FUTURE LONG BASELINE NEUTRINO EXPERIMENTS

FRANCESCA DI LODOVICO (QMUL)

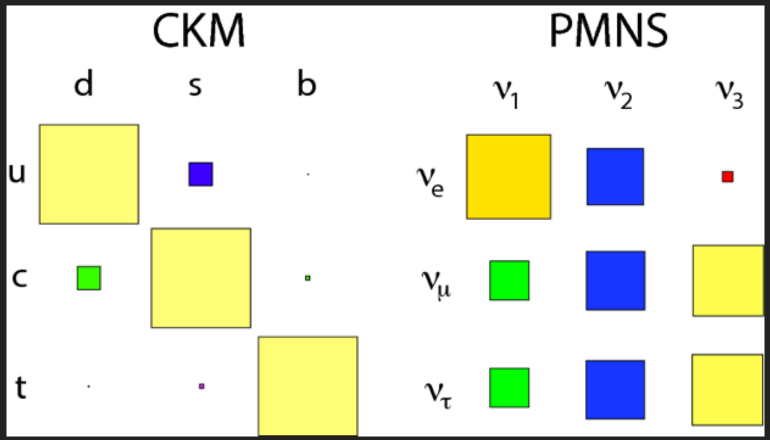
OUTLINE

- Current status and open questions
- Hyper-Kamiokande
- DUNE (talk by Antonio Ereditato)
- Studies for other long baseline neutrino experiments
- Conclusions

CURRENT STATUS

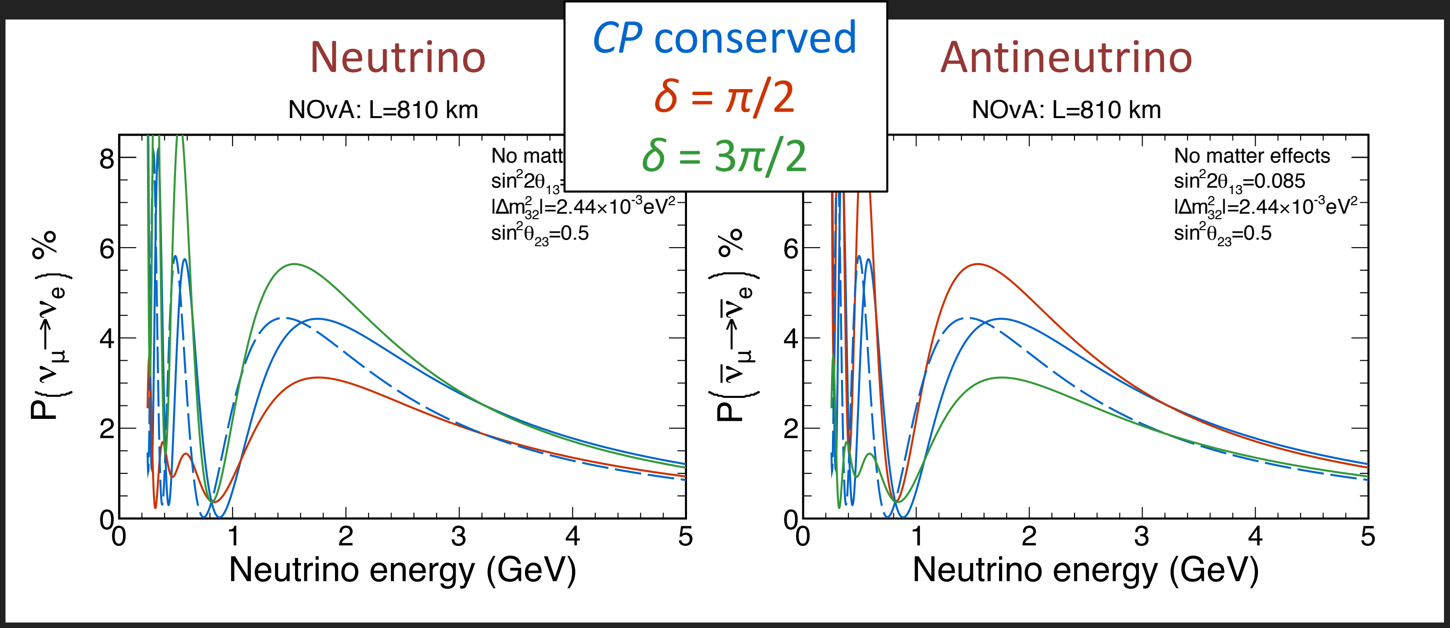
nuFIT

- $\theta_{12} = (33.62^{+0.78}_{-0.76})°$
- $\theta_{23} = (47.2^{+1.9}_{-3.9})°$
- $\theta_{13} = 8.54 \pm 0.15°$
- δ_{CP} =? [only unknown param]
- $|\Delta m^2_{32}| = (2.494 \pm 0.032) \times 10^{-3}\ \mathrm{eV}^2$
- $\Delta m^2_{12} = (7.60 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2$
- Very different from the CKM matrix



OPEN QUESTIONS

Do neutrino oscillations violate CP symmetry?



- Only in an *appearance* measurement since *CPT* requires the disappearance probabilities to be the same

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)\ ?$$

- Possibly relevant for understanding origin of matter-dominated Universe (Leptogenesis)

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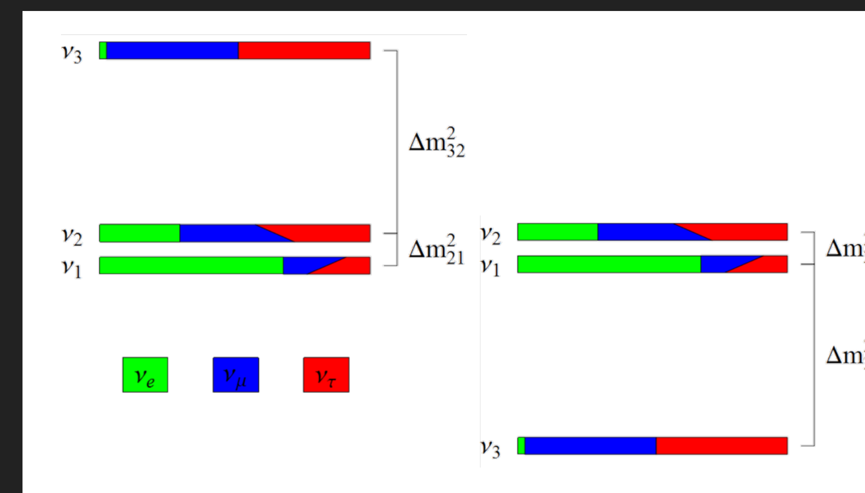
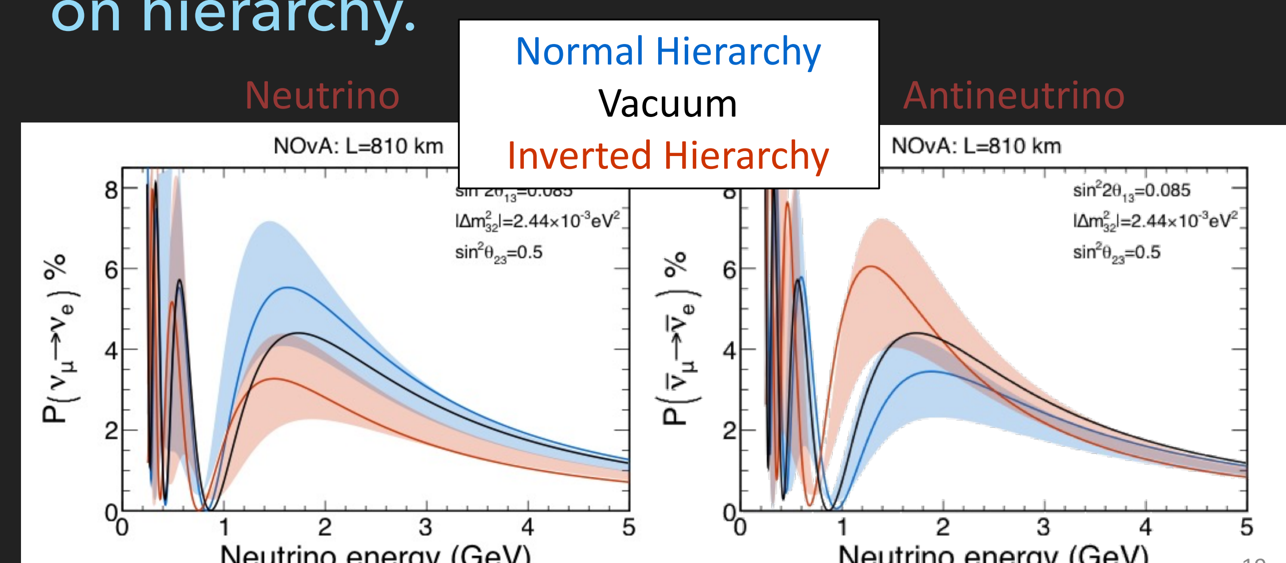
OPEN QUESTIONS

Is the mass hierarchy "normal" (NH) or "inverted" (IH)?



- Also called "mass ordering"
- Enhancement or suppression depending on hierarchy.



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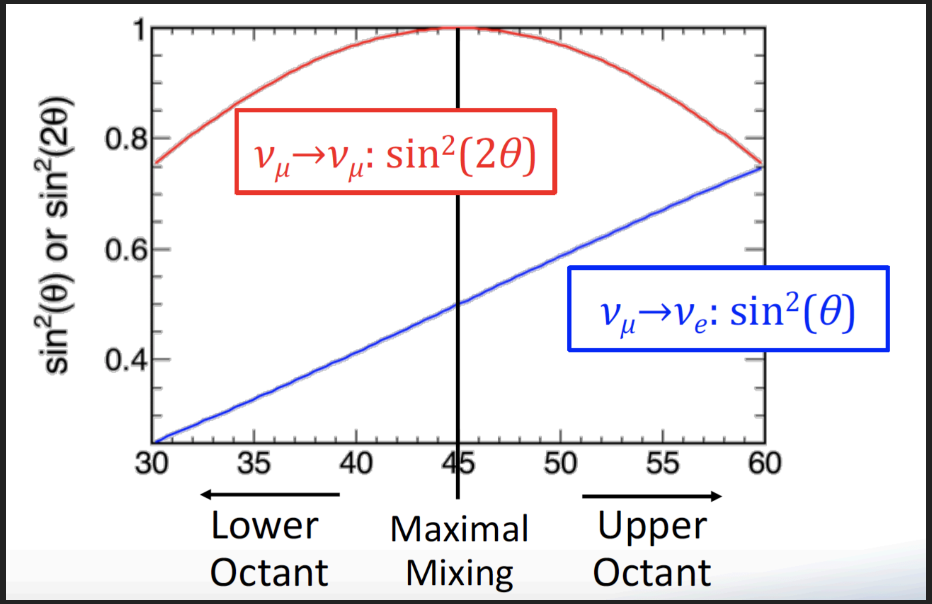
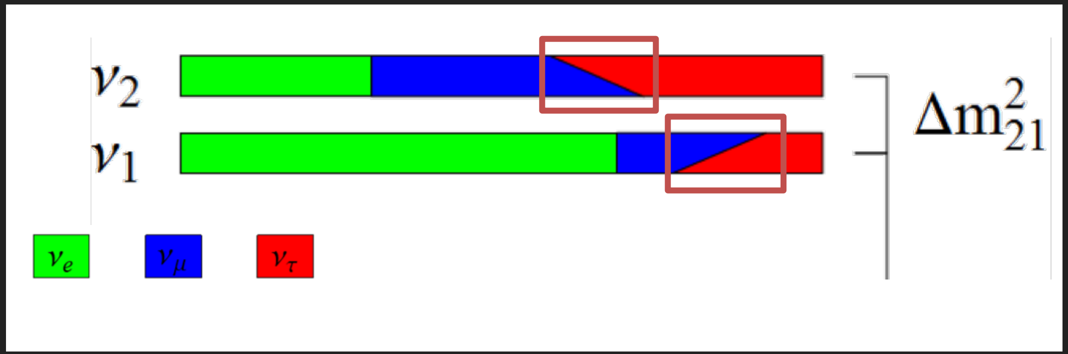
OPEN QUESTIONS

θ_{23} degeneracy (how close to 45°?)



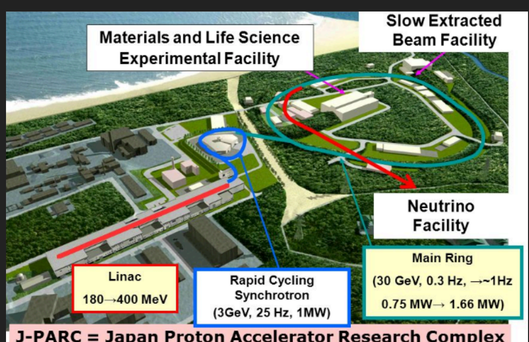
- What is the "octant" of θ_{23}?
- What is the balance ν_μ and ν_τ?
- Or is the mixing "maximal" (e.g. even split)?

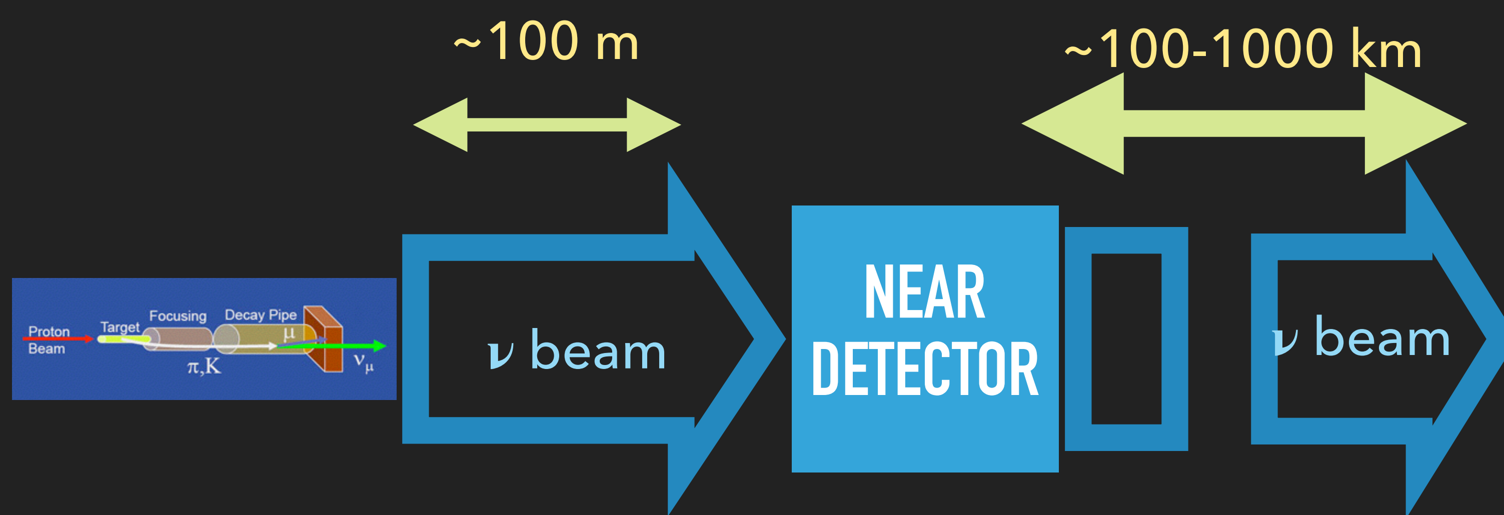


CP VIOLATION PROSPECTS

- Large θ_{13} makes the search for CP possible but not ideal.
- Degeneracy with the mass hierarchy.
- CP violating effects are more pronounced at lower energies.
- More intense beam power and larger detectors are needed for the next generation of long baseline experiments to measure CP violation.
- Two main experiments are planned:
  - Hyper-Kamiokande (Japan): 295 km baseline from J-PARC. Water Cherenkov technology.
  - DUNE (US): 1300km baseline w/ Fermilab beam. Liquid Argon technology. Please see today's talk by Antonio Ereditato
- The feasibility of other future projects worldwide is also being investigated.

LONG BASELINE EXPERIMENTS IN A NUTSHELL





$$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\varepsilon_{ND}$$

Neutrino flux prediction	Neutrino cross section model	Near detector selection, efficiency

- Predicted events in the Near Detector.

$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\varepsilon_{FD}P(\nu_\alpha \rightarrow \nu_\beta)$$

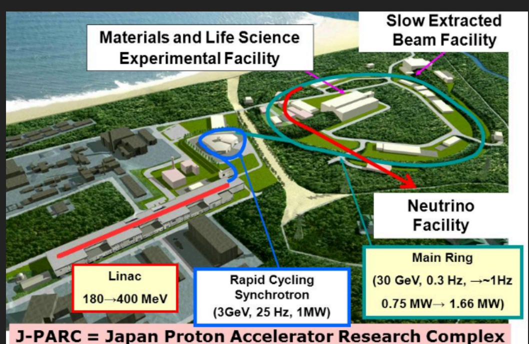
Neutrino flux prediction	Neutrino cross section model	Far detector selection, efficiency

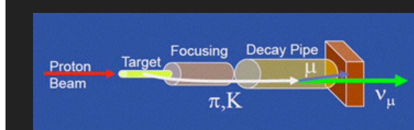
- Predicted events in the Far Detector.

