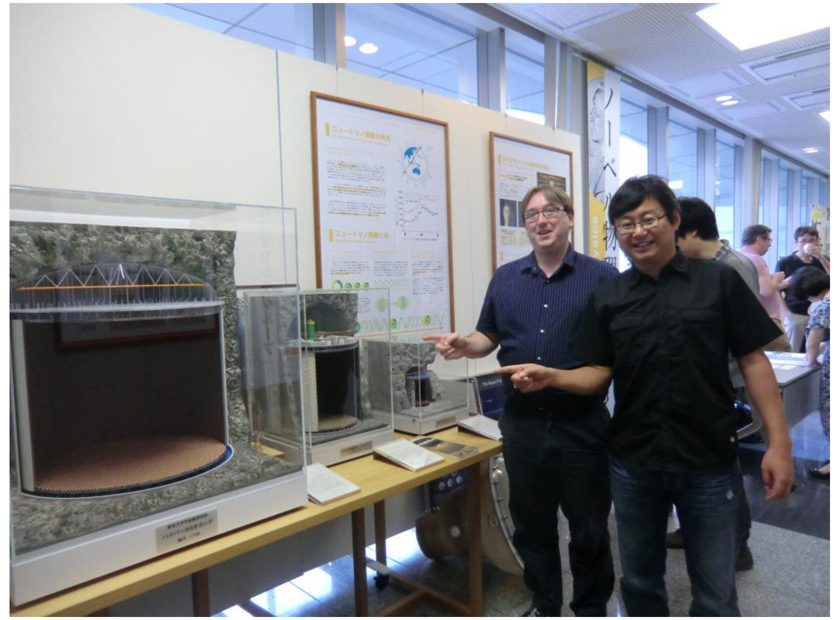
Hyper Kamiokande



NEIL MCCAULEY

UNIVERSITY OF LIVERPOOL

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

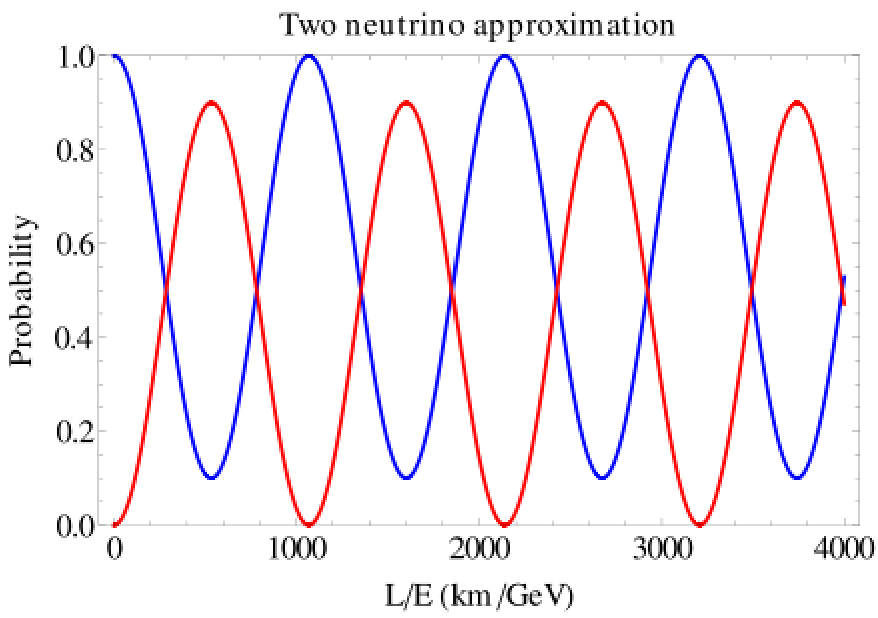
Neutrino Oscillations

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



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

Neutrino Physics

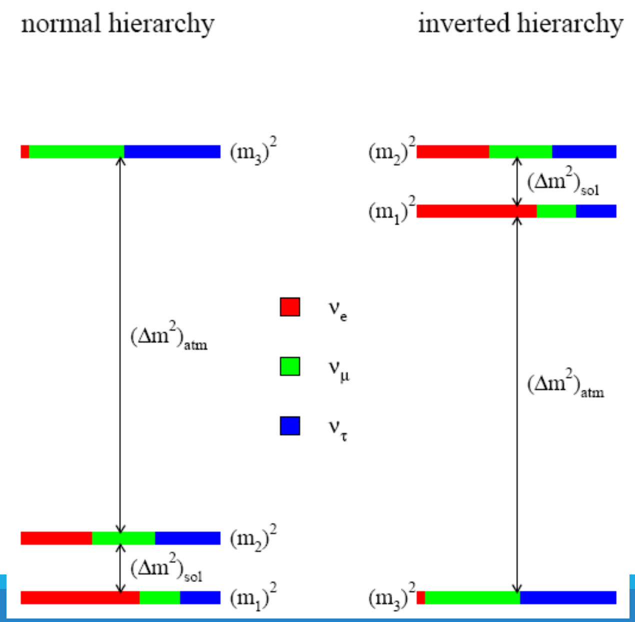
Neutrino mixing is characterised by the PMNS matrix.

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

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



Neutrino Oscillations from ν_μ to ν_e

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

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

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

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

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

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

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

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.

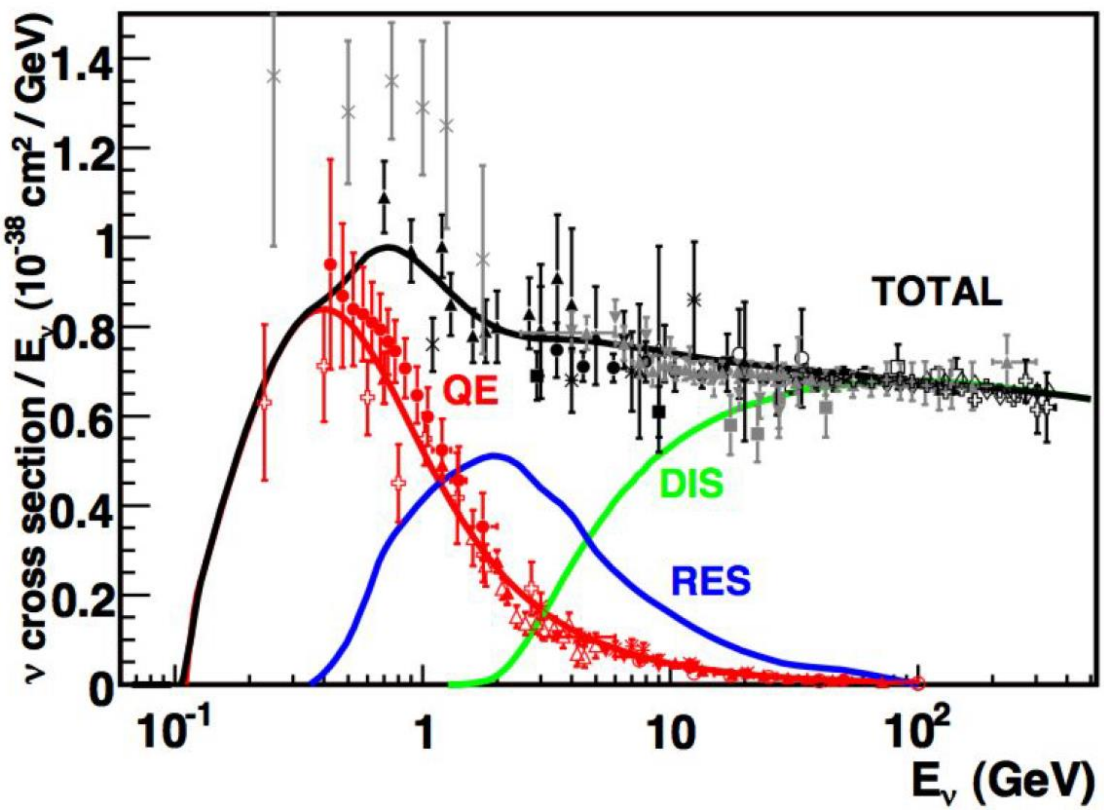
- It varies dramatically as energy rises past 1 GeV.

< 1 GeV Quasi-Elastic interactions

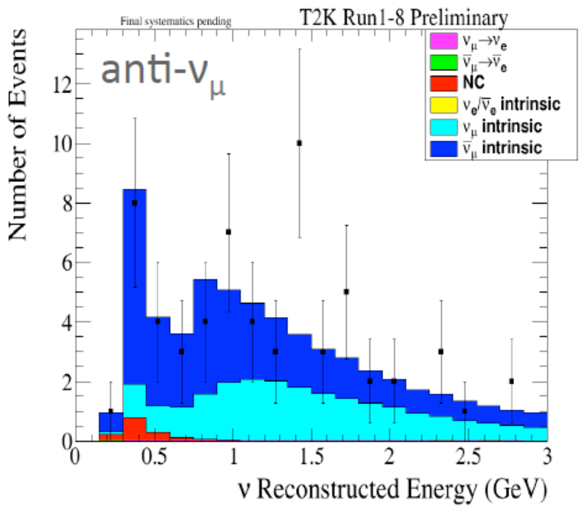
- Reconstruct neutrino energy from lepton kinematics
- Systematics due to incomplete nuclear models (e.g. 2p2h)

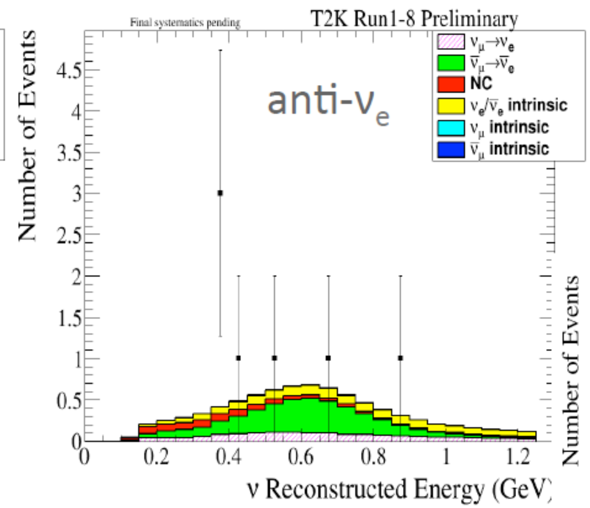
> 1 GeV Resonance -> DIS

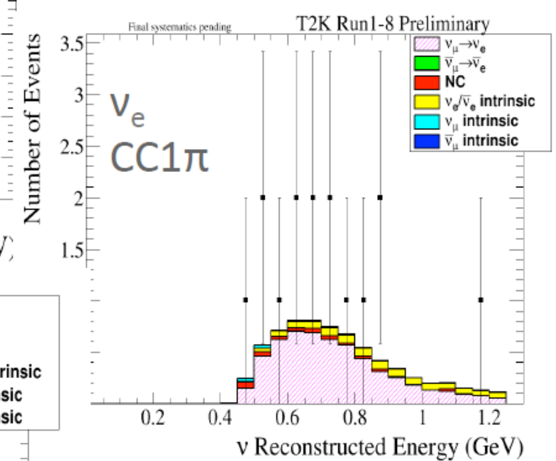
- Multi particle final states
- Need to reconstruct everything to determine neutrino energy

