstruct everything to determine neutrino energy

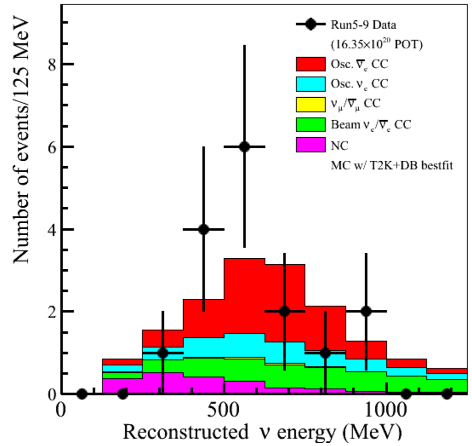


State of play: T2K Results

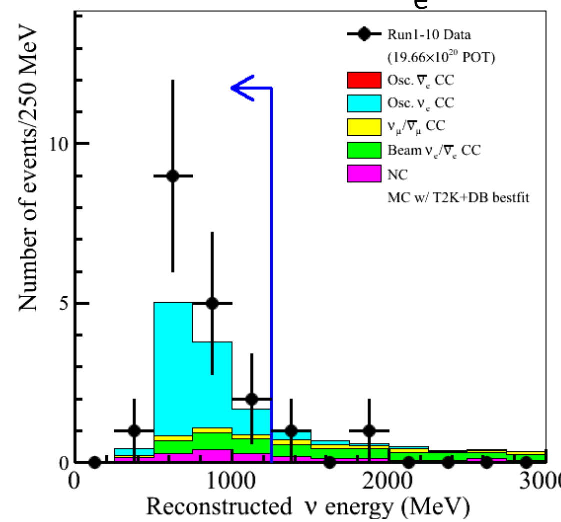
Antineutrino Mode ν_μ



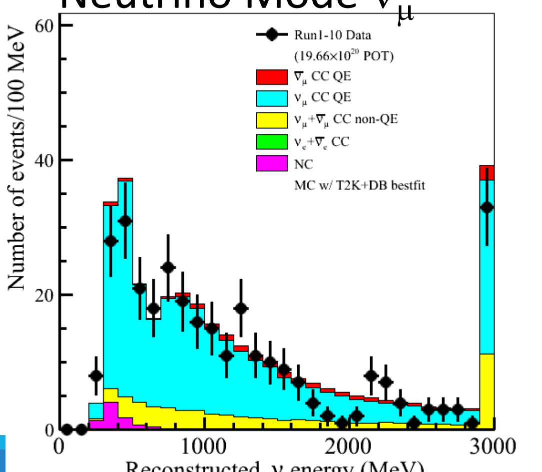
Antineutrino Mode ν_e



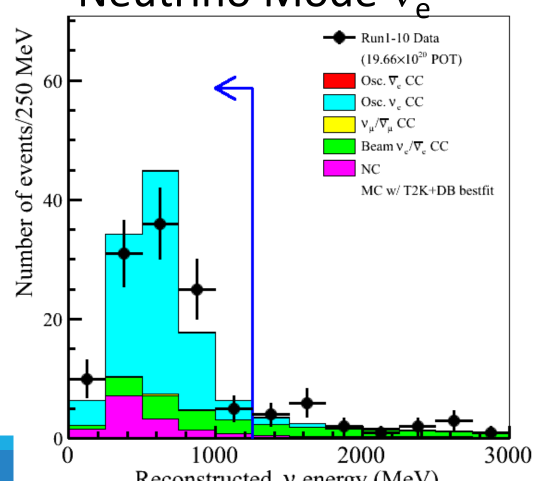
Neutrino Mode ν_e + 1de



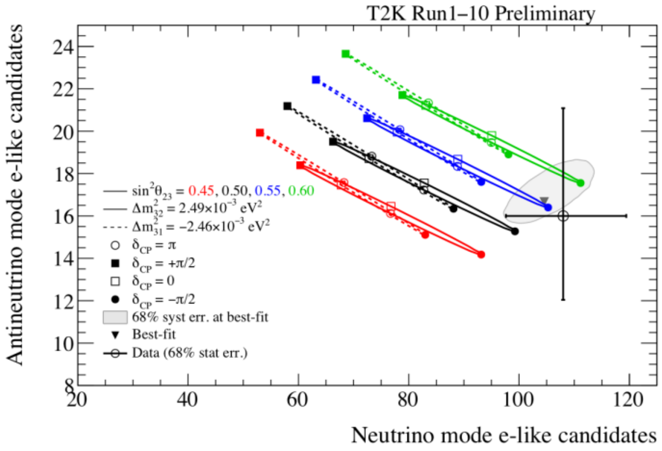
Neutrino Mode ν_μ

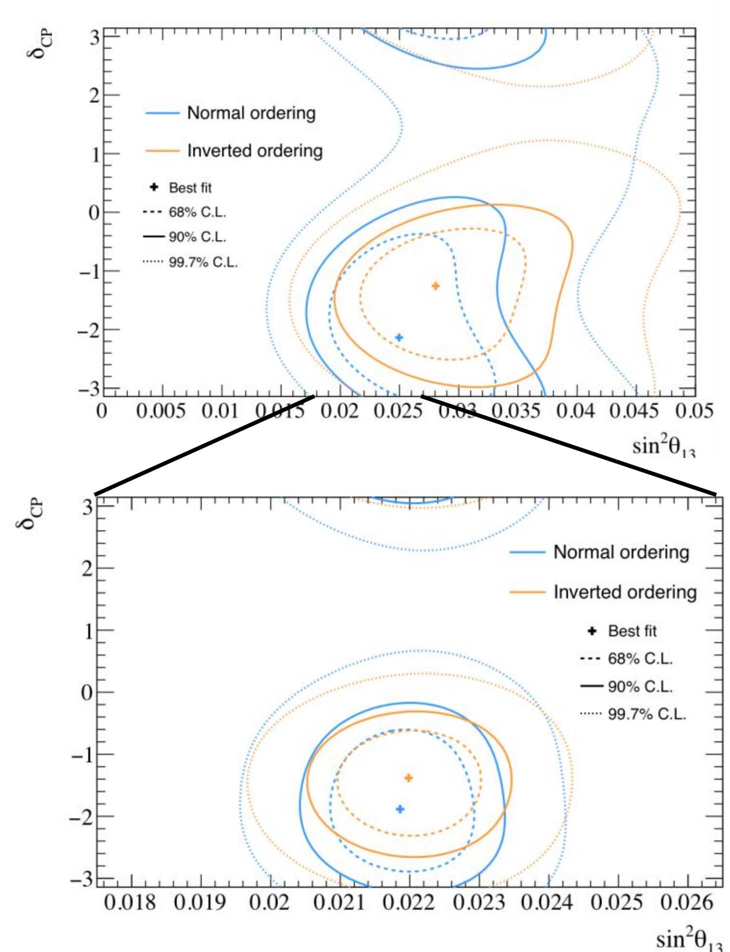


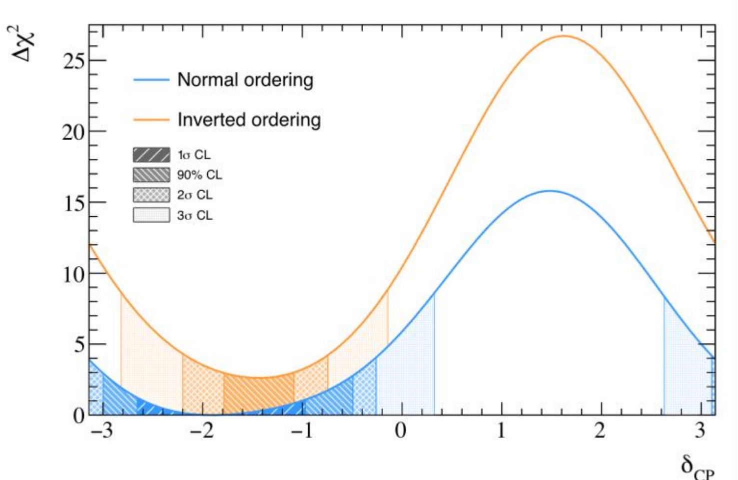
Neutrino Mode ν_e



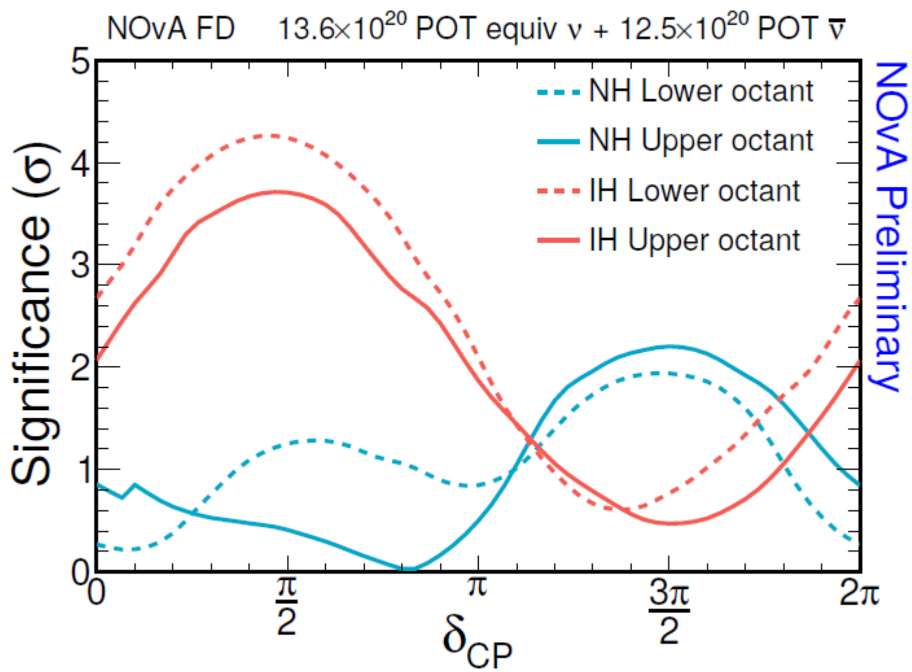
State of play: T2K Results

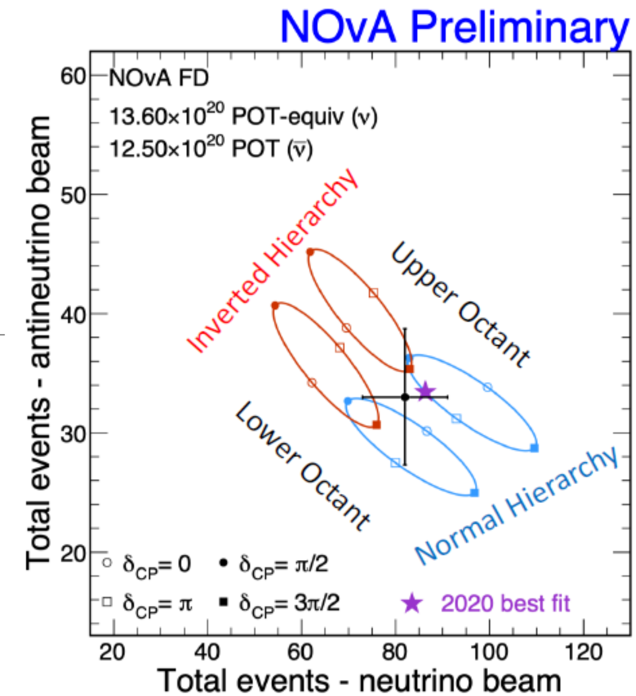


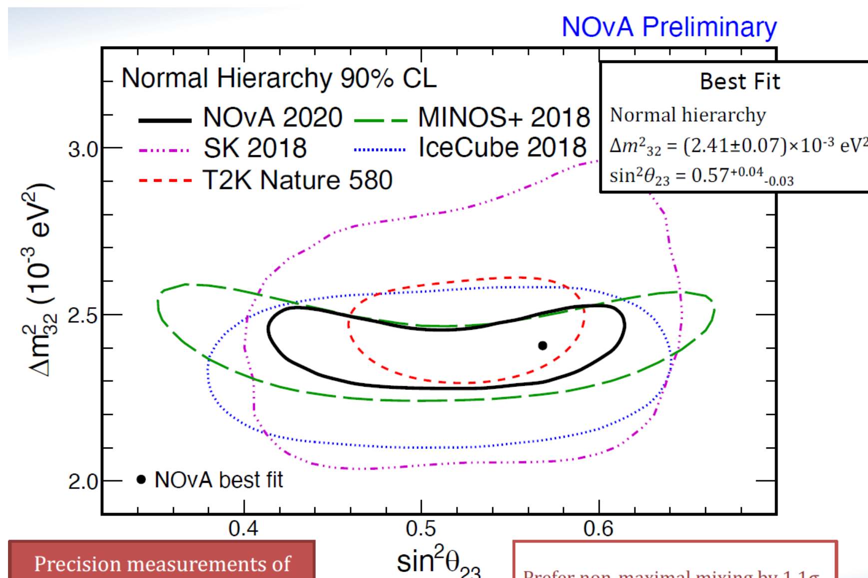




State of play: Nova





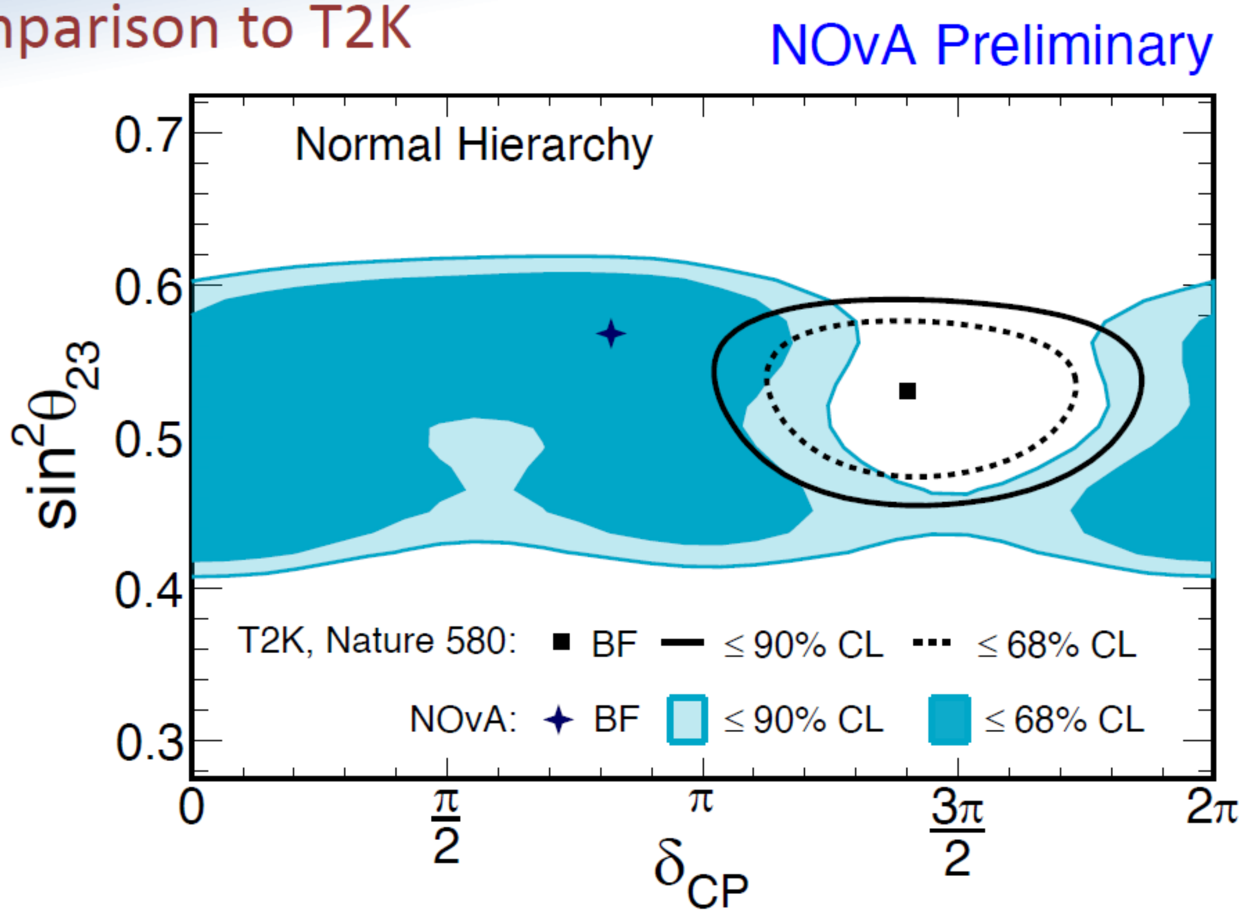


Precision measurements of Δm^2_{32} (3%) and $\sin^2\theta_{23}$ (6%).

Prefer non-maximal mixing by 1.1σ.

