Исследование осцилляций нейтрино в ускорительных и реакторных экспериментах

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Neutrino Oscillations in Brief

- Neutrinos are produced by the weak interaction in weak interaction eigenstates: ν_e, ν_μ, ν_τ
- There is no reason for these eigenstates to be identical to the mass eigenstates: ν_1, ν_2, ν_3
- They are related by a unitary transformation:

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

- The mass eigenstates propagate as $e^{-iEt/\hbar}$. Thus, different masses develop different phases with time, resulting in oscillations in the weak eigenstates:
- If we consider only 2 states, then

$$\nu_\alpha = \nu_1 \cos\theta + \nu_2 \sin\theta$$
$$\nu_\beta = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

and

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \text{ where}$$

$\Delta m^2 \equiv (m_1^2 - m_2^2)$ is in $(\mathrm{eV}/c^2)^2$, L is in km, and E is in GeV.

- In addition to the vacuum oscillations an important effect due to propagation in matter was pointed out by Mikheev, Smirnov and Wolfenstein (MSW).

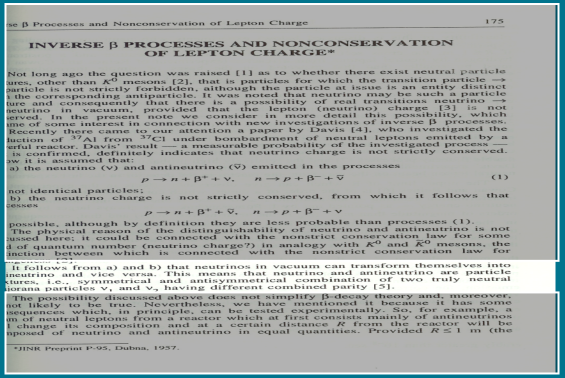
Genesis of Neutrino Oscillations

1957-1958 First proposal by Pontecorvo

1962 Maki, Nakagawa and Sakata

1968-1969 Pontecorvo and Gribov

Since 1970 Pontecorvo and Bilenky carefully and systematically studied possible oscillation scenarios and suggested their experimental tests


rse β Processes and Nonconservation of Lepton Charge 175

INVERSE β PROCESSES AND NONCONSERVATION OF LEPTON CHARGE*

Not long ago the question was raised [1] as to whether there exist neutral particle tures, other than K^0 mesons [2], that is particles for which the transition particle → particle is not strictly forbidden, although the particle at issue is an entity distinct n the corresponding antiparticle. It was noted that neutrino may be such a particle ture and consequently that there is a possibility of real transitions neutrino → neutrino in vacuum, provided that the lepton (neutrino) charge [3] is not served. In the present note we consider in more detail this possibility, which ame of some interest in connection with new investigations of inverse β processes.

Recently there came to our attention a paper by Davis [4], who investigated the luction of ^{37}Al from ^{37}Cl under bombardment of neutral leptons emitted by a verful reactor. Davis' result — a measurable probability of the investigated process — is confirmed, definitely indicates that neutrino charge is not strictly conserved. ow it is assumed that:

a) the neutrino (ν) and antineutrino ($\tilde{\nu}$) emitted in the processes

$$p \to n + \beta^+ + \nu, \quad n \to p + \beta^- + \tilde{\nu} \qquad (1)$$

not identical particles;

b) the neutrino charge is not strictly conserved, from which it follows that cesses

$$p \to n + \beta^+ + \tilde{\nu}, \quad n \to p + \beta^- + \nu$$

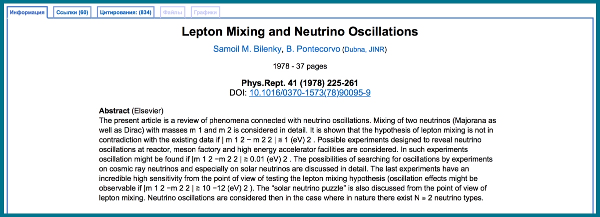
possible, although by definition they are less probable than processes (1).

The physical reason of the distinguishability of neutrino and antineutrino is not cussed here; it could be connected with the nonstrict conservation law for some d of quantum number (neutrino charge?) in analogy with K^0 and $\tilde{K}^0$ mesons, the tinction between which is connected with the nonstrict conservation law for

It follows from a) and b) that neutrinos in vacuum can transform themselves into ineutrino and vice versa. This means that neutrino and antineutrino are particle xtures, i.e., symmetrical and antisymmetrical combination of two truly neutral jorana particles ν_1 and ν_2 having different combined parity [5].

The possibility discussed above does not simplify β-decay theory and, moreover, not likely to be true. Nevertheless, we have mentioned it because it has some sequences which, in principle, can be tested experimentally. So, for example, a m of neutral leptons from a reactor which at first consists mainly of antineutrinos l change its composition and at a certain distance R from the reactor will be nposed of neutrino and antineutrino in equal quantities. Provided $R \leq 1$ m (the

*JINR Preprint P-95, Dubna, 1957.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Lepton Mixing and Neutrino Oscillations

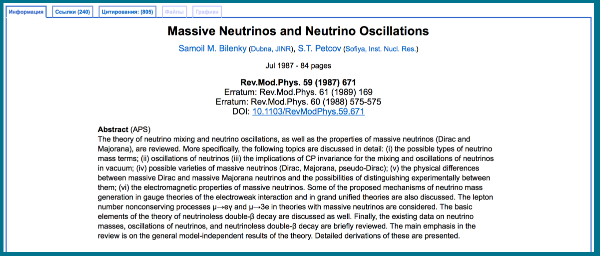
Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR)

1978 - 37 pages

Phys.Rept. 41 (1978) 225-261
DOI: 10.1016/0370-1573(78)90095-9

Abstract (Elsevier)
The present article is a review of phenomena connected with neutrino oscillations. Mixing of two neutrinos (Majorana as well as Dirac) with masses m 1 and m 2 is considered in detail. It is shown that the hypothesis of lepton mixing is not in contradiction with the existing data if | m 1 2 − m 2 2 | ≦ 1 (eV) 2 . Possible experiments designed to reveal neutrino oscillations at reactor, meson factory and high energy accelerator facilities are considered. In such experiments oscillation might be found if |m 1 2 −m 2 2 | ≧ 0.01 (eV) 2 . The possibilities of searching for oscillations by experiments on cosmic ray neutrinos and especially on solar neutrinos are discussed in detail. The last experiments have an incredible high sensitivity from the point of view of testing the lepton mixing hypothesis (oscillation effects might be observable if |m 1 2 −m 2 2 | ≧ 10 −12 (eV) 2). The "solar neutrino puzzle" is also discussed from the point of view of lepton mixing. Neutrino oscillations are considered then in the case where in nature there exist N ⩾ 2 neutrino types.

1978
Review by Bilenky and Pontecorvo
(500+)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Massive Neutrinos and Neutrino Oscillations

Samoil M. Bilenky (Dubna, JINR), S.T. Petcov (Sofiya, Inst. Nucl. Res.)

Jul 1987 - 84 pages

Rev.Mod.Phys. 59 (1987) 671
Erratum: Rev.Mod.Phys. 61 (1989) 169
Erratum: Rev.Mod.Phys. 60 (1988) 575-575
DOI: 10.1103/RevModPhys.59.671

Abstract (APS)
The theory of neutrino mixing and neutrino oscillations, as well as the properties of massive neutrinos (Dirac and Majorana), are reviewed. More specifically, the following topics are discussed in detail: (i) the possible types of neutrino mass terms; (ii) oscillations of neutrinos (iii) the implications of CP invariance for the mixing and oscillations of neutrinos in vacuum; (iv) possible varieties of massive neutrinos (Dirac, Majorana, pseudo-Dirac); (v) the physical differences between massive Dirac and massive Majorana neutrinos and the possibilities of distinguishing experimentally between them; (vi) the electromagnetic properties of massive neutrinos. Some of the proposed mechanisms of neutrino mass generation in gauge theories of the electroweak interaction and in grand unified theories are also discussed. The lepton number nonconserving processes μ→eγ and μ→3e in theories with massive neutrinos are considered. The basic elements of the theory of neutrinoless double-β decay are discussed as well. Finally, the existing data on neutrino masses, oscillations of neutrinos, and neutrinoless double-β decay are briefly reviewed. The main emphasis in the review is on the general model-independent results of the theory. Detailed derivations of these are presented.

1987
Review by Bilenky and Petcov
(500+)

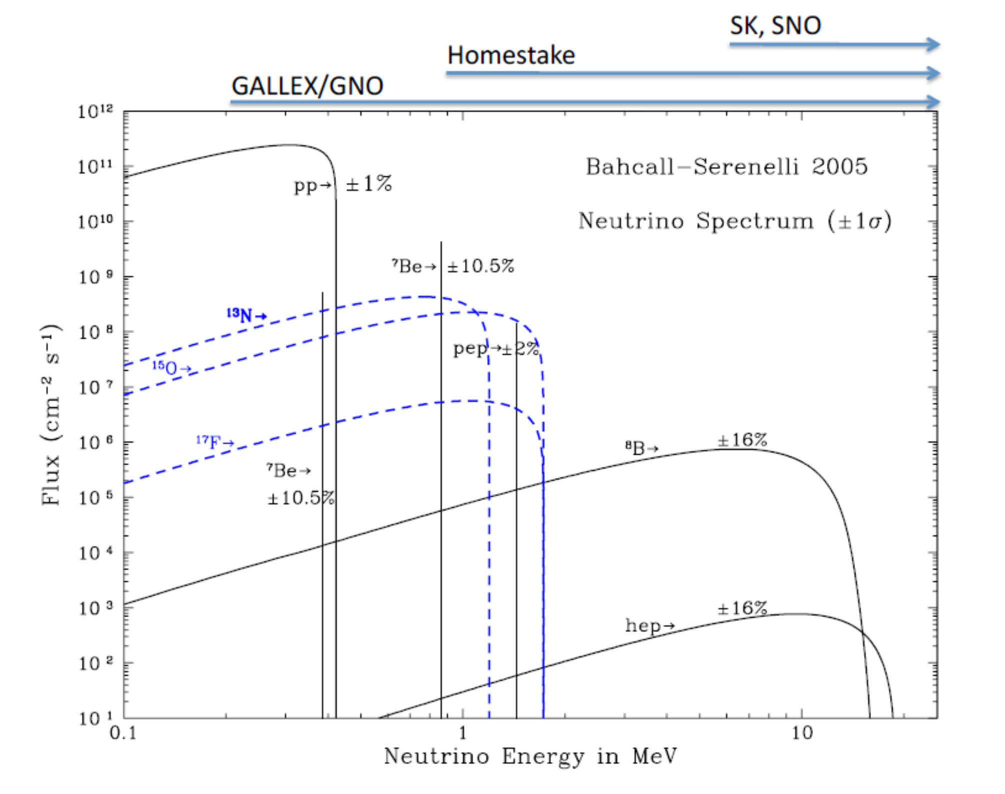
Discovery of Neutrino Oscillations

Deficit of the Solar neutrino flux was observed using radiochemical methods:

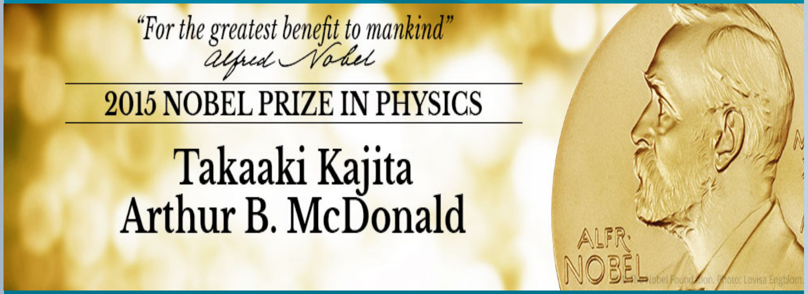
(neutrino + Cl → Ar + electron) – proposed by B.Pontecorvo and used by R.Davis in Homestake

(neutrino + Ga → Ge + electron) – suggested by V.Kuzmin and applied in SAGE at Baksan and GALLEX/GNO at Gran Sasso