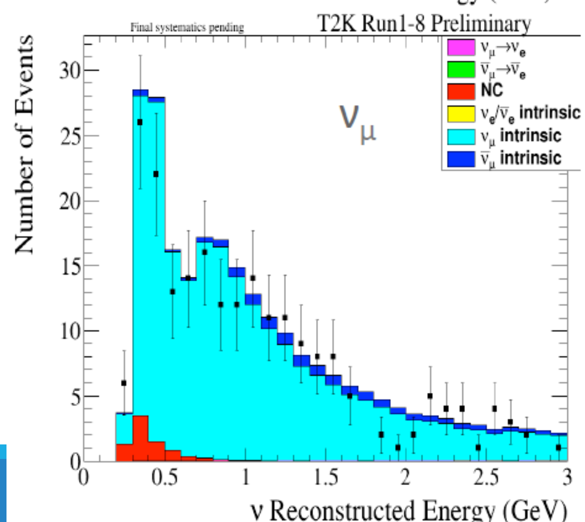


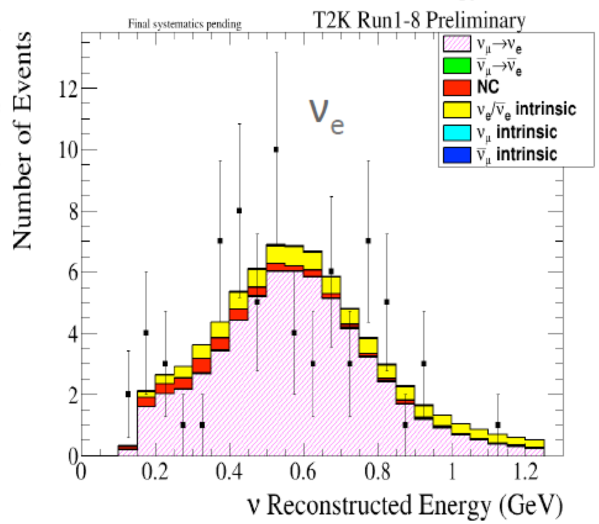
State of play: T2K Results



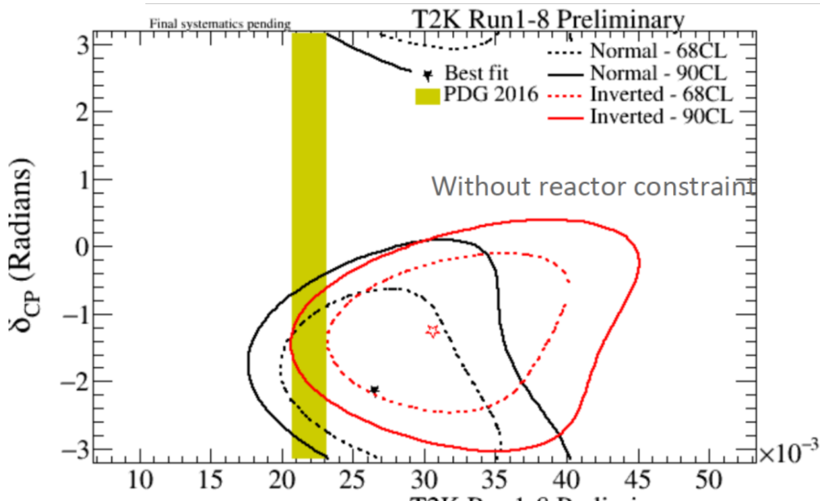


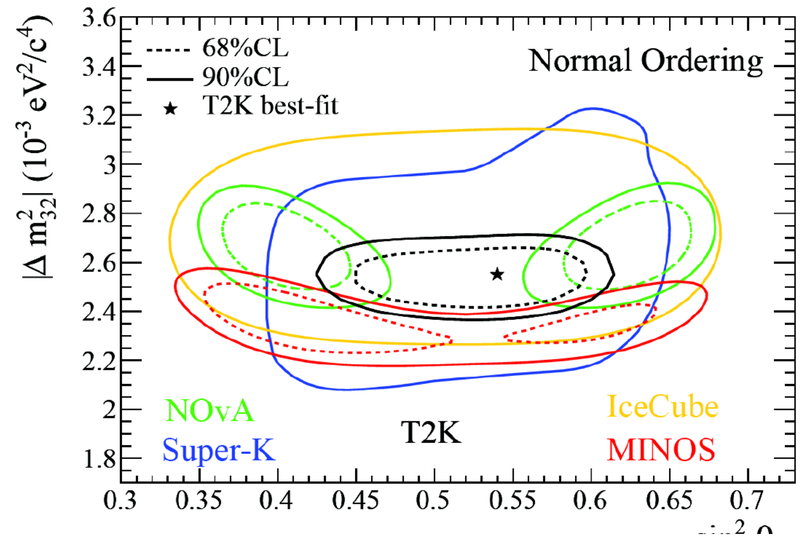


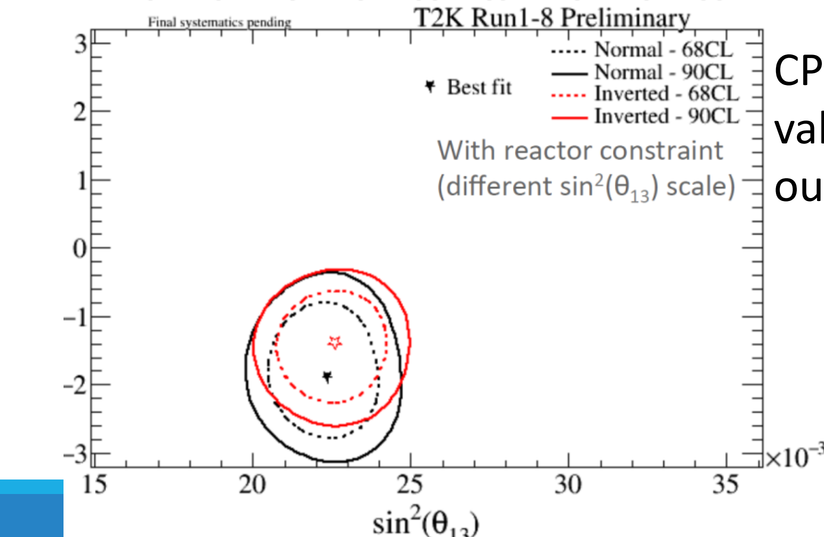




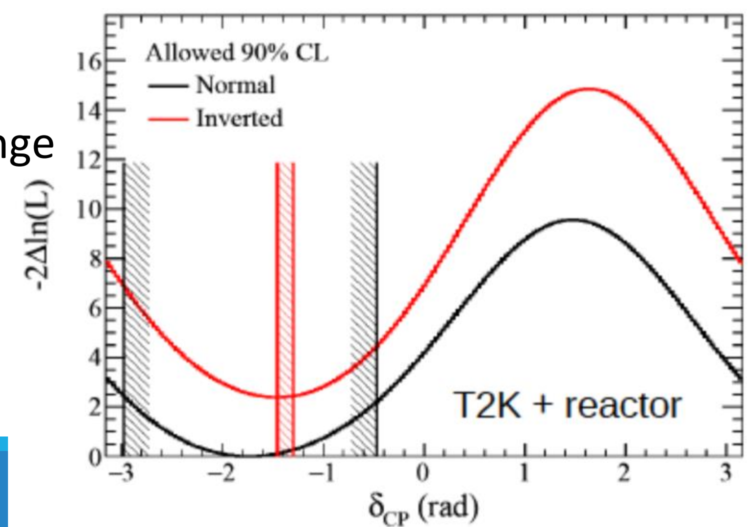
State of play: T2K Results



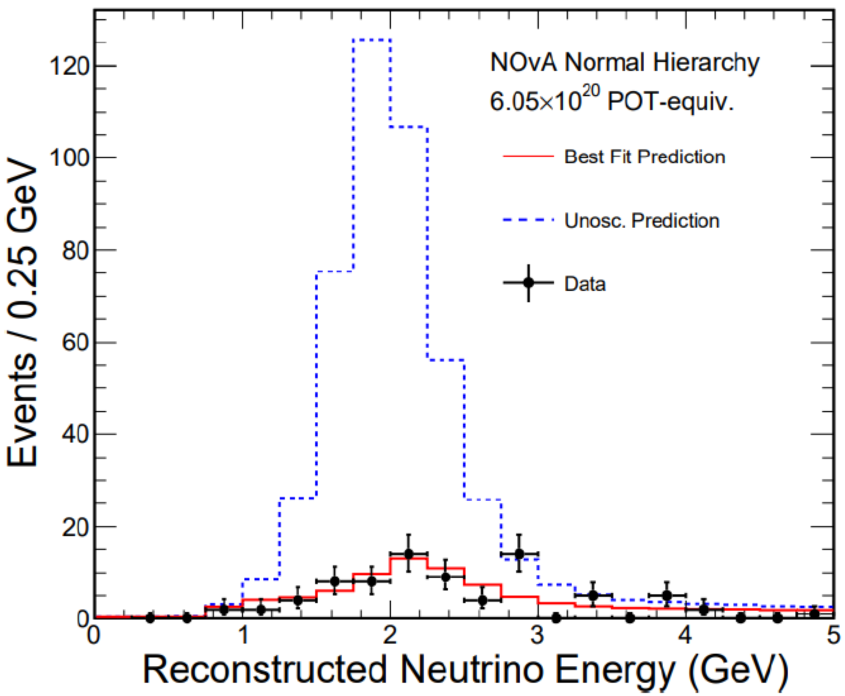


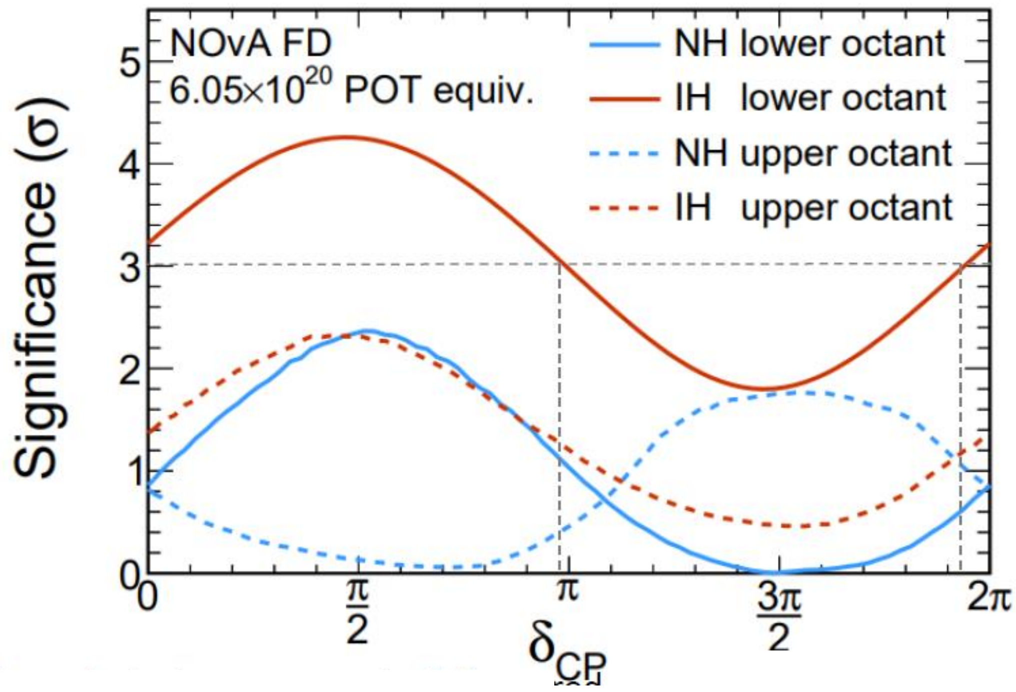


CP conserving values $(0,\pi)$ outside 2 σ range



State of play: Nova





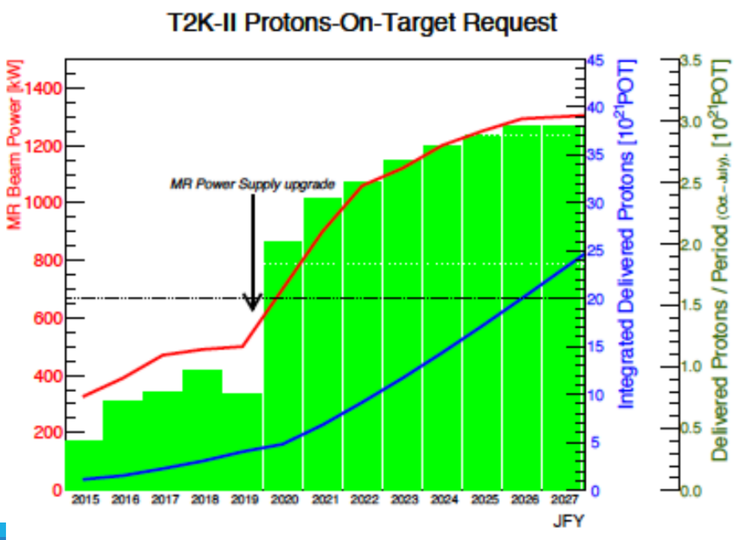
Prospects: 2025

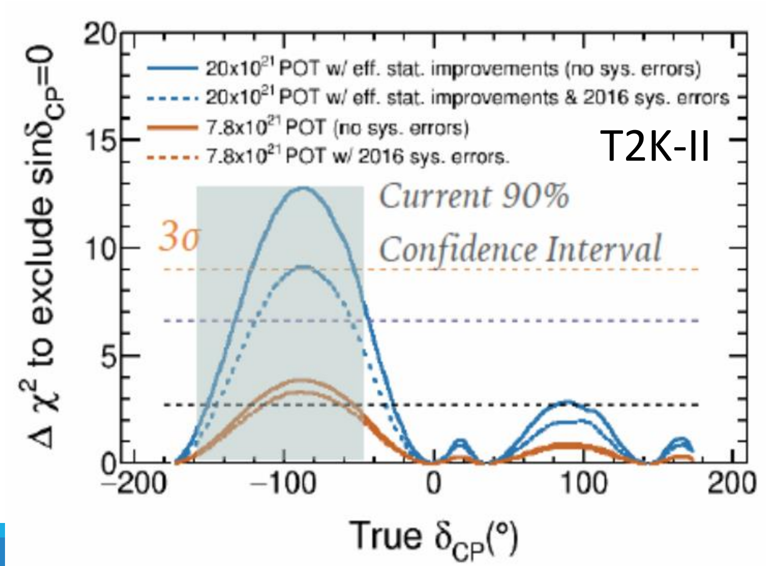
Continued T2K and Nova running.

- Significantly increased statistics, but even optimistically won't get CP discovery (5σ)
- Precision measurement no possible

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

- Potential to discover mass hierarchy at 3σ level.





HK Proto-Collaboration

15 Countries

300 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.

