Neutrino Oscillations: From detector construction to parameter measurement and beyond

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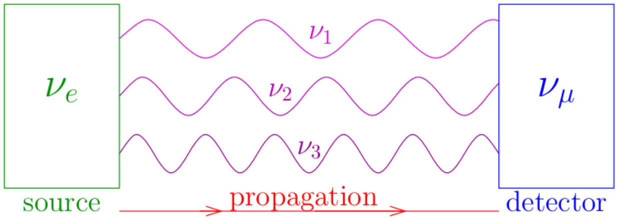
Outline

1. Introduction
   - Neutrino Oscillation
   - Current Status Open Questions
2. Double Chooz and Reactor Neutrinos
   - θ_{13} Measurement
3. $\Delta\tilde{m}^2_{31}$ and Mass Hierarchy
4. Sterile ν Search
5. Summary

Neutrino Oscillation

- Phenomenon beyond the Standard Model of Fundamental Particles and their Interactions
- Describes the relation between the three known neutrino flavours

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



Neutrino Oscillation

- Relation between neutrino flavour $(\nu_e, \nu_\mu, \nu_\tau)$ and mass (ν_1, ν_2, ν_3) eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha,i} |\nu_i\rangle$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

where

$$c_{jk} = \cos\theta_{jk} \quad \text{and} \quad s_{jk} = \sin\theta_{jk}$$

Neutrino Oscillation

- A neutrino of energy E, travelling a distance L, is described by:

$$|\nu_\alpha(L)\rangle = \sum_i U^*_{\alpha,i} e^{-i\frac{m_i^2}{2E}L} |\nu_i\rangle$$

- Since it is mixed, it has a probability of change (or maintain) its flavour state, defined as:

$$\begin{aligned} P\left(\nu_\alpha \to \nu_\beta\right) &= |\langle\nu_\beta|\nu_\alpha(L)\rangle|^2 = \left|\sum_i U^*_{\alpha,i} U_{\beta,i} e^{-i\frac{m_i^2}{2E}L}\right|^2 \\ &= \sum_i \left|U_{\alpha,i} U^*_{\beta,i}\right|^2 + 2Re\left(\sum_{i>j} U_{\alpha,i} U^*_{\beta,i} U^*_{\alpha,j} U_{\beta,j} e^{-i\frac{\Delta m_{ij}^2}{2E}L}\right) \end{aligned}$$

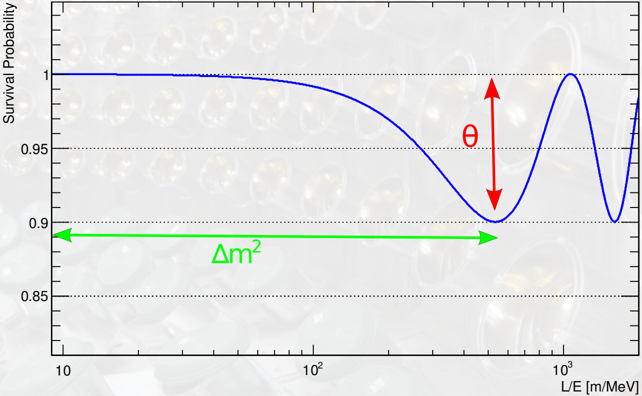
Neutrino Oscillation

- Six parameters describe this relation (on the standard parametrization):
  - Three mixing angles: θ_{12}, θ_{13}, θ_{23}
  - Two independent squared mass difference: $\Delta m^2_{jk} = m^2_j - m^2_k$
  - One CP violating imaginary phase: δ

Neutrino Oscillation

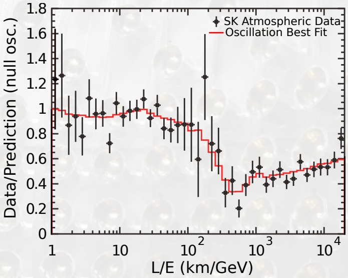
For the simplified, two neutrino flavours, assumption:

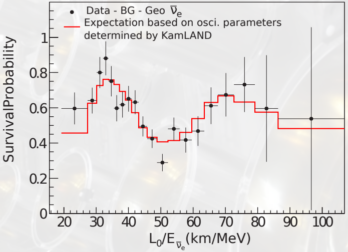
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{E}\right)$$

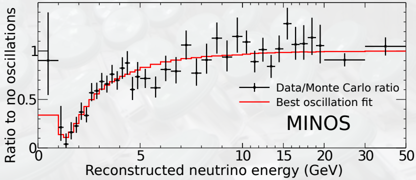


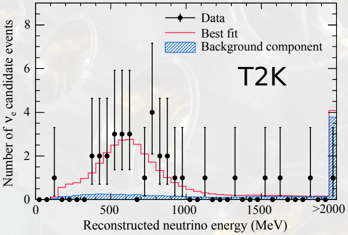
Neutrino Oscillation

Disappearance and Appearance Past Results (leading to Nobel Prize of 2015)









Neutrino Oscillation

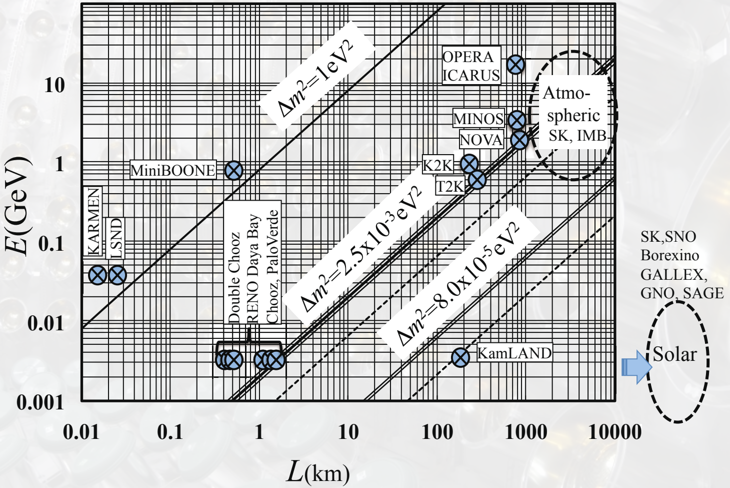
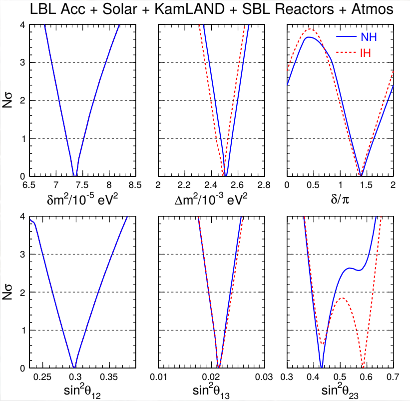


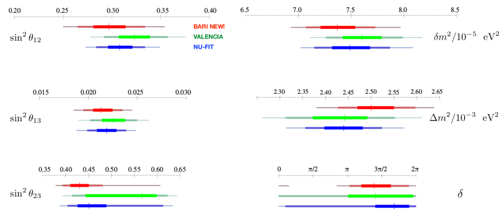
Diagram by F.Suekane (Neutrino Oscillations, LNP 898, Springer, p78)

Current Status

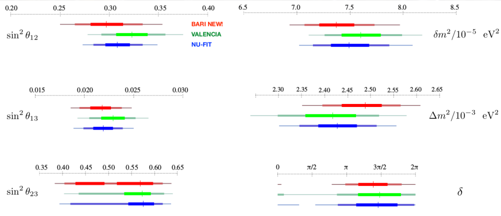


Marrone *et al* @ Neutrino 2016

Normal Hierarchy



Inverted Hierarchy

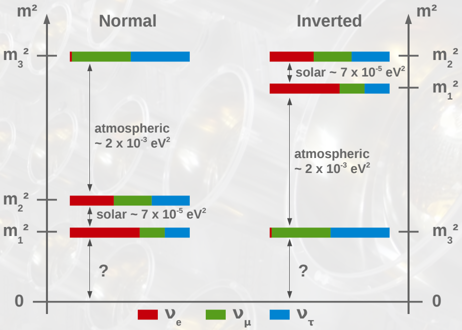


Neutrino Oscillation as for 2009

Open questions:

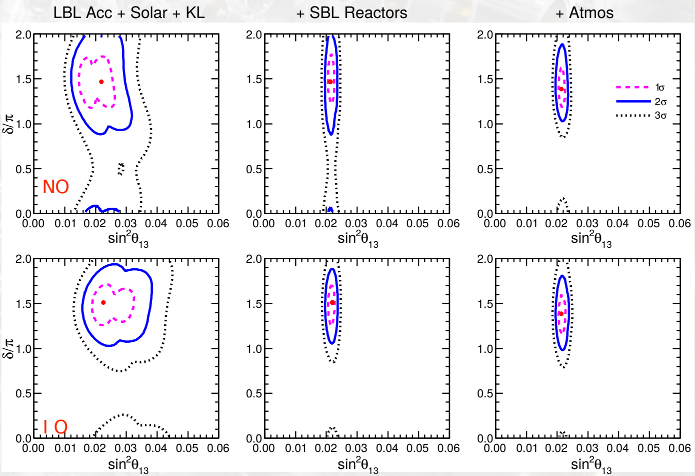
1. is $\sin^2 2\theta_{13} > 0$?
2. is $\Delta m^2_{31} \approx \Delta m^2_{32}$?
3. Mass hierarchy;
4. Sign of $\cos 2\theta_{23}$;
   - ν_3 mostly ν_μ or ν_τ?
5. Value of CP violating phase, δ_{CP};
6. Is there a sterile neutrino flavour?

- Beyond Oscillations:
  1. Absolute mass scale;
  2. Dirac or Majorana nature.



Double Chooz and θ_{13}

Why measure θ_{13}?



- θ_{13} measurement has critical implication on CPV search
- $J_r = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}\cos\delta$ (Jarlskog Inv.)

The θ_{13} race

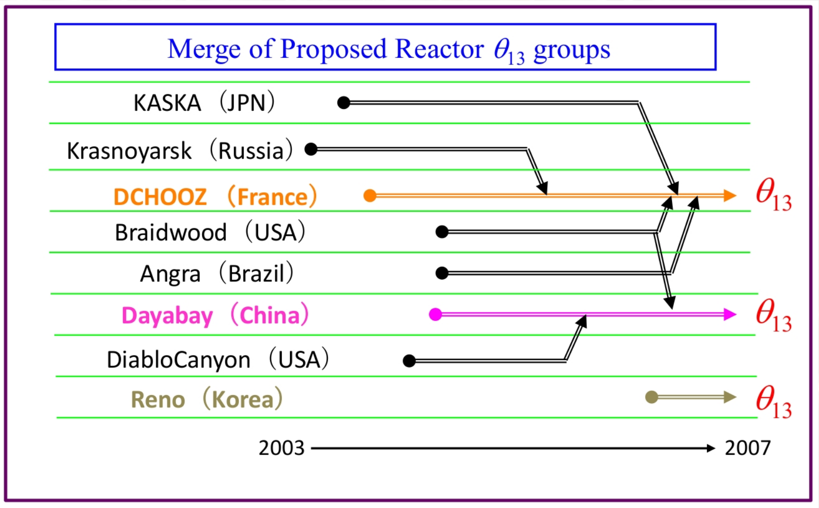
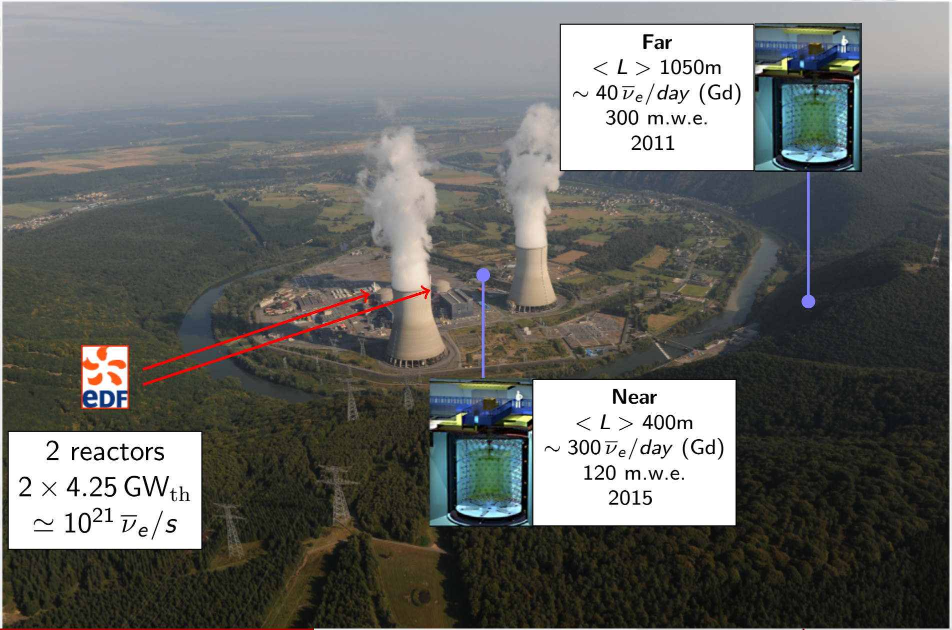


Diagram by F.Suekane (more on this history at Nucl.Phys.B, v908, 74-93 (2016))

The Double Chooz experiment



Far

$< L >$ 1050m

$\sim 40\,\overline{\nu}_e/day$ (Gd)

300 m.w.e.

2011

Near

$< L >$ 400m

$\sim 300\,\overline{\nu}_e/day$ (Gd)

120 m.w.e.

2015

2 reactors

$2 \times 4.25\ \mathrm{GW_{th}}$

$\simeq 10^{21}\,\overline{\nu}_e/s$

Double Chooz Collaboration

Brazil
- CBPF
- UNICAMP
- UFABC

France
- APC
- CEA/DSM/IRFU:
  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC

Germany
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München
- U. Hamburg

Japan
- Tohoku U.
- Tokyo Inst.Tech.
- Tokyo Metro.U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima Inst. Tech.

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

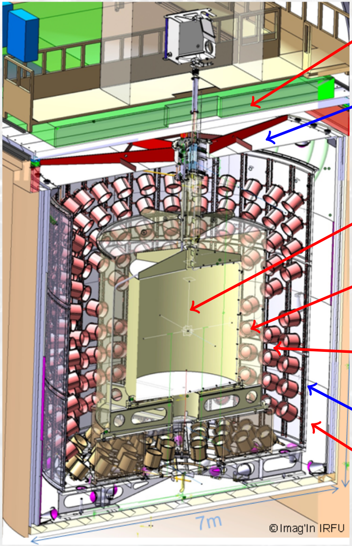
USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

The Double Chooz detector



Outer Veto (OV) : Plastic Scintillator 5 cm wide strips

Cosmic μ detection

Steel shield (15 cm width)

Inner Detector (ID)

ν-**target**: 10.3 m^3 Liquid Scintillator Gd-loaded

IBD sensitive region (Gd-n)

γ-**catcher**: 22.3 m^3 Liquid Scintillator

Escaping γ measurement (Gd-n)
IBD sensitive region (H-n)

Buffer : 110 m^3 Mineral Oil & 390 Photomultiplier

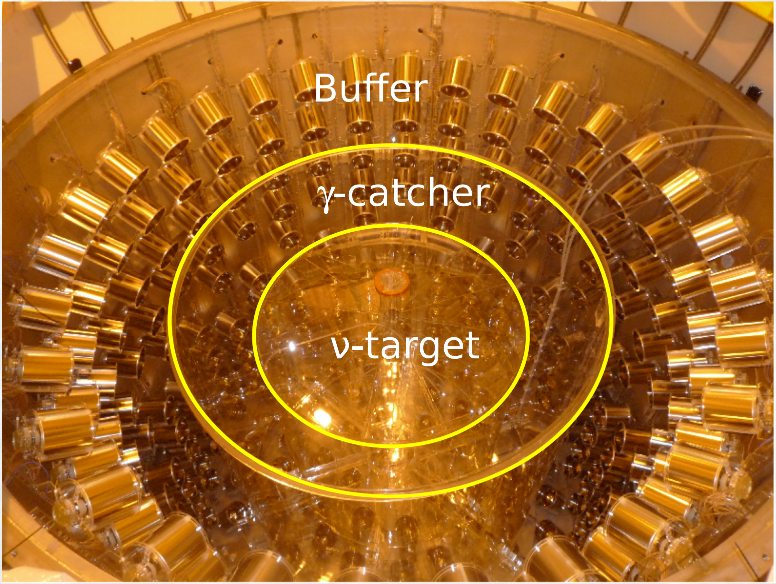
PMTs radioactivity shielding

Steel tank (3 mm width)

