Neutrino oscillations: status and prospects of accelerator and reactor experiments

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OUTLINE

- Neutrino oscillations
- Recent oscillation results
  - Accelerators: T2K, NOVA
  - IceCube
  - Reactors: Daya Bay, RENO, Double Chooz
  - Search for CP violation
- Future oscillation experiments
  - JUNO
  - DUNE
  - HyperKamiokande
- Light sterile neutrinos
  - current status: pro et contra
  - coming results

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}

Physics beyond the Standard Model

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

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

$$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times10^{-3}\,\mathrm{eV}^2$$

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

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

$$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times10^{-5}\,\mathrm{eV}^2$$

two independent Δm^2

Physics beyond the Standard Model

Main goals of oscillation experiments

- CP violation in lepton sector

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

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

Strength of CP violation in neutrino oscillations

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu2}U^*_{e2}U^*_{\mu1}) = \mathrm{Im}(U_{e2}U_{\mu3}U^*_{e3}U^*_{\mu2})$$
$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

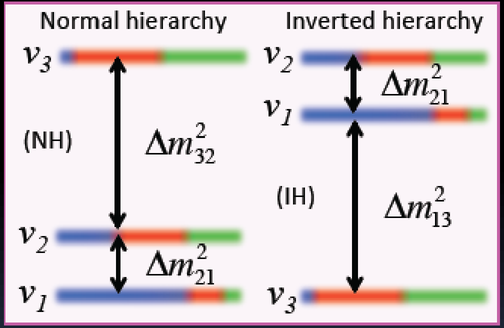
Quark sector $J_{CP} \approx 3\times10^{-5}$

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

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

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

- Neutrino mass hierarchy



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

Neutrino cross sections

- Sterile neutrinos

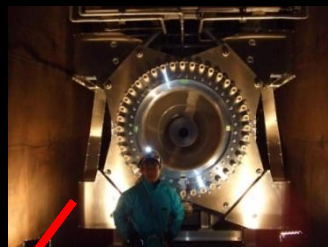
Current experiments

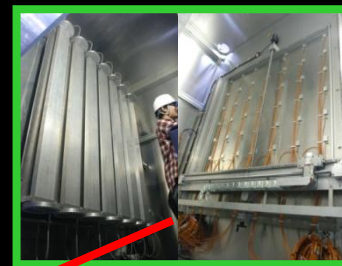
LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

about 500 members
59 institutions
from 11 countries

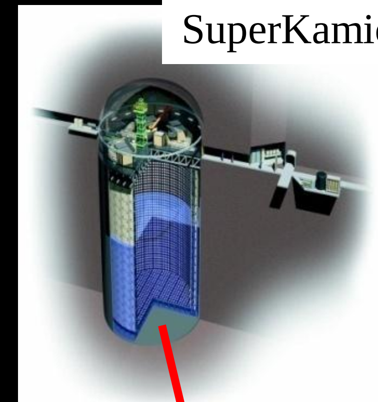
T2K experiment

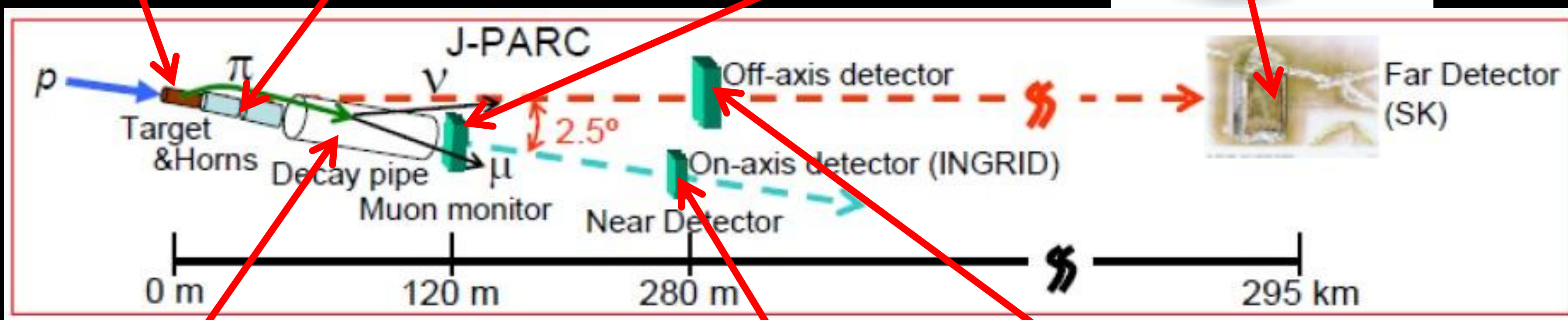
Data taking since 2010



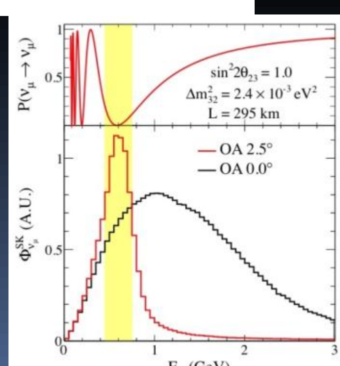


Far neutrino detector
SuperKamiokande

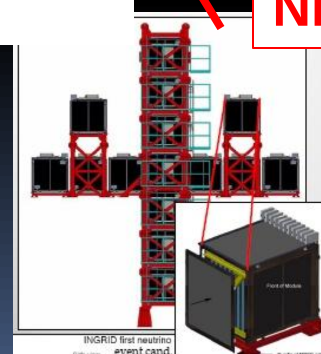




Off-axis neutrino
beam

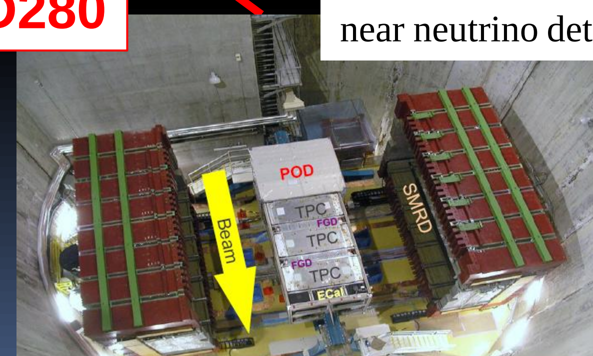


Neutrino monitor
INGRID



ND280

Off-axis
near neutrino detector



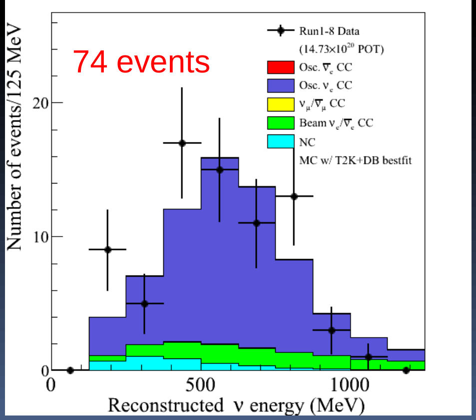
T2K: appearance

By Summer 2017

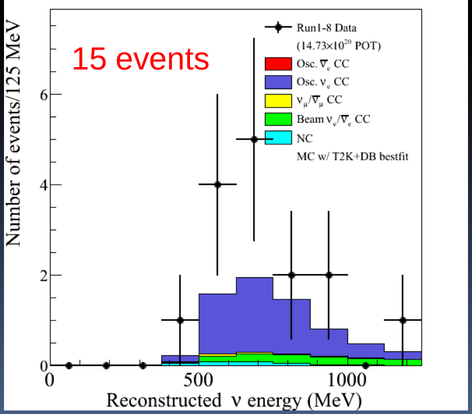
Neutrino beam 14.7×10^{20} POT
Antineutrino beam 7.6×10^{20} POT

Sample	Predicted events $\delta_{CP}=-\pi/2$	Predicted events $\delta_{CP}=0$	Predicted events $\delta_{CP}=\pi/2$	Predicted events $\delta_{CP}=\pi$	Observed events
CCQE 1-Ring e-like ν-mode	**73.5**	61.5	49.9	62.0	**74**
CC1π 1-Ring e-like ν-mode	**6.92**	6.01	4.87	5.78	**15**
CCQE 1-Ring e-like $\bar{\nu}$-mode	**7.93**	9.04	10.04	8.93	**7**
CCQE 1-Ring μ-like ν-mode	**267.8**	267.4	267.7	268.2	**240**
CCQE 1-Ring μ-like $\bar{\nu}$-mode	**63.1**	62.9	63.1	63.1	**68**

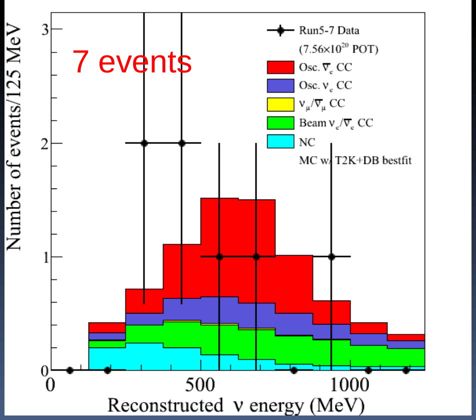
neutrino e-like



neutrino e-like + 1π

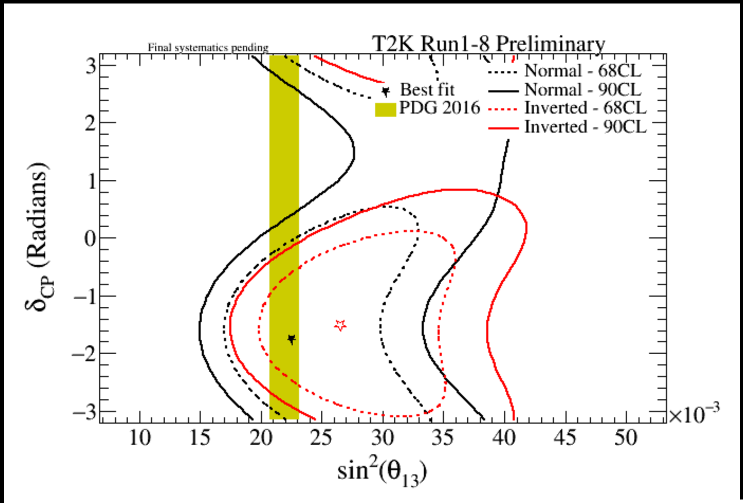


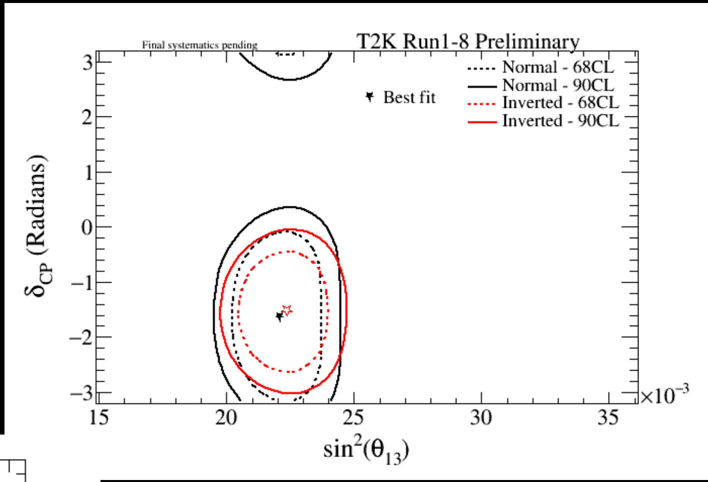
antineutrino e-like

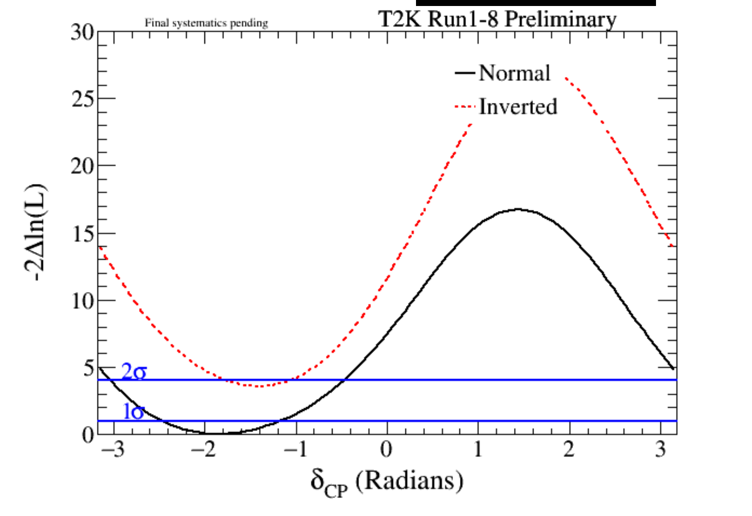


T2K: CP

M.Antonova, talk at ICPPA2017







- CP-conservation hypothesis ($\sin\delta_{CP}$ = 0 or π) **outside 2σ interval**

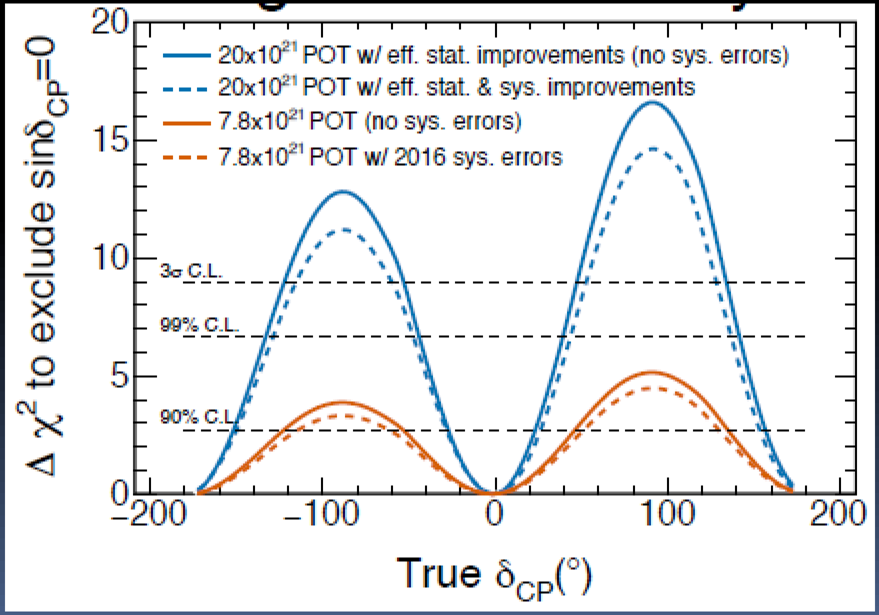
-Confidence intervals, rad: [- 2.49 – -1.23] (NH, 1σ) [-2.98 - -.60] (IH, 2σ)

T2K data favour $\delta_{CP} \sim -\pi/2$ and normal hierarchy

T2K: future plan

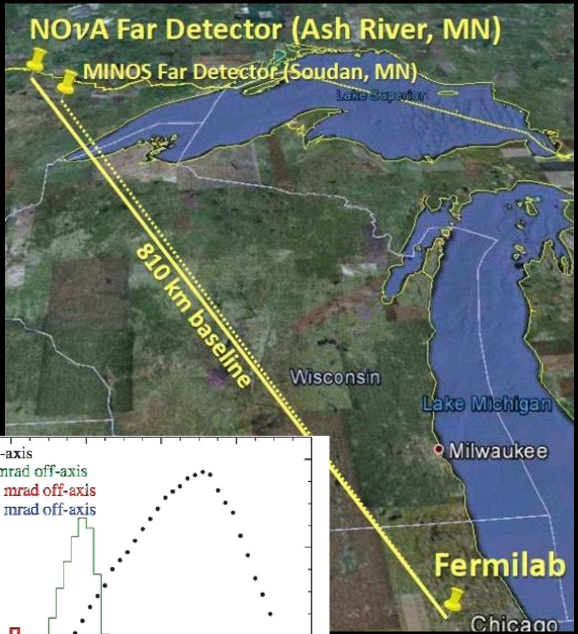
T2K expected to accumulate 7.8x10^{21} POT around 2021

