Status
of neutrino oscillations

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OUTLINE

- ☐ **Neutrino oscillations**
  - **- 3-neutrino scheme**
  - **- running accelerator and reactor experiments**
  - **- future projects**

- ☐ **Light sterile neutrinos**
  - **- neutrino anomalies**
  - **- new experimental tests**

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

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

***U* parameterization:**

three mixing angles θ_{12} θ_{23} θ_{13}

CP violating phase δ_{CP}

atmospheric

link between atmospheric and solar

solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

SuperK, K2K,
MINOS, T2K, NovA(?)

$\theta_{23} \sim 45^0$

$$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times 10^{-3}\,\mathrm{eV}^2$$

T2K
MINOS

Daya Bay, RENO
Double Chooz

$\theta_{13} \approx 9^0$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

Solar experiments, SuperK
KamLAND

$\theta_{12} \approx 34^0$

$$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times 10^{-5}\,\mathrm{eV}^2$$

two independent Δm^2

Main goals of oscillation experiments

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = \mathrm{Im}(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2})$$
$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

all mixing angles $\neq 0$ →
→ $J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

quarks

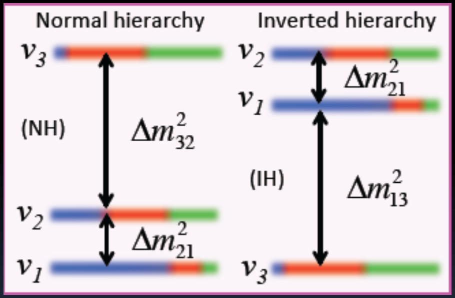
$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Quark sector $J_{CP} \approx 3\times10^{-5}$

Lepton sector $J_{CP} \sim 0.02\times\sin\delta_{CP}$

First indication from T2K: $\delta_{CP} = -\pi/2$

- Neutrino mass hierarchy



- θ_{23} – maximal? If not, what octant ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$)?

Neutrino cross sections

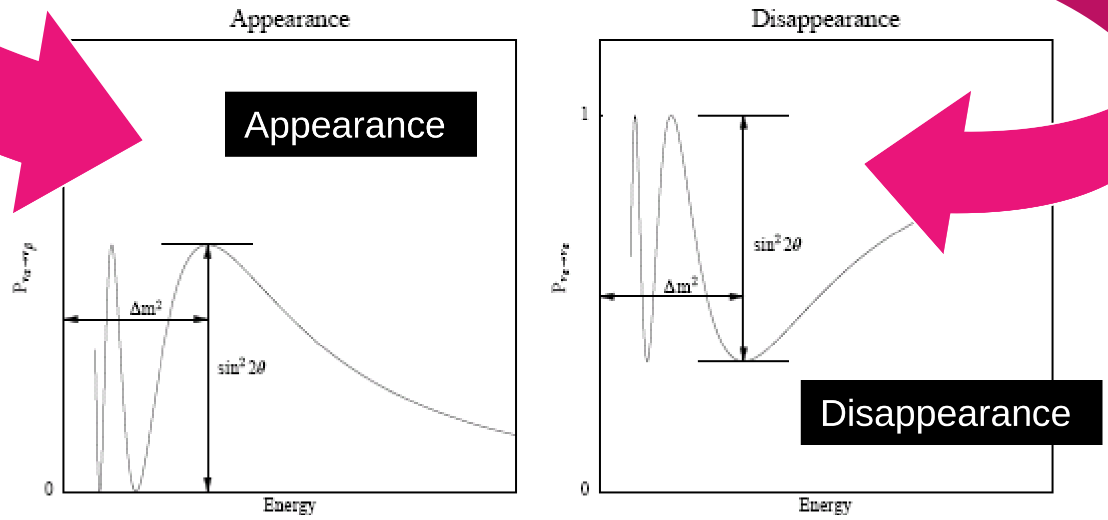
- Sterile neutrinos

Experimental methods

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\Phi_{ij} \mp 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Phi_{ij}$$

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2 \underline{2\theta} \sin^2\left(\frac{\underline{\Delta m}^2 L}{4E}\right),$$

$$P_{\nu_\alpha\to\nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Search for CP violation in neutrino oscillations

$$A_{CP} = \frac{P(\nu_\mu\to\nu_e) - P(\bar\nu_\mu\to\bar\nu_e)}{P(\nu_\mu\to\nu_e)+P(\bar\nu_\mu\to\bar\nu_e)} \cong \frac{\Delta m^2_{12}L}{4E_\nu}\cdot\frac{\sin 2\theta_{12}}{\sin\theta_{13}}\cdot\sin\delta$$

Matter effect

Mass Hierarchy

Current experiments

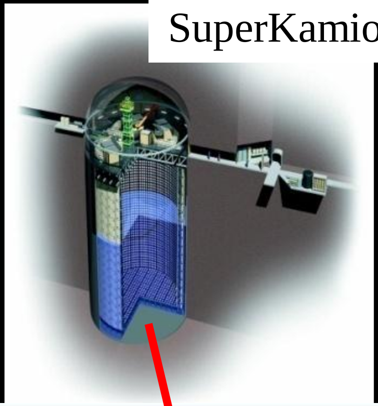
about 500 members
59 institutions
from 11 countries

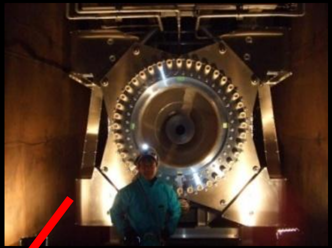
LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

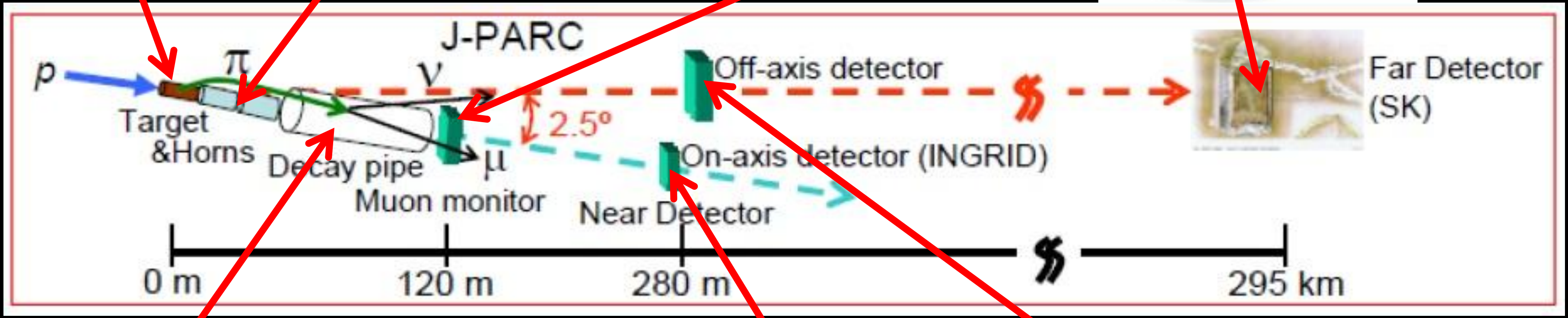
T2K experiment

Collect data since 2010

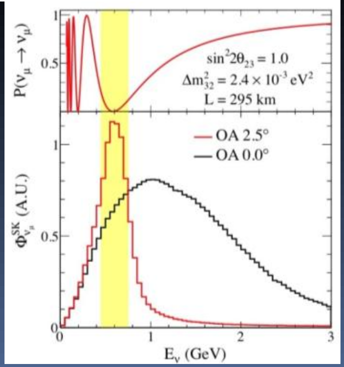
Far neutrino detector
SuperKamiokande



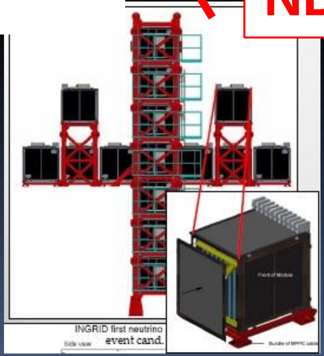




Off-axis neutrino beam

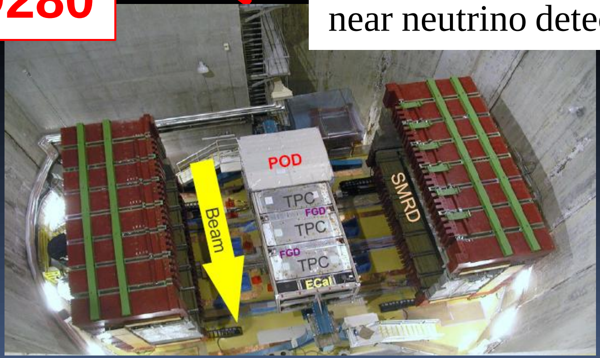


Neutrino monitor
INGRID



ND280

Off-axis
near neutrino detector

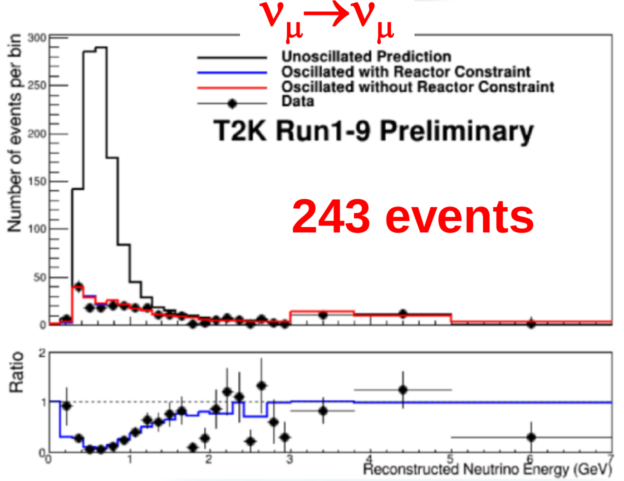


T2K data

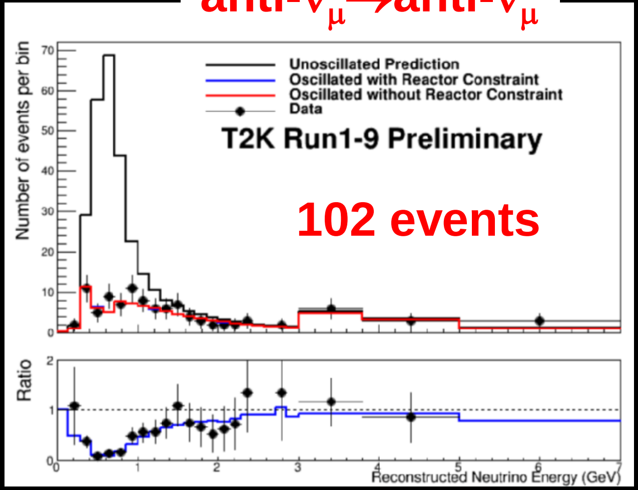
P.Litchfield, ICHEP2018

Neutrino mode 1.49×10^{21} POT
Antineutrino mode 1.12×10^{21} POT

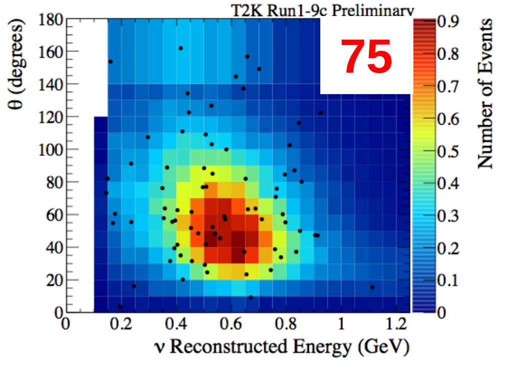
$\nu_\mu \rightarrow \nu_\mu$



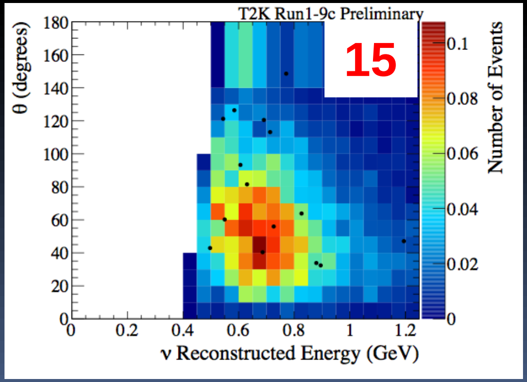
anti-ν_μ→anti-ν_μ



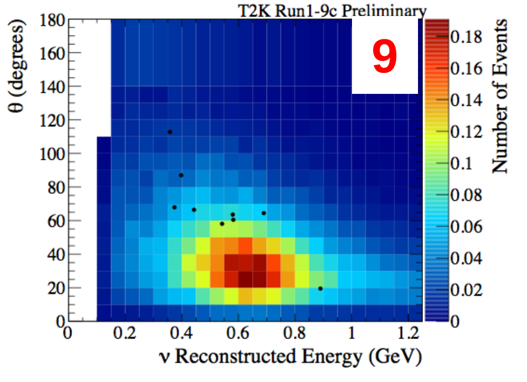
$\nu_\mu \rightarrow \nu_e$



$\nu_\mu \rightarrow \nu_e + 1\pi$



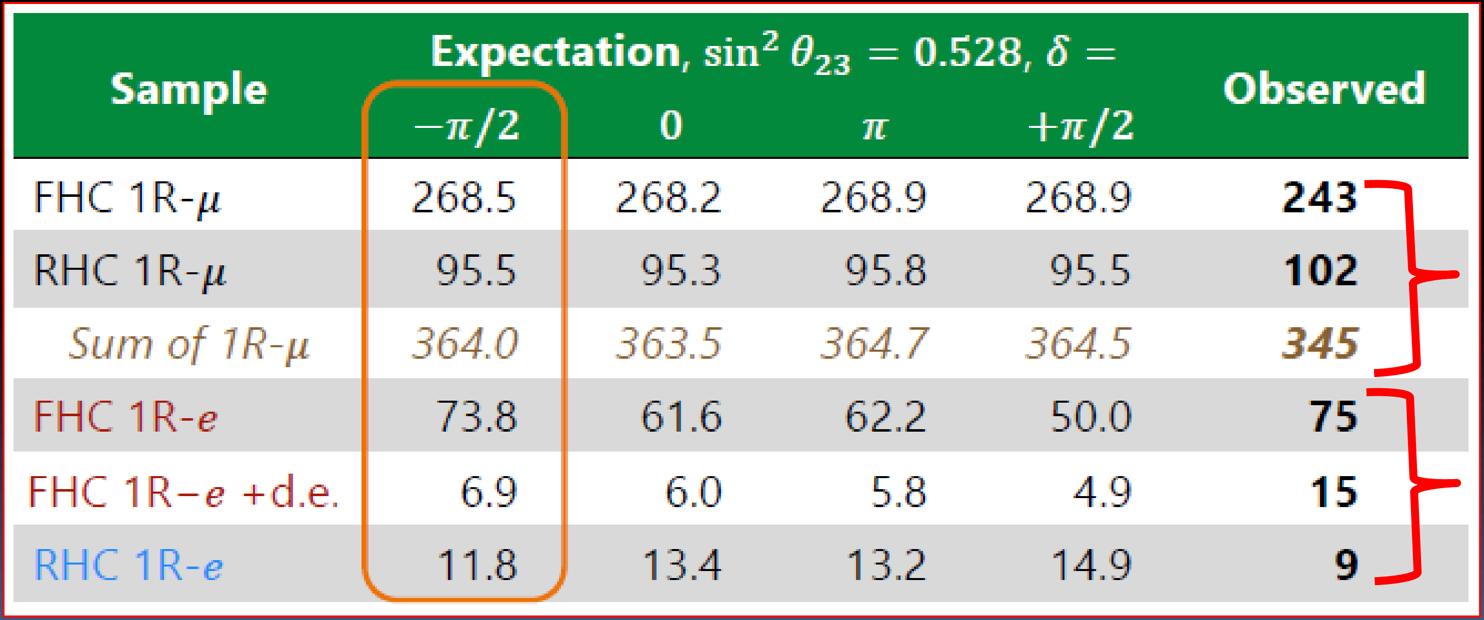
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



T2K data and expectation

Event rate			
Beam mode	**Not Oscillated**	**Oscillated (maximal mixing)**	**Observed**
neutrino	**1211.4**	**268.2**	**243**
antineutrino	**314.3**	**95.3**	**102**

Systematic error		
Beam mode	**w/o ND280**	**ND280 constrained**
neutrino	**14.5%**	**4.9%**
antineutrino	**12.2%**	**4.3%**



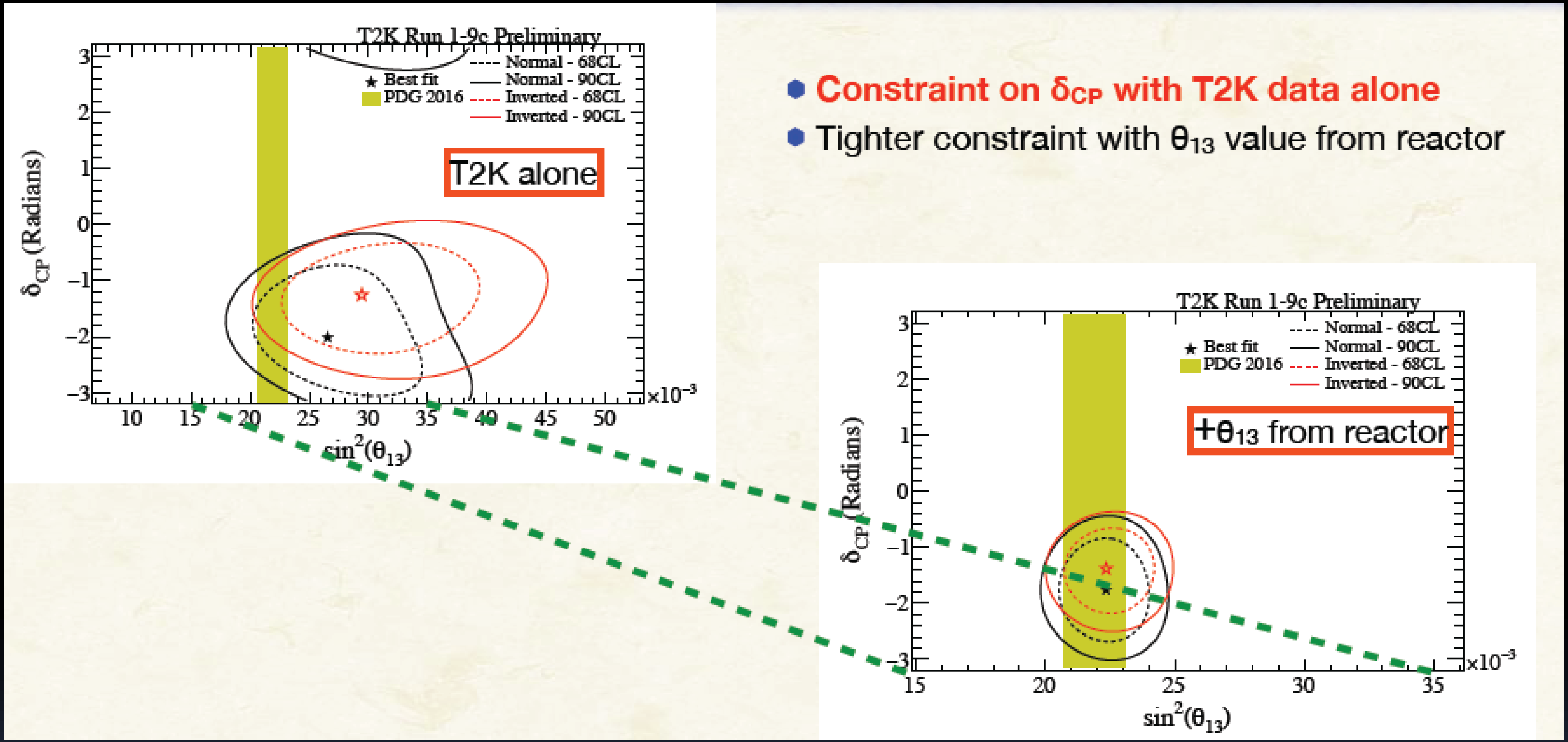
Sample	**Expectation**, $\sin^2\theta_{23} = 0.528, \delta =$				**Observed**
	$-\pi/2$	0	π	$+\pi/2$	
FHC 1R-μ	268.5	268.2	268.9	268.9	**243**
RHC 1R-μ	95.5	95.3	95.8	95.5	**102**
Sum of 1R-μ	*364.0*	*363.5*	*364.7*	*364.5*	***345***
FHC 1R-e	73.8	61.6	62.2	50.0	**75**
FHC 1R$-e$ +d.e.	6.9	6.0	5.8	4.9	**15**
RHC 1R-e	11.8	13.4	13.2	14.9	**9**

disappearance

appearance

T2K result

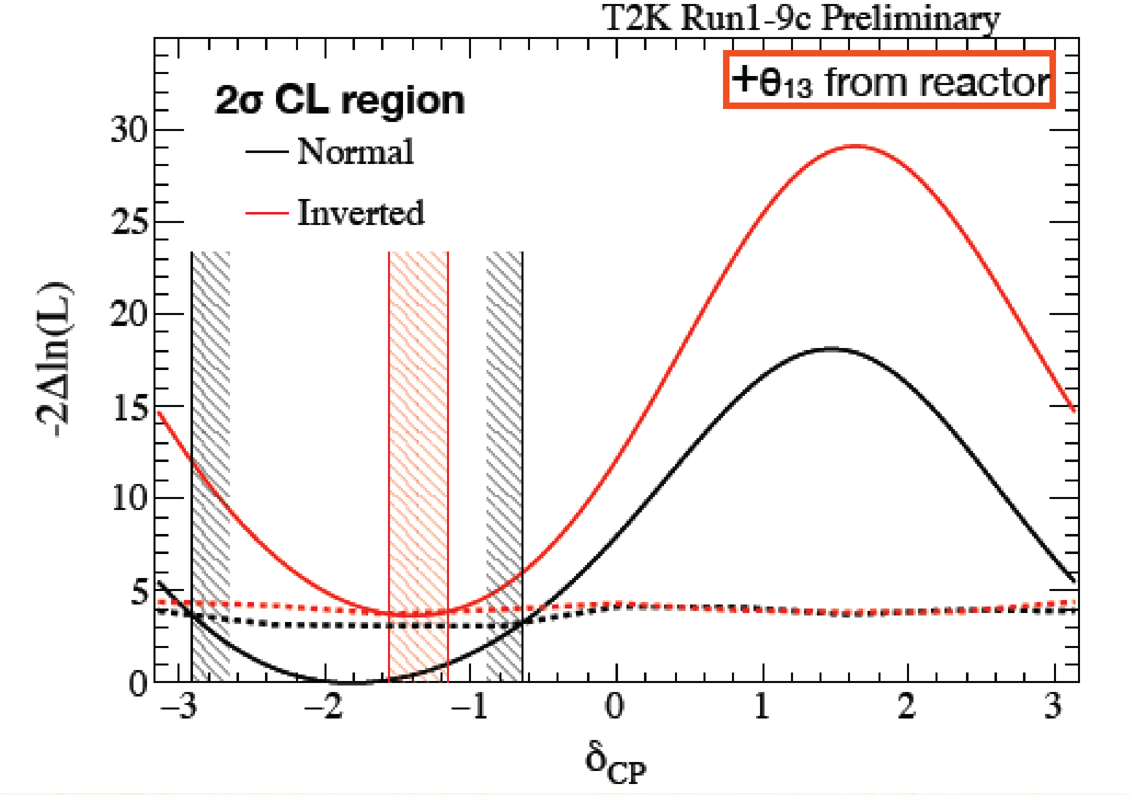
T2K ν_e / anti- ν_e



- **Constraint on δ_{CP} with T2K data alone**
- Tighter constraint with θ_{13} value from reactor