Inner Veto (IV) : 90 m^3 Liquid Scintillator & 78 PMTs

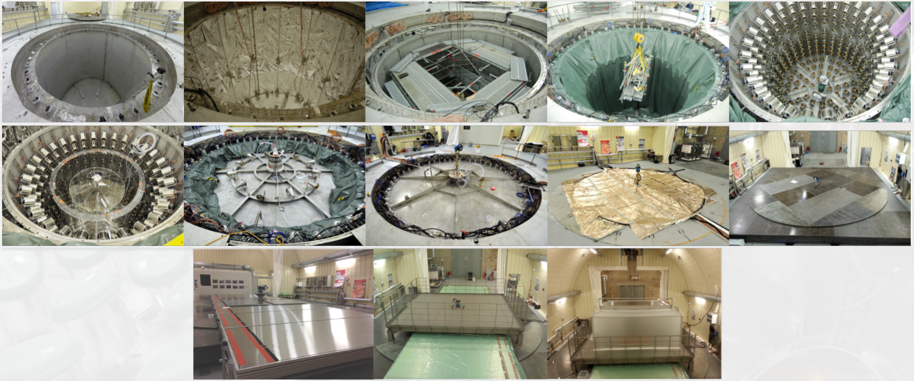
Cosmic μ, fast neutrons and rock γ's detection

Double Chooz Detector



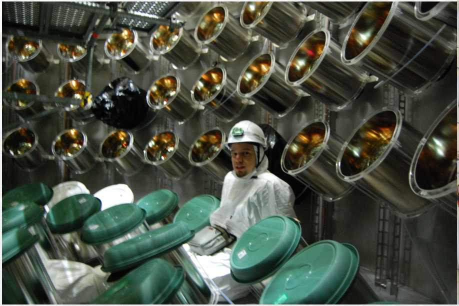
The Near Detector

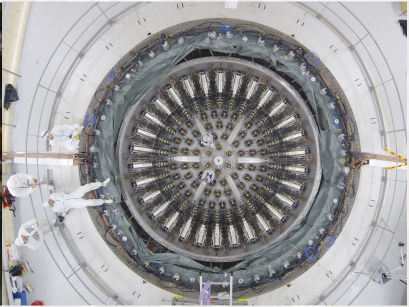
- 2011 - Tunnel and Cave digging
- 2012 - Detector pit and lab construction
- 2013 - Water shield, IV, Buffer, wall and bottom PMTs
- 2014 - Acrylics, lids, filling, commissioning, OV
- 2015 - Official data-taking started (January)

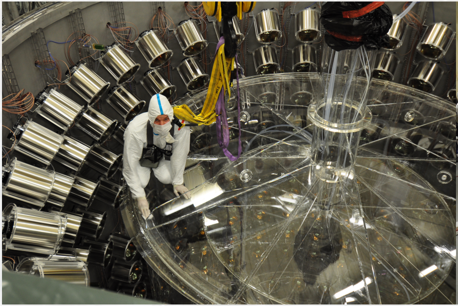


ND construction short film

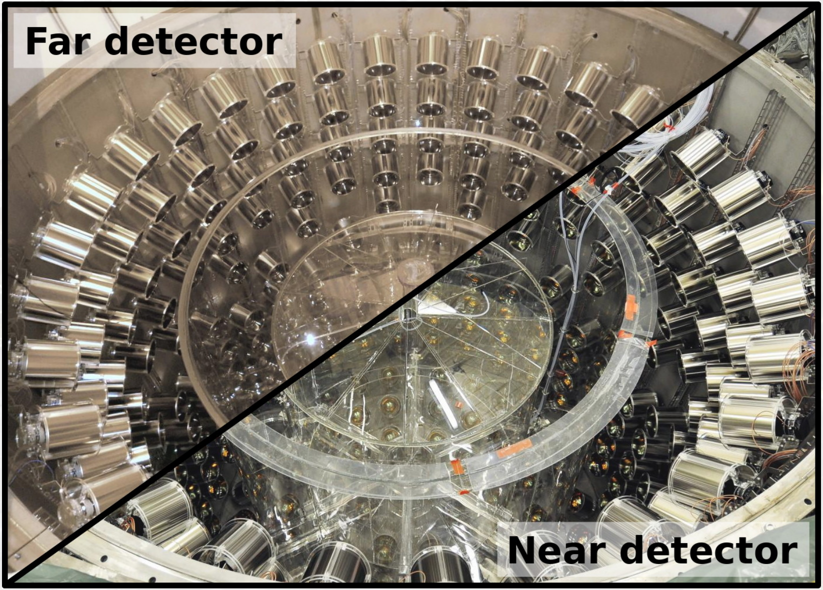
The Near Detector (2013/2014)





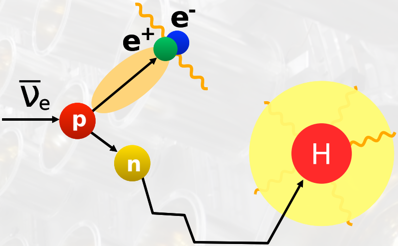


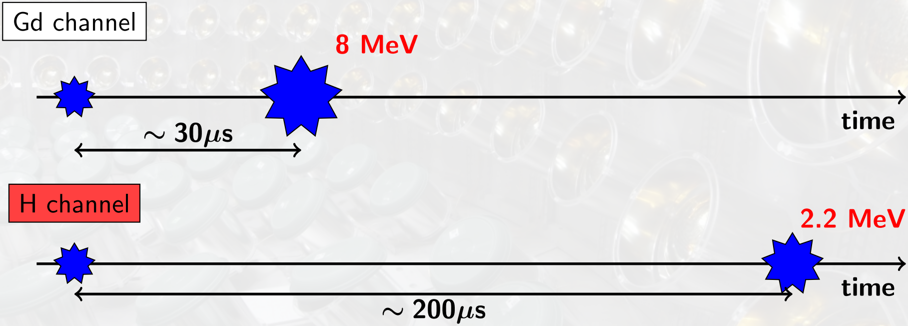
Near and Far Detectors



Neutrino detection

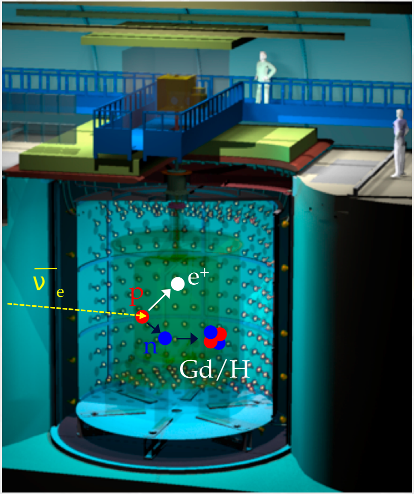
- **Inverse Beta Decay (IBD)**:
  - $\overline{\nu}_e + p \rightarrow n + e^+$
- **Prompt signal**: E_{e^+} + annihilation γ's ($1 \sim 9$ MeV, $E_{\text{vis}} \simeq E_{\overline{\nu}_e} - 0.8\,\text{MeV}$)
- **Delayed signal**: γ's from neutron capture on Gd or H
- **Delayed coincidence**



