Neutrino Oscillations: Status and Perspectives

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21st August 2019

Neutrino oscillations

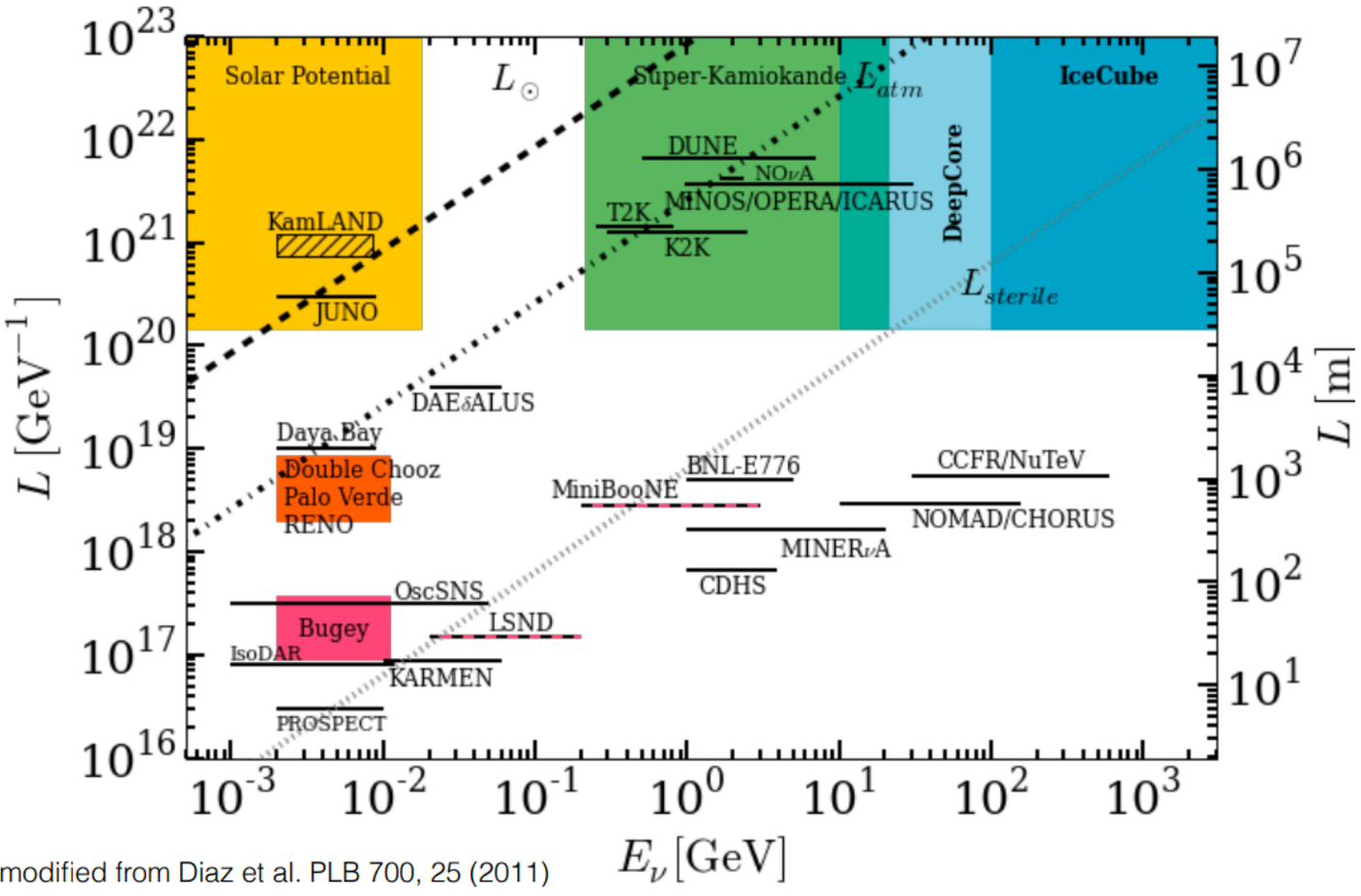
Neutrinos oscillate ($\Delta m^2_{ij} \neq 0$) → neutrinos have non-zero mass

$$P(\overset{(-)}{\nu_\alpha} \to \overset{(-)}{\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2(\Delta m^2_{ij}\frac{L}{4E}) \pm 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin(\Delta m^2_{ij}\frac{L}{2E})$$

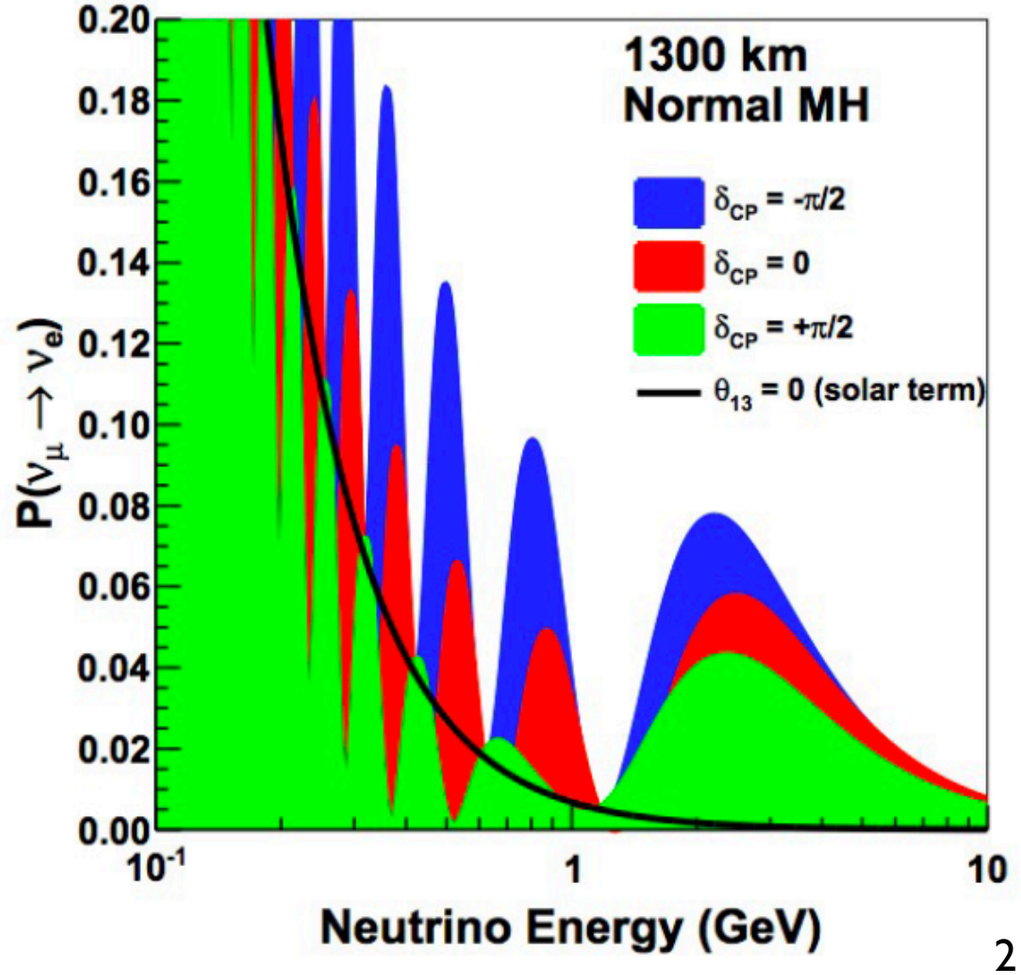
L: neutrino flight path

E: neutrino energy

Responsible for CP violation ($\pm$: $+$ for ν, $-$ for $\bar{\nu}$)



modified from Diaz et al. PLB 700, 25 (2011)



Oscillation parameters

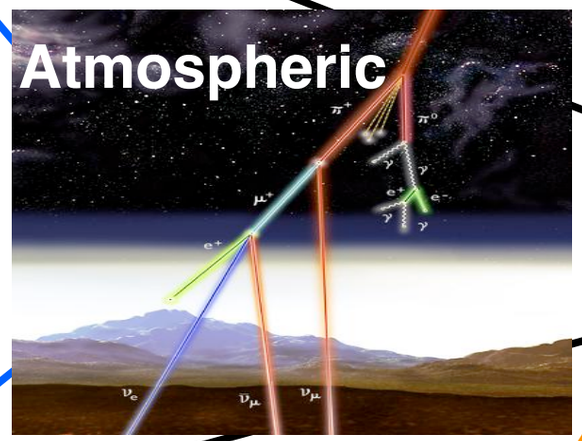
Need many experiments at different L/E to measure all the oscillation parameters

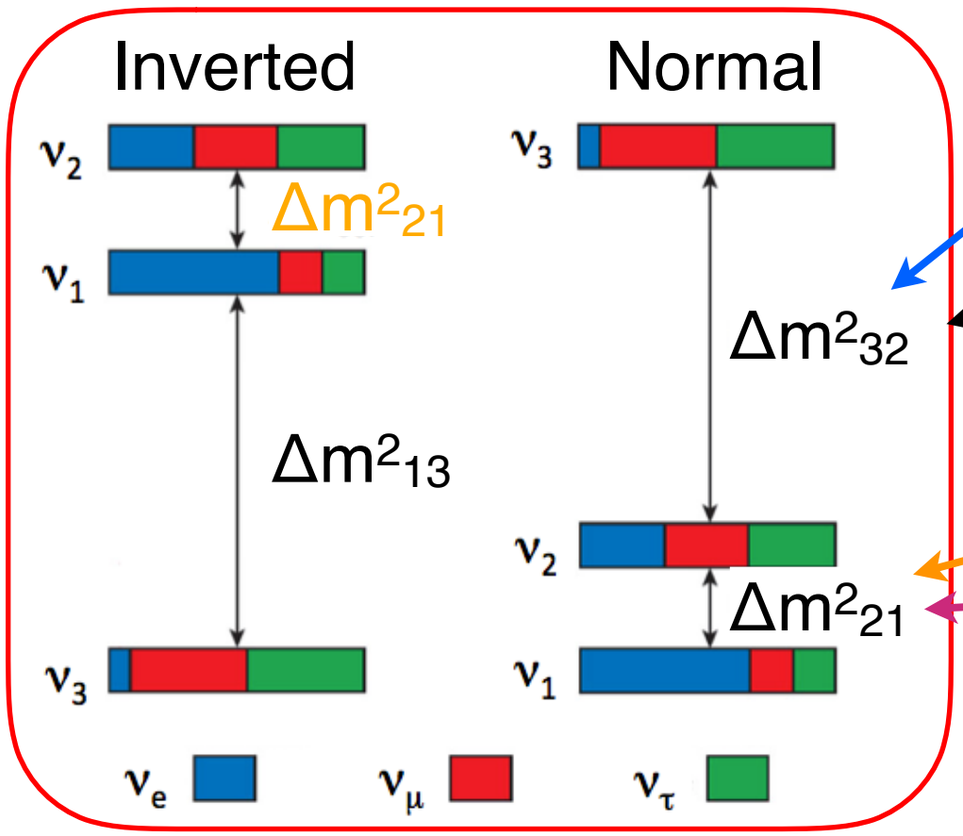
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

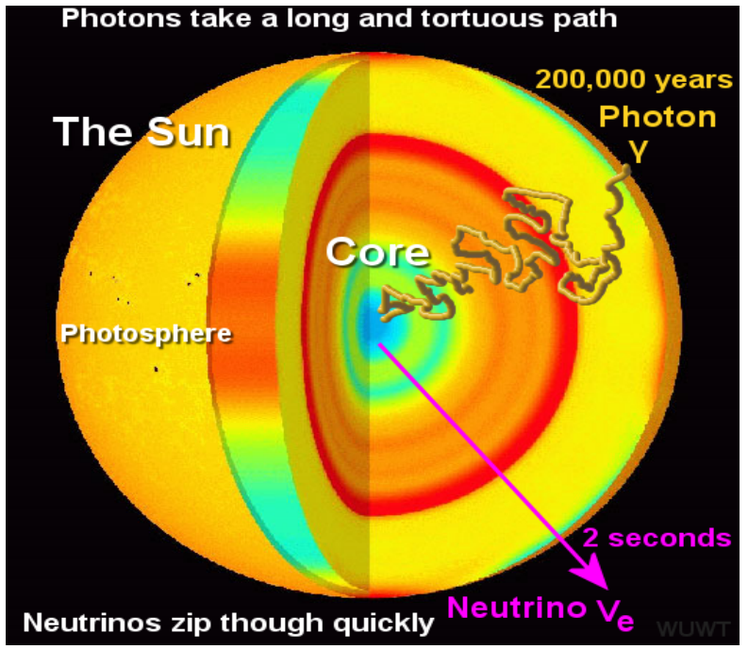
CP is violated if $\delta_{CP} \neq 0,\pi$

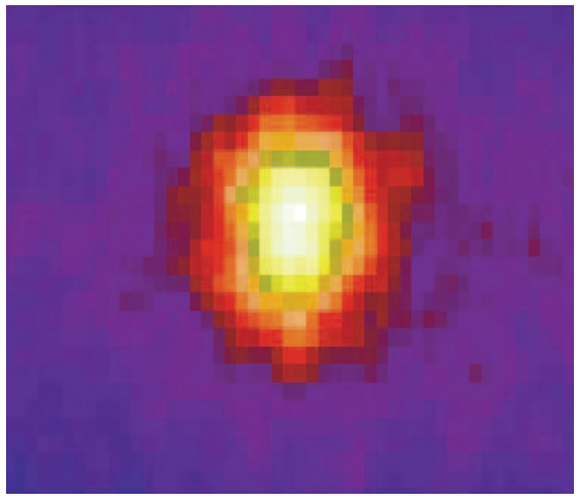




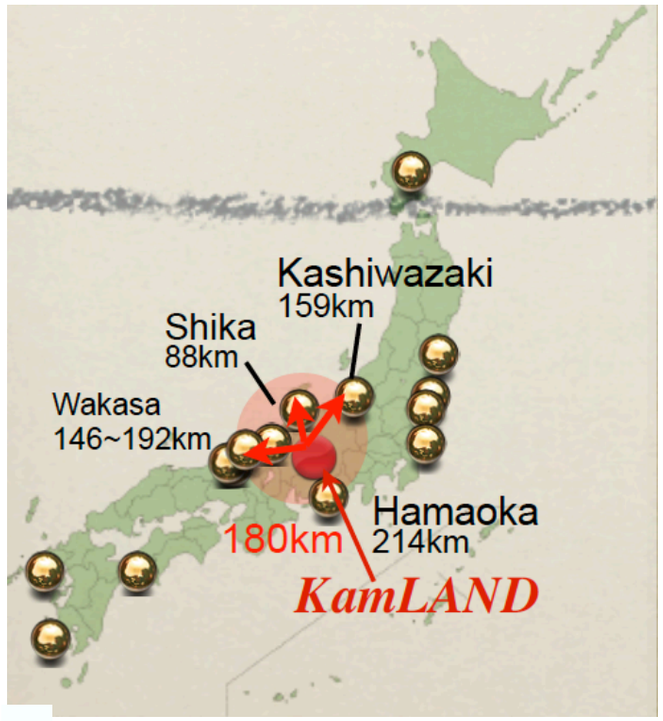
The solar parameters (“12”)

