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Review of θ_{13} reactor experiments:

Th. Lasserre
CEA / Irfu

APC-Paris, June 20th 2012

Reactor Neutrino Overview



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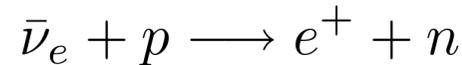
- **Electron antineutrinos emitted through Decays of Fission Products of ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu**

- **Nuclear reactors** : $1 \text{ GW}_{\text{th}} \Leftrightarrow 2 \cdot 10^{20} \bar{\nu}/\text{s}$

- **Neutrino Luminosity** : $N_{\bar{\nu}} = \gamma(1 + k)P_{\text{th}}$
 γ : reactor constant
 k : fuel evolution correction up to 10%

- **Common Detection**

- Inverse Beta-Decay reaction (xsec: $\sigma_{\text{V-A}}$)

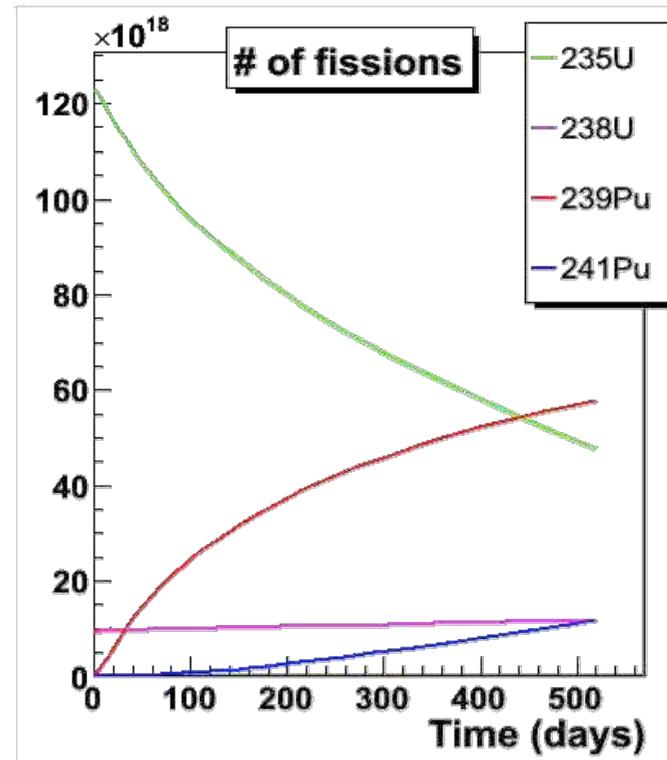


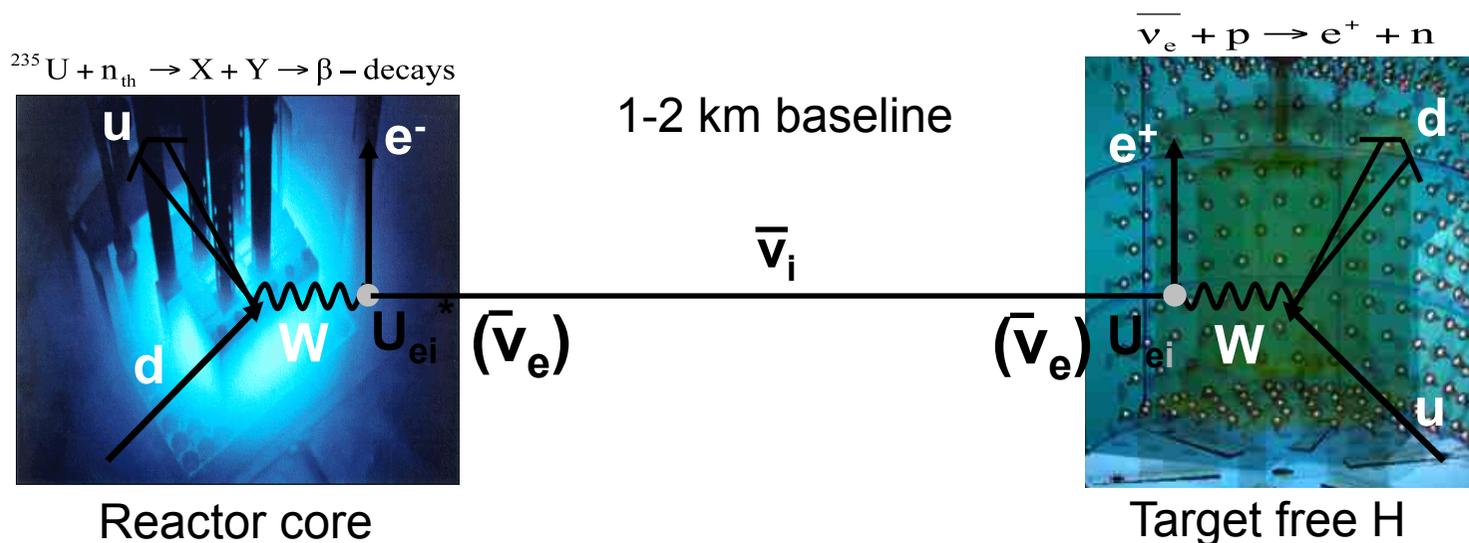
- Threshold 1.8 MeV. E_{ν} extend to 10 MeV
- Measure anti- ν_e of interaction rate

$$n_{\nu} = \frac{1}{4\pi R^2} \frac{P_{\text{th}}}{\langle E_f \rangle} N_p \varepsilon \sigma_f \longrightarrow \sigma_f^{\text{meas.}} = \frac{4\pi R^2 n_{\nu}^{\text{meas.}} \langle E_f \rangle}{N_p \varepsilon P_{\text{th}}}$$

- Comparison of σ_f to prediction

$$\sigma_f^{\text{pred.}} = \int_0^{\infty} \phi_f^{\text{pred.}}(E_{\nu}) \sigma_{\text{V-A}}(E_{\nu}) dE_{\nu}$$

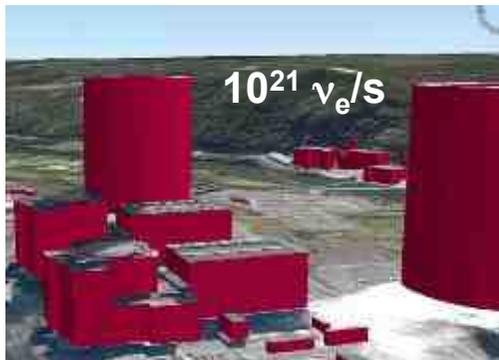
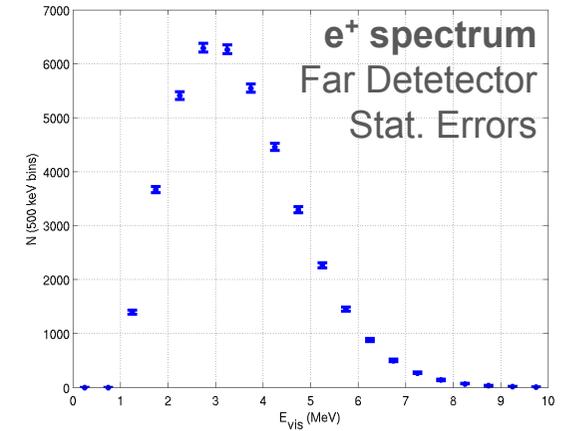
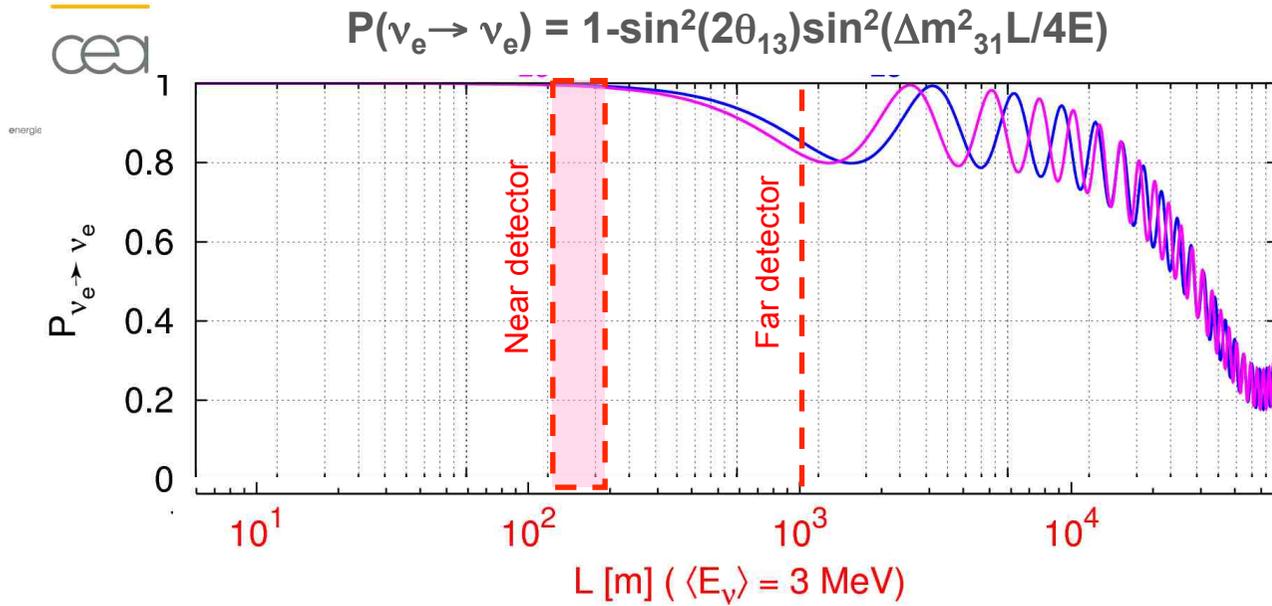




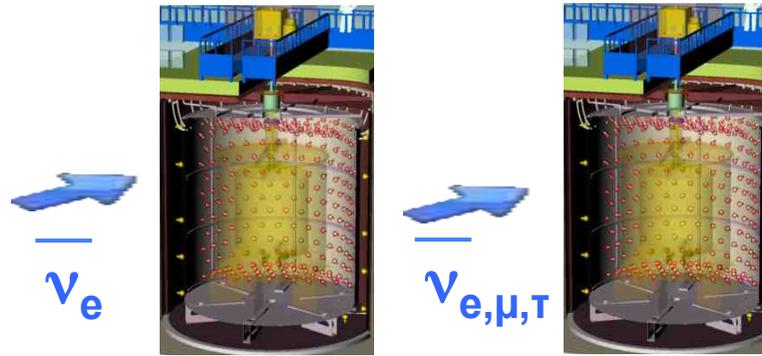
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \left[\sin\left(1.27 \frac{\Delta m_{\text{atm}}^2 (\text{eV}^2) L (\text{m})}{E (\text{MeV})}\right) + O\left(\frac{\Delta m_{\text{sol}}^2}{\Delta m_{\text{atm}}^2}\right) \right]$$

- **Straightforward oscillation formula** : weak dependence on Δm_{sol}^2
 - MeV electron antineutrinos : only **disappearance** experiments
 - $\sin^2(2\theta_{13})$ measurement **independent of δ -CP**
 - $\sin^2(2\theta_{13})$ measurement **independent of $\text{sign}(\Delta m_{13}^2)$**
- } **'clean'** information on θ_{13}

The concept from Lev Mikaelyan (Kurchatov, 2000)

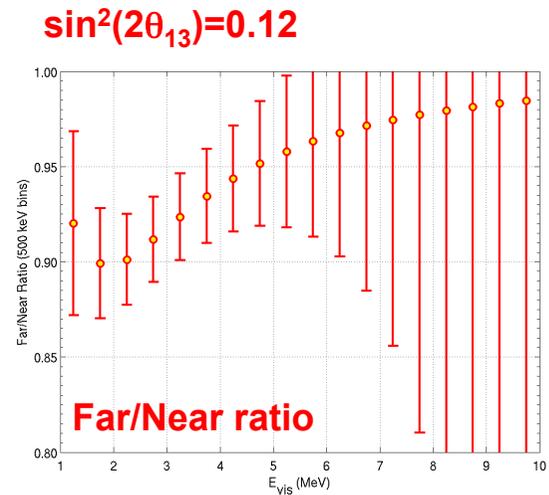


Chooz Nuclear Power Station
2 cores of 4.3 GW_{th} each



Near detector
400 m

Far detector
1050 m



Similar Detector Designs

New 4-region large detector concept from Double Chooz Coll. (2003)

http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre1.doc
http://bama.ua.edu/~busenitz/rnu2003_talks/suekane1.pdf

Outer Veto: plastic scintillator strips (400 mm)