State of play

Comparison to T2K



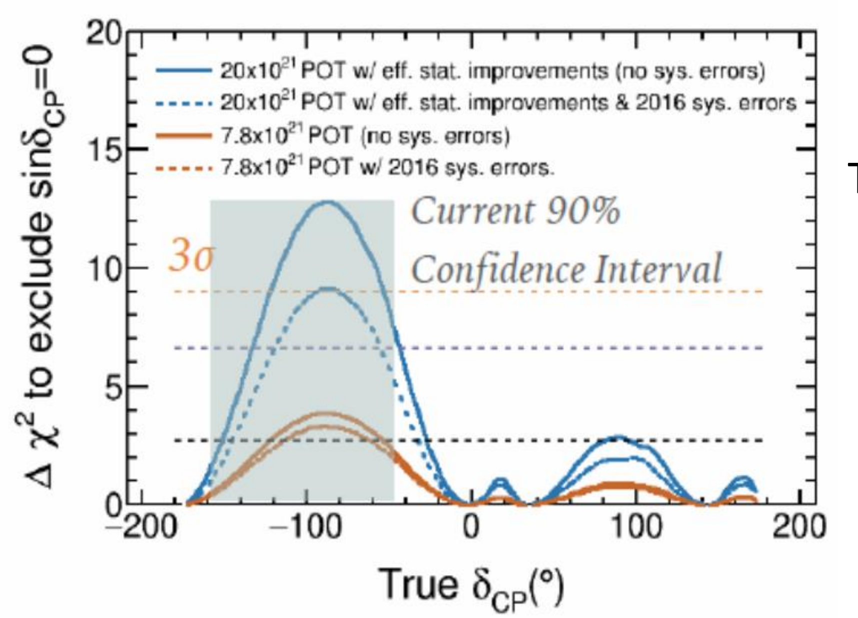
Prospects: 2027

Continued T2K and Nova running.

- Significantly increased statistics, but even optimistically won't get CP discovery (5σ)
- Precision measurement not possible

JUNO, PINGU/Icecube, Nova+T2K, SK Atmospheric

- Potential to discover mass hierarchy at 3σ level.



T2K-II

Hyper Kamiokande

2020 February : First year construction budget approved by Japanese Diet
2020 May: Univ. of Tokyo President and KEK Director General signed MOU

KEK will upgrade and operate the J-PARC accelerator to produce a high-intensity neutrino beam

The University of Tokyo will construct and operate the Hyper-Kamiokande detector

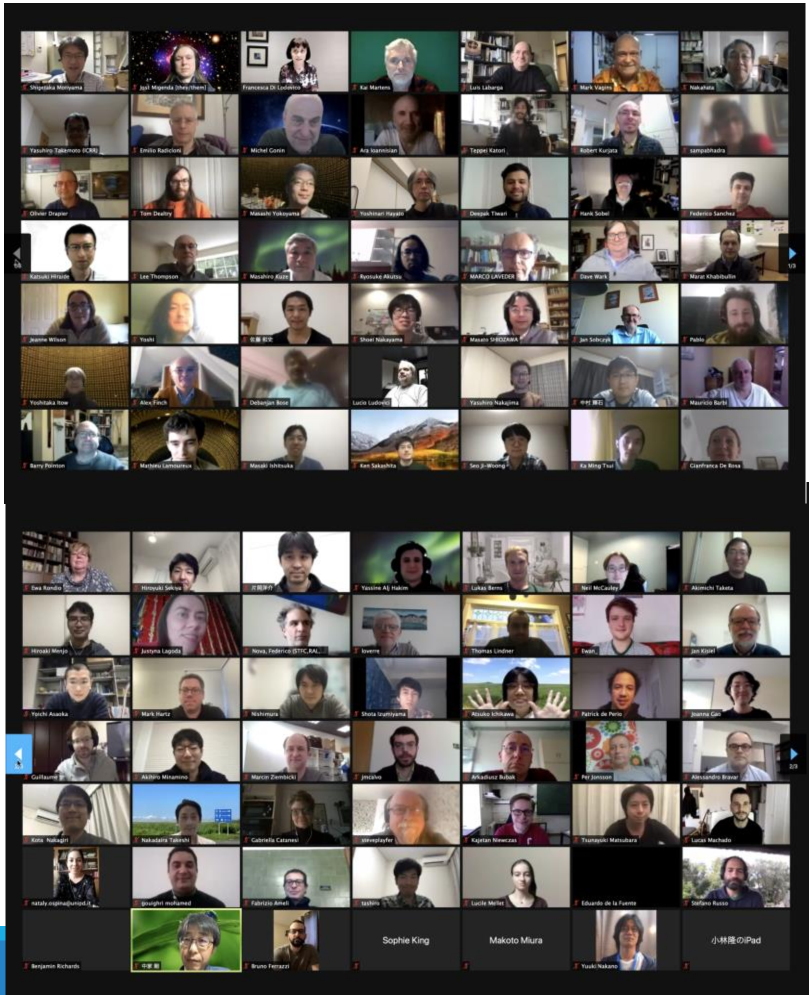
Hyper-K is under construction
Operation will begin in 2027

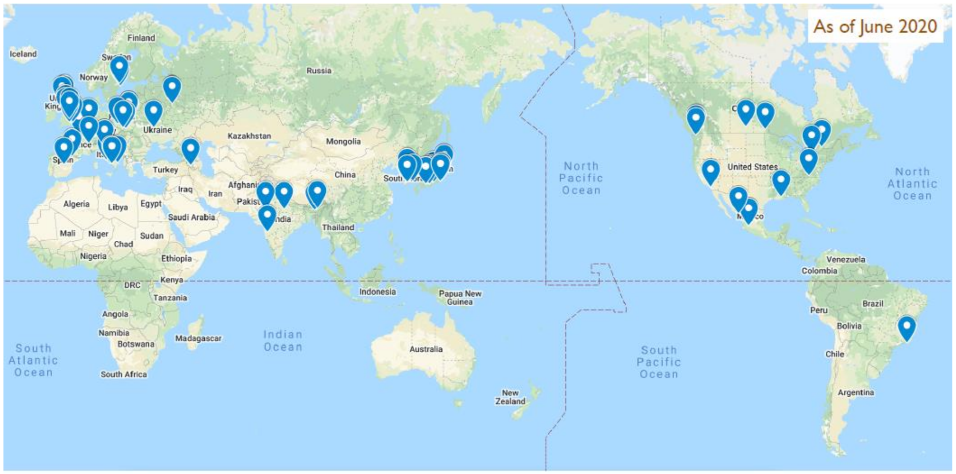
18 Countries

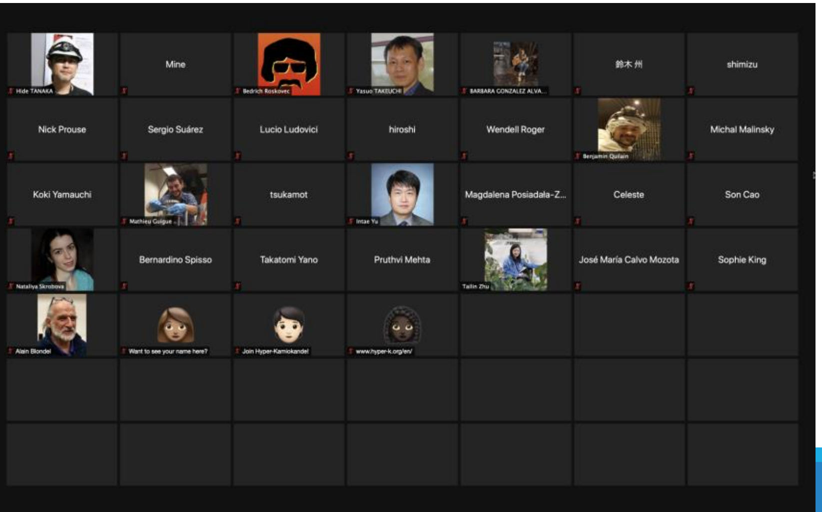
HK Collaboration

82 Institutes

390 members







Hyper-Kamiokande

Aim for order of magnitude larger detector for neutrino and proton decay physics

Increased coverage compared to SK to improve measurement precision

Increased beam power + upgraded near detectors

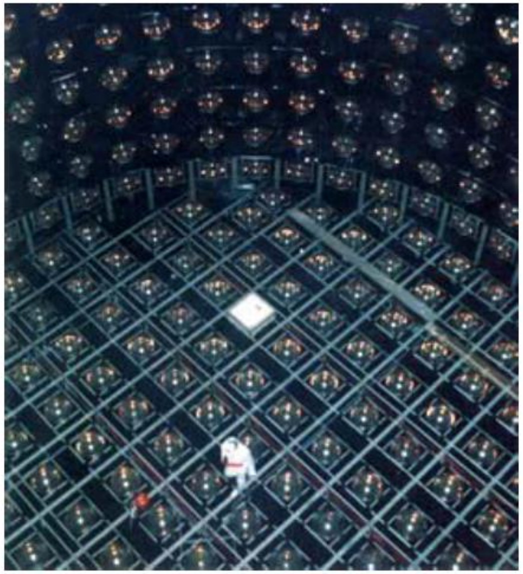
Neutrino Physics

- Maximise coverage for detection of CP violation
- Mass Hierarchy determination – Beam + Atmospherics
- Octant determination
- Unprecedented supernova neutrino sensitivity, burst and diffuse
- Solar day/night, low energy MSW upturn and HeP sensitivity

Proton Decay

- Extend lifetime limits in multiple modes and setup for detection if a signal is present.

3rd generation underground water Cherenkov detector in Kamioka

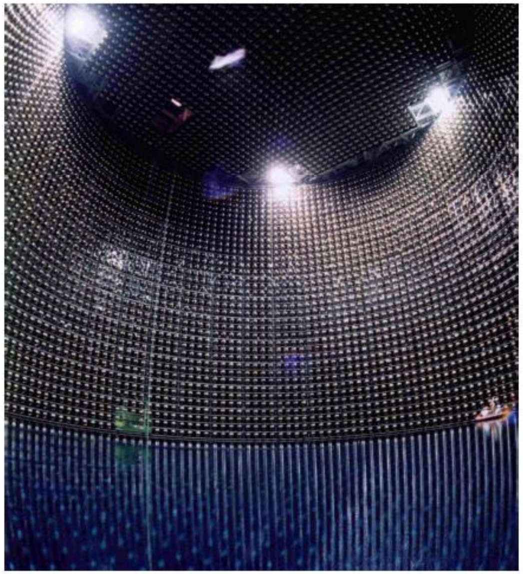


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Birth of neutrino astrophysics

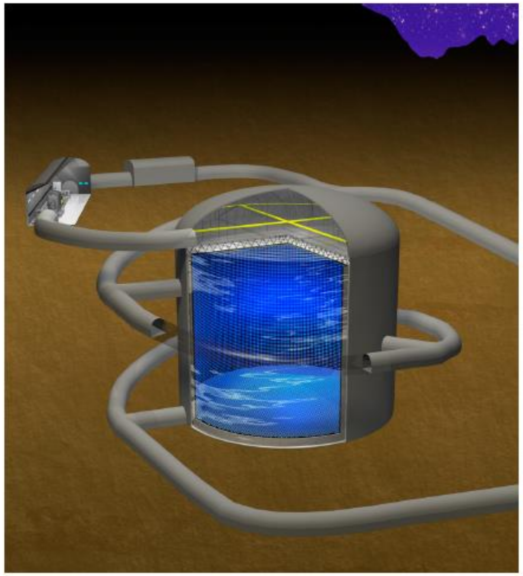


Super-Kamiokande

(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

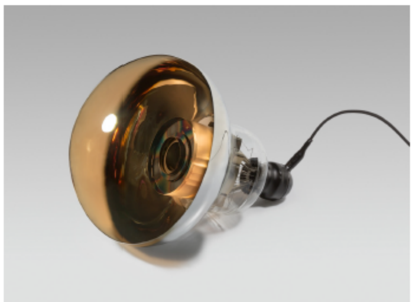
(start operation in 2027)

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

Explore new physics

The Hyper-Kamiokande detector

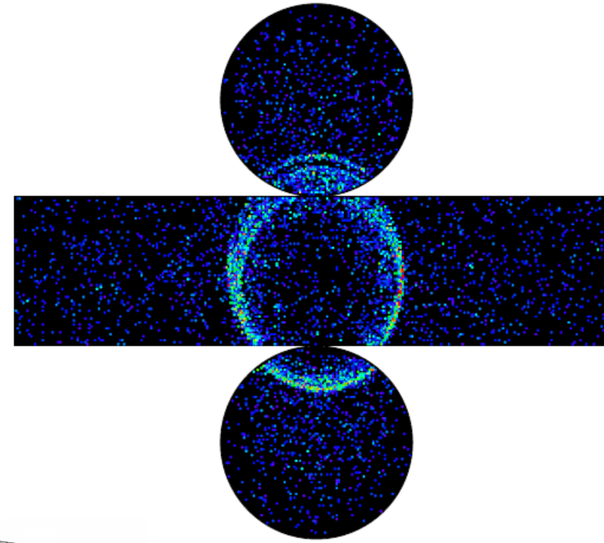
High QE Box&Line PMT



×2 photon detection

×2 timing resolution

Precision measurement



Recent update:

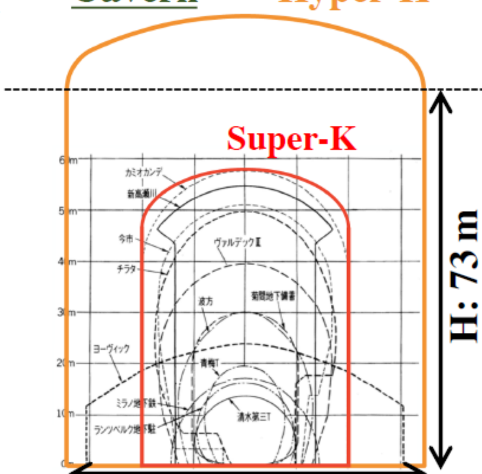
- Lower dark rate (similar level to SK)
- Lower radioactive contamination

×2 pressure tolerance

New detector design (cost reduction)

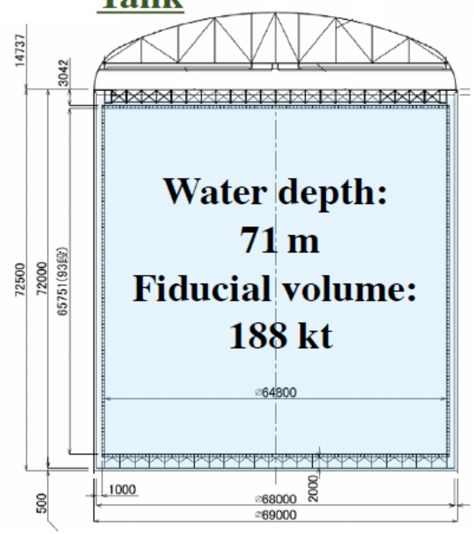
R&D for large cavern

Cavern Hyper-K



Φ: 69 m

Tank



High statistics neutrino data

New detector design by synergy of different technologies

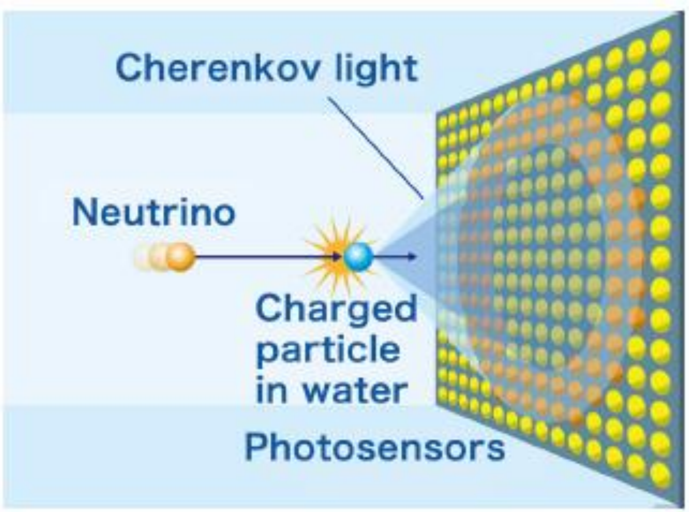
Water Cherenkov Technique

Observe the Cherenkov Ring from charged particles

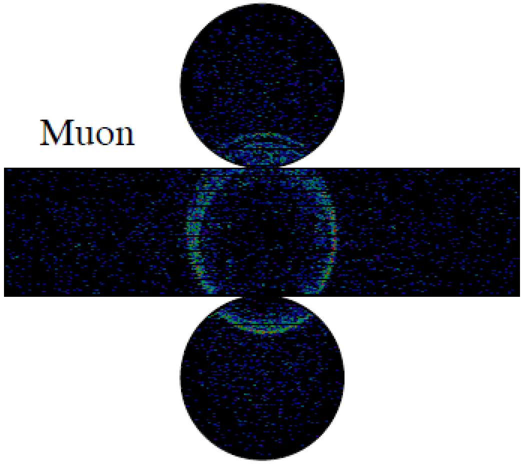
- Optical "Sonic Boom" from faster than light (in water) particles

