

Latest reactor neutrino oscillation results

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CIEMAT

PACT-IFT Workshop, October 24, 2013



Outline

I. Neutrino oscillations in reactor experiments

- Antineutrino detection (signal & background)
- Oscillation physics: Δm^2_{12} , θ_{12} and θ_{13} + mass hierarchy
- Reactor anomaly: sterile neutrinos?

II. The θ_{13} measurement:

- Double Chooz
- Daya Bay
- RENO

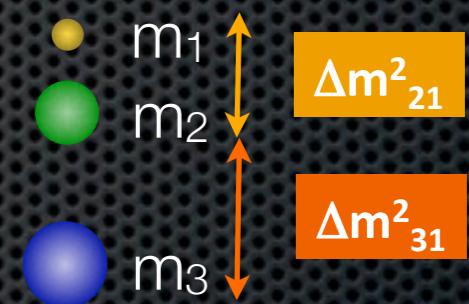
III. Future experimental prospects:

- JUNO, RENO-50, sterile experiments

Brief introduction

Neutrino oscillations

Atmospheric + LBL	Reactors + LBL	Solar + KamLAND	
$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$	θ_{atm}	$\theta_{13}, \delta_{\text{CP}}$	θ_{solar}



- Measured parameters: θ_{12} , Δm^2_{21} , θ_{23} , Δm^2_{31}
- Recently discovered: θ_{13}
- Unknown parameters: mass hierarchy (sign of Δm^2_{31}), δ_{CP} , octant θ_{23}

General panorama of oscillation measurements

Global 6-parameter fit (including δ_{CP}):

- **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
- **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4;
- **Reactor**: KamLAND + Chooz + Palo-Verde
+ Double-Chooz + Daya-Bay + Reno;
- **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);

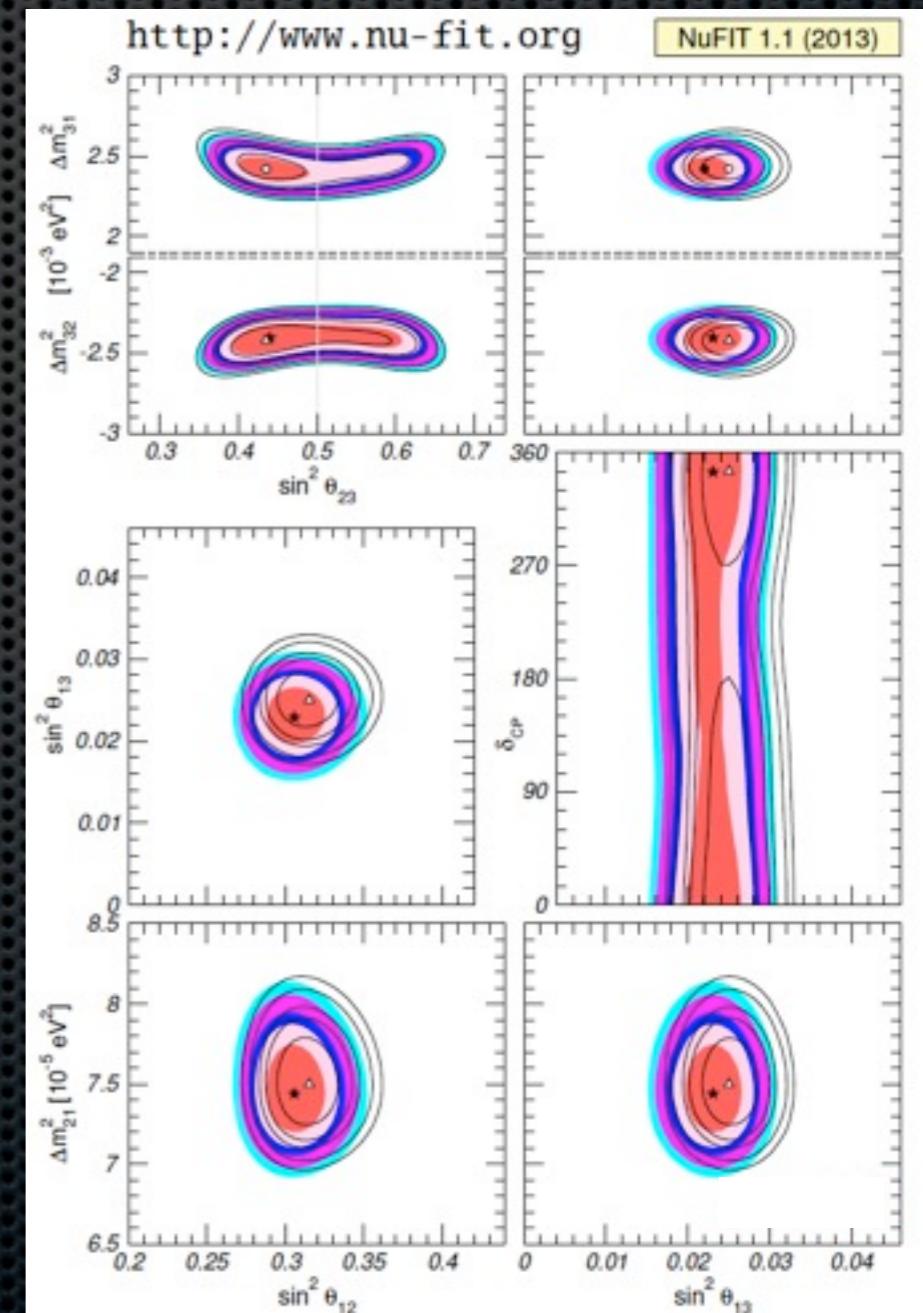
From Maltoni, EPS-HEP 2013

best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 33.57^{+0.77}_{-0.75} \left({}^{+2.44}_{-2.19} \right), \quad \Delta m_{21}^2 = 7.45^{+0.19}_{-0.16} \left({}^{+0.60}_{-0.47} \right) \times 10^{-5} \text{ eV}^2,$$

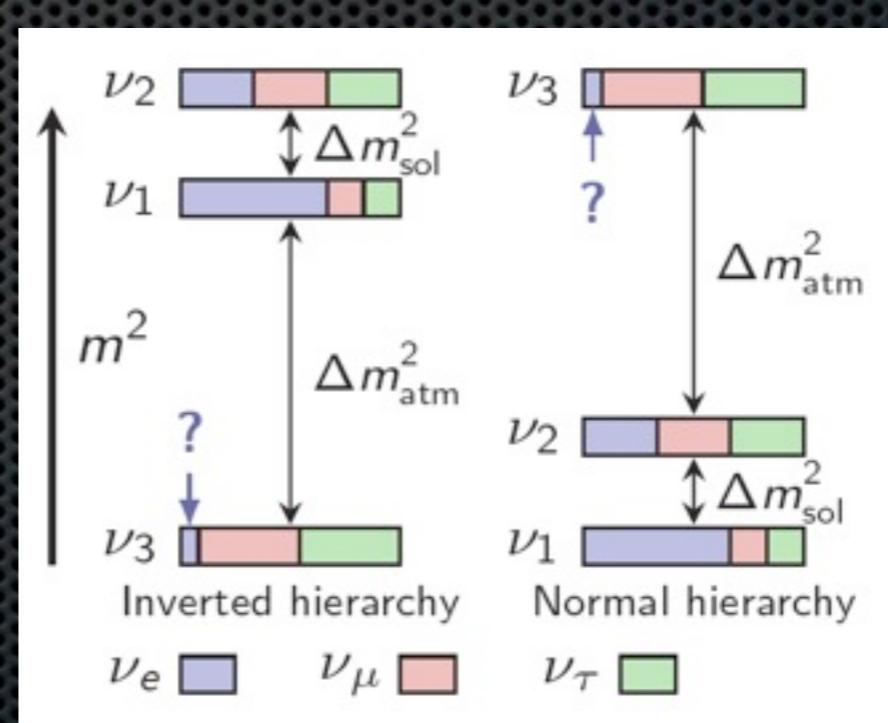
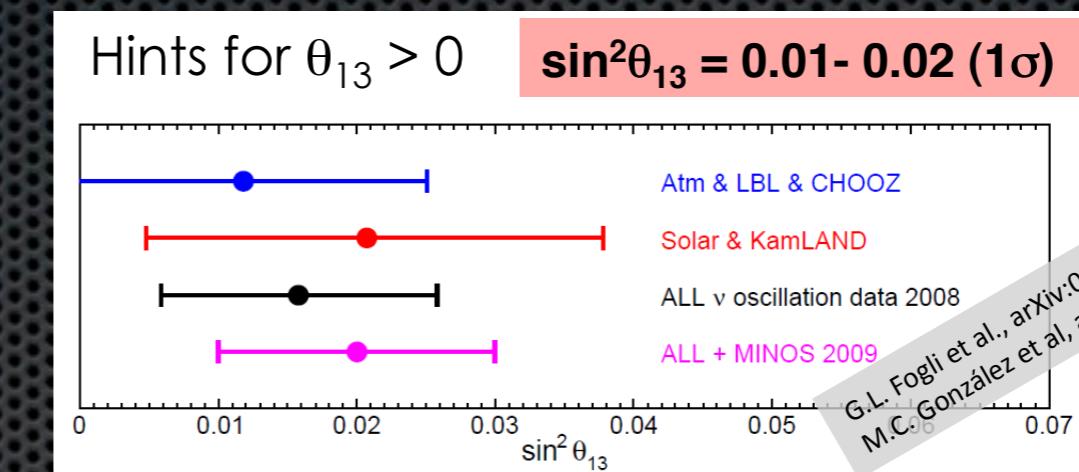
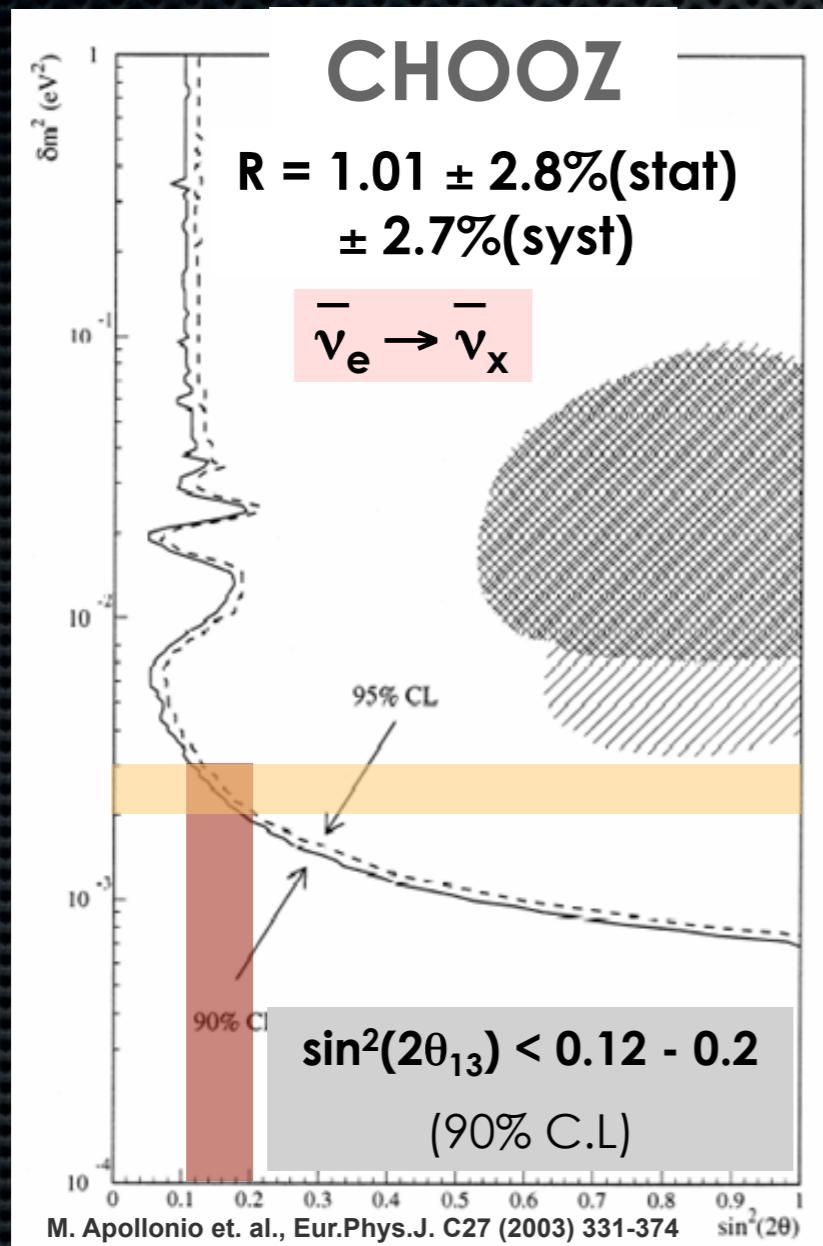
$$\theta_{23} = 41.4^{+3.5}_{-1.8} \left({}^{+12.6}_{-4.7} \right), \quad \Delta m_{31}^2 = \begin{cases} -2.403^{+0.062}_{-0.063} \left({}^{+0.184}_{-0.193} \right) \times 10^{-3} \text{ eV}^2, \\ +2.421^{+0.022}_{-0.023} \left({}^{+0.191}_{-0.173} \right) \times 10^{-3} \text{ eV}^2, \end{cases}$$

$$\theta_{13} = 8.75^{+0.42}_{-0.44} \left({}^{+1.21}_{-1.46} \right), \quad \delta_{\text{CP}} = 341^{+58}_{-46} \text{ (any)};$$



(Until 2011...)