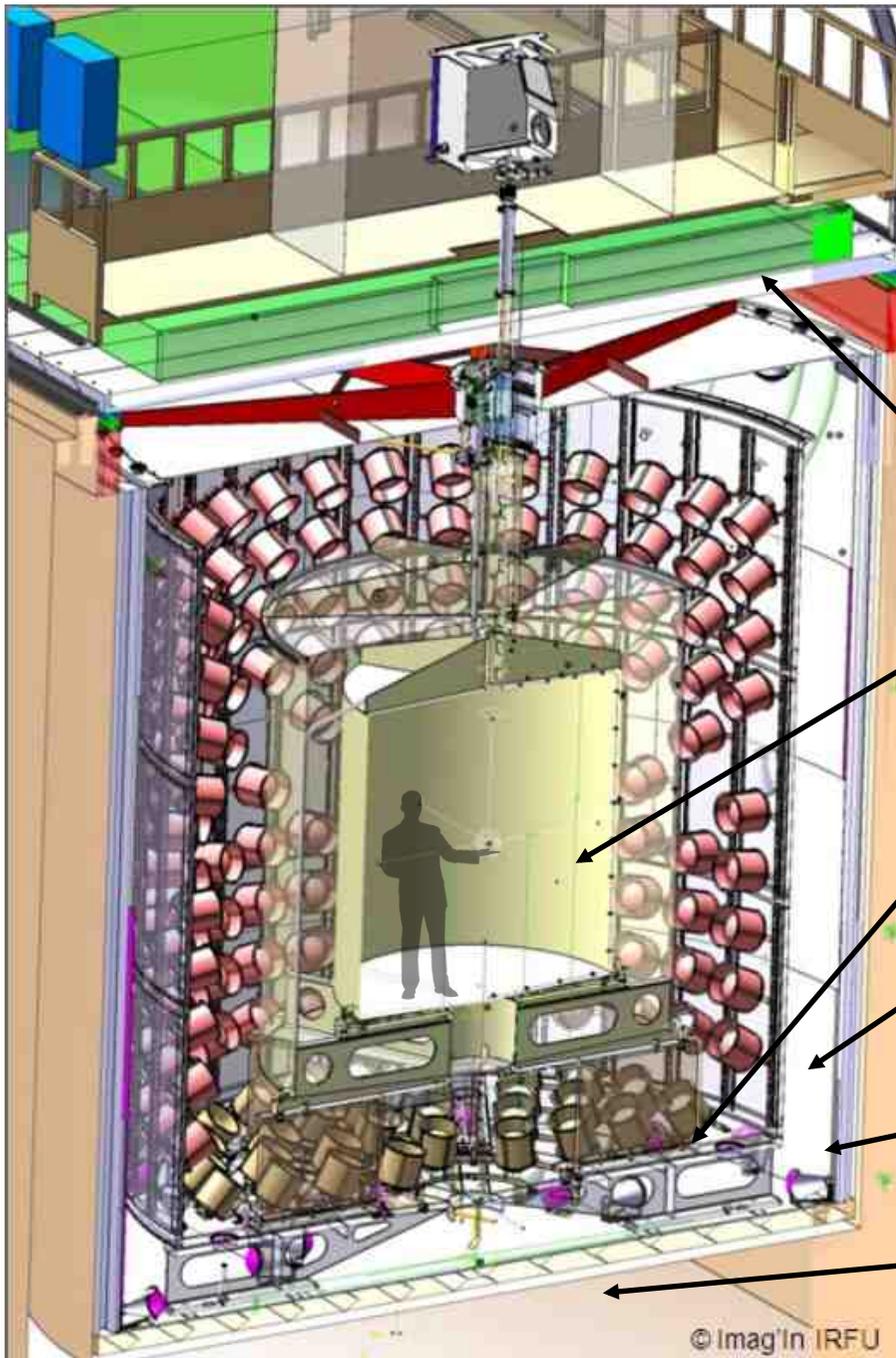
ν -Target: 10,3 m³ scintillator doped with 1g/l of Gd compound in an acrylic vessel (8 mm)

γ -Catcher: 22,3 m³ scintillator in an acrylic vessel (12 mm)

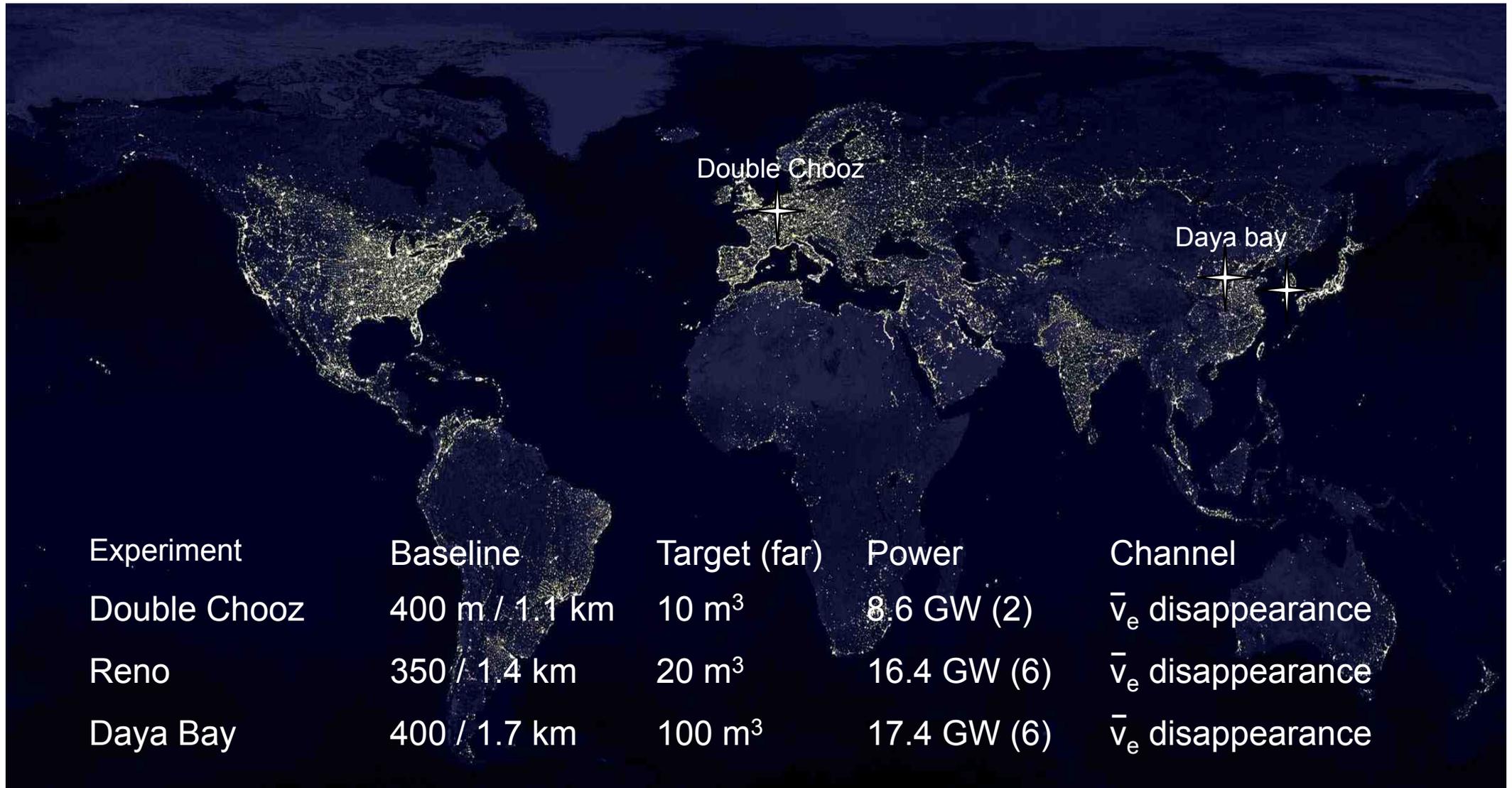
Buffer: 110 m³ of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

Inner Veto: 90m³ of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & Steel Shielding (150 mm)



Reactor Neutrino Experiments



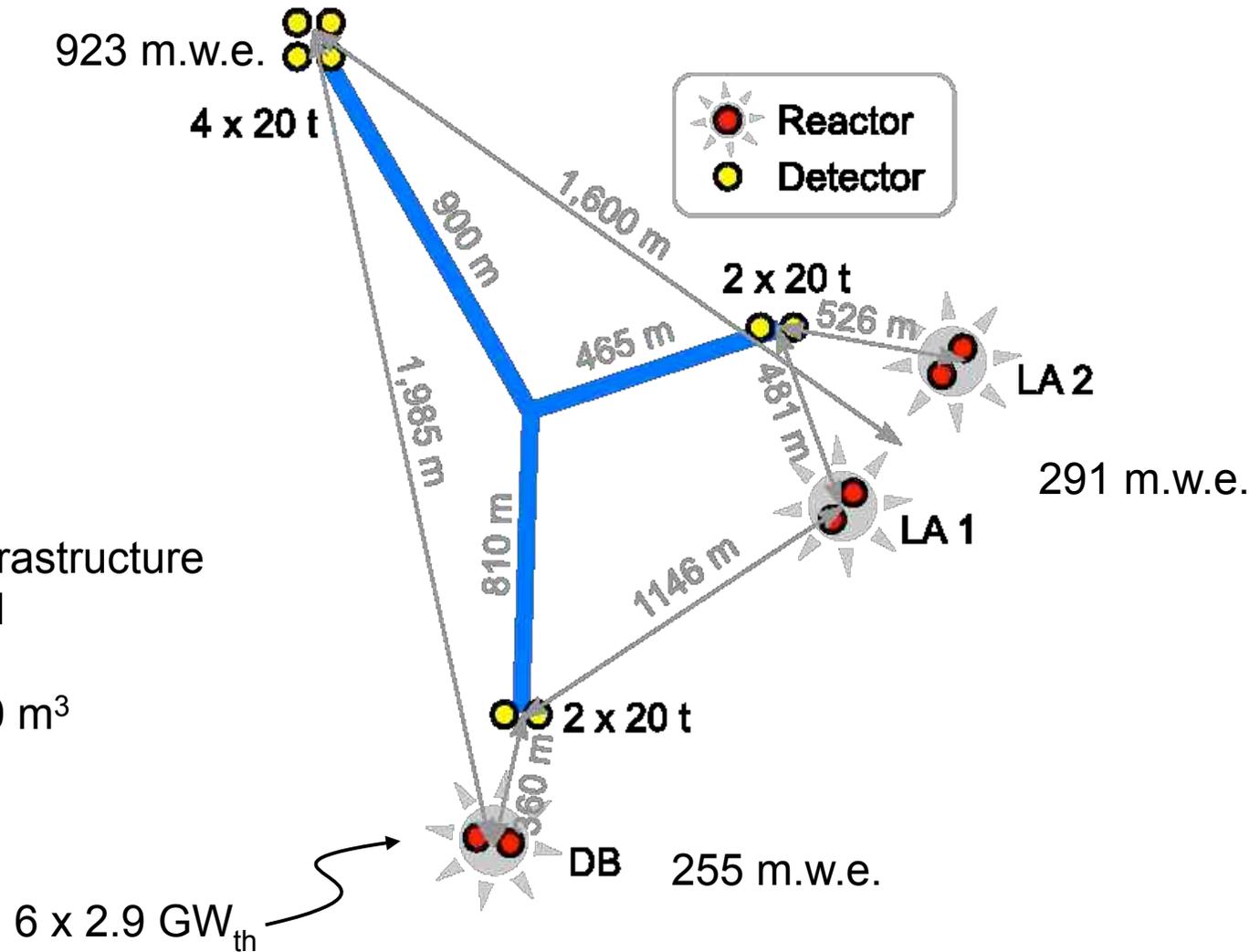
Daya Bay

Daya Bay nuclear power station in China



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>3 km tunnel
New surface infrastructure
3 laboratory hall
8 detectors
Gd-volume: 200 m³



Daya Bay



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Collaboration

China & USA - 230 people

Site:

Daya Bay Plant (11.6+6 GW_{th})

Near: 1 km tunnel + laboratory

Far: 2 km tunnel + laboratory

8x20 tons detector modules (fiducial)

Based on Double Chooz concept

Near: 4x20 tons – 360-500 m – 200 mwe

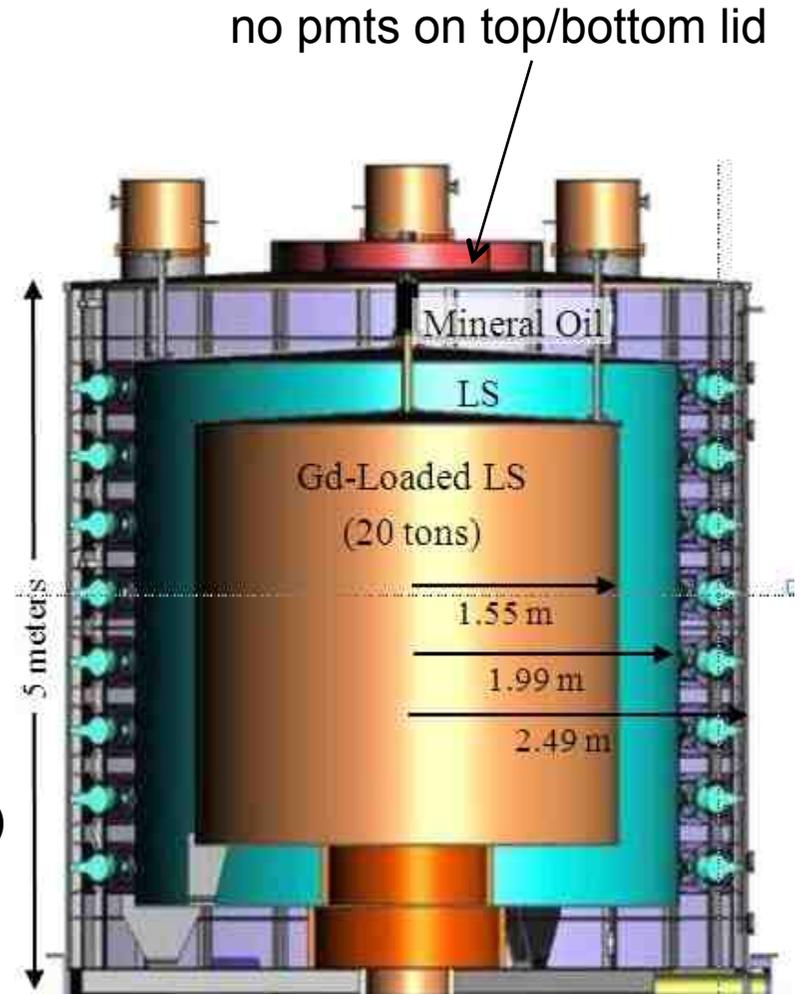
Far: 4x20 tons - 1.6-1.9 km – 1000 mwe

Movable detector concept (in water pools)

Expected Sensitivity

0.36% systematic error

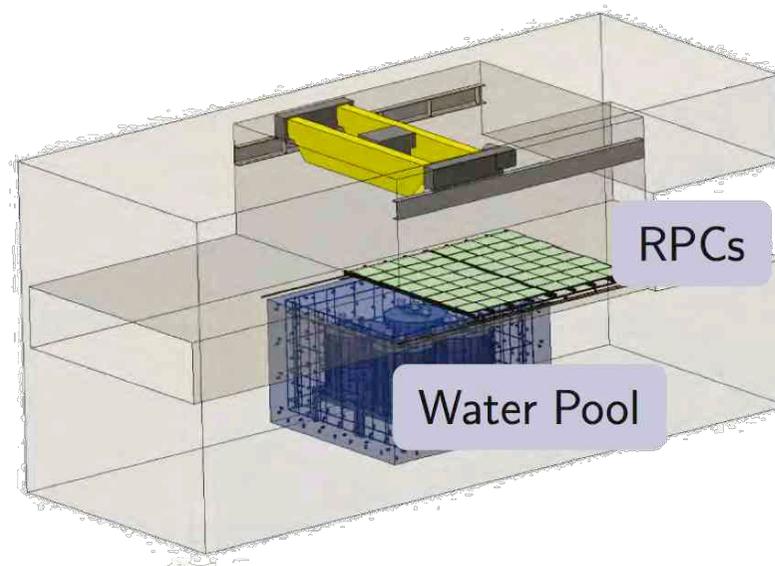
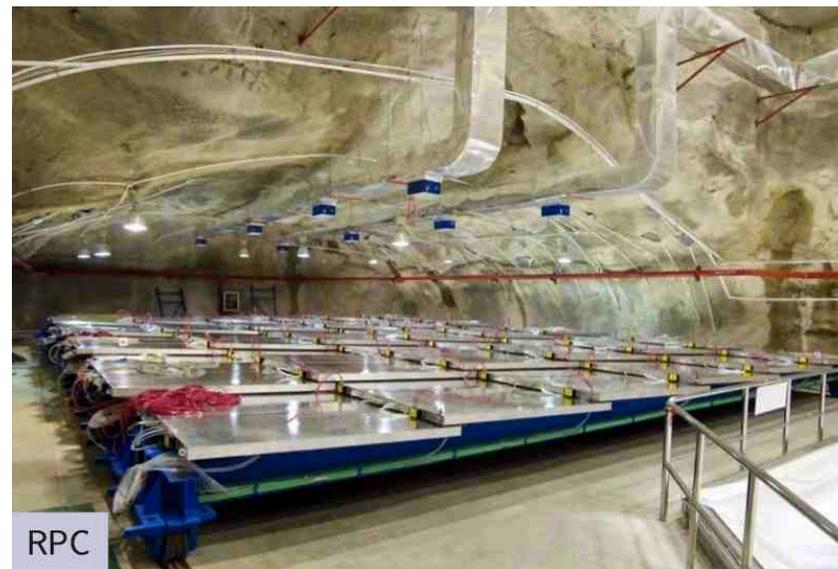
5 years, $\sin^2(2\theta_{13}) < 0.01$ (90% C.L.)