T2K ν_e / anti- ν_e + reactor θ_{13}

T2K result



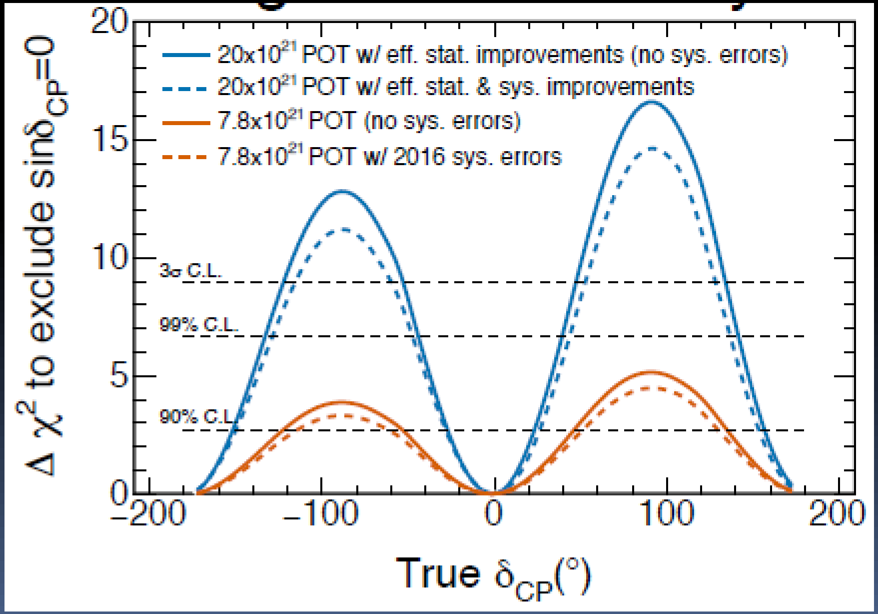
Best fit
δ_{cp} = -1.6 rad
for NH

CP-conservation hypothesis ($\sin\delta_{CP} = 0, \pi$) excluded at 2σ level
- **First hint for CP violation in the lepton sector**
- **T2K data favour $\delta_{CP} \sim -\pi/2$ and normal hierarchy**

Future plans

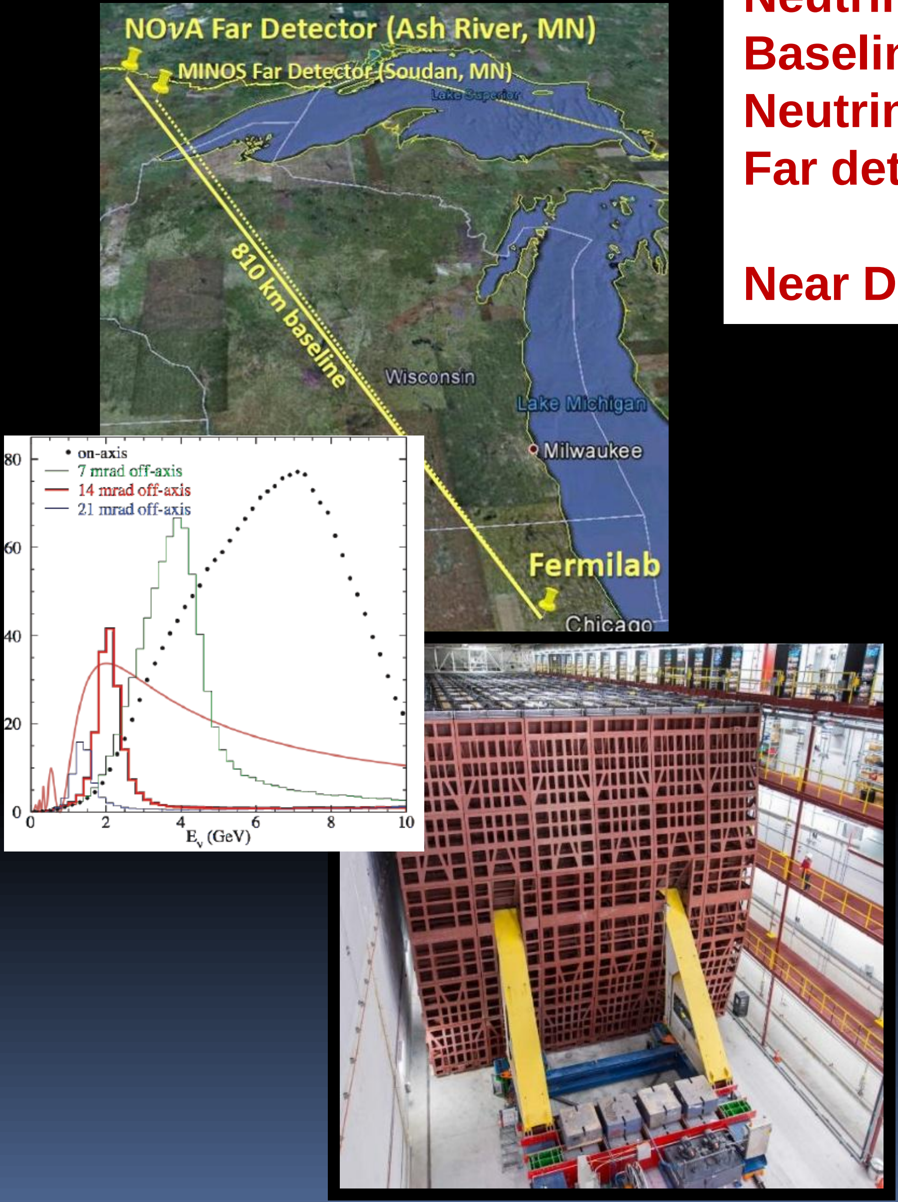
T2K expected to accumulate 7.8x10^{21} POT around 2021
(now 3x10^{21} POT)

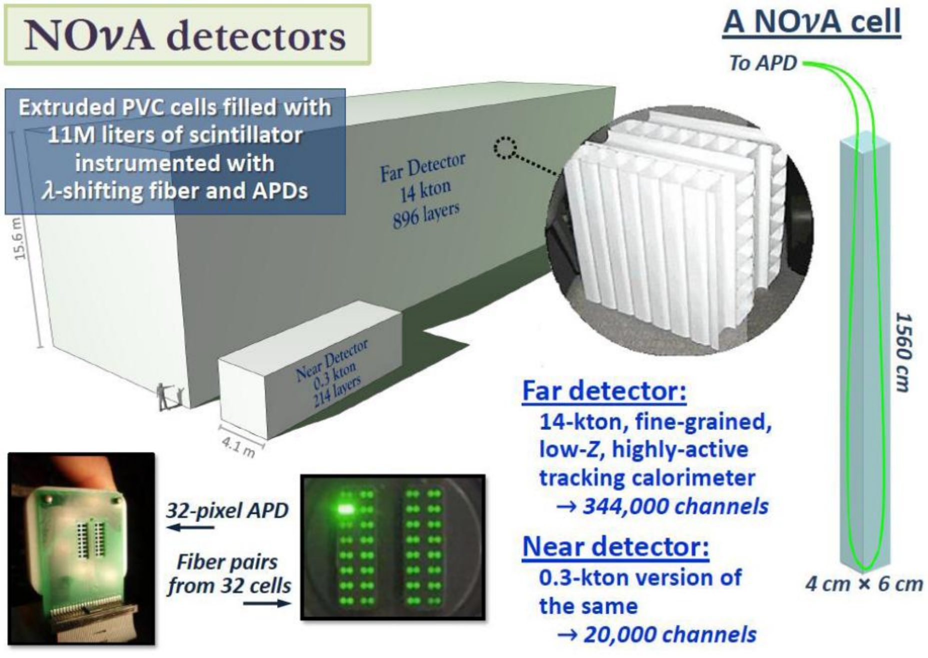
- **Upgrade of near detectors to improve systematic uncertainties**
  18% (2011) → 9% (2014) → 5% (2018) → goal ≤4% (2021)
- **Plan to increase the beam intensity up to 1 MW in 2021**
- **Beam power up to 1.3 MW in ~2026**
- **T2K-II: proposed extension up to 2026 for 20x10^{21} POT**
  3σ sensitivity to CP violation for δ_{CP} ~ -π/2



NOvA

Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter





Taking data since Summer 2014
Study of $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ oscillations

NOvA: $\nu_\mu \to \nu_\mu$

J.Bian ICHEP2018

Neutrino beam: 8.85×10^{20} POT
Antineutrino beam: 6.9×10^{20} POT

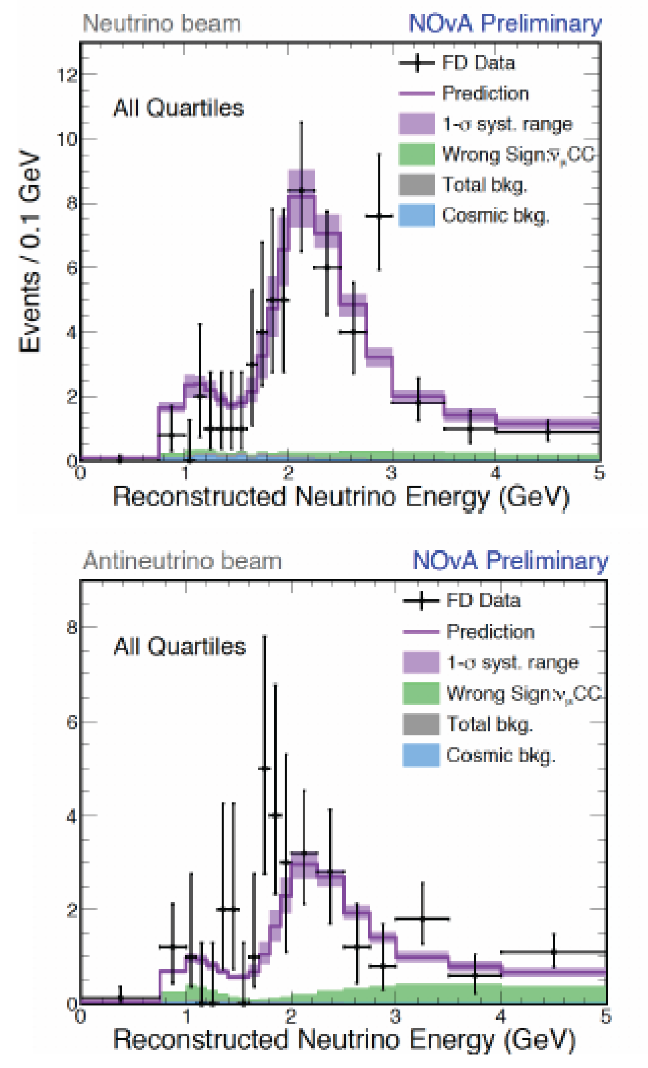
Far detector

Neutrino beam:

- Observe 113 events
- Expect 730 +38/-49(syst.) w/o oscillations

Antineutrino beam:

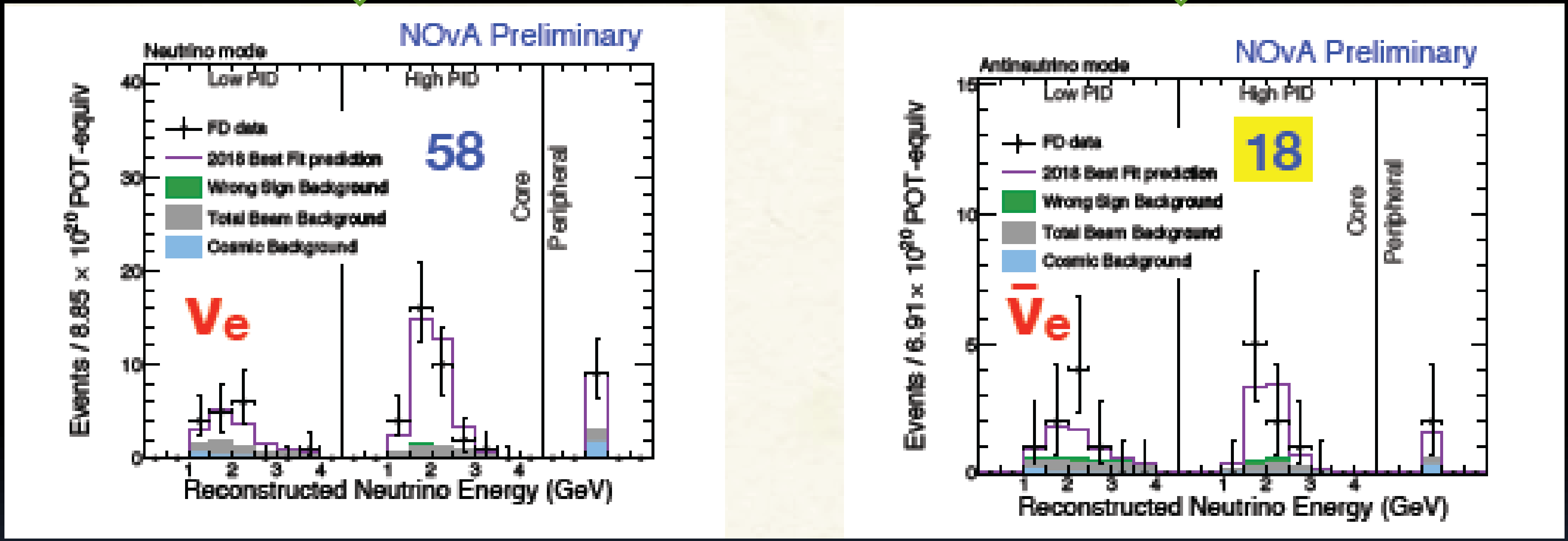
- Observe 65 events
- Expect 266 +12/-14(syst.) w/o oscillations



NOvA: ν_e/anti-ν_e

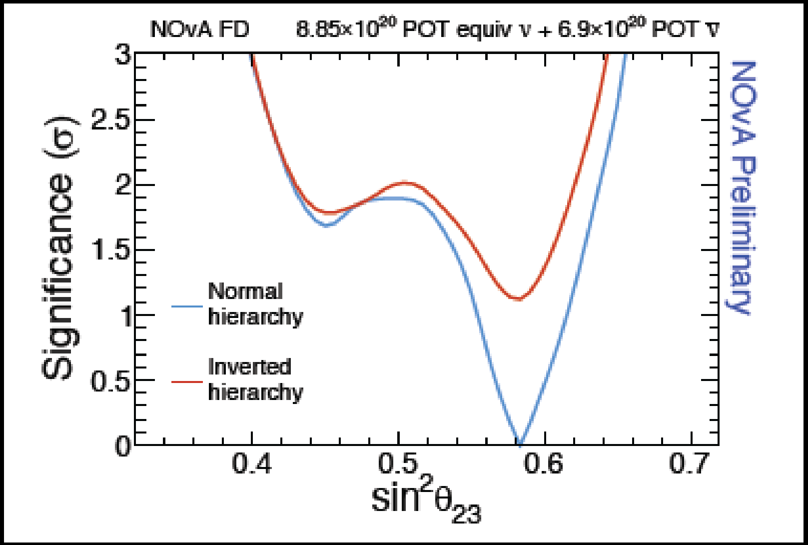
ν_e
58 events observed
15 background events expected

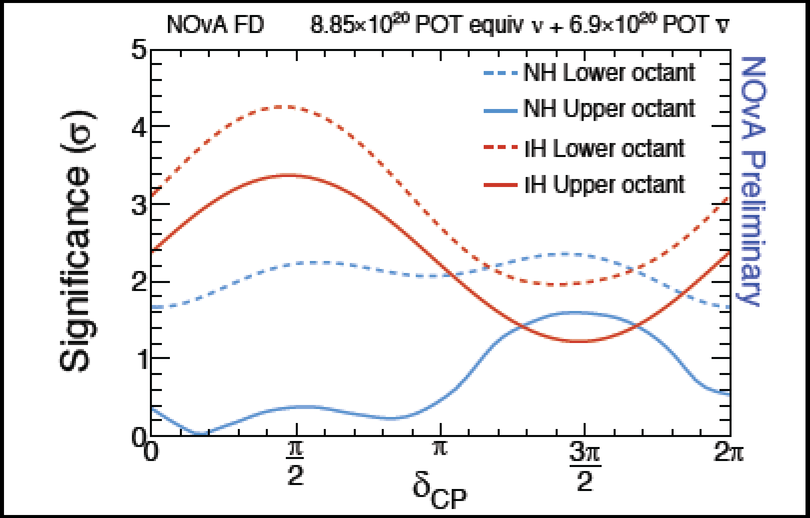
anti-ν_e
18 events observed
5.3 background events expected



$$\bar{\nu}_e \ \text{appearance} > 4\sigma$$

NOvA results

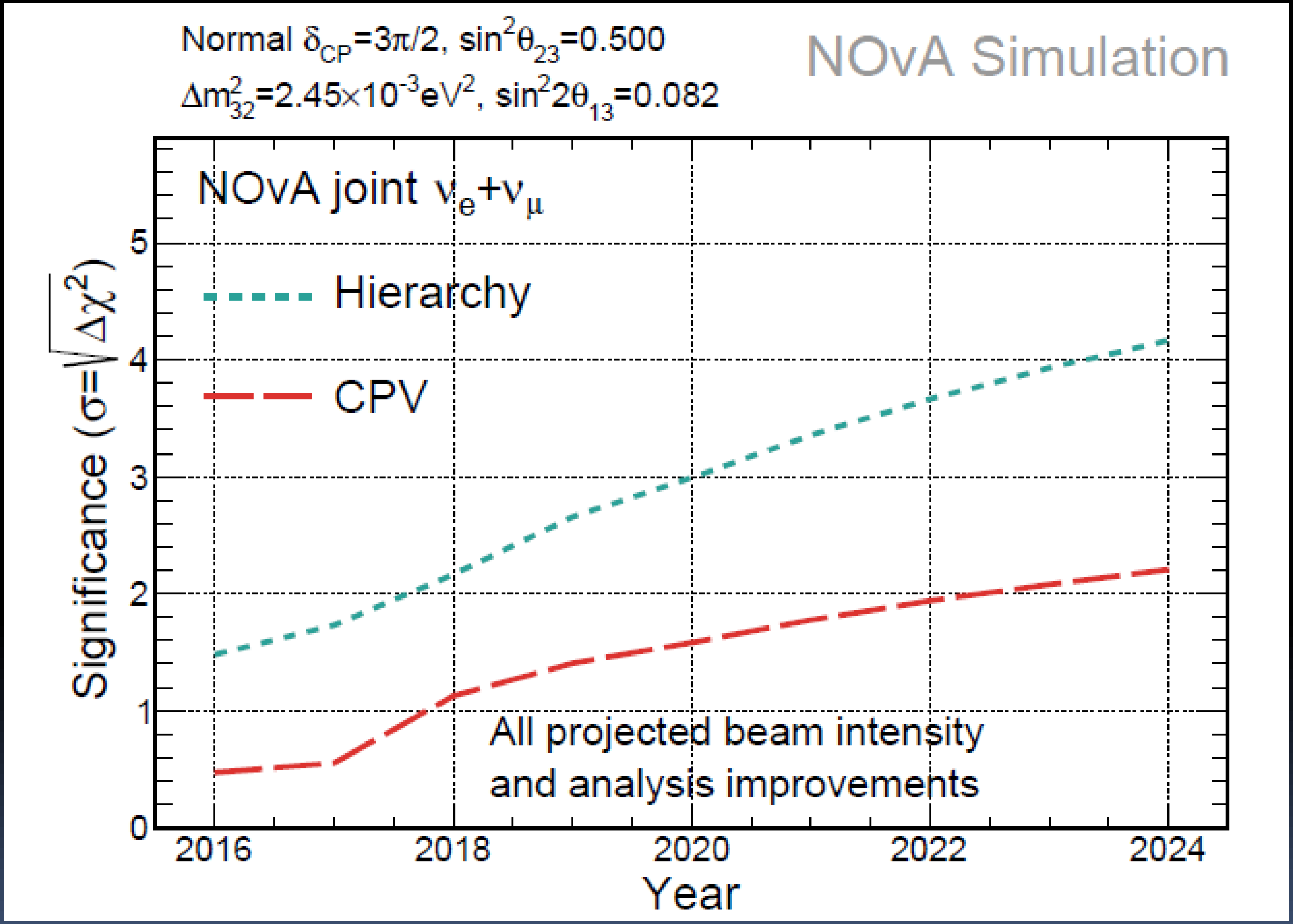




NOvA prefers
Normal Hierarchy at 1.8σ

Best fit:
- Normal Hierarchy
- $\delta_{CP} = 0.17\pi$ but consistent with all δ_{CP} values at $<1.6\sigma$