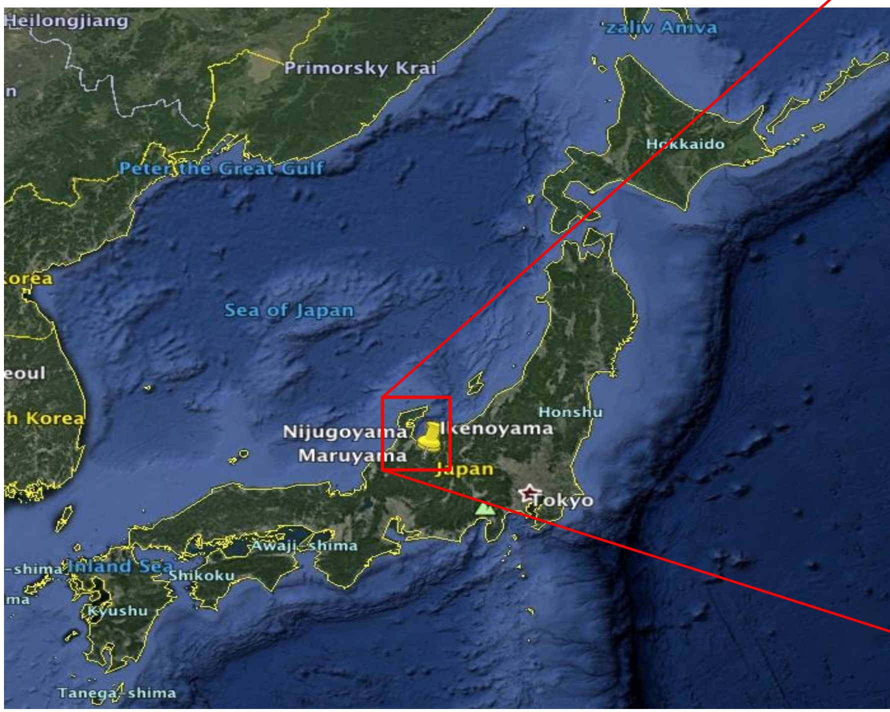
Hyper-K Detector

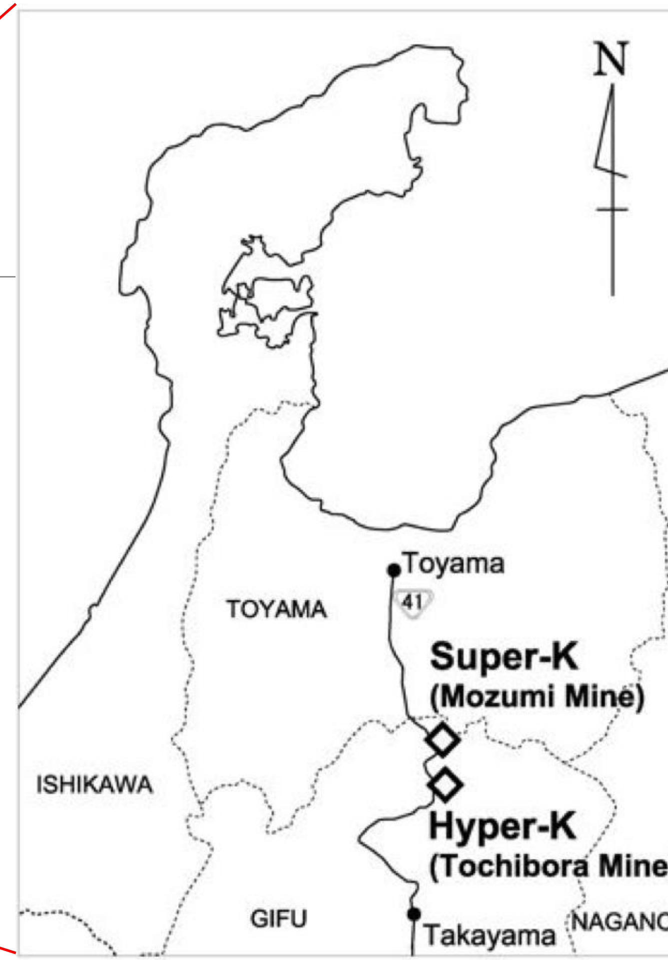
	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**×2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

~10 Fiducial Mass

High PDE photosensors and low background to maintain low energy physics and enhance physics sensitivities.

Detector Site

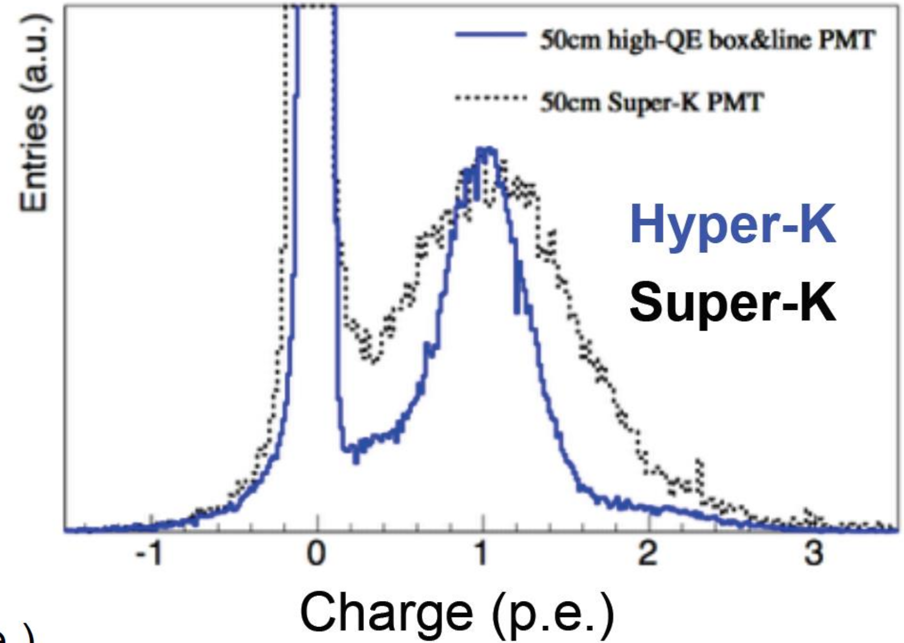




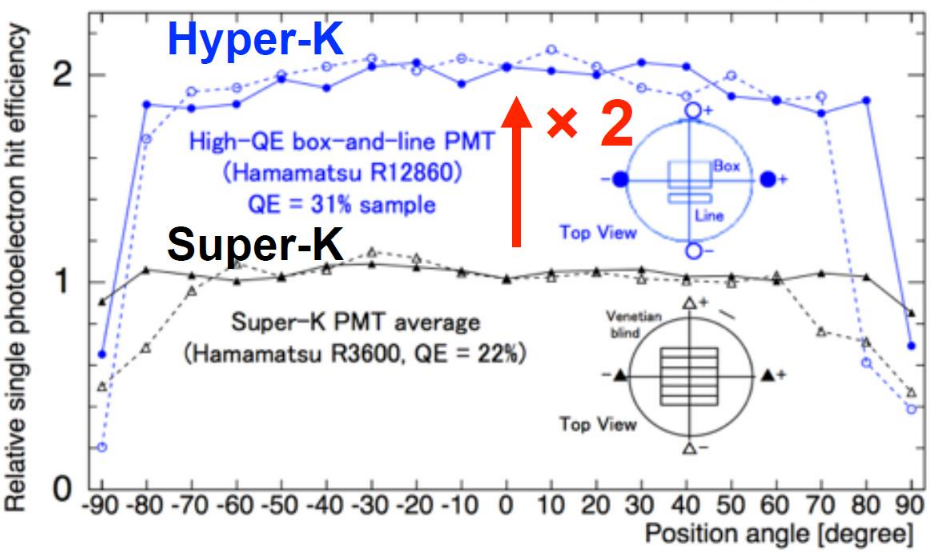
The candidate site is located under Mt. Nijugo-yama
~8km south from Super-K
Identical baseline (295km) and off-axis angle (2.5deg) to T2K
Overburden ~650m (~1755 m.w.e.)

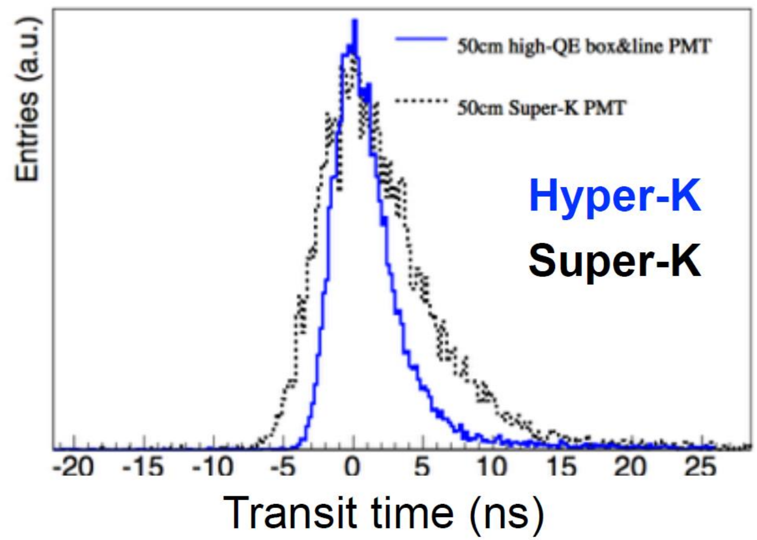
Photosensors

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

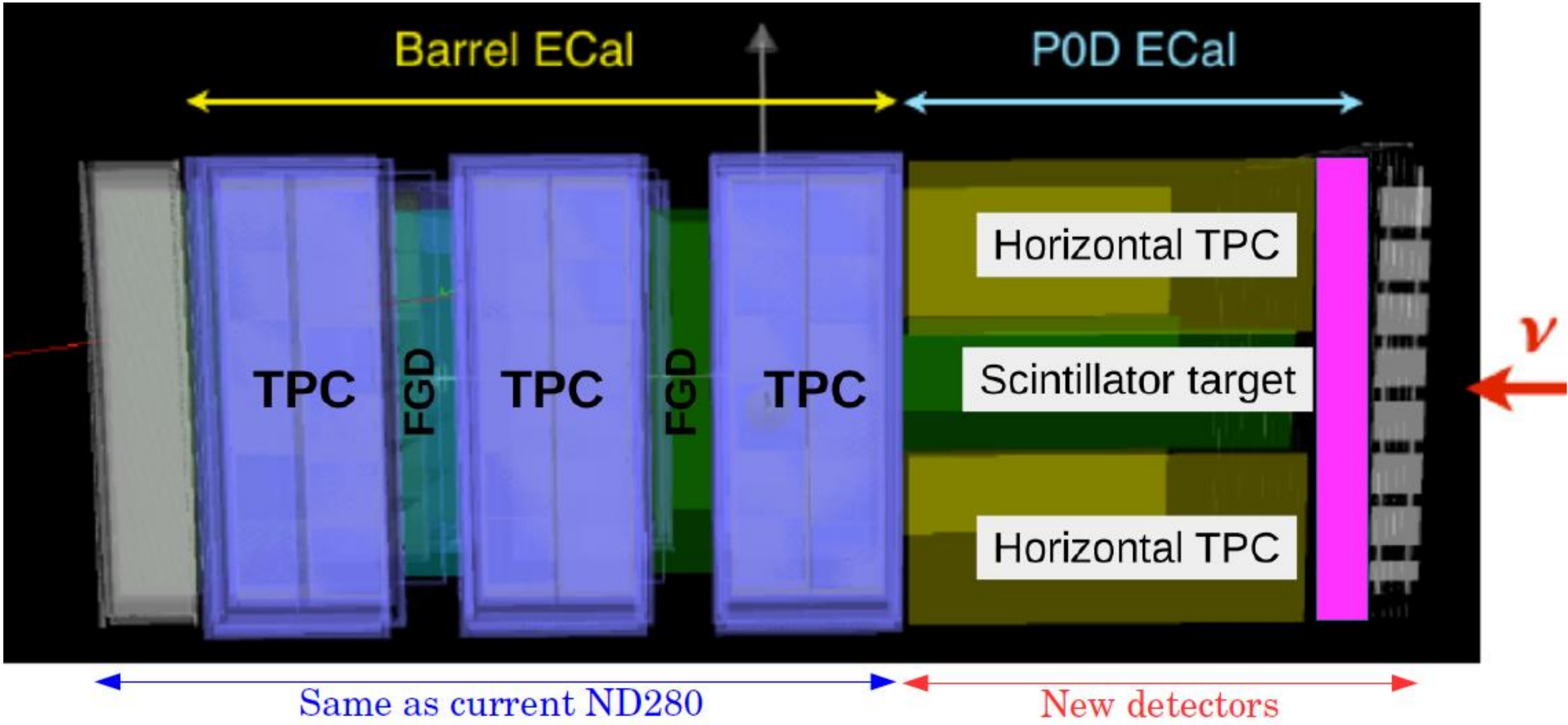


relative photo detection efficiency (p.e.)