Status of Daya Bay Infrastructure

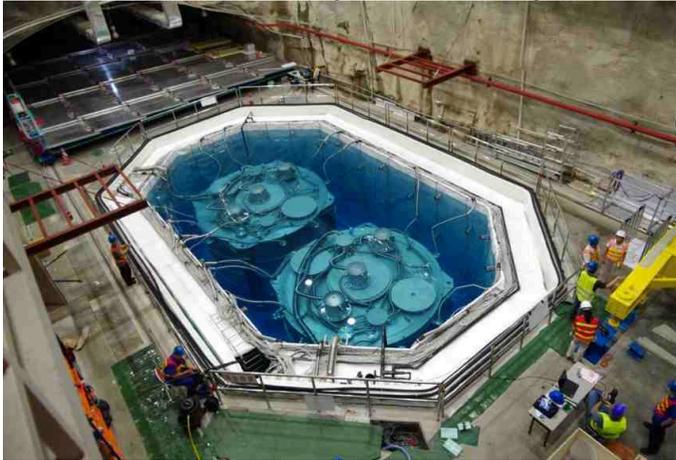


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Daya Bay Setup

Hall 1 (08/2011)



Hall 2 (11/2011)



Hall 3 (Dec. 24th 2011)



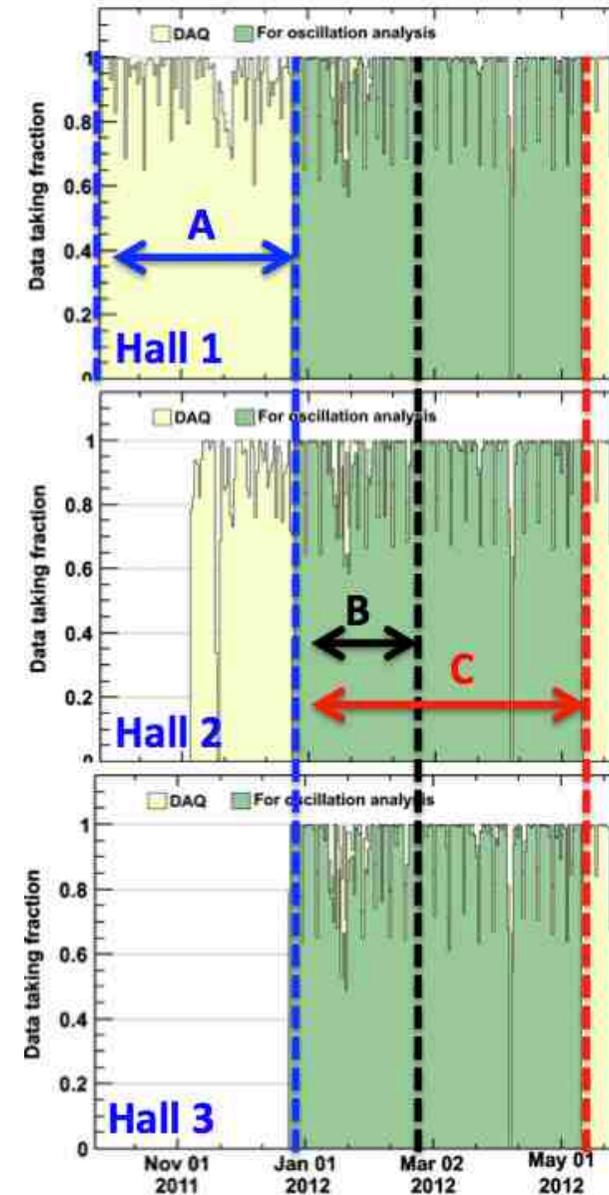
cea

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Daya Bay Oscillation Results



- **1st Result in March 2012**
All 3 halls (6 ADs) operating
Observation of ν_e disappearance
Phys. Rev. Lett. 108, 171803 (2012)
- **New Result at Neutrino 2012**
- **Data Taking**
Dec. 24, 2011 – May 11, 2012
Life Time \approx 127 days
Far: 75 int/day/det. (x3)
Near: 650 int/day/det (x3)
More than 2.5x previous data set



Daya Bay: Systematics

	Detector		
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

For near/far oscillation, only uncorrelated uncertainties are used.

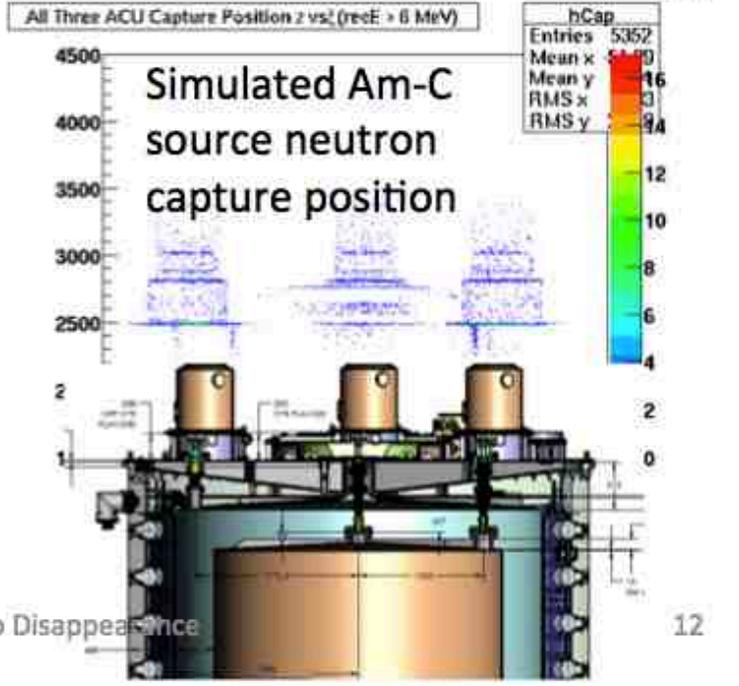
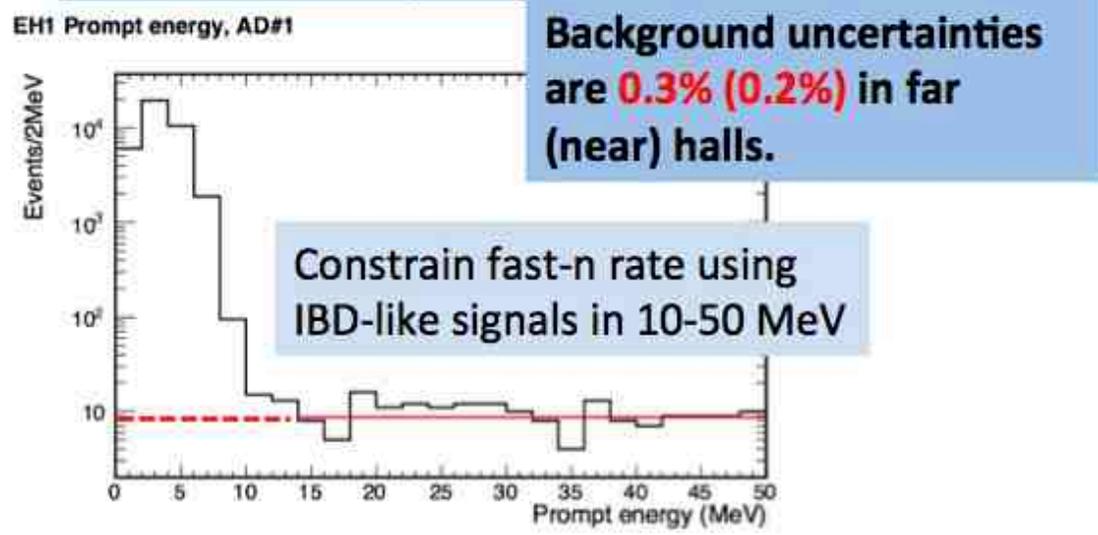
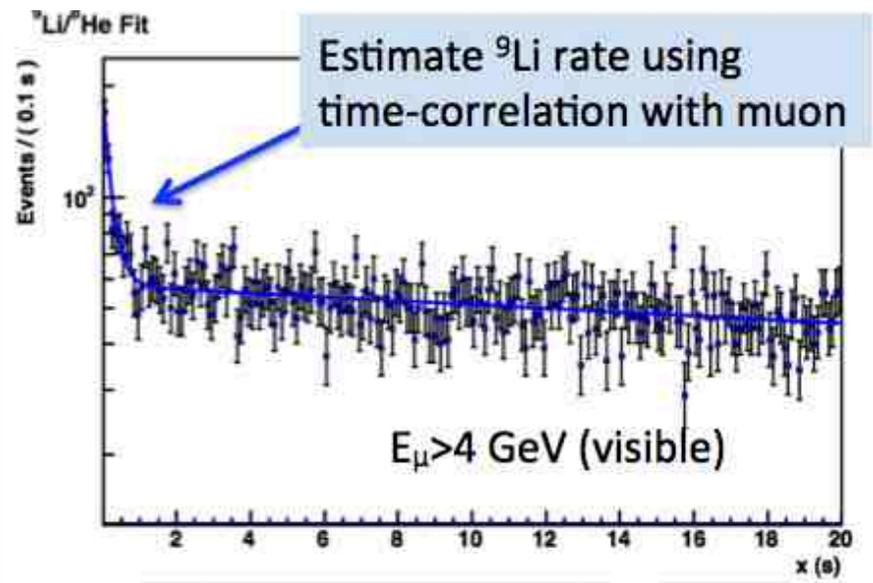
Largest systematics are smaller than far site statistics (~1%)

	Reactor	
	Correlated	Uncorrelated
Energy/fission	0.2%	Power 0.5%
$\bar{\nu}_e$ /fission	3%	Fission fraction 0.6%
		Spent fuel 0.3%
Combined	3%	Combined 0.8%

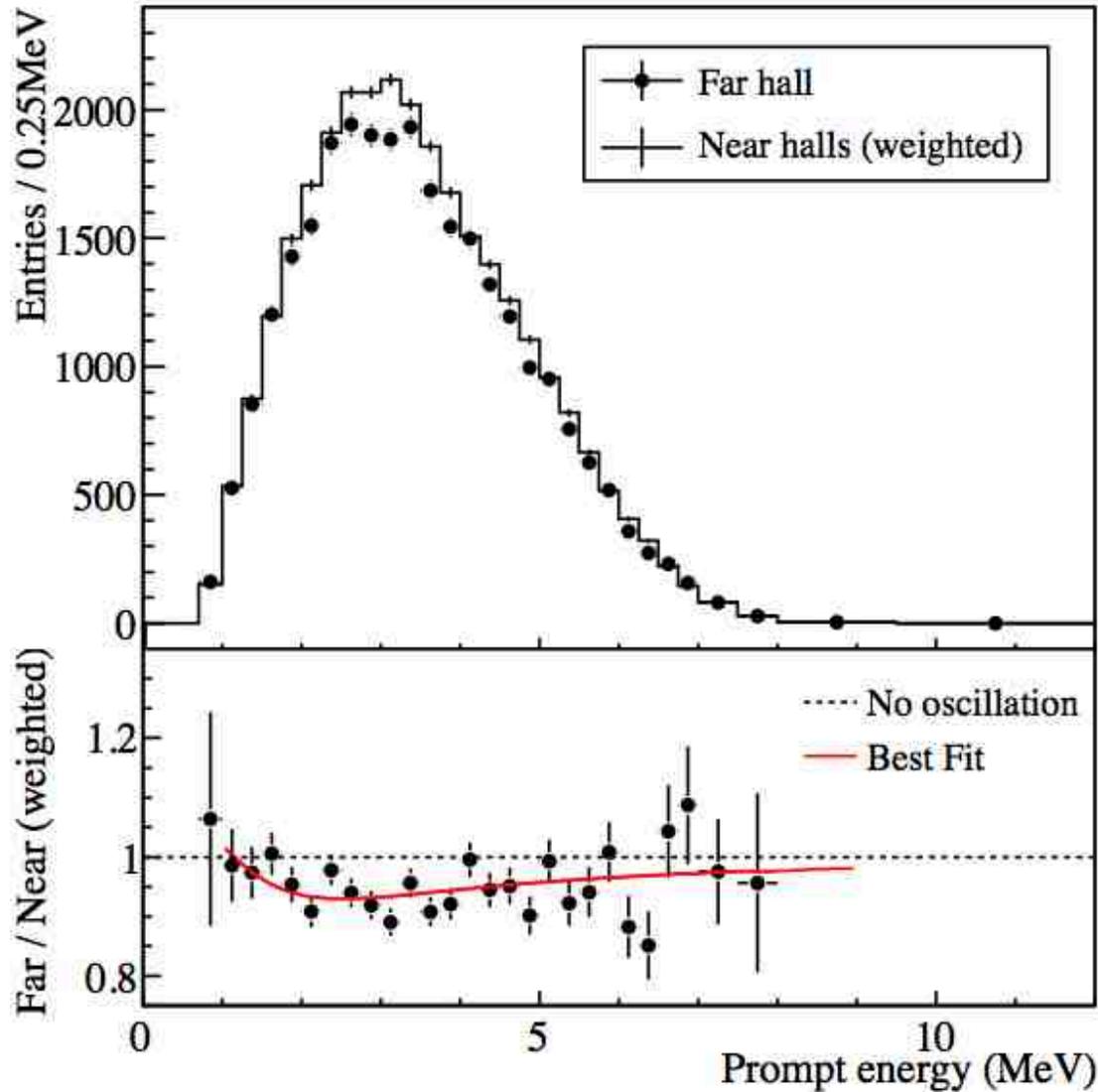
Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Daya Bay: Backgrounds