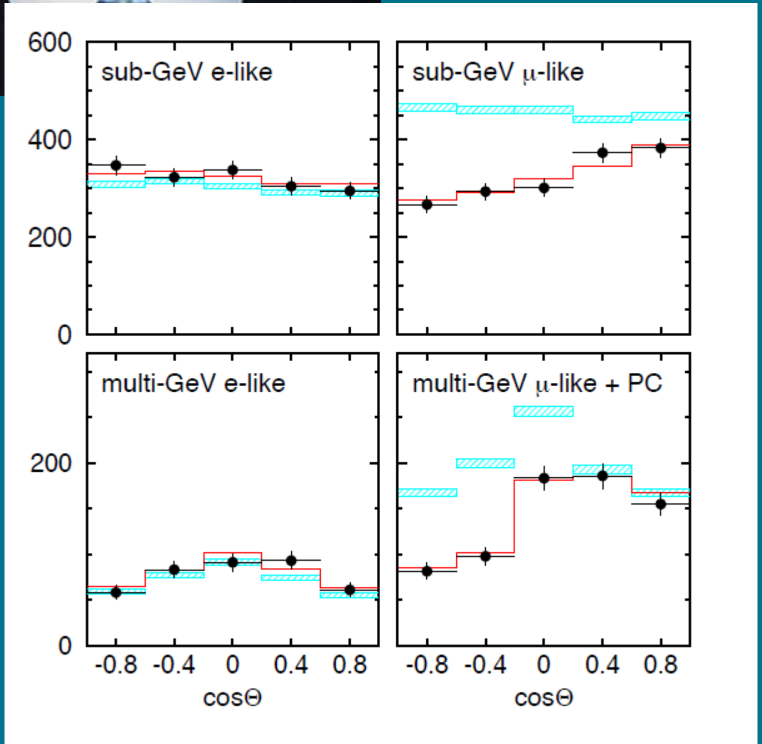
also Water Cherenkov detectors Kamiokande and SK observed this effect

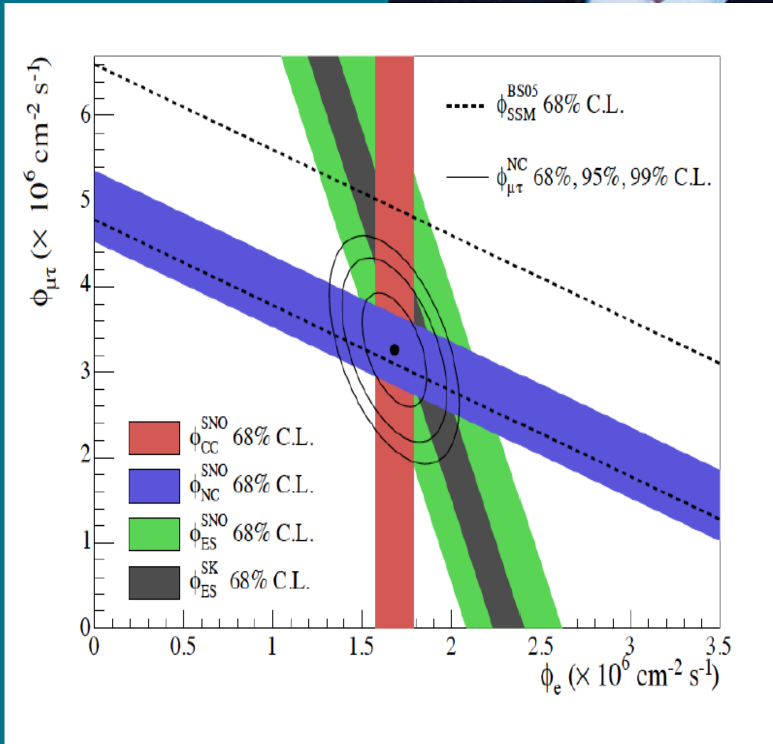


Oscillations were the most plausible explanation of the deficit but there was a suspicion in the theoretical uncertainties of the Solar neutrino flux prediction



for the discovery of ***neutrino oscillations,*** *which shows that* ***neutrinos have mass***





PMNS today

What We Know

atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

Flavor

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

Mass

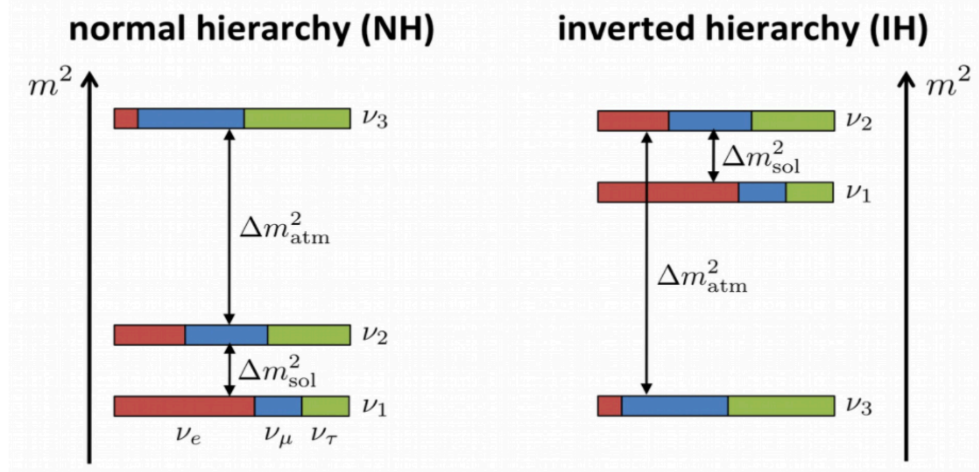
$$\theta_{23} \approx 45^\circ \qquad \theta_{13} \approx 9^\circ \qquad \theta_{12} \approx 34^\circ$$

It is known that

- $m_2 > m_1$
- $\Delta m_{31}^2 >> \Delta m_{21}^2$

However, we don't know

$m_3 > m_{1,2}$ or $m_3 < m_{1,2}$



How to measure θ_{13} ?

- Disappearance probability at reactors:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}$$

Clean θ_{13} measurement, best at a distance of ~ 1.8 km

- Appearance probability at accelerators:

$$P(\nu_\mu \to \nu_e) \sim \frac{\sin^2\theta_{23}\sin^2 2\theta_{13}}{(1-\rho_m L)^2} - 0.04\frac{\sin 2\theta_{13}}{(1-\rho_m L)}\sin\delta_{CP}$$

Very rich - apart from θ_{13} sensitive to θ_{23}, δ_{CP} and MO, but this introduce degeneracy of these parameters

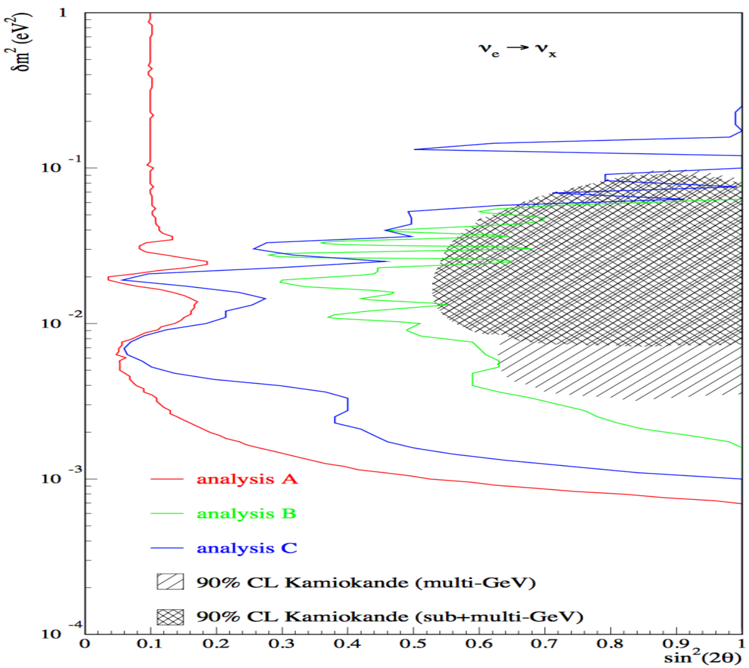
- Clear strategy for complementary measurements at reactors and accelerators.

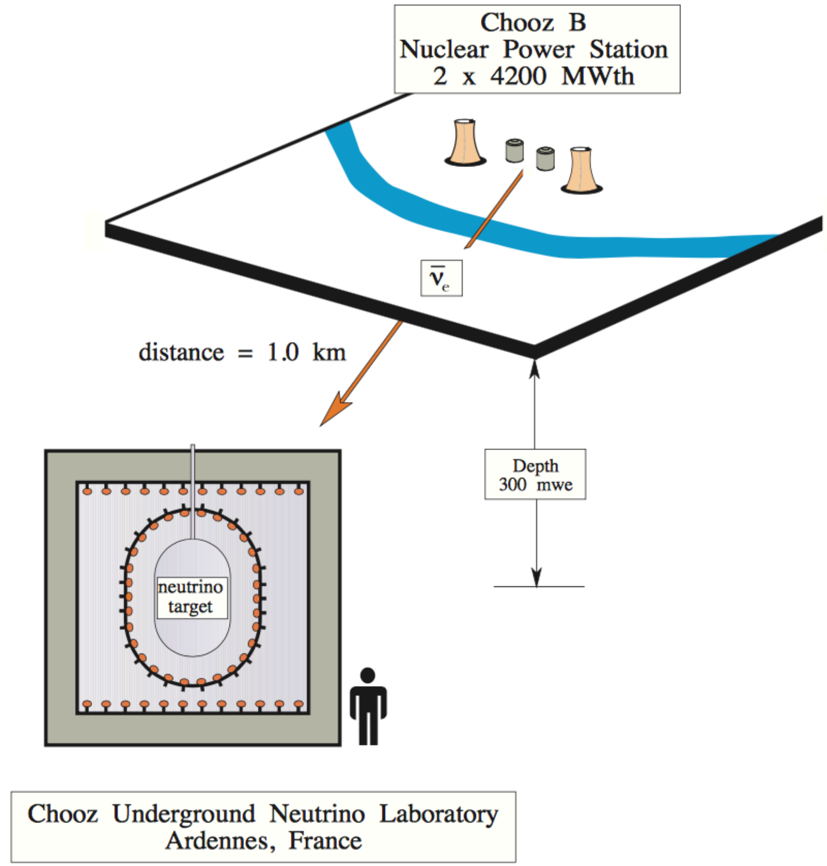
CHOOZ Limit on θ_{13}

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Inverse β−decay

$$n + Gd \rightarrow Gd^\star \rightarrow Gd + \sum_i \gamma_i$$





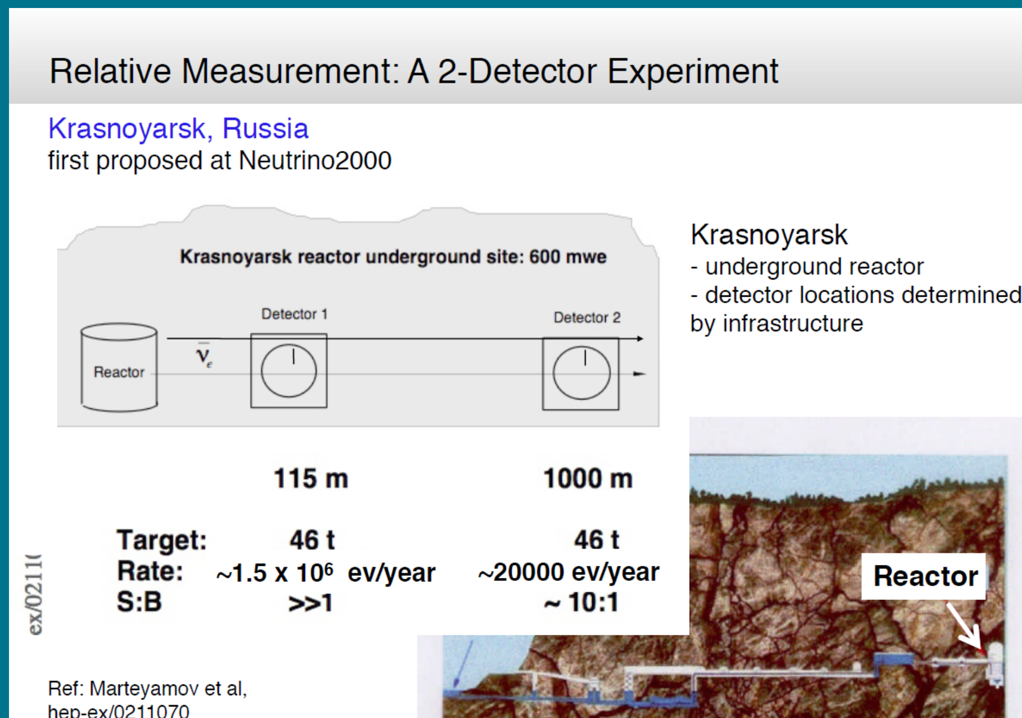
$\sin^2 2\theta_{13}$ <0.10 at 90% CL, PLB 466 (1999) 415

Limited by systematic uncertainties of the flux.

