New results and perspectives in neutrino physics

Yury Kudenko
Institute for Nuclear Research, Moscow

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OUTLINE

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

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

- **Neutrino mass**
  - direct measurements
  - $0\nu 2\beta$ decay
  - cosmology

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}$$

***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, 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

Main goals

- 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

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

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

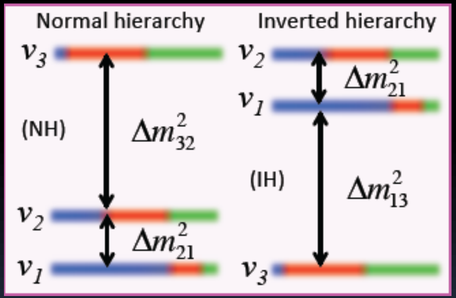
Lepton sector $J_{CP} \sim 0.02\times\sin\delta_{CP}$

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

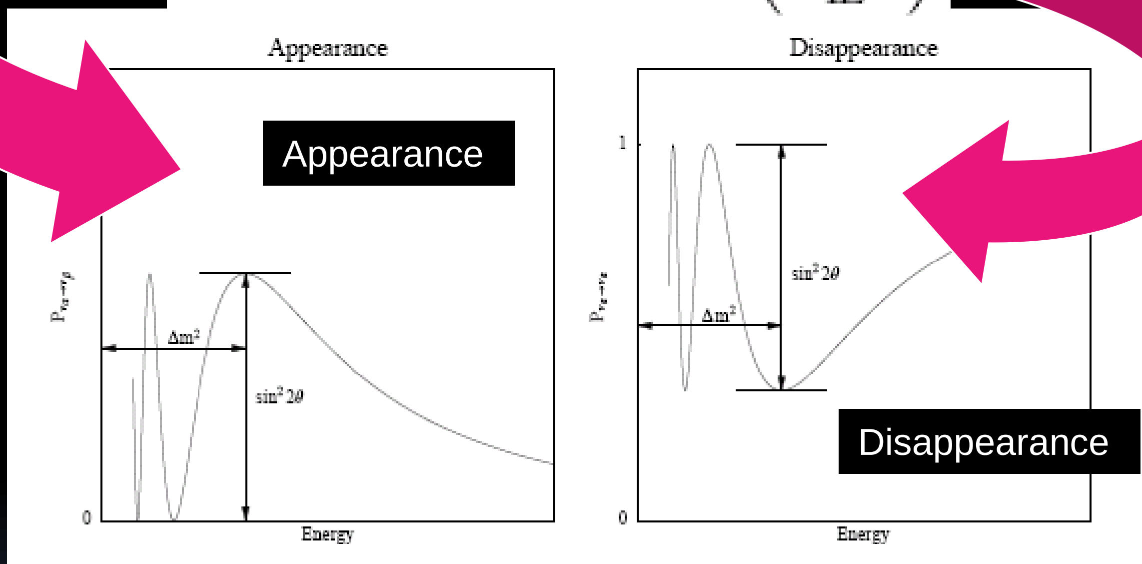
- Sterile neutrinos **- Absolute mass scale** **- Dirac or Majorana**

Experimental methods

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

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

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



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 LBL experiments

T2K

LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

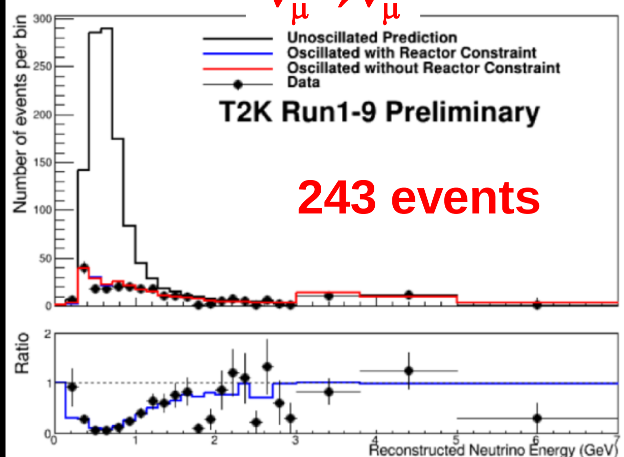
about 500 members
59 institutions
from 11 countries

T2K data

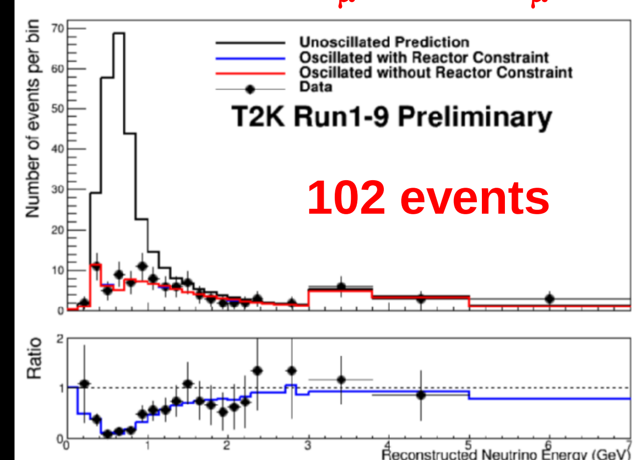
Neutrino mode 1.49×10^{21} POT
Antineutrino mode 1.12×10^{21} POT

P.Litchfield, ICHEP2018

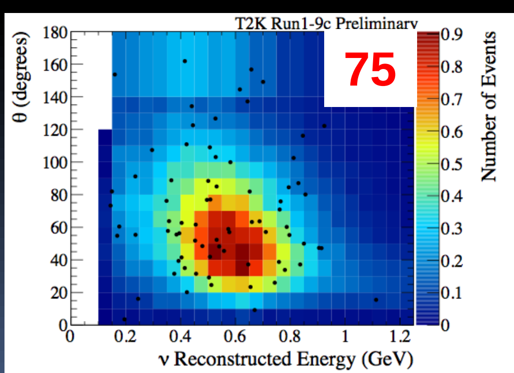
$\nu_\mu\rightarrow\nu_\mu$



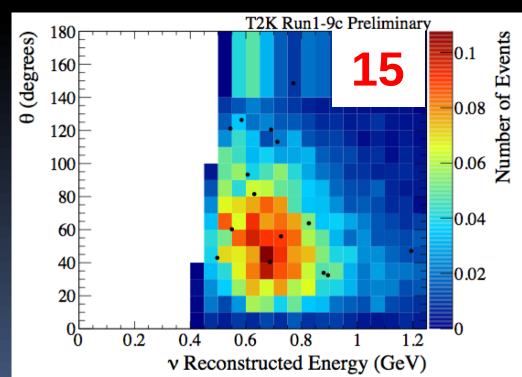
anti-$\nu_\mu\rightarrow$anti-ν_μ



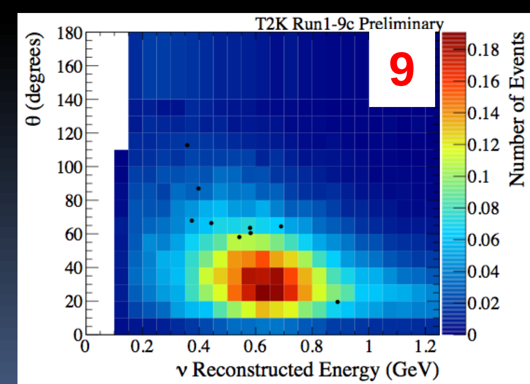
$\nu_\mu\rightarrow\nu_e$



$\nu_\mu\rightarrow\nu_e$ +1π



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



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%

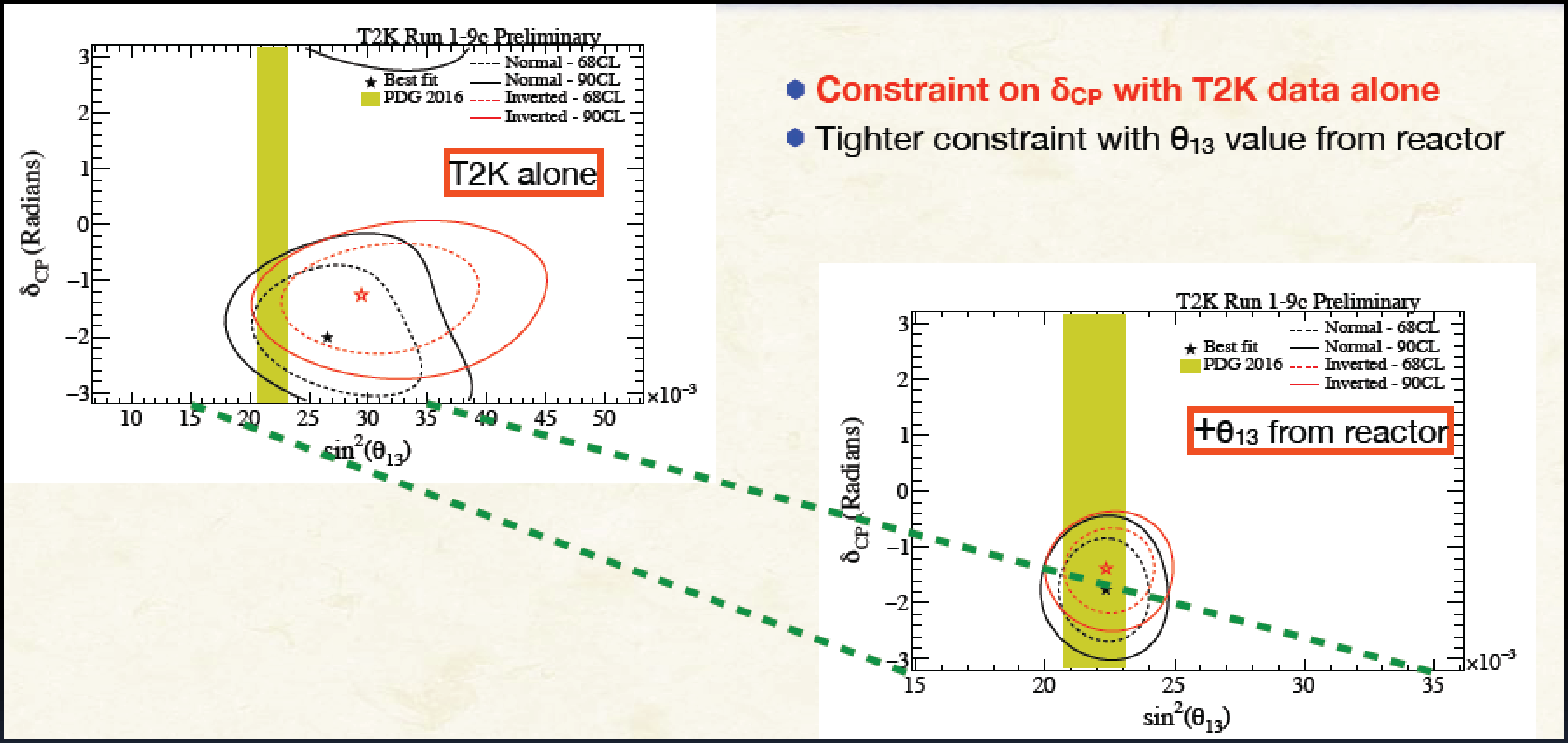
Sample	Expectation, $\sin^2\theta_{23} = 0.528$, $\delta =$ $-\pi/2$	0	π	$+\pi/2$	Observed
FHC 1R-μ	268.5	268.2	268.9	268.9	**243**
RHC 1R-μ	95.5	95.3	95.8	95.5	**102**
Sum of 1R-μ	*364.0*	*363.5*	*364.7*	*364.5*	***345***
FHC 1R-e	73.8	61.6	62.2	50.0	**75**
FHC 1R−e +d.e.	6.9	6.0	5.8	4.9	**15**
RHC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

disappearance (FHC 1R-μ, RHC 1R-μ, Sum of 1R-μ)

appearance (FHC 1R-e, FHC 1R−e +d.e., RHC 1R-e)

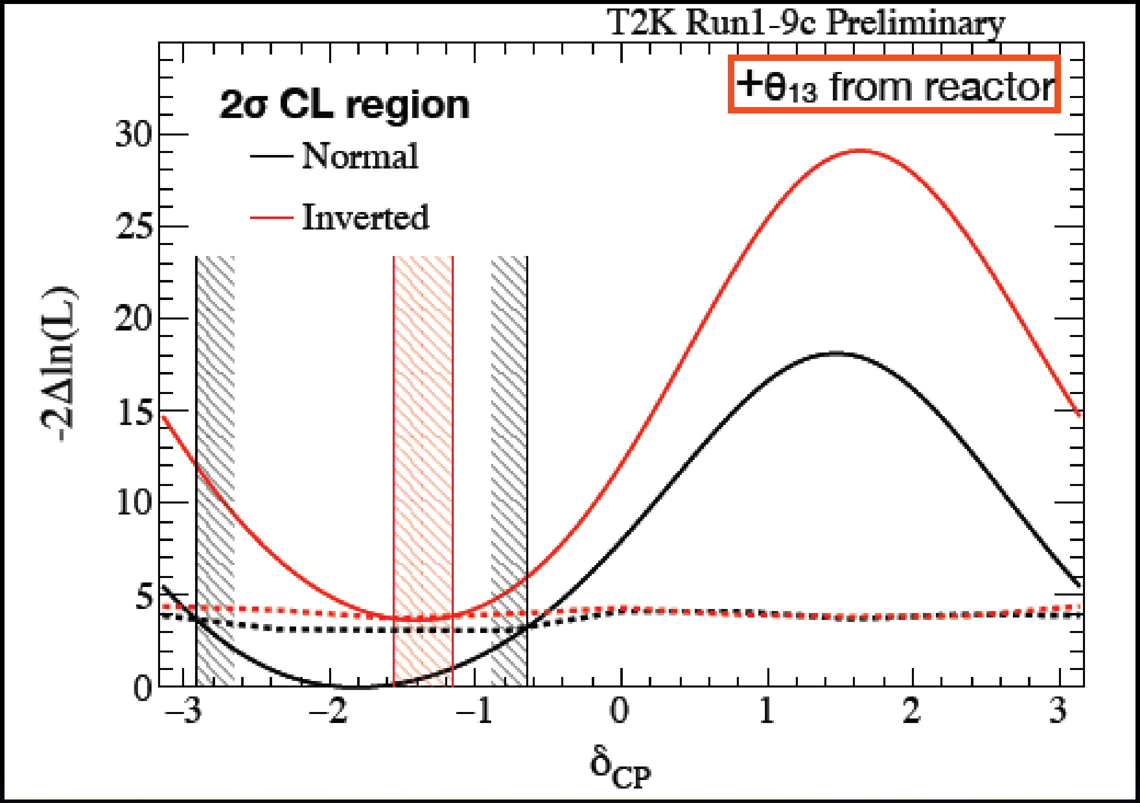
CP: T2K result

T2K ν_e / anti- ν_e



T2K ν_e / anti- ν_e + reactor θ_{13}

CP: T2K result



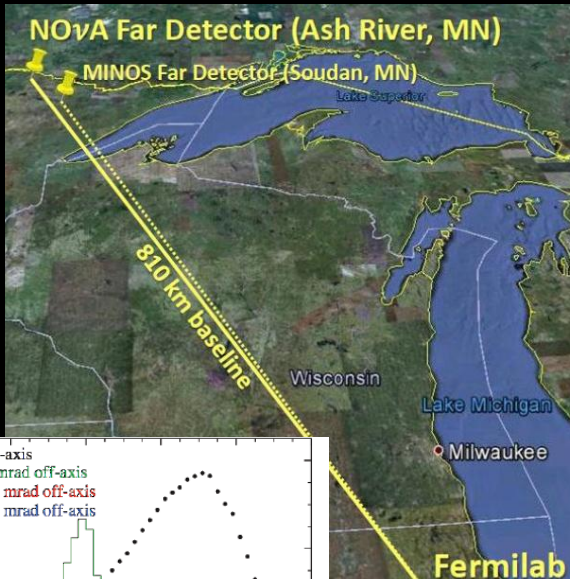
Best fit
δ_{cp} = -1.6 rad
for NH

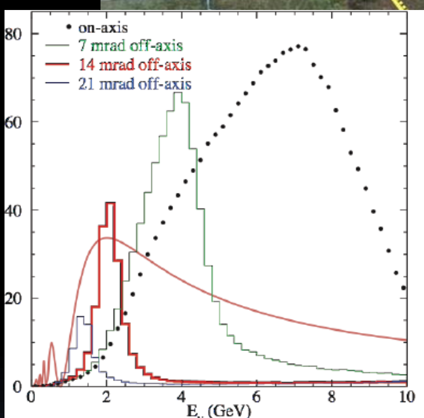
CP-conservation hypothesis ($\sin\delta_{CP} = 0, \pi$) excluded at 2σ level

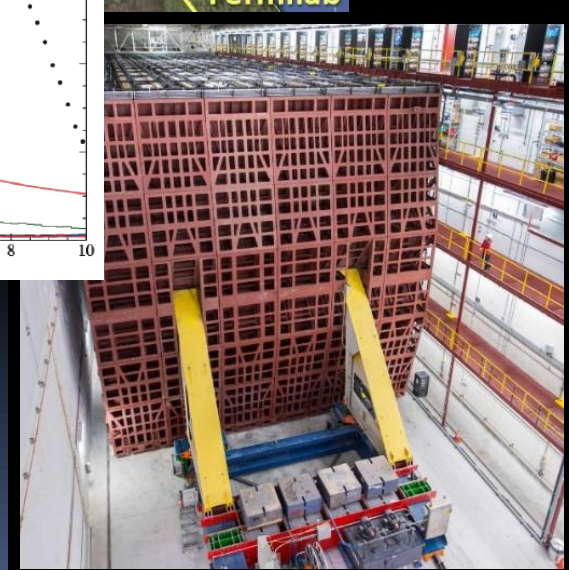
- **First hint for CP violation in the lepton sector**
- **T2K data favour $\delta_{CP} \sim -\pi/2$ and normal hierarchy**