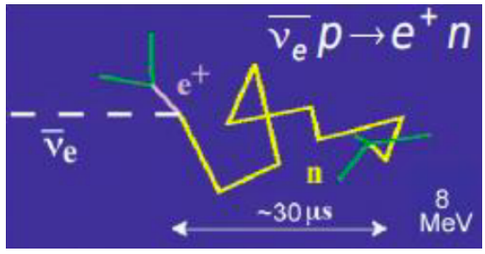
Solar experiments



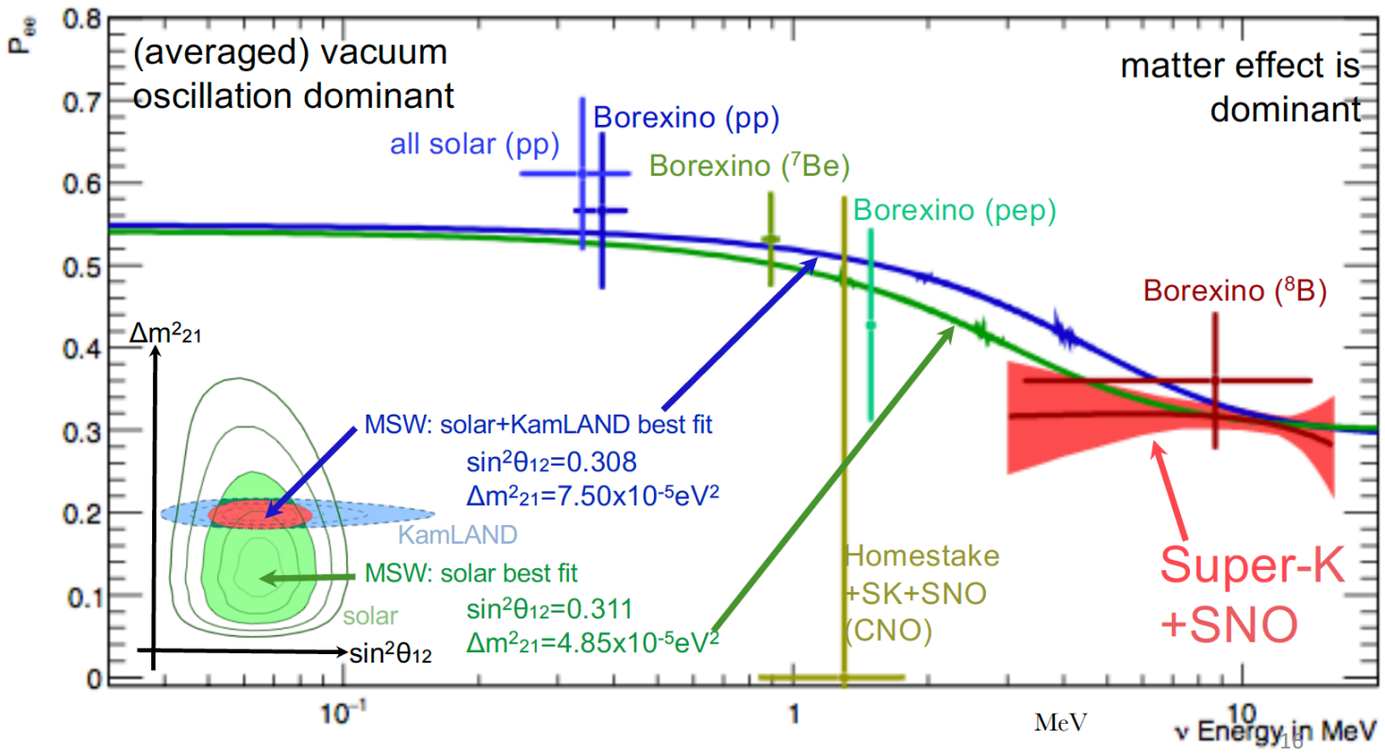


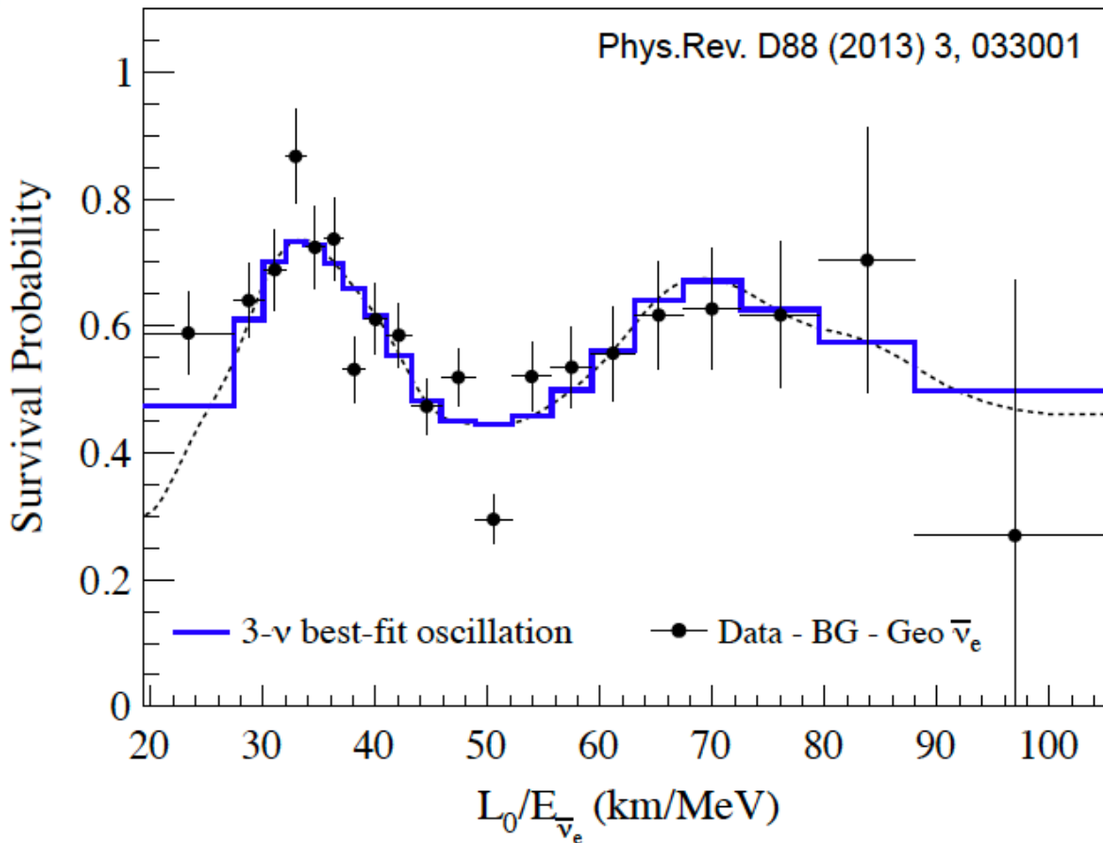
KAMLAND experiment





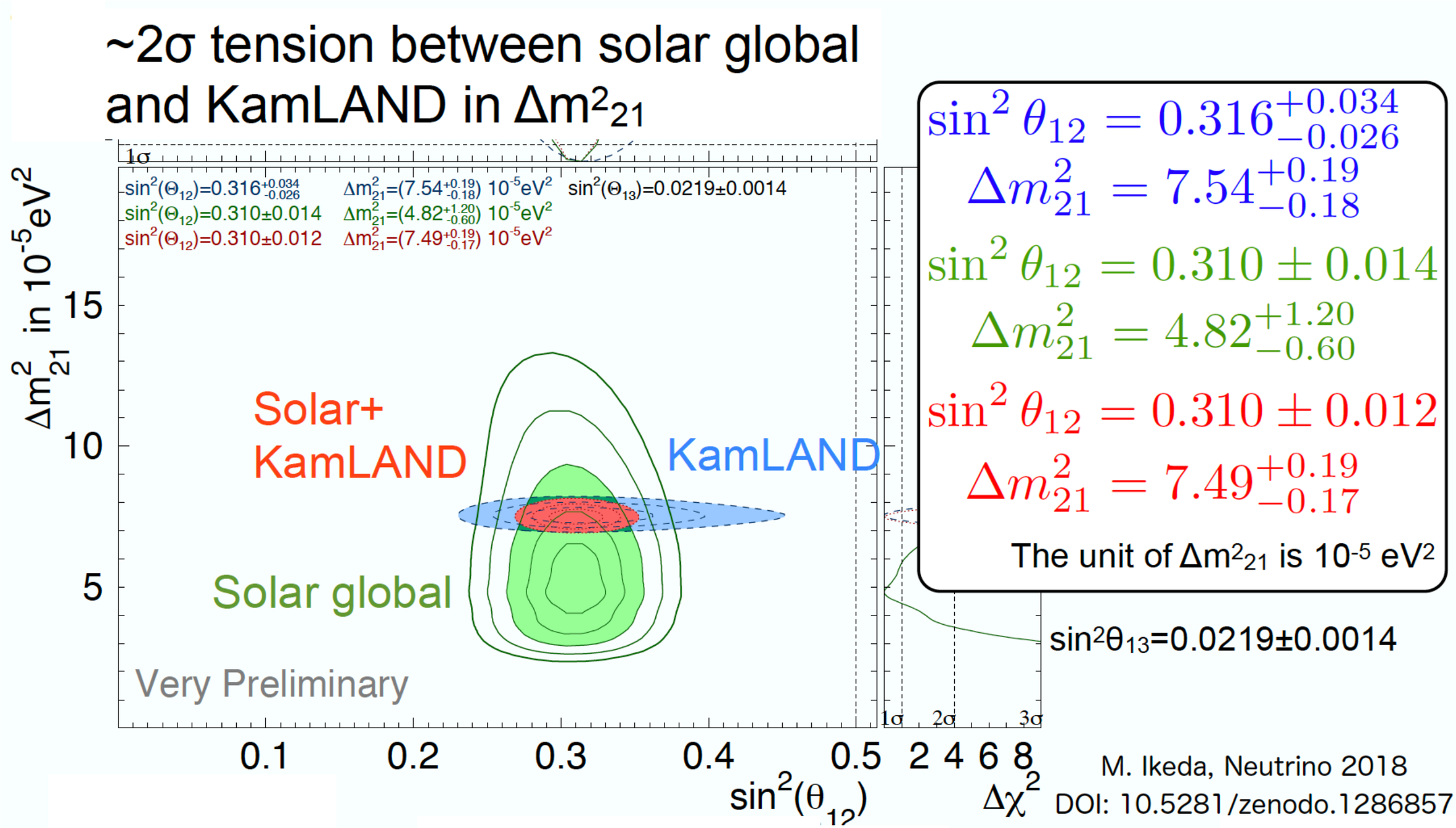
NuE flux from reactors in Japan on a baseline of 180 km





M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857

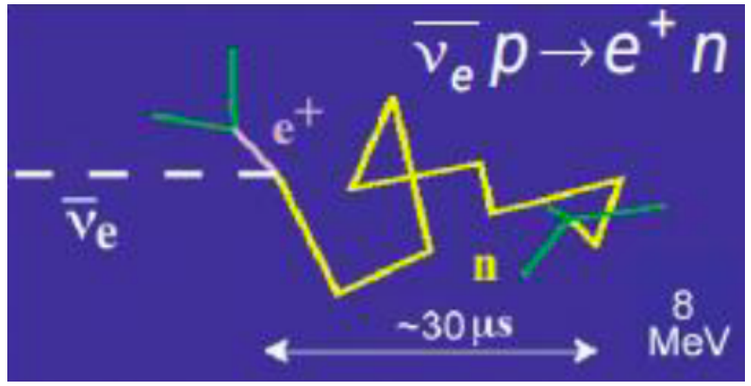
The solar parameters (“12”)

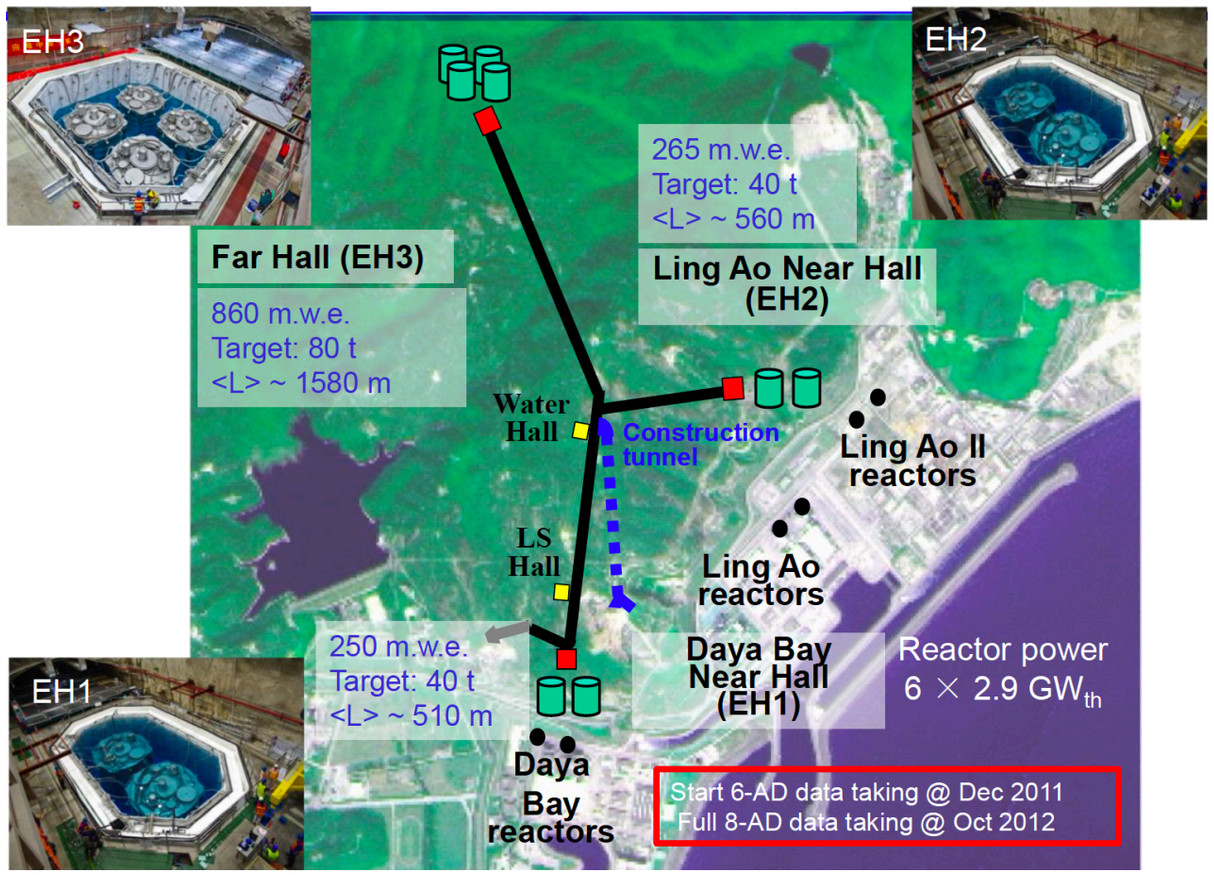


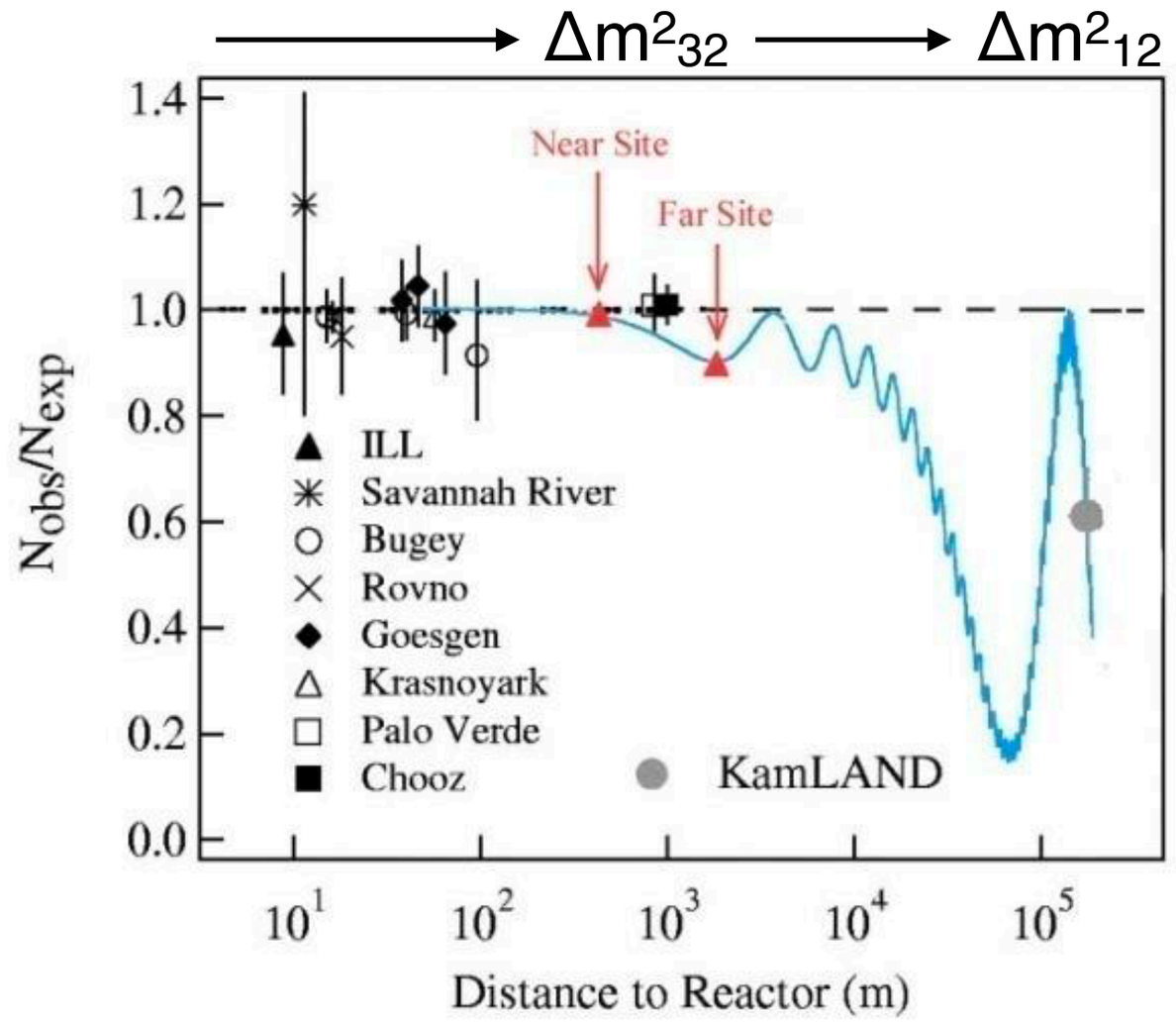
Future experiments like Hyper-K, JUNO and DUNE clarify the tension

