

Current and Future Neutrino Experiments in Asia

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HKUST, 27 June 2017



130th Anniversary in 2011

Neutrino mixing

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

PMNS matrix
(Pontecorvo-Maki-
Nakagawa-Sakata)

ν_e, ν_μ, ν_τ : flavor eigenstates.

ν_1, ν_2, ν_3 : mass eigenstates of $m = m_1, m_2, m_3$.

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{23} = \cos\theta_{23}$, etc.

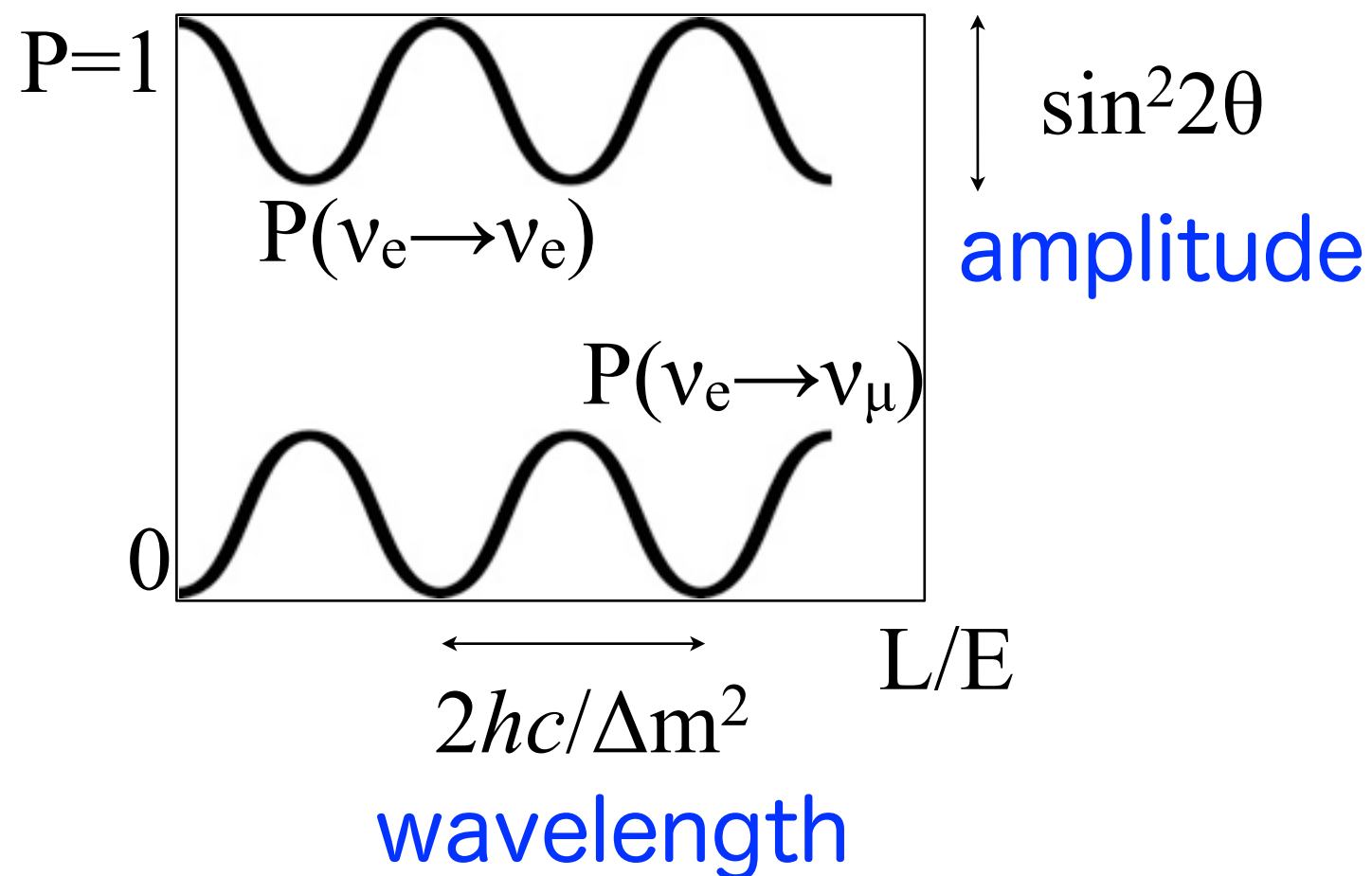
3 mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) + 1 complex phase (δ) $\leftarrow$ CP violation

Neutrino oscillation

IF $\theta \neq 0$ AND $\Delta m^2 \neq 0$, flavor transmutation occurs.

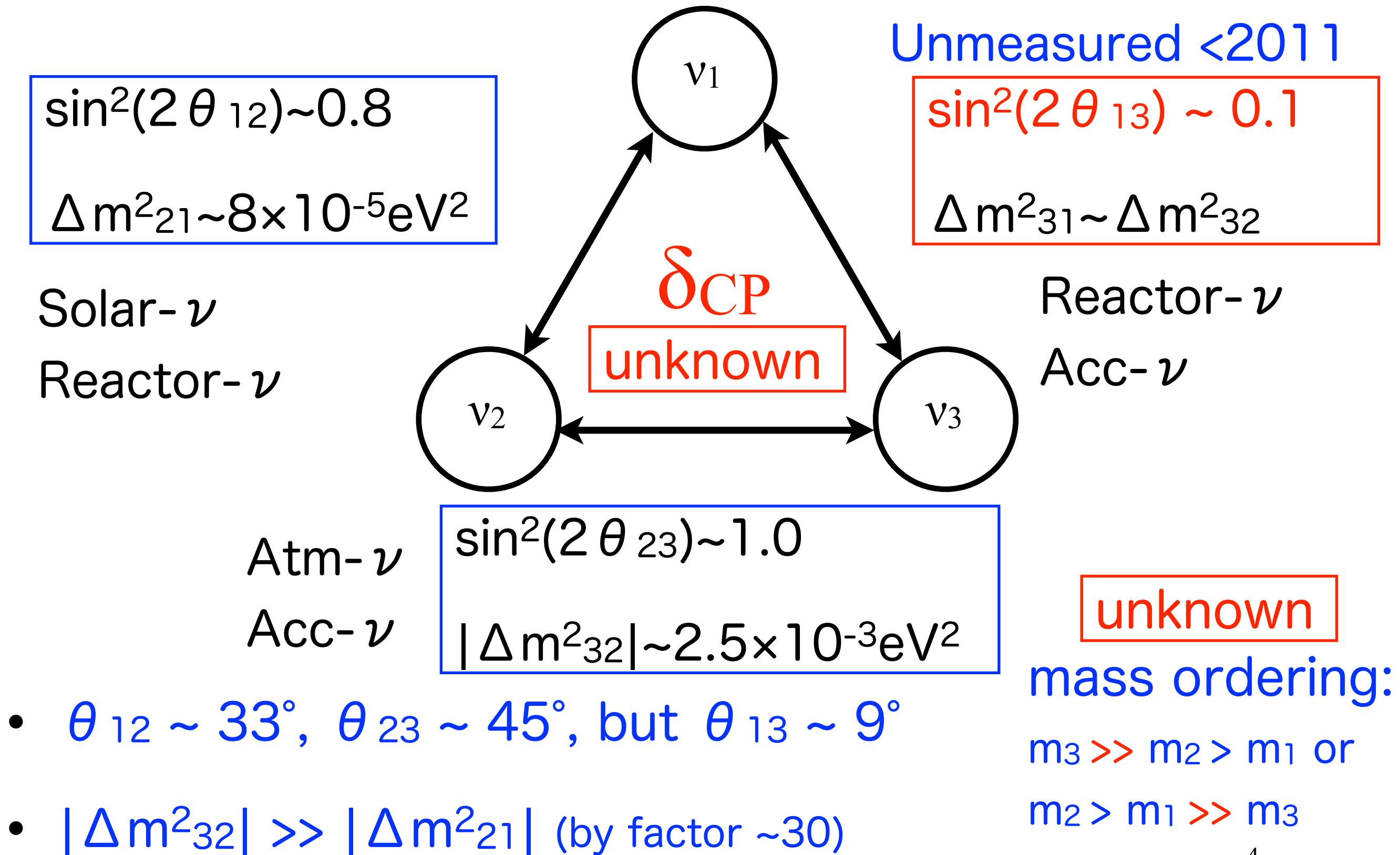
$$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \times \sin^2(1.27 \Delta m^2 L/E) \quad (2 \text{ flavor approx.})$$

Δm^2 in (eV^2), L/E in (km/GeV or m/MeV)



- 3 mixing angles
 $\theta_{12}, \theta_{23}, \theta_{13}$
- 2 (independent) mass² differences
 $\Delta m^2_{32} = m_3^2 - m_2^2$
 $\Delta m^2_{21} = m_2^2 - m_1^2$
($\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$)
- 1 complex phase (CPV) δ

Oscillation parameters



Outstanding issues in neutrino physics

- PMNS matrix:

All 3 mixing angles θ_{ij} are measured.

Octant of θ_{23} not yet known ($> 45^\circ$ or $< 45^\circ$)

CP violation phase δ_{CP} is unknown.

- Neutrino masses:

Both mass² differences Δm_{32}^2 and Δm_{21}^2 measured.

Sign(Δm_{32}^2) still unknown - Mass Hierarchy (Mass Ordering)

$m_3 \gg m_2 > m_1$ (normal) or $m_2 > m_1 \gg m_3$ (inverted)

Absolute m_ν not measurable with ν oscillation

→ $0 \nu 2 \beta$ (if Majorana) / direct β measurement (KATRIN) and cosmological constraints on Σm_ν (ν osc. → $\Sigma m_\nu > 0.05$ eV)

Experimental approaches and Asian experiments

- Accelerator neutrino:
T2K, T2K-II, T2HK (Japan), T2HKK (+Korea)
- Reactor neutrino:
RENO (Korea), Daya Bay, JUNO (China)
- Atmospheric neutrino:
Super-K, SK-Gd, Hyper-K (Japan), INO (India)
- Not covered here: Astro. ν (Solar, SN, ...), KamLAND

Oscillation maximum:

$$1.27\Delta m^2(\text{eV}^2)L(\text{km})/E(\text{GeV})=(2n+1)\pi/2$$

1st maximum at $L \sim E/\Delta m^2$ ($\times 1.57/1.27$)

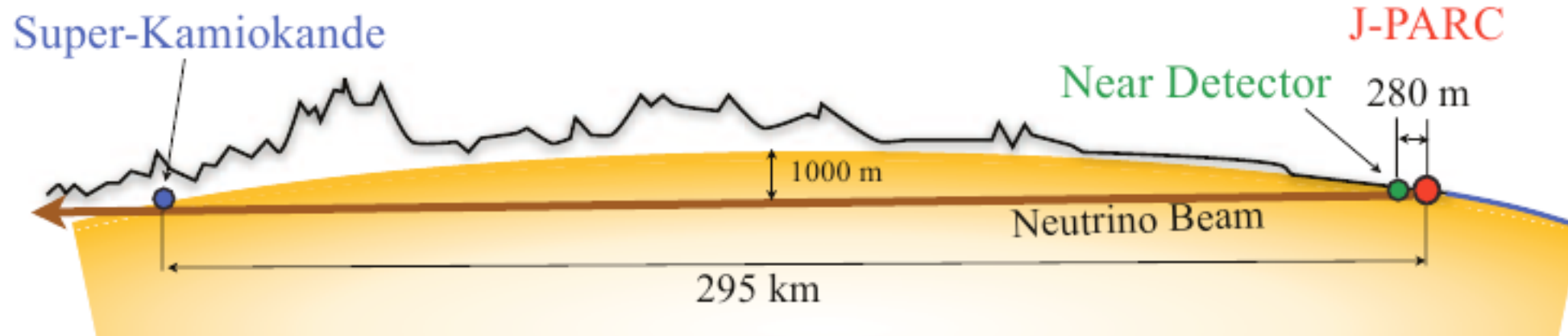
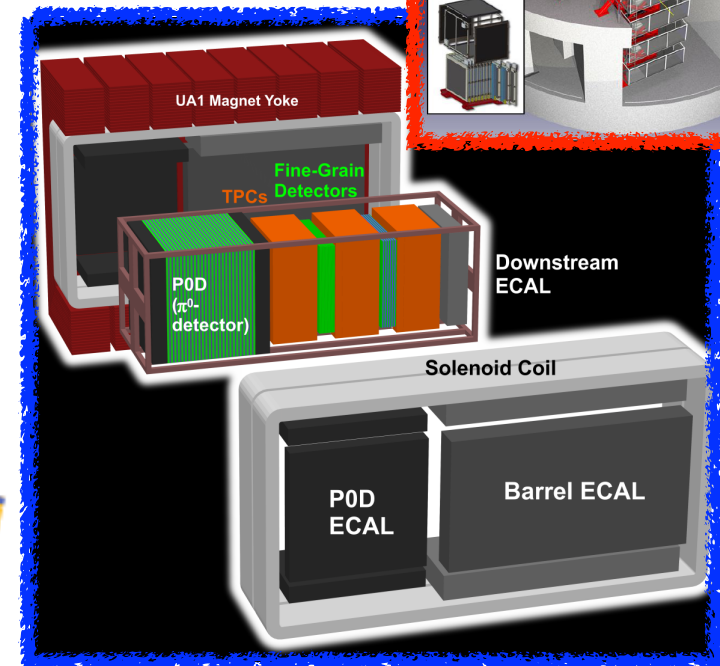
- For $\Delta m^2_{32(31)} \sim 2.5 \times 10^{-3} \text{ eV}^2$ and $E \sim 1 \text{ GeV}$,
→ $L \sim O(400\text{km})$: accelerator long-baseline experiments
(T2K, MINOS, NOvA)
- For $\Delta m^2_{32(31)} \sim 2.5 \times 10^{-3} \text{ eV}^2$ and $E \sim 4 \text{ MeV}$,
→ $L \sim O(1.5\text{km})$: reactor mid-baseline experiments
(Daya Bay, Double Chooz, RENO)
- For $\Delta m^2_{21} \sim 0.8 \times 10^{-4} \text{ eV}^2$ and $E \sim 4 \text{ MeV}$,
→ $L \sim O(50\text{km})$: reactor long-baseline exp't (JUNO, KL)

T2K experiment in Japan

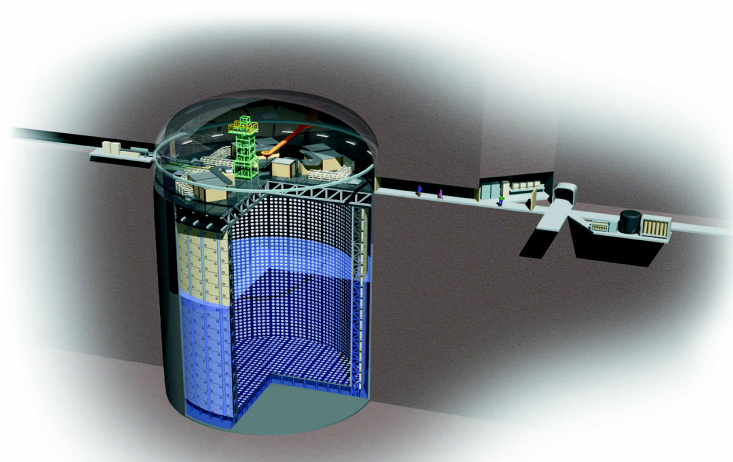
- Tokai (J-PARC) to Kamioka (SK)
Long-BaseLine accelerator ν exp.