Total backgrounds are 5% (2%) in far (near) halls.	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
Fast neutrons	0.12	0.05	0.07	0.03
${}^9\text{Li}/{}^8\text{He}$	0.4	0.2	0.3	0.2
${}^{241}\text{Am}-{}^{13}\text{C}$	0.03	0.03	0.3	0.3
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	0.01	0.006	0.05	0.03



Daya Bay: Results



- Rate Only Analysis
- $\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)
- Very low systematic error
- Energy distortion is the imprint of neutrino oscillation. But spectral Shape not yet understood.
High statistics \rightarrow shape-only $\sin^2 2\theta_{13}$ must be consistent with the rate-only information

RENO

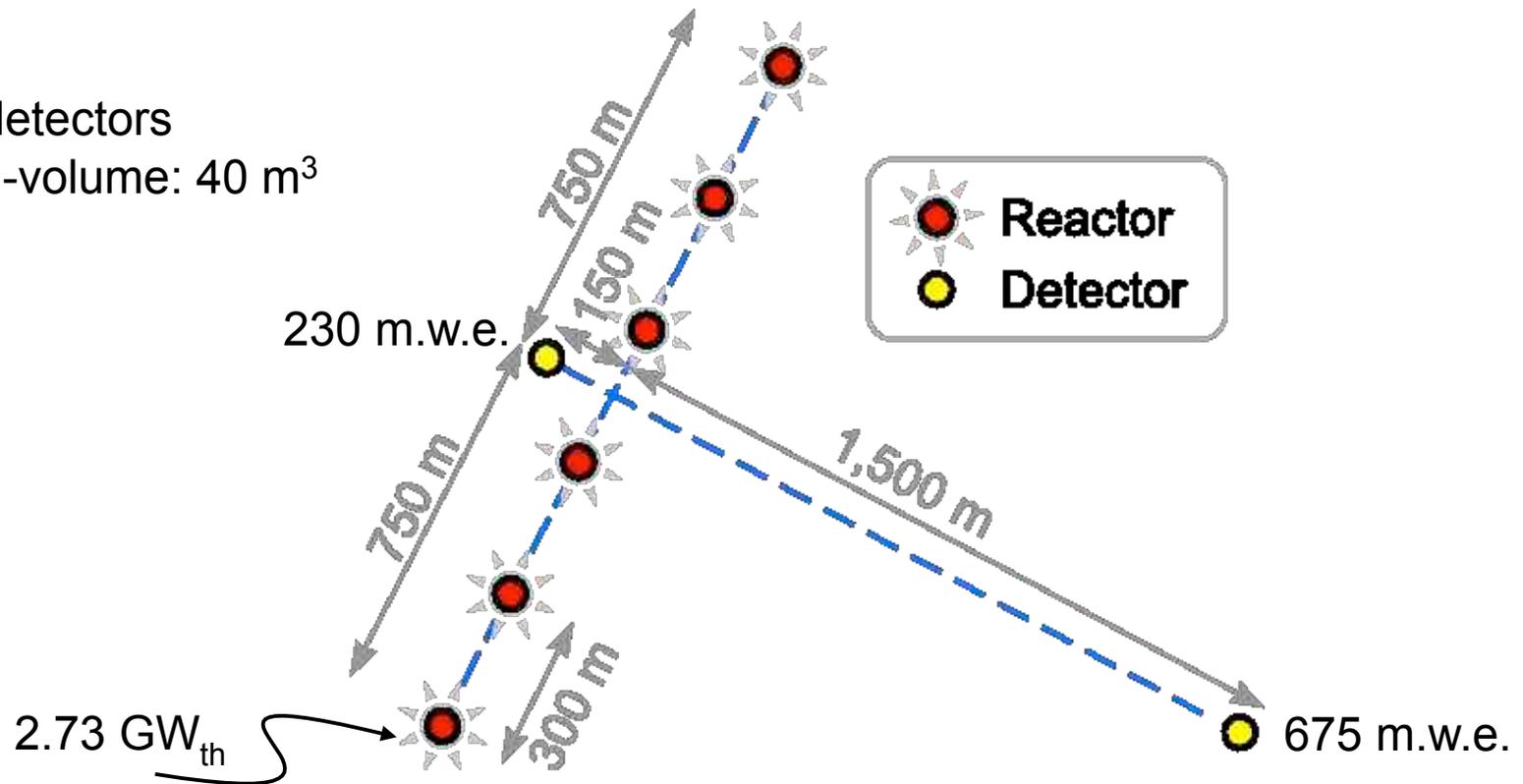
Yong gwang nuclear power station in Korea



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2 detectors

Gd-volume: 40 m³



RENO



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Collaboration

Korea – 40 people

Site: Youngwang

6 cores, 16 GW

Two 20 tons detectors

Near: 20 tons - 350 m – 200 mwe

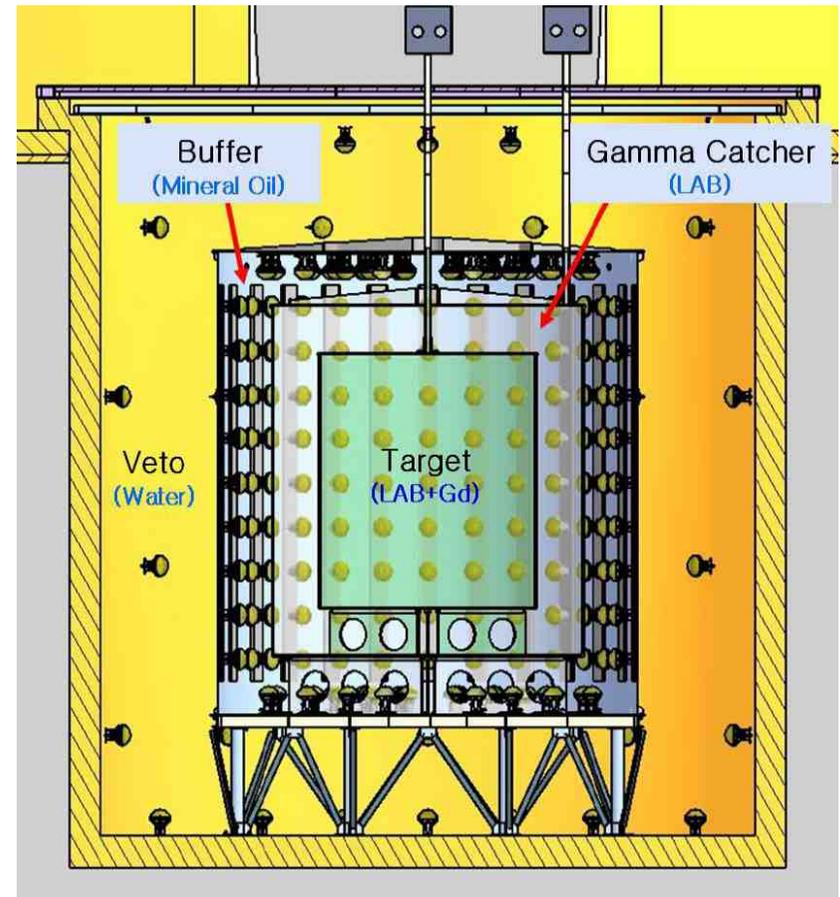
Far: 20 tons - 1.4 km - 700 mwe

Copy and Paste of Double Chooz

Sensitivity

0.45% systematic error

$\sin^2(2\theta_{13}) < 0.02$ (90% C.L.), 3 y



Civil engineering completed in 2009

(2008.6~2009.3)



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RENO Results



RENO Results April 3rd 2012

The RENO experiment has observed the disappearance of reactor electron antineutrinos, consistent with neutrino oscillations, with a significance of 6.3 standard deviations. Antineutrinos from six 2.8 GW_{th} reactors at Yonggwang Nuclear Power Plant in Korea, are detected by two identical detectors located at 294 m and 1383 m, respectively, from the reactor array center. In the 229 day data-taking period of 11 August 2011 to 26 March 2012, the far (near) detector observed 17102 (154088) electron antineutrino candidate events with a background fraction of 4.9% (2.7%). A ratio of observed to expected number of antineutrinos in the far detector is $0.922 \pm 0.010(\text{stat.}) \pm 0.008(\text{syst.})$. From the deficit, we find $\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$ based on a rate-only analysis.

RENO Results April 8th 2012

The RENO experiment has observed the disappearance of reactor electron antineutrinos, consistent with neutrino oscillations, with a significance of 4.9 standard deviations. Antineutrinos from six 2.8 GW_{th} reactors at the Yonggwang Nuclear Power Plant in Korea, are detected by two identical detectors located at 294 m and 1383 m, respectively, from the reactor array center. In the 229 day data-taking period between 11 August 2011 and 26 March 2012, the far (near) detector observed 17102 (154088) electron antineutrino candidate events with a background fraction of 5.5% (2.7%). The ratio of observed to expected numbers of antineutrinos in the far detector is $0.920 \pm 0.009(\text{stat.}) \pm 0.014(\text{syst.})$. From this deficit, we determine $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$ based on a rate-only analysis.

RENO: Systematics & Backgrounds



Detector	Near	Far
Selected events	154088	17102
Total background rate (per day)	21.81 ± 6.67	3.77 ± 0.52
IBD rate after background subtraction (per day)	778.99 ± 6.96	73.25 ± 0.79
DAQ Live time (days)	192.42	222.06
Detection efficiency (ϵ)	0.647 ± 0.014	0.745 ± 0.014
Accidental rate (per day)	4.30 ± 0.06	0.68 ± 0.03
${}^9\text{Li}/{}^8\text{He}$ rate (per day)	12.51 ± 6.67	2.12 ± 0.52
Fast neutron rate (per day)	5.00 ± 0.13	0.97 ± 0.06

RENO results April 3rd 2012

Detector	Near	Far
Selected events	154088	17102
Total background rate (per day)	21.75 ± 5.93	4.24 ± 0.75
IBD rate after background subtraction (per day)	779.05 ± 6.26	72.78 ± 0.95
DAQ Live time (days)	192.42	222.06
Detection efficiency (ϵ)	0.647 ± 0.014	0.745 ± 0.014
Accidental rate (per day)	4.30 ± 0.06	0.68 ± 0.03
${}^9\text{Li}/{}^8\text{He}$ rate (per day)	12.45 ± 5.93	2.59 ± 0.75
Fast neutron rate (per day)	5.00 ± 0.13	0.97 ± 0.06

RENO results April 8th 2012

${}^9\text{Li}$ decrease in Near Det, error decrease (12%)
 ${}^9\text{Li}$ increase in Far Det, error increase (50%)

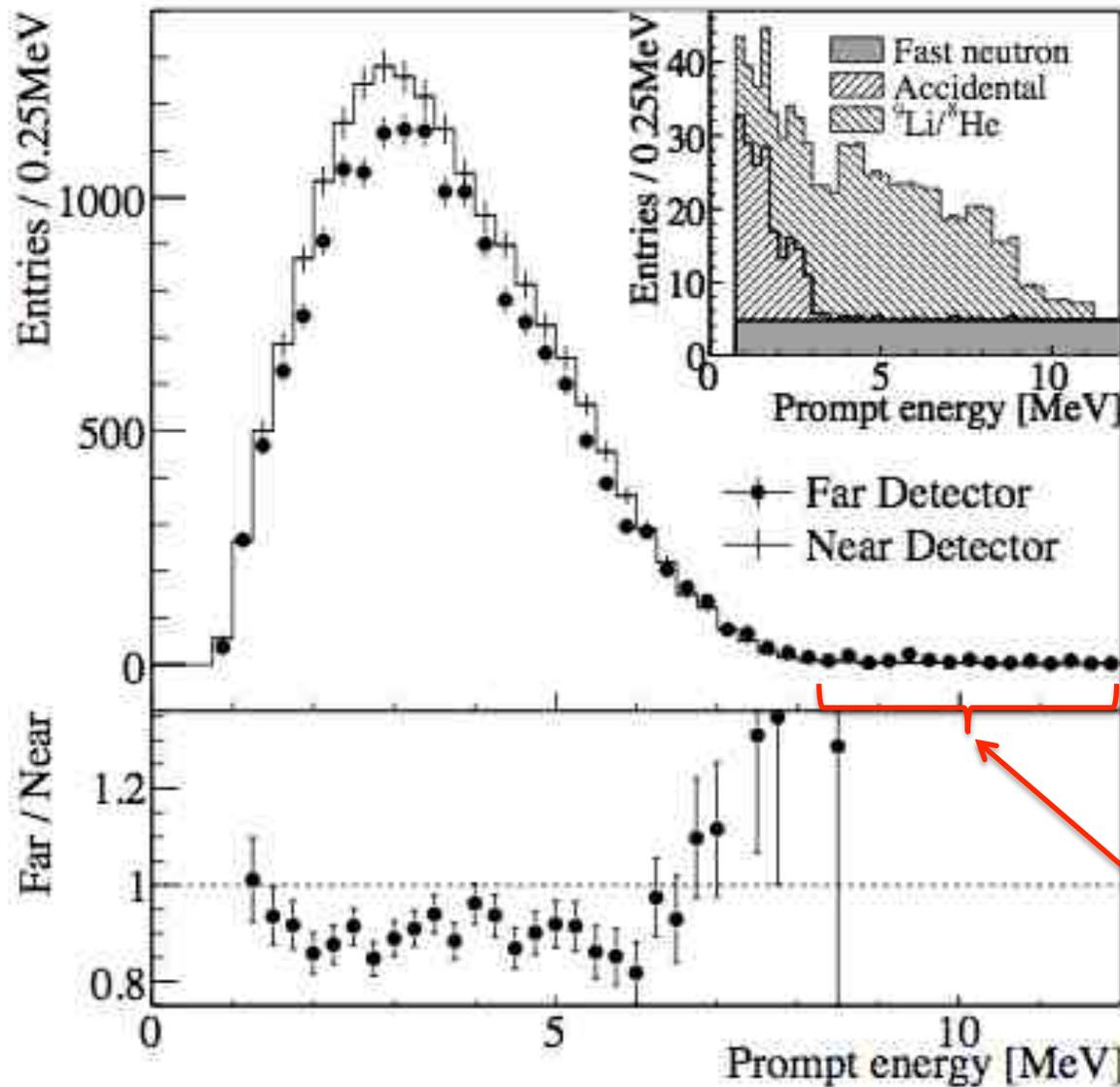
RENO Systematics



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Reactor		
	Uncorrelated	Correlated
Thermal power	0.5%	—
Fission fraction	0.7%	—
Fission reaction cross section	—	1.9%
Reference energy spectra	—	0.5%
Energy per fission	—	0.2%
Combined	0.9%	2.0%
Detection		
	Uncorrelated	Correlated
IBD cross section	—	0.2%
Target protons	0.1%	0.5%
Prompt energy cut	0.01%	0.1%
Flasher cut	0.01%	0.1%
Gd capture ratio	0.1%	0.7%
Delayed energy cut	0.1%	0.5%
Time coincidence cut	0.01%	0.5%
Spill-in	0.03%	1.0%
Muon veto cut	0.02%	0.02%
Multiplicity cut	0.04%	0.06%
Combined (total)	0.2%	1.5%