Solution for the flux uncertainty problem

Absolute Reactor Flux:
Largest uncertainty in previous measurements

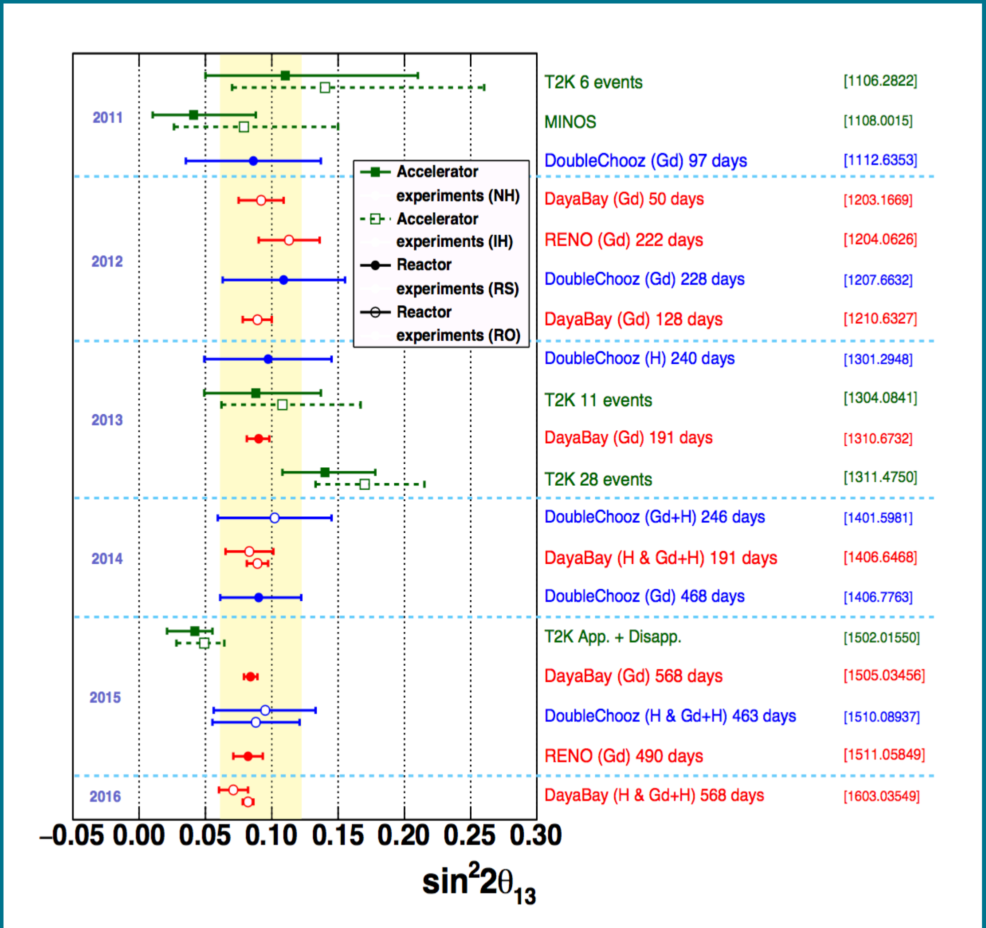
Relative Measurement:
Multiple detectors remove absolute uncertainty



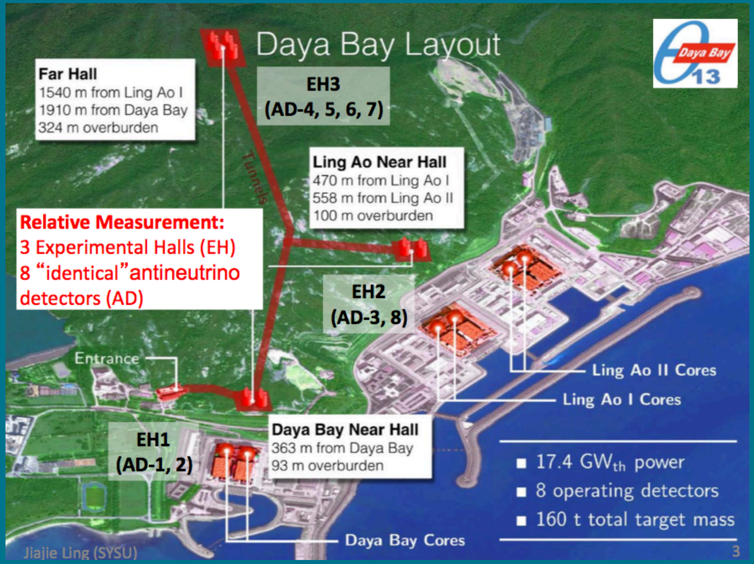
First proposed by L. A. Mikaelyan and V.V.Sinev at NANP-99, Phys. Atomic Nucl. 63 (2000) 1002, hep-ex/9908047.

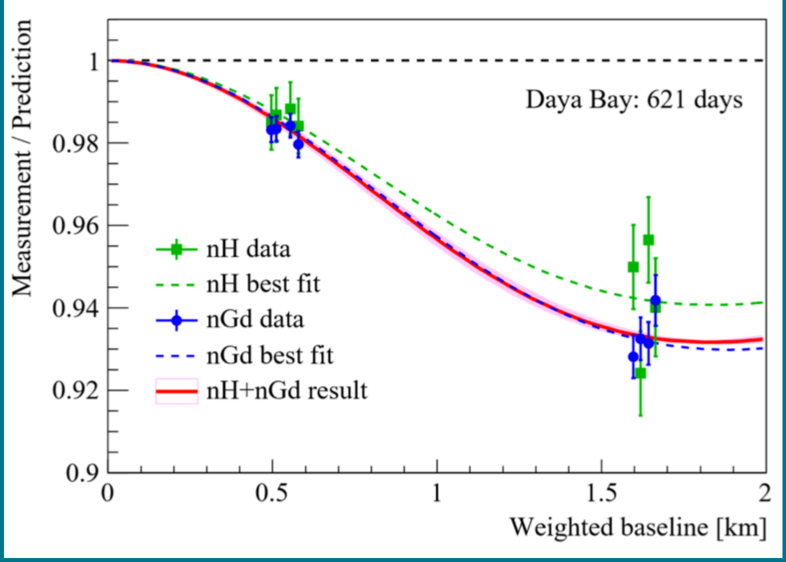
Discovery of a non-zero θ_{13}

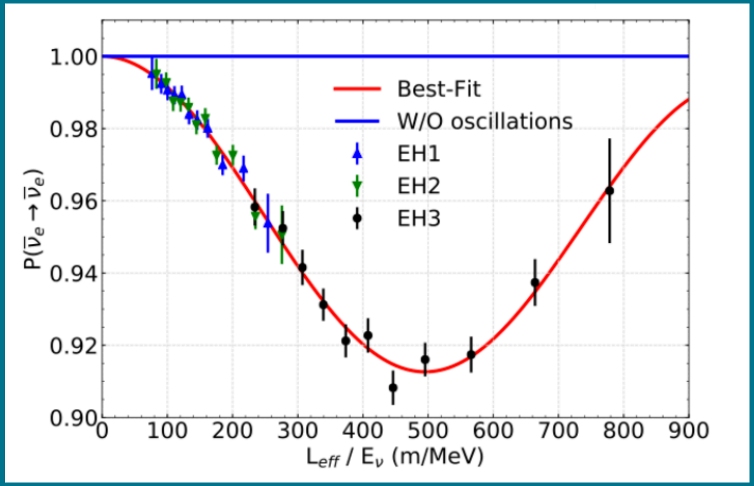
- >10 proposals were suggested to measure θ_{13} at reactors
- later on joined around three:
  - Double CHOOZ (with INR participation)
  - Daya Bay
  - RENO



Daya Bay measurement of θ_{13}







$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

DB@Neutrino 2020

Physics Prospects

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

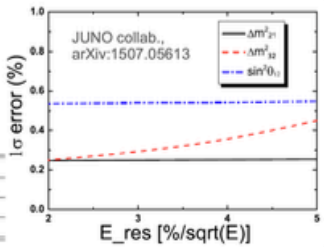
Neutrino mass ordering

- 3σ neutrino mass ordering sensitivity within 6 years.
- 4σ with Δm^2_{32} input from accelerator experiments.
- > 5σ combined analysis with IceCube within 3–7 years or PINGU in 2 years (arXiv: 1911.06745)

Neutrino oscillation parameters

- Sub-percent accuracy for θ_{12} , Δm^2_{21} and Δm^2_{31}
- Current precision

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%



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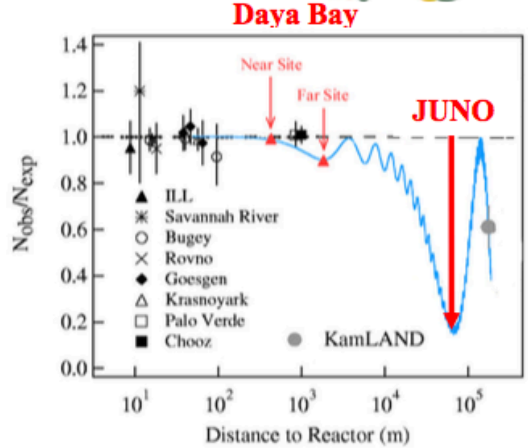
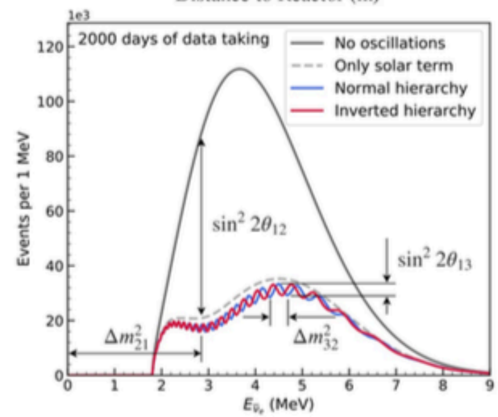




From CERN Courier

MO measurement in oscillations at reactors were for the first time noted by S.Bilenky and S.Petcov in early 2000's

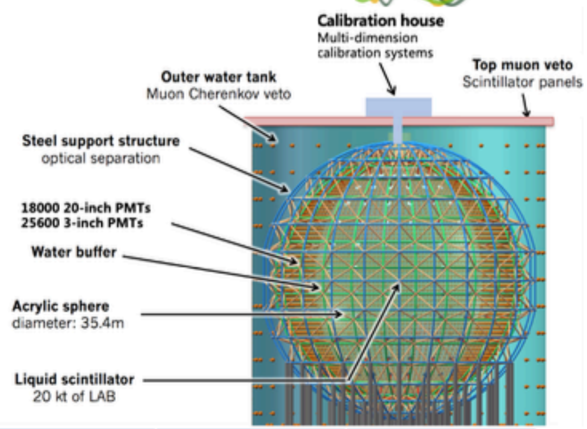
Keys for the JUNO detector

1. Optimal baseline for the detector
2. Large statistics
   - 26.6 GW_{th} power
   - ~60 IBD events per day
3. Energy resolution < 3%/√E between 1 MeV and 8 MeV

$$\frac{\sigma_{E_{vis}}}{E_{vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{vis}}\right)^2}$$

a: the statistical term
b: a constant term independent of the energy, dominated by position non-uniformity
c: the contribution of a background noise term

4. Energy scale uncertainty < 1%
   - Comprehensive calibration strategy
5. Background control



Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [tons]	8 x 20	~300	~1,000	20,000
Photo electron collection [p.e./MeV]	~160	~500	~250	~1200
Energy resolution	~8.5%	~5%	~6%	~3%
Photocathode coverage	12%	34%	34%	75%
Energy calibration uncertainty	0.5%	1%	2%	<1%

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Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	FZJ-IKP
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Mainz
Brazil	PUC	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	UEL	China	UCAS	Italy	INFN Catania
Chile	PCUC	China	USTC	Italy	INFN di Frascati
Chile	UTFSM	China	U. of South China	Italy	INFN-Ferrara
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	CAGS	China	Xi'an JT U.	Italy	INFN-Padova
China	ChongQing University	China	Xiamen University	Italy	INFN-Perugia
China	CIAE	China	Zhengzhou U.	Italy	INFN-Roma 3
China	DGUT	China	NUDT	Latvia	IECS
China	ECUST	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	Guangxi U.	China	ECUT-Nanchang City	Russia	INR Moscow
China	Harbin Institute of Technology	Croatia	PDZ/RBI	Russia	JINR
China	IHEP	Czech	Charles U.	Russia	MSU
China	Jilin U.	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jinan U.	France	LAL Orsay	Taiwan-China	National Chiao-Tung U.
China	Nanjing U.	France	CENBG Bordeaux	Taiwan-China	National Taiwan U.
China	Nankai U.	France	CPPM Marseille	Taiwan-China	National United U.
China	NCEPU	France	IPHC Strasbourg	Thailand	NARIT
China	Pekin U.	France	Subatech Nantes	Thailand	PPRLCU
China	Shandong U.	Germany	FZJ-ZEA	Thailand	SUT
China	Shanghai JT U.	Germany	RWTH Aachen U.	USA	UMD
China	IGG-Beijing	Germany	TUM	USA	UC Irvine
China	IGG-Wuhan	Germany	U. Hamburg		

