T2K & HK

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Long Baseline Neutrinos in Japan

T2K	T2K-II	HK
now	~2021	~2026
Current Status Latest Results	ND280 Upgrade SK-Gd Beamline Upgrade 750 kW	HK Detector Beamline Upgrade > 1 MW E61 Wide Physics Programme

Beam Status

Milestones this year:

- **exceeded 3×10²¹ POT;**
- **achieved 500 kW beam power!**

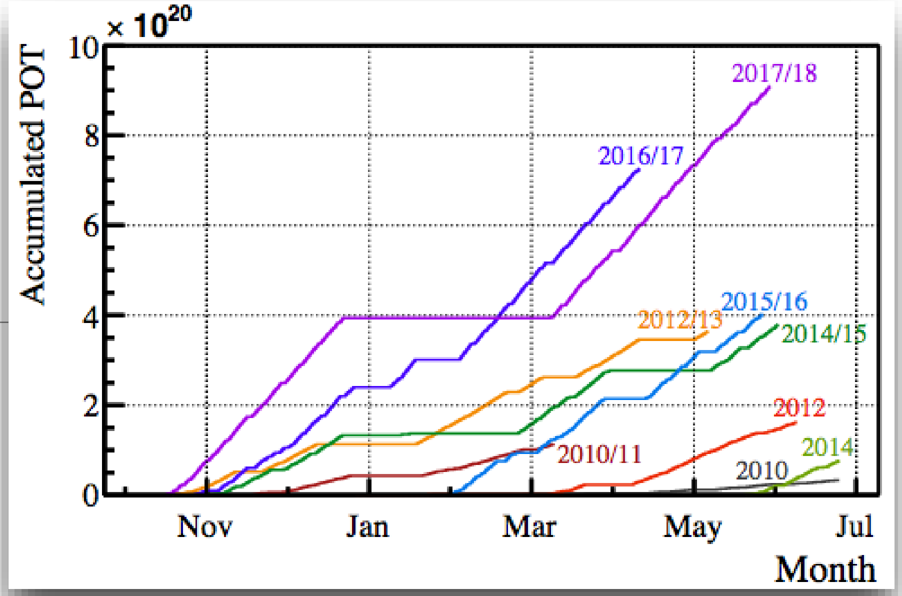
Beam delivery summary

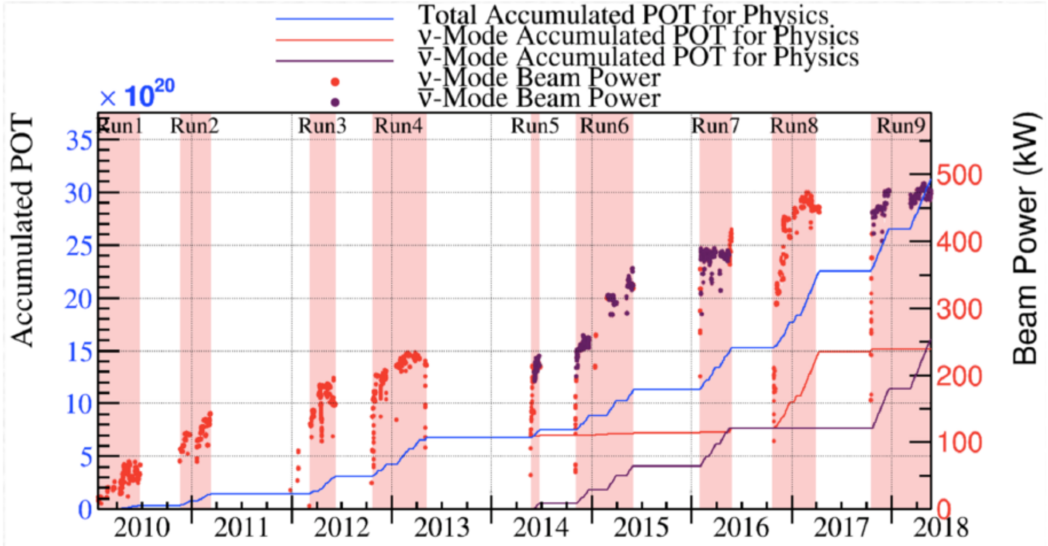
- **3.16×10²¹ POT TOTAL**
- 1.51×10²¹ POT ν-mode (FHC)
- 1.65×10²¹ POT ν̄-mode (RHC)
- Beam operated stably at **485 kW**!
- **More than double ν̄ data set in 2017/18!**

For current analysis:

- 1.49×10²¹ POT ν-mode
- 1.12×10²¹ POT ν̄-mode

Stable neutrino rates and beam direction demonstrated by INGRID and MUMON





T2K also continues to publish new neutrino interaction results.

Latest T2K Oscillation Results

Compare observed rates at SK to predictions under oscillation hypothesis, tuned with ND data

Oscillation Probability — Constrained by near detector fit

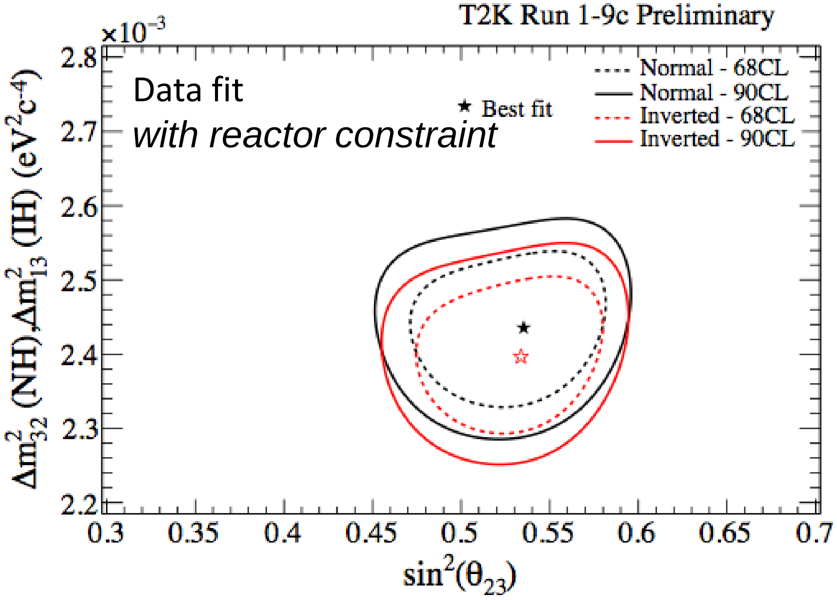
$$N(p_k,\theta_k;\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)=\sum_i^{E_\nu \text{ bins}}\sum_j^{flavors}\boxed{P_{\nu_j\to\nu_k}(E_{\nu,i};\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)}\boxed{\Phi_j^{far}(E_{\nu,i})\sigma_k(E_{\nu,i},p_k,\theta_k)}\epsilon(p_k,\theta_k)M_{det}$$