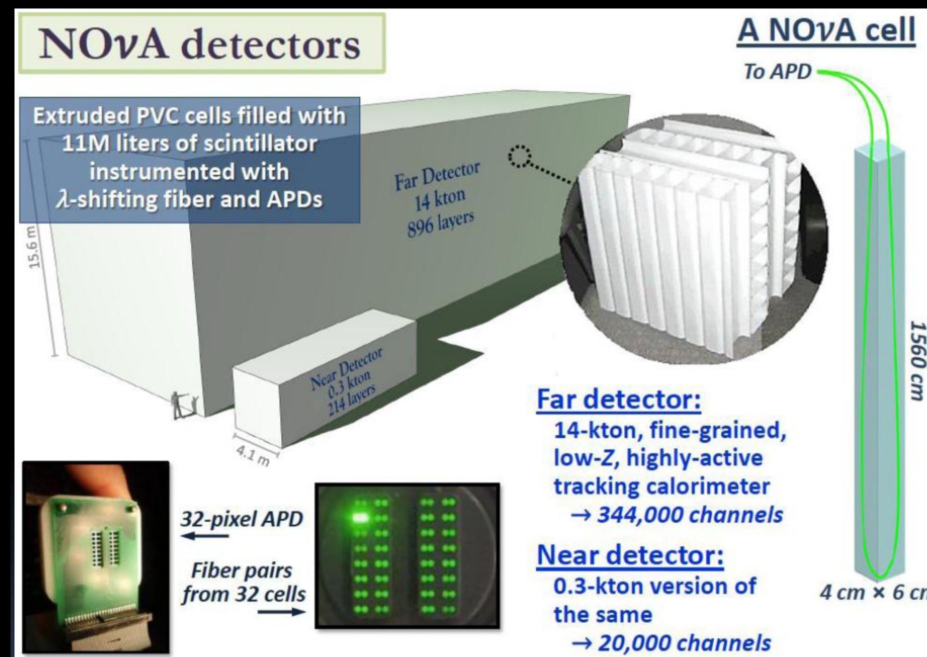
NOvA

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

J.Bian ICHEP2018

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

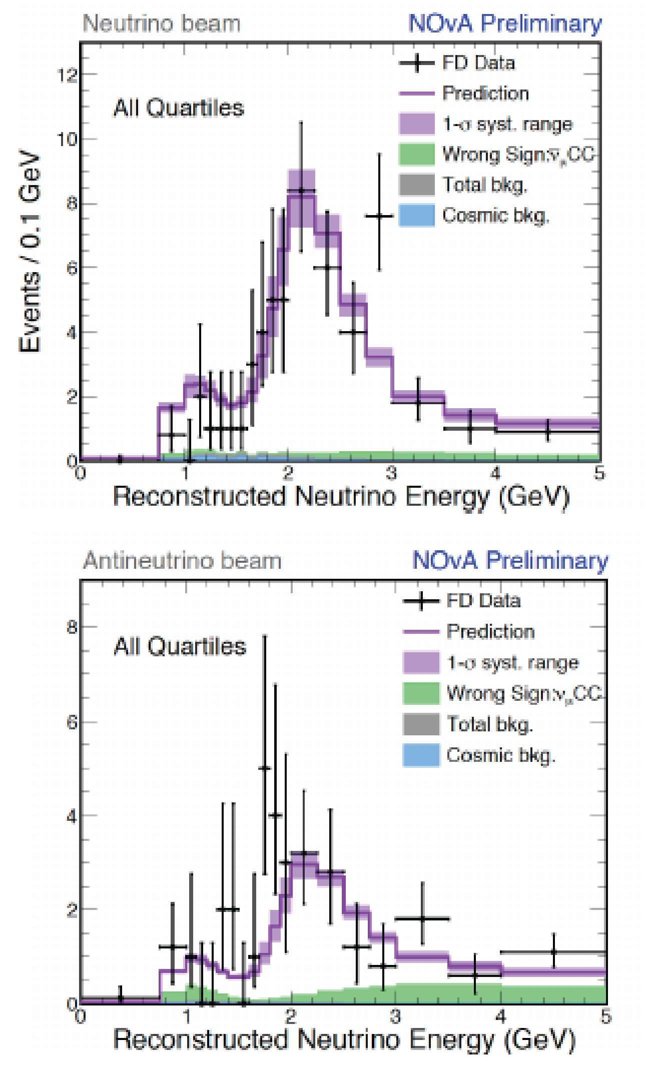
Far detector

Neutrino beam:

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

Antineutrino beam:

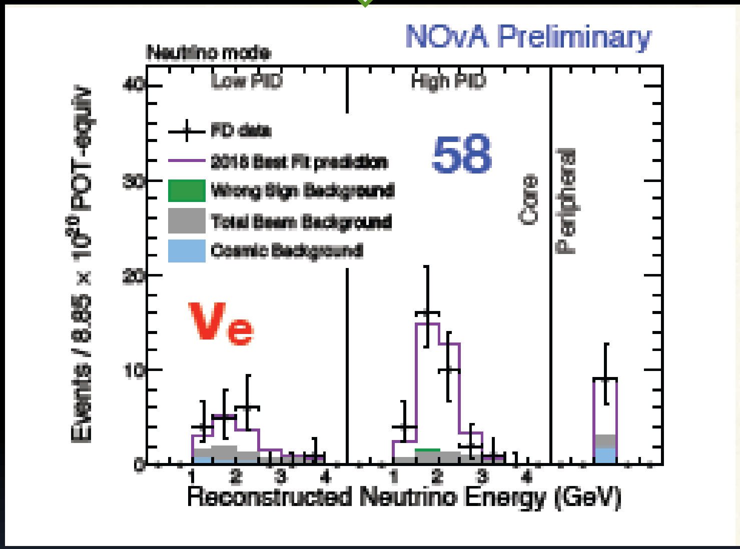
- Observe 65 events
- Expect 266 +12/-14(syst.) w/o oscillations

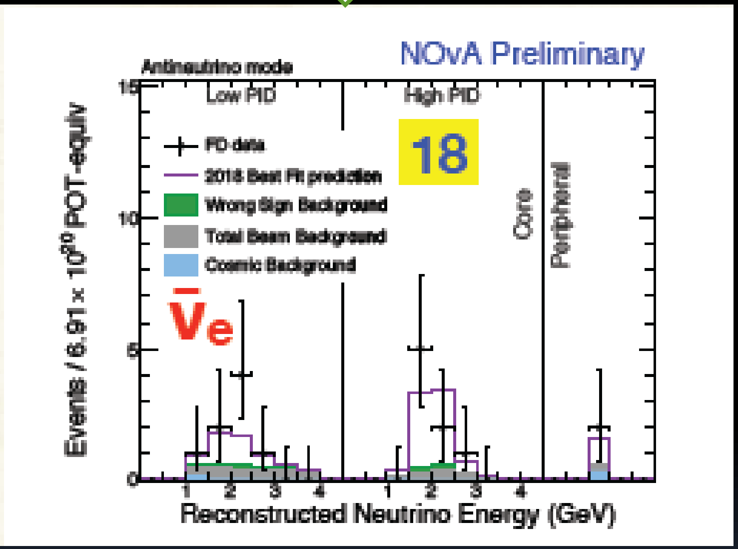


NOvA: ν_e/anti-ν_e

ν_e
58 events observed
15 background events expected

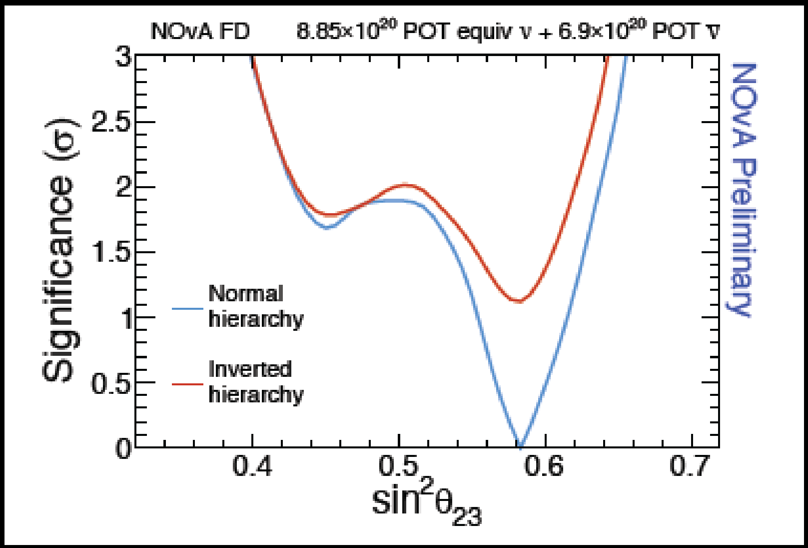
anti-ν_e
18 events observed
5.3 background events expected

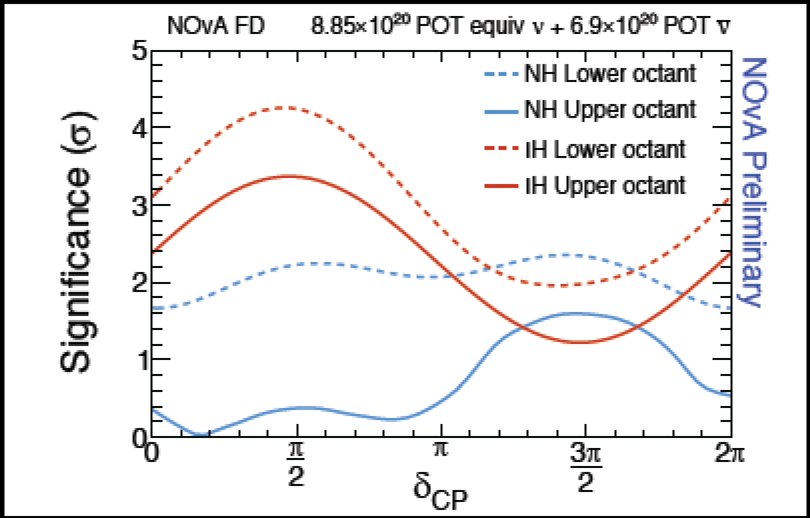




$$\bar{\nu}_e \ \text{appearance} > 4\sigma$$

NOvA results



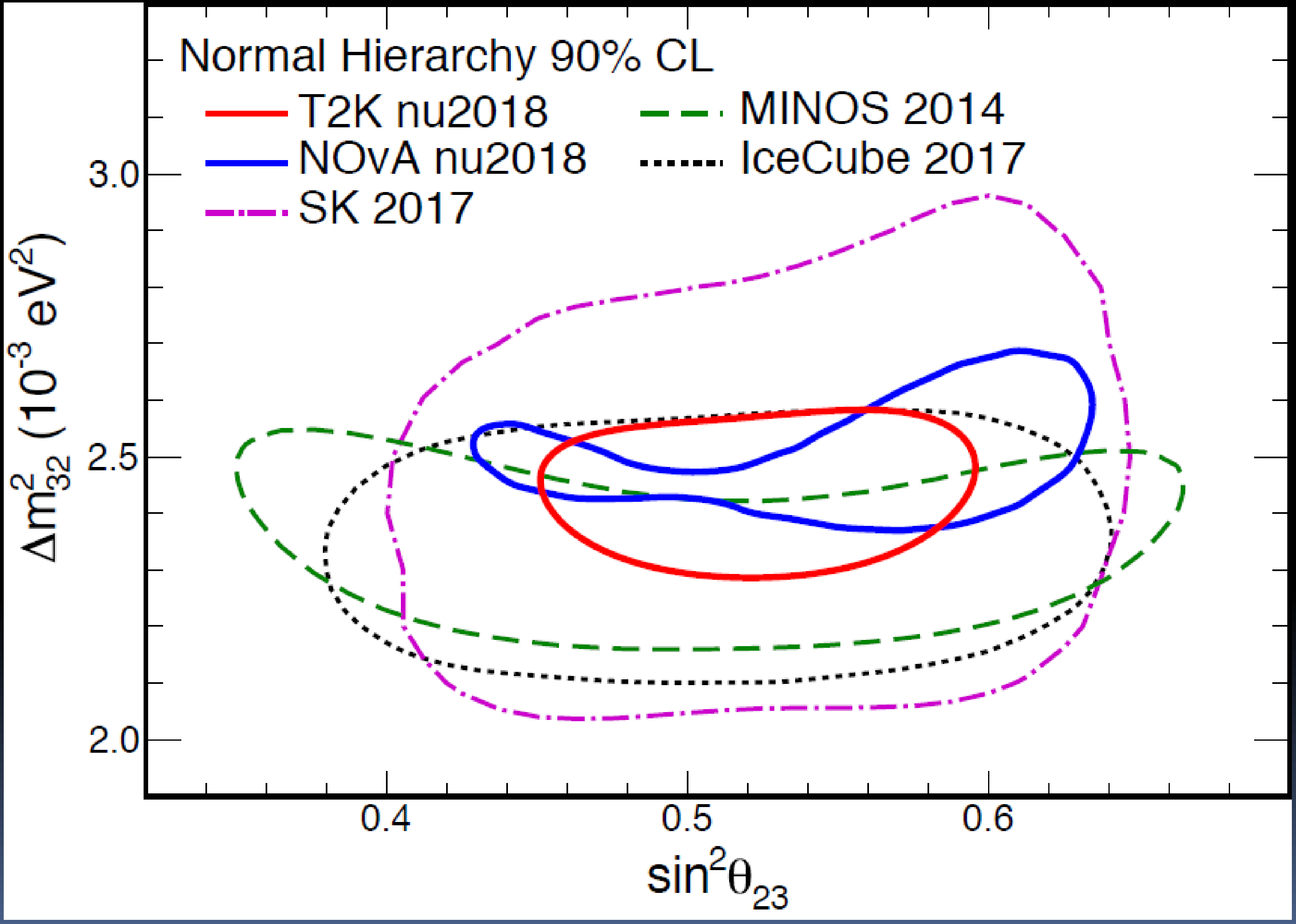


NOvA prefers
Normal Hierarchy at 1.8σ

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

Oscillation parameters: $\Delta m^2_{32} - \sin^2\theta_{23}$

M.Yokoyama ICHEP2018



Future LBL Projects

- Reactor experiment JUNO
- Accelerator LBL experiment DUNE
- Hyper-Kamiokande and T2HK

Reactor experiment JUNO

China

77 institutions
~ 600 collaborators

Main target:
Measurement of neutrino mass hierarchy

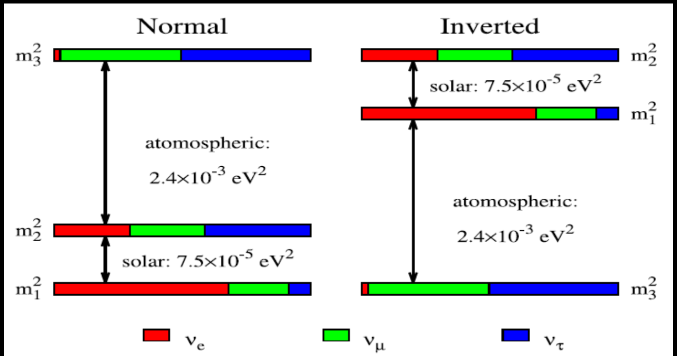
- **700 m deep underground**
- **36 GW reactor power**
- **53 km baseline -> oscillation maximum θ_{12}**
- **20 kton LS detector**
- **3% energy resolution at 1MeV**
- **<1% energy scale uncertainty**

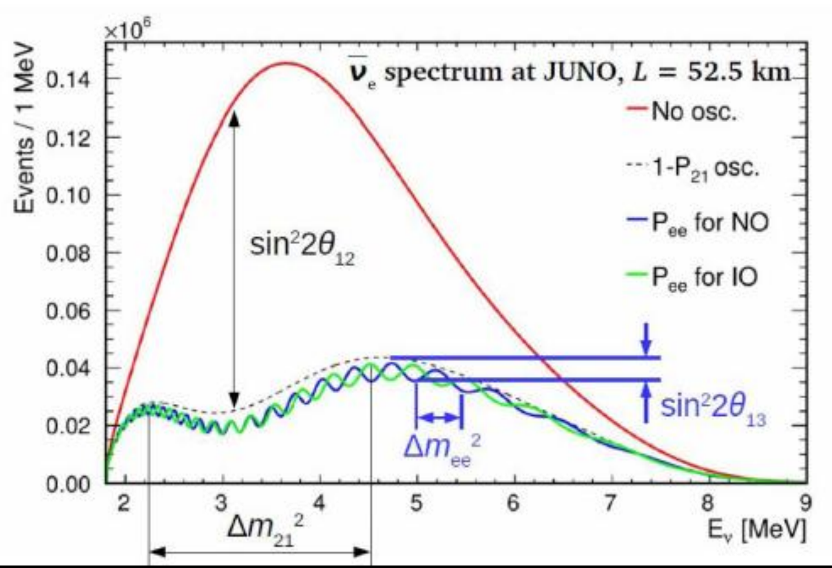
!?

JUNO goals

Yaping Cheng, NuPhys2018

Main goal: determination of neutrino mass hierarchy





Running time 6 years

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

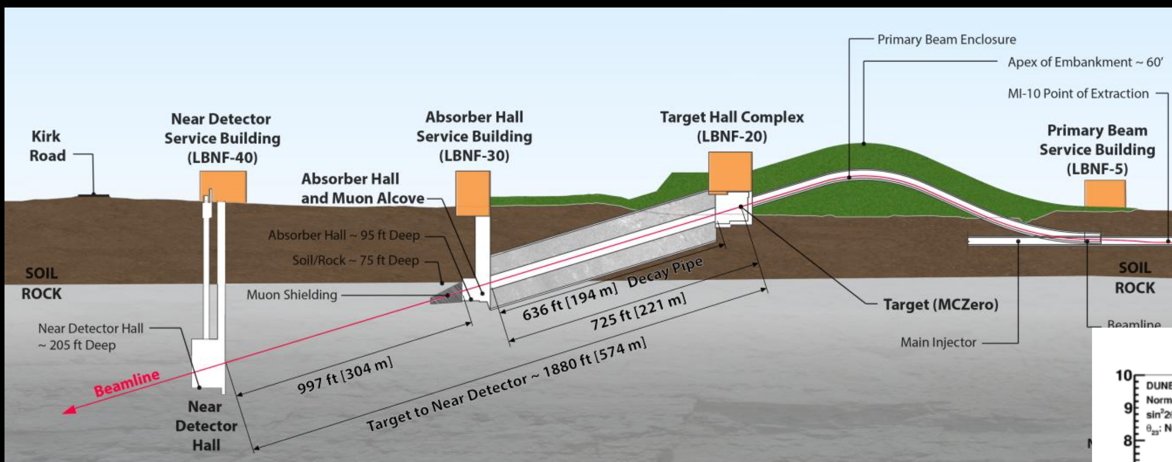
LBNF/DUNE Project

Flagship FNAL project

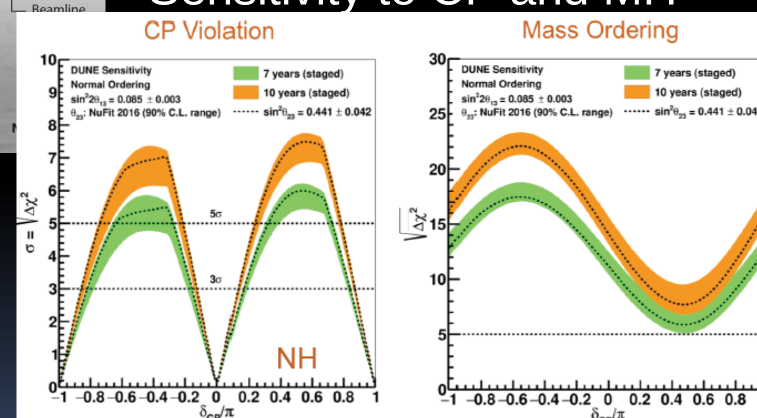
Main goals: - discovery of CP violation in leptonic sector
- neutrino mass hierarchy at >5σ level
- neutrino astronomy
- proton decay search

32 countries
>1100 collaborators

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

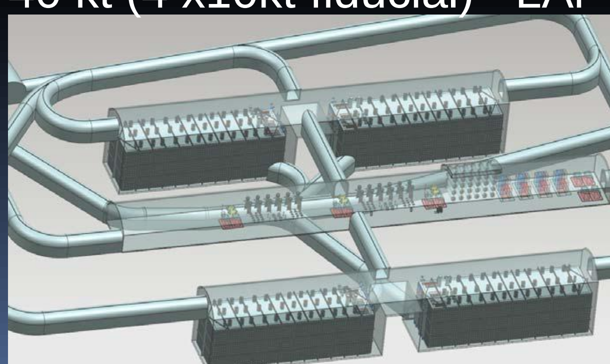


Sensitivity to CP and MH



Far detector 40 kt (4 x10kt fiducial) LAr TPC

Single
and
Dual
phase
detectors

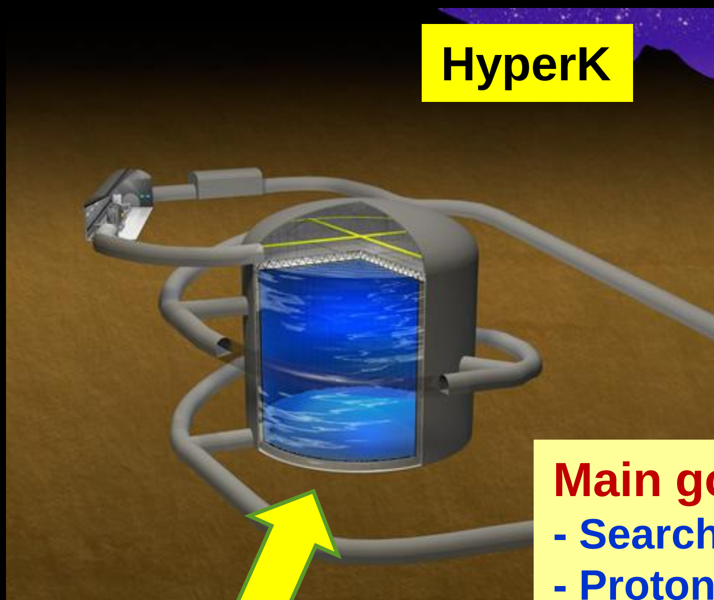


2021 – installation of 1st far detector
2024 – 2 modules operational
2026 – deliver neutrino beam