>99% μ/e separation

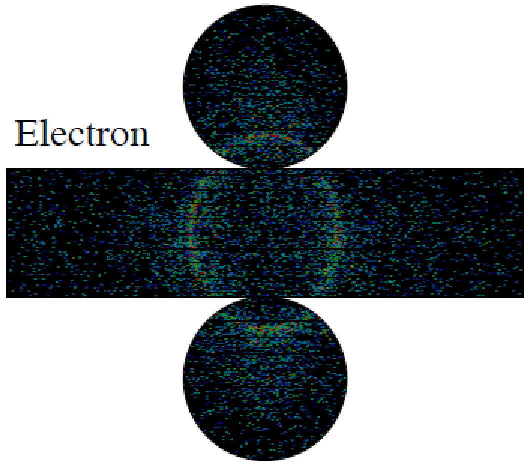
Momentum Reconstruction



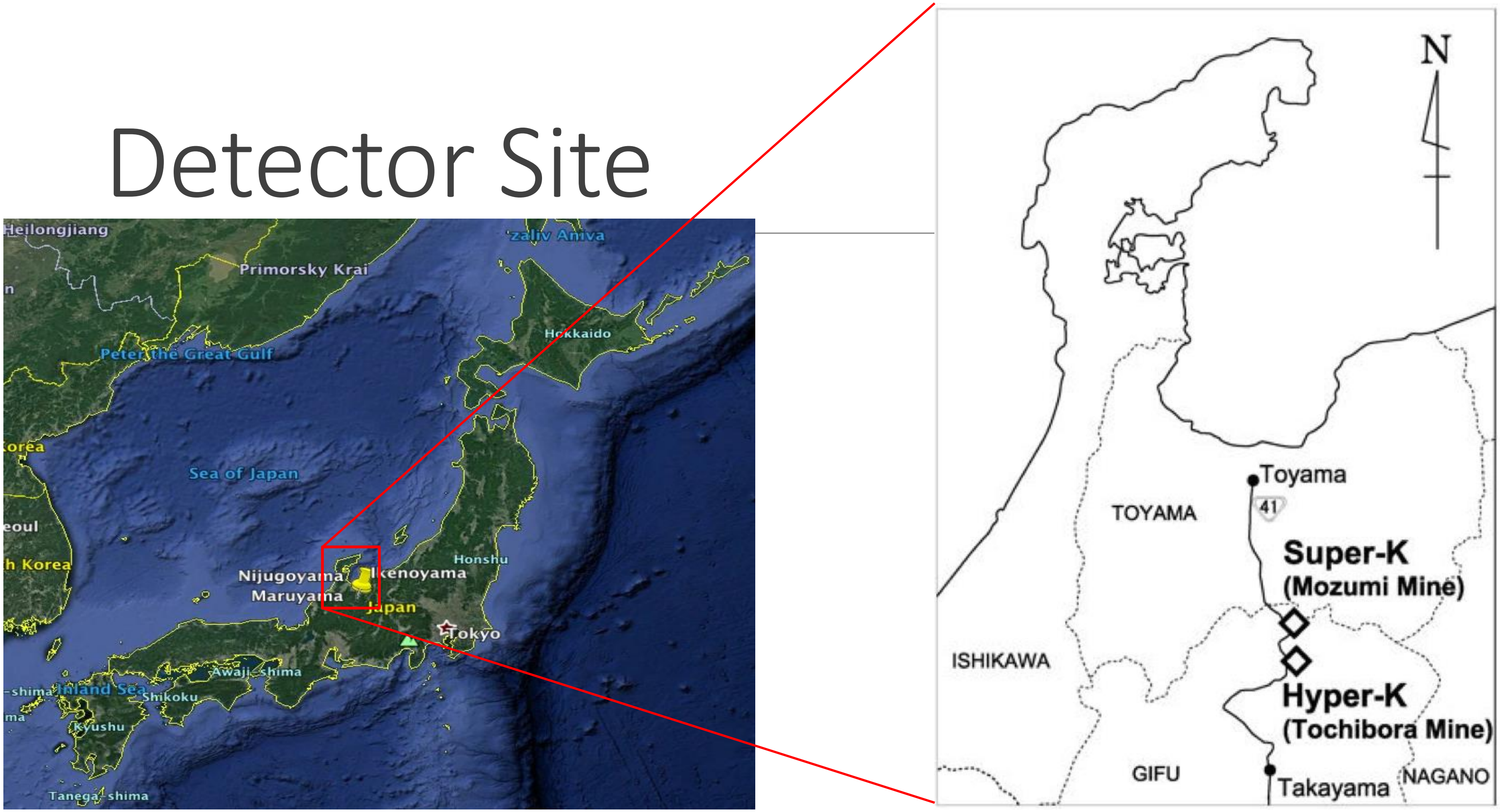
Sharp Ring



Fuzzy Ring



Detector Site

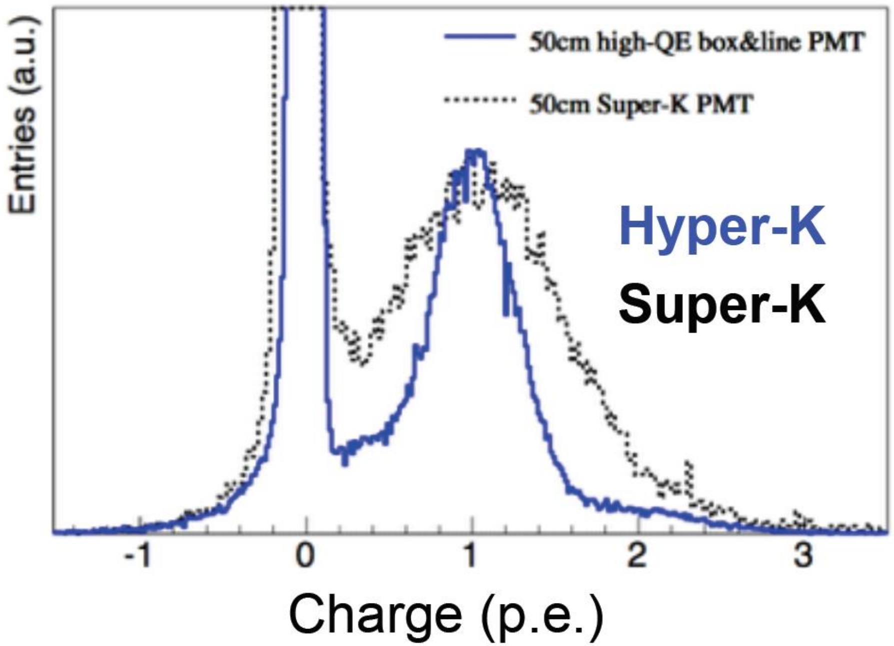


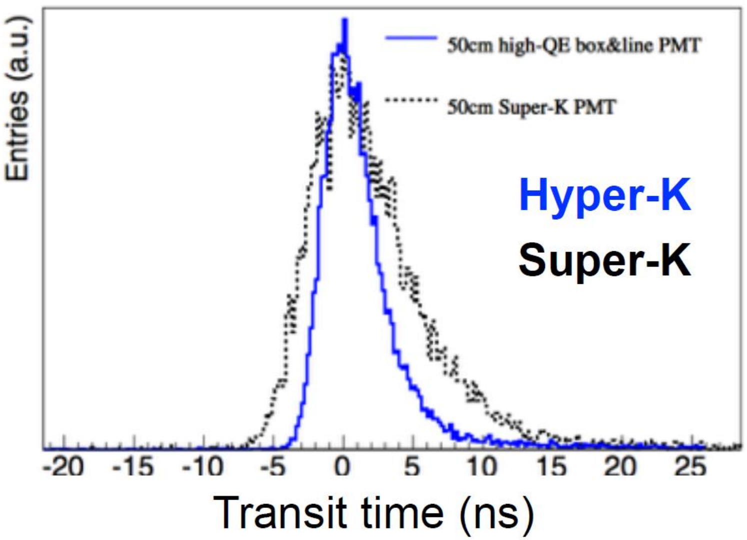
The detector will be located under Mt. Nijugo-yama
~8km south from Super-K
Identical baseline (295km) and off-axis angle (2.5deg) to T2K
Overburden ~650m (~1755 m.w.e.)

Photosensors

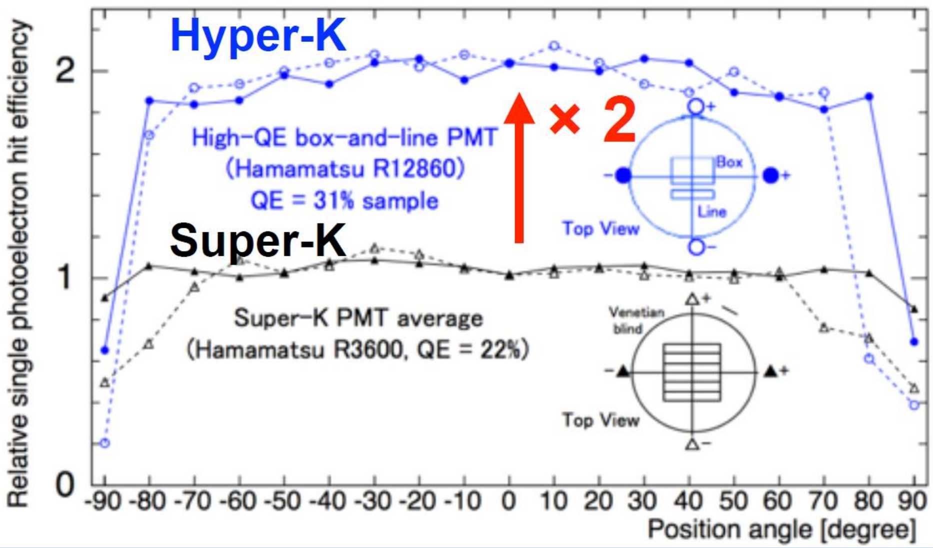
20 000 B&L PMTs

High Q.E. 50 cm box-and-line PMT (Hamamatsu)





relative photo detection efficiency (p.e.)



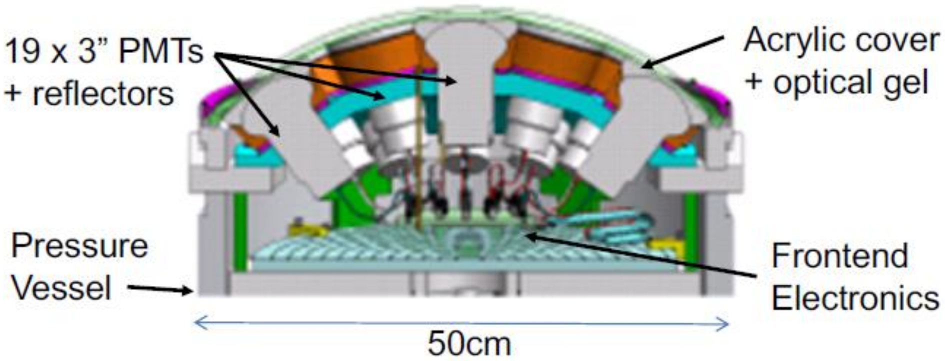
mPMTs

Develop optical DOM module from KM3Net, ICECUBE etc

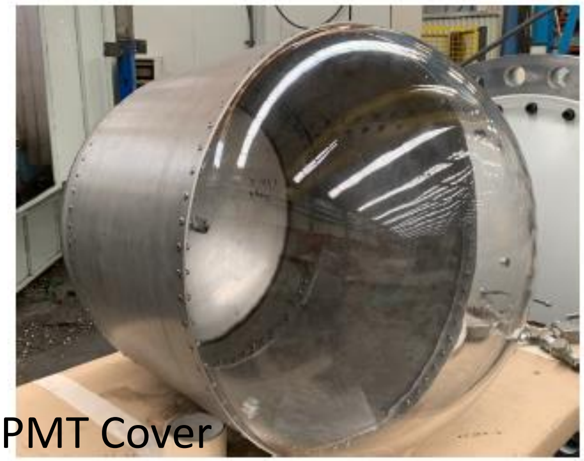
- 19 3” PMTs + reflectors inside optical module
- Faster PMTs, Improved measurement of ring
- Smaller photocathode area / unit

Photosensor Option for IWCD

Up to 5000 to be added to HK

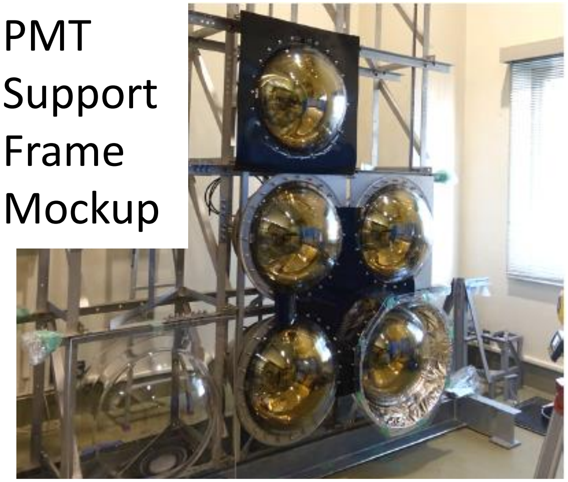


Detector System Development

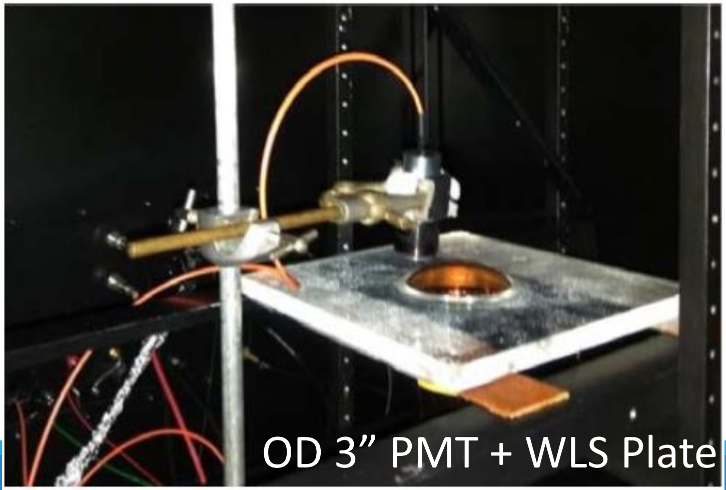


PMT Cover

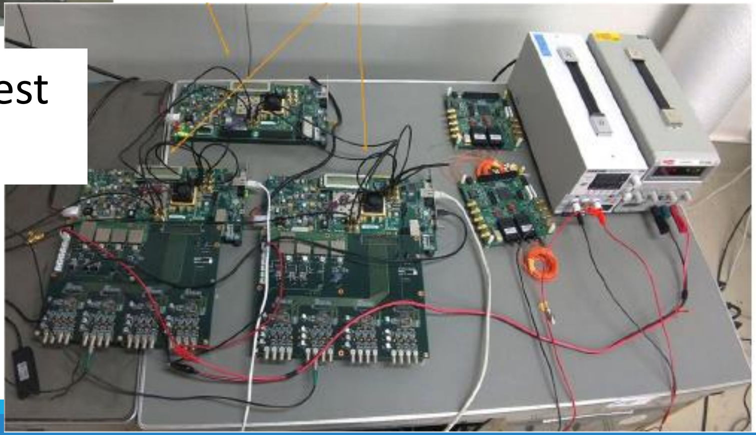
Underwater Electronics Boxes



PMT Support Frame Mockup



OD 3” PMT + WLS Plate



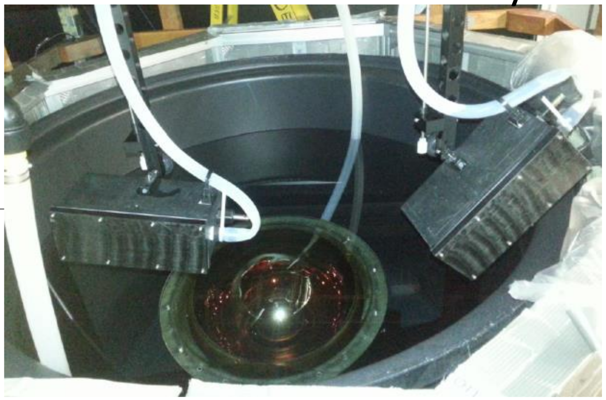
Clock Test Stand

Detector Calibration

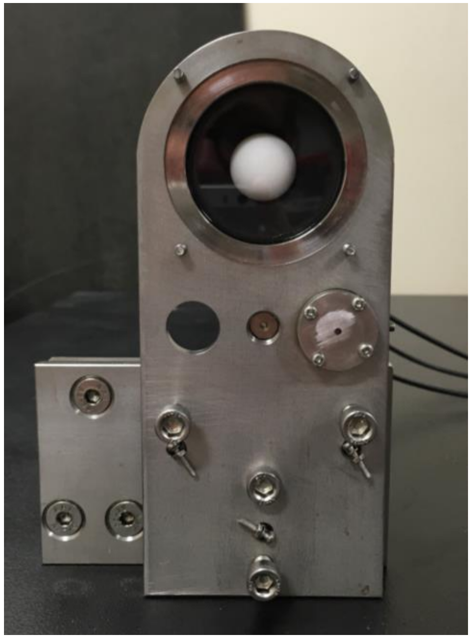
Wide programme of detector calibration to meet systematic needs

- Light Injection
- Diffuse Light source
- Electron LINAC (3-24 MeV)
- DT Generator – ^{16}N cloud
- CfNi Source
- AmBe Source
- Precalibration Programme