LONG BASELINE EXPERIMENTS IN A NUTSHELL

~100 m

~100-1000 km



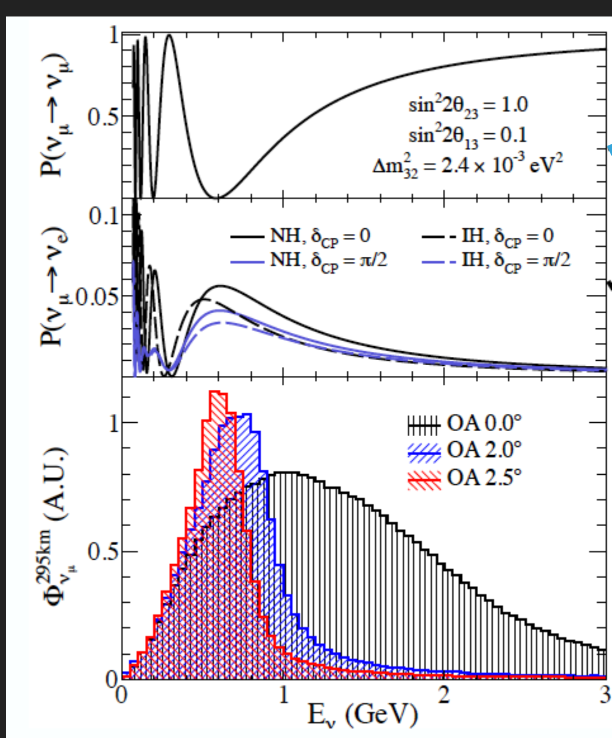


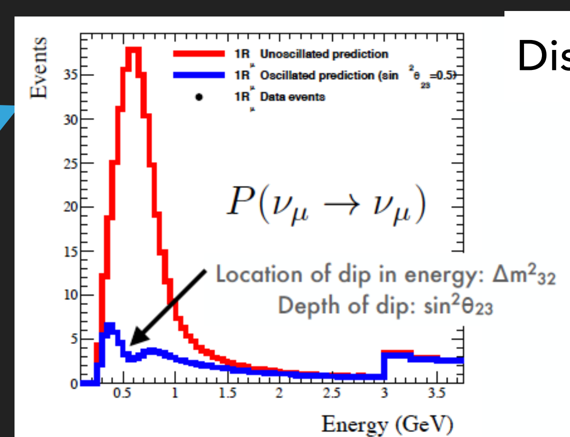
ν beam

NEAR DETECTOR

ν beam

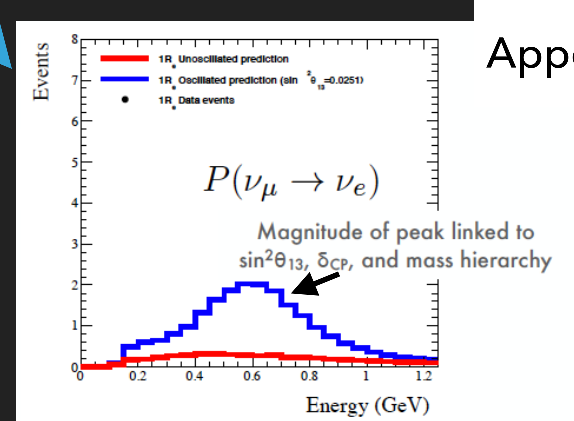
FAR DETECTOR





Disappearance Channel

Location of dip: Δm^2_{32}
Depth of dip: $\sin^2 2\theta_{23}$



Appearance Channel

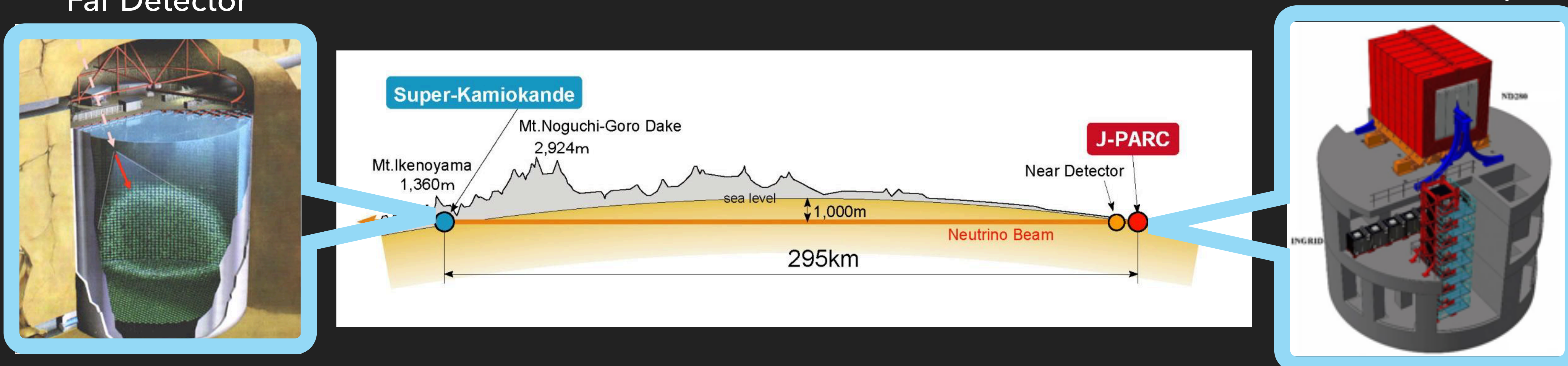
Magnitude of peak:
$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}

CURRENT AND FUTURE LONG BASELINE EXPERIMENTS IN JAPAN

T2K (now) - See talk by Nguyen Thi Hong Van

Far Detector

Near Detector complex



2.5deg off-axis

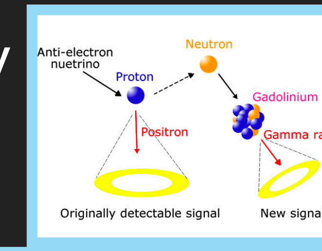
2.5deg off-axis

T2K phase 2 (or T2KII) ~2021 - see next slides

Hyper-Kamiokande - future generation long baseline neutrino experiment

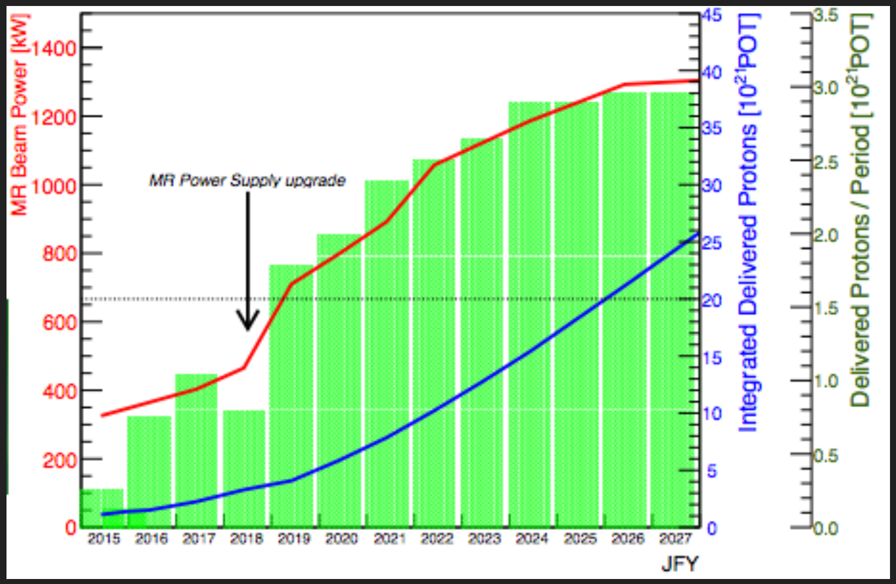
T2K PLANS

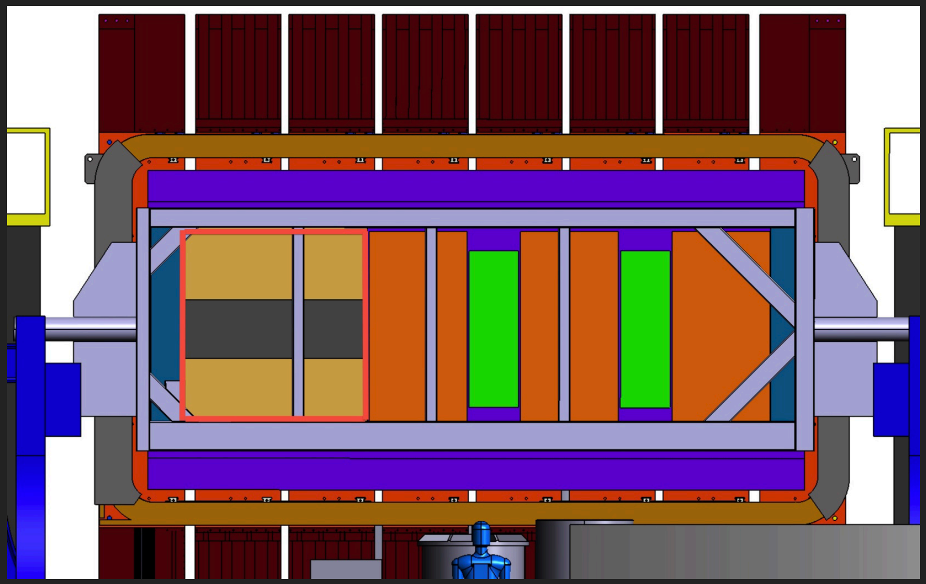
- $\bar{\nu}$ beam has been operating at 475kW from last Autumn to May. This will equalize the ν to $\bar{\nu}$ beam ratio.
- Summer 2018 SK has been opened for PMT repair and leak fixing, then Gd (see talk by Yuuchi Nakano)

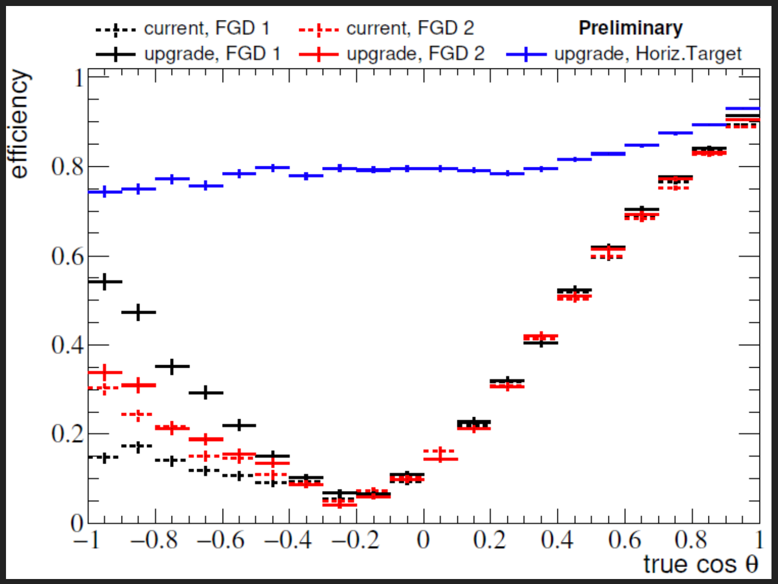


- enhance neutron detection capability
- • improves low energy antineutrino detection

- T2K originally approved to take 7.8x10^{21} POT (~2021).
- T2K-II: proposal to extend T2K running to 20x10^{21} POT (~2026).
- Exclude CP conserving values of δ_{CP} at 3σ if δ_{CP} is near current best fit.
- Refurbished near detector to reduce systematic errors.







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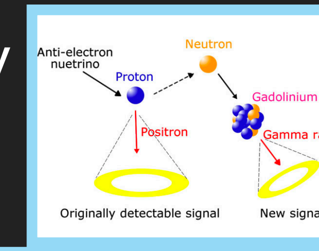

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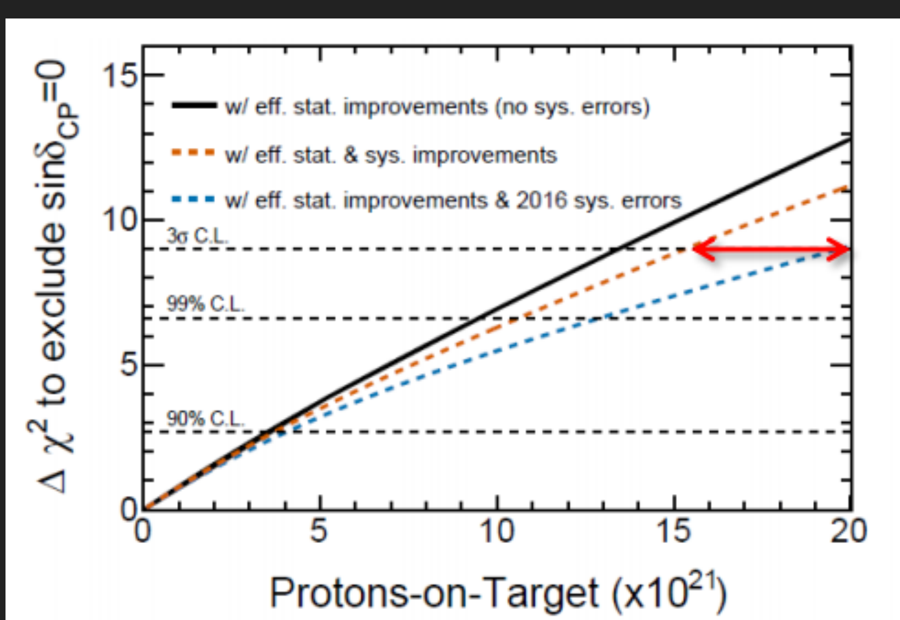
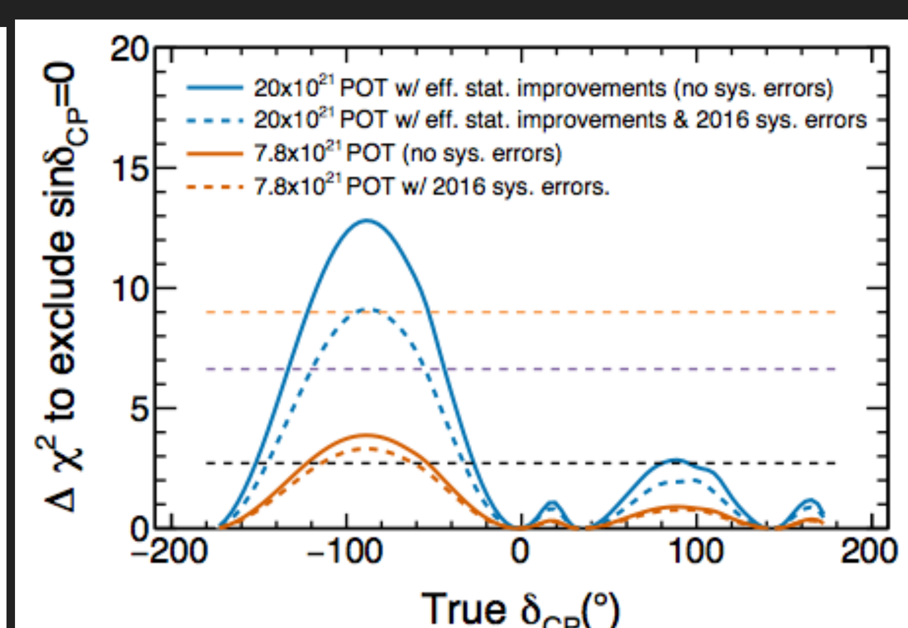
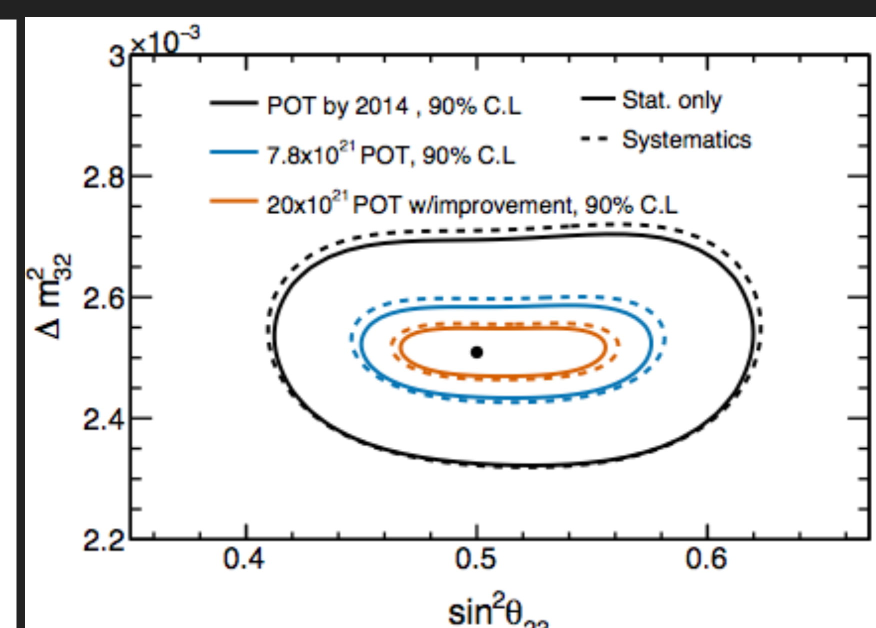
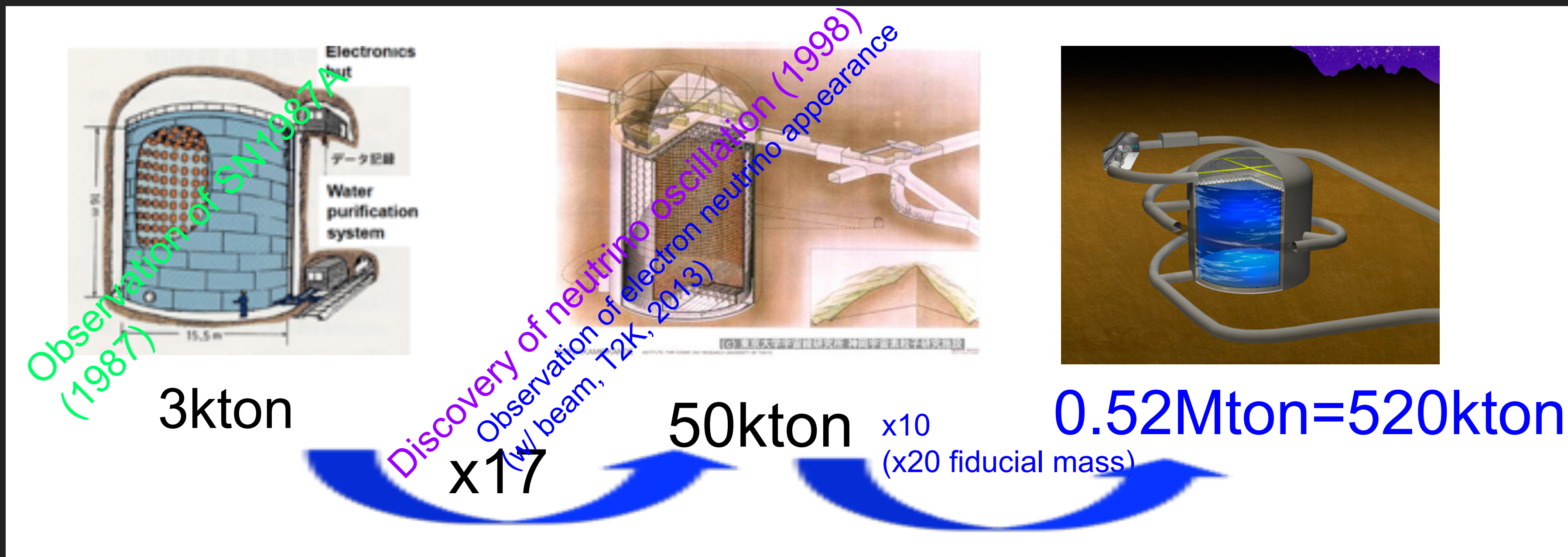
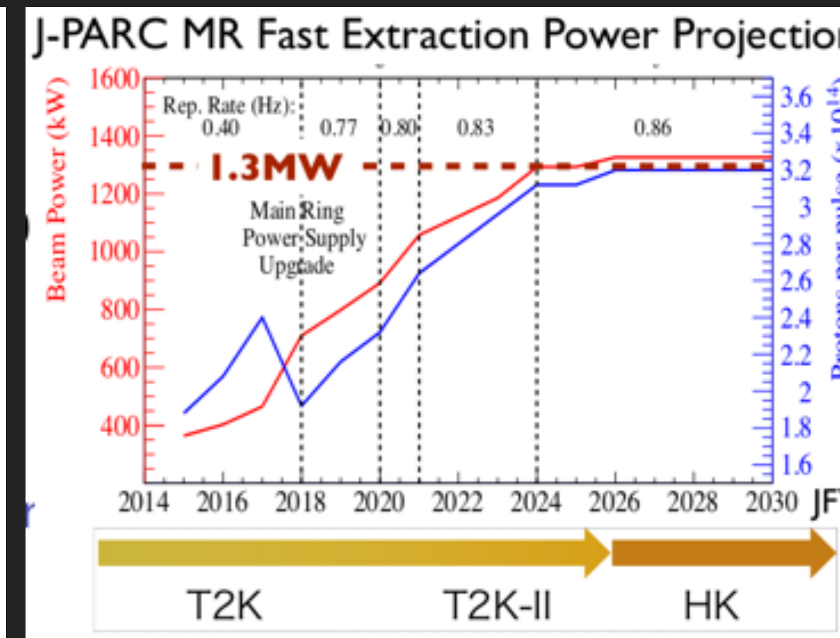