HyperKamiokande

Japan

15 countries
76 institutes
> 300 members
Expected data taking start in ~2027

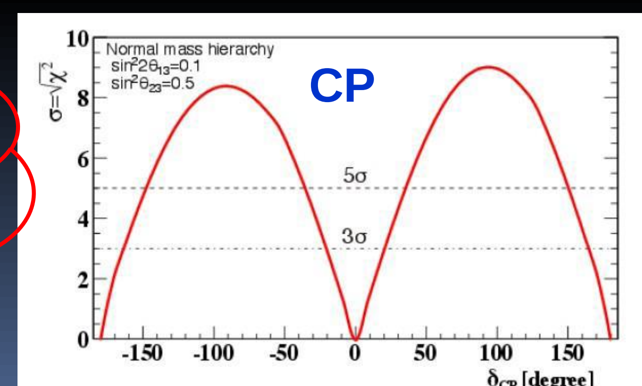


- **Upgrade of JPARC to 1.3 MW beam power**
- **New/upgrade of near neutrino detectors**

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

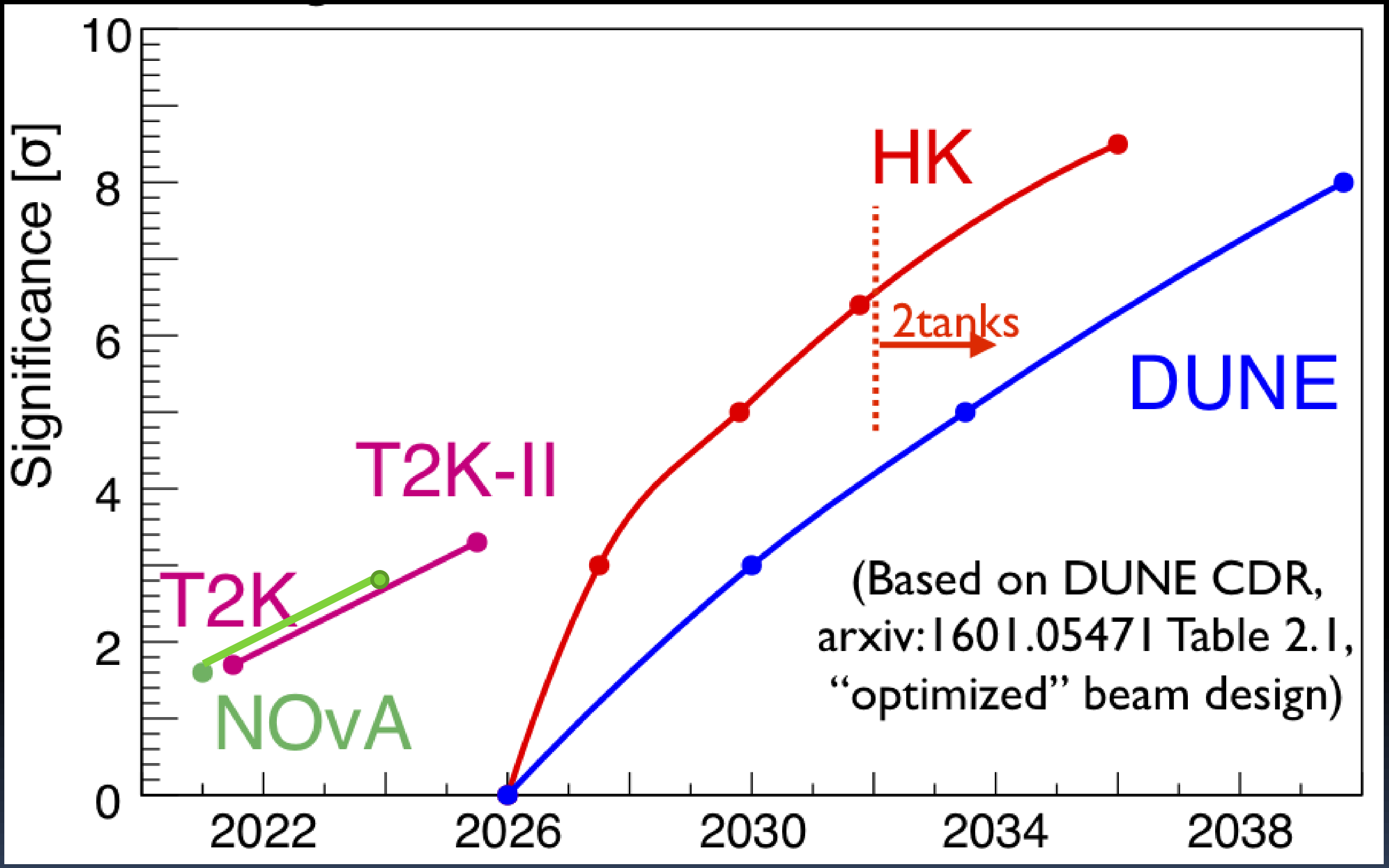
Tank
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt ~10xSuperK
PMT coverage 40%
40000 PMTs
2.5°off-axis
peak energy 600 MeV

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



Expected sensitivity to CP

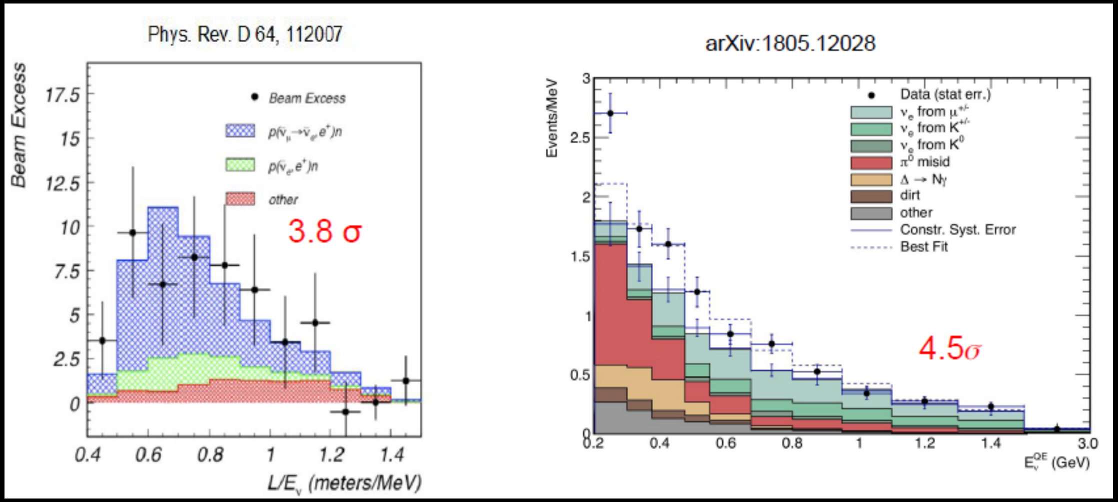
Significance for δ_{CP} = - $\pi/2$



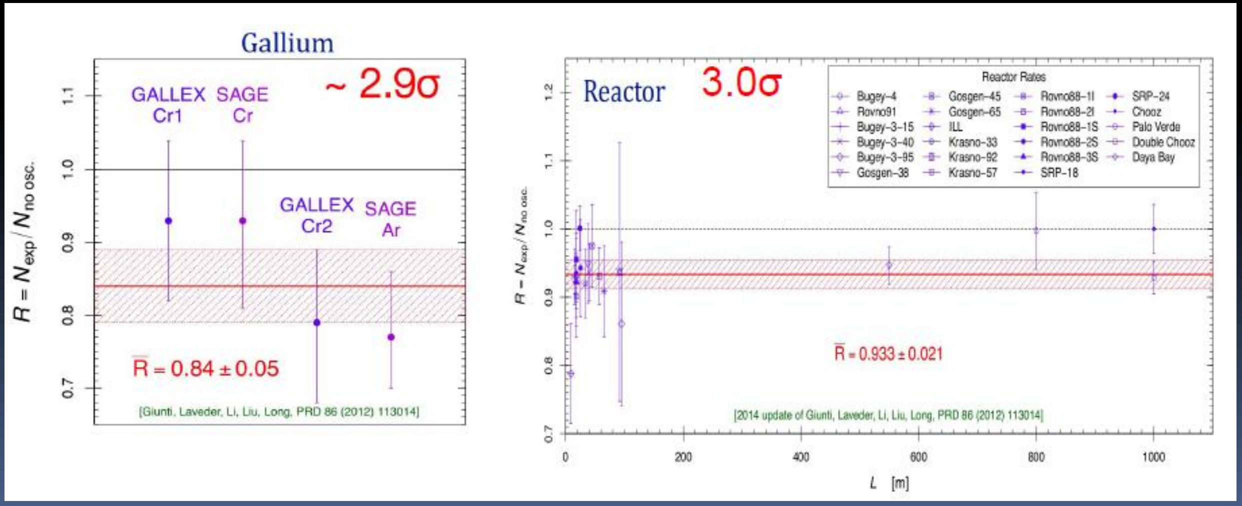
Light sterile neutrinos

Neutrino anomalies

LSND/MiniBooNe anomaly



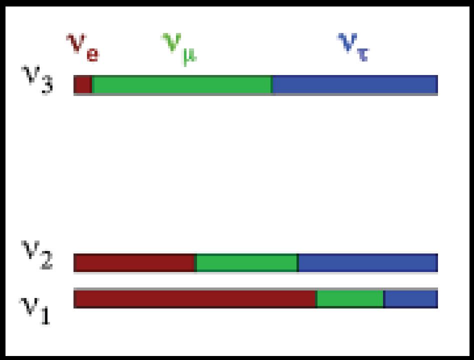
Gallium and Reactor anomalies



These anomalies can be interpreted as oscillations involving sterile neutrino with $\Delta m^2 \sim 1\ eV^2$

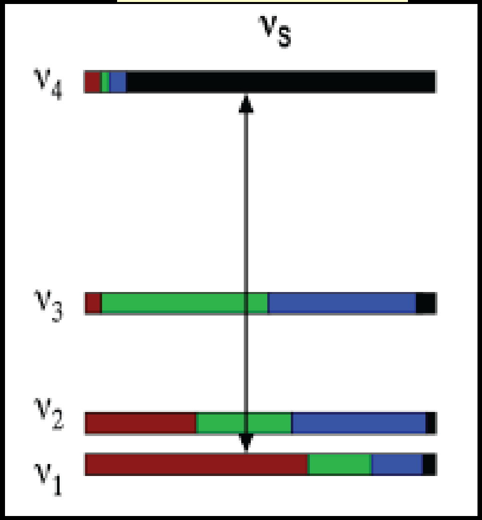
Sterile neutrino?

3ν



?

3ν + 1s



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

PNMS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

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

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

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

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

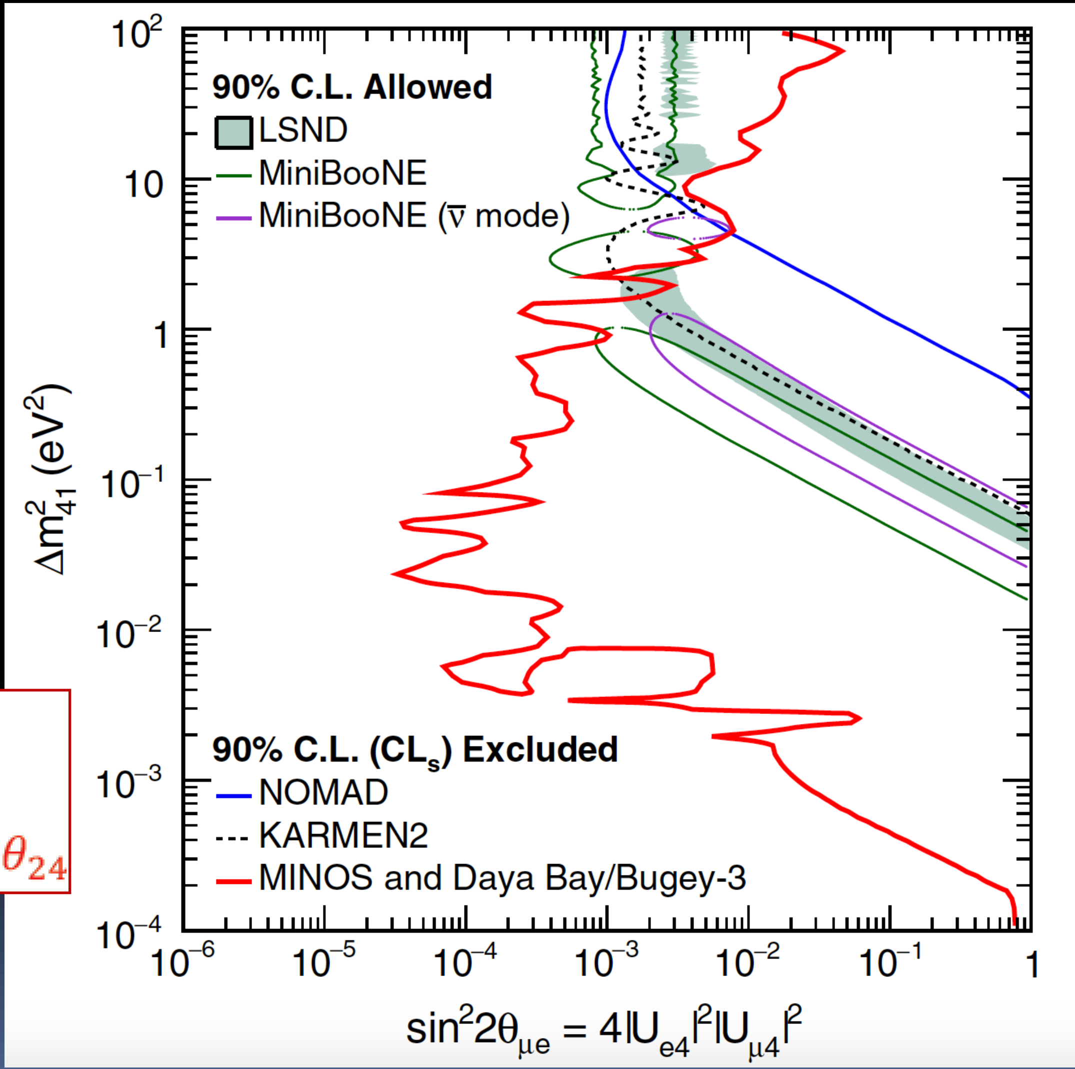
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

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 $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \cdot \sin^2 \theta_{24}$

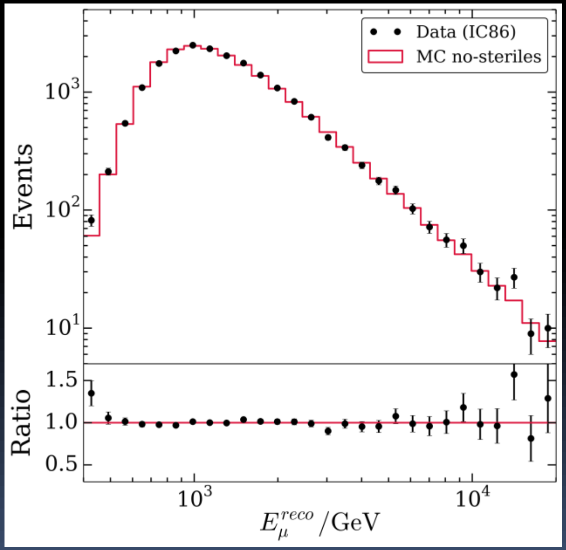
Sterile ν's: IceCube

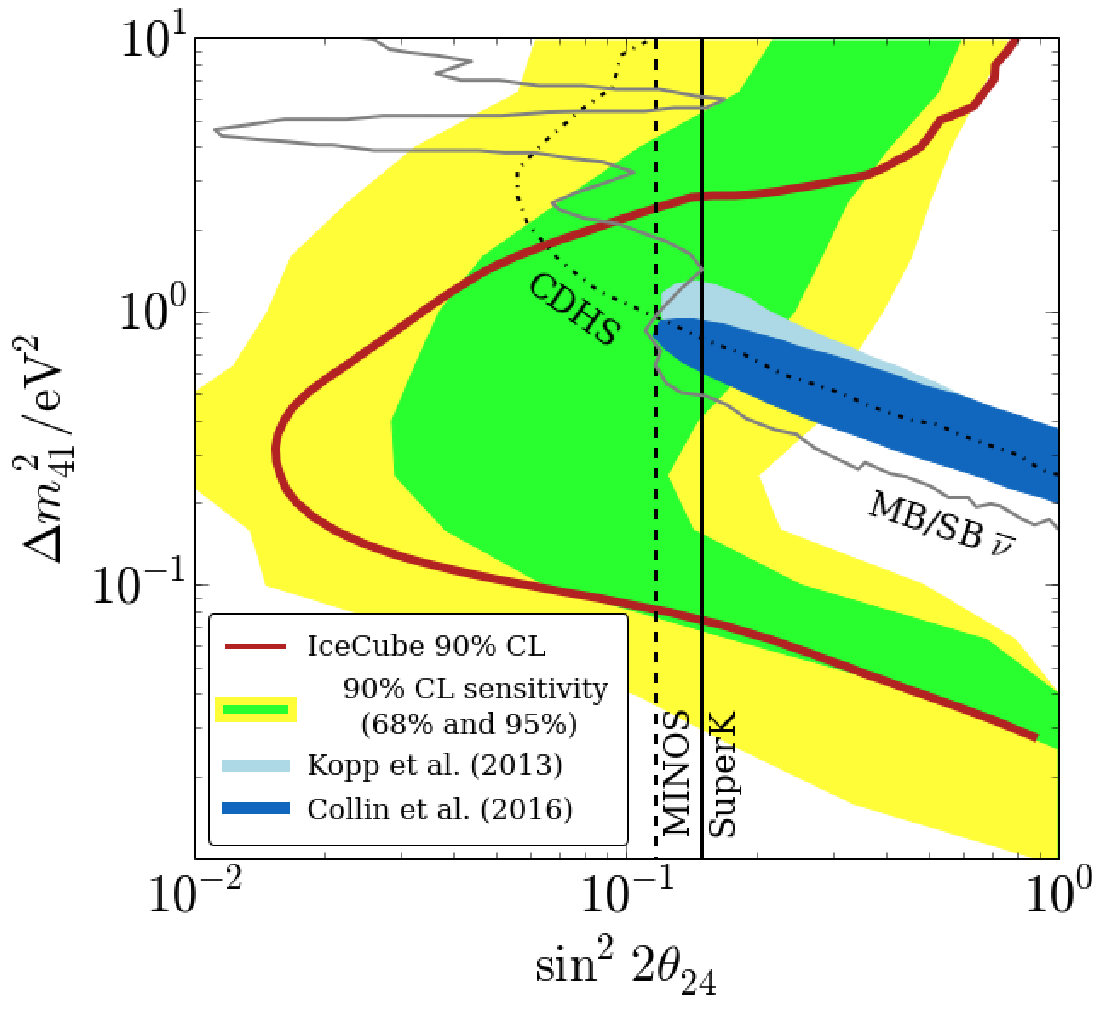
PRL 117 (2016) 071801

Eν = 320 GeV – 20 TeV

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

- 1 year of data
- statistics limited

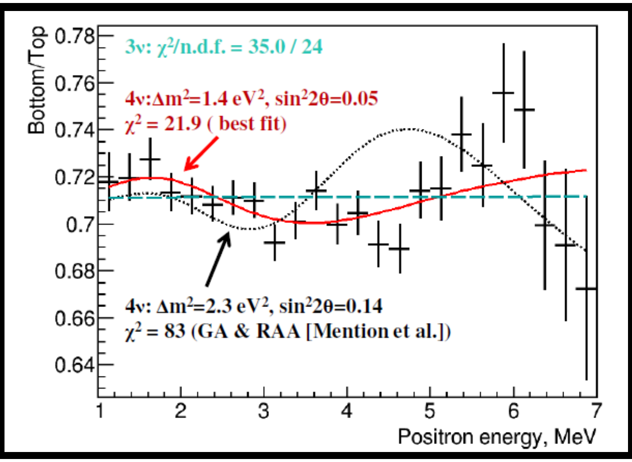




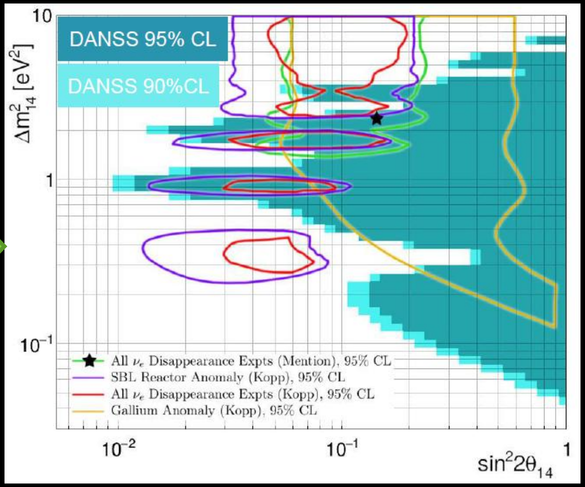
Result compatible with no-sterile hypothesis