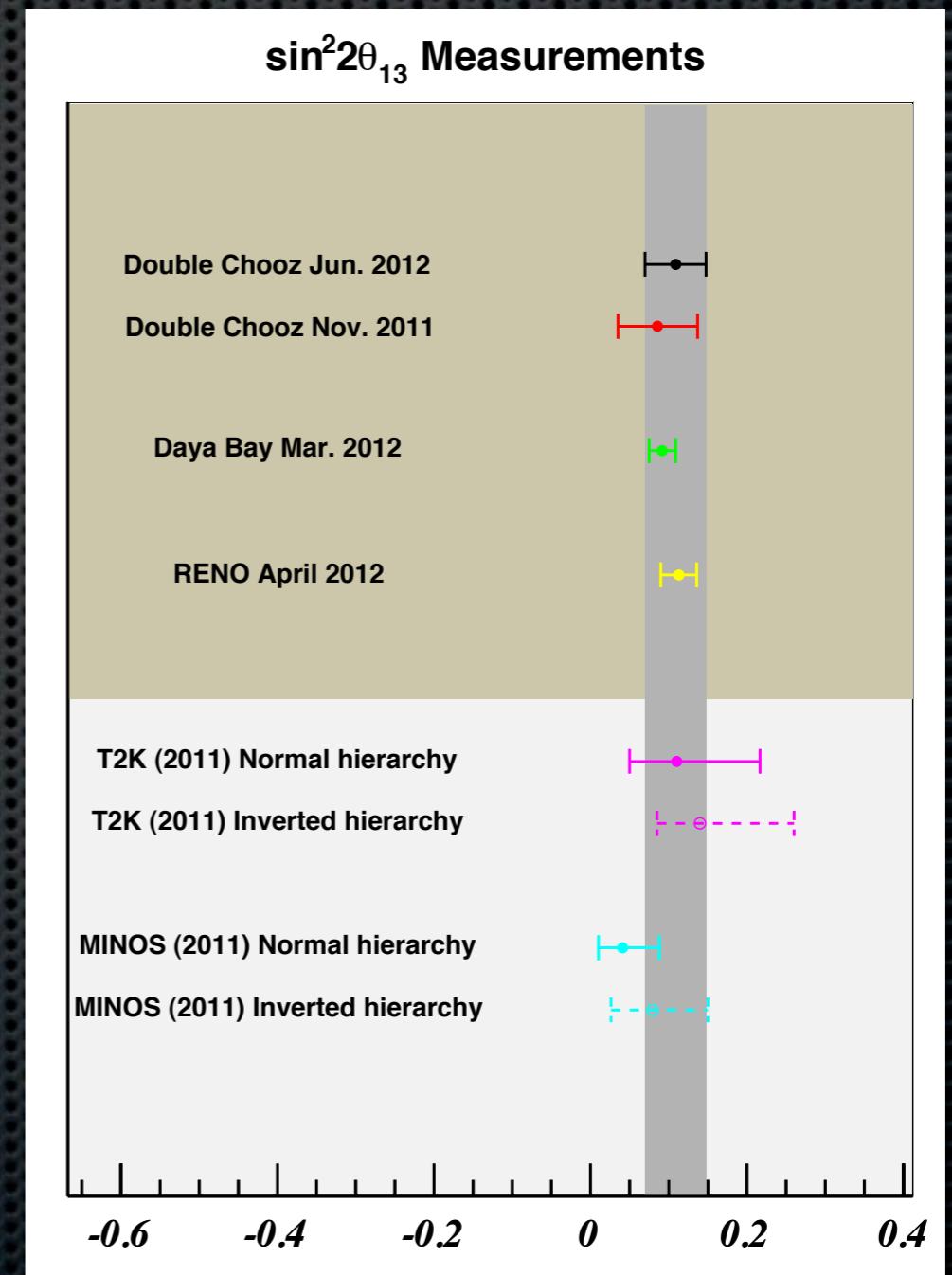
The big unknown: θ_{13}



+ T2K

The revolution of reactor experiments in 2012

- Double Chooz is the first reactor neutrino experiment in providing indications of $\theta_{13} \neq 0$ in Nov. 2011
- Daya Bay and RENO presented their first result in April 2012 based on rate-only oscillations ($\sim 5\sigma$ for $\theta_{13} \neq 0$)
- Improved analyses with larger statistics and systematics reduction and cross-checks with independent analyses



Reactor vs accel. neutrinos

- **Accelerator**

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta) \\
 & + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,
 \end{aligned}$$

- Dependencies on θ_{13} , θ_{23} octant, sign of Δm_{31}^2 and δ_{CP} phase
 - Parameter correlations and degeneracies
- Matter effects sensitive
- Possibility to measure δ_{CP} using ν_μ , $\bar{\nu}_\mu$ beams
- Experimental challenges: ν beam intensity, flavor contamination, flux properties, ν -N interactions

- **Reactors**

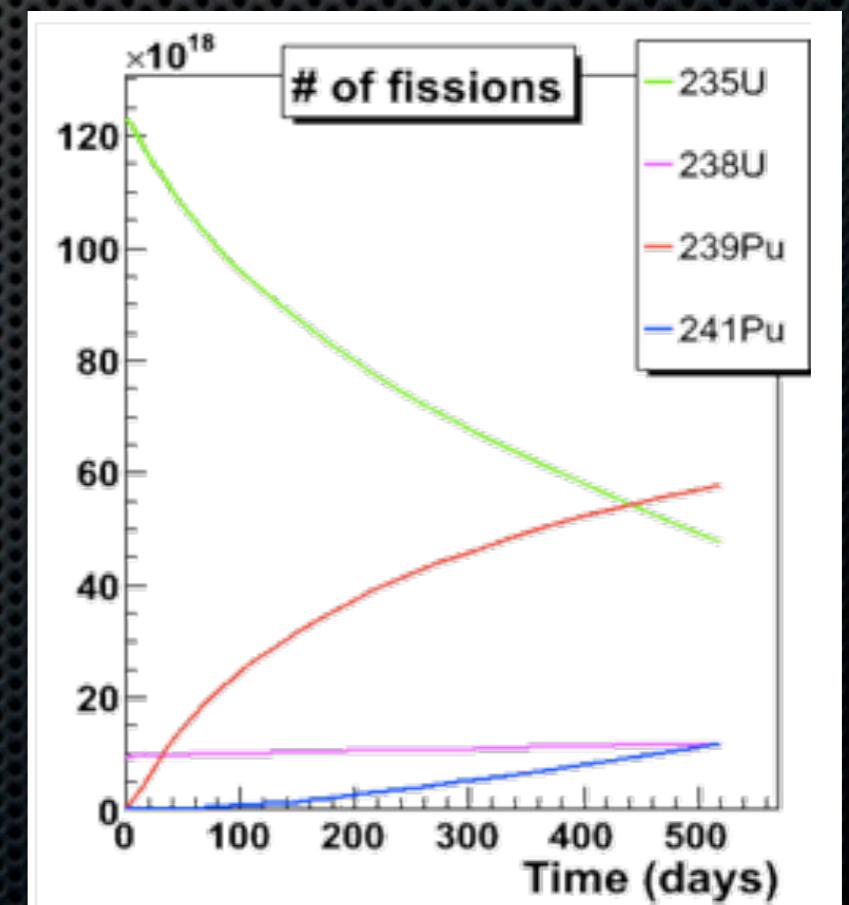
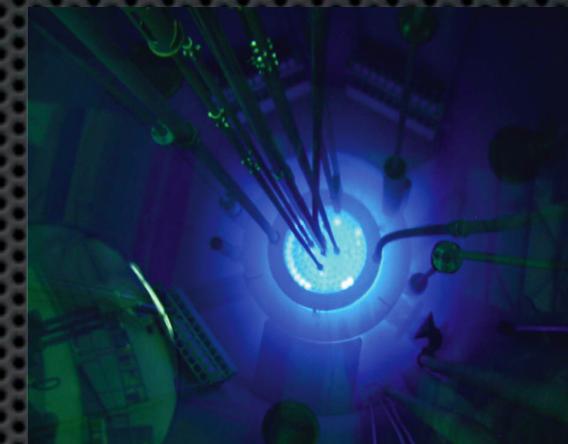
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{13}^2 L}{4E_\nu} \right) + O(10^{-3})$$

- No dependence on δ_{CP} , no matter effects
- Experimental challenges: backgrounds, systematic uncertainties

I. Neutrino oscillations in reactor experiments

$\bar{\nu}_e$ from nuclear reactors

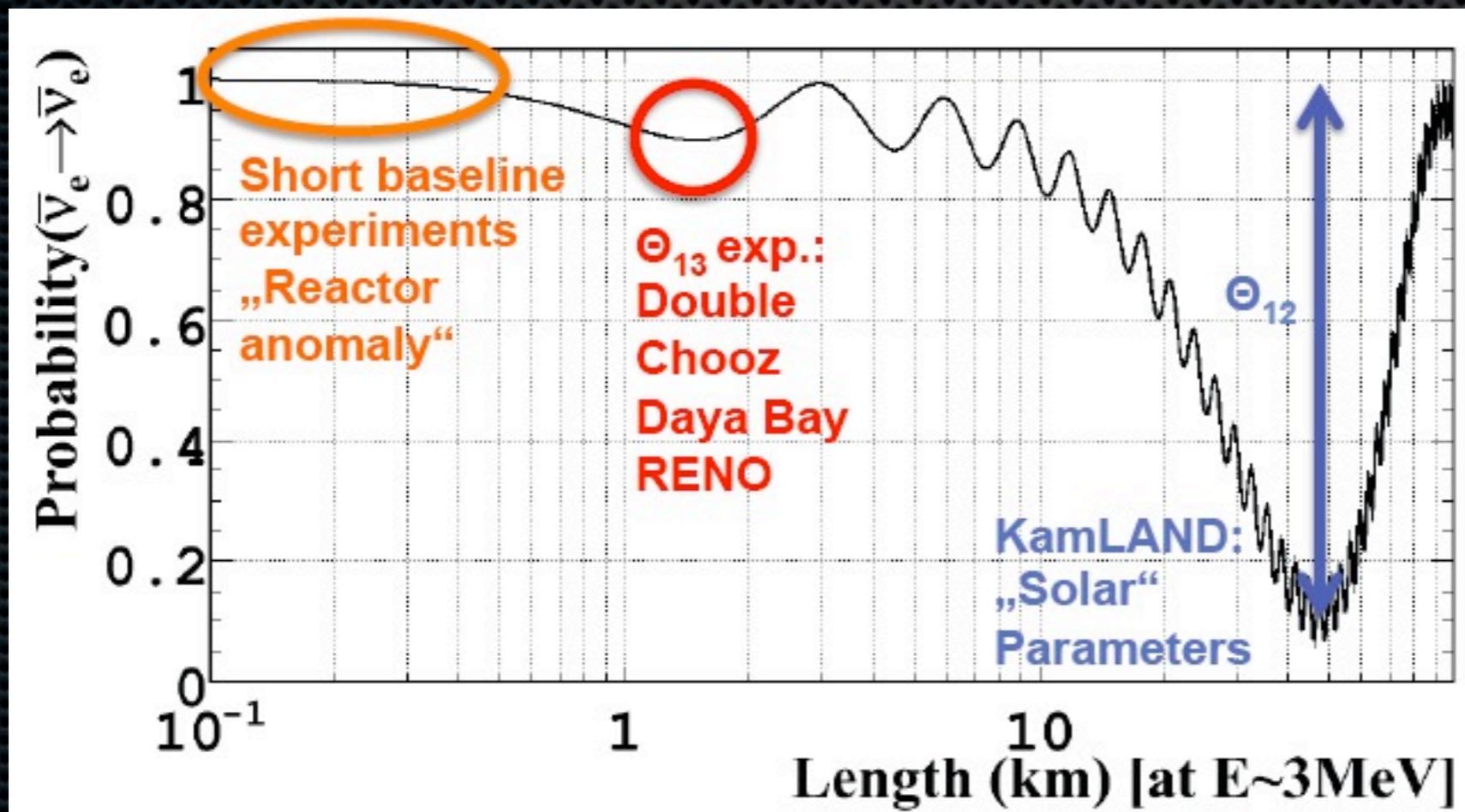
- Electron antineutrinos emitted through β^- decays of fission products of ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu
 - ~200 MeV/fission is released
 - ~6 antineutrinos / fission
- Nuclear reactors: $1 \text{ GW}_{\text{th}} \approx 2 \times 10^{20} \bar{\nu}/\text{s}$
- Neutrino luminosity:
$$N_{\bar{\nu}} = \gamma(1 + k)P_{\text{th}}$$
 - γ : reactor constant
 - k : fuel evolution correction up to 10%



Reactor neutrino oscillations

Electron antineutrino survival probability

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{13}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

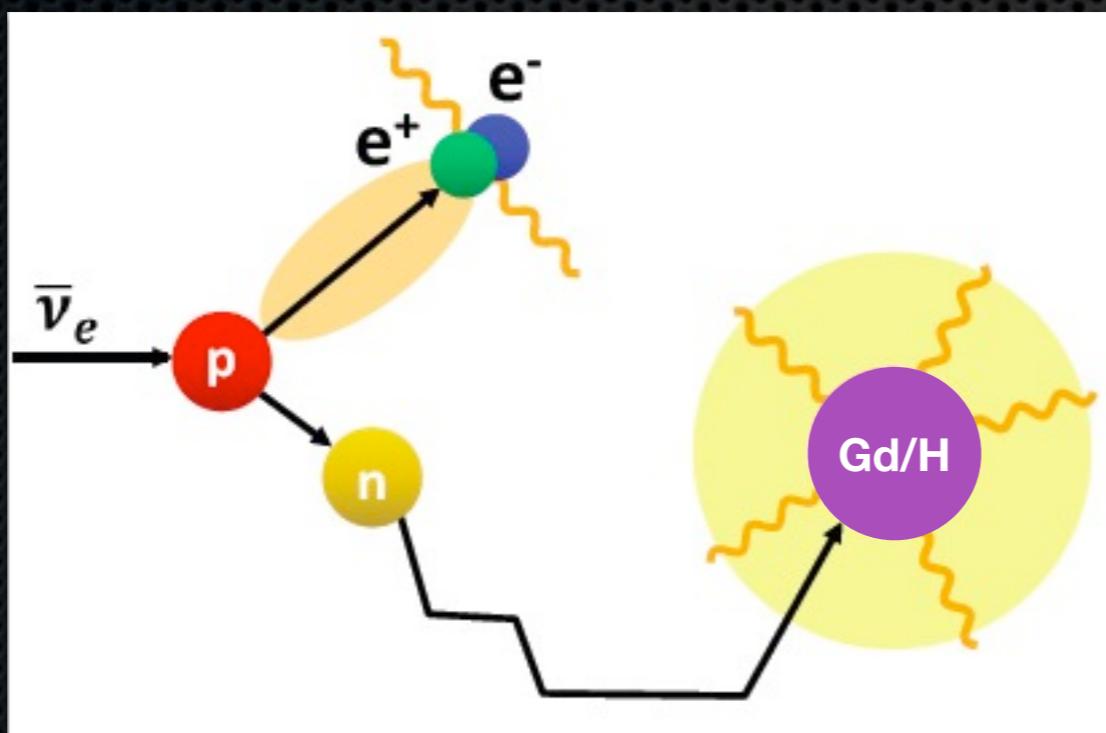


Three regimes:

- I. Short-baseline (~m): neutrino anomaly
- II. Medium-baseline (~1 km): θ_{13} searches
- III. Long-baseline (~100 km): solar oscillations

Antineutrino detection

- Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$



Prompt signal

e^+ scintillation + annihilation
 $E_{\text{prompt}} \approx E_{\bar{\nu}e} - 0.8 \text{ MeV}$