Reactor experiments: θ_{13}

Liquid scintillator to detect inverse beta decay





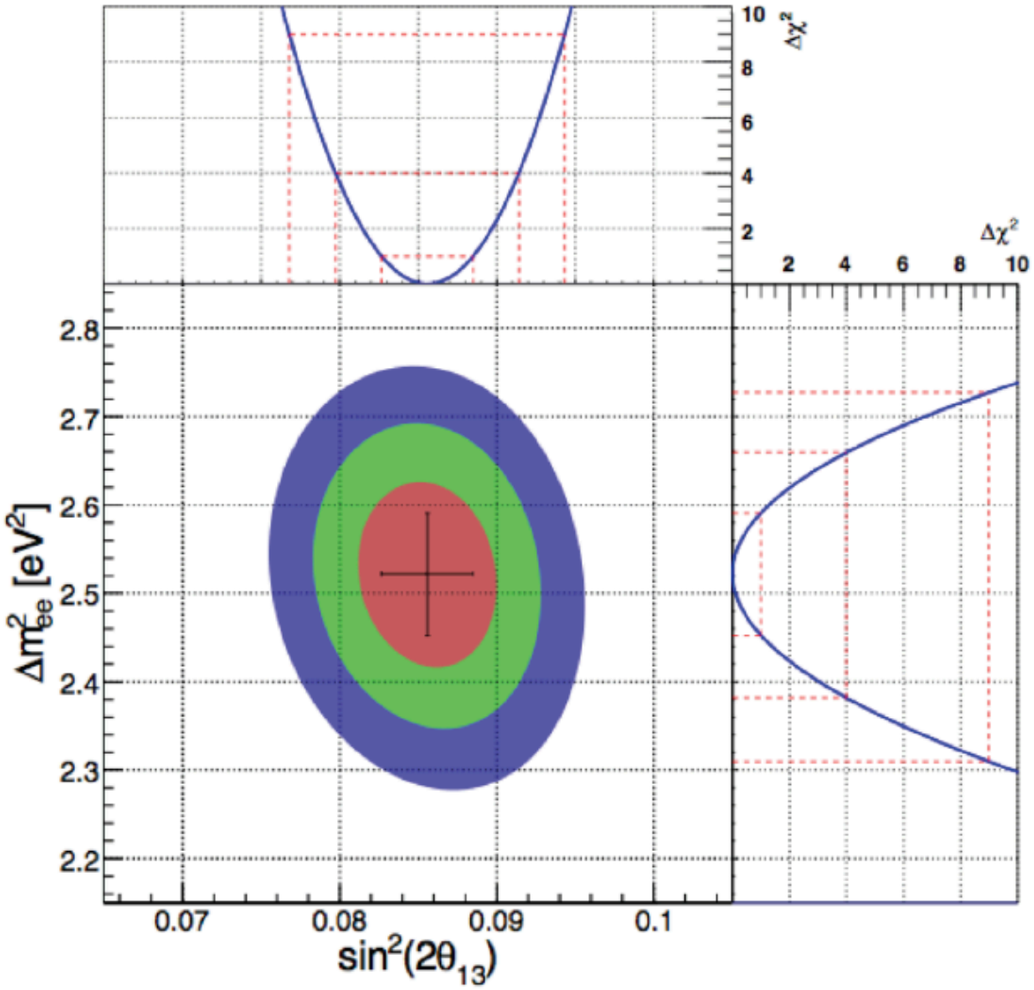


	Reactor [GW$_{th}$]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250

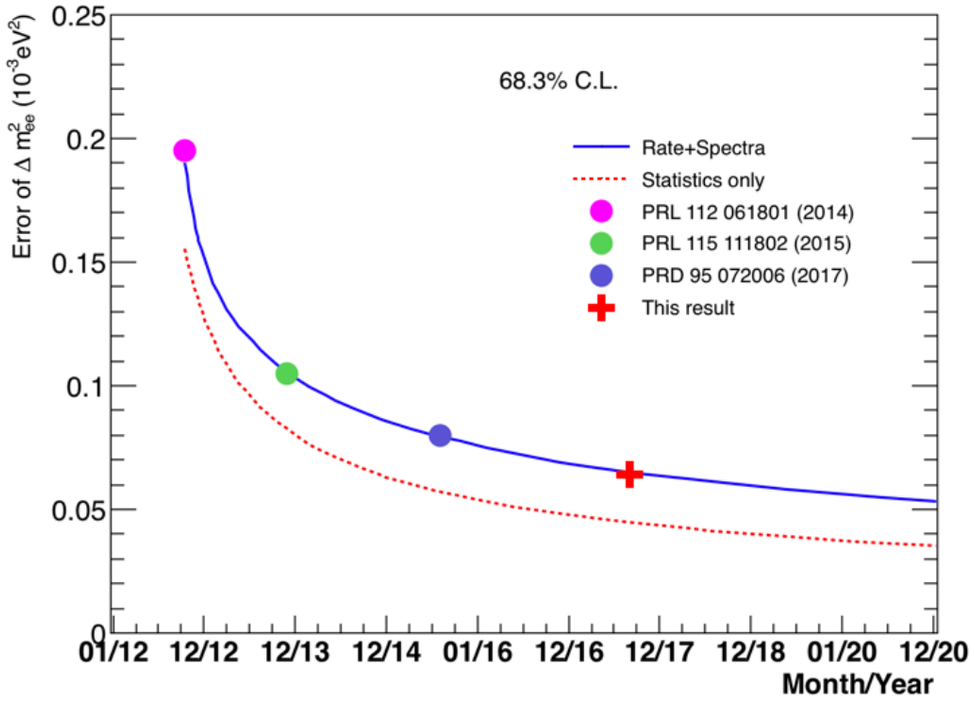
Other reactor experiments that measure θ_{13} are Double CHOOZ (France) and RENO (S.Korea)

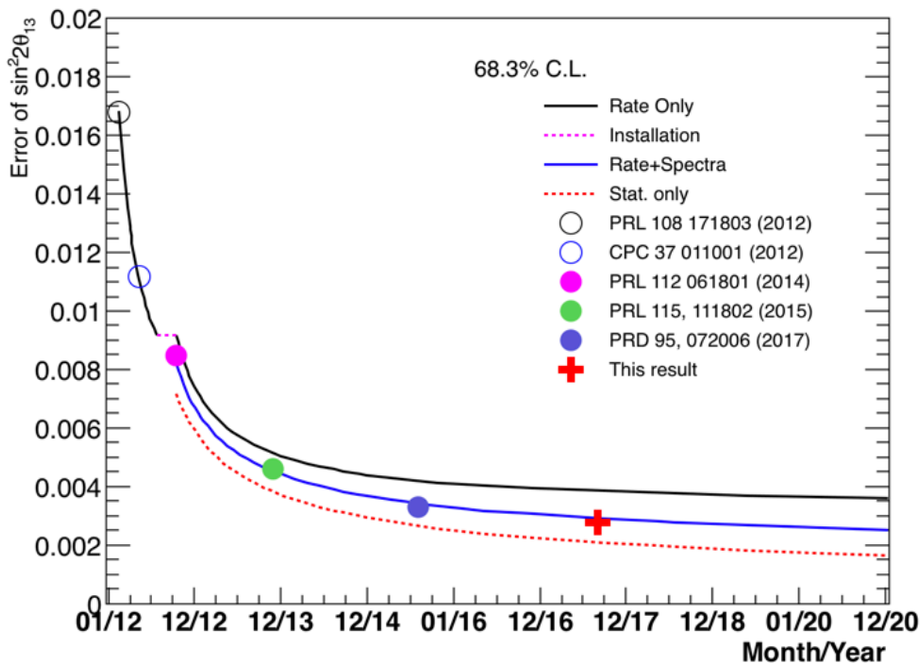
Reactor experiments: θ_{13}

Phys. Rev. Letts 121, 241805 (2018)



$$sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3} \text{eV}^2 \text{ (NO)}$$
$$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3} \text{eV}^2 \text{ (IO)}$$



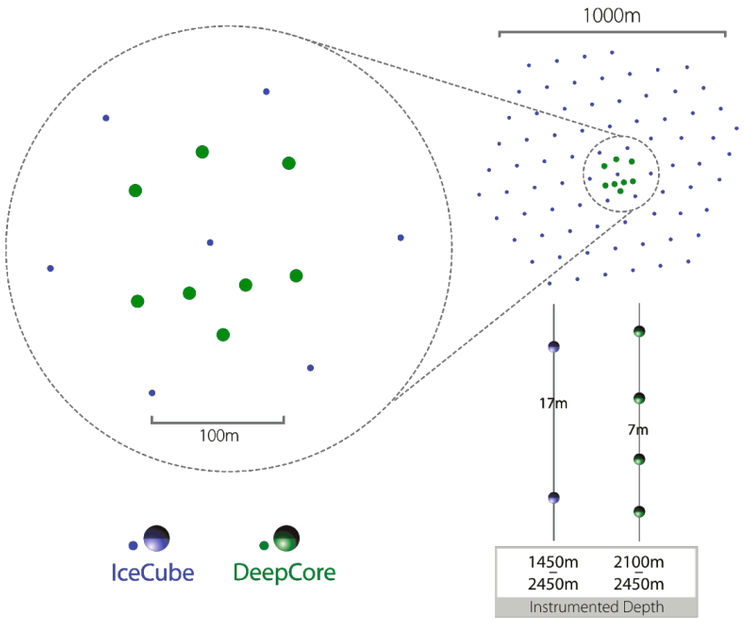


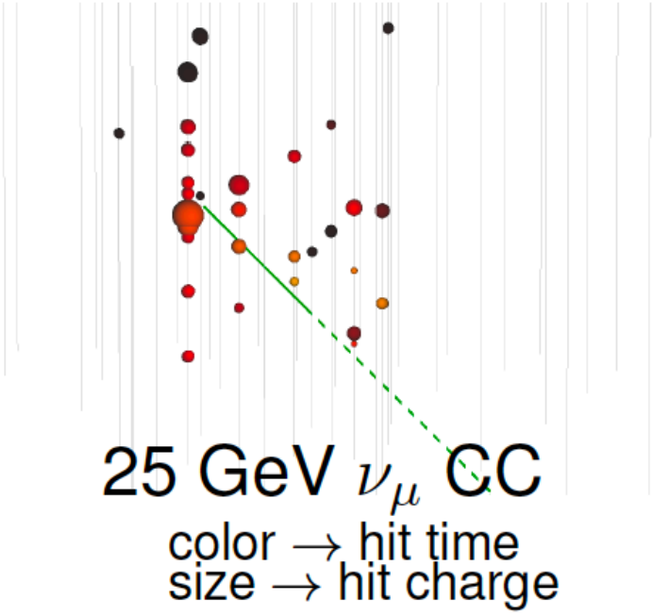
Daya Bay will continue running until 2020 to reach precision of ~3% on θ_{13}

Atmospheric neutrinos (“23” parameters)

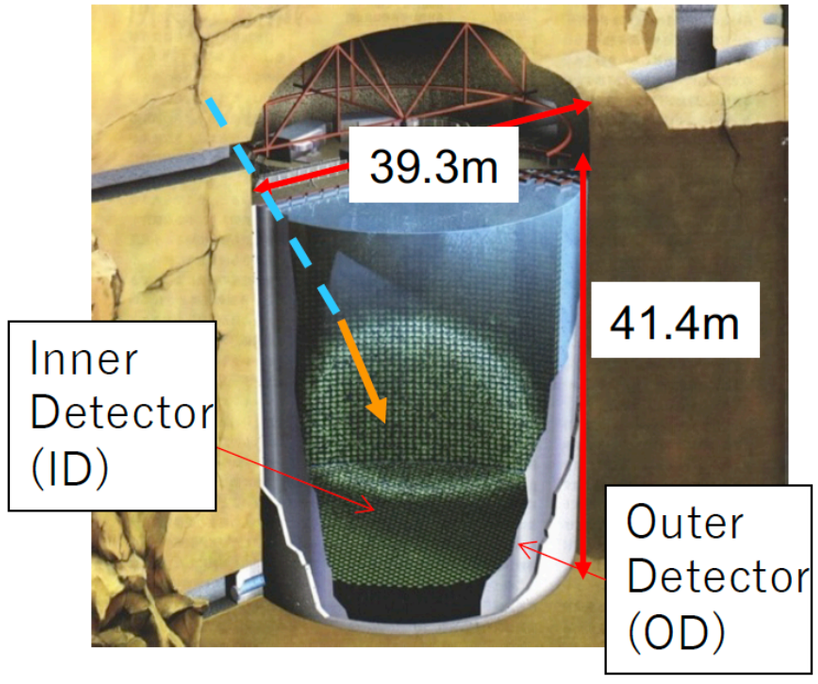
Water Cherenkov: large volume, good directionality and energy resolution