ИЯИ, ОИЯИ, МГУ

77 institutes
669 members

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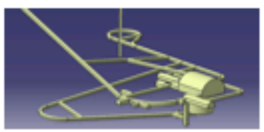
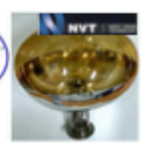
JUNO Timeline

2014
- International collaboration established
- Conceptual design

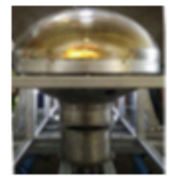


2015
- PMT production line setup
- CD parts R&D
- Civil construction start

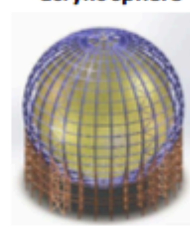
2016
- PMT production start
- CD parts production start
- Yellow book published



2017
- PMT testing start
- TT arrived



2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere



2019-2021
- Electronics production starts
- Civil construction and lab preparation completed
- Detector construction

2022
- Detector ready for data taking

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Other Physics with JUNO

- **JUNO will be an exceptional detector**

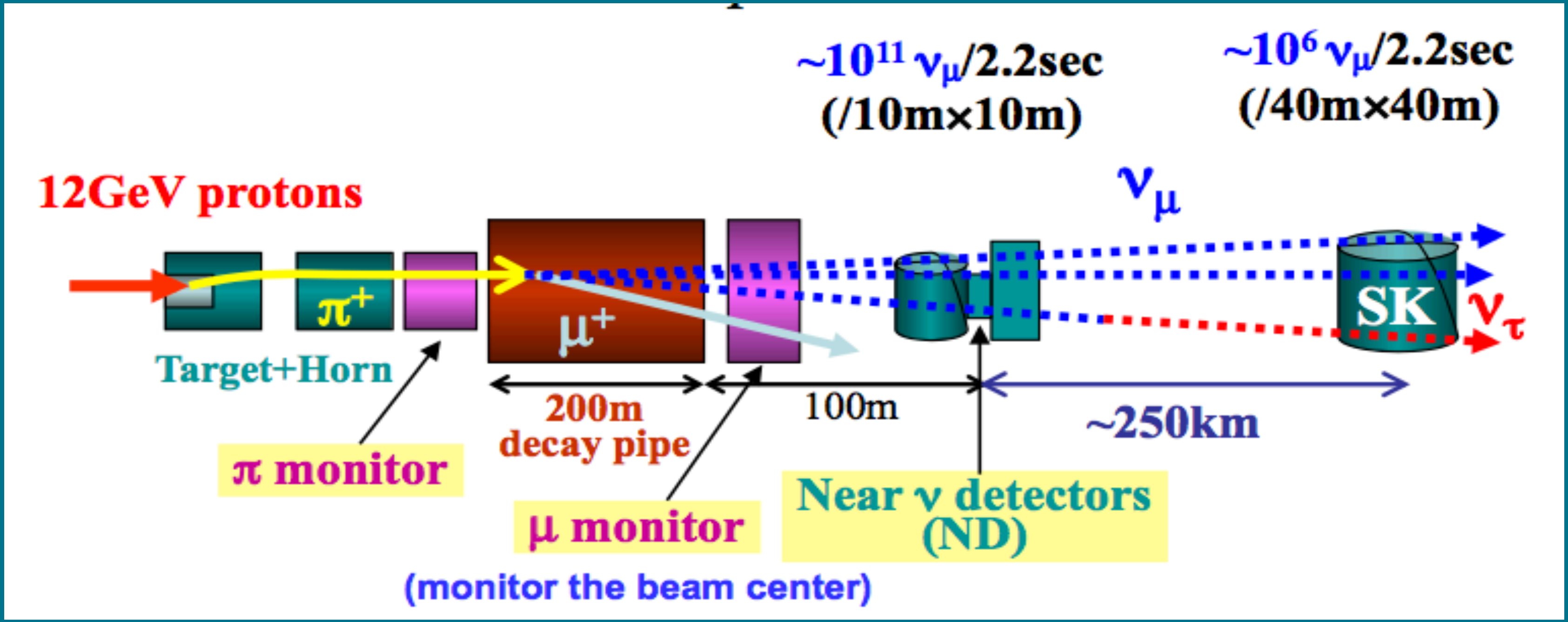
	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Light yield [p.e./MeV]	250	500	200	1200
Energy resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy calibration	1.4%	1%	1%	< 1%

→ Rich additional physics program:

- Supernova ν
- Diffuse supernova ν
- Geo-neutrinos
- Solar ν
- Proton decay
- Atmospheric ν
- Sterile ν
- Indirect dark matter searches
- Other exotic searches

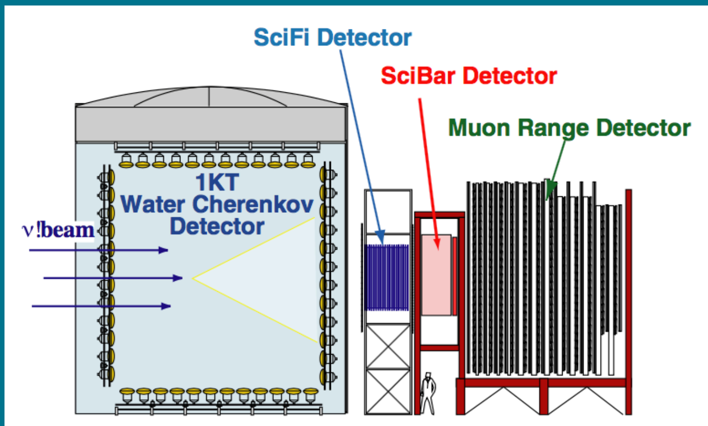
K2K experiment

- Constructed in 1996-1999 with the goal of exploring Kamiokande hint for atmospheric neutrino oscillations



- The K2K collaboration started with three countries: Japan, the USA and Korea, and later included Canada, France, Italy, Poland, Russia (INR), Spain, and Switzerland

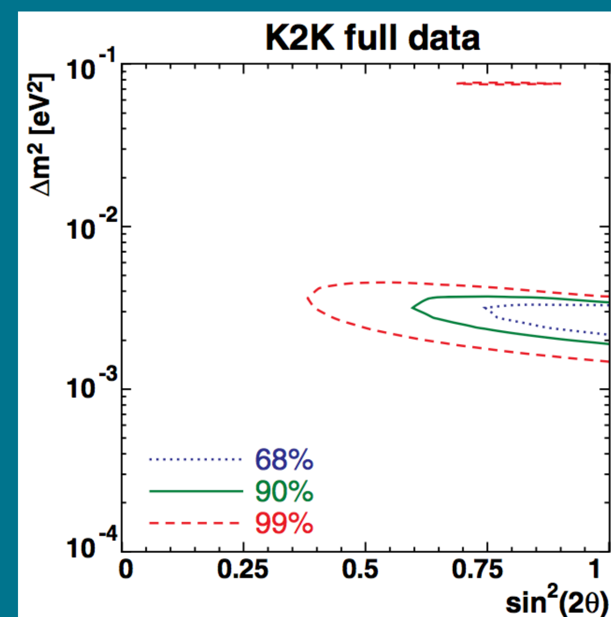
K2K experiment



Challenges: Neutrino production spectrum, cross sections and detector response

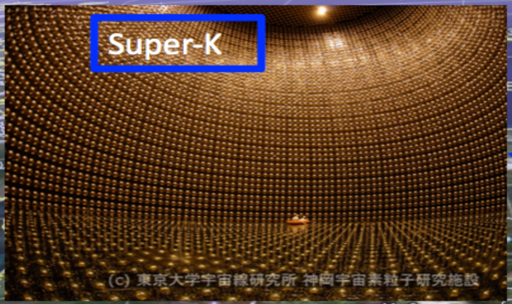
Solution: Elaborated ND, external measurements (HARP), Monte Carlo development

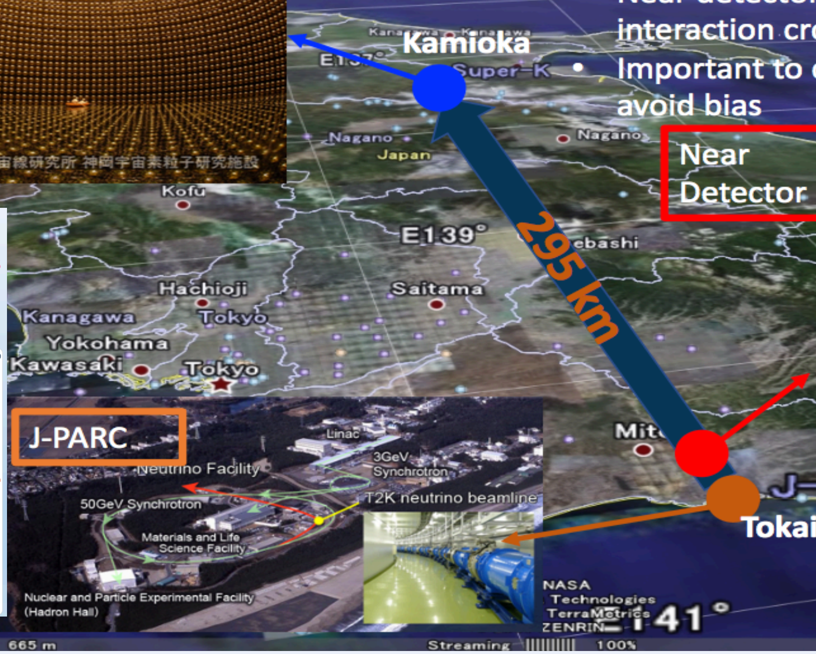
K2K accelerator neutrino experiment confirms neutrino oscillations observed in atmospheric neutrinos

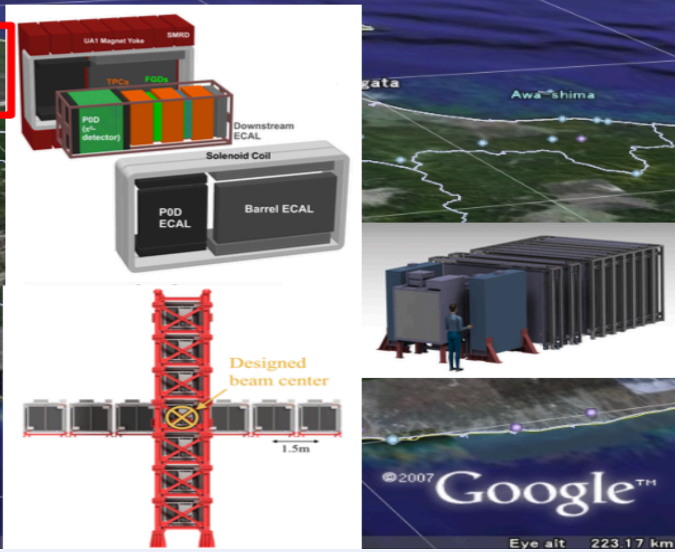


The T2K Experiment

- Muon (anti) neutrino beam generated at J-PARC
- Beam travels 295 km to large SK far detector to be measured after oscillations
- Near detector complex, ND280 constrains beam flux and interaction cross-section before oscillation
- Important to constrain non-oscillation parts of model to avoid bias