RENO Results



$$R = 0.920$$
$$\pm 0.009(\text{stat})$$
$$\pm 0.014(\text{syst})$$

$$\sin^2 2\theta_{13} = 0.113$$
$$\pm 0.013(\text{stat.})$$
$$\pm 0.019(\text{syst.})$$

used in the rate analysis

Attempt understanding RENO data



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- **Recover independently Near and Far data**
 - Background subtracted data from 8 to 12 MeV
 - Recover <0.15% of expected neutrino flux...
 - **RENO ratio weighted average between 1 and 6 MeV :**
 $R=0.9071 \pm 0.0178$
 - Find similar results as for analysis of the published ratio in Fig 4 lower pad
 - Would imply **$\sin^2(2\theta_{13})=0.135$**
 - **Correct $\sin^2(2\theta_{13})$ taken from the RENO data?**
 - **RENO ratio weighted average between 1 and 12 MeV :**
 $R=0.9190 \pm 0.0177$
 - Find similar ratio R as published in arXiv:1203.0626v2...
 - Transformation to oscillation constraint leads to **$\sin^2(2\theta_{13})=0.115$**
 - Including ratio of data points between 8-12 MeV change the $\sin^2(2\theta_{13})$ value by 20% - pathologic...
-

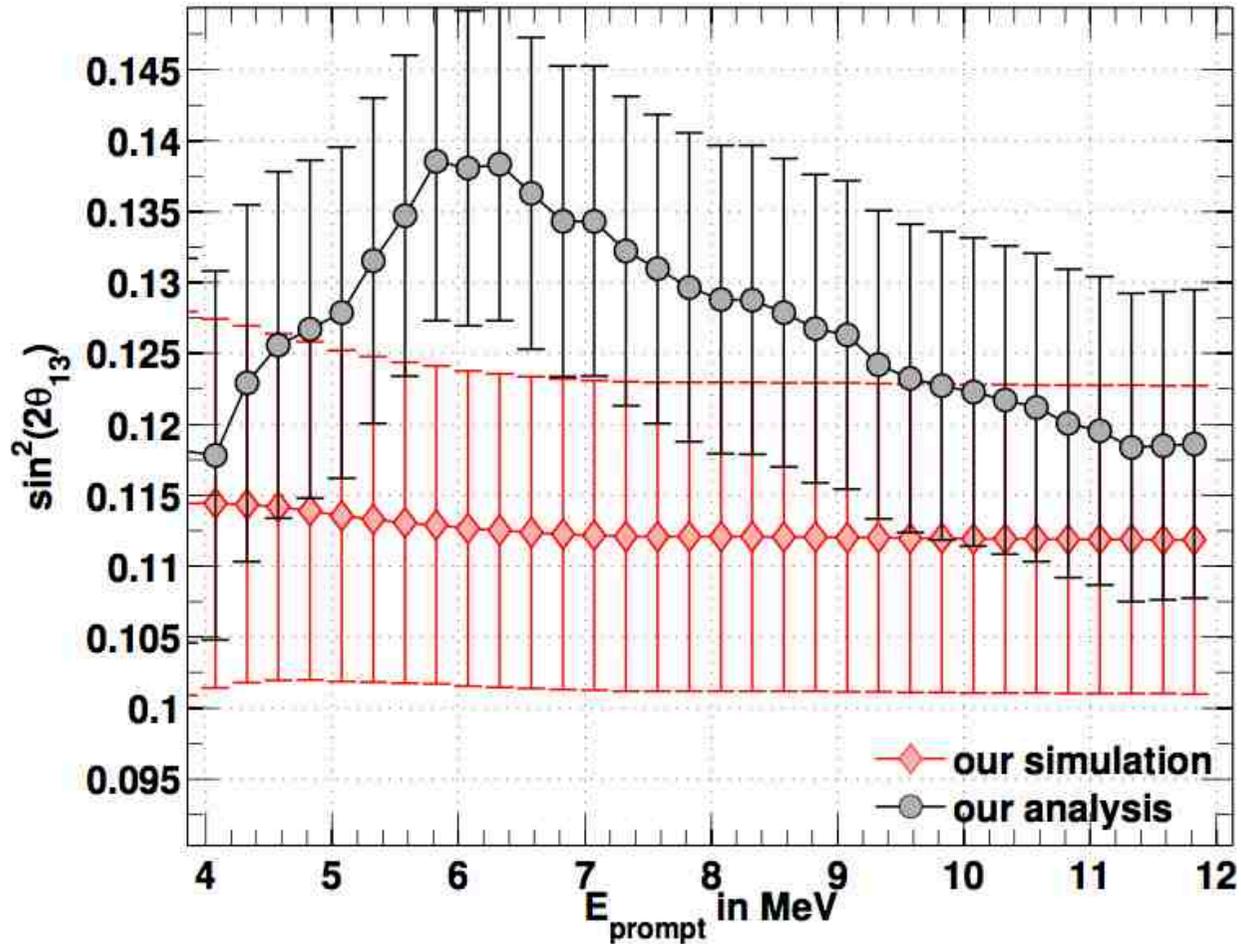
Comment on RENO Results



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$$\delta(E_{\text{high}}) = \frac{\int_{1\text{MeV}}^{E_{\text{high}}} S(E)(1 - P_{\text{survival}}(E_{\nu}(E)))dE}{\int_{1\text{MeV}}^{E_{\text{high}}} S(E)dE}$$

E_{high} (MeV)	3	4	5	6	8
$\delta(E_{\text{high}})/\delta(E_{12\text{MeV}})$	0.495	0.782	0.926	0.981	0.9997

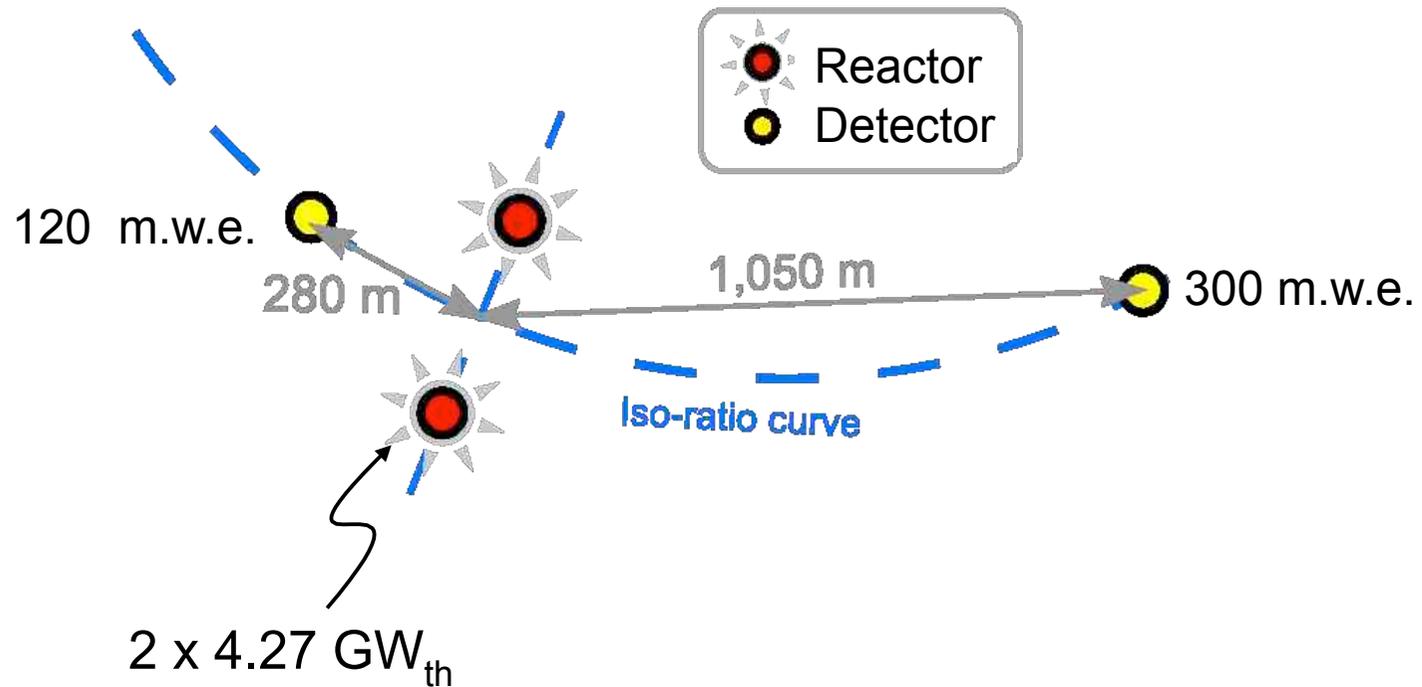


Double Chooz



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Dedicated talk of V. Durand on the last results



Double Chooz collaboration



Brazil

CBPF
UNICAMP
UFABC



France

APC
CEA/DSM/
IRFU:
SPP
SPhN
SEDI
SIS
LENAC
CNRS/IN2P3:
Subatech
IPHC
ULB/VUB



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



UK

Sussex



USA

U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National
Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)

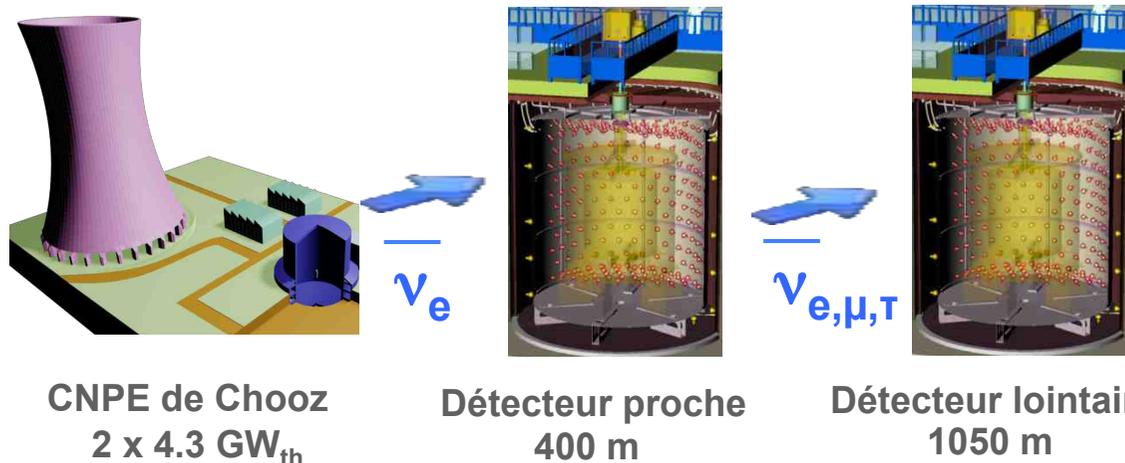
Project Manager: Ch. Veyssière (CEA-Saclay)

Analysis coordinator: Th. Lasserre (CEA-Saclay)



Web Site: www.doublechooz.org/

Double Chooz: Concept & historique



2002 : Lancement du projet

2003 : Conception du détecteur et choix du site de Chooz

2004 : Conseils scientifiques (CEA & CNRS)

2004 : Lettre d'intention

2006 : Proposal de l'expérience

2007: TDR, les détecteurs sont financés à 80%.

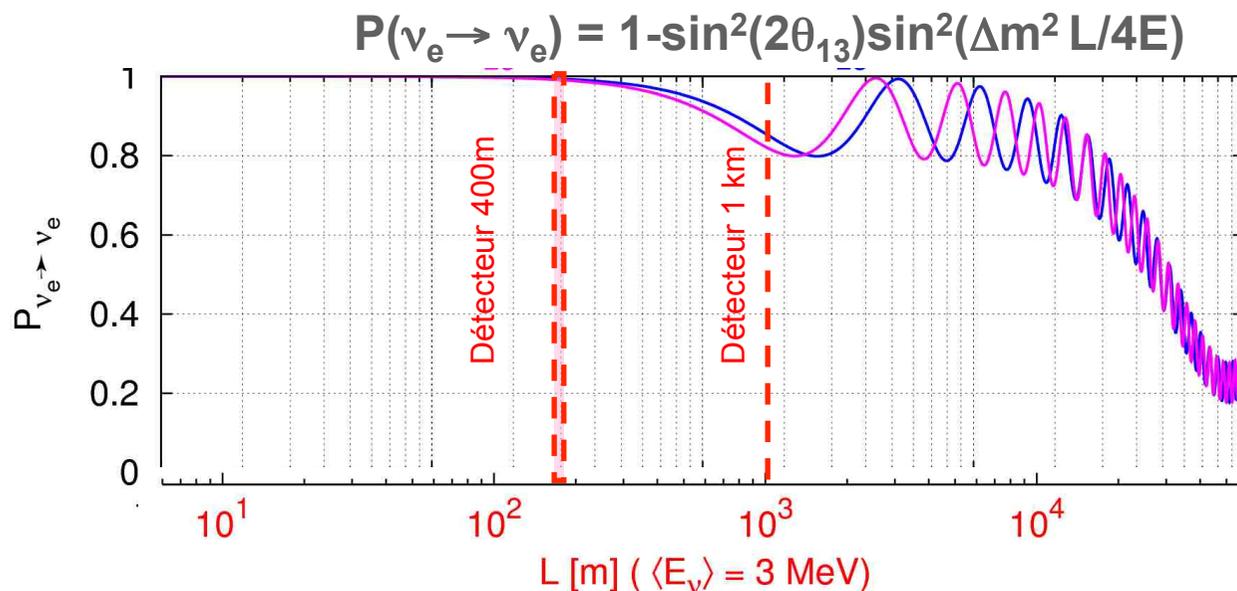
2008 : Début de l'intégration.