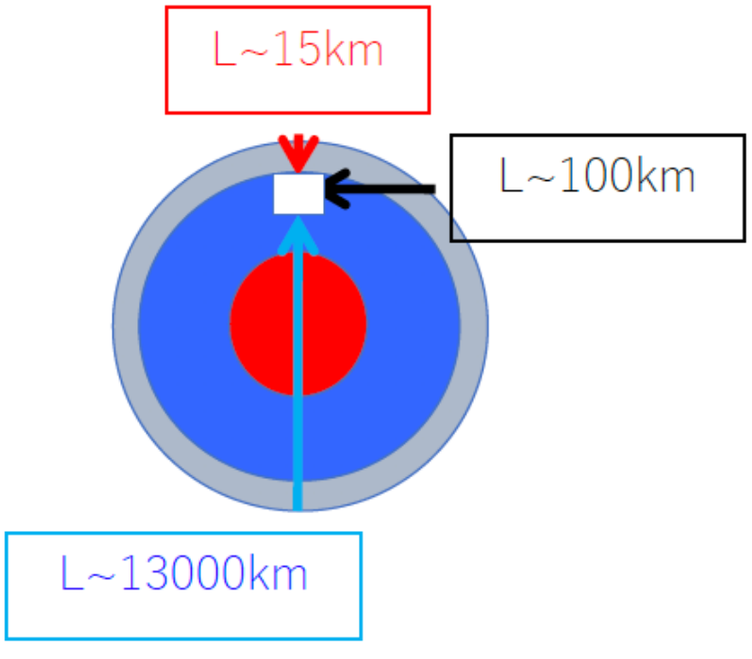
IceCube



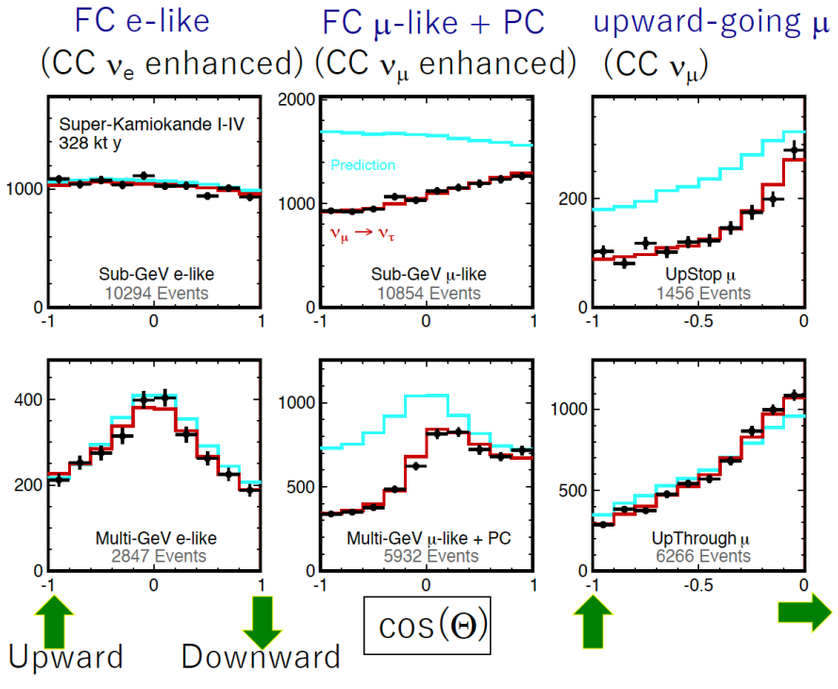


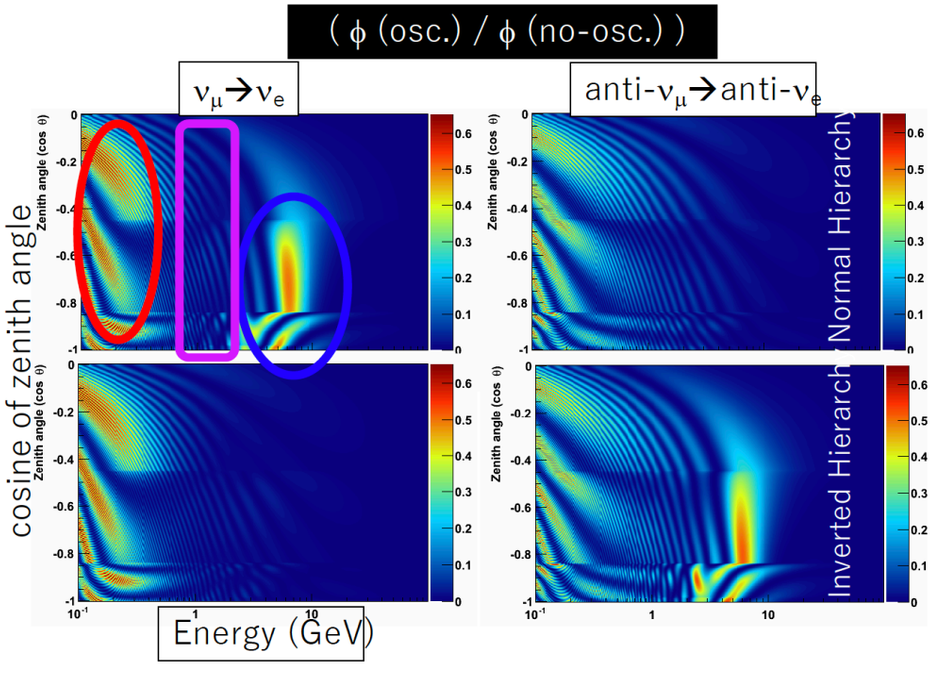
Super-Kamiokande



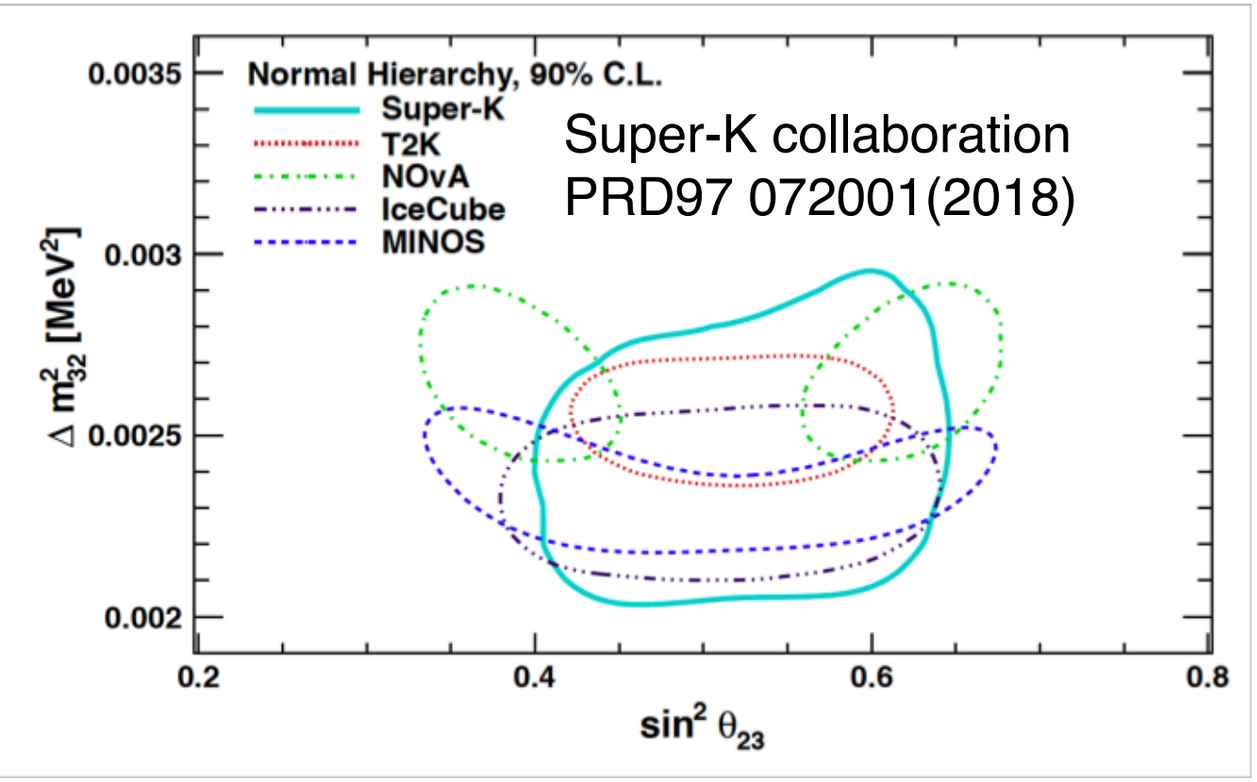


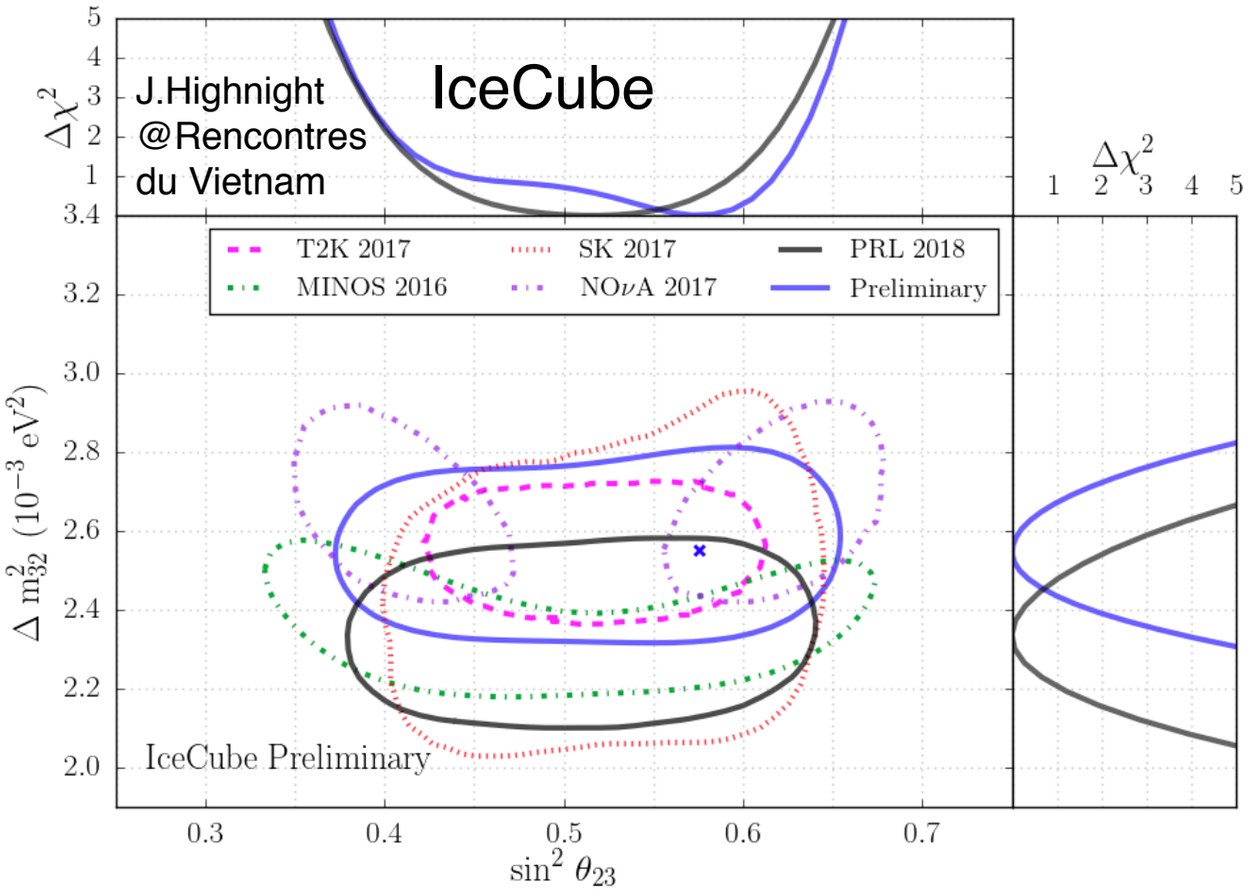
Super-K I+II+III+IV data (5300 days)

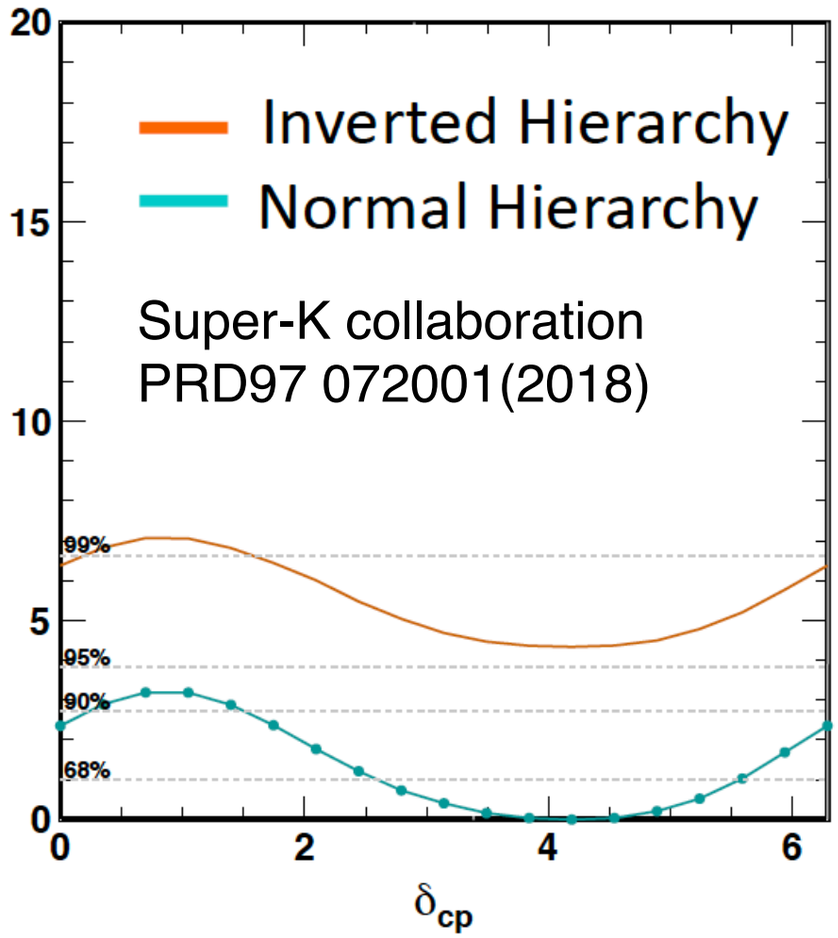




Atmospheric neutrinos (“23” parameters)





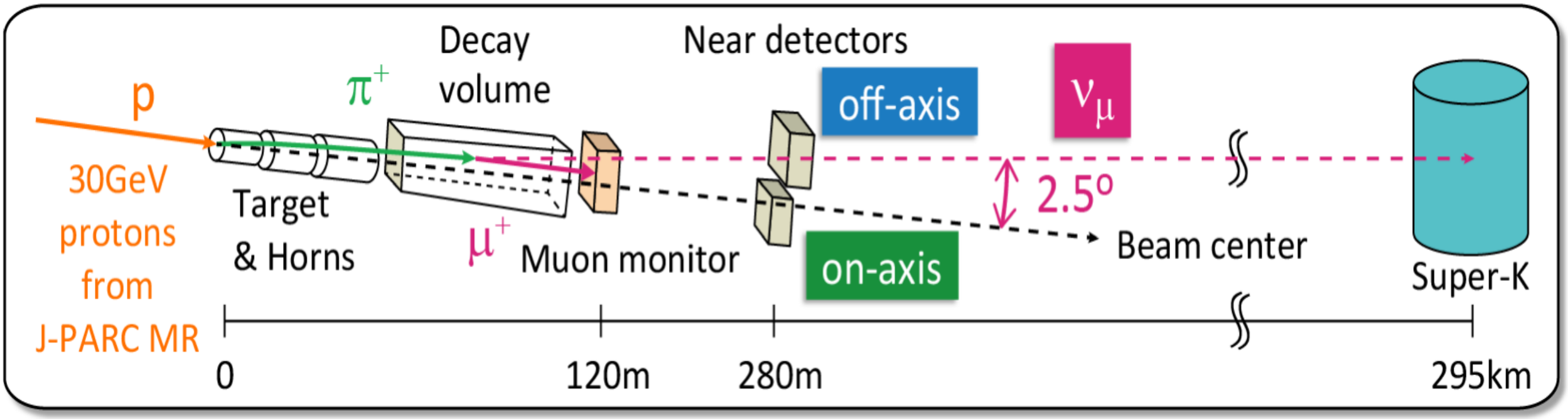


- Atmospheric parameters (“23”) in agreement with the long-baseline accelerator results (see later)

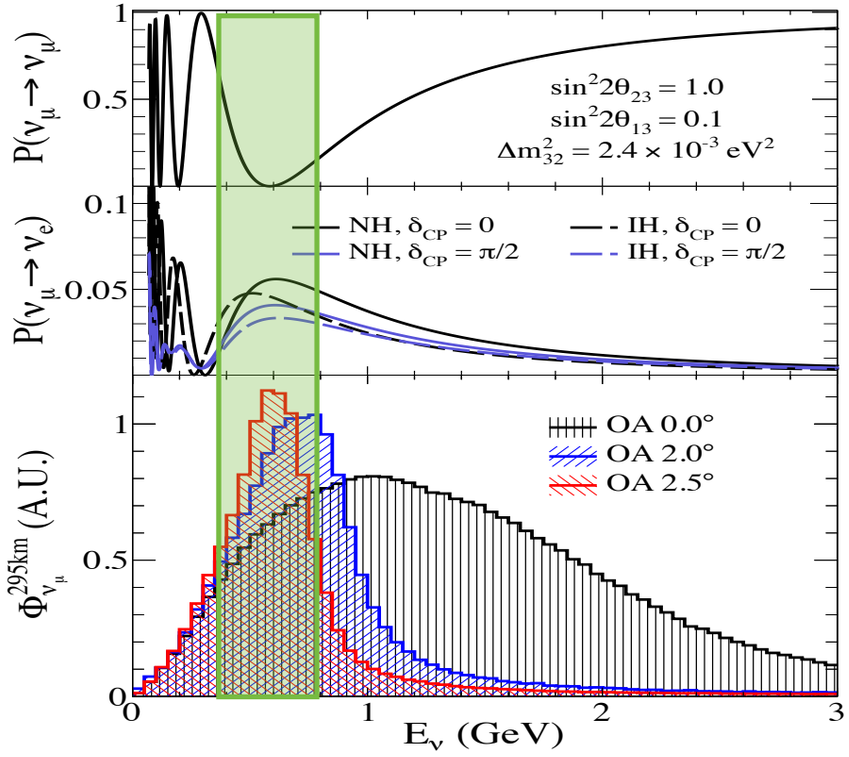
- Preference for Normal Ordering in Super-K data is driven by excess of upward-going e-like events