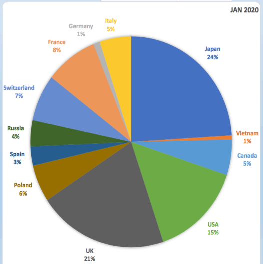
T2K Collaboration

~500 members, 69 institutes, 12 countries

Asia	117
Japan	114
Vietnam	3

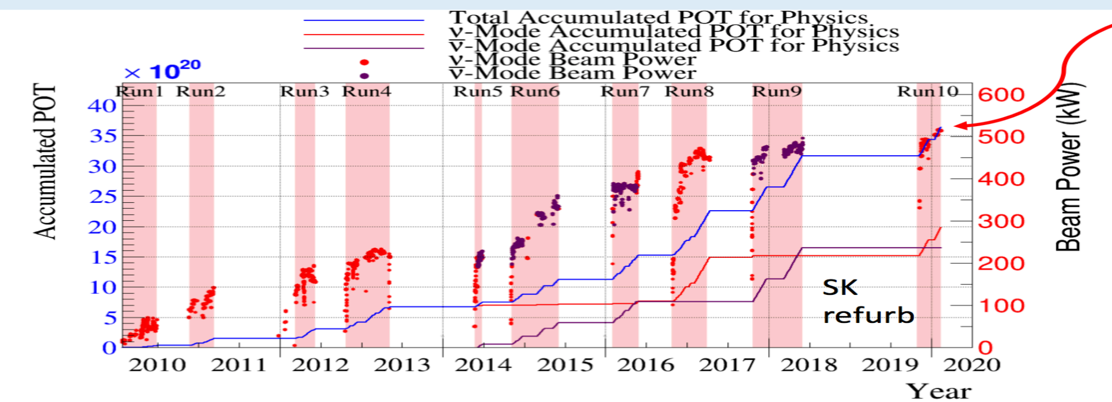
Americas	96
Canada	26
USA	70

Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99



Data taken to date

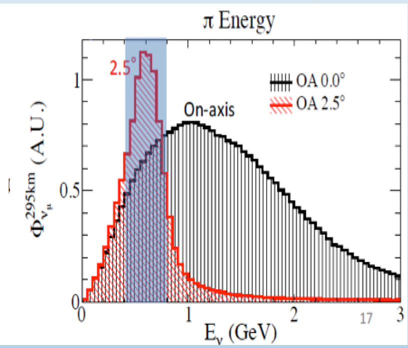
- 515 kW stable operation achieved this year



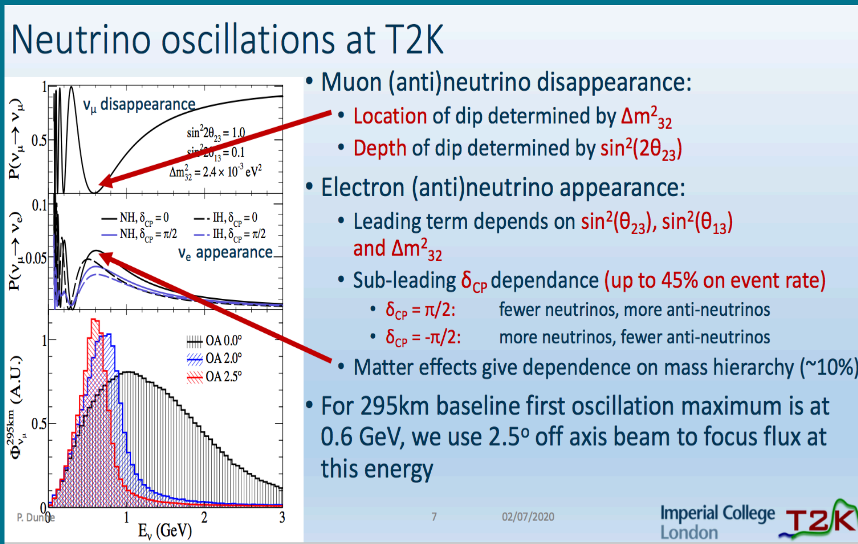
On- vs. Off-axis

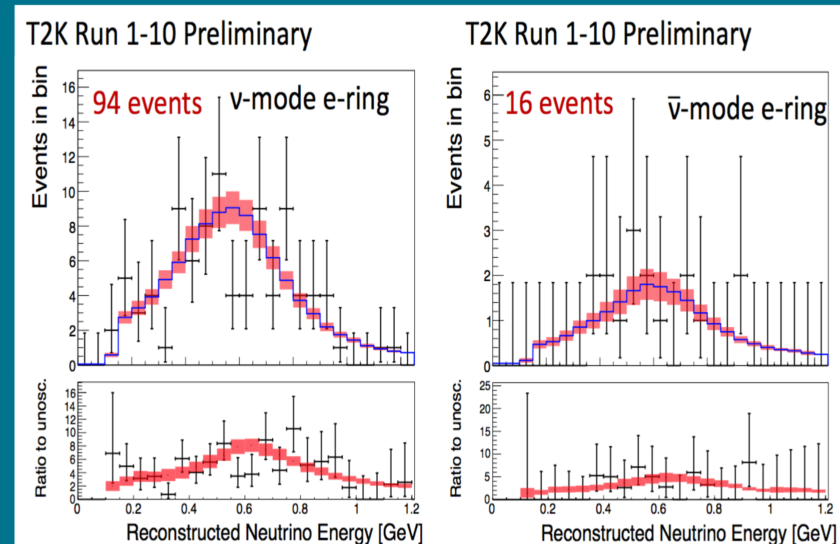
2.5° off-axis angle

- 2-body π decay gives narrow range of ν energies



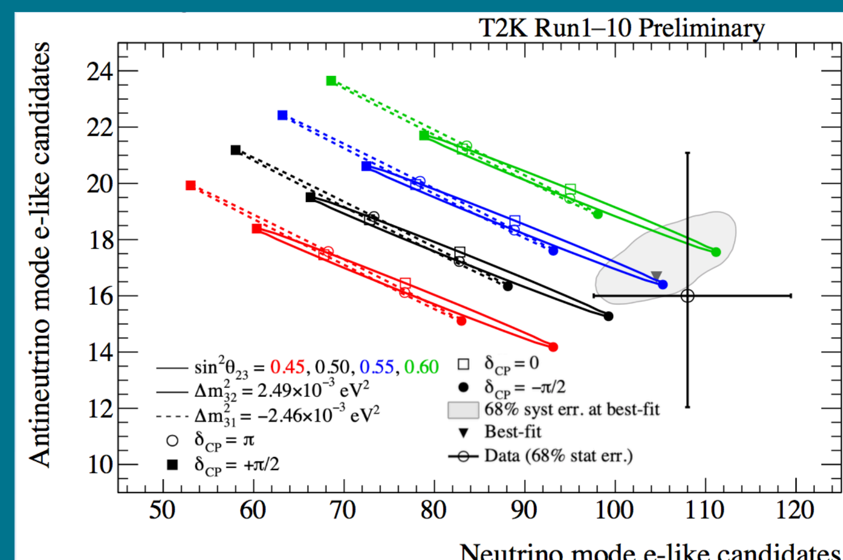
The T2K Experiment



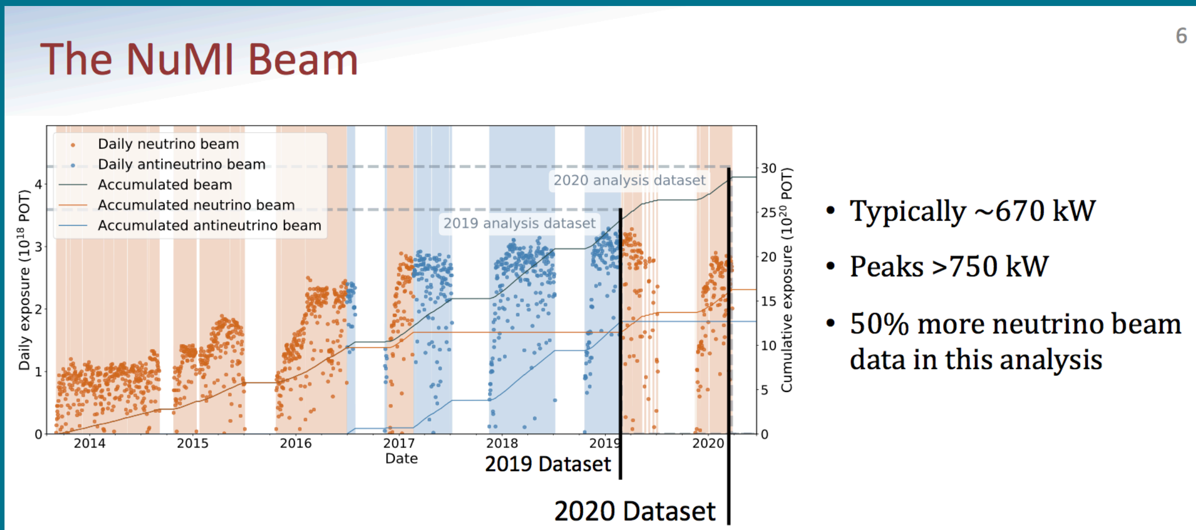


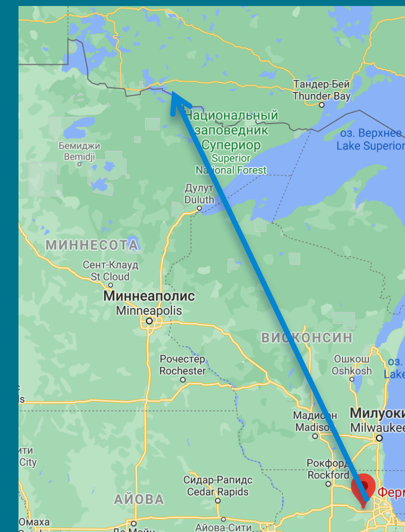
Total of 1.97×10^{21} protons on target (POT) in ν-mode and 1.63×10^{21} in $\bar{\nu}$-mode data shows:

- Preference for Normal Ordering
- Slight preference for upper octant of θ_{23}
- Best fit value $\delta_{CP} = -1.97$ (rad)



NuMI and NOvA

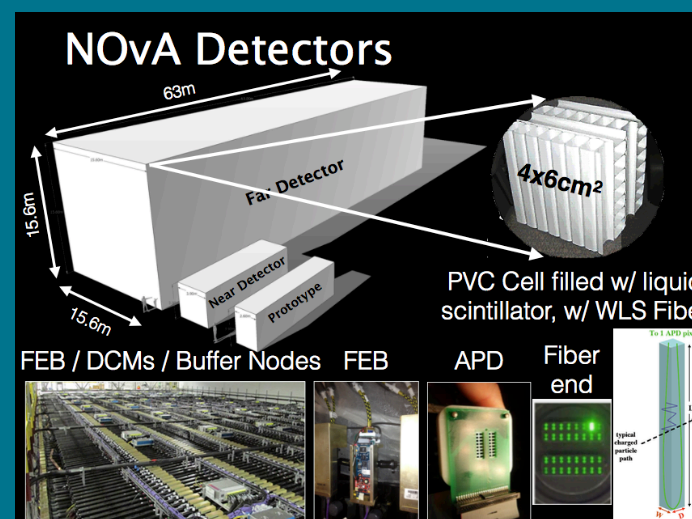




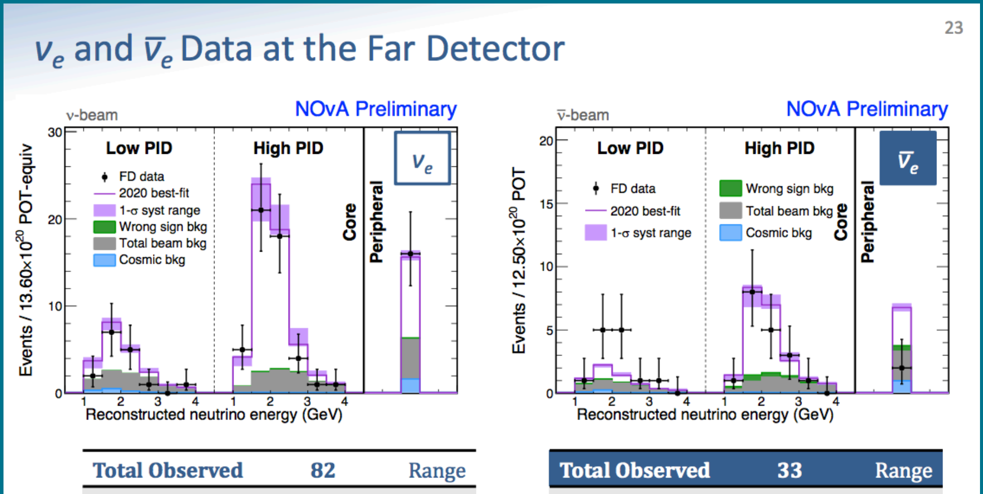
14 mrad off-axis (E_ν ~ 2 GeV)