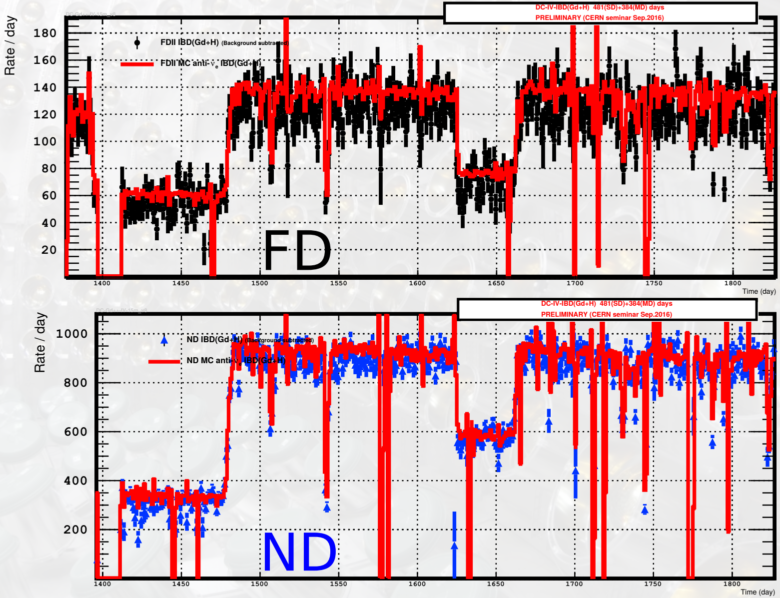


Neutrino Selection

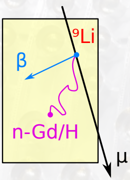
1. Muon Veto
2. Prompt Event
3. Delayed Event
4. Time Coincidence
5. Multiplicity
6. Spatial Coincidence
7. Further BG reduction

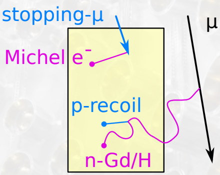


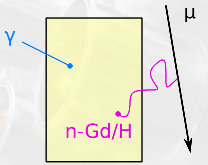
$\bar{\nu}_e$ Candidates



Backgrounds in Double Chooz



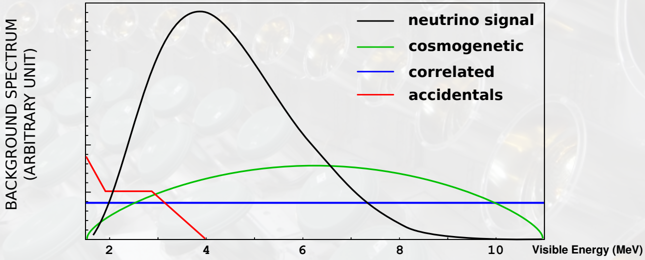




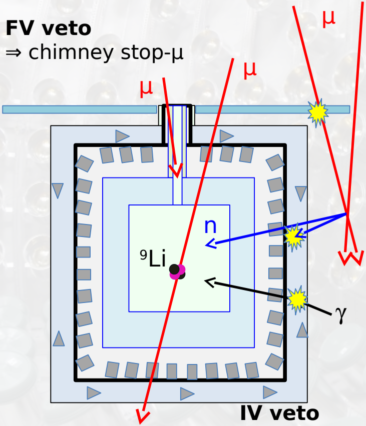
COSMOGENETIC
long lifetime β-n emitter (mainly ^{9}Li)

CORRELATED
fast neutrons from μ spallation, stopping-μ (acceptance hole)

ACCIDENTALS
natural radioactivity: ^{40}K, ^{208}Tl
→ dominant in H-analysis

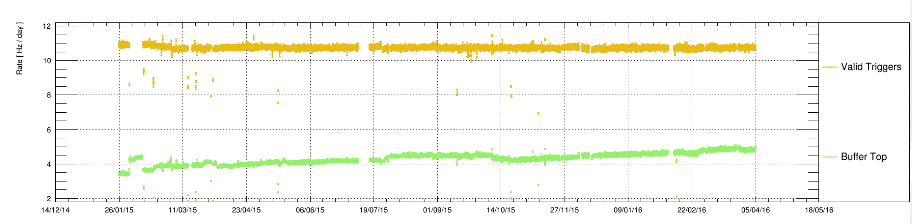


Background Vetoes



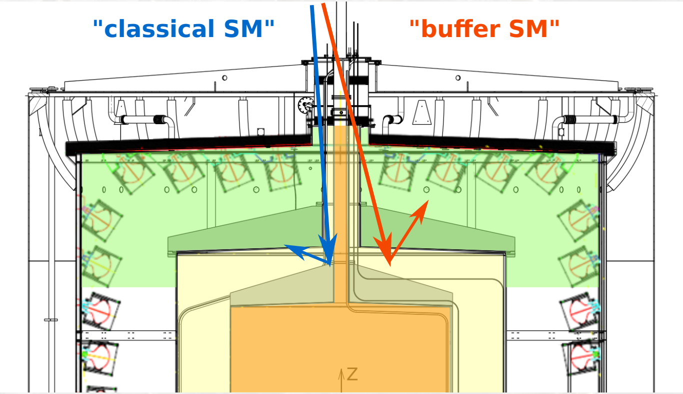
Cut	Information used	Target of cut
μ veto	1ms veto after μ	μ, cosmogenic
Multiplicity	unicity condition	multiple-n
FV veto	vertex likelihood	chimney stop-μ
CPS veto	chimney likelihood	chimney stop-μ
Δ(BJ)	Vtx displacement	chimney stop-μ
IV veto	IV activity	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	cosmogenic
LN cut	PMT hit pattern & time	light emission from PMT
Qratio	Max Q/ Tot. Q	ND buffer stop-μ
ANN	Time & Space Corr. Delayed Energy	Accidentals

(leak) ND with small amount of scint. at Buffer

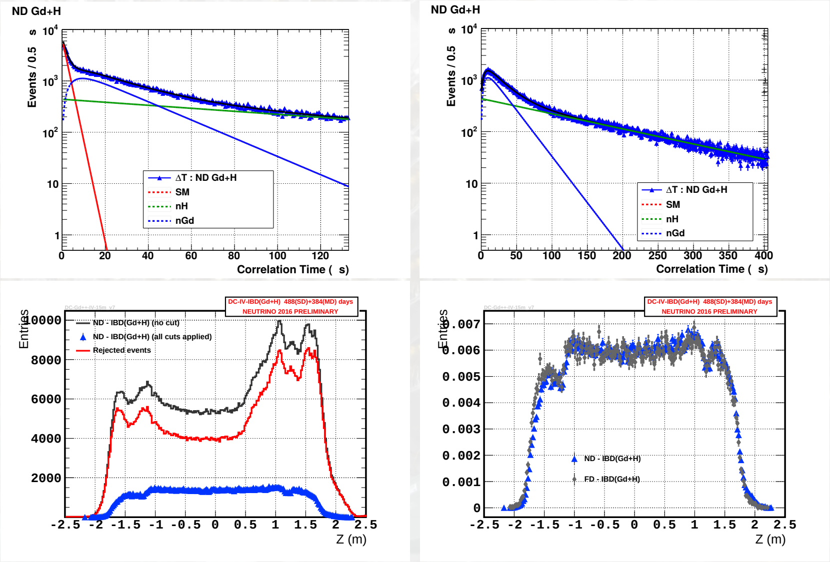


- Discovered during commissioning
- Seems to happened during filling. Still evolving, but very slow ($<$ 2 Hz/year from $\sim$3.5 Hz at start)

(leak) ND with small amount of scint. at Buffer

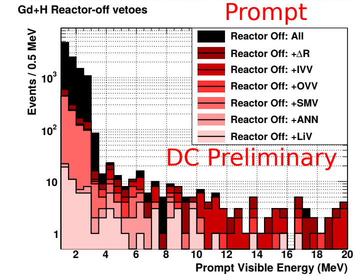


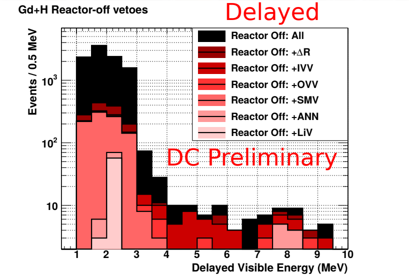
Validating Stopping-μ contamination



SM upper limit contamination below 0.2% of the IBD sample

DC Background Suppression

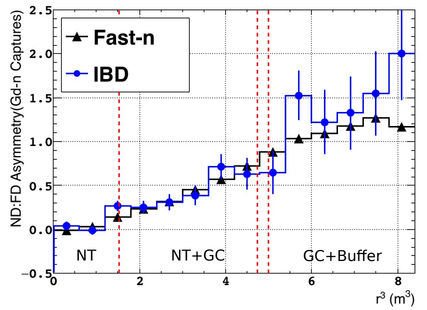


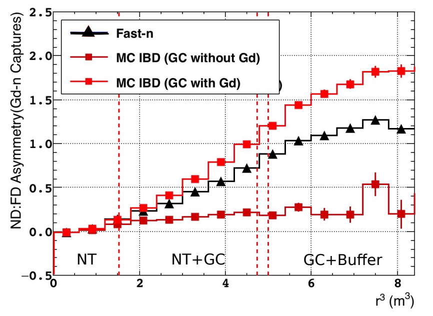


- DC Precious Reactor-Off data ($\sim$ 7 days on FD);
- $\sim 10^4$ to $< 10^2$ BG suppression;
- 6:1000 selection with 95.00 ± 0.03 of IBD efficiency.