Prospects for NOvA

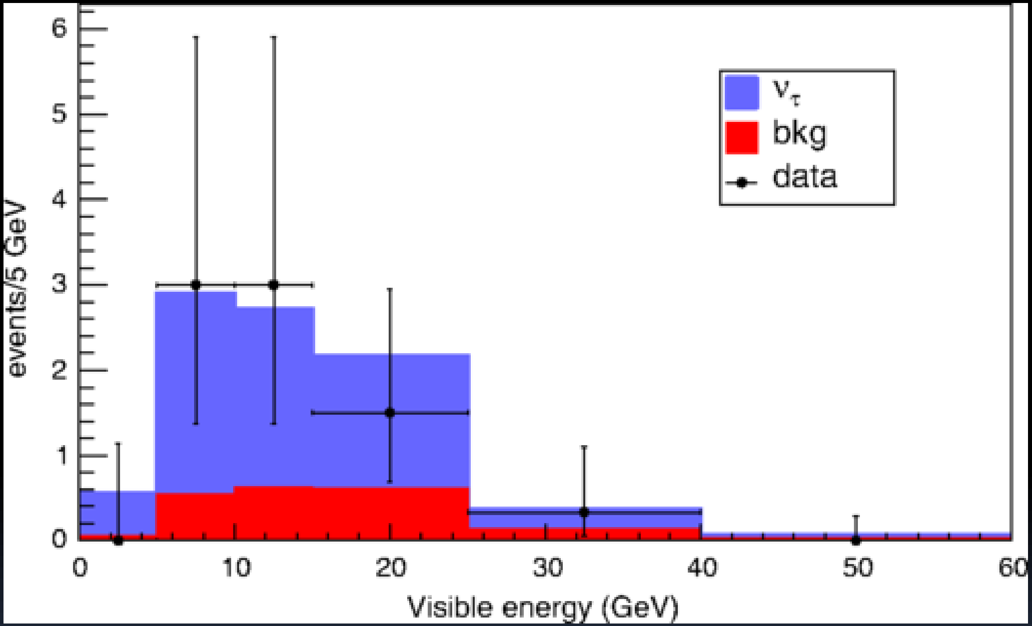


OPERA: final result

$\nu_\mu \to \nu_\tau$ appearance

PRL 120 (2018) 211801

10 ν_τ events observed for 18×10^{19} POT
Expected 6.4 events for $\Delta m^2_{23} = 2.5\times10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$
Expected background 2.0±0.4 events



Significance of ν_τ appearance 6.1σ

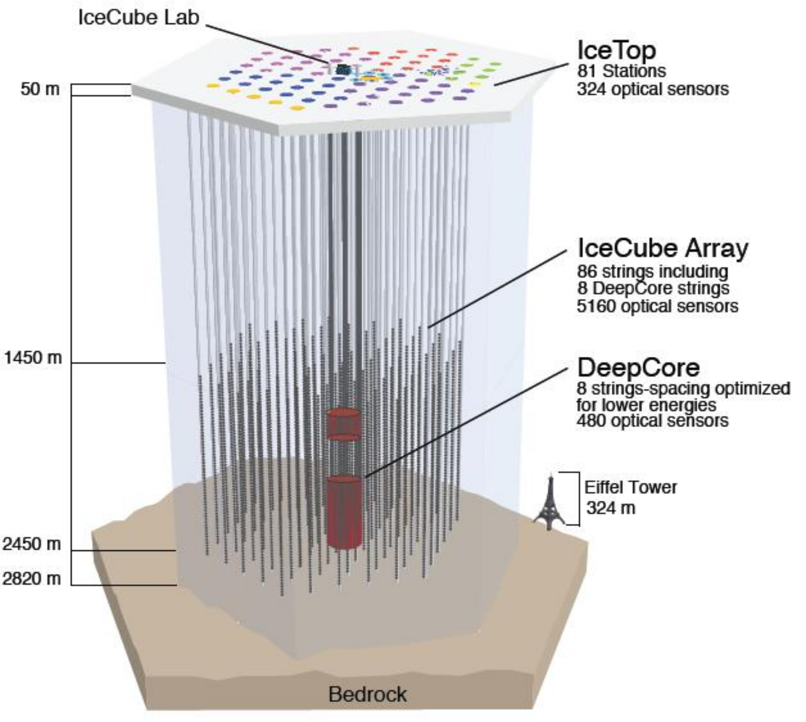
OPERA: $\Delta m^2_{23} = (2.7 + 0.7 - 0.6)\times10^{-3}$ eV^2, assuming $\sin^2 2\theta_{23} = 1.0$

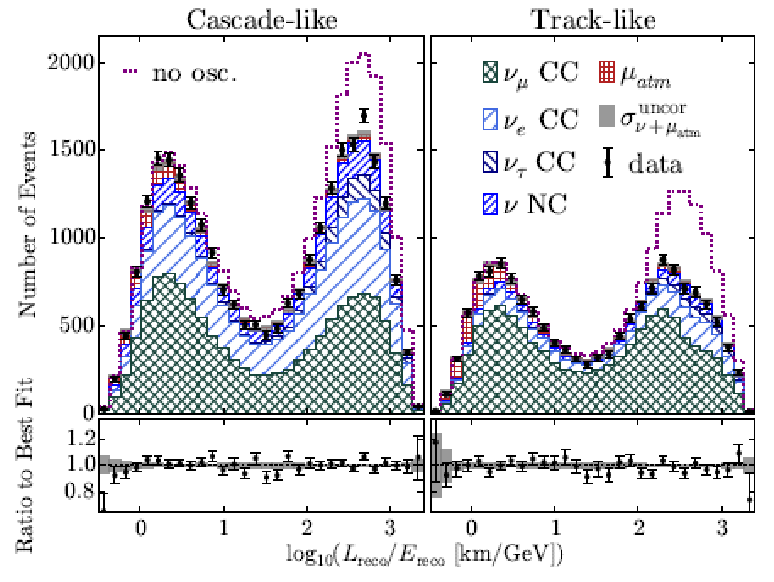
IceCube

Neutrinos have the first maximum of disappearance at about 25 GeV
Energy threshold
of Deep Core = 5 GeV

PRL 120 (2018) 071801

Data taking for 3 years

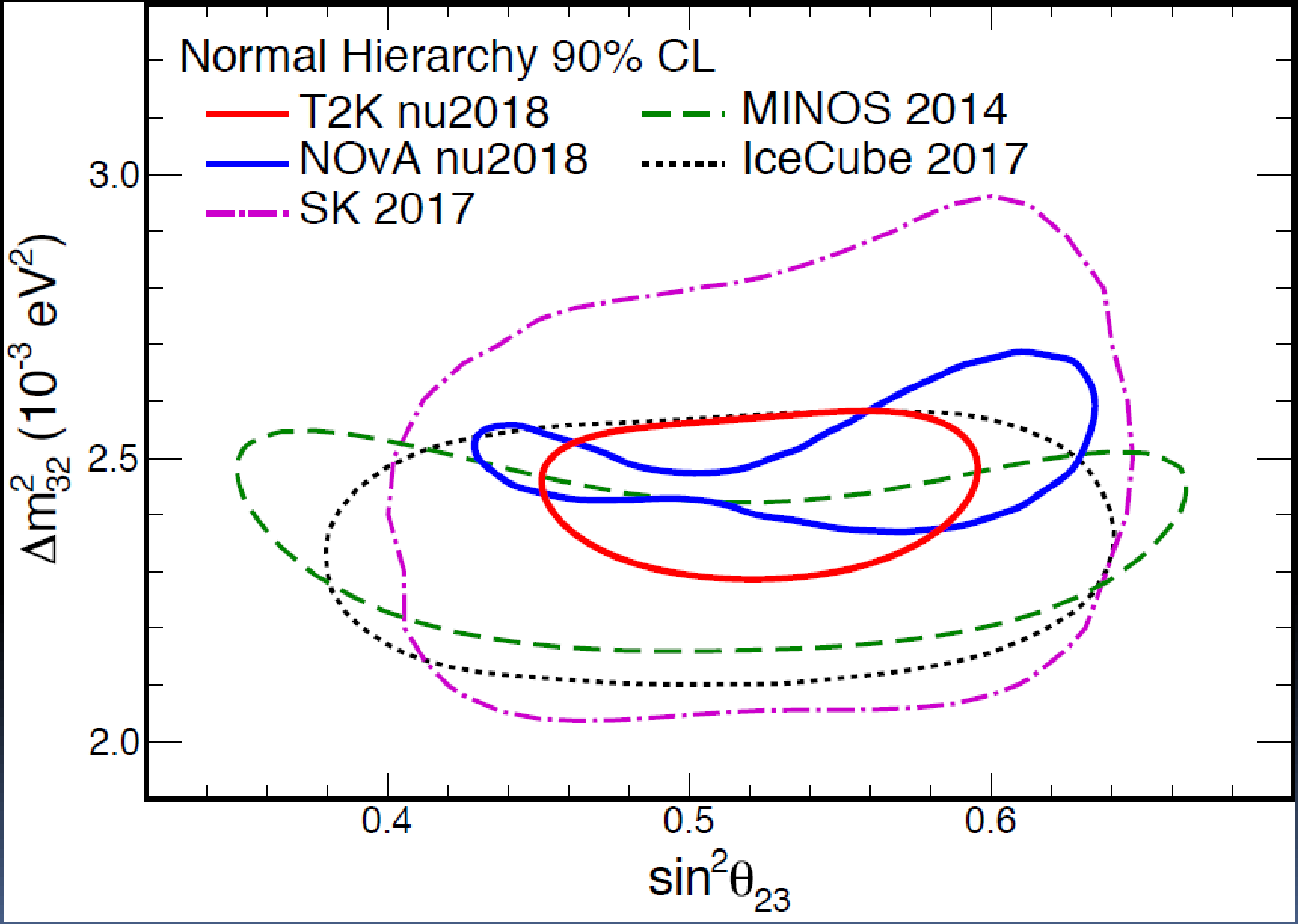




Δm^2_{32} = (2.31 +011-0.13)x10^{-3} eV^2 $\sin^2\theta_{23}$ = 0.51 +0.07 -0.09 for NH

Oscillation parameters: Δm^2_{32} – $\sin^2\theta_{23}$

M.Yokoyama ICHEP2018



Reactor experiments

Measurement of θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Daya Bay, China

Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW$_{th}$ power, 35 × 10^{20} neutrinos per second

Spectral Oscillation Measurement at Daya Bay: D. Dwyer 7

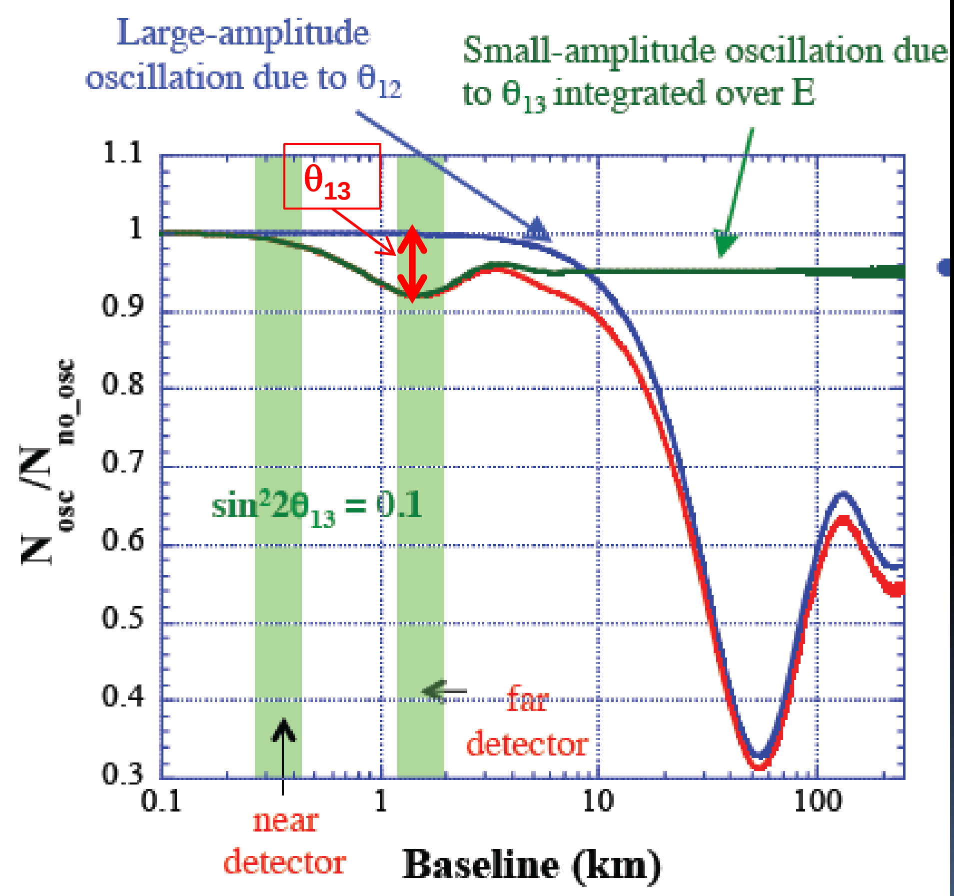
17.4 GW

RENO, Korea

16 GW

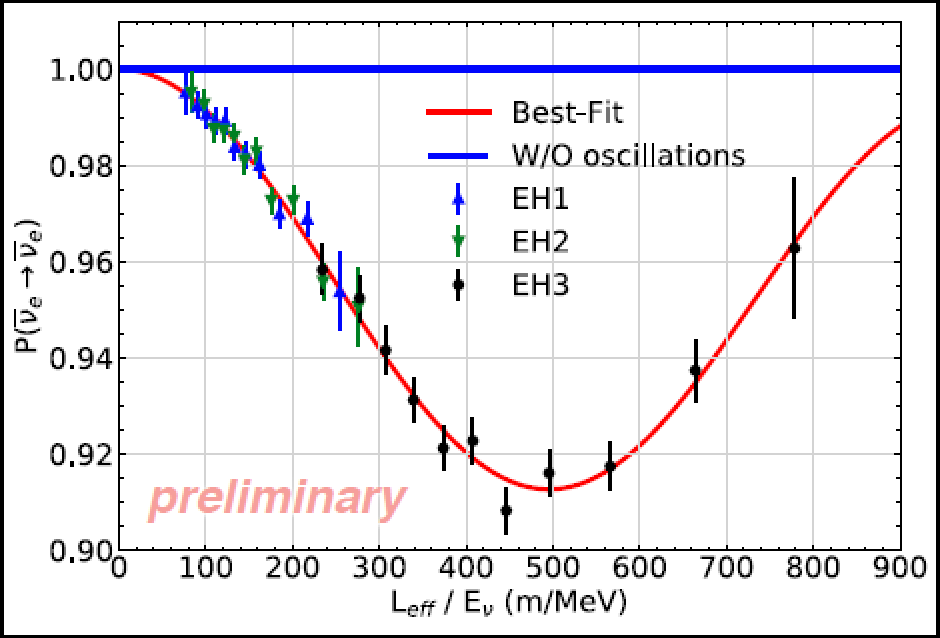
Double Chooz, France

8.5 GW

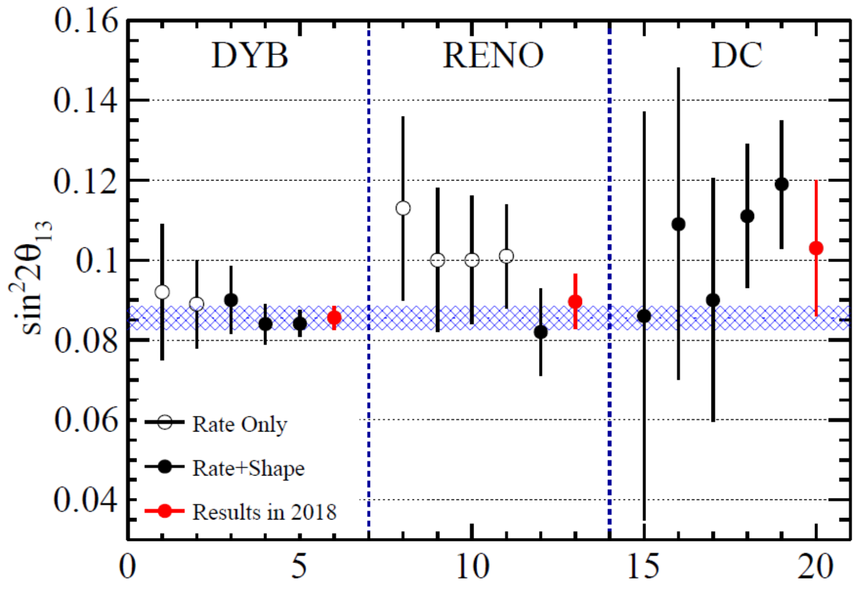


Oscillation results

Daya Bay



Liang Zhan, ICHEP2018



$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

Future LBL Projects

- Reactor experiment JUNO
- Accelerator LBL experiment DUNE
- HyperKamiokande and T2HK

Reactor experiment JUNO

China

Start data taking in 2020

66 institutions
> 400 collaborators

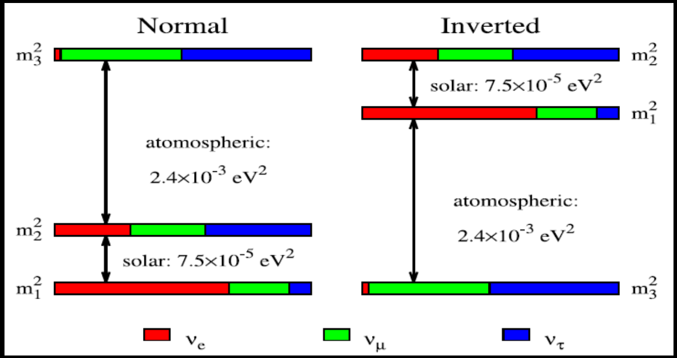
Main target:
Measurement of neutrino mass hierarchy

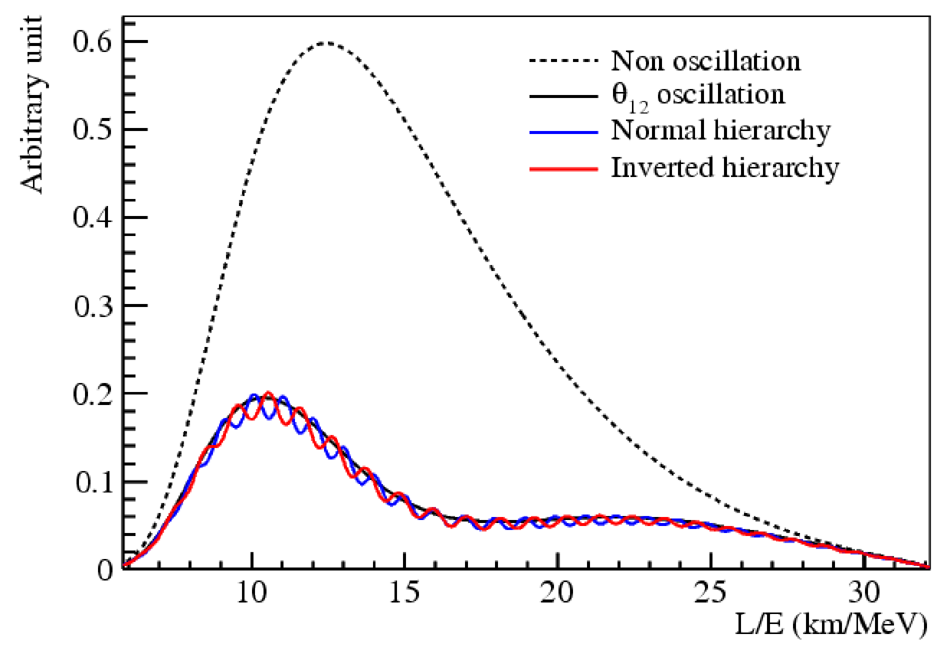
- **700 m deep underground**
- **36 GW reactor power**
- **53 km baseline -> oscillation maximum θ_{12}**
- **20 kton LS detector**
- **3% energy resolution at 1MeV**
- **<1% energy scale uncertainty**

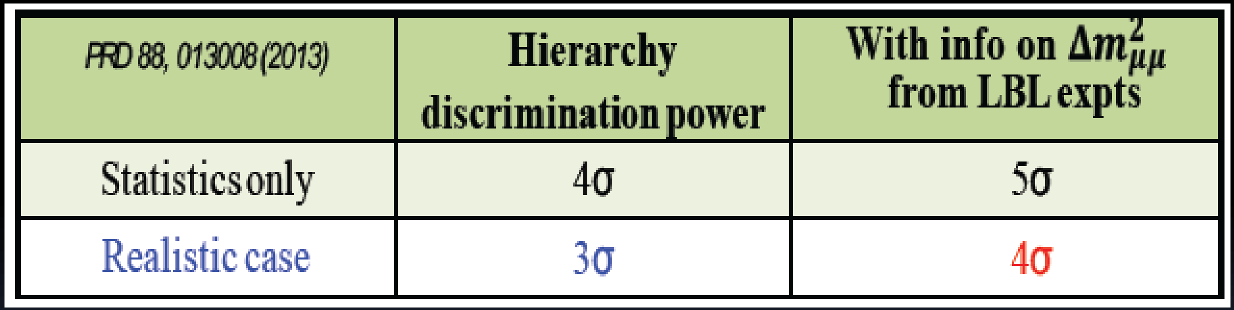
!?