INGRID@0deg

ND280@2.5deg



Super-K@Kamioka

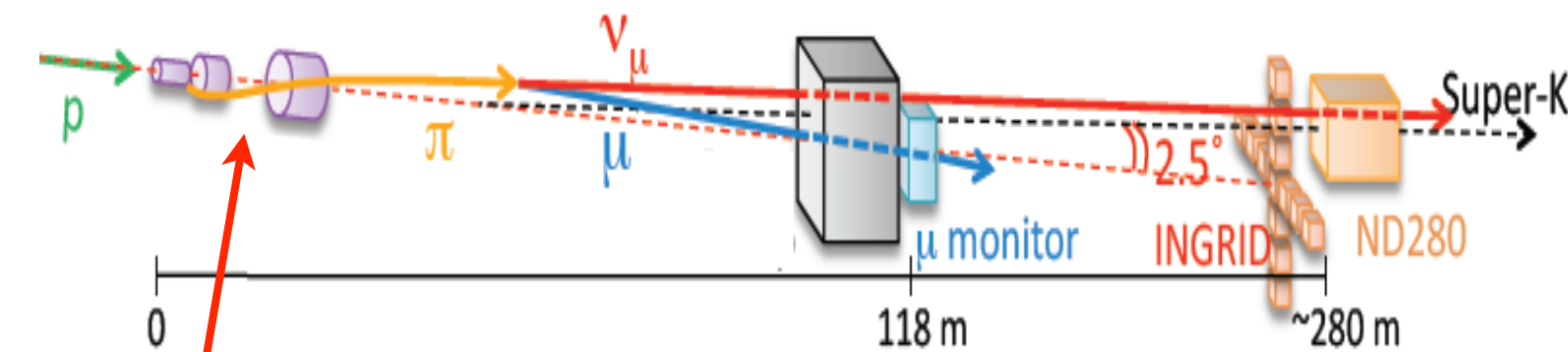


ND280 @Tokai

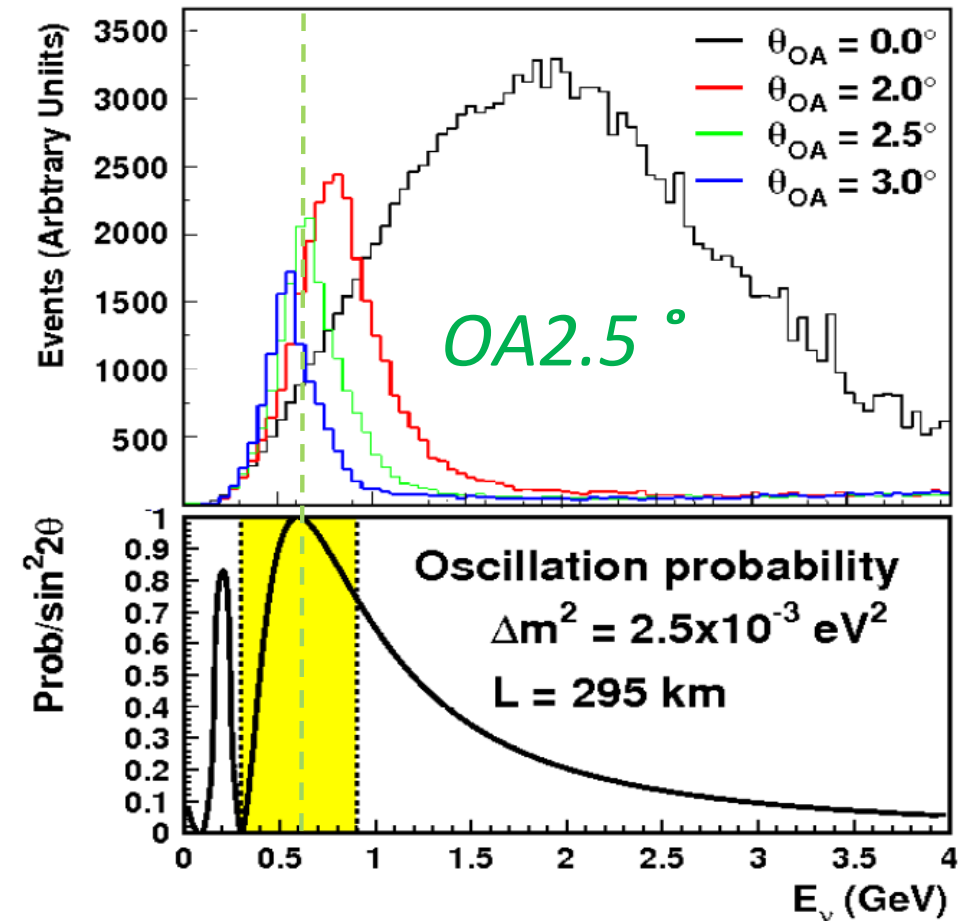
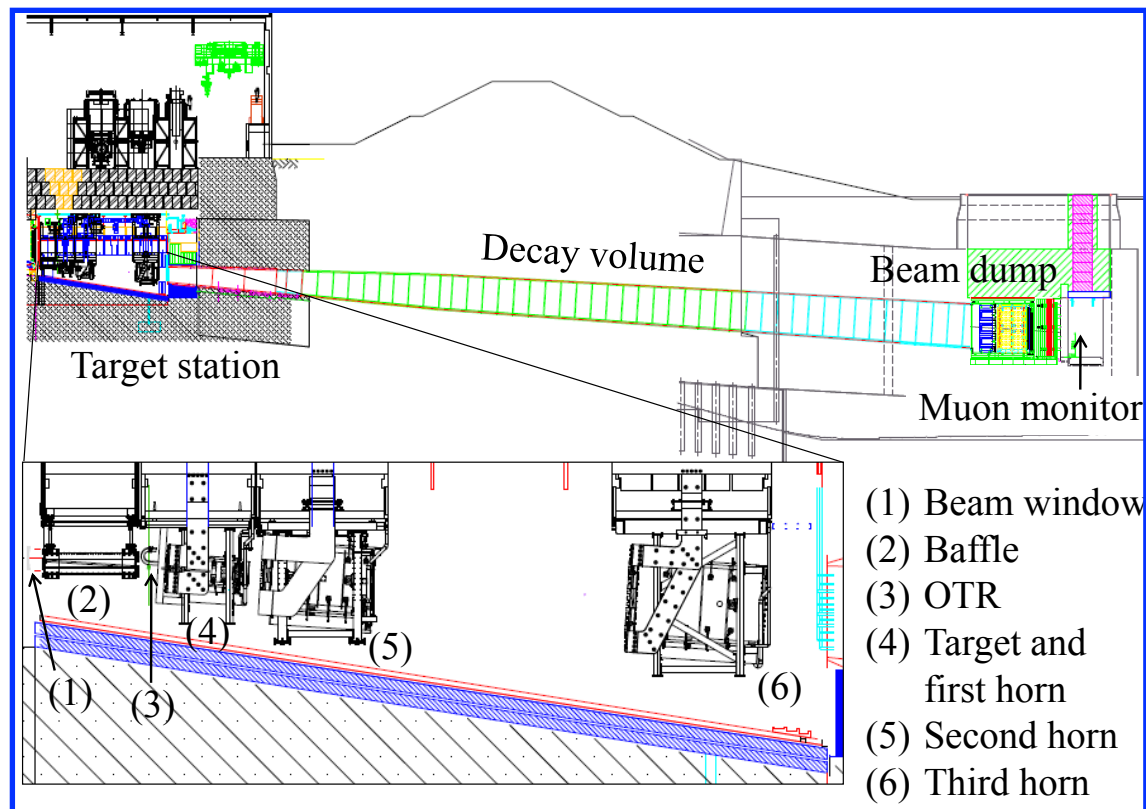


Off-Axis ν_μ beam

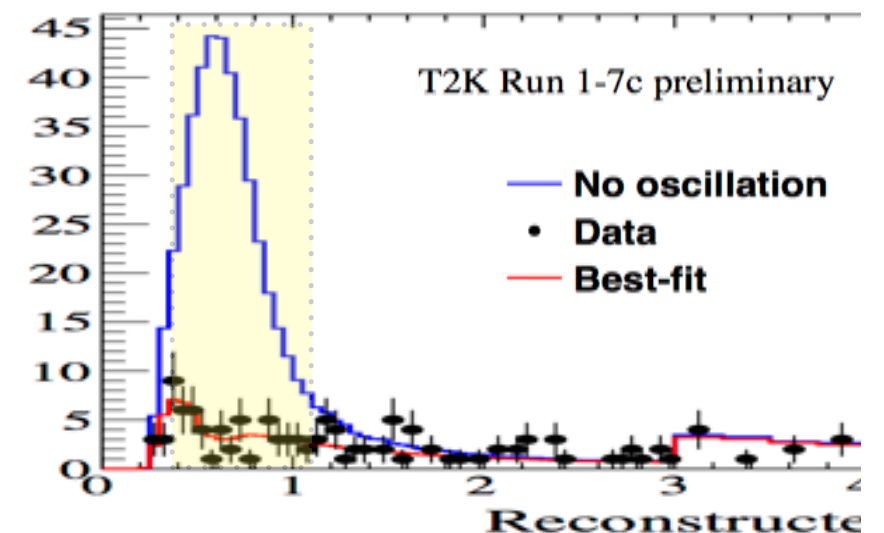
- Narrow-band beam, peak at 0.6 GeV (Δm^2_{32} 1st osc. max.)
- Reduce BG from high-E tail



Horns

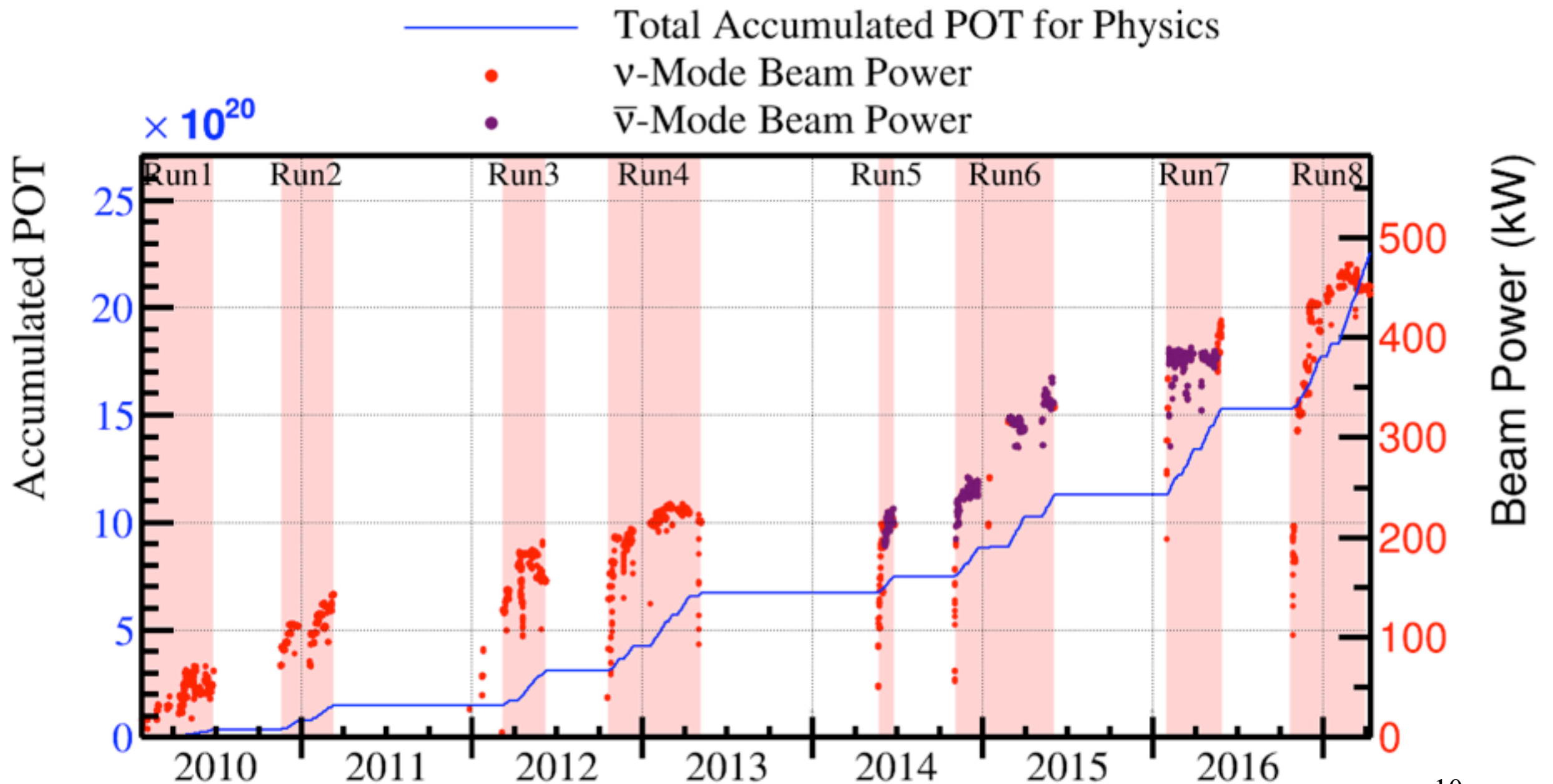


T2K 2016 ν_μ disappearance



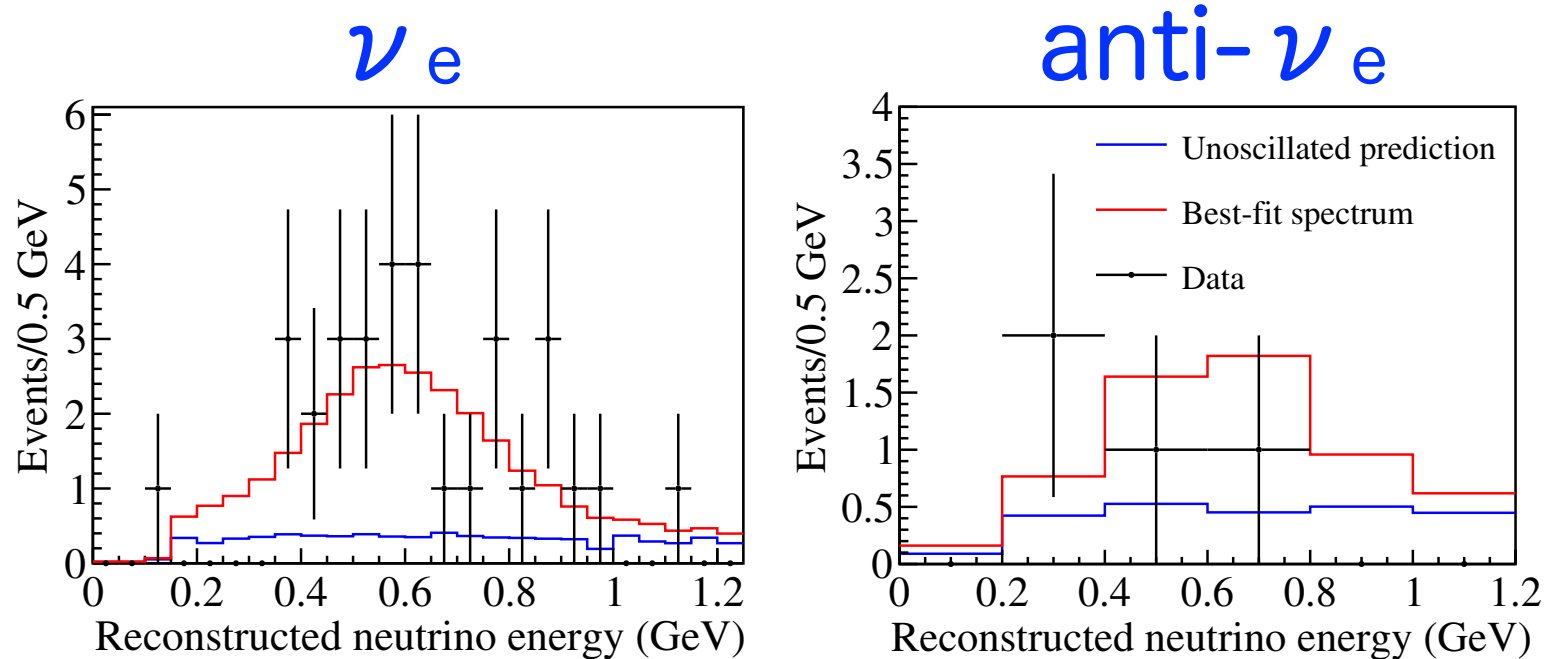
Protons On Target (POT)

- 14.7×10^{20} for ν mode (Forward Horn Current)
- 7.5×10^{20} for anti- ν mode (Reverse Horn Current)
- Beam power ~470kW now

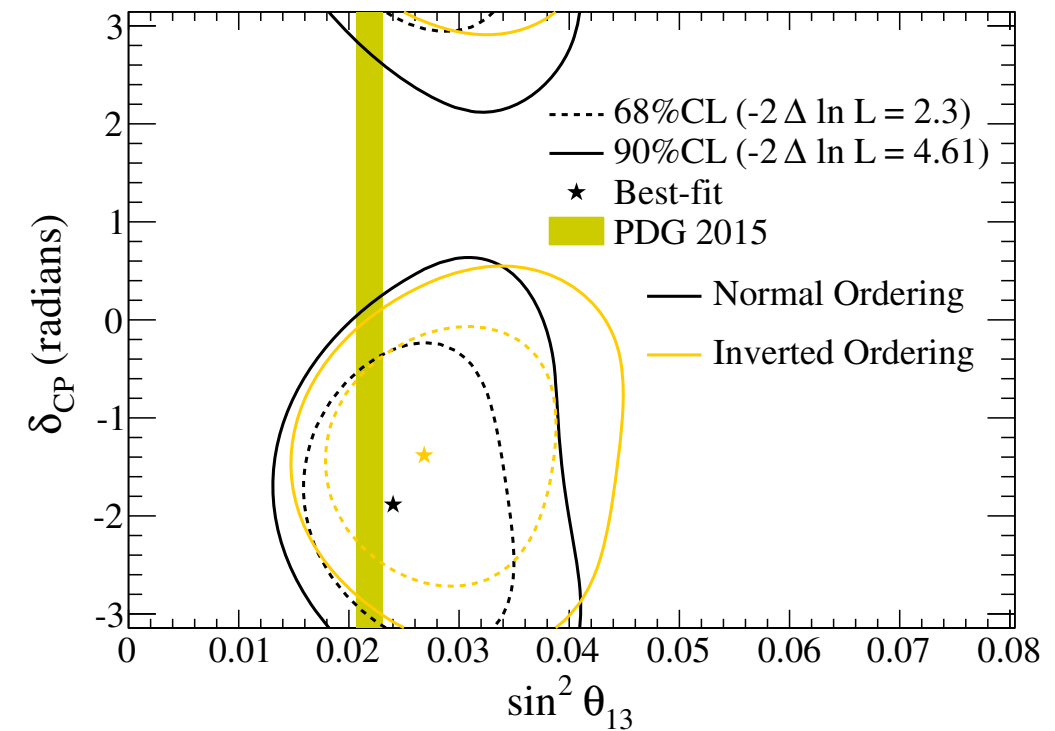


T2K results on δ_{CP}

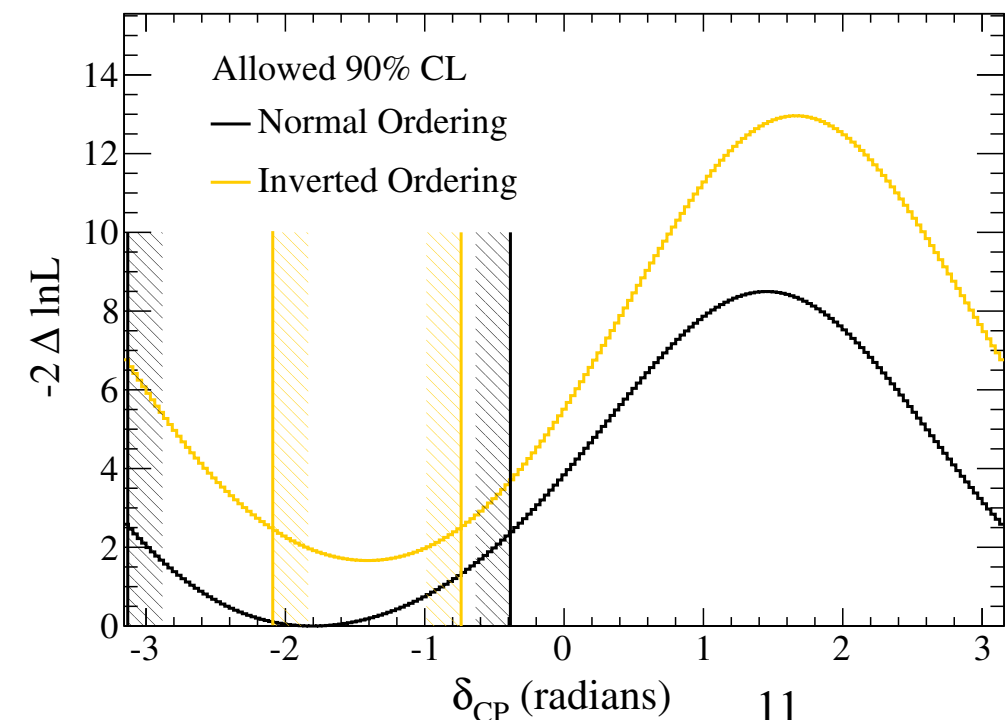
- Compare $\nu_{\mu} \rightarrow \nu_e$ appearance between ν and anti- ν
- Using reactor θ_{13} constraint,
 $\delta=0$ or π excluded at 90% C.L.



	Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e		28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$		6.0	6.9	7.7	6.8	4
Inverted		$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e		25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$		6.5	7.4	8.4	7.4	4

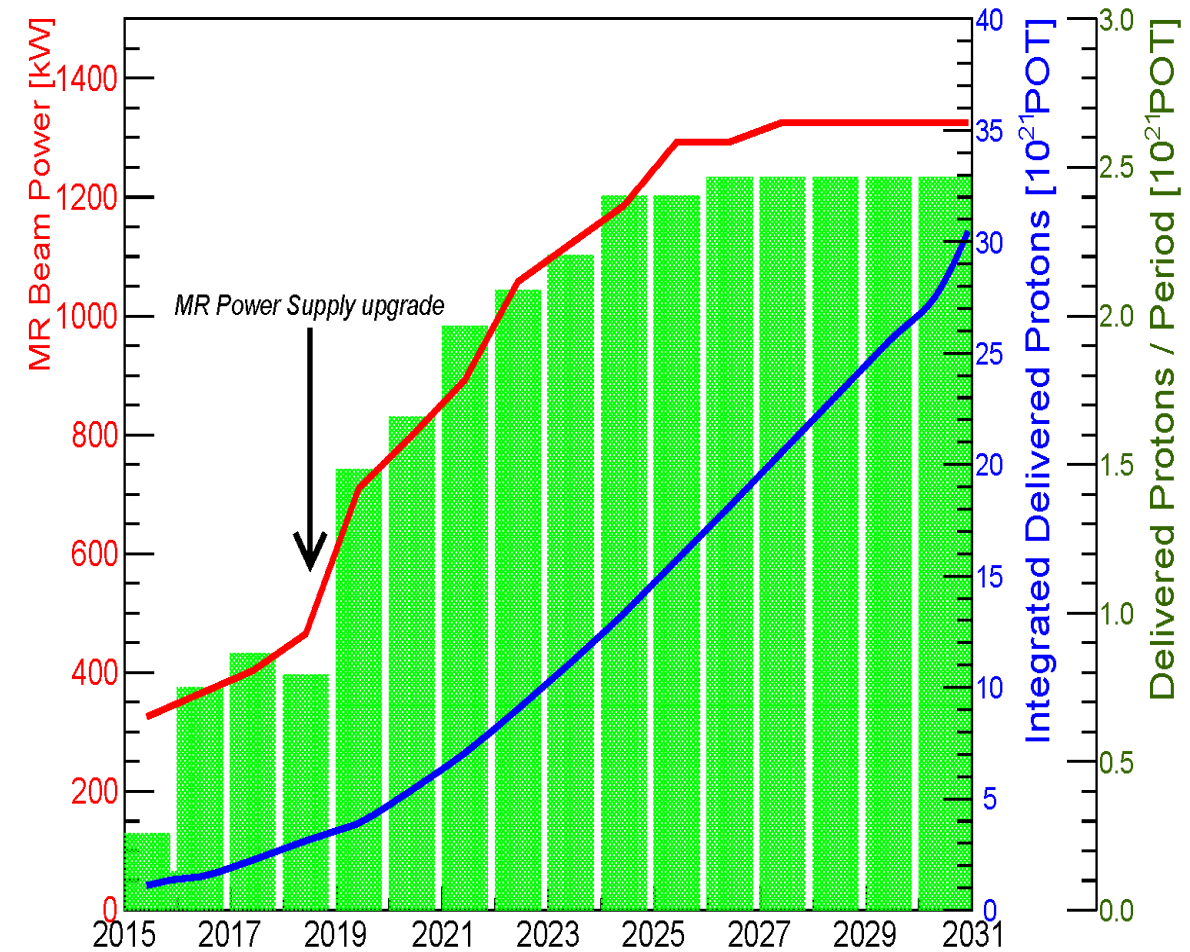


PRL118, 151801 (2017)

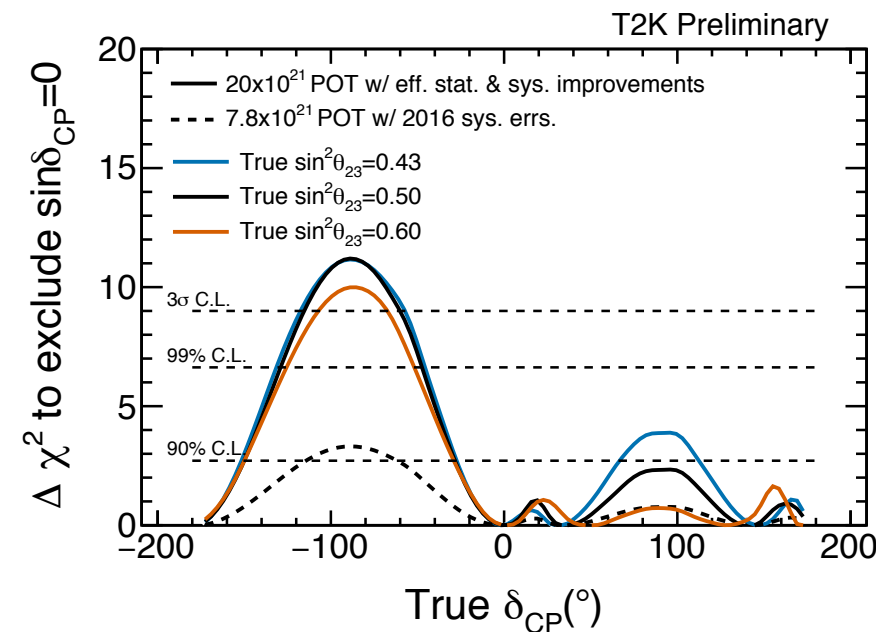


T2K → T2K-II → T2HK

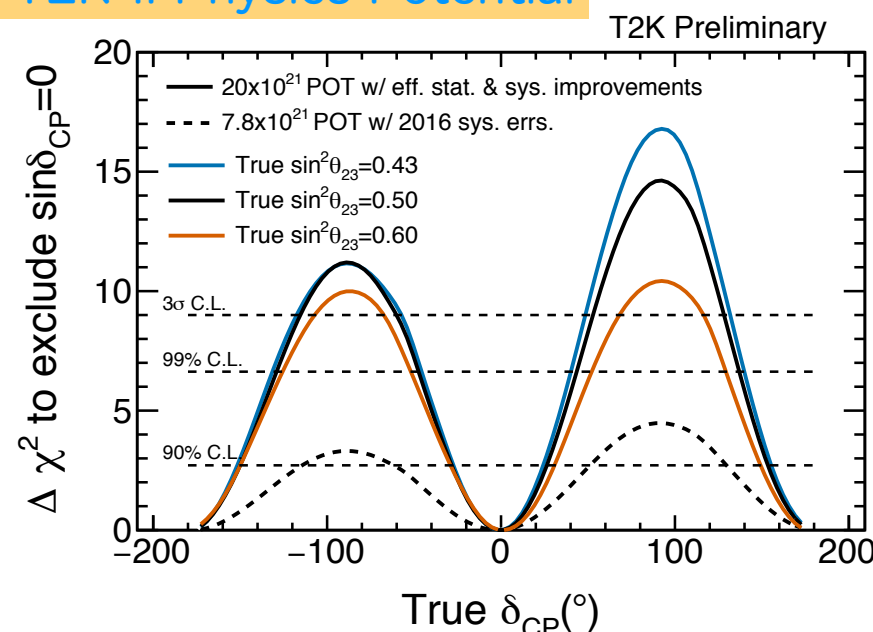
- T2K was proposed with $7.8\text{E}20$ POT
 - So far accumulated $1.5\text{E}20$
- T2K-II (till ~2026) to collect $20\text{E}20$
 - MR Power Supply upgrade (>750kW)
 - $\sim 3\sigma$ evidence if $\delta \sim -90\text{deg}$
- T2HK (from ~2026) with 1.3MW beam
 - Hyper-K as the Far Detector
 - Definite observation of CP violation



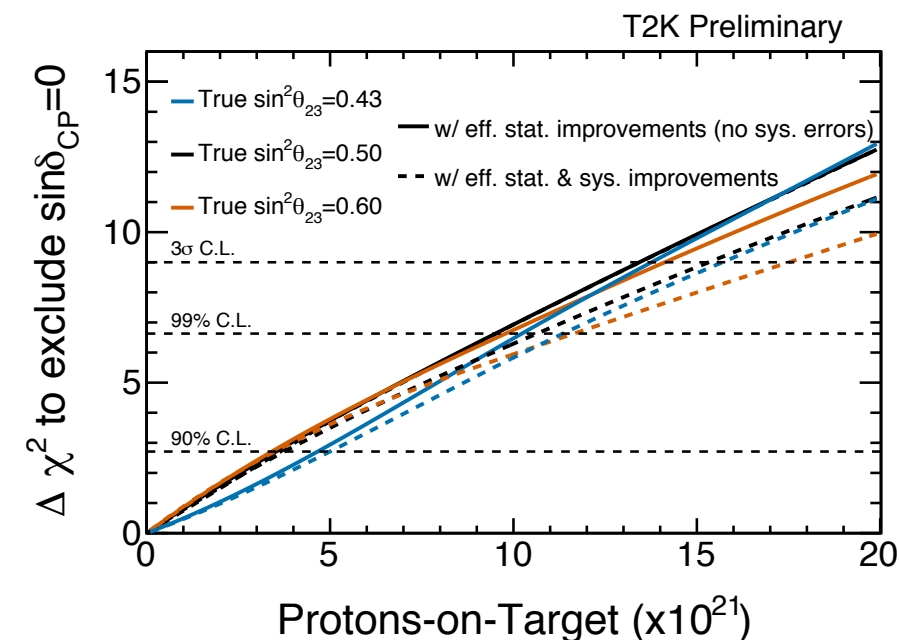
T2K-II Physics Potential



hierarchy unknown



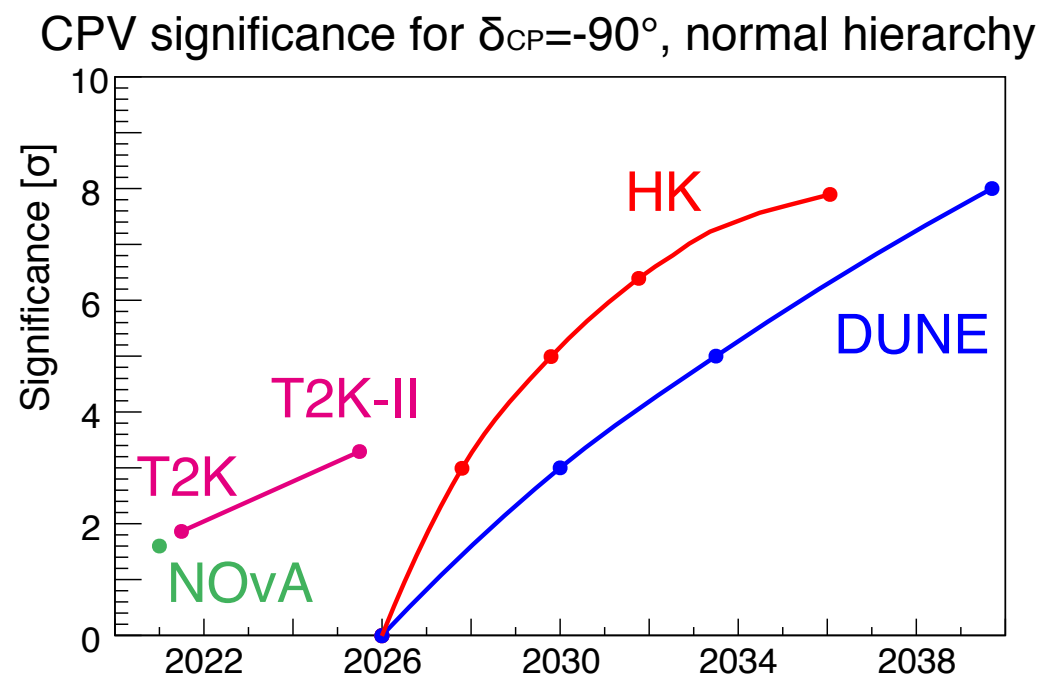
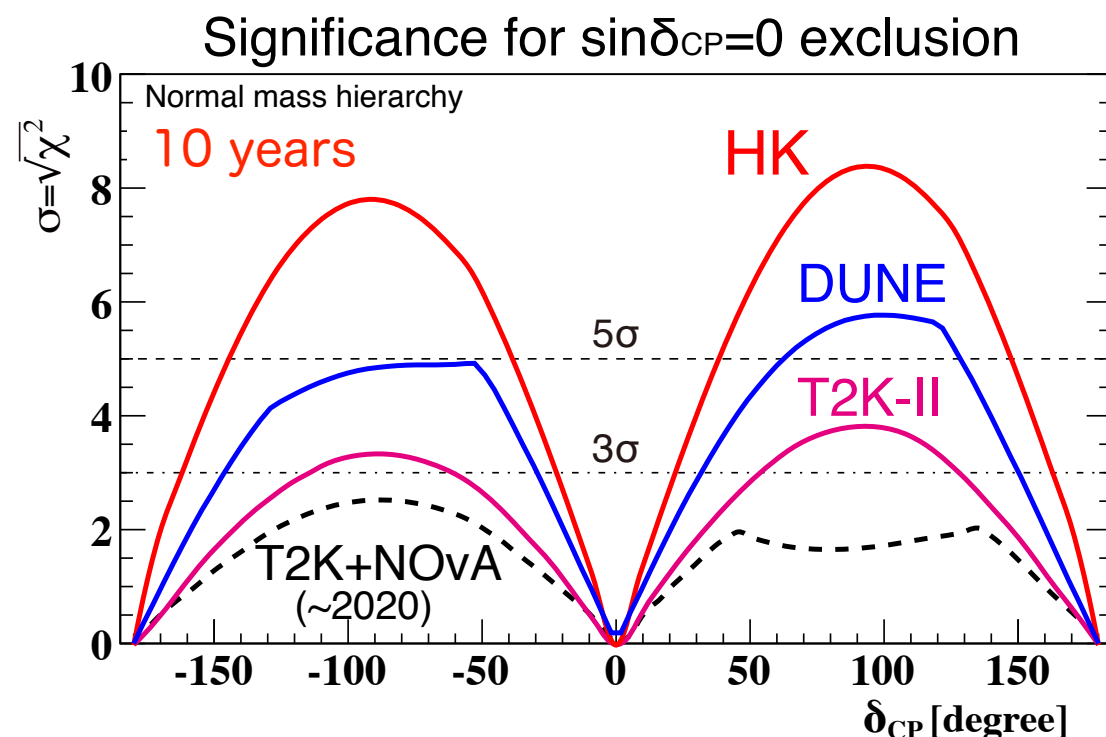
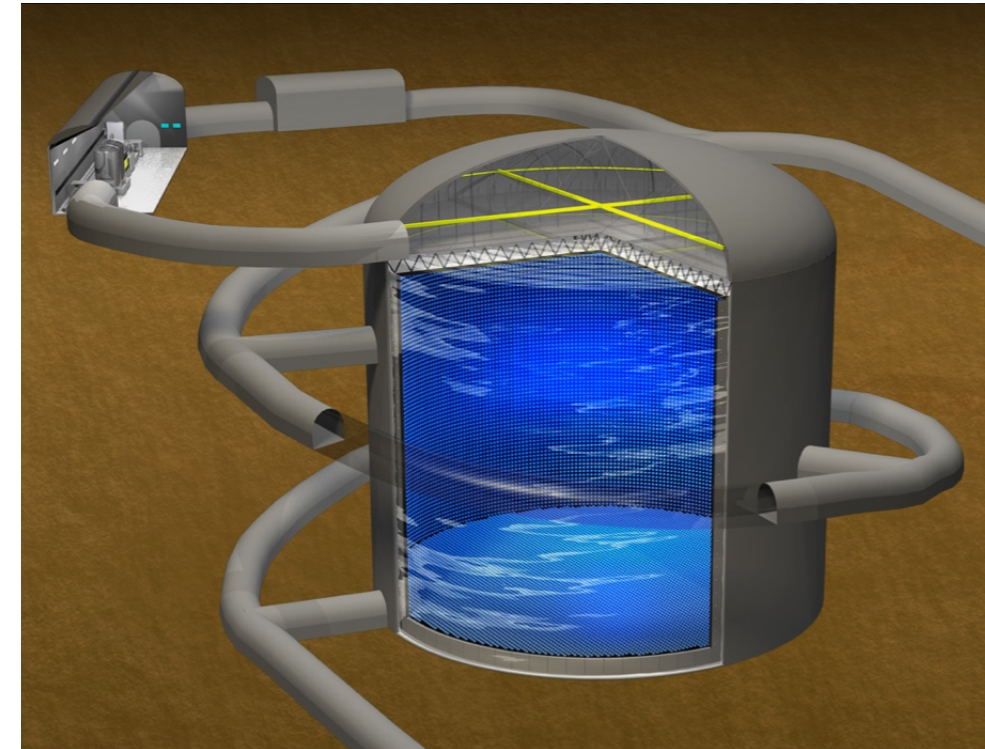
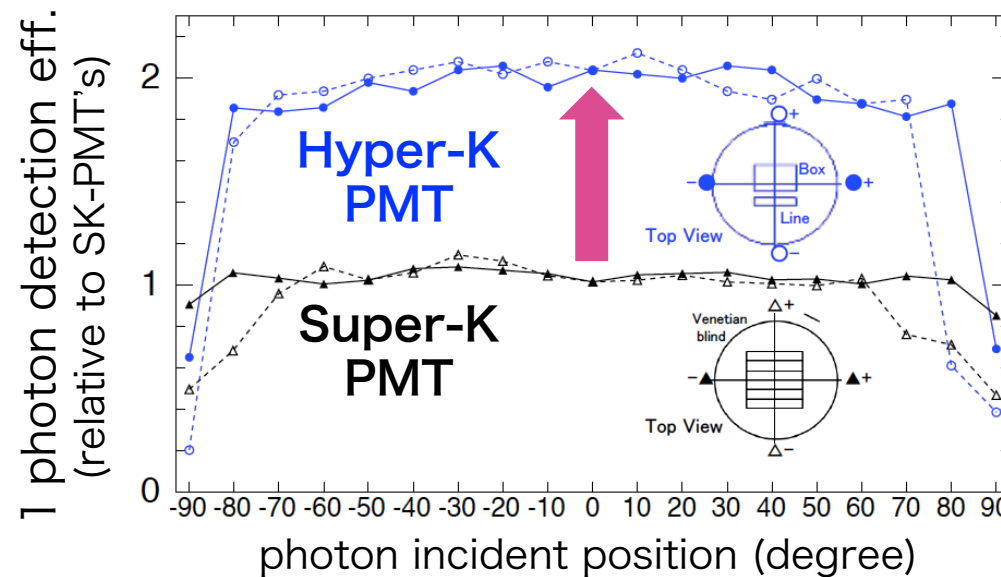
external hierarchy input