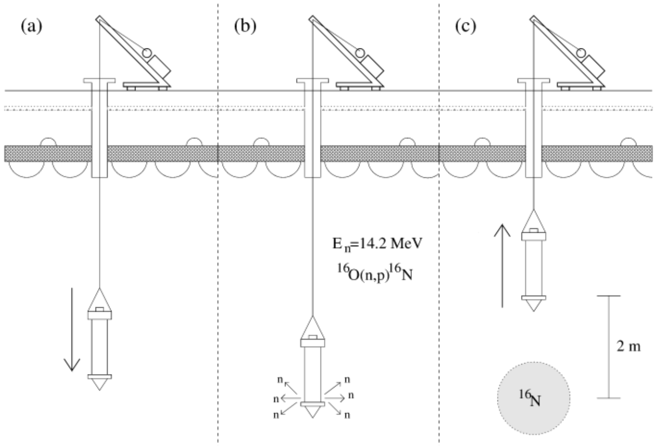
PhotoSensor Test Facility

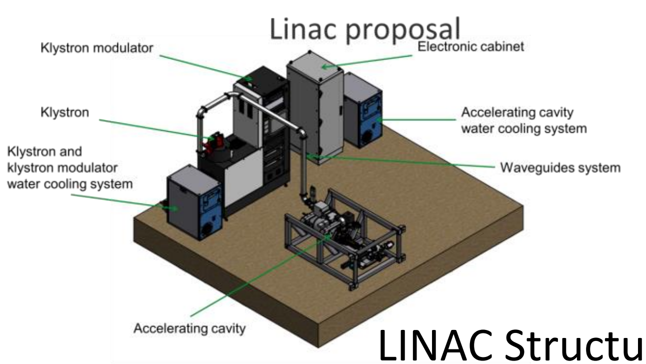


Light Injection Multi Injector



DT Operation





LINAC Structure

Long baseline setup

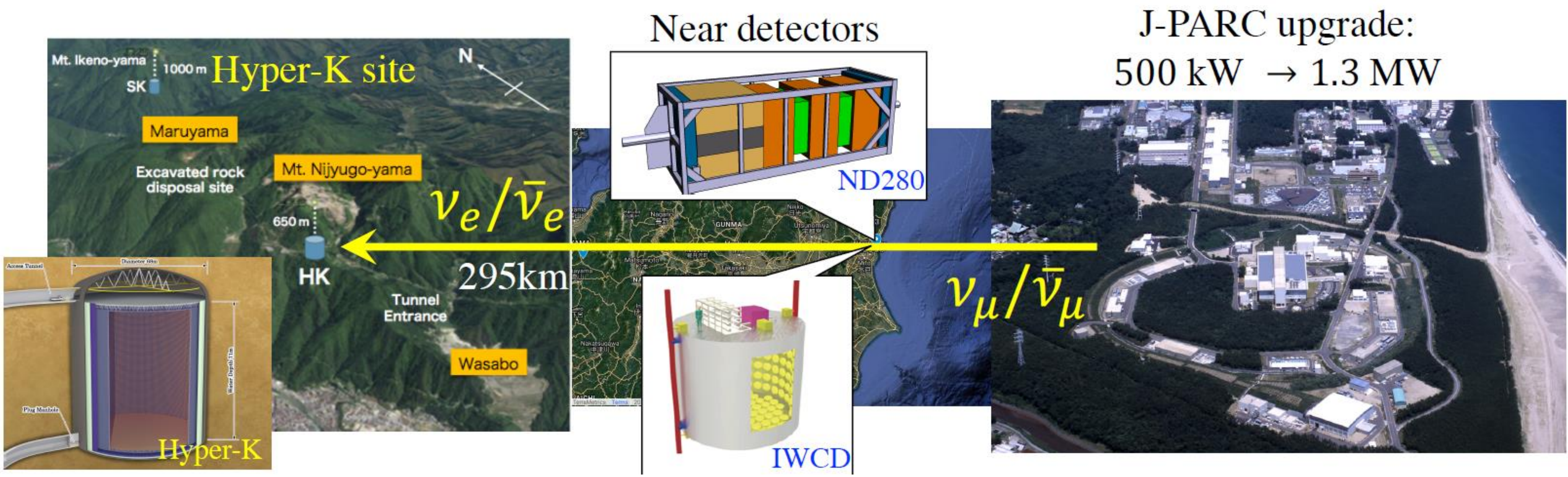
Off axis angle 2.5o same as T2K, 600 MeV flux peak

Beam power upgrades -> 1.3 MW +

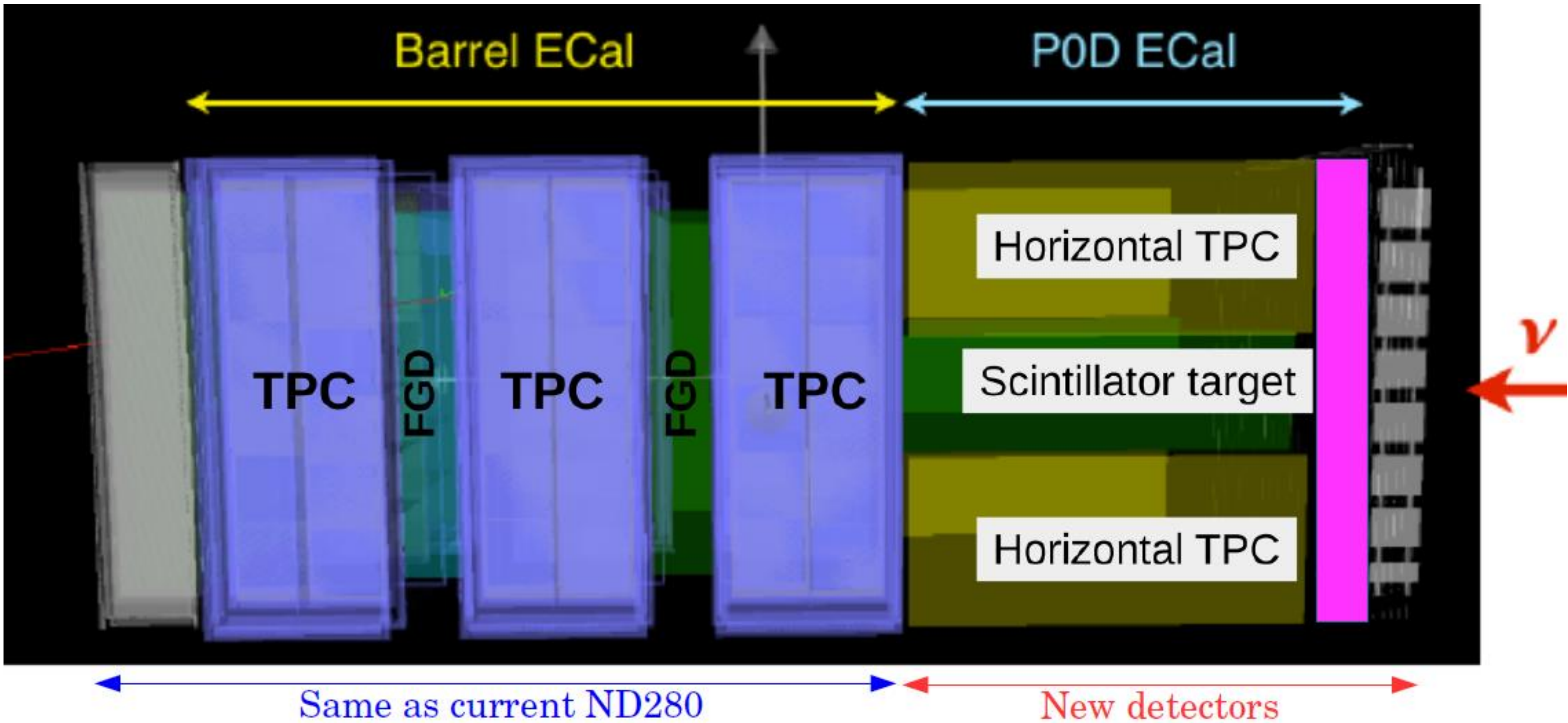
Fiducial volume 8.4X SK

Overall statistics increase of 20X from T2K.

Upgraded near detectors improving systematics



Near Detector Upgrade



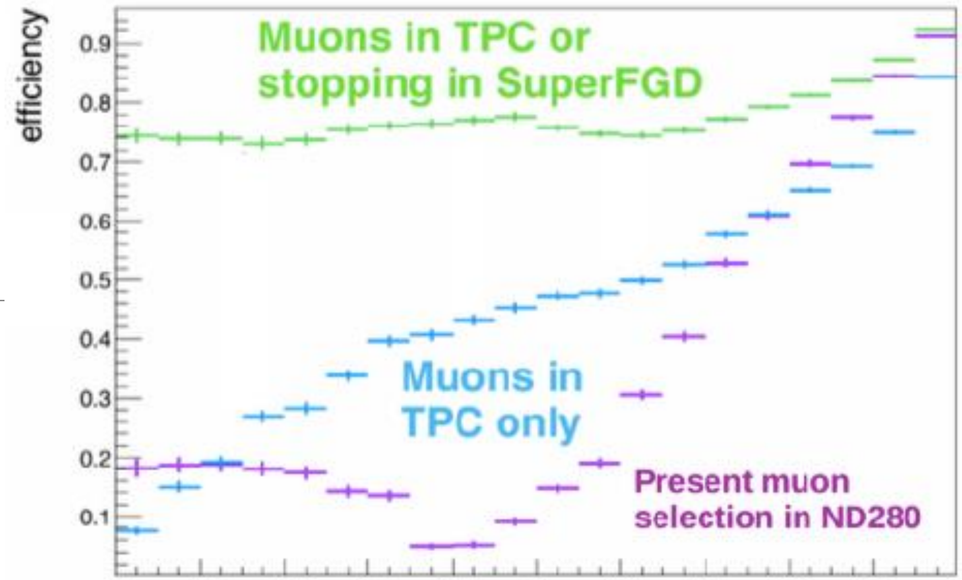
ND Upgrade

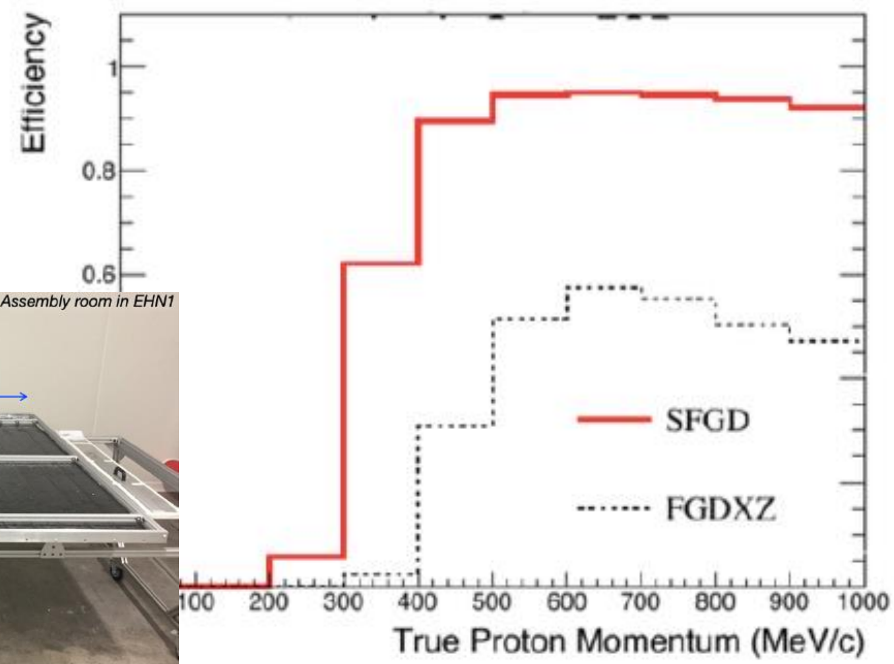
sFDG target

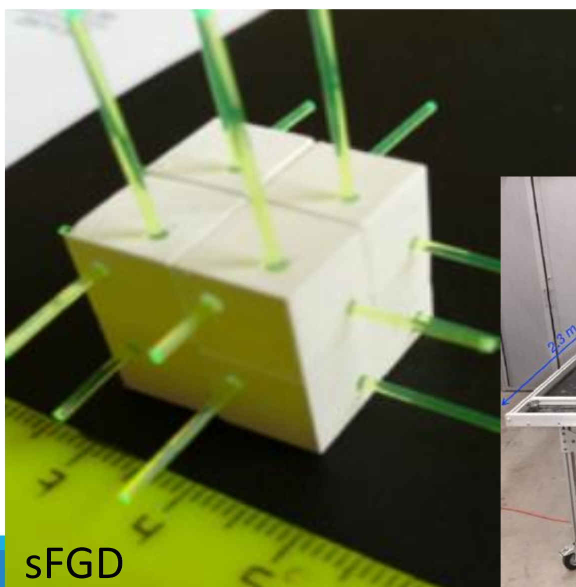
Horizonal TPCs

Time of flight detectors

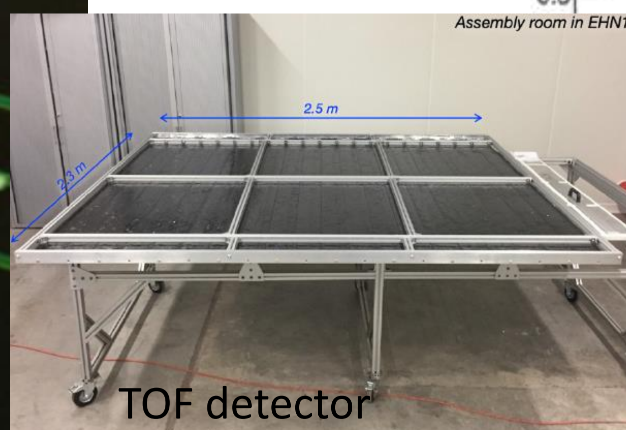
Improved angular efficiency particle thresholds and PID





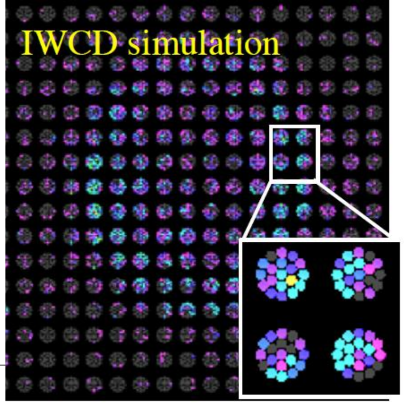


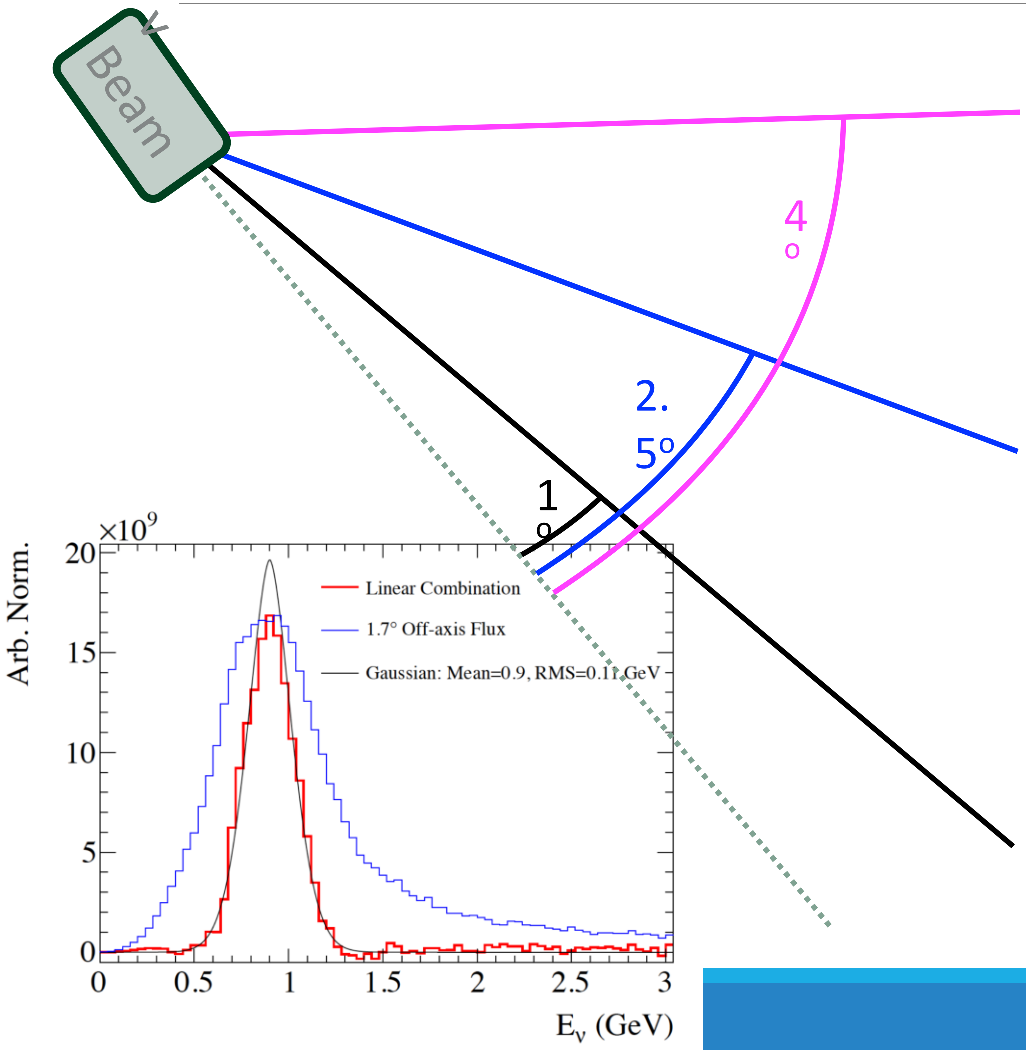
sFGD

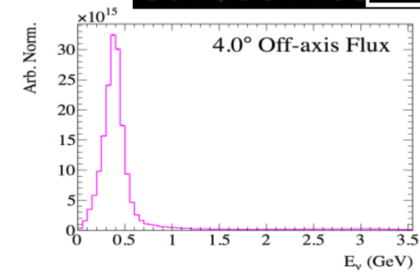


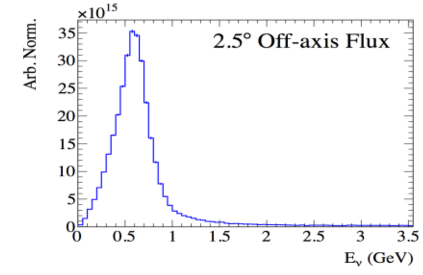
TOF detector

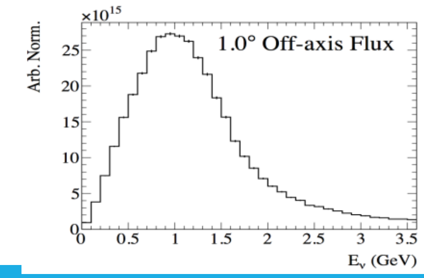
Intermediate detector







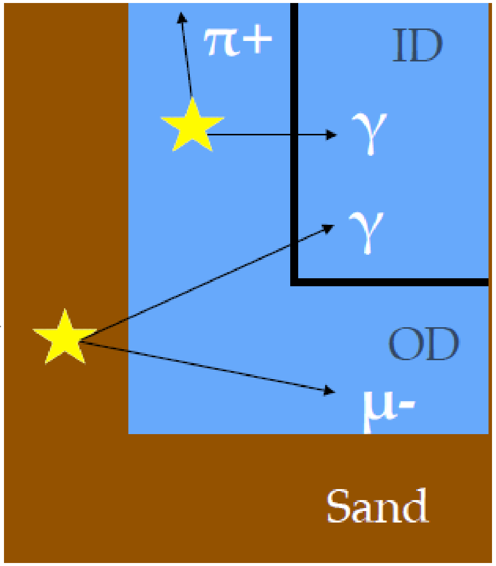




IWCD

1 kton scale water Cherenkov

- Use mPMTs for readout
- Move detector up and down shaft to sample different off axis angles