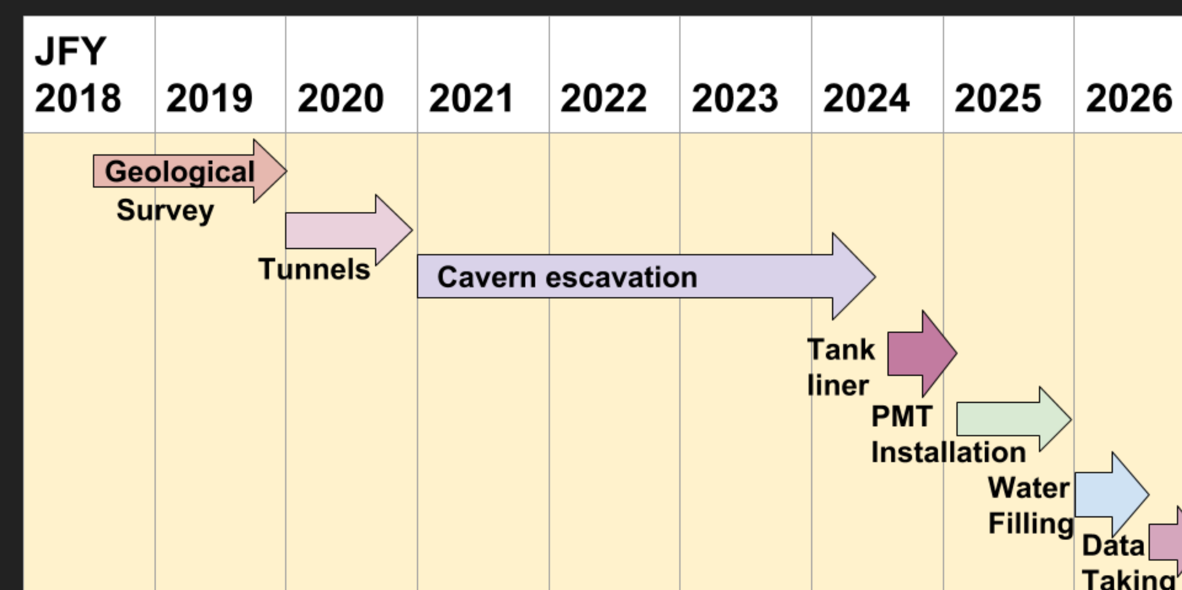


HYPER-KAMIOKANDE



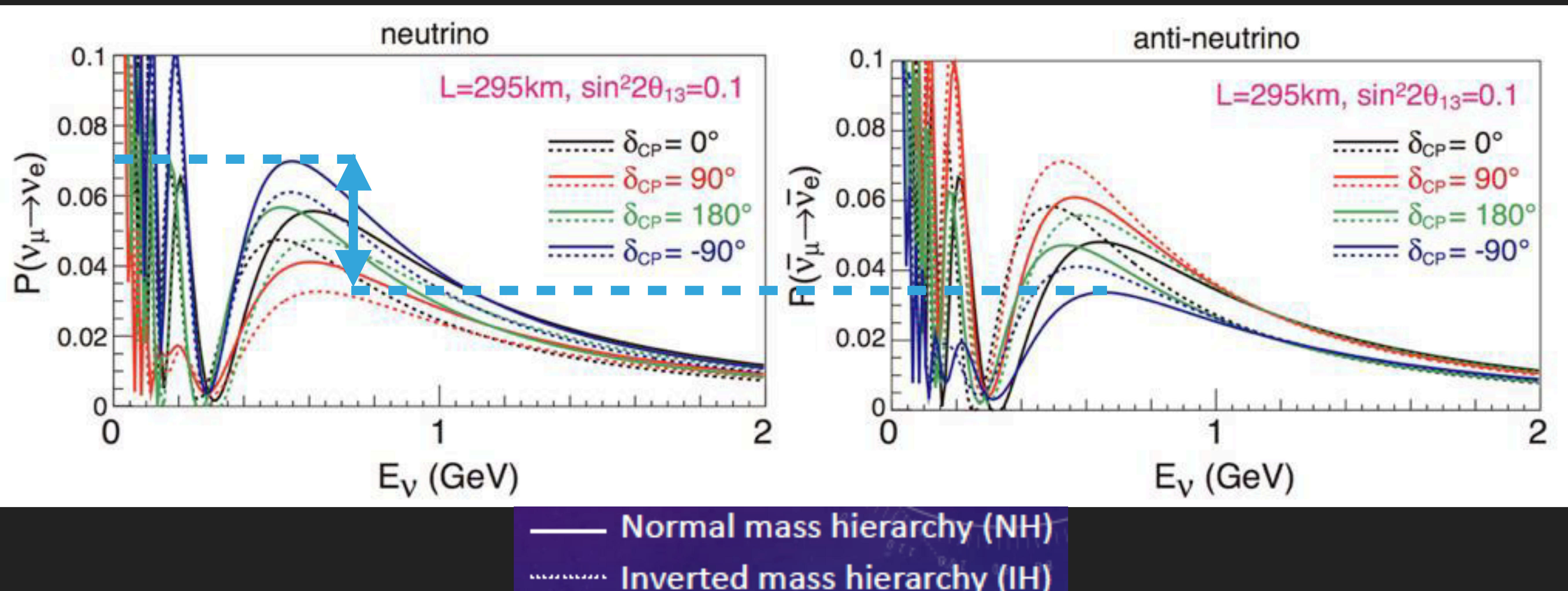


- Scale up from SK and T2K. Continuous upgrade plan: T2K-II, near detector upgrades, HK far detector



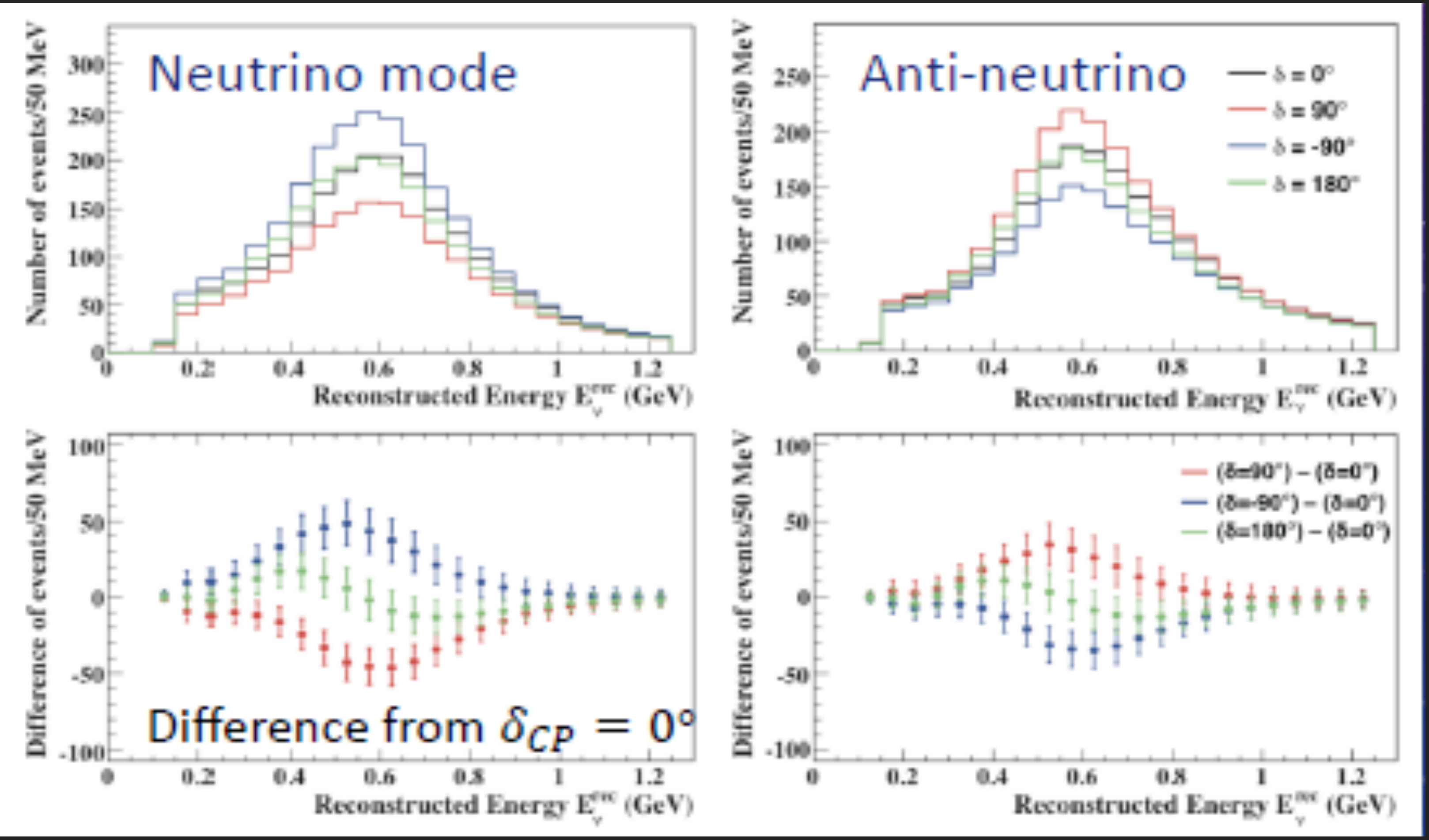
- Requires beam power increase to 1.3MW
- Data taking expected to start in 2026
- Option to put second detector in Korea
- The results from Hyper-K are from the HK Design Report (arXiv:1805.04163 [physics.ins-det])

MEASUREMENT OF CP ASYMMETRY



- Comparison between the probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Up to ~±30 % variation at δ_{CP} = -90°in NH (or 90°in IH) wrt $\sin\delta_{CP}=0$

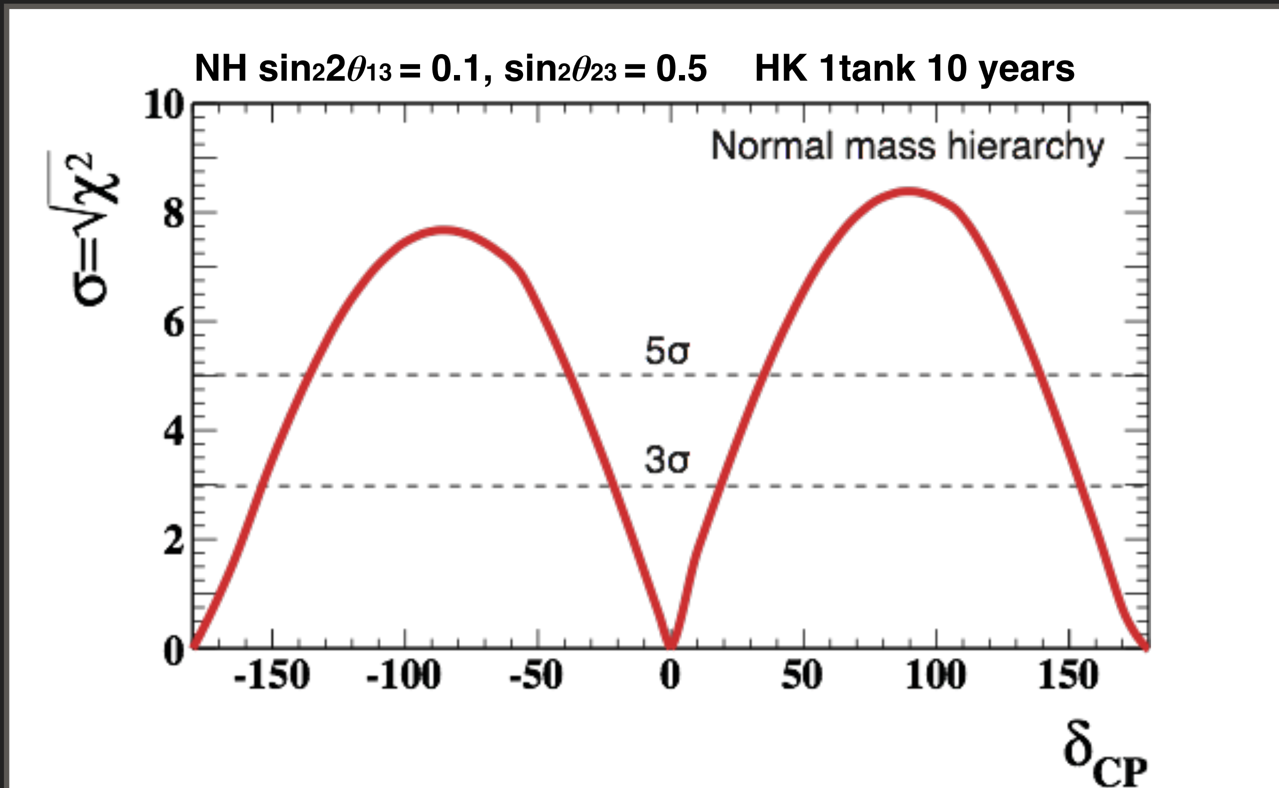
EXPECTED EVENTS IN HYPER-KAMIOKANDE LBN PROJECT

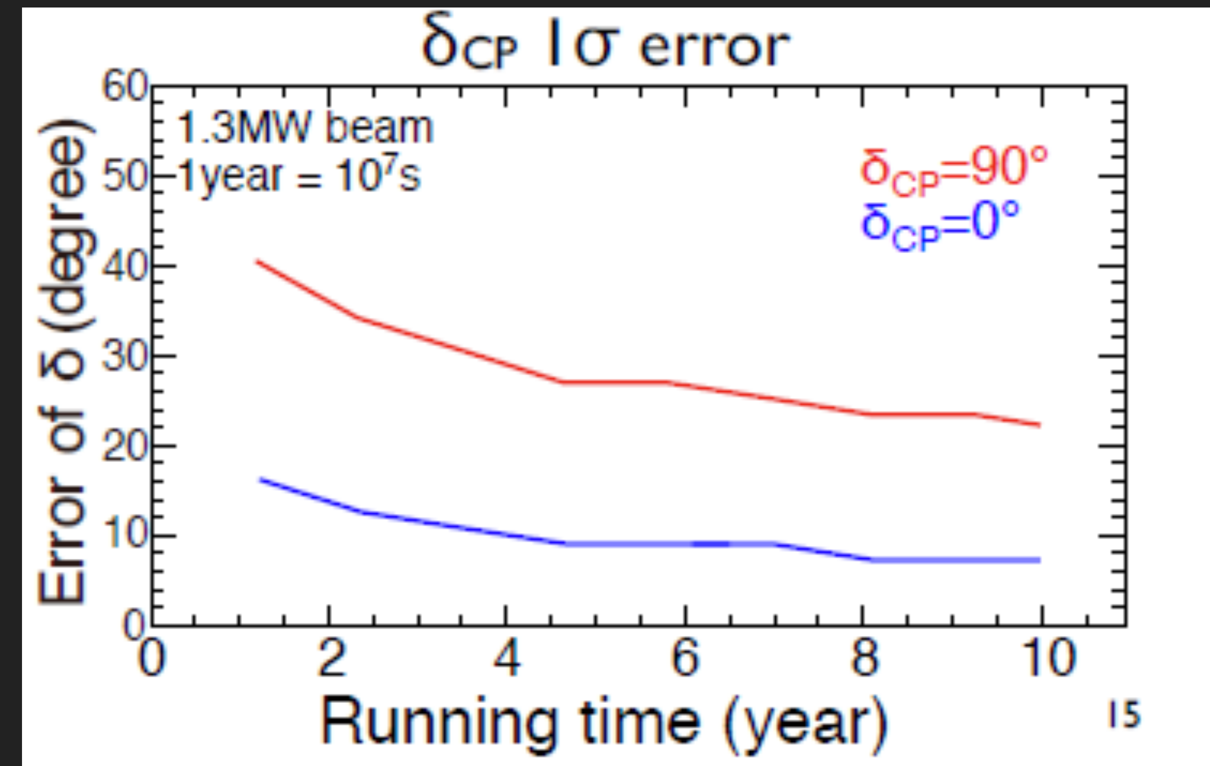


- ComparisonA few % stat. uncertainties on $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signals
- $E\nu$ is reconstracted from (p, θ) of e or μ
- Realistic estimates of wrong sign & NC BG contamination are based on T2K

for $\delta_{CP} = 0$	Signal $\nu_\mu \rightarrow \nu_e$ CC	Wrong sign appearance	$\nu_\mu / \overline{\nu}_\mu$ CC	Beam $\nu_e / \overline{\nu}_e$ contamination	NC
ν beam	1,643	15	7	259	134
$\overline{\nu}$ beam	1,183	206	4	317	196

