

Study of oscillations with accelerator and reactor neutrinos

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QUARKS2018, Valdai, Russia, 29 May 2018

OUTLINE

- **Neutrino oscillations**
 - **running accelerator and reactor experiments**
 - **future projects**

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



ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

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

T2K
MINOS

Daya Bay, RENO
Double Chooz

Solar experiments, SuperK
KamLAND

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

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

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

$$|\Delta m_{32}^2| \cong |\Delta m_{31}^2| =$$
$$|\Delta m_{atm}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

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

$$\Delta m_{21}^2 = \Delta m_{sol}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

two independent Δm^2



Main goals of oscillation experiments

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

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

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

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

neutrinos

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

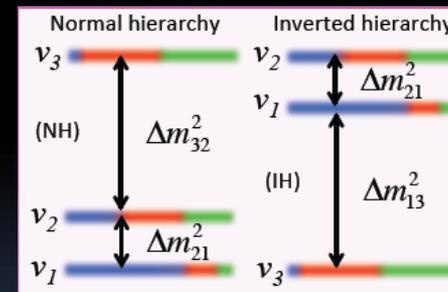
quarks

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

Quark sector $J_{CP} \approx 3 \times 10^{-5}$

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

- Neutrino mass hierarchy



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

Neutrino cross sections

- Sterile neutrinos

Current experiments



about 500 members
59 institutions
from 11 countries

LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT



Super-K

Toyama
Kamioka Mine



JPARC
Tokai



JAPAN

Tokyo



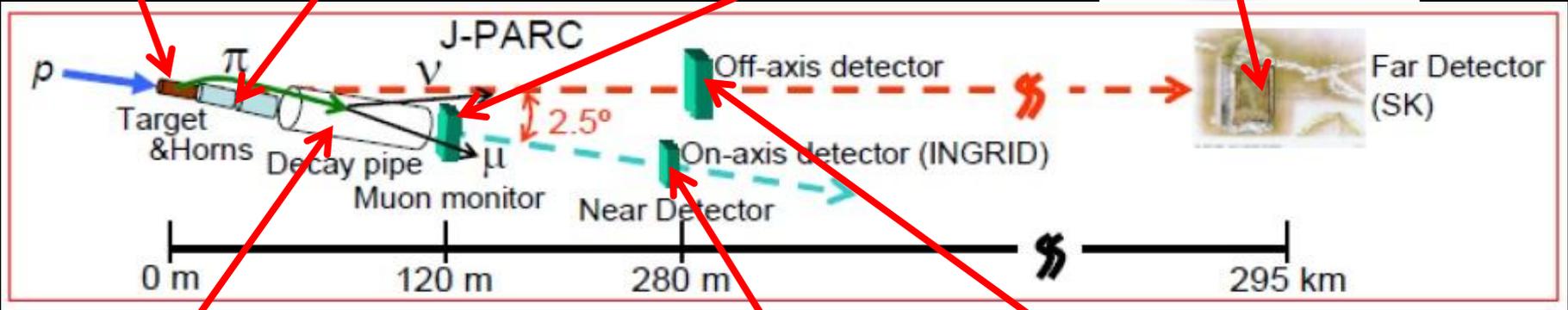
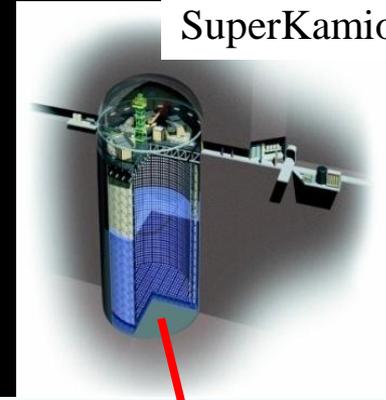
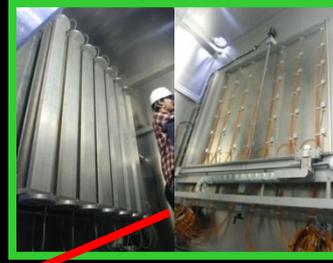
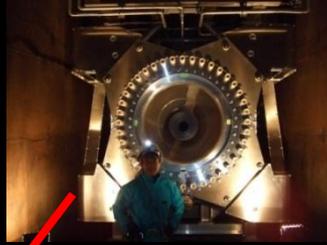
Tokyo/Narita Airport



T2K experiment

Data taking since 2010

Far neutrino detector
SuperKamiokande

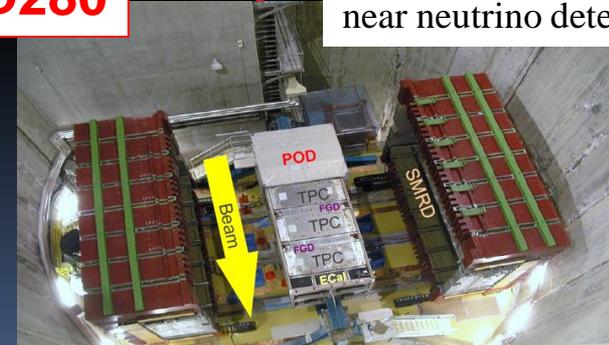
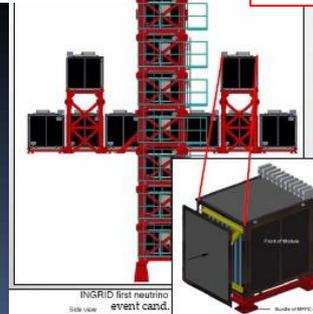
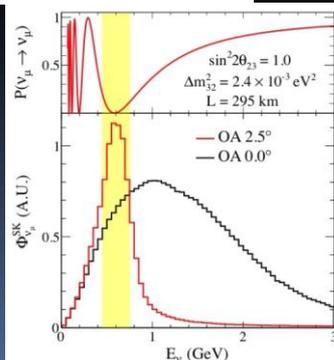


Off-axis neutrino beam

Neutrino monitor
INGRID

ND280

Off-axis near neutrino detector



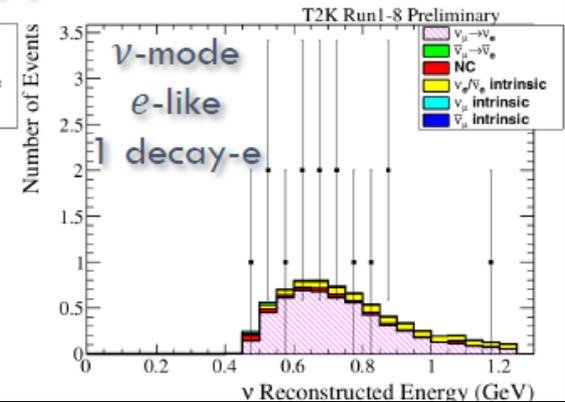
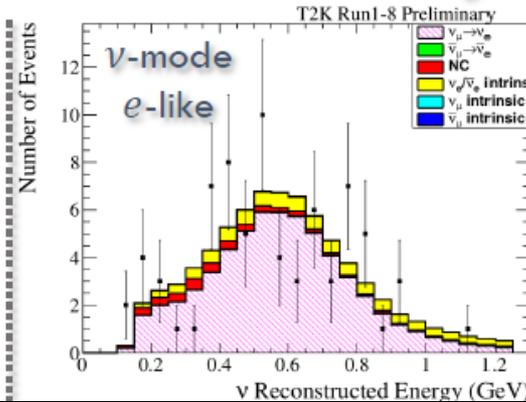
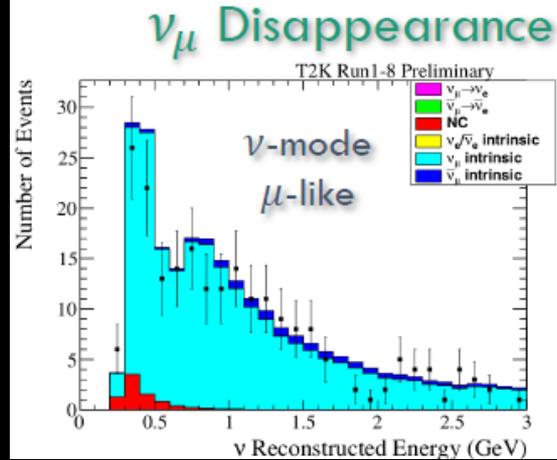


T2K results (I)

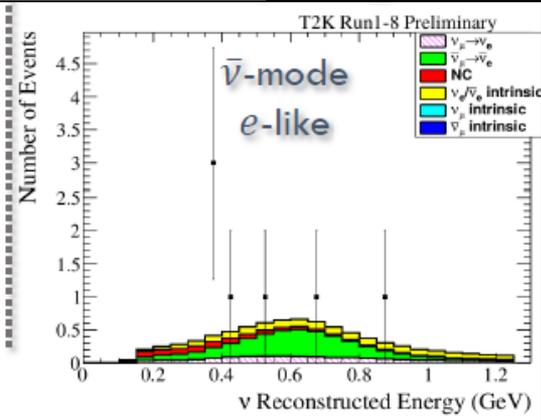
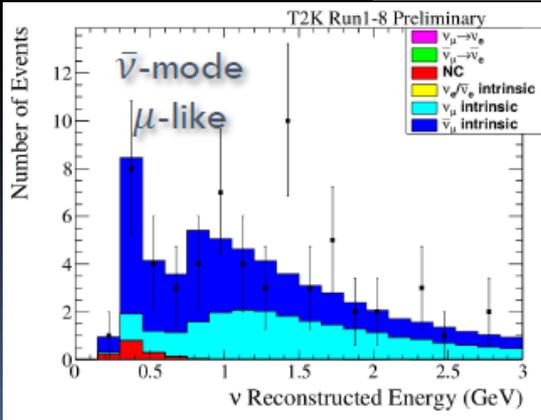
Neutrino mode (14.7×10^{20} POT)

Antineutrino mode (7.6×10^{20} POT)

Neutrino mode



Antineutrino mode



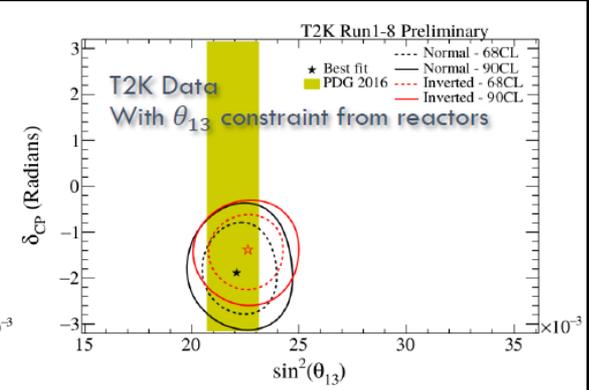
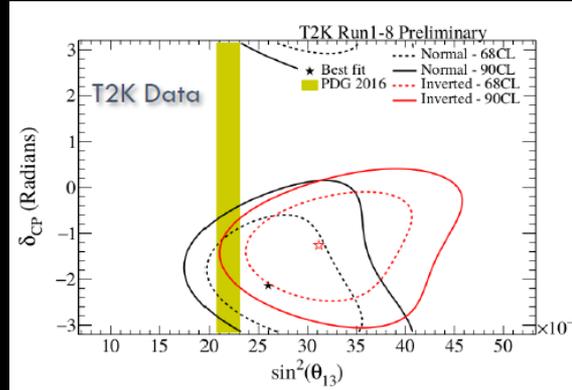
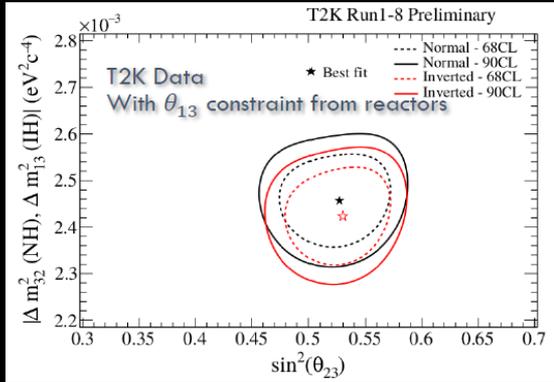
Events

	Observed events		
	μ -like	e -like	e -like 1 dcy-e
ν -mode	240	74	15
$\bar{\nu}$ -mode	68	7	

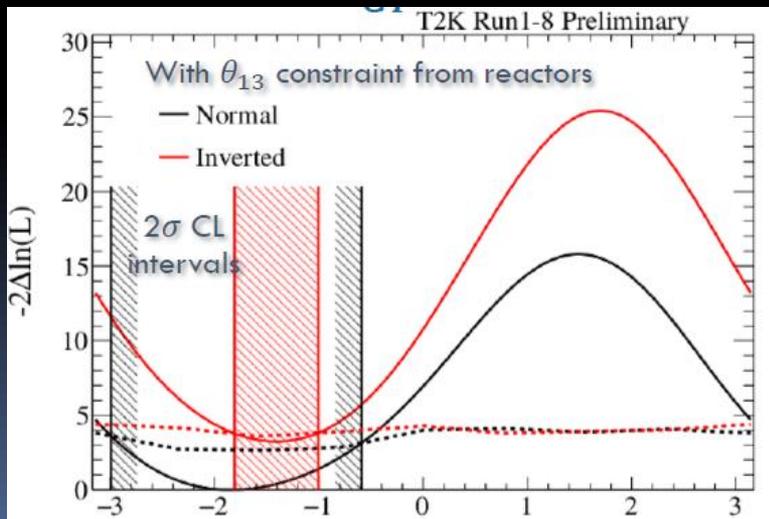


T2K results (II)

M.Khabibullin, QUARKS 2018



- CP-conservation hypothesis ($\sin\delta_{CP} = 0, \pi$) excluded at 2σ level
 - Confidence intervals, rad (90% CL): $[-2.98 - 0.60]$ (NH) $[-1.54 - 1.19]$ (IH)
- T2K data favour $\delta_{CP} \sim -\pi/2$ and normal hierarchy**



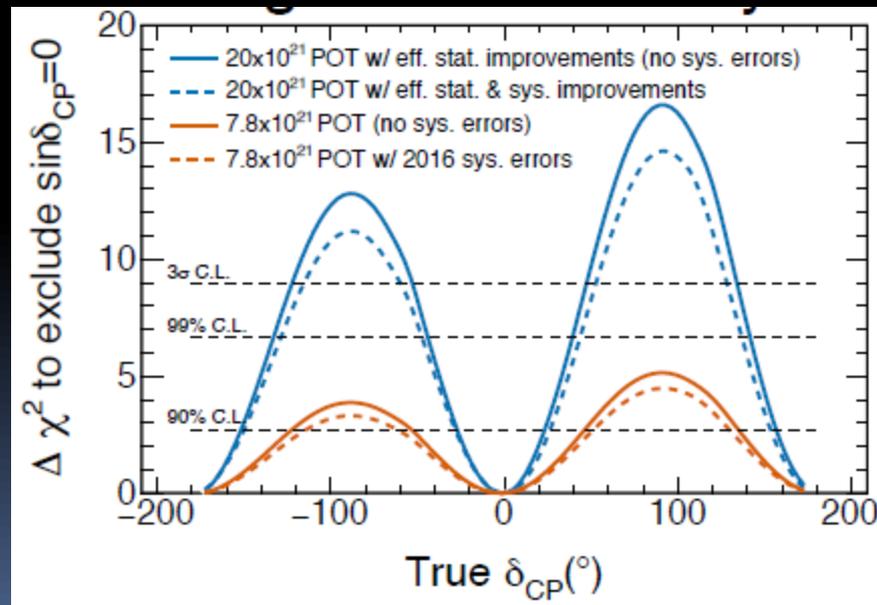
Best fit
 $\delta_{cp} = -1.83$ rad
 for NH