Delayed signal

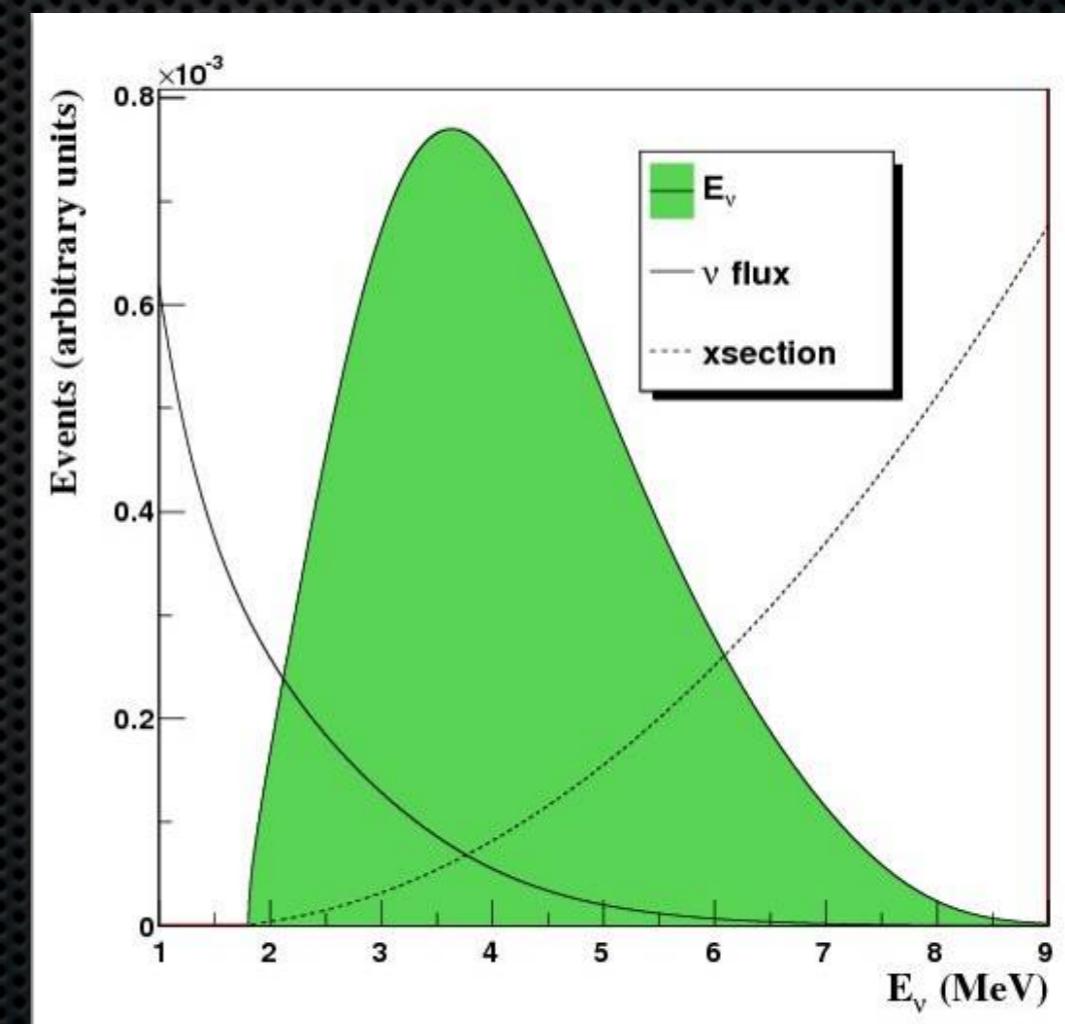
n capture on Gd $\rightarrow \gamma$ cascade
 $E_d \sim 8 \text{ MeV}; \Delta t \sim 30 \mu\text{s}$

OR

n capture on H \rightarrow single γ
 $E_d \sim 2.2 \text{ MeV}; \Delta t \sim 200 \mu\text{s}$

Reactor antineutrino spectrum

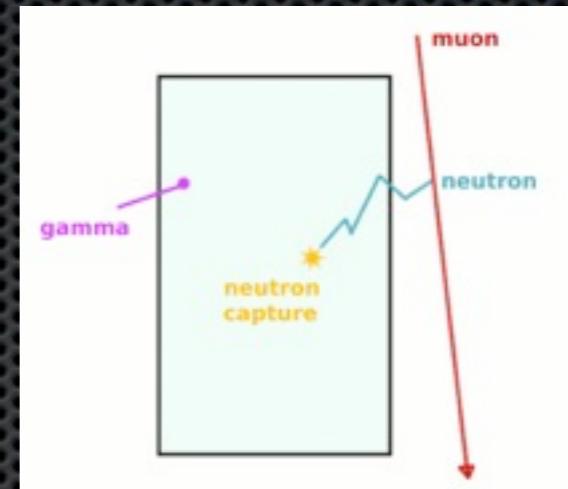
- Large cross section
 $\sigma \sim 10^{-43} \text{ cm}^2$
- Large reactor neutrino flux
- Neutrino detection threshold: 1.8 MeV
- Disappearance experiments



Main backgrounds

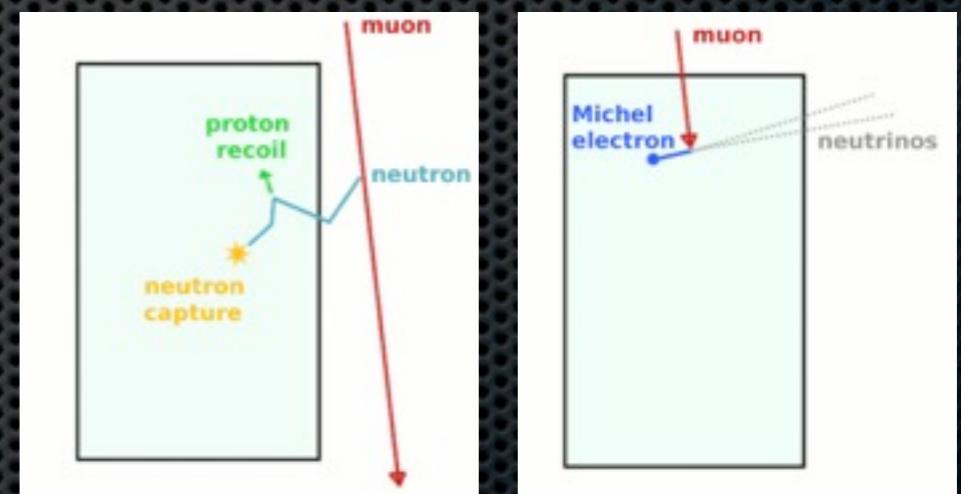
1. Accidental background: accidental coincidences

- *Prompt*: gammas from radioactivity from materials, rock...
- *Delay*: neutrons from cosmic muons, β decay of cosmogenic isotopes



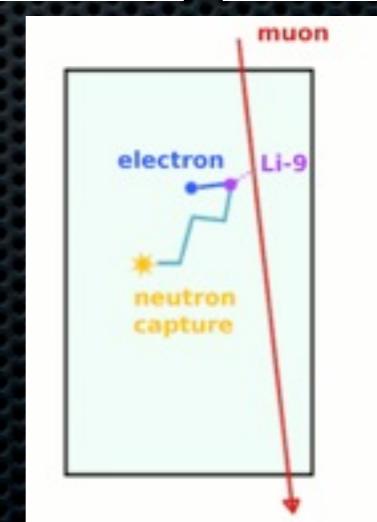
2. Correlated background: muon induced fast-neutrons and stopping muons

- *Prompt*: recoil proton from neutron scattering or muon track
- *Delay*: neutron capture or Michel electrons

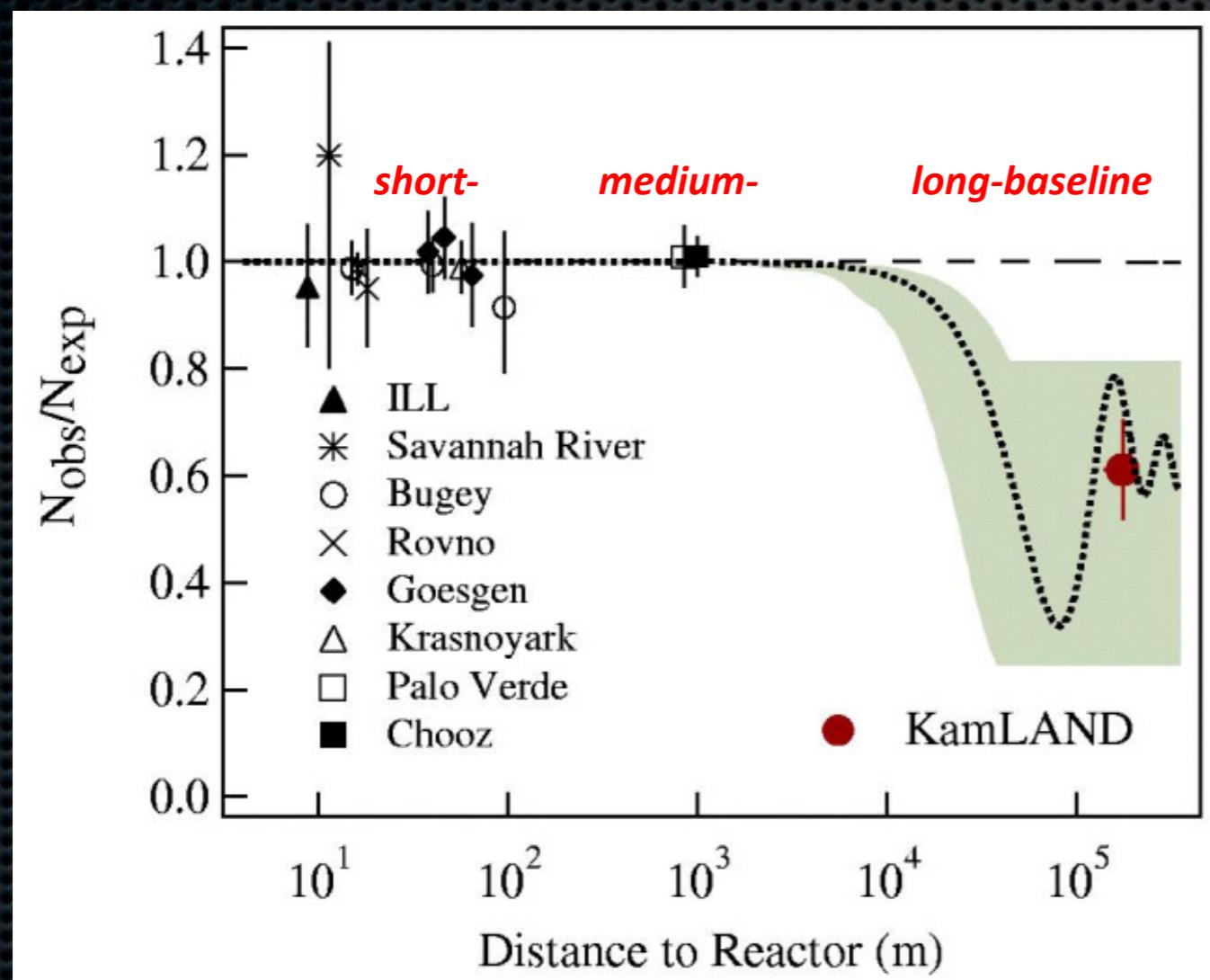


3. Cosmogenic background: muon induced spallation βn emitters (${}^9\text{Li}$ or ${}^8\text{He}$)

- *Prompt*: electron
- *Delay*: neutron capture



Measurements of reactor experiments until 2011



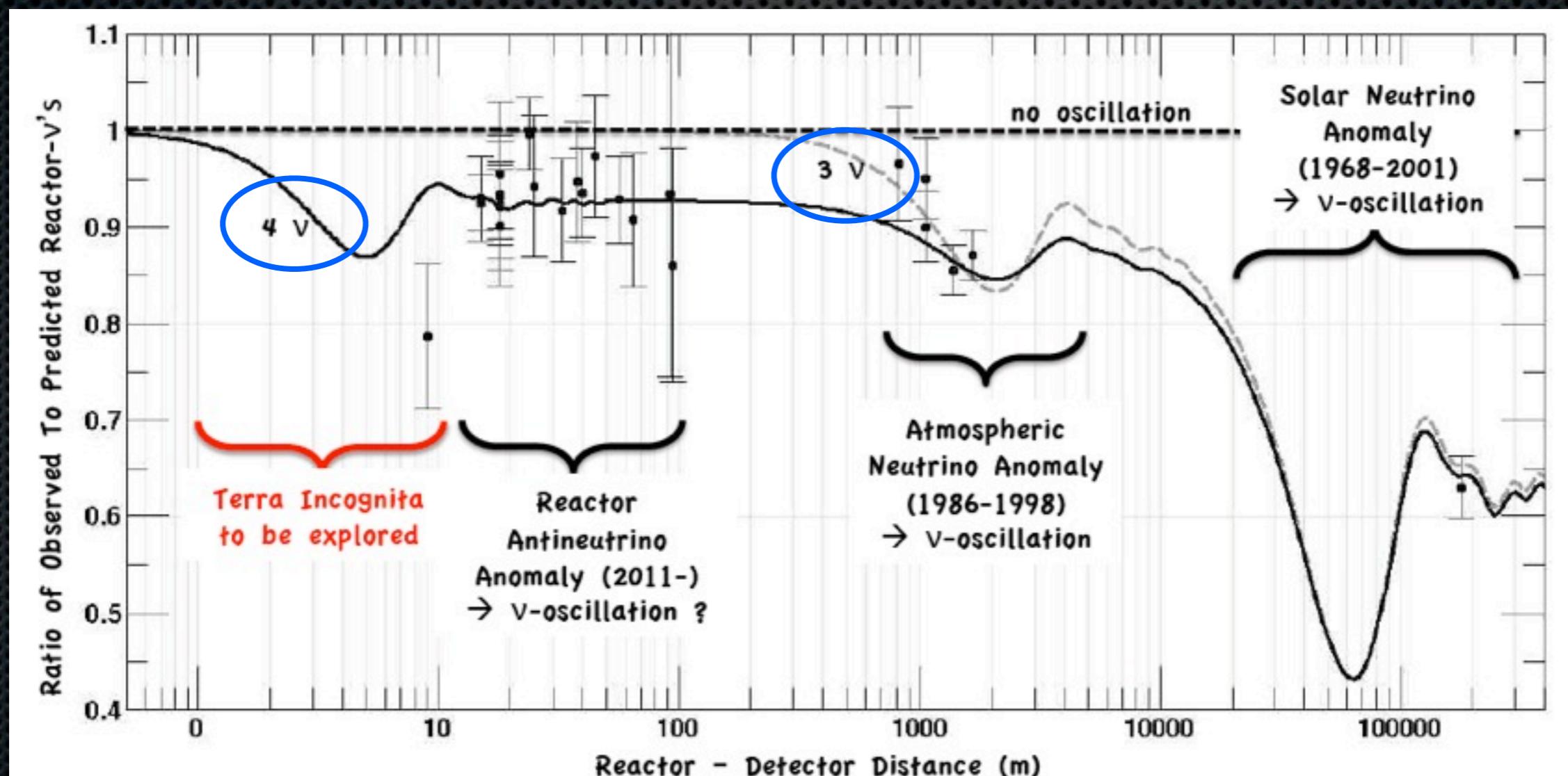
- No oscillations observed at short- and medium-baselines:
 - CHOOZ limit: $\sin^2 2\theta_{13} < 0.15$ (90% CL)
- LBL oscillations observed by KamLAND (in ~2002)

Main neutrino physics in nuclear reactors

- Determination of Δm^2_{12} , θ_{12} (KamLAND)
- Discovery of θ_{13} (Double Chooz, Daya Bay, RENO)
- Mass hierarchy (future?)
- Sterile neutrinos?