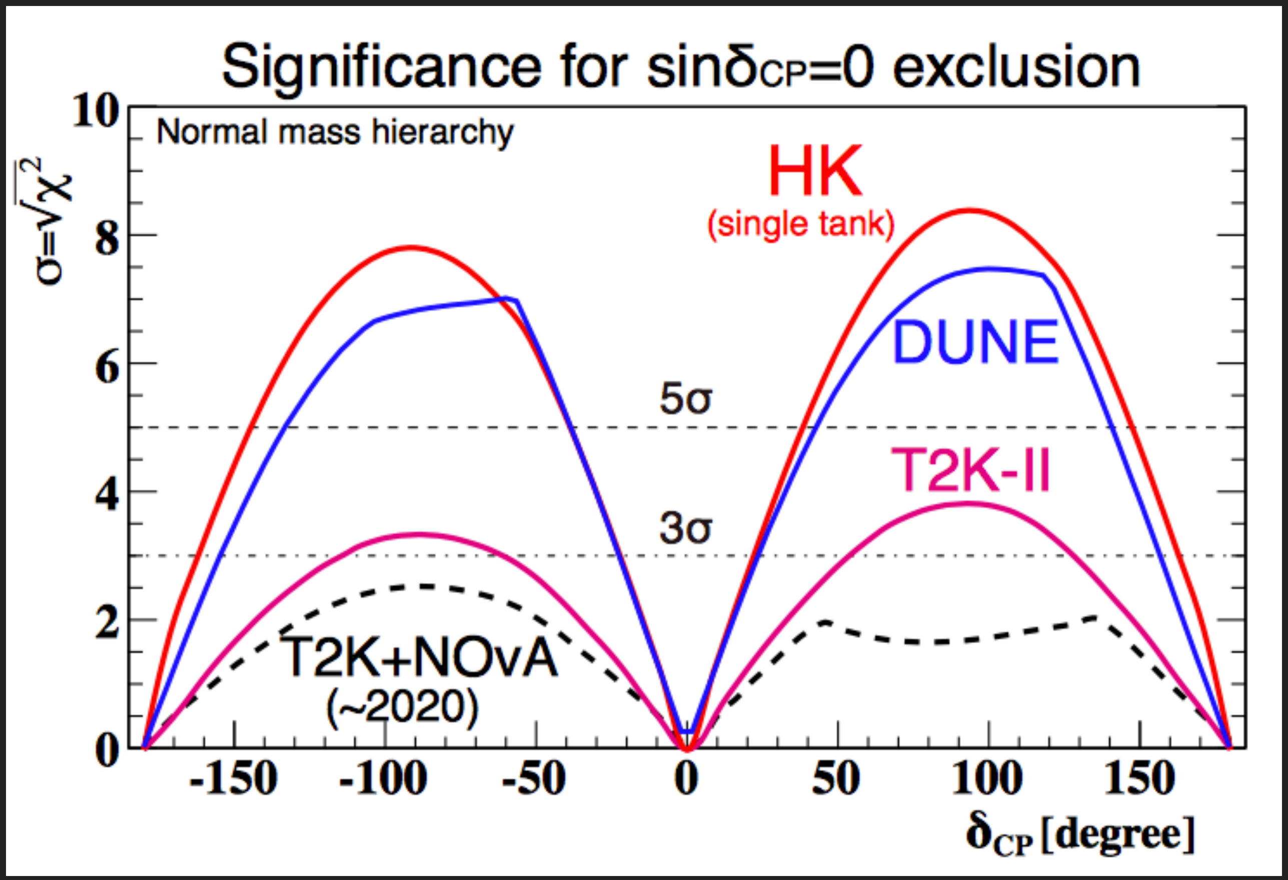
CP VIOLATION SENSITIVITY

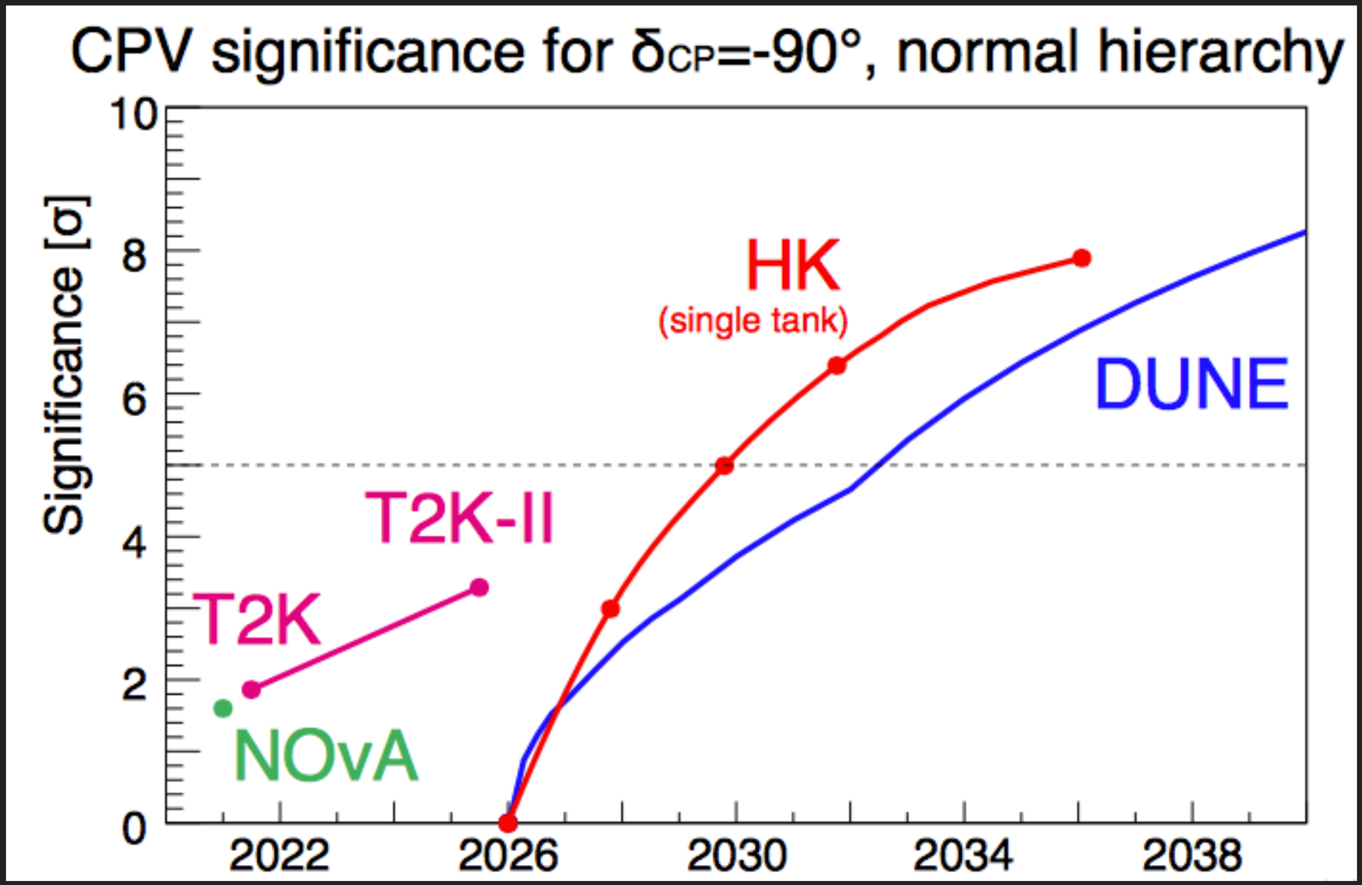




- Exclusion of sinδ_{CP} = 0
  - 8σ for δ = -90°(T2K best fit)
  - 80 % of coverage of δ parameter space for CPV discovery > 3σ
- δ_{CP} precision measurement
  - 22°for δ = -90°
  - 7°for δ = 0°
- After 10 years of running, HK will be able to measure ~50% of the δ_{CP} space to better than 5σ

CP VIOLATION SENSITIVITY





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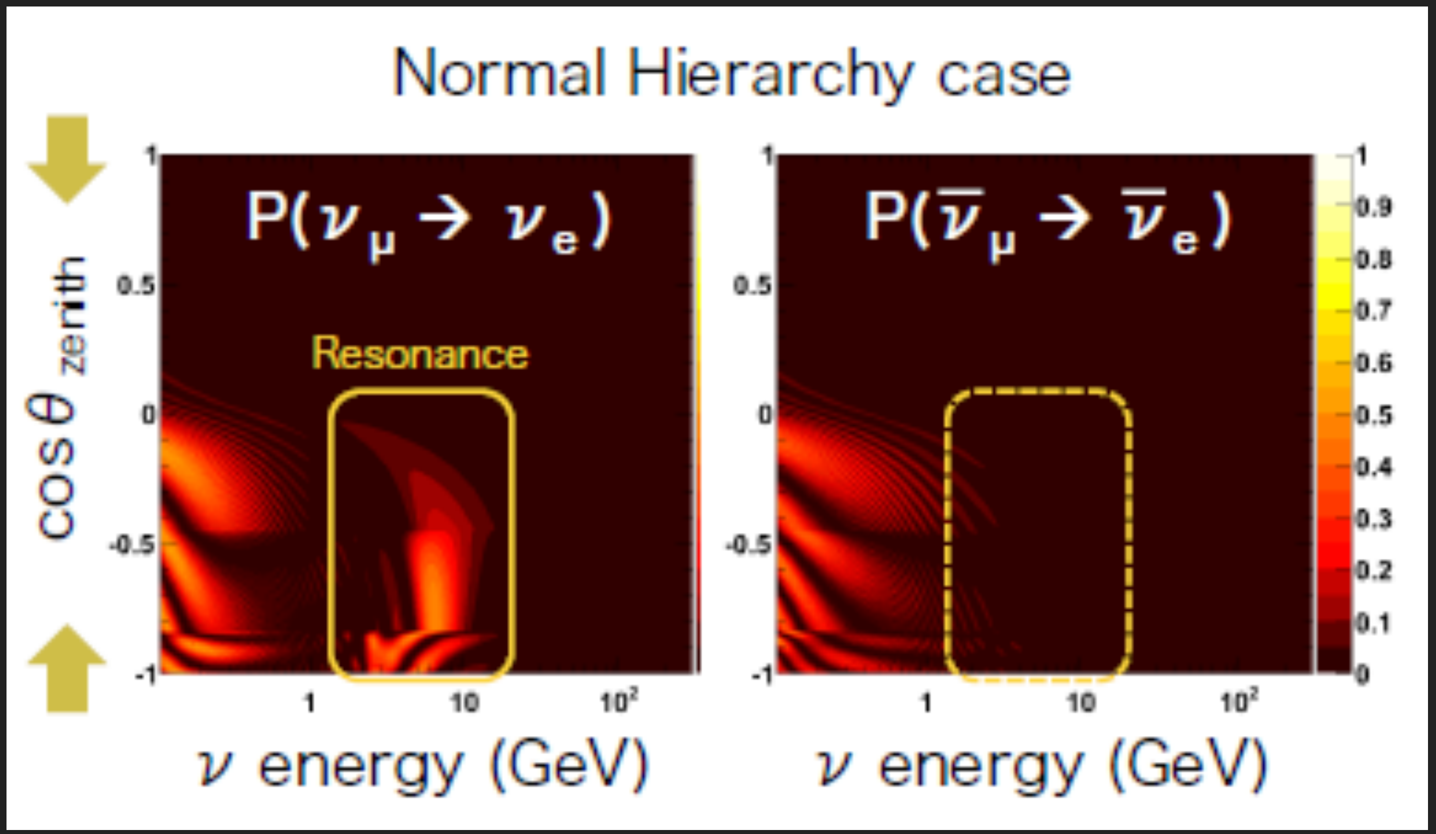
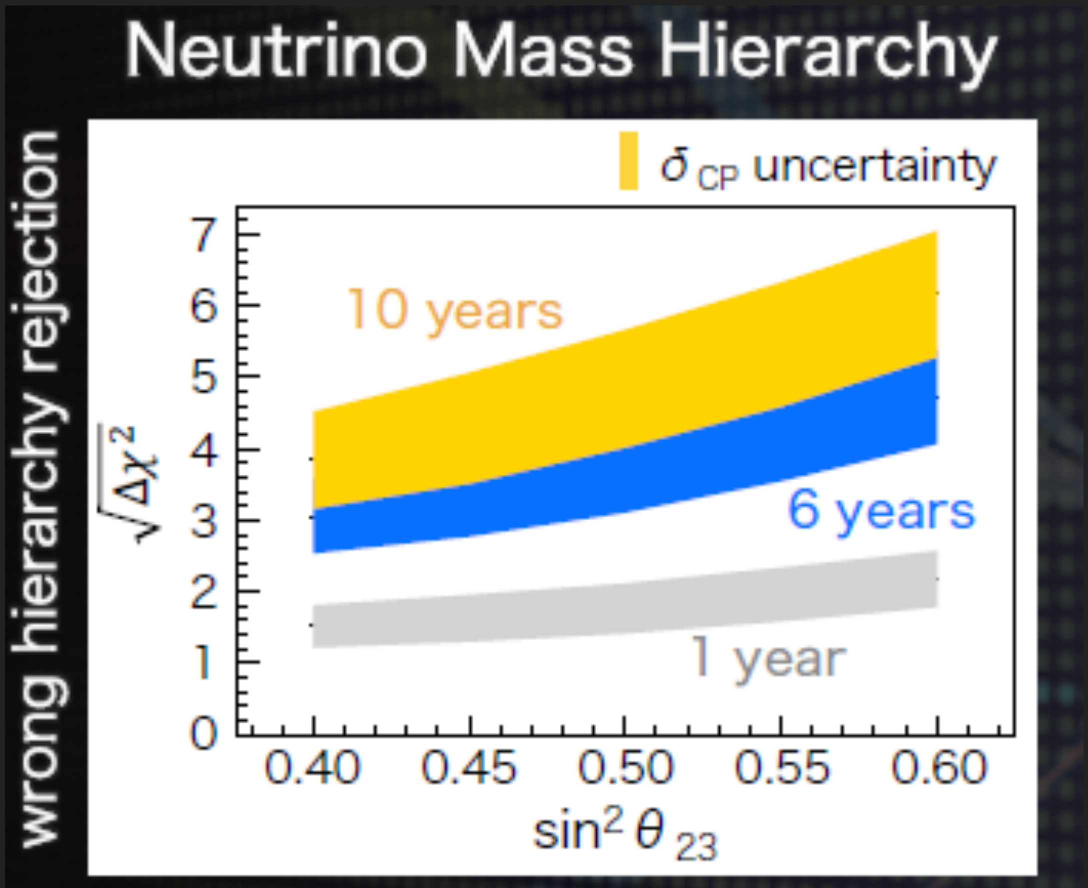
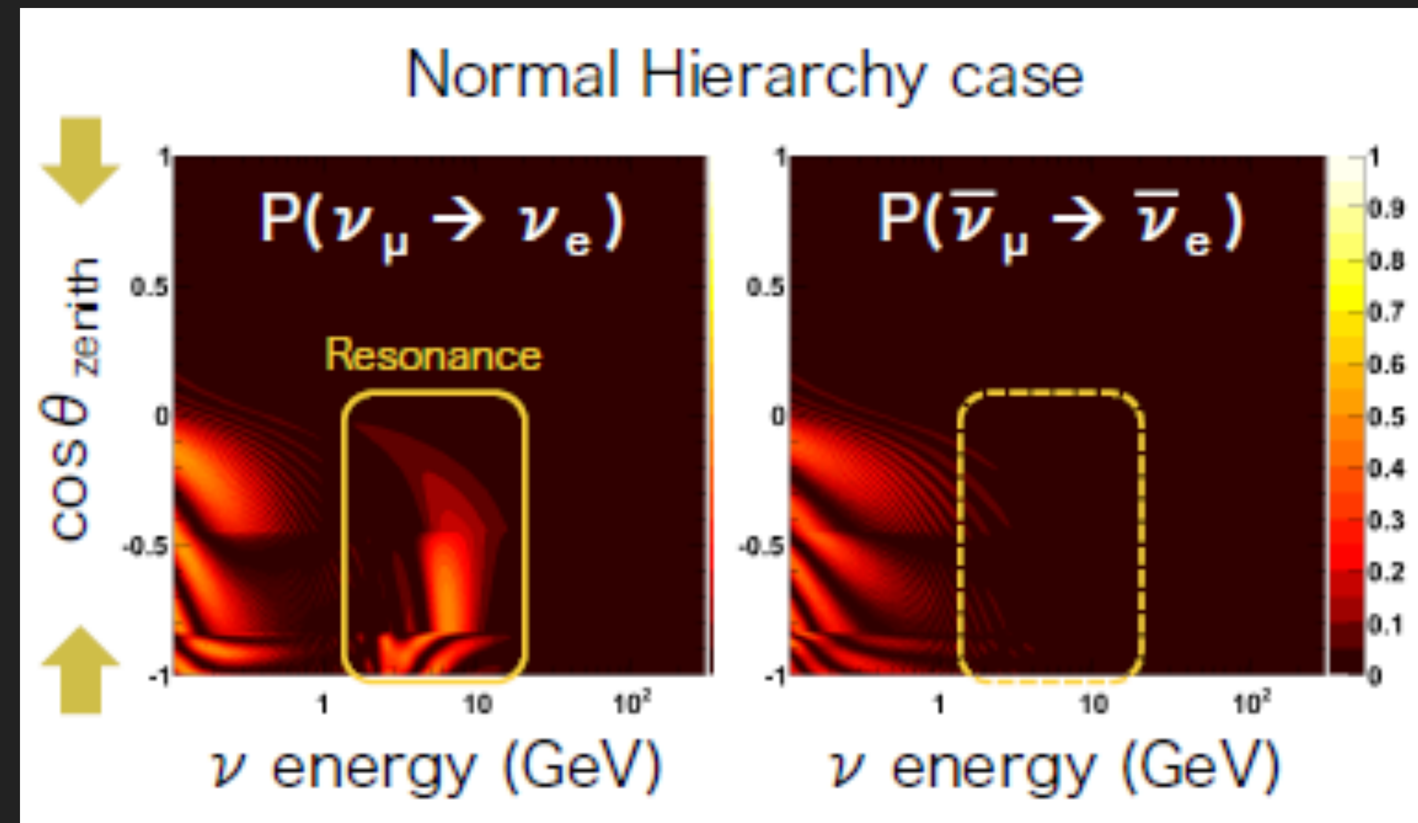
MASS HIERARCHY SENSITIVITY

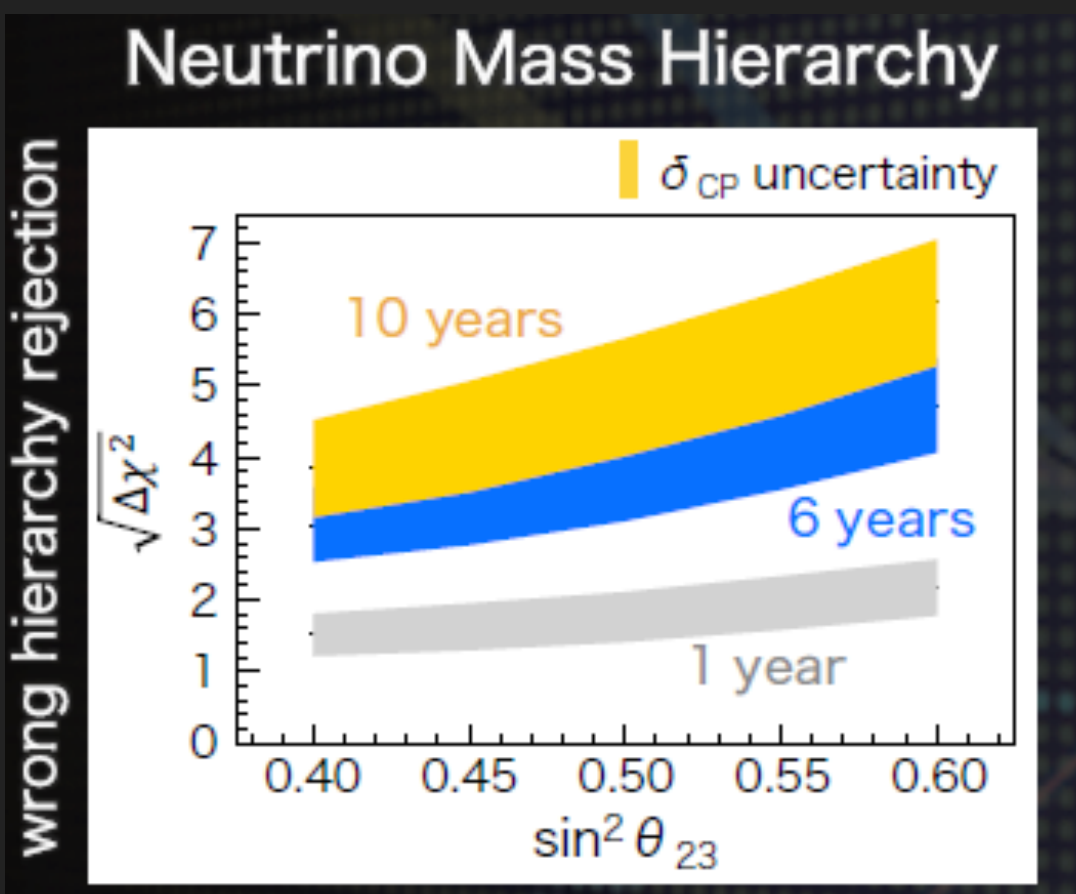




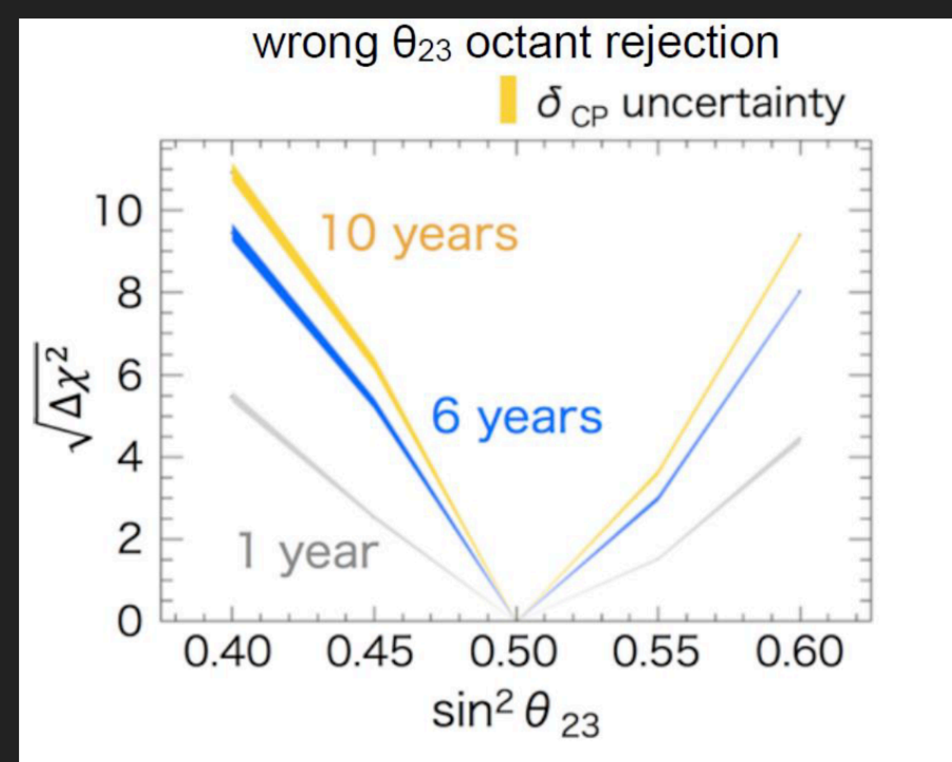
- The resonance appears for ν_e ($\bar{\nu}_e$) in NH (IH) case.
- Sensitivity enhanced by combining atm & beam ν data.
- Determination possible by ~5 years. ($\sin_2\theta_{23}$=0.5) at HK.