SBL reactor experiments (I)

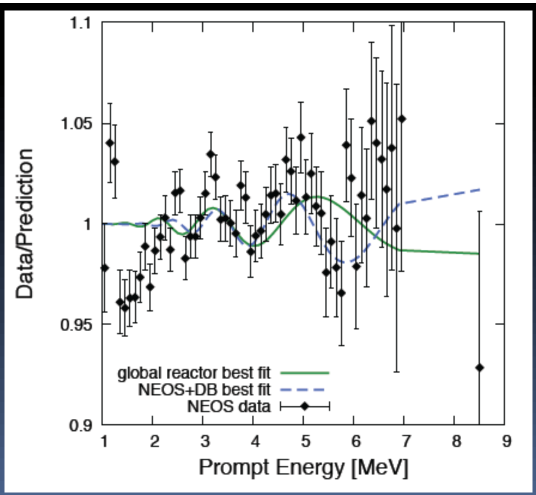
DANSS, (I.Alexeev et al. PL B787 (2018) 56)
Kalinin power station 3.1 GW
Segnebted detector 1 m3



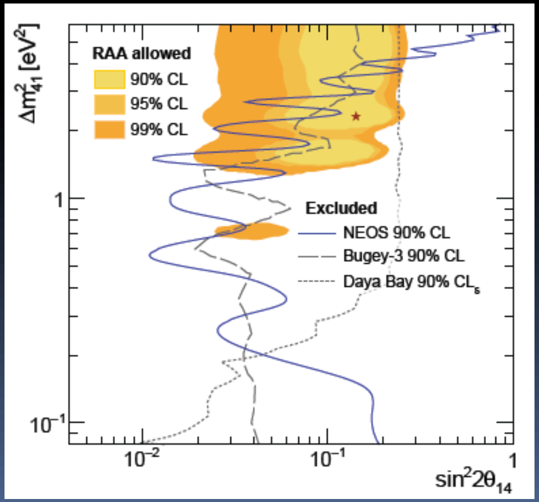
Reactor anomaly excluded at 5σ



NEOS (PRL 118 (2017) 121802)
Korea, Reactor 2.8 GW Active zone ∅3.1 м h=3.8 м
Detector 1t LS + Gd

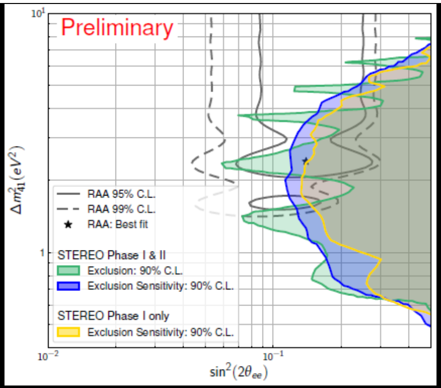


No evidence for ν_s with mass ~ 1 eV

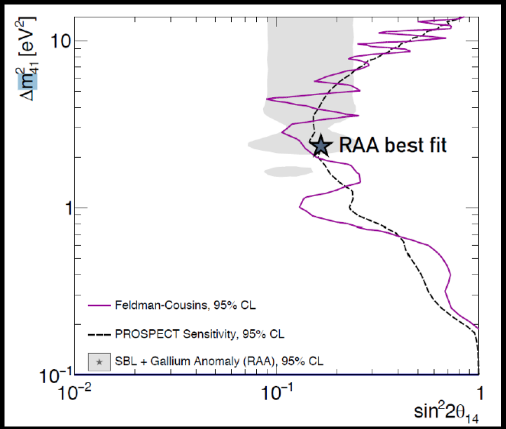


SBL reactor experiments (II)

STEREO (L.Bernard, ICHEP2018)
ILL, Grenoble, France, Reactor 58.3 MW
Active zone ∅40x80 cm
Detector ~4t LS + Gd

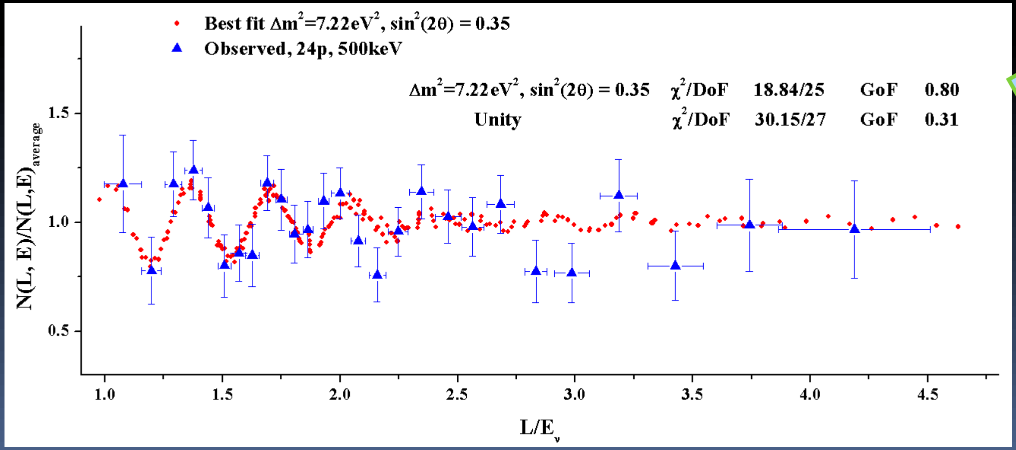


PROSPECT (arXiv:1806.02784)
HIFR, USA, Reactor 84 MW
Active Zone ∅43x h50 cm
Segmented detector ~4t LS + ^{6}Li

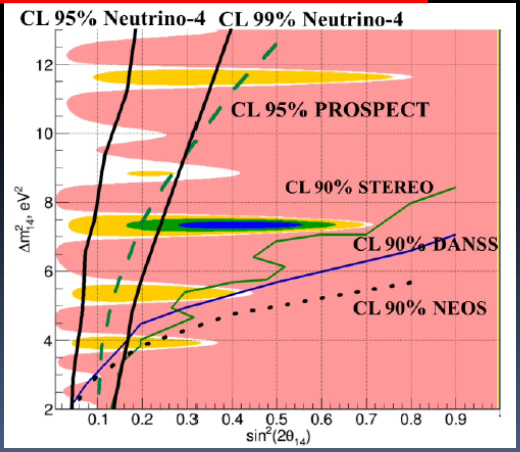


Both experiments exclude Reactor anomaly at 98-99%

Neutrino-4 (A.Serebrov et al. arXiv:1809.10561)
Dimitrovgrad, Reactor Active Zone 35×42×42 cm
Segmented detector 1.8t LS + Gd



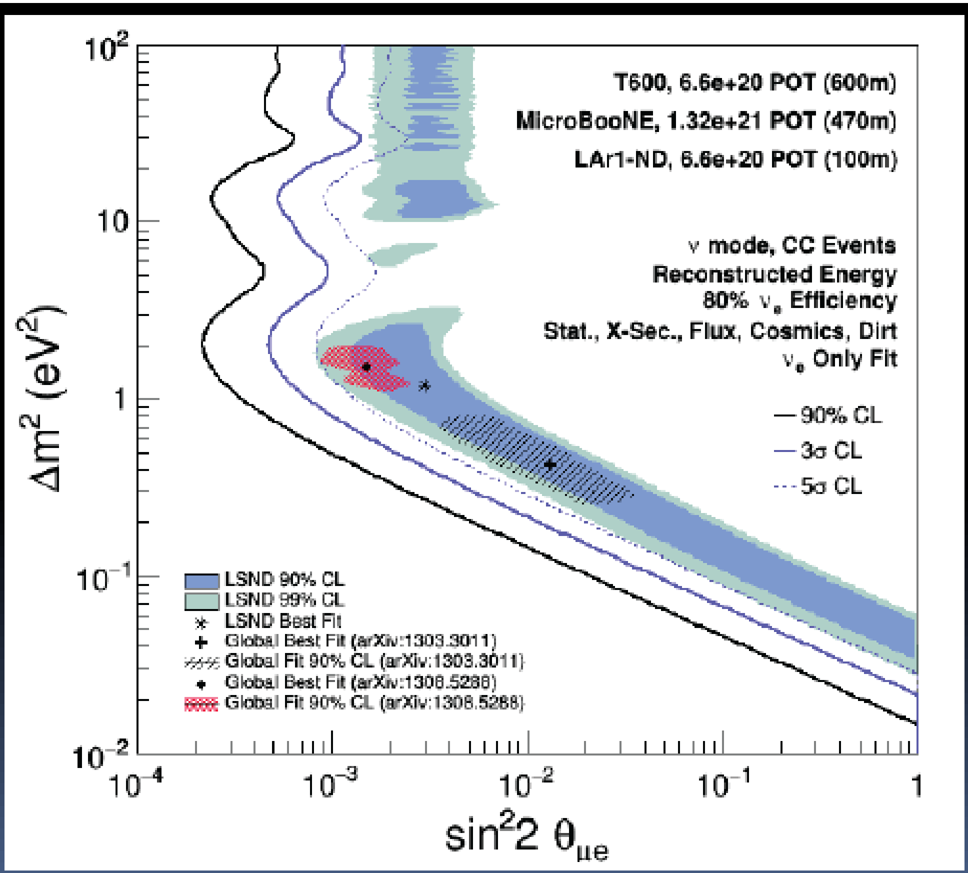
$$\Delta m^2_{14} \approx 7.34 eV^2 \;,\quad \sin^2 2\theta_{14} \approx 0.39$$



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



Absolute scale of neutrino mass

Neutrino mass

Three methods to determine neutrino mass

1. Kinematics of **β- decay**
   - model independent

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

2. **0ν2β- decay**
   - model dependent (heavy neutrinos, nuclear matrix elements…)
   - neutrino – Majorana particles

$$< m_{\beta\beta} > = \left| \sum_{i=1}^{3} U_{ei}^{\,2} m_i \right| = \left| U_{e1}^2 m_1 + U_{e2}^2 e^{i\alpha_2} m_2 + U_{e3}^2 e^{i\alpha_3} m_3 \right|$$

3. **Cosmology** ΛCDM
   - model dependent (cosmology model)

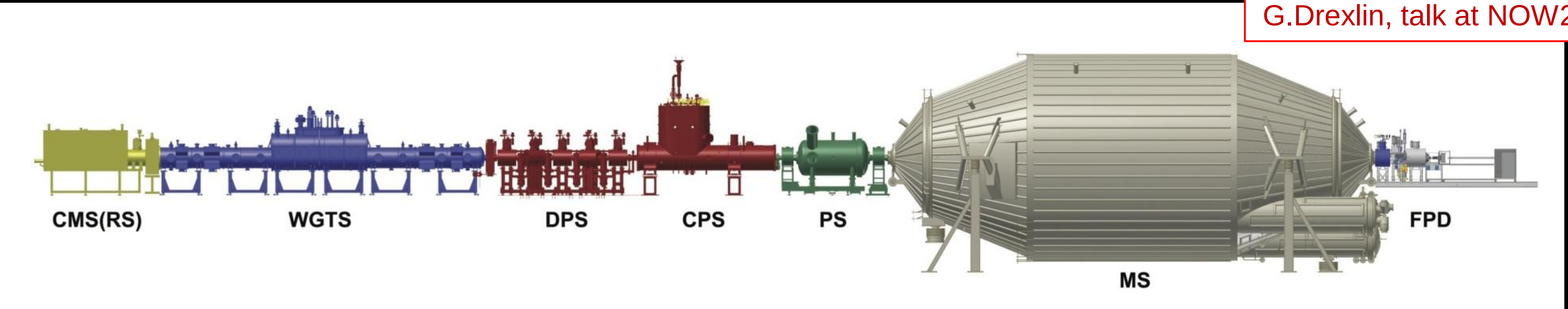
$$m_{tot} = \sum_{i=1}^{3} m_i$$

Direct measurement of ν mass

KATRIN, Karlsrue, Germany

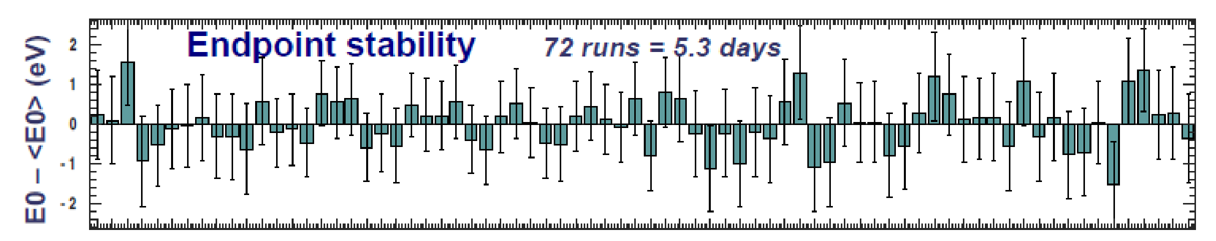
Present limit
$m(\nu_e) < 2$ эВ
-Troitsk nu-mass
- Mainz

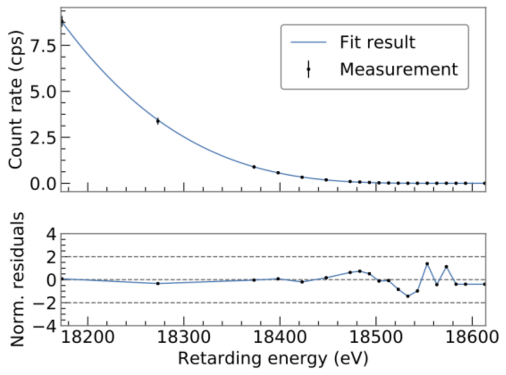
G.Drexlin, talk at NOW2018



Energy resolution <1 эВ
Sensitivity to $m(\nu_e)$ ~ 0.2 эВ

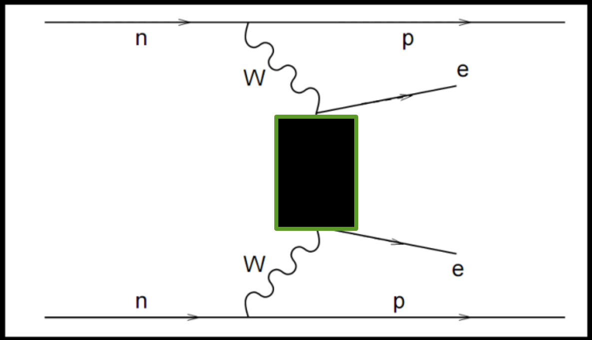
First run - June 2018
Energy interval 400 эВ
Data taking 2019-2023





Neutrinoless double β-decay

0ν2β

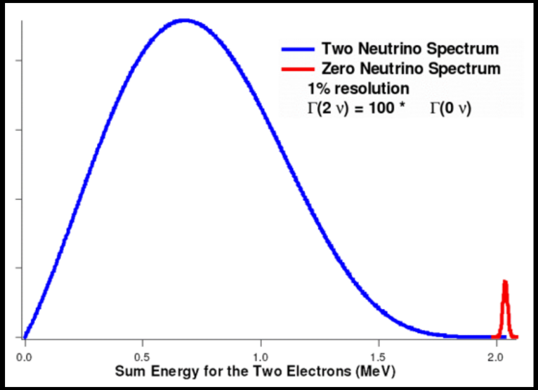


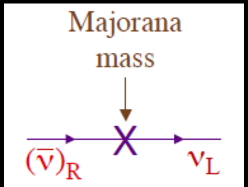
- 0ν2β forbidden in SM
- violation of lepton number
- neutrino - Majorana particles

$$\frac{1}{T_{1/2}^{0\nu}} = G_\nu^0 \left| \frac{m_{\beta\beta}}{m_e} \right|^2 g_A^4 \left| M^{0\nu} \right|^2$$

$M^{0\nu}$ - nuclear matrix element
$G^{0\nu}$ - phase space

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 \, m_i \right|$$





Majorana particles: mix neutrino and antineutrino
violate lepton number

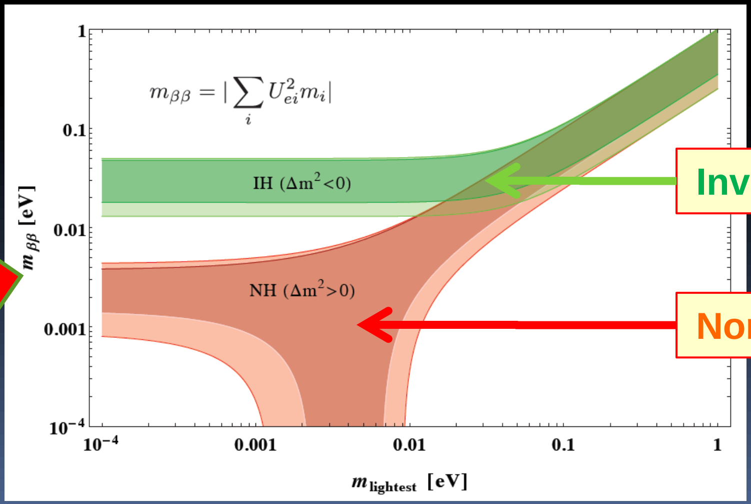
Background = 0

$$T_{1/2}^{0\nu} \propto M \cdot t \quad \text{kg·year}$$

Background ≠0

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

ΔE – resolution, keV
B – background, events number/(keV·kg·year)