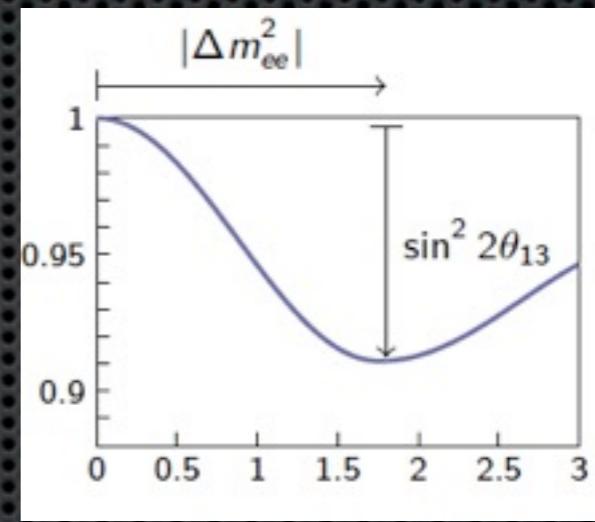
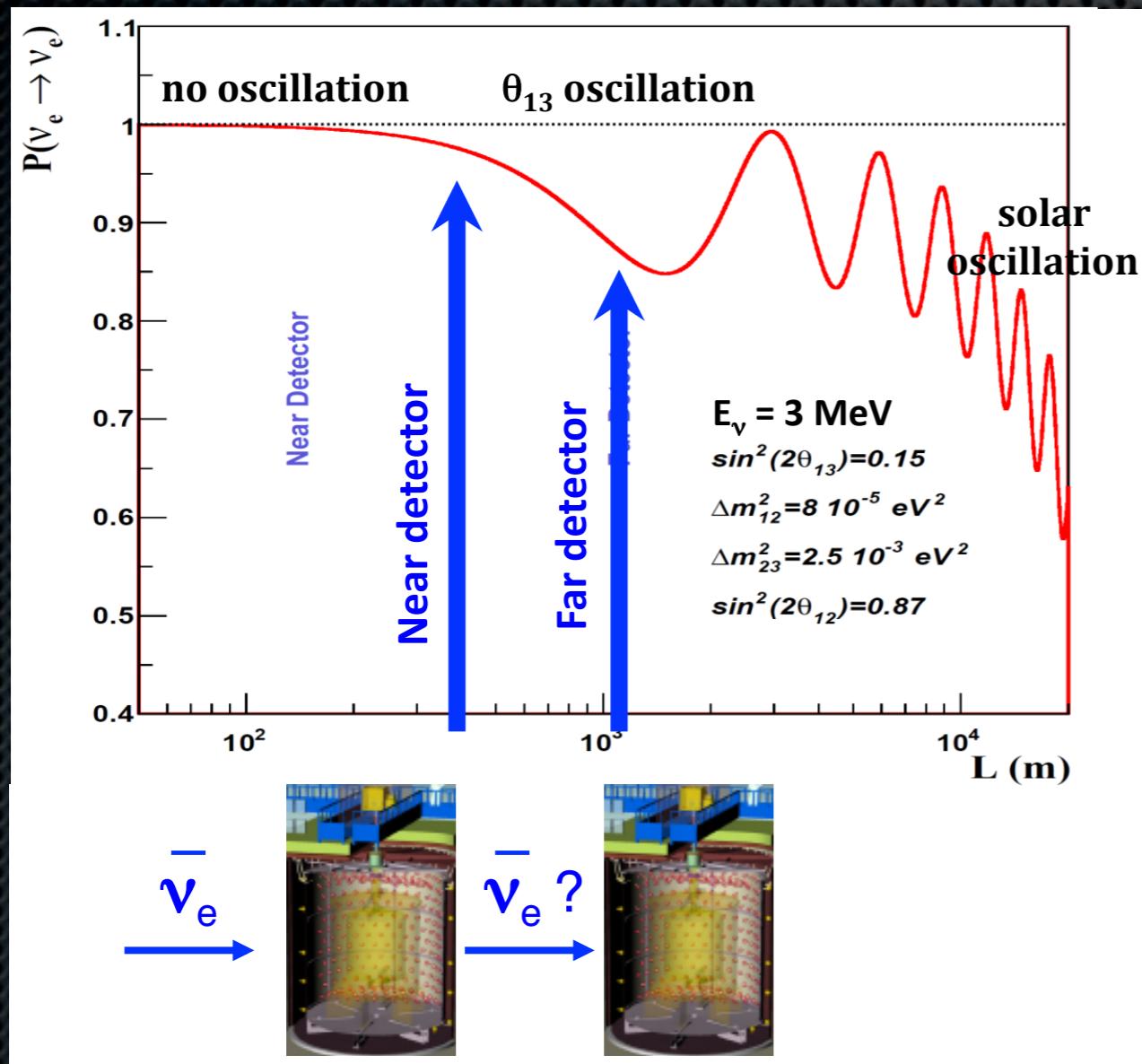
Reactor antineutrino anomaly

- Reevaluation of reactor $\bar{\nu}_e$ spectra and flux: Phys. Rev. C83 (2011) 054615, Phys. Rev. C84 (2011) 024617
- Reanalysis of past reactor experiments: Phys. Rev. D83 (2011) 073006
- Small increase of the flux by about 3.5% → all reactor SBL experiments observe a deficit!



II. The measurement of θ_{13}

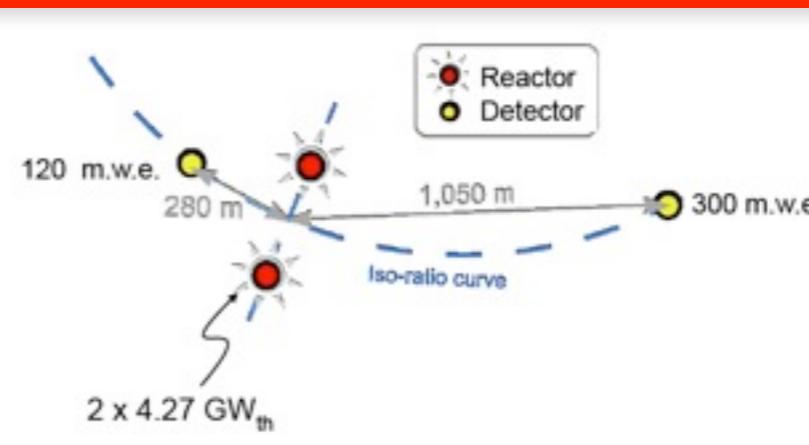
The detection strategy



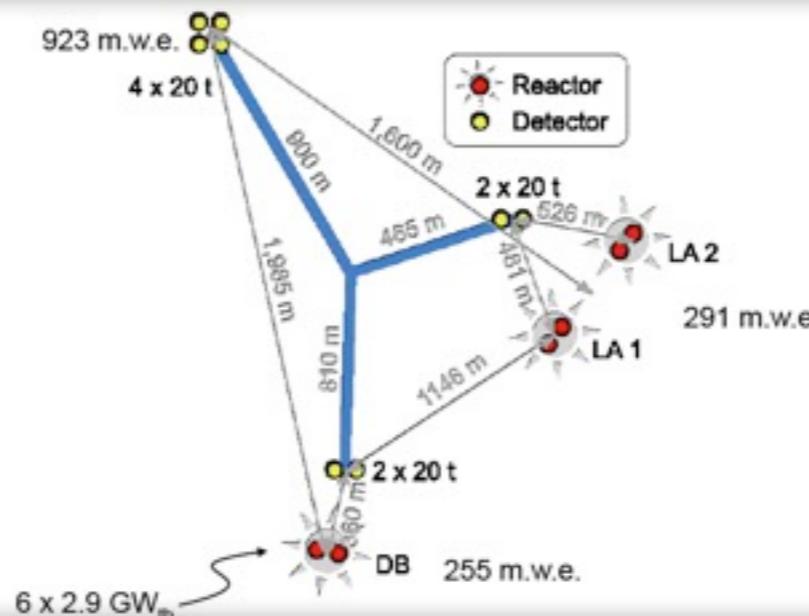
- Two identical detectors
 - Reactor flux uncertainty cancellation
 - ND: reduce correlated inter-detector systematic uncertainties
- Rate deficit and spectral distortion at FD

θ_{13} ongoing reactor experiments

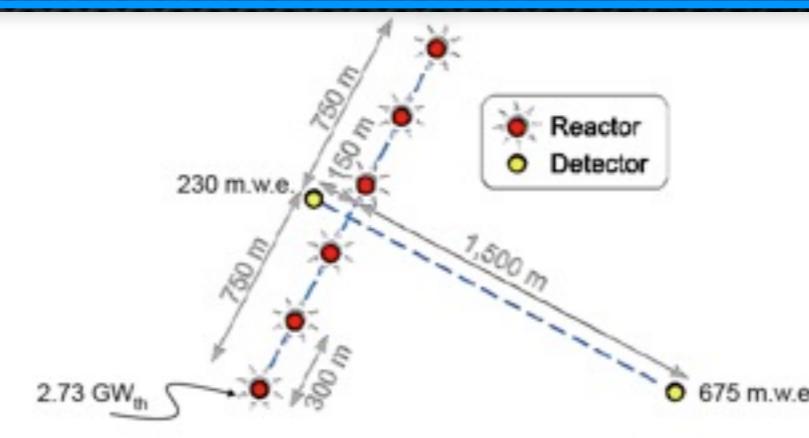
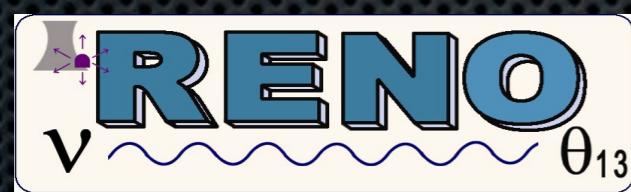
- Double Chooz (France)



- Daya Bay (China)



- RENO (Korea)



Comparison

Reference CHOOZ:

$$R_{\text{obs}}/R_{\text{exp}} = 1.01 \pm 2.8\% \text{ (stat.)} \pm 2.7\% \text{ (syst.)}$$

$$\sin^2 2\theta_{13} < 0.15 \text{ (90\% C.L.)} \text{ (for } \Delta m^2_{13} = 2.5 \times 10^{-3} \text{ MeV}^2)$$

Experiment	Location	Baseline Near/Far	Power (cores)	FD size	Designed sensitivity (90%CL)
Double Chooz	France	400/1050 m	8.6 GW (2)	8.3 ton	0.03
Daya Bay	China	470/576/1650 m	17.4 GW (6)	80 ton	0.01
RENO	Korea	409/1444 m	16.4 GW (6)	16 ton	0.02

Double Chooz

Results presented on behalf of the
Double Chooz collaboration



Outlook

- ❖ Experiment overview
- ❖ Latest results:
 - ❖ Gd and H oscillation analyses
 - ❖ Reactor-off background measurements
 - ❖ First combined Gd + H fit
 - ❖ Reactor Rate Modulation analysis
- ❖ Prospects



Double Chooz collaboration



Brazil

CBPF
UNICAMP
UFABC



France

APC
CEA/DSM/IRFU:
SPP
SPN
SEDI
SIS
SENAC
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



USA

U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee
Virginia Tech.



Website:

www.doublechooz.org

Spokesperson:

Hervé de Kerret (IN2P3)

Project manager:

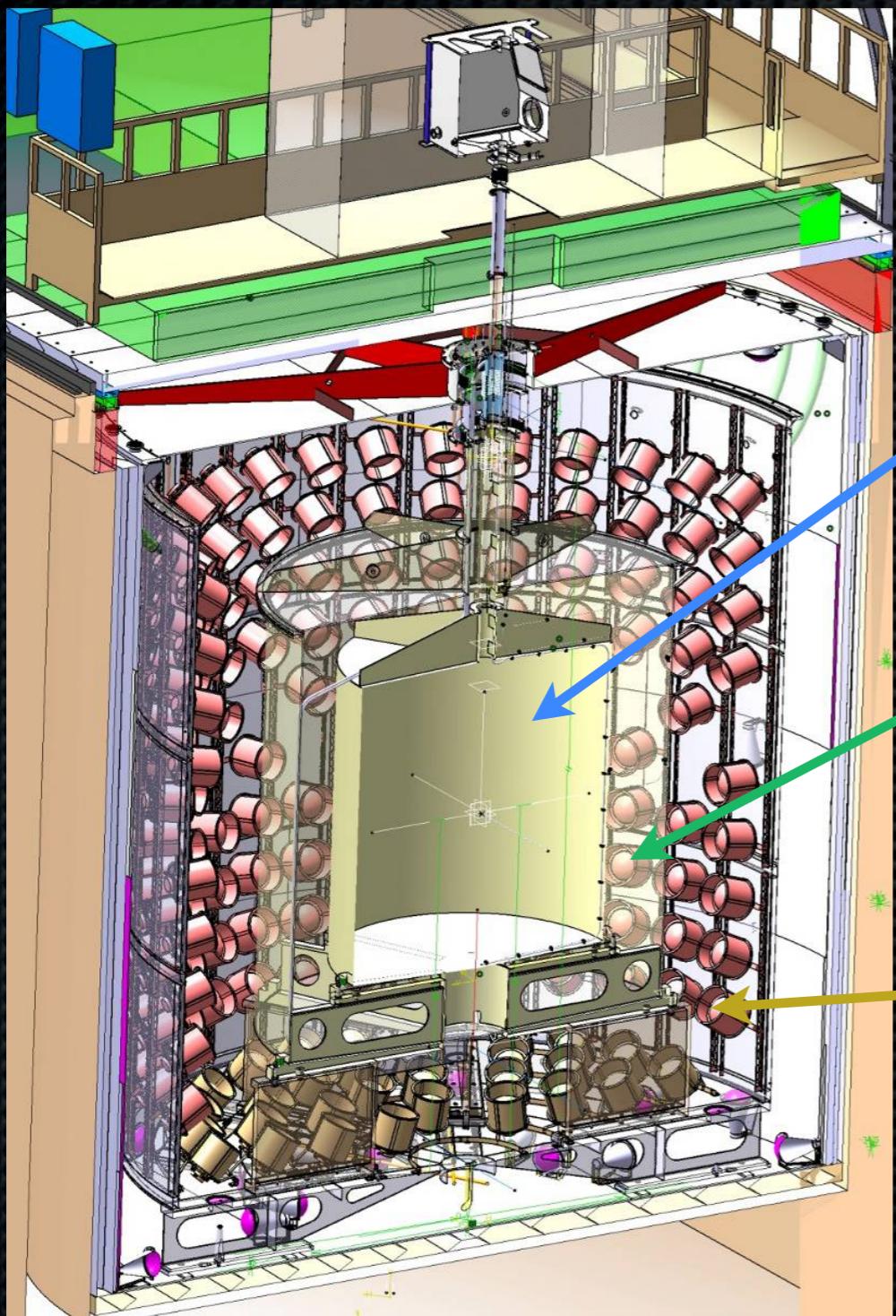
C. Veyssi  re (CEA-Saclay)

Double Chooz site

Running since April 2011
Overburden ≈ 300 mwe



Detector design



Inner detector

Neutrino target

Gd-doped liquid scintillator (8.3 tons)
in acrylic vessel (8 mm)