Future plans

T2K expected to accumulate **7.8×10^{21} POT** around 2021
(now **3×10^{21} POT**)

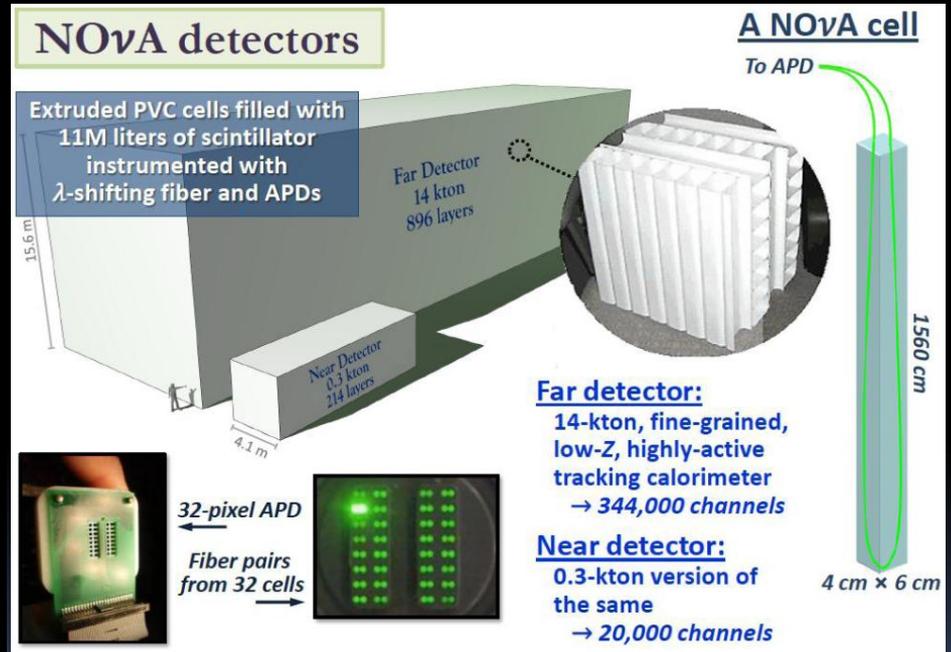
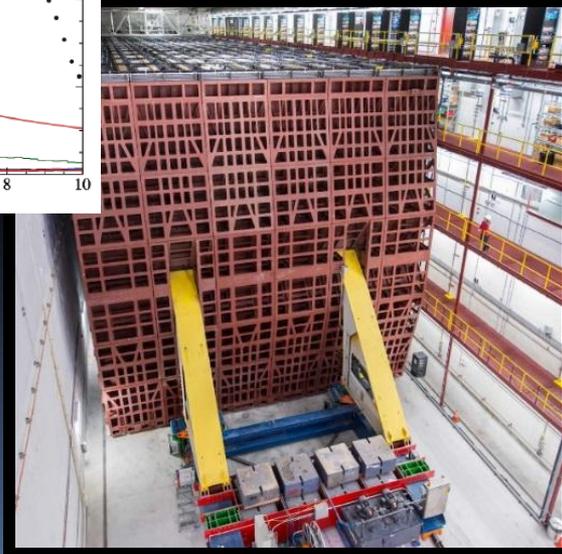
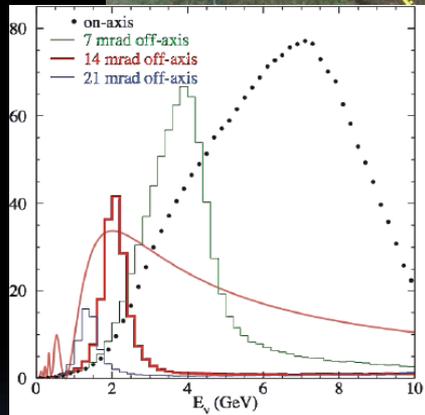
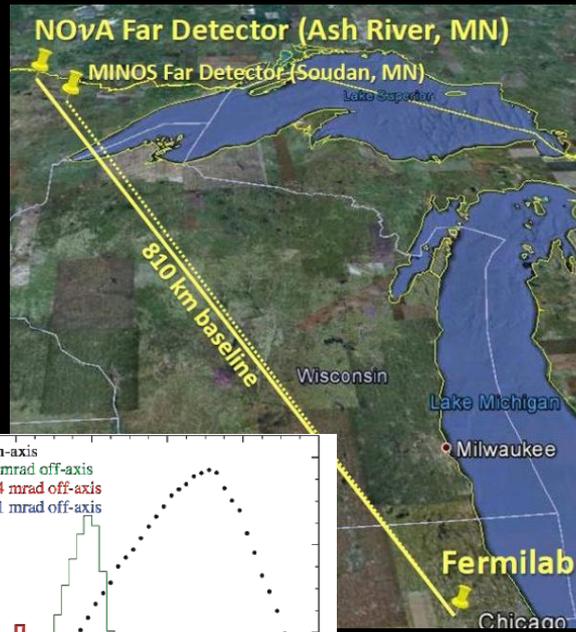
- Upgrade of near detectors to improve systematic uncertainties **18% (2011) \rightarrow 9% (2014) \rightarrow 6% (2016) \rightarrow goal 4% (2020)**
- Plan to increase the beam intensity up to 1 MW in 2021
- Beam power up to 1.3 MW in \sim 2026
- T2K-II: proposed extension up to 2026 for **20×10^{21} POT**
 3σ sensitivity to CP violation for $\delta_{CP} \sim -\pi/2$





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 $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations

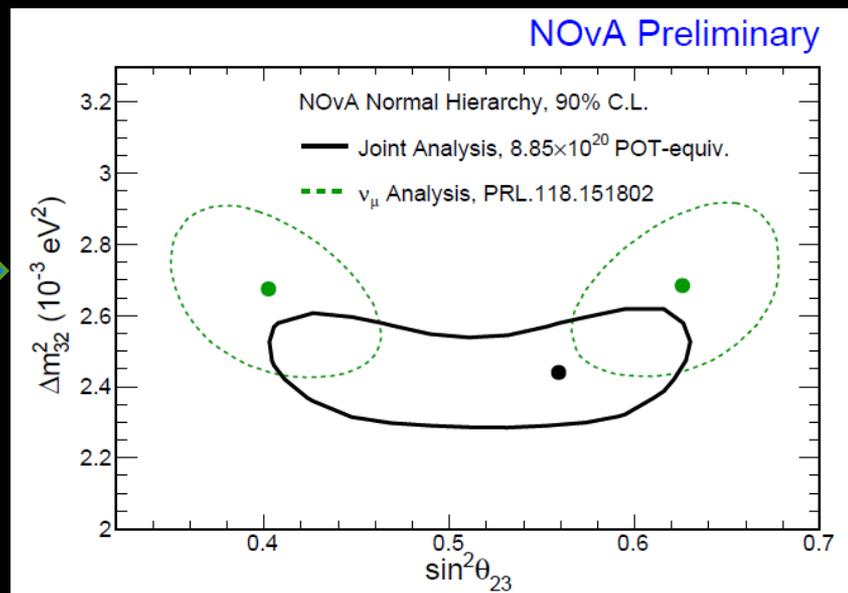
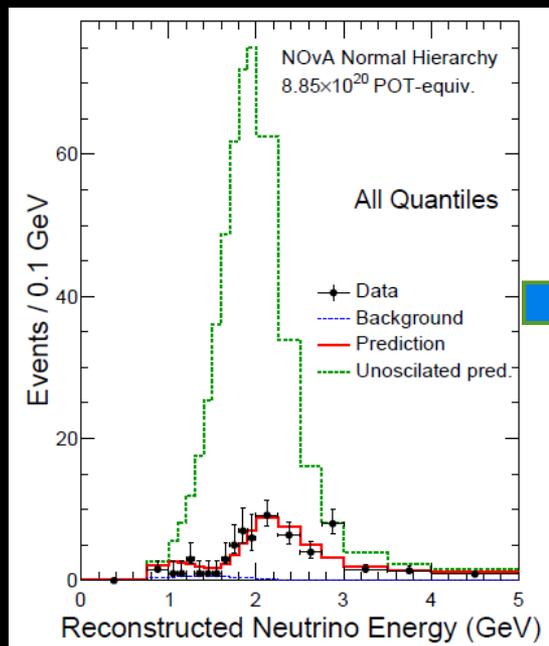


NOvA result (I)

63 events expected w/o oscillations

126 events observed

L.Kolupaeva, talk at NuHoRizons2018

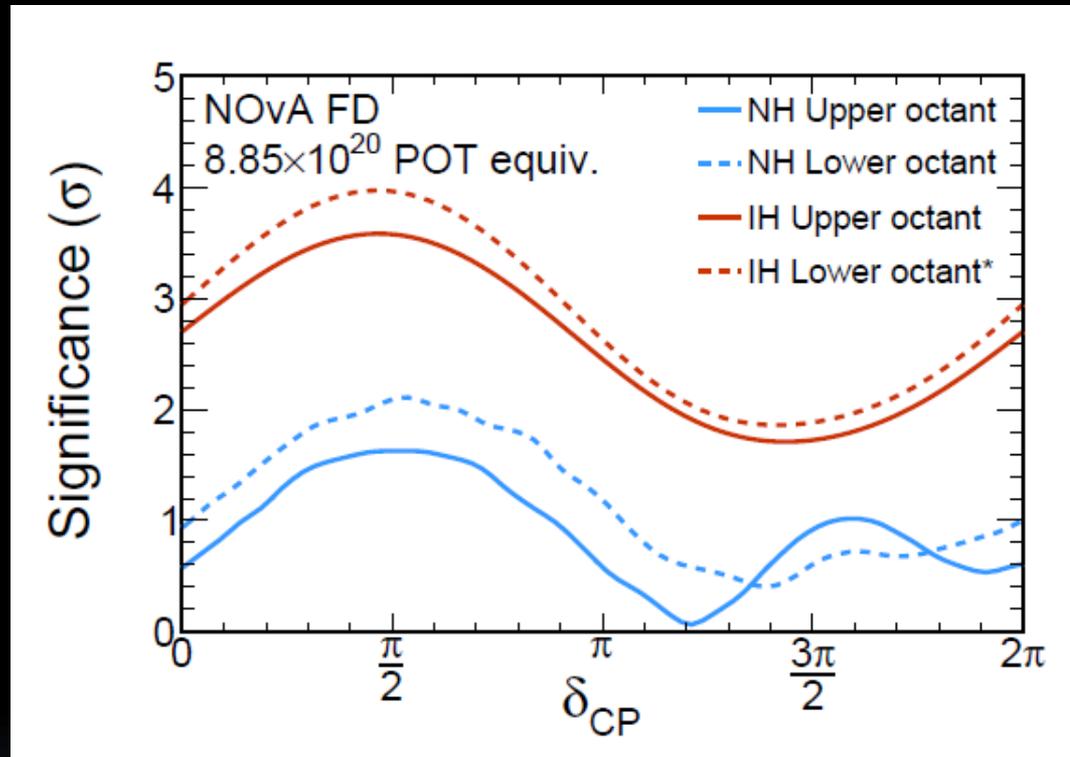


$$\Delta m_{32}^2 = 2.444_{-0.077}^{+0.079} \times 10^{-3} \text{ eV}^2$$
$$\sin^2 \theta_{23} = 0.558_{-0.033}^{+0.041} \quad \text{Upper octant } (\theta_{23} > \pi/4)$$
$$\sin^2 \theta_{23} = 0.475_{-0.044}^{+0.036} \quad \text{Lower octant } (\theta_{23} < \pi/4)$$



NOvA result (II)

O.Samoylov, QUARKS 2018

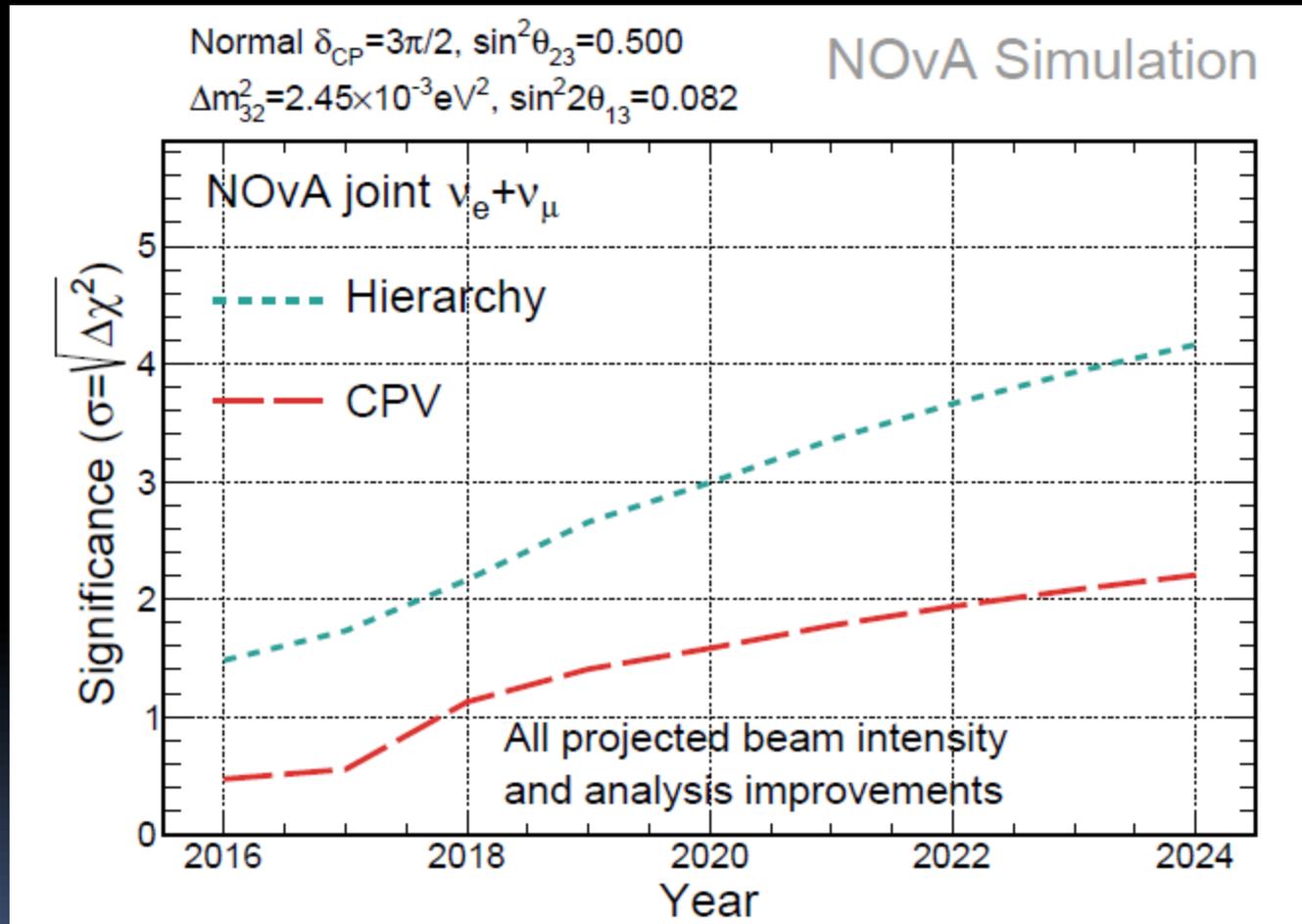


Best Fit: $\delta_{CP} = 1.21\pi$, Upper Octant, Normal Hierarchy.
Upper octant is preferred at 0.2σ .
Exclude $\delta_{CP} = \pi/2$ region in the IH at $> 3\sigma$.