- Future: gadolinium loading at Super-K this year

Accelerator experiments: the T2K example

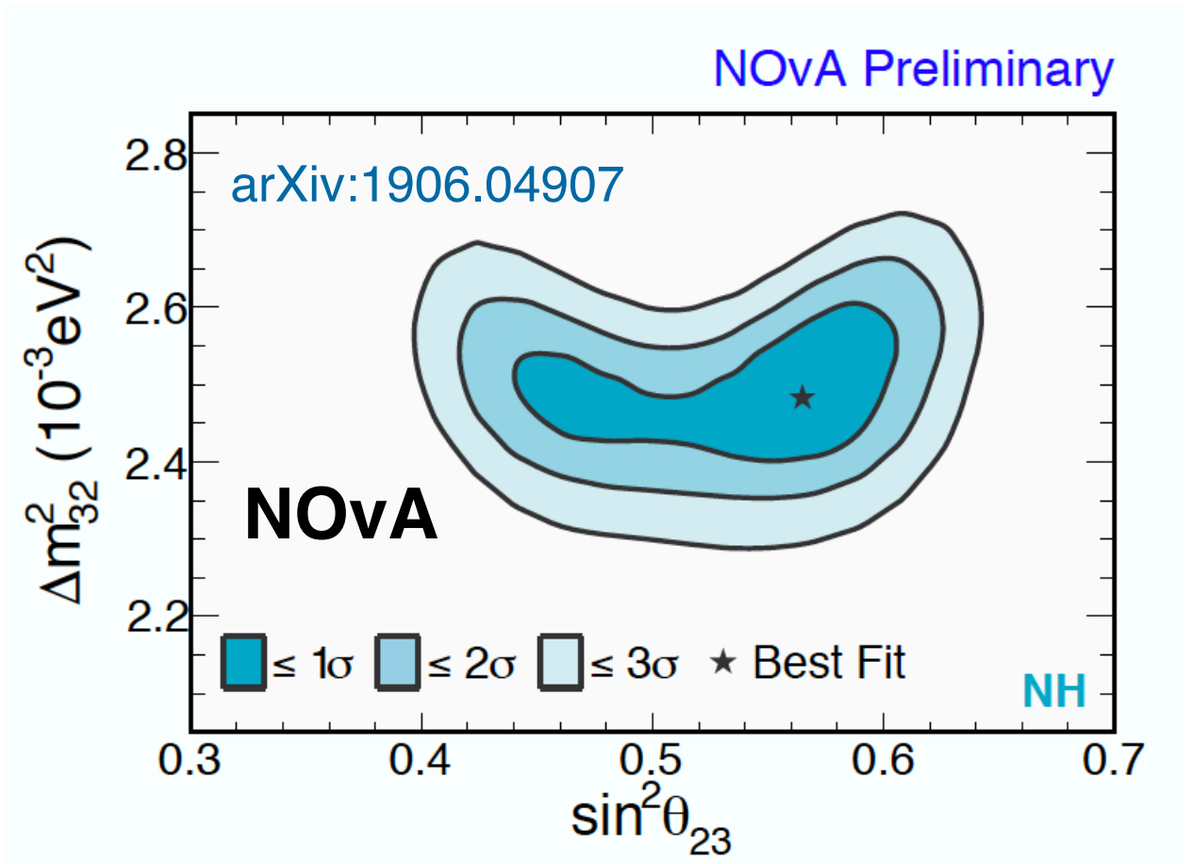


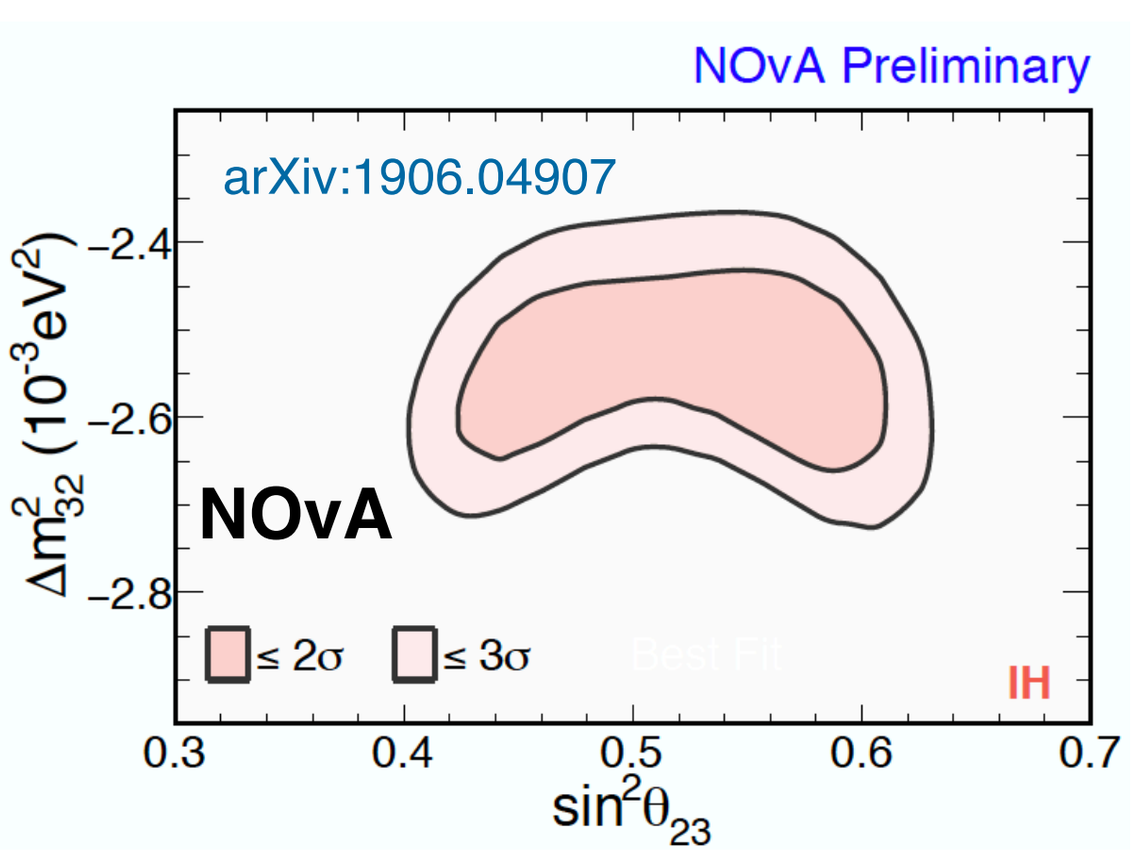
- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\bar{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Invert magnet polarity to produce a $\bar{\nu}_\mu$ beam

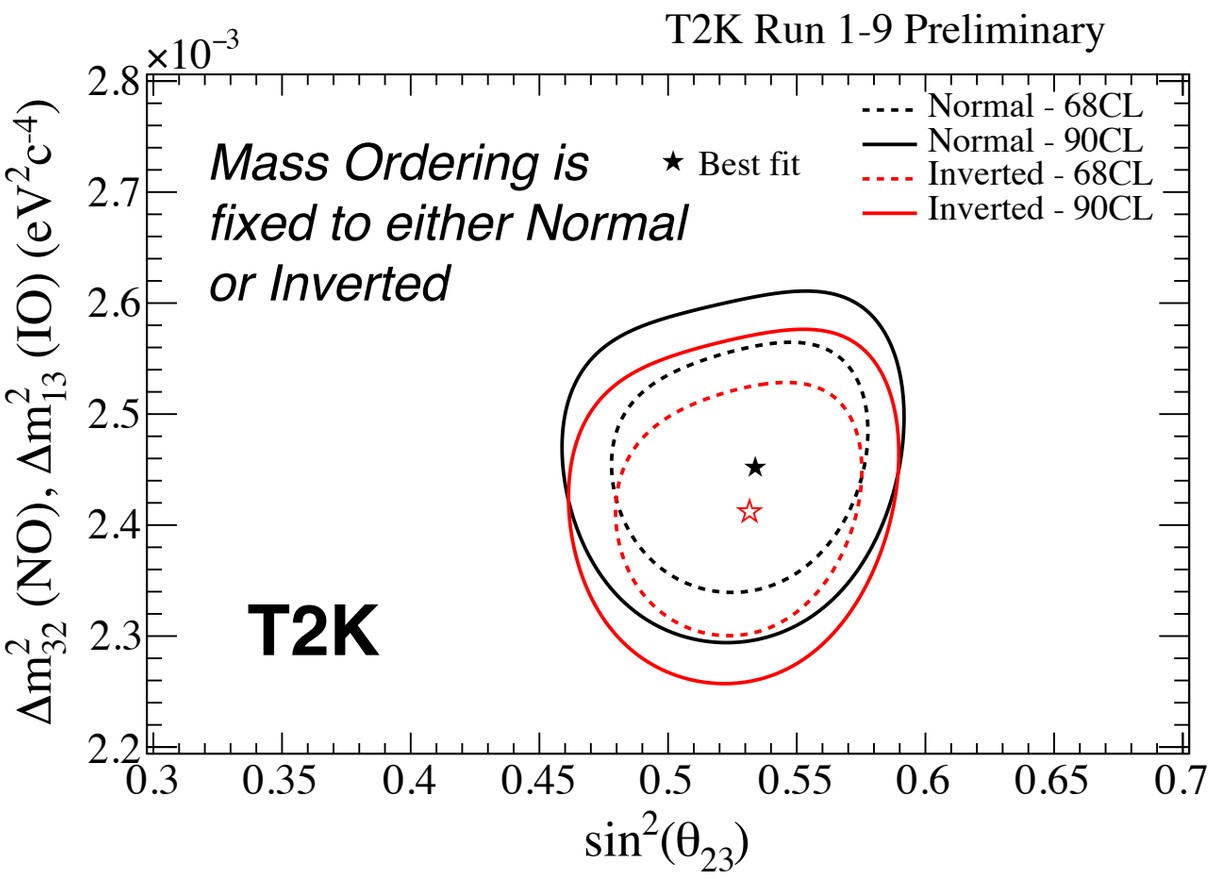


- The detectors can be off-axis wrt the neutrino beam to obtain a narrow-band beam (T2K, NOvA, HK). Other experiments have on-axis beam (DUNE, MINOS)

The atmospheric parameters (“23”): NOvA and T2K



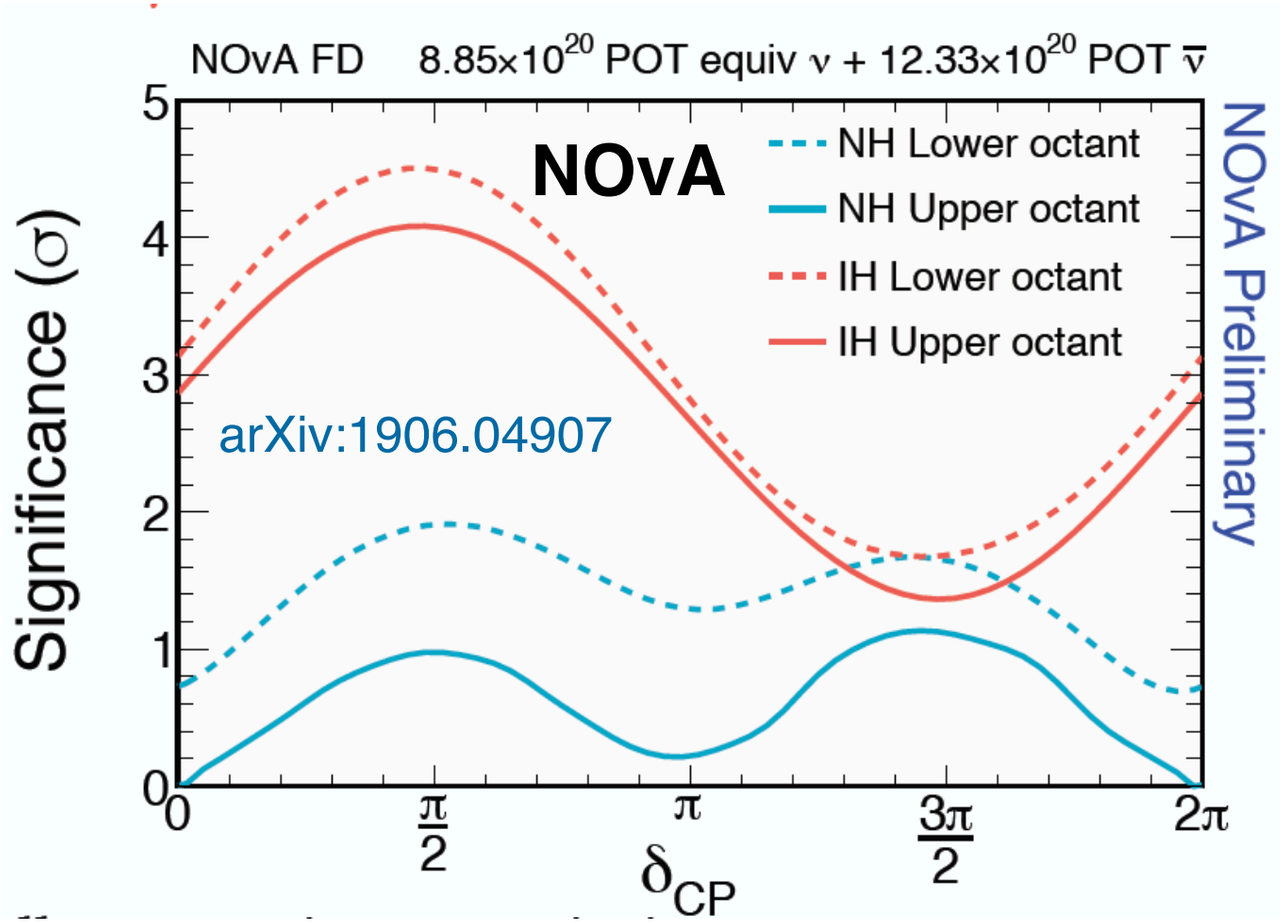


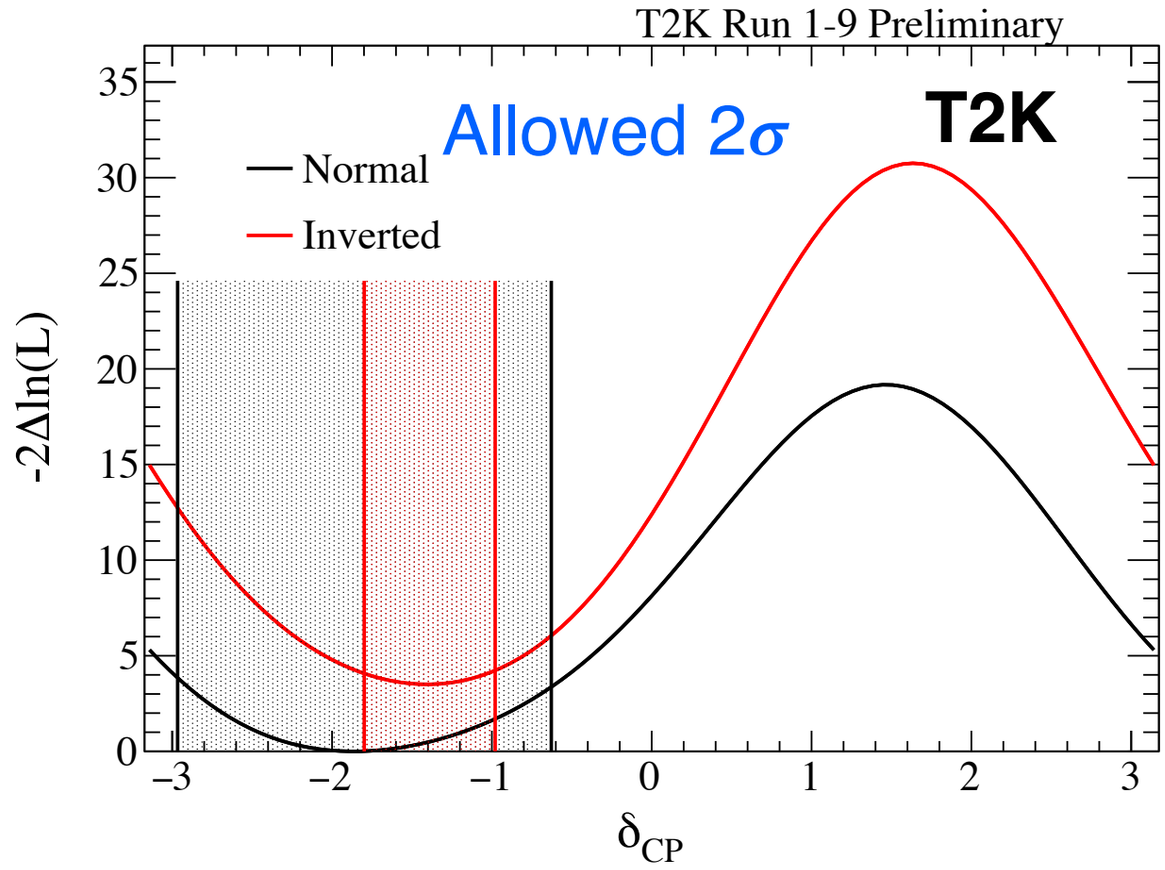


Best-fit	T2K	NOvA
$\sin^2\theta_{23}$	0.532	0.56
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.45	2.48

Both experiments prefer $\sin^2\theta_{23} > 0.5$ (upper octant)