(leak) Small fraction of Gd in GC

- Use neutron from muon spallation processes;
- Calibrate and monitor the detectors.



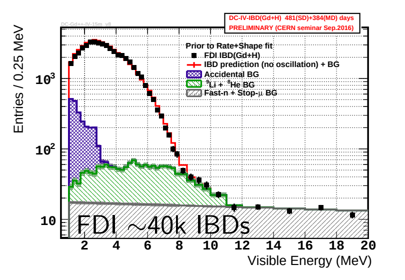


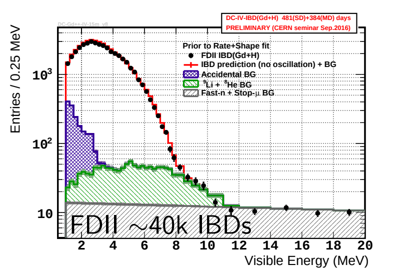
IBD $\approx$ Fast-n agreement
($\Rightarrow$ use FN to track IBD)
measure Gd in GC
(to high precision)

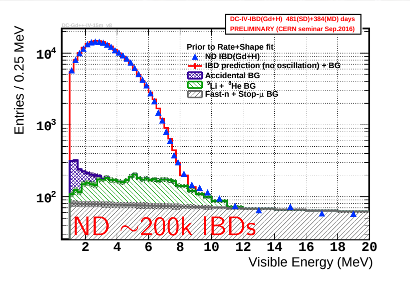
2 IBD MC used
($\Rightarrow$ covers leak full dynamics)
validate Gd impact

note: no Gd in ND $\Rightarrow$ asymmetry to FD $\rightarrow$ 0.0

Double Chooz Data and Prediction

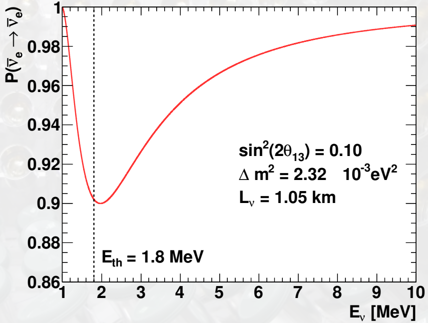


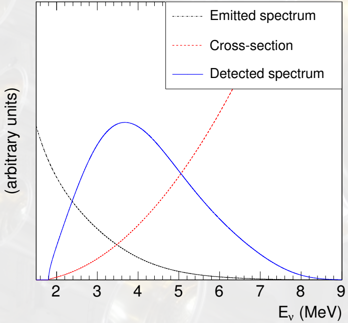




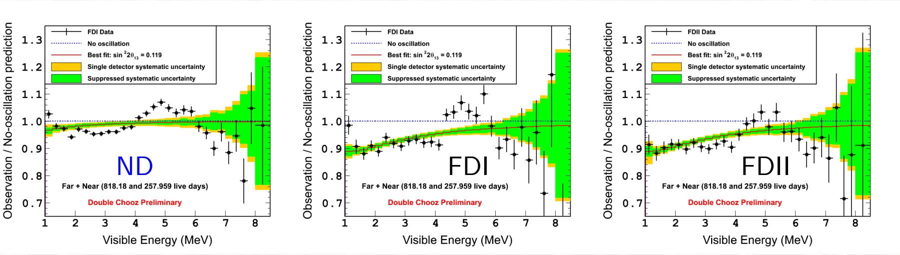
Oscillation Analysis Method

- Look for E/L Dependence on the survival probability





θ_{13} Oscillation Fit Result



$$\sin^2 2\theta_{13} = 0.119 \pm 0.016 \quad \text{with } \chi^2/\ \text{ndf} = 236.2\ /\ 114$$

marginalized over $\Delta m^2 = (2.44 \pm 0.09) \times 10^{-3}\text{eV}^2$

Parke *et al.* arXiv:1601.07464)

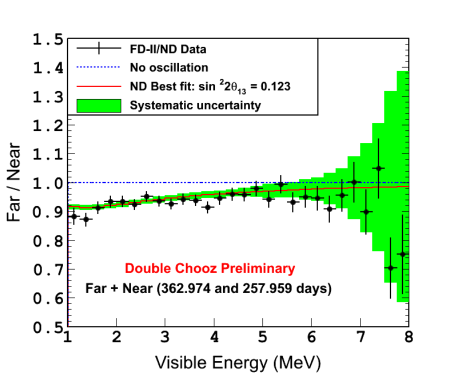
θ_{13} Oscillation Fit Result Cross-check

Data-data fit: ND as a prediction for the FD

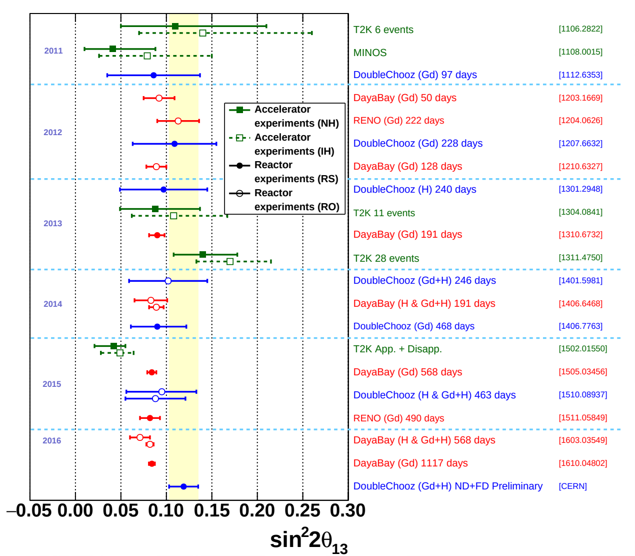
Scaled by proton#, vetoes, baseline, survival probability and DAQ-time

$$\chi^2 = \sum_{ij} (N_i^{\mathrm{FD}} - \omega_i N_i^{\mathrm{ND}}) M_{ij}^{-1} (N_j^{\mathrm{FD}} - \omega_j N_j^{\mathrm{ND}})^T + \mathrm{Penalty\ Terms}$$

$$\omega_i = \frac{T_{live}^{\mathrm{FD}}}{T_{live}^{\mathrm{ND}}} \times \frac{N_p^{\mathrm{FD}}}{N_p^{\mathrm{ND}}} \times \frac{\varepsilon^{\mathrm{FD}}}{\varepsilon^{\mathrm{ND}}} \times \frac{\sum_r \phi_r^{\mathrm{FD}} (1/L_r^{\mathrm{FD}})^2}{\sum_r \phi_r^{\mathrm{ND}} (1/L_r^{\mathrm{ND}})^2} \times \frac{\mathrm{Prob}_{\mathrm{surv.(i)}}^{\mathrm{FD}}}{\mathrm{Prob}_{\mathrm{surv.(i)}}^{\mathrm{ND}}}$$

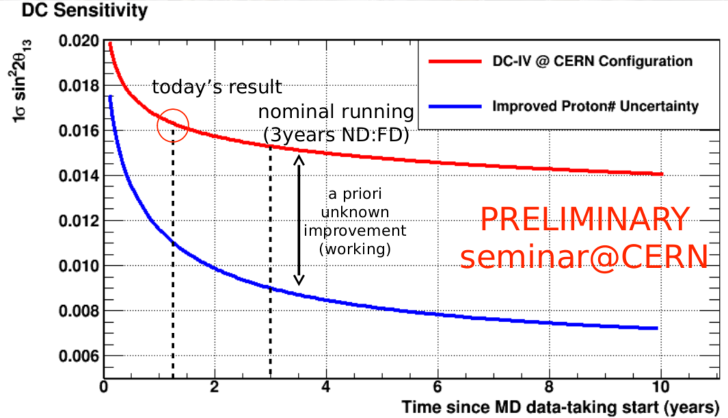


θ_{13} measurement evolution



updated from Nucl.Phys.B, v908, 74-93 (2016)

What do we expect?