2009: Accord CEA/CNRS/EDF/Région

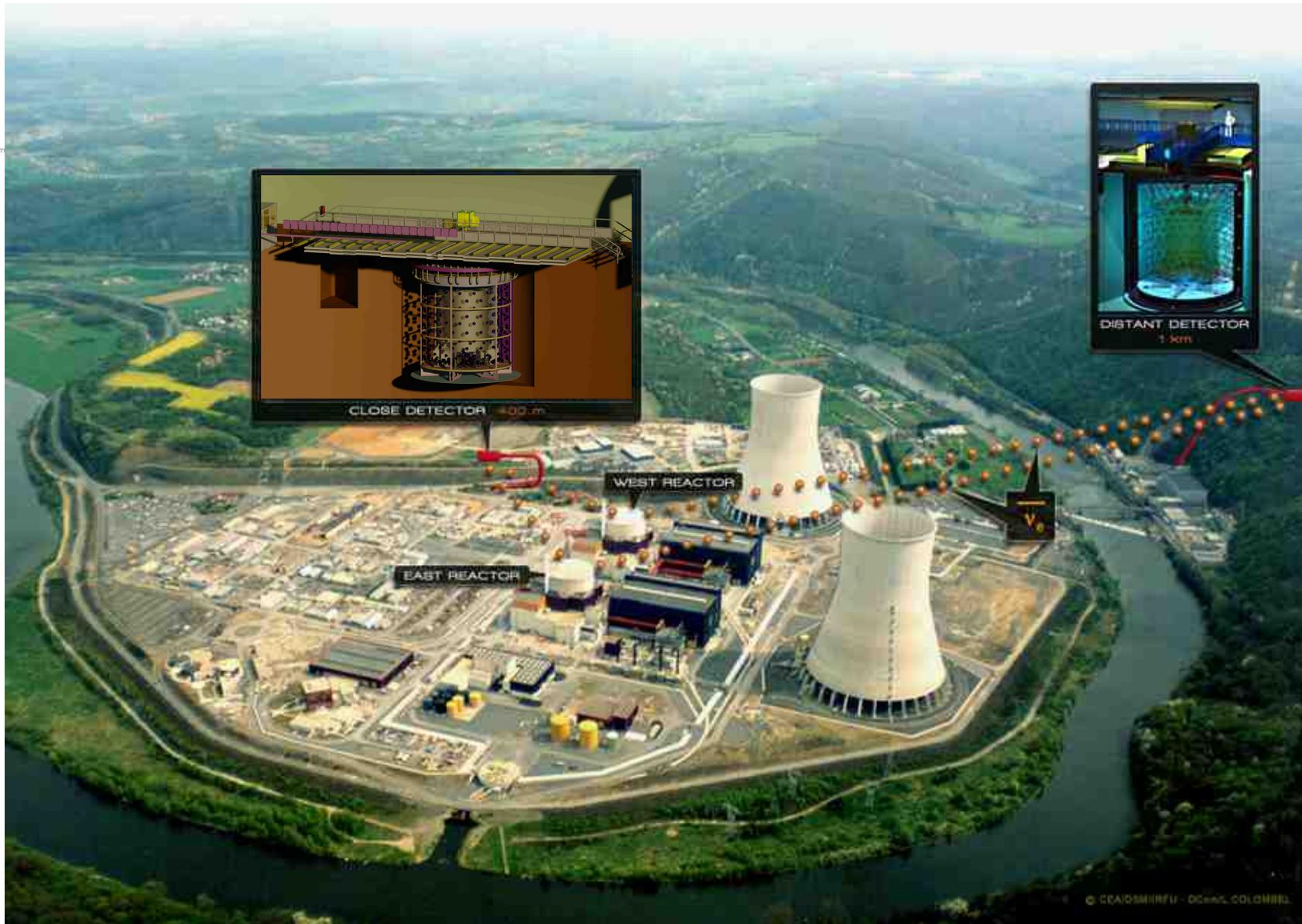
2010: Début de la prise de données

2011: Première expérience 'réacteur' de 2^{ème} génération à fournir des résultats sur θ_{13}

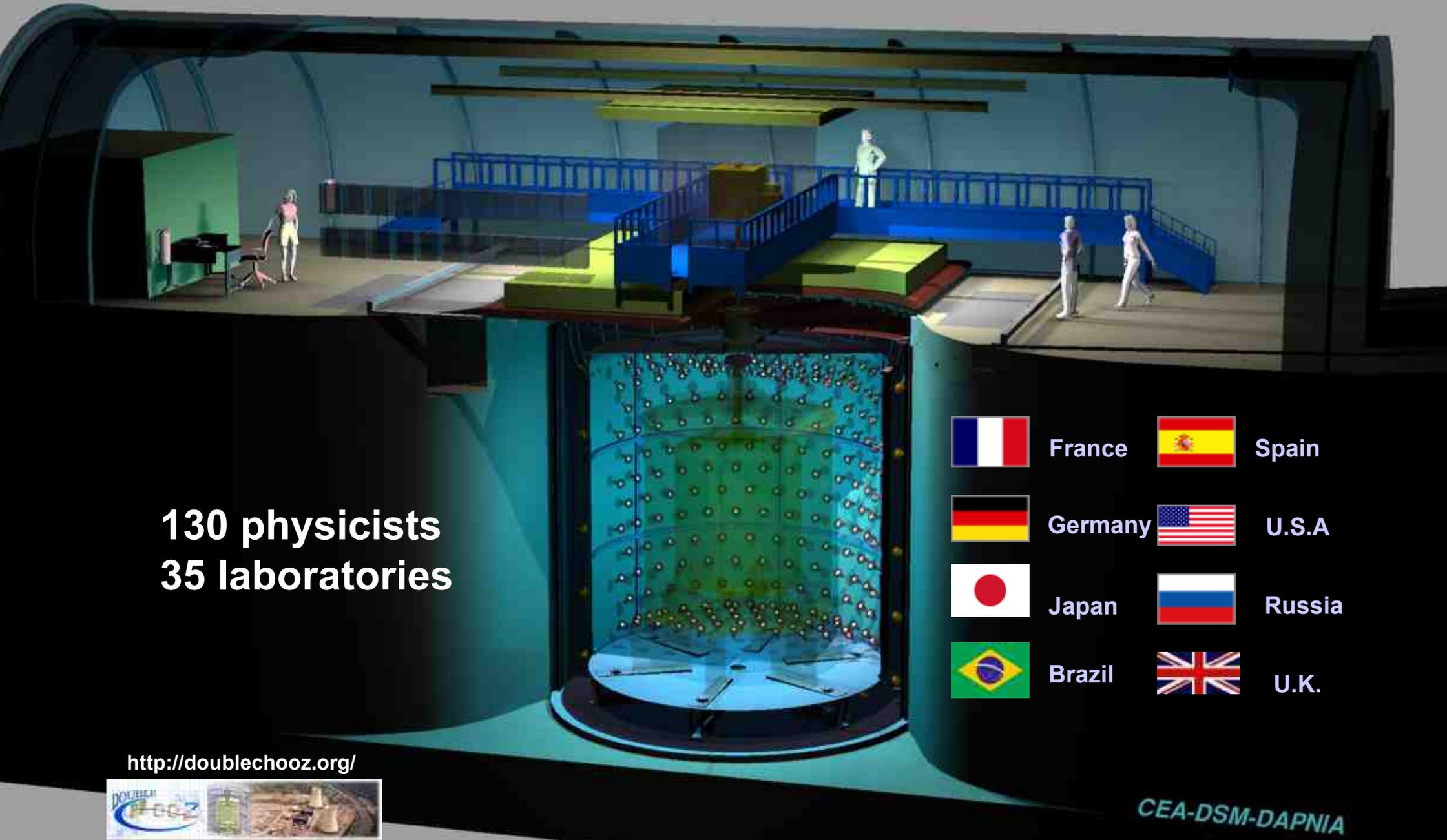
2012: Mesure de θ_{13} (3σ)



Double Chooz Sites (France)



Double Chooz



130 physicists
35 laboratories

- | | | | |
|---|---------|---|--------|
|  | France |  | Spain |
|  | Germany |  | U.S.A |
|  | Japan |  | Russia |
|  | Brazil |  | U.K. |

<http://doublechooz.org/>

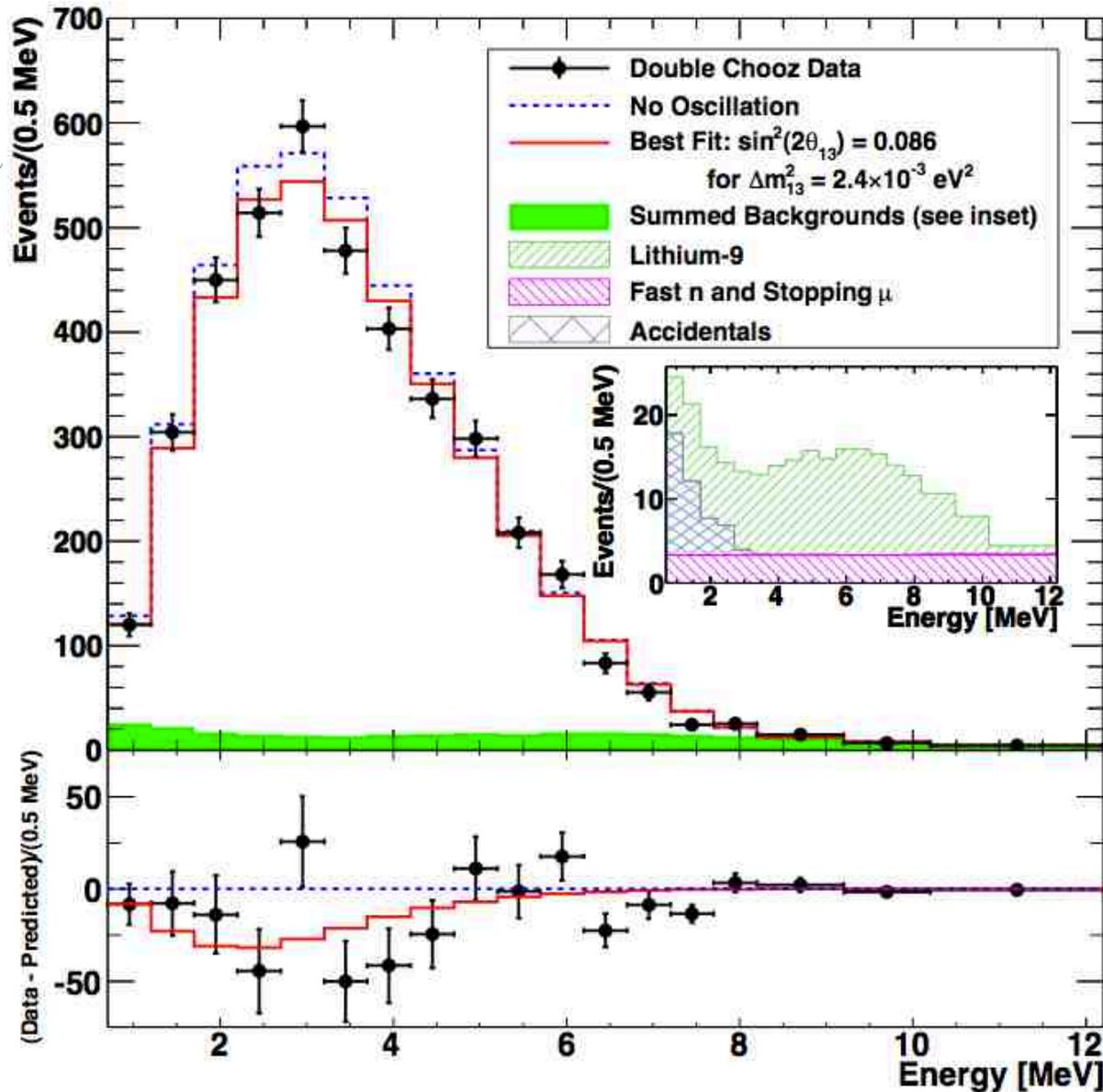


CEA-DSM-DAPNIA



Challenging “4-layer vessel” detector concept, invented by Double Chooz in 2002 has proved to be possible

First Results (11/2011)



Data Taking Starts
on April 18th 2011

101 days of data

Blind Analysis

Rate & Shape

Analysis:

$\sin^2(2\theta_{13}) =$
0.086

+/- 0.029 (stat)

+/- 0.042 (syst)