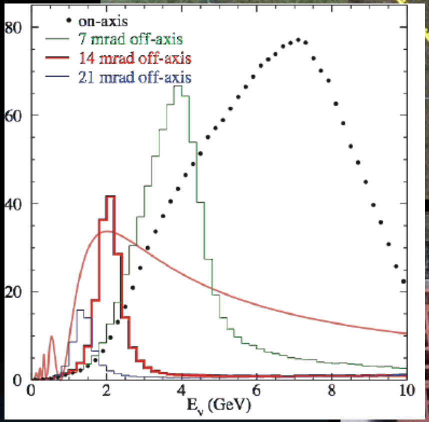
- Upgrade of near detectors to improve systematic uncertainties
  18% (2011) → 9% (2014) → 6% (2016) → goal 4% (2020)
- Plan to increase the beam intensity up to 1 MW in 2021
- Beam power up to 1.3 MW in ~2026
- T2K-II: proposed extension up to 2026 for 20x10^{21} POT
  3σ sensitivity to CP violation for $\delta_{CP} \sim -\pi/2$

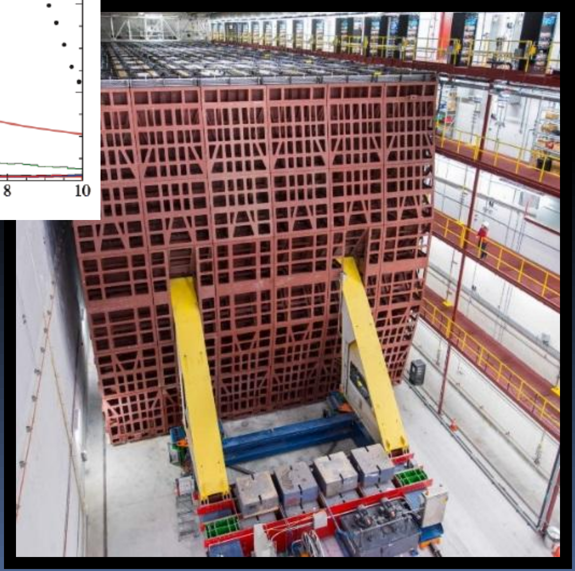


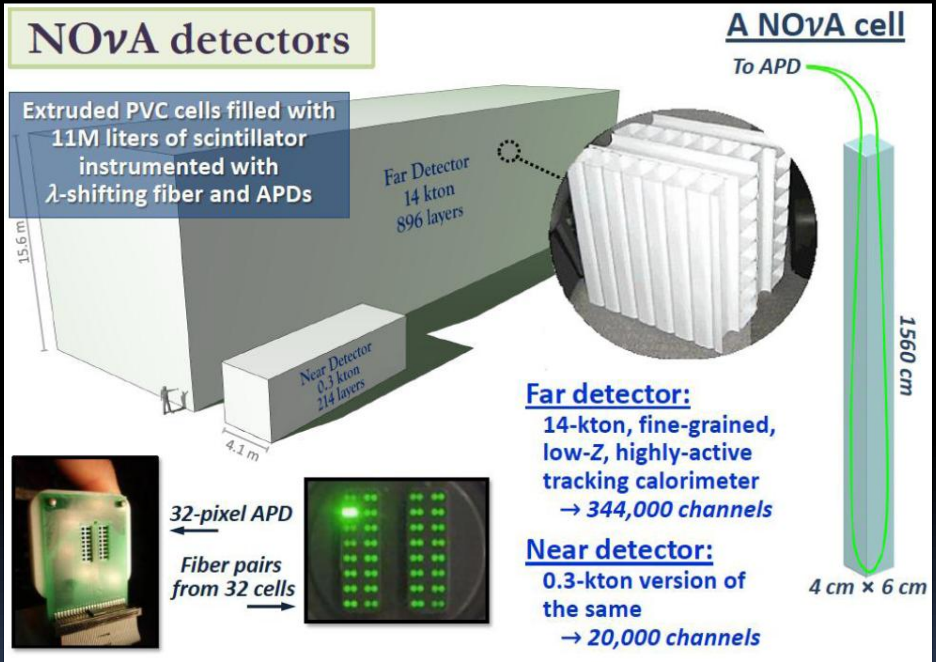
NOVA

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

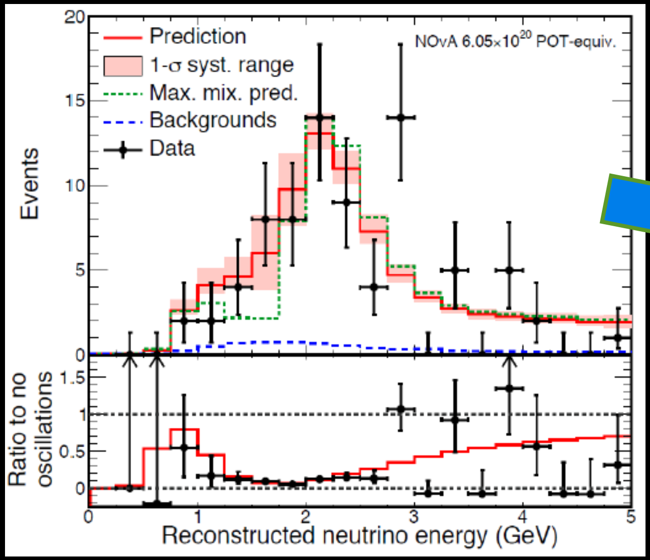
NOvA results

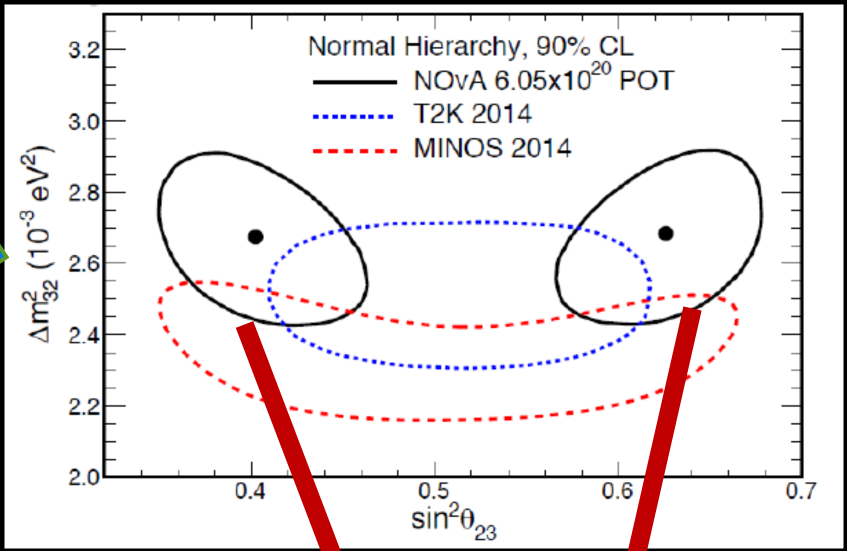
ν_μ disappearance

PRL 118 (2017)151802

473 ±30 events expected w/o oscillations
78 events observed

Neutrino mode 6.05x10^5 POT

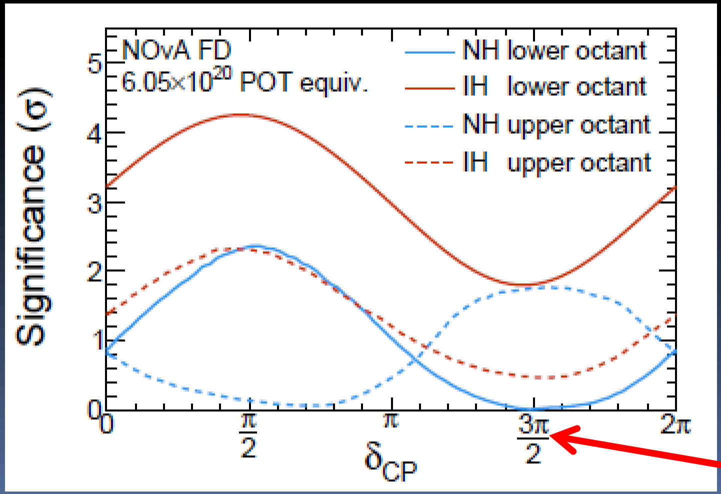




PRL 118 (2017) 231801

ν_e appearance

33 events detected
8.2 background



-π/2 in T2K notation

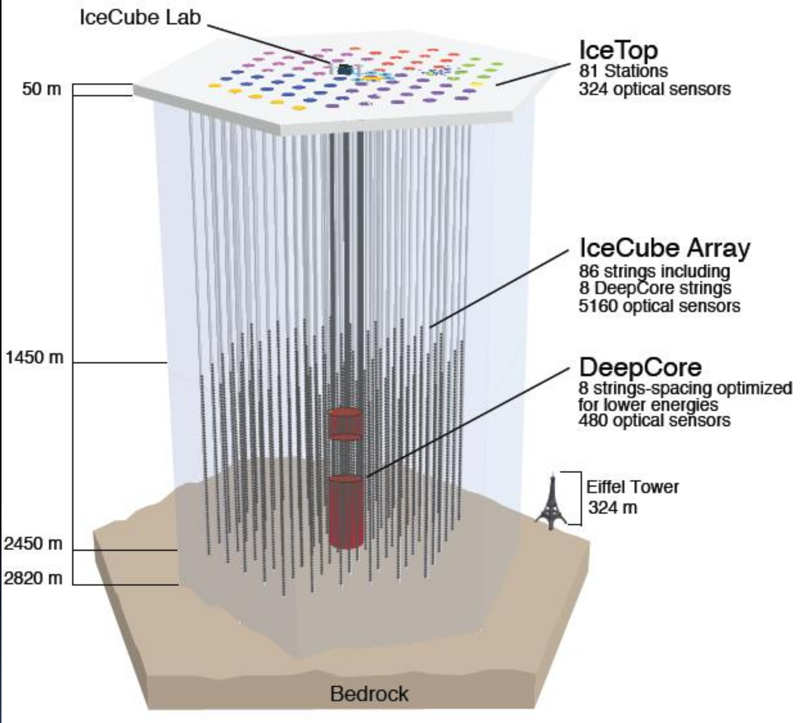
Maximal mixing disfavored at 2.6 σ

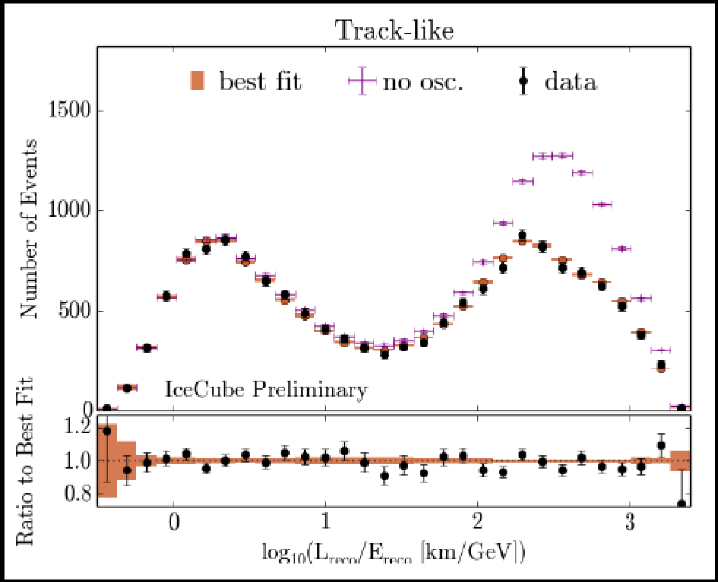
NOvA runs with anti-ν_μ beam since February 2017

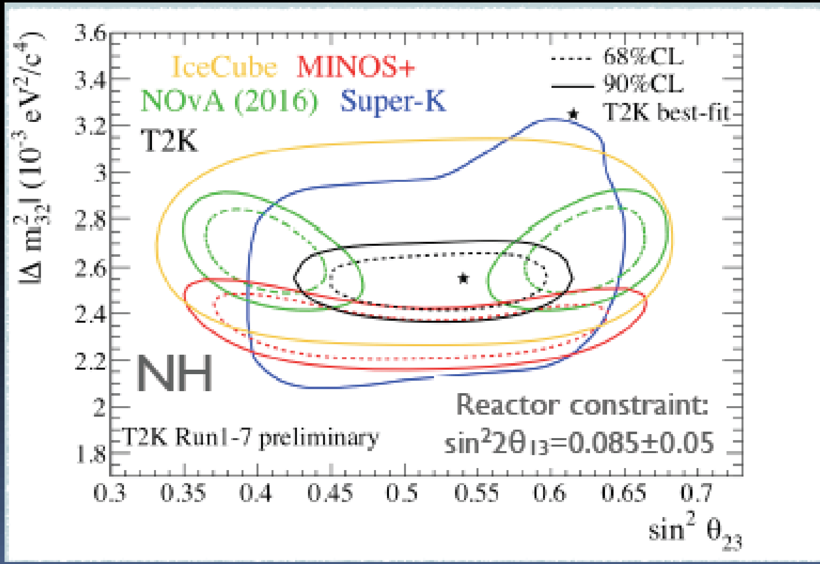
IceCube

J.Hignight, talk at CoSSURF 2017

Neutrinos have the first maximum of disappearance at about 25 GeV







Reactor experiments

Daya Bay, China

17.4 GW

RENO, Korea

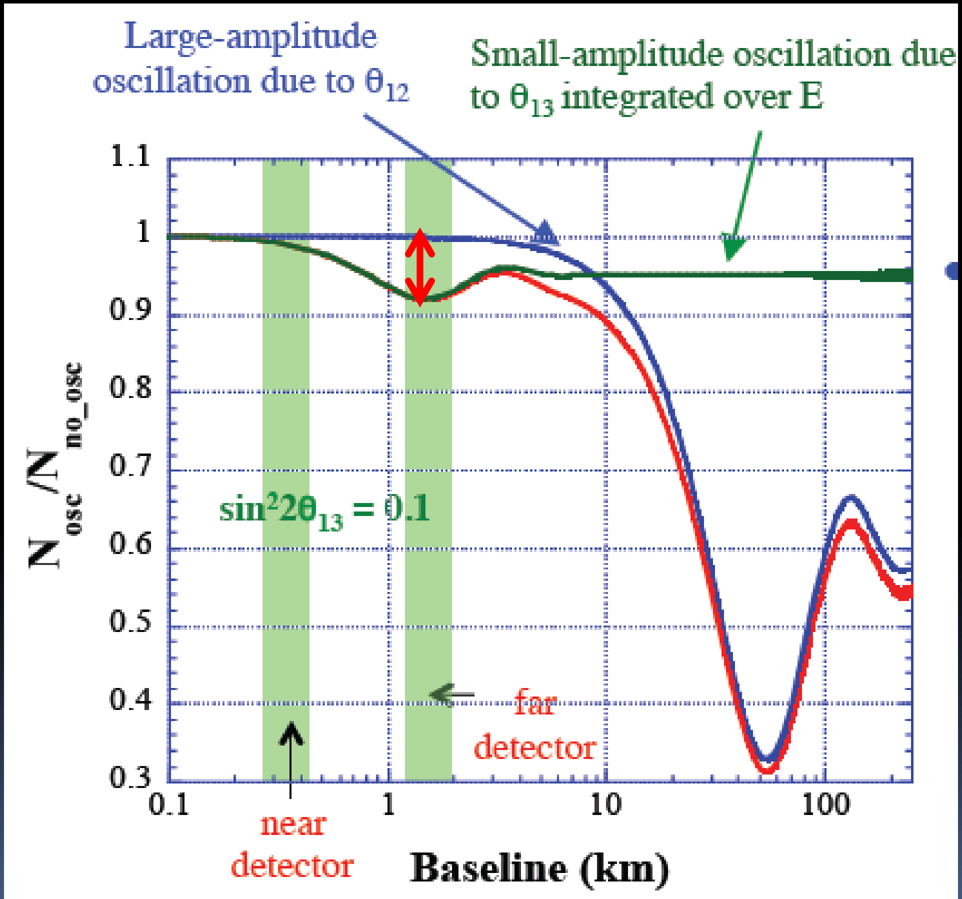
16 GW

Double Chooz, France

8.5 GW

Measurement of θ_{13}

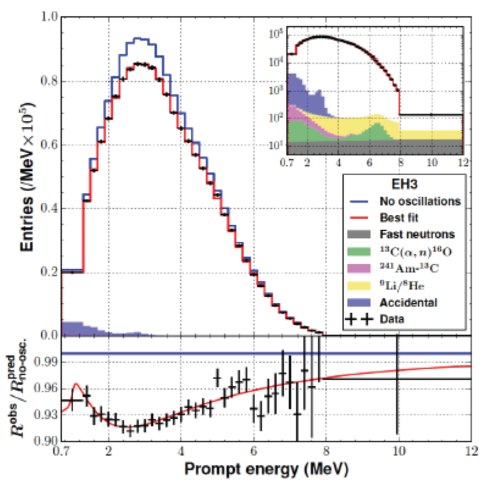
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