- Largely dominated by proton# → possible to improve
  - most conservative assumptions assumed for now

Reactor θ_{13} workshops

Daya Bay $\oplus$ Double Chooz $\oplus$ RENO

- (0^{th}) discussion/planning $\rightarrow$ @ Neutrino 2016, London (UK)
- 1^{st} workshop $\rightarrow$ October 2016 (Seoul, South Korea)

  (systematics review, results consistency)
- 2^{nd} workshop $\rightarrow$ June 2017 (Paris, France)

  (Cosmogenic BG combined, further systematics understanding)

Final goal: combination of θ_{13} (many results)

(likely) most precise input to θ_{13} for several decades

$\Delta\tilde{m}^2_{31}$ and Mass Hierarchy

Measurement of $\Delta \tilde{m}^2_{31}$

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

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \left(c^2_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + s^2_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right) + O(-3)$$

$$\Delta \tilde{m}^2_{31} = c^2_{12} \left| \Delta m^2_{31} \right| + s^2_{12} \left| \Delta m^2_{32} \right|$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \begin{pmatrix} (s^2_{12} + s_{13} t_{23} \sin 2\theta_{12} \cos \delta) \sin^2 \frac{\Delta m^2_{31}}{4E} \\ +(c^2_{12} - s_{13} t_{23} \sin 2\theta_{12} \cos \delta) \sin^2 \frac{\Delta m^2_{32}}{4E} \end{pmatrix} + O(-2)$$

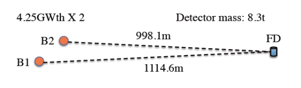
$$\Delta \tilde{m}^2_{32} = (s^2_{12} + s_{13} t_{23} \sin 2\theta_{12} \cos \delta) \left| \Delta m^2_{31} \right| + (c^2_{12} - s_{13} t_{23} \sin 2\theta_{12} \cos \delta) \left| \Delta m^2_{32} \right|$$

$$\frac{2(\Delta \tilde{m}^2_{31} - \Delta \tilde{m}^2_{32})}{\Delta \tilde{m}^2_{31} + \Delta \tilde{m}^2_{32}} \sim \pm 0.012 \times (1 \pm 0.3)$$

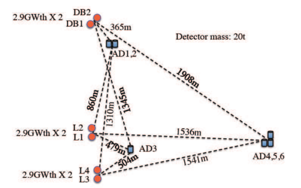
Measurement of $\Delta\tilde{m}^2_{31}$ - Global Fit (2013)

- Search for the oscillation parameters, using each experiment's reactor-detector baseline
- Do a combined analysis (Global Fit) with experiments data
- Current Reactor Neutrino Experiments

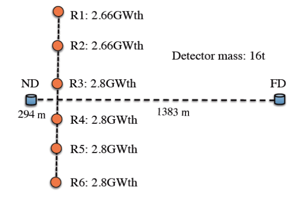
Double Chooz



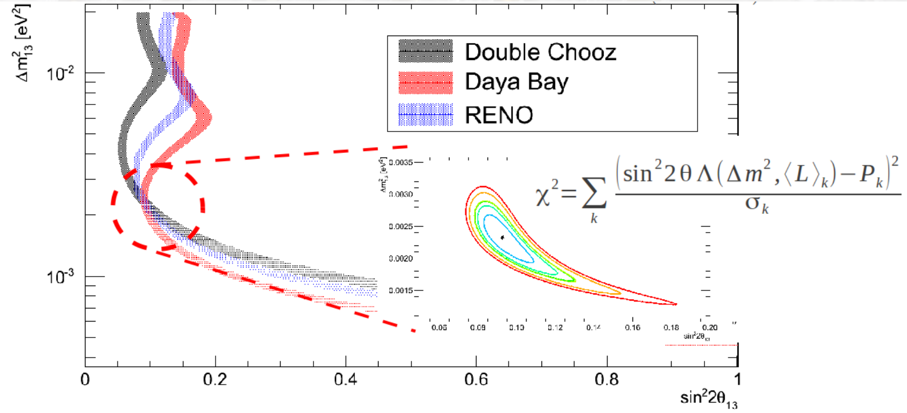
Daya Bay



RENO



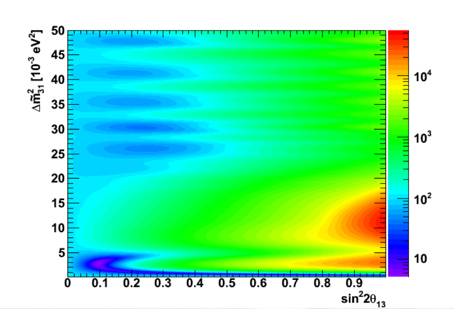
Measurement of $\Delta\tilde{m}^2_{31}$ - Global Fit (2013)

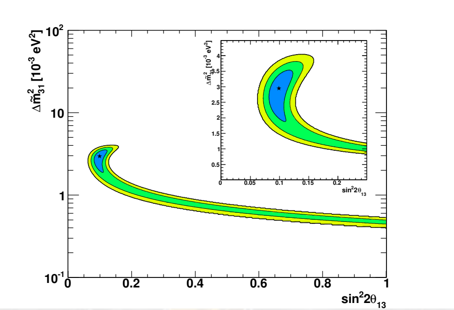


Measurement of $\Delta\tilde{m}^2_{31}$ - Global Fit (2013)

- Combined Data

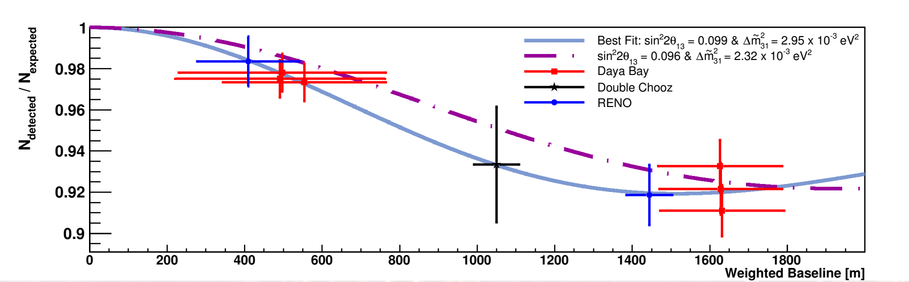
$$\chi^2_{\min} = 5.14\,/\,6\ \mathrm{DoF}$$
$$\Delta\tilde{m}^2_{31} = 2.95^{+0.42}_{-0.61} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2 2\theta_{13} = 0.099^{+0.016}_{-0.012}$$





Measurement of $\Delta\tilde{m}^2_{31}$ - Global Fit (2013)

- Combined Data

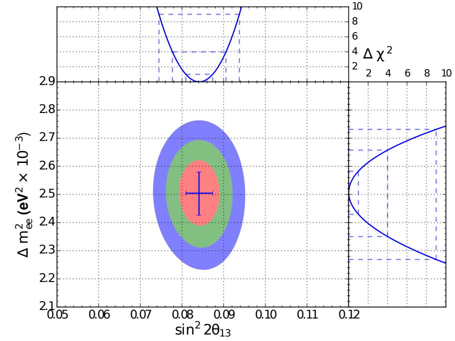


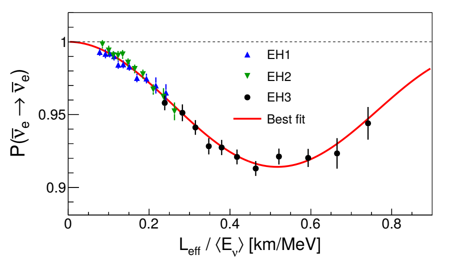
- $\Delta\tilde{m}^2_{31}$ in agreement with $\Delta\tilde{m}^2_{32}$ measured by accelerator experiments;
- Confirms standard three neutrino flavour oscillation model;
- $\sin^2 2\theta_{13}$ obtained independently from $\Delta\tilde{m}^2_{32}$.