JUNO goals

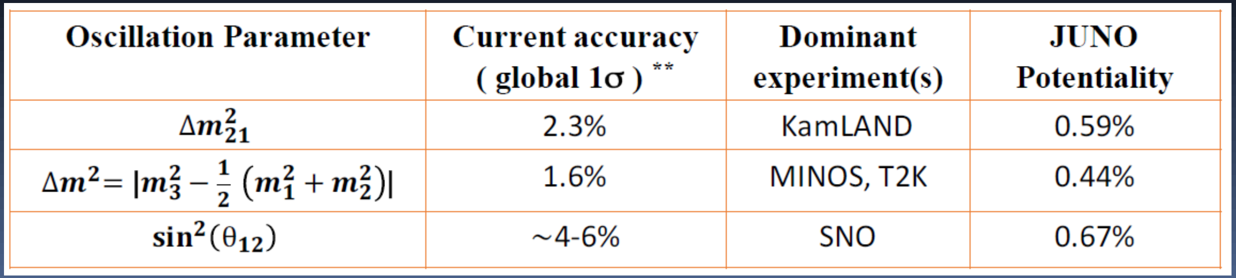
Main goal: determination of neutrino mass hierarchy







PRD 88, 013008 (2013)	Hierarchy discrimination power	With info on $\Delta m^2_{\mu\mu}$ from LBL expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ

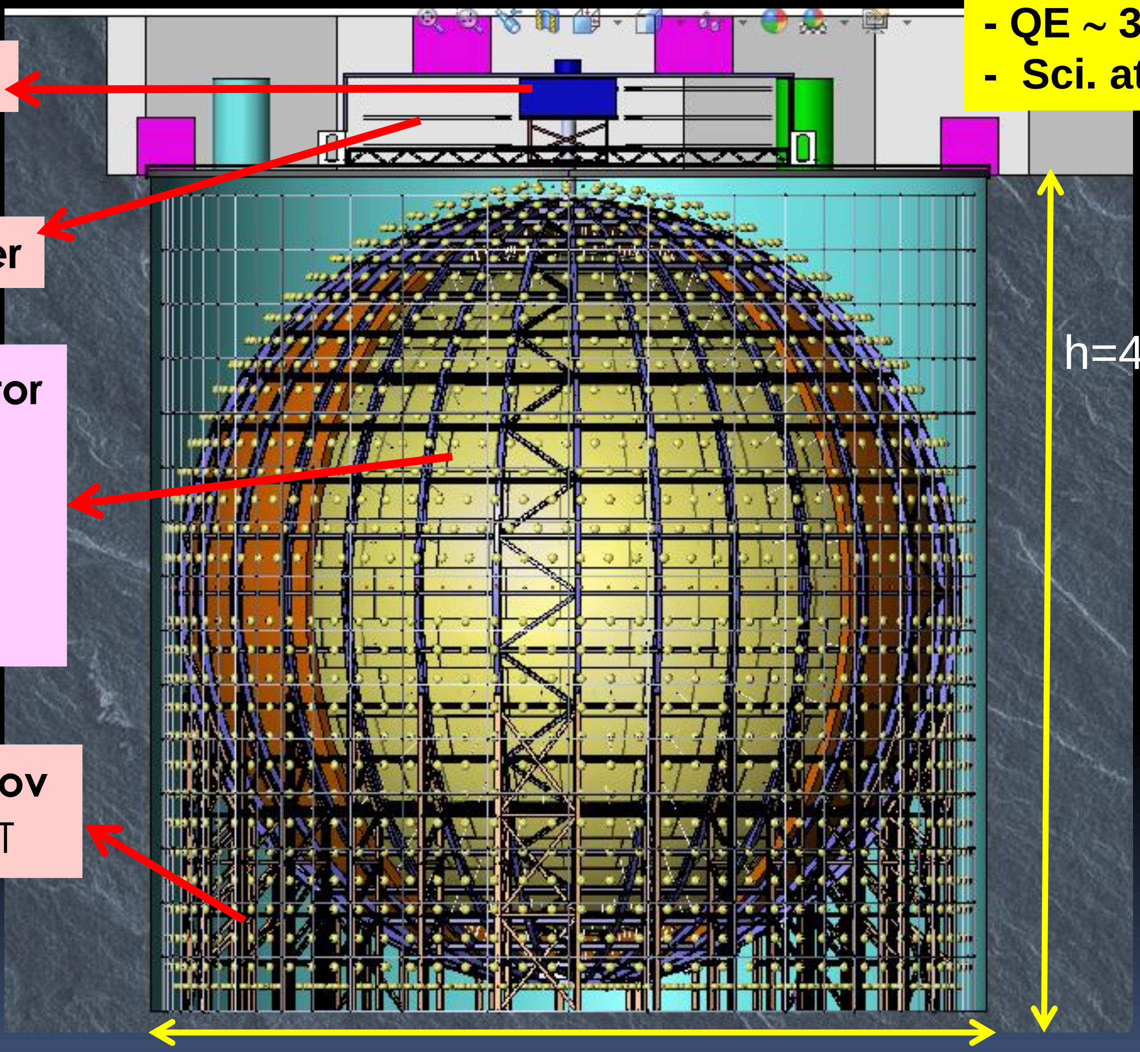


Oscillation Parameter	Current accuracy (global 1σ) **	Dominant experiment(s)	JUNO Potentiality
Δm^2_{21}	2.3%	KamLAND	0.59%
$\Delta m^2 = \lvert m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)\rvert$	1.6%	MINOS, T2K	0.44%
$\sin^2(\theta_{12})$	~4-6%	SNO	0.67%

+ Supernova neutrino
Geoneutrinos
Solar neutrinos

Detector JUNO

Requirements:
- **PMT coverage 75% of total surface**
- **QE ~ 35%**
- **Sci. att. length >20 m**



Calibration

Top Tracker

Central detector
Acrylic sphere
20kt Liquid Scin
~17000 20'' PMT
~36000 3'' PMT

Water Cherenkov
~2000 20'' PMT

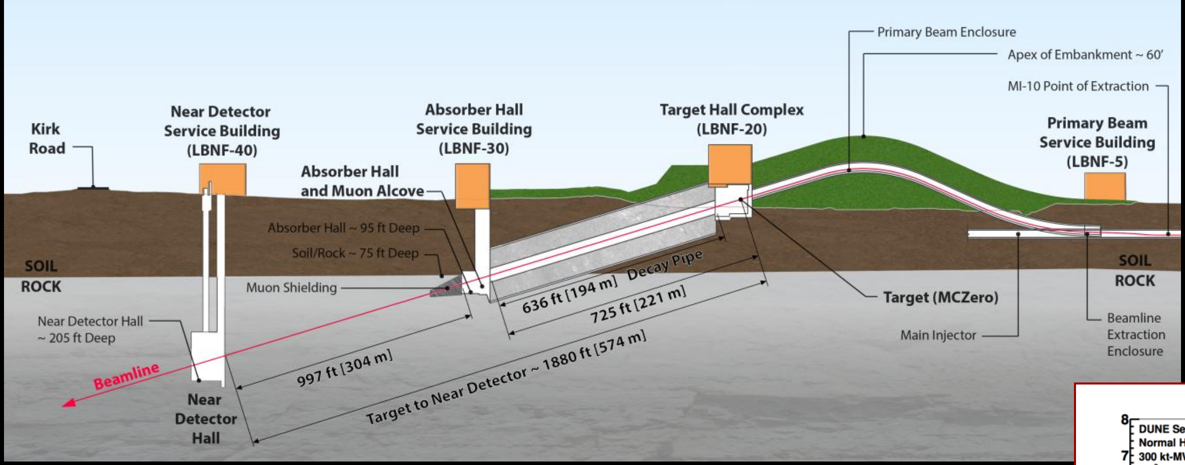
LBNF/DUNE Project

Flagship FNAL project

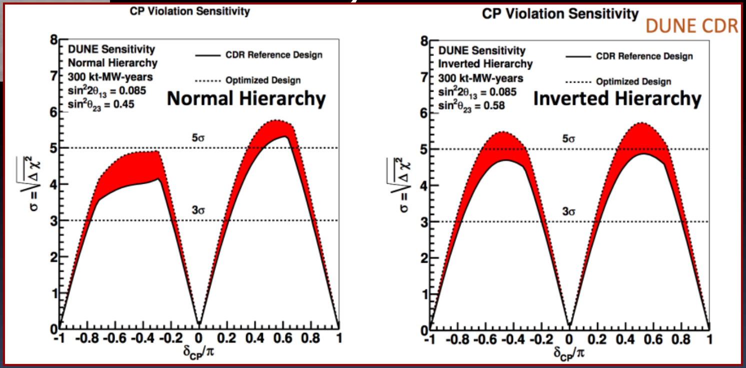
Main goals: **- discovery of CP violation in leptonic sector**
- neutrino mass hierarchy at >5σ level
- neutrino astronomy
- proton decay search

30 countries
161 institutions
~1000 collaborators

E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
Eν ~ 1- 6 GeV
L=1300 km from FNAL to SURF, S.Dakota

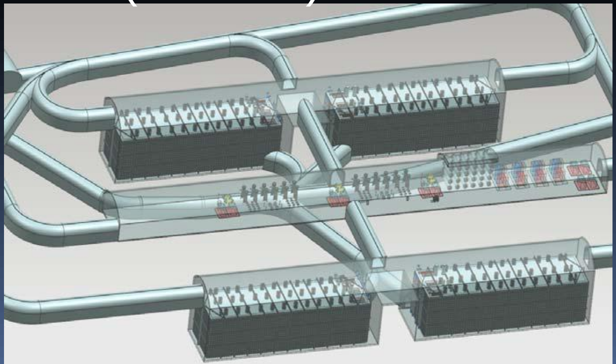


Sensitivity to CP violation



Far detector 40 kt (4 x 10kt) LAr TPC

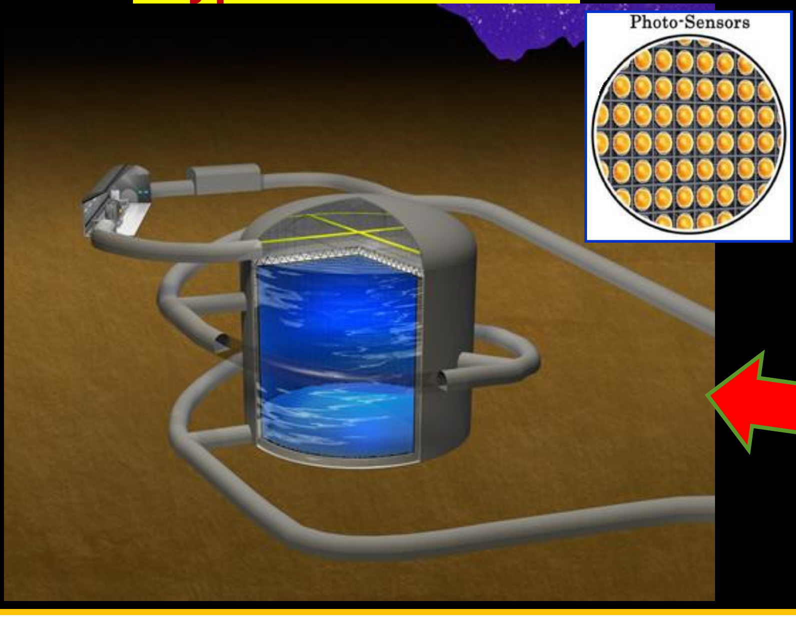
Single
and
Dual
phase
detectors



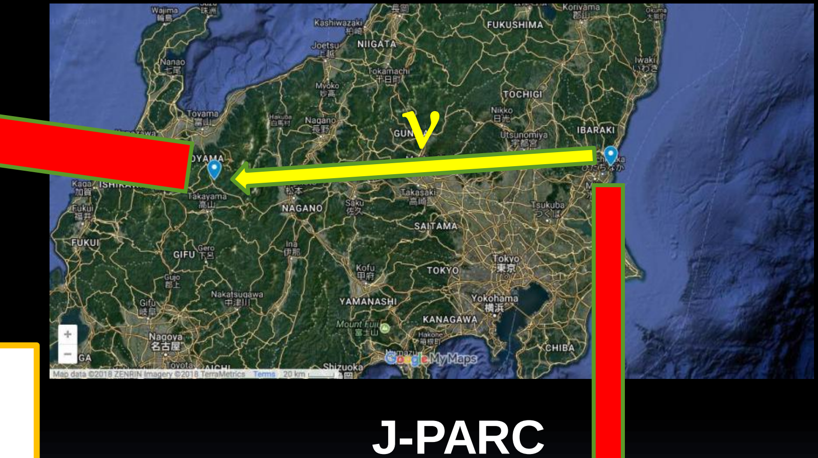
2021 – installation of 1st far detector
2024 – 2 modules operational
2026 – deliver neutrino beam

Hyper-Kamiokande project

Hyper-K water

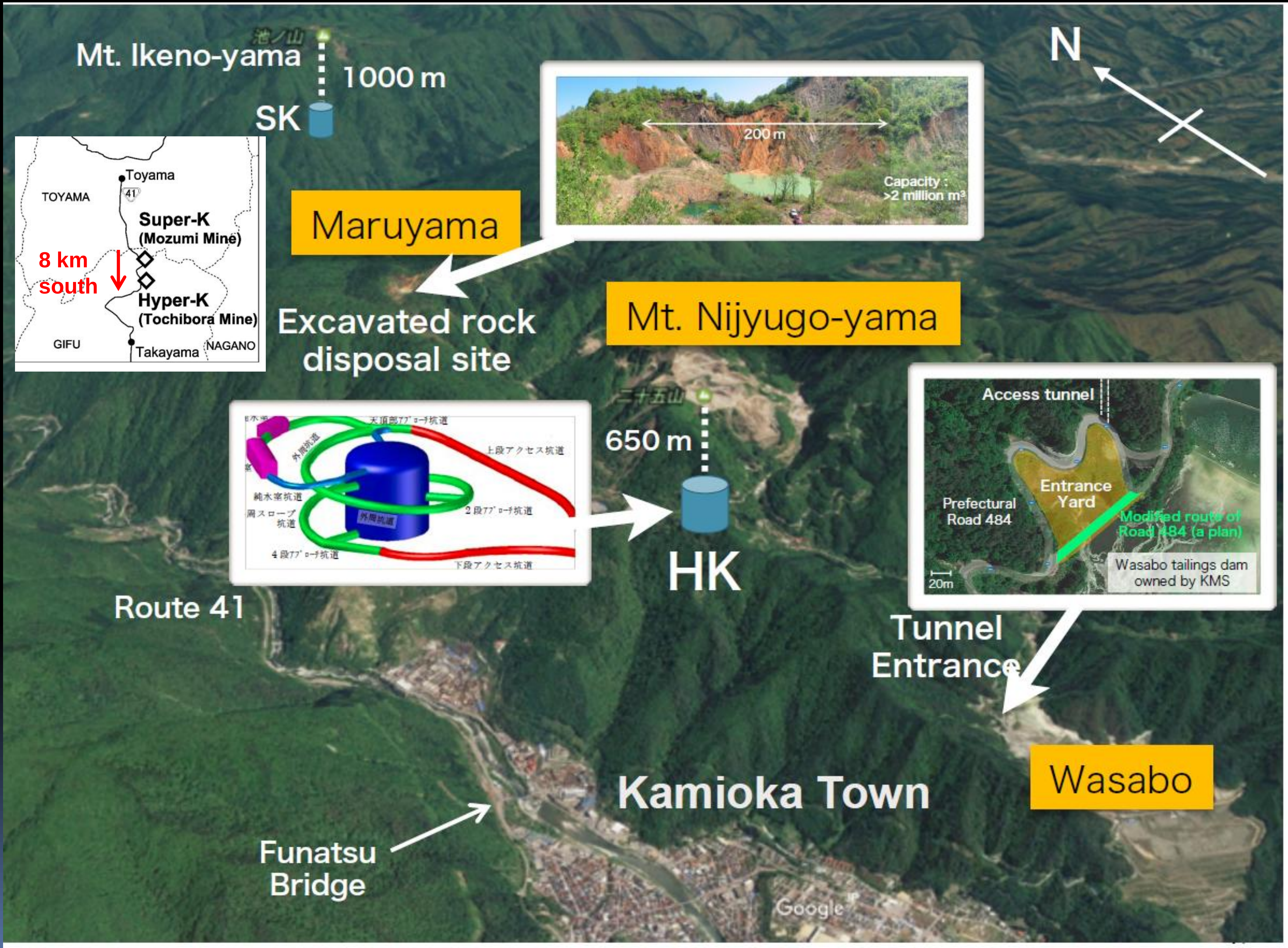


Main goals:
- Search for CP violation
- Proton decay
- Neutrino astrophysics



J-PARC

Water tank 60 m(H) x 74m(D)
Total volume 260 kt
Fiducial volume 190 kt ~10xSuper-K
40000 50 cm ID PMTs
PMT coverage 40%
6700 20 cm OD PMT's
Photon sensitivity ~2 times better than Super-K
Construction of 2nd tank in Korea (1-3 deg off axis, 2nd oscill. maximum) is under study

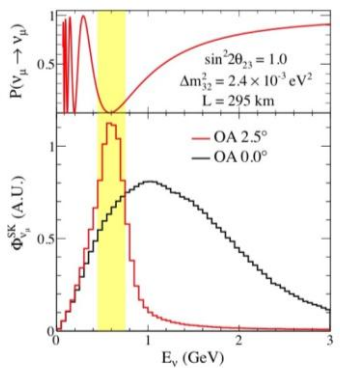

Mt. Ikeno-yama
池ノ山
1000 m
SK
N
200 m
Capacity : >2 million m³
Maruyama
Toyama
41
TOYAMA
Super-K (Mozumi Mine)
8 km south
Hyper-K (Tochibora Mine)
GIFU
Takayama
NAGANO
Excavated rock disposal site
Mt. Nijyugo-yama
二十五山
650 m
天頂部アプローチ坑道
外周抗道
上段アクセス坑道
純水室坑道
周スロープ坑道
外周抗道
2段アプローチ坑道
4段アプローチ坑道
下段アクセス坑道
HK
Access tunnel
Entrance Yard
Prefectural Road 484
Modified route of Road 484 (a plan)
Wasabo tailings dam owned by KMS
20m
Route 41
Tunnel Entrance
Wasabo
Kamioka Town
Funatsu Bridge
Google

T2HK (Tokai-to-Hyper-Kamiokande)

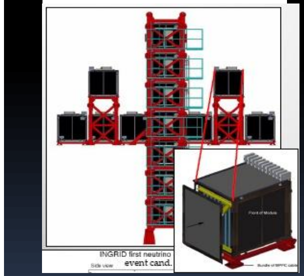
Hyper-K

J-PARC

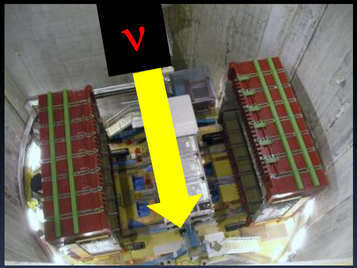
Off-axis neutrino beam



Neutrino monitor
INGRID



Off-axis
near neutrino detector



Near neutrino detector at 280 m from target

Decay tunnel

Horn

Target

Neutrino beam elements

J-PARC neutrino beam

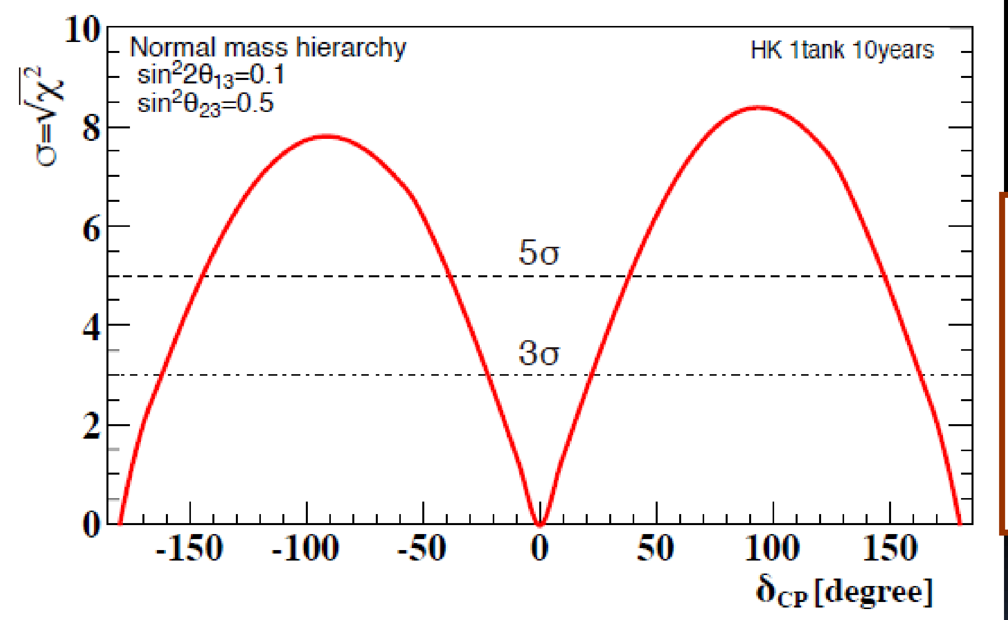
2.5°off-axis, peak energy 600 MeV (oscillation maximum), current beam power 485 kW