No-Oscillation

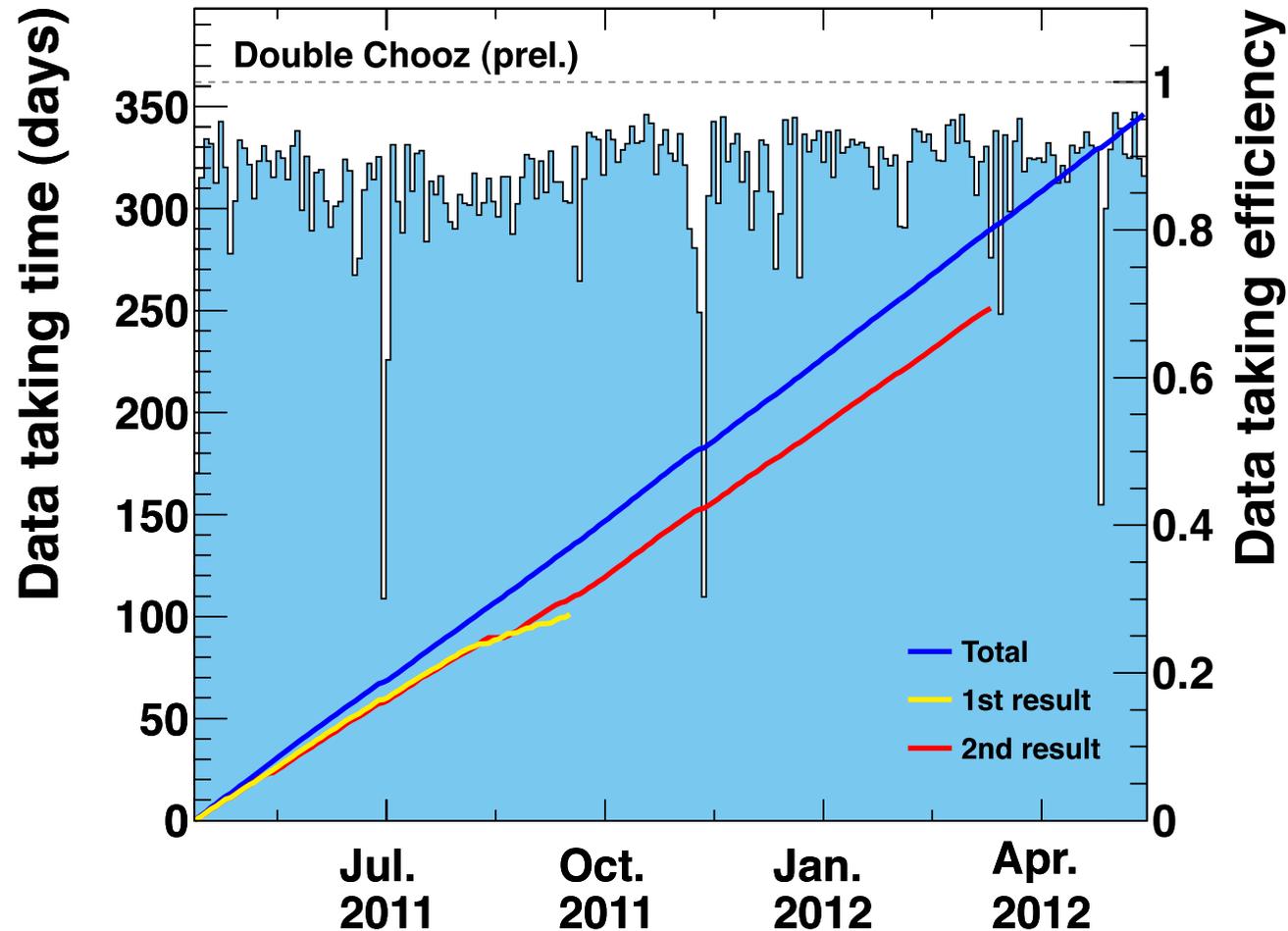
Excluded at

92.9 %

Stable Data Taking since April 13th 2011



- New result with 227.9 days live time (previous with 101 days)



- 8249 neutrino candidates (Improved analysis → see V. Durand's talk)

No-Oscillation Neutrino Rate/Spectrum Prediction



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Reactor neutrino flux calculation



Inverse β decay reaction (whole volume)



Detector simulation (Geant4 base)



Readout and trigger simulation

Neutrino yield per fission

$$N_v^{\text{exp}}(E, t) = \frac{N_p \varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

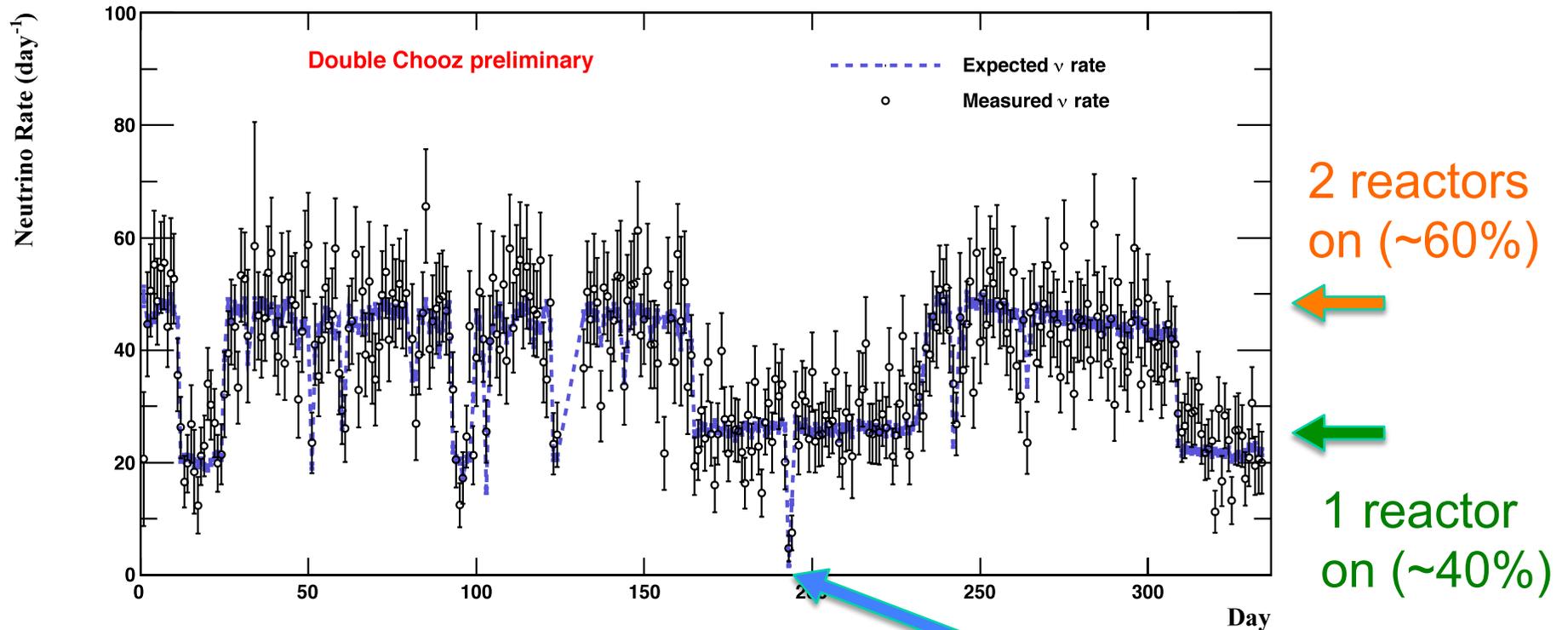
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{\text{Bugey}} + \sum_k \left(\alpha_k^{\text{DC}}(t) - \alpha_k^{\text{Bugey}} \right) \langle \sigma_f \rangle_k$$

Bugey4 measurement as anchor point

Fission fraction in CHOOZ core

- Result decoupled from the reactor antineutrino anomaly
- Uncertainty on neutrino flux suppressed using Bugey4 measurement: 2.7% \rightarrow 1.8%

Neutrino candidates: time variation



- Background not subtracted
- Neutrino rate consistent with expectation

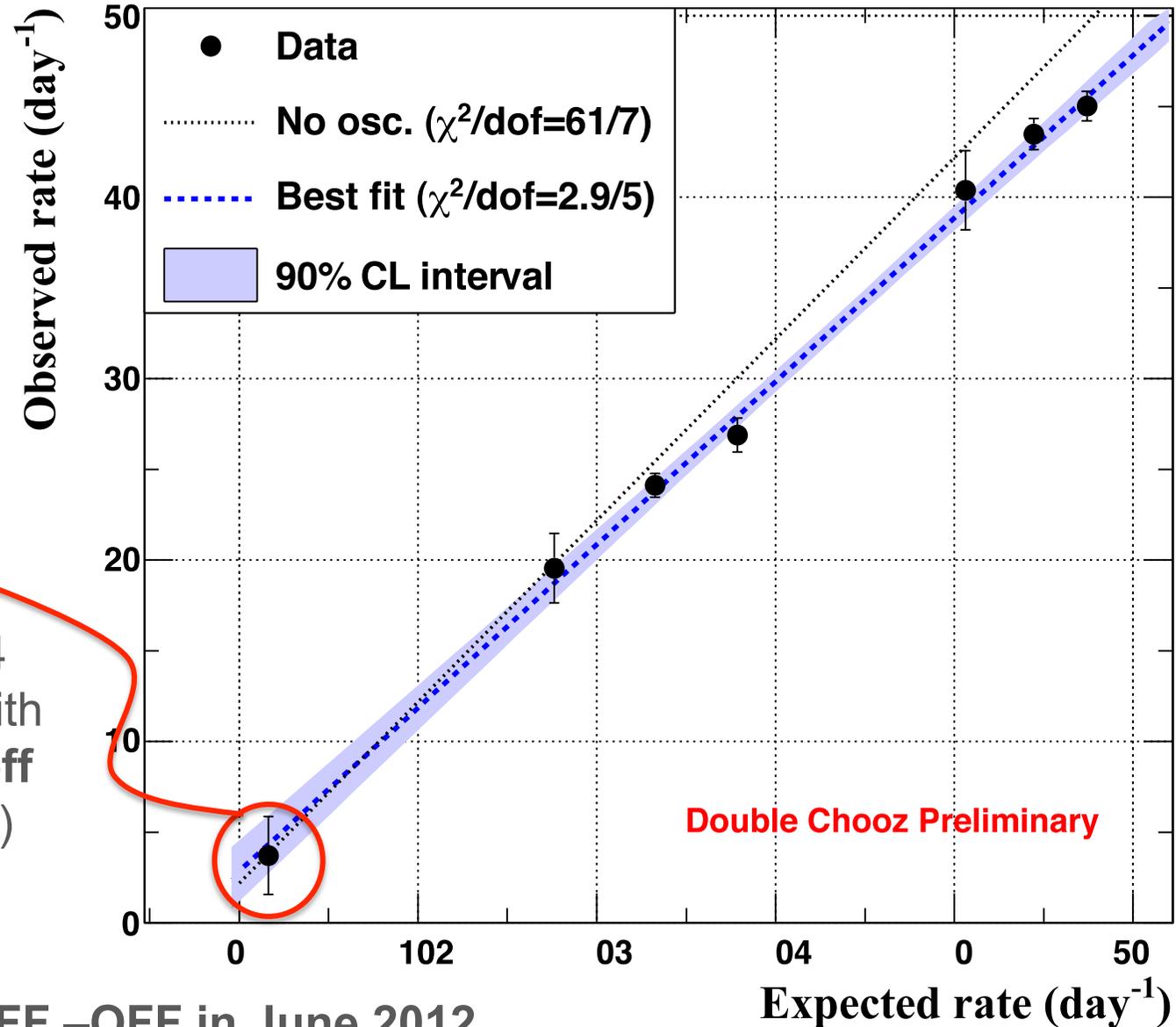
Systematic uncertainties on rate



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Source		Uncertainty w.r.t. signal (previous analysis)	
Statistics		1.1% (1.6%)	
Flux		1.7%	
Detector	Energy response	0.3% (1.7%)	1.0% (2.1%)
	E_{delay} containment	0.7%	
	Gd fraction	0.3%	
	Δt cut	0.5%	
	Spill in/out	0.3%	
	Trigger efficiency	<0.1%	
	Target H	0.3%	
Background	Accidental	<0.1%	1.6% (3.0%)
	Fast neutron + stop μ	0.5% (0.9%)	
	${}^9\text{Li}$	1.4% (2.8%)	

Reactor Off-Off Background Meas.



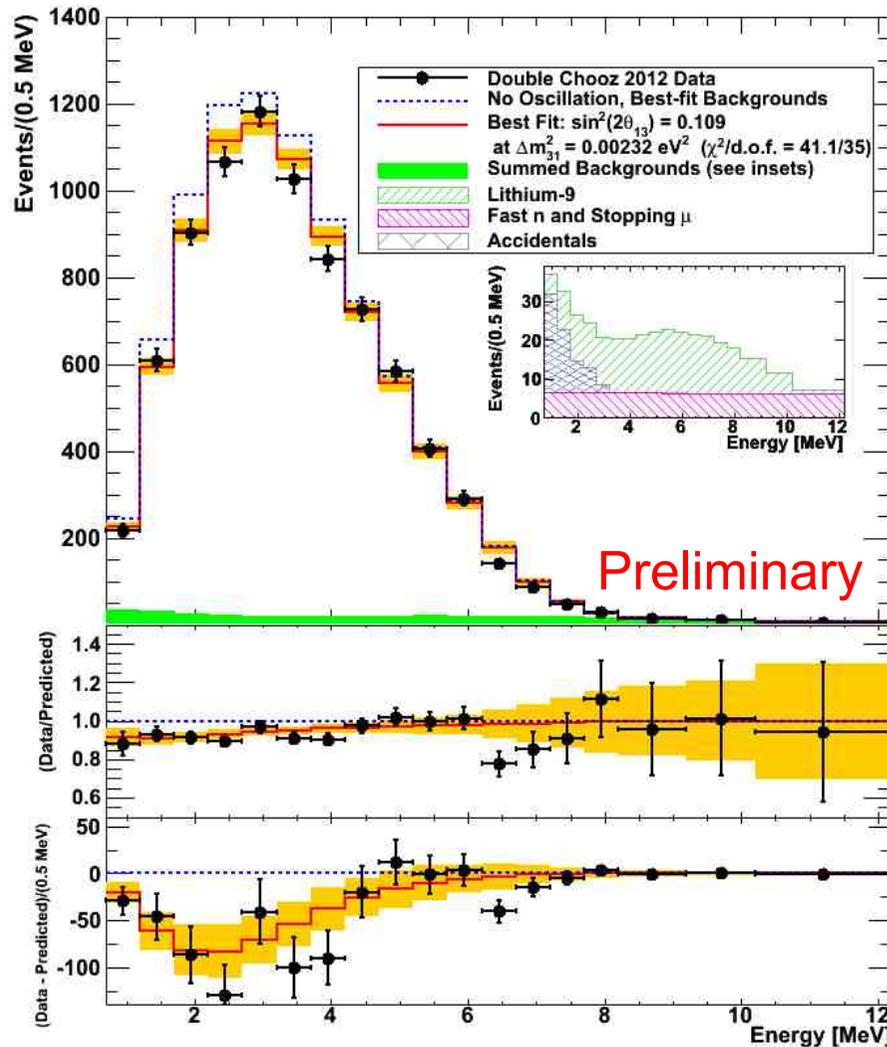
NEW: 7 days OFF –OFF in June 2012

Double Chooz new results



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$\sin^2 2\theta_{13} = 0$ is excluded at 99.9% (3.1σ) (frequentist study)



Rate only:
 $\sin^2 2\theta_{13} = 0.170$
 $\pm 0.035(\text{stat})$
 $\pm 0.040(\text{syst})$

Rate+Shape:
 $\sin^2 2\theta_{13} = 0.109$
 $\pm 0.030(\text{stat})$
 $\pm 0.025(\text{syst})$

(background further constrained by the fit)

Double Chooz future projects



- **Precise measurement of θ_{13}**
 - Essential for future projects – CP violation, mass hierarchy. No add. dedicated measurement planned
 - Test unitarity of mixing matrix – sterile neutrino admixture ?