Search for CP violation: NOvA and T2K

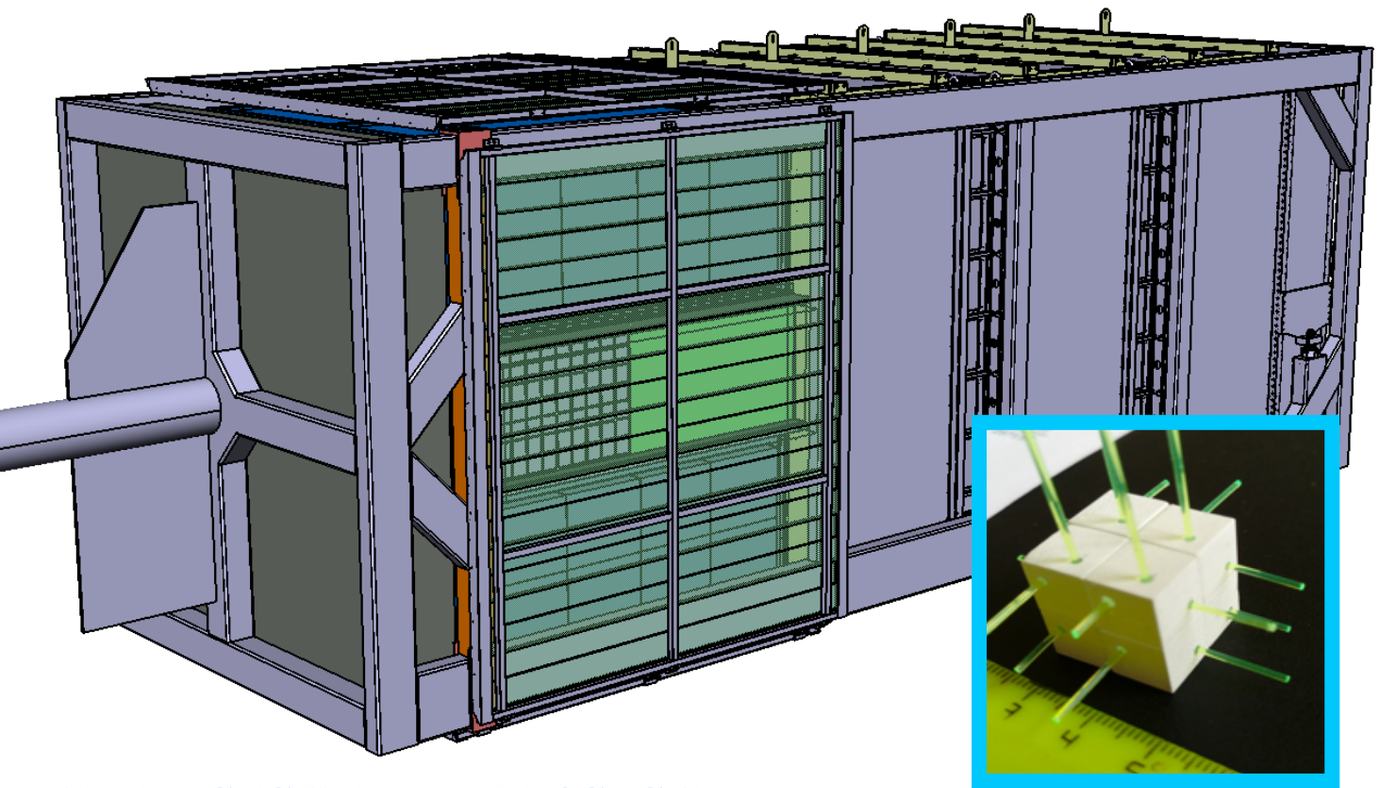




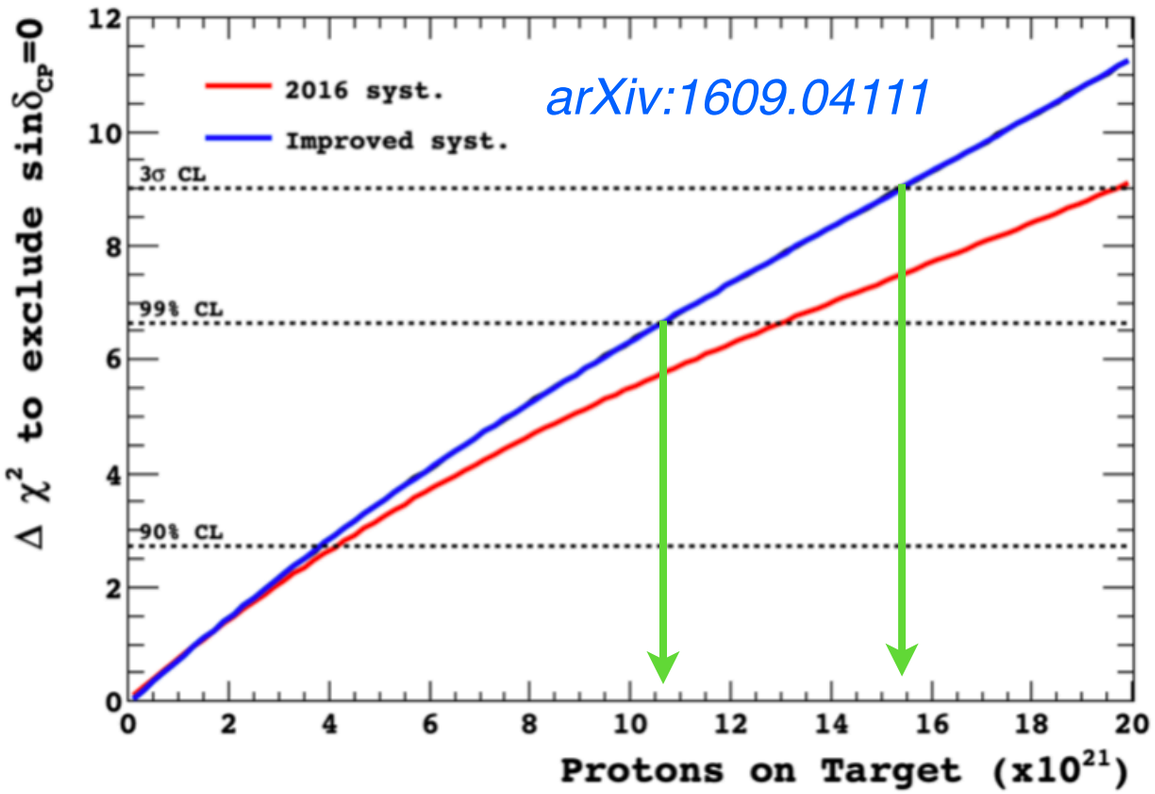
- Both NOvA and T2K prefer the Normal neutrino mass ordering
- NOvA still statistically limited for δ_{CP}
- T2K shows a hint for CP violation but more data are needed to confirm (or not) the current results
  - The T2K best-fit is $\delta_{CP} = -1.89$ radians and Normal Ordering
  - Current T2K data exclude the CP conserving hypothesis at 2σ CL
- Joint NOvA+T2K data fit foreseen for 2021

Prospects for the future: T2K-II

- T2K-II T2K data taking will be extended to phase II up to 2025
- Increase beam intensity up to ~1 MW in 2021
- Upgrade of the Near Detector to reduce the neutrino cross-section systematic uncertainties

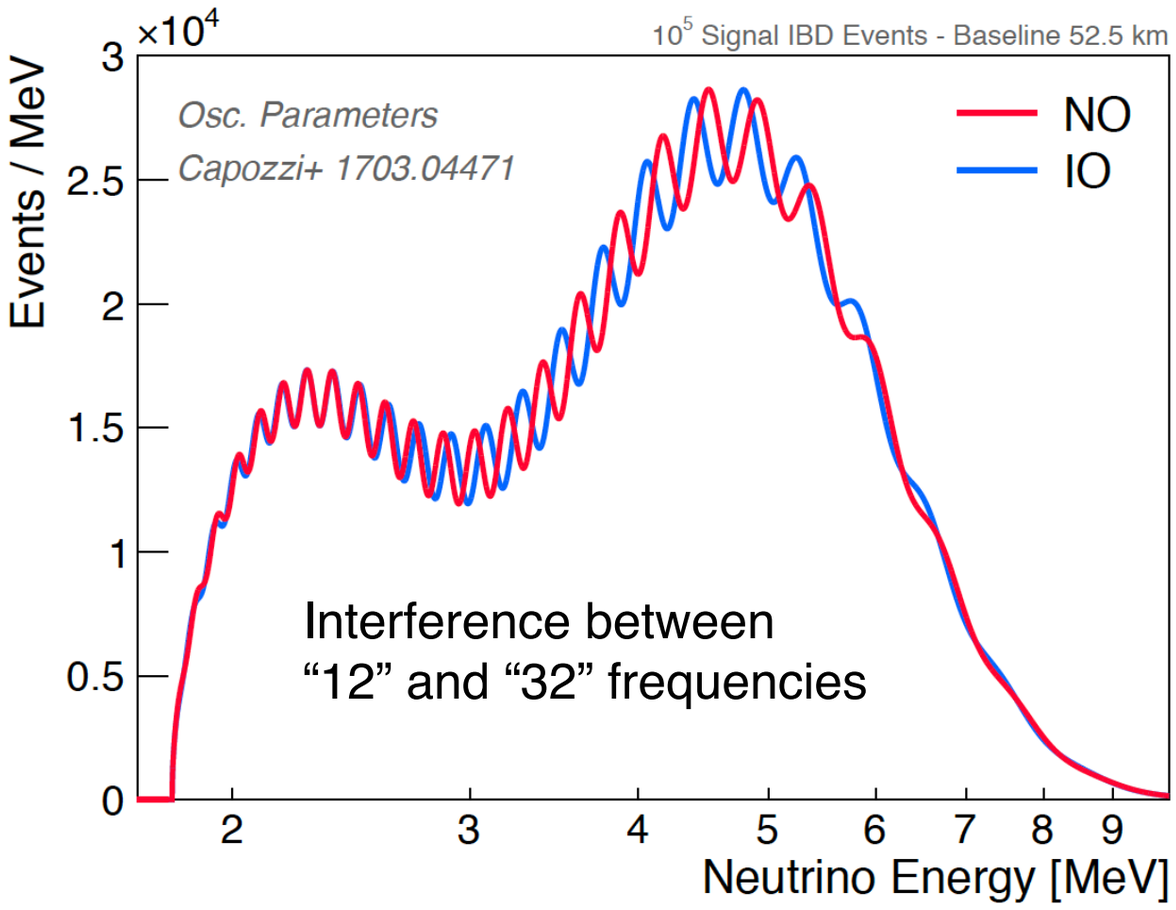


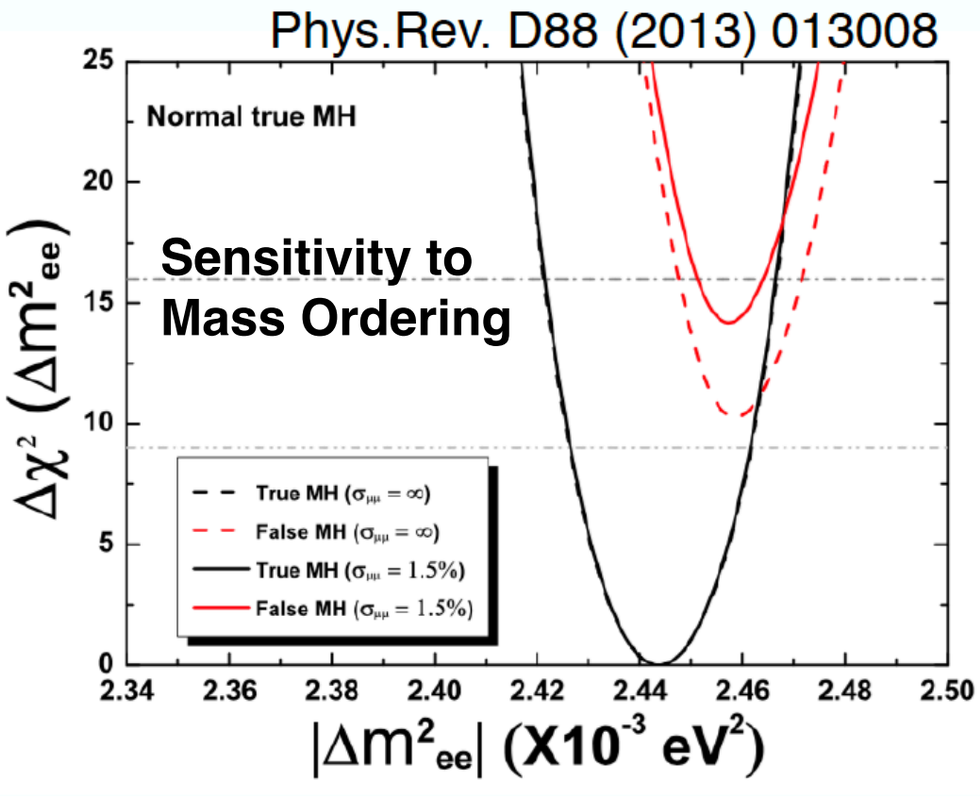
CERN-SPSC-2018-001 / SPSC-P-357



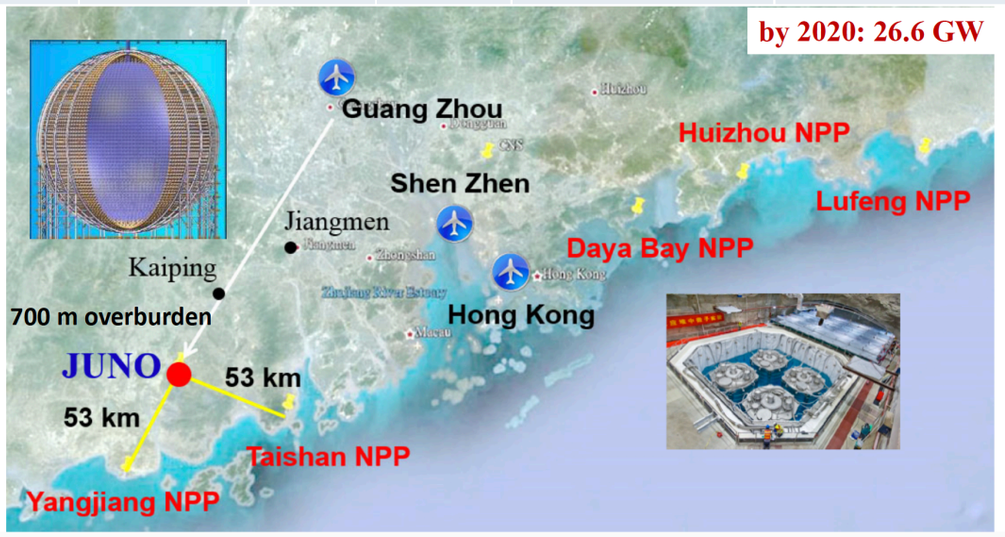
Sensitivity to exclude the CP conserving hypothesis better than 3**σ** for a wide range of δ_{CP} values

The Mass Ordering: JUNO experiment





NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

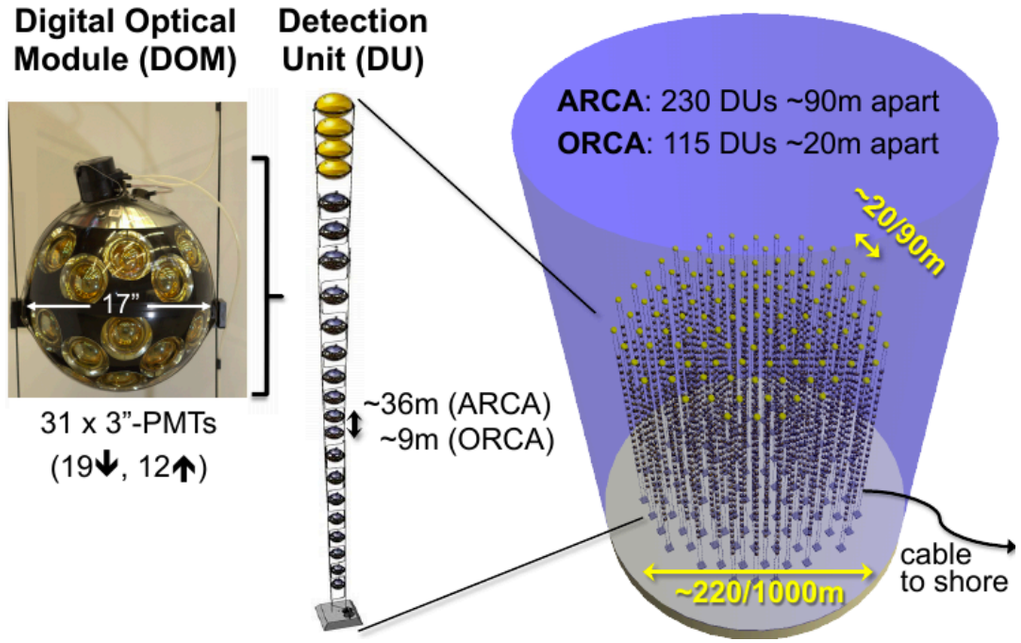


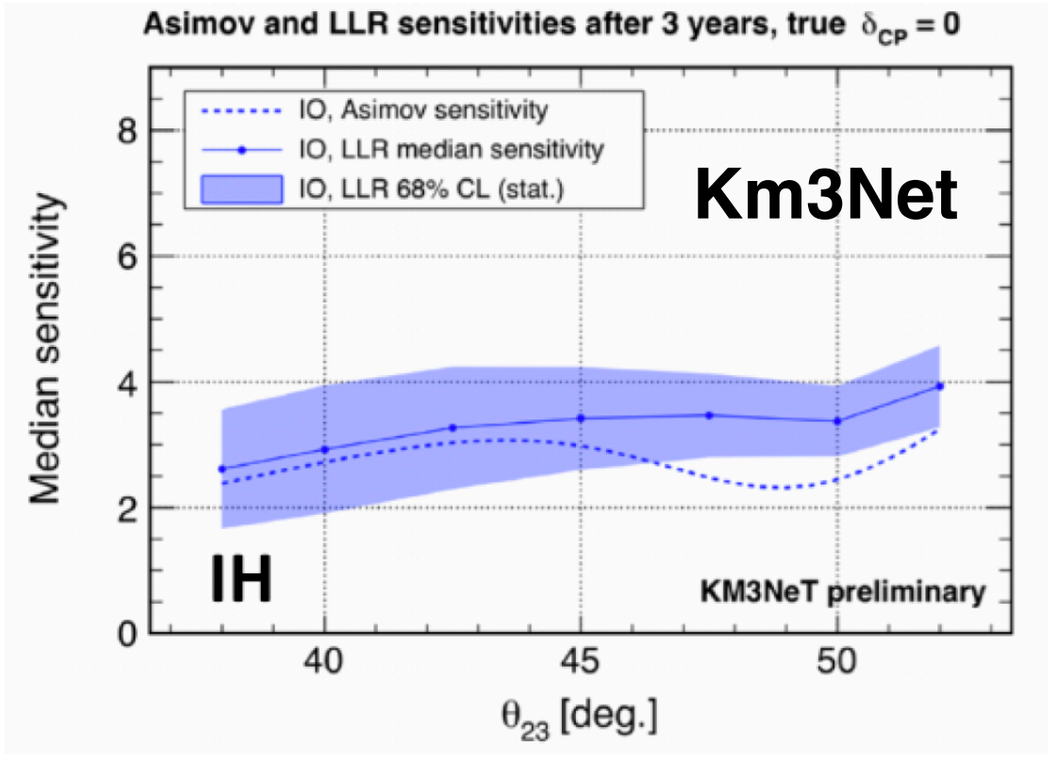
DETECTOR	TARGET MASS	RESOLUTION
KamLAND	1000 t	6%/√E
Double Chooz	8 t	8%/√E
RENO	16 t	
Daya Bay	20 t	
Borexino	300 t	5%/√E
JUNO	20000 t	3%/√E

- Sensitivity to MO better than 3-4σ
- Also aim to measure solar and Δm^2_{32} parameters with sub-% precision
- Will start collecting data in 2021

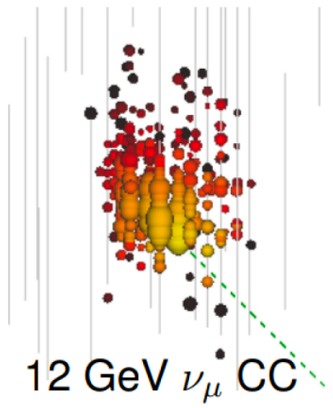
The Mass Ordering: atmospheric experiments