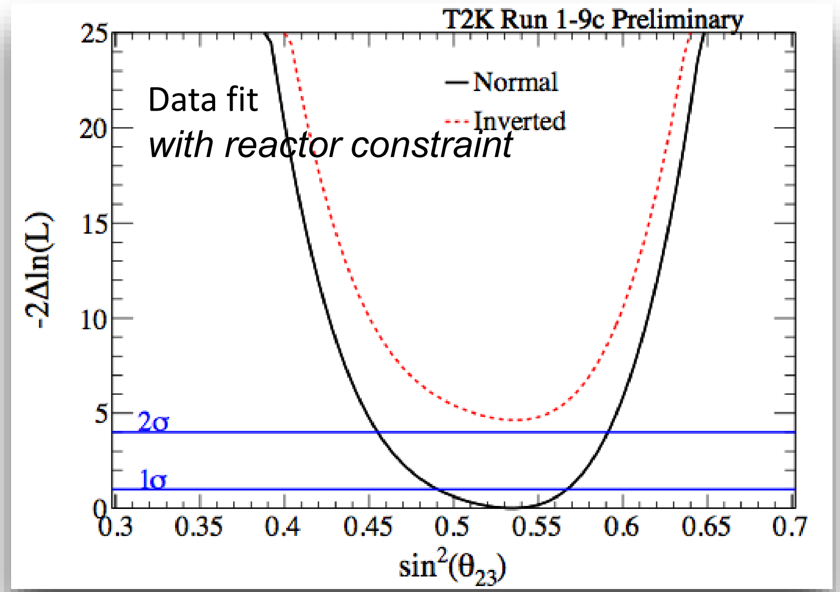
SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
RHC 1Rμ	95.5	95.3	95.5	95.8	102
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9

SK event rates are in line with expectations based on oscillation model.

Of note: 15 events observed in CC1π ν_e sample, with prediction of 6.9 maximum p-value for up/down fluctuation in 1 of 5 samples is: ~5% (1% with single sample).

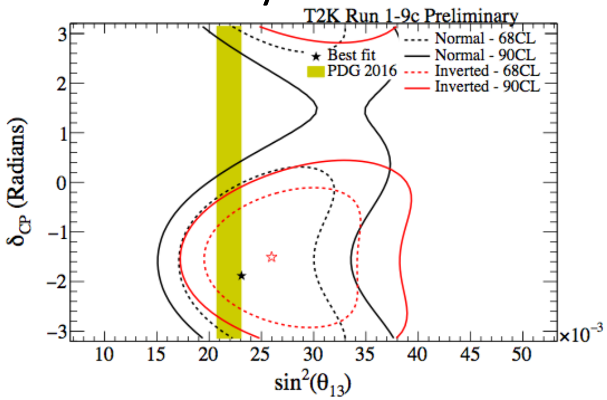
Atmospheric sector: θ_{23}, $\Delta m^2_{32(1)}$



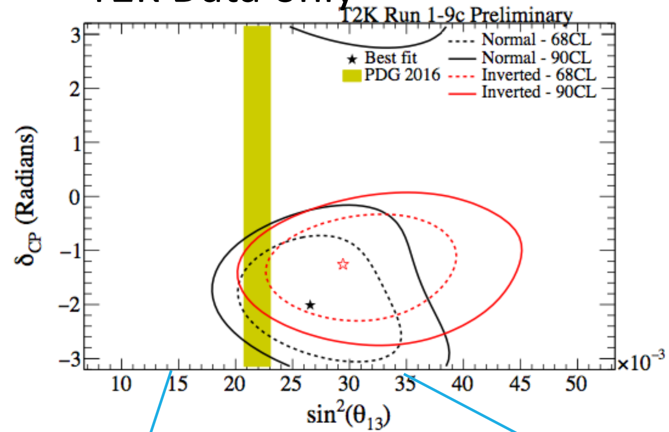


δ_{CP} vs. $\sin^2\theta_{13}$

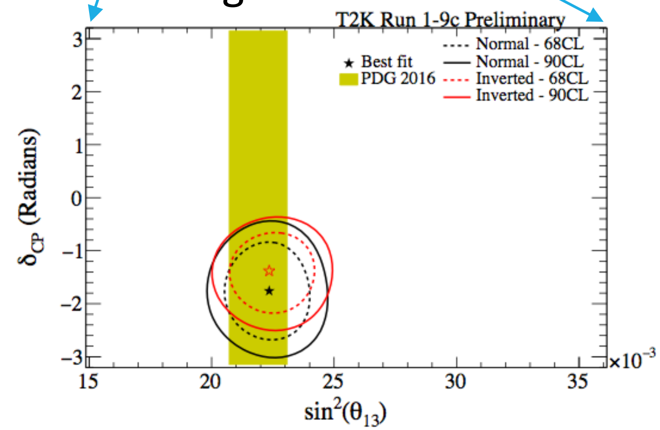
Sensitivity



T2K Data only



Including reactors



sensitivity assumptions:

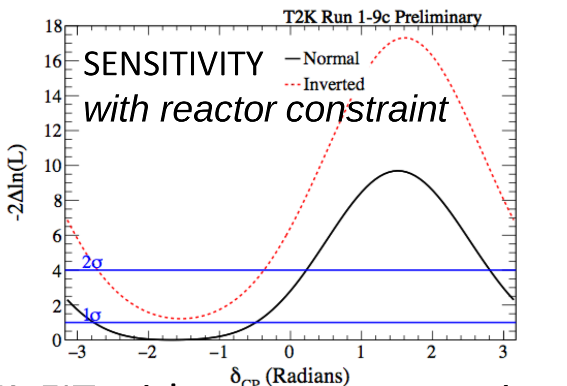
$\sin^2\theta_{13}$= 0.0219 (2016 PDG)