Prospects for NOvA

NOvA runs with anti- ν_μ beam since February 2017





OPERA: final result

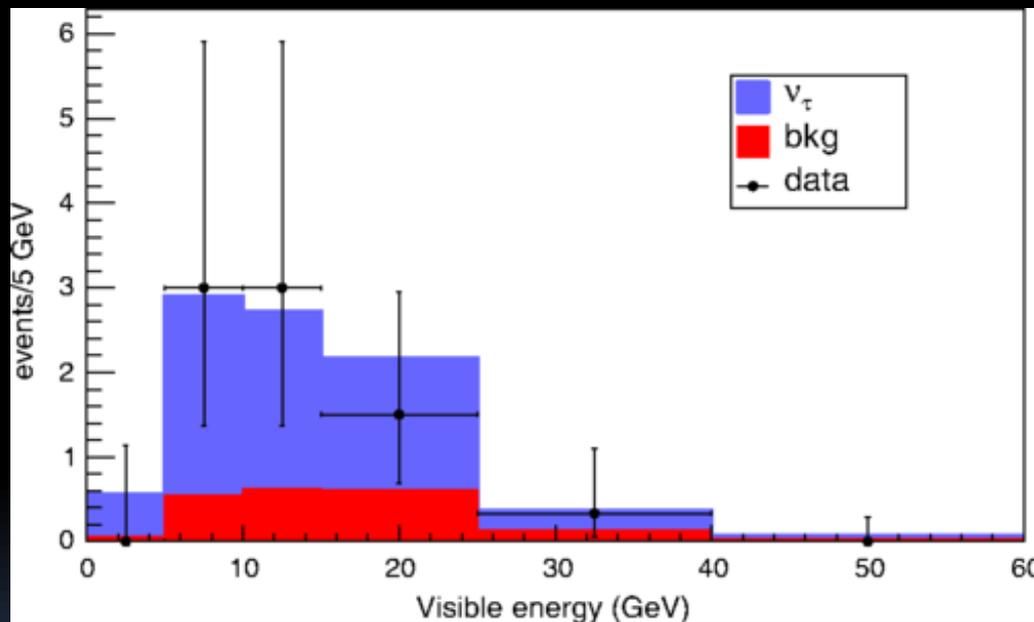
PRL 120 (2018) 211801

$\nu_{\mu} \rightarrow \nu_{\tau}$ appearance

10 ν_{τ} events observed for 18×10^{19} POT

Expected 6.4 events for $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1.0$

Expected background 2.0 ± 0.4 events



Significance of ν_{τ} appearance 6.1σ

OPERA: $\Delta m_{23}^2 = (2.7 + 0.7 - 0.6) \times 10^{-3} \text{ eV}^2$, assuming $\sin^2 2\theta_{23} = 1.0$

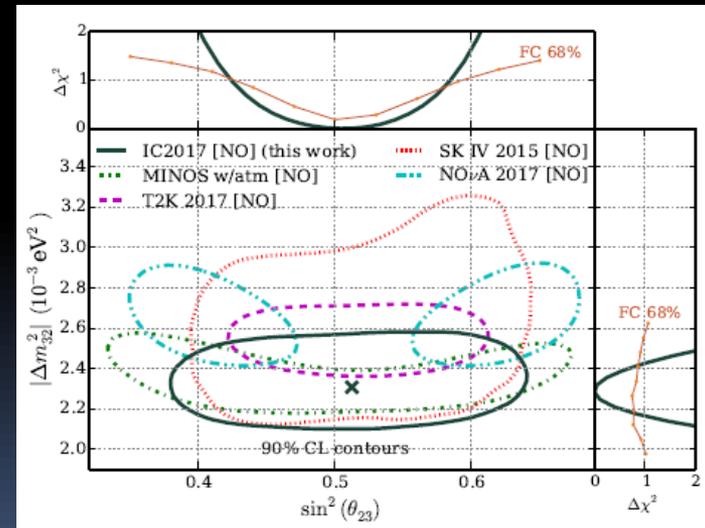
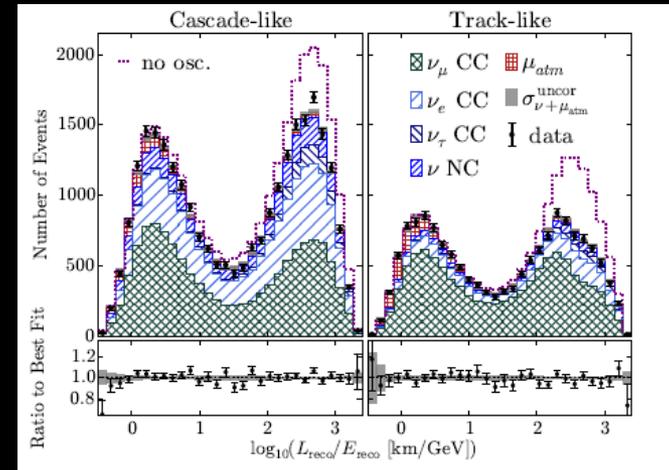
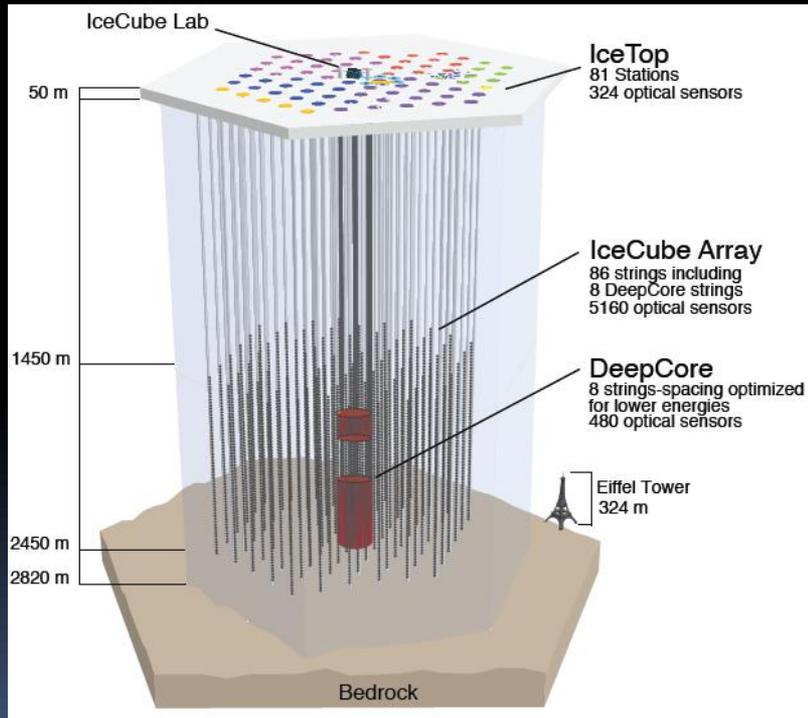


IceCube

PRL 120 (2018) 071801

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

Data taking for 3 years



$$\Delta m_{32}^2 = (2.31 +0.11 -0.13) \times 10^{-3} \text{ eV}^2 \quad \sin^2 \theta_{23} = 0.51 +0.07 -0.09 \text{ for NH}$$



Reactor experiments

Measurement of θ_{13}

Daya Bay, China



17.4 GW

RENO, Korea



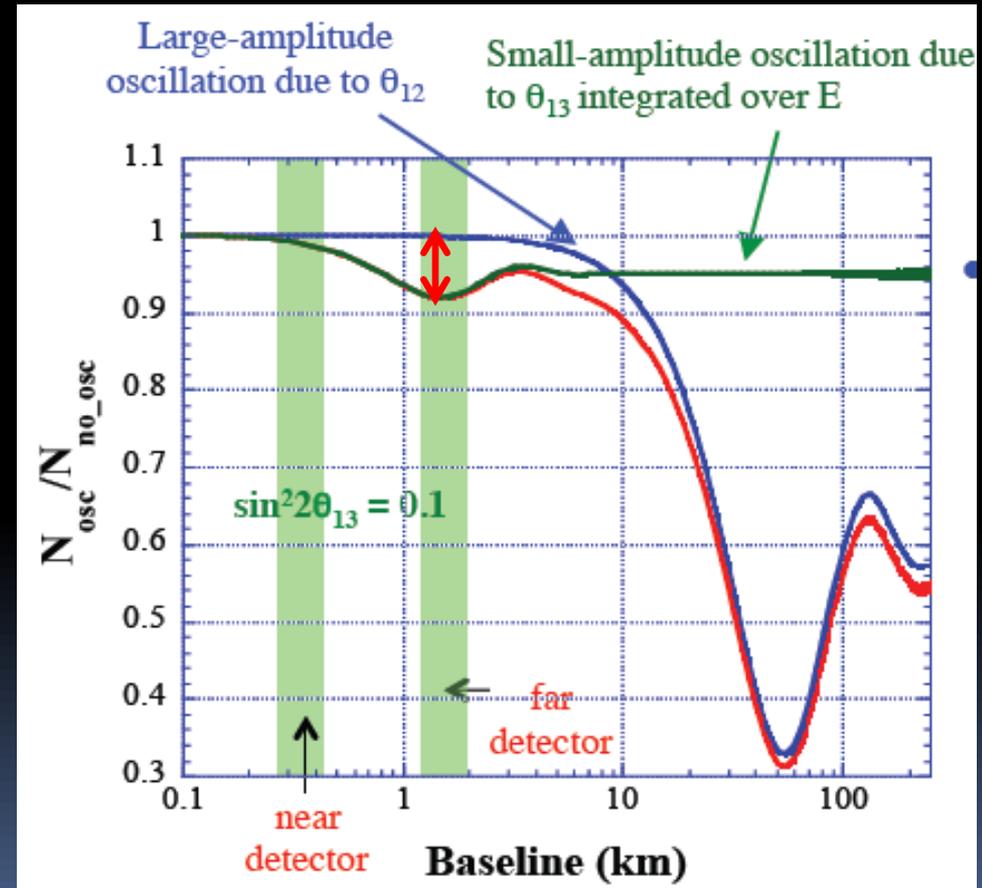
16 GW

Double Chooz, France



8.5 GW

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

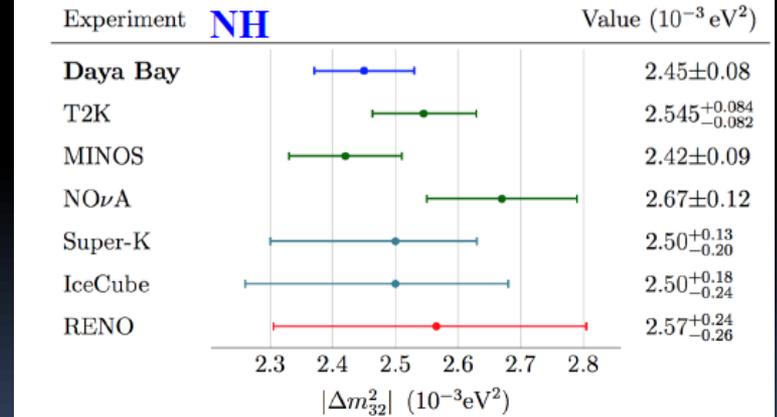
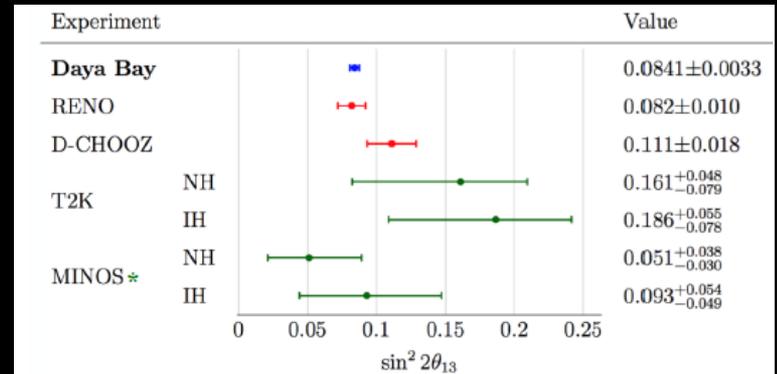
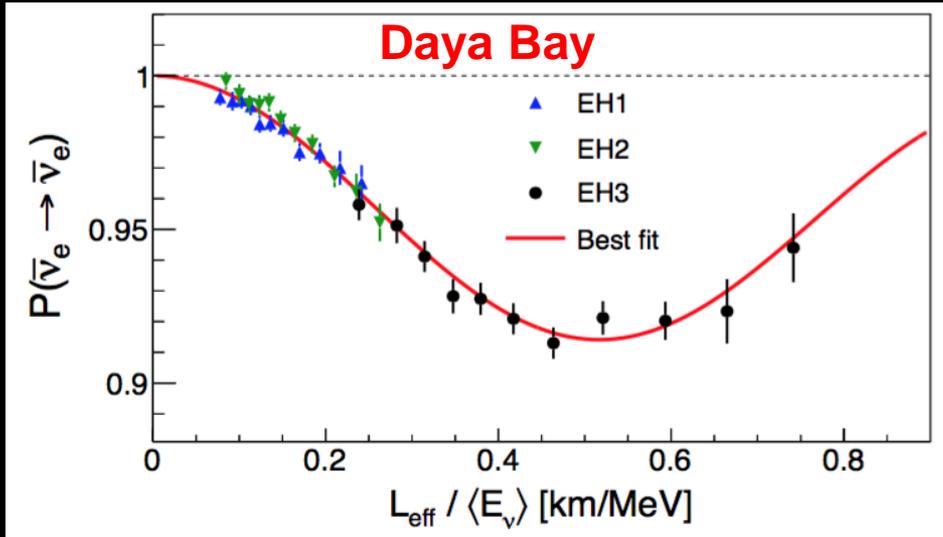




Oscillation results

Reactor and accelerator
 θ_{13} and Δm_{32}^2

V.Vorobel, HEP2018



* Combined fit results for $2\sin^2\theta_{23}\sin^22\theta_{13}$

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$$

$$|\Delta m_{ee}^2| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3} \text{eV}^2$$

Future LBL Projects

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



Reactor experiment JUNO

China



66 institutions
> 400 collaborators

Main target:
Measurement of
neutrino mass hierarchy

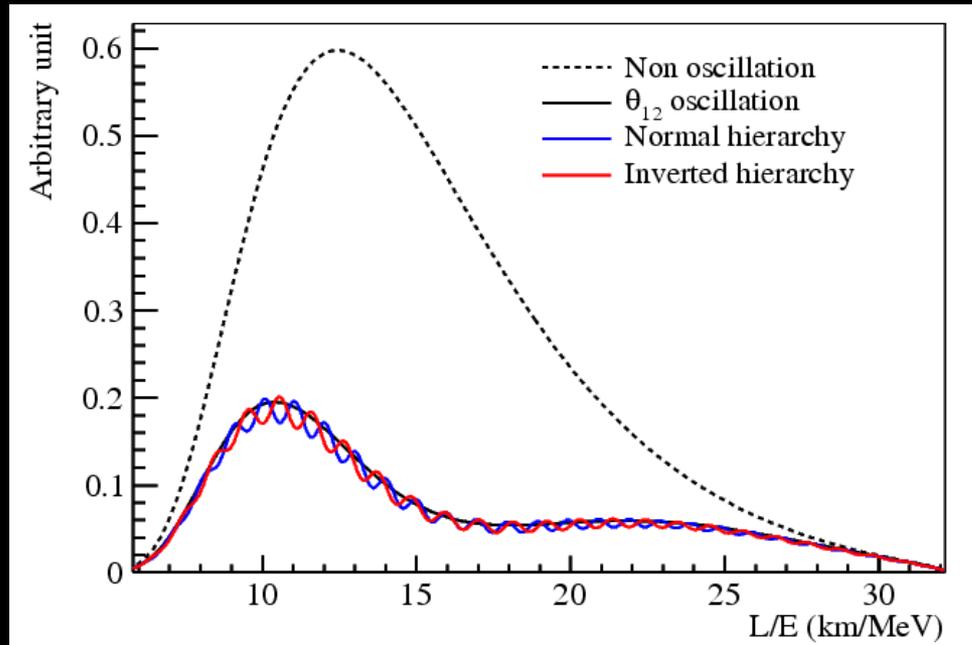
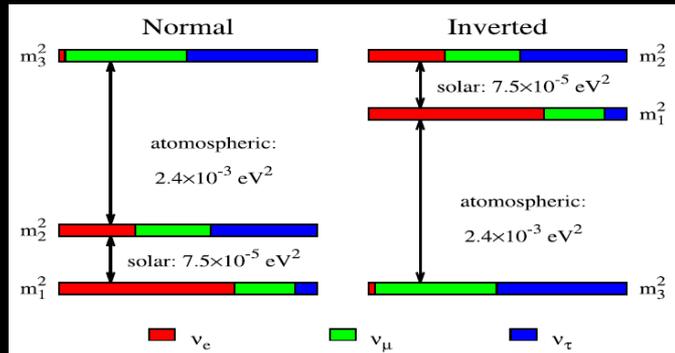
- 700 m deep underground
- 36 GW reactor power
- 53 km baseline -> **oscillation maximum θ_{12}**
- 20 kton LS detector
- **3%** energy resolution at 1MeV
- **<1%** energy scale uncertainty

!?