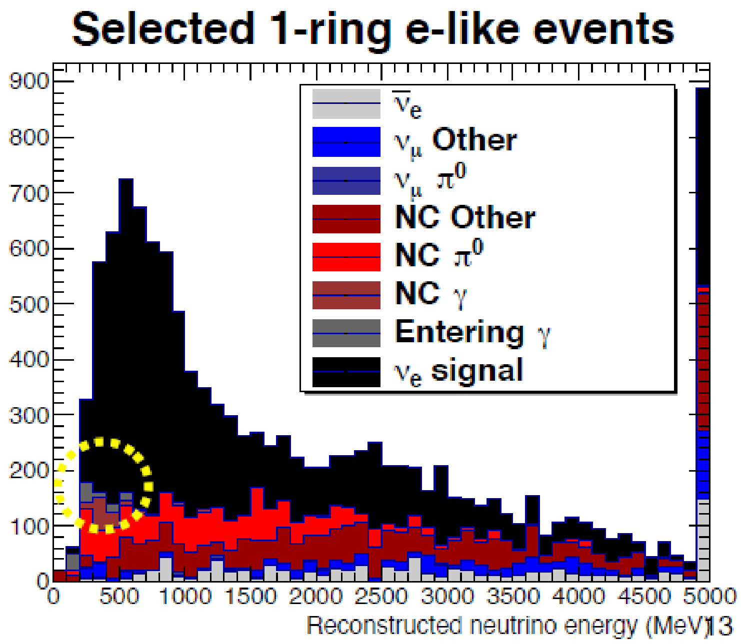
Constrain neutrino energy misreconstruction

- Improved measurement of relationship between neutrino energy and lepton kinematics

Can load with Gd to measure neutron production

Measure electron neutrino cross sections

- Self shielding, protects from entering gamma ray
- Major constraint in measurements in ND280



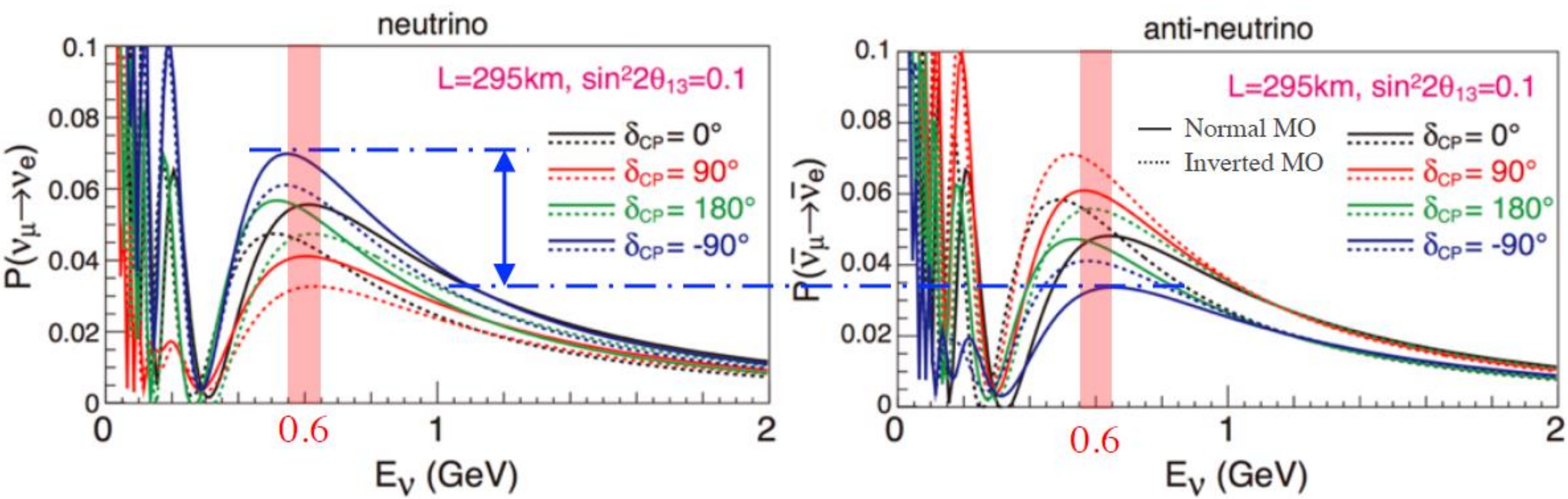
Oscillations

Measure CP violation through υ_e appearance

Few % statistical uncertainty after 10 years operation with > 1000 υ_e and $\overline{\upsilon_e}$ signal events

Requires improved interaction and detector systematics

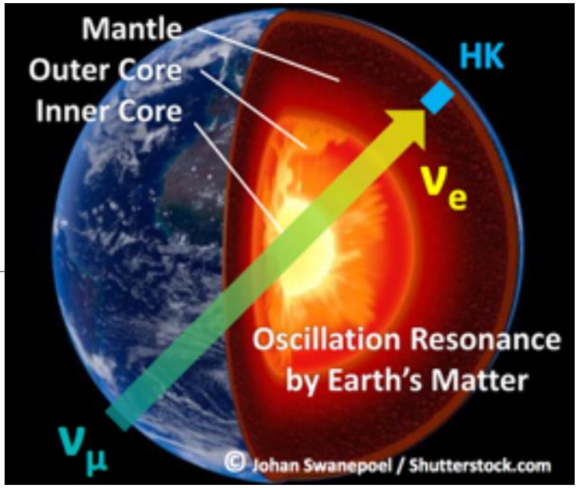
Break parameter degeneracies with atmospheric neutrinos

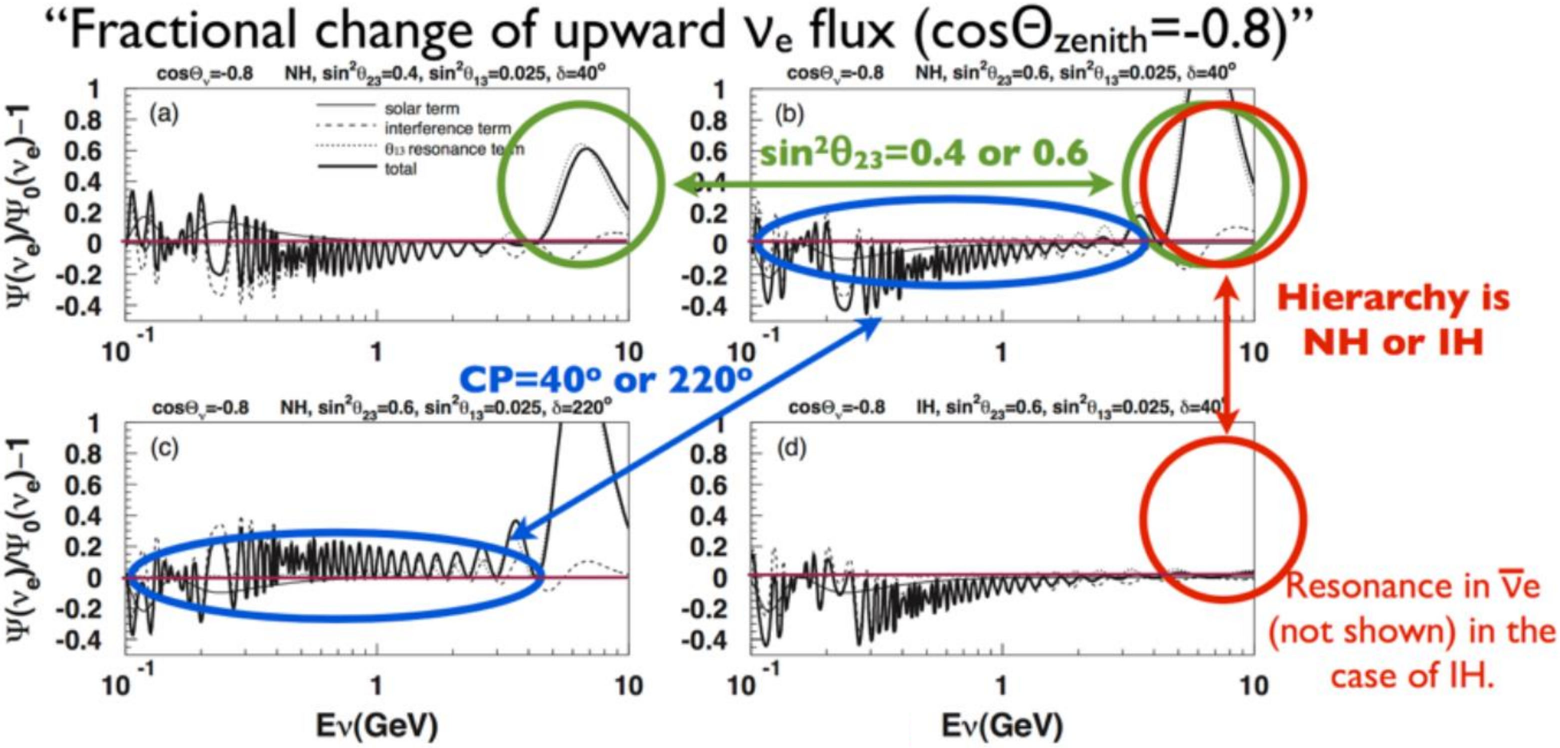


Atmospheric Neutrinos

Exploit the matter effect for atmospheric neutrinos as they pass thought the mantle and core

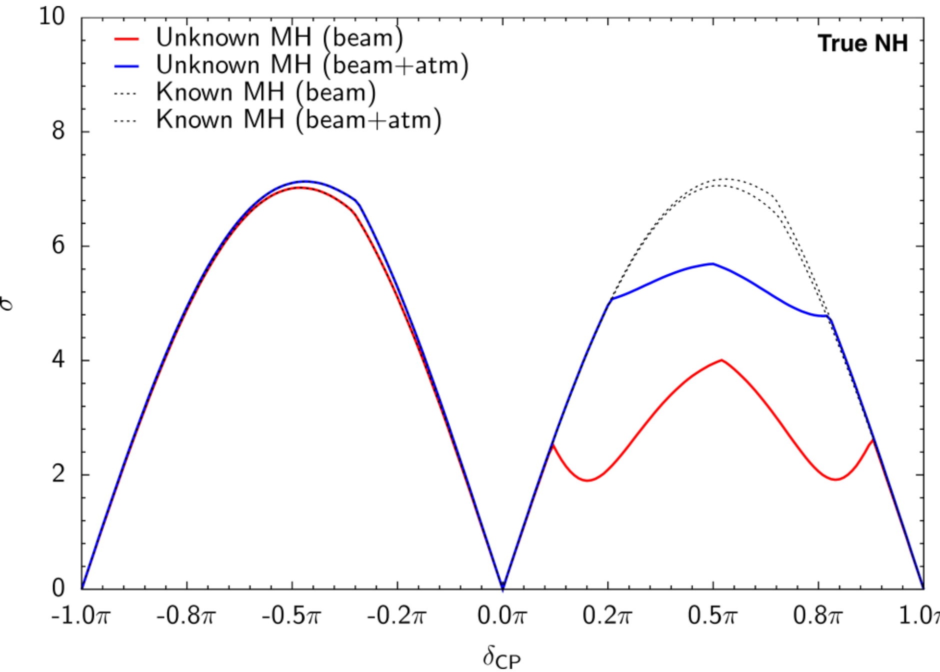
Sensitivity to mass hierarchy, δ_{CP} and octant

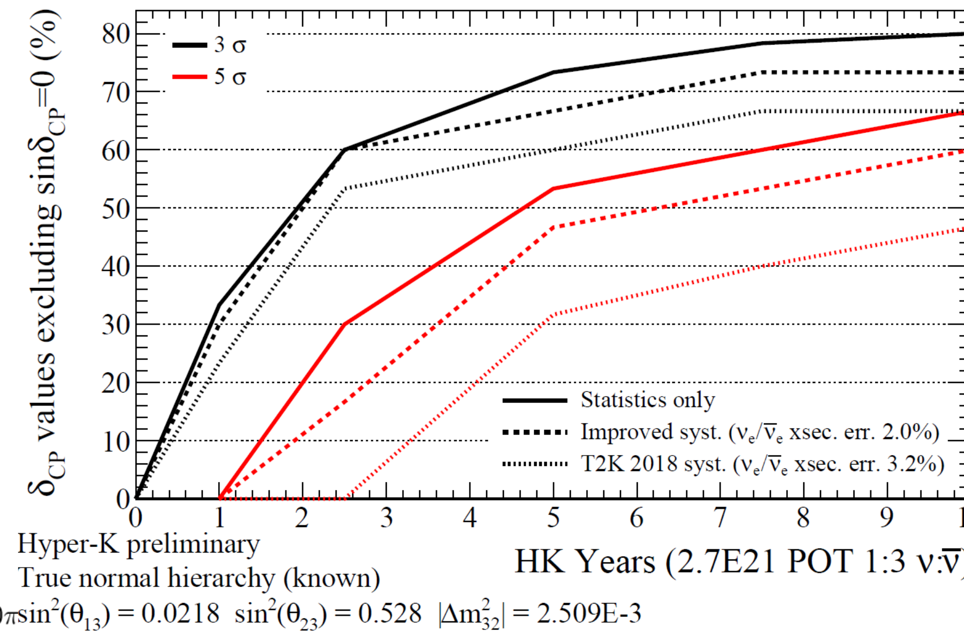




CP Violation Sensitivity

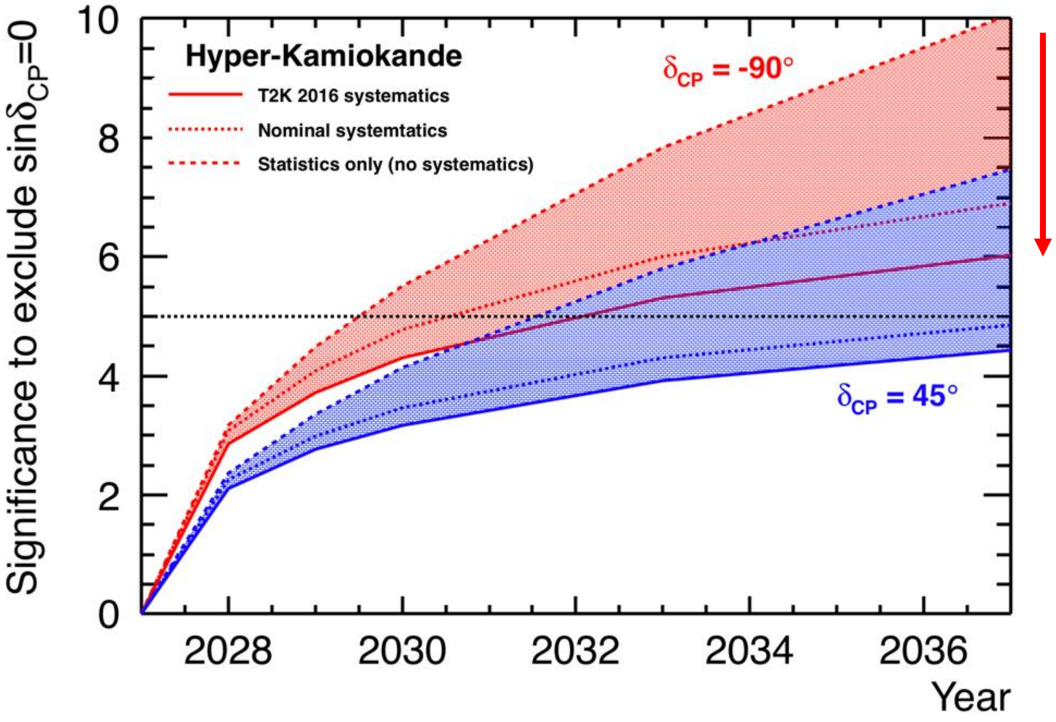
Exclusion for $sin\delta_{CP} = 0$





~8σ exclusion of $sin\delta_{CP} = 0$ at $\delta_{CP} = -90°$ (T2K favoured value)

CP Measurement Prospects

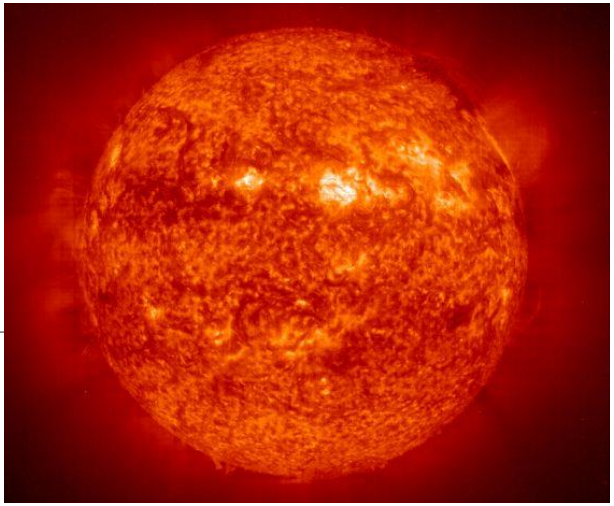


Impact of Systematic Uncertainties
Statistics – T2K 2016
Shows importance of improved uncertainty estimations