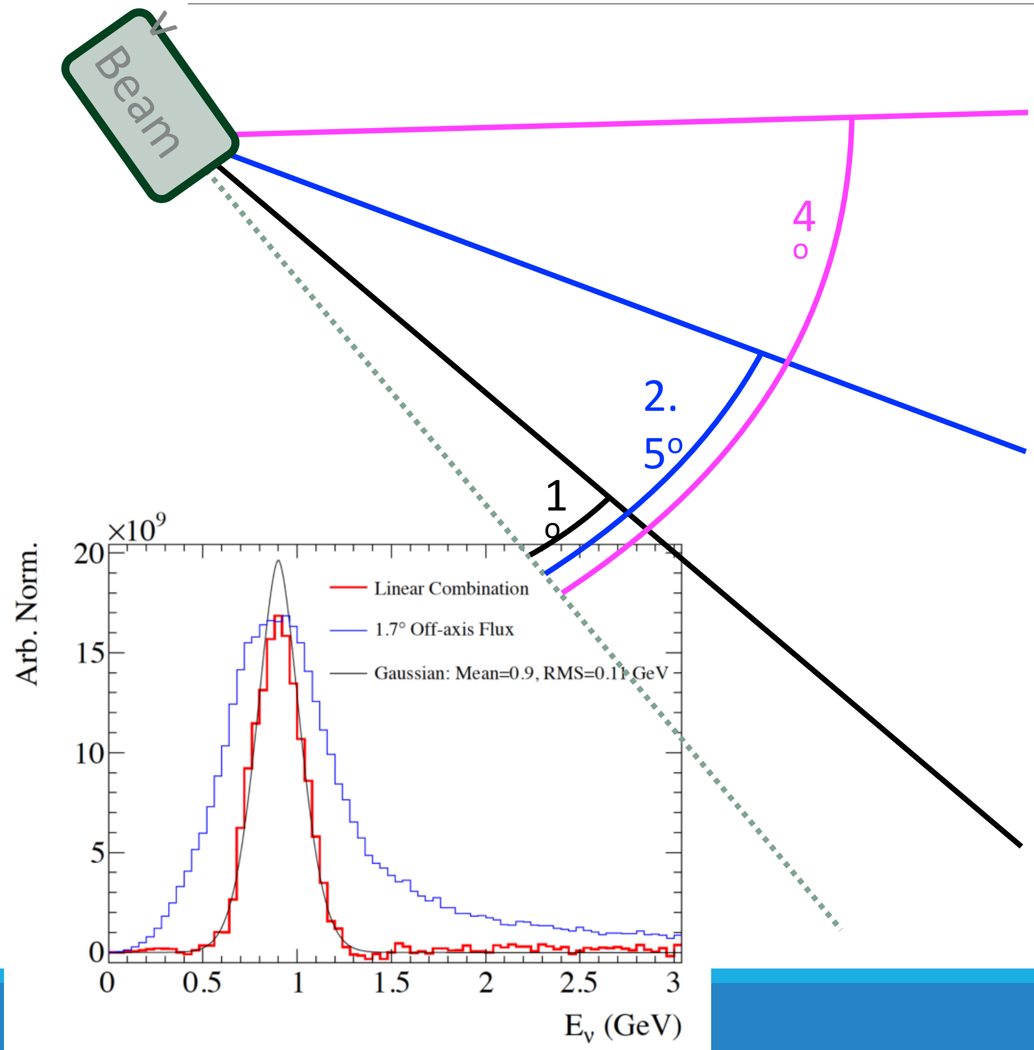


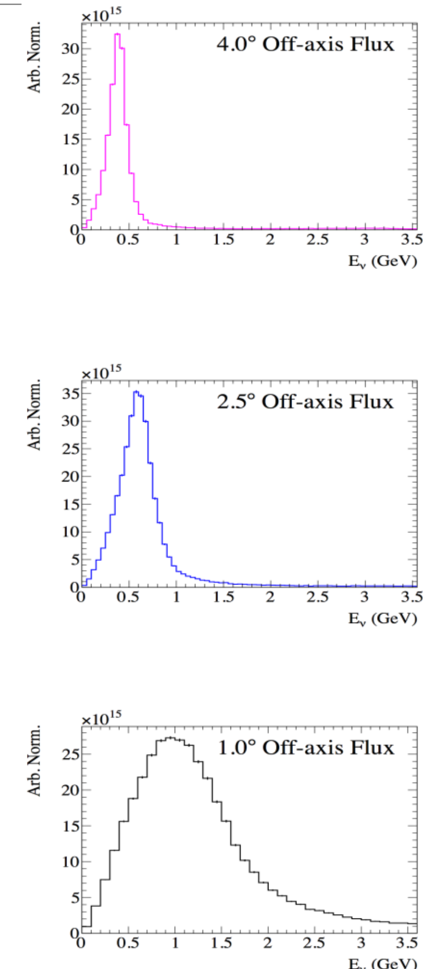


Near Detector Upgrade



Intermediate detector



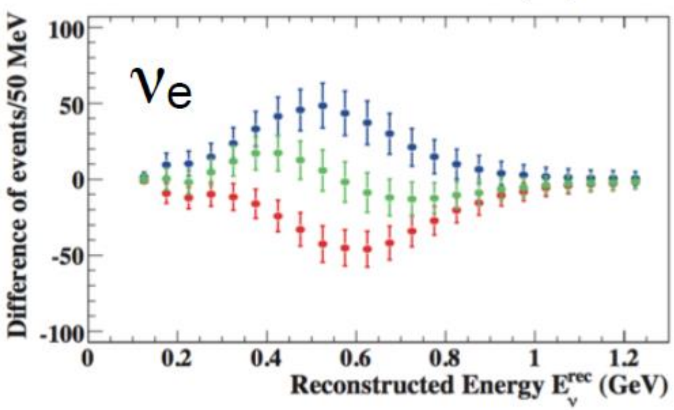


Oscillation Signal

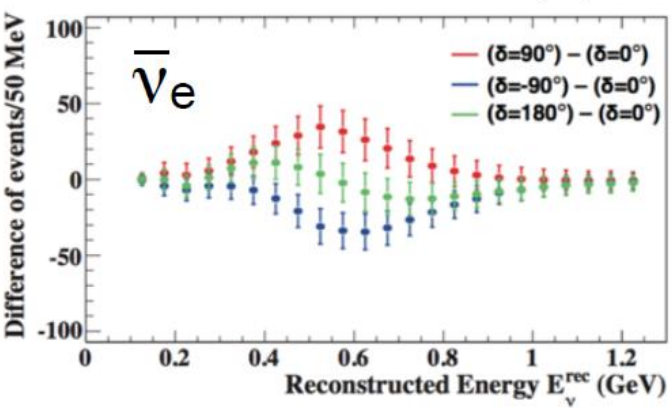
expected number of event in ν_e / $\overline{\nu}_e$ appearance (10 years)

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	$\boxed{1643}$	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	$\boxed{1183}$	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

difference of reconstructed E_ν spectra

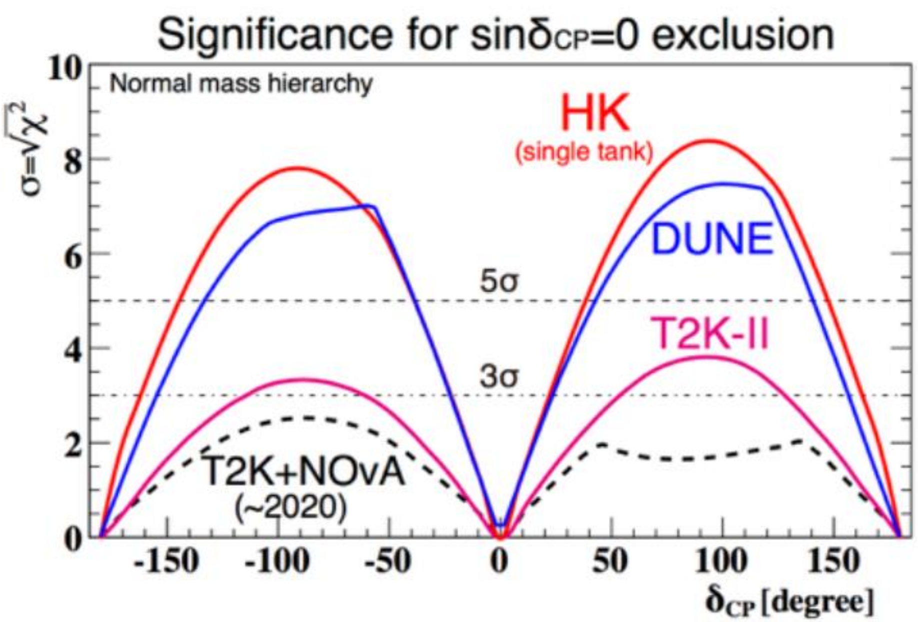


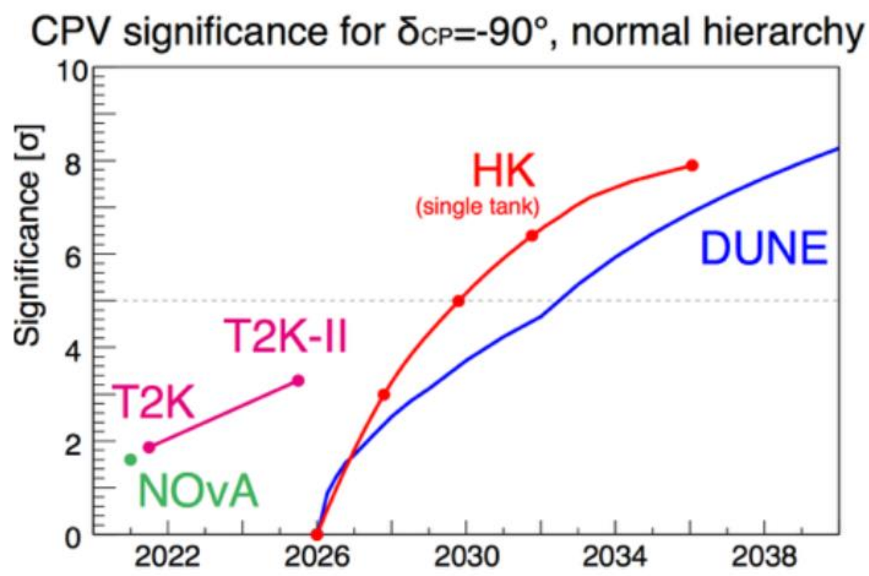
difference of reconstructed E_ν spectra



1.3 MW x 10 years $\nu : \bar{\nu} = 1:3$

CP Violation Sensitivity





CP violation observed at 5σ for 58% of parameter space

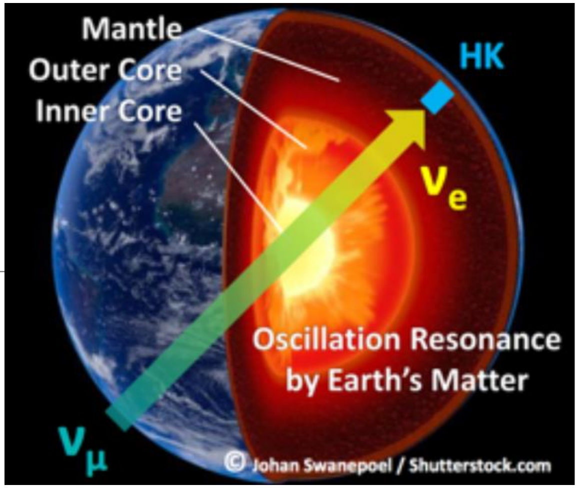
Uncertainty on δ_{CP}

$$\sim 22° \; for \; \delta_{CP} = \pm\frac{\pi}{2}$$

$$\sim 8° \; for \; \delta_{CP} = 0, \pi$$

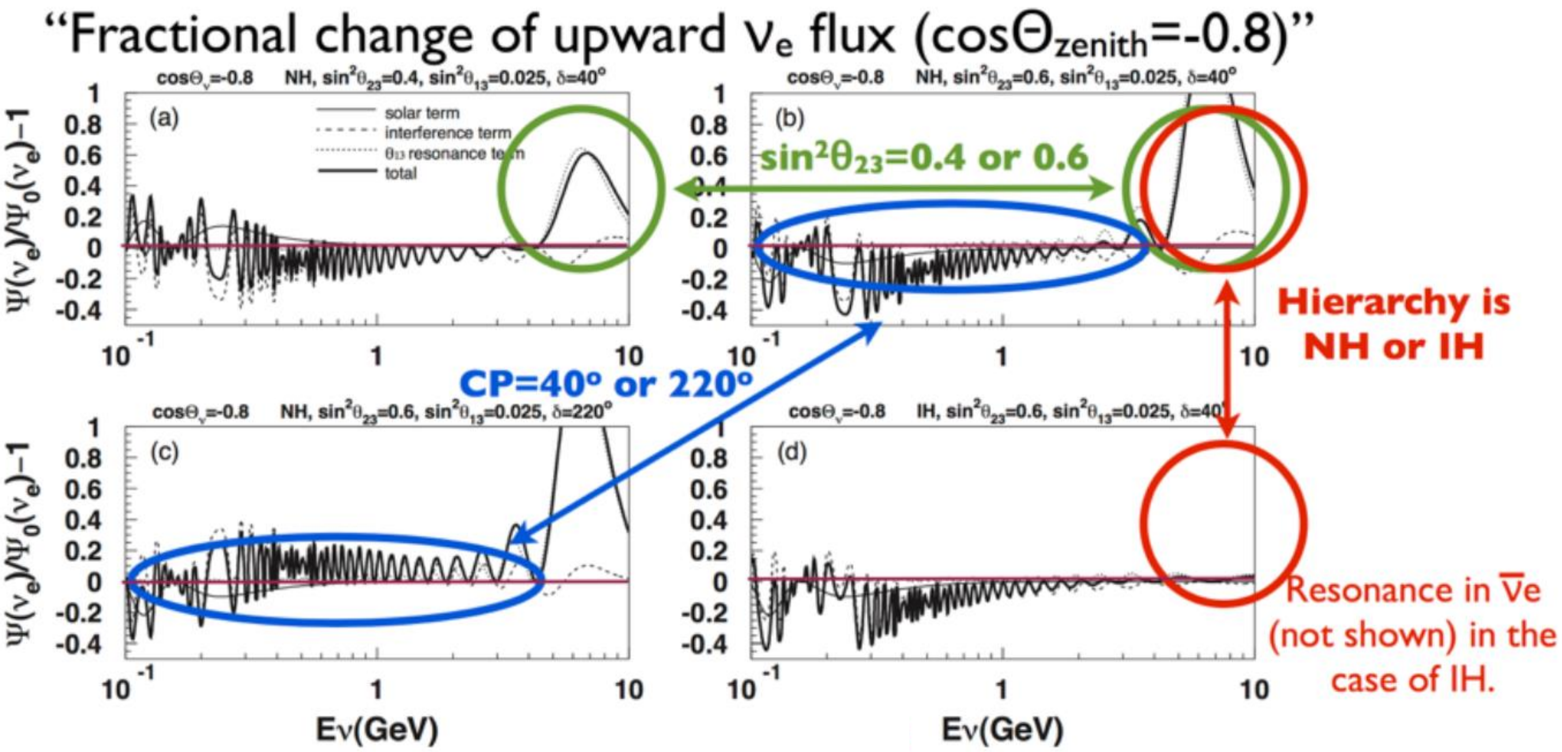
Assuming 3-4% uncertainty (T2K is 5-6%)