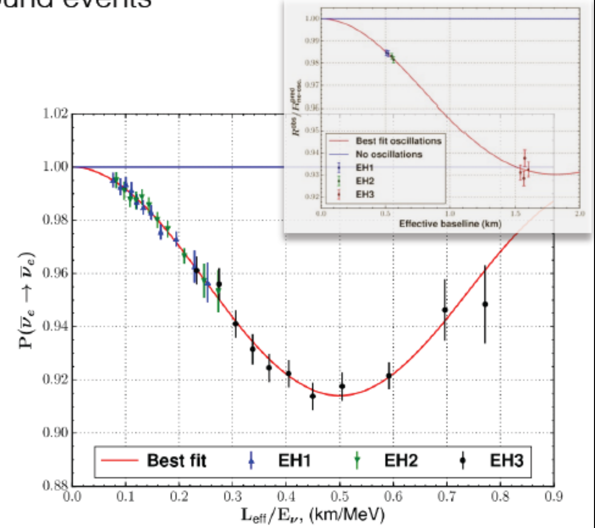


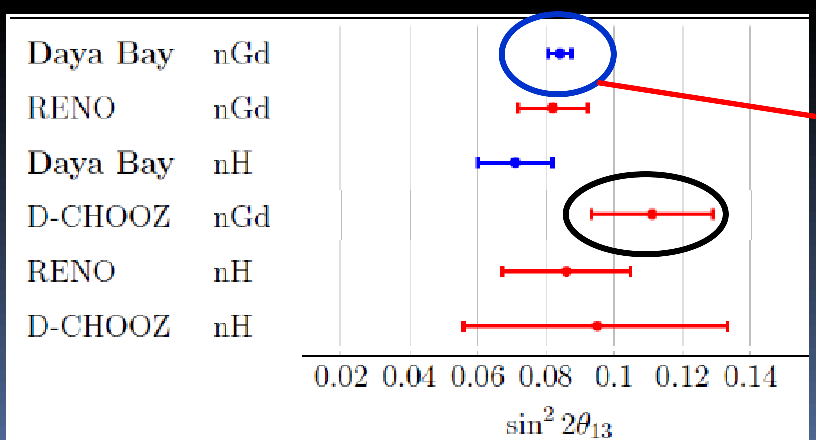
θ_{13} from reactors

- nGd 1230 days
  - 217 days of full 6-AD data set
  - 1013 days of 8-AD data sample
  - Improved energy response model and energy calibration
  - Reduced uncertainties in background events

Daya Bay







$\sin 2\theta_{13} = 0.085 \pm 0.05$

$\theta_{13} = 8.4$ deg

Future LBL Projects

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

Reactor experiment JUNO

China

66 institutions
> 500 collaborators

Start data taking in 2020

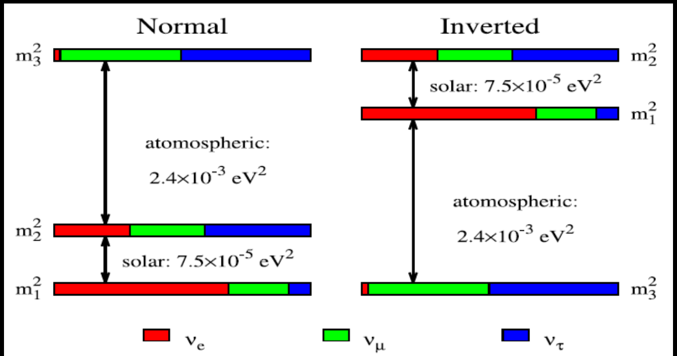
Main target:
Measurement of
neutrino mass hierarchy

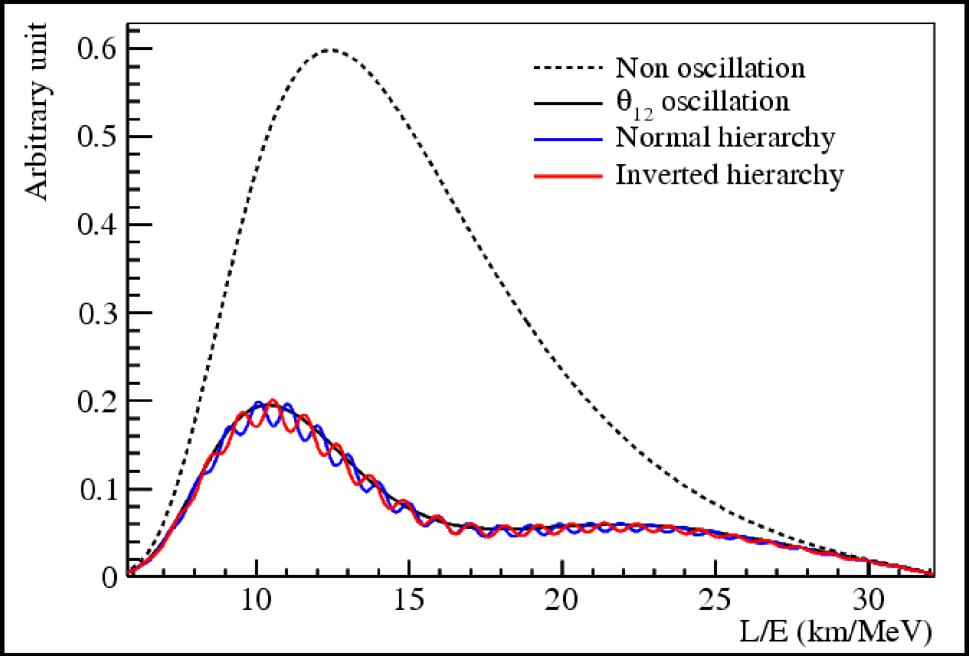
- **700 m deep underground**
- **36 GW reactor power**
- **53 km baseline -> oscillation maximum θ_{12}**
- **20 kton LS detector**
- **3% energy resolution at 1MeV**
- **<1% energy scale uncertainty**

!?

JUNO targets

Main goal: determination of neutrino mass hierarchy





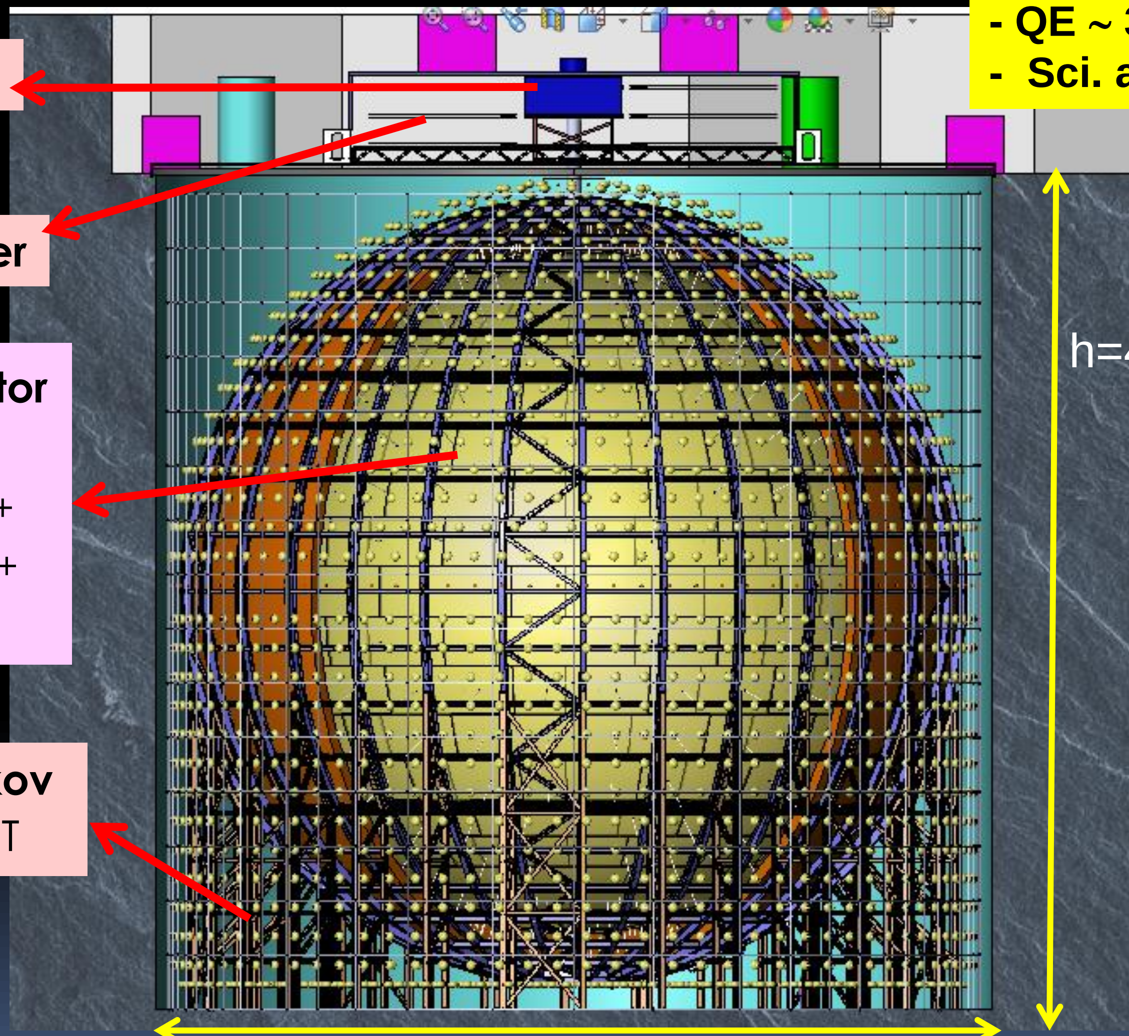
PRD 88, 013008 (2013)	Hierarchy discrimination power	With info on $\Delta m^2_{\mu\mu}$ from LBL expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ

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**



LBNF/DUNE Project

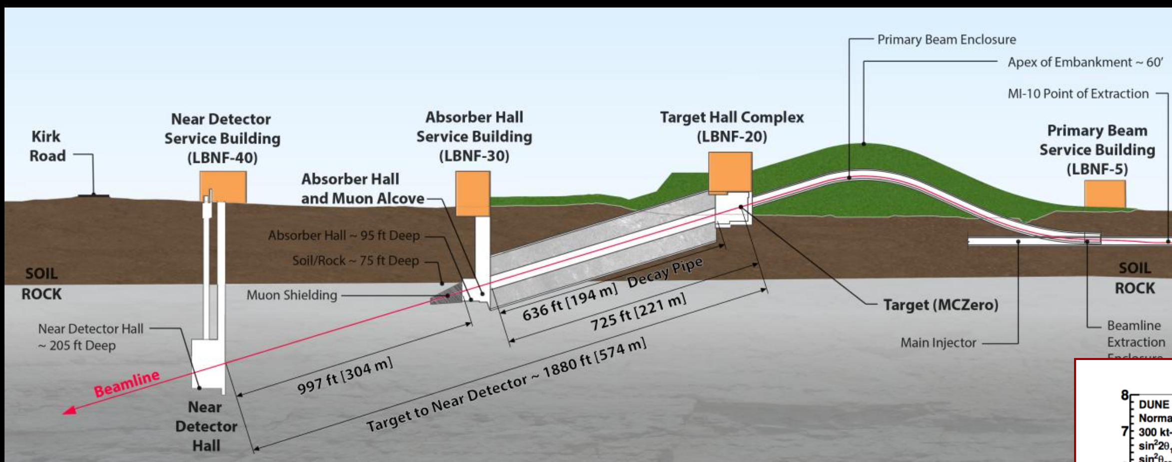
Groundbreaking ceremony at SURF - July 2017

Flagship FNAL project

30 countries
161 institutions
≥1000 collaborators

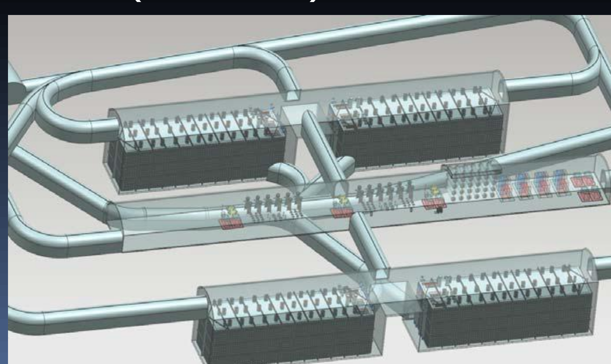
Main goals:
- **discovery of CP violation in leptonic sector**
- **neutrino mass hierarchy at >5σ level**
- **neutrino astronomy**
- **proton decay search**