H.A. Tanaka, Neutrino 2016

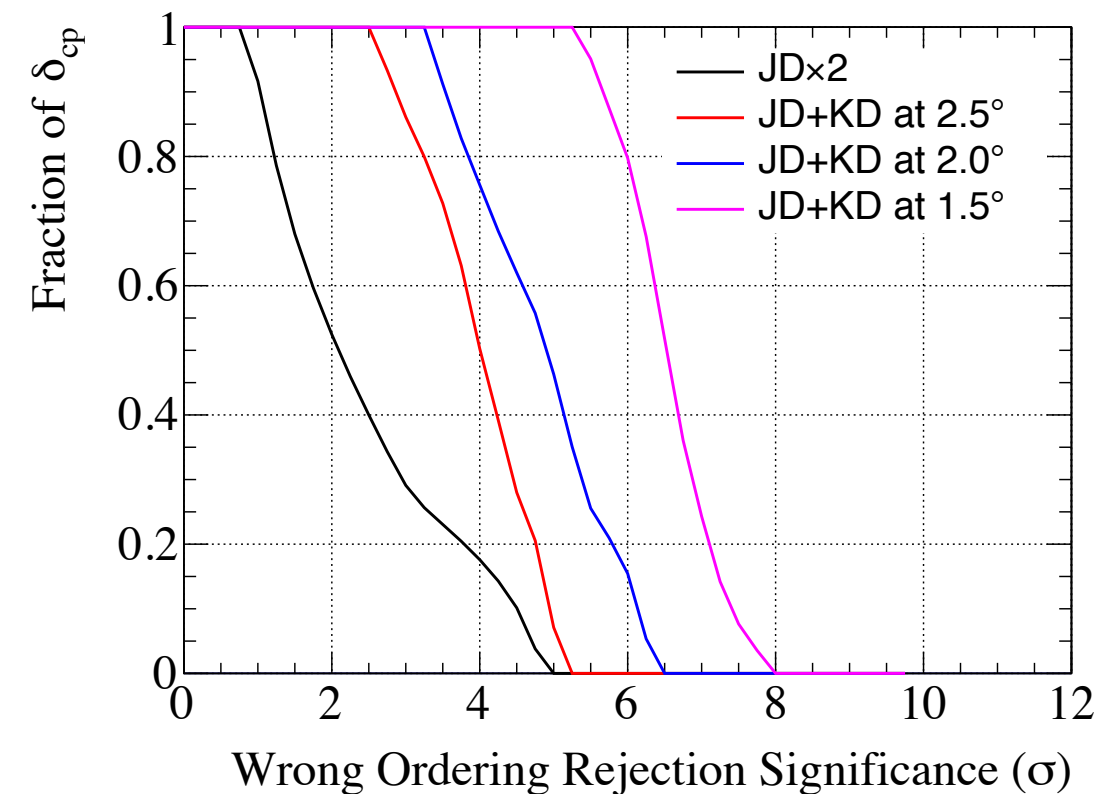
Hyper-Kamiokande

- 260kton tank (D74m×H60m)
- 190kton fiducial mass ($\sim \times 10$ of Super-K)
- 40,000 PMTs with 2x eff.
- $>5\sigma$ discovery in wide δ_{CP} range

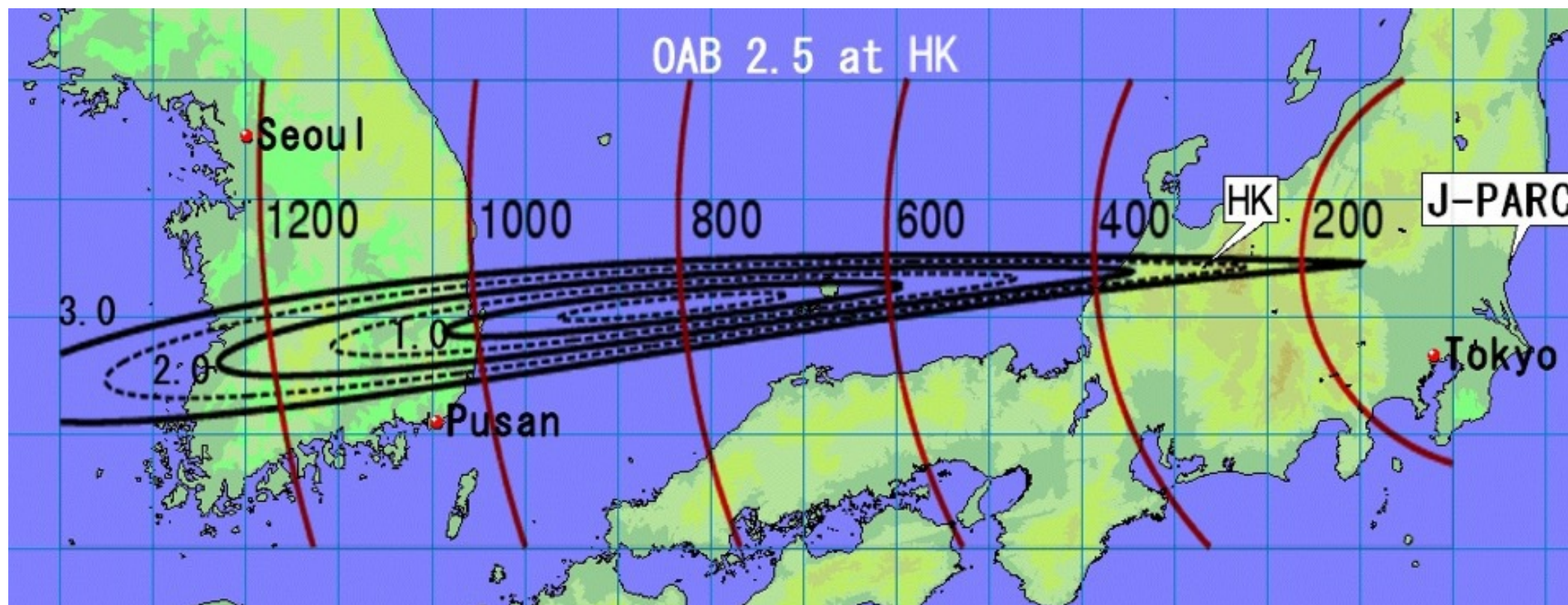


T2HKK (Tokai 2 HK & Korea)

- Idea to build a 2nd tank in Korea (“lower” Off-Axis beam reaches Earth surface in Korea)
- $L \sim 1100\text{km}$ $\rightarrow$ large matter effect $\rightarrow$ Mass Hierarchy sensitivity
- $> 5\sigma$ for any δ_{CP} value
- Also δ_{CP} precision improves