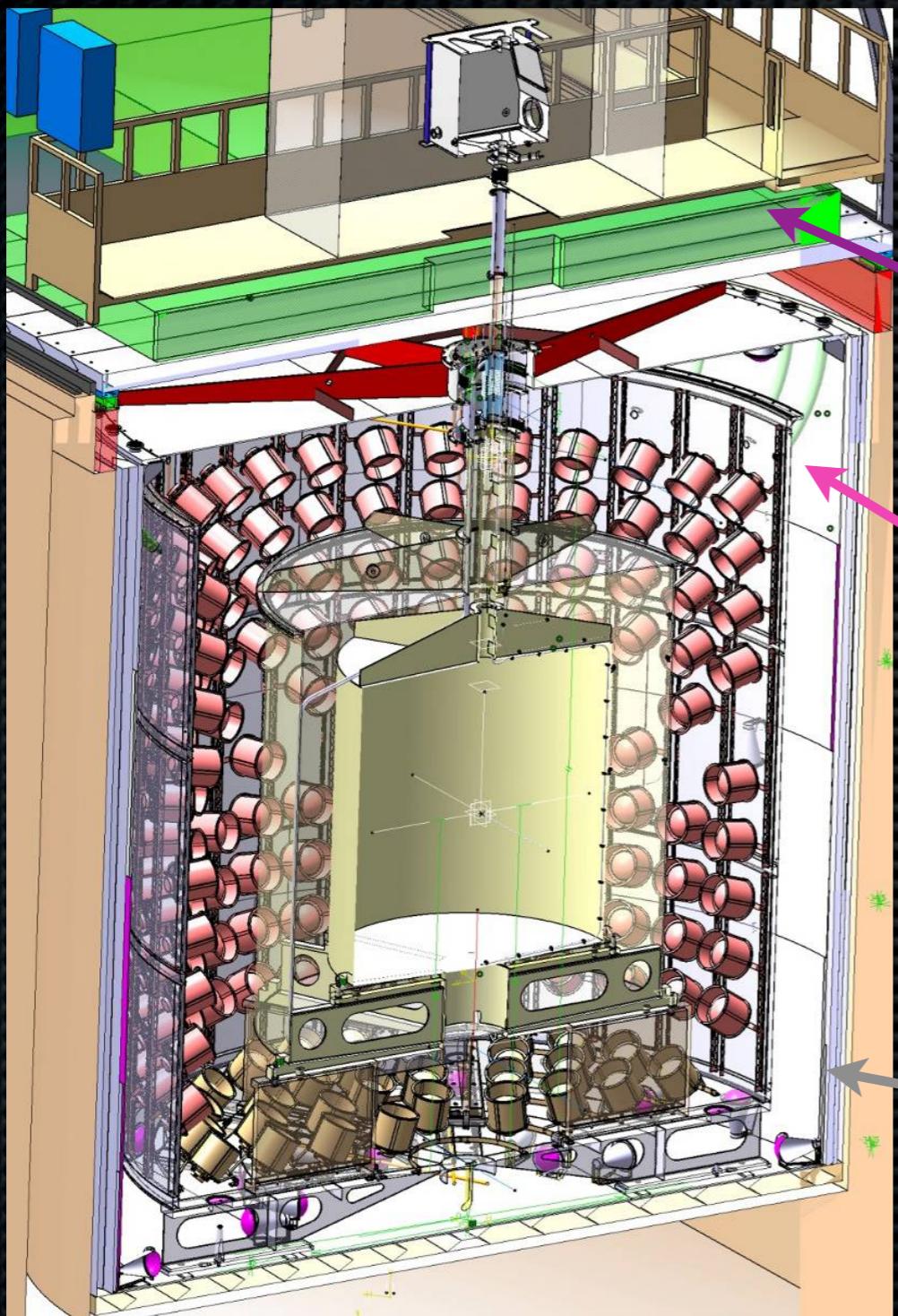
Gamma Catcher

Undoped liquid scintillator (18 tons)
in acrylic vessel (12 mm)

Buffer

Non-scintillating mineral oil (80 tons)
390 10" PMTs in stainless steel vessel (3
mm)

Detector design



Cosmic ray veto systems

Outer Veto

Array of plastic scintillator strips
13 m x 7 m

Inner Veto

Undoped liquid scintillator (70 tons)
78 10" PMTs in steel vessel (8 mm)