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

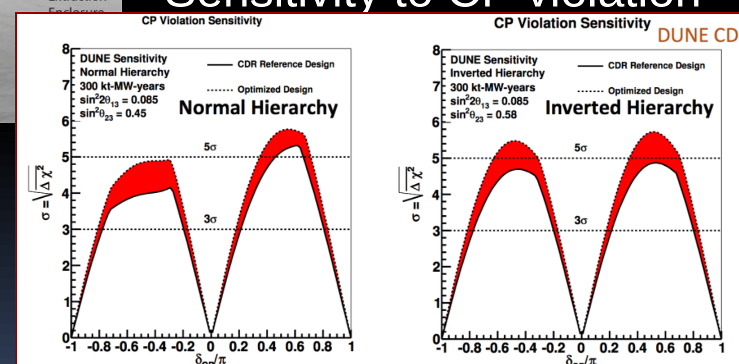


Far detector 40 kt (4 x 10kt) LAr TPC

Single and **Dual** phase detectors

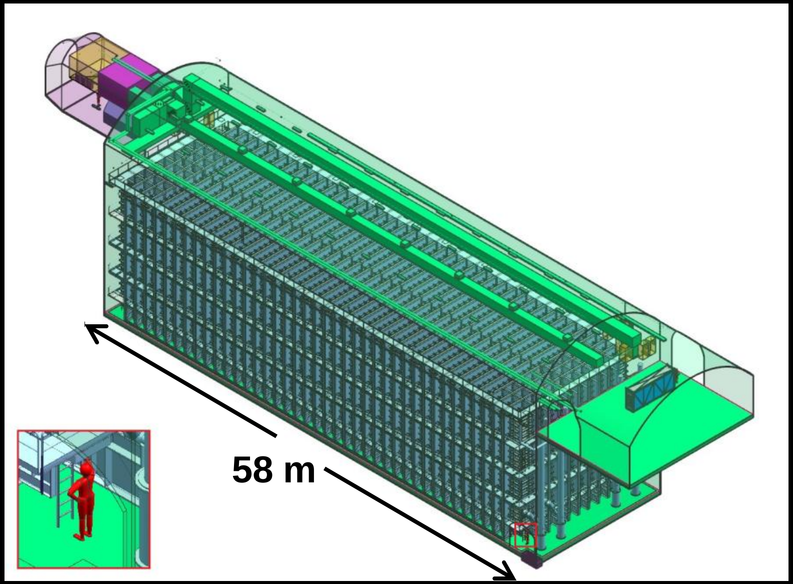


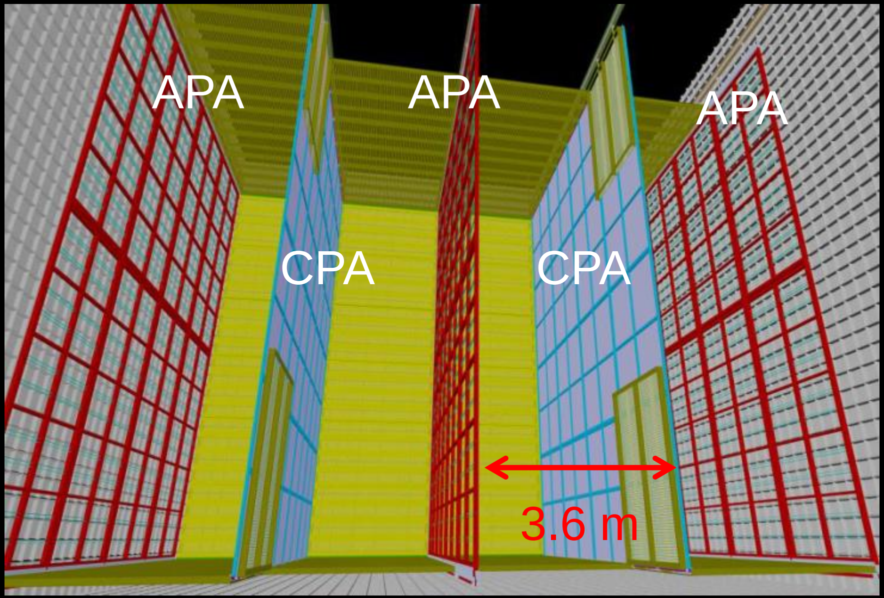
Sensitivity to CP violation



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

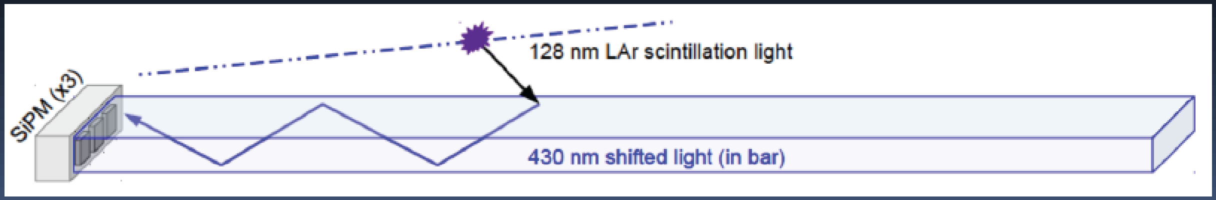
Single-phase LAr TPC





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

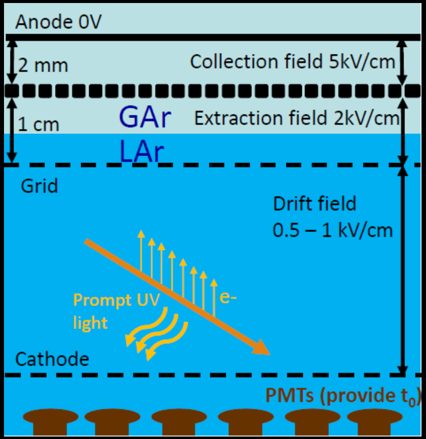
J.Insler, talk at LLWI2017



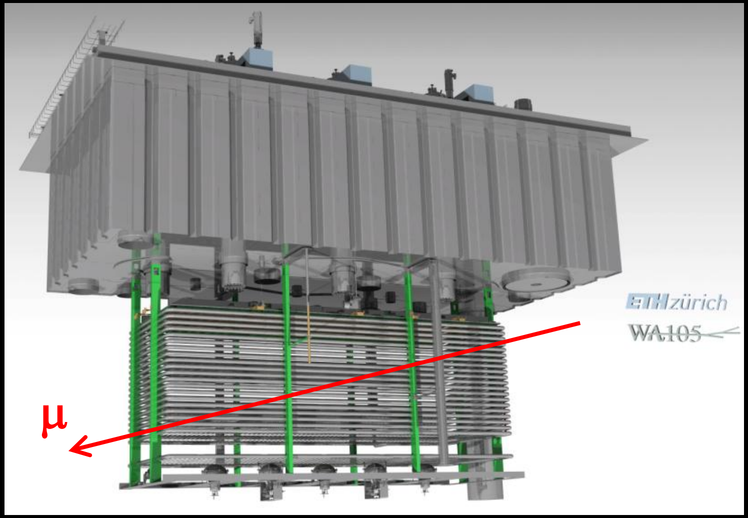
LAr detectors at CERN Neutrino Platform

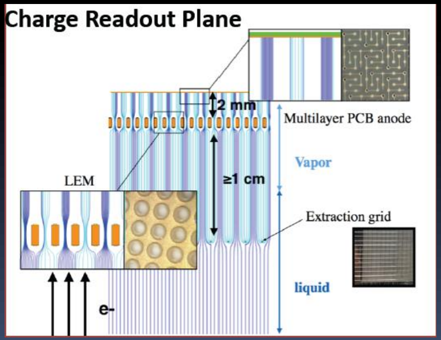
S.Murthy, talk at TPC-2016

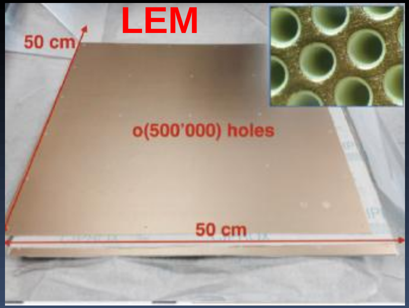
NP02: WA105
(DP demonstrator + ProtoDUNE DP)



Demonstrator: 3x1x1 m^3 – 5 tons

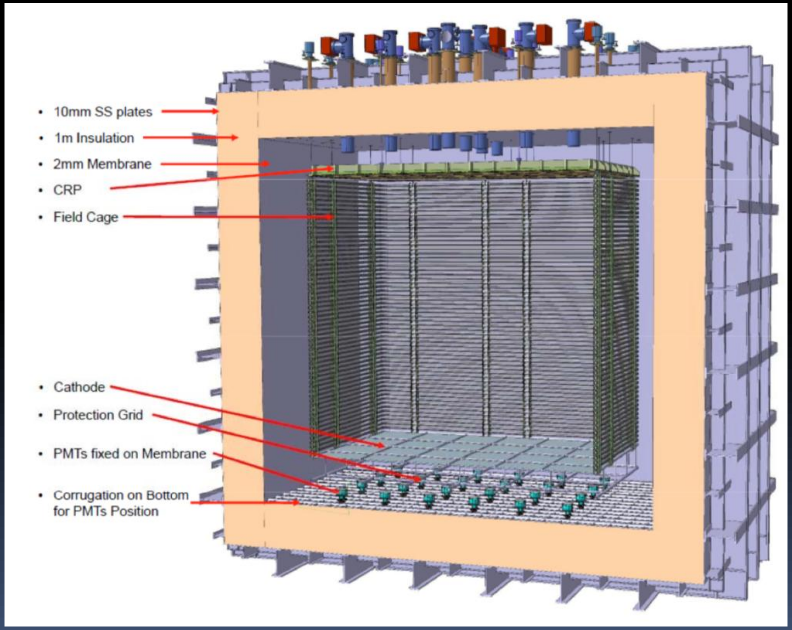






Cosmic data taking

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



Measurements with test beam in 2018

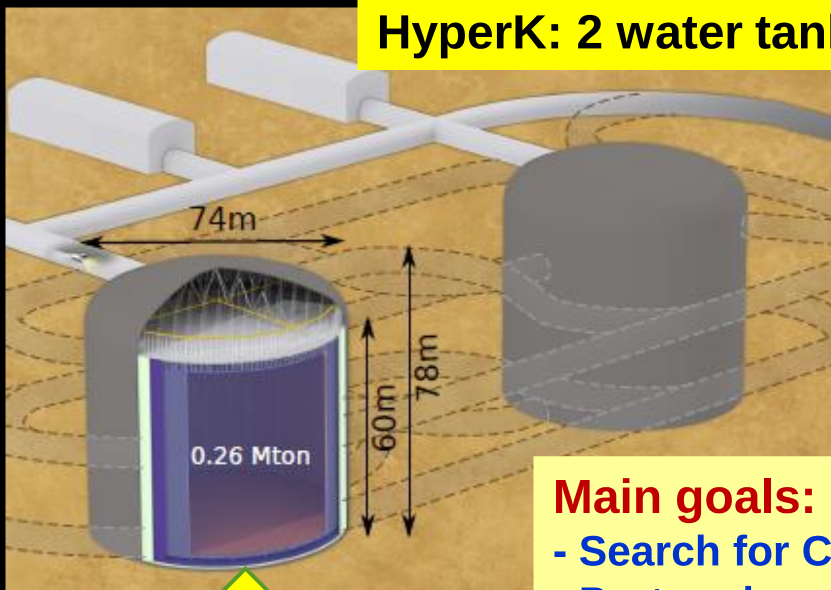
HyperKamiokande

Japan

Included in the MEXT Large Projects Roadmap in August 2017

12 countries
70 institutes
~300 members
Expected data taking start 2026

HyperK: 2 water tanks

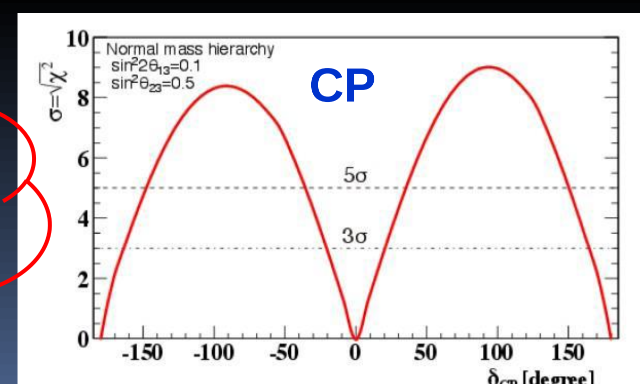


- Upgrade of JPARC to 1.3 MW beam power
- New/upgrade of near neutrino detectors

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

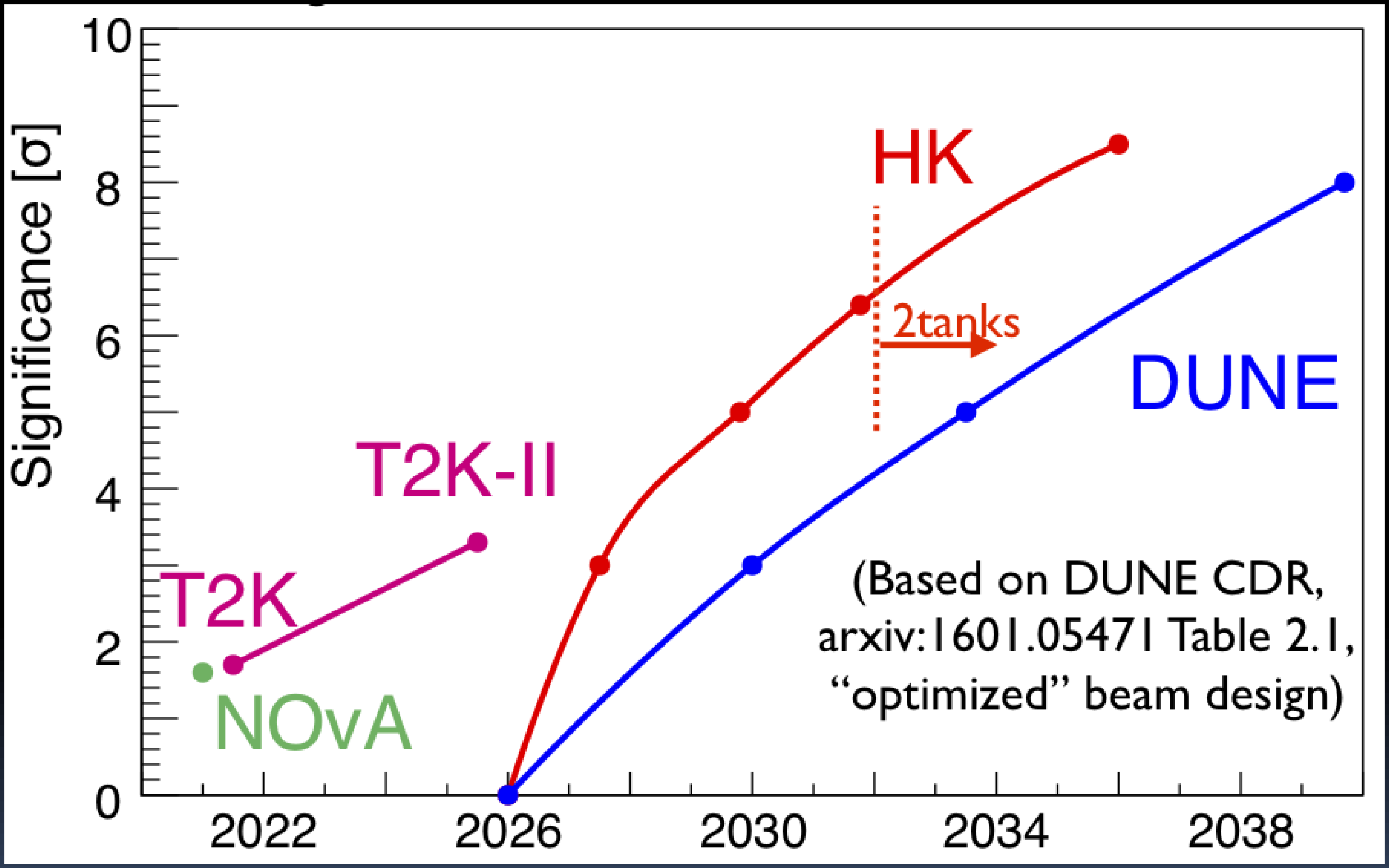
1 tank
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt
~10xSuperK
PMT coverage 40%
40000 PMTs