Sensitivity depends on true value of δ_{CP}

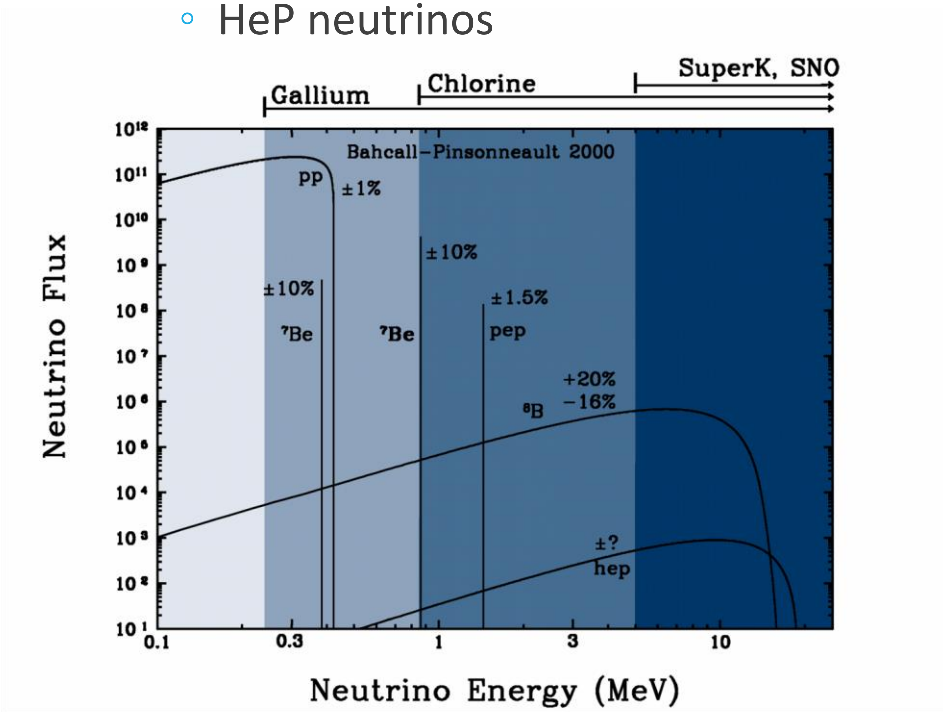
Non Accelerator Physics

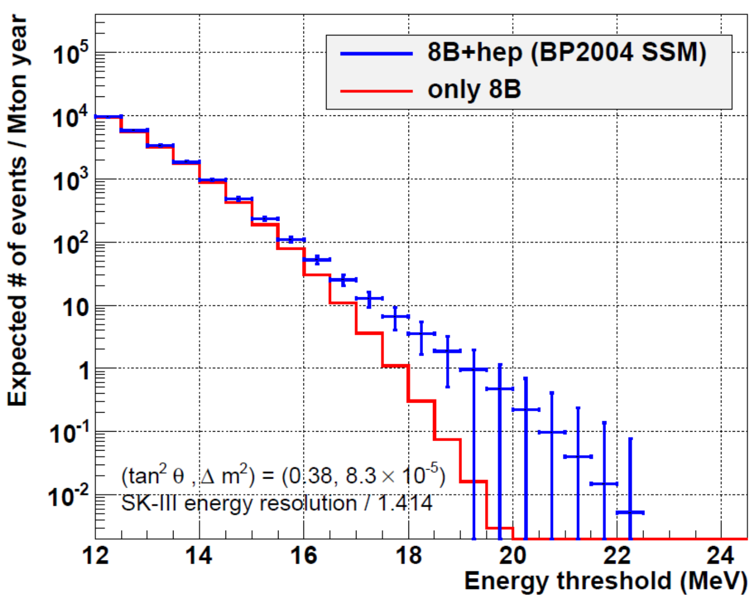
Solar Neutrinos



Search for:

- Day – Night Asymmetery
- MSW upturn
- HeP neutrinos

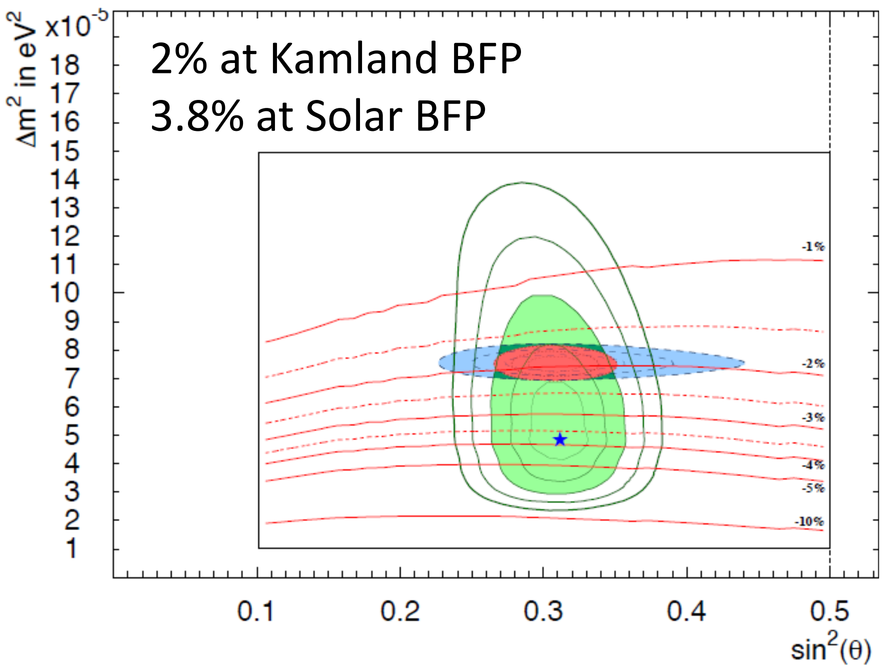


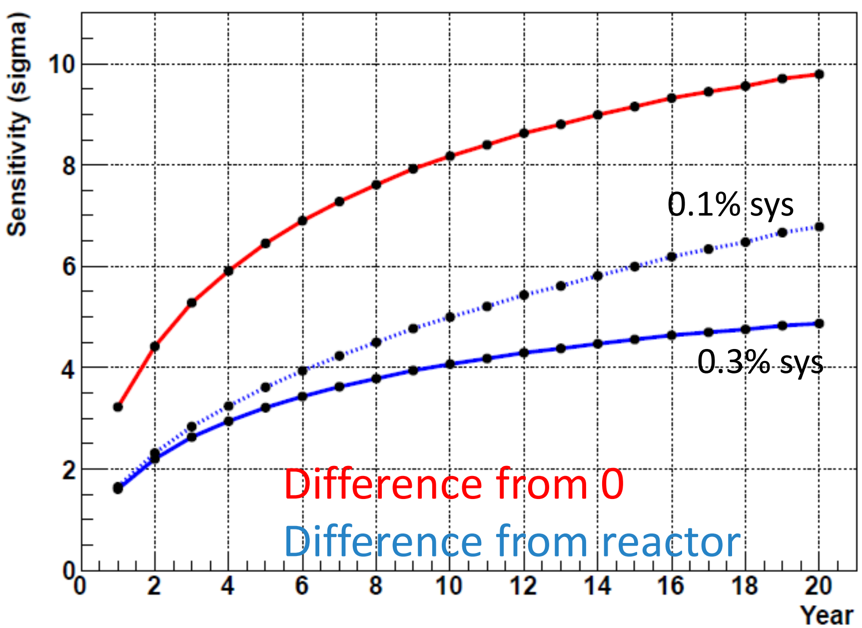


Day-Night Asymmetry

Regeneration of ν_e as solar neutrinos pass through the Earth.

- Sensitive to Δm^2
- Probe of minor tension between solar and Kamland results.

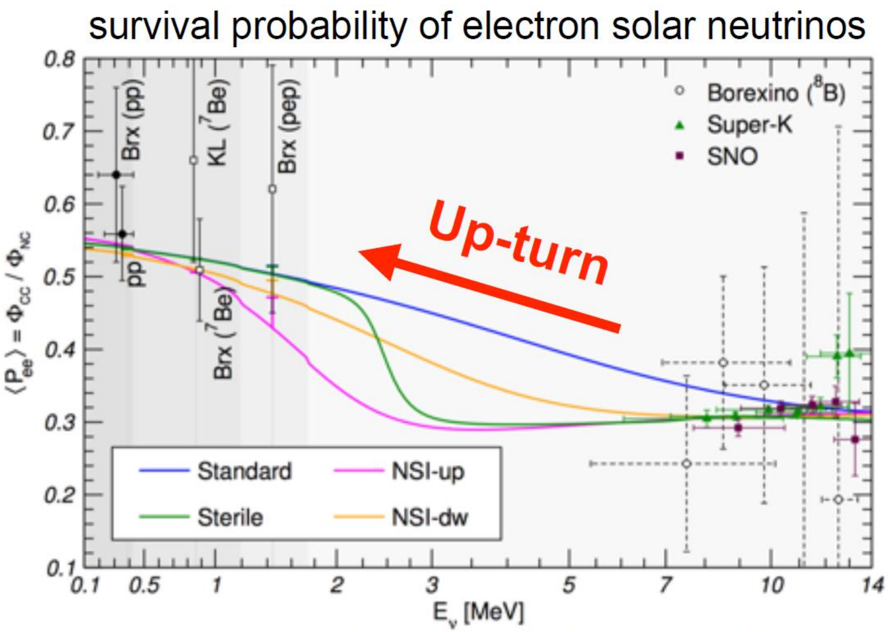




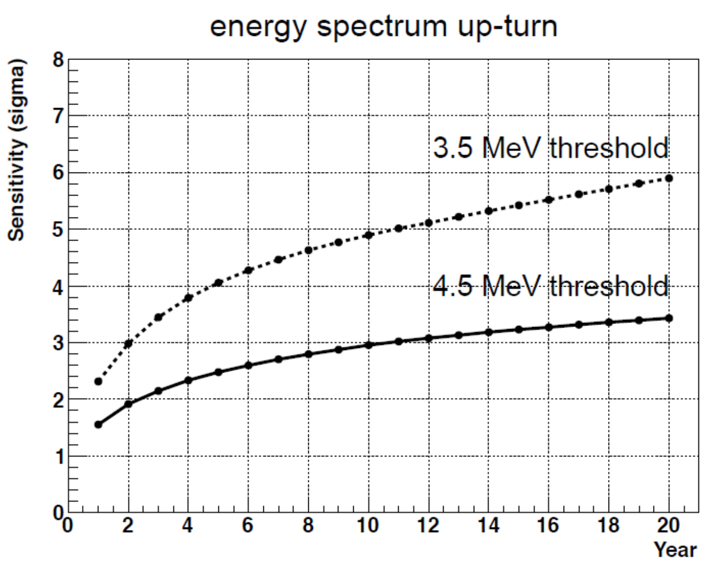
MSW Upturn

Upturn in survival probability expected in ^{8}B neutrino spectrum

- Depends upon details of matter effect
- Probe of non standard interactions

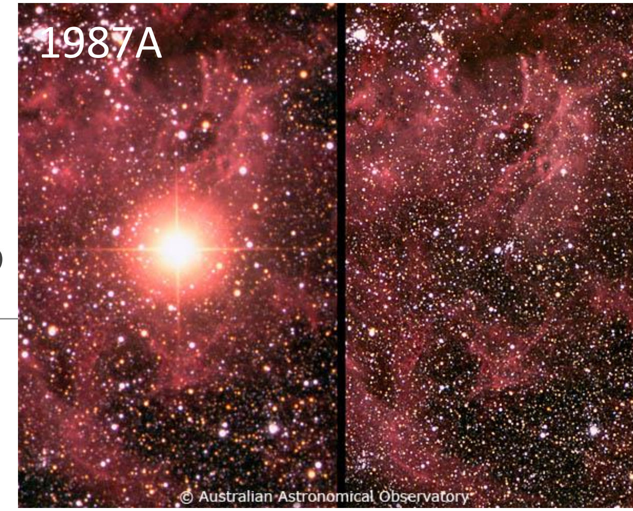


M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



Requires similar detector performance and backgrounds to SK with improved calibration

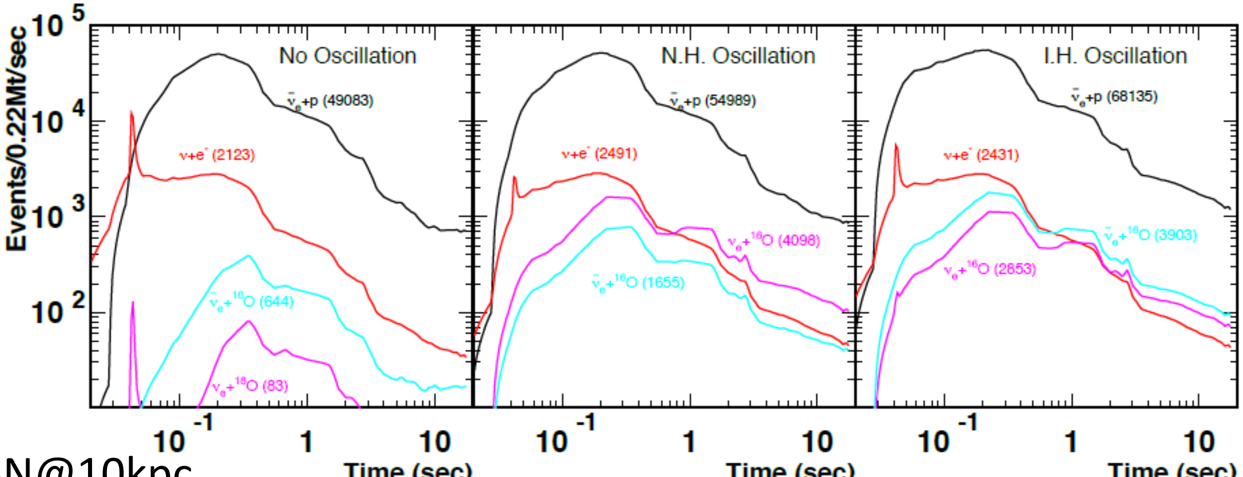
Supernova Neutrinos

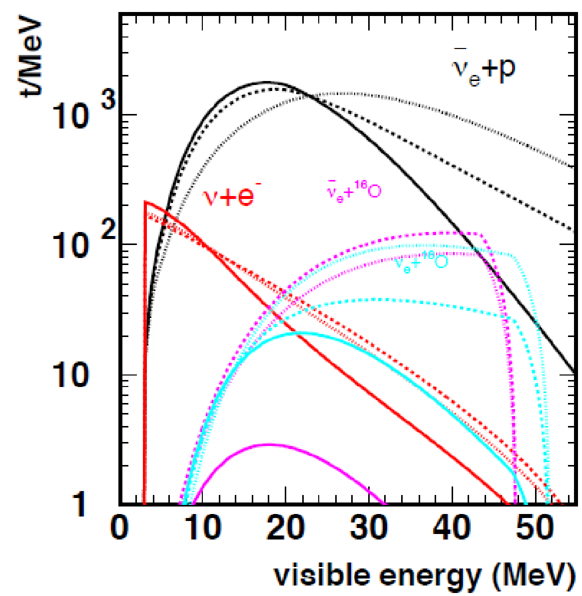


Hyper-K will be the most sensitive detector for Supernova neutrinos

- Access to oscillation physics
- Supernova physics
- Early warning for optical telescopes