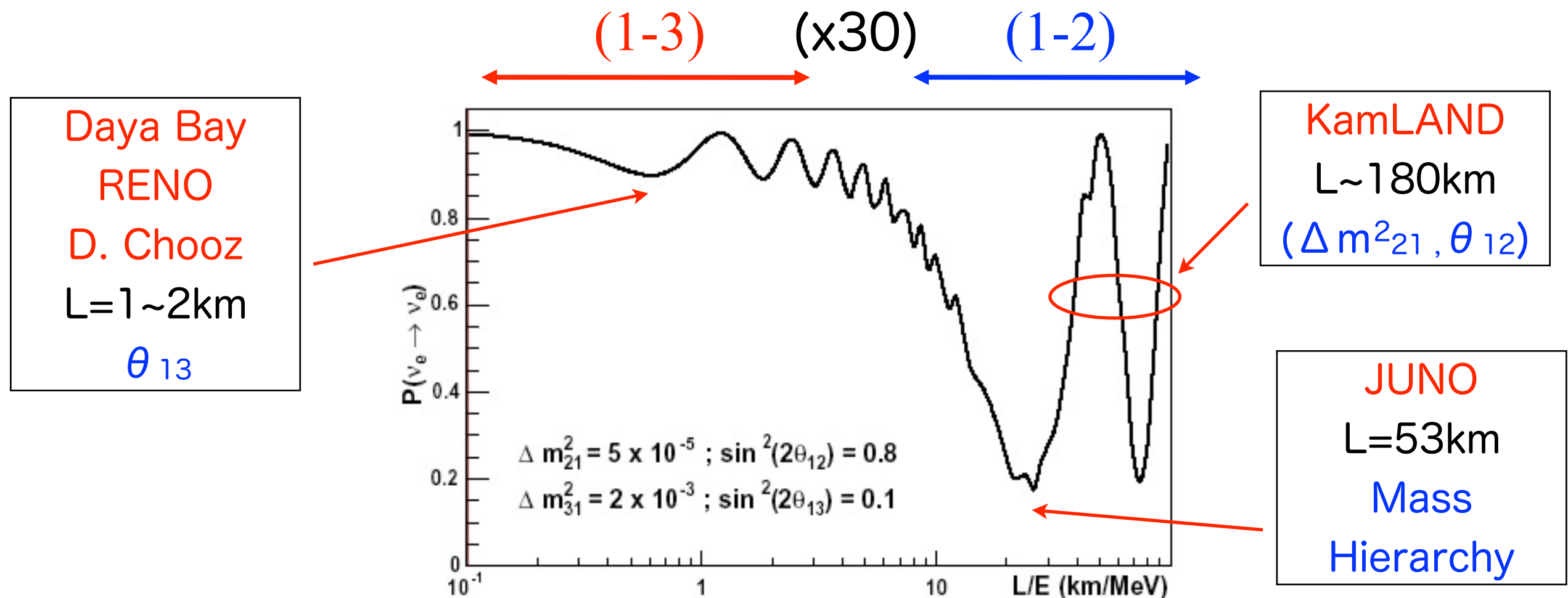
T2HKK White Paper
1611.06118



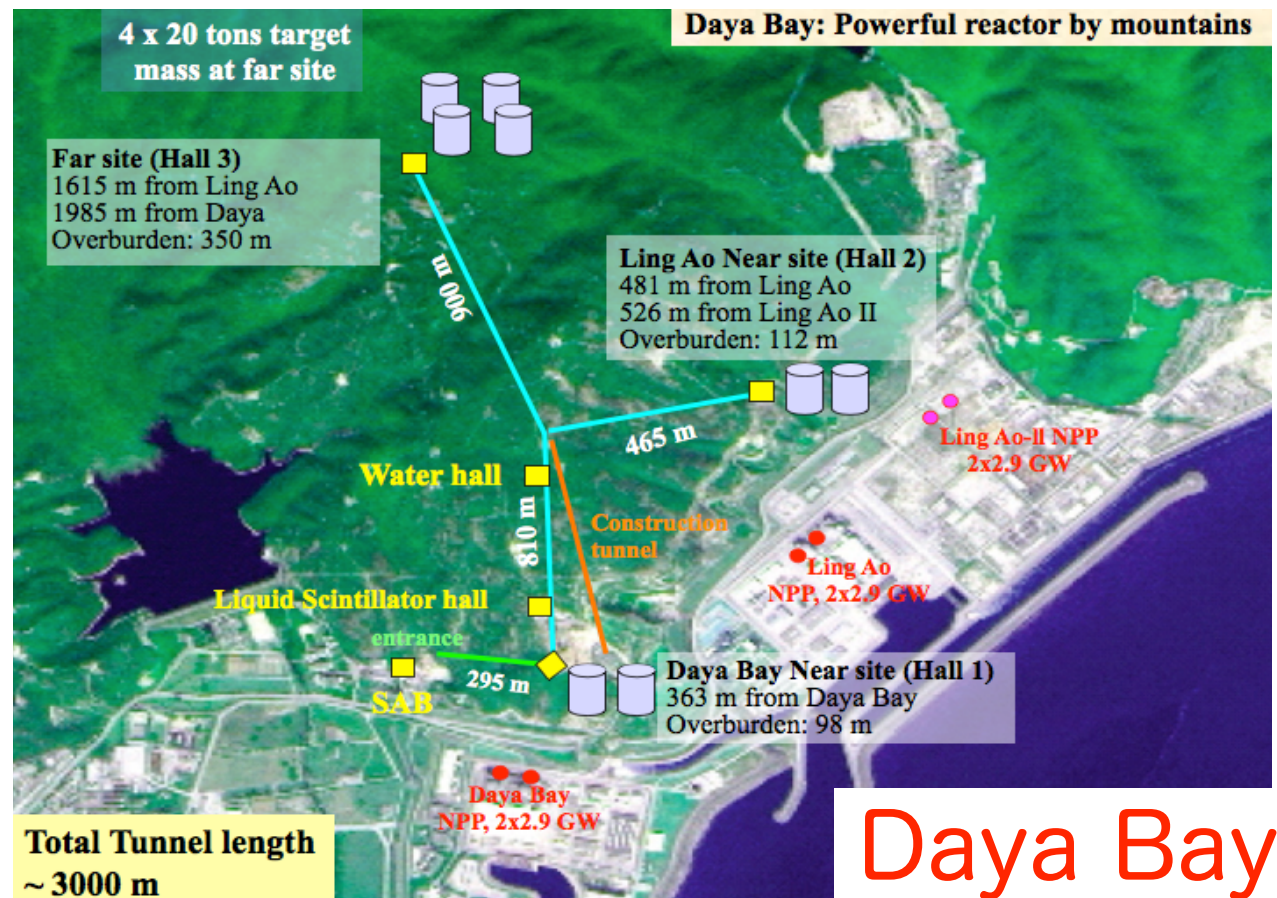
PLB 637(2006)266
PRD 76(2007)093002

Reactor- ν experiments

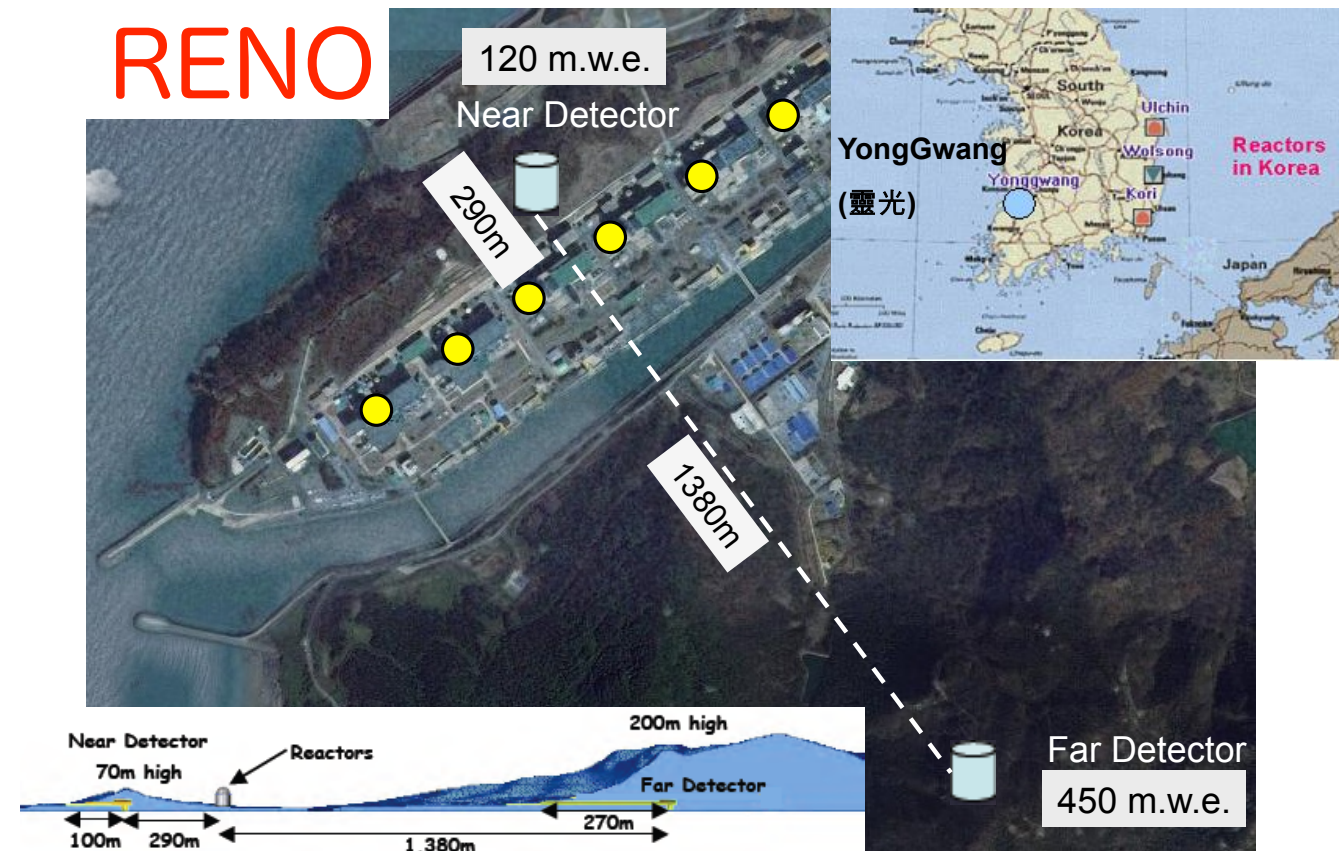
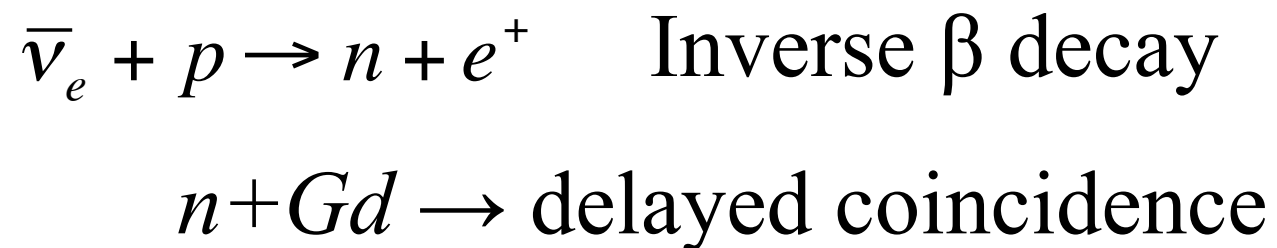
- At middle distances ($L=1\sim 2\text{km}$) Δm^2_{31} osc. dominant
 $\rightarrow \theta_{13}$ measurements (Daya Bay, RENO, Double Chooz)
- At long distances ($L>50\text{km}$) large Δm^2_{21} osc.
 $\rightarrow$ JUNO at 1st osc. maximum (M.H.) and KamLAND@180km
- Only disappearance experiments ($E_\nu \ll m_\mu$)



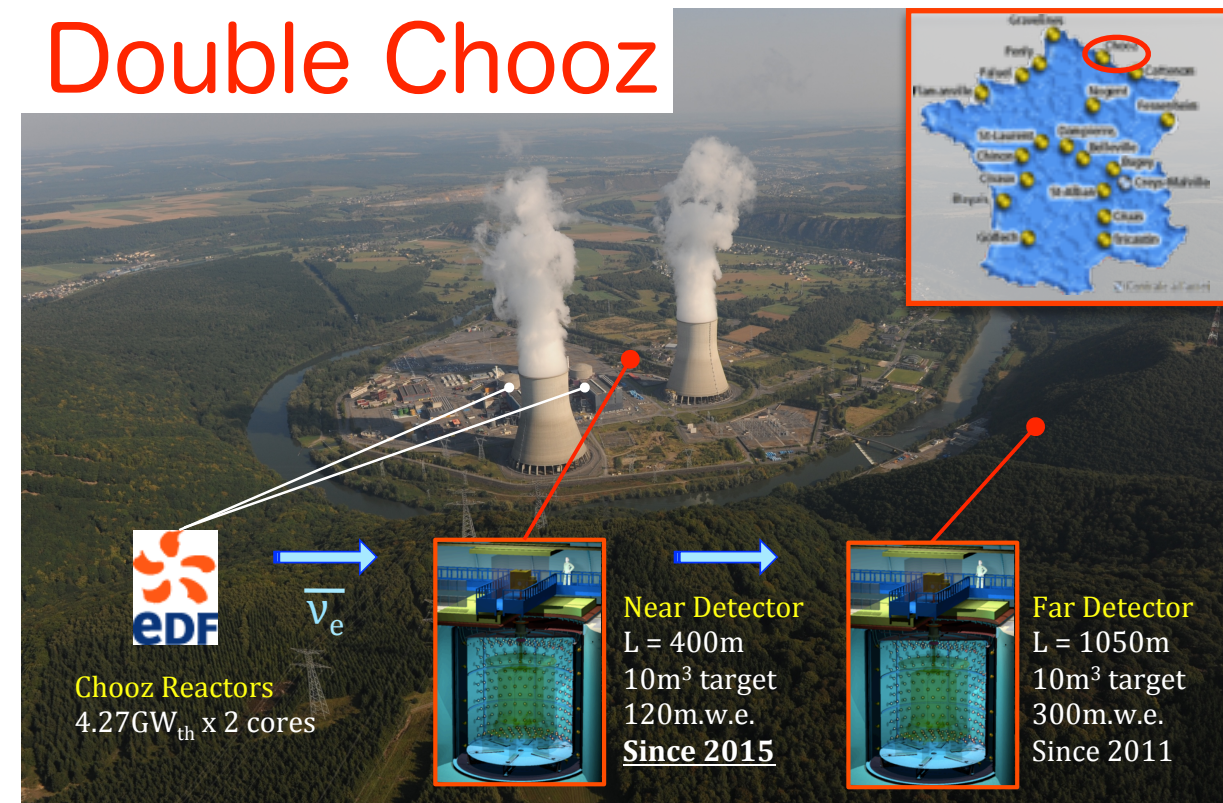
Reactor θ_{13} experiments



- Near+Far detectors to cancel flux uncertainty
- Gd-doped Liquid Scint.

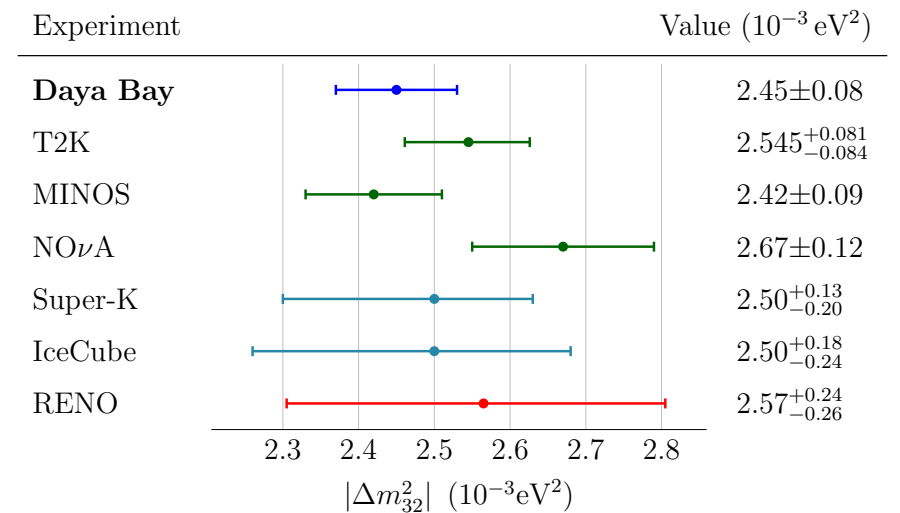
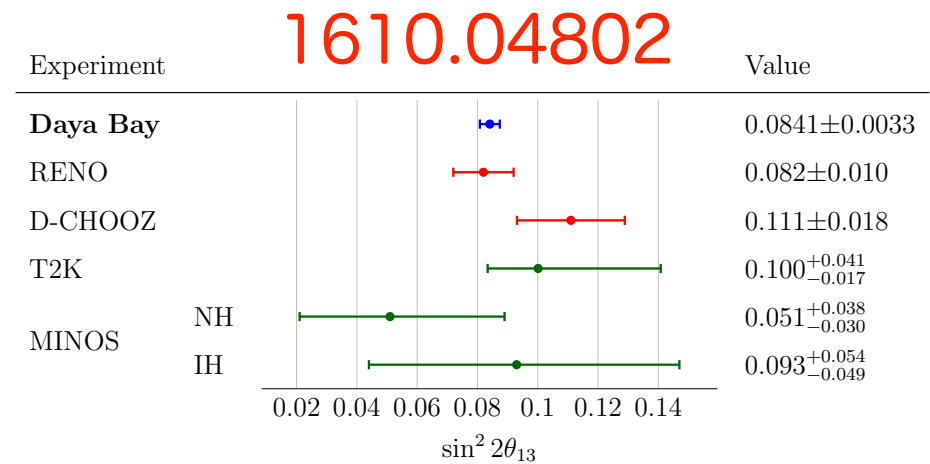
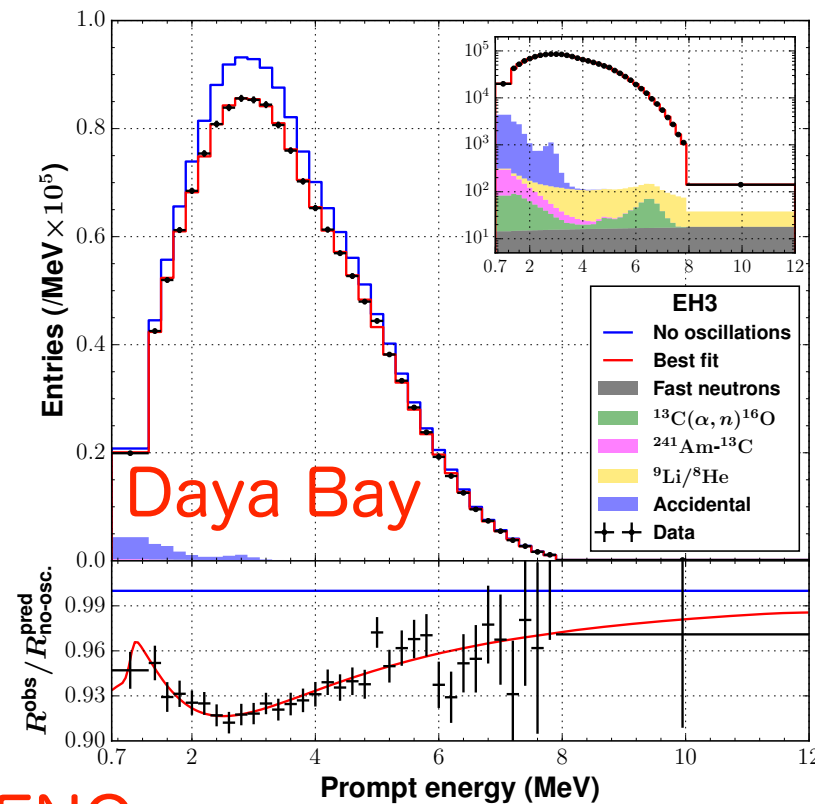
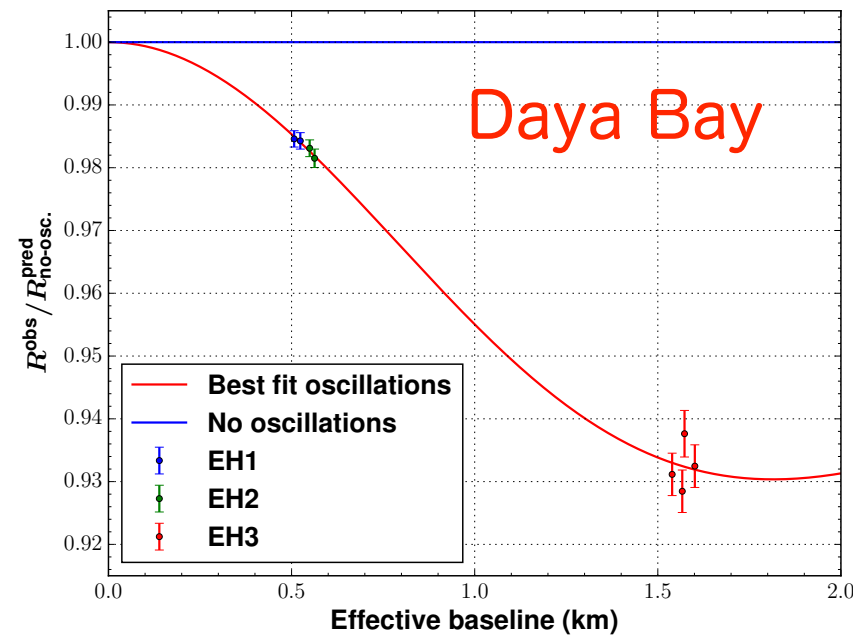


Double Chooz

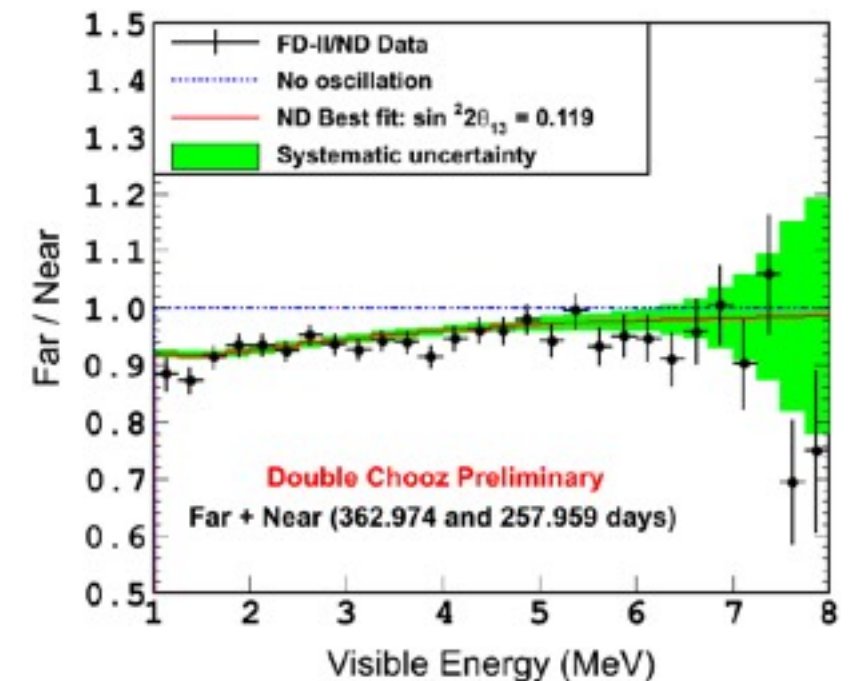
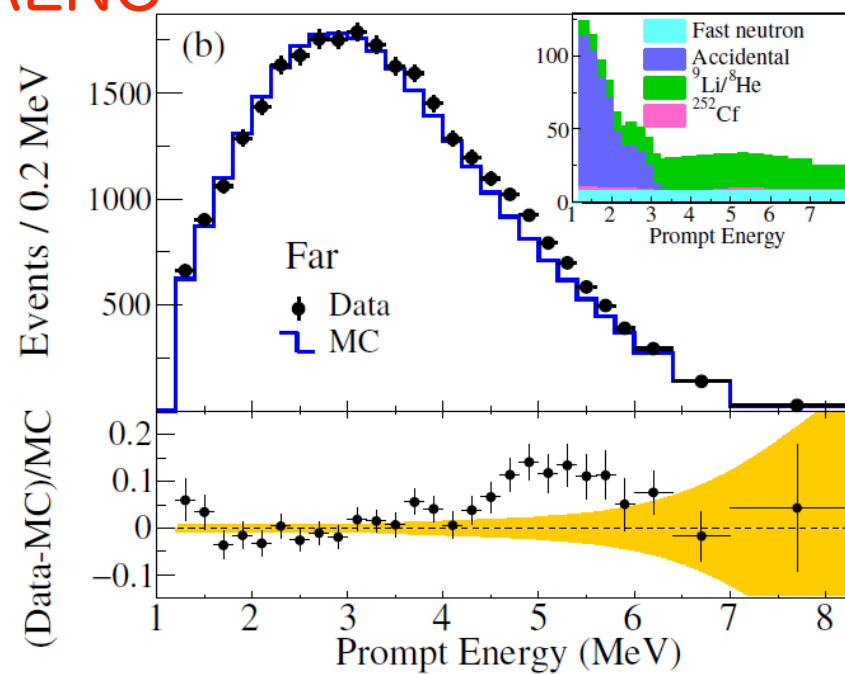
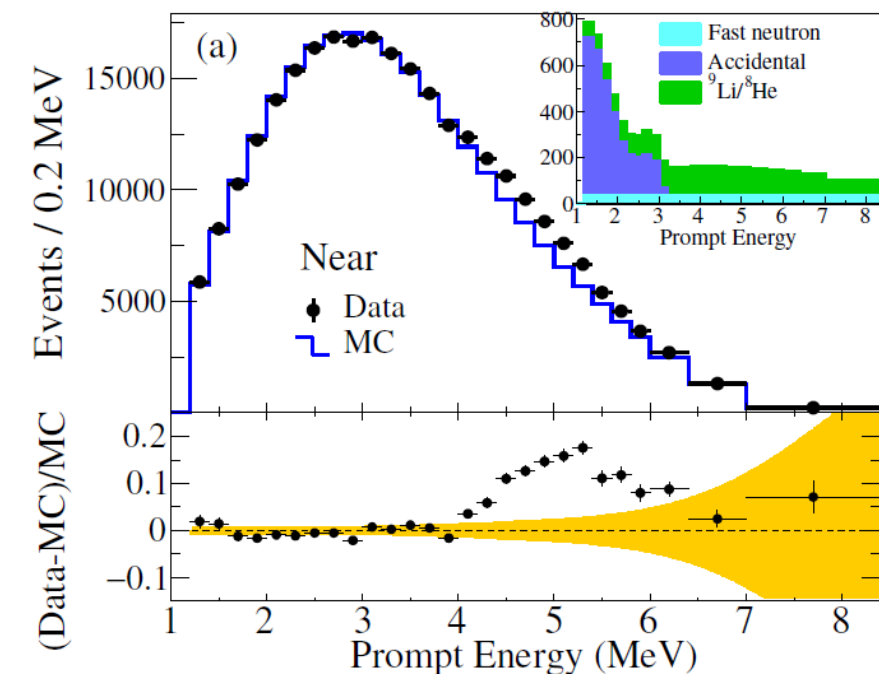