External shield

Steel shielding
15 cm steel



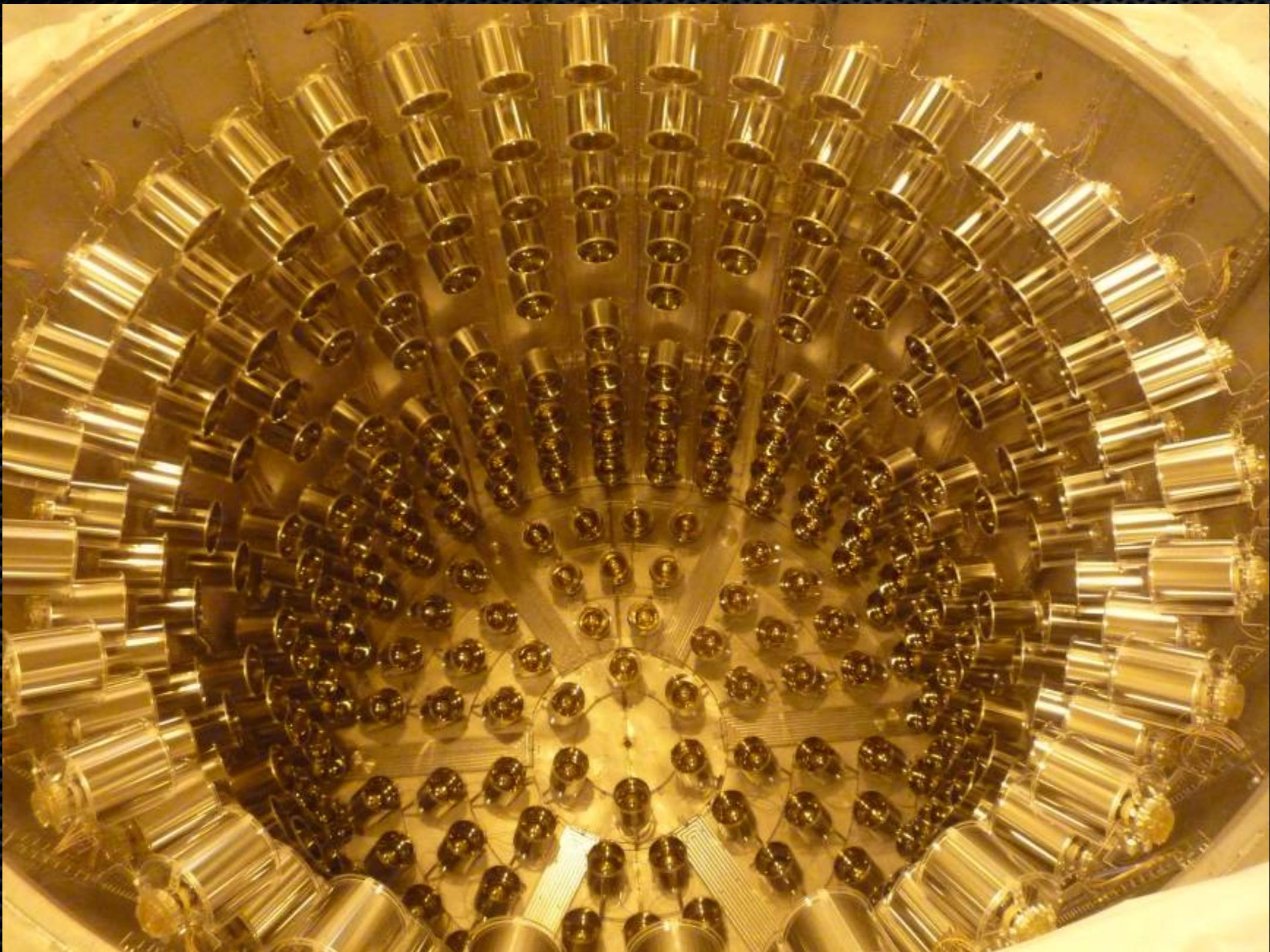
Far detector construction

2008-2010

IV PMTs installed



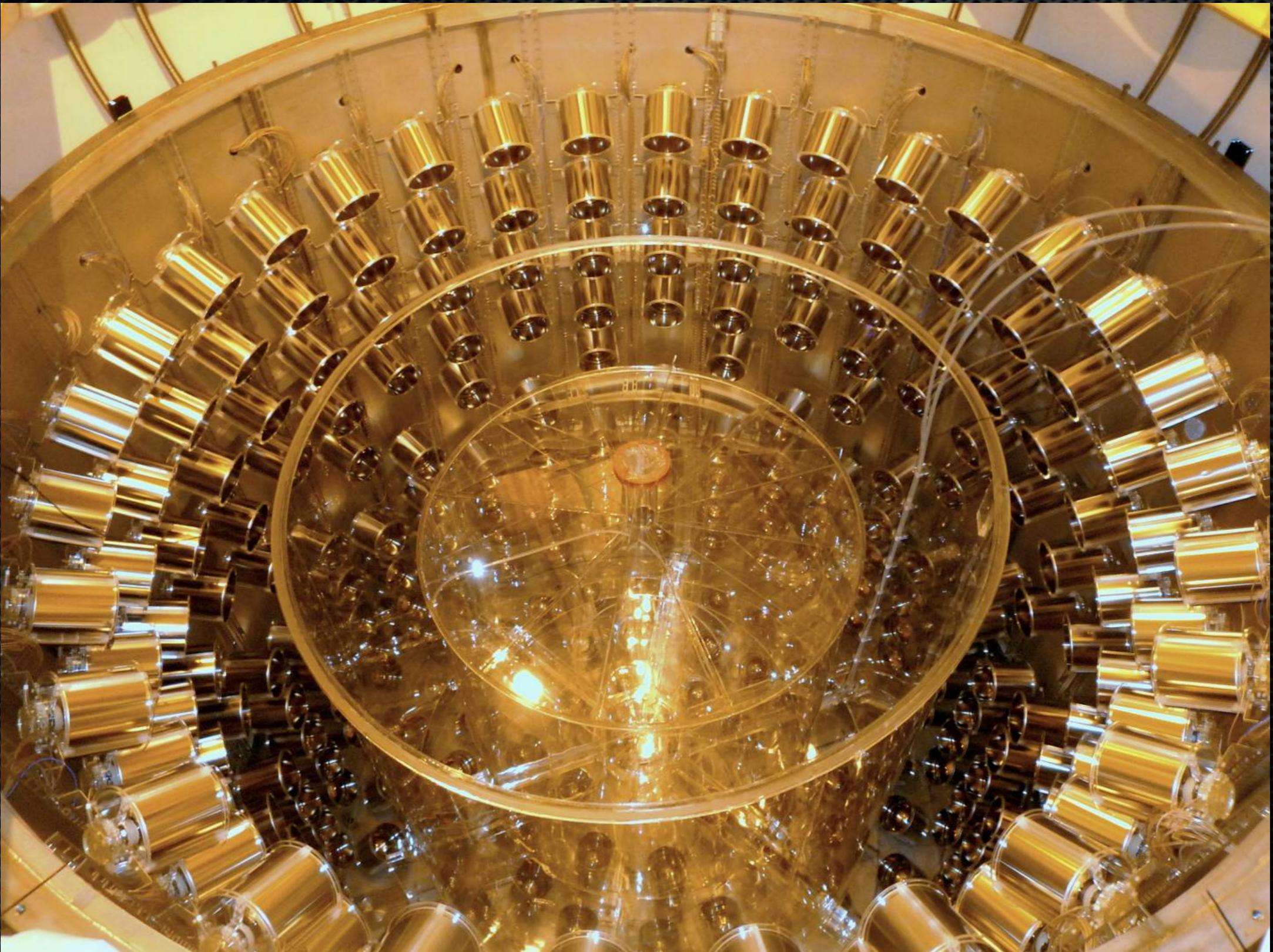
Buffer PMTs installed



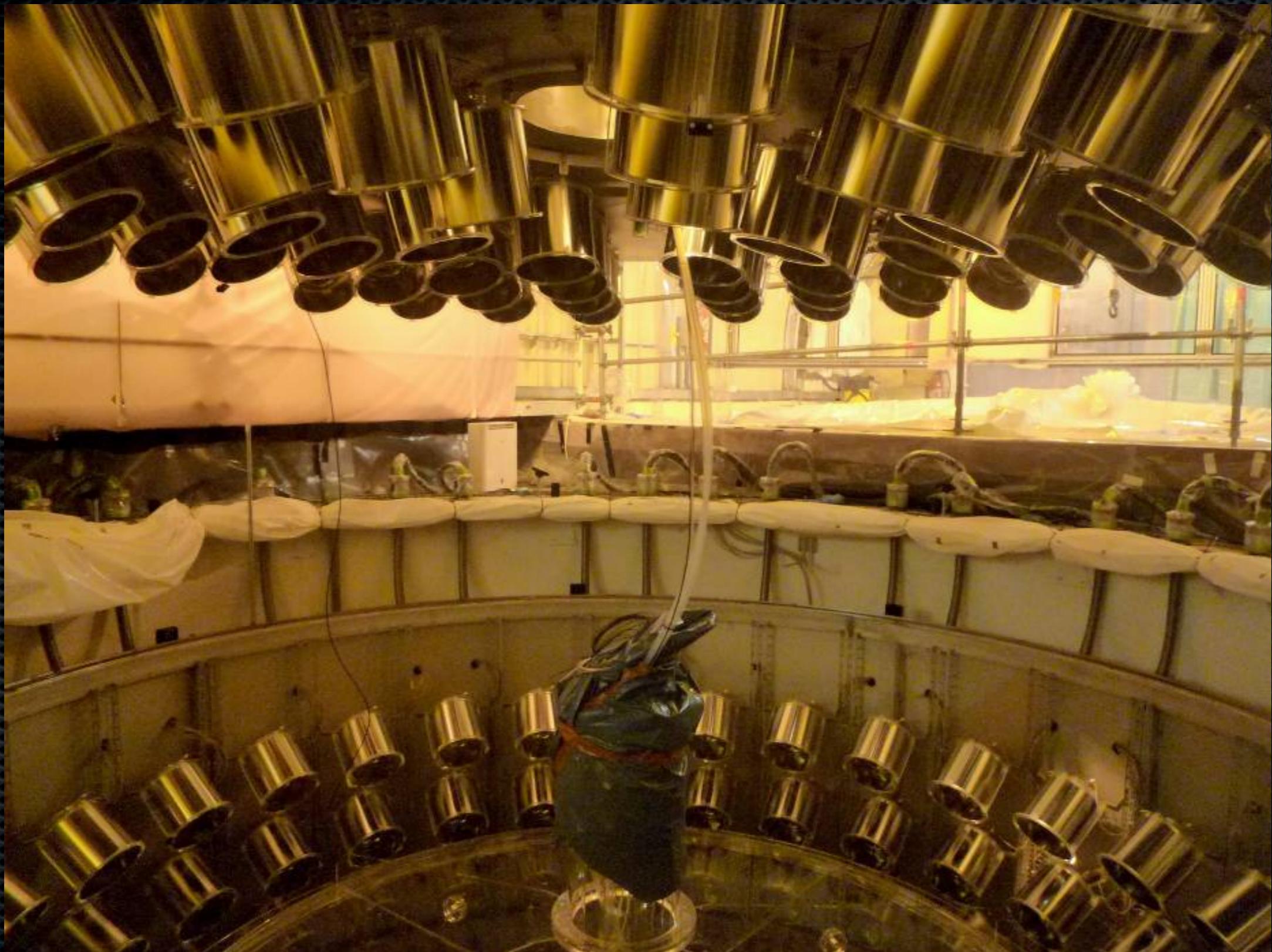
Acrylic vessels installation



Acrylic vessels and PMTs installed



Lid closure



Buffer volume closed



Steel shield installed

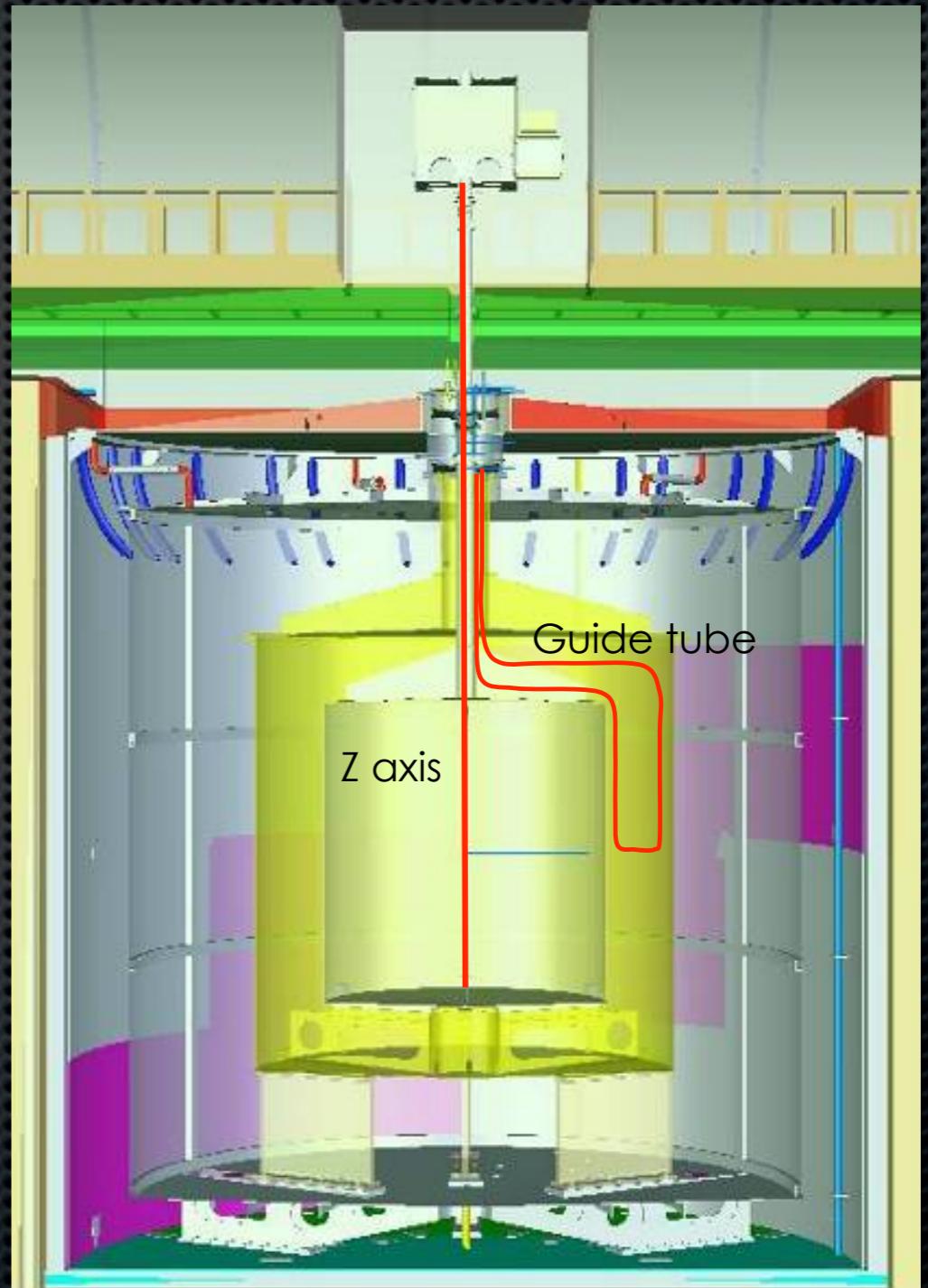


Outer veto installed



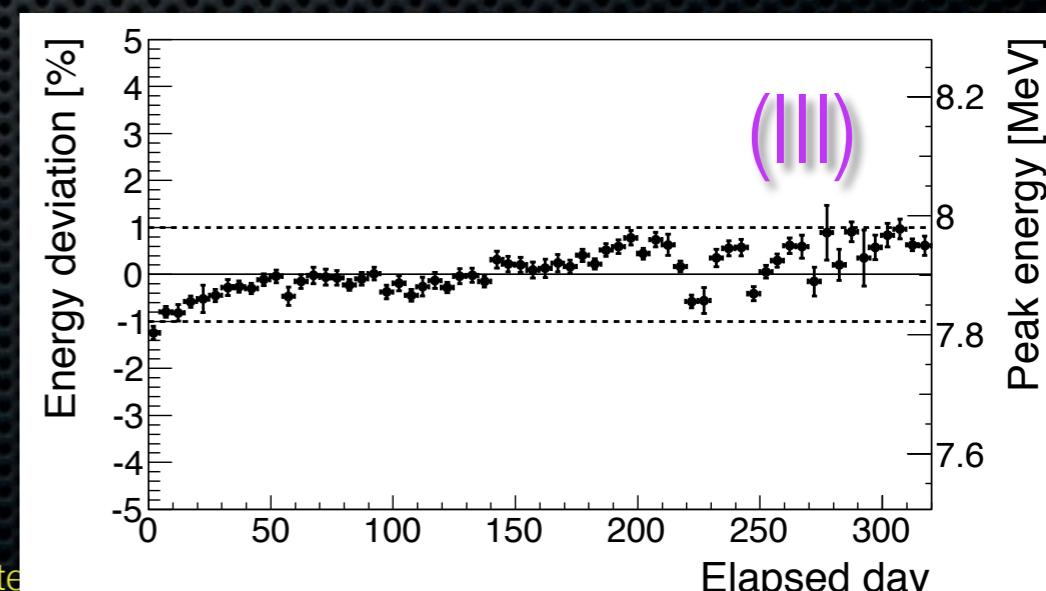
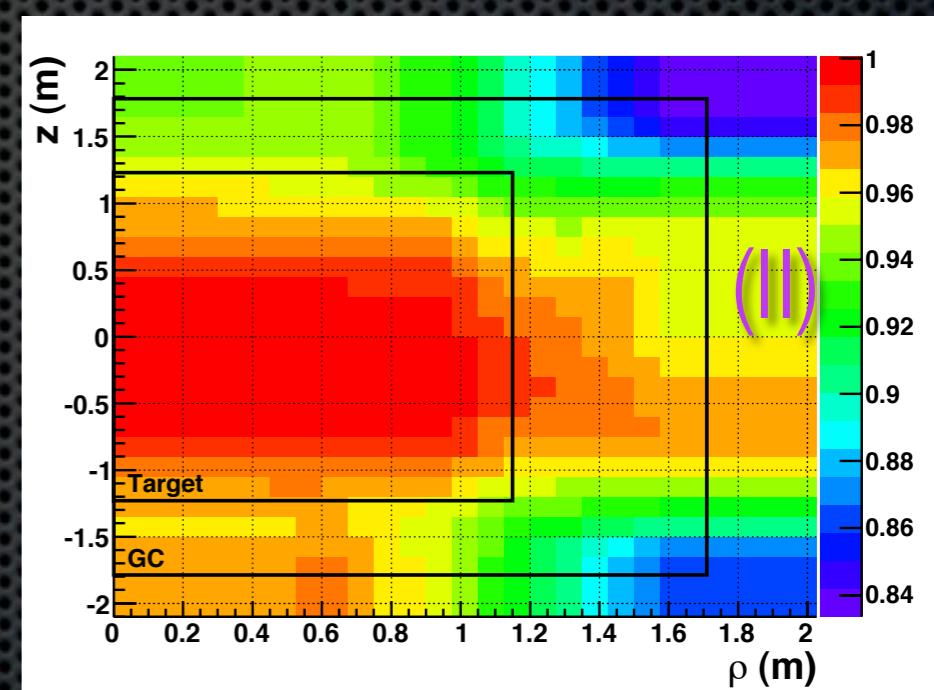
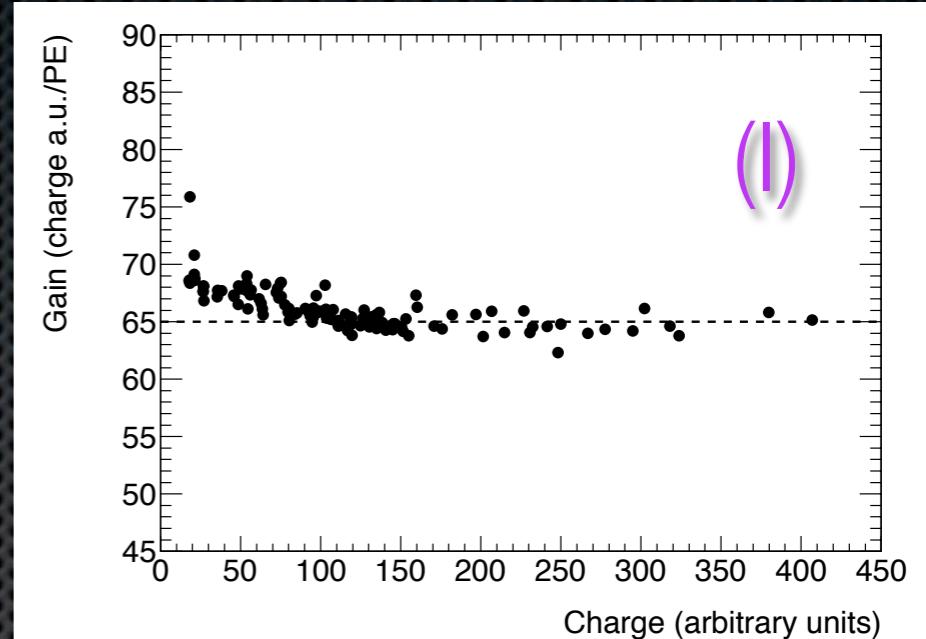
Calibration

- Light injection in ID and IV:
 - Monitor stability of readout (timing, gain) and scintillator
- Radioactive sources:
 - Sources deployed in Z axis in target and guide tube in GC
 - ^{137}Cs , ^{68}Ge , ^{60}Co (energy scale and stability), ^{252}Cf (n detection efficiency)
- Spallation neutrons generated by cosmic rays



Energy reconstruction

- Charge to PE
 - Gain nonlinearity correction (I)
- Detector nonuniformity correction (II)
 - Response maps of cosmogenic neutron captures on H across volume
- Time instability correction (III)
 - Using cosmogenic neutron captures on Gd peak variation
- Absolute MeV scale (PE/MeV)
 - H capture peak from ^{252}Cf at center of target



Double Chooz main results

- “Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment”, *Phys. Rev. Lett.* 108 (2012) 131801
 - 101 days, 1 detector F (Rate + Shape fit)
 - $\sin^2(2\theta_{13}) = 0.086 \pm 0.041$ (stat.) ± 0.030 (syst.) (no-osc excluded at 94.6% CL)
- “Reactor electron antineutrino disappearance in the Double Chooz experiment”, *Phys. Rev. D* 86, 052008 (2012)
 - 227.9 days, 1 detector F (Rate + Shape fit)
 - $\sin^2(2\theta_{13}) = 0.109 \pm 0.030$ (stat.) ± 0.025 (syst.) (no-osc excluded at 2.9σ)
- “First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment”, *Phys. Lett. B* 723 (2013) 66-70
 - 240.1 days, 1 detector F (Rate + Shape fit)
 - $\sin^2(2\theta_{13}) = 0.097 \pm 0.034$ (stat.) ± 0.034 (syst.) (no-osc excluded at 2.0σ)
- “Direct Measurement of Backgrounds using Reactor-Off Data in Double Chooz”, *Phys. Rev. D* 87 (2013) 0111012R
- Sept 2013: Combination of Gd + H analyses: R+S fit & RRM analyses (*not published yet*)

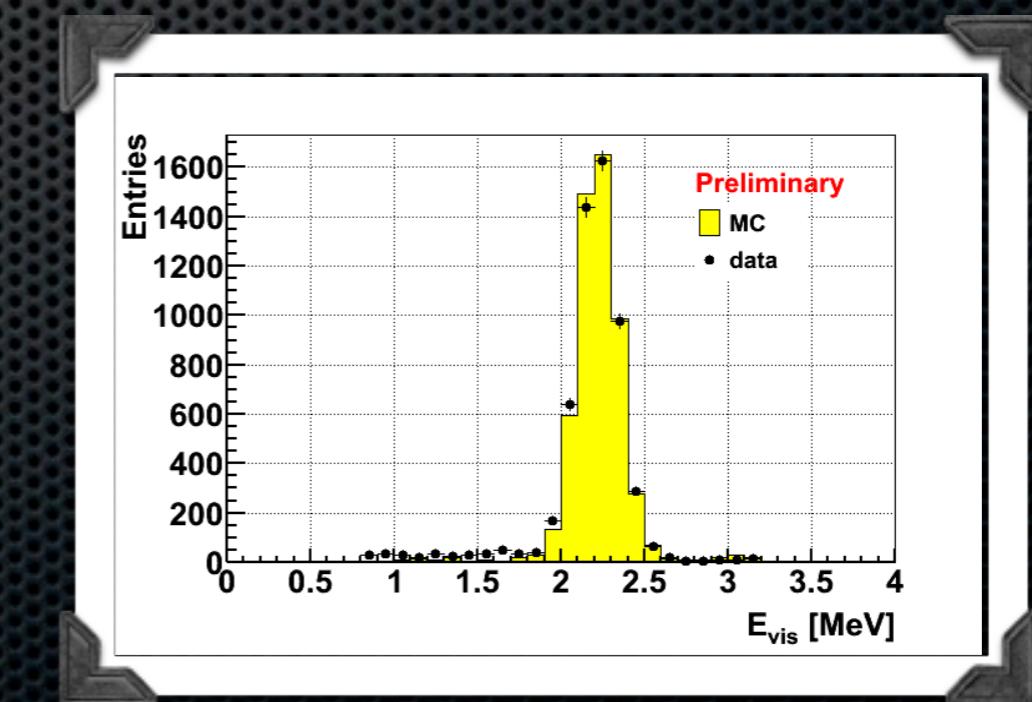
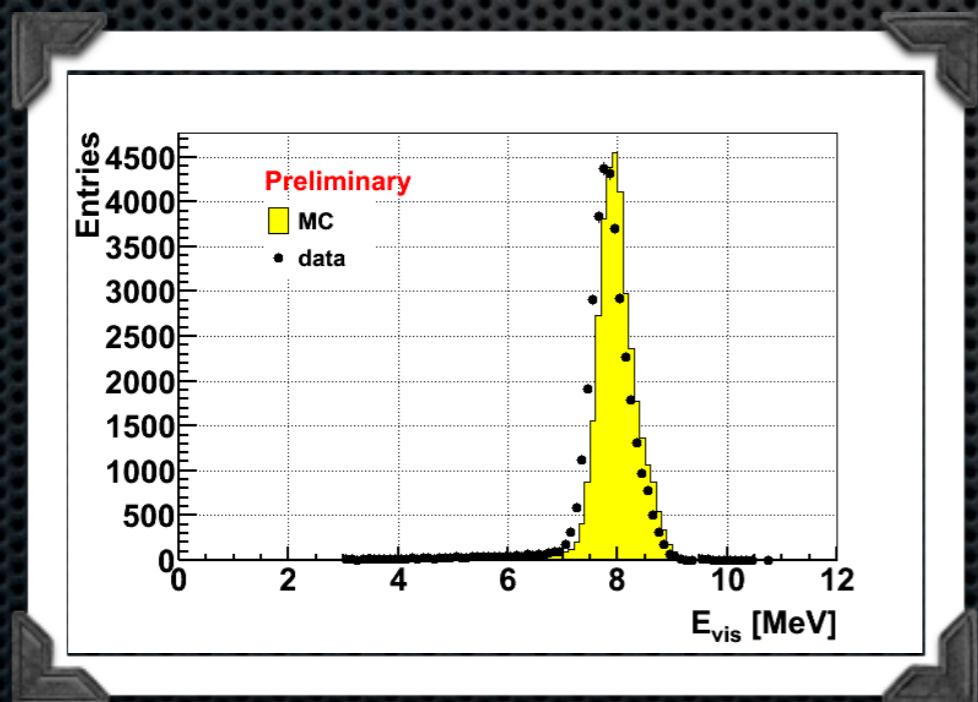
Oscillation analysis: two neutrino detection channels