Phys. Lett. B, 725 (2013) 271-276

$\Delta\tilde{m}^2$ by Spectral Analysis

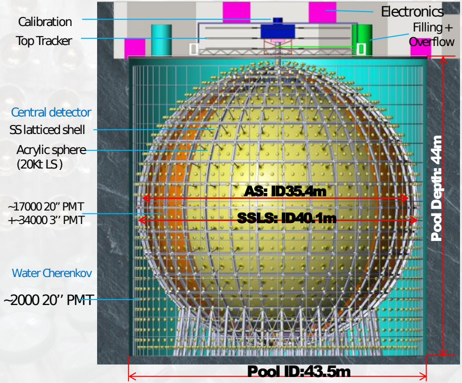
- arXiv:1610.04802 (Daya Bay Collab.)

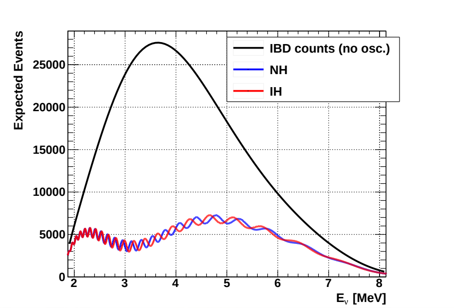




MH with Reactor Neutrinos

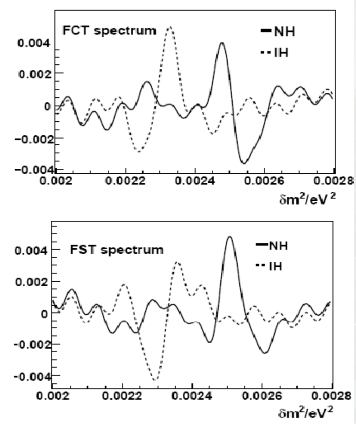
JUNO : Jiangmen Underground Neutrino Observatory

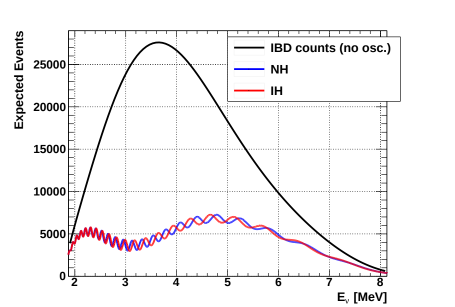




MH with Reactor Neutrinos

JUNO : Jiangmen Underground Neutrino Observatory

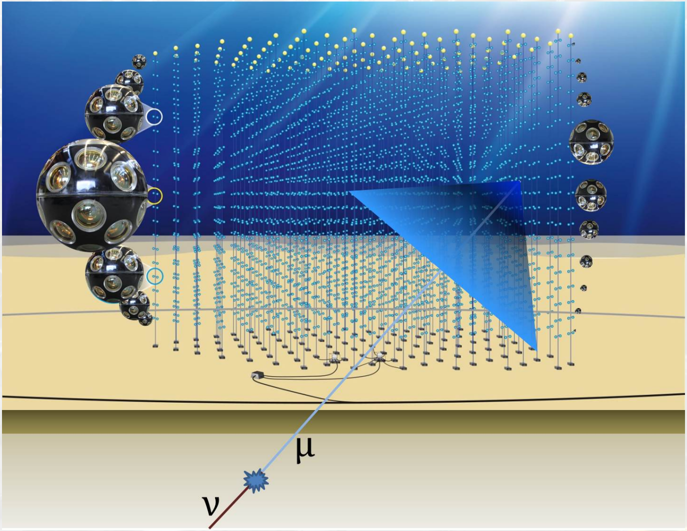




S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned etal., Phys.Rev. D78 (2008)071302
Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103
PRD79:073007, 2009

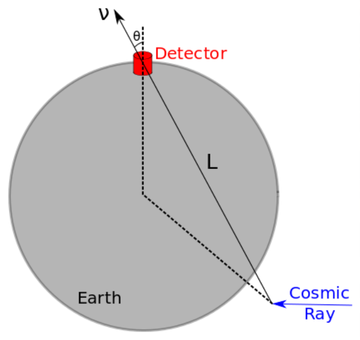
MH with Atmospheric Neutrinos

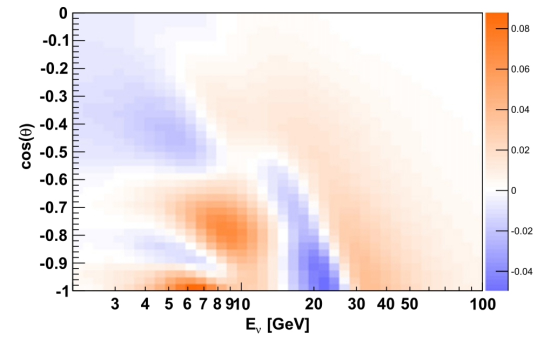
ORCA : Oscillation Research with Cosmics in the Abyss



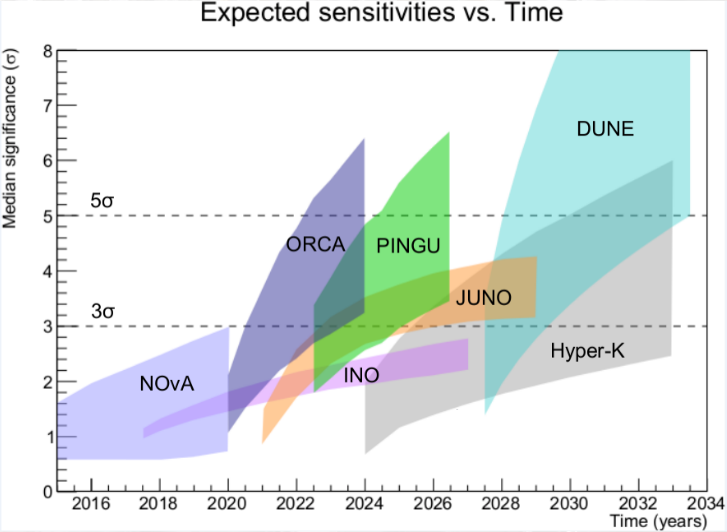
MH with Atmospheric Neutrinos

ORCA : Oscillation Research with Cosmics in the Abyss





MH Promising Future



from L.Stanco @ NuPhys2016

Sterile Neutrinos

Forth Neutrino Flavour?