Atmospheric Neutrinos



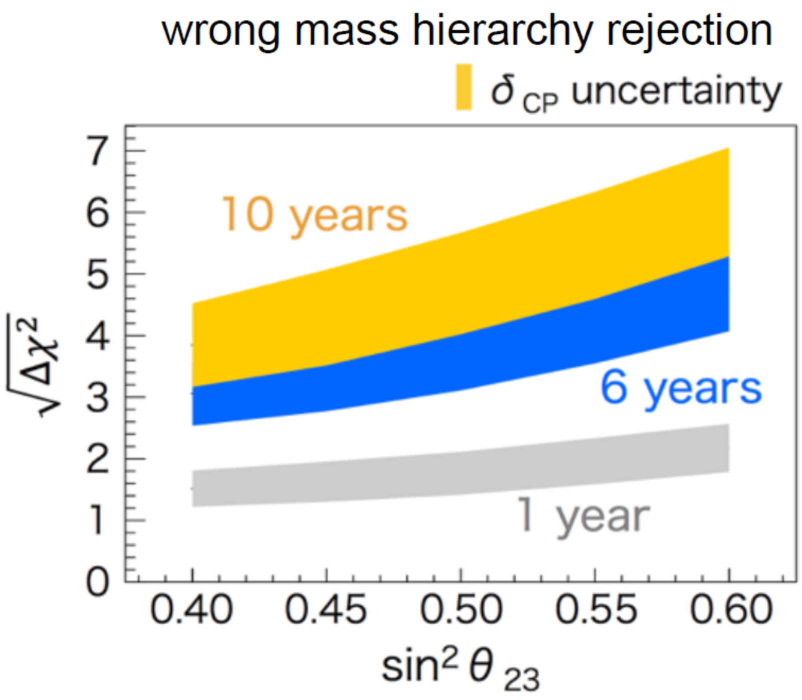
Exploit the matter effect for atmospheric neutrinos as they pass thought the mantle and core

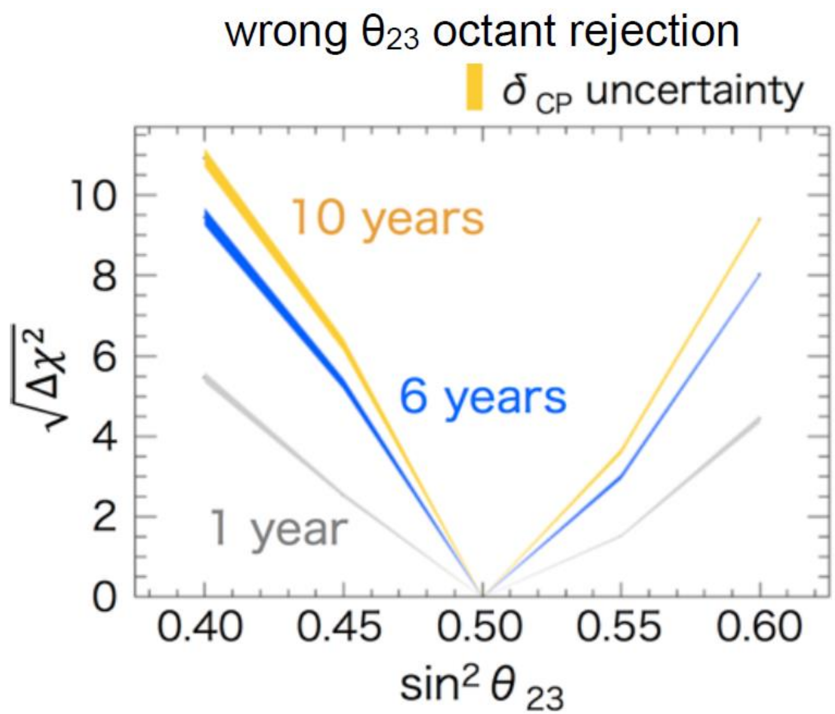
Sensitivity to mass hierarchy, δ_{CP} and octant



Mass Hierarchy and Octant

Combination of beam + atmospherics gives powerful increase in sensitivity and scope of measurements.

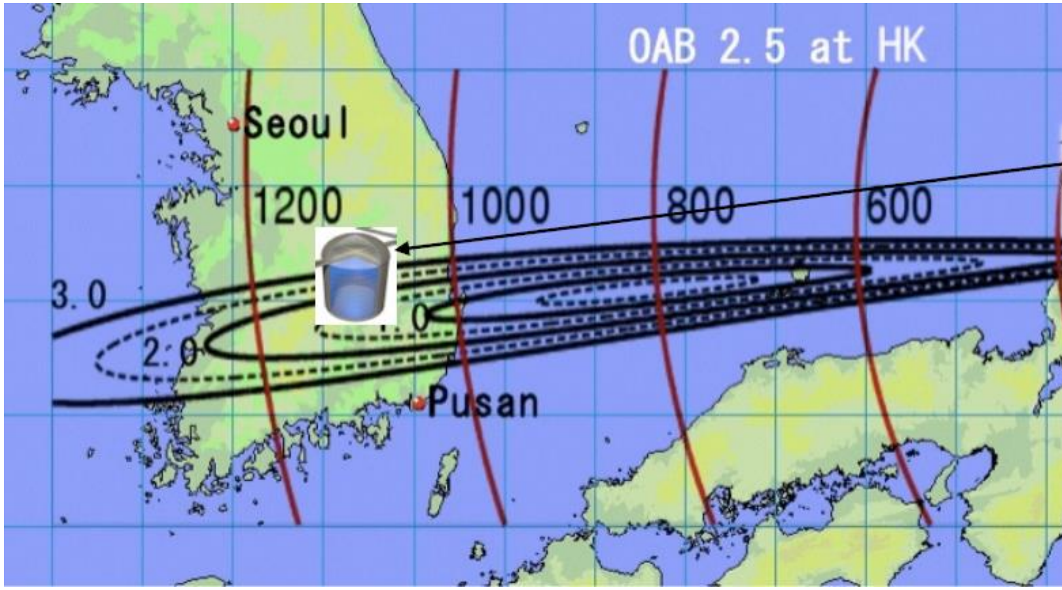




A second tank in Korea?

Longer baseline, but same energy

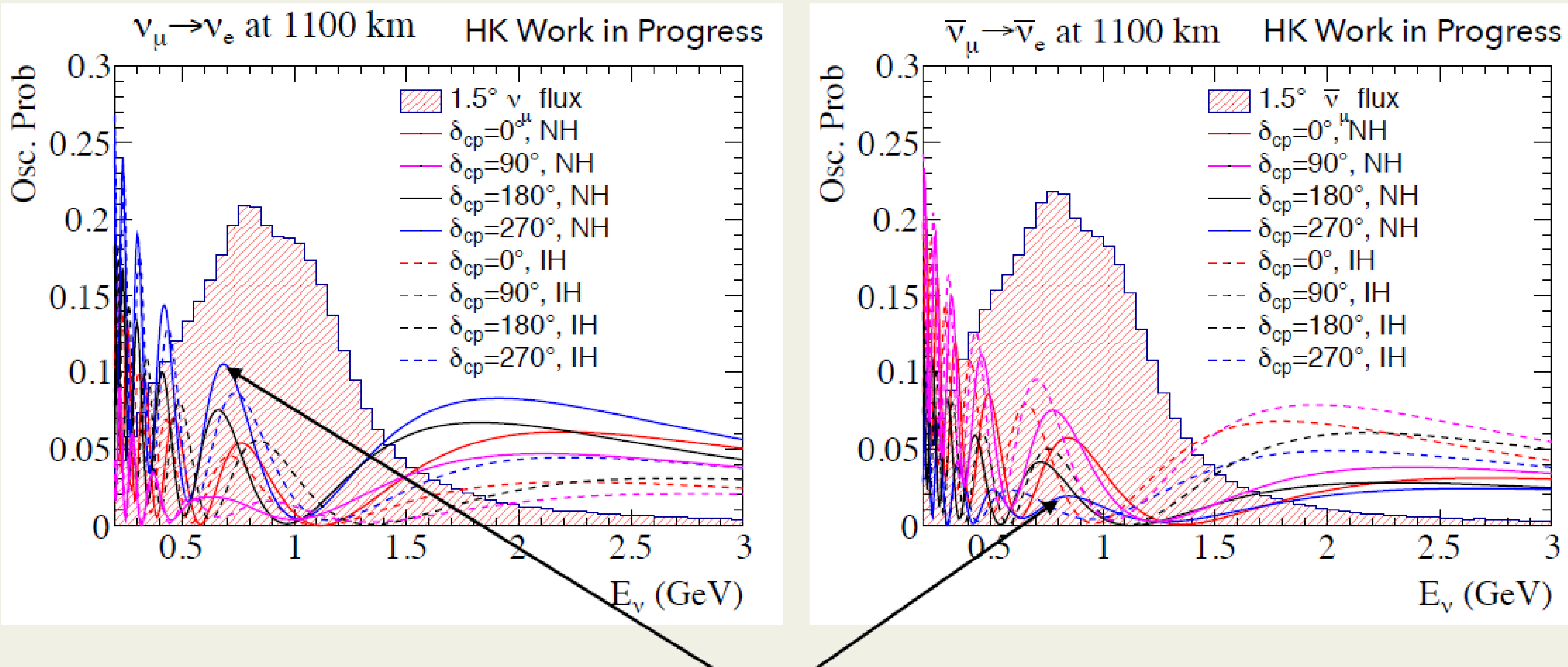
- Examine second oscillation maximum
- Increased sensitivity and dependence on the extra terms in oscillation probability
- More sensitivity to physics.



Phys.Rev.D72:033003 (2005), Phys.Lett.B637:266-273 (2006)

Second Oscillation Maximum

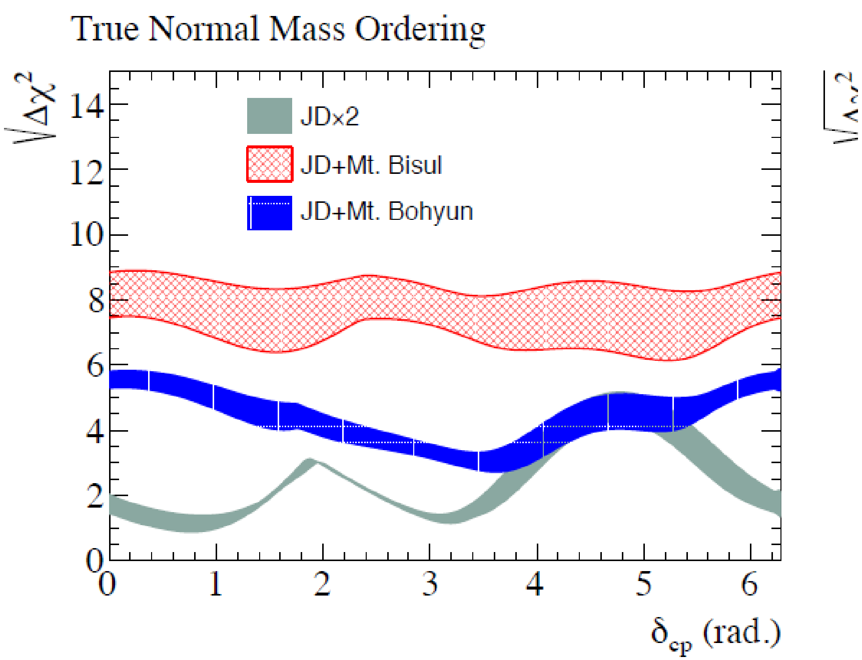
At a baseline of ~1100 km and energy of ~700 MeV, the detector in Korea will probe the second oscillation maximum

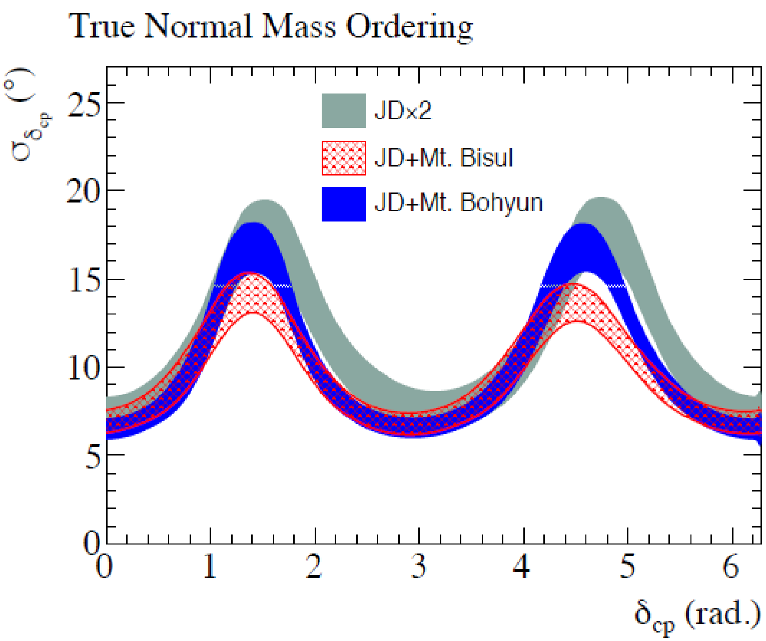


The CP asymmetry between neutrinos and antineutrinos is about 3 times larger at the second oscillation maximum

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

Physics Potential



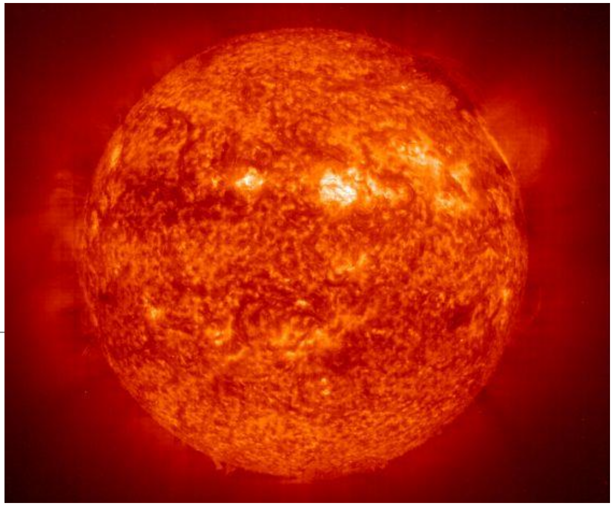


Similar results for inverted hierarchy

Band width depends on θ_{23}.