MASS HIERARCHY SENSITIVITY





Octant Determination

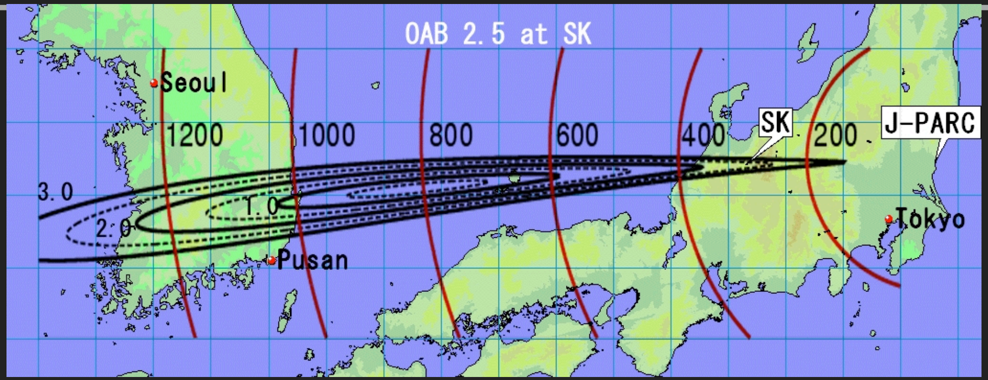


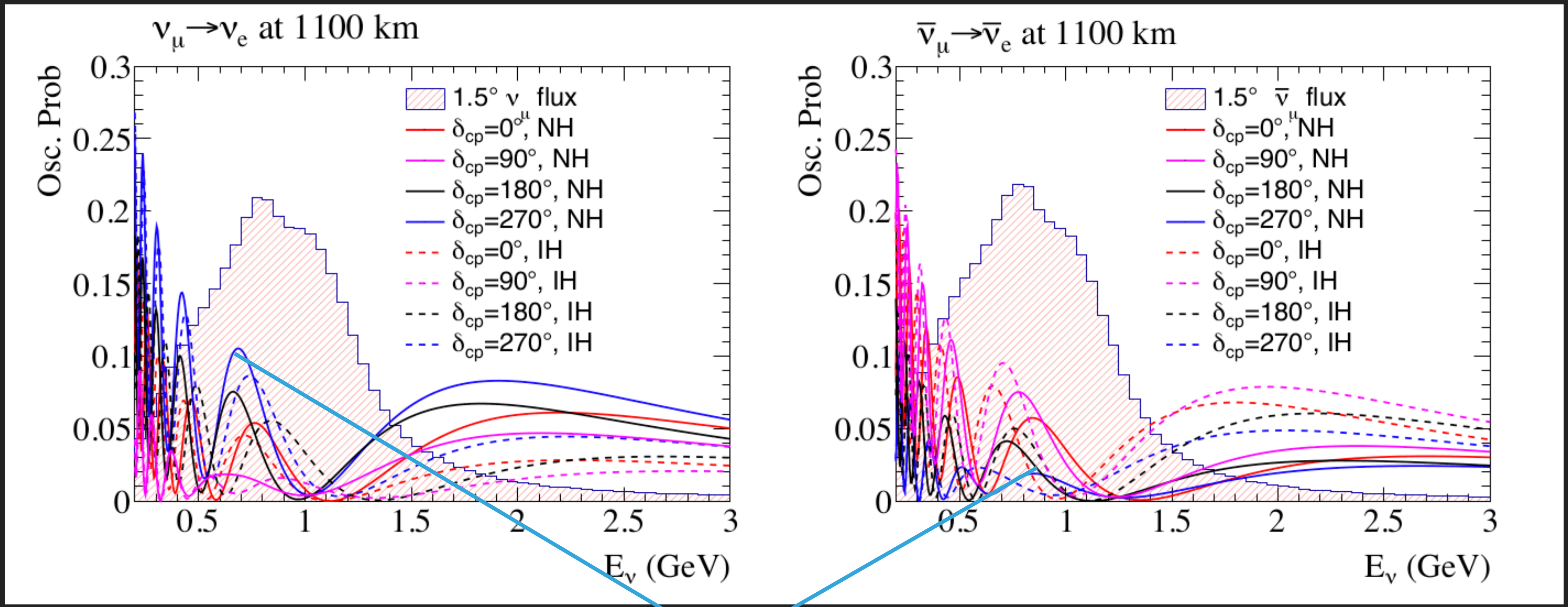
Octant determination > 3 σ CL @

$|\theta_{23} - 45^\circ| > 2.3^\circ$

SECOND DETECTOR IN KOREA FOR HYPER-KAMIOKANDE

- Investigating second detector in Korea to enhance mass hierarchy and δ_{CP} sensitivities
  - 1000 – 1200 km baseline
  - 1.3° - 3.0° off-axis beam direction

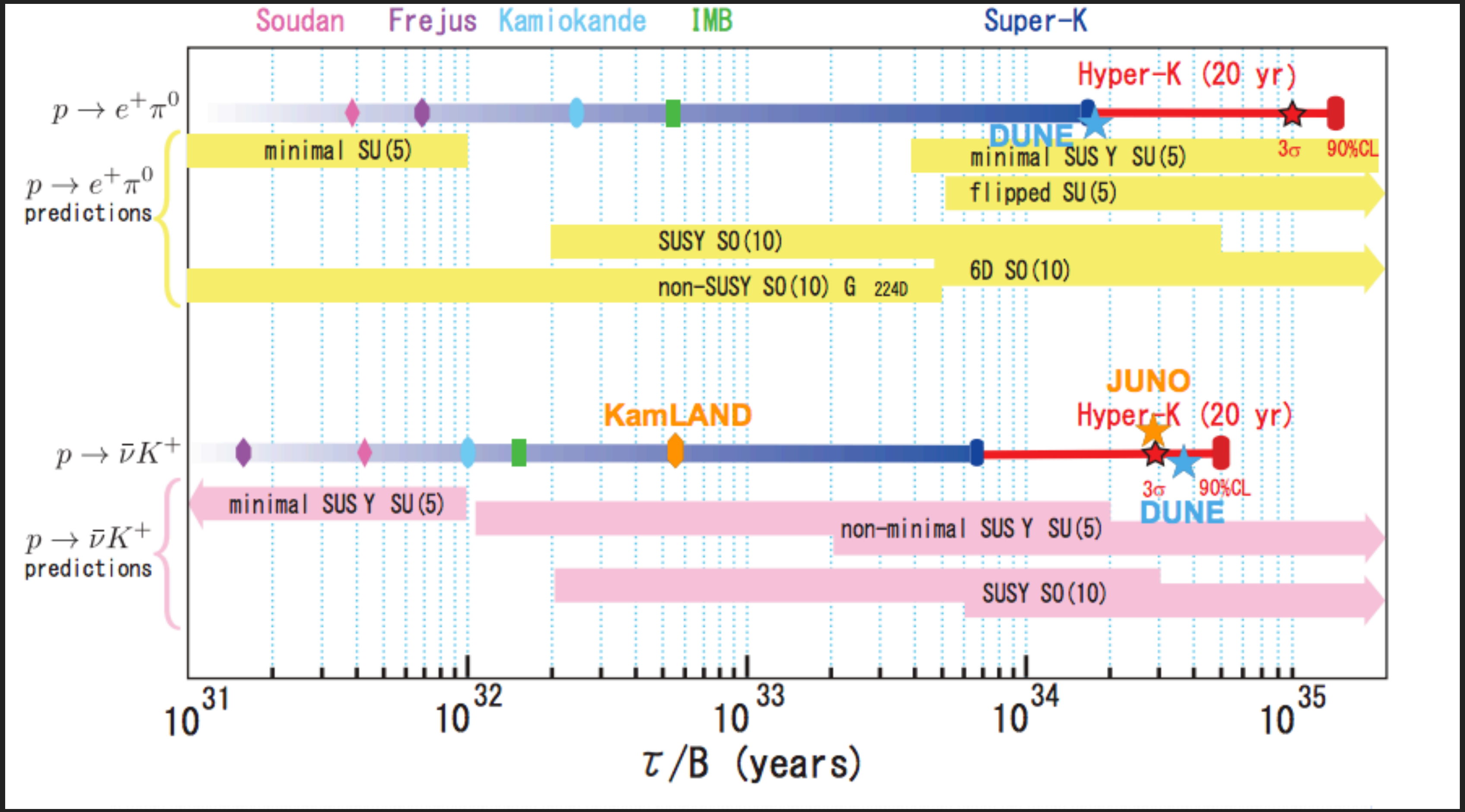




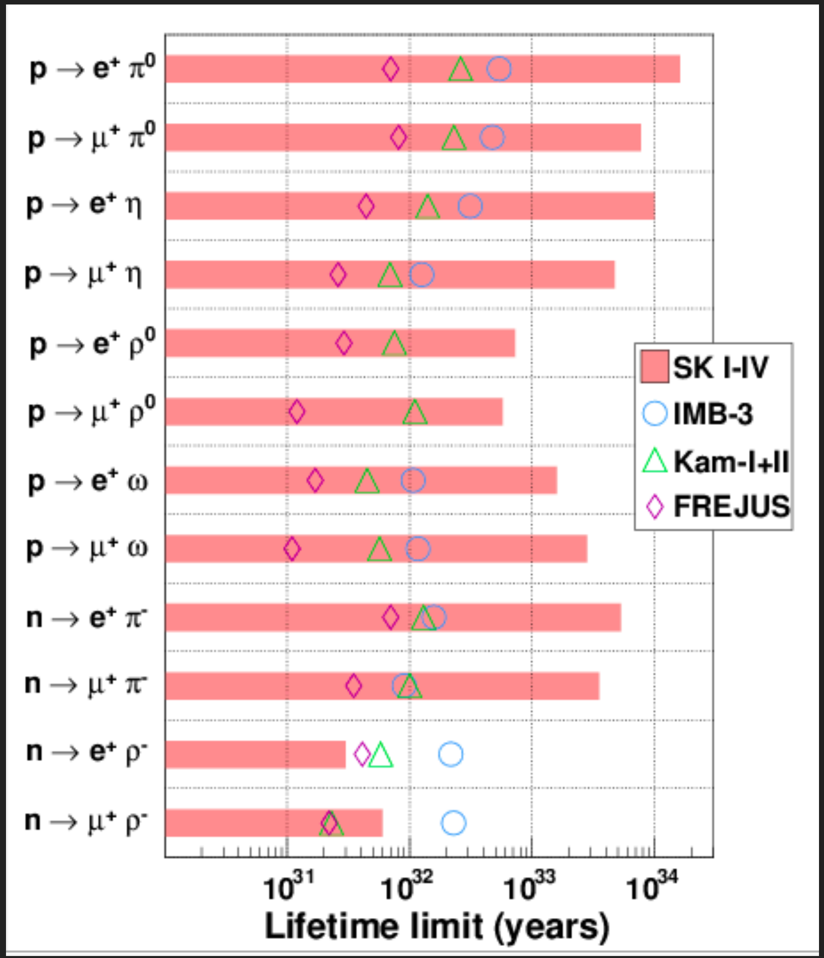
- CP asymmetry between ν and $\bar{\nu}$ is 3 times larger than the 1st oscillation maximum
  - Less sensitive to systematics errors due to larger CP effect
  - Compensate for factor of 3.7 reduction in statistical significance due to flux reduction for longer baseline
- Longer baseline(1100km) leads to larger matter effects
  - MH better determination

PROTON DECAY

- Processes with ΔB ≠ 0, including proton decay, are a general prediction of grand unified theories.
- Hyper-Kamiokande will be able to address the proton decays on a a wide variety of final states

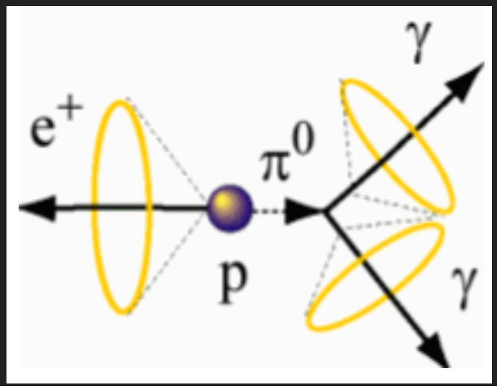


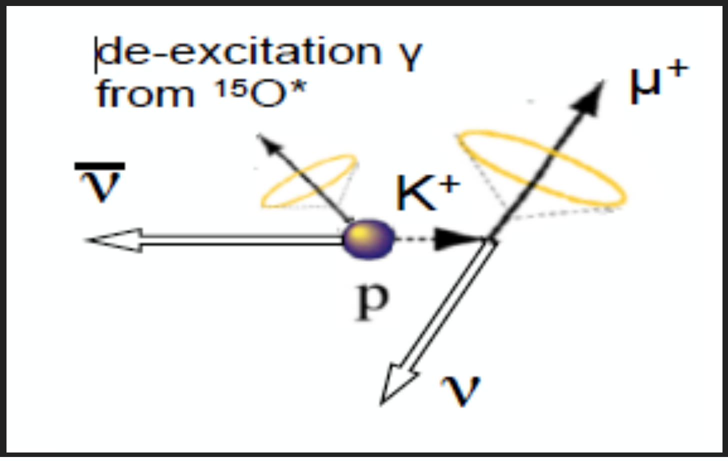
Super-K PRD 96, 012003 (2017)