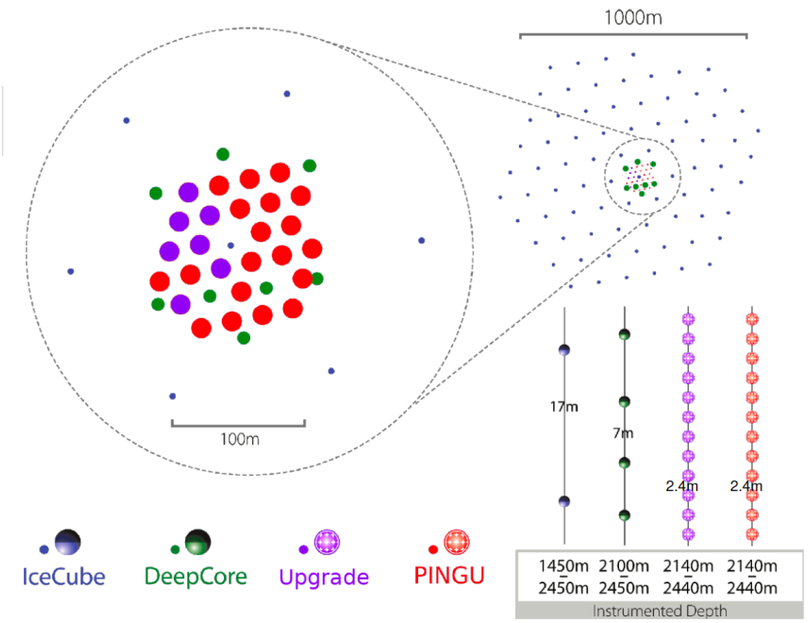
Km3NeT

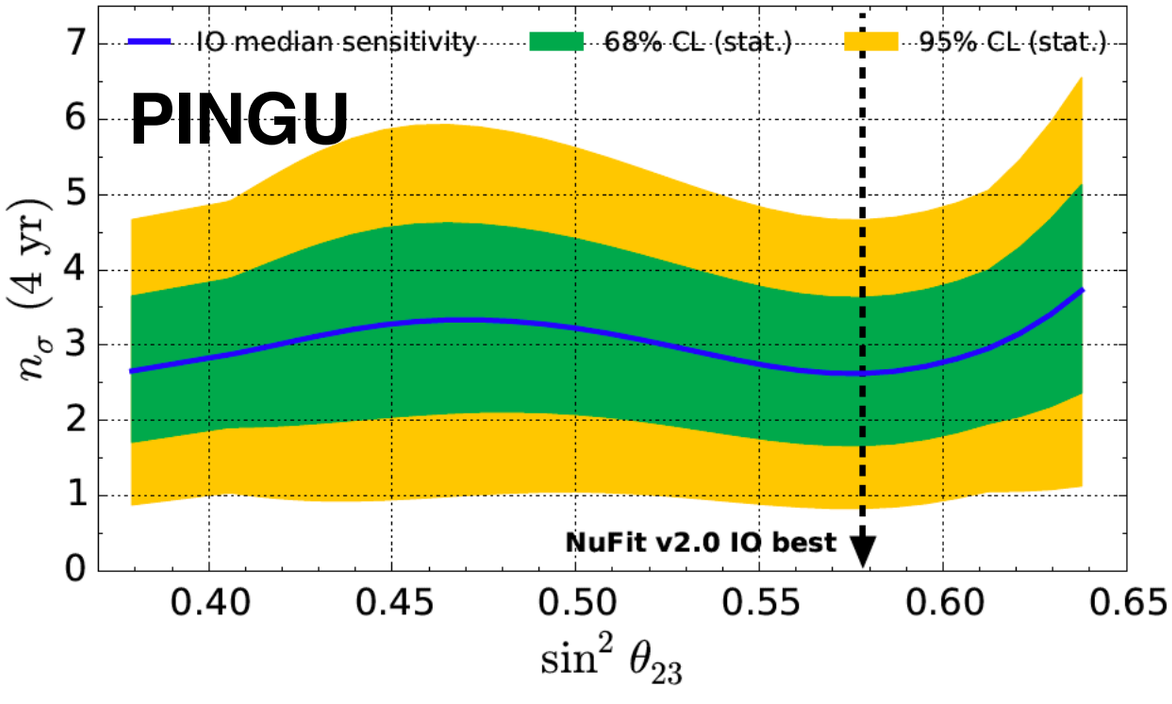




IceCube / PINGU



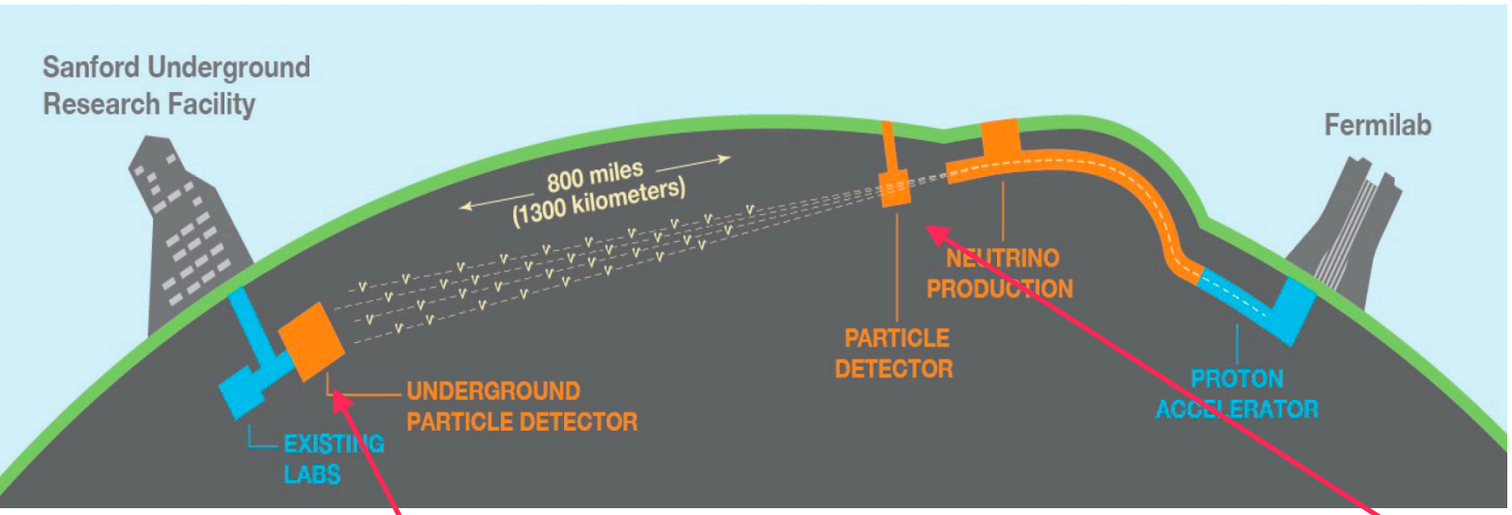


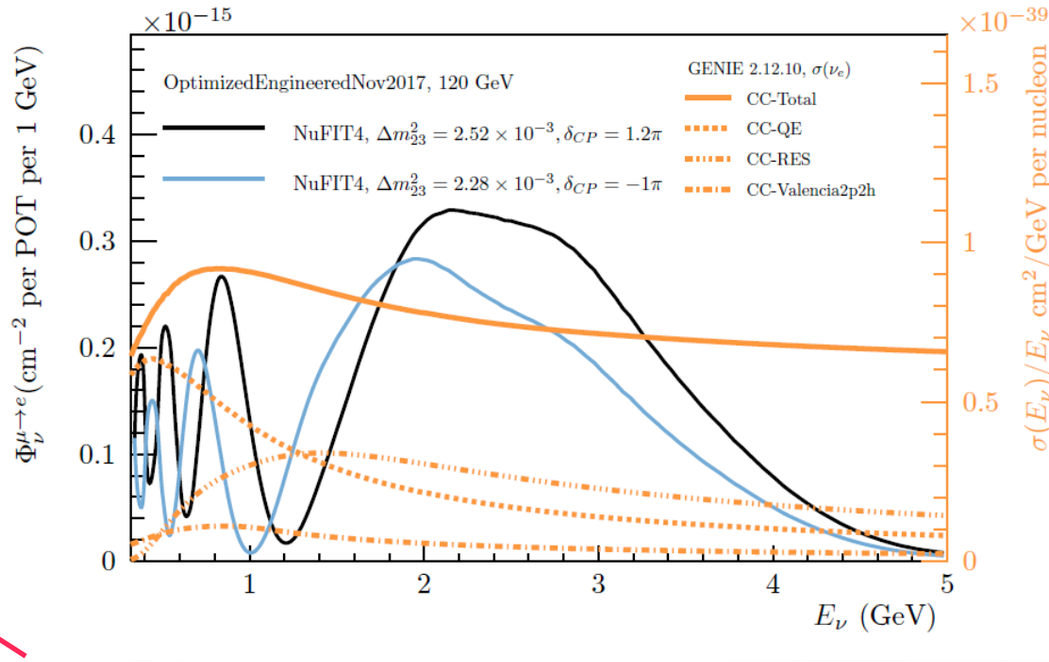


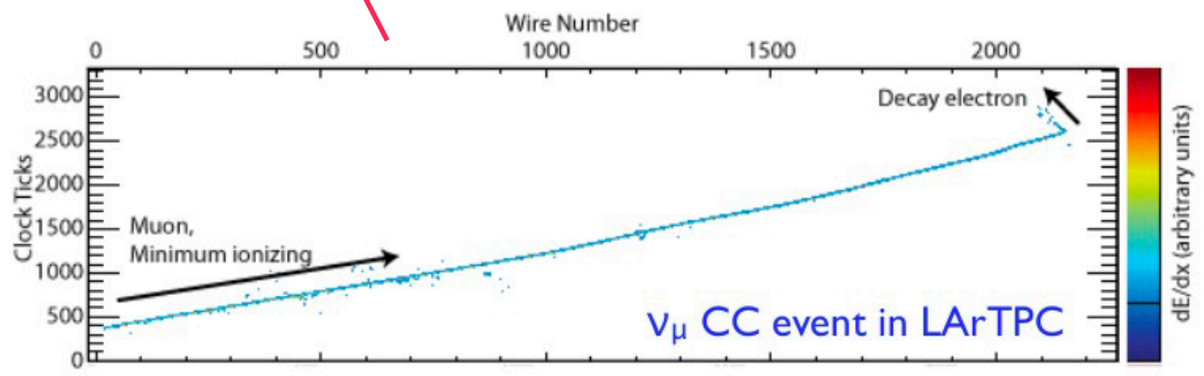
Median sensitivity of 3σ with 3-4 years of data for current best-fit values

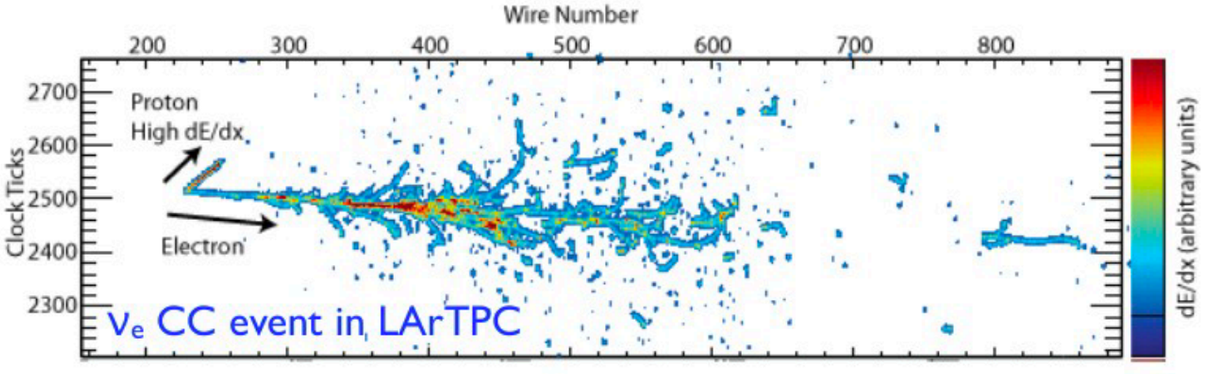
Future long-baseline experiments: DUNE

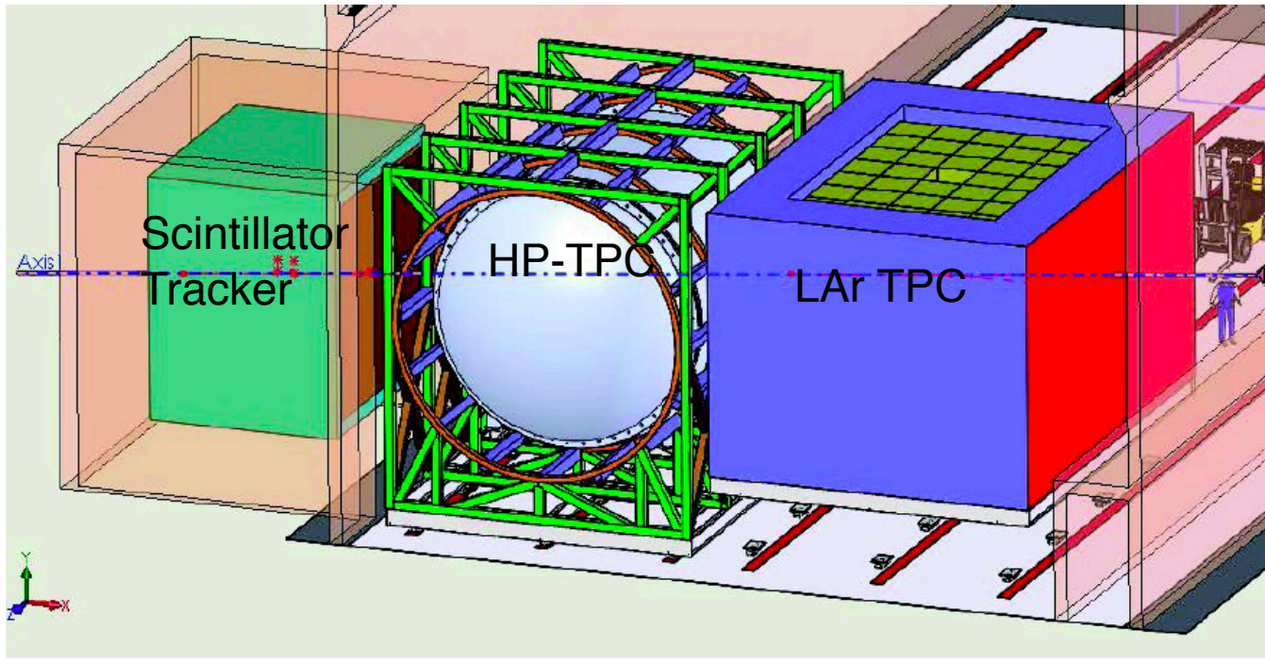
- Baseline of 1,300 km —> enhance sensitivity to Mass Ordering
- 40 kton Liquid-Argon detector. R&D driven by ProtoDUNE@CERN
- Detectors are on the neutrino beam axis





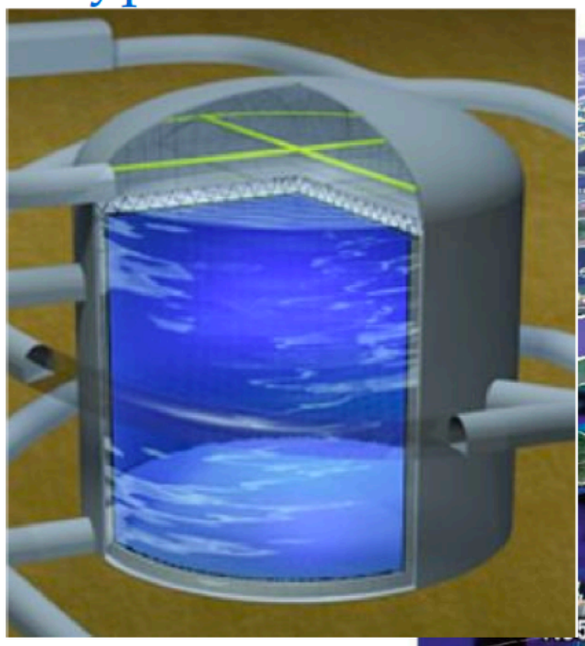






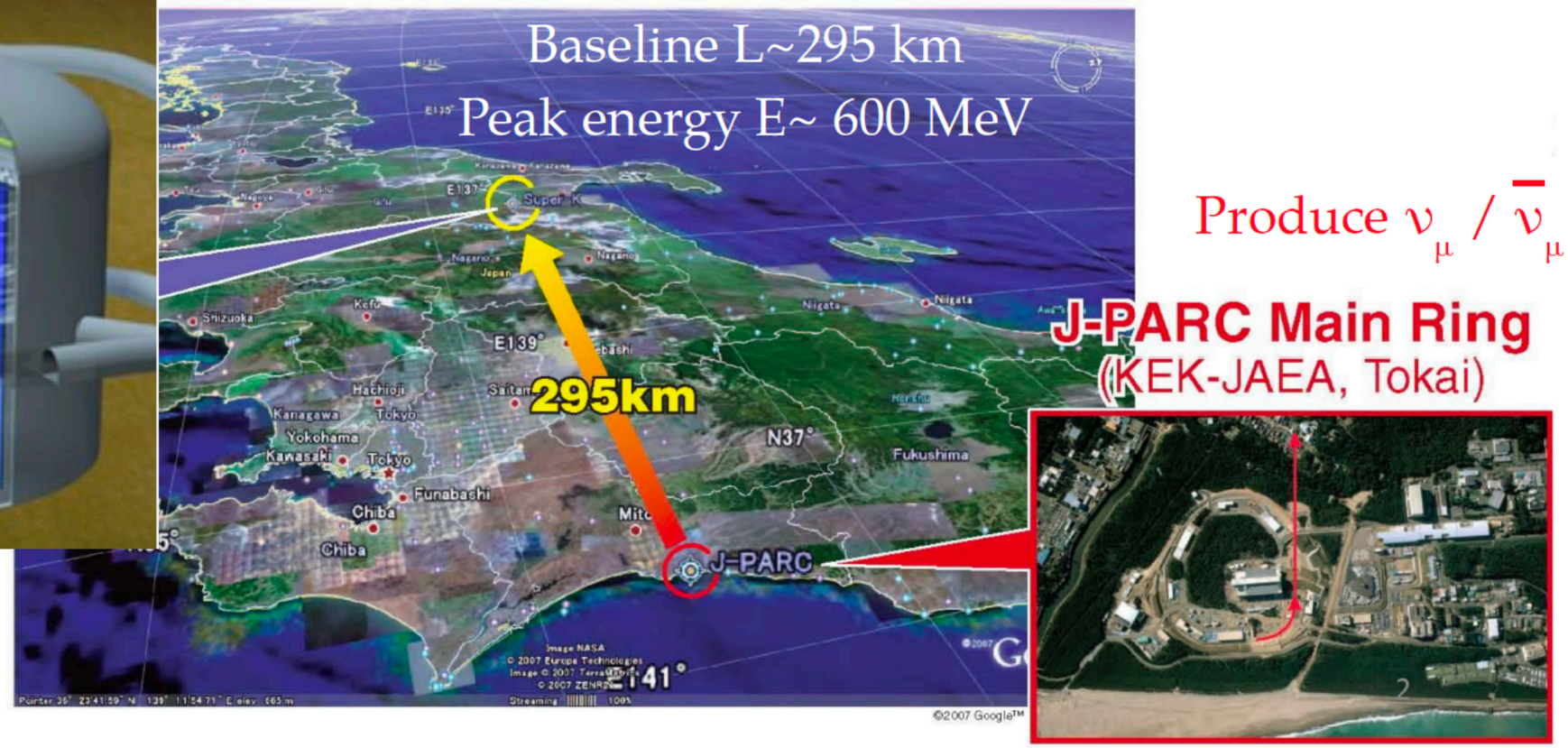
Future long-baseline experiments: Hyper-K