- **Other physics possibilities**
 - n-H capture event analysis (Improve statistics)
 - Neutrino directionality study
 - ${}^9\text{Li}$ production from muon capture
 - Reactor Off-Off background measurement
 - Constraint to $|\Delta m_{31}^2|$
 - Reactor complementarities with different baselines

Prospects with the Near Detector



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- Near detector laboratory excavation completed
- Start data taking by 2014



Experimental Comments



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▪ Daya Bay

- Cons: 9 baselines / 6 nuclear cores – No PMT on top/bottom lids
- Pros: 160 tons of active volume, opt. baseline, corr. bkg

▪ RENO

- Cons: Near/Far asymmetric configuration, accidental bkg, calibration?
- Pros: Quick civil construction

▪ Double Chooz

- Cons: Shorter baseline - Late
- Pros: 2 cores → reactor off-off, calibration, accidental bkg, E spectrum

▪ New 4-region large detector concept similar for all experiments

DC conceptual design adopted by Daya Bay and RENO But:

Double Chooz syst: 0.6%
Already ACHIEVED

RENO sys:0.45%
0.2%

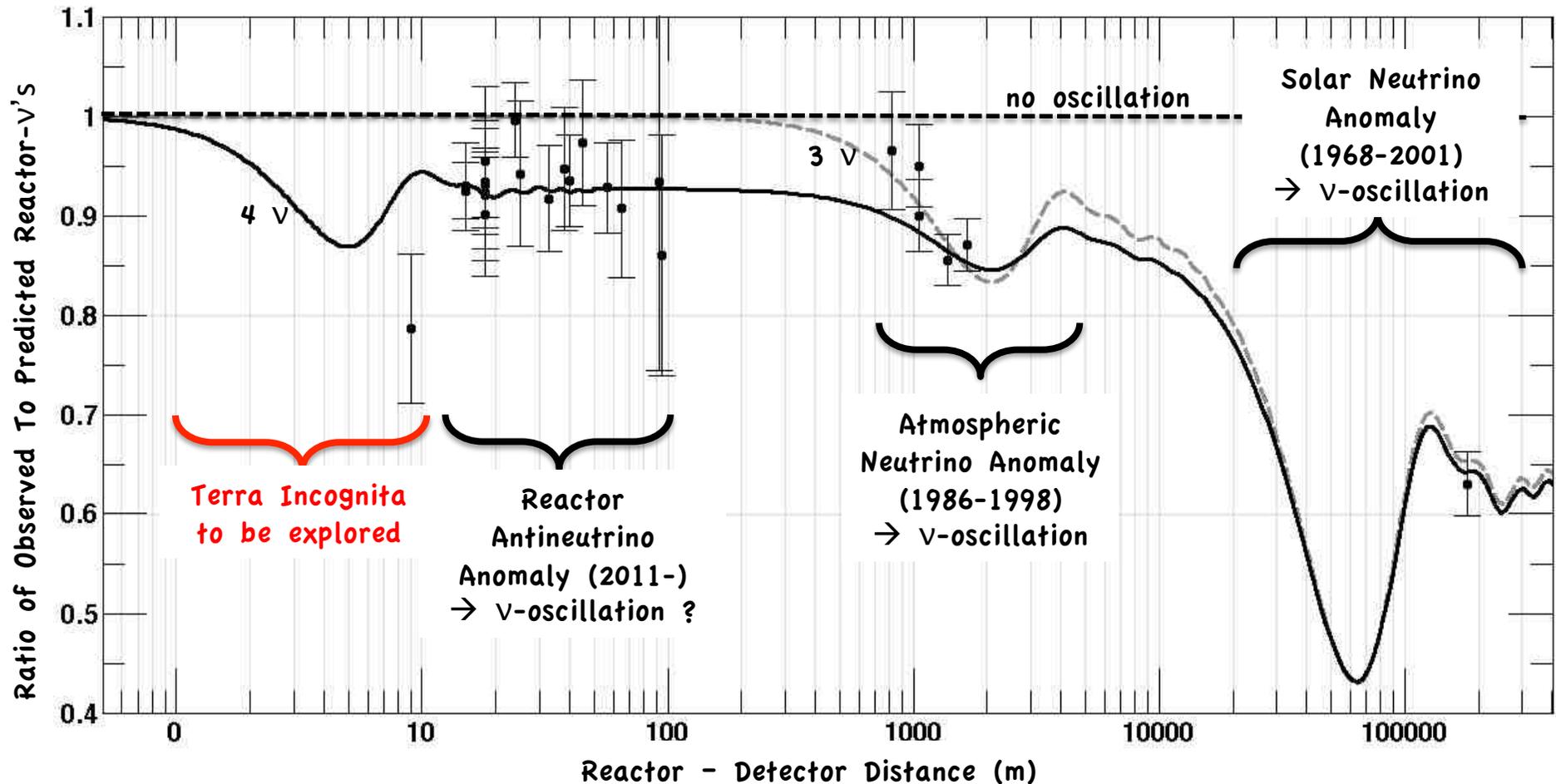
Daya Bay sys: 0.38%
0.2%

Impact of the Reactor Anomaly



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- Reevaluation of reactor ν_e flux & spectra
- Reanalysis of past reactor- ν_e experiments
→ Reactor Antineutrino Anomaly (3σ)



Implication of the Reactor Anomaly for θ_{13}

- Double Chooz normalize its ν -flux expectation to Bugey-4 (15m)
→ Absolute measurement

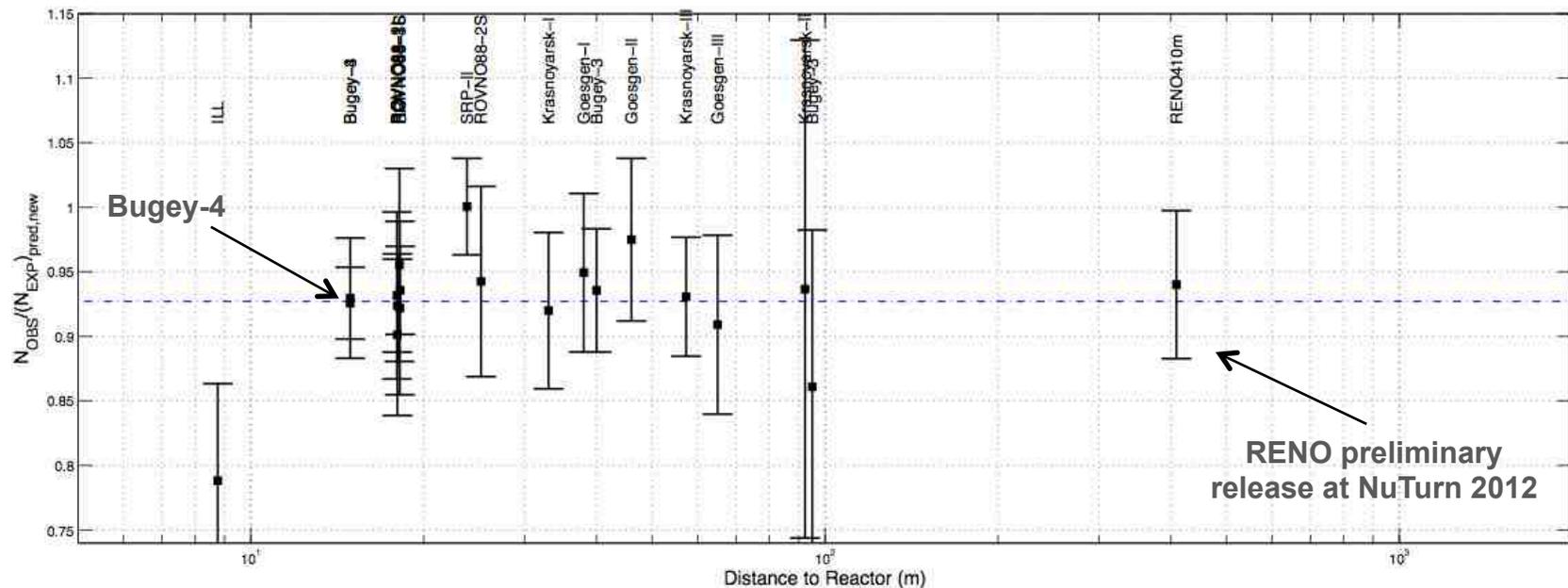


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- RENO & Daya Bay fit both far and near rate with a free ν -flux normalization

→ **Double Chooz & RENO/Daya Bay are not yet strictly comparable**

→ Need to check if RENO/Daya Bay cross section per fission measured at their near sites is consistent with Bugey-4



Conclusion on θ_{13} determination

Double Chooz

Daya Bay

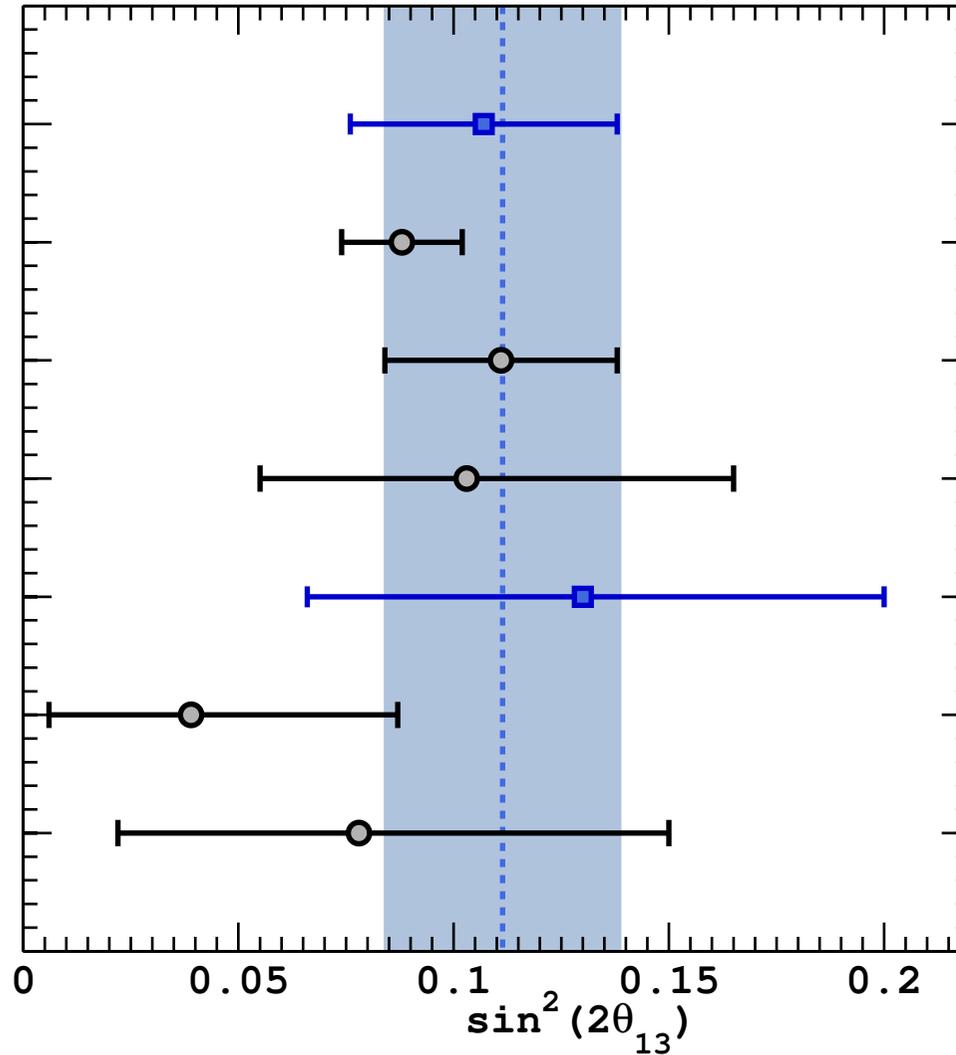
RENO

T2K NH

T2K IH

Minos NH

Minos IH



Impact of the measurement of θ_{13}



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- **Experimental Sectors Impacted**
 - Solar Neutrinos
 - Atmospheric Neutrinos
 - Dominant factor for Supernovae neutrinos
 - Neutrinoless Double Beta Decay

 - **Theoretical implication for the understanding of the underlying theory of neutrino masses**

 - **Door towards the determination of the neutrino mass hierarchy and the measurement of the lepton CP phase**

 - **Need precise and reliable measurement of θ_{13}**
 - Most precise measurement with middle baseline reactor experiments (Daya Bay, Double Chooz, RENO). No more...
 - Complementarily with accelerator based experiments (T2K, Nova)
-

Impact of large θ_{13}



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- **For the first time we know all the three lepton mixing angle**
 - $\theta_{12} = 34^\circ$
 - $\theta_{23} = 45^\circ$
 - $\theta_{13} \approx 9^\circ \rightarrow$ no need to run for small θ_{13} !
 - **Next Step for completing the three neutrino mixing framework**
 - Determination of the mass hierarchy
 - Measurement of the lepton CP phase
 - **Large θ_{13} offer good prospects for the determination of the neutrino mass hierarchy (10-20 year time scale?)**
 - **BUT large θ_{13} does not guarantee that CP measurement will be easier... (20-more year time scale?)**
 - **Determination of the neutrino mass hierarchy and leptonic CP phase may or may not done with the same experiment?**
-

Towards the Mass hierarchy



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- **Large θ_{13} opens the door to a variety of experimental programs towards the determination of the neutrino mass hierarchy**
 - **Matter Effects on θ_{13} mixing**
 - Supernovae Neutrinos
 - Atmospheric Neutrinos (INO, Pingu)
 - Long Baseline Beam Neutrinos (LBNO, LBNE)
 - **Precise measurement of Δm_{atm}^2 and mixing angle at 10-70 km away from reactors (HLMA, Daya Bay II)**
 - **Cosmology ($\sum m$) - Planck**
 - **Double beta decay (many programs)**
-