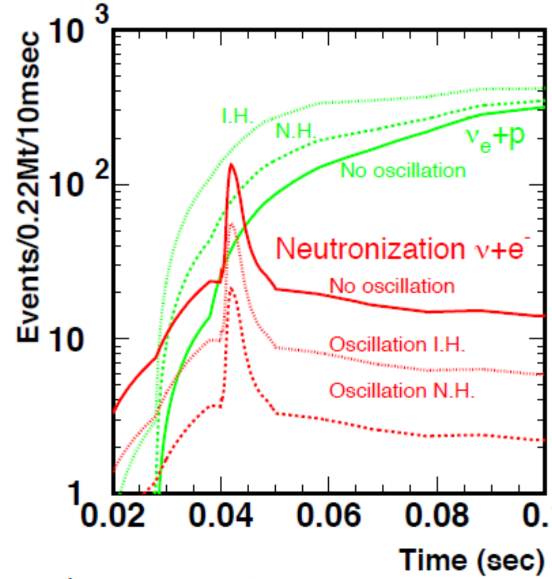
1987A 11 + 8 events





SN@10kpc

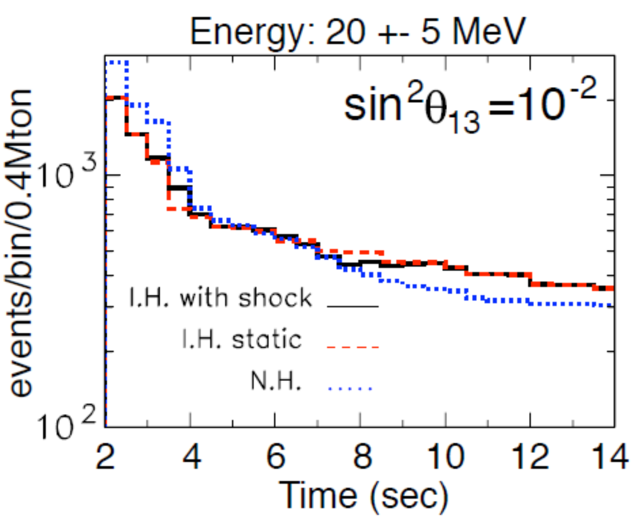
Supernova Neutrinos

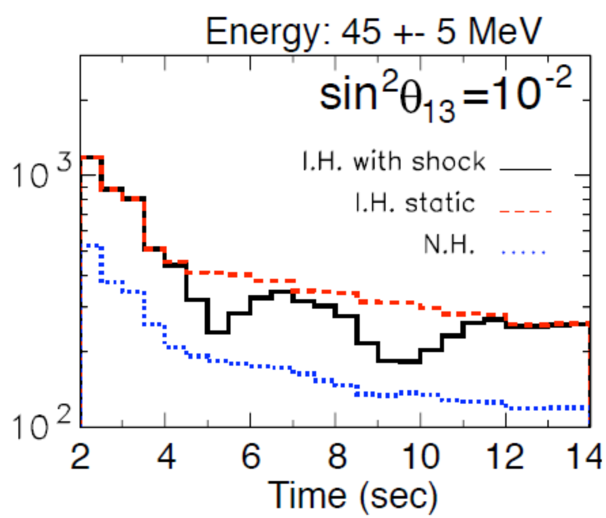


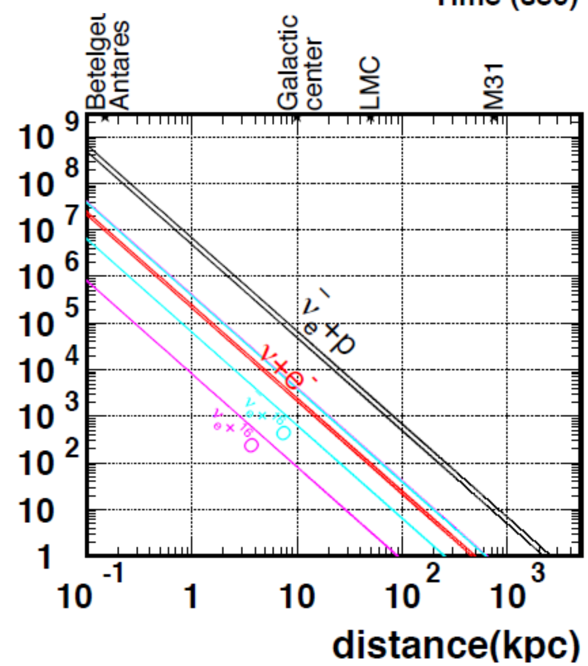
Access to key physics of Supernova explosion

- Explosion physics embedded in neutrino signal
- Neutronization burst clearly visible
- Neutrino shockwave imprinted in time profile

HK expands reach of SN detection to include M31 (~10 events)



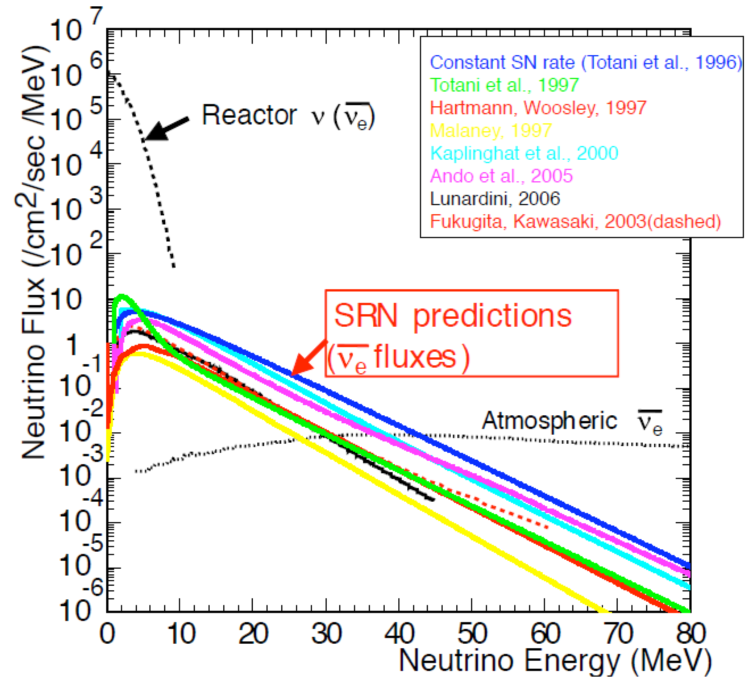


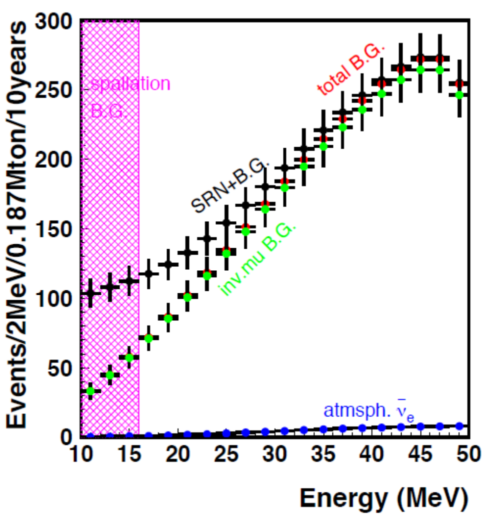


Diffuse Supernova Neutrinos

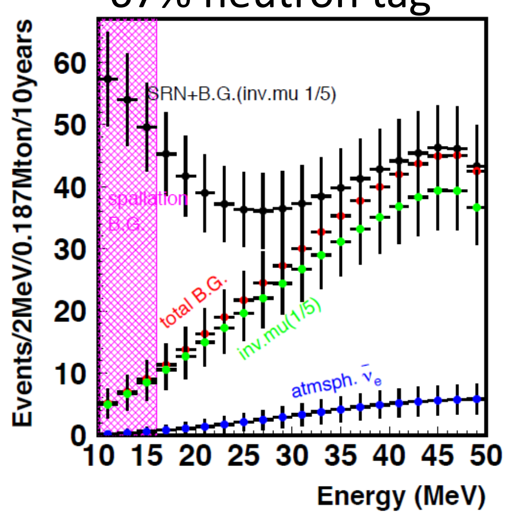
Can also measure the background of neutrinos from all supernova

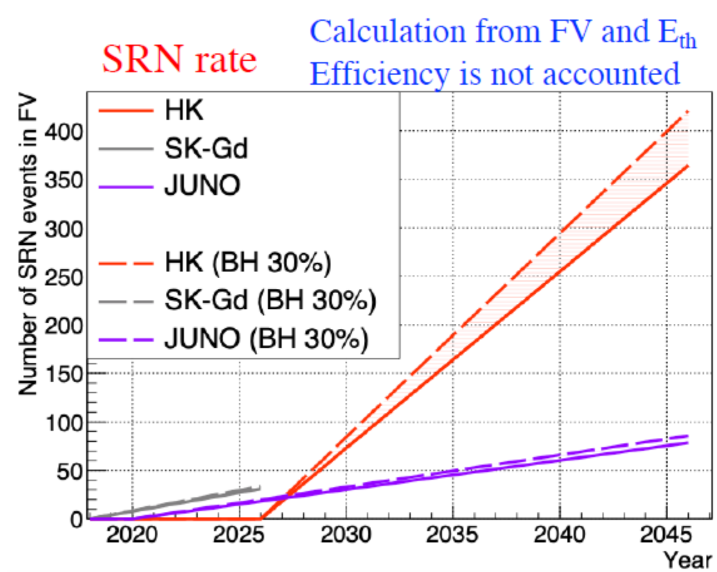
- Rate depends on SN rate vs redshift
- SN physics and cosmological evolution



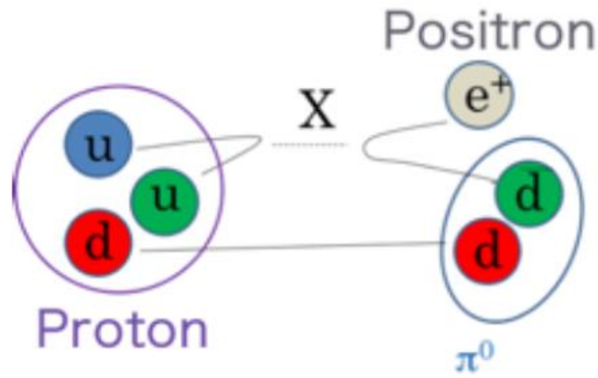


67% neutron tag





Proton decay



Predicted by grand unification theories

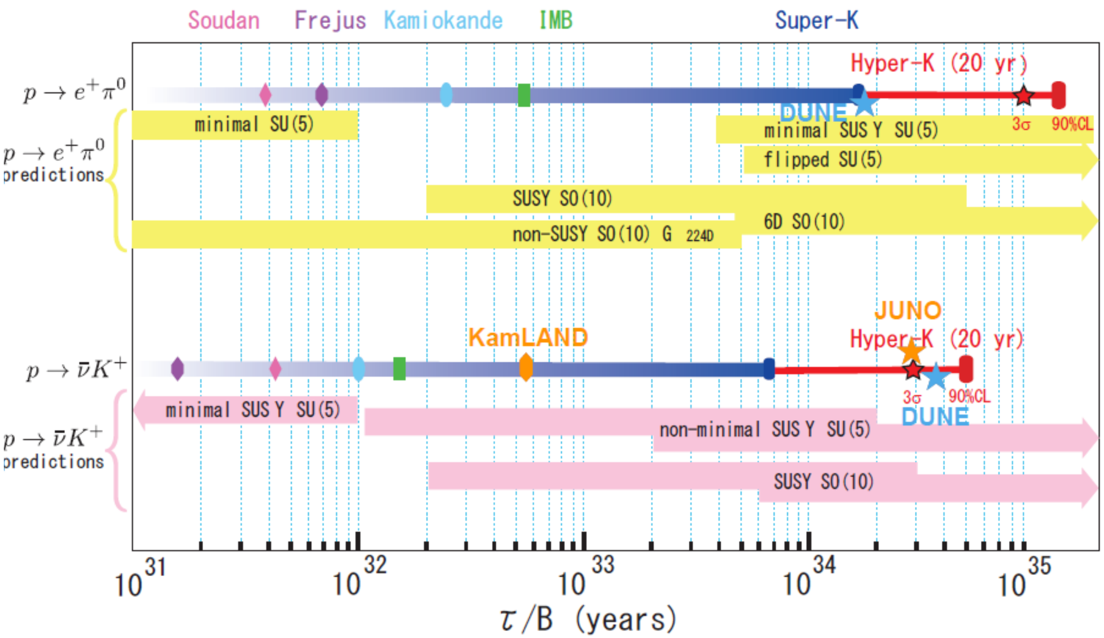
Suppressed by $\frac{1}{M_X^4}$

Many channels but $e^+\pi^0$ and $\bar{\nu}K^+$ are most common

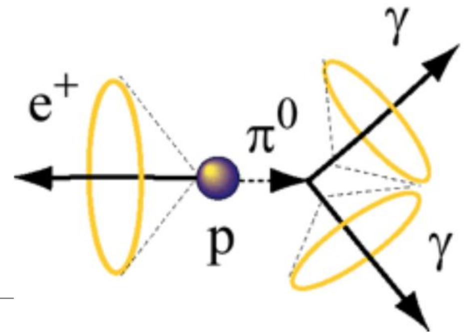
Rate is predicted by various GUT models and many have been rules out.

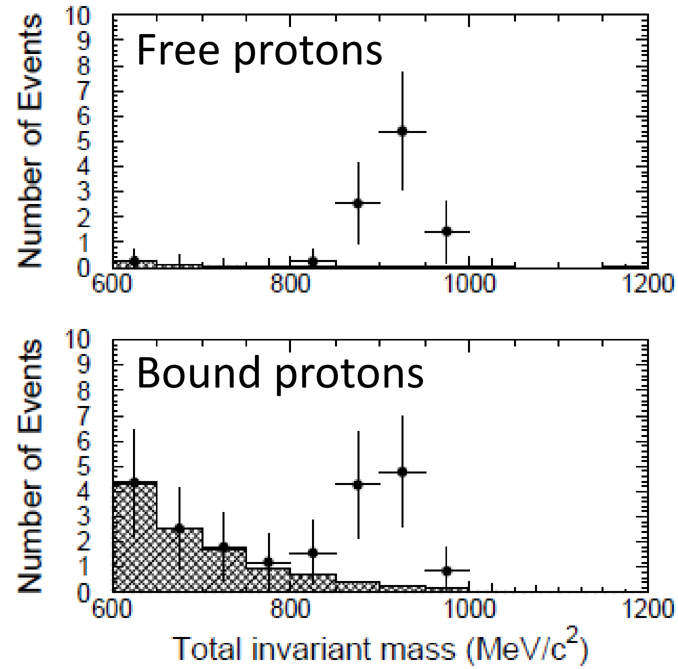
- Target 10^{35} years to significantly increase model coverage

The actual reason Kamiokande and IMB were built!



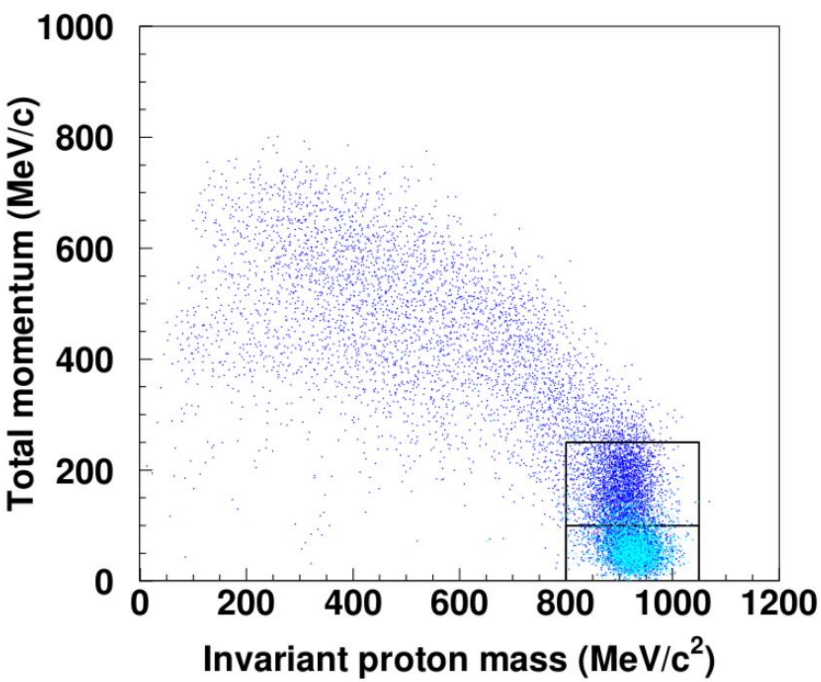
$p \rightarrow e^{+}\pi^{0}$



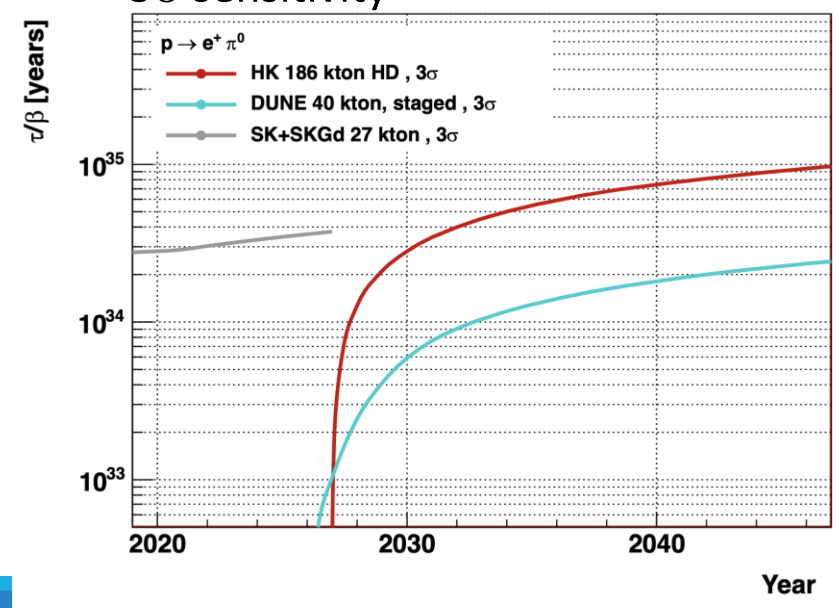


Very clean signal

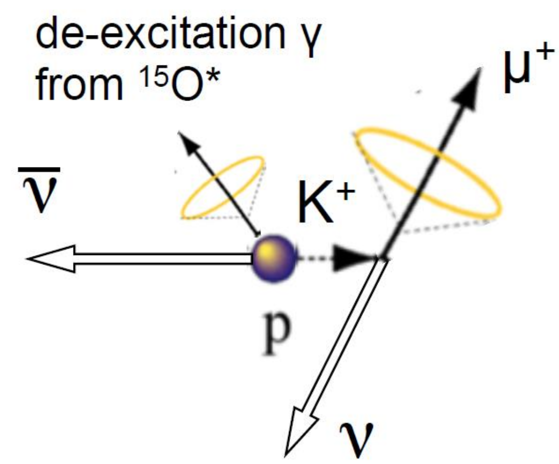
- Background from atmospheric neutrinos reduced by neutron tagging to almost zero in signal box