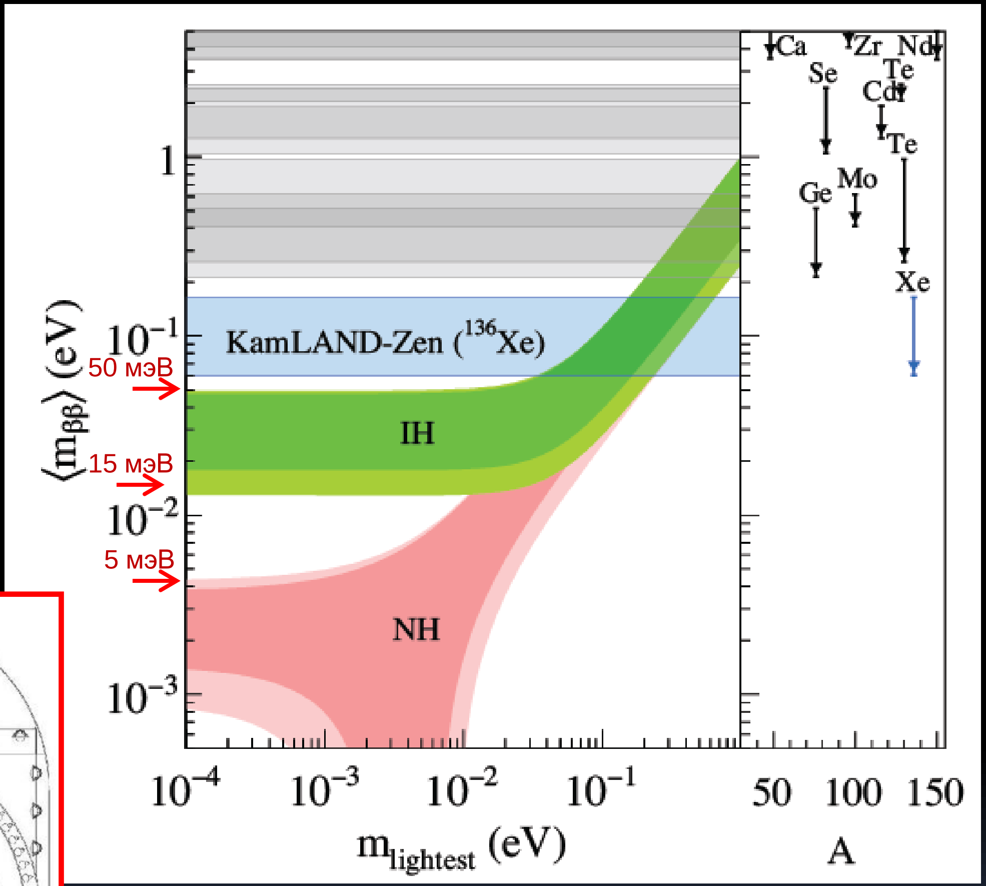
Inverted mass order

Normal mass order

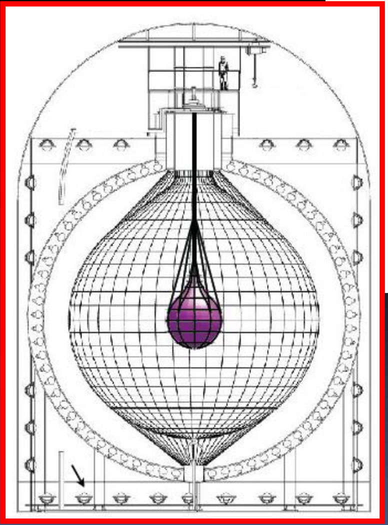
Limits on $<m_{\beta\beta}>$

$T^{0\nu}_{1/2}$ (90% C.L.)

Isotope, mass	$Q_{\beta\beta}$, keV	b x ΔE x M, counts/yr	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV	Experiment, technique
^{76}Ge, 40kg	2039	0.07	> 0.9 x 10^{26}	< 0.11-0.25	GERDA, HPGe
^{82}Se, 5kg	2998	0.4	> 2.4 x 10^{24}	< 0.38-0.77	CUPID-0, scintillating bolometers
^{100}Mo, 7kg	3034	1.5	> 1.1 x 10^{24}	< 0.33-0.62	NEMO-3, tracko-calo
^{130}Te, 200kg	2528	21	> 1.5 x 10^{25}	< 0.13-0.50	CUORE, bolometers
^{136}Xe, 380kg	2458	1	> 1.07 x 10^{26}	< 0.06-0.16	KamLAND-Zen, doped LS



KamLAND –ZEN – 400
90.6% enriched ^{136}Xe
σ_E ~ 6.6.-7.3%√E (MэB)

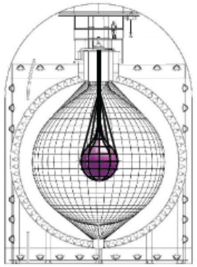


$<m_{\beta\beta}>$ < 61-160 meV (90 CL)

Prospects

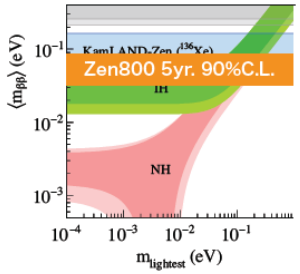
Near future

KamLAND-ZEN-800: Xe-136



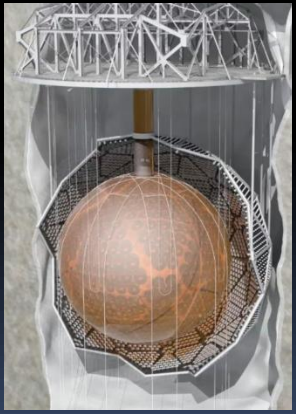
KamLAND-Zen 800

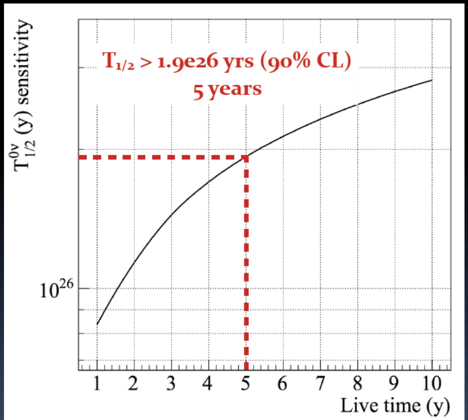
- ✓ R = 1.92m mini-balloon
- ✓ ~750 kg of xenon gas
- ✓ This phase will begin this winter



σ(2.6MeV)=4% → < 2.5%
Target $\langle m_{\beta\beta}\rangle$ ~20meV in 5 yrs

SNO+: Te-130





Far future

LEGEND: Ge-76

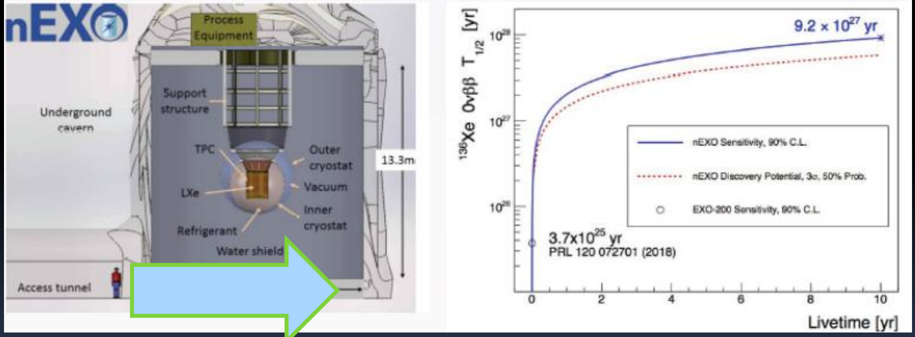
LEGEND-200 (first phase):

- up to 200 kg of detectors
- BI ~0.6 cts/(FWHM t yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t yr
- Sensitivity 10^{27} yr
- Isotope procurement ongoing
- Start in 2021

LEGEND-1000 (second phase):

- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM t yr)
- Location tbd
- Design exposure 12 t yr
- 1.2 x10^{28} yr

nEXO: Xe-136



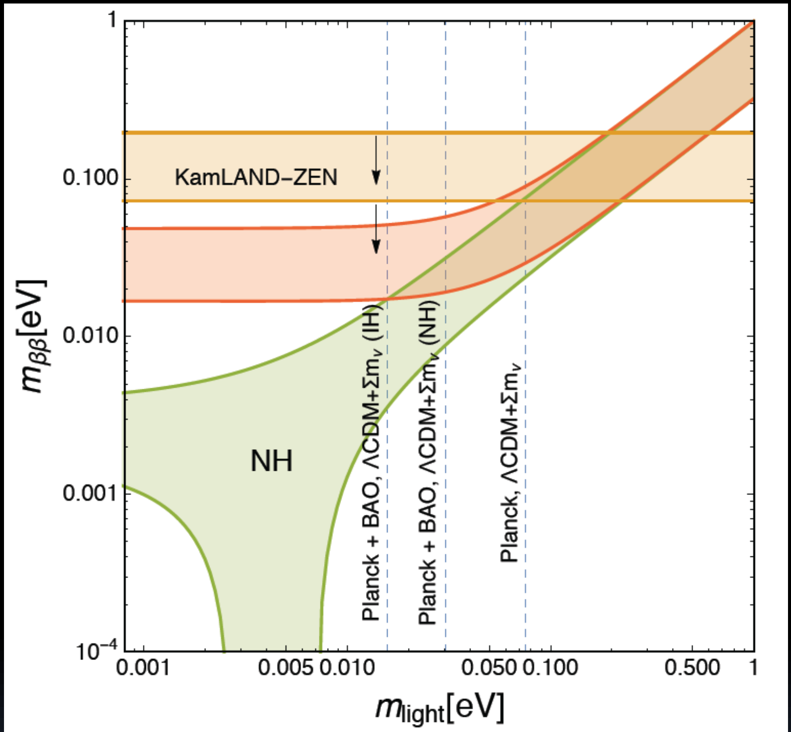
5000kg Xe-136

Inverted mass hierarchy can be tested within 5-10 years

Cosmology: neutrino properties

M.Lattanzi, talk at NuPhys18

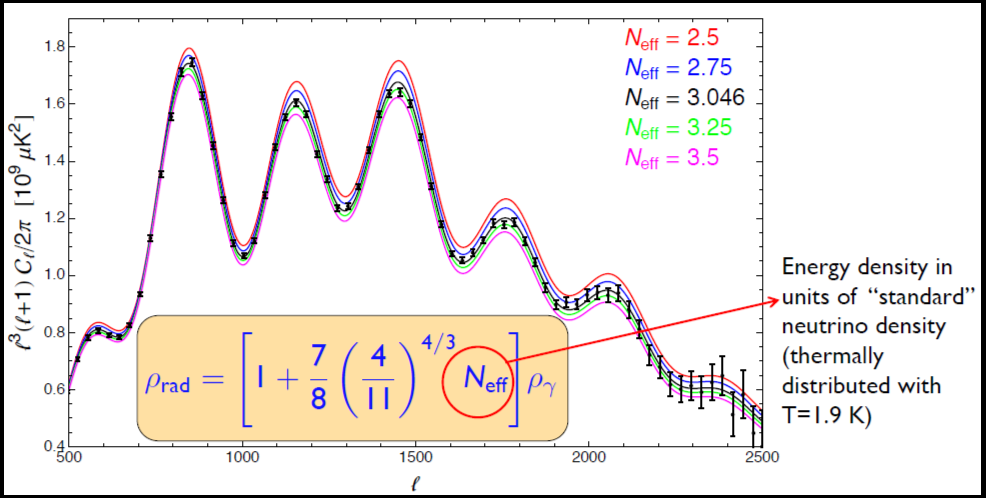
KamLAND-ZEN → 95% CL upper limit



Oscillation data used, normal hierarchy

Σm_ν < 0.24 eV Planck18
Σm_ν < 0.12 eV Planck18 + BAO

Planck2018 + BAO



N_{eff} = 2.99 ± 0.17
no need in sterile neutrinos
for interpretation of cosmological data,
but 1 eV νs are allowed if they are
not thermalised

Conclusion

Neutrino physics – laboratory to study New Physics beyond SM

Neutrino oscillations → $m_\nu \neq 0$
Large mixing
$L_e, L_\mu, L_\tau \neq 1$

- CP violation in neutrino oscillations? Connection to BaU?
- Why different mixing of neutrino and quarks?
- Normal or inverted mass order?
- Neutrino: Dirac or Majorana particles?
- Absolute scale of neutrino mass?
- Generation of neutrino mass, «see-saw» mechanism?
- Sterile neutrinos ?
- ………..
- ……….

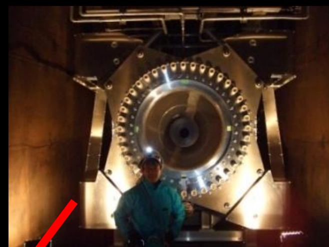
Thank you for your attention!