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



Expected sensitivity to CP

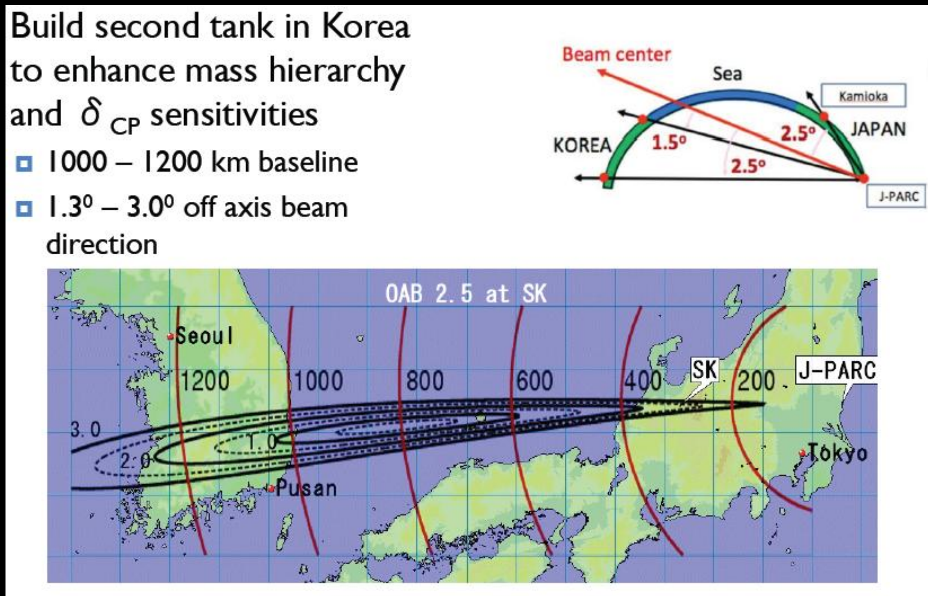
Significance for δ_{CP} = - π/2



T2HKK

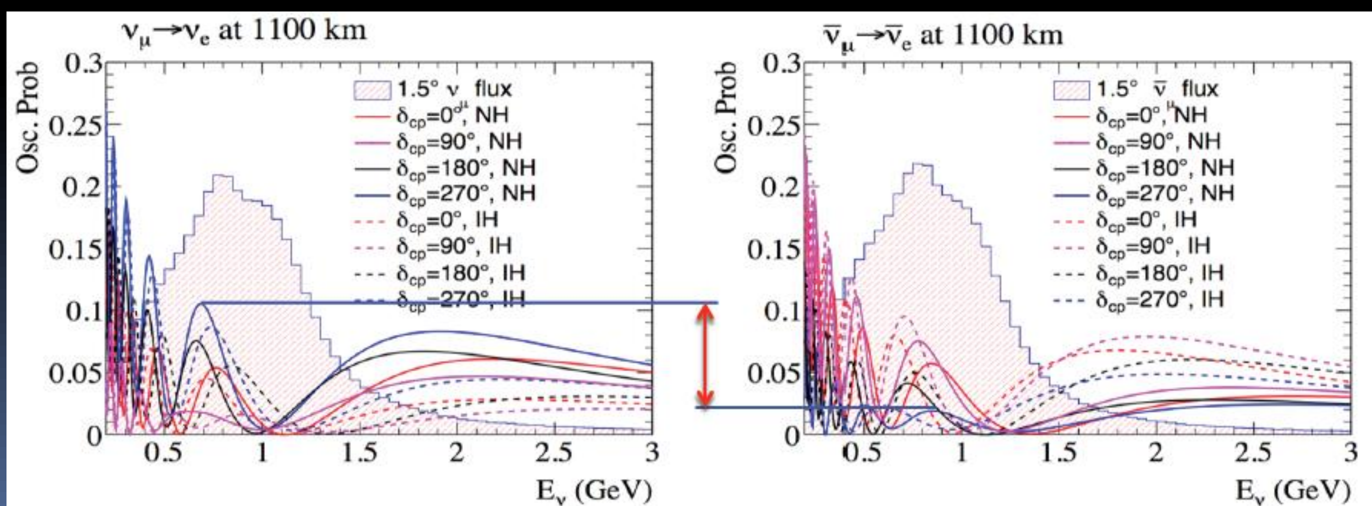
Second tank in Korea

arXiv:1611.06118



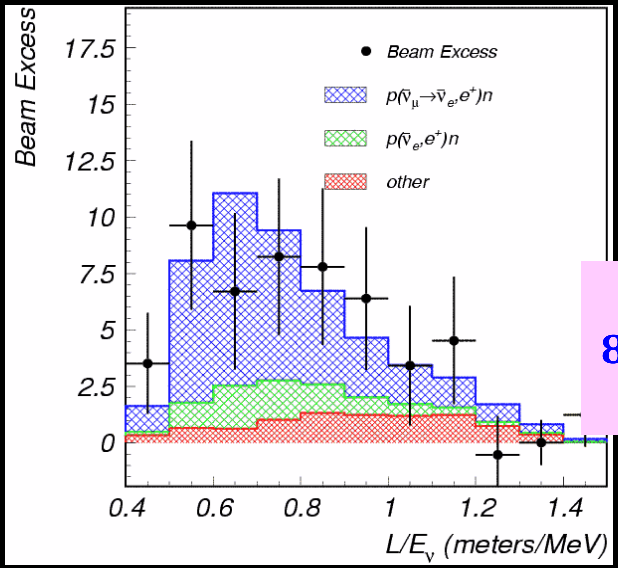
Neutrino and antineutrino
spectra in T2HKK
cover 1st and 2nd oscillation maximum

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



Sterile neutrinos

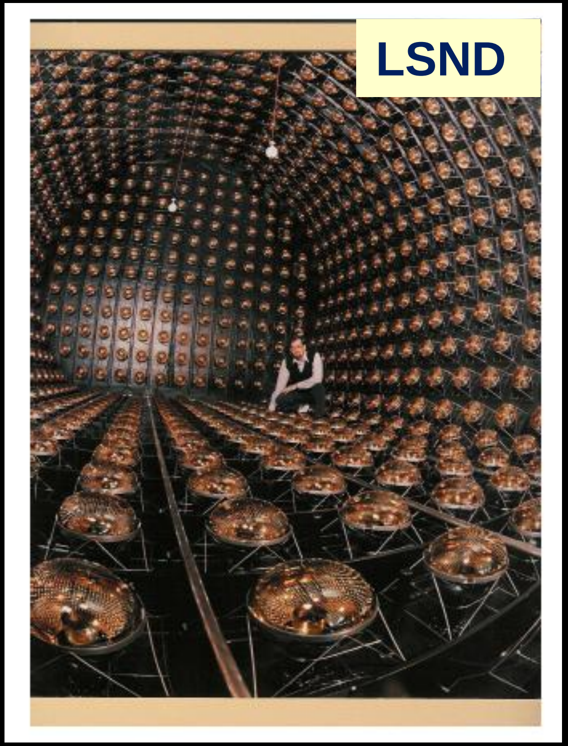
LSND

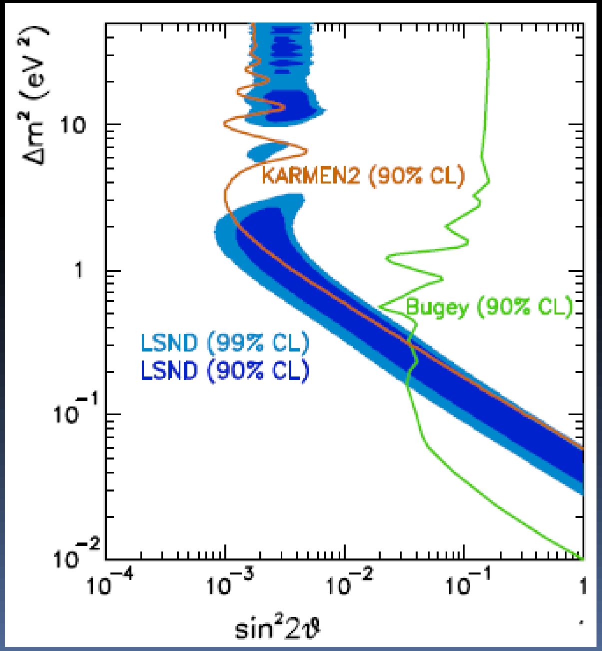


anti-ν_μ → anti-ν_e

87.9 ± 22.4 ± 6.0 events

Excess 3.8σ



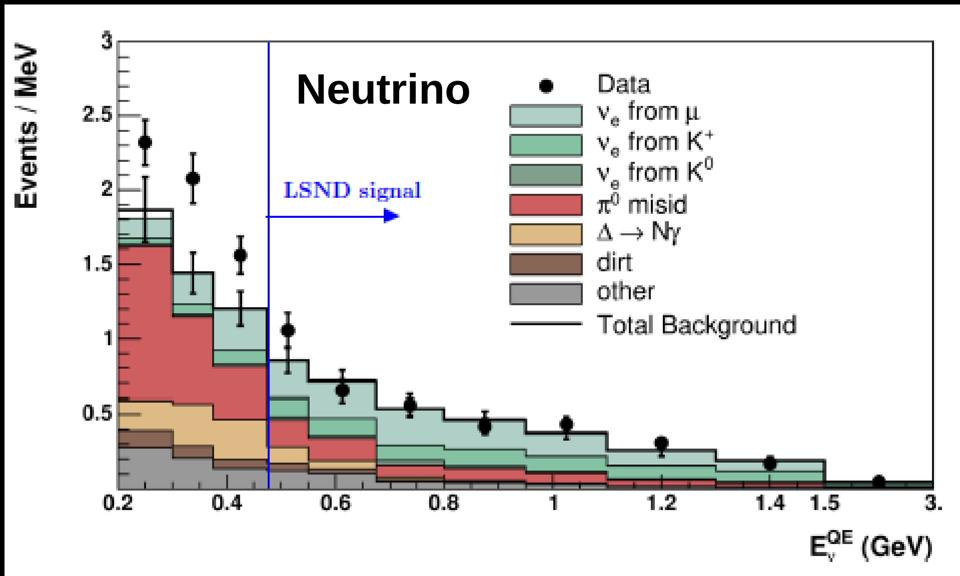


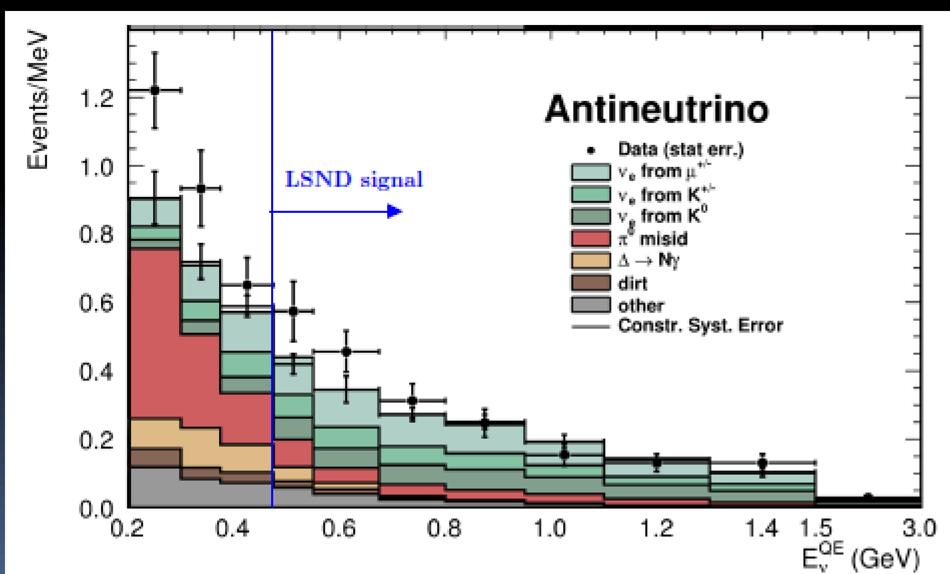
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right) = 0.245 \pm 0.067 \pm 0.045\ \%$$

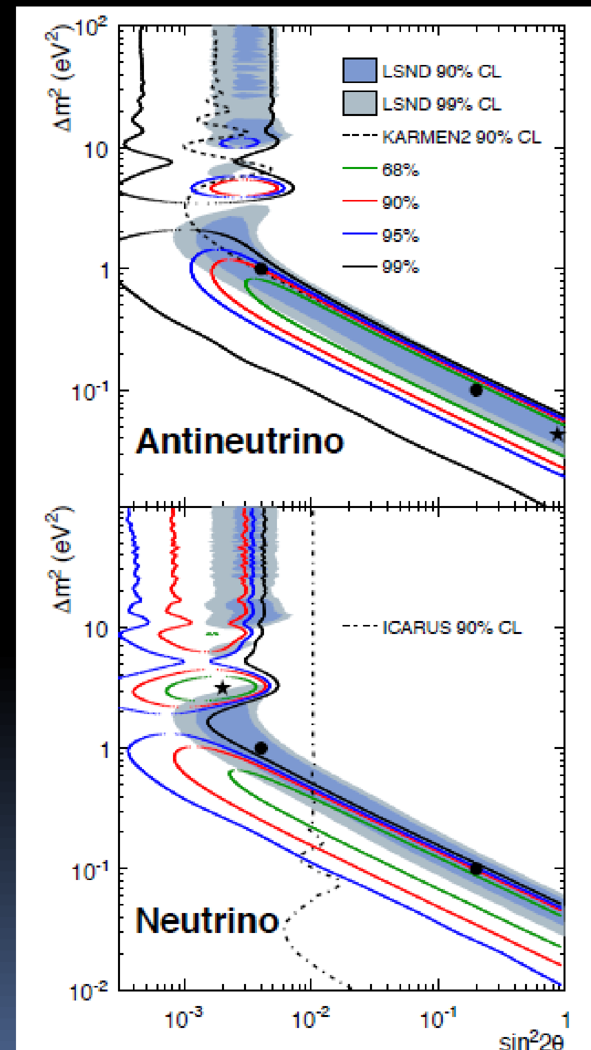
$$0.2 \leq \Delta m^2 \leq 1\ \text{эВ}^2 \qquad 2\times 10^{-3} \leq \sin^2 2\theta \leq 4\times 10^{-2}$$