Sensitivity to CP

Integrated beam power 1.3 MW x 10^8 s

→ 2.7 x 10^{22} POT with 30 GeV proton beam

$\sin^2 2\theta_{13} = 0.1$



Hyper-K: uncertainties of expected number events

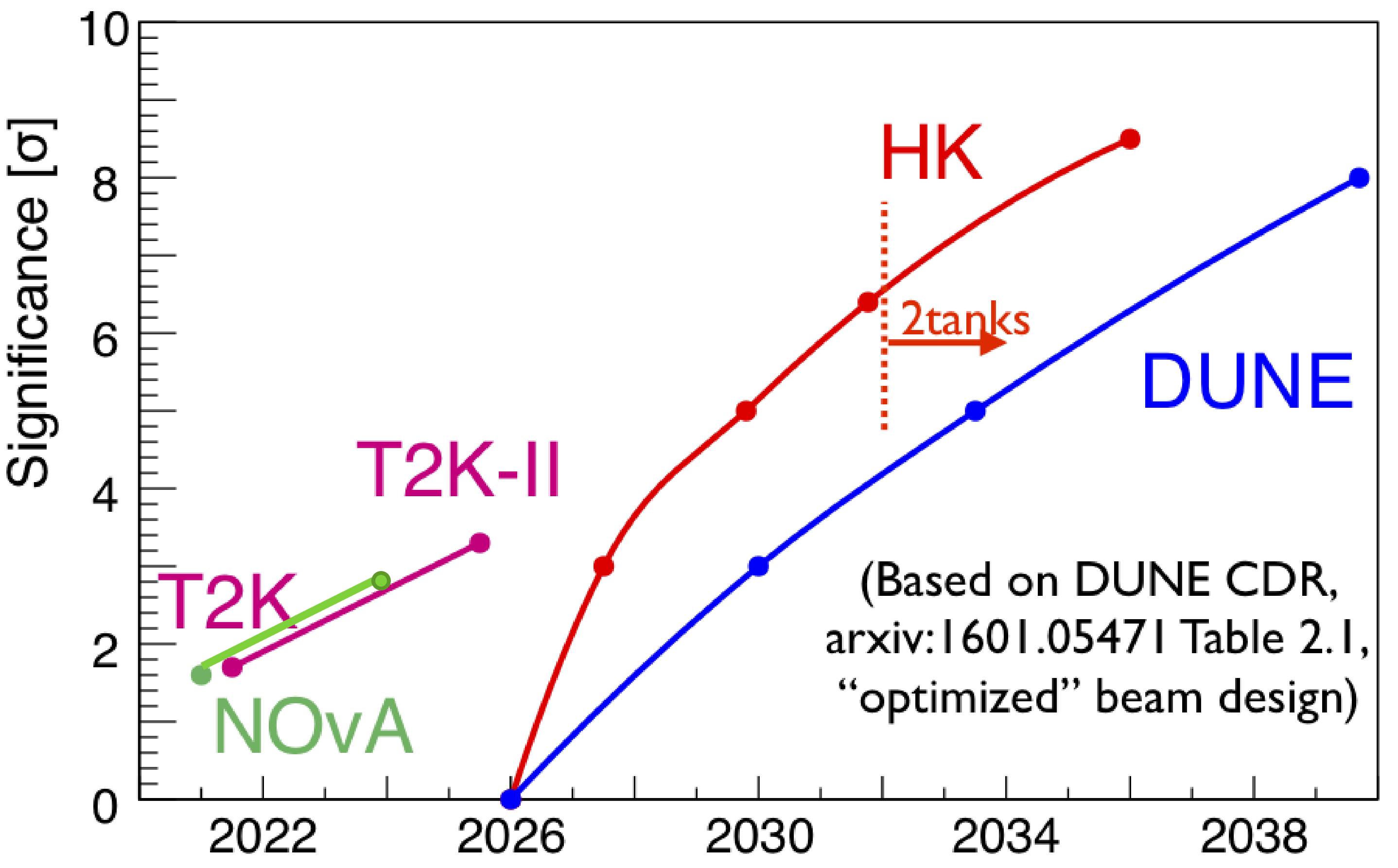
$\nu_\mu \rightarrow \nu_e$	3.2%
$\nu_\mu \rightarrow \nu_\mu$	3.6%
================	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.9%
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	3.6%

T2K systematic uncertainties 5-6 %

Exclusion of δ=0 at 8σ (for δ= -π/2)
5σ (3σ) significance for 57 (80)% of possible δ values

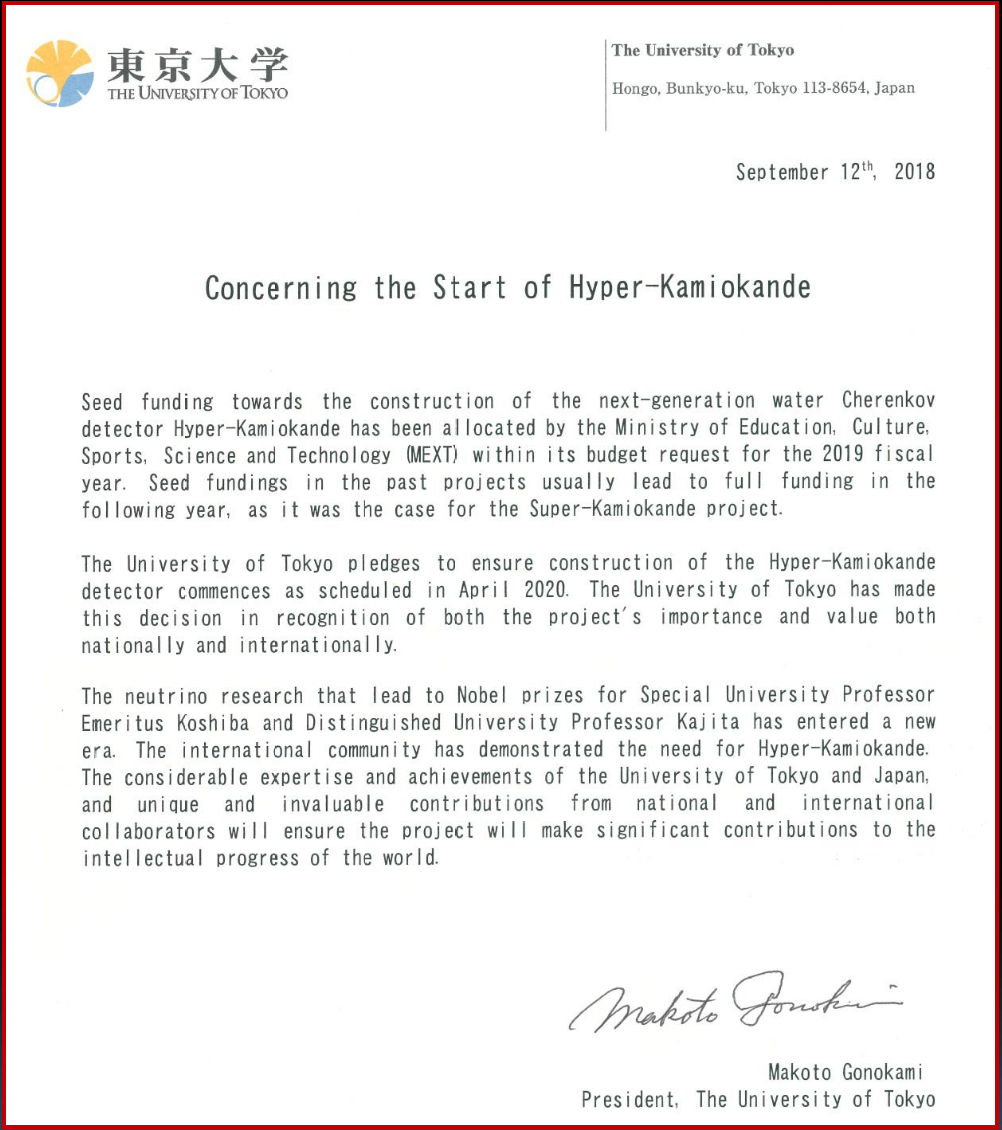
Expected sensitivity to CP

Significance for $\delta_{CP} = -\pi/2$



Start of Hyper-Kamiokande

- Seed funding is allocated within 2019 fiscal year in Japan
- Construction will start in April 2020



東京大学
THE UNIVERSITY OF TOKYO

The University of Tokyo
Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

September 12th, 2018

Concerning the Start of Hyper-Kamiokande

Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

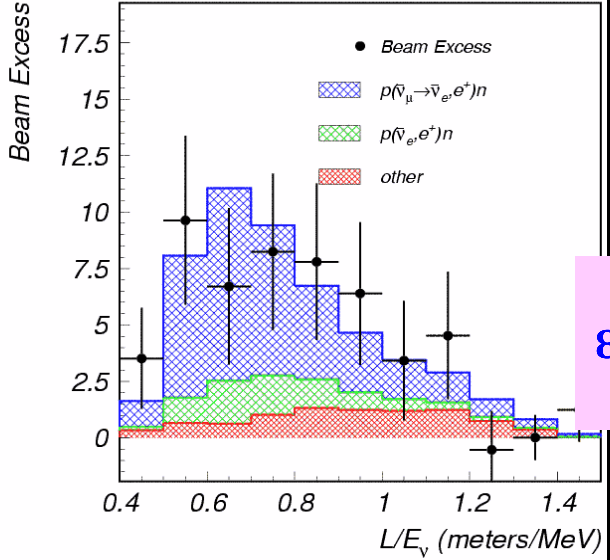
The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

Makoto Gonokami

Makoto Gonokami
President, The University of Tokyo

Light sterile neutrinos

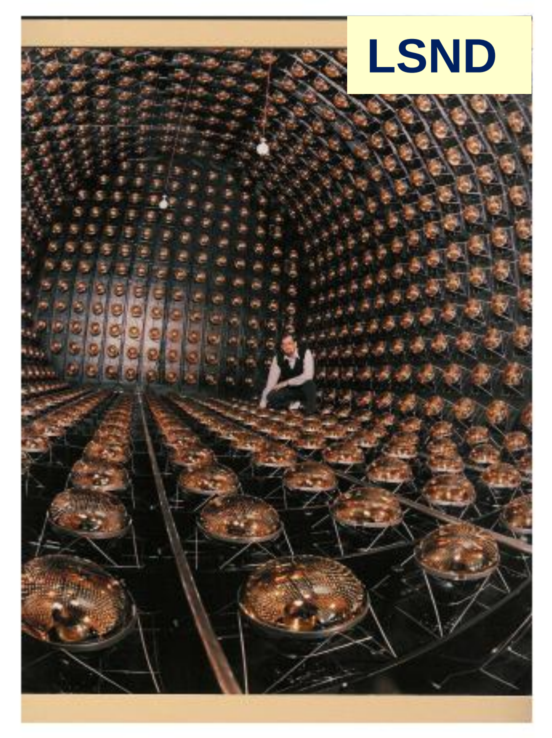
LSND

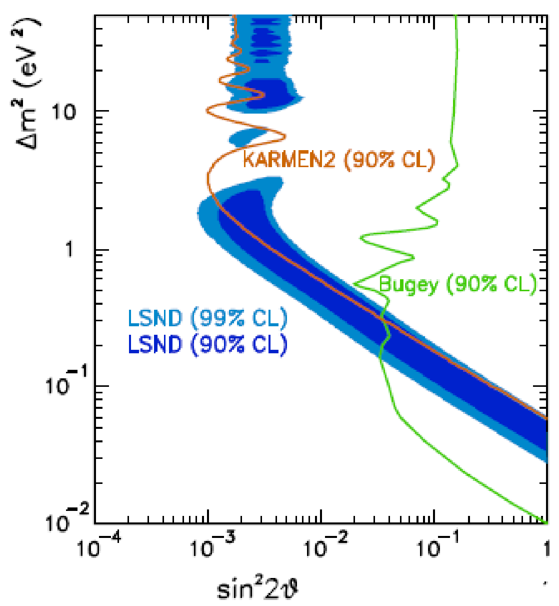


anti-ν_μ → anti-ν_e

87.9 ± 22.4 ± 6.0 events

Excess 3.8σ



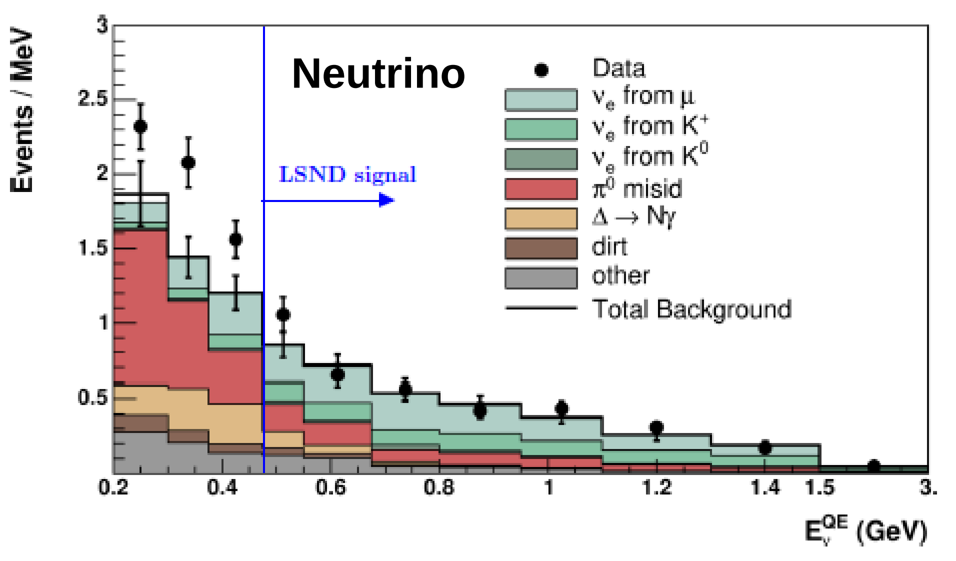


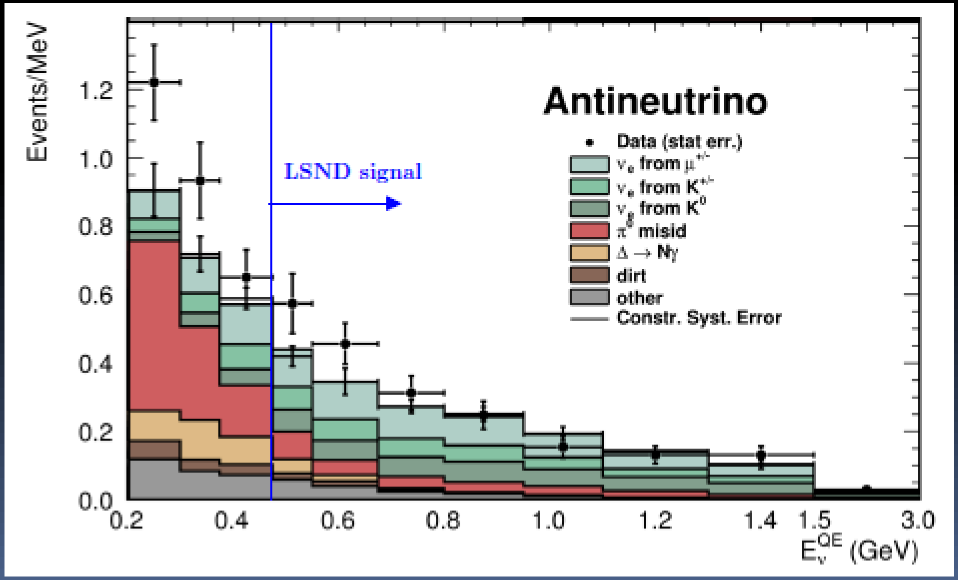
$$
\begin{aligned}
P(\bar{\nu}_\mu \to \bar{\nu}_e) &= \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\ \Delta m^2}{E}\right) \\
&= 0.245 \pm 0.067 \pm 0.045\ \%
\end{aligned}
$$

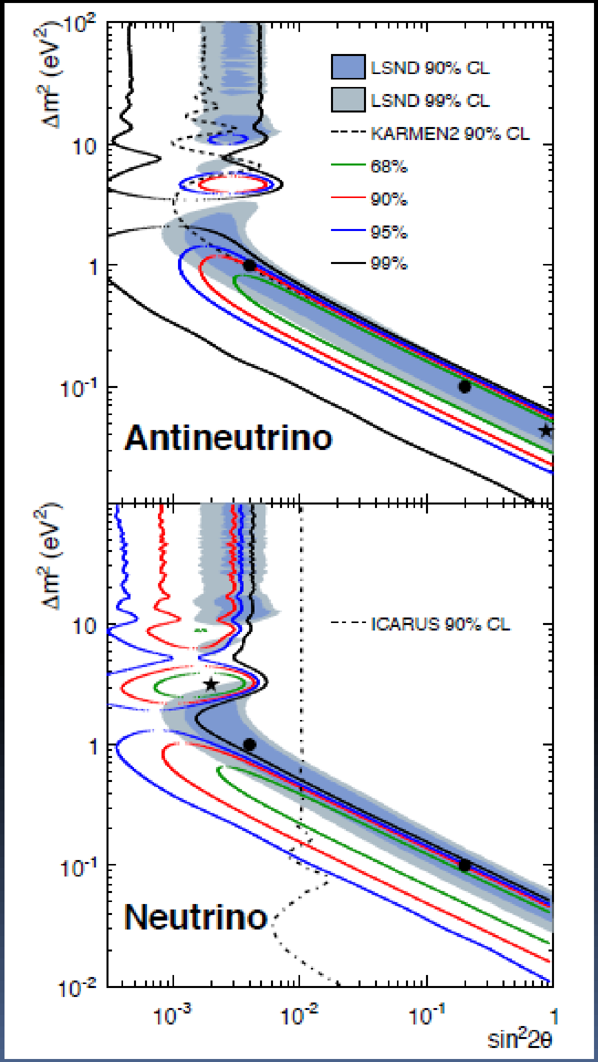
$$0.2 \le \Delta m^2 \le 1\ \text{эВ}^2 \qquad 2\times 10^{-3} \le \sin^2 2\theta \le 4\times 10^{-2}$$

MiniBooNe

$\nu_\mu \to \nu_e$
anti-$\nu_\mu \to$ anti-ν_e
L≈ 540 m   Eν = 0.2-3 GeV

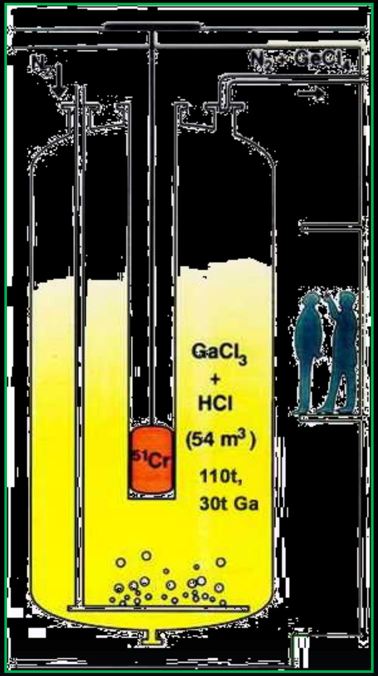




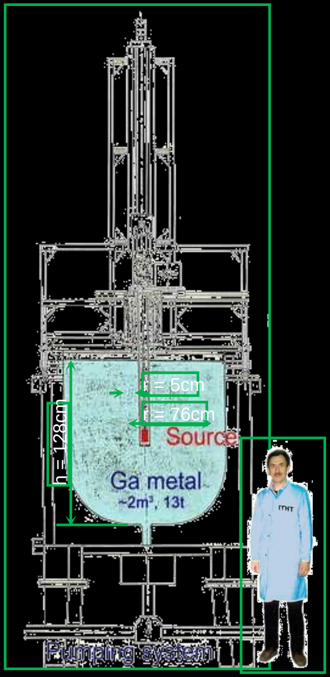


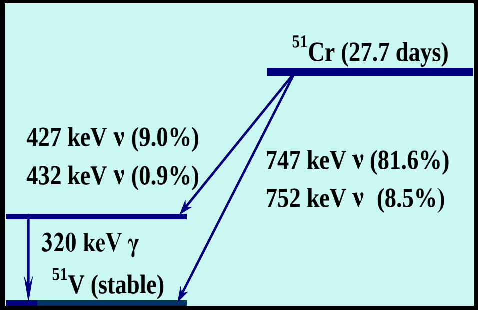
Gallium anomaly

GALLEX



SAGE





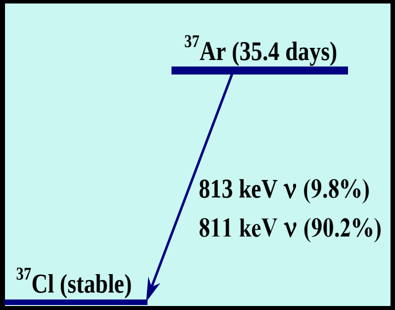
^{51}Cr (27.7 days)