Near Detector (0.3 kt) at FNAL

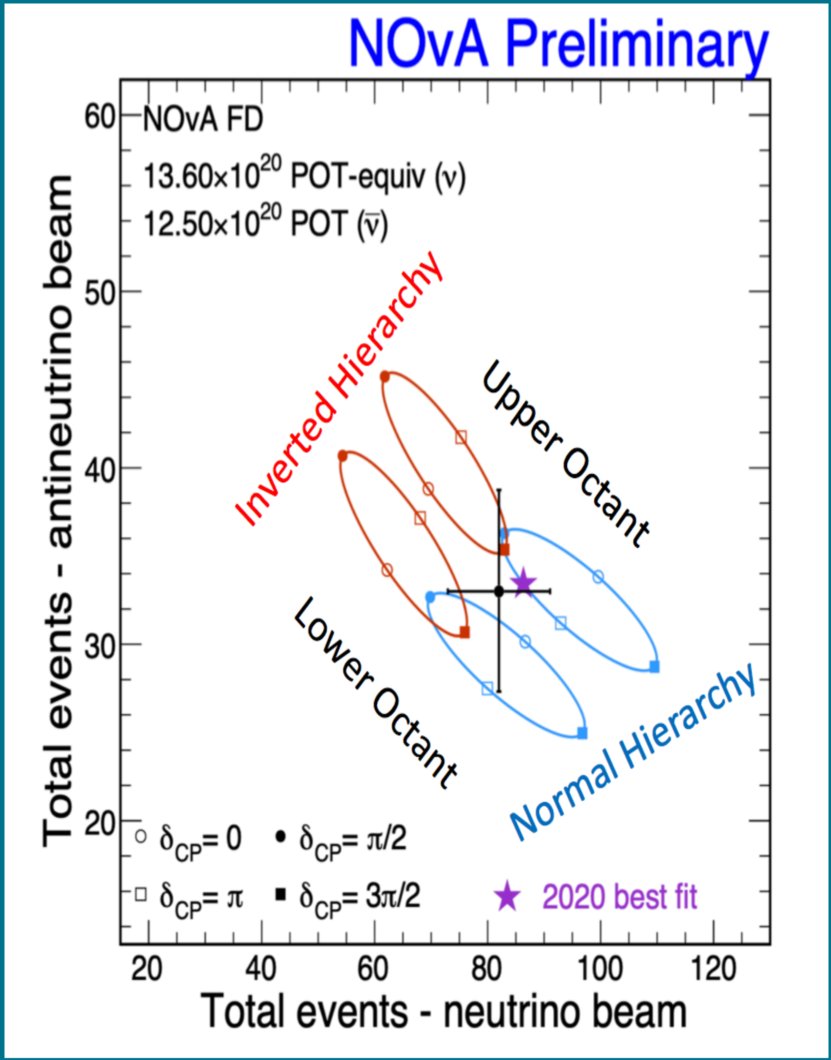
Far Detector (14 kt) 810km away



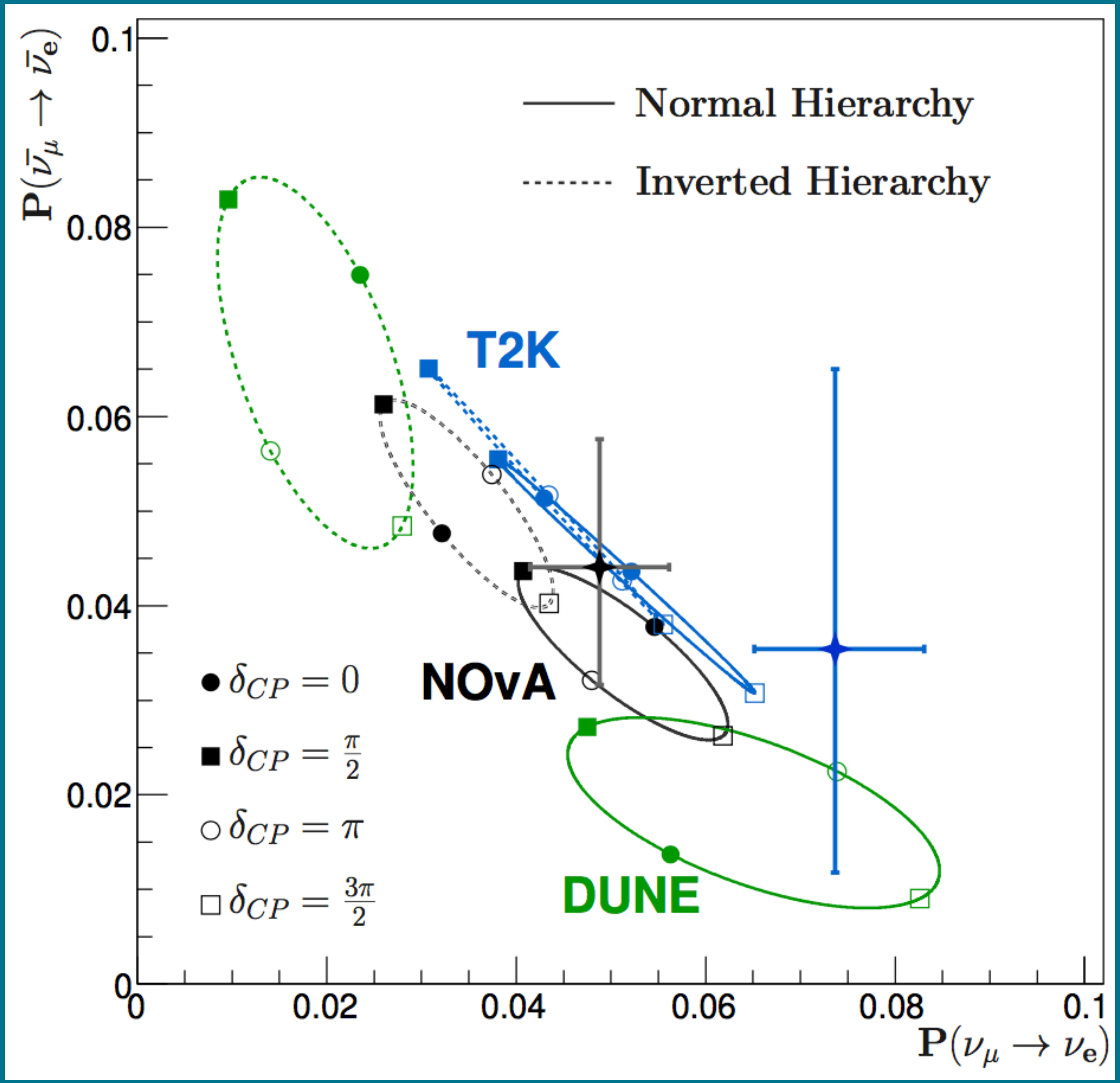
The NOvA Experiment



- New 3-flavor oscillation results:
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$
  - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
  - exclude IH, $\delta = \pi/2$ at $> 3\sigma$,
  - disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$.



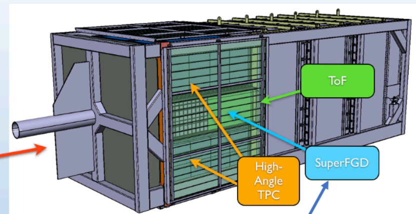
T2K and NOvA comparison

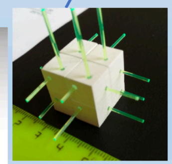


T2K and NOvA: prospects for data taking and common analysis

Future upgrades

- J-PARC Main Ring power supply upgrade already mentioned
  - 515kW->810kW by FY2022
- ND280 will be upgraded in 2022 with a new higher angular coverage TPC and 3D Super-FGD subdetector [arXiv:1901.03750v1]
  - Better hadron tagging and more similar phase space coverage to SK (S. Dolan's talk)
- SK-Gd loading for neutron tagging imminent (Y. Nakajima's talk)
- Oscillation analyses using our near detectors at other off-axis angles (WAGASCI/BabyMIND)





Future joint fits

- Experiments with different neutrino energies have different oscillation probabilities and systematic uncertainties
- Combined analysis of data allows degeneracies to be broken and maximises impact of data taken
- Agreements signed with NOvA and SK and work towards T2K+NOvA and T2K+SK atmospheric analyses is underway

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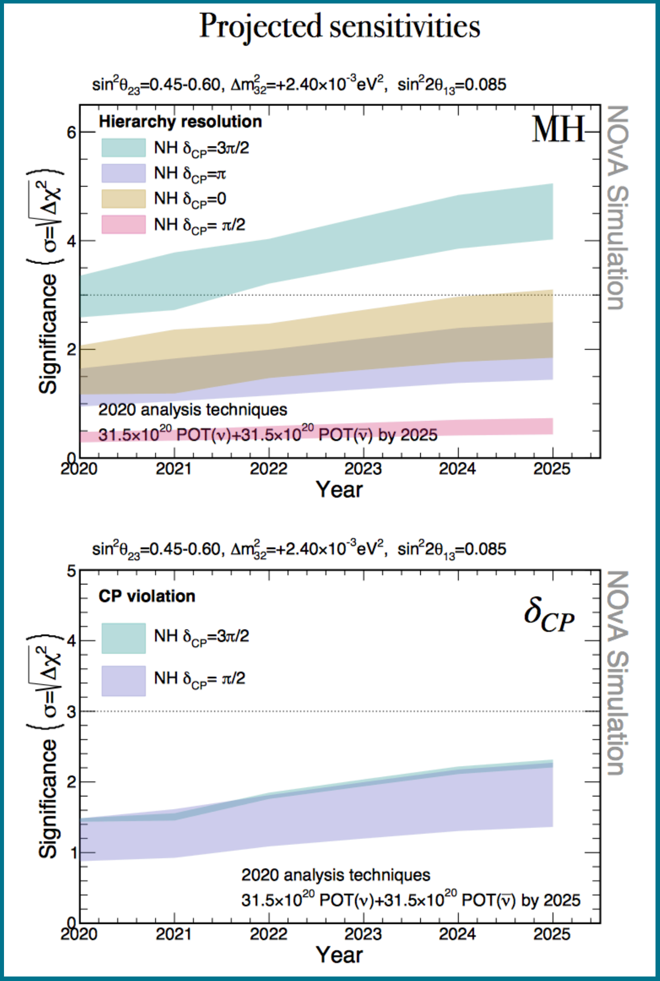
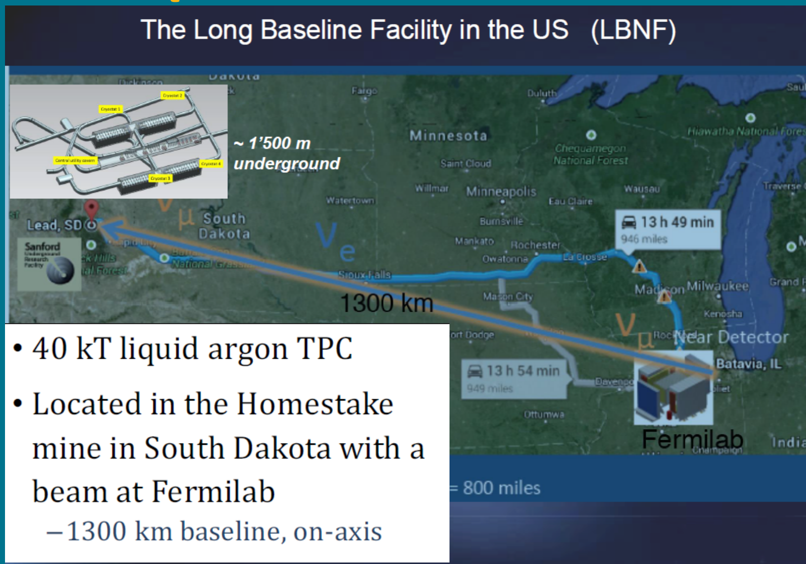
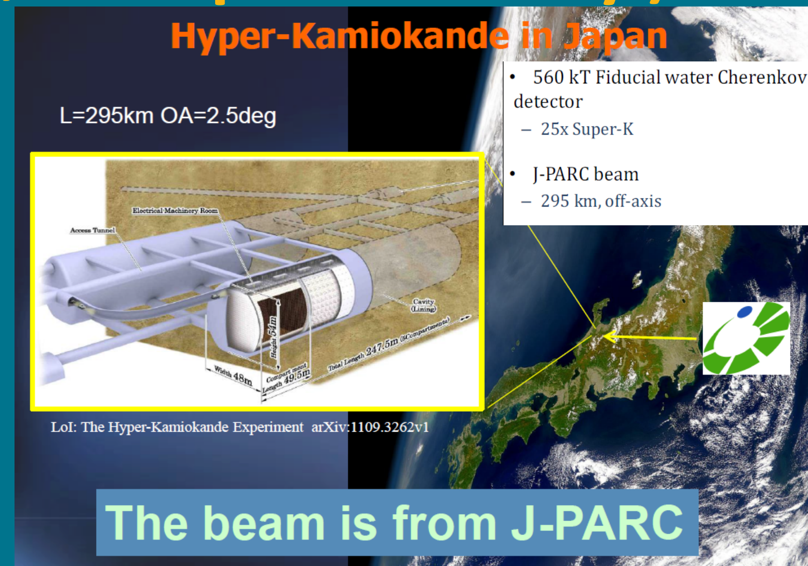
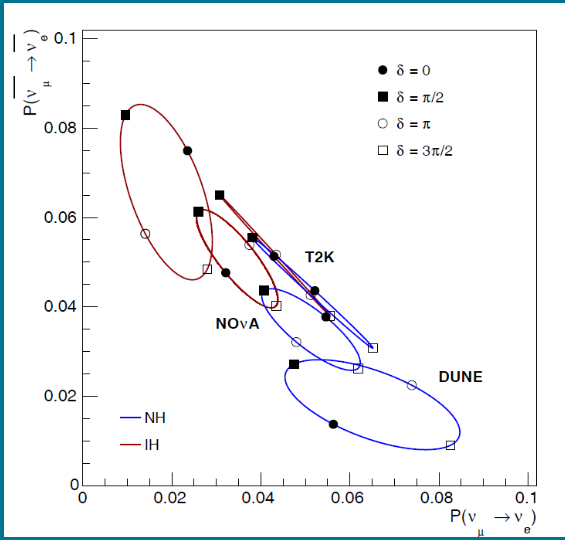
Imperial College London T2K