Reactor θ_{13} results

- All experiments measure θ_{13} with $>5\sigma$
- 'bump' seen in ν spectrum



RENO



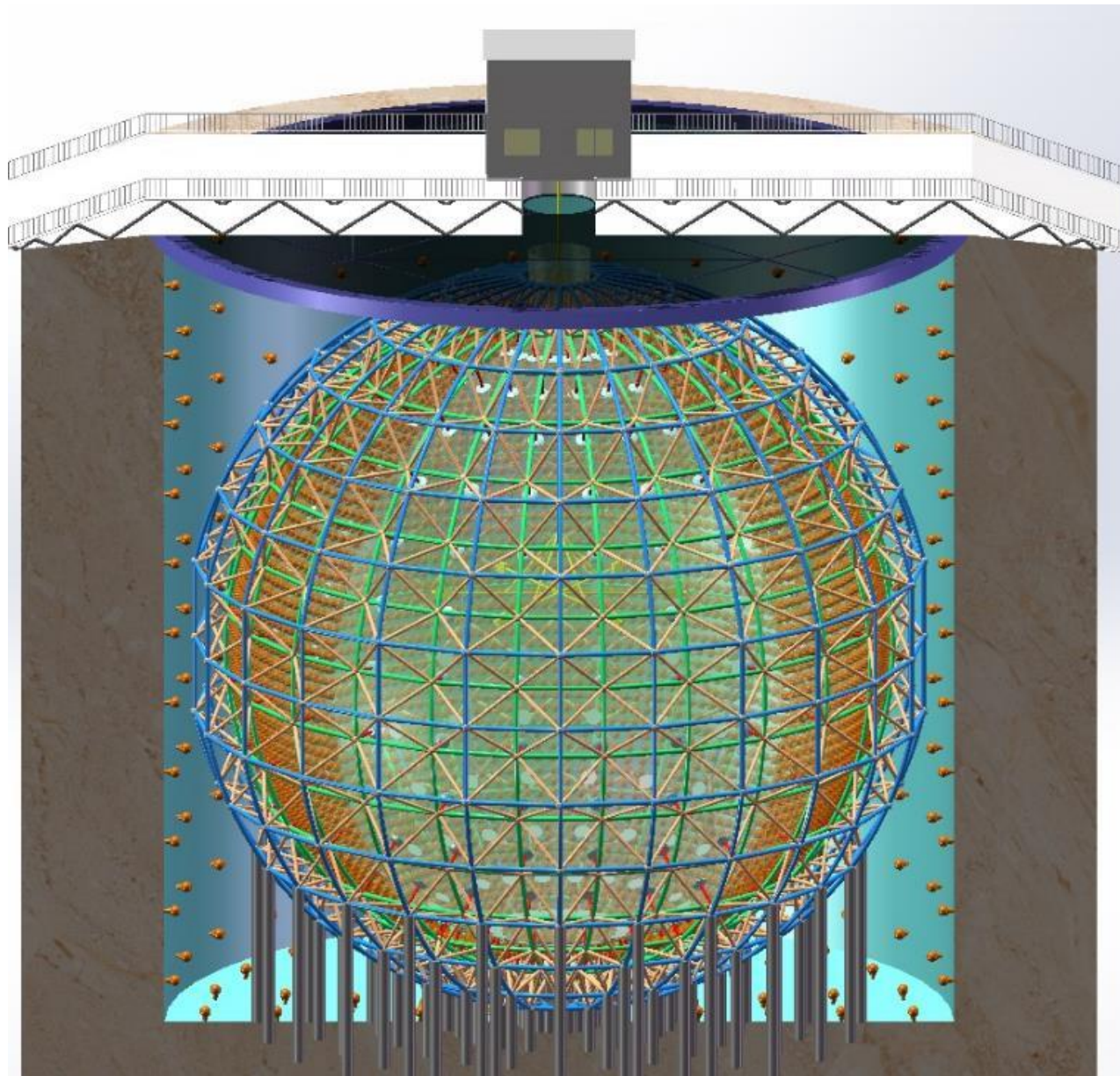
JUNO for Mass Hierarchy



The JUNO Experiment



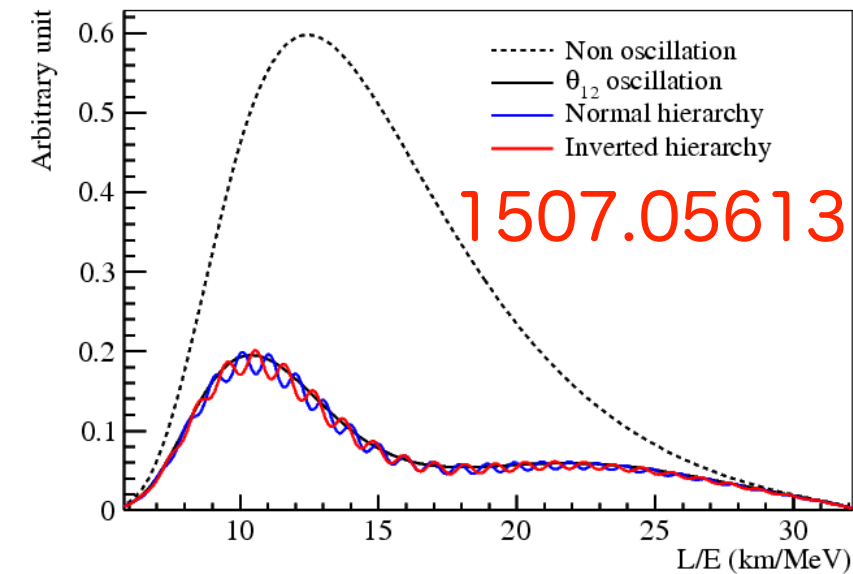
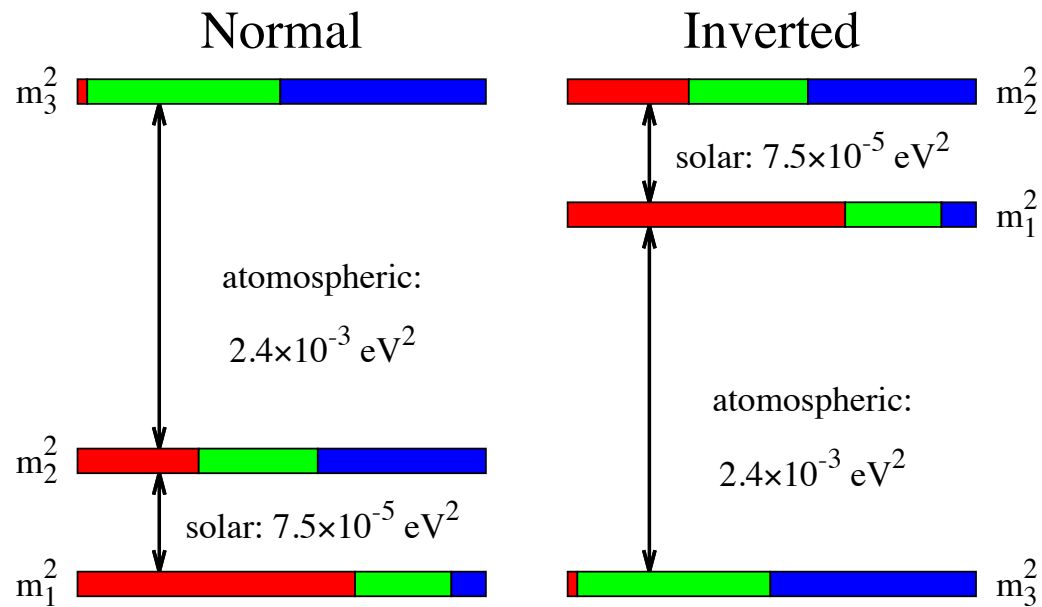
- ◆ Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M\$.



- ◆ 20 kton LS detector
- ◆ 3% energy resolution
- ◆ 700 m underground
- ◆ Rich physics possibilities
 - ⇒ Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
 - ⇒ Supernovae neutrino
 - ⇒ Geoneutrino
 - ⇒ Solar neutrino
 - ⇒ Atmospheric neutrino
 - ⇒ Exotic searches

How to access Mass H.?

- Detect θ_{13} 'ripple' at θ_{12} osc. max. (53km)
- Energy resolution is the key (80% PMT coverage)

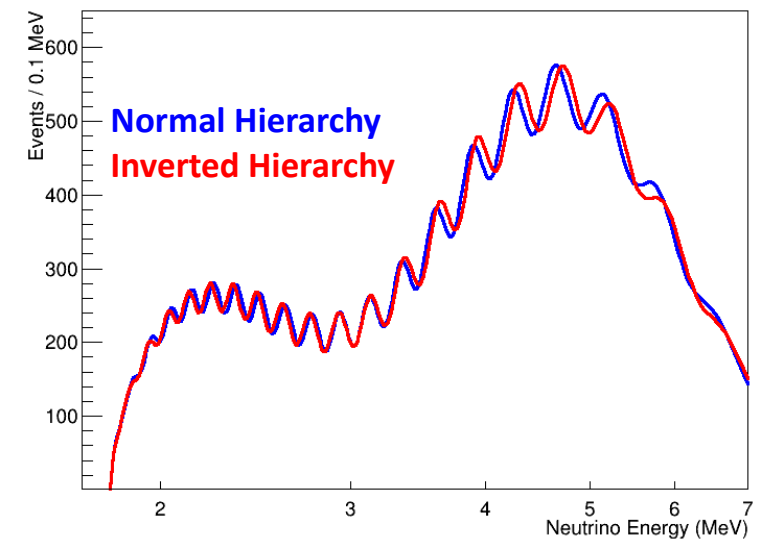


True energy

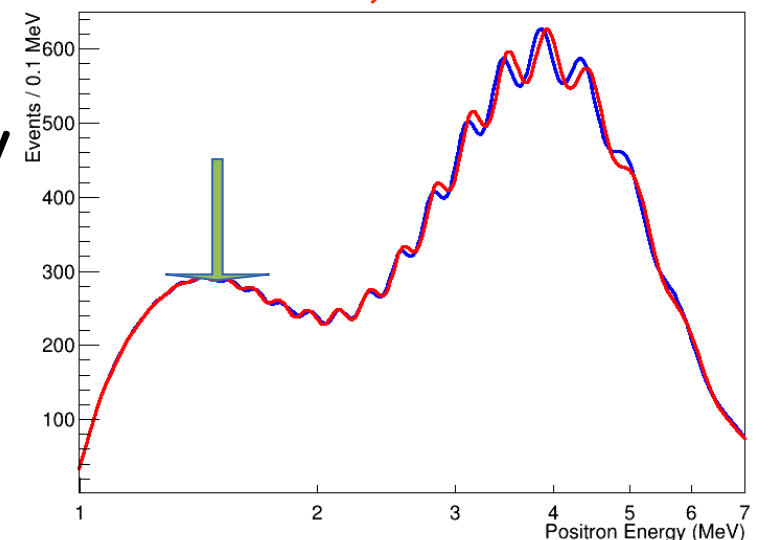


Visible energy

$$\sigma(E)/E = 3\%/\sqrt{E(\text{MeV})}$$



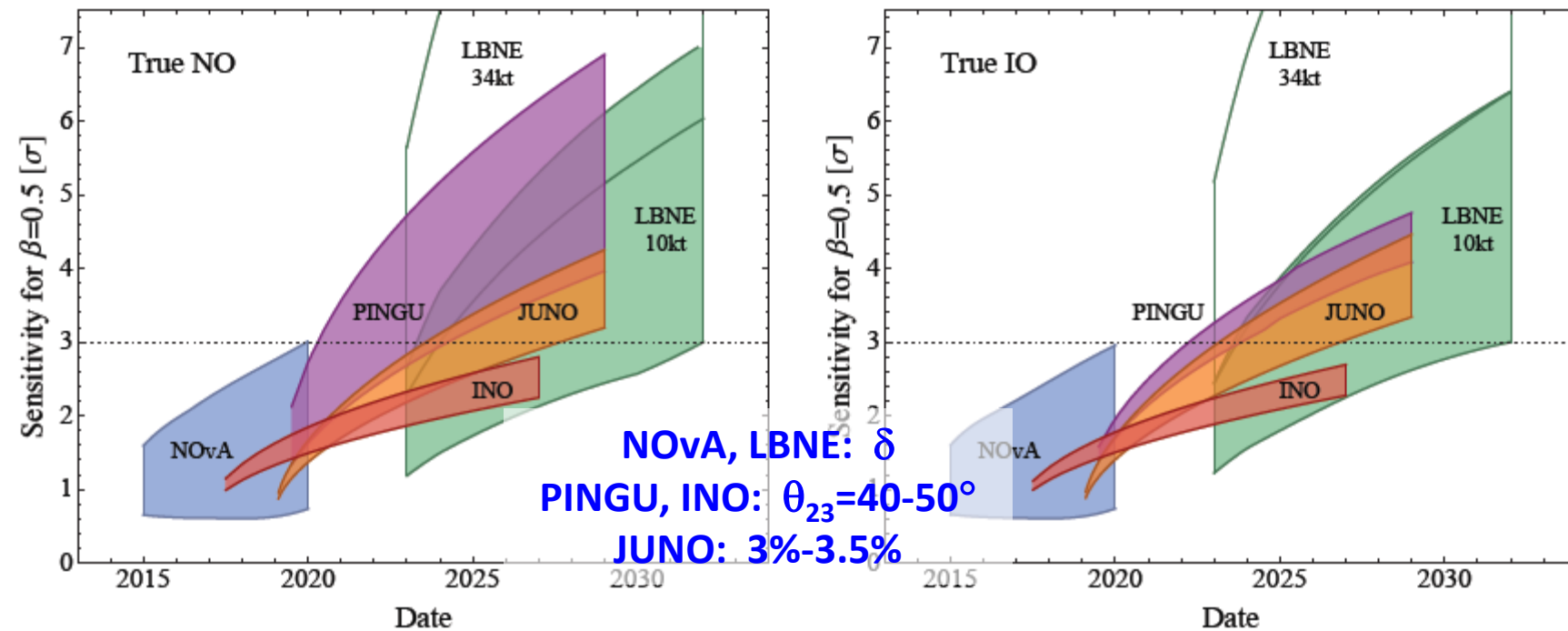
G. Ranucci, Neutrino 2016



JUNO in construction

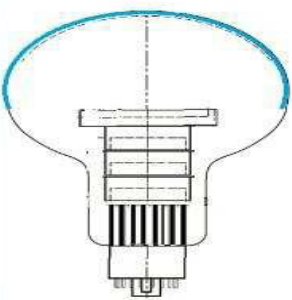
J. Cao, NuTel 2015

M. Blennow et al., JHEP 1403 (2014) 028



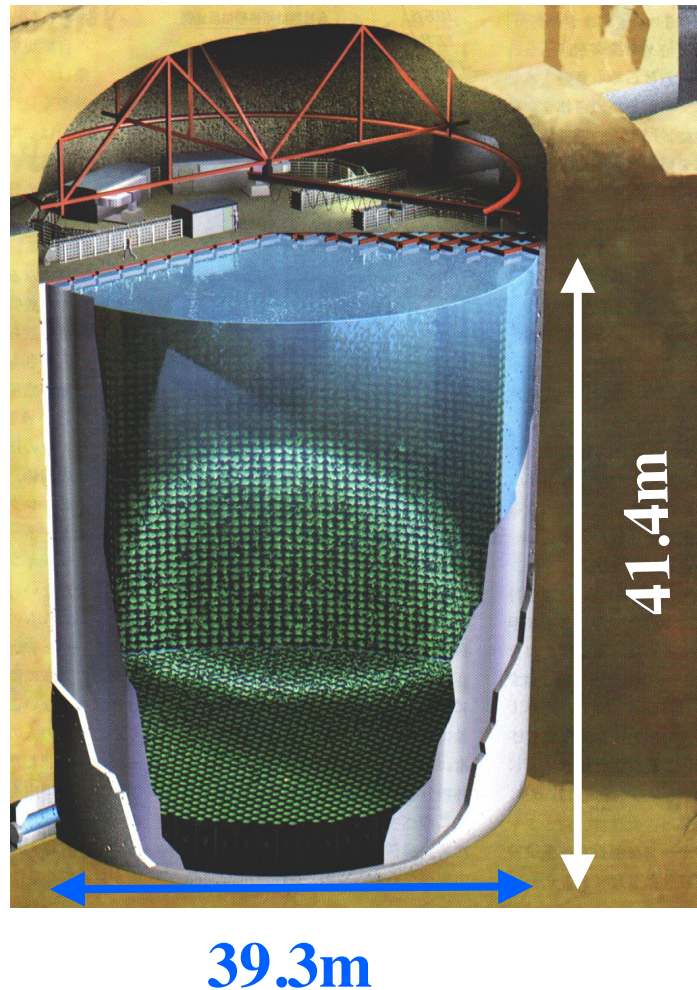
- Expect to start in 2020
- Determine MH with $>3\sigma$ in 6 years
- More physics with high-stat. natural ν 's



20-inch Hamamatus PMT Dynode Ellipsoidal Glass	20-inch IHEP MCP-PMT Horizontal MCPs Ellipsoidal Glass
 	 
HQE 1#, 2#, 3#	76#, 77#, 78#, 79#



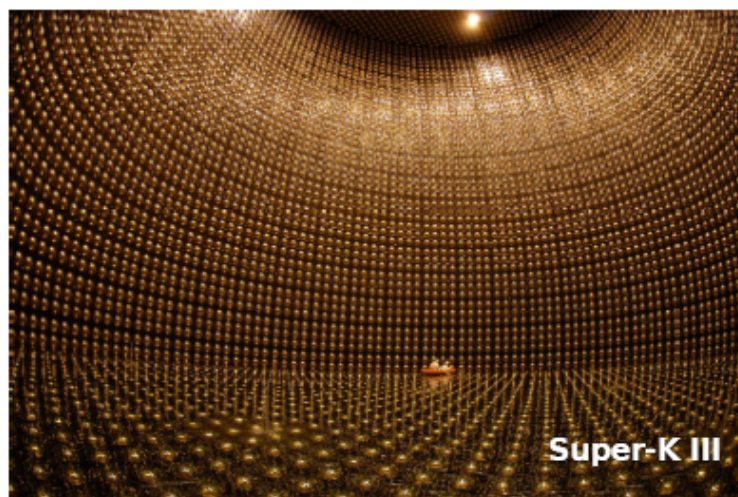
Super-Kamiokande (since 1996)



- 50kt Water Cherenkov (fiducial: 22.5kt)
- Under 1km rock (2700m.w.e.)
- 11129 20-inch PMTs (+outer veto det.)
- e/μ separation with Cherenkov ring
- GPS timing for T2K beam coincidence:
no accidental b.g.