JUNO goals

Main goal: determination of neutrino mass hierarchy



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

Oscillation Parameter	Current accuracy (global 1 σ) **	Dominant experiment(s)	JUNO Potentiality
Δm_{21}^2	2.3%	KamLAND	0.59%
$\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2) $	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

h=44 m

3'' PMT

d=43.5 m

20'' PMT



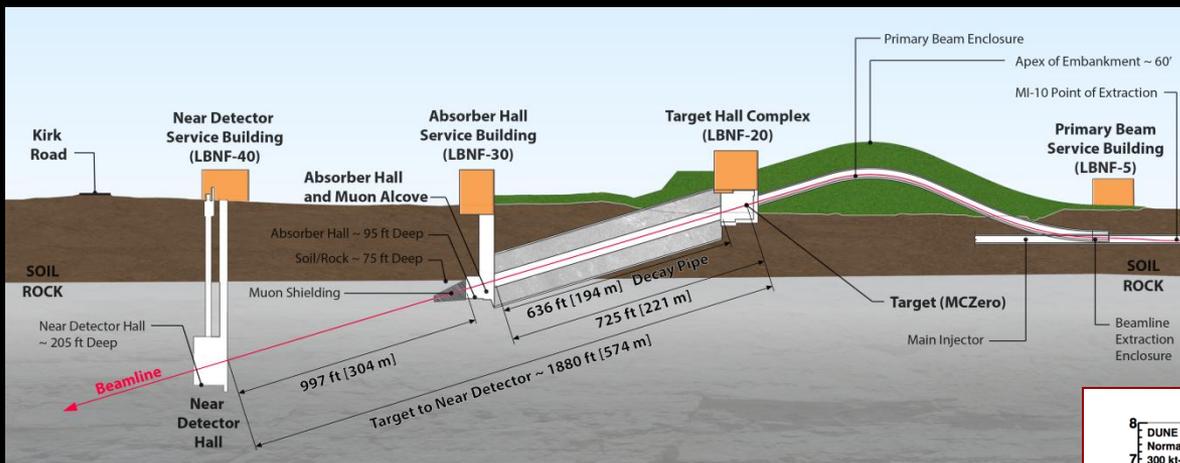
LBNF/DUNE Project

Flagship FNAL project

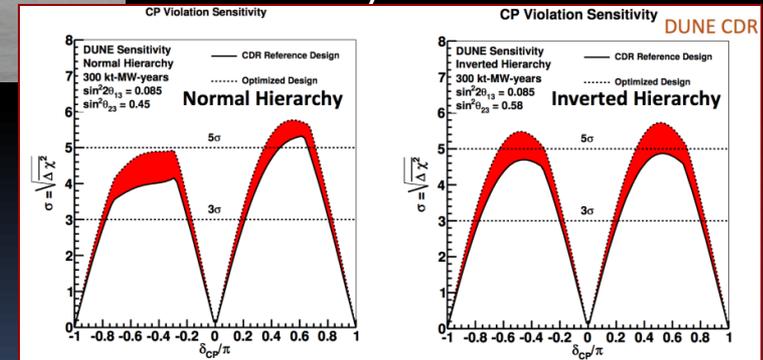
- Main goals:**
- discovery of CP violation in leptonic sector
 - neutrino mass hierarchy at $>5\sigma$ level
 - neutrino astronomy
 - proton decay search

30 countries
 161 institutions
 ~1000 collaborators

$E_p = 60-120$ GeV
 Beam power 1.2 \rightarrow 2.4 MW
 On axis neutrino beam
 $E_\nu \sim 1-6$ GeV
 $L=1300$ km from FNAL to SURF, S.Dakota

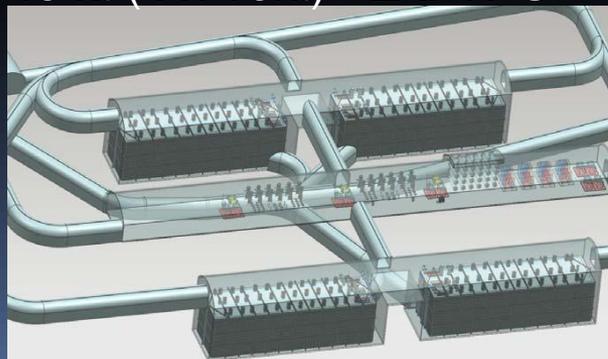


Sensitivity to CP violation



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



HyperKamiokande

Japan

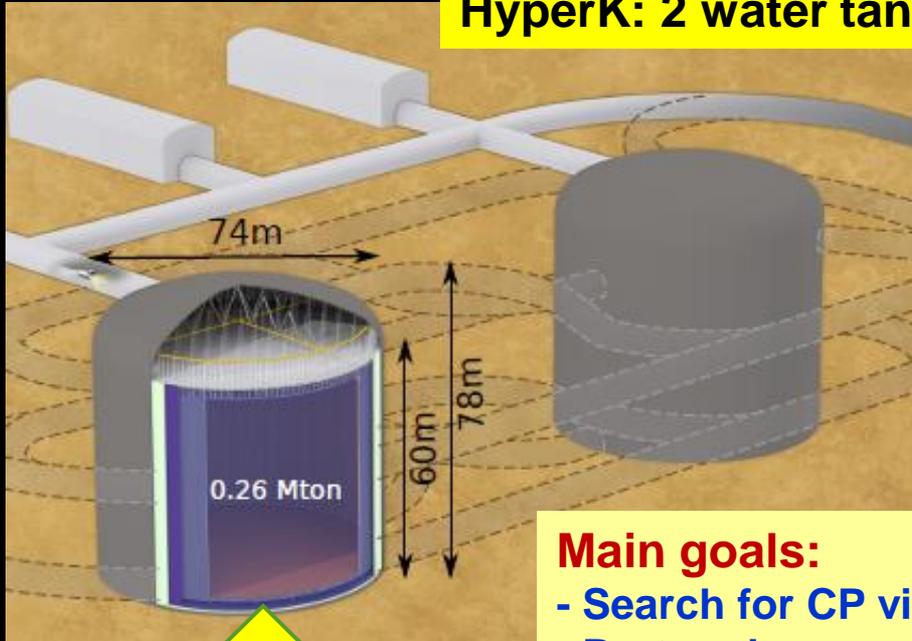
HyperK: 2 water tanks

12 countries

70 institutes

~300 members

Expected data taking start 2026



- Upgrade of JPARC to 1.3 MW beam power
- New/upgrade of near neutrino detectors

Main goals:

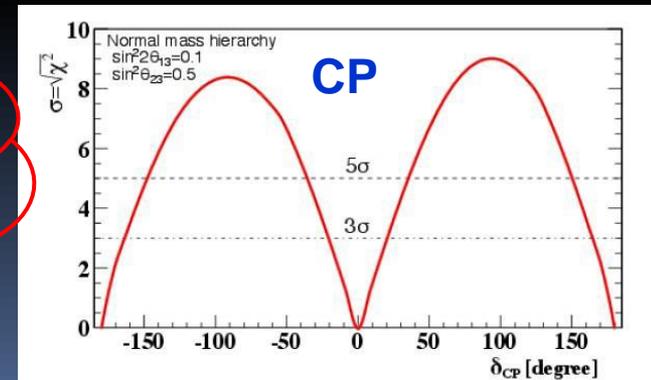
- Search for CP violation
- Proton decay
- Neutrino astrophysics

1 tank

60 m(H)x74m(D)
 Total volume 260 kt
 Fiducial volume 190 kt
 ~10xSuperK
 PMT coverage 40%
 40000 PMTs

10 years of running:

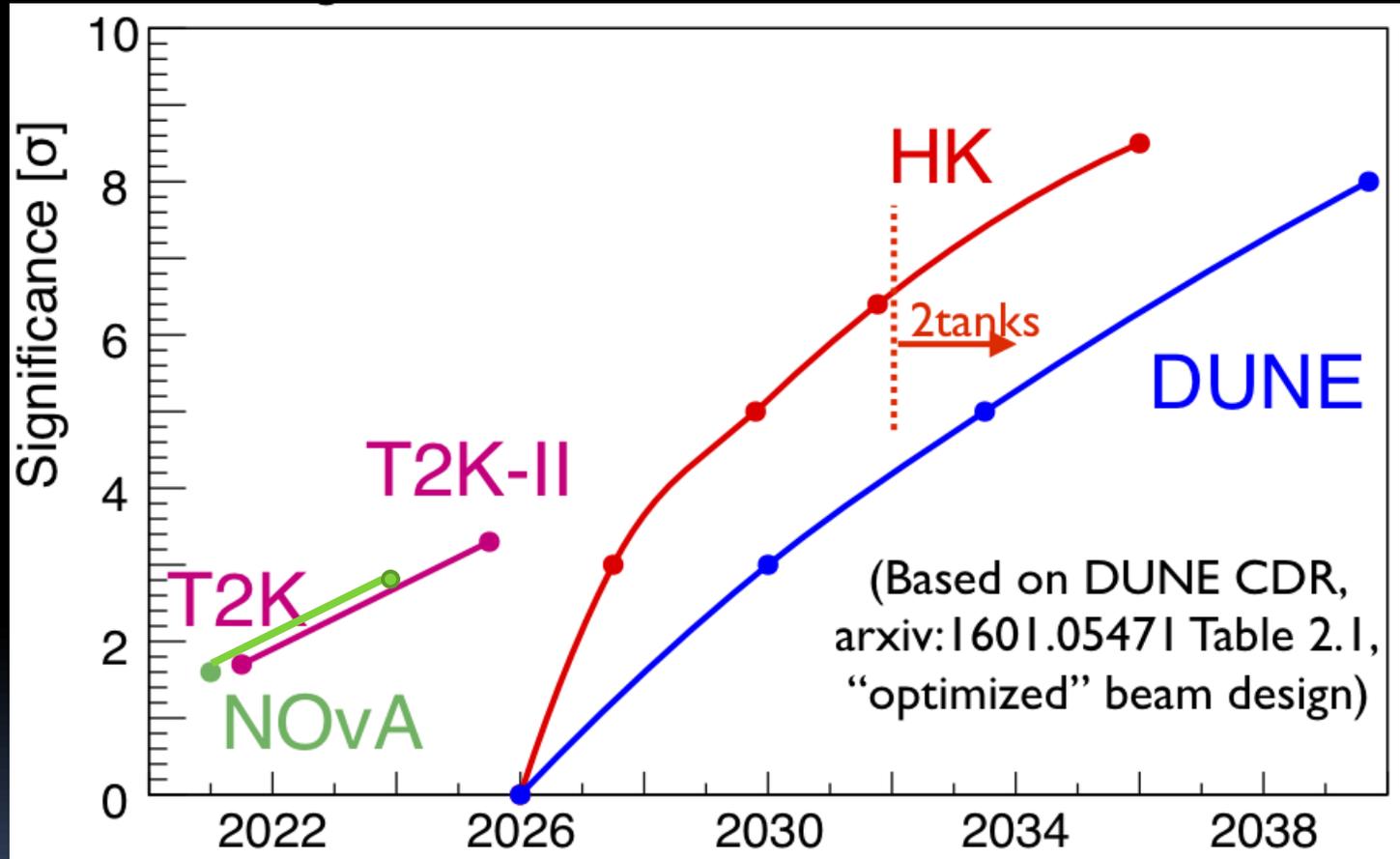
- 8σ for $\delta_{CP} = -\pi/2$
- 80% coverage of δ_{CP} parameter space with $>3\sigma$
- $p \rightarrow \pi^0 e^+ > 10^{35} \text{ y}$





Expected sensitivity to CP

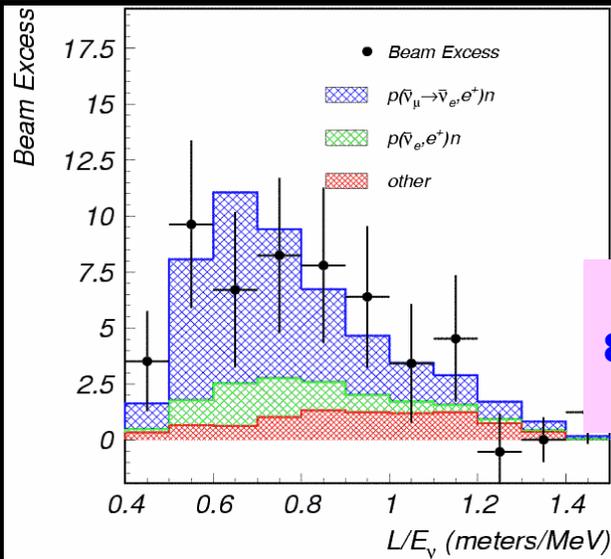
Significance for $\delta_{CP} = -\pi/2$



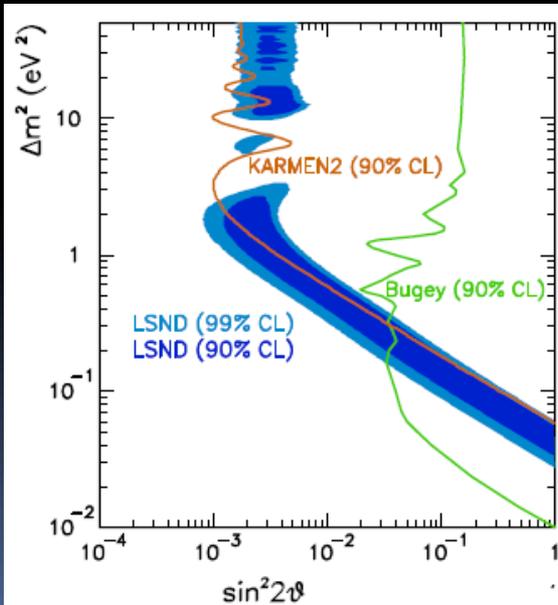
Light sterile neutrinos



LSND

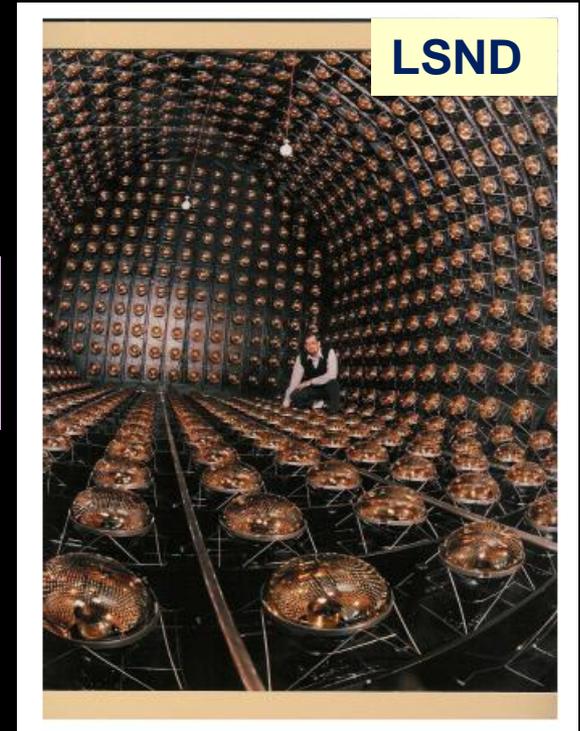


$\text{anti-}\nu_{\mu} \rightarrow \text{anti-}\nu_e$
 $87.9 \pm 22.4 \pm 6.0$ events
 Excess 3.8σ