427 keV ν (9.0%)
432 keV ν (0.9%)

747 keV ν (81.6%)
752 keV ν (8.5%)

320 keV γ

^{51}V (stable)



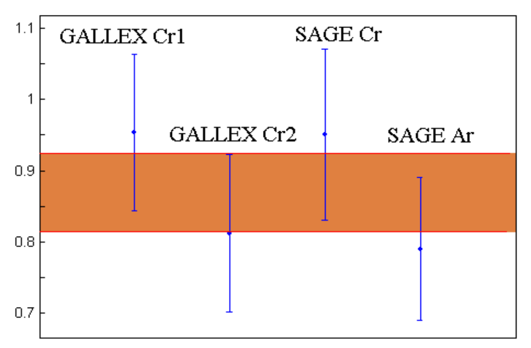
^{37}Ar (35.4 days)

813 keV ν (9.8%)
811 keV ν (90.2%)

^{37}Cl (stable)

Detection process: $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

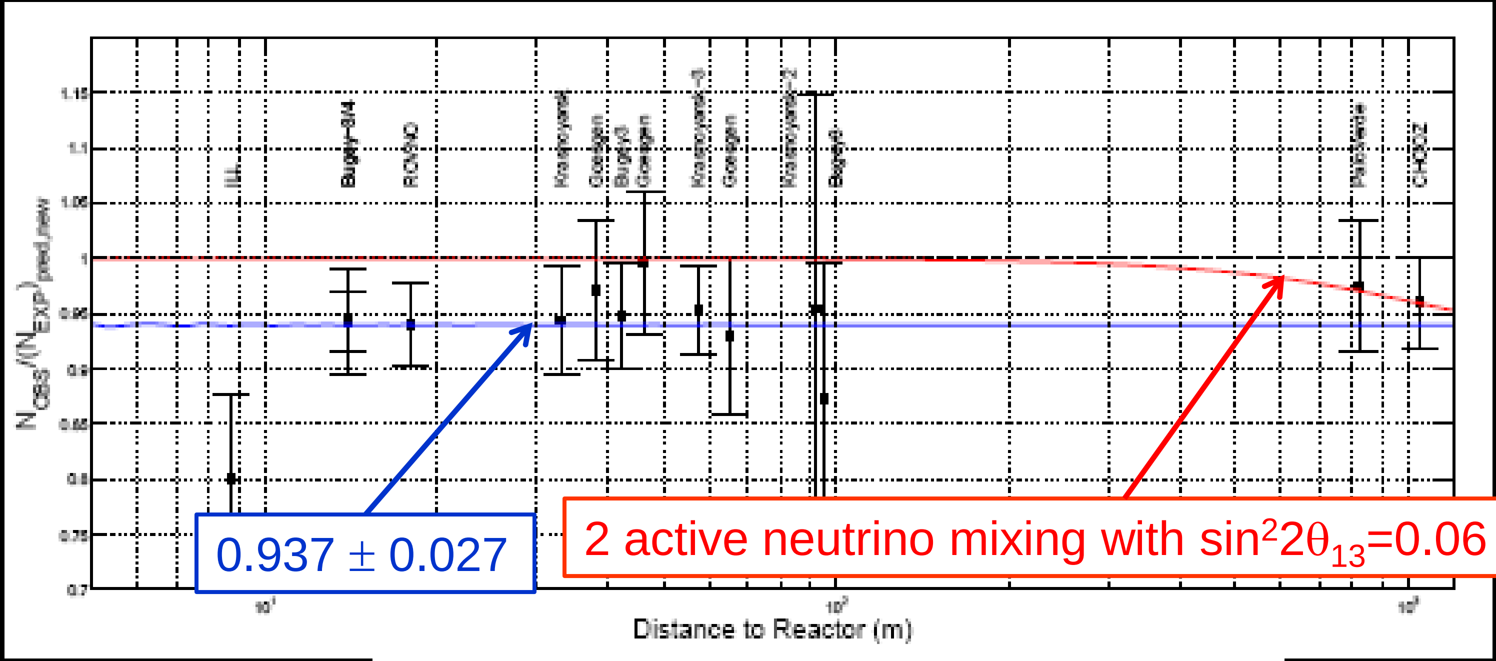
	GALLEX m(Ga)=30 t		SAGE m(Ga)=13 t	
Source	^{51}Cr -1	^{51}Cr -2	^{51}Cr	^{37}Ar
Intensity (Mci)	1.714	1.868	0.517	0.409
R = (p_{exp}/p_{theory})	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.10
R_{comb}	0.88 ± 0.08		0.86 ± 0.08	



$$R = p_{exp}/p_{theory} = 0.87 \pm 0.05$$

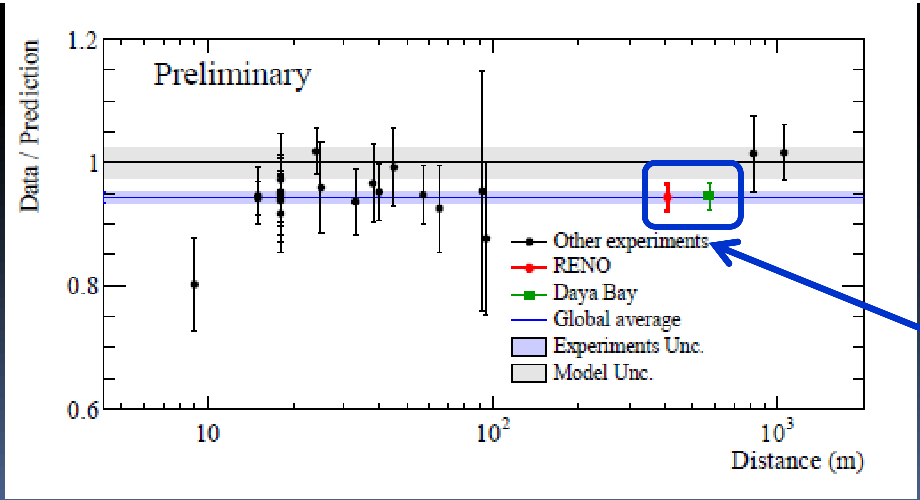
Reactor anomaly

anti-$\nu_e \rightarrow$ anti-ν_e



0.937 ± 0.027

2 active neutrino mixing with $\sin^2 2\theta_{13}=0.06$

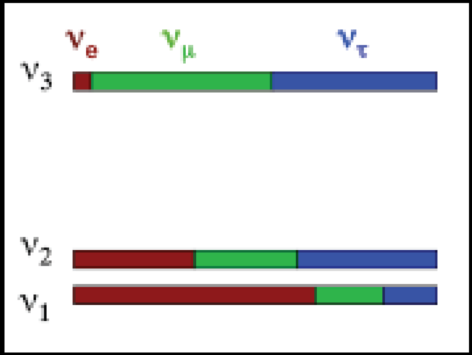


S.Gariazzo et al
arXiv:1703.08860

Daya Bay and RENO

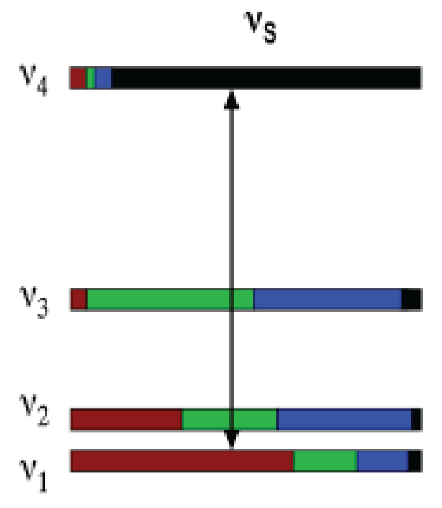
Sterile neutrino?

3ν



?

3ν + 1s



$\Delta m^2_{14} \sim 1\ \mathrm{eV}^2$

PNMS matrix

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix} = \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

$$|U_{\mu4}|^2 = \sin^2\theta_{24}\cdot\cos^2\theta_{14}$$

$$|U_{\tau4}|^2 = \sin^2\theta_{34}\cdot\cos^2\theta_{24}\cdot\cos^2\theta_{14}$$

$$P_{\nu_e\to\nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

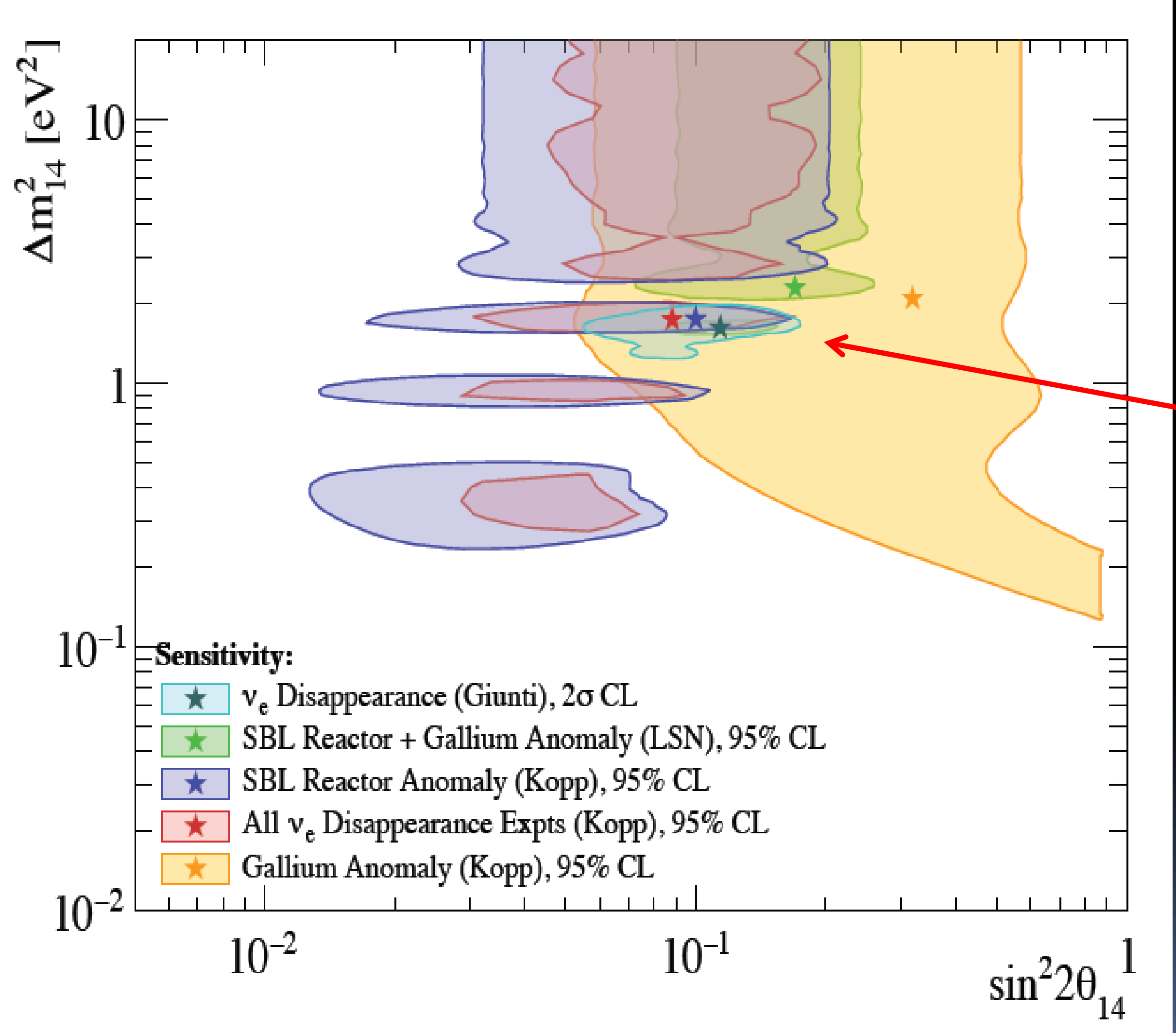
$$P_{\nu_\mu\to\nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$$

$$P_{\nu_\mu\to\nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$

ν_e and anti-ν_e disappearance

arXiv:1512.02202

Global fit of reactor and Gallium data

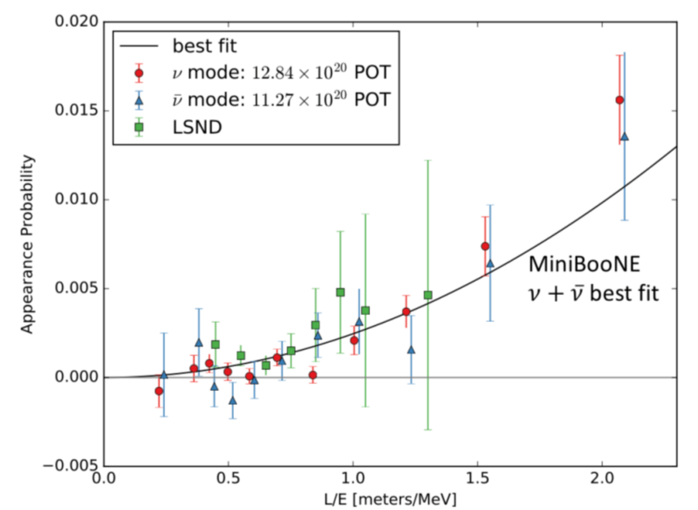


$\Delta m^2 \approx 2$ eV^2

$\sin^2 2\theta \sim 0.1$

New MiniBooNe result

arXiv:1805.12028



MiniBooNe doubled

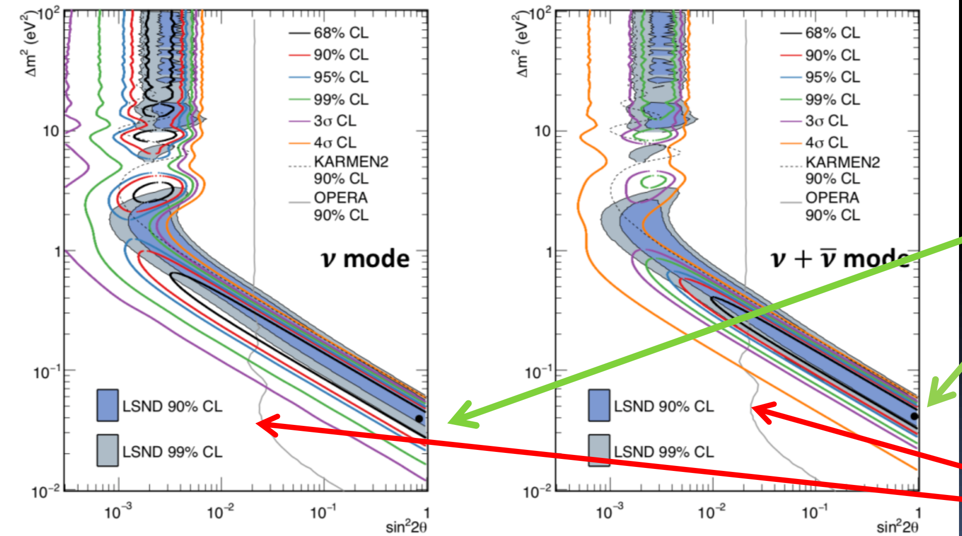
ν data since 2012

ν 12.84×10^{20} POT

anti-ν 11.27×10^{20} POT

neutrino +antineutrino total excess

460.5 ± 95.8 events (4.8σ)



$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

Best fit point:

Δm^2_{41} = 0.041 eV^2

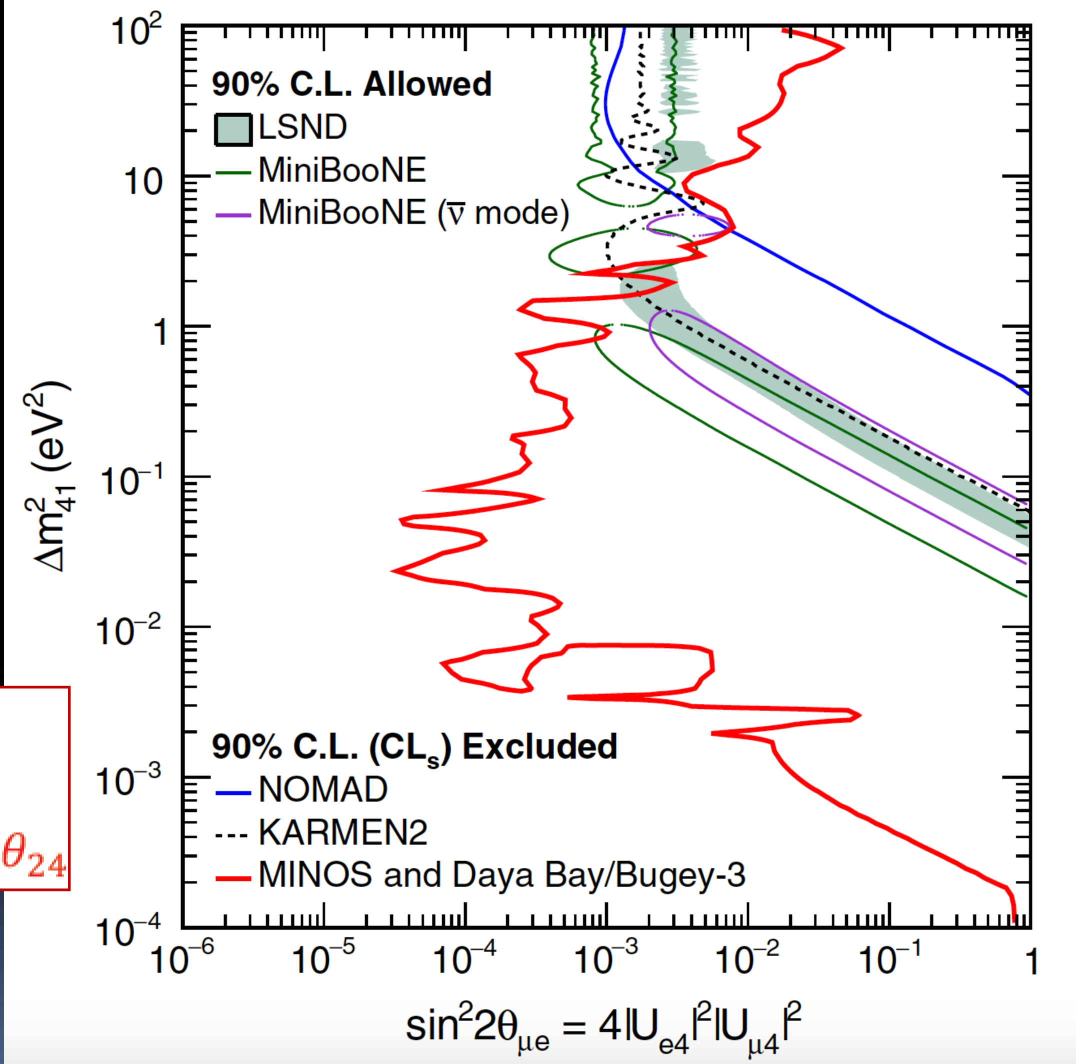
$\sin^2 2\theta$ = 0.958

Excluded by OPERA and ICARUS

Sterile ν's: Daya Bay + MINOS+ Bugey-3

PRL117 (2016) 151801

- Daya Bay data
  - Constrains Δm^2_{41}(mainly 10^{-4} to 10^{-1} eV^2) and $\sin^2 2\theta_{14}$
- Bugey-3 data
  - constrains Δm^2_{41} (mainly 10^{-1} to 10 eV^2) and $\sin^2 2\theta_{14}$
- MINOS data
  - Constrains Δm^2_{41} (mainly 10^{-3} to 10^2 eV^2) and $\sin^2 \theta_{24}$



- Combined all three
  - Constrains Δm^2_{41} and $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \cdot \sin^2 \theta_{24}$