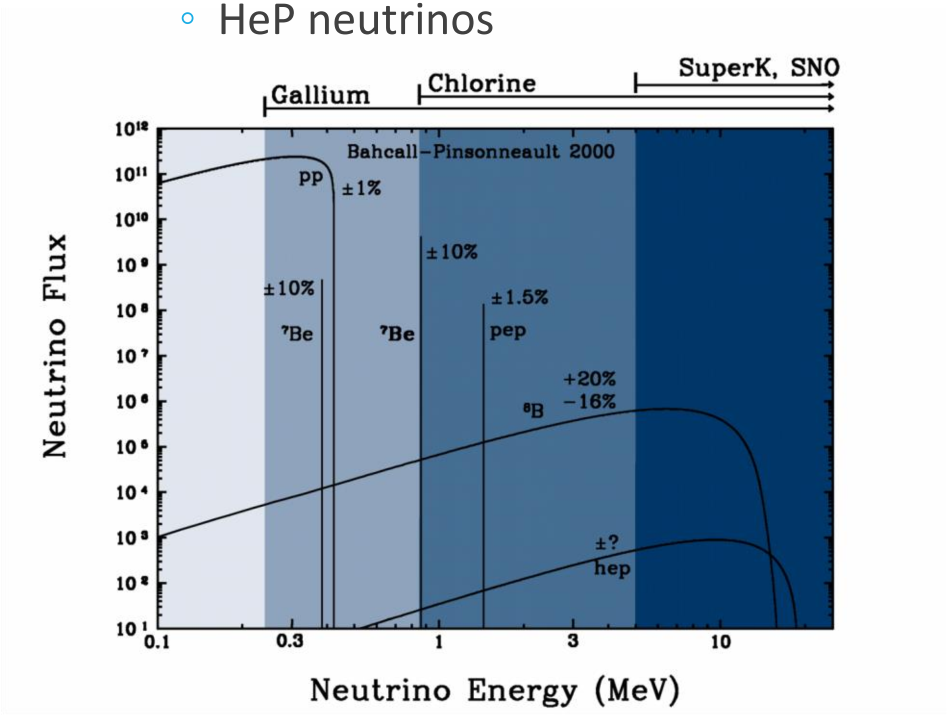
Non Accelerator Physics

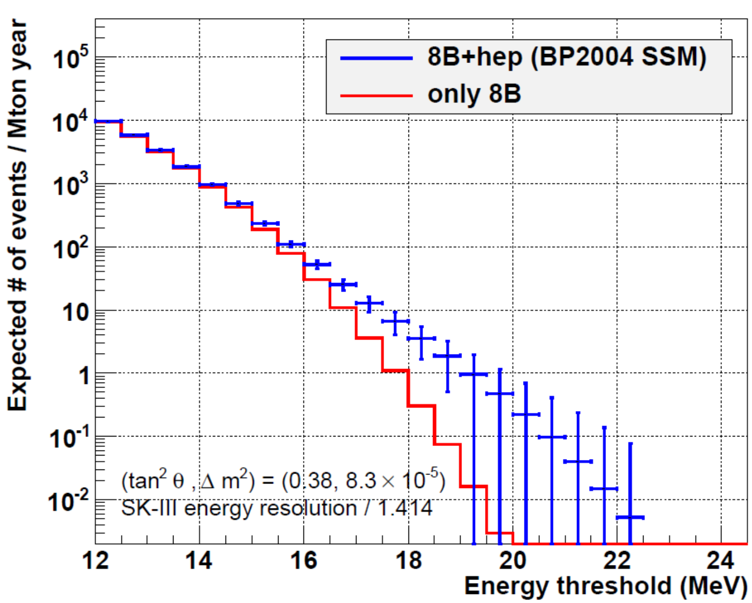
Solar Neutrinos



Search for:

- Day – Night Asymmetery
- MSW upturn
- HeP neutrinos

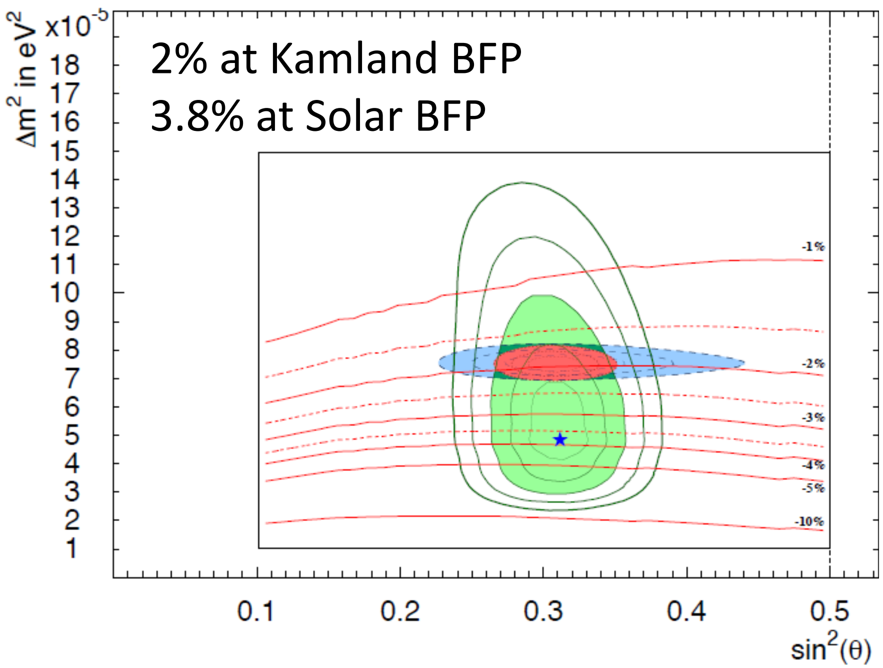


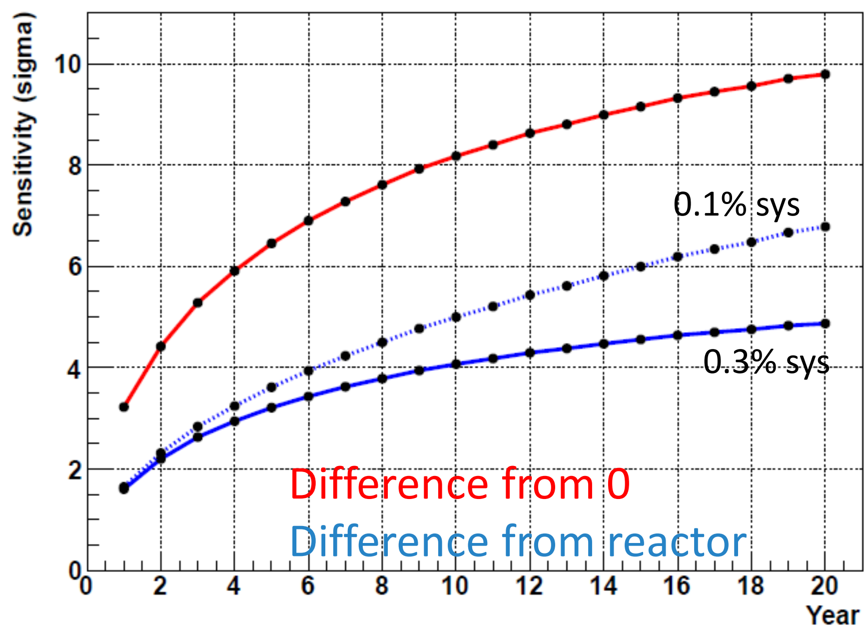


Day-Night Asymmetry

Regeneration of ν_e as solar neutrinos pass through the Earth.