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

$$0.2 \leq \Delta m^2 \leq 1 \text{ eV}^2 \quad 2 \times 10^{-3} \leq \sin^2 2\theta \leq 4 \times 10^{-2}$$

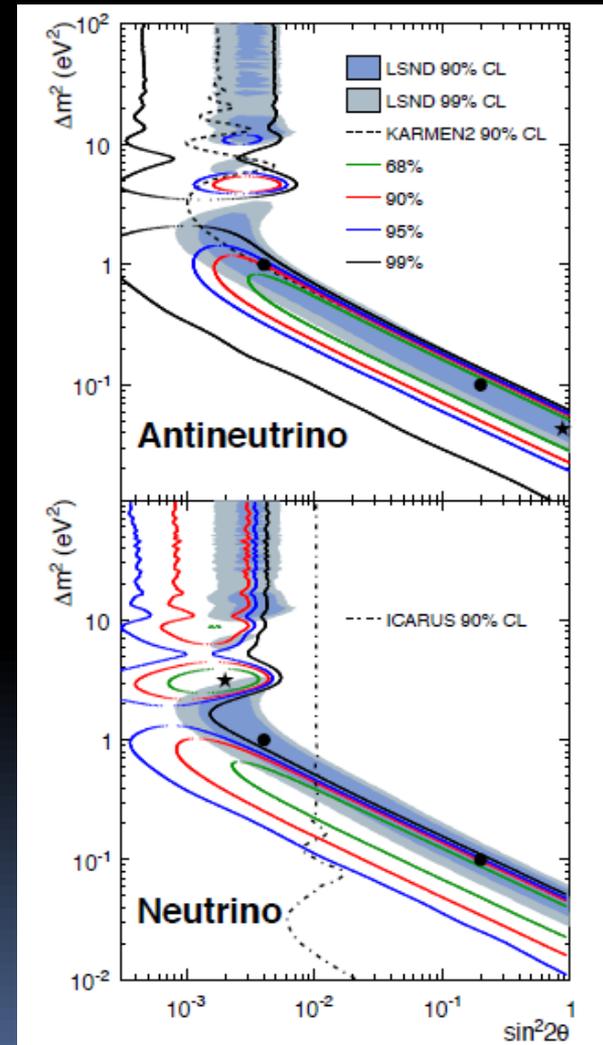
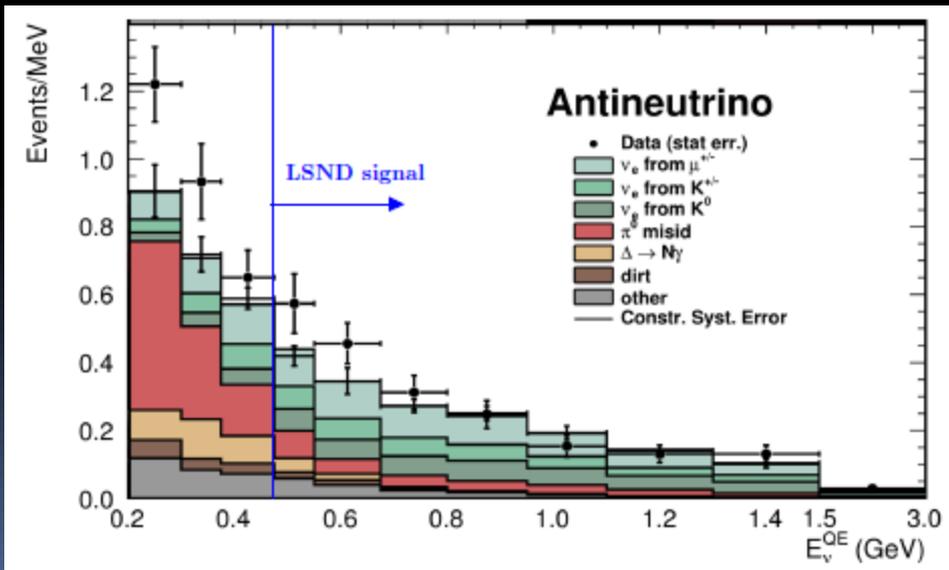
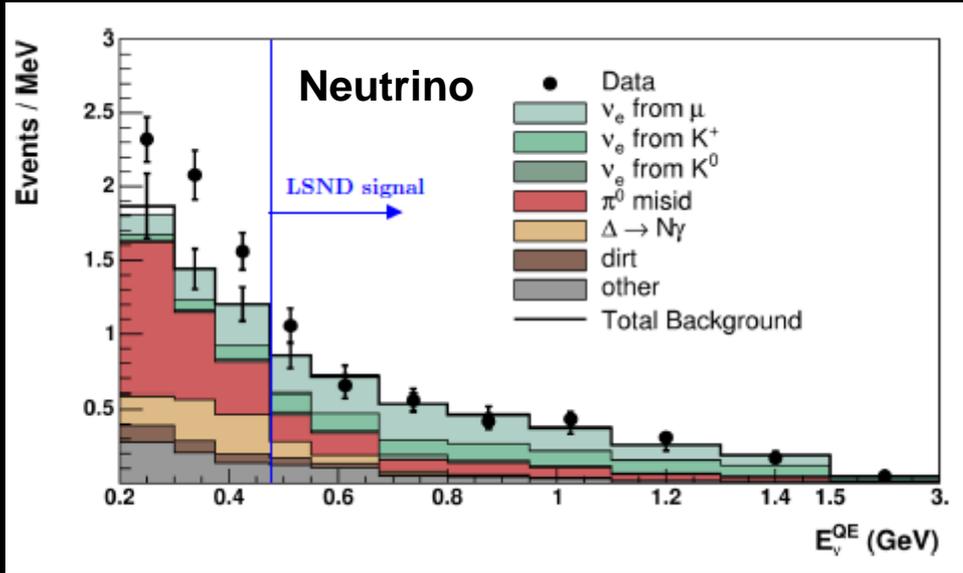


LSND



MiniBooNe

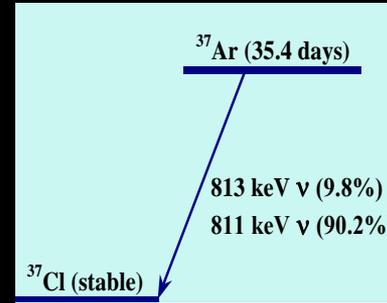
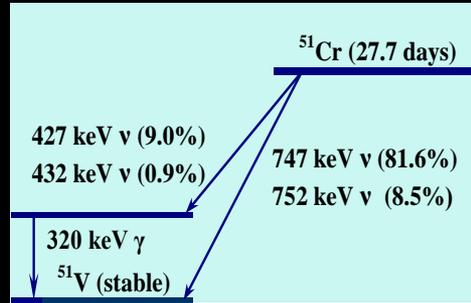
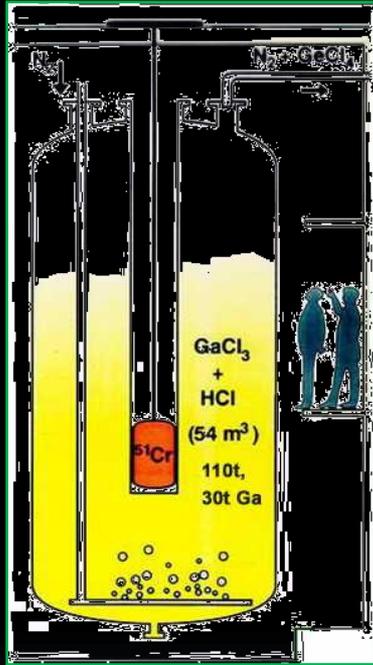
$\nu_{\mu} \rightarrow \nu_e$
 $\text{anti-}\nu_{\mu} \rightarrow \text{anti-}\nu_e$
 $L \approx 540 \text{ m}$ $E_{\nu} = 0.2\text{-}3 \text{ GeV}$



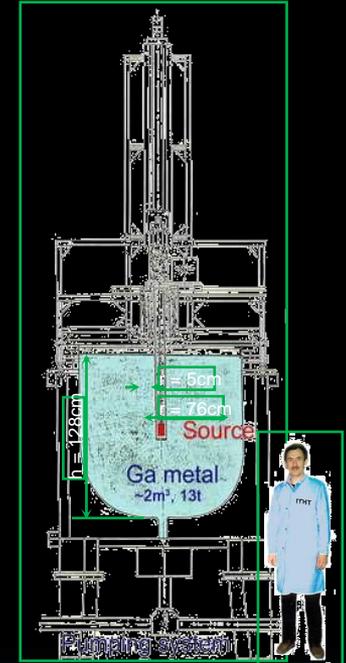


Gallium anomaly

GALLEX

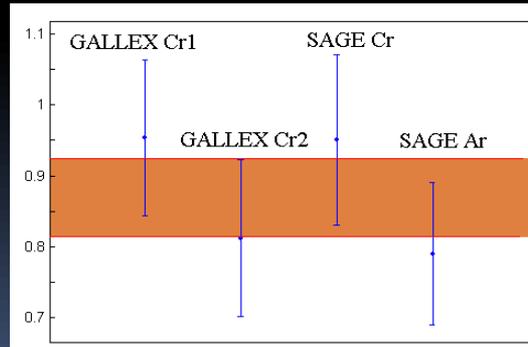


SAGE



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

	GALLEX m(Ga)=30 t		SAGE m(Ga)=13 t	
Source	${}^{51}\text{Cr}$ -1	${}^{51}\text{Cr}$ -2	${}^{51}\text{Cr}$	${}^{37}\text{Ar}$
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	

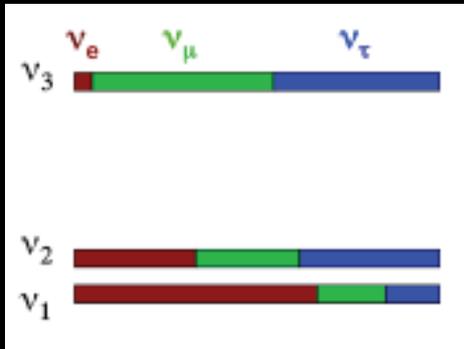


$$R = p_{exp}/p_{theory} = 0.87 \pm 0.05$$

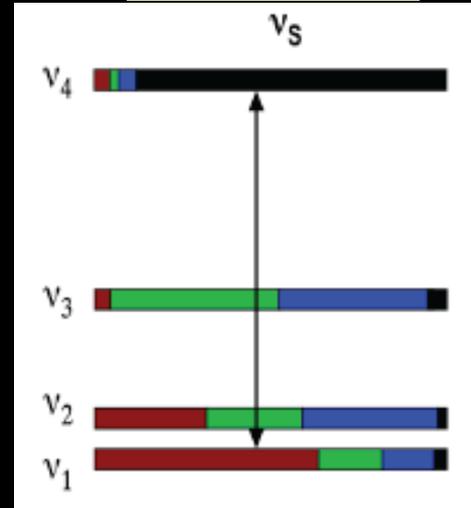


Sterile neutrino?

3ν



3ν + 1s



$$\Delta m_{14}^2 \sim 1 \text{ eV}^2$$

?



PNMS matrix

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

$$\left. \begin{aligned} |U_{e4}|^2 &= \sin^2 \theta_{14} \\ |U_{\mu4}|^2 &= \sin^2 \theta_{24} \cdot \cos^2 \theta_{14} \\ |U_{\tau4}|^2 &= \sin^2 \theta_{34} \cdot \cos^2 \theta_{24} \cdot \cos^2 \theta_{14} \end{aligned} \right\}$$

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

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

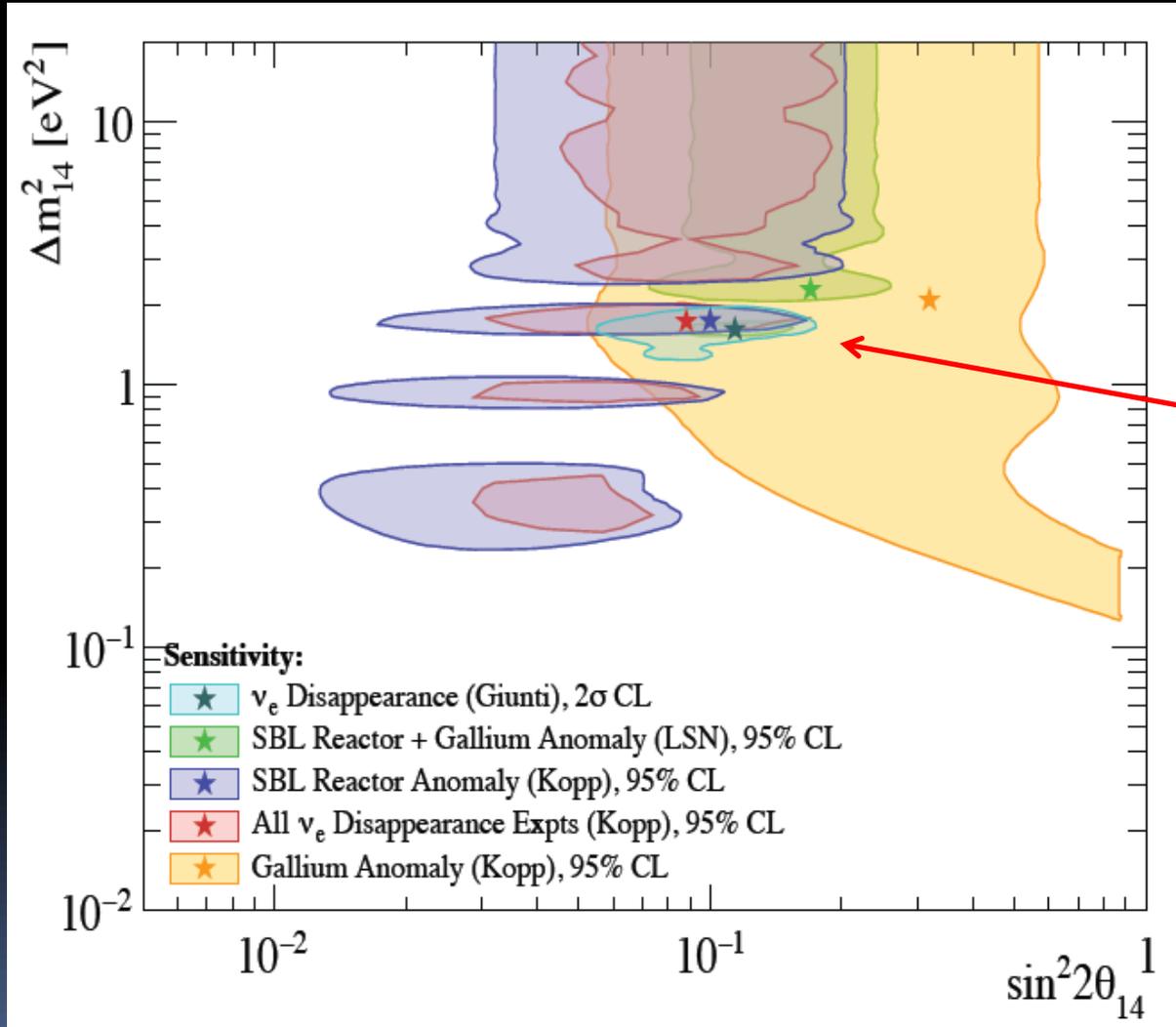
$$P_{\nu_\mu \rightarrow \nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$