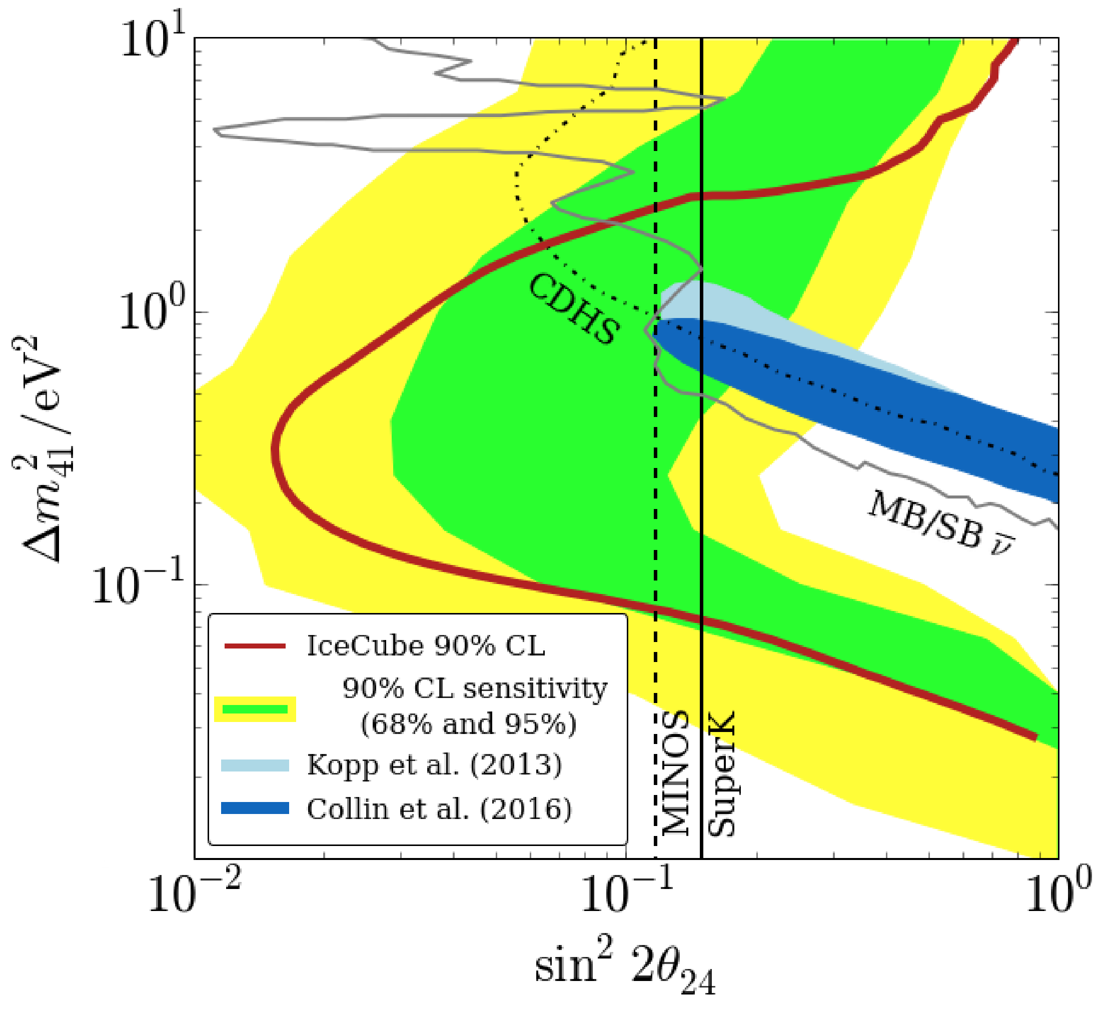
Sterile ν's: IceCube

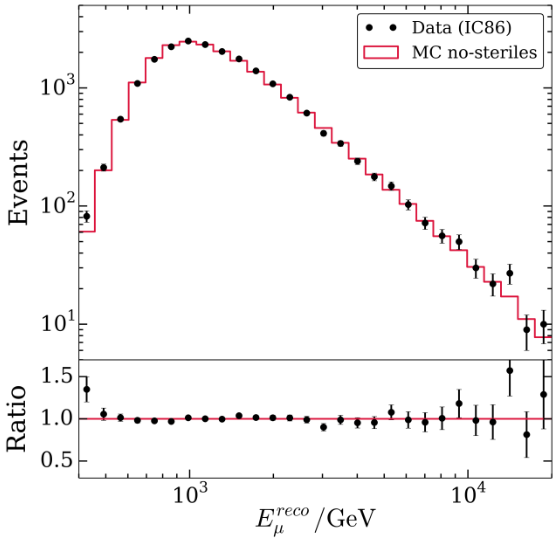
PRL 117 (2016) 071801

Eν = 320 GeV – 20 TeV

sterile neutrinos produce distortions of νμ + anti-νμ flux (energy and angle) in the range
0.01 ≤ Δm² ≤ 10 eV²

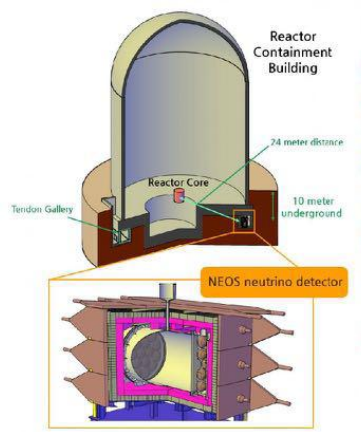
- 1 year of data
- statistics limited





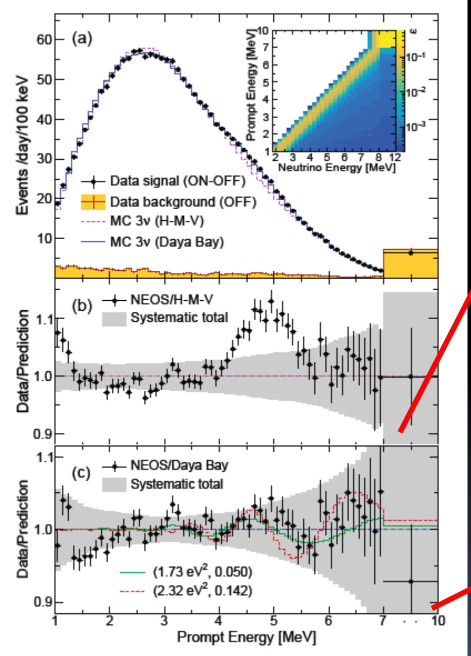
Result compatible with no-sterile hypothesis

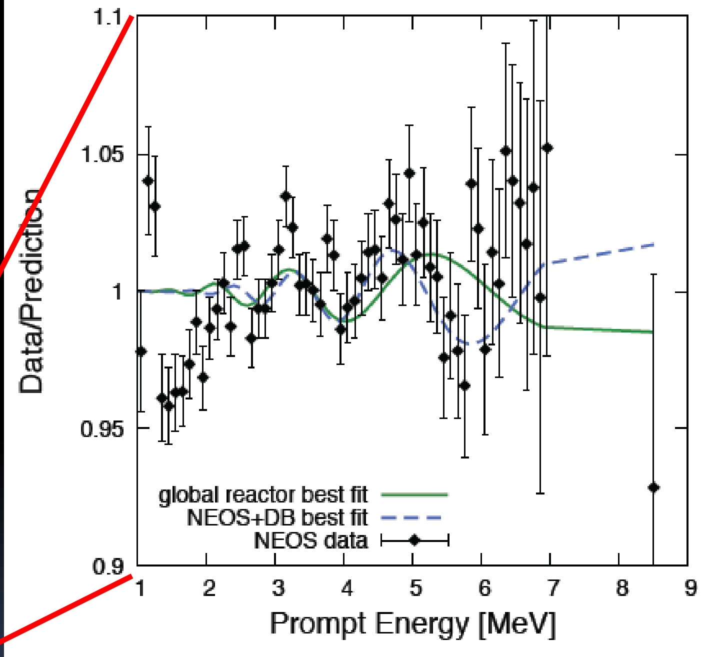
NEOS: reactor anti-ν disappearance

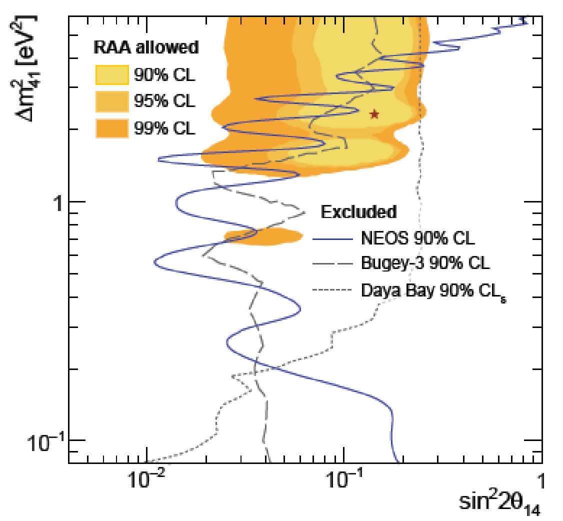


Korea, Reactor 2.8 GW
Core: ∅3.1 m h=3.8 m
Detector 1t LS + Gd, 24 m from reactor core
S/N ~ 22

PRL 118 (2017) 121802







No evidence for sterile neutrino with mass ~ 1 eV

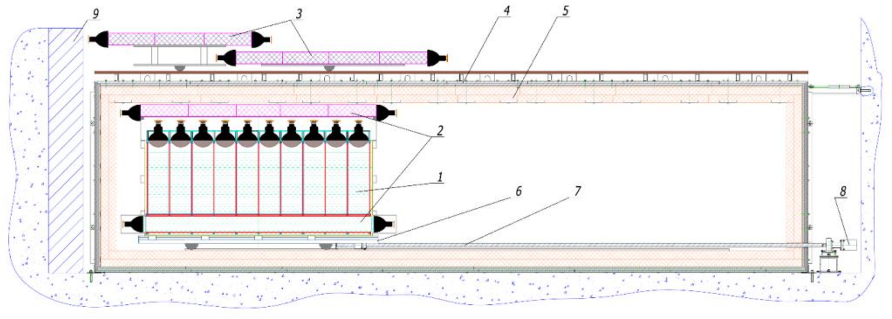
Neutrino-4

arXiv:1708.00421

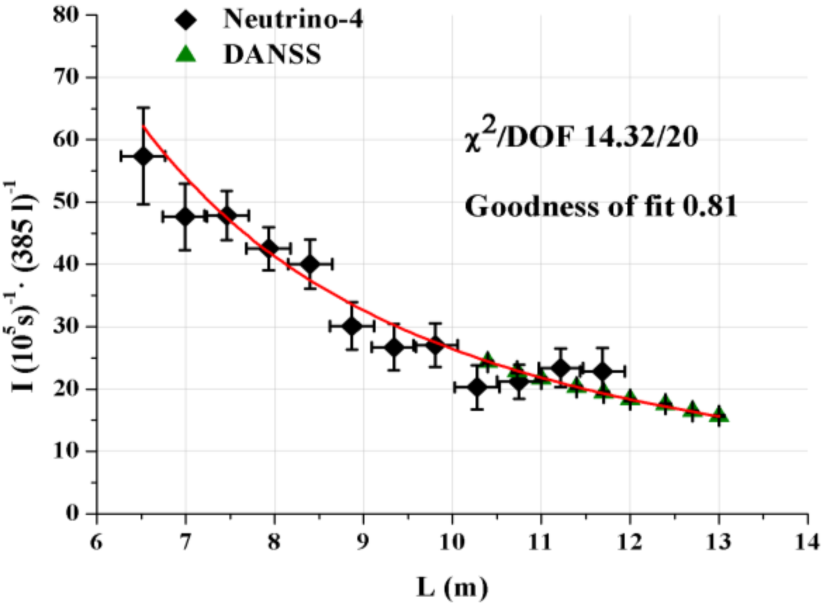
SM-3 reactor, Dimitrovgrad

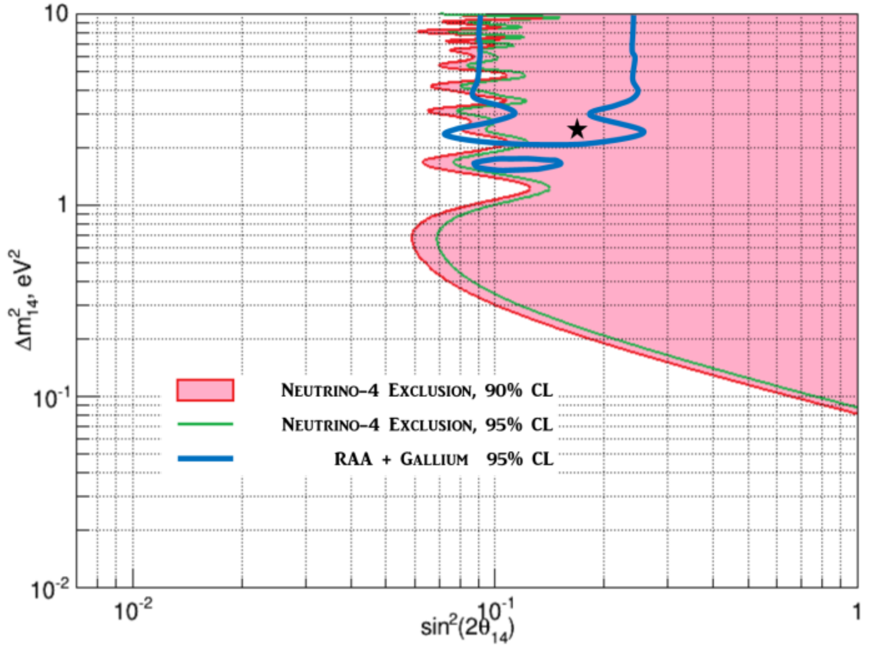
Detector on Earth surface
Signal/background = 0.6

Detector



~ 6.5 – 11.5 m from active zone



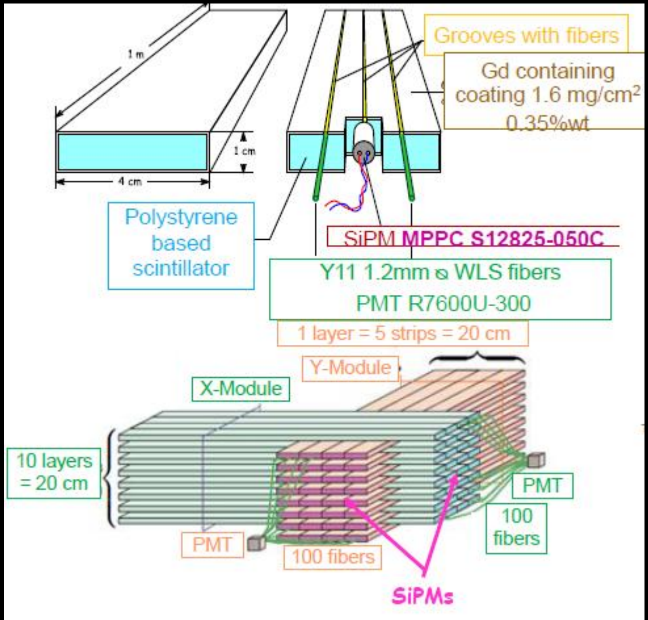


Best fit point of Reactor and Gallium anomalies excluded at 95% CL

DANSS experiment

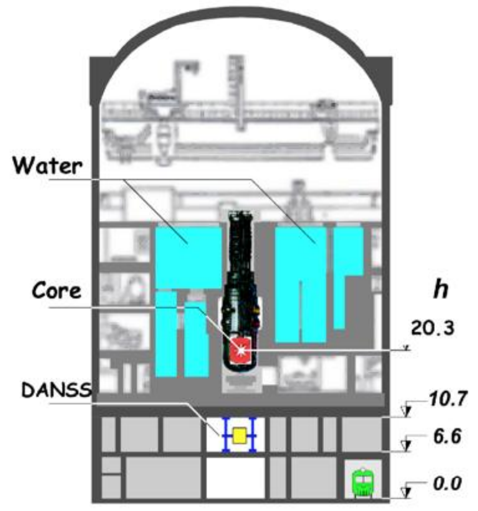
3.1 GW_{th} Kalinin Power Plant

Detector configuration



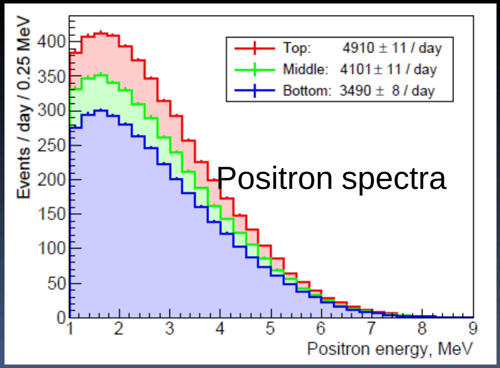
arXiv:1804.0404

- **2500 scintillator strips with Gd containing coating for neutron capture**
- **Light collection with 3 WLS fibers**
- **Central fiber read out with individual SiPM**
- **Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module**

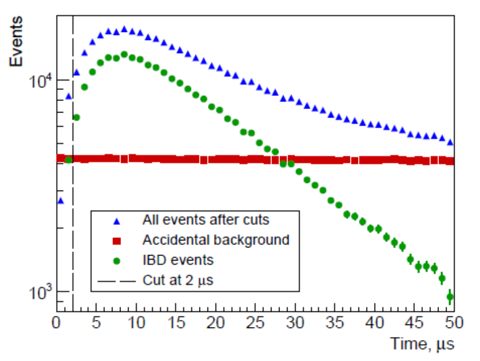


Distance from the reactor core 10.7-12.7 m

5000 anti-ν_e detected per day with < 3% cosmic background



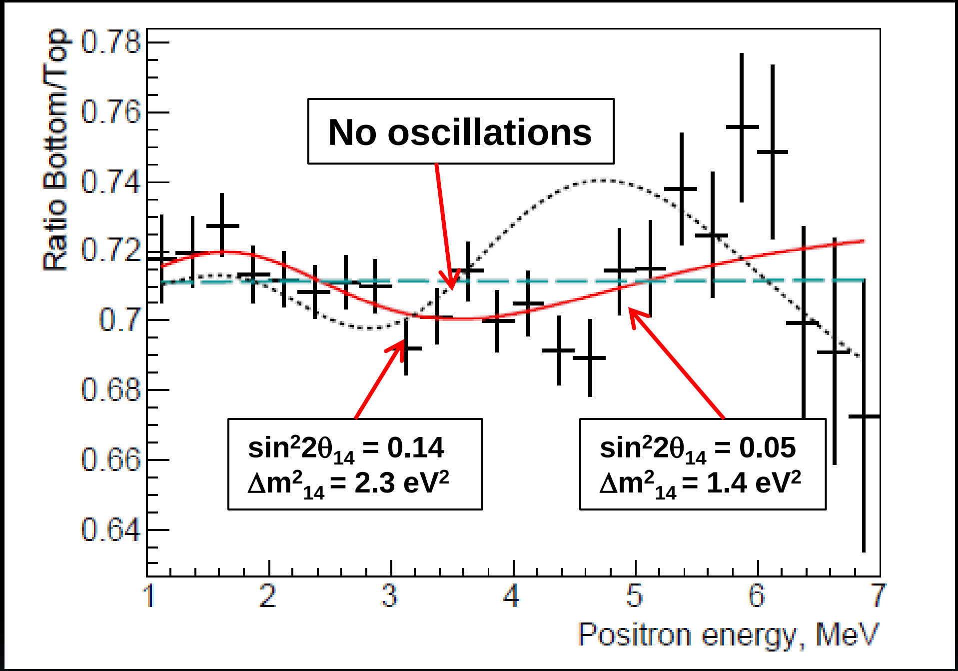
Positron spectra



DANSS result

arXiv:1804.0404

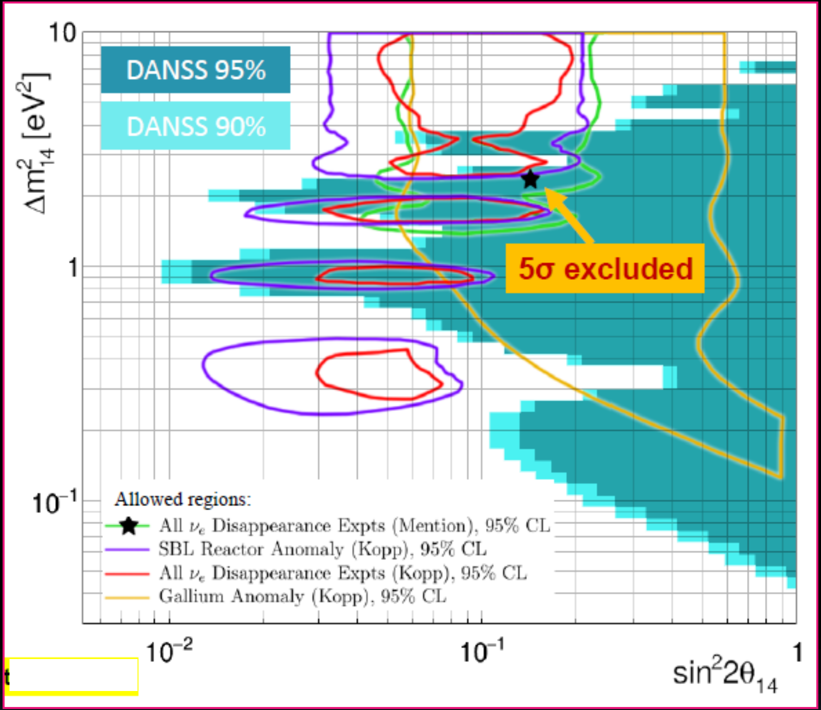
Result is based on 663×10^3 events



No oscillations

$\sin^2 2\theta_{14} = 0.14$
$\Delta m^2_{14} = 2.3$ eV^2

$\sin^2 2\theta_{14} = 0.05$
$\Delta m^2_{14} = 1.4$ eV^2

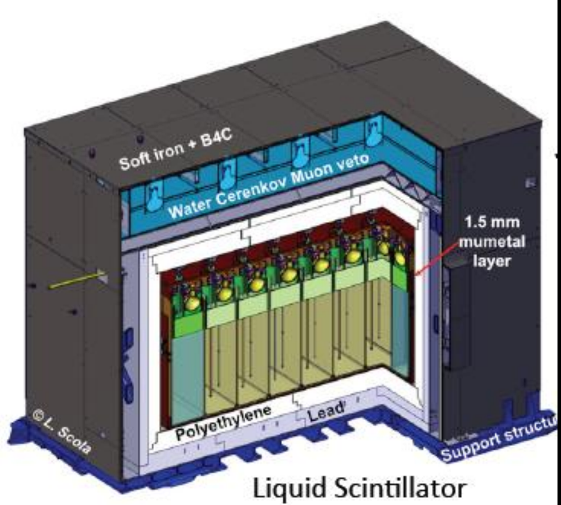


5σ excluded

The Reactor Anomaly best fit point
($\sin^2 2\theta_{14} = 0.14$ $\Delta m^2_{14} = 2.3$ eV^2) is excluded at $> 5\sigma$ CL

STEREO experiment

ILL, Grenoble, France,
58.3 MW_{th}
compact core ∅40x80 cm

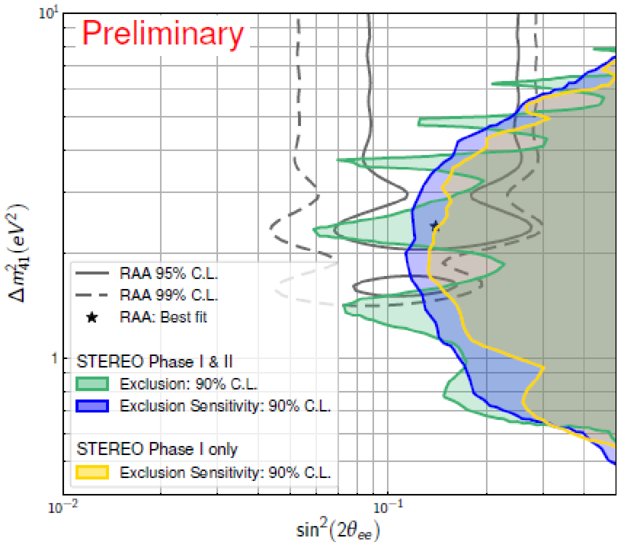


L.Bernard, ICHEP2018

- Detector 6 identical cells
- Gd loaded (0.2% in mass)
- $V_{tot} = 2.2x0.9x0.9\ m^3$
- 15 mwe overburden
- Neutrino rate 396/day
- First result based on 65.8 days of data taking

The **first results using ratios of cells compatible with no oscillation**, rejects the best fit of the Reactor Antineutrino Anomaly at 98.8% C.L.