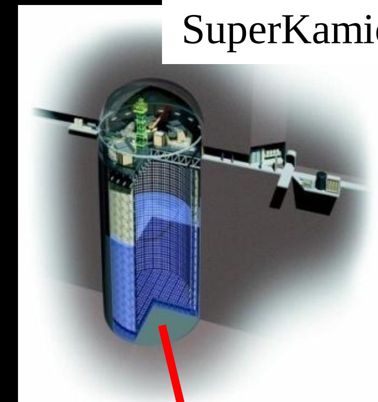
Backup slides

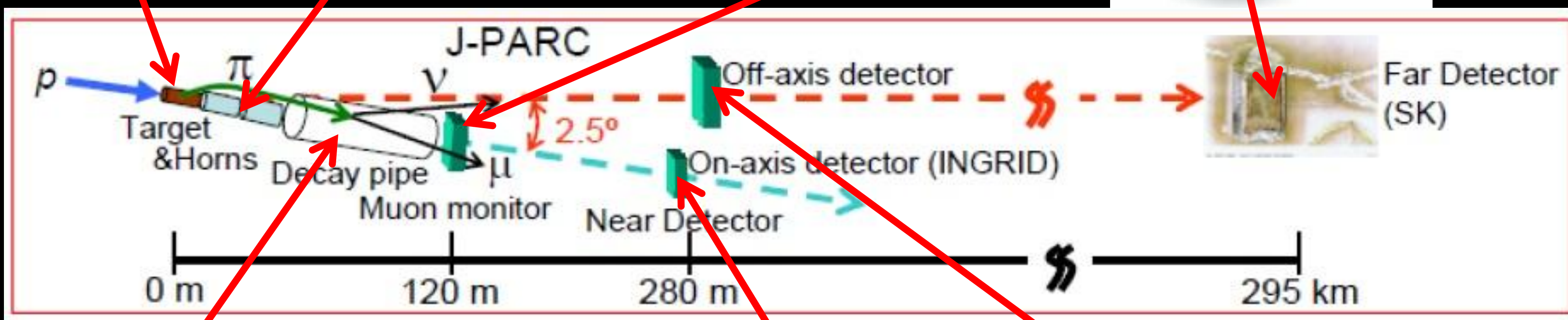
T2K experiment

Collect data since 2010

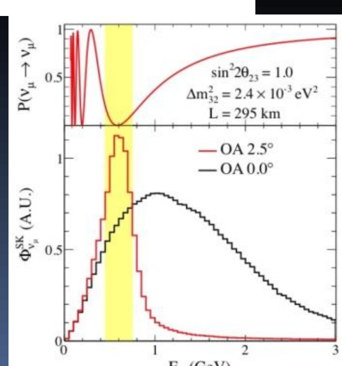
Far neutrino detector
SuperKamiokande



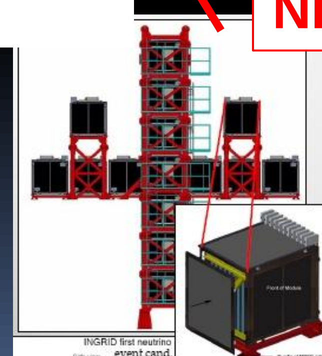




Off-axis neutrino
beam

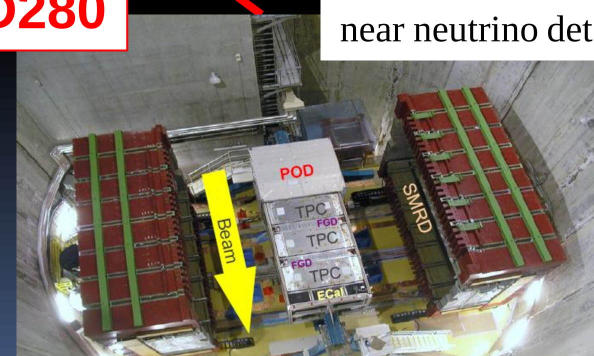


Neutrino monitor
INGRID



ND280

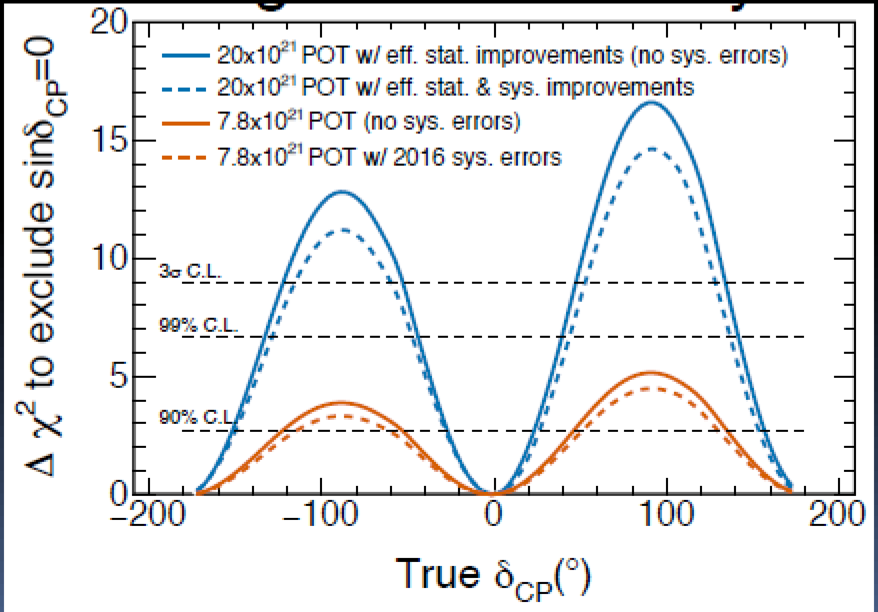
Off-axis
near neutrino detector



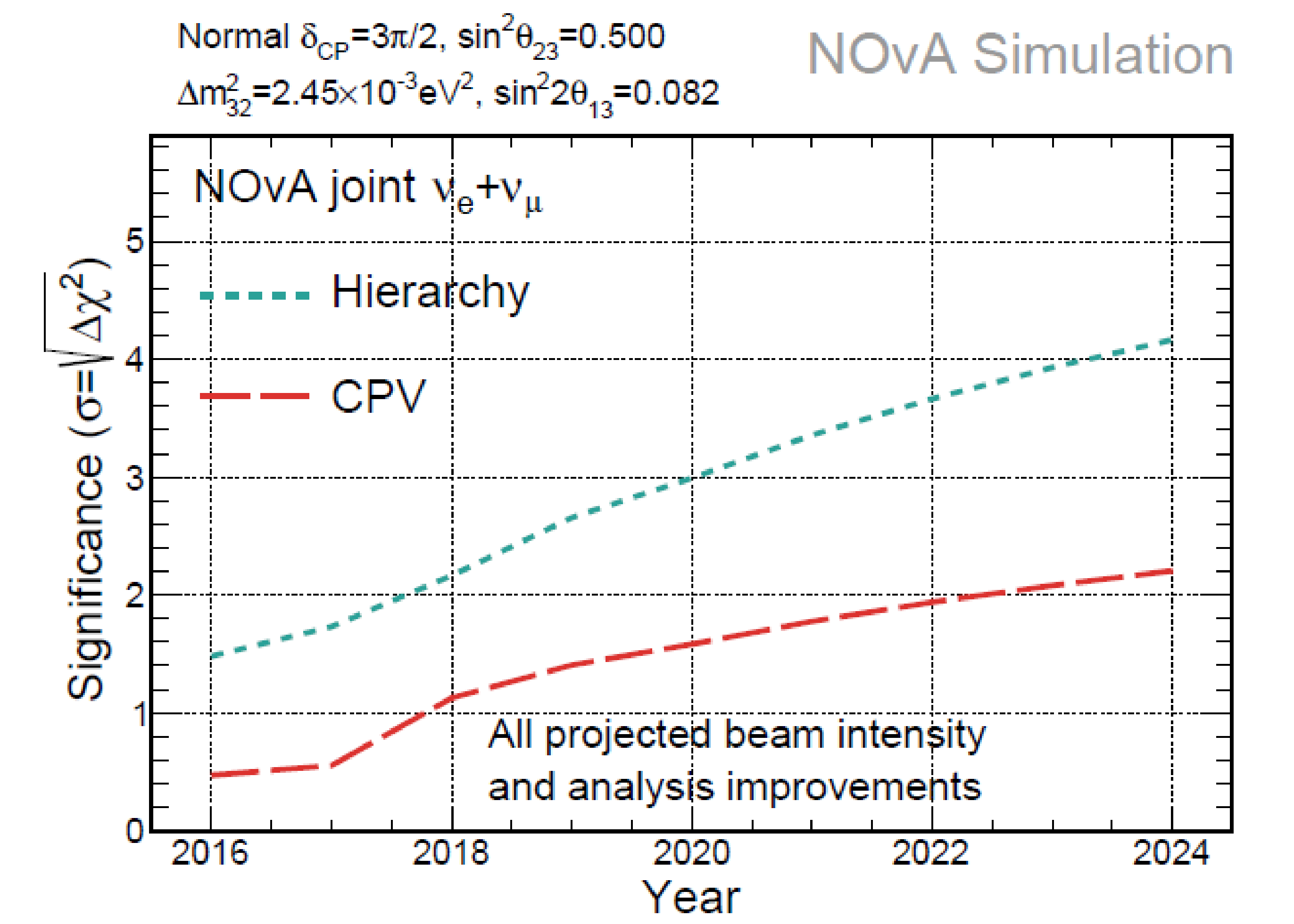
Future plans

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

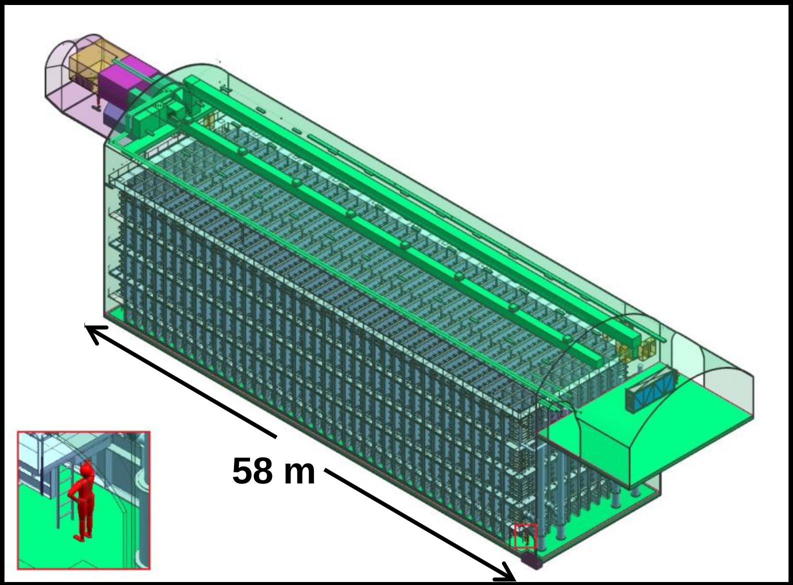
- Upgrade of near detectors to improve systematic uncertainties
  18% (2011) → 9% (2014) → 5% (2018) → goal ≤4% (2021)
- Plan to increase the beam intensity up to 1 MW in 2021
- Beam power up to 1.3 MW in ~2026
- T2K-II: proposed extension up to 2026 for 20×10^{21} POT
  3σ sensitivity to CP violation for $\delta_{CP} \sim -\pi/2$

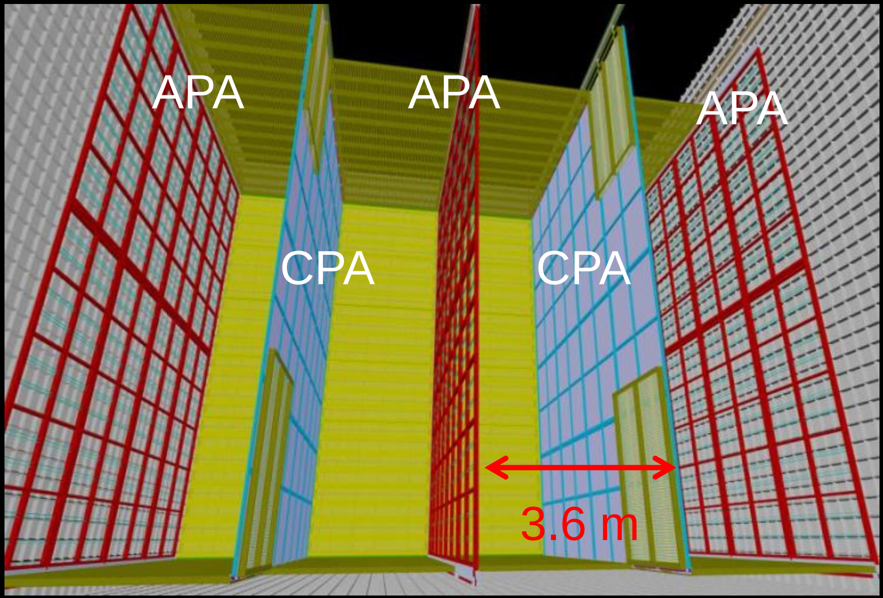


Prospects for NOvA



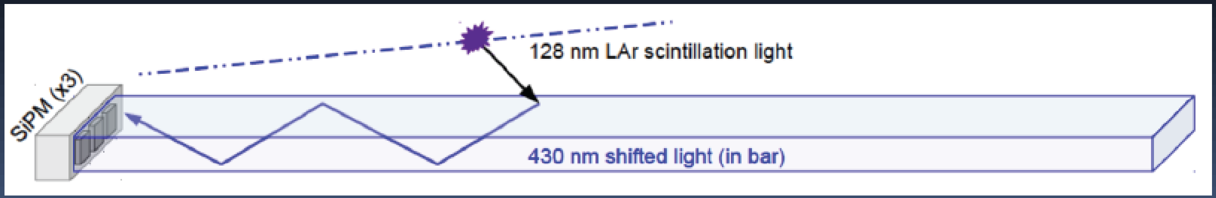
Single-phase LAr TPC





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

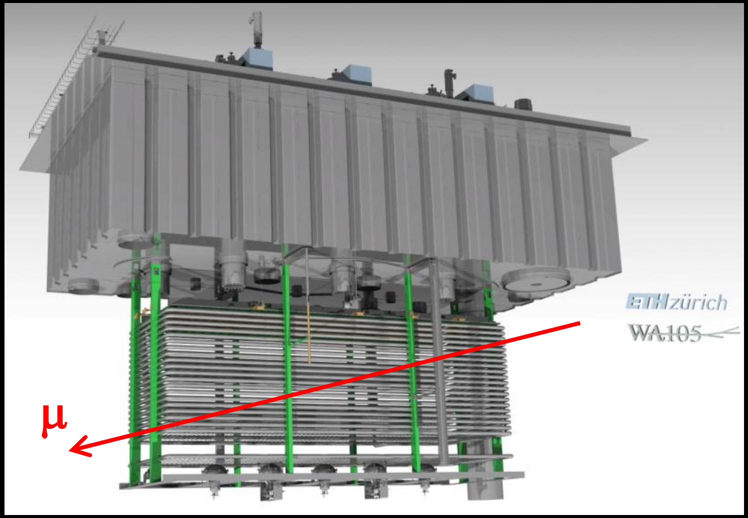


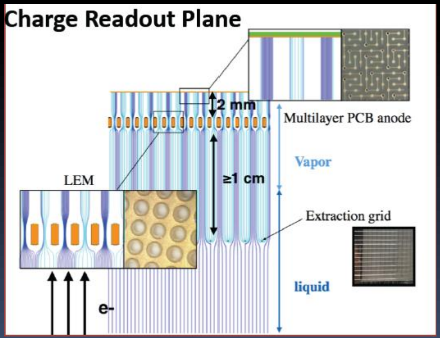
LAr detectors at CERN Neutrino Platform

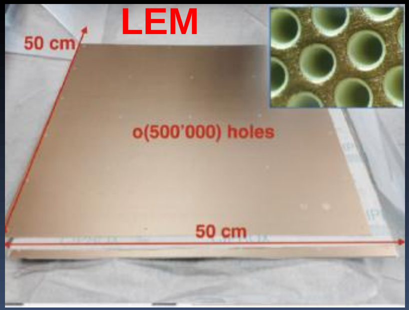
NP02: WA105
(DP demonstrator + ProtoDUNE DP)

S.Murthy, talk at TPC-2016

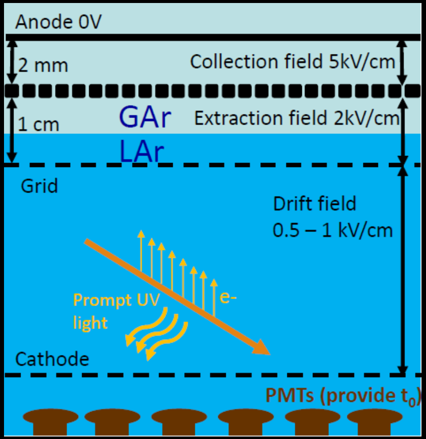
Demonstrator: 3x1x1 m^3 – 5 tons



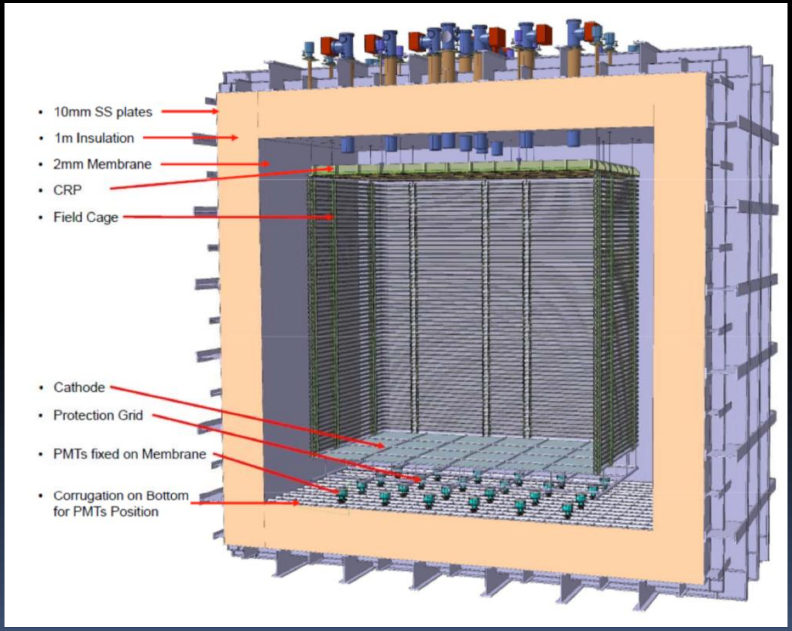




Cosmic data taking gas begun



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

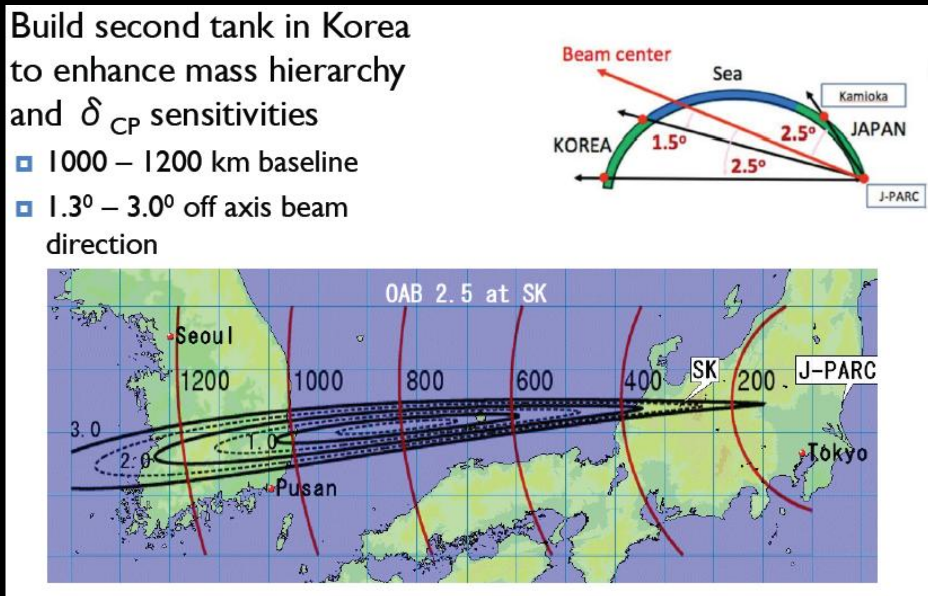


Measurements with test beam in 2018

T2HKK

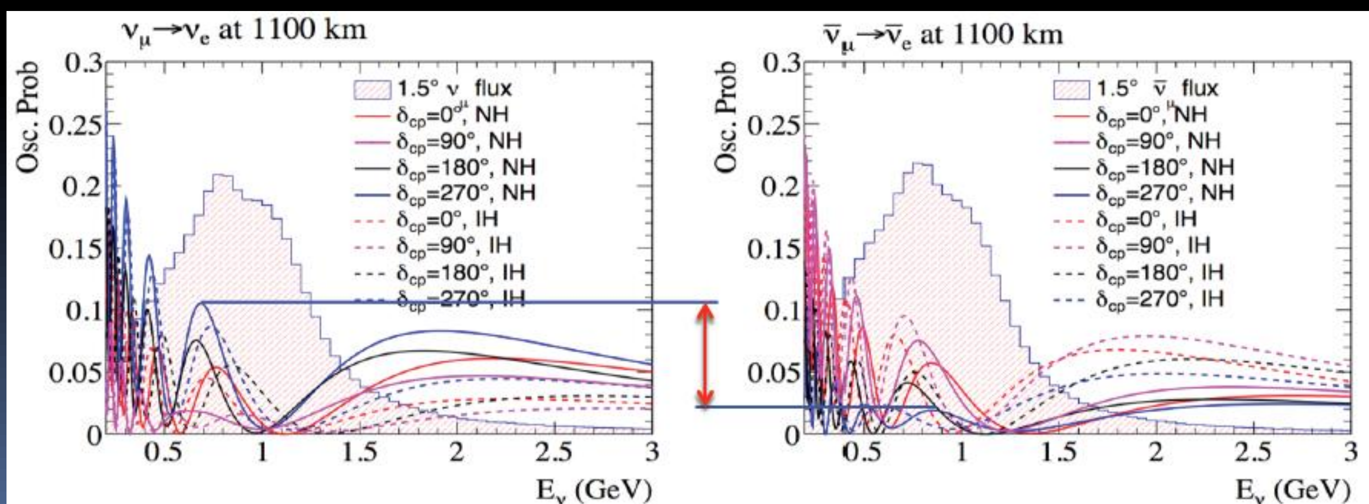
Second tank in Korea

arXiv:1611.06118

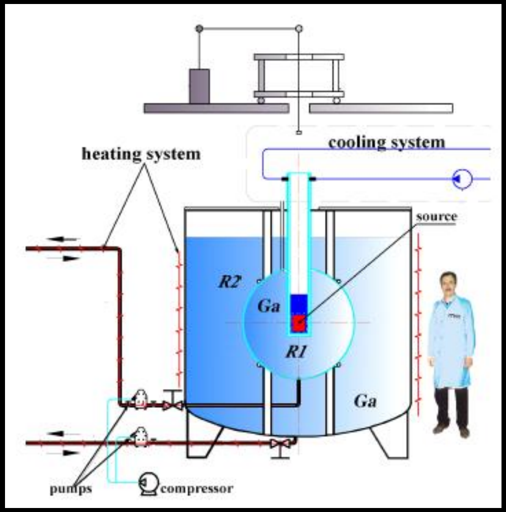


Neutrino and antineutrino spectra in T2HKK cover 1st and 2nd oscillation maximum

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



Source experiments

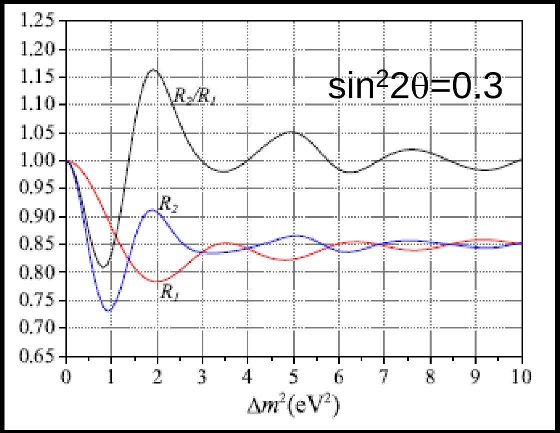


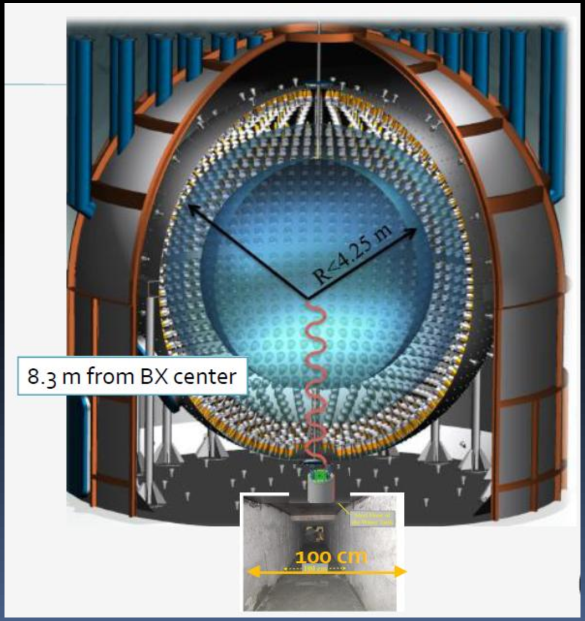
BEST

3 MCi ^{51}Cr source

Two-zone 50 t
liquid Ga metal target

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





SOX (terminated)

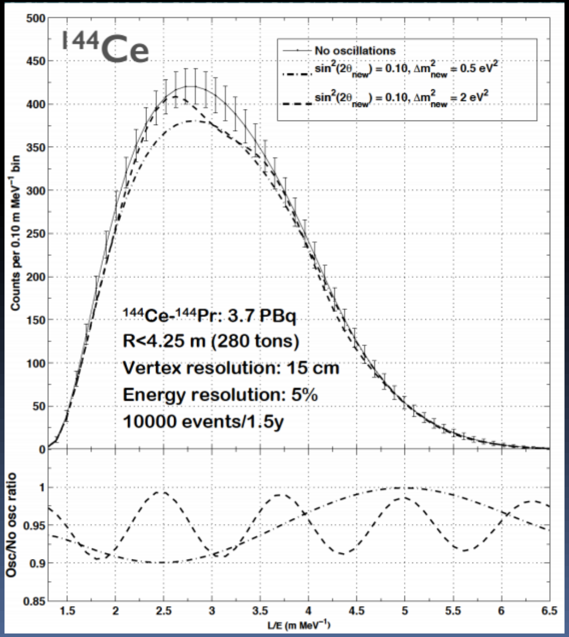
Ultra-low radioactive background
- Spatial resolution: 12 cm @ 2 MeV
- Energy resolution: ~3,5% @ 2 MeV