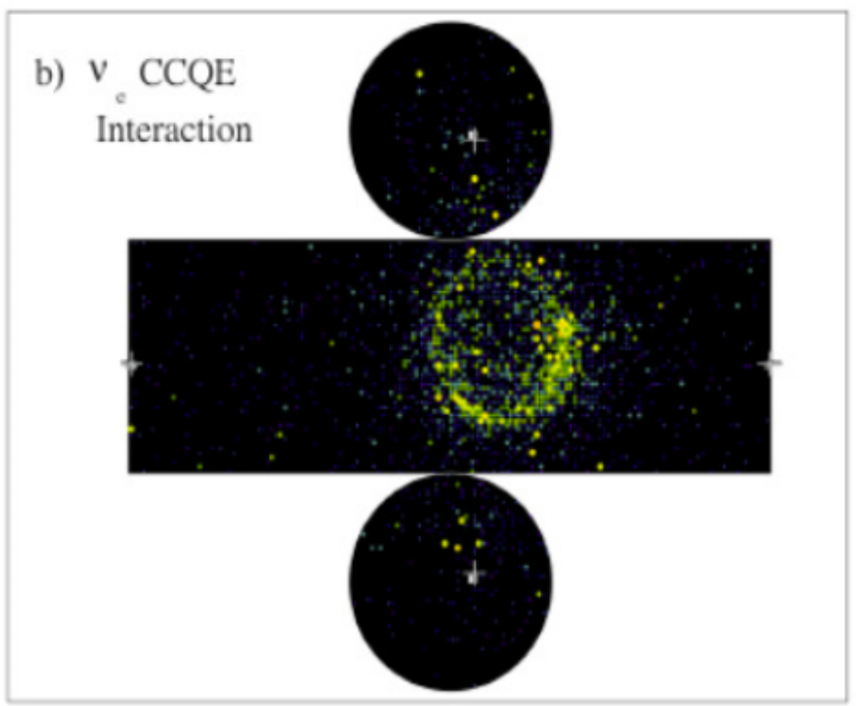
Hyper-Kamiokande



Detect

$\nu_\mu, \nu_e / \bar{\nu}_\mu, \bar{\nu}_e$



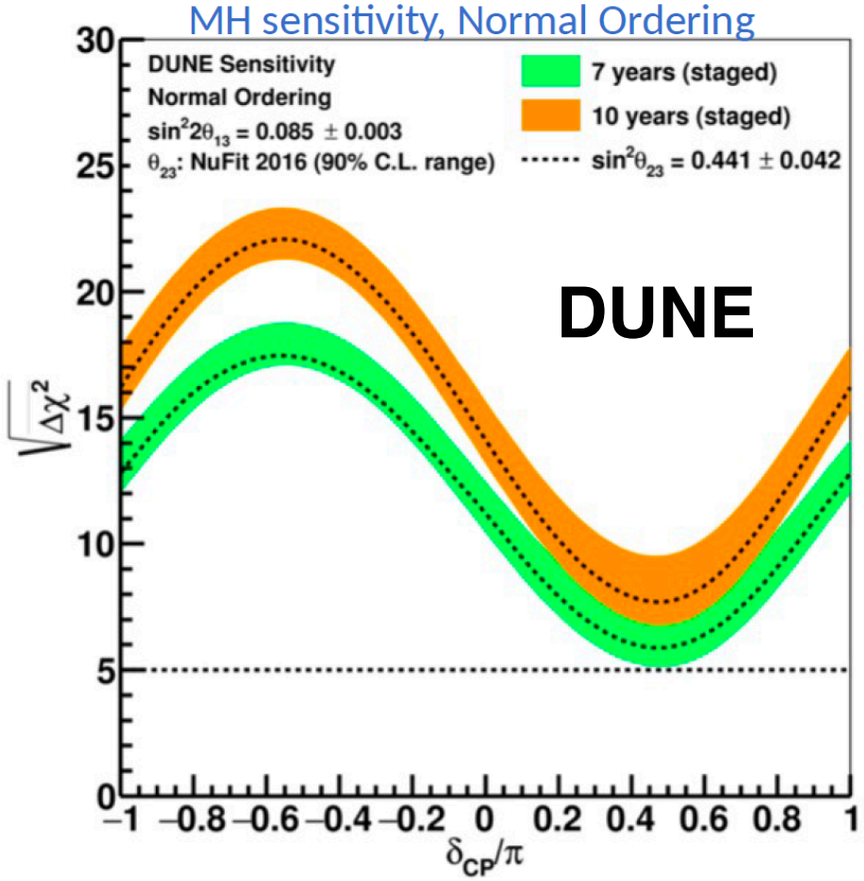


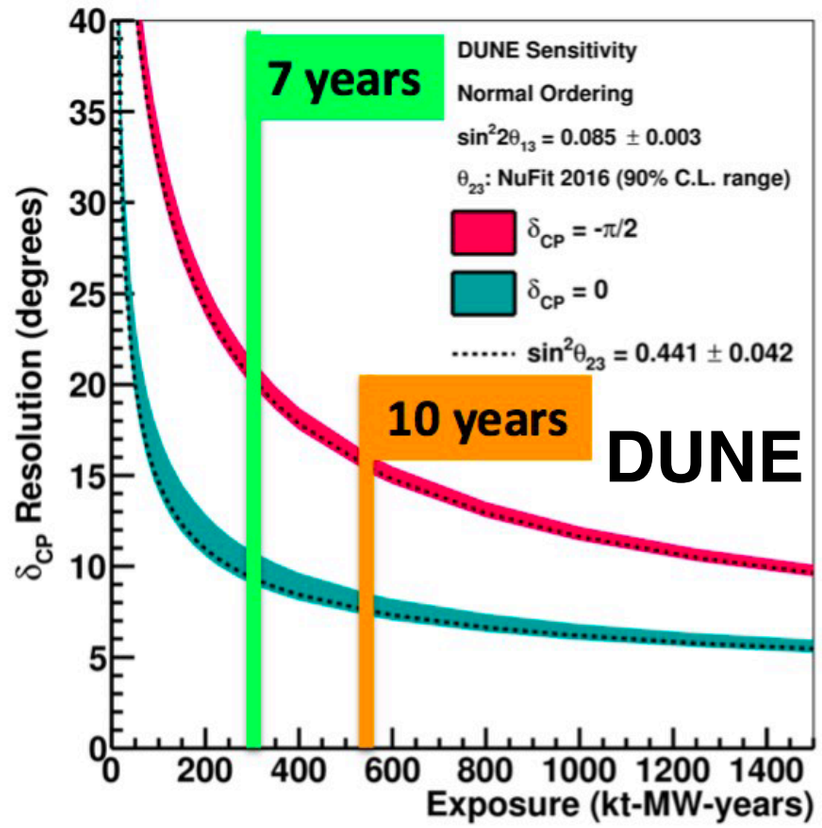
- 260 kton water Cherenkov detector (2.5 degrees off-axis) in Japan (possibility for a 2nd far detector in S.Korea)
- High-intensity beam at 1.3 MW
- The far detector will also be sensitive to atmospheric and solar neutrinos
- Near detectors will be: ND280 and an intermediate (~1km) water Cherenkov detector

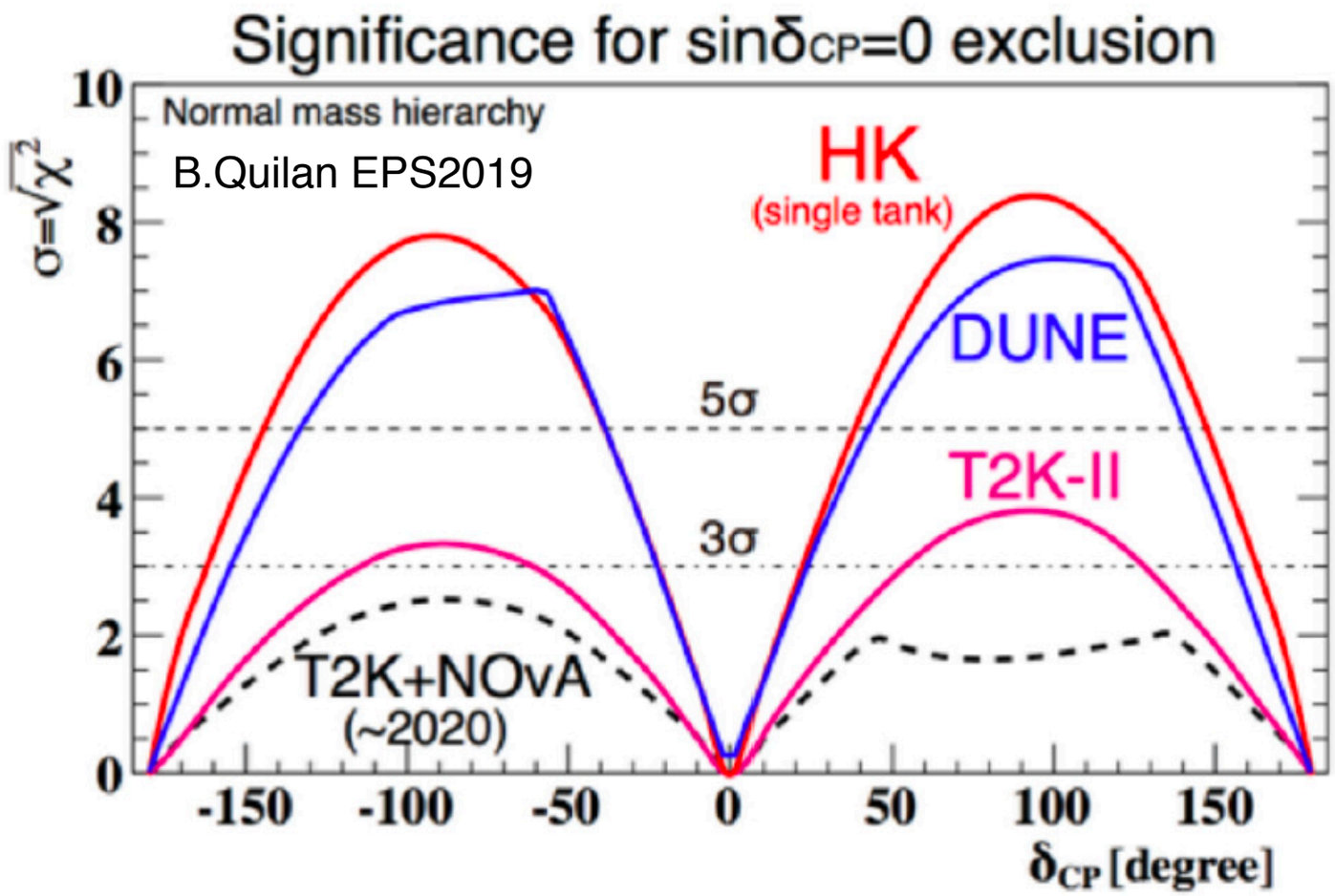
Future long-baseline oscillation experiments

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

MH sensitivity, Normal Ordering







- DUNE will measure the Mass Ordering with a significance better than 5**σ**
- Both have sensitivity to exclude CP conserving hypothesis at 5**σ** for a wide range of δ_{CP} and the measure it with < 20-30º resolution
- Great sensitivity to atmospheric parameters (“23”)
- First neutrino beam foreseen in 2026

Conclusions

- All the parameters have been measured except the neutrino Mass Ordering and the CP violating phase

- Tension in the solar sector (“12”) to be clarified by future experiments

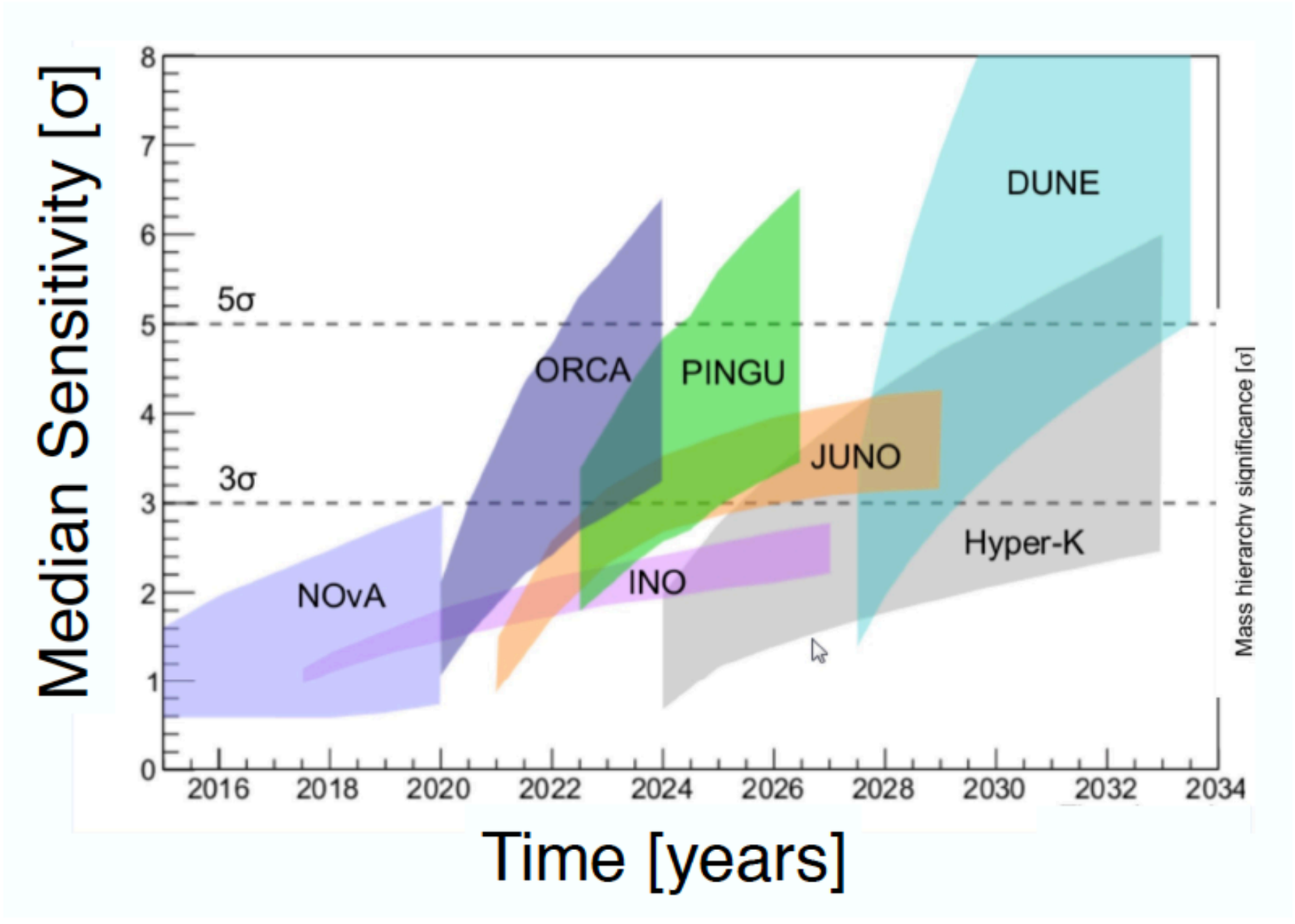
- Atmospheric parameters (“23”) and θ_{13} measured with good precision. θ_{23} octant not yet measured. Future experiments aim to sub-% precision

- Many different and complementary experiments with sensitivity to Mass Ordering starting collecting data in the next few years

- DUNE and Hyper-K have great sensitivity to discover CP violation in the leptonic sector

BACKUP

The neutrino Mass Ordering



Many experiments will measure the neutrino Mass Ordering in the near future with different and complementary techniques