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

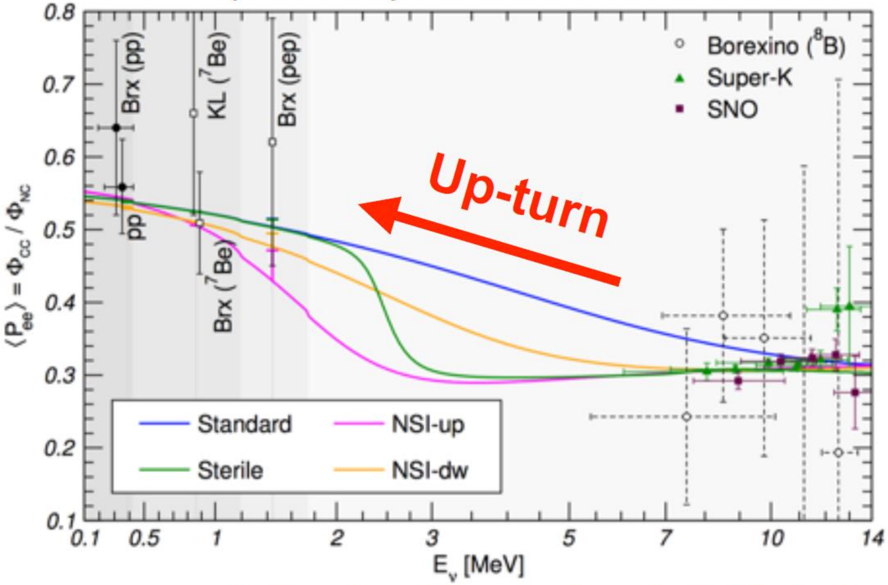




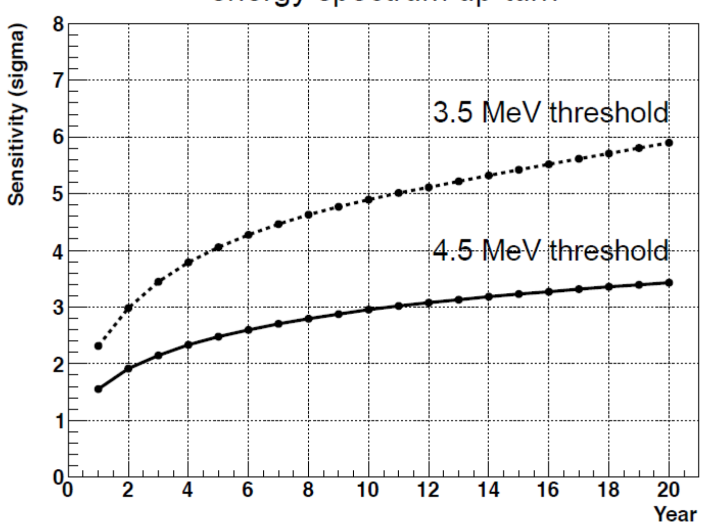
MSW Upturn

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

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

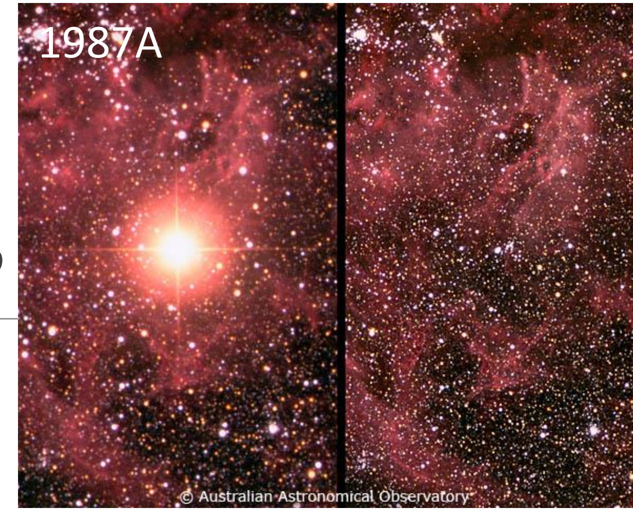


M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



Requires similar detector performance and backgrounds to SK

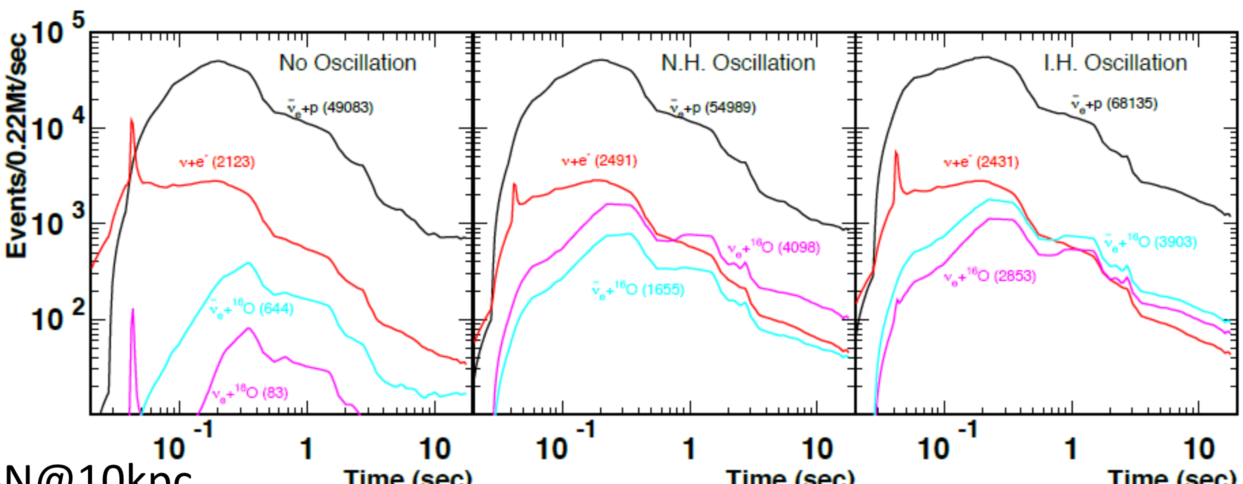
Supernova Neutrinos



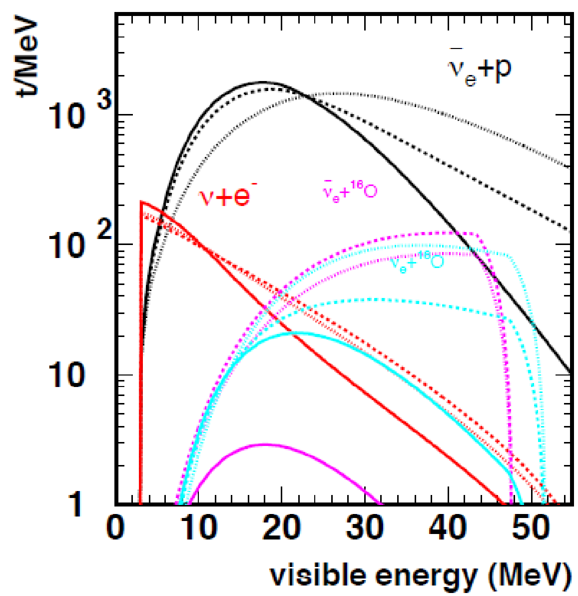
Hyper-K will be the most sensitive detector for Supernova neutrinos

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

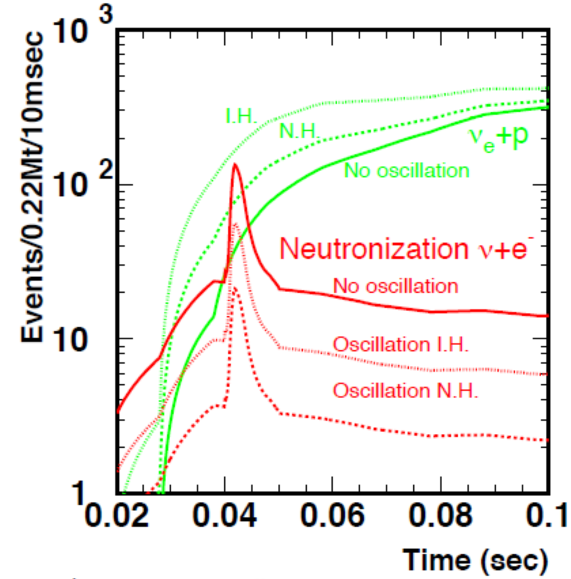
1987A 11 + 8 events



SN@10kpc



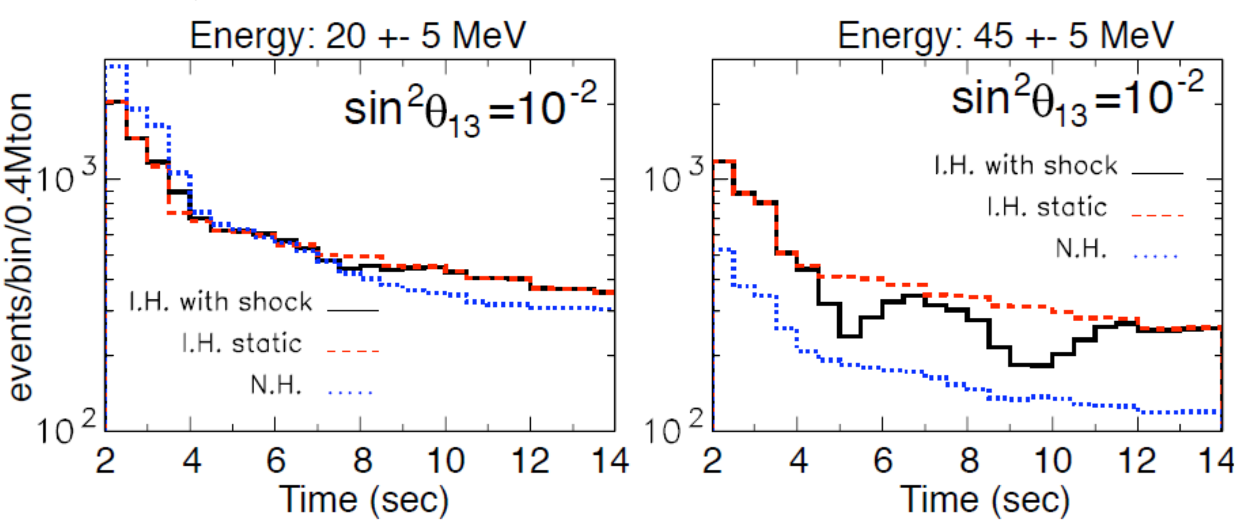
Supernova Neutrinos

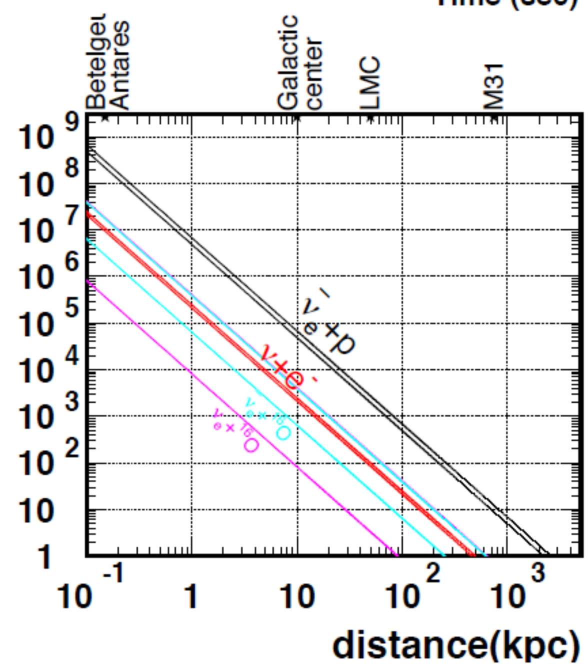


Access to key physics of Supernova explosion

- 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)

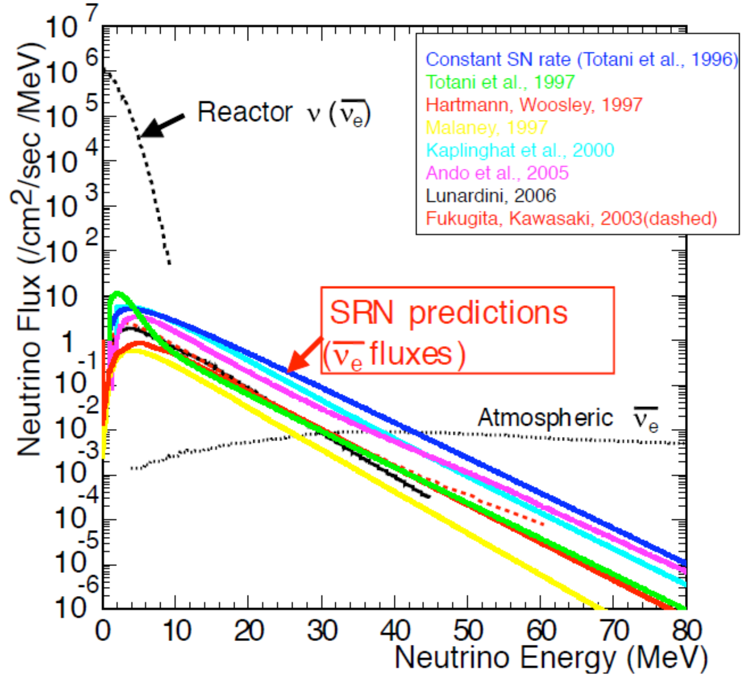


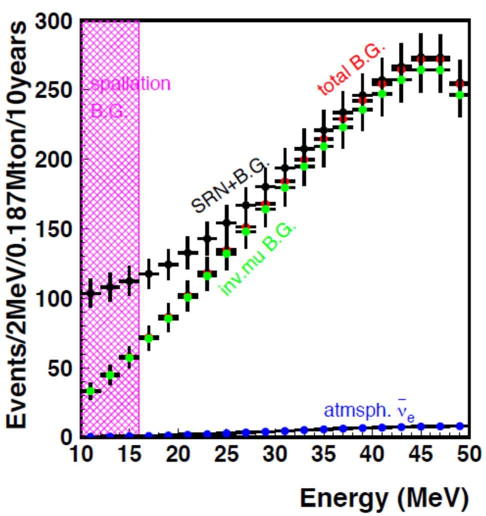


Diffuse Supernova Neutrinos

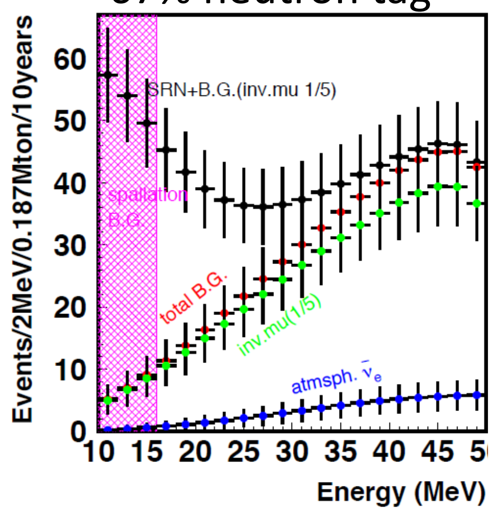
Can also measure the background of neutrinos from all supernova

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

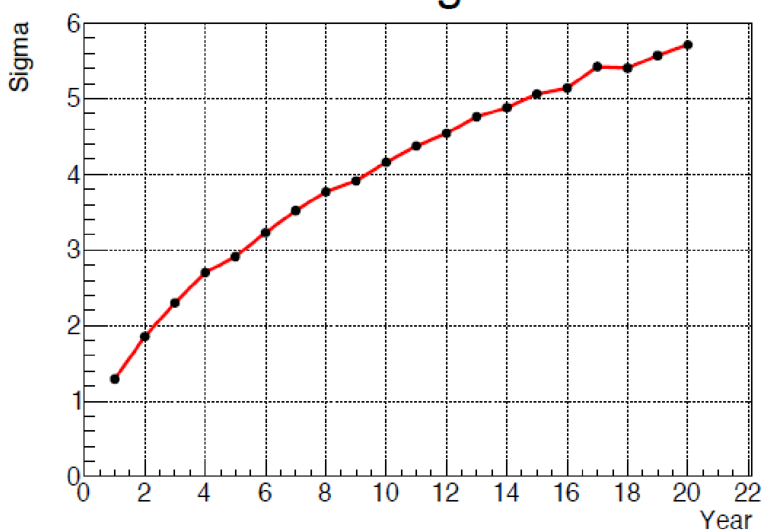




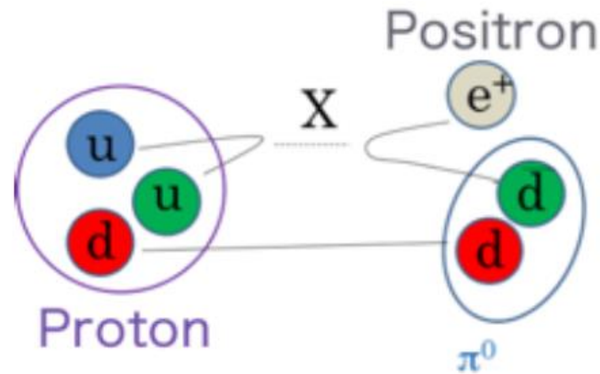
67% neutron tag



Detection significance



Proton decay



Predicted by grand unification theories

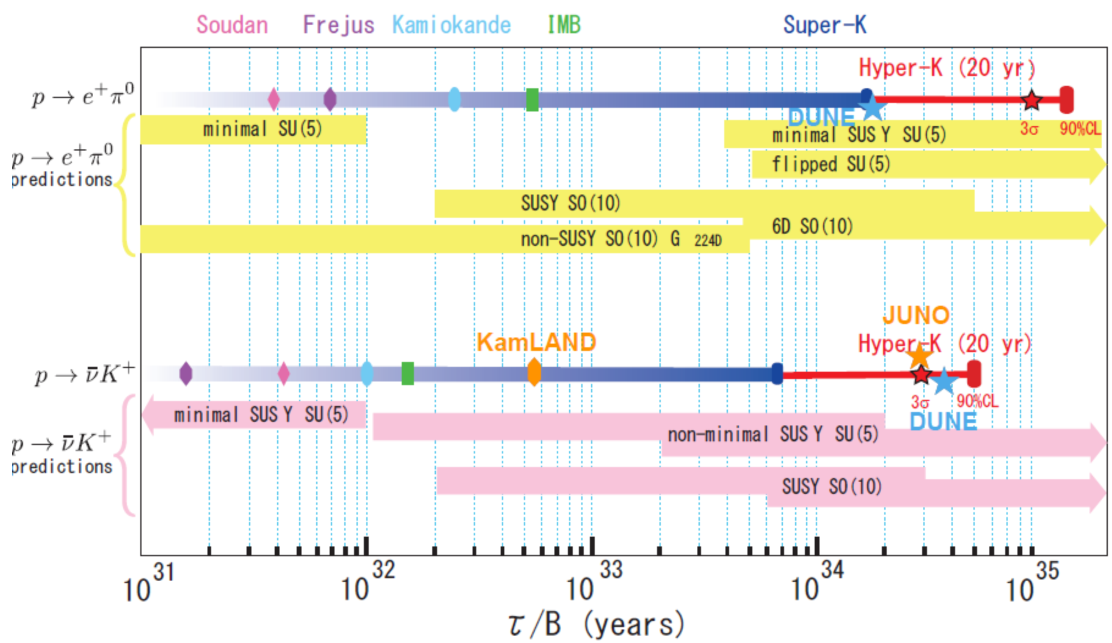
Suppressed by $\frac{1}{M_X^4}$

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

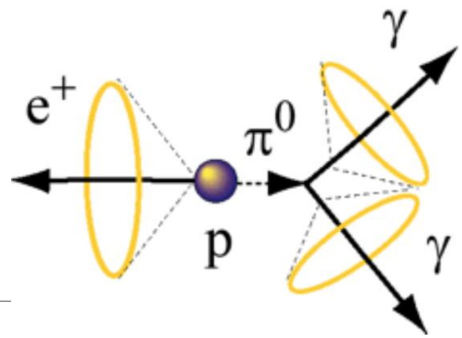
Rate is predicted by various GUT models and many have been rules out.