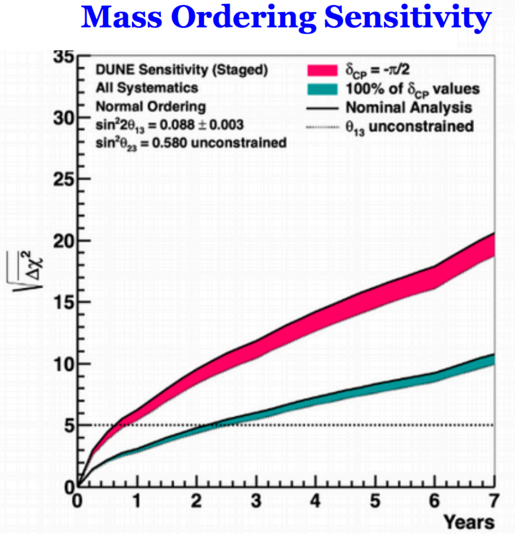


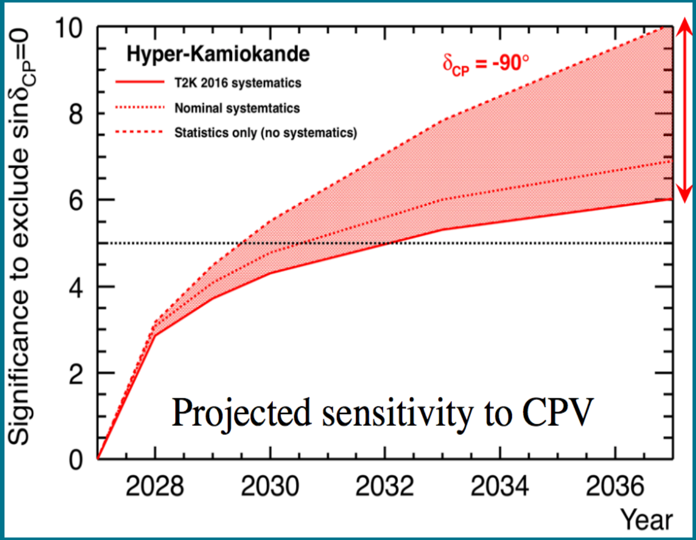
Future projects: DUNE and T2HK (2025 and 2027, respectively)







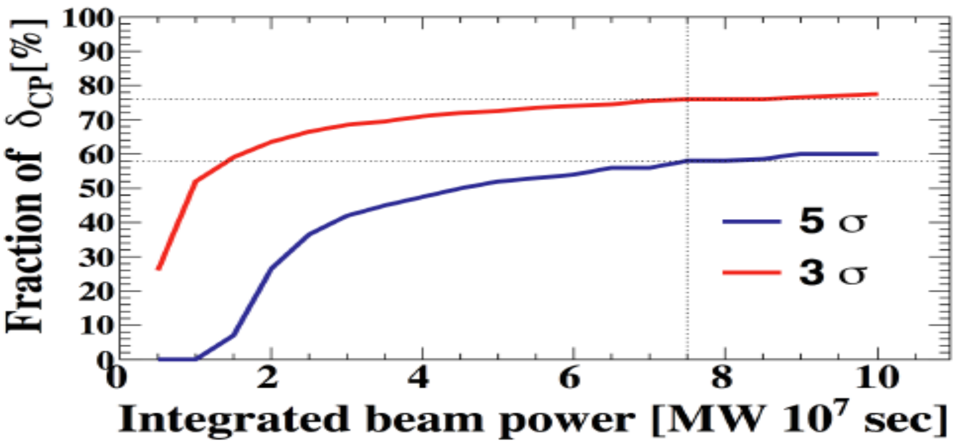


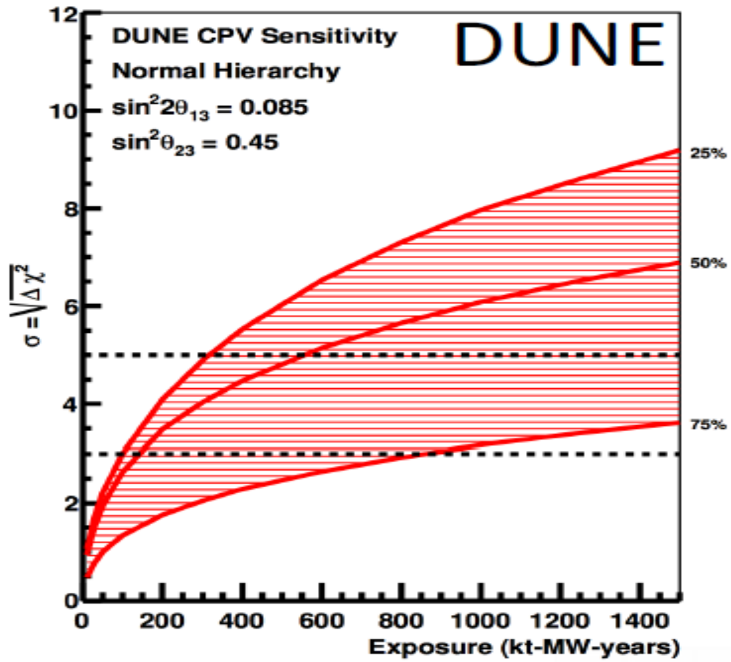


Physics reach of DUNE and T2HK

CP Violation Sensitivity

Hyper-K





Prog. Theor. Exp. Phys. (2015) 053C02

DUNE CDR

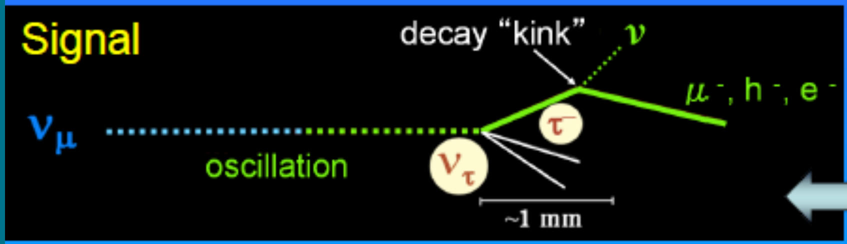
Both experiments, when fully realized, are capable of excluding $\delta_{cp} = 0$ across a wide range of values

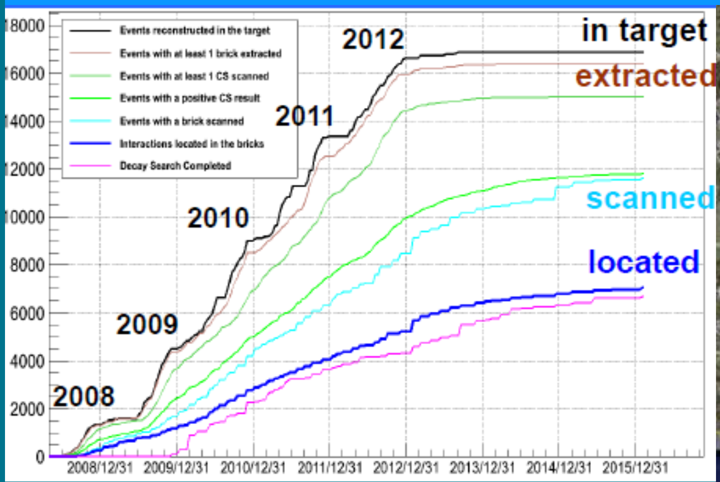
Alex Himmel 36

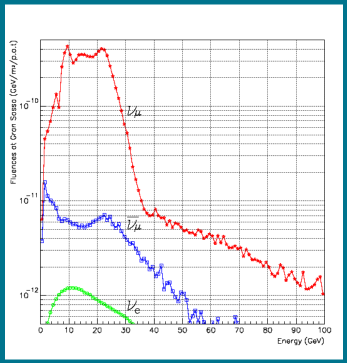
ν_τ detection

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \rightarrow \tau^- + X$$

Search for τ decay topology on an event by event basis.





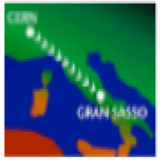


conventional ν beam

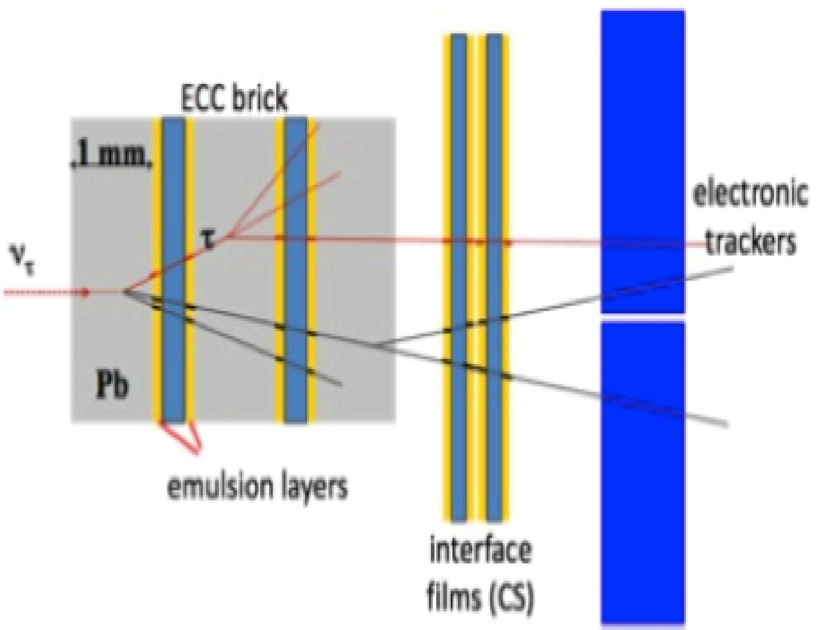
$\langle E\nu \rangle$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %*
$\bar{\nu}_\mu$ / ν_μ	2.1 %*
ν_τ prompt	Negligible*

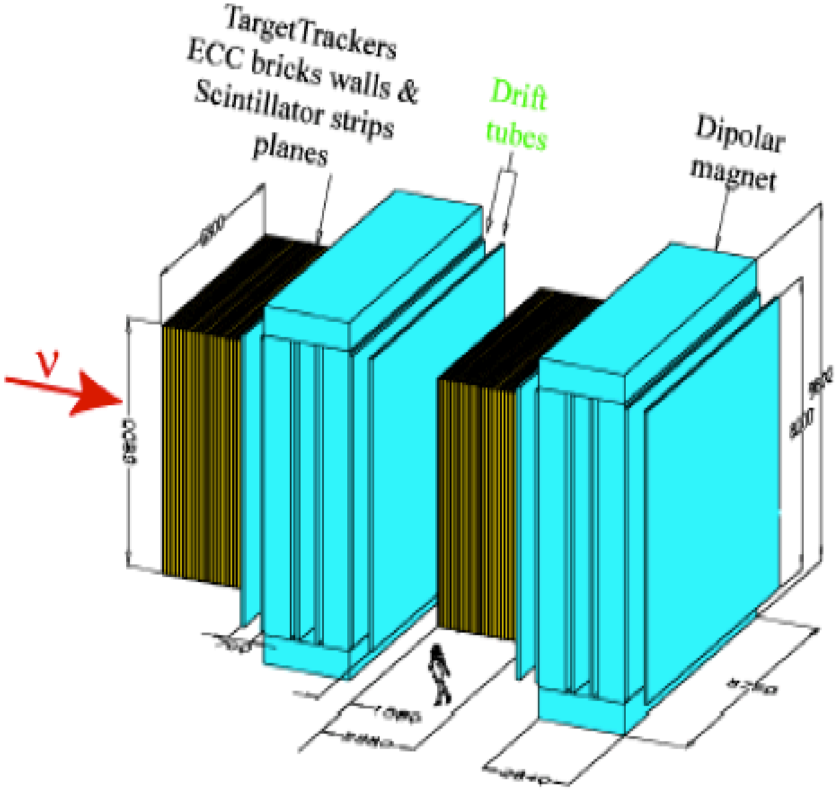
* Interaction rate at LNGS

The OPERA goal — observation of $\nu_\mu \to \nu_\tau$ oscillation via registration of ν_τ appearance in ν_μ beam from CERN (17 GeV, 732 km).