MiniBooNe

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

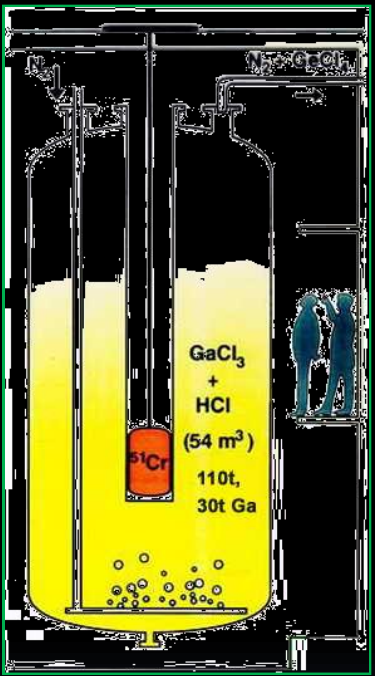


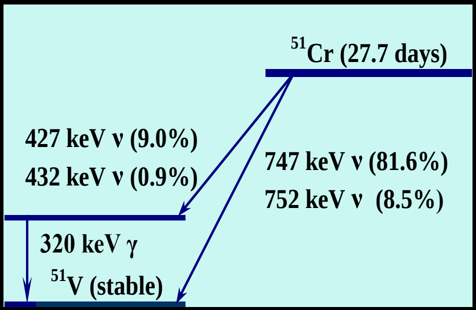


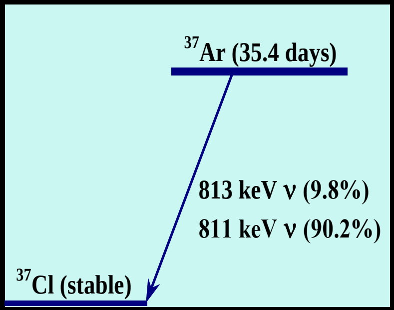


Gallium anomaly

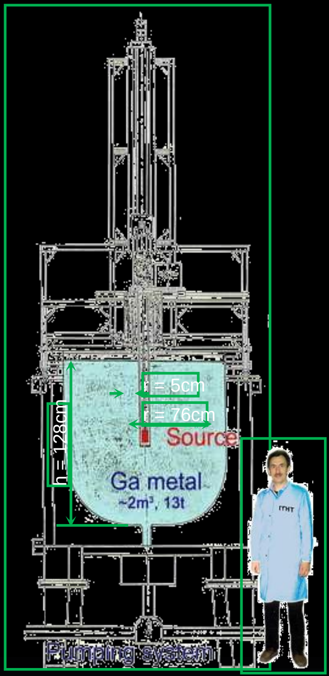
GALLEX





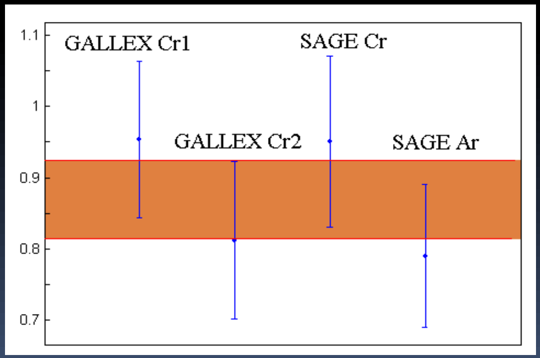


SAGE



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

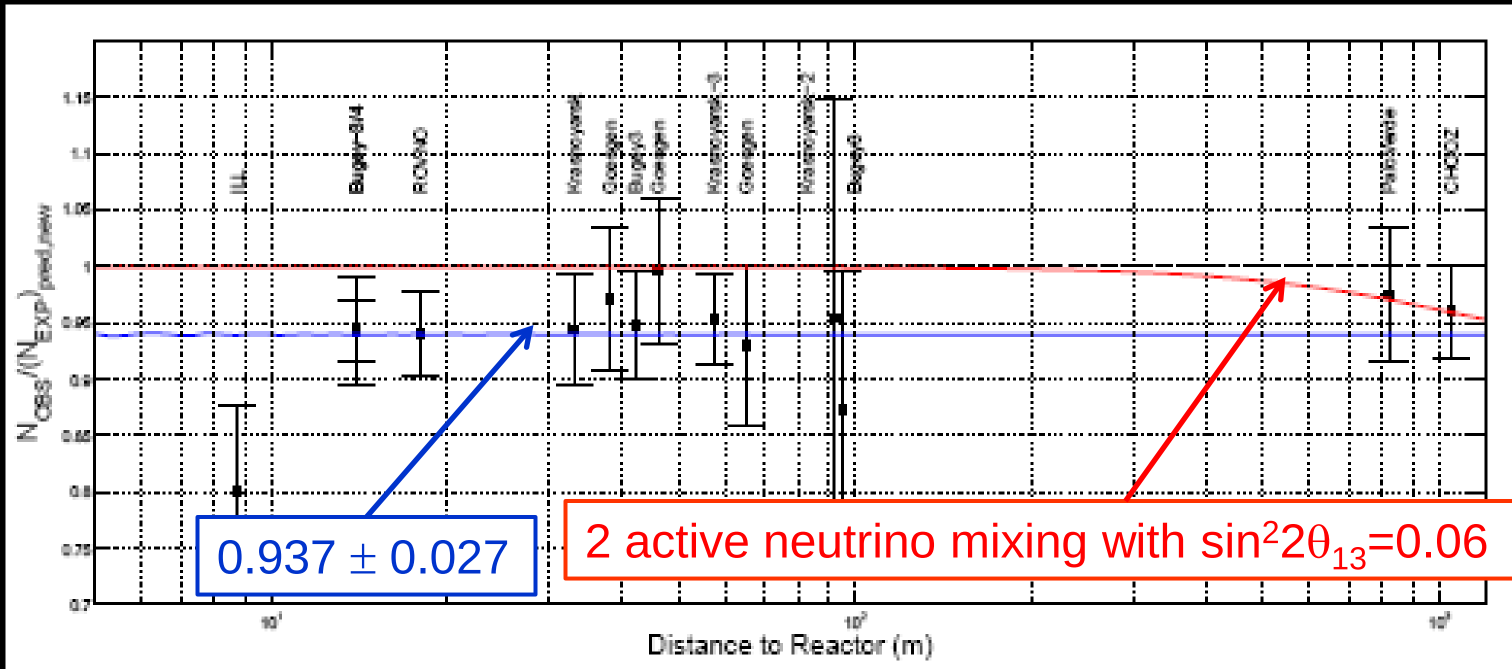
	GALLEX m(Ga)=30 t		SAGE m(Ga)=13 t	
Source	^{51}Cr -1	^{51}Cr -2	^{51}Cr	^{37}Ar
Intensity (Mci)	1.714	1.868	0.517	0.409
$R = (p_{exp}/p_{theory})$	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.10
R_{comb}	0.88 ± 0.08		0.86 ± 0.08	

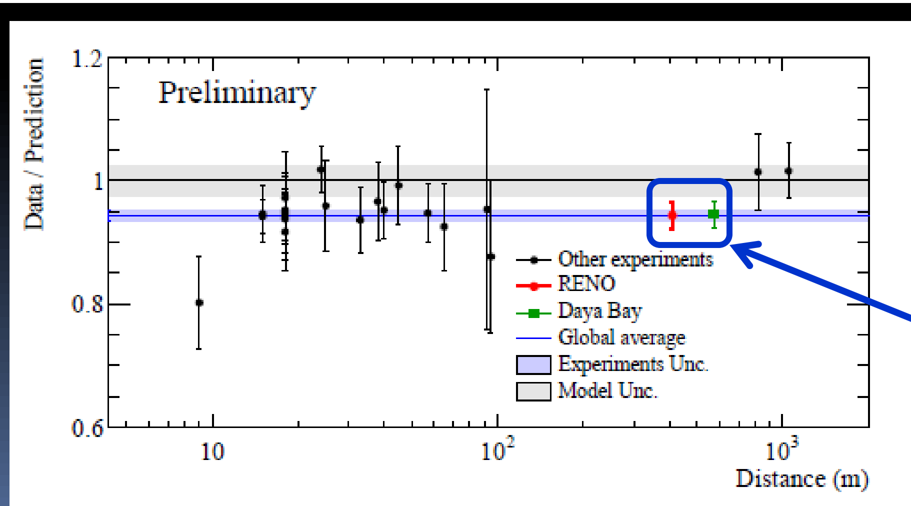


$$R = p_{exp}/p_{theory} = 0.87 \pm 0.05$$

Reactor anomaly

anti-$\nu_e \rightarrow$ anti-ν_e



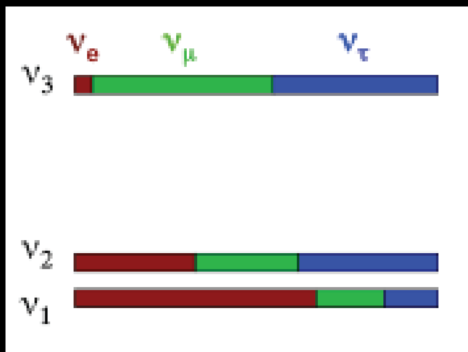


S.Gariazzo et al
arXiv:1703.08860

Daya Bay and RENO

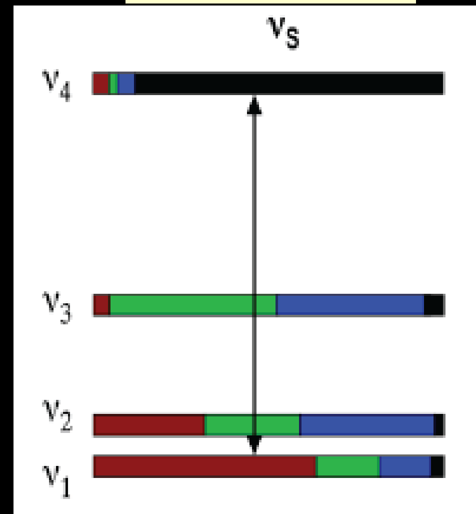
Sterile neutrino?

3ν



?

3ν + 1s



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

PNMS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s1} & U_{s1} & U_{s1} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

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

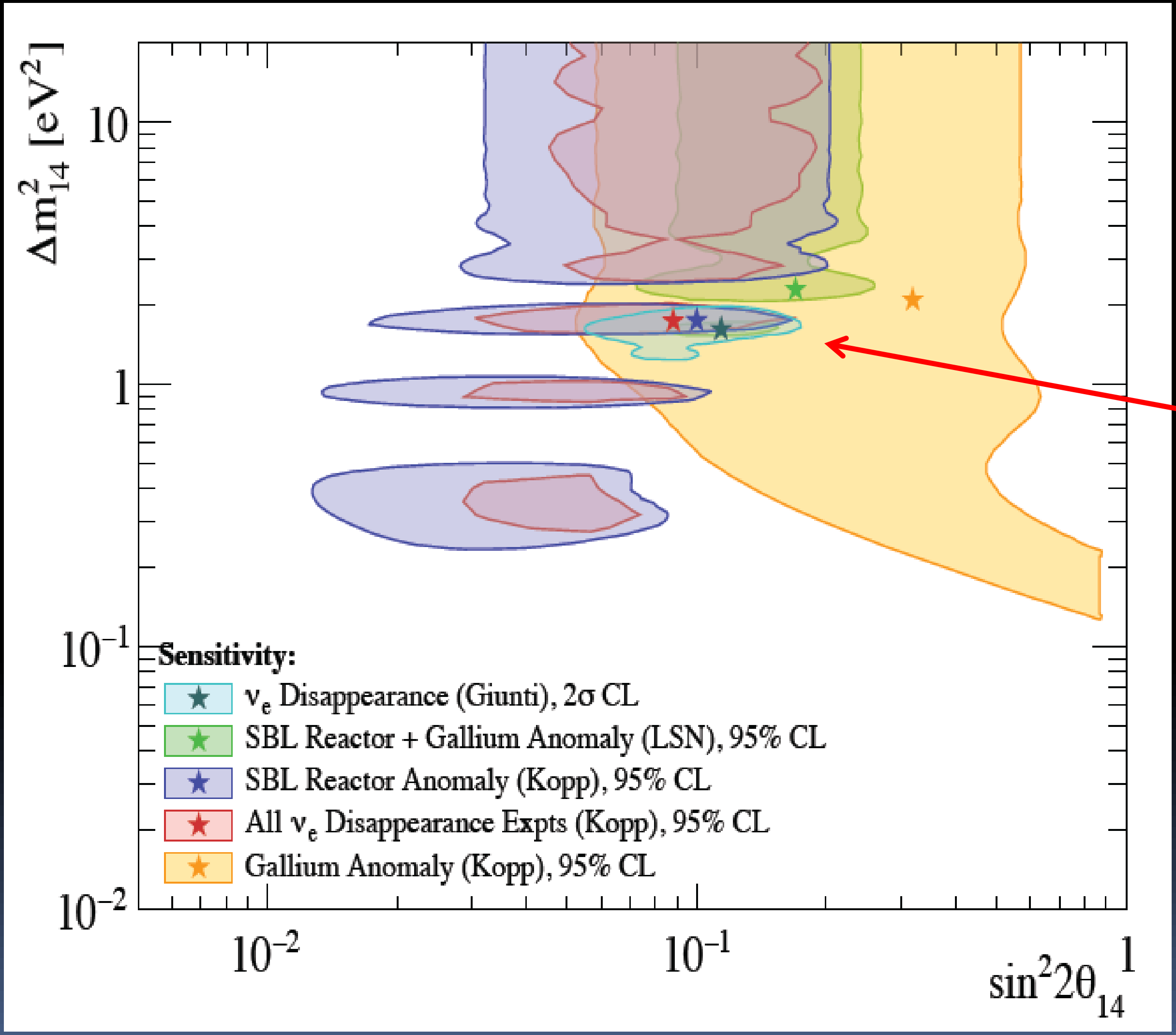
$$|U_{\mu 4}|^2 = \sin^2\theta_{24} \cdot \cos^2\theta_{14}$$

$$|U_{\tau 4}|^2 = \sin^2\theta_{34} \cdot \cos^2\theta_{24} \cdot \cos^2\theta_{14}$$

ν_e and anti-ν_e disappearance

arXiv:1512.02202

Global fit of reactor and Gallium data



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

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

Hunting for sterile neutrinos

Accelerator

MINOS
SBN at FNAL

Reactor *(running or under construction)*

Daya Bay, RENO, Double Chooz
DANSS
Neutrino-4
NEOS
STEREO
Solid
PROSPECT
NuLat

Neutrino sources

BEST
SOX

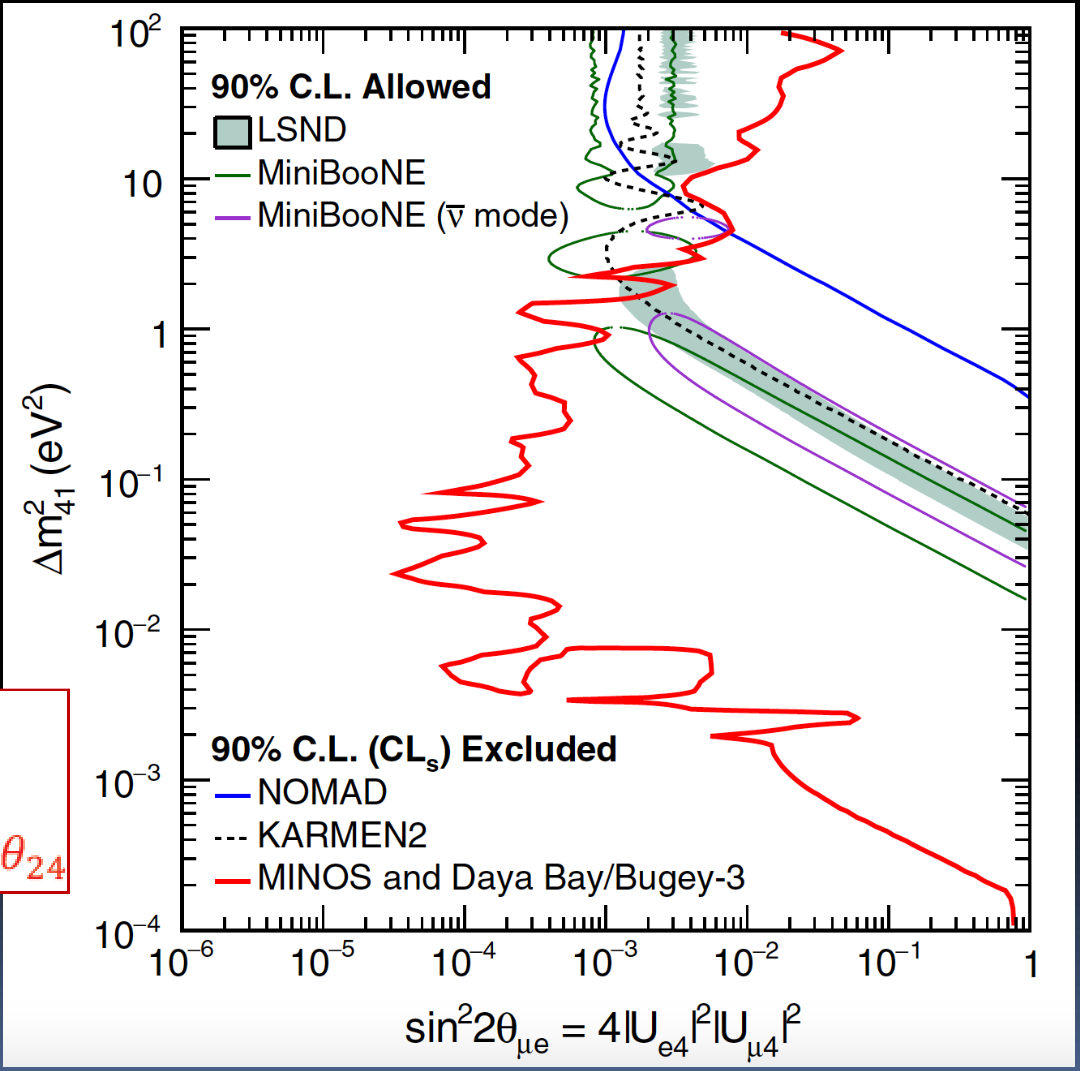
Atmospheric neutrinos

SuperKamiokande
IceCube

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

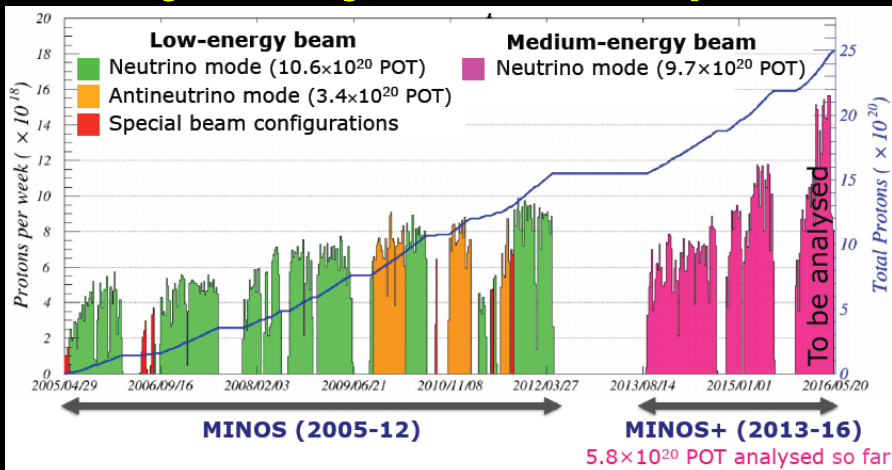
- Daya Bay data
  - Constrains Δm^2_{41}(mainly 10^{-4} to 10^{-1} eV²) and $\sin^2 2\theta_{14}$
- Bugey-3 data
  - constrains Δm^2_{41} (mainly 10^{-1} to 10 eV²) and $\sin^2 2\theta_{14}$
- MINOS data
  - Constrains Δm^2_{41} (mainly 10^{-3} to 10^2 eV²) and $\sin^2 \theta_{24}$