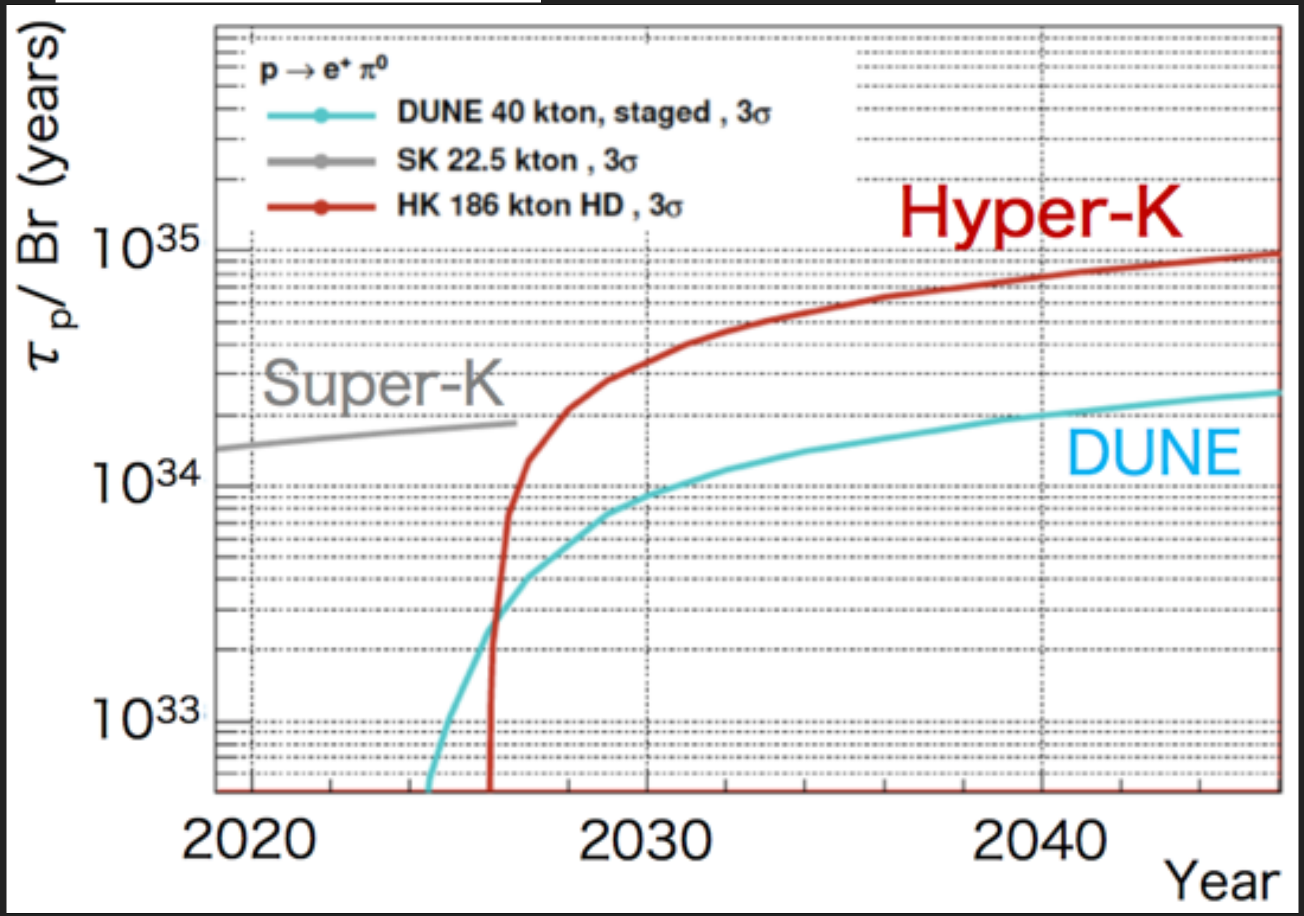


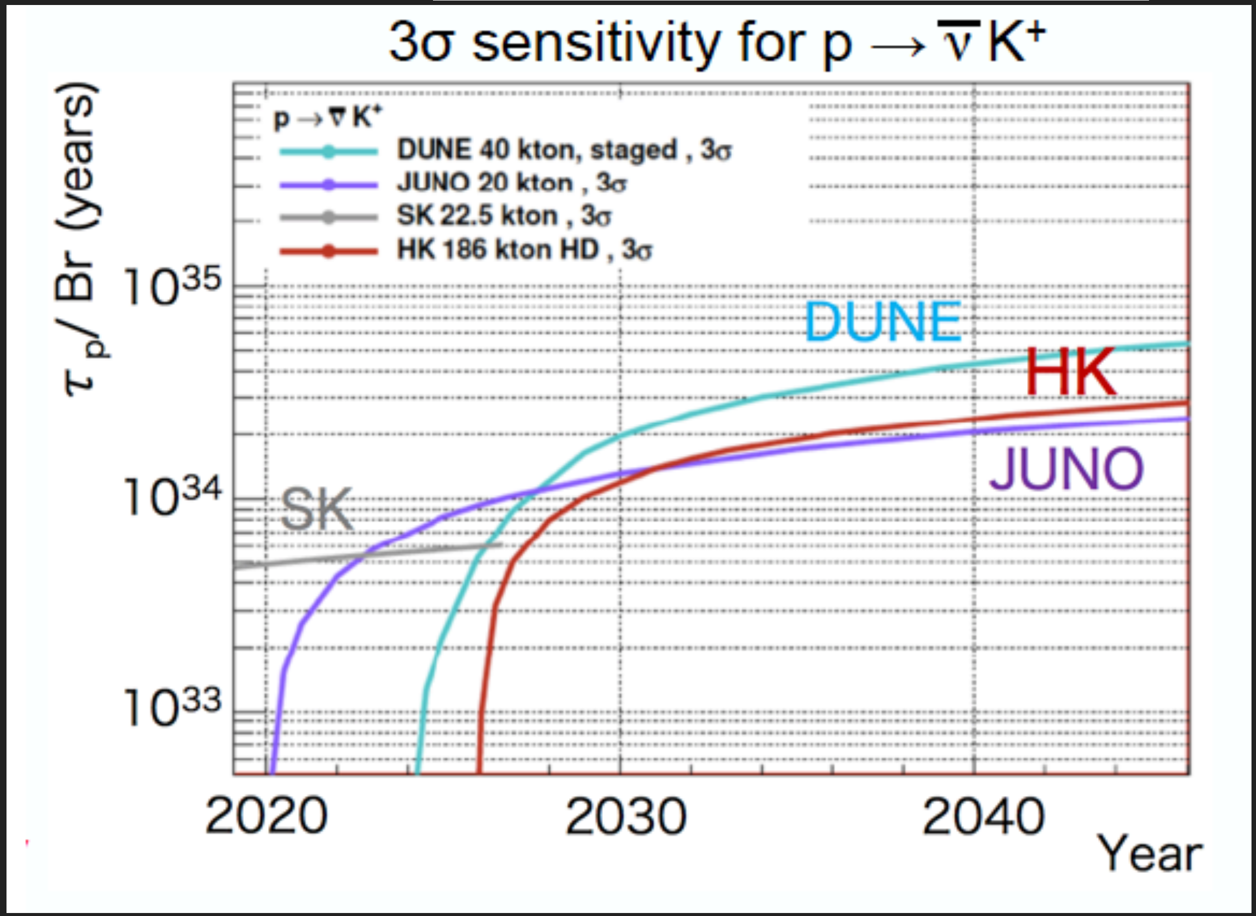
PROTON DECAY

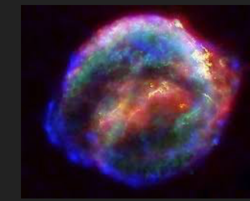
- $p \rightarrow e^+ \pi^0$ favoured by non super-symmetric GUTs a nearly model independent reaction
- $p \rightarrow K^+ \overline{\nu}$ feature of SuperSymmetric GUT



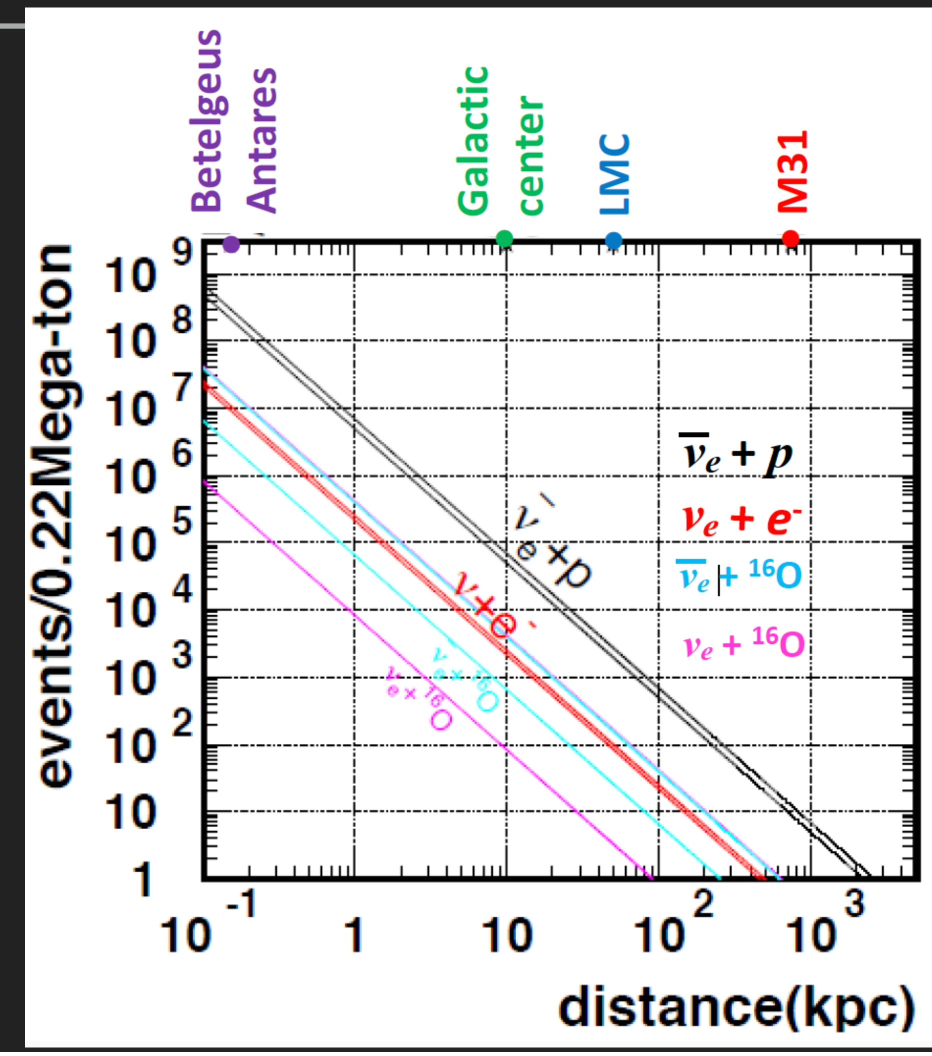








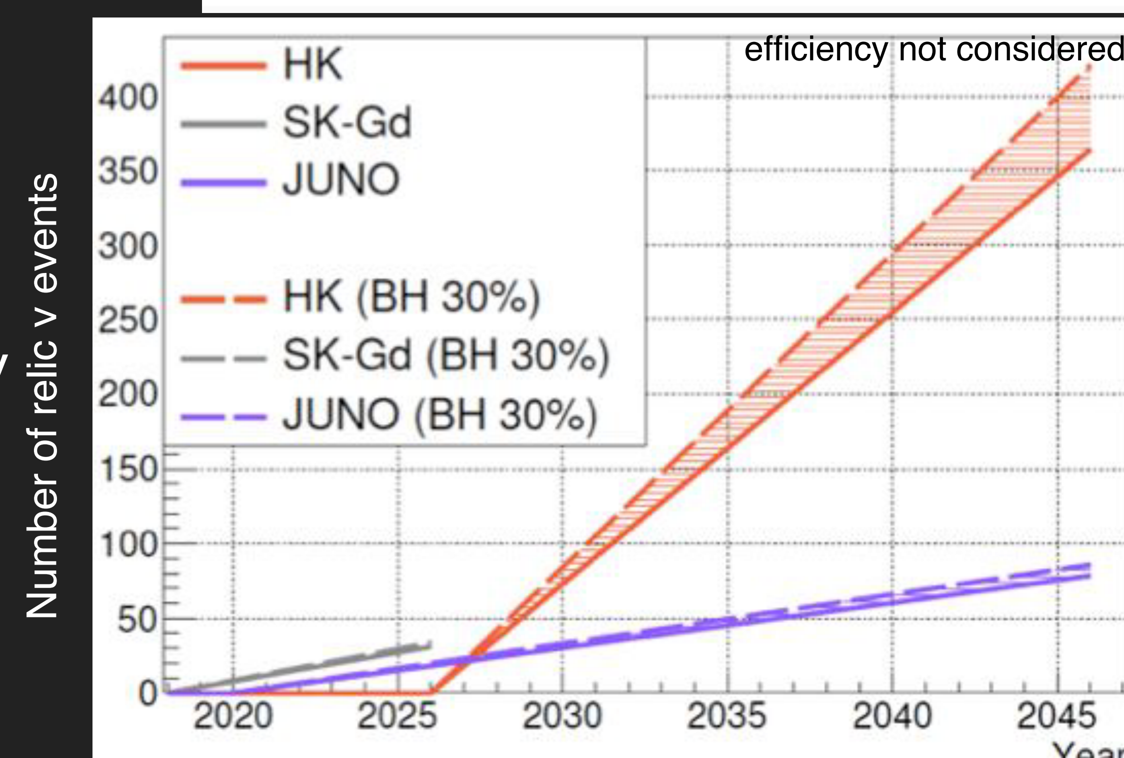
NEUTRINO ASTROPHYSICS/ASTRONOMY



SN BURST

- ~50 – 80 k events/SN @ Galactic Centre (10 kpc)
- Probe of Core-Collapse SN (CCSN) in detail: Explosion mechanism (model identification); Generation of proto-neutron star; Nucleosynthesis in SN
- Physics property of neutrinos
- Multi-messenger measurement: Time & energy profiles with high statistics; 1°pointing for SN @ 10 kpc

SN RELIC NEUTRINOS



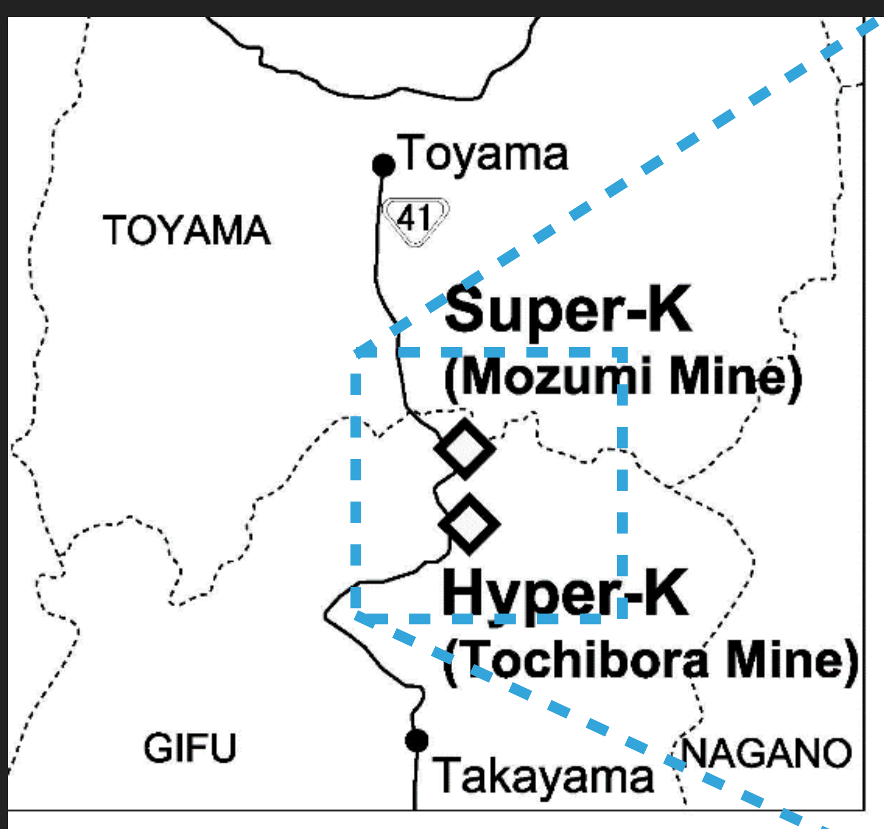
- SRN could be observed by HK in 20y with 140±25 events (5.7σ, with 1 tank). We will go beyond the discovery and aim to measurement, e.g. model constrain.1st discovery by SK-Gd

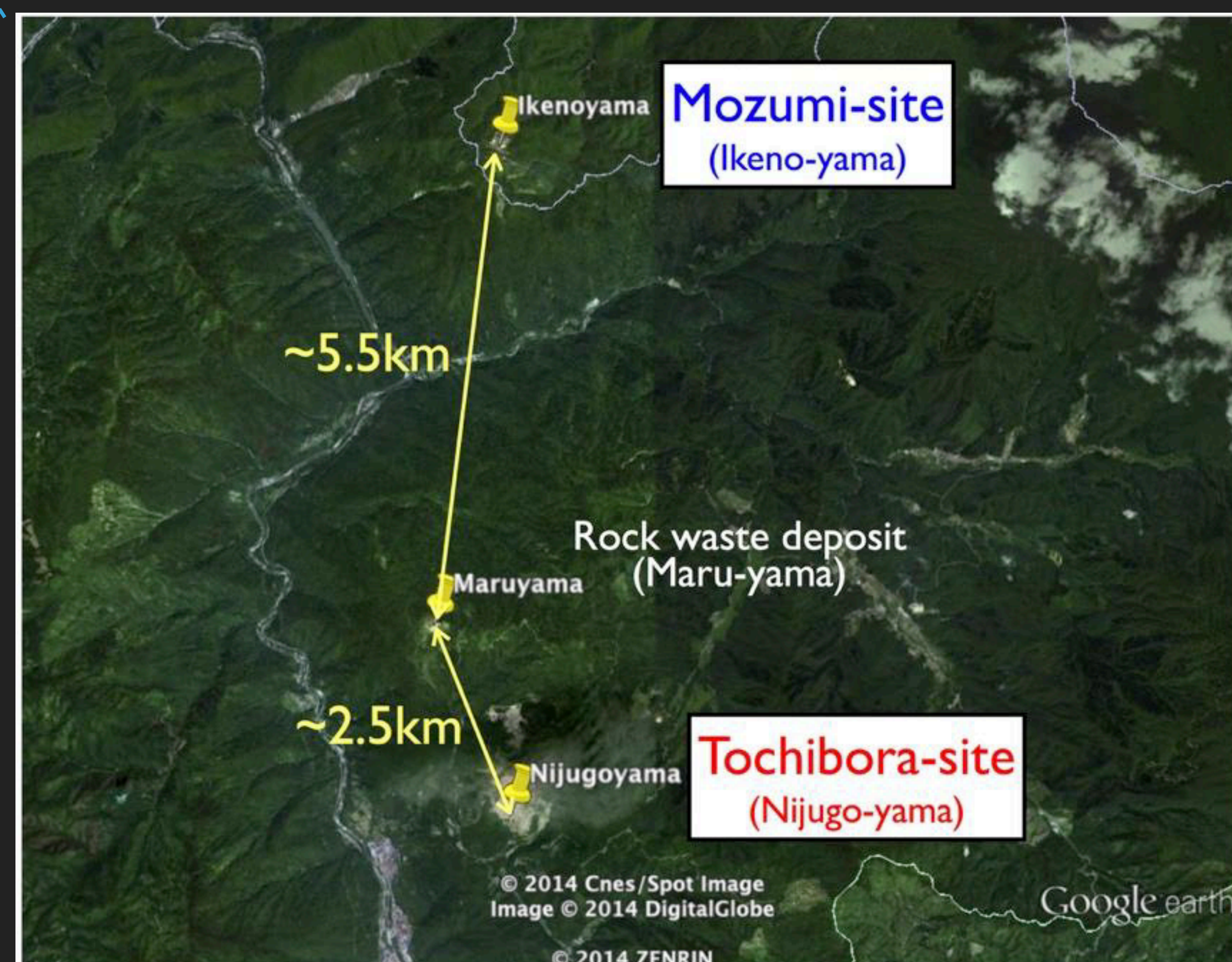
OTHERS

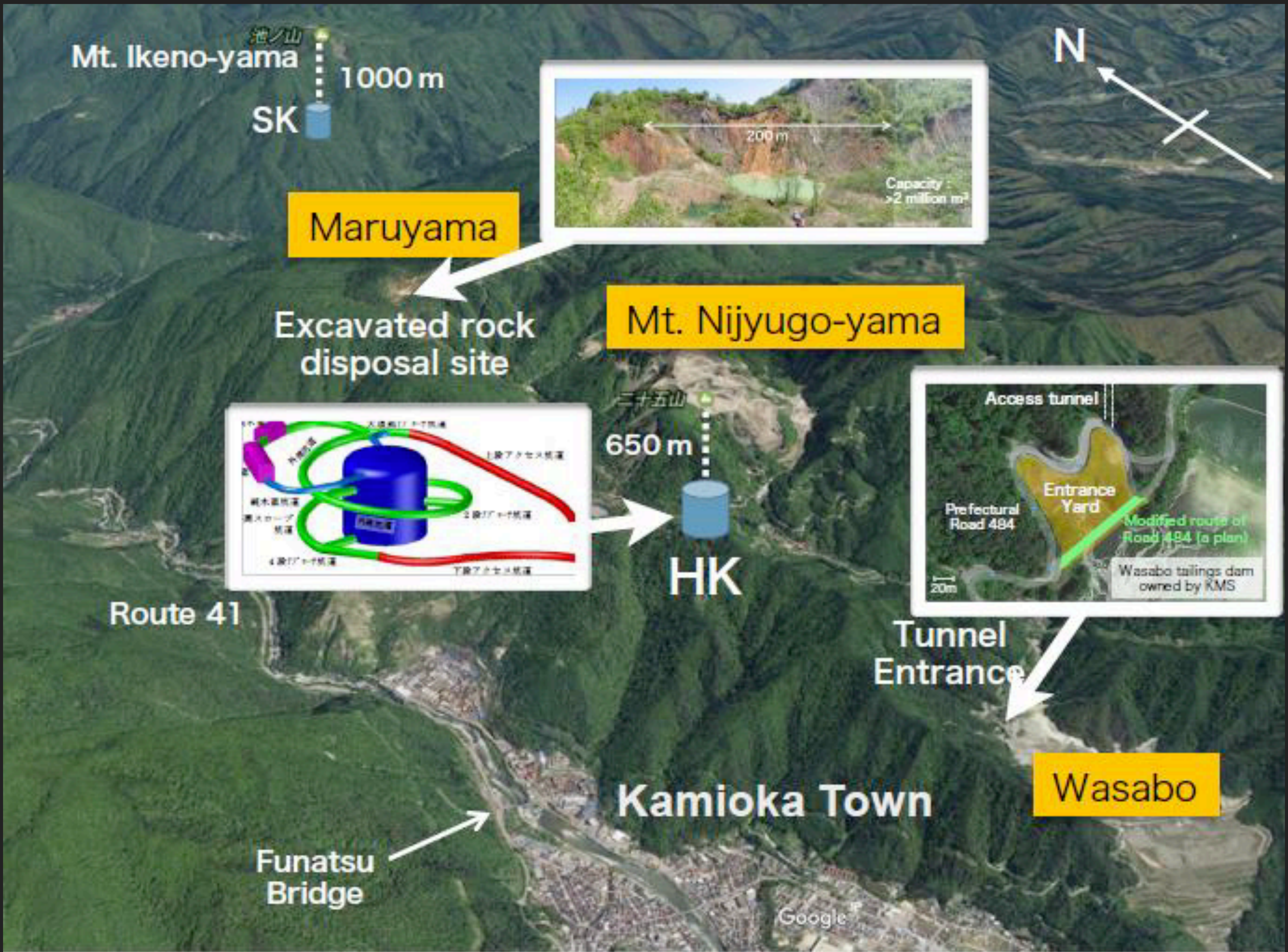
- 1st discovery by SK-Gd Solar ν (day/night, upturn, Hepν), WIMP ν, surprise?