Gd analysis

- Standard analysis
- High cross section for capture of thermal neutrons
- Capture time $\sim 30\mu\text{s}$
- Delayed energy: 8 MeV

H analysis

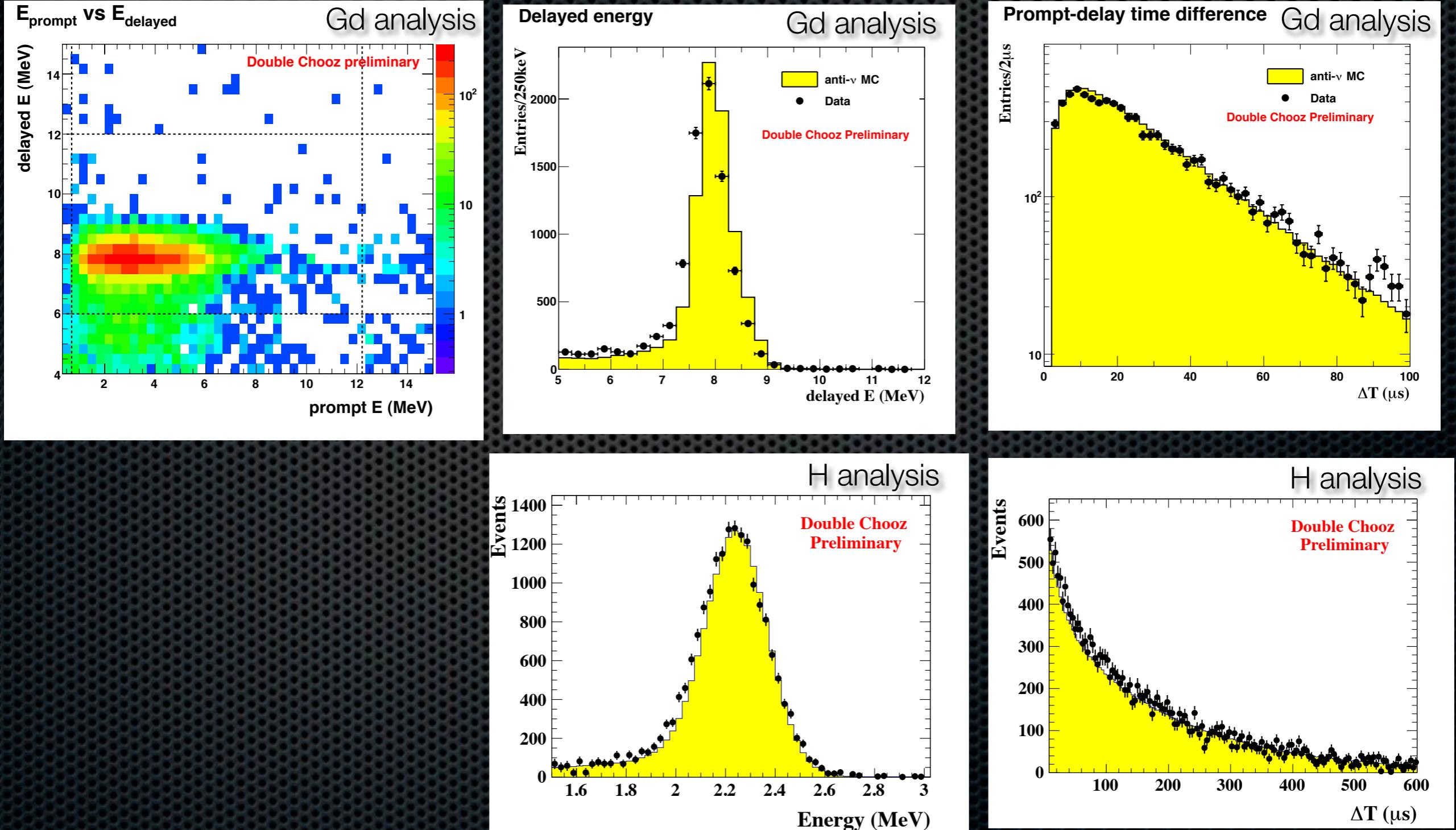
- Factor 2 more statistics: includes GC volume
- Different systematics
- Capture time $\sim 180\mu\text{s}$
- Delayed energy: 2.2 MeV



Neutrino selection

	Gd analysis	H analysis
Muon veto	$\Delta t > 1 \text{ ms}$	
Light noise rejection	$Q_{\max}/Q_{\text{tot}} < 0.09 \text{ (0.055)}$ & $\text{RMS}(\tau_{\text{start}}) < 40 \text{ ns}$	
E_{prompt}		0.7-12.2 MeV
E_{delayed}	6.0-12.0 MeV	1.5-3.0 MeV
ΔT	2-100 μs	10-600 μs
Δd	—	< 0.9 m
Multiplicity	No additional triggers around signal	
OV veto	No OV hit coincident with prompt	
Showering muon veto	$\Delta t_\mu (E_\mu > 600 \text{ MeV}) > 0.5 \text{ s}$	—

Candidates distributions



IBD candidates

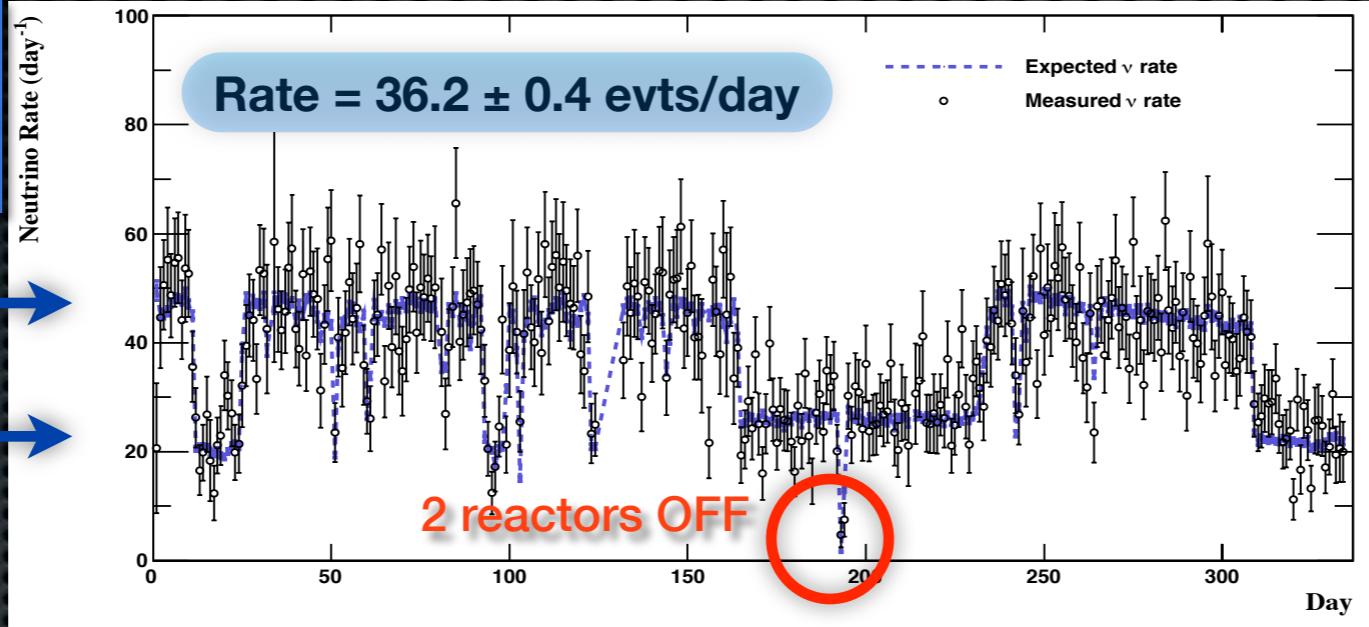
(April 2011-March 2012)

Gd analysis

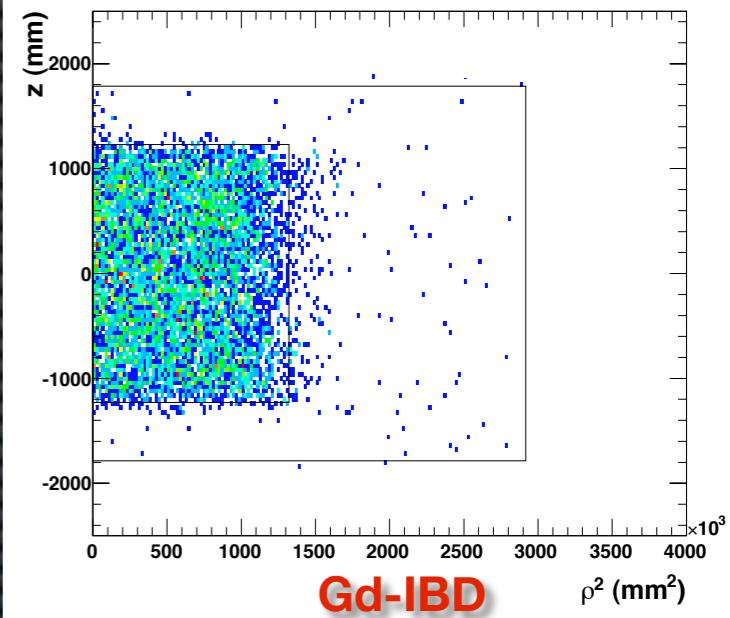
Live time = 227.93 days
Candidates = 8249