^{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

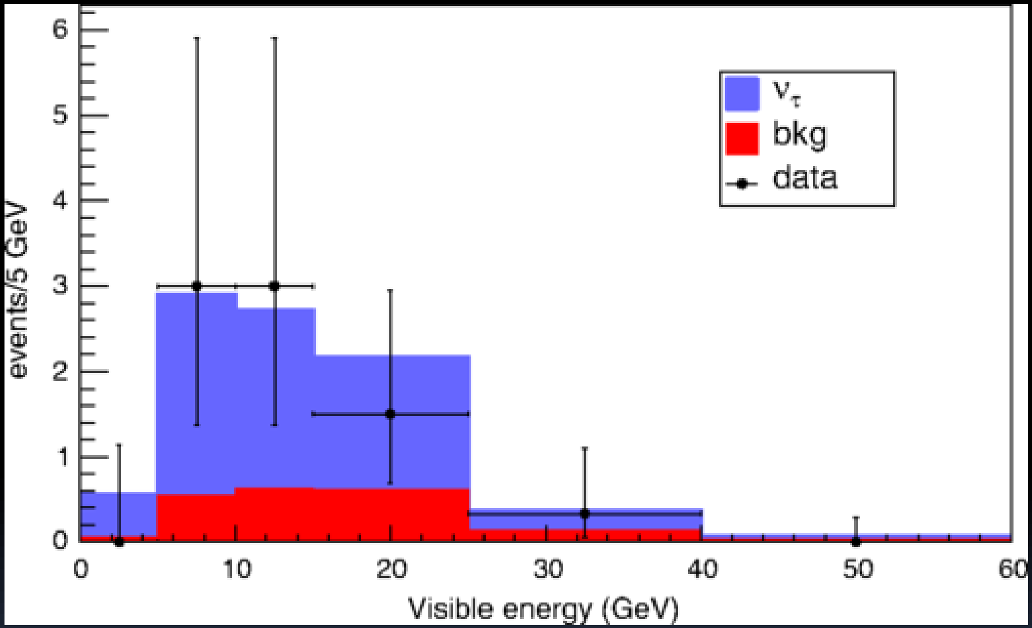


OPERA: final result

$\nu_\mu \rightarrow \nu_\tau$ appearance

PRL 120 (2018) 211801

10 ν_τ events observed for 18x10^{19} POT
Expected 6.4 events for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$
Expected background 2.0±0.4 events



Significance of ν_τ appearance 6.1σ

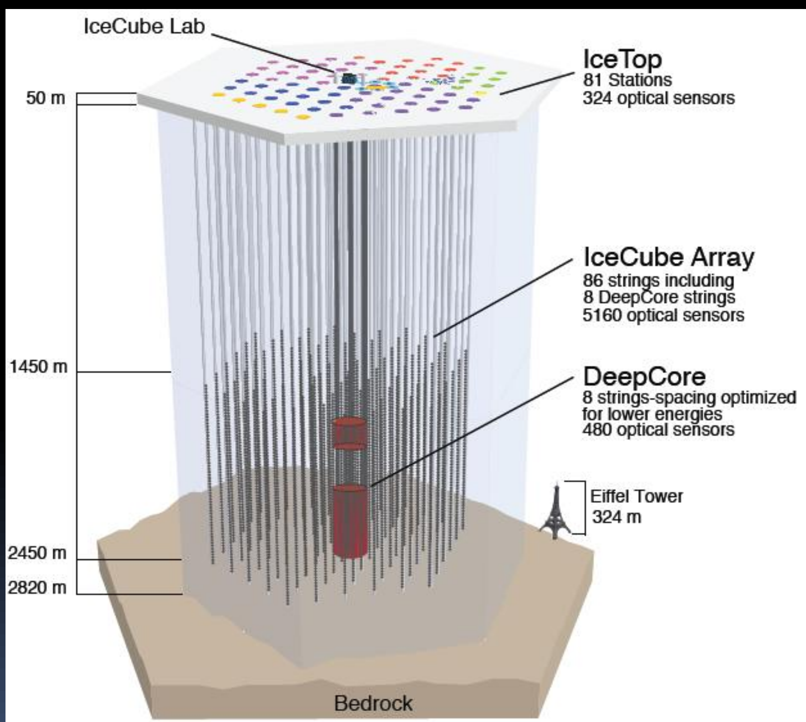
OPERA: $\Delta m^2_{23} = (2.7 + 0.7 - 0.6) \times 10^{-3}$ eV^2, assuming $\sin^2 2\theta_{23} = 1.0$

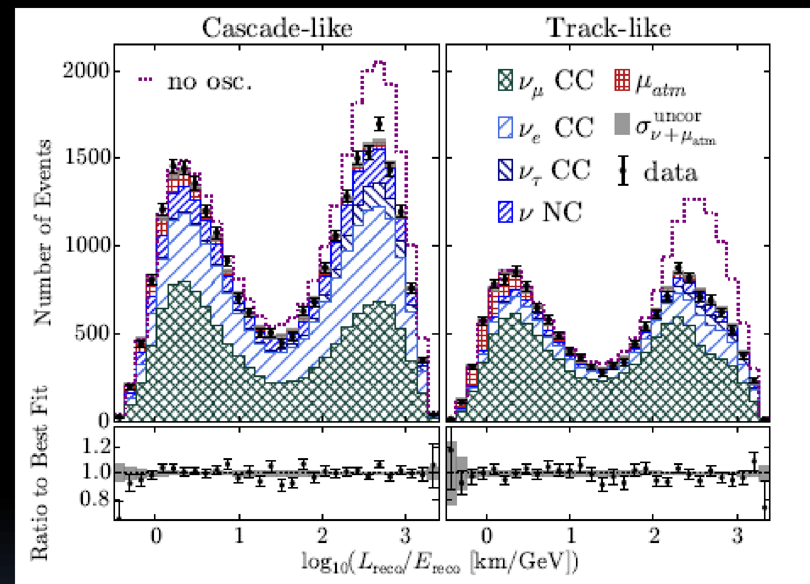
IceCube

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

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

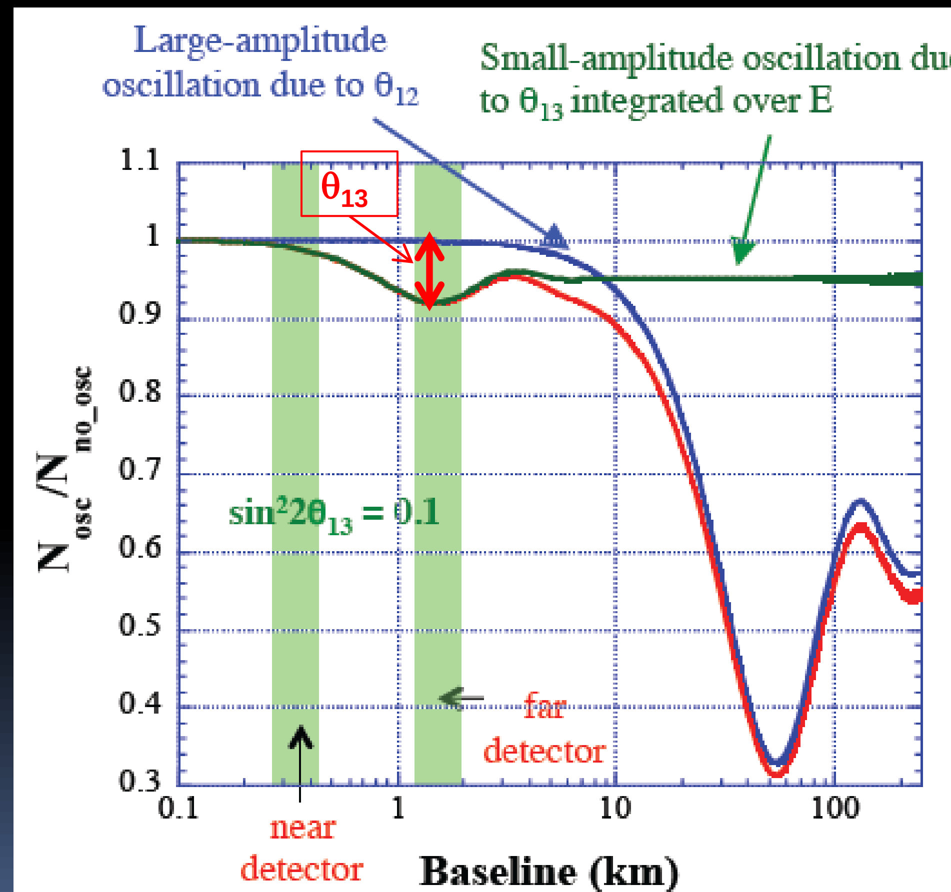
17.4 GW

RENO, Korea

16 GW

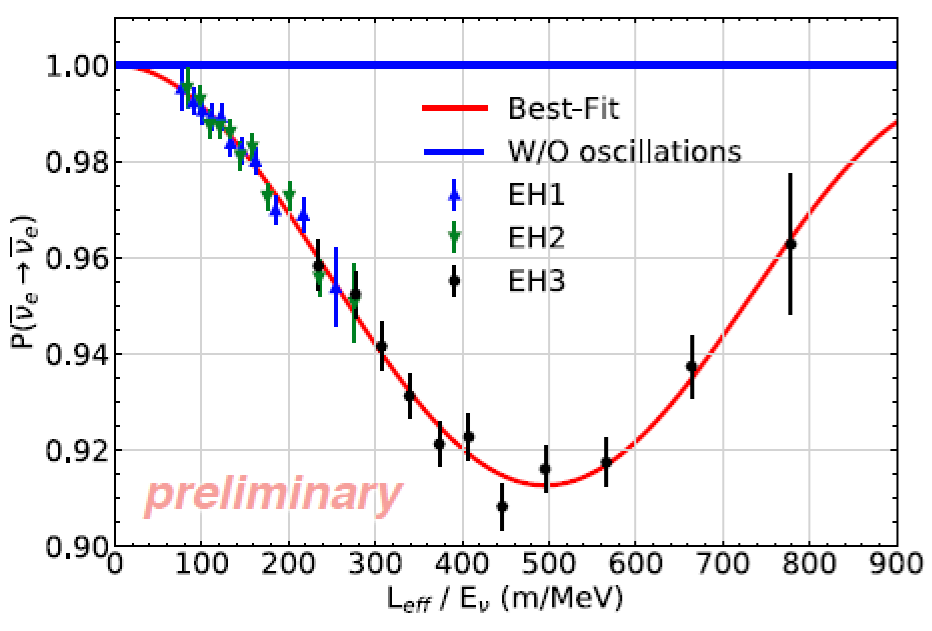
Double Chooz, France

8.5 GW

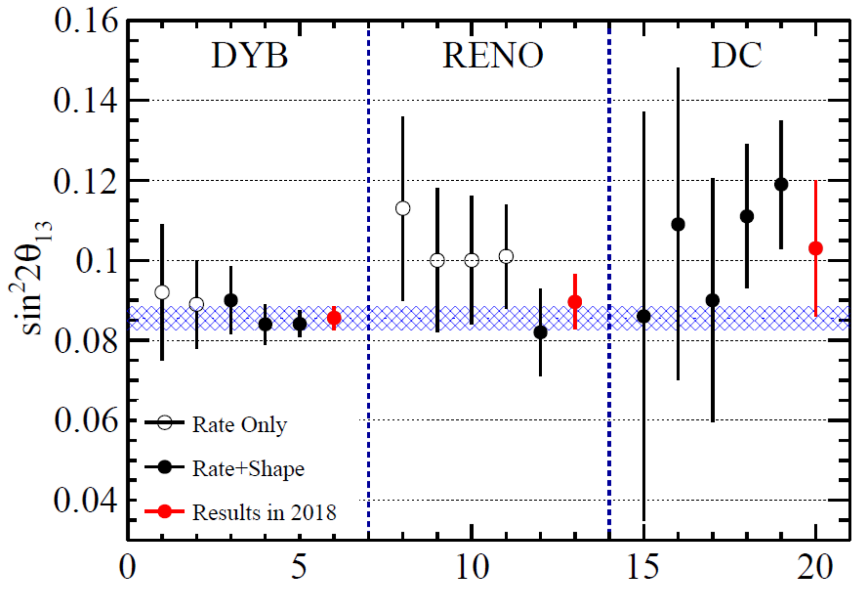


Oscillation results

Daya Bay



Liang Zhan, ICHEP2018



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

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

Detector JUNO

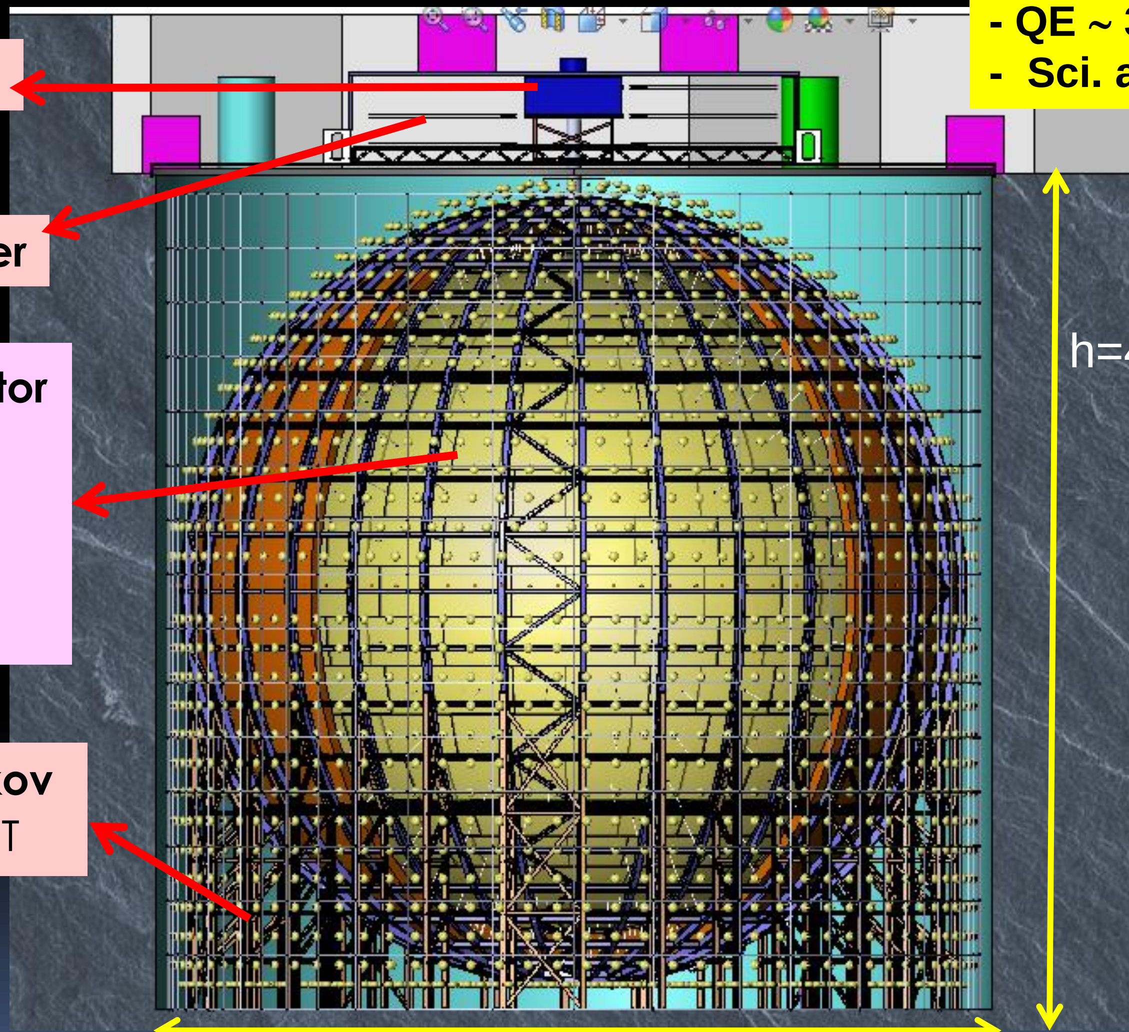
Requirements:
- **PMT coverage 75% of total surface**
- **QE ~ 35%**
- **Sci. att. length >20 m**