ν_e and anti- ν_e disappearance

arXiv:1512.02202

Global fit of reactor and Gallium data



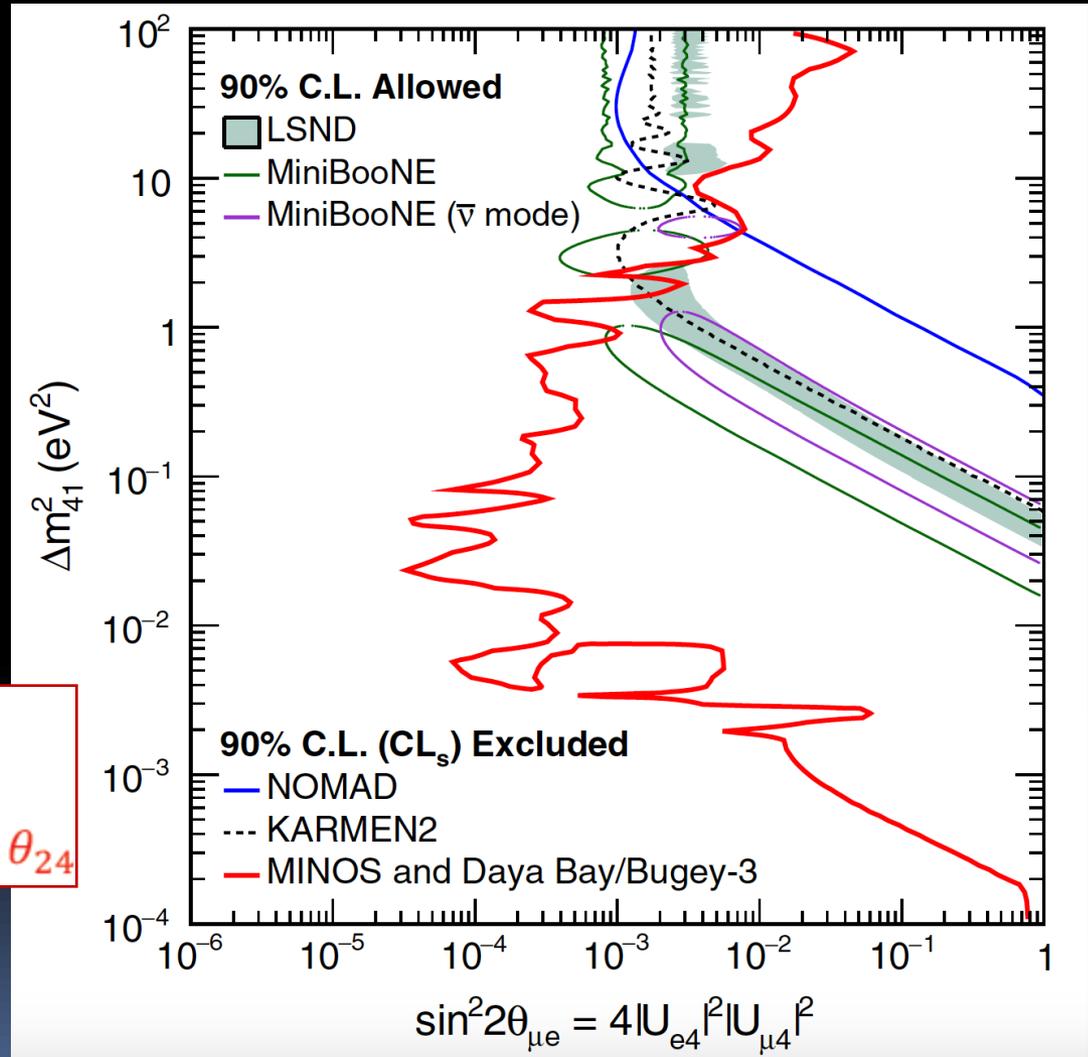


Sterile ν 's: Daya Bay + MINOS+ Bugey-3

PRL117 (2016) 151801

- Daya Bay data
 - Constrains Δm_{41}^2 (mainly 10^{-4} to 10^{-1} eV²) and $\sin^2 2\theta_{14}$
- Bugey-3 data
 - constrains Δm_{41}^2 (mainly 10^{-1} to 10 eV²) and $\sin^2 2\theta_{14}$
- MINOS data
 - Constrains Δm_{41}^2 (mainly 10^{-3} to 10^2 eV²) and $\sin^2 \theta_{24}$

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





Sterile ν 's: IceCube

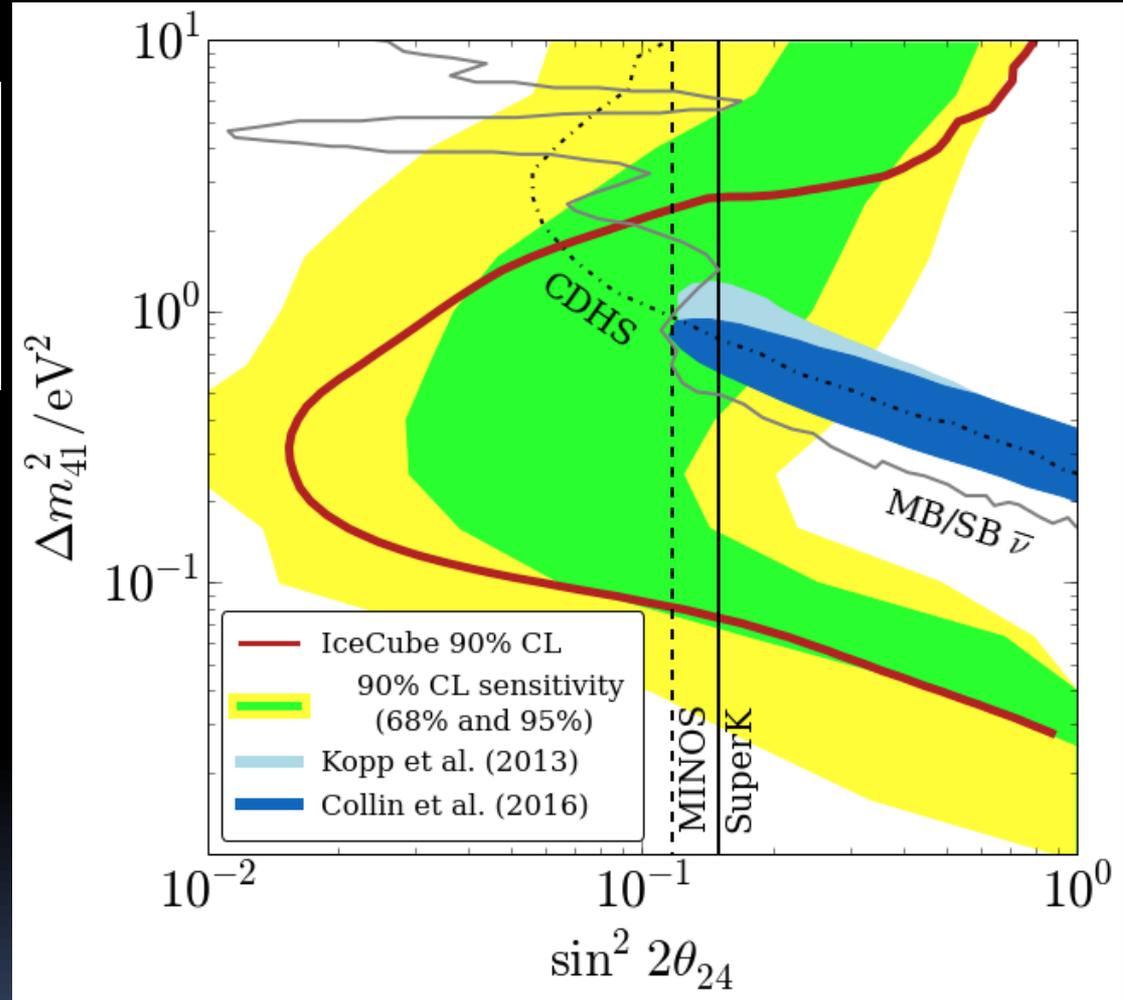
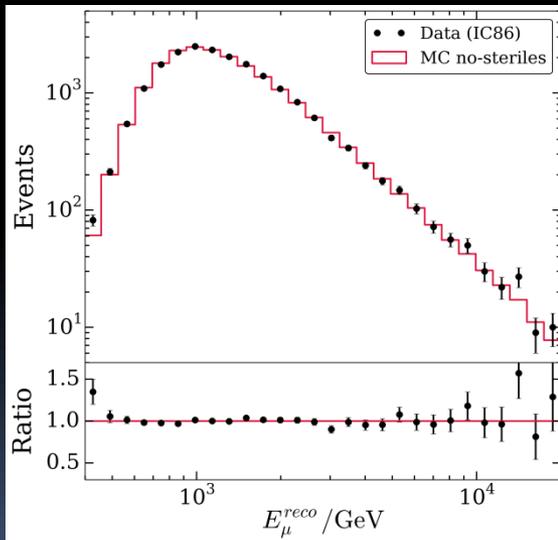
PRL 117 (2016) 071801

$E_\nu = 320 \text{ GeV} - 20 \text{ TeV}$

sterile neutrinos produce distortions of $\nu_\mu + \text{anti-}\nu_\mu$ flux (energy and angle) in the range

$$0.01 \leq \Delta m^2 \leq 10 \text{ eV}^2$$

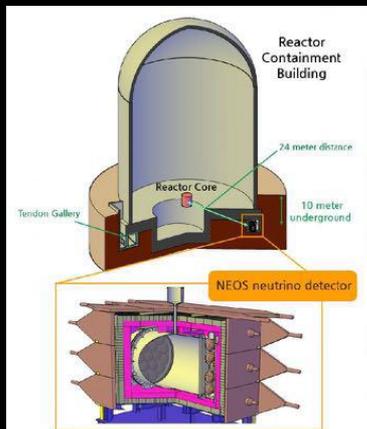
- 1 year of data
- statistics limited



Result compatible with **no-sterile** hypothesis

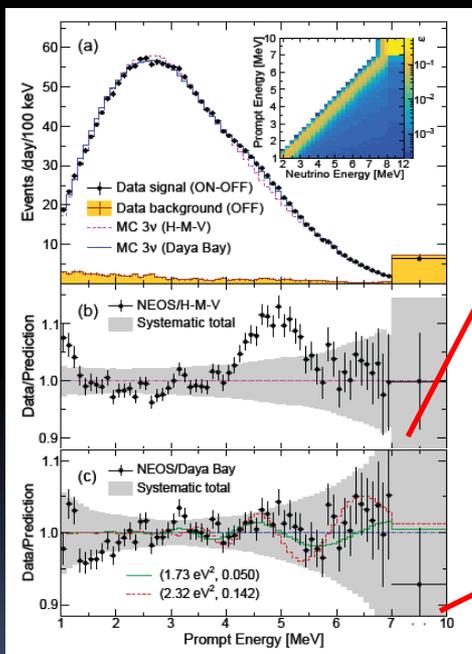
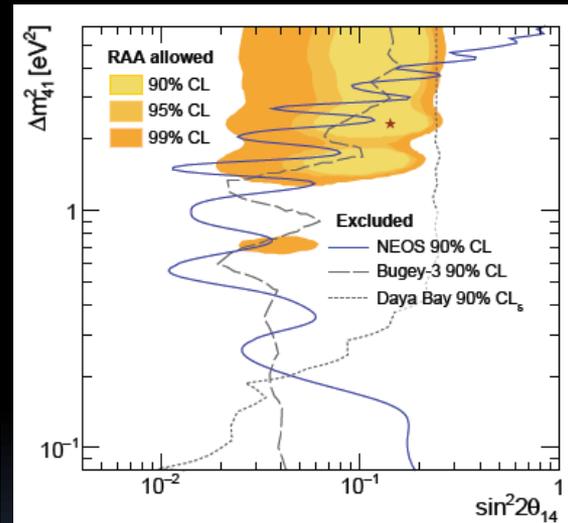
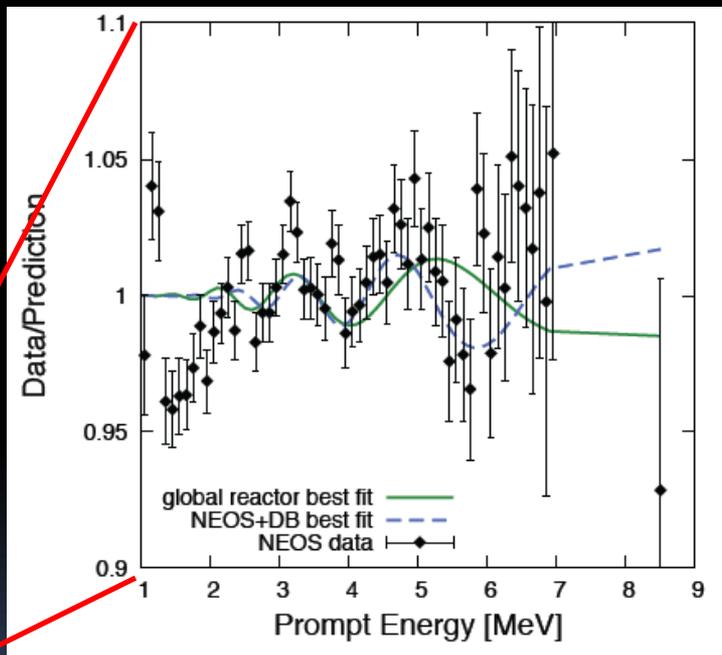


NEOS: reactor anti- ν disappearance



Korea, Reactor 2.8 GW
Core: $\varnothing 3.1$ 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