(Not only as) Far detector of T2K

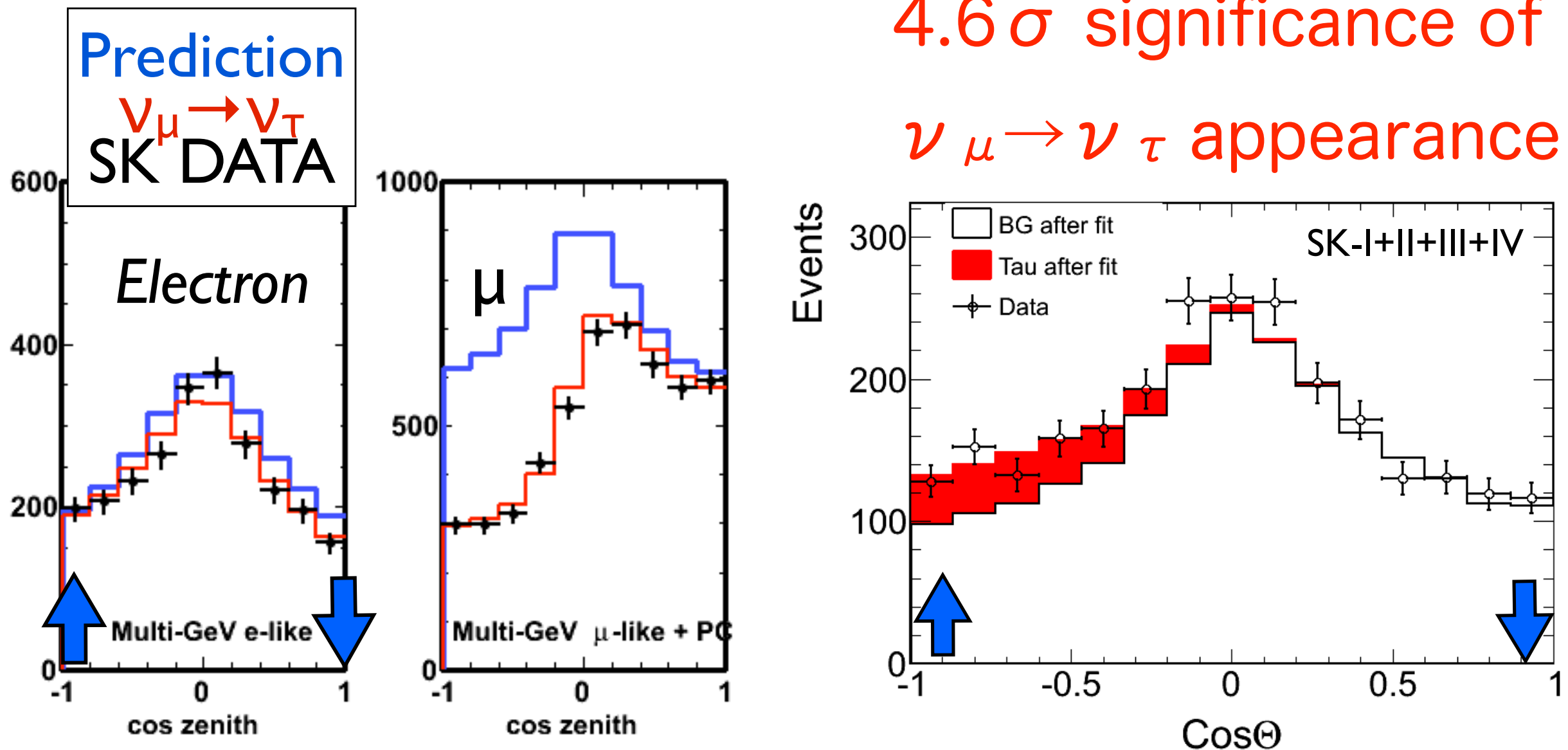
- Atmospheric- ν
- Solar- ν
- Supernova- ν
- Nucleon decay!



Atmospheric- ν by SK

- Oscillation of ν_μ while flying through the Earth
- τ appearance selection with neural net

4.6 σ significance of
 $\nu_\mu \rightarrow \nu_\tau$ appearance

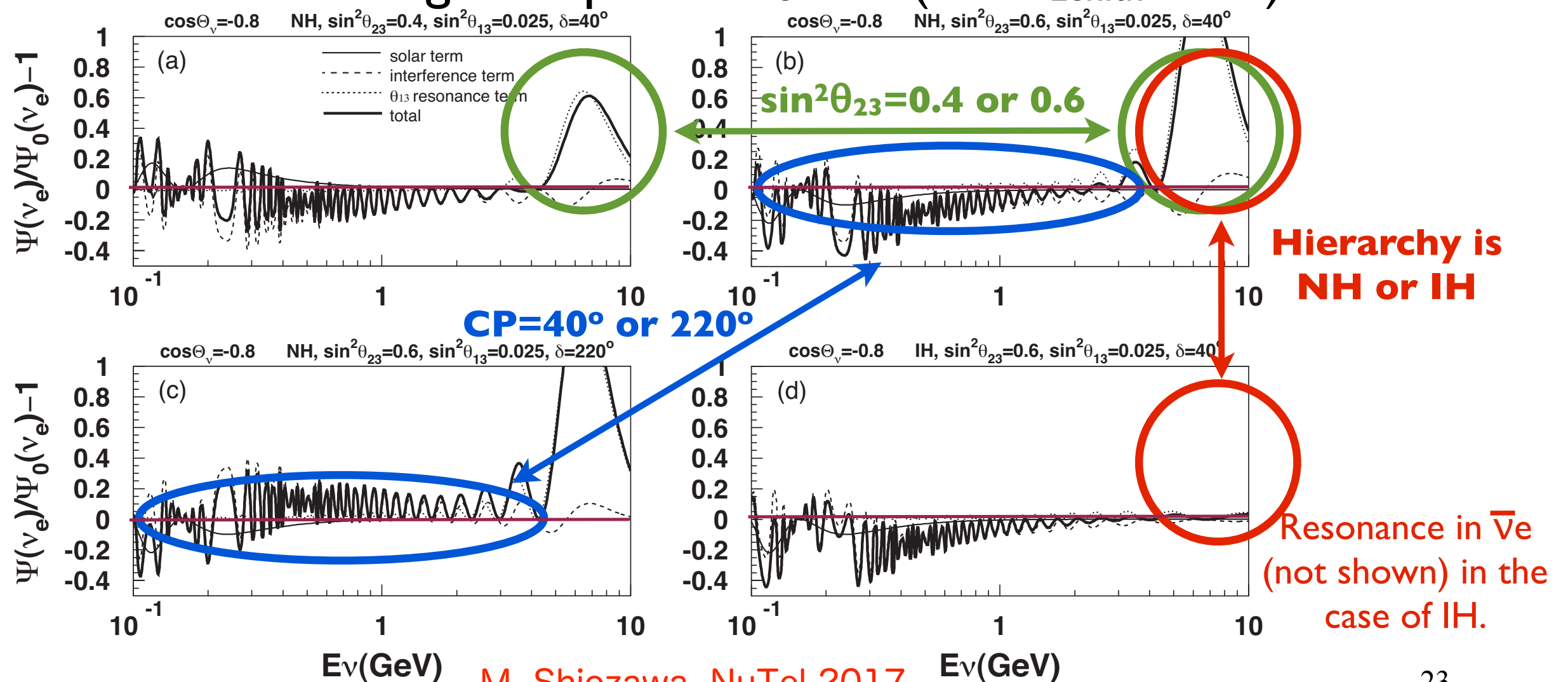


M. Shiozawa, NuTel 2017

Accessing M.H. by SK

- Matter effect: resonant enhancement of ν_e oscillation at certain energy/zenith-angle
- Effect reverses for Normal and Inverted H.

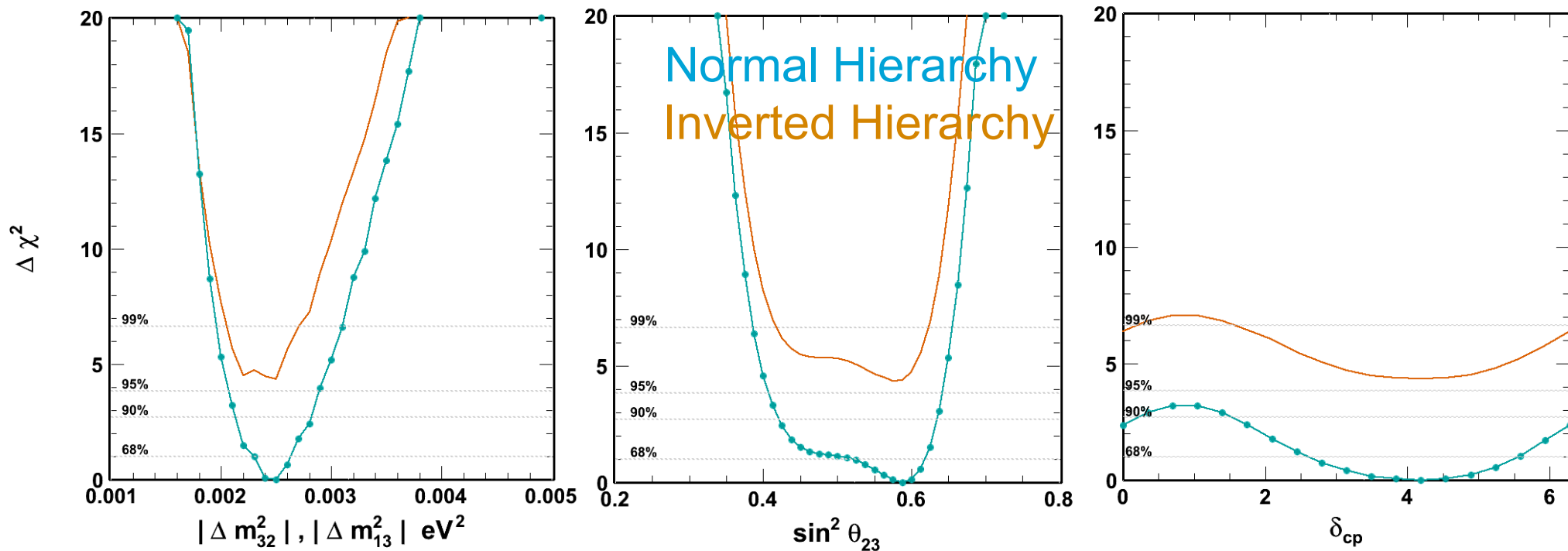
“Fractional change of upward ν_e flux ($\cos\Theta_{\text{zenith}}=-0.8$)”



Moderate preference on NH

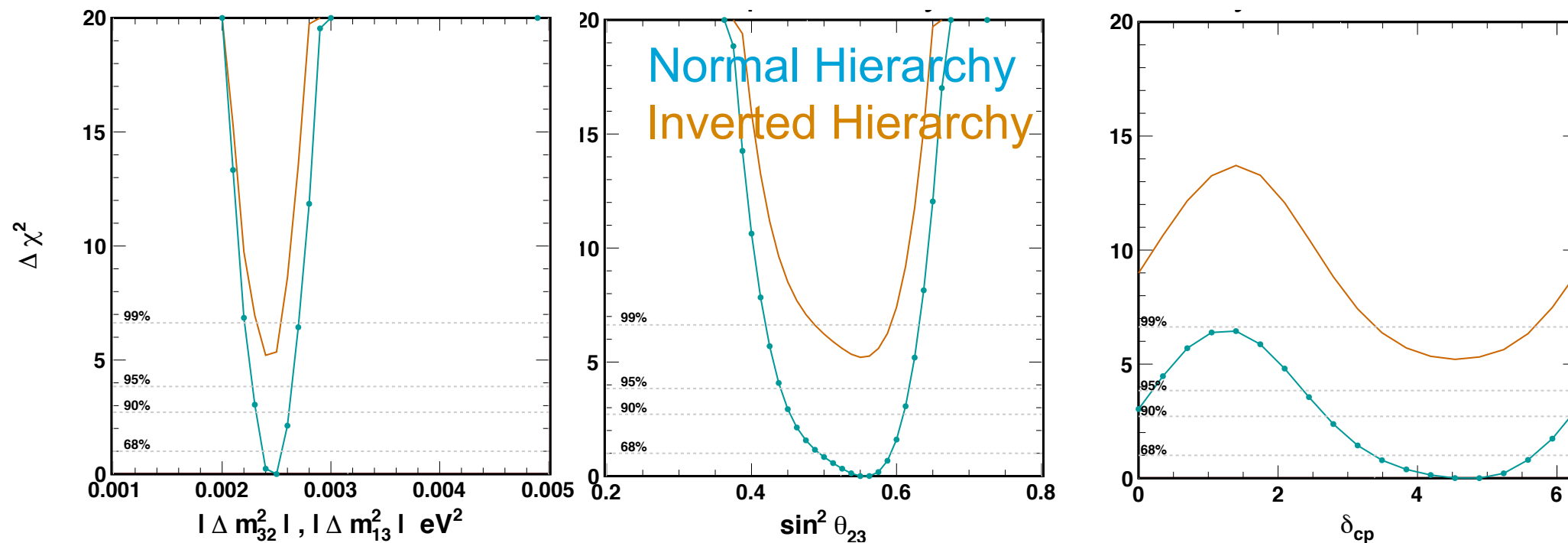
- SK Atm- ν + fixed θ_{13}

$$\Delta\chi^2 = -4.3$$



- + T2K θ_{23} and Δm^2_{32}

$$\Delta\chi^2 = -5.2$$

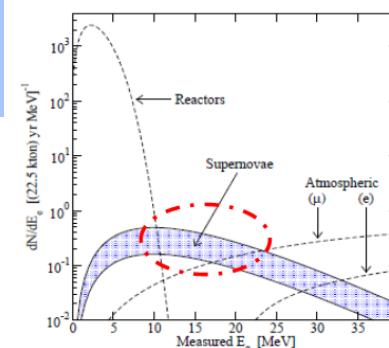


Near-future of SK: SK-Gd

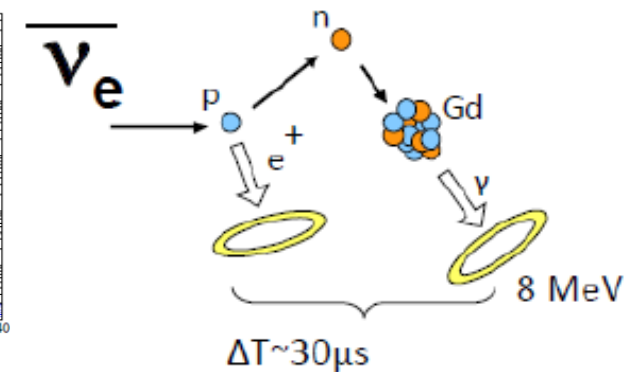
- Main motivation: Supernova relic ν
- Also reduces p-decay BG

SK-Gd

- Discovery of relic SN neutrinos is expected by $O(1)$ sensitivity improvement
- 0.1% Gd loading to tag $\bar{\nu}e + p \rightarrow e + n$, $Gd + n \rightarrow Gd + \gamma$ s
- R&D in test tank and water system construction going on
- Start SK-Gd in a few yrs



Phys. Rev. Lett. 93 (2014) 171101.