Calibration

Top Tracker

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

Water Cherenkov
~2000 20'' PMT



h=44 m

d=43.5 m

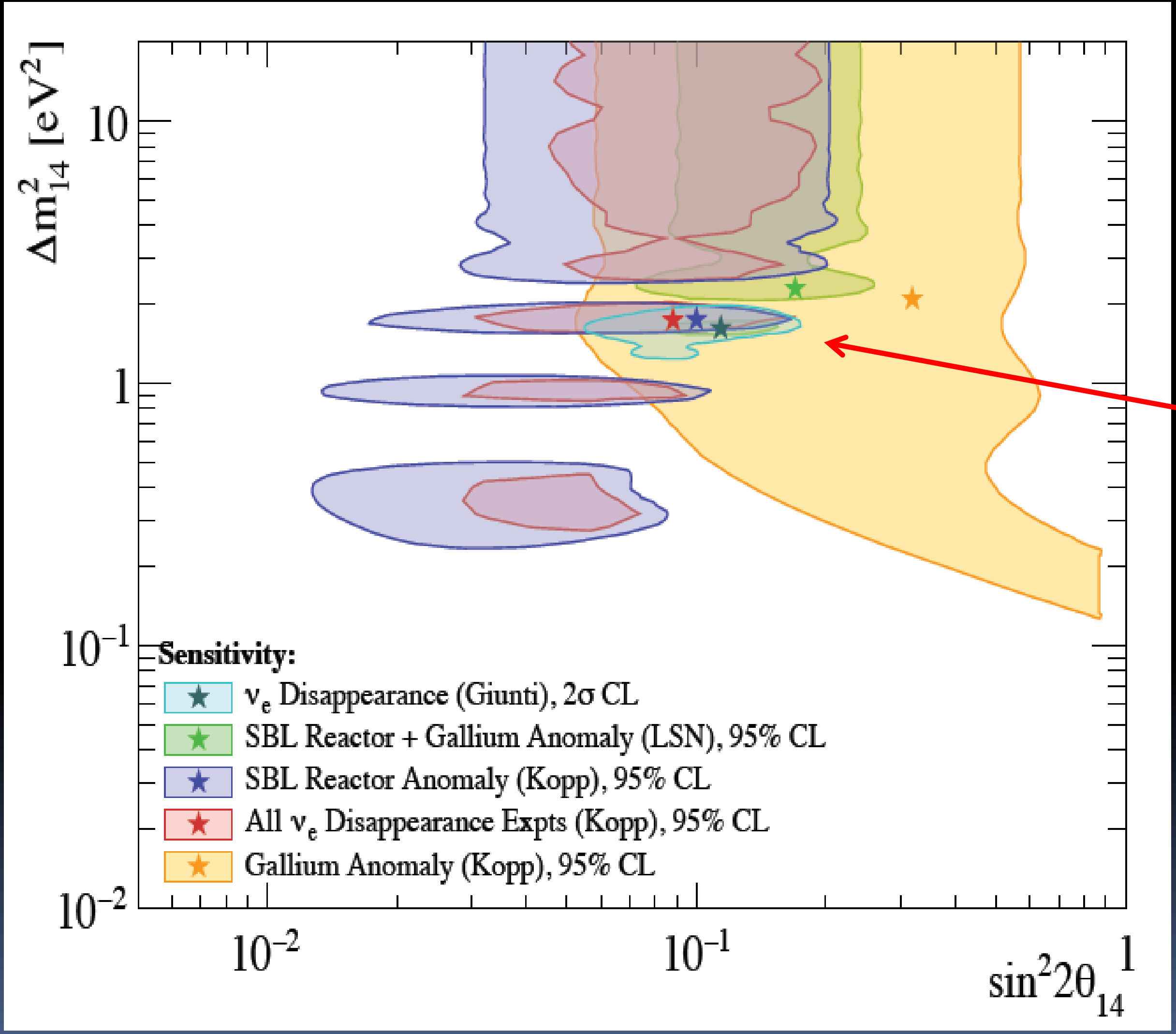
3" PMT

20" PMT

ν_e and anti-ν_e disappearance

arXiv:1512.02202

Global fit of reactor and Gallium data

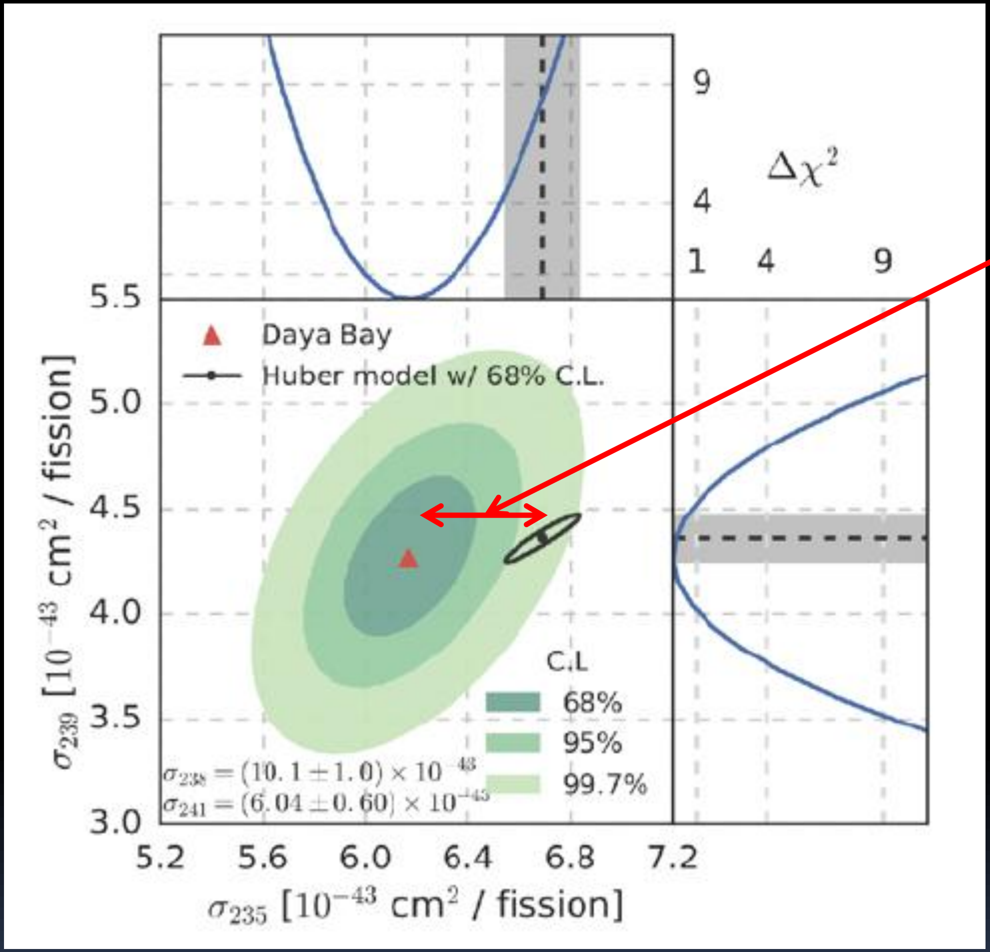


$\Delta m^2 \approx 2$ eV^2

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

Daya Bay: anti-neutrino flux

PRL 118 (2017) 251801



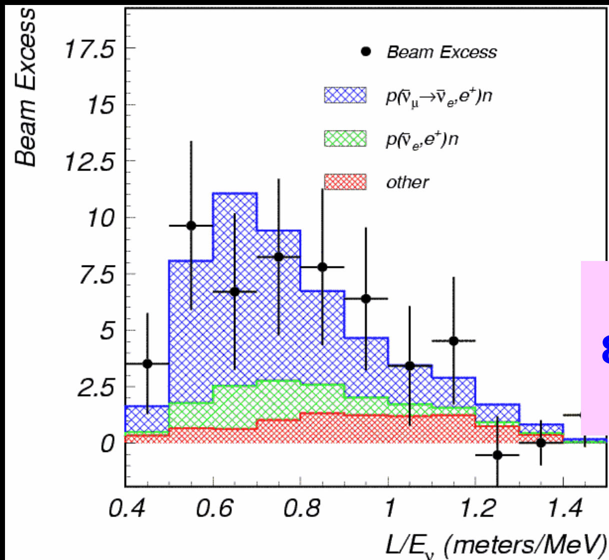
This discrepancy gives an overestimation of predicted antineutrino flux by 7.8%.

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

Short baseline experiments at U-enriched reactors are needed

LSND anomaly

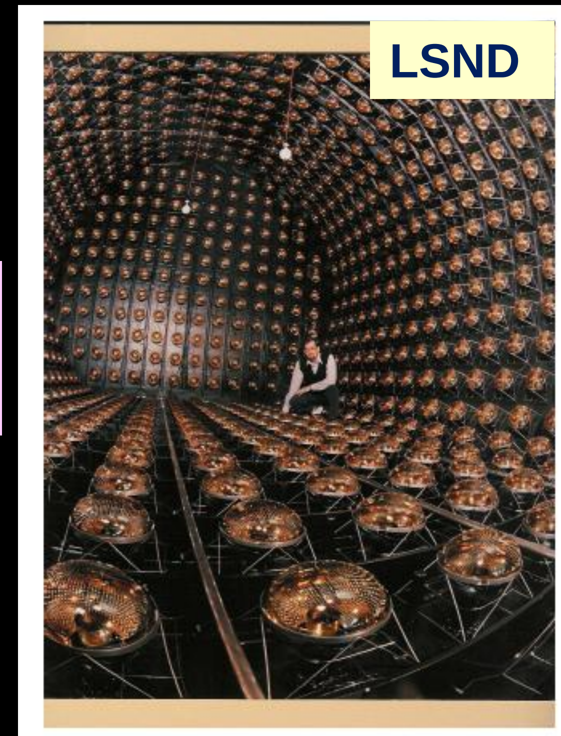
PRL 77 (1996) 3082

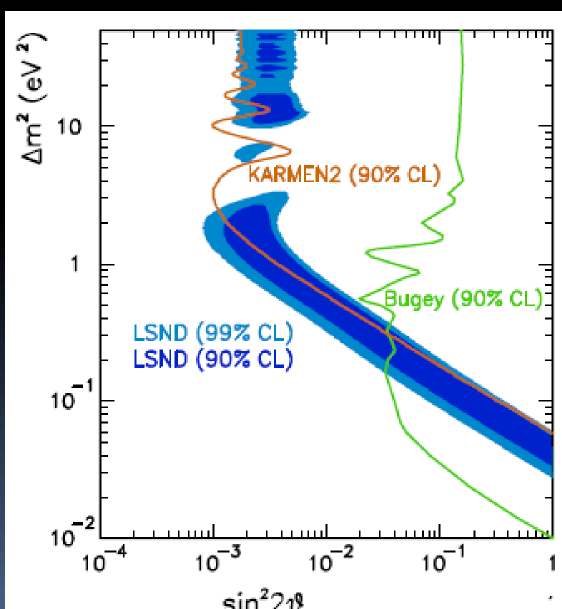


anti-ν_μ → anti-ν_e

87.9 ± 22.4 ± 6.0 events

Excess 3.8σ





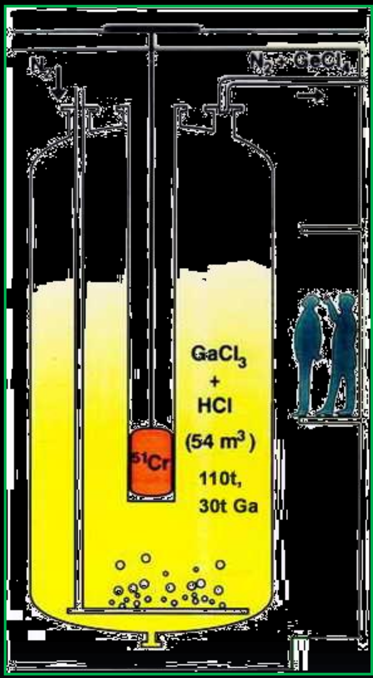
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right) = 0.245 \pm 0.067 \pm 0.045\ \%$$

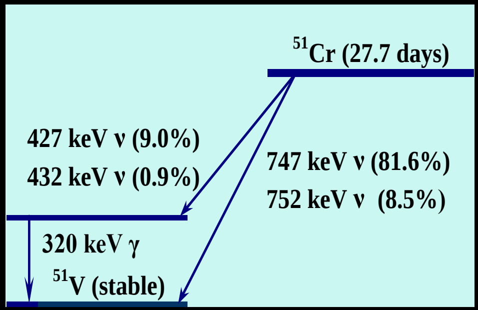
$$0.2 \le \Delta m^2 \le 1\ \text{эВ}^2 \qquad 2\times 10^{-3} \le \sin^2 2\theta \le 4\times 10^{-2}$$

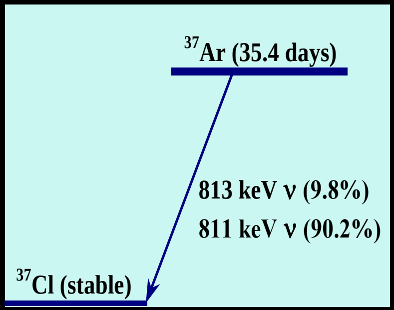
Possible explanation:
4th (sterile) neutrino с m ~ 1 эВ

Gallium anomaly

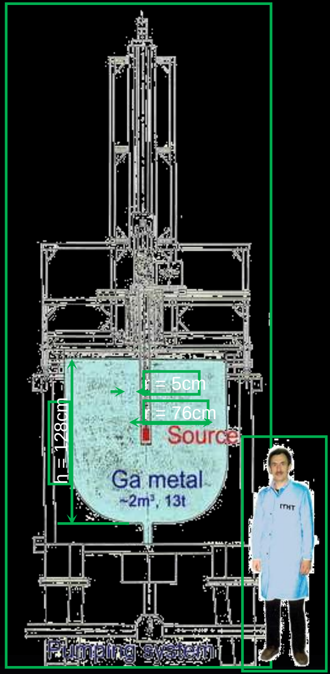
GALLEX





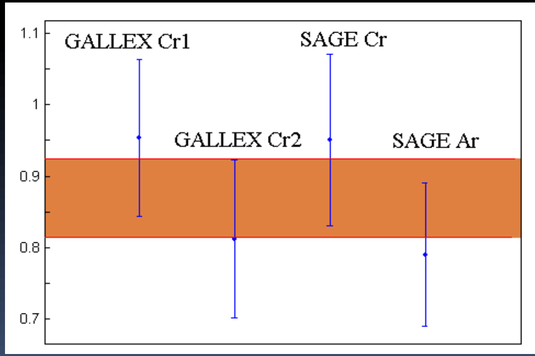


SAGE



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

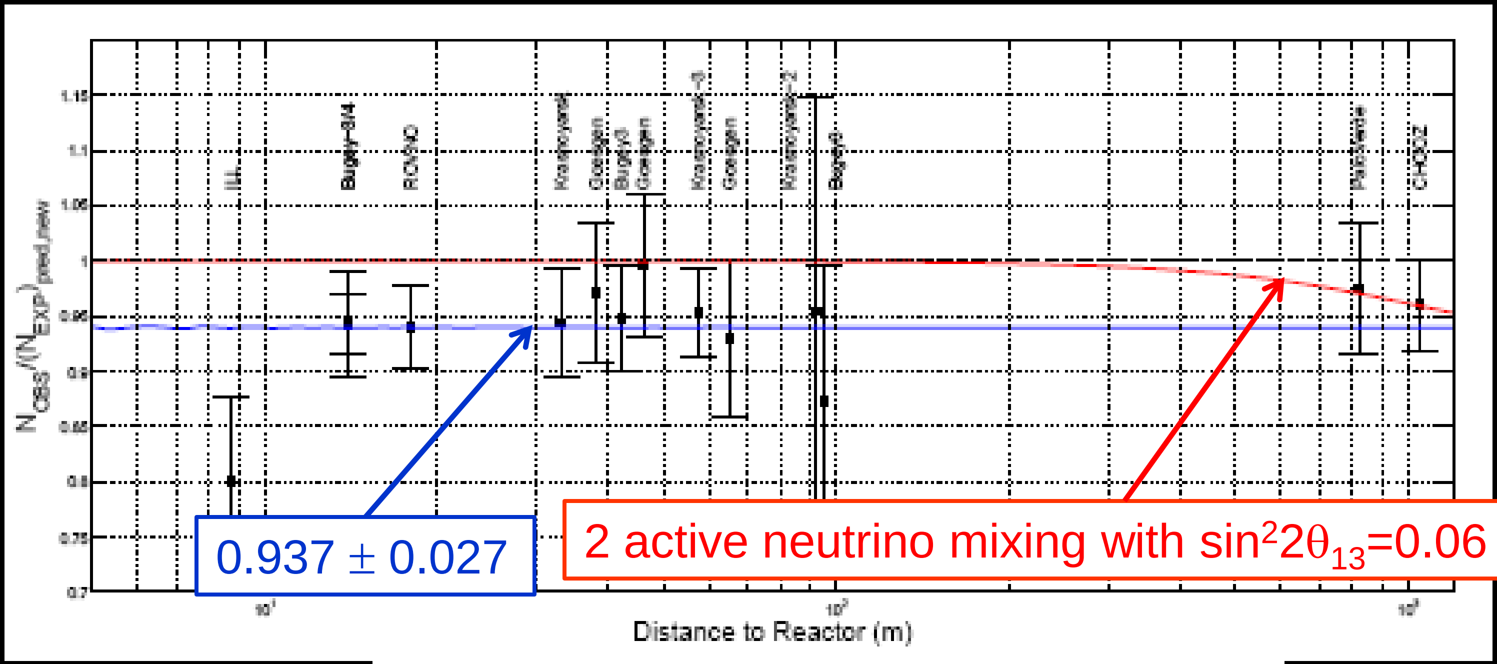
	GALLEX m(Ga)=30 t		SAGE m(Ga)=13 t	
Source	^{51}Cr -1	^{51}Cr -2	^{51}Cr	^{37}Ar
Intensity (Mci)	1.714	1.868	0.517	0.409
$R = (p_{exp}/p_{theory})$	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.10
R_{comb}	0.88 ± 0.08		0.86 ± 0.08	

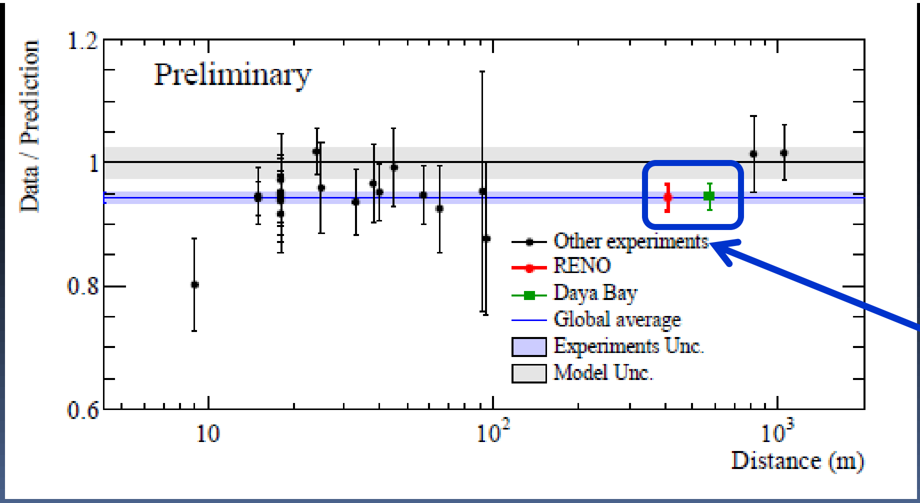


$$R = p_{exp}/p_{theory} = 0.87 \pm 0.05$$

Reactor anomaly

anti-$\nu_e \rightarrow$ anti-ν_e



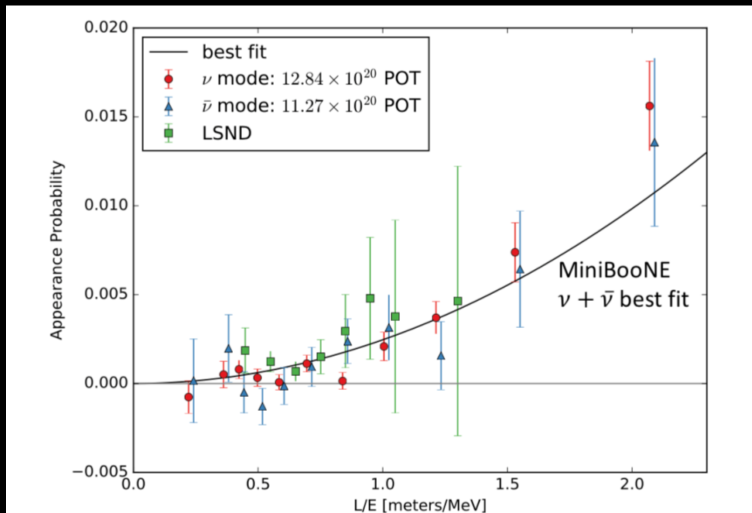


S.Gariazzo et al
arXiv:1703.08860

Daya Bay and RENO

New MiniBooNe result

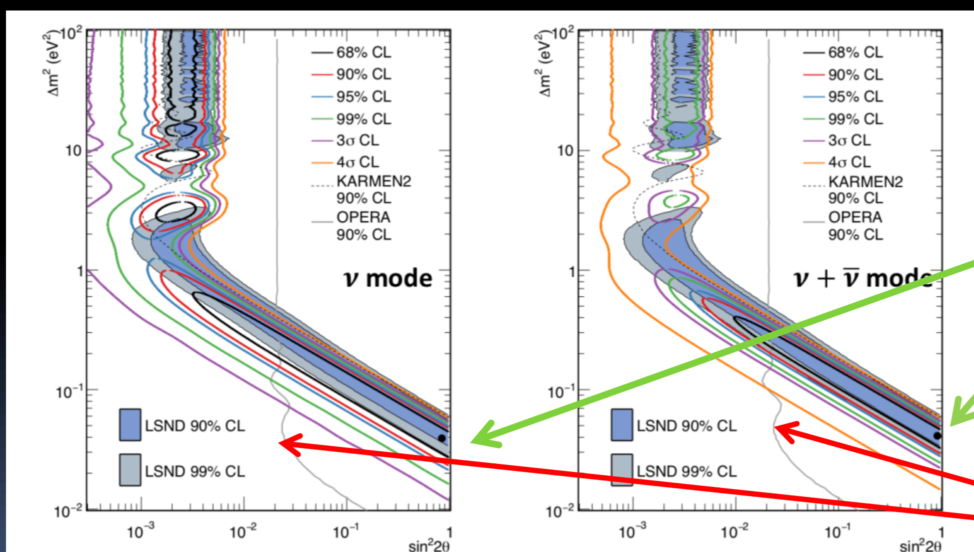
arXiv:1805.12028



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)

Best fit point:
$\Delta m^2_{41} = 0.041$ eV^2
$\sin^2 2\theta = 0.958$



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

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

Excluded by OPERA and ICARUS