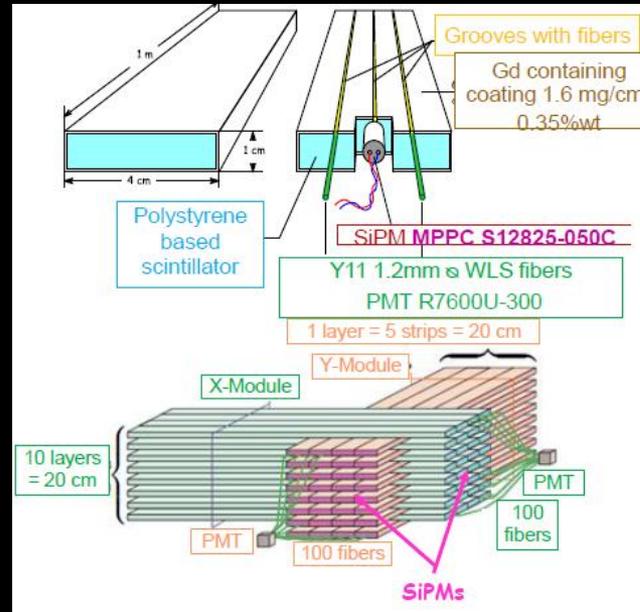


DANSS experiment

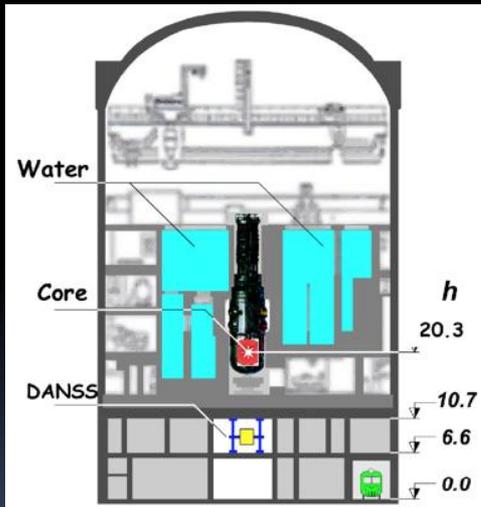
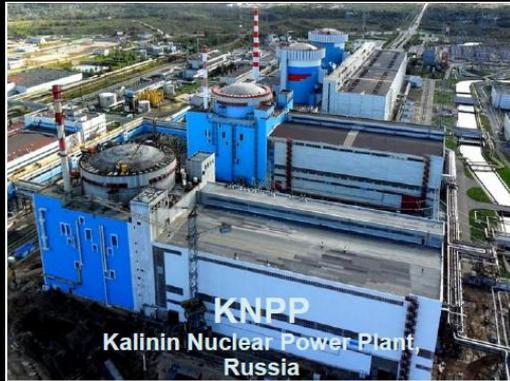
arXiv:1804.0404

Detector configuration

- 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

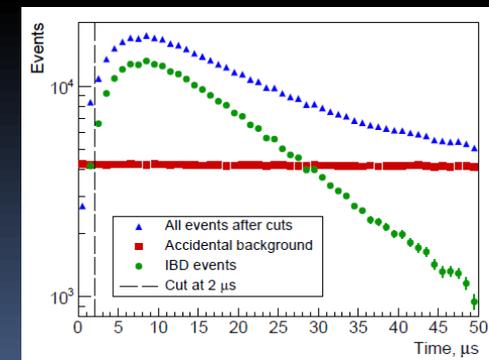
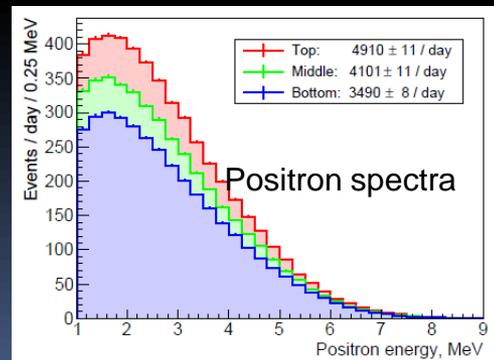


3.1 GW_{th} Kalinin Power Plant



Distance from the reactor core 10.7-12.7 m

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

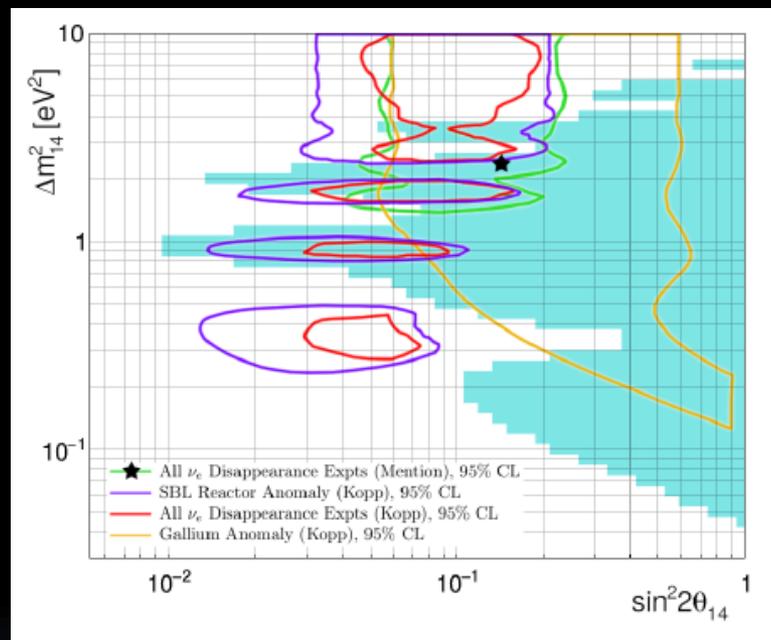
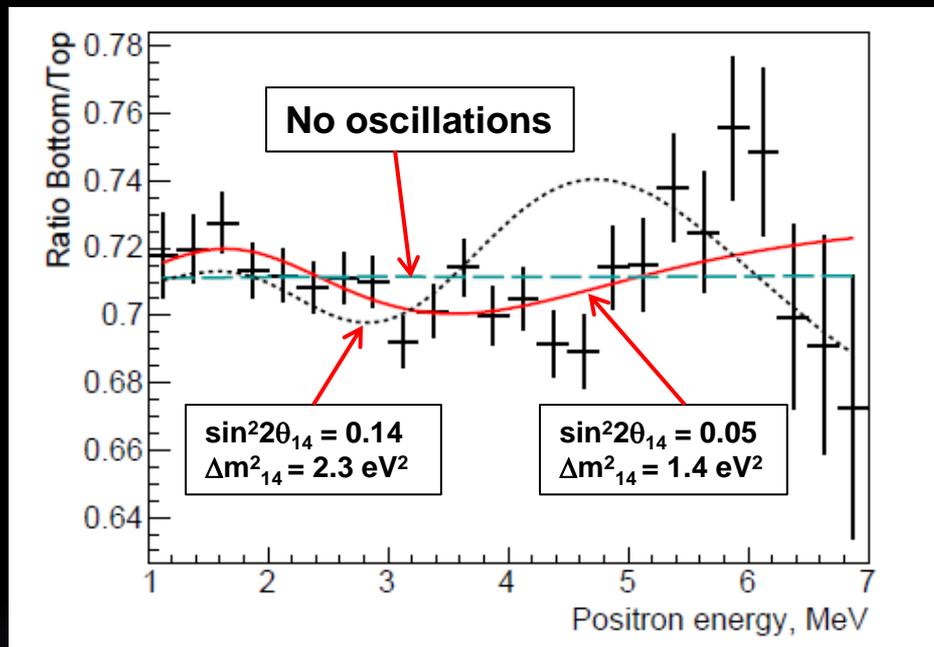




DANSS result

arXiv:1804.0404

Result is based on 663×10^3 events

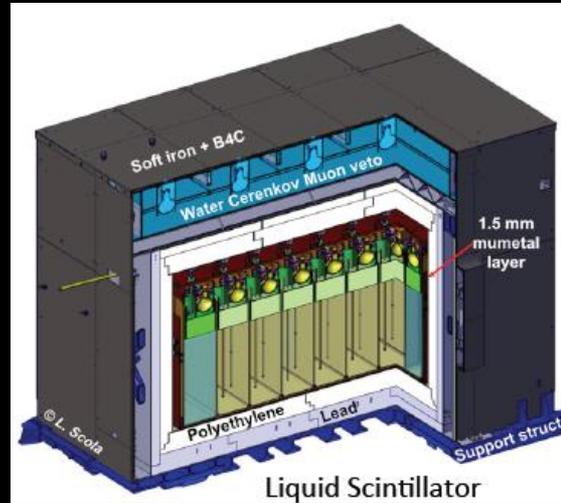


**The Reactor Anomaly best fit point
($\sin^2 2\theta_{14} = 0.14$ $\Delta m^2_{14} = 2.3 \text{ eV}^2$) is excluded at $> 5\sigma$ CL**



STEREO experiment

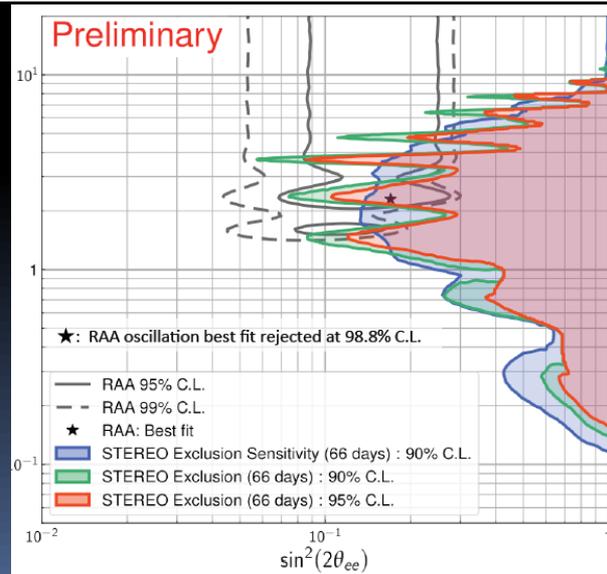
ILL, Grenoble, France,
58.3 MW_{th}
compact core Ø40x80 cm



D.Lhuillier, Moriond EW 2018

- Detector 6 identical cells
- Gd loaded (0.2% in mass)
- $V_{\text{tot}} = 2.2 \times 0.9 \times 0.9 \text{ m}^3$
- 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.

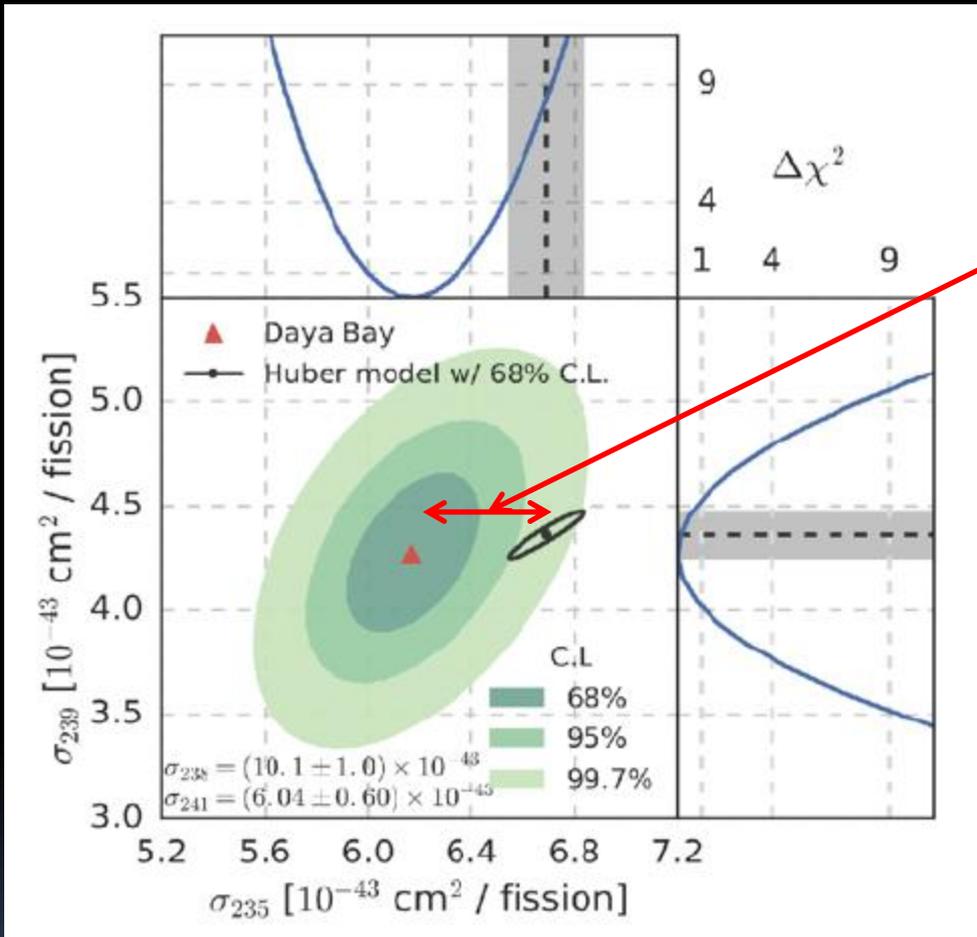


Preliminary result is compatible with no oscillation.
The best fit of the Reactor Anomaly is rejected at 98.8%.



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



Sterile ν 's: « + » and « - »

+



LSND/MinBooNe
Reactor anomaly
Ga anomaly

-



MINOS Disappearance
MINOS/Daya Bay/Bugey combined result
IceCube
NEOS
DANSS
STEREO

?



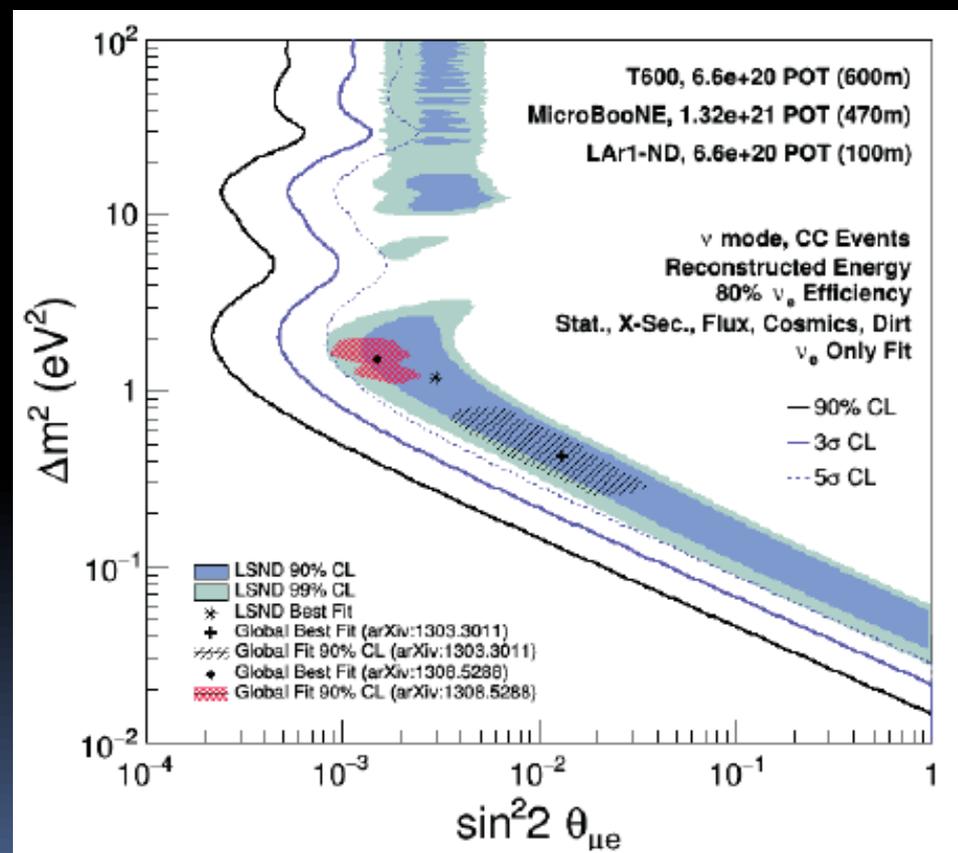
NEW results: next week at NEUTRINO 2018



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

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}

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

JUNO (MH) *under construction*

DUNE (CP, MH) *approved*

HyperK and T2HK (CP) *approval in progress*

Light sterile neutrinos:

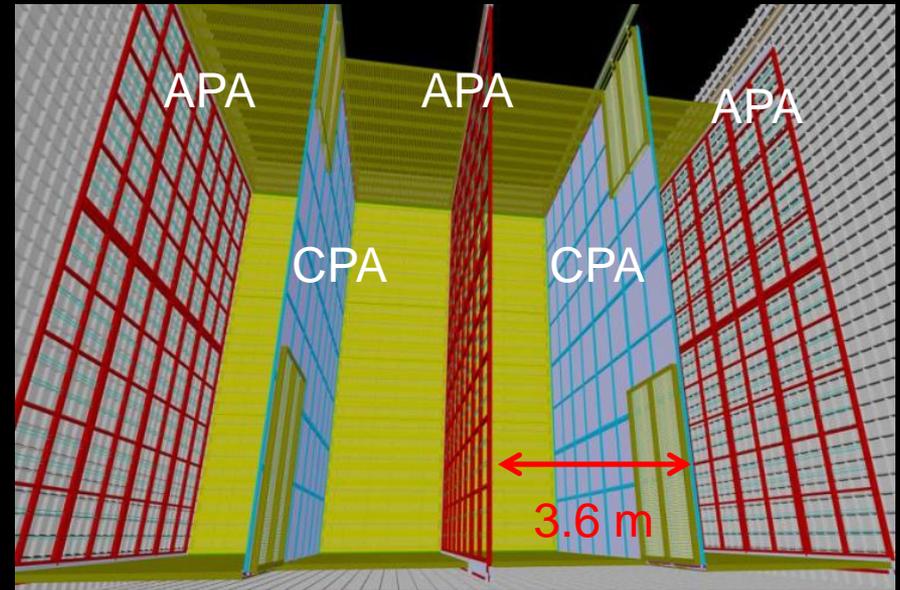
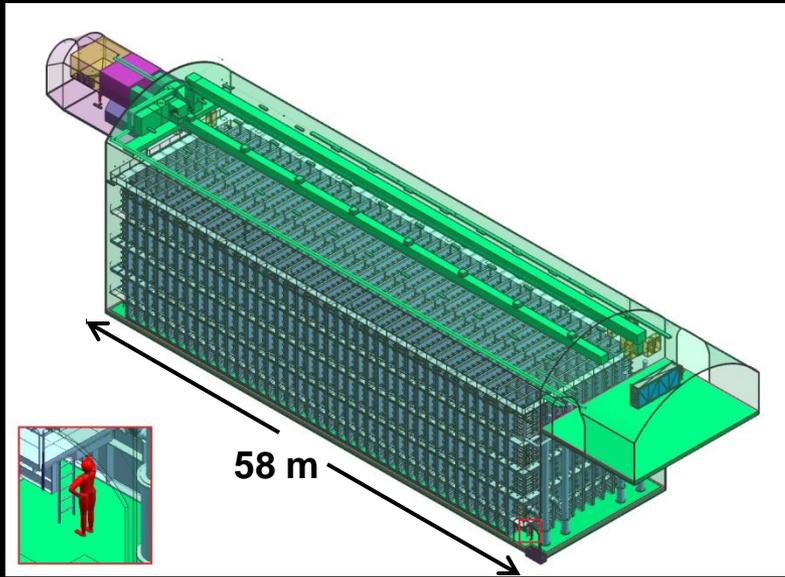
- no positive signal from running experiments
- crucial tests in progress

Thank you!

Backup slides

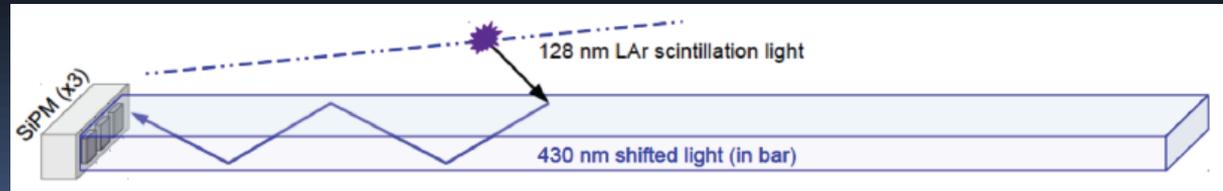


Single-phase LAr TPC



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





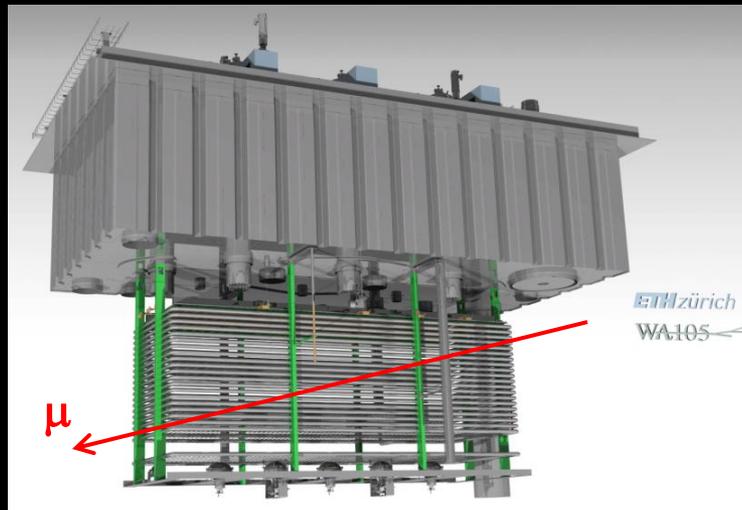
LAr detectors at CERN Neutrino Platform

NP02: WA105

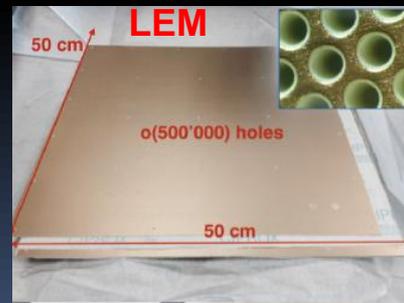
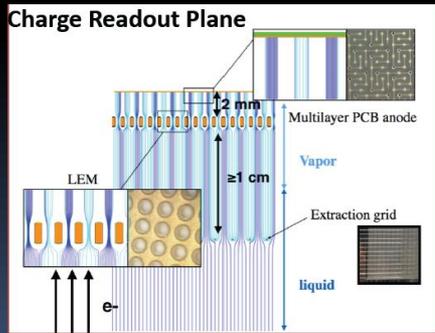
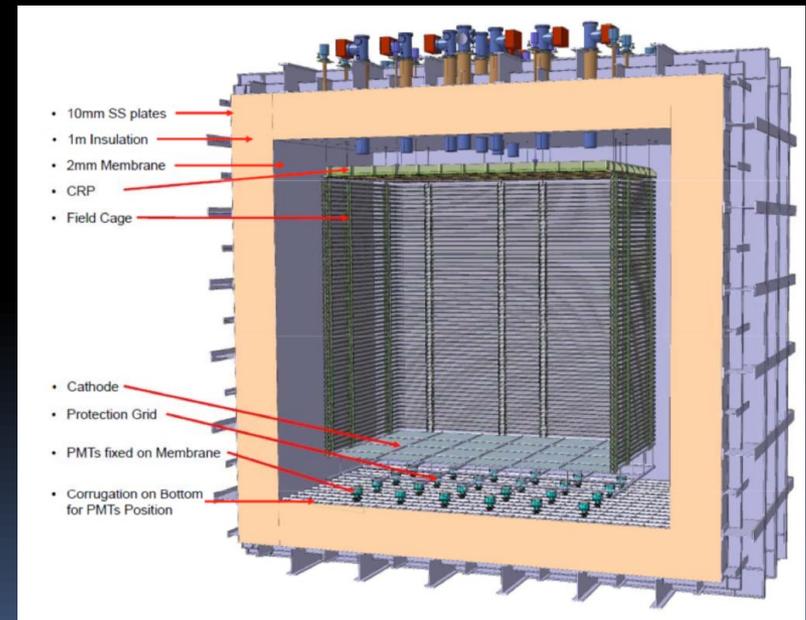
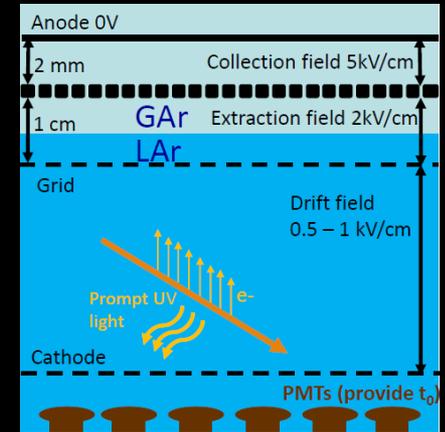
(DP demonstrator + ProtoDUNE DP)

S.Murthy, talk at TPC-2016

Demonstrator: $3 \times 1 \times 1 \text{ m}^3$ – 5 tons



ProtoDUNE DP:
 $6 \times 6 \times 6 \text{ m}^3$
300 tons active mass



Cosmic data taking gas begun

Measurements with test beam in 2018



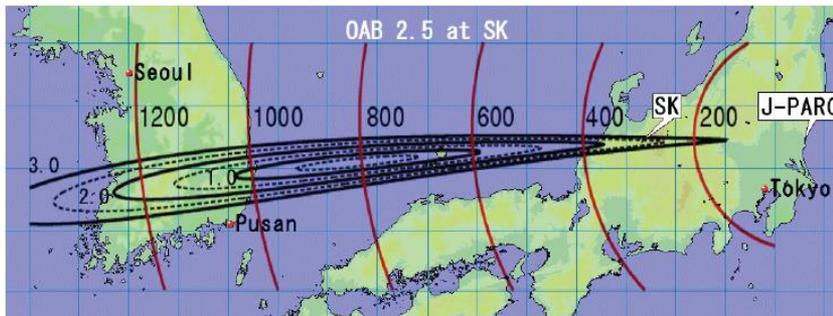
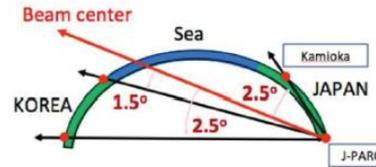
T2HKK

Second tank in Korea

arXiv:1611.06118

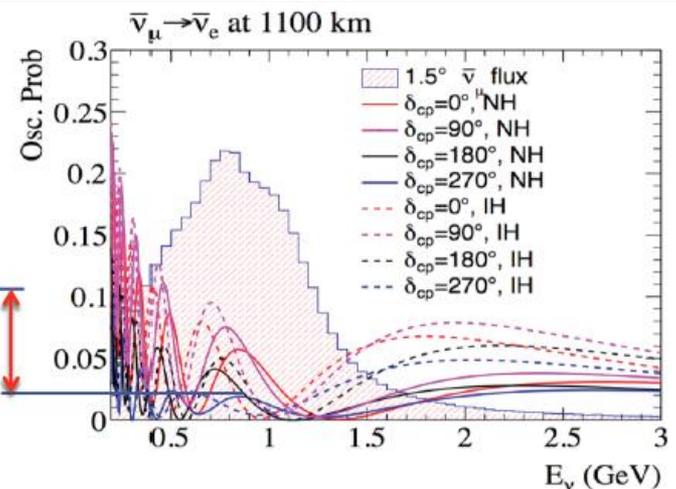
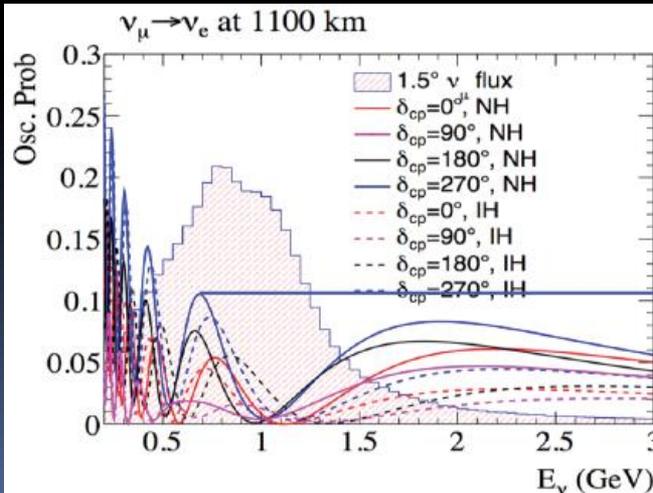
Build second tank in Korea to enhance mass hierarchy and δ_{CP} sensitivities

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



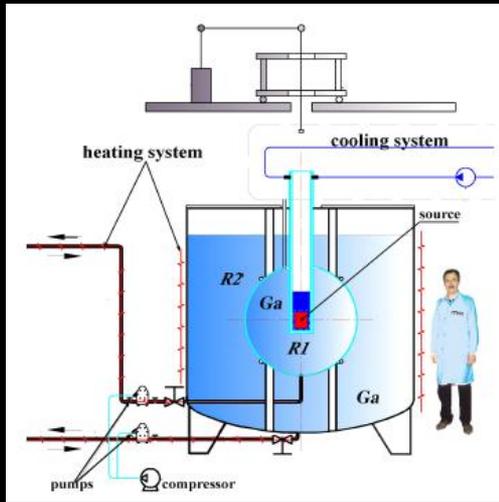
Neutrino and antineutrino spectra in T2HKK cover 1st and 2nd oscillation maximum

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





Source experiments

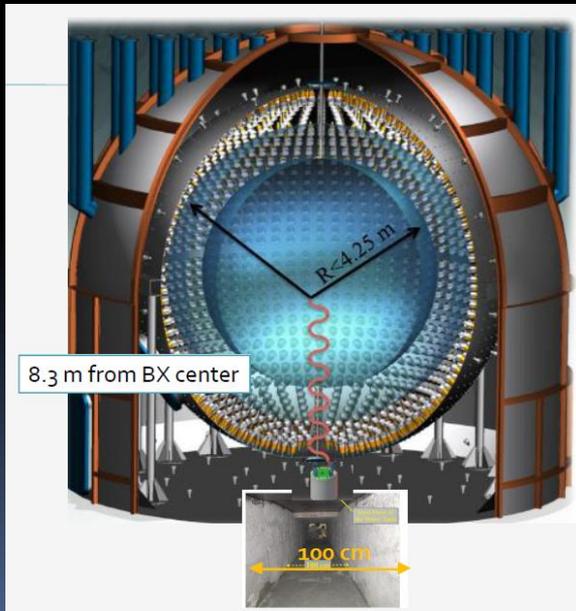
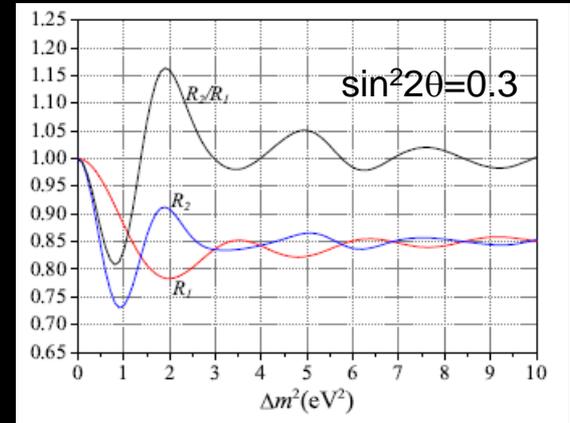


BEST

3 MCi ^{51}Cr source

Two-zone 50 t
liquid Ga metal target

J.Phys.Conf.Ser. 798 (2017) 012113



SOX

Ultra-low radioactive background

- Spatial resolution: 12 cm @ 2 MeV
- Energy resolution: ~3,5% @ 2 MeV

^{144}Ce - ^{144}Pr $\bar{\nu}_e$ source (100-150 kCi)

Source will be produced
at Mayak, Russia

Start data taking in 2018

PRD 91 (2015) 072005