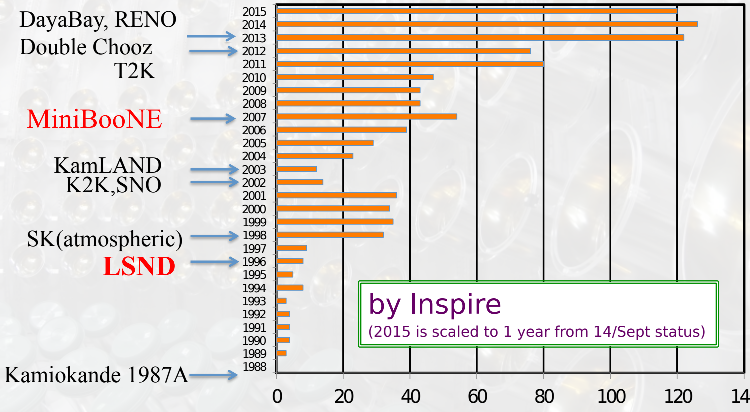
Short baseline "anomalies"

Experiment	ν source	Mode	Significance
LSND	Decay-At-Rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8σ
MiniBooNE	Decay-In-Flight	$\nu_\mu \to \nu_e$	3.4σ
		$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8σ
Ga	e-capture	$\nu_e \to \nu_x$	2.7σ
Reactor	β decay	$\bar{\nu}_e \to \bar{\nu}_x$	3.0σ

- LSND shows the most significant result
    - Necessary to validate its result, with same production and detection modes, but with better sensitivity
    - Otherwise, its "ghost" remains forever
- Reactor anomaly in question, since experiments question the current predictions available

Sterile "Gold-rush"

Number of papers with "Sterile Neutrino" in the title, per year



by F.Suekane on NuPhys2015

JSNS^2

JSNS^2
(J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source)

Proposal:
A Search for Sterile Neutrino at J-PARC Materials and Life Science Experimental Facility

September 2, 2013

M. Harada, S. Hasegawa, Y. Kasugai, S. Meigo, K. Sakai, S. Sakamoto, K. Suzuya
JAEA, Tokai, Japan

E. Iwai, T. Maruyama, K. Nishikawa, R. Ohta
KEK, Tsukuba, JAPAN

M. Niiyama
Department of Physics, Kyoto University, JAPAN

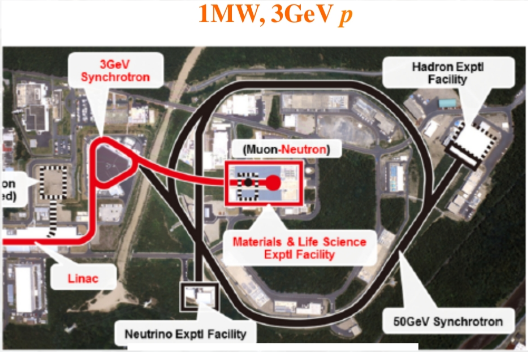
S. Ajimura, T. Hiraiwa, T. Nakano, M. Nomachi, T. Shima
RCNP, Osaka University, JAPAN

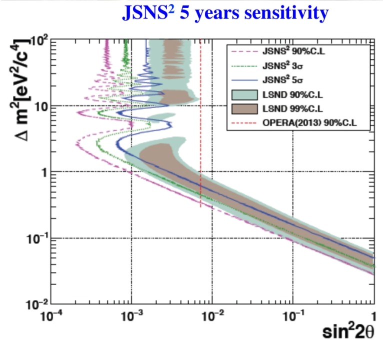
T. J. C. Bezerra, E. Chauveau, T. Enomoto, H. Furuta, H. Sakai, F. Suekane
Research Center for Neutrino Science, Tohoku University, JAPAN

M. Yeh
Brookhaven National Laboratory, Upton, NY 11973-5000, USA

G. T. Garvey, W. C. Louis, G. B. Mills, R. Van de Water
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

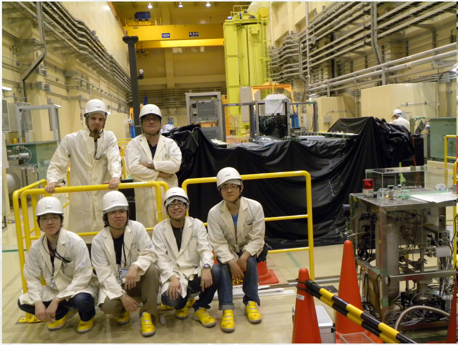
JPARC as $\bar{\nu}_\mu$ source



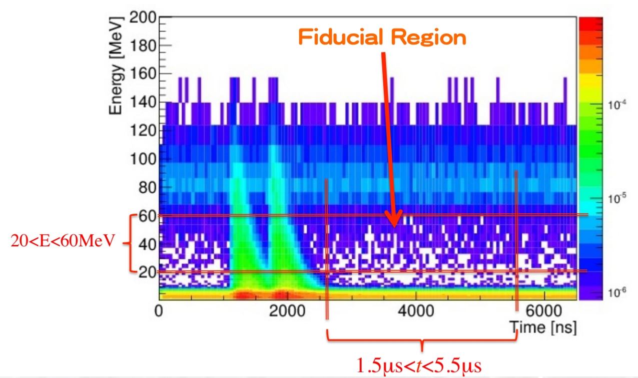


With two DC-like detectors of 25 tonnes each

Background Measurement (2014)



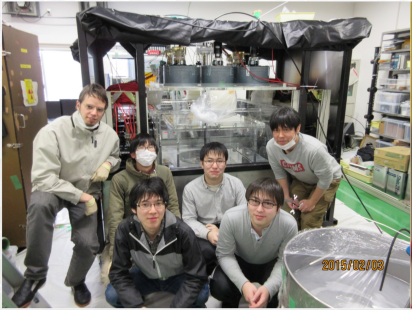
Background Measurement (2014)

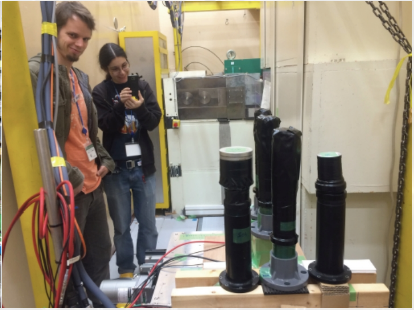


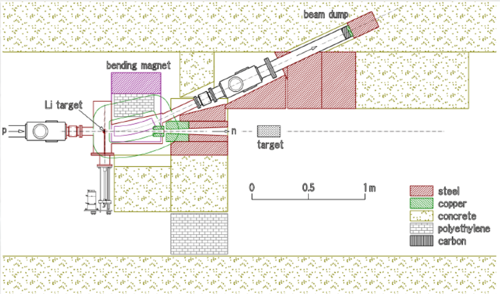
Beam related background will not be a problem!

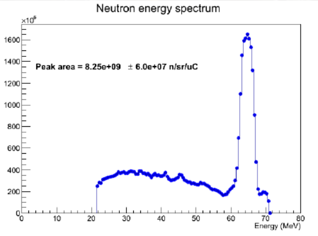
Prog. Theor. Exp. Phys. (2015) 063C01 doi: 10.1093/ptep/ptv078

LS Development (2015)



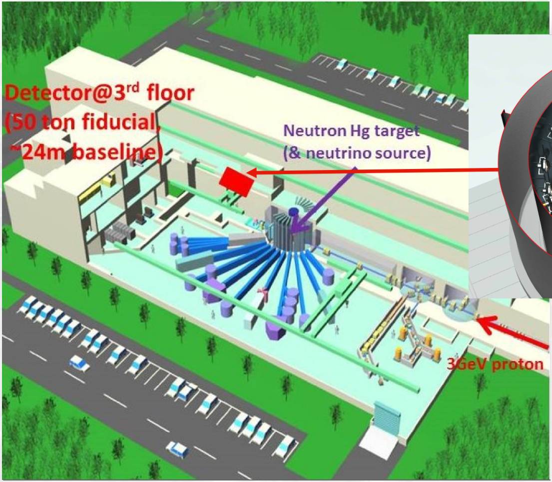


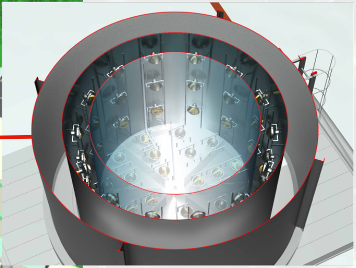




Stage 1 Approval

- Approval and support from J-PARC PAC;
- Funding of one detector (25 tons)





Summary

- It's being an amazing time to work with neutrinos
- Nobel Prize on 2015 for Neutrino Oscillations
- All the opens questions are being addressed soon
- Double Chooz is a big part of the effort to uncover
- Near Detector with $\sim$15 months of data
  - Iso-flux position $\rightarrow$ systematic cancellation
  - $\sin^2 2\theta_{13} = 0.119 \pm 0.016$
  - Clean single reactor spectrum $\rightarrow$ DC questions current reactor flux predictions
  - Broad physics program beyond θ_{13}
- Exciting new results to come, stay tuned!

Thank you!