Model Tv	10-16MeV Eve/10yrs	16-28MeV Eve/10yrs	Total (10-28MeV)	Significance 2 energy bin
8 MeV	11.3	19.9	31.2	5.3 σ
6 MeV	11.3	13.5	24.8	4.3 σ
4 MeV	7.7	4.8	12.5	2.5 σ
1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	---

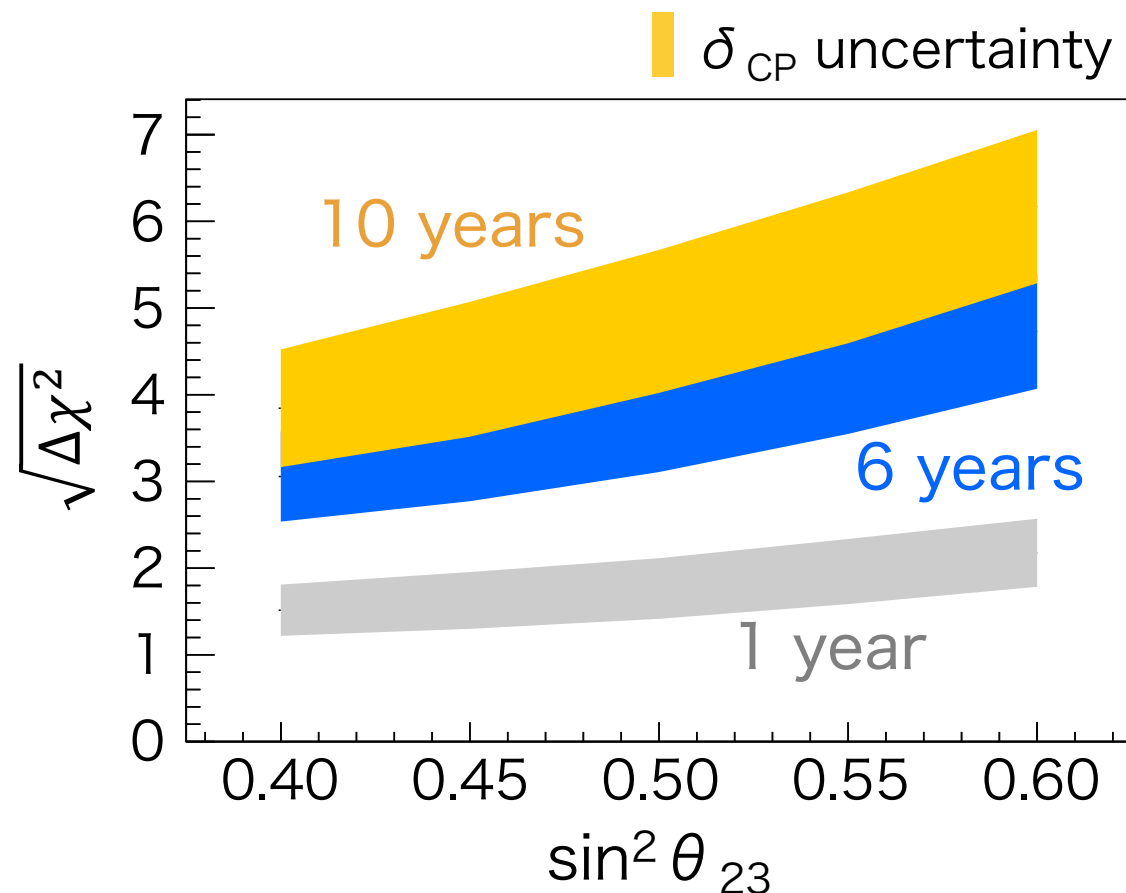
Model: Phys. Rev. D 79 (2009) 083013.



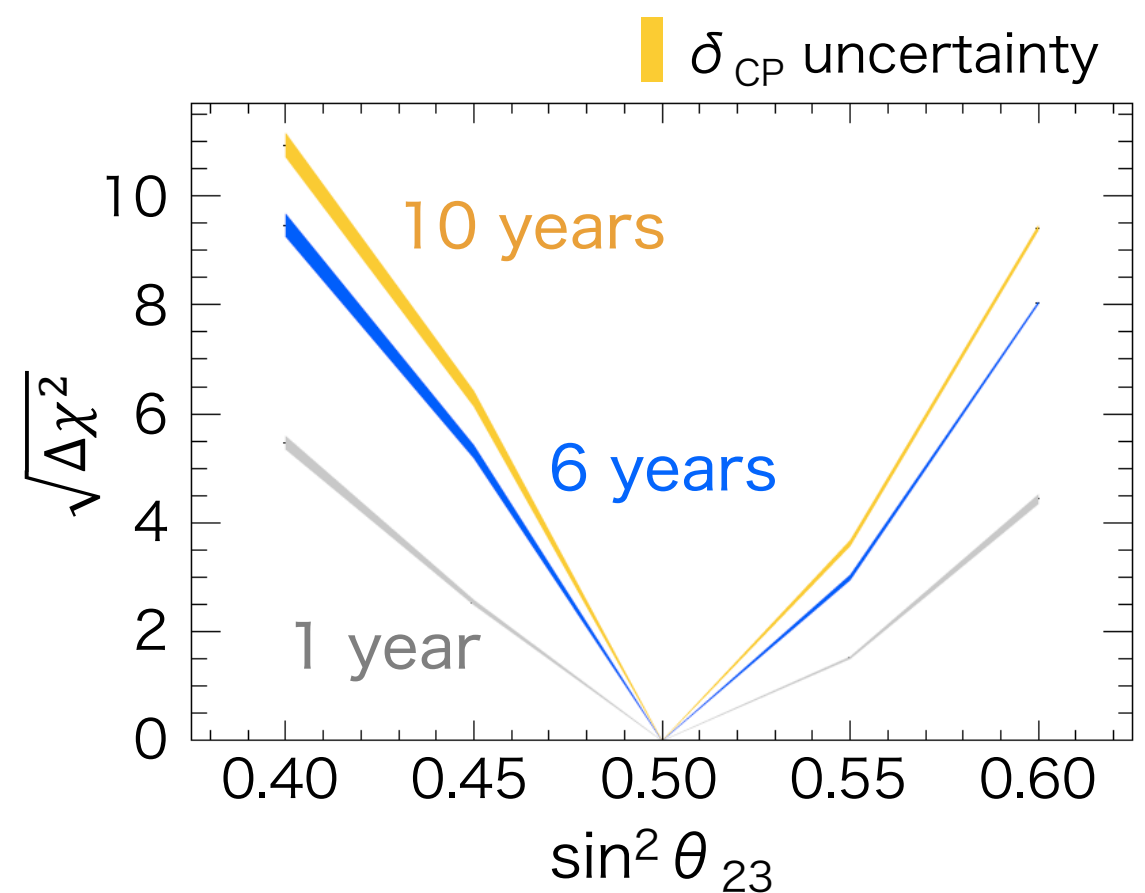
Atmospheric ν in Hyper-K

- Combining Atm- ν and Beam- ν data

wrong MH rejection



wrong octant rejection

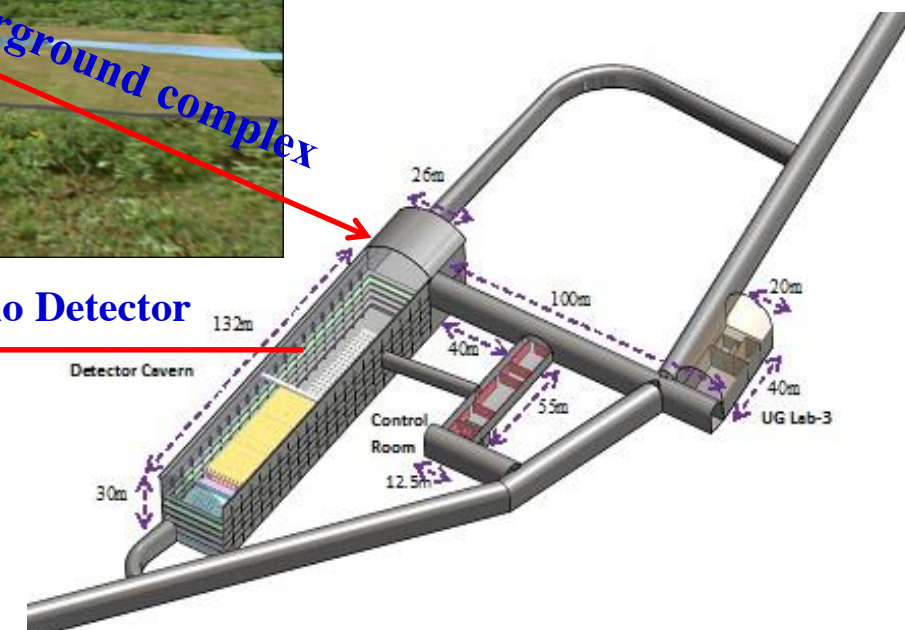
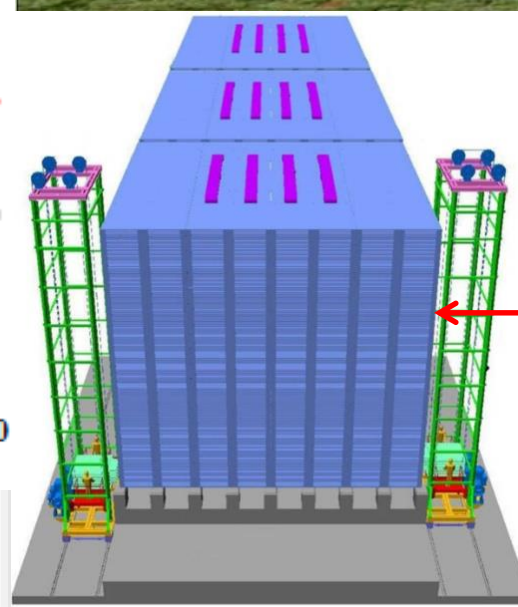
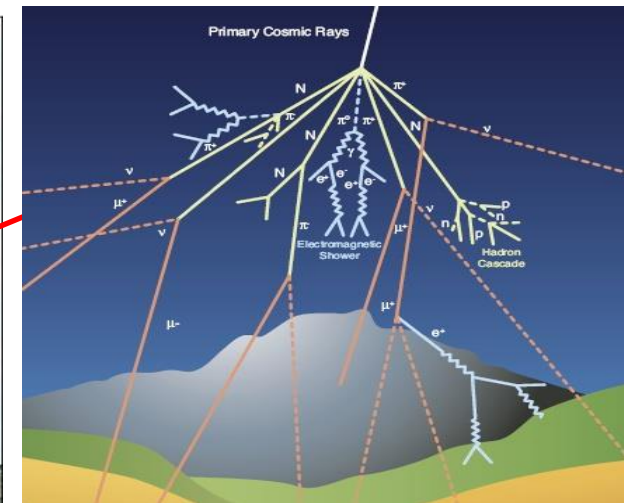
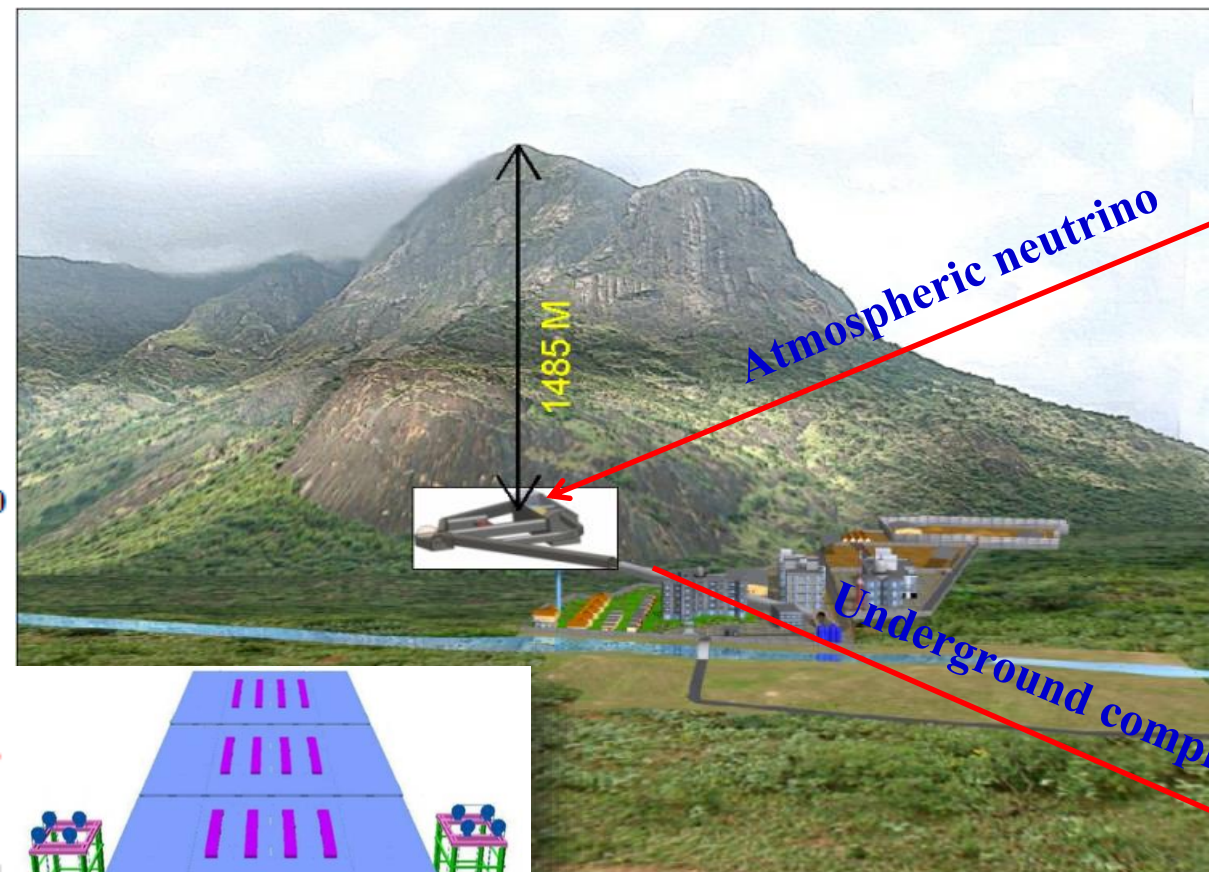
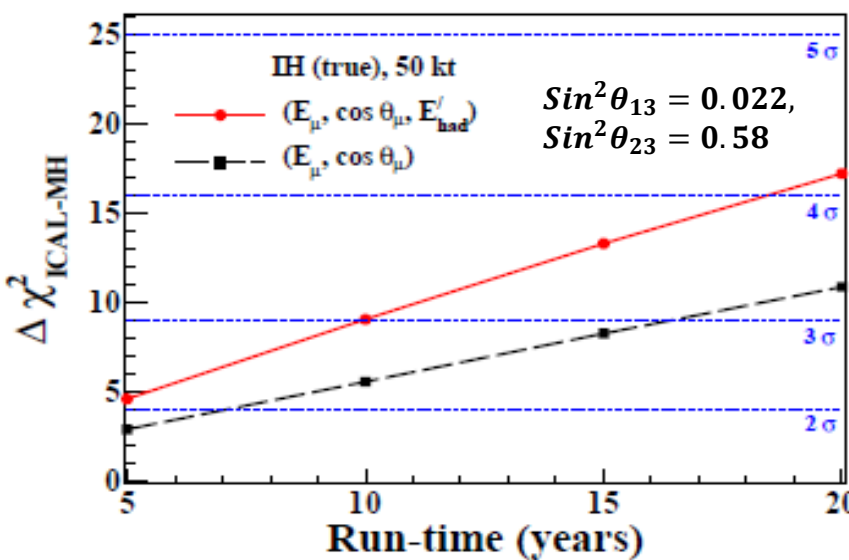
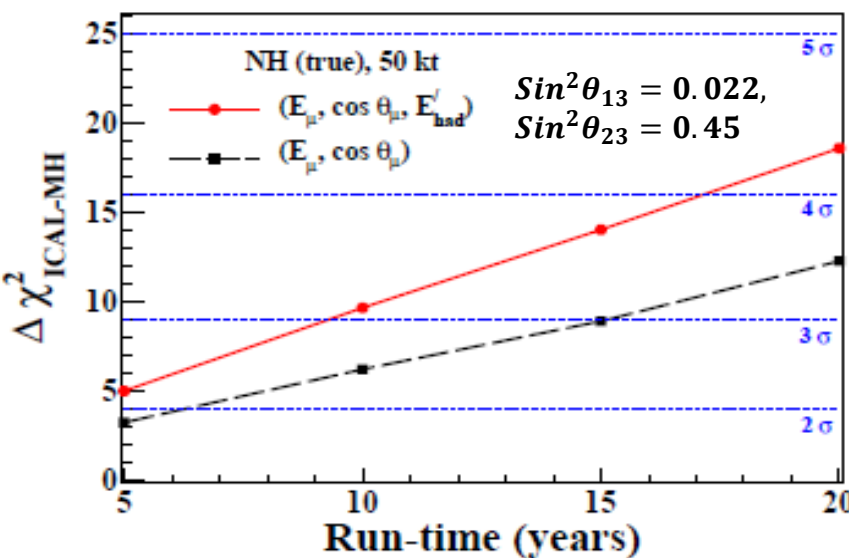


- Budget request being submitted
- Aiming to start operation in 2026

India-based Neutrino Observatory

- Magnetized Iron Calorimeter for direct charge separation → M.H.
- R&D ongoing

INO site at BodiHills



Summary

- While Europe operates the energy-frontier hadron collider, **neutrino experiments flourish in Asia** (and in the US!).
- Exciting findings in the past and now, next target being **CP violation** phase, **mass hierarchy** and θ_{23} octant.
- Determination of these information (as well as absolute ν masses) should bring hints on **physics beyond SM**.
- **T2K-II, JUNO, SK-Gd, INO** will run in next 10 years and **Hyper-K/T2HK(K)** proposed to start ~2026.
- Collaboration is already very **international** (e.g. T2K, JUNO), and **new countries in Asia** are emerging (e.g. initiative to form an experimental ν group in Vietnam <http://www-he.scphys.kyoto-u.ac.jp/member/nuICISE/>).