$\sin^2\theta_{23}$ = 0.528

NH, δ_{CP} = -1.601

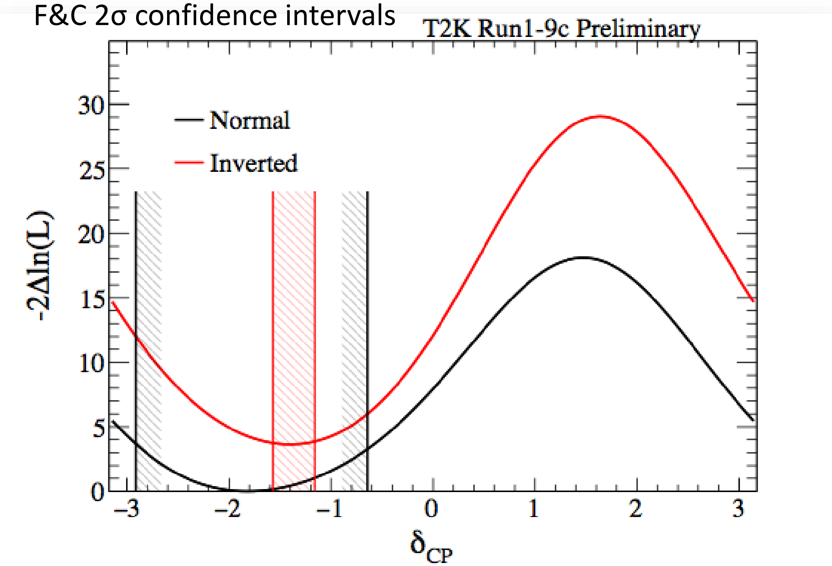
Data fit stronger than sensitivity

δ_{CP} 1D contours



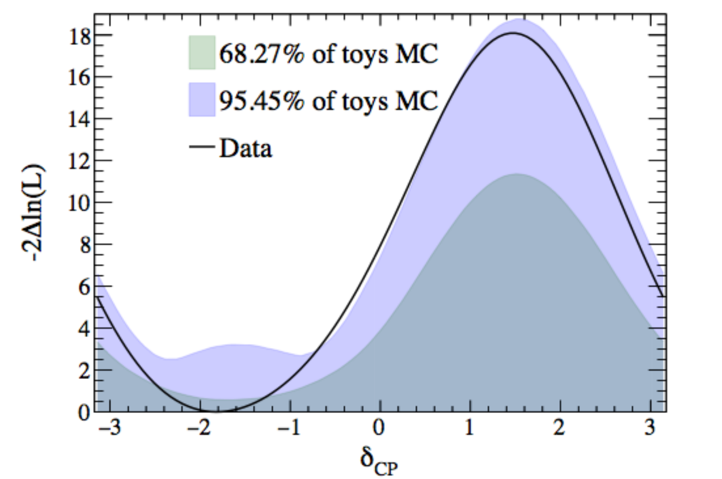
DATA FIT with reactor constraint

F&C 2σ confidence intervals



CP conserving values outside of 2σ region for both hierarchies

19% of toys exclude CP conservation at 2σ CL (both δ_{CP}=0 & δ_{CP}=π)



δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

T2K-II

Increase in approved running up to $20x10^{21}$ pot

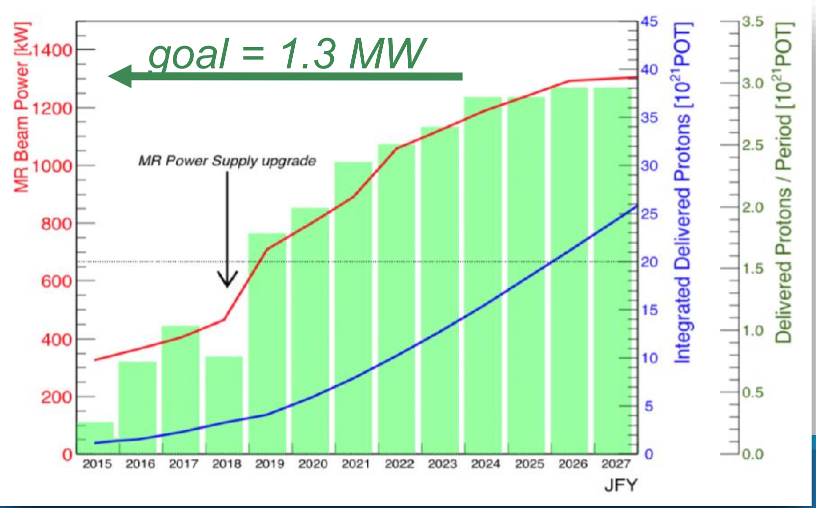
- Has stage 1 status from KEK/J-PARC
- Gives T2K median 3σ sensitivity to CPV.

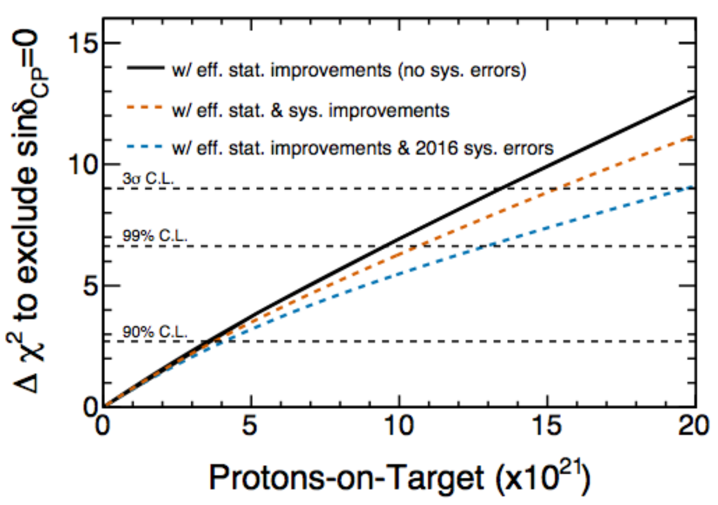
Beamline upgrade 2021-2022

- Power Supply upgrade - Increase rep rate 2.48 s -> 1.32 s
- Achieve 750 kW

Will be the only STFC funded long baseline experiment running prior to DUNE/HK era

- At least two PhD student lifecycles



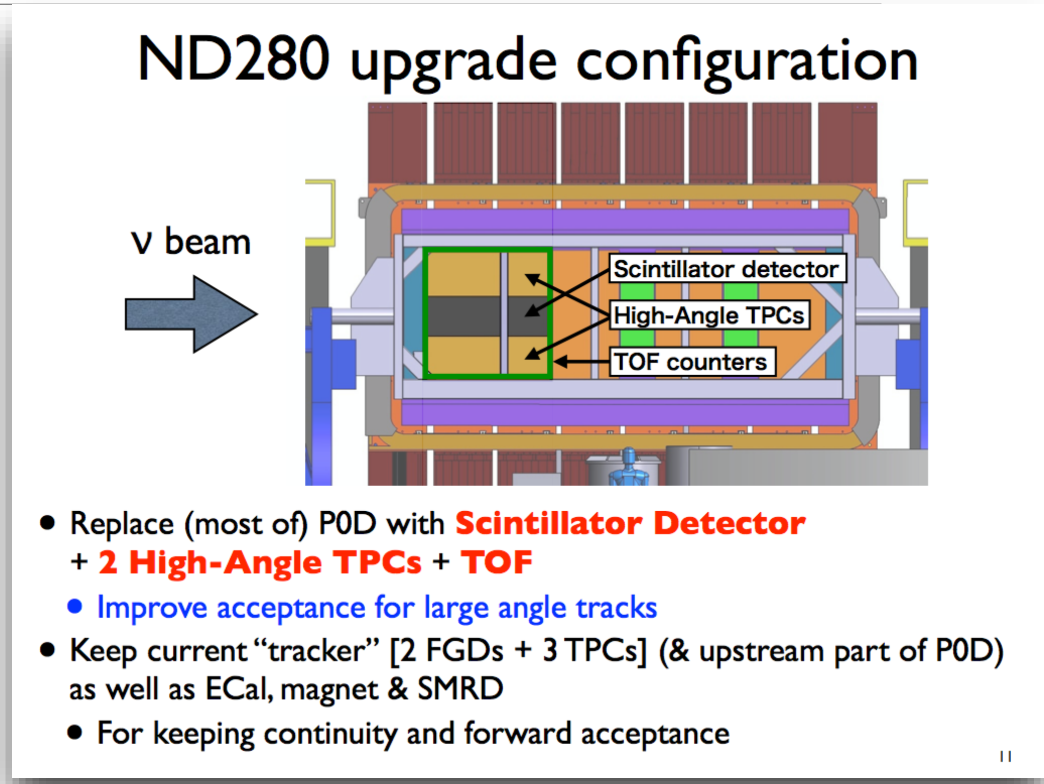


ND280 Upgrade

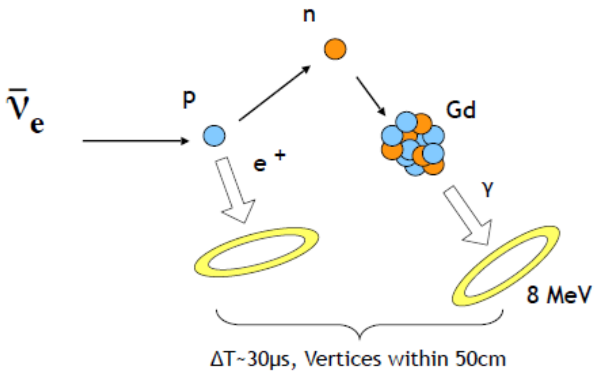
Aim to reduce systematics
- Better match acceptance to SK
  - High Angle TPCs
- Reduce systematic errors to 4%

Strong involvement from Europe (including CERN), Japan and US

UK involvement through DAQ, software support and basket.
- UK led tasks
- Support request through CG line
- Large component of T2K CG request.



SK-Gd



As part of HK programme we joined SK.

- Provides great opportunity to develop for HK and access SK physics

SK is currently open for refurbishment to allow deployment of Gd

- Enhance neutron sensitivity
- Access diffuse supernova neutrino background
- Sensitivity to wrong sign events in T2K.

UK participation

- Deployment of HK light injection prototype
- Counting of Gd samples at Boulby low background counting facility
- Gd concentration measurement/monitoring
- Neutron Calibration

Hyper-K

Target neutrino CP violation with a wide physics programme
- Proton Decay
- Atmospheric neutrinos
- Supernova neutrinos
- And more

Increase size of far detector by a factor ~10
- Improve low energy physics by increasing effective coverage

Increase beam power

Improve near detectors

Public Design Report: arXiv:1805.04163

Now writing HK technical report to exactly specify detector
- Identify and resolve remaining design option by March 2019
- Includes schedule, costs and allocation of responsibilities

Proto-collaboration Structure

as of 2018/5/25

Project leader

Project Leader Shiozawa
co-leader F.Di Lodovico

International Steering Committee

Nakaya (chair), Y.Itow (co-chair)
D.Wark, Nakahata, Kobayashi, Shiozawa, F.Di Lodovico, Yokoyama, Aihara, A.Blondel, G.Catanesi, E.Kearns, J.M.Poutissou, S.B.Kim

International Board of Representative

D.Wark (UK,chair), A. Ioannisian (Armenia), H. Nunokawa (Brazil), S. Bhadra (Canada), A. Konaka (Canada), M. Gonin (France), M. Zito (France), M. G. Catanesi (Italy), T. Kobayashi (JP), T. Nakaya (JP), M. Shiozawa (JP), M.Y.Pac (Korea), E. Rondio (Poland), Y. Kudenko (Russia), L. Labarga (Spain), A. Blondel (Switzerland), V. Aushev (Ukraine), F. Di Lodovico (UK), E. Kearns (USA), M. Wilking (USA)

Speakers Board

Yokoyama, G.Catanesi, E.Kearns

Technical Coordinators

HK detector: S. Moriyama, Steve Playfer
HK Beam+ND: M. Hartz, M. Yokoyama

Conveners Board *WG leaders

- WG1: *Nakayama, Tanaka, M.Smy
- WG2: *Sekiya, Vagins
- WG3: *Nishimura, Feusels, De Rosa
- WG4: *Hayato, T.Lindner, A.Bravar
- WG5: *Miura, O'Sullivan
- WG6: *McCauley, Koshio, Mine
- WG7: *Hartz, J.R.Wilson
- WG8: *Fujii, Densham
- Physics WG: *Ishitsuka
  - Phys-WG1: Friend
  - Phys-WG2: Wendell
  - Phys-WG3: Takeuchi, Shimizu
- WG10: *Seon-Hee Seo

WG1: Cavity and Tank
WG2: Water
WG3: Photo-sensor
WG4: Electronics and DAQ
WG5: Software
WG6: Calibration
WG7: Near Detectors
WG8: Beam & Accelerator
WG9: Physics
WG10: 2nd detector in Korea

Phys-WG1: Accelerator
Phys-WG2: Atmν+Nucleon decays
Phys-WG3: Astroparticle Physics

Far Detector

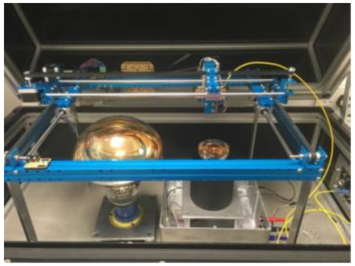
~10 Fiducial Mass

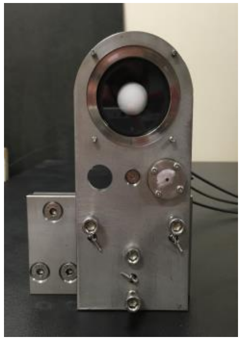
High PDE photosensors and low background to maintain low energy physics and enhance physics sensitivities.

Tochibora, new site near Mozumi also 2.5° off axis

Aim to start in 2026

UK contributions
- Outer Detector
- Calibration
- DAQ





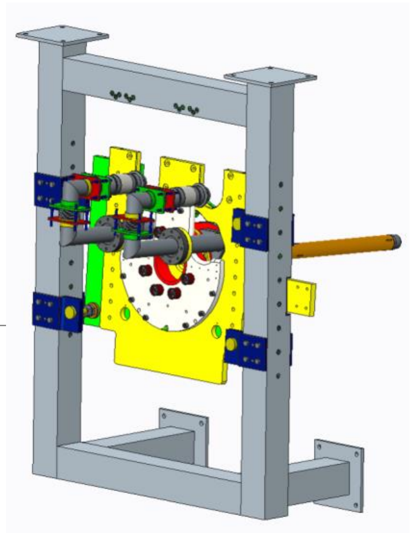
	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (×2 sensitivity)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

Beamline

Redesigning the target for 1.3 MW operation

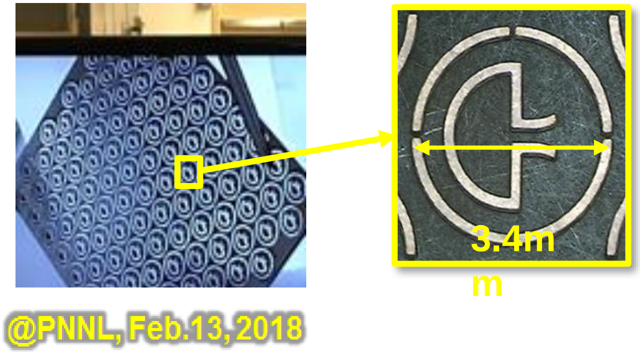
Need to redesign supports to ensure location inside horn

- Ambient temperature fluctuates between 30-50°C at 500kW
- Vibration from horn pulsing to increase with 320kA upgrade

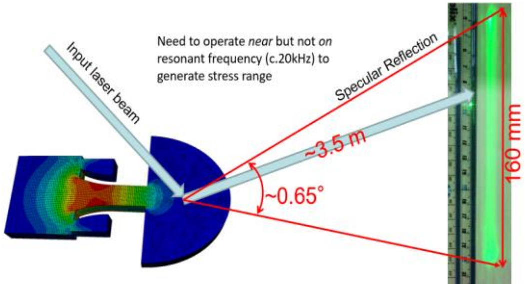


Testing material integrity under irradiation

- Setting up a meso-fatigue test rig at Cullum to do this.



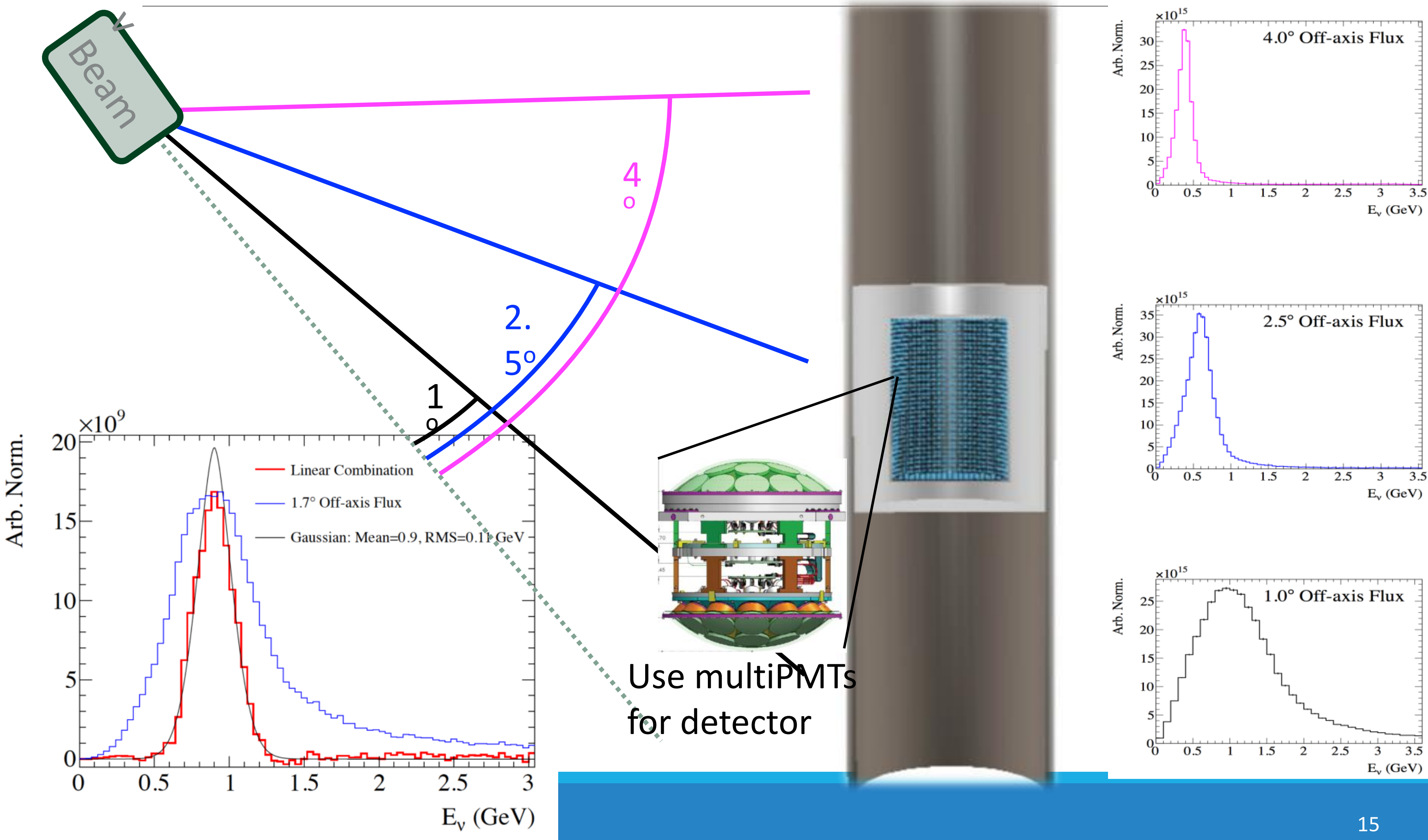
Core UK contribution to T2K continued in HK



E61

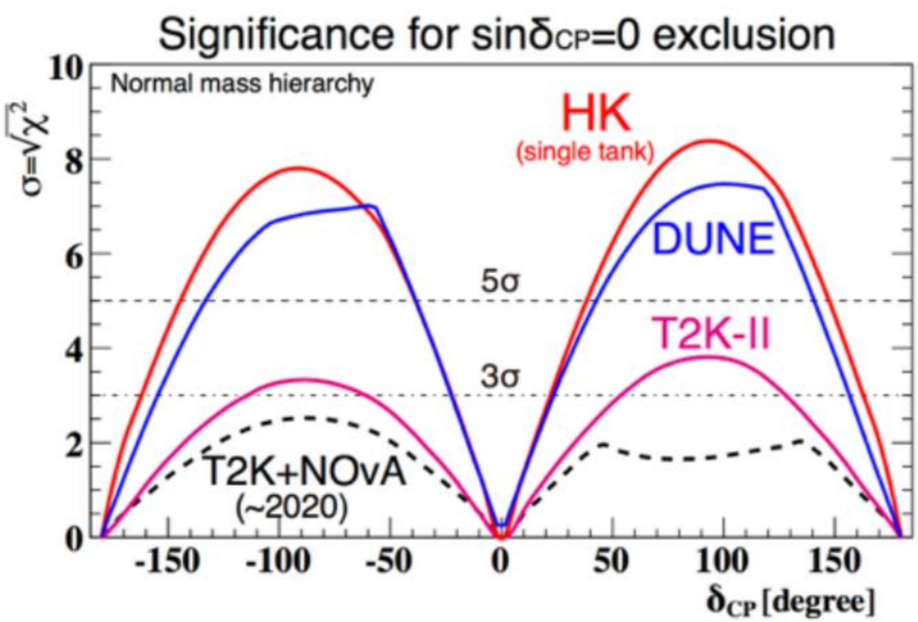
Water Cherenkov – same physics as far detector
Sample off axis angles
- Probe neutrino energy reconstruction

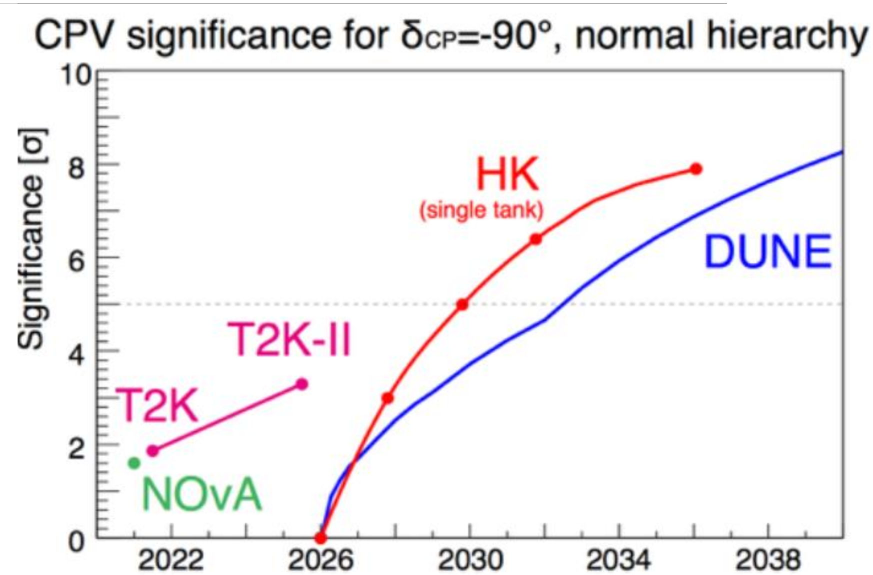
Gd doped to provide neutron tagging



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}

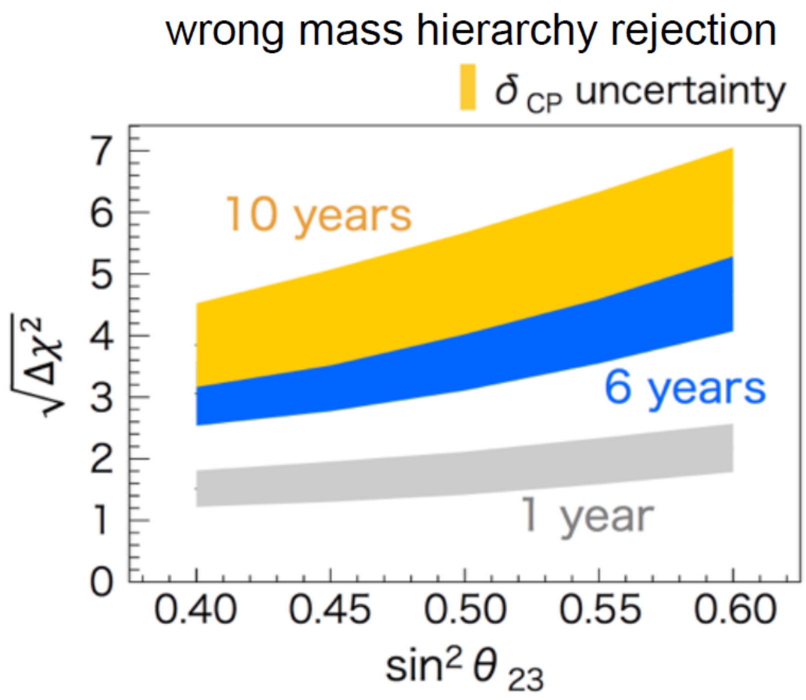
$$\sim 22° \; for \; \delta_{CP} = \pm\frac{\pi}{2}$$

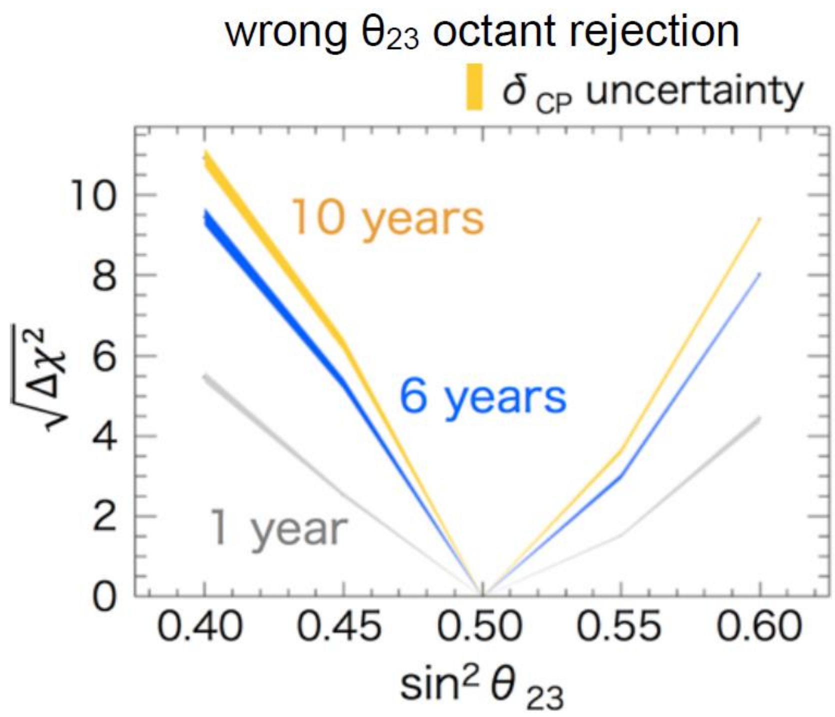
$$\sim 8° \; for \; \delta_{CP} = 0, \pi$$

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

Mass Hierarchy and Octant

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





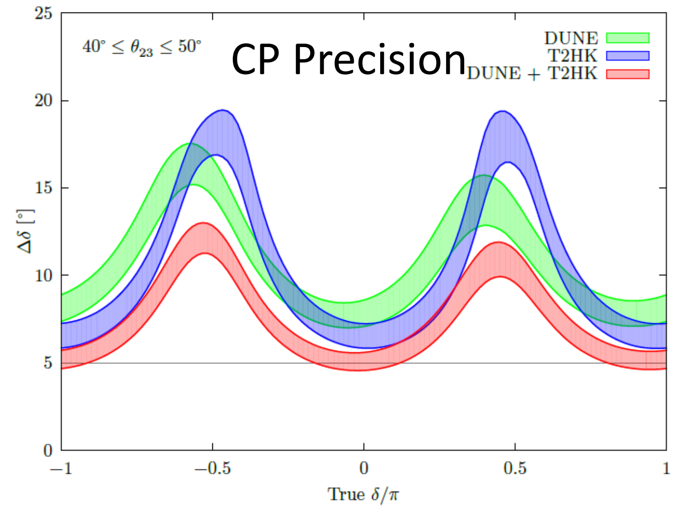
Figures from Ballet *et.al.* arXiv:1612.07275

HK and DUNE

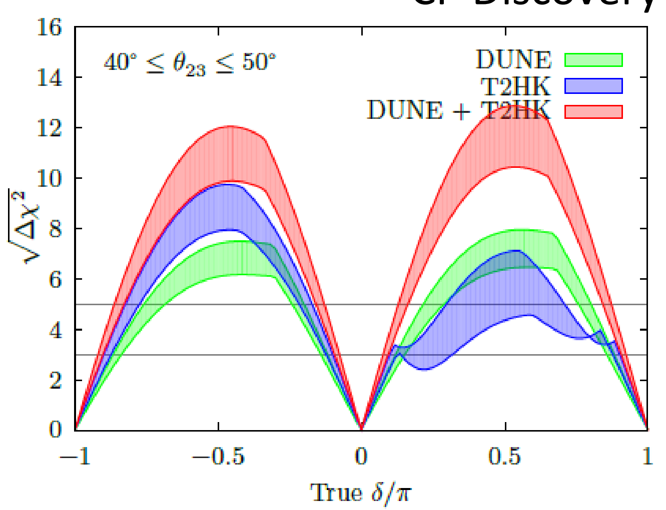
DUNE and HK are complementary
- DUNE – large matter effect, spectral distortions
- HK – Smaller matter effect, CP dominated, high statistics

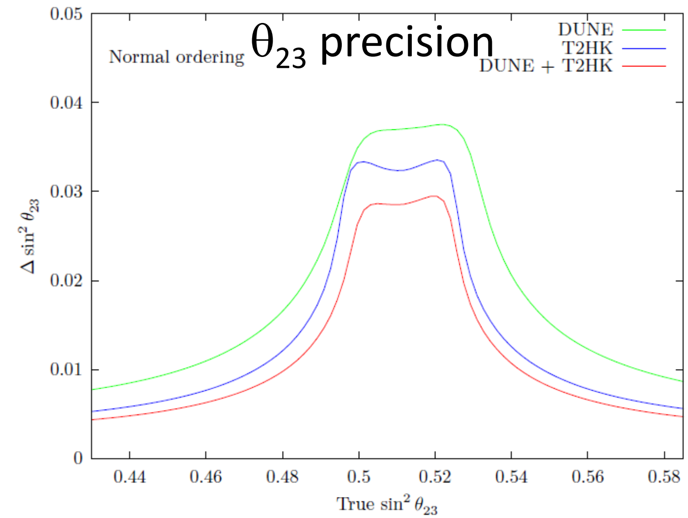
Differences in oscillations allow PMNS parameters to be better disentangled.
- Also test fundamental PMNS model

Allows higher precision measurements of parameters
- Improved discovery
- Precision for model testing

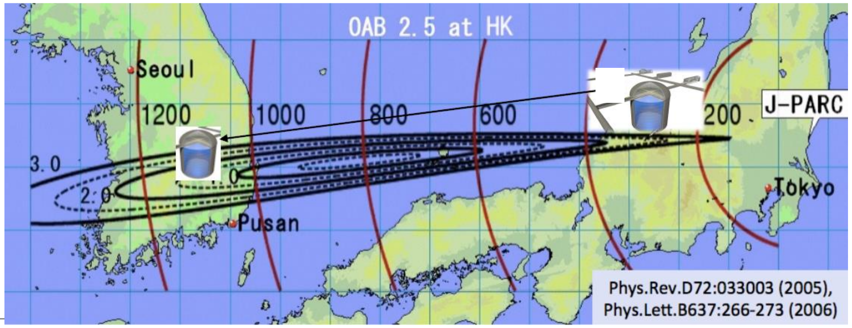


CP Discovery

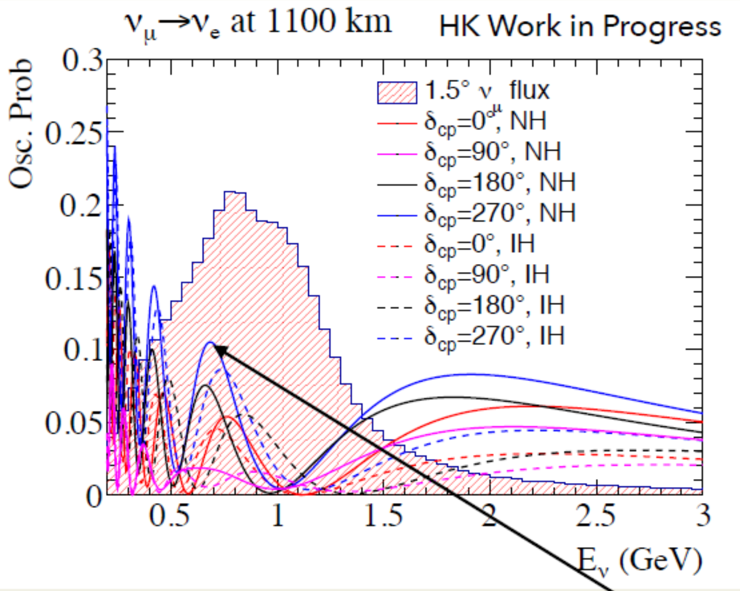


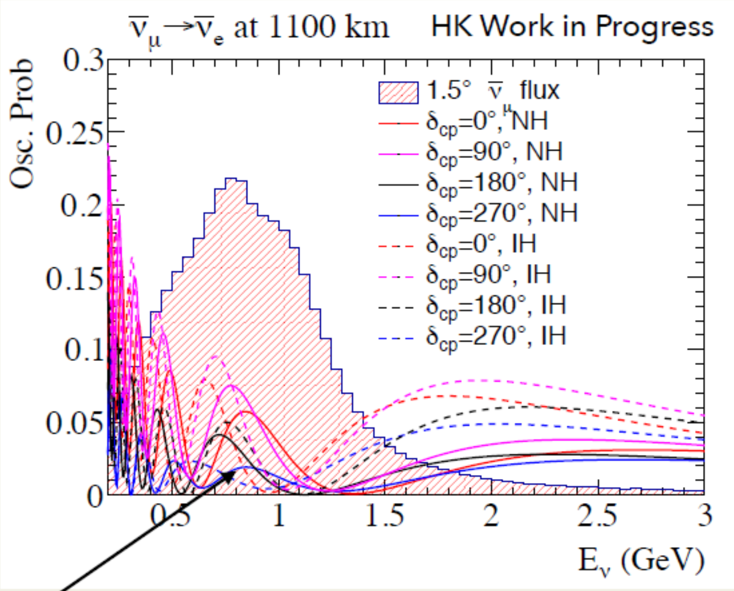


Korean Option



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

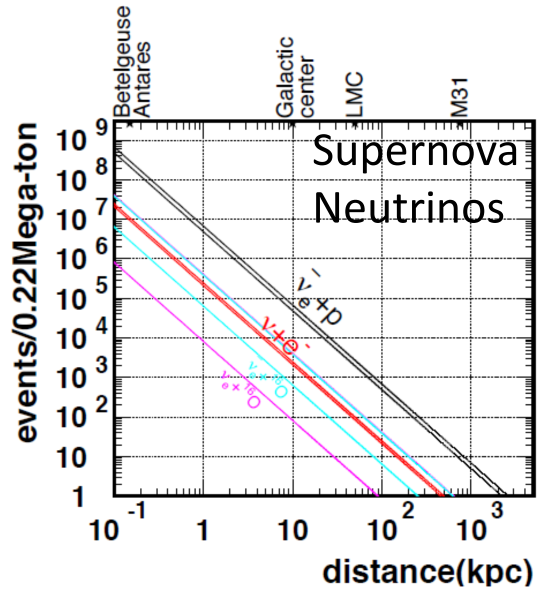
Wider Physics Programme

Also:
- Indirect dark matter
- Astrophysical neutrinos
- Geoneutrinos

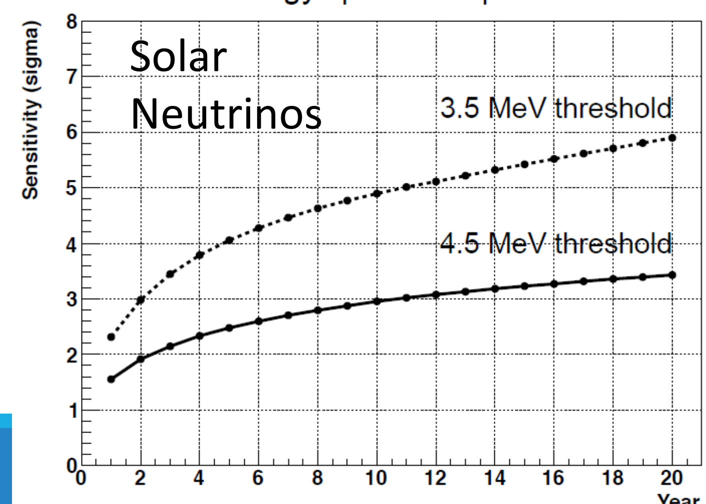
Proton Decay
- Access to many modes
- Estimates based on SK with improved neutron tagging

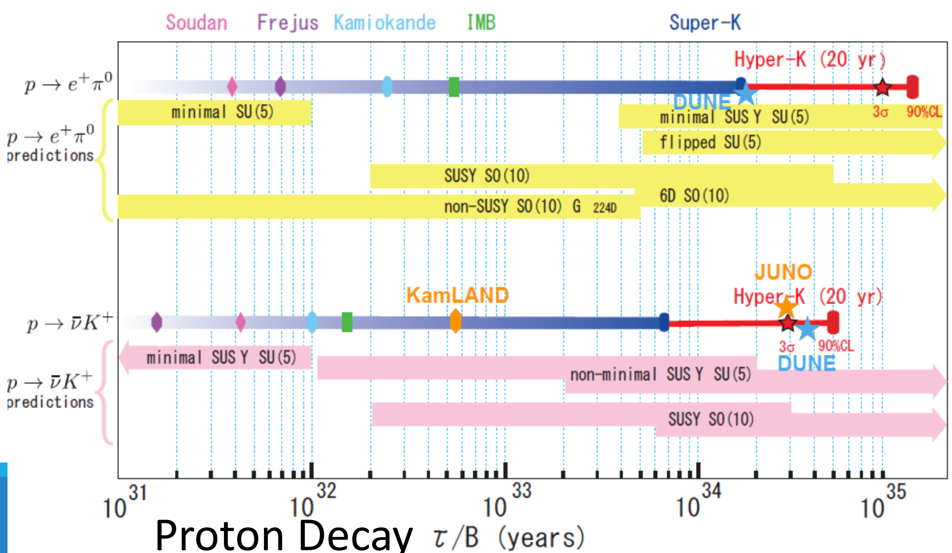
Solar neutrinos
- Sensitivity to day night and MSW upturn

Supernova neutrinos
- Sensitivity to physics of the explosion with increased statistics
- Can see supernova in M31
- Access to diffuse supernova neutrino background



energy spectrum up-turn





Royal Society Exhibit

Successful exhibit at Royal Society last week

Neutrinos, SK and HK

https://www.youtube.com/watch?v=Qv-uf-suaus&feature=youtu.be

Funding Prospects

Awaiting funding decision from Japan
- Will hear from MEXT with request to Ministry of Finance by end of August.
- Will hear from Ministry of Finance by end of March

Design will be fixed when design report completed.

New neutrino organisation setup to support HK

International funding will follow Japanese decision.
- Approval for the tank in Korea will be pursued assuming HK approval in Japan.

In UK aim to apply to UKRI funds for capital
- HK Outer detector system, including PMTs
- Calibration systems
- DAQ
- Items designated by Japan as a foreign contribution.

Working with industry for our items – e.g. OD PMTs

Conclusions

Firm plan for long baseline neutrinos in Japan

- T2K
  - Improved CP results
- T2K-II
  - ND280 Upgrade, SK-Gd, Beamline upgrades
  - Enhanced Statistics
- HK
  - Excellent CP discovery potential, precision CP measurements
  - Wide physics programme including proton decay, supernovae, atmospheric neutrinos
  - Strong UK leadership in HK