The experiment is located 1400 m underground In the Gran Sasso Laboratory.





CNGS1 (OPERA) Experiment

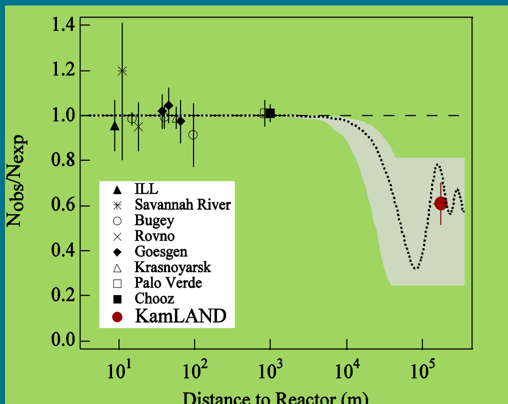
37 Institutes (including INR, JINR, Lebedev and MSU from RU)

- Constructed the detector
- Collected data (2008 till 2012)
- Scanned emulsions
- Analyzed events and reported:

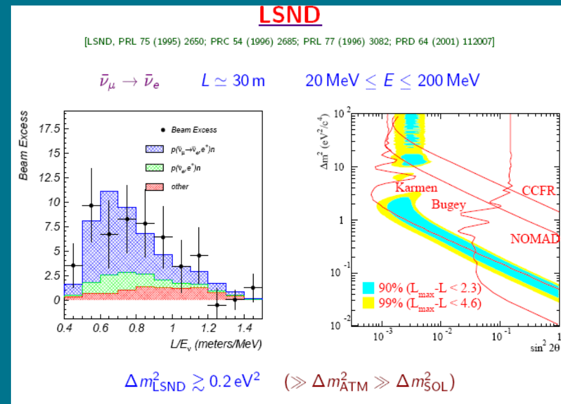
◆*Discovery of ν_μ ➔ ν_τ oscillations in appearance mode at 6.1 sigma confidence level (10 (2) signal (background) events)*

◆*In addition, ν_e appearance and ν_μ disappearance measurements allowed an interesting one-experiment combined analysis of 3 and (3+1) flavor oscillations*

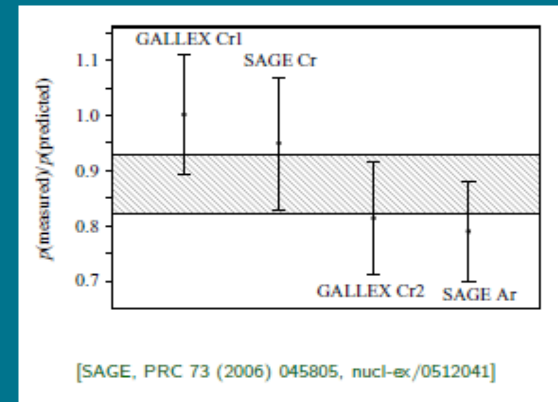
Additional (Sterile) Neutrino from oscillation data ?



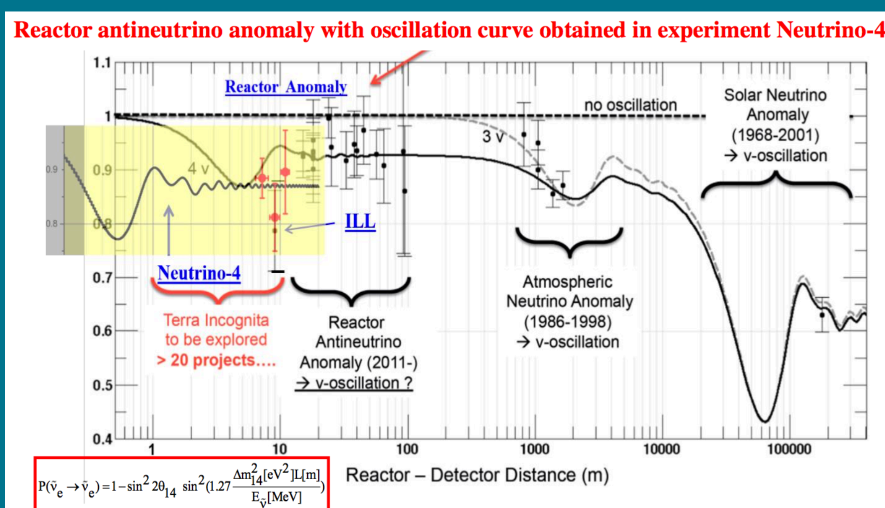
«Reactor Anomaly»

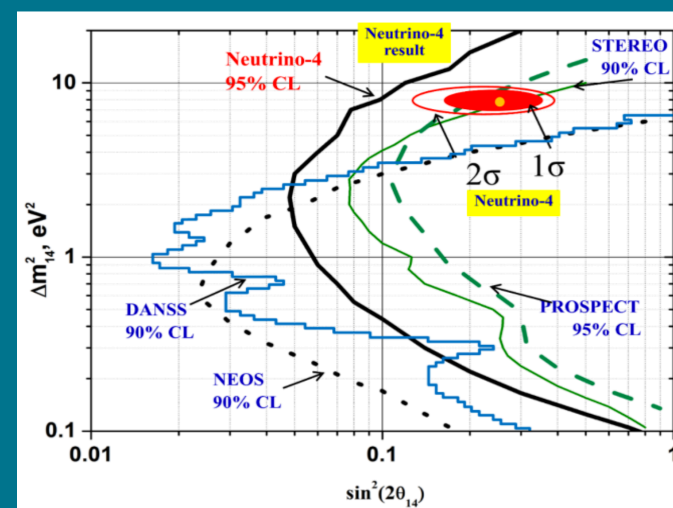


«LSND Anomaly»



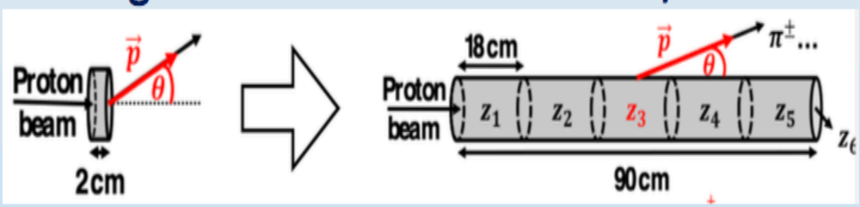
Ga Calibration

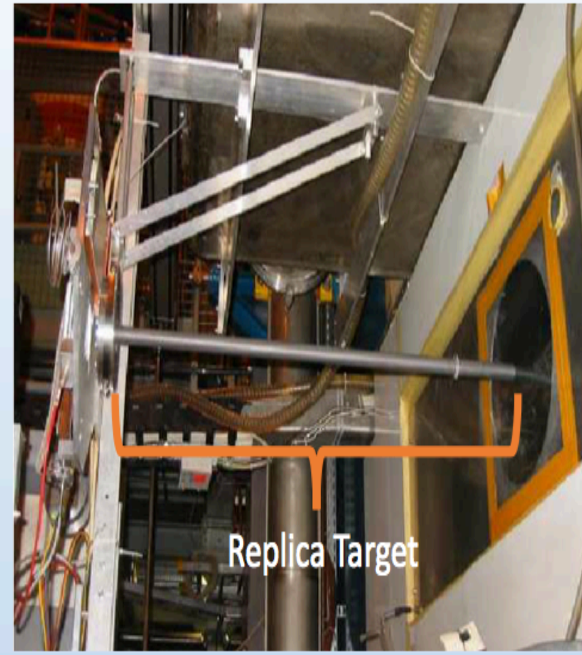




Neutrino flux modelling

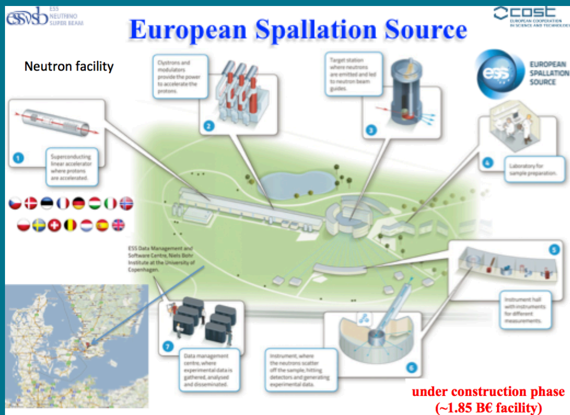
- Primary interaction in target simulated with FLUKA
- We reweight this MC to match NA61/SHINE data

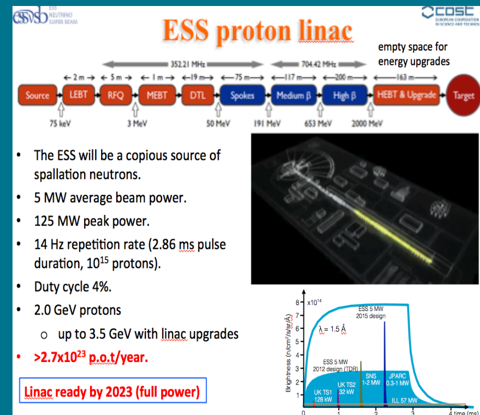


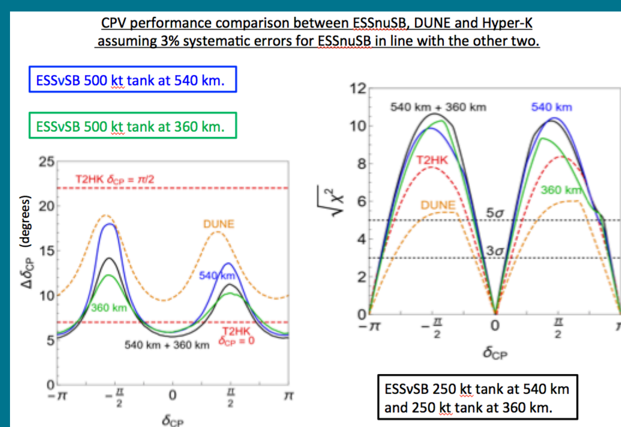


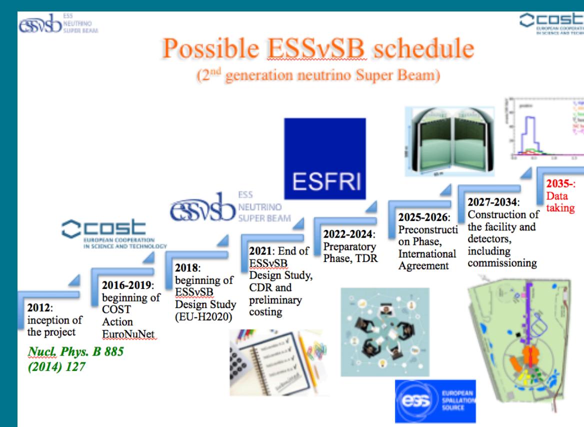
- Previous analyses used NA61/SHINE data taken with a thin graphite target
  - Initial pion production reweighted in momentum and angle to match data then subsequent propagation through target was simulated
- New for this year we use NA61/SHINE data with a replica of T2K's target [EPJC 76, 84 (2016)]
  - MC spectrum now reweighted to match data in momentum, angle and target exit point
- Allows significant reduction in input flux uncertainty on SK rate from ~8% to ~5%

ESSnuSB









High Precision CP violation measurement possible,
but on the timescale of 2035+

Summary

- Изучение осцилляций нейтрино в реакторных и ускорительных экспериментах внесло существенный вклад в исследование этого явления
- Инструмент осцилляций позволяет в ближайшее время получить такую важную информацию, как иерархия масс нейтрино и лептонное CP-нарушение
- Ученые из ИЯИ РАН вносят всесторонний творческий вклад в динамичное развитие этого направления
- Поздравляю коллег и весь коллектив Института с 50-летием и желаю дальнейших творческих успехов!