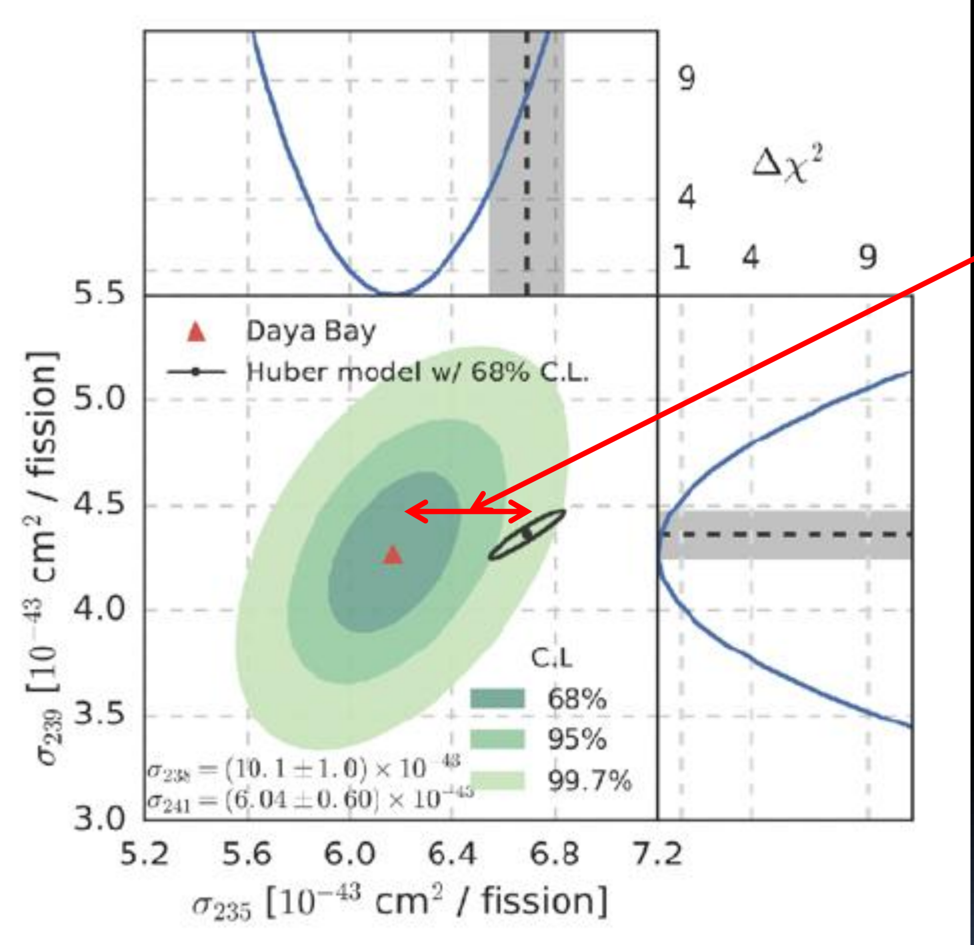
Phase-I + Phase-II
combined results
(66+47) days reactor-ON
$(396 \pm 4)\ \bar{\nu}_e\ \text{day}^{-1}$



Preliminary result is compatible with no oscillation. The best fit of the Reactor Anomaly is rejected at 98%.

Daya Bay: anti-neutrino flux

PRL 118 (2017) 251801



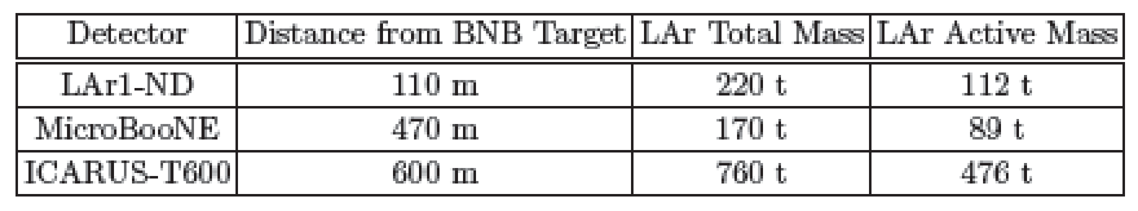
This discrepancy gives an overestimation of predicted antineutrino flux by 7.8%.

U-235 is a possible source of the Reactor Anomaly?

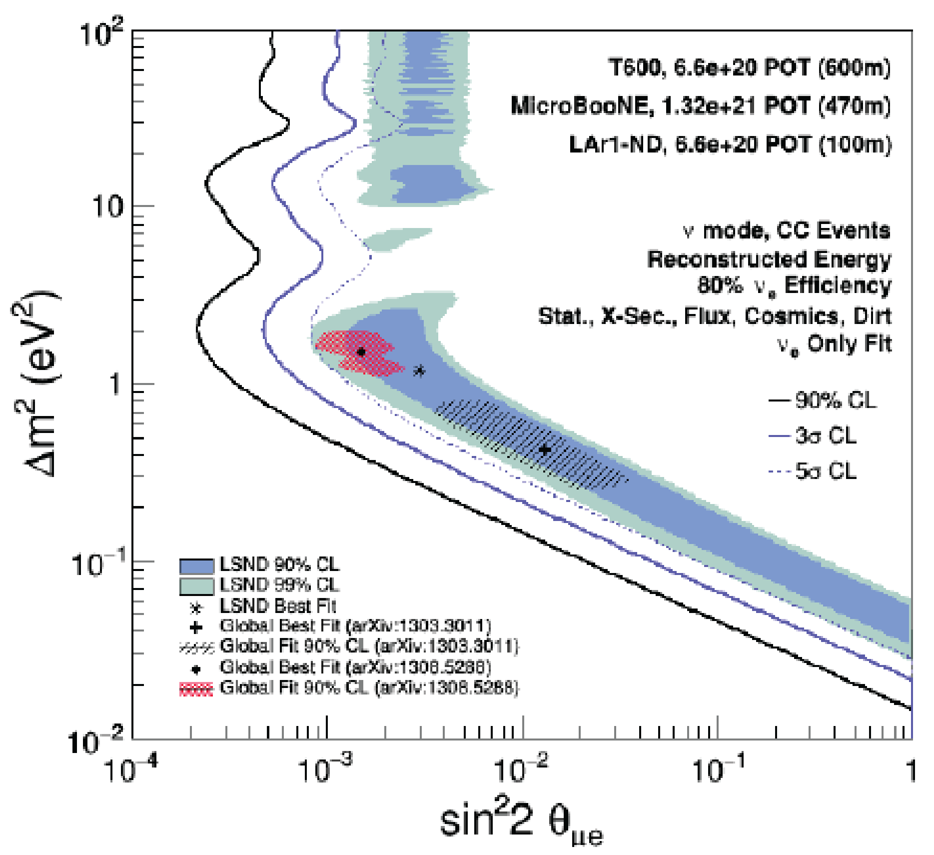
Short baseline experiments at U-enriched reactors are needed

FNAL: Short Baseline Neutrino program

arXiv:1503.01520



Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t



Hunting for light sterile neutrinos

Accelerator

MiniBooNe
MINOS+
SBN at FNAL

Reactor *(running or under construction)*

Daya Bay
DANSS
Neutrino-4
NEOS
STEREO
Solid
PROSPECT
NuLat

Neutrino sources

BEST

Atmospheric neutrinos

SuperKamiokande
IceCube

Conclusion

Current LBL experiments T2K + NOvA
main goals: CP violation (3σ), Mass Hierarchy, θ_{23}
T2K: first hint of CP violation in lepton sector

Next generation experiments: discovery/measurement of CP violation, determination of Mass Hierarchy

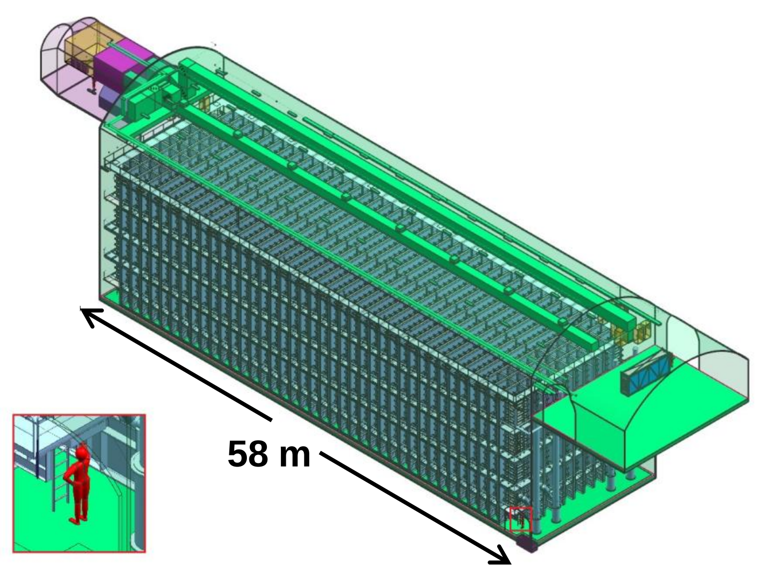
JUNO	**(MH)**	***under construction***
DUNE	**(CP, MH)**	***approved***
HyperK and T2HK	**(CP)**	***approved, seed funding***

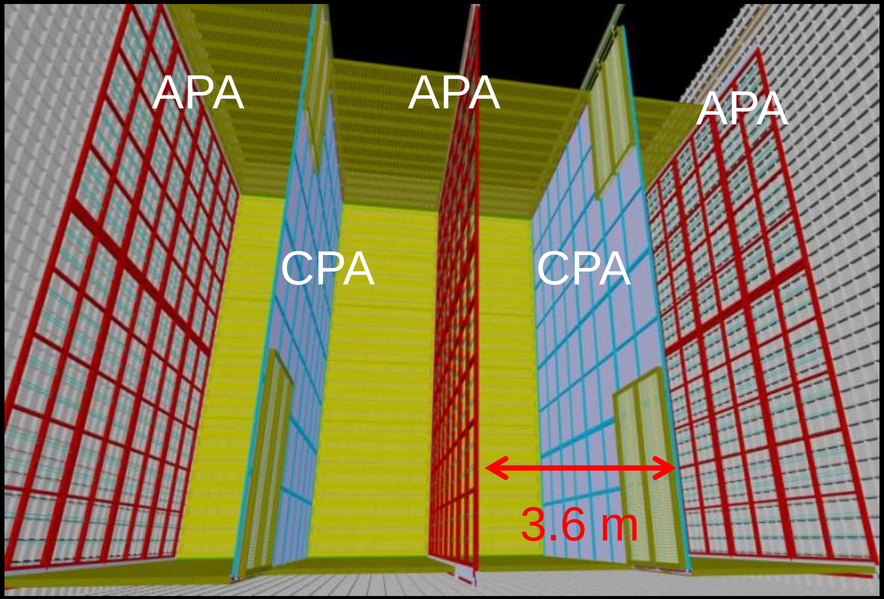
Light sterile neutrinos:
- no positive signal from running experiments
- crucial tests are coming

Thank you for attention!

Backup slides

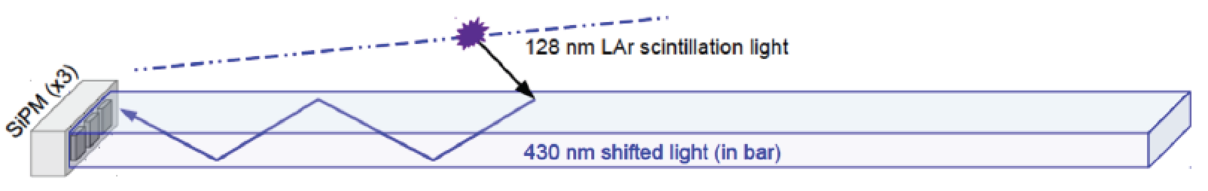
Single-phase LAr TPC





1st 10 kt module of DUNE - single-phase TPC
6m x 2.3 m anode and cathode planes 3.6 m spacing
Photon detectors – light guides + SiPMs embedded in APAs

J.Insler, talk at LLWI2017

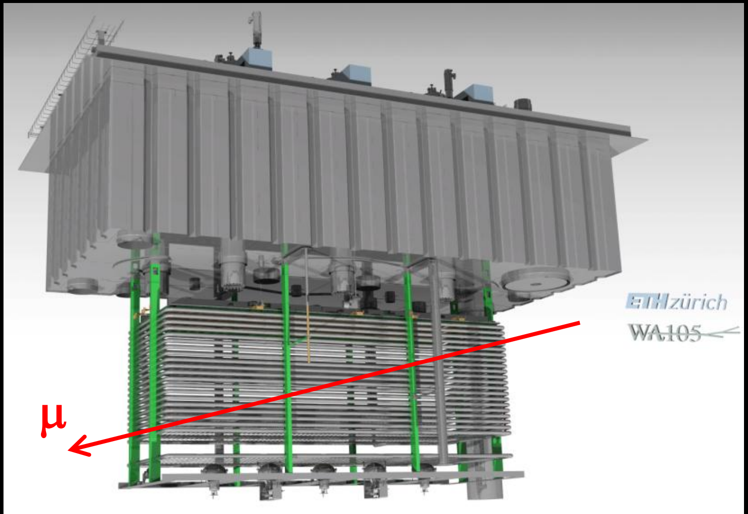


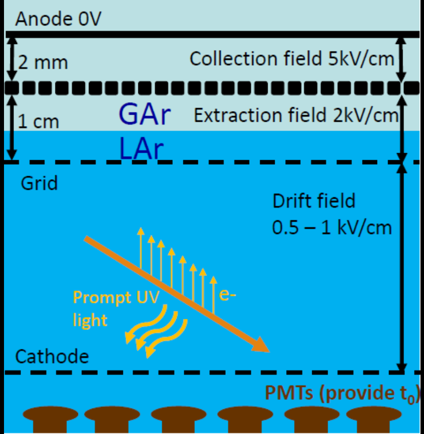
LAr detectors at CERN Neutrino Platform

NP02: WA105
(DP demonstrator + ProtoDUNE DP)

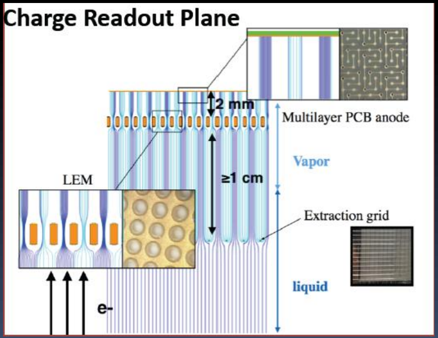
S.Murthy, talk at TPC-2016

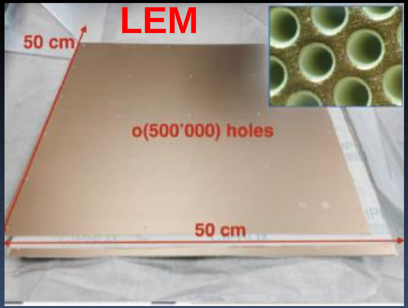
Demonstrator: 3x1x1 m^3 – 5 tons

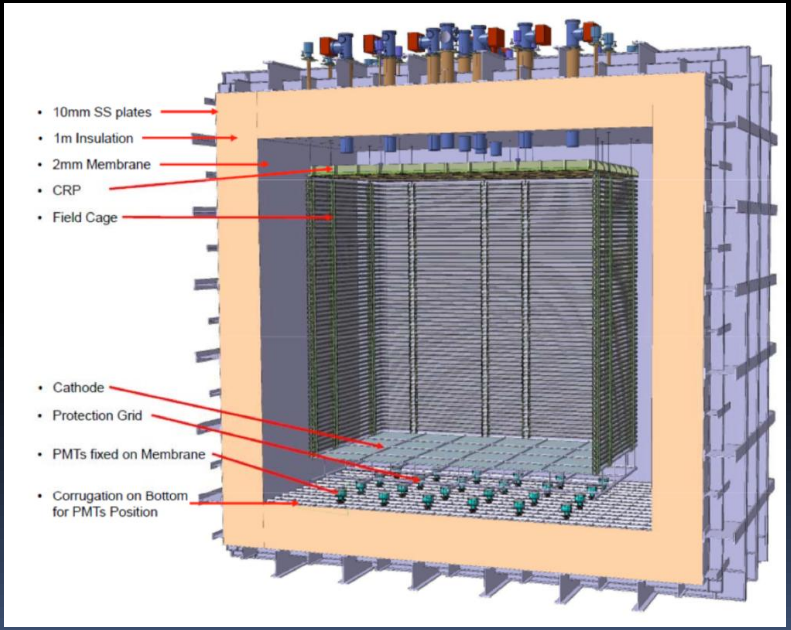




ProtoDUNE DP:
6x6x6 m^3
300 tons active mass







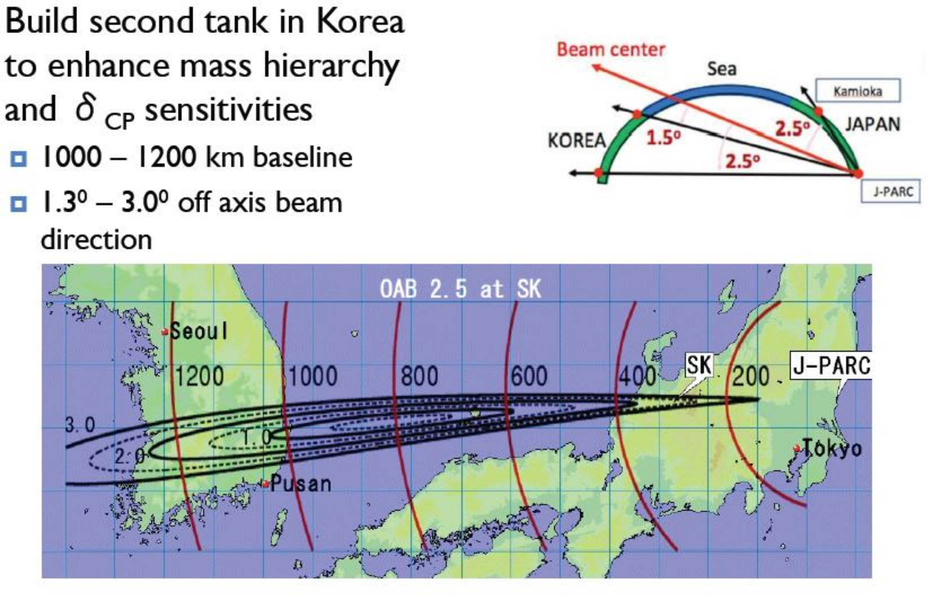
Cosmic data taking gas begun

Measurements with test beam in 2018

T2HKK

Second tank in Korea

arXiv:1611.06118



Build second tank in Korea to enhance mass hierarchy and δ_{CP} sensitivities

- 1000 – 1200 km baseline
- 1.3° – 3.0° off axis beam direction

Neutrino and antineutrino spectra in T2HKK cover 1st and 2nd oscillation maximum

- A_{CP} ~3 times larger in 2nd maximum
- Sensitivity to MH