2 reactors ON

1 reactor ON

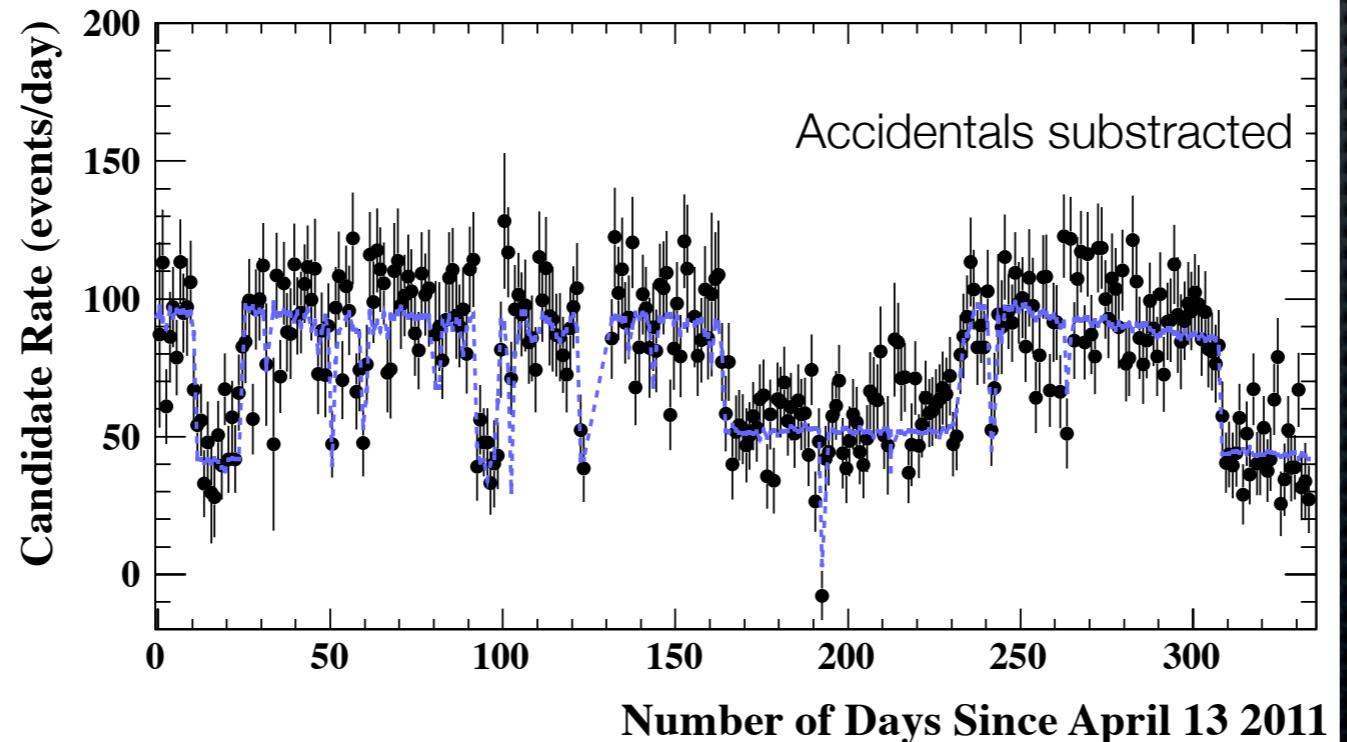


Vertex distribution

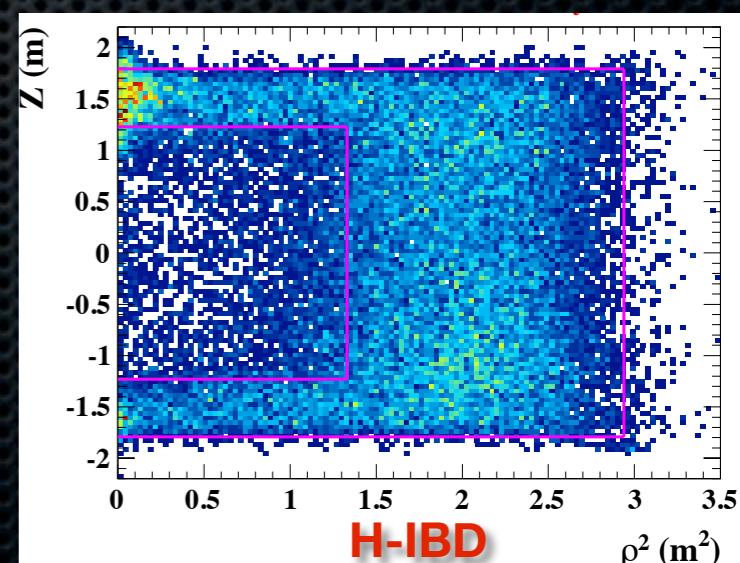


H analysis

Live time = 240.1 days
Candidates = 36284



$S/B \approx 17$

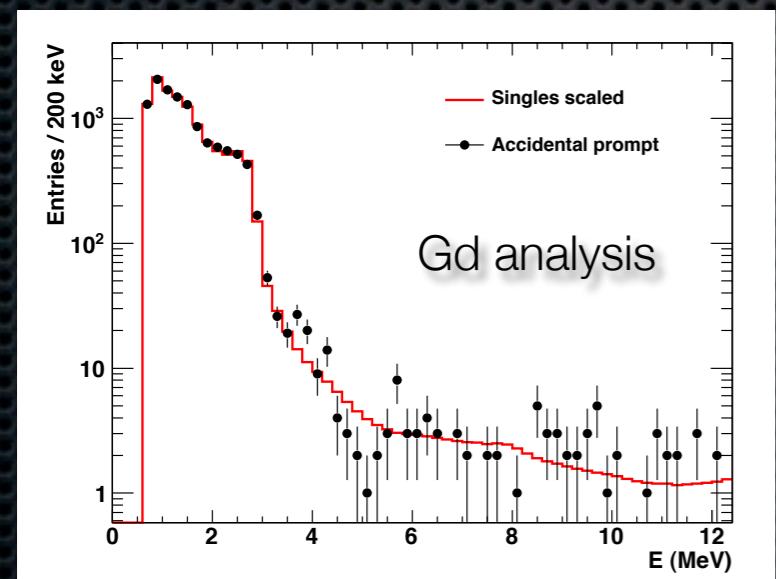


$S/B \approx 1$

Background estimations

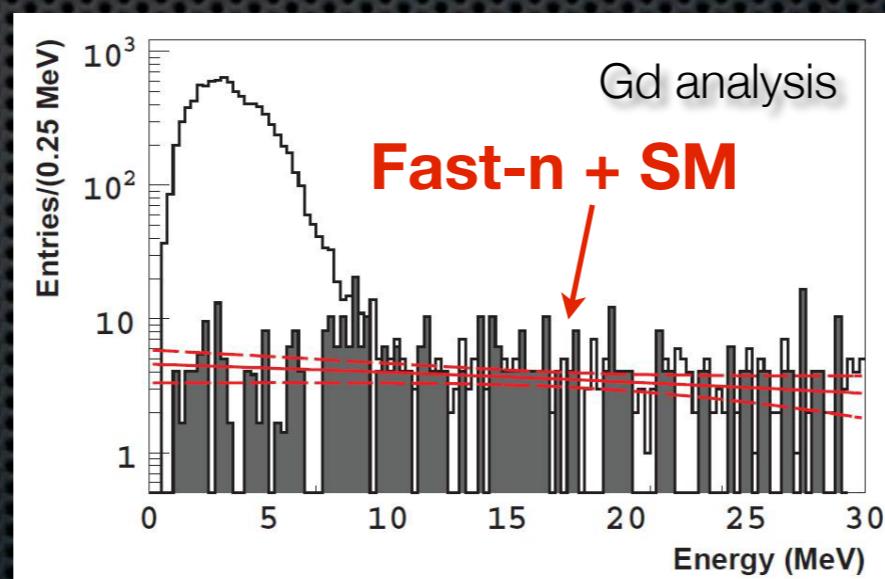
Accidentals:

- Stable along data taking period
- Determined by off-time window
 - Gd: 0.261 ± 0.002 evts/day
 - H: 73.5 ± 0.2 evts/day
- Rate and shape: data-driven



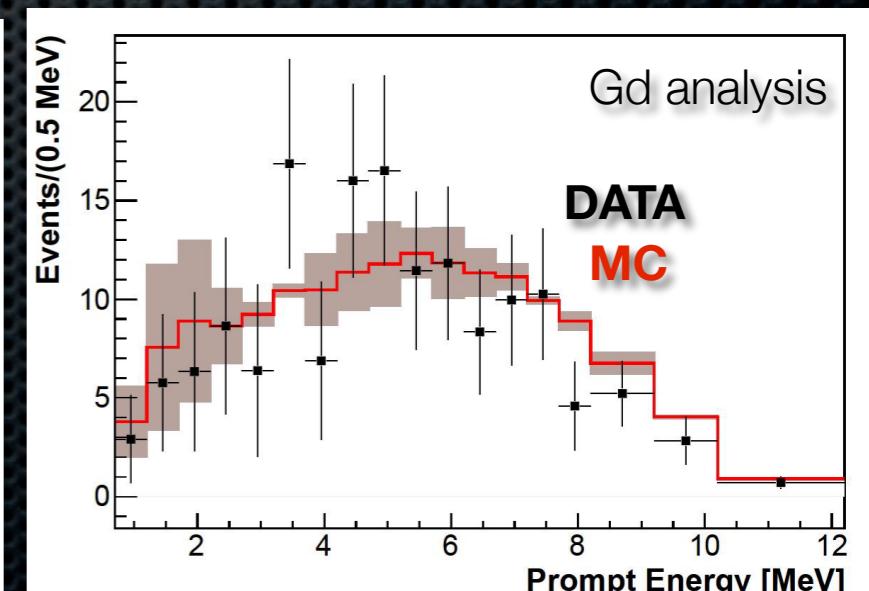
Fast-n and stopping μ 's:

- Prompt energy extended up to 30 MeV
- Rate: IV-tagged events
 - Gd: 0.67 ± 0.20 evts/day
 - H: 2.5 ± 0.5 evts/day
- Shape: from fit to tagged events



Cosmogenic background:

- ${}^9\text{Li}$ rate from Δt between showering muon and prompt event
 - Gd: 1.25 ± 0.54 evts/day
 - H: 2.8 ± 1.2 evts/day
- Energy spectrum from MC (poorly known)



Reactor neutrino flux prediction

Dominant source of systematic errors in DC phase-I

Expected neutrino flux

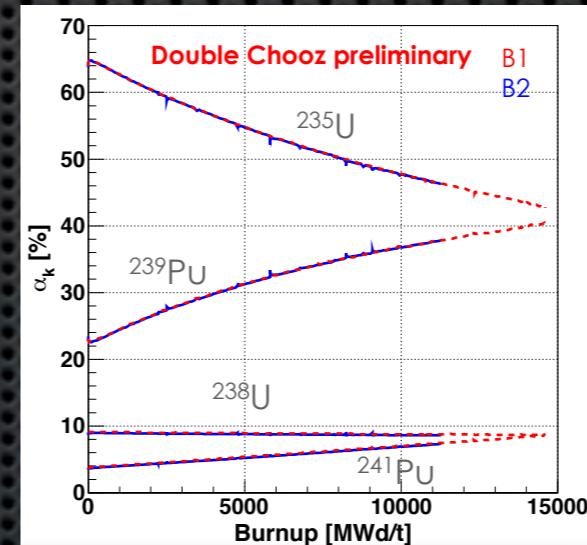
$$N_\nu^{\text{exp}}(t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

- ϵ = detection efficiency
- N_p = number of protons in fiducial volume
- L = distance between reactor and far detector
- $P_{th}(t)$ = thermal power of reactor

Average energy per fission:

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle \quad (\text{from EdF & simulations})$$

$\alpha_k(t)$ = **fractional fission rate** of k isotope
 $k = {}^{235}\text{U}, {}^{238}\text{U}, {}^{239}\text{Pu}, {}^{241}\text{Pu}$

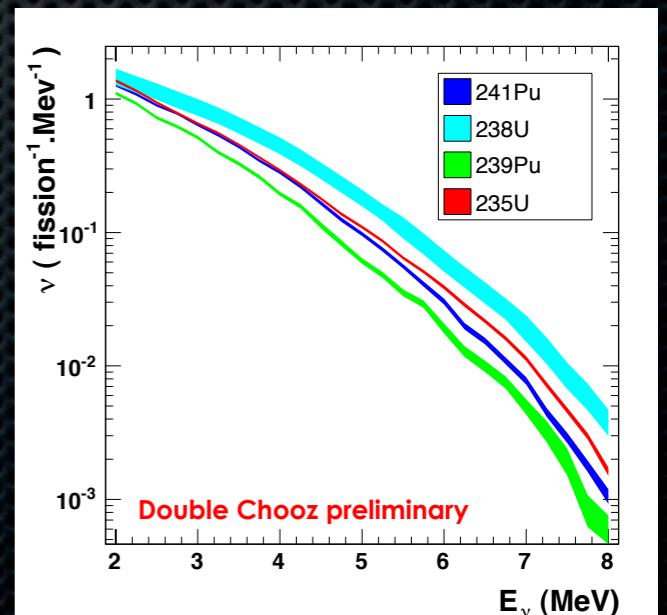


Average cross section per fission:

→ anchored to Bugey4 measurement at $L=15\text{m}$

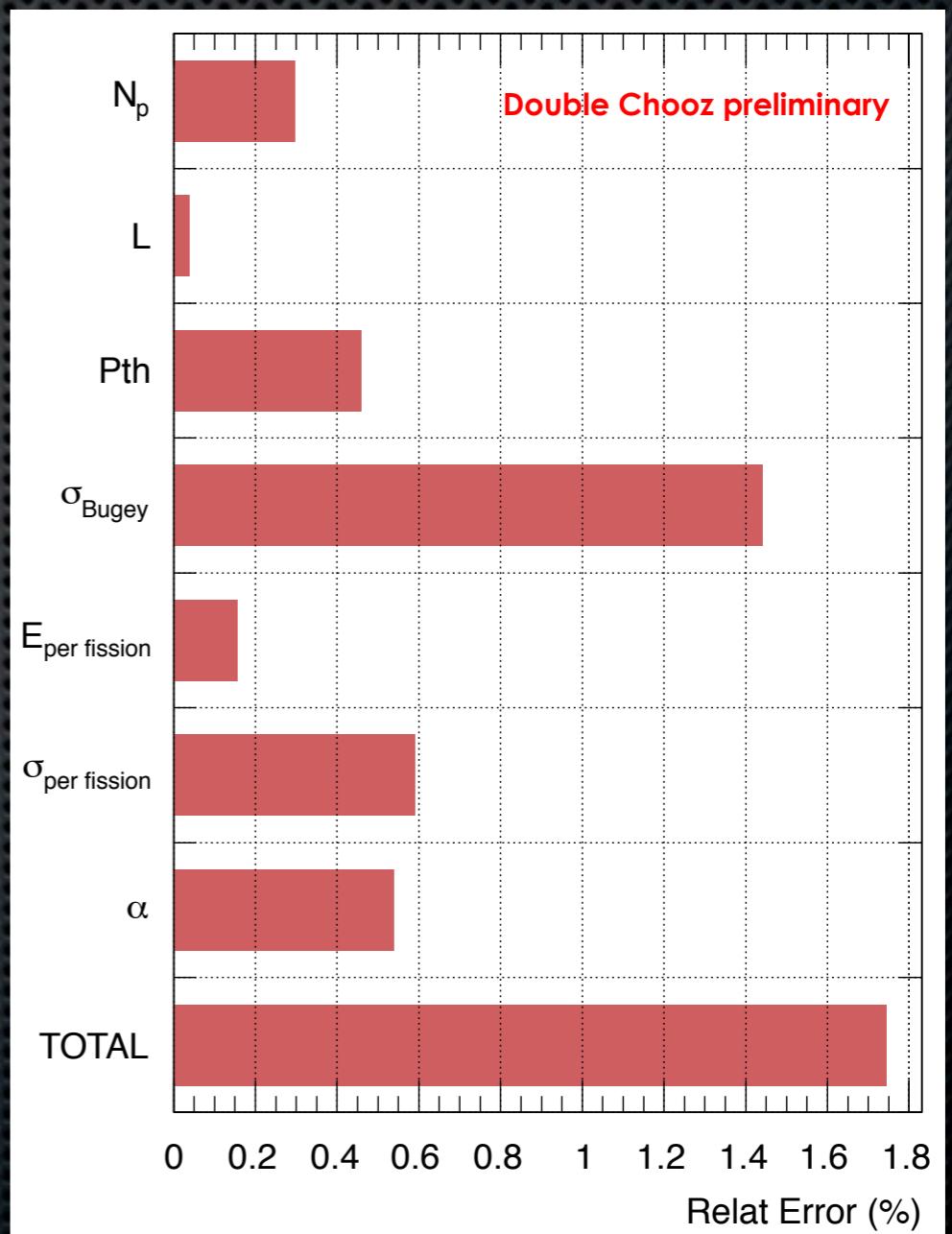
$$\langle \sigma_f \rangle_k = \int_0^\infty dE S_k(E) \sigma_{IBD}(E)$$

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{\text{Bugey}} + \sum_k (\alpha_k^{DC}(t) - \alpha_k^{\text{Bugey}}(t)) \langle \sigma_f \rangle_k \quad (\text{from simulations & measurements})$$



Total relative error on the predicted neutrino rate

- Bugey4 measurement suppresses sensitivity to reference spectra (σ_f)
- Accurate reactor simulation with MURE keep contribution of the uncertainty on fission rates low
- **TOTAL = 1.75% of total error**



Summary of signal and background events

	Gd analysis	H analysis
Livetime (days)	227.93	240.1
IBD candidates (evts)	8249	36284
Neutrino prediction (no-osc)	8439.6	17690
Cosmogenic isotopes	284.9	680
Correlated Fast-n + SM	152.7	600
Accidentals	59.5	17630
Light noise	—	80
Total prediction	8936.7	36680

Uncertainties

- Normalization uncertainties (relative to signal):

	Gd analysis	H analysis
Statistical error	1.1%	1.1%
Reactor antineutrino flux	1.7%	1.7%
Energy scale	0.3%	0.3%
Efficiency	1.0%	1.6%
${}^9\text{Li}$ rate	1.4%	1.6%
Fast-n + SM rate	0.5%	0.6%
Accidentals rate	<0.1%	0.2%
Light noise	—	0.1%
TOTAL	2.7%	3.1%

- Spectrum shape uncertainties:

- Reactor $\bar{\nu}_e$ spectrum
- Energy scale
- Li spectrum
- Fast-n + SM spectrum

Rate + shape fit strategy

- Unique Double Chooz fit strategy

- Improves upon rate-based analysis by adding spectrum information
- Constrains backgrounds
- Fits data with specific oscillation shape

$$\chi^2 = \sum_{i,j}^{36} (N_i - N_i^{\text{pred}}) \times (M_{ij})^{-1} (N_j - N_j^{\text{pred}})^T$$

$$+ \frac{(\epsilon_{\text{FN/SM}} - 1)^2}{\sigma_{\text{FN/SM}}^2} + \frac{(\epsilon_{^9\text{Li}} - 1)^2}{\sigma_{^9\text{Li}}^2} + \frac{(\alpha_E - 1)^2}{\sigma_{\alpha_E}^2}$$
$$+ \frac{(\Delta m_{31}^2 - (\Delta m_{31}^2)_{\text{MINOS}})^2}{\sigma_{\text{MINOS}}^2}.$$

Covariance matrices, including spectrum shape uncertainties

$$M_{ij} = M_{ij}^{\text{sig}} + M_{ij}^{\text{det}} + M_{ij}^{\text{stat}} + M_{ij}^{\text{eff}} + \sum_b^{\text{Bkgnds}} M_{ij}^b.$$