3σ sensitivity



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

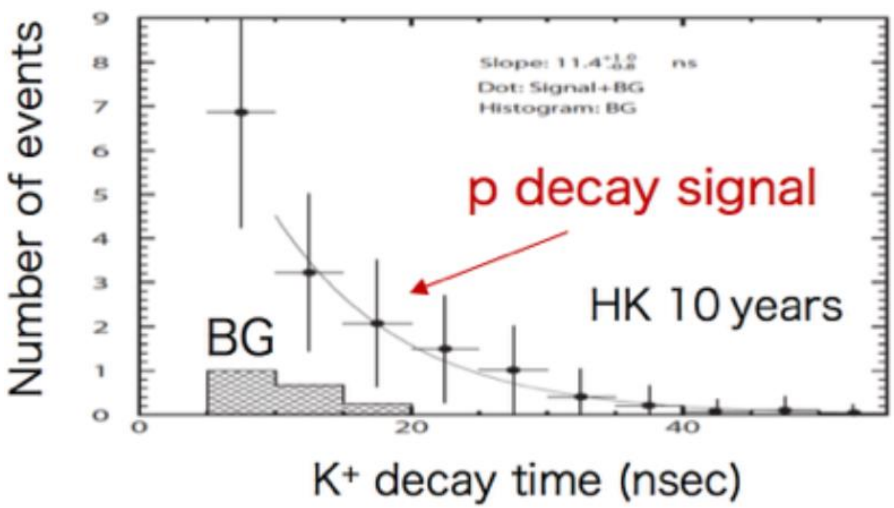


Clean signatures

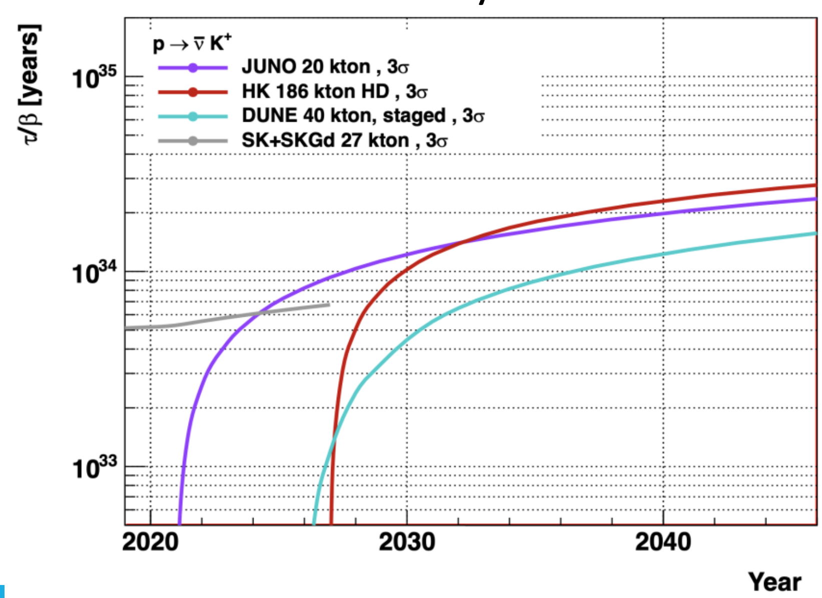
$K^+ \to \mu^+\nu$ (64%) 236 MeV μ^+

decay electron, 6MeV gamma

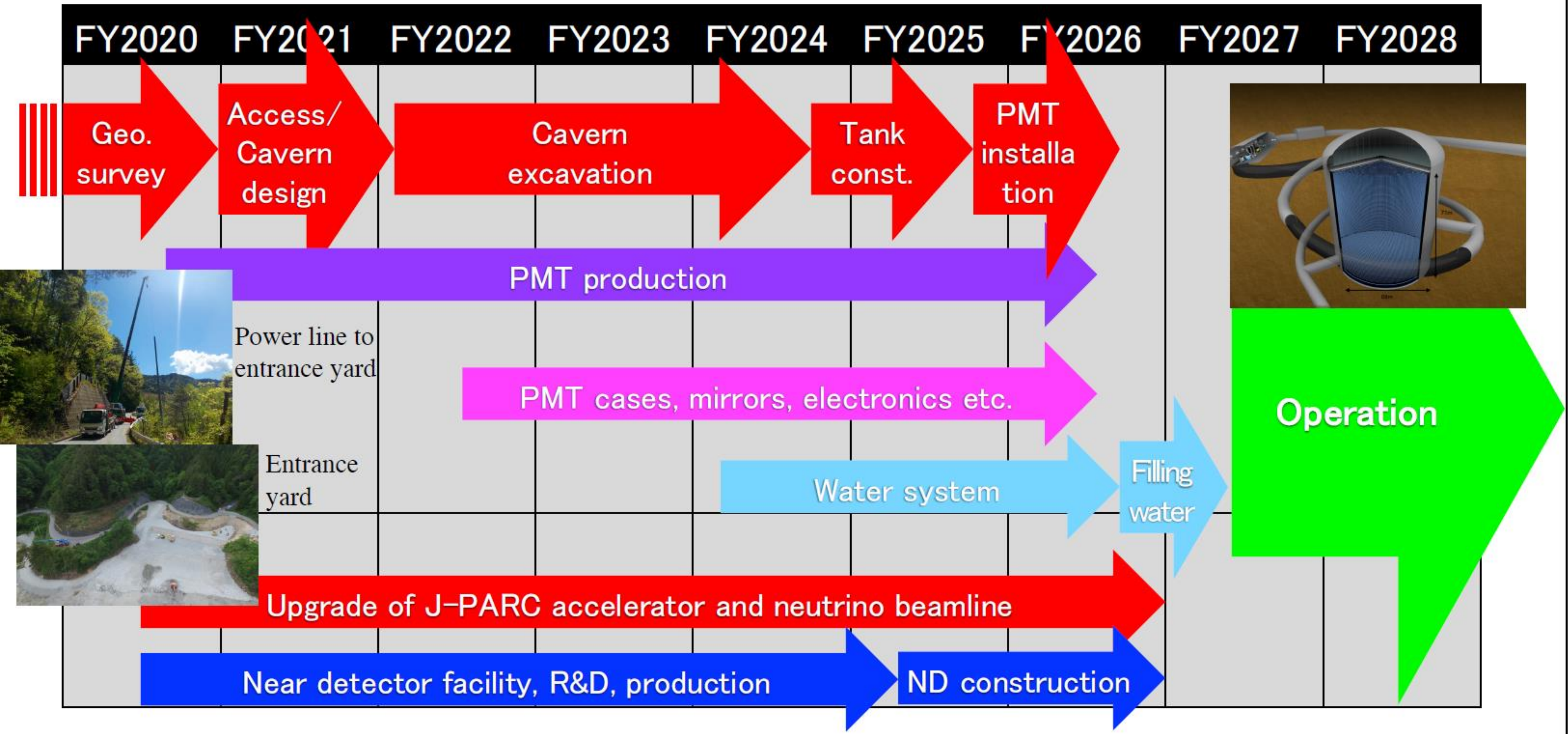
$K^+ \to \pi^+\pi^0$(21%) 205 MeV π^+ back to back



3σ sensitivity



Timeline



FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028
Geo. survey
Access/ Cavern design
Cavern excavation
Tank const.
PMT installation
PMT production
Power line to entrance yard
PMT cases, mirrors, electronics etc.
Entrance yard
Water system
Filling water
Operation
Upgrade of J-PARC accelerator and neutrino beamline
Near detector facility, R&D, production
ND construction

Summary

The project is approved and construction has started

- First data due 2027

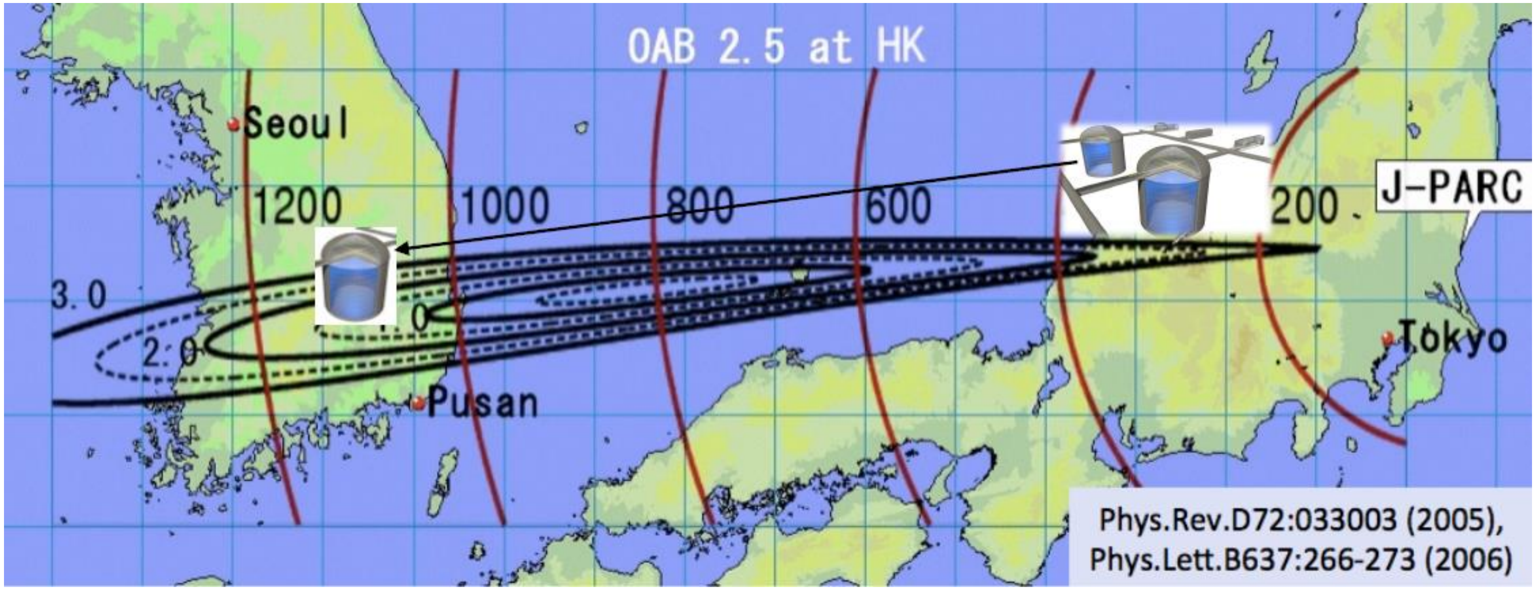
The Hyper-Kamiokande experiment has a wide physics program of

- Neutrino Oscillations
- Super nova neutrinos
- Proton Decay
- + dark matter, geo neutrinos, …..

A second tank in Korea?

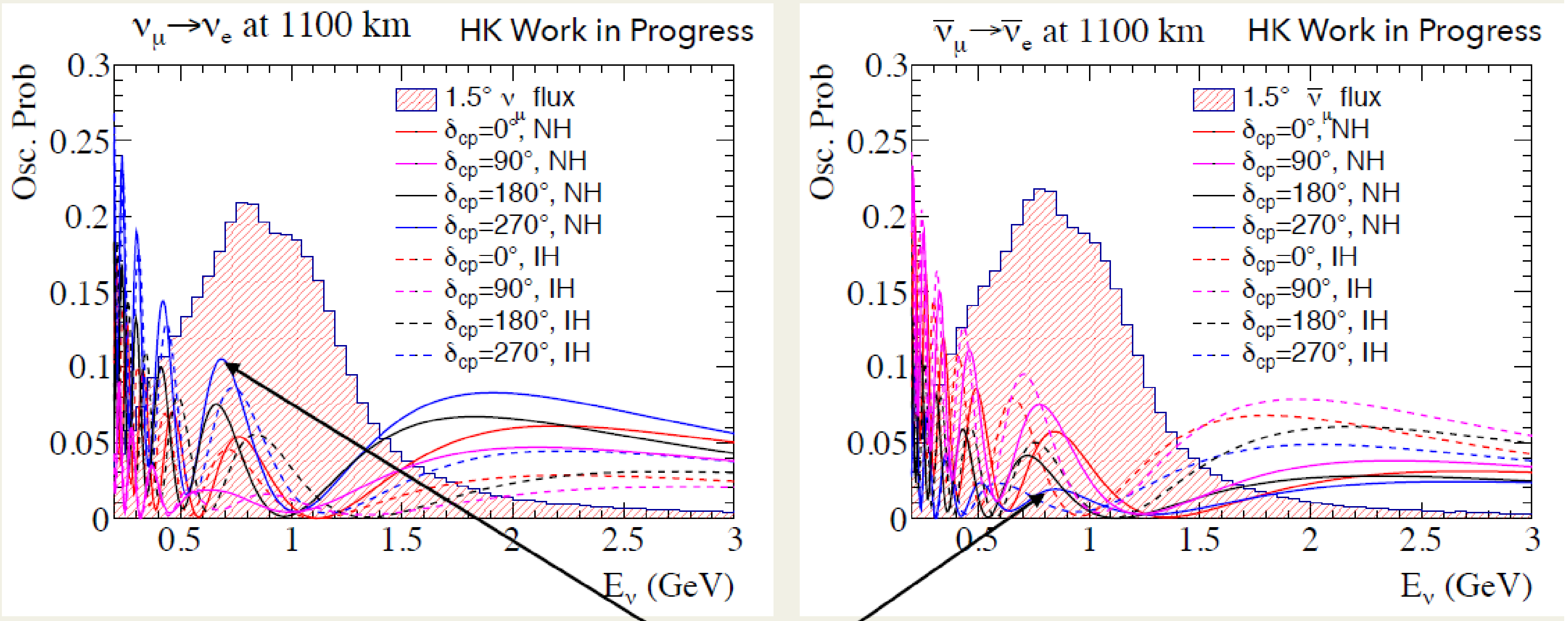
Longer baseline, but same energy

- Examine second oscillation maximum
- Increased sensitivity and dependence on the extra terms in oscillation probability
- More sensitivity to physics.



Second Oscillation Maximum

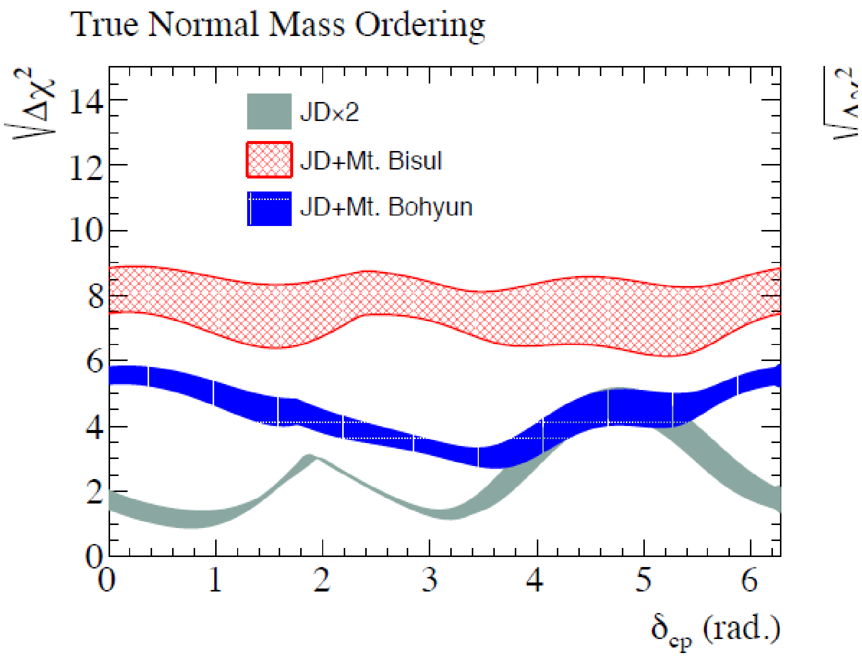
At a baseline of ~1100 km and energy of ~700 MeV, the detector in Korea will probe the second oscillation maximum

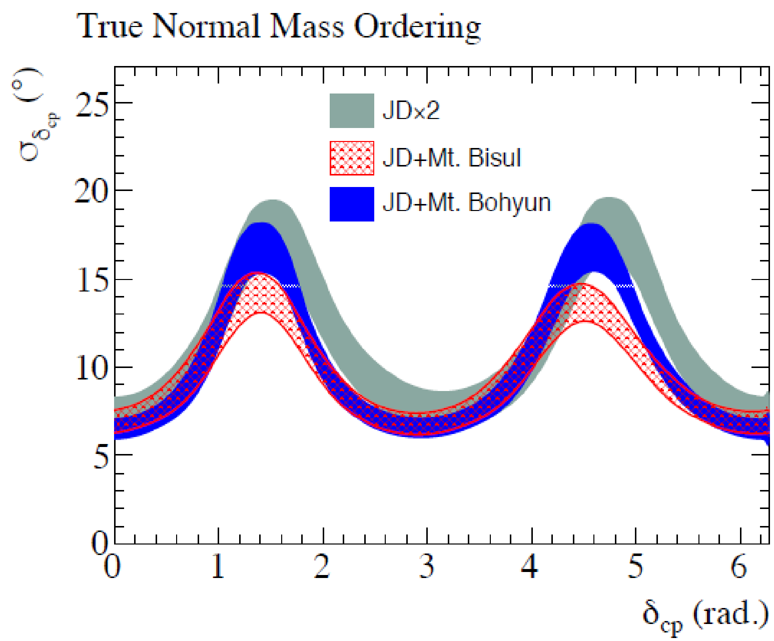


The CP asymmetry between neutrinos and antineutrinos is about 3 times larger at the second oscillation maximum

Compensates for factor of 3.7 reduction in statistical significance due flux reduction to longer baseline

Physics Potential





Similar results for inverted hierarchy

Band width depends on θ_{23}.