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

The actual reason Kamiokande and IMB were built!

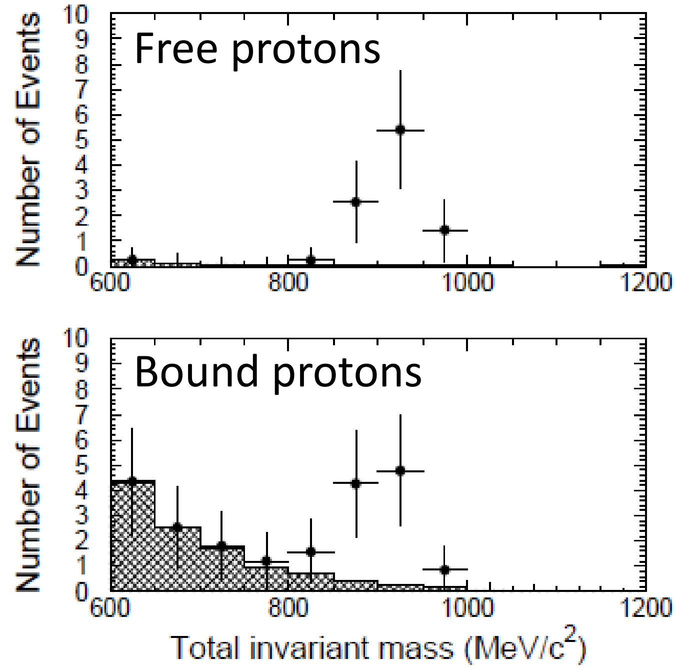


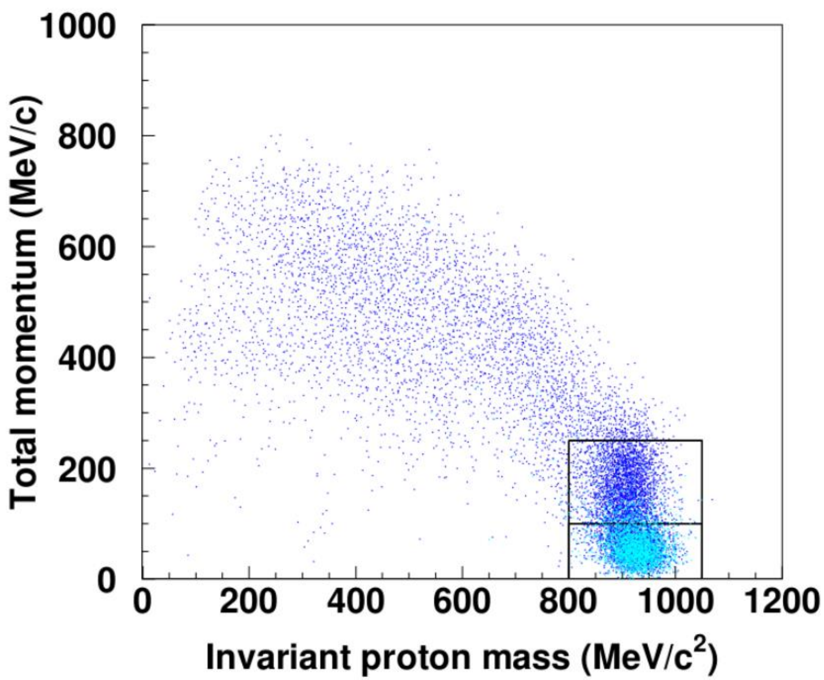
$p \rightarrow e^{+}\pi^{0}$

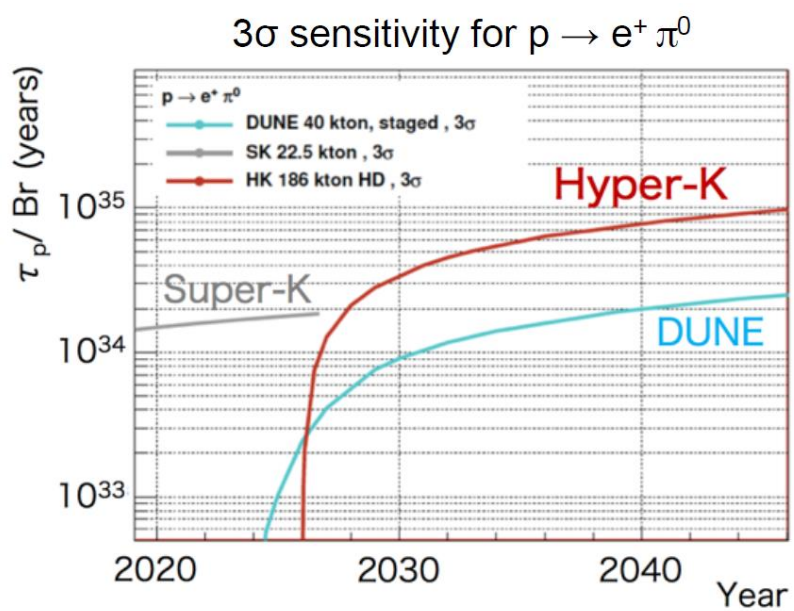


Very clean signal

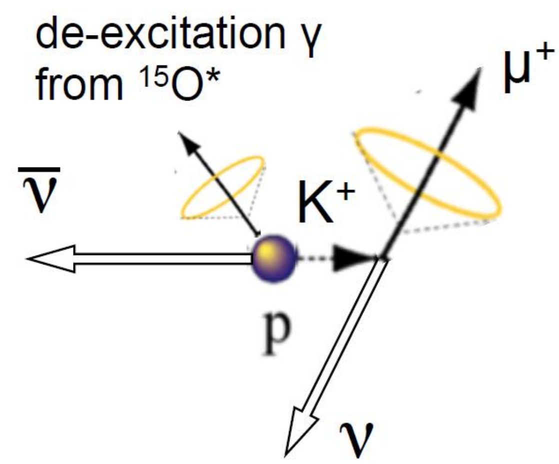
- Background from atmospheric neutrinos reduced by neutron tagging to almost zero in signal box







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

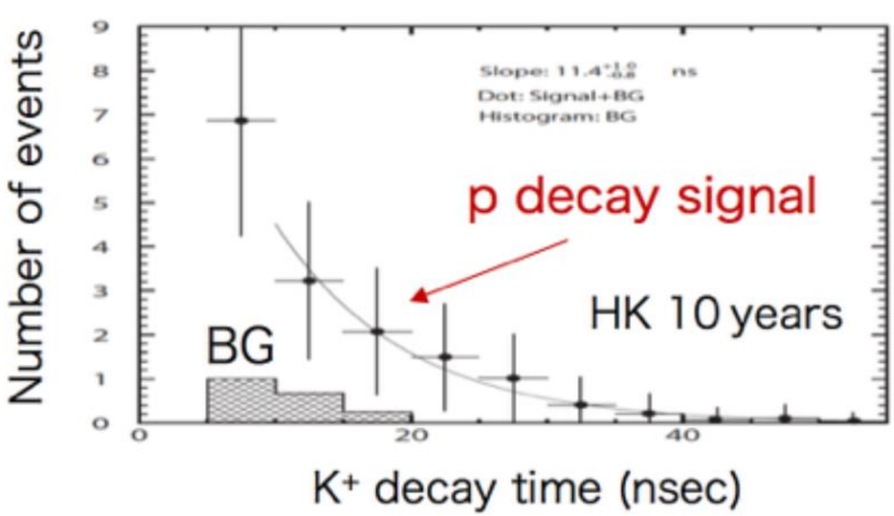


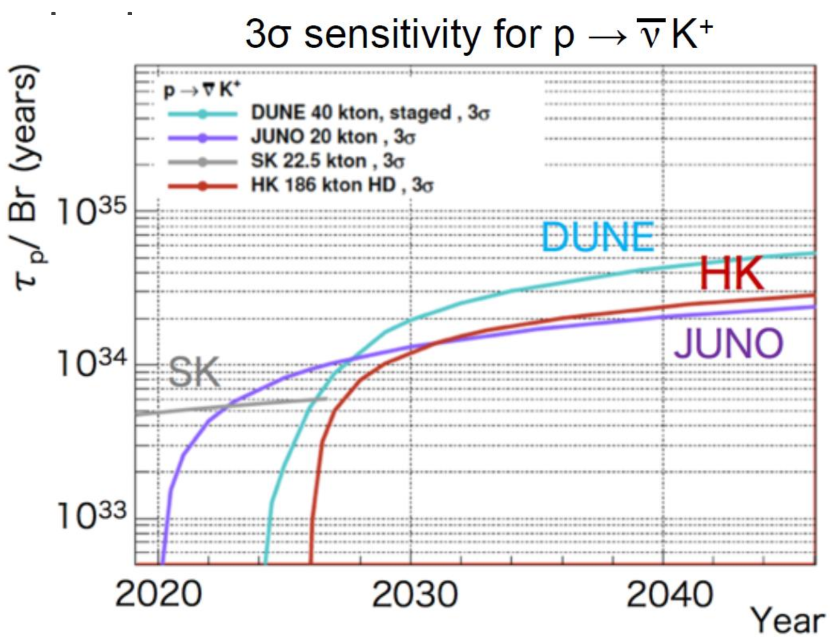
Clean signatures

$K^{+} \to \mu^{+}\nu$ (64%)   236 MeV μ^+

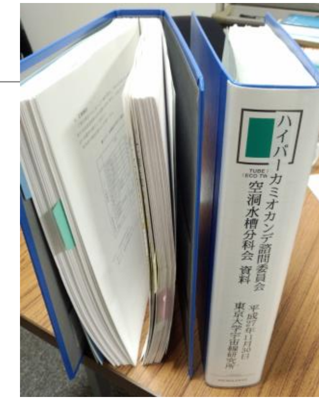
decay electron, 6MeV gamma

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





Project Status in Japan



“Hyper-K Design Report” released:
  KEK preprint 2016-21, ICRR-Report-701-2016-1

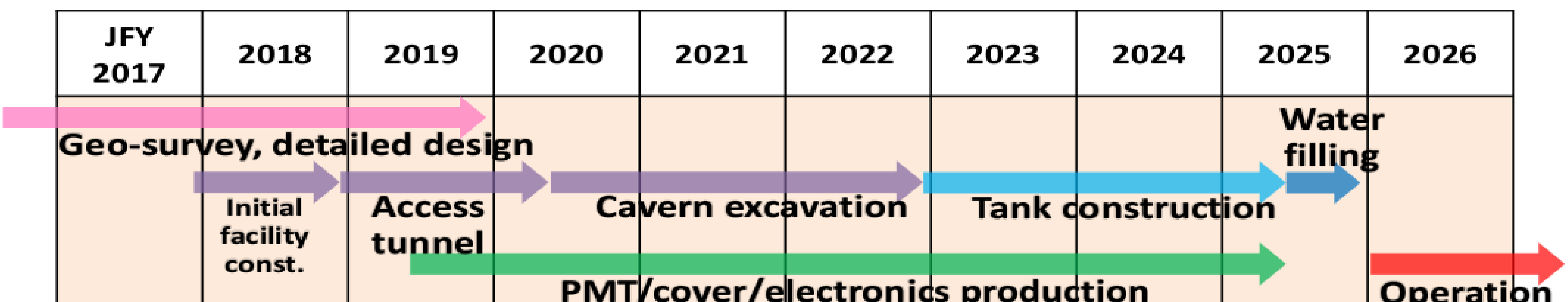
Strong commitment from host institutes:
  ICRR, U. Tokyo and KEK (MoU for Hyper-K)

Strong support from Japanese communities
  Cosmic-ray (CRC) and high-energy (JAHEP)

Science Council of Japan selected Hyper-K as one of the top priority large-scale projects in ‘Master Plan 2017’

MEXT (funding agency) will soon release the official ‘Roadmap 2017’
  Hyper-K is selected in the preliminary version of the Roadmap released on July 18, 2017

Budget request being submitted, aiming to begin the construction in JFY 2018 & begin operation in JFY 2026



Summary

The Hyper-Kamiokande experiment has a wide physics program of

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

The programme is progressing well and is on the MEXT roadmap for future experiments and one of the top projects for the next large projects for the Japanese science council