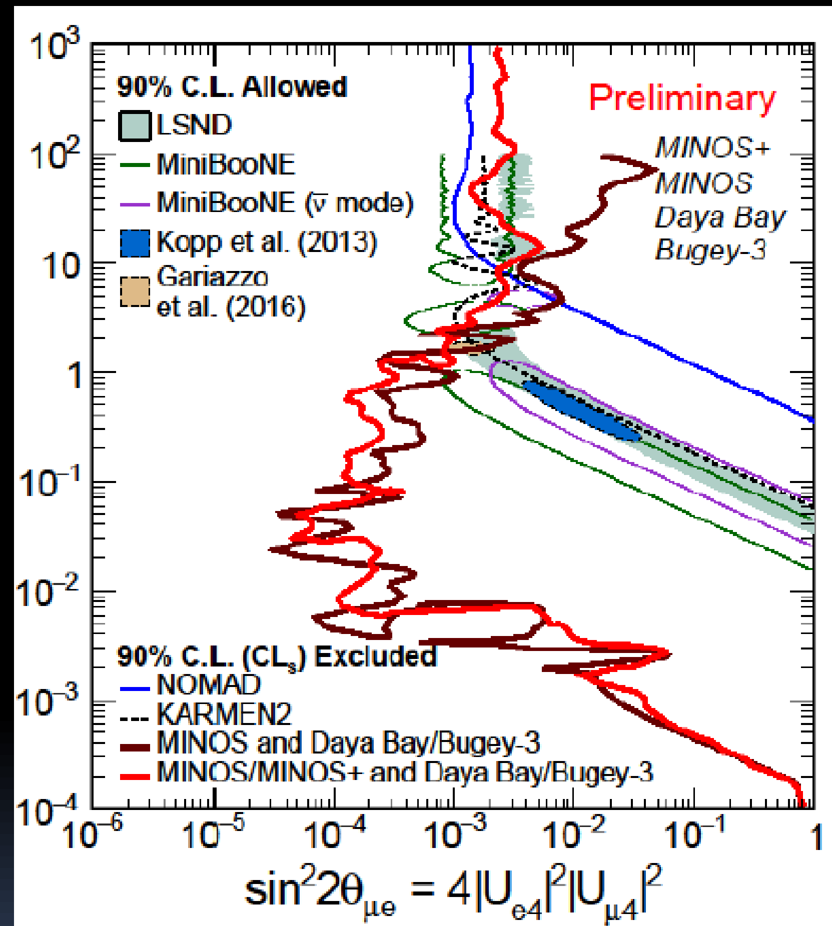
- Combined all three
  - Constrains Δm^2_{41} and $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \cdot \sin^2 \theta_{24}$

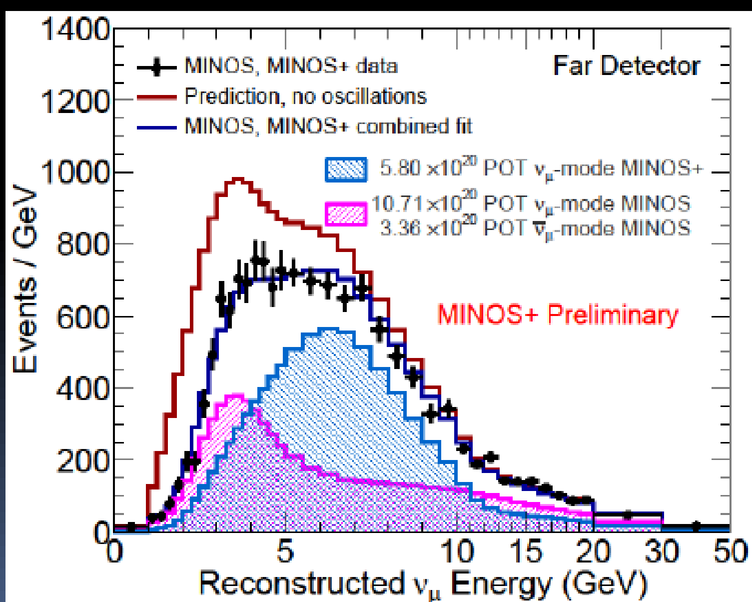


Sterile ν's:
Daya Bay + MINOS/MINOS$^+$ + Bugey-3

A.Blake, talk at NuFact 2017, September 2017







No evidence for 3+1 sterile neutrino oscillations

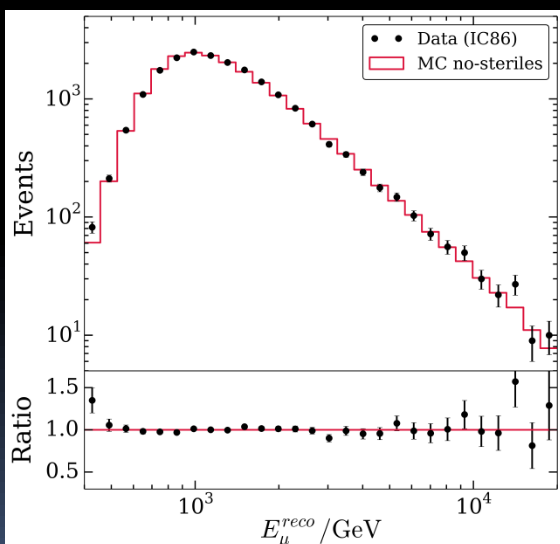
Sterile ν's: IceCube

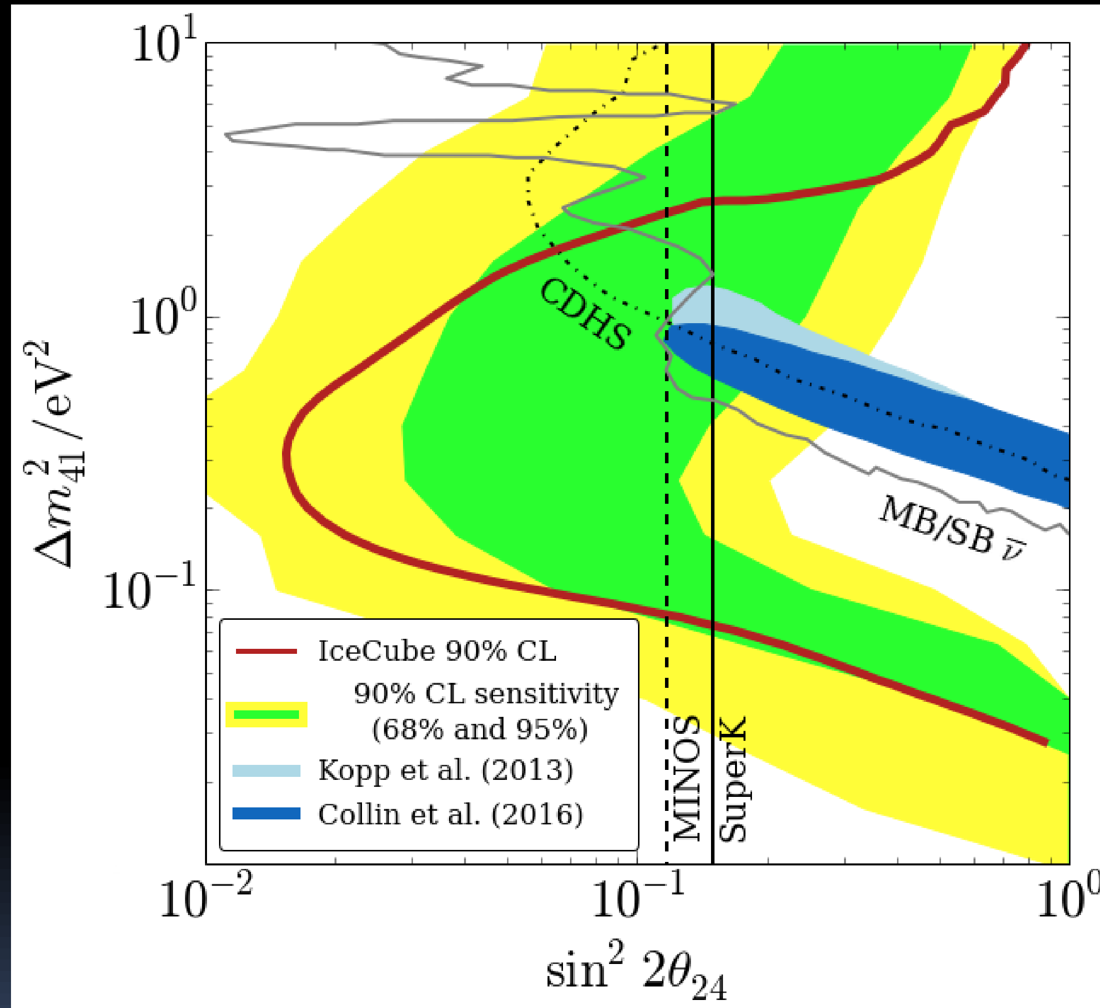
PRL 117 (2016) 071801

Eν = 320 GeV – 20 TeV

sterile neutrinos produce distortions of νμ + anti-νμ flux (energy and angle) in the range
$0.01 \leq \Delta m^2 \leq 10$ eV^2

- 1 year of data
- statistics limited



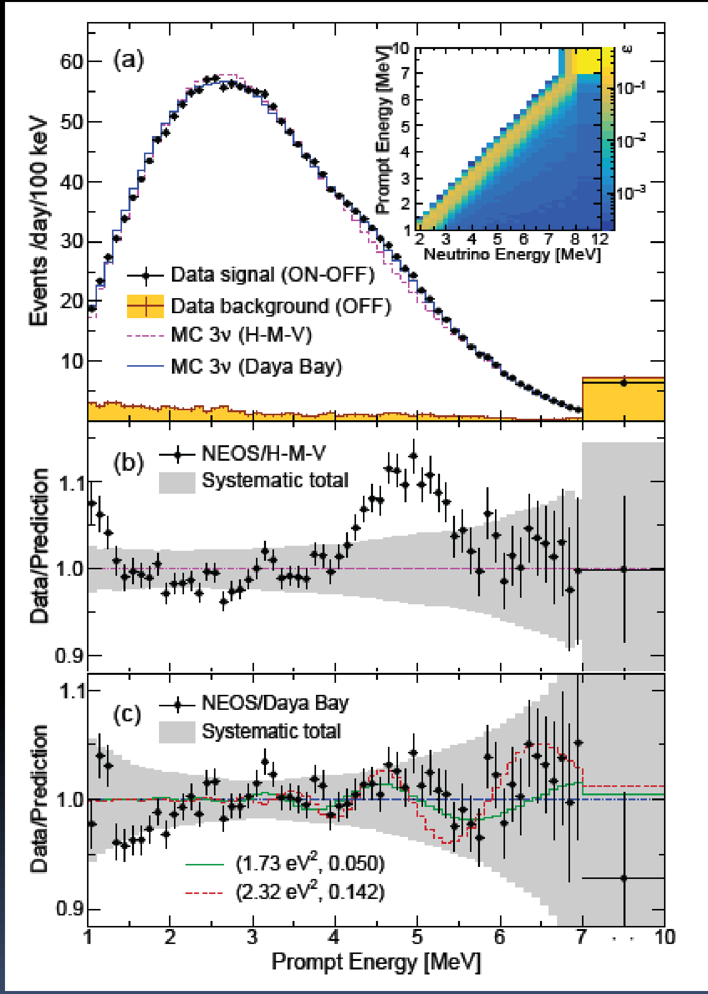


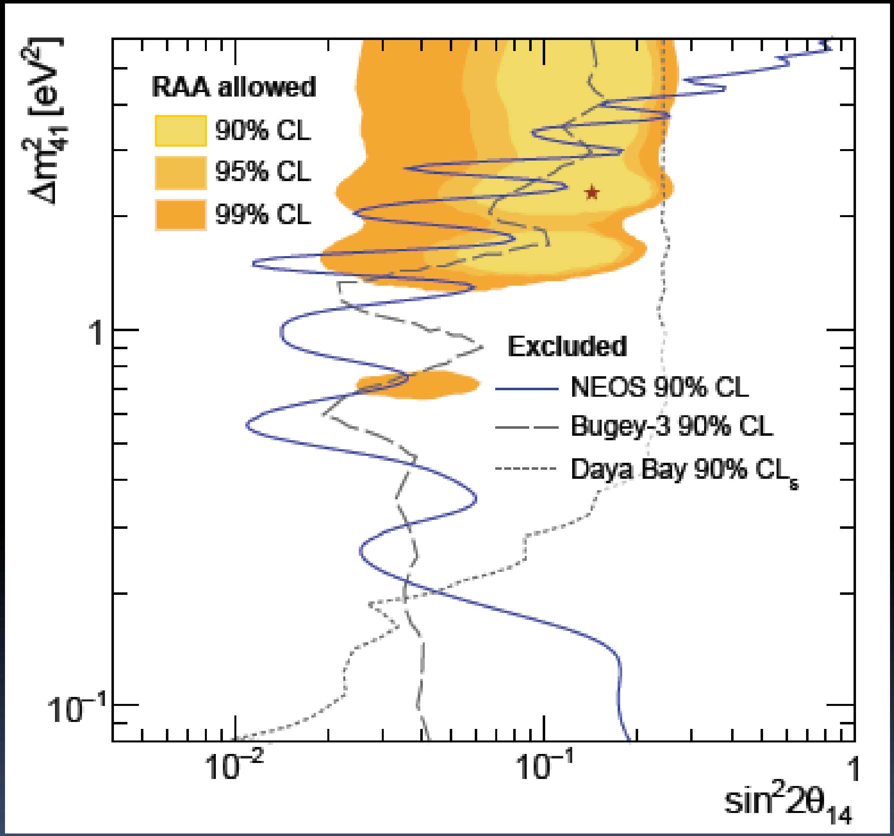
Result compatible with no-sterile hypothesis