DETECTOR SITE

- Tochibora mine in Kamioka
- ~8km south from Super-K
- Identical baseline (295km) and off-axis angle (2.5^{o}) to Super-K for J-PARC beam
- Overburden ~650m (~1755m.w.e.) cf. SK ~2700m.w.e.

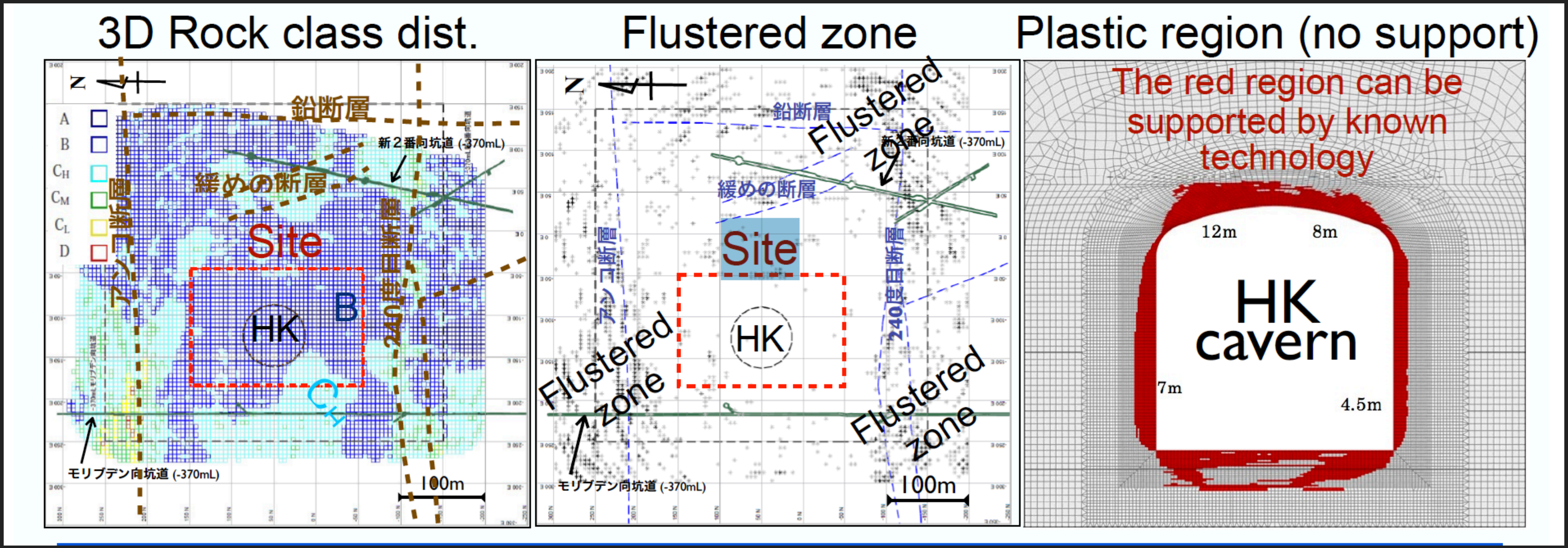





池ノ山
Mt. Ikeno-yama
1000 m
SK
N
200 m
Capacity :
>2 million m²
Maruyama
Excavated rock
disposal site
Mt. Nijyugo-yama
二十五山
650 m
HK
Access tunnel
Entrance
Yard
Prefectural
Road 484
Modified route of
Road 484 (a plan)
20m
Wasabo tailings dam
owned by KMS
Tunnel
Entrance
Route 41
Wasabo
Kamioka Town
Funatsu
Bridge
Google

SURVEY AND CAVERN DESIGN

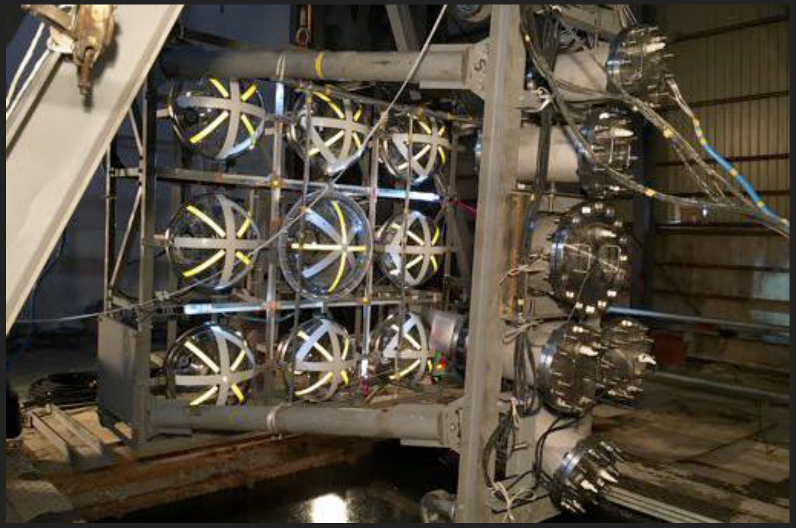
- Seismic tomography and reflection imaging were conducted for $(400\ m)^3$ wide area
- An excellent site was identified

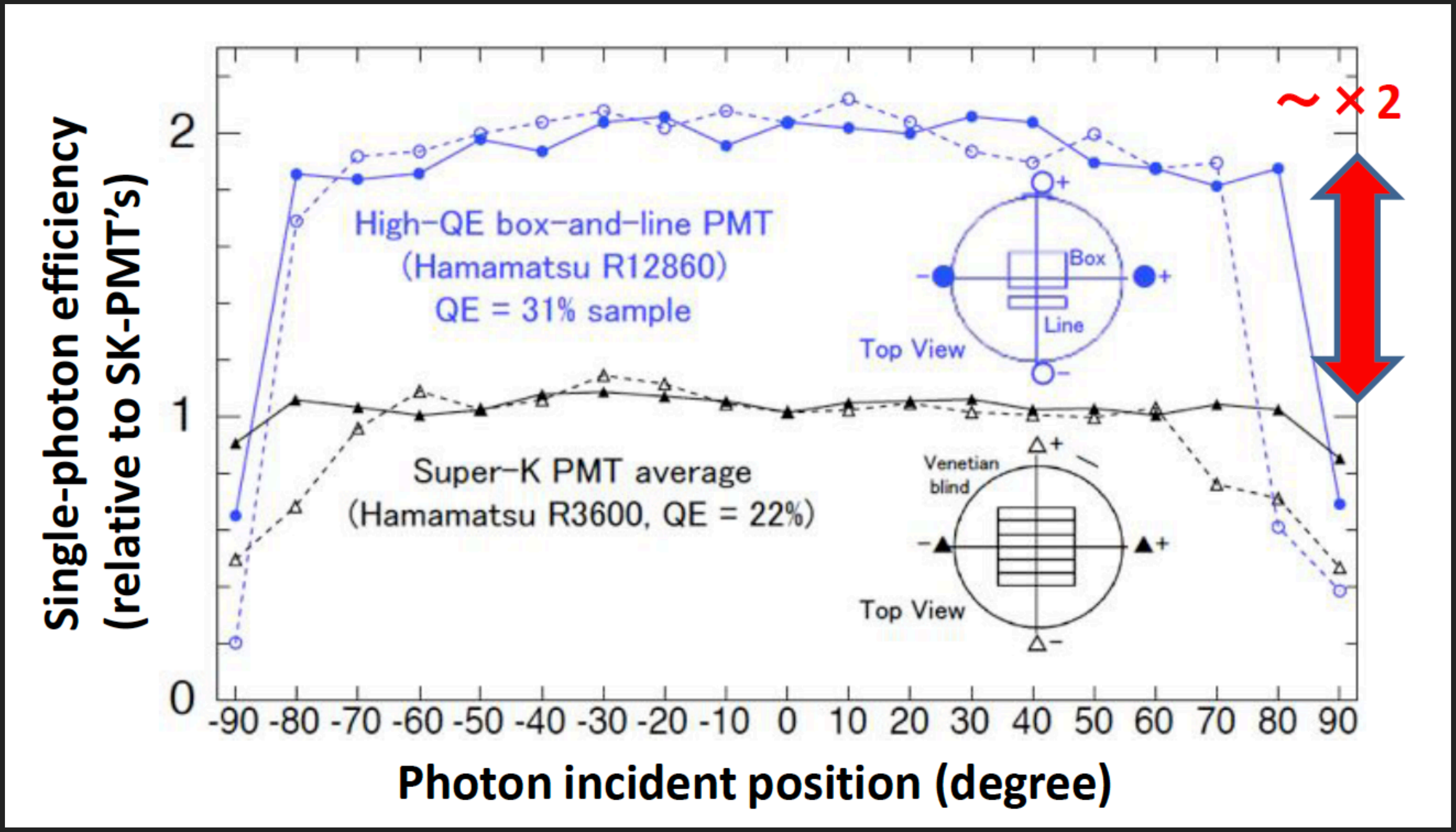


PHOTOSENSORS R&D

- Sensitivity: 2×SK
- Time resolution: ½×SK
- Pressure tolerance: 2×SK

Cover test @ Kamisunagwa, Hokkaido



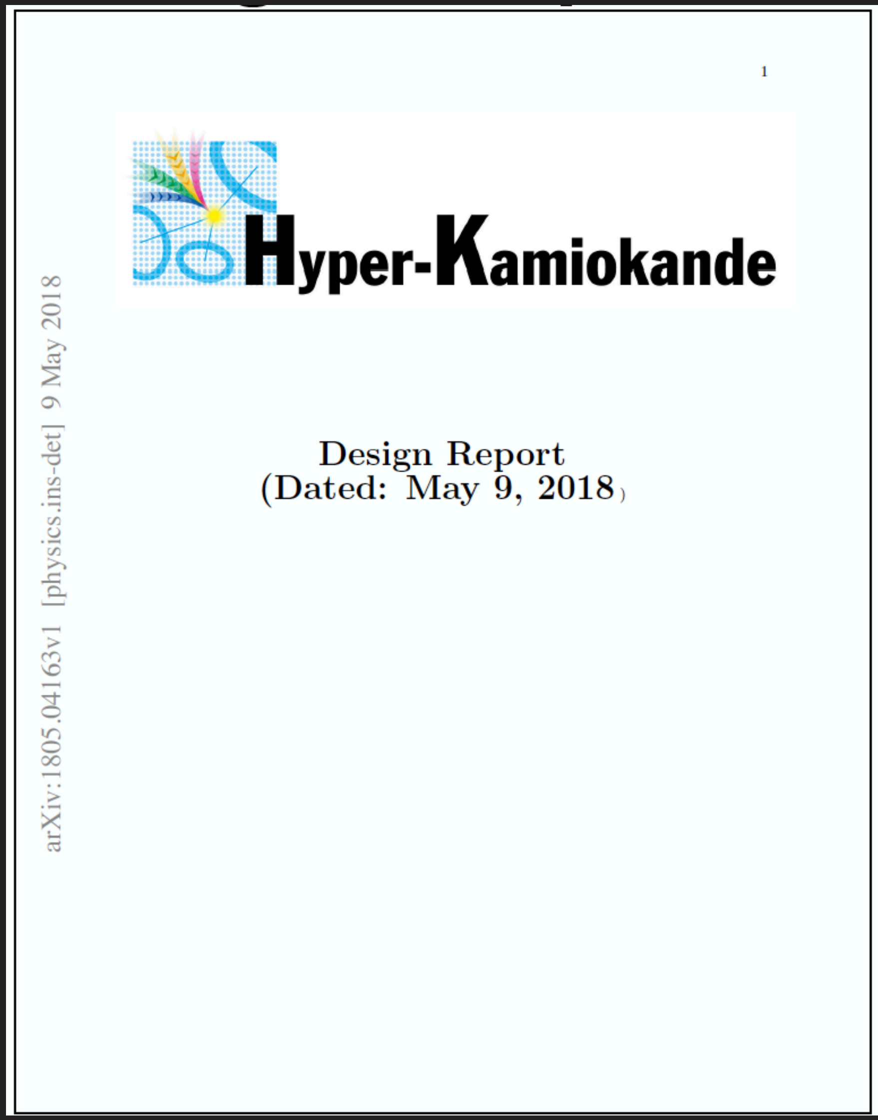


- ~140 new PMT's are being installed in Super-K during tank opening.
  - Performance check w/ Cherenkov light for years.
- Continuous effort for improvements. Noise reduction, cover design, light concentrator, etc. under study

THE INTERNATIONAL ORGANISATION

- International Hyper-K proto-collaboration
  - 15 countries, 73 institutes, ~300 members, ~75% from abroad
  - International project leaders, steering members, WG conveners
- 2 host institutes: UTokyo/ICRR and KEK/IPNS (MoU of cooperation for HK)
- UTokyo launched a institute for HK construction: Next Generation Neutrino Science Organization (NNSO)
- External review by Advisory Committee

DESIGN REPORT HAS BEEN RELEASED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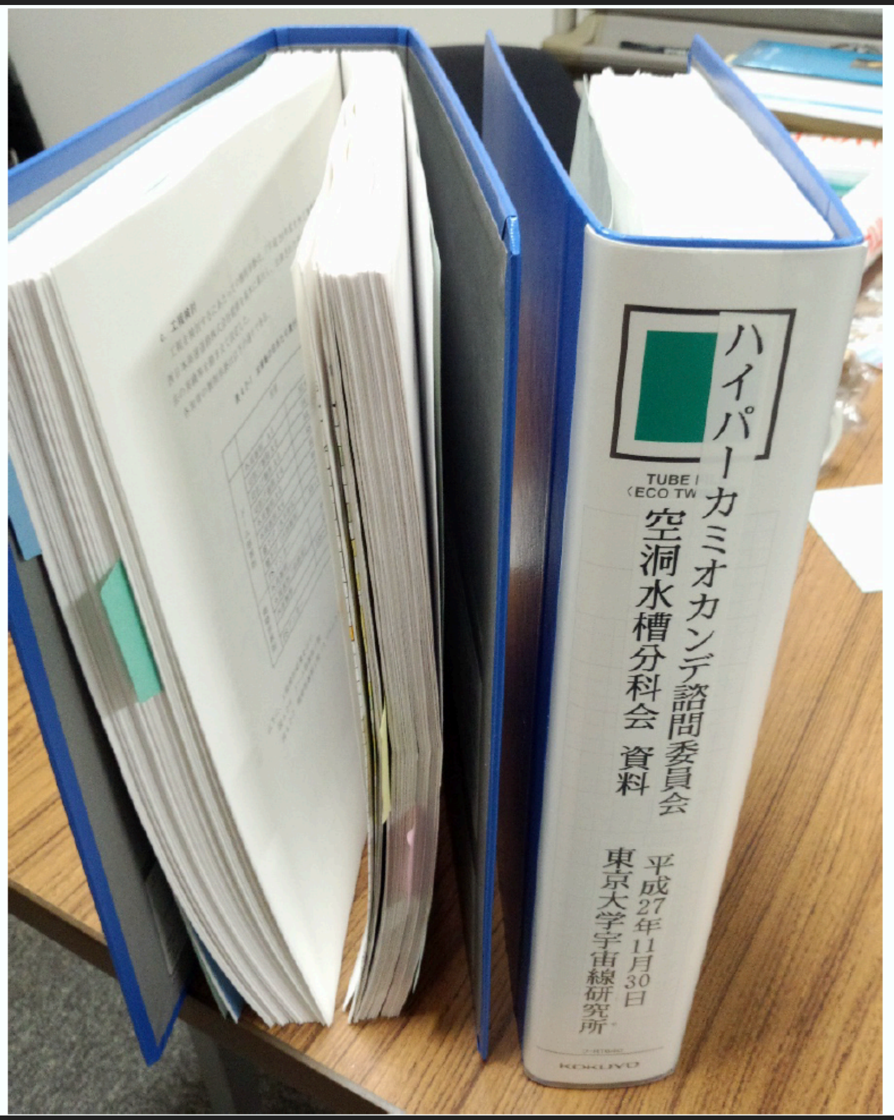
Hyper-Kamiokande

Design Report
(Dated: May 9, 2018)

arXiv:1805.04163v1 [physics.ins-det] 9 May 2018



- “Hyper-Kamiokande Design Report”, arXiv:1805.04163 May 9, 2018. 333 pp.
- “Hyper-Kamiokande Technical Report” is being written - timescale for completion early 2019.
- Other recent references:
  - Physics potentials with the second Hyper-Kamiokande detector in Korea PTEP 2018 (2018) no.6, 063C01

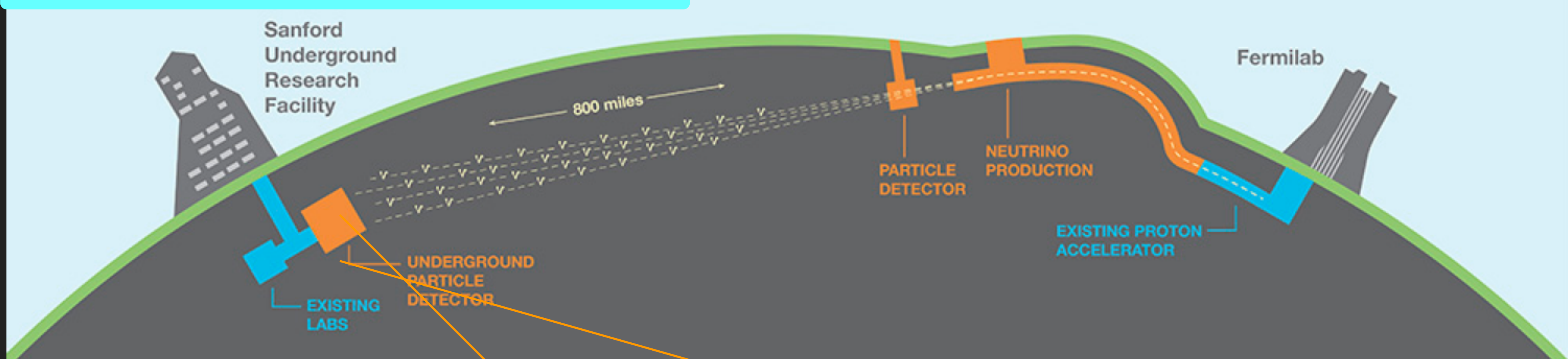

DUNE

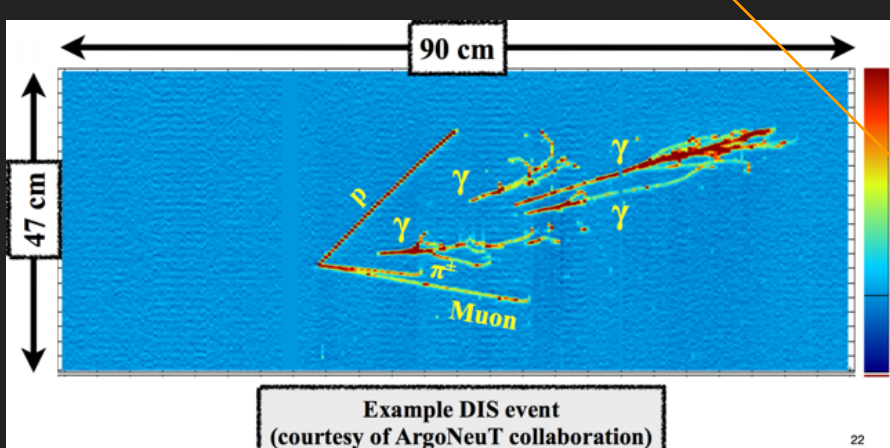
LONG BASELINE NEUTRINO PROGRAMME IN THE US

- Current LBN experiment NOvA (talk by Brajesh Choudhary)
- Future LBN experiment DUNE (Antonio Ereditato & protoDUNEs: Matthew Worcester)

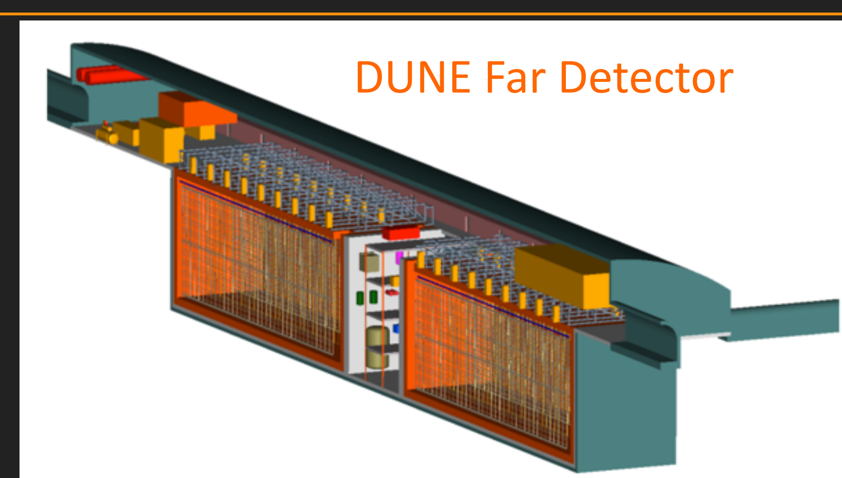
DUNE:
40 kt LAr-TPC Far Detector
(1300 km baseline)
- Near Detector systems
- Science collaboration

LBNF (Long-baseline Neutrino Facility)
- 1.2 MW wide-band ν beam, upgradable to 2.4 MW
- Conventional facilities at Fermilab and SURF
- Cryostats and cryogenic systems at SURF





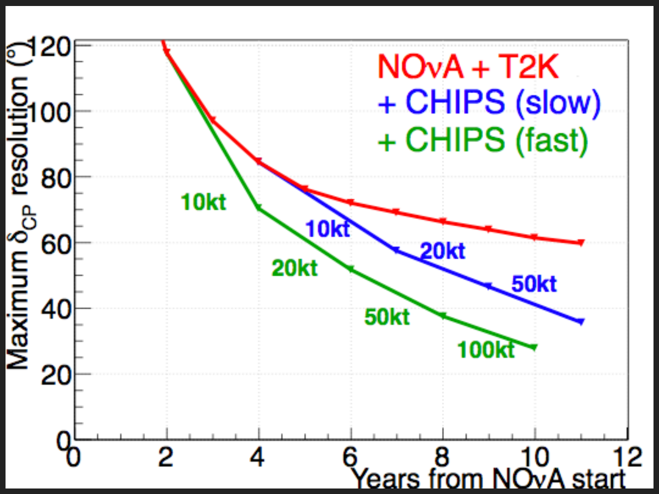
Example DIS event
(courtesy of ArgoNeuT collaboration)

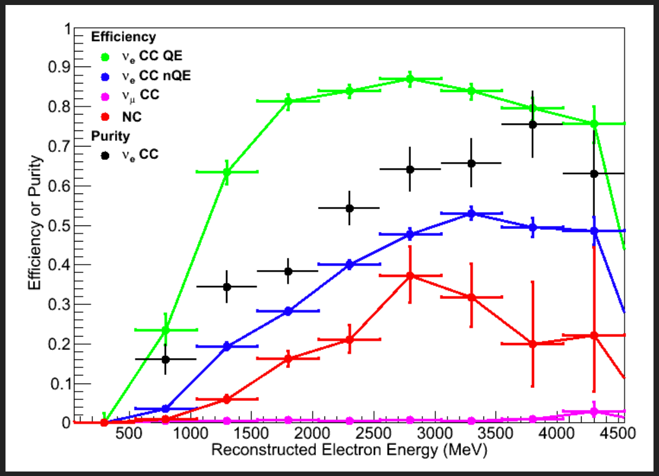


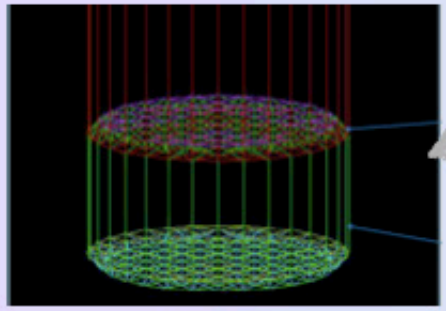
STUDIES FOR OTHER LONG BASELINE NEUTRINO EXPERIMENTS

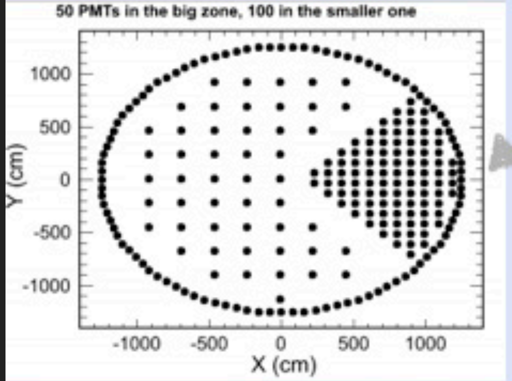
CHIPS

- CHIPS (CHerenkov detectors In mine PitS) has two goals: to prove that a detector costing **$200-300k/kiloton** is viable for measuring accelerator produced neutrinos
- To contribute to world knowledge of the mixing parameters **$\sin^2 2\theta_{23}$, $\sin^2\theta_{13}$** and to **δ_{CP}, MH**
- **arXiv:1307.5918**



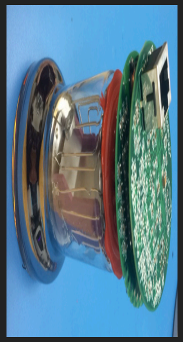






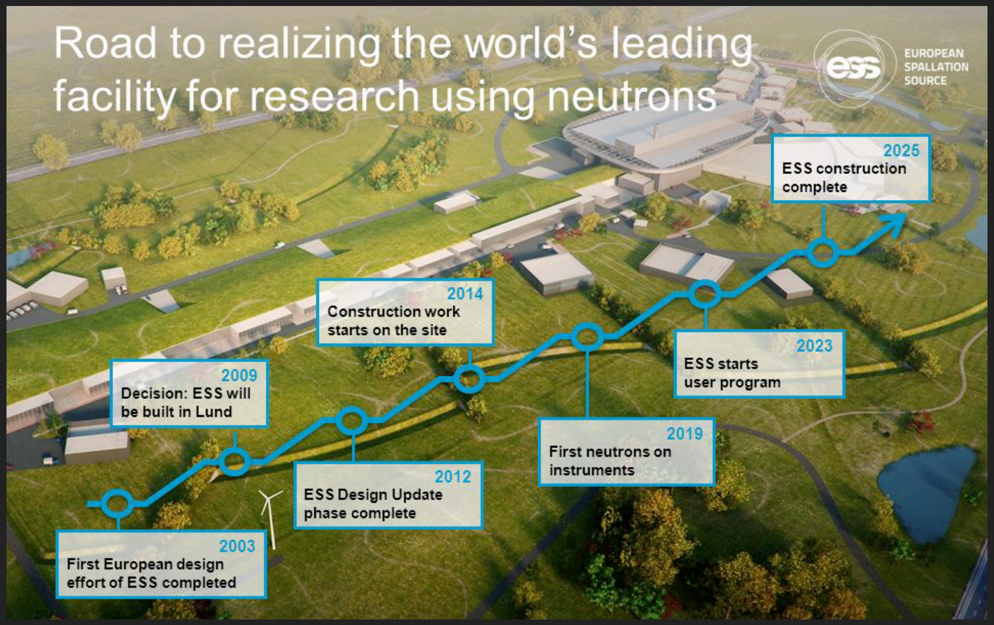
1) **Location**
   sunk in a flooded mine pit in the path of the NuMI neutrino beam, will make use of the water for cosmic overburden and mechanical support;
2) **Structure design**
   will allow it to grow in size with time but with no financial penalty beyond the instrumentation costs
3) **PMT choice and layout**
   3” PMT’s good position and time resolution and beam optimized layout
4) **Electronics**
   will make use of ubiquitous mobile phone and communications technology and already developed KM3Net Solutions
5) **Simple water purification plant**
   will use straightforward filtering to maintain water clarity.

- CHIPS 5kton detector are being deployed this Summer.
- Baseline 712km, 7mrad off-axis.
- Data expected for Oct 2018.

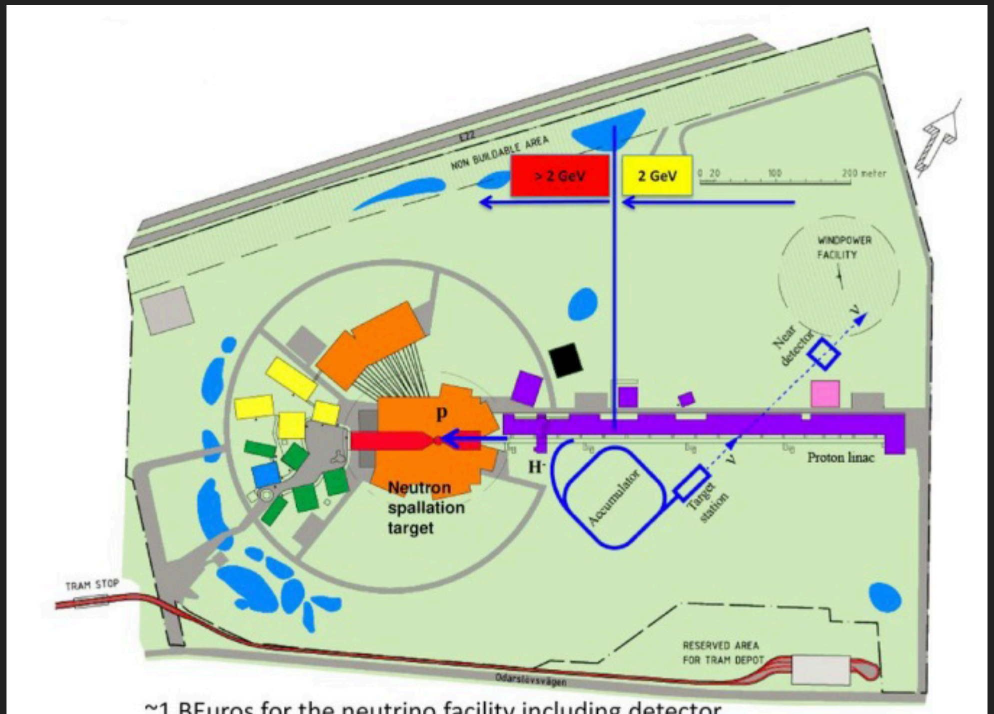


ESSNUSB

- The ESS will be a copious source of spallation neutrons.
- **5 MW** average beam power, 125 MW peak power, 2.0 GeV protons, >$2.7\text{x}10^{23}$ p.o.t/year.
- ESSnuSB Design Study funded by H2020



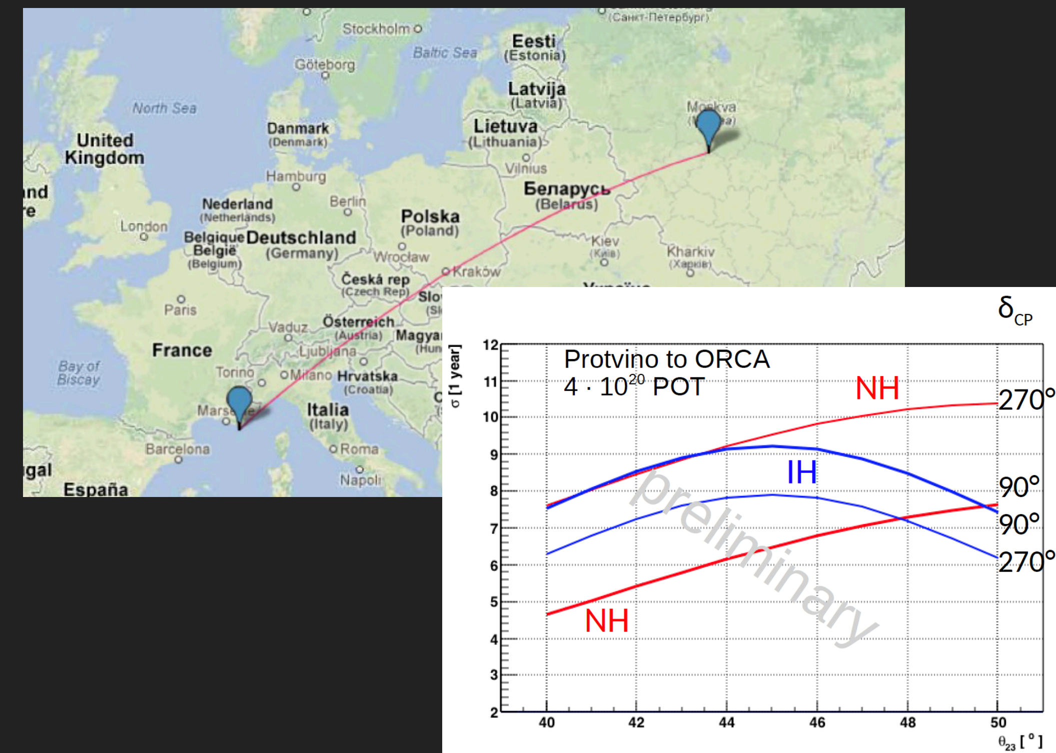
- How to add a neutrino line to SSB:
  - **Linac**: double the pulse rate (14 Hz→ 28 Hz)
  - **Accumulator** (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA)
  - **Target station** (studied in EUROv).
  - **Underground detector** (WC à la Hyper-K)



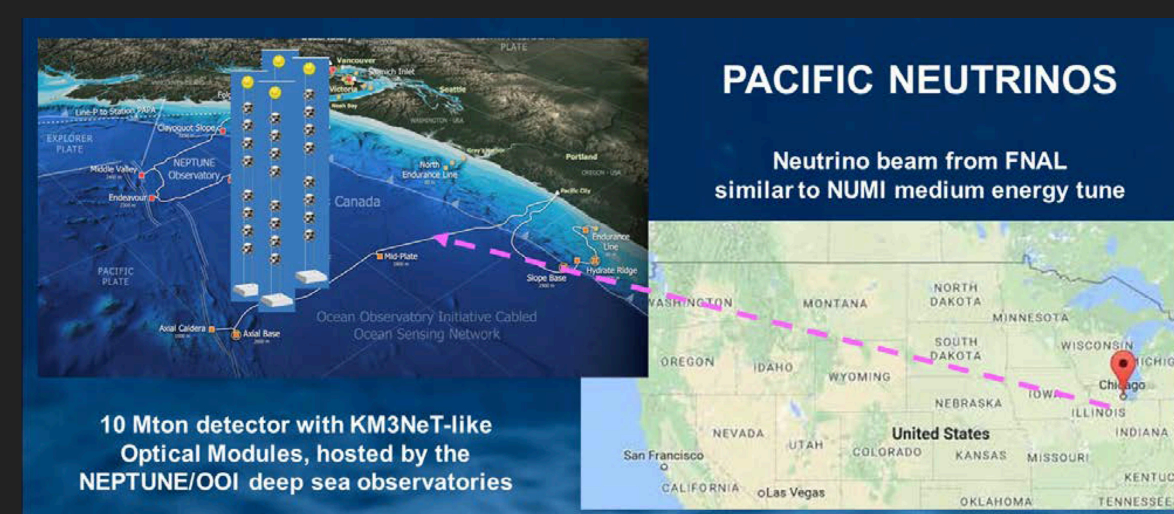
~1 BEuros for the neutrino facility including detector

ALTERNATIVE CONFIGURATIONS OF LBN EXPERIMENTS

- **P2O (Adv. High Energy Phys.2013, 782538 (2013)):**
  - Use ORCA as far detector and create a neutrino beam at Protvino (Omega project, 70 GeV, 450 kW).
  - Baseline: 2590 km. Excellent sensitivity on MH, mild sensitivity on CP



- **Pacific (arXiv:1610:08655):**
  - neutrino beam from FNAL similar to NUMI medium energy tune, fired to a 10 Mton KM3NeT-like detector placed at a baseline of 3100 km (Neptune/OOI deep sea observatories).
  - E_ν ~ 6.2 GeV. It would accumulate 100 more events than Dune for the same number of pot.



CONCLUSIONS

- Open questions in neutrino physics being addressed by current long baseline neutrino experiments, T2K and NOvA
  - CP violation limits
  - Mixing parameters
  - Mass hierarchy
- Hyper-Kamiokande and DUNE will definitely be able to address neutrinos oscillations and CP violation
- Further physics will be addressed as proton decays and astro neutrinos.
- Several studies for new LBN experiments are ongoing: CHIPS, ESSnuSB, P2O, PACIFIC.