NEOS: reactor anti-ν disappearance

PRL 118 (2017) 121802

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

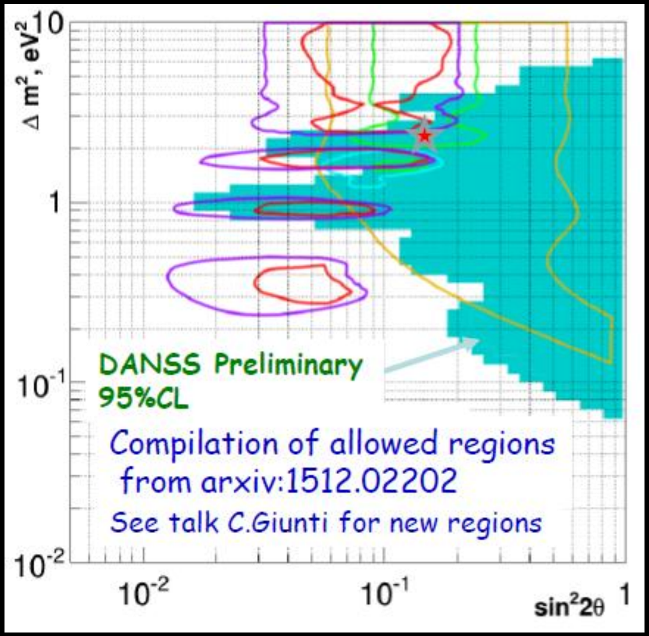


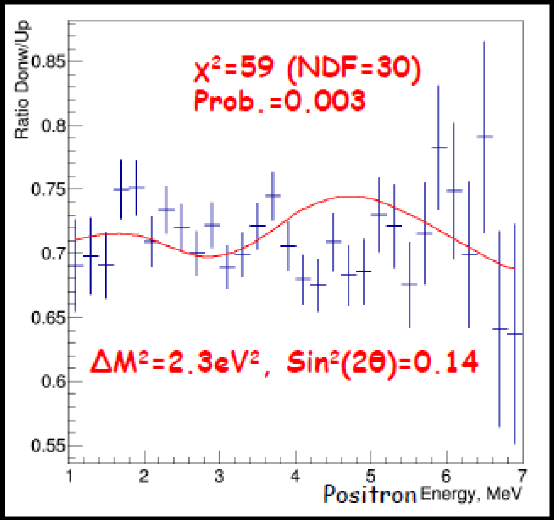


No evidence for sterile neutrino with mass ~ 1 eV

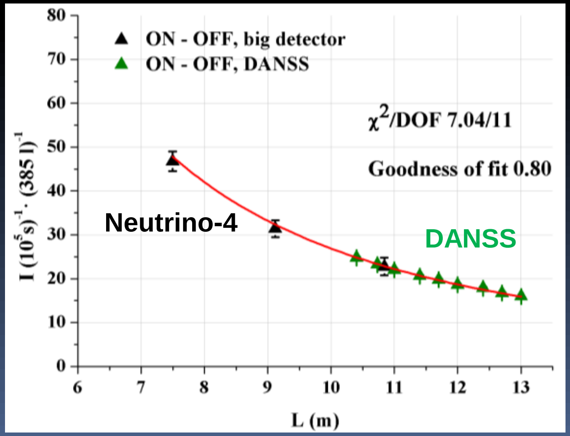
DANSS and Neutrino-4

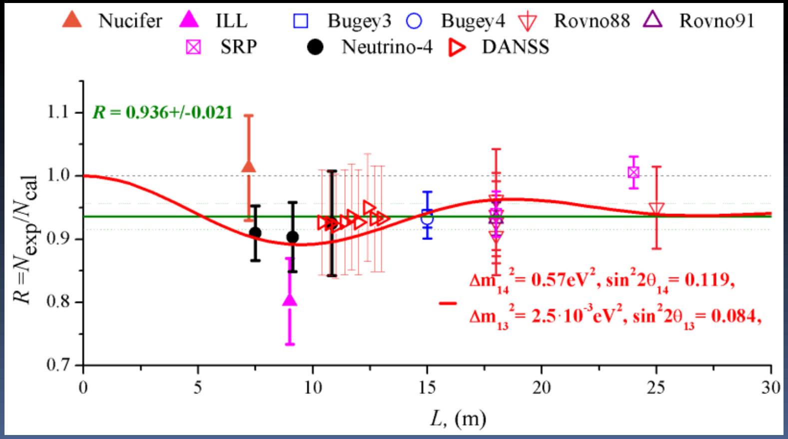
M.Danilov, talk at 52 Moriond EW 2017



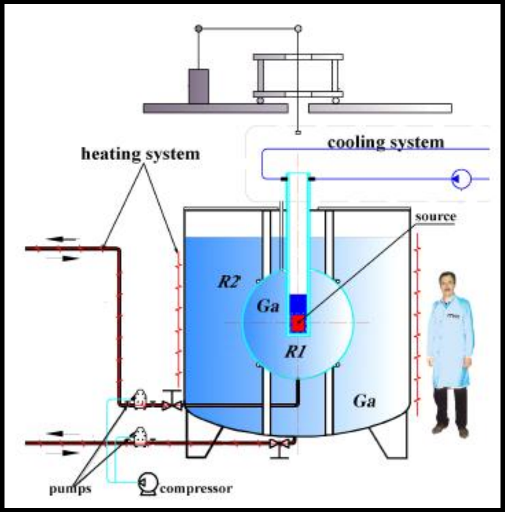


R. Samoilov, talk at ICPPA 2017





Source experiments

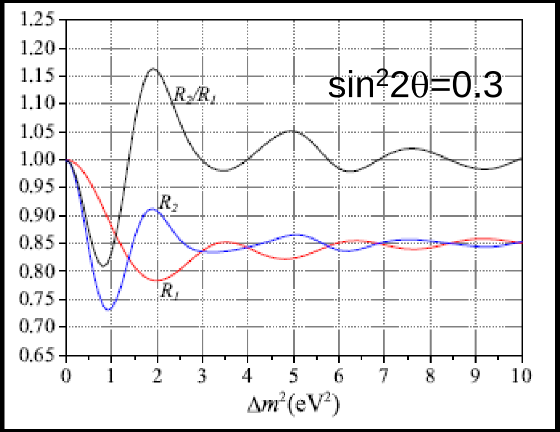


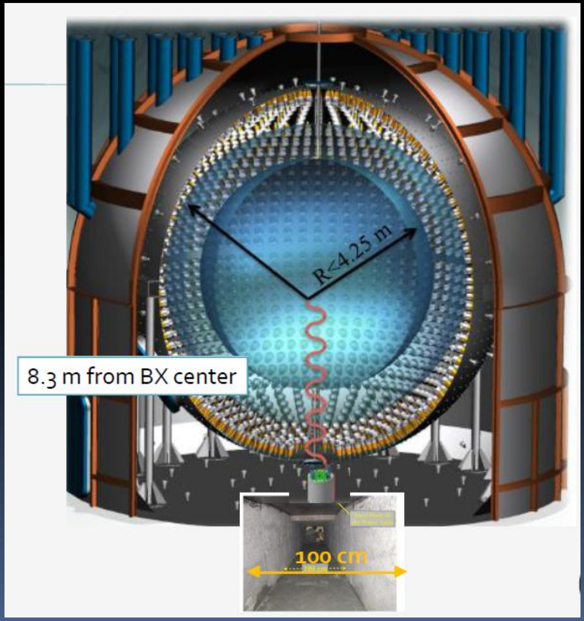
BEST

3 MCi ^{51}Cr source

Two-zone 50 t
liquid Ga metal target

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





SOX

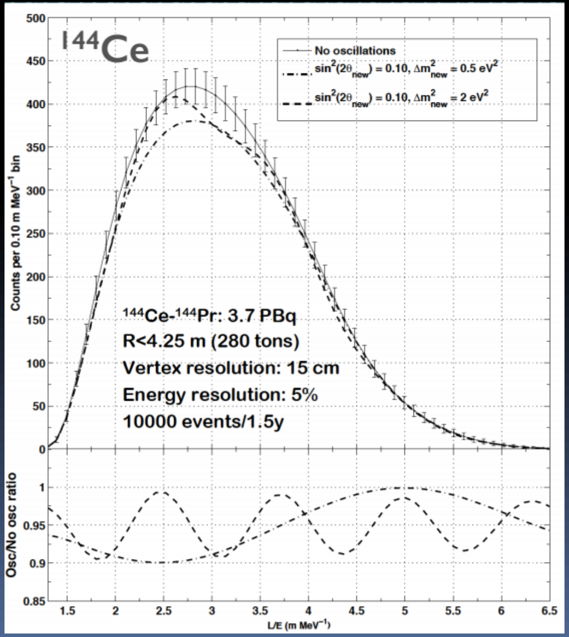
Ultra-low radioactive background
- Spatial resolution: 12 cm @ 2 MeV
- Energy resolution: ~3,5% @ 2 MeV

^{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

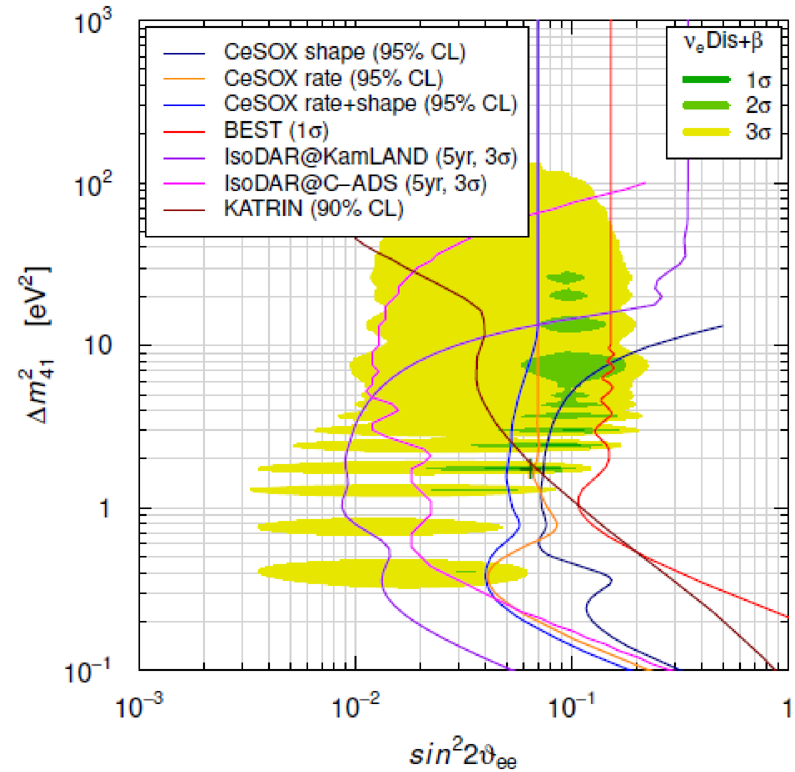


Expected sensitivity

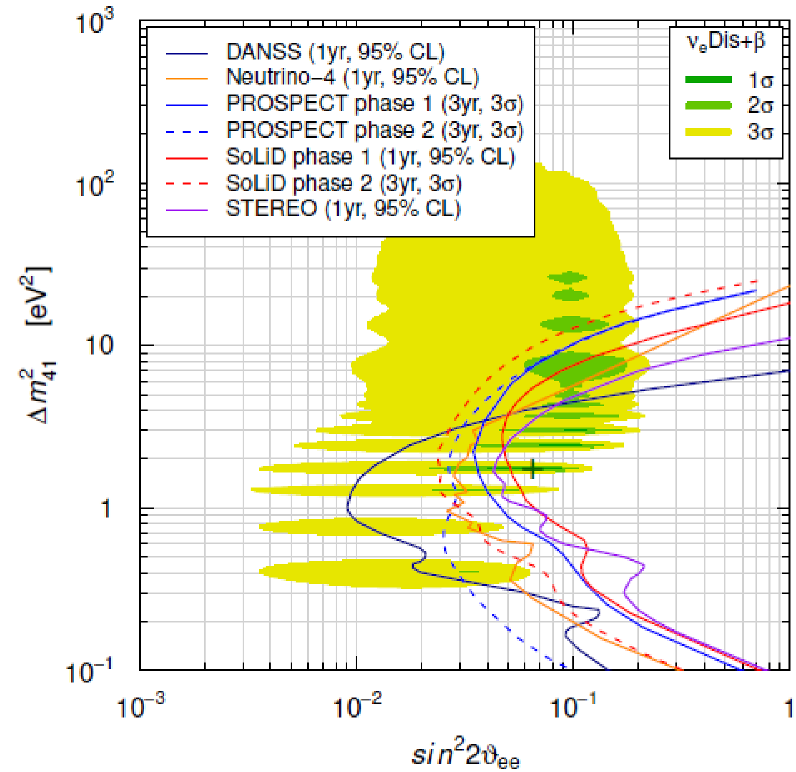
ν_e and anti-ν_e disappearance

C.Giunti, Moriond EW-2017

source



reactor



CeSOX (Gran Sasso, Italy) $^{144}\text{Ce} \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

BEST (Baksan, Russia) $^{51}\text{Cr} \to \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

IsoDAR@KamLAND (Kamioka, Japan)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

IsoDAR@C-ADS (Guangdong, China)
$^{8}\text{Li} \to \bar{\nu}_e$ $L \simeq$ 15m [JHEP 1601 (2016) 004]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]

Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]

PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]

SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]

STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

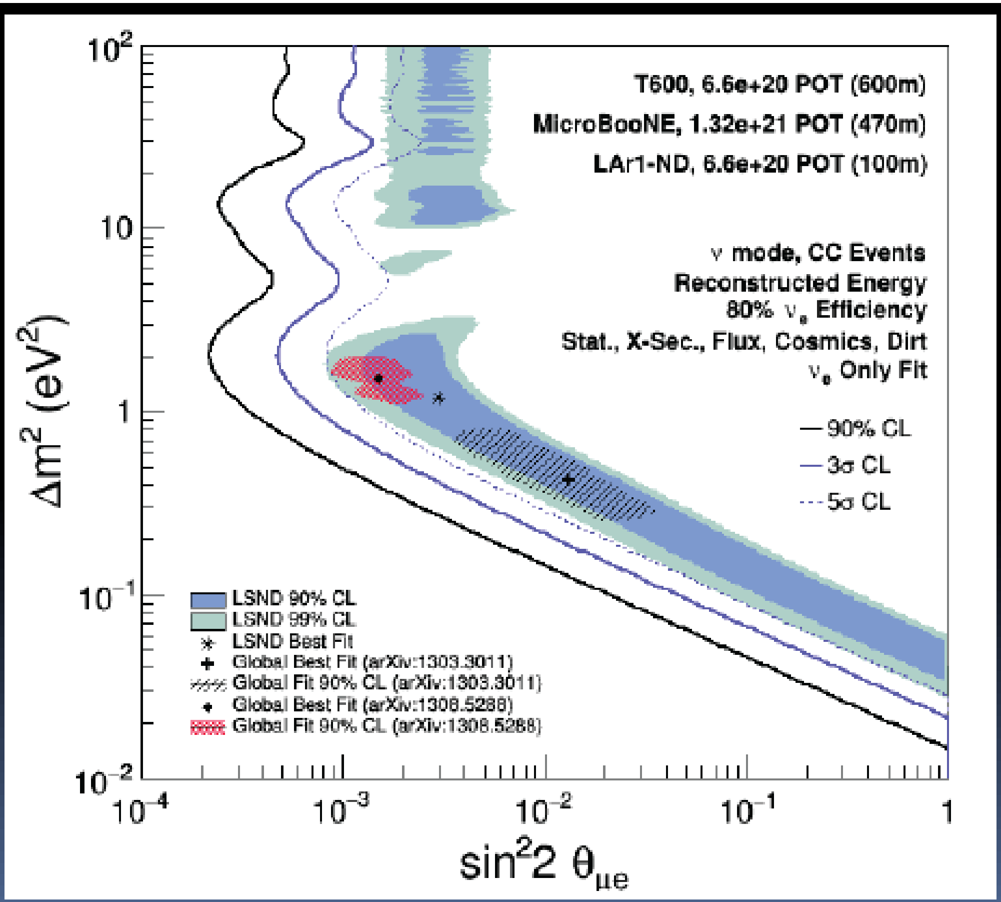
KATRIN (Karlsruhe, Germany) $^{3}\text{H} \to \bar{\nu}_e$ [Drexlin@NOW2016]

FNAL: SBN

arXiv:1503.01520

Short baseline experiments: three LAr detectors

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



Data taking to start in 2020

Sterile ν's: « + » and « - »

+

LSND/MinBooNe
Reactor anomaly + Daya Bay RENO flux measurements
Ga anomaly

-

MINOS Disappearence
MINOS/Daya Bay/Bugey combined result
IceCube
NEOS, DANSS, Neutrino-4

?

More results from
accelerator, reactor, source experiments coming soon

Conclusion

Current LBL experiments T2K + NOvA

main goals: CP violation (3σ), Mass Hierarchy, θ_{23}

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

JUNO **(MH)** ***under construction***

DUNE **(CP, MH)** ***approved***

HyperK and T2HK **(CP)** ***included in roadmap***

Light sterile neutrinos: crucial tests in experiments with neutrinos from accelerators, reactors, atmosphere and neutrino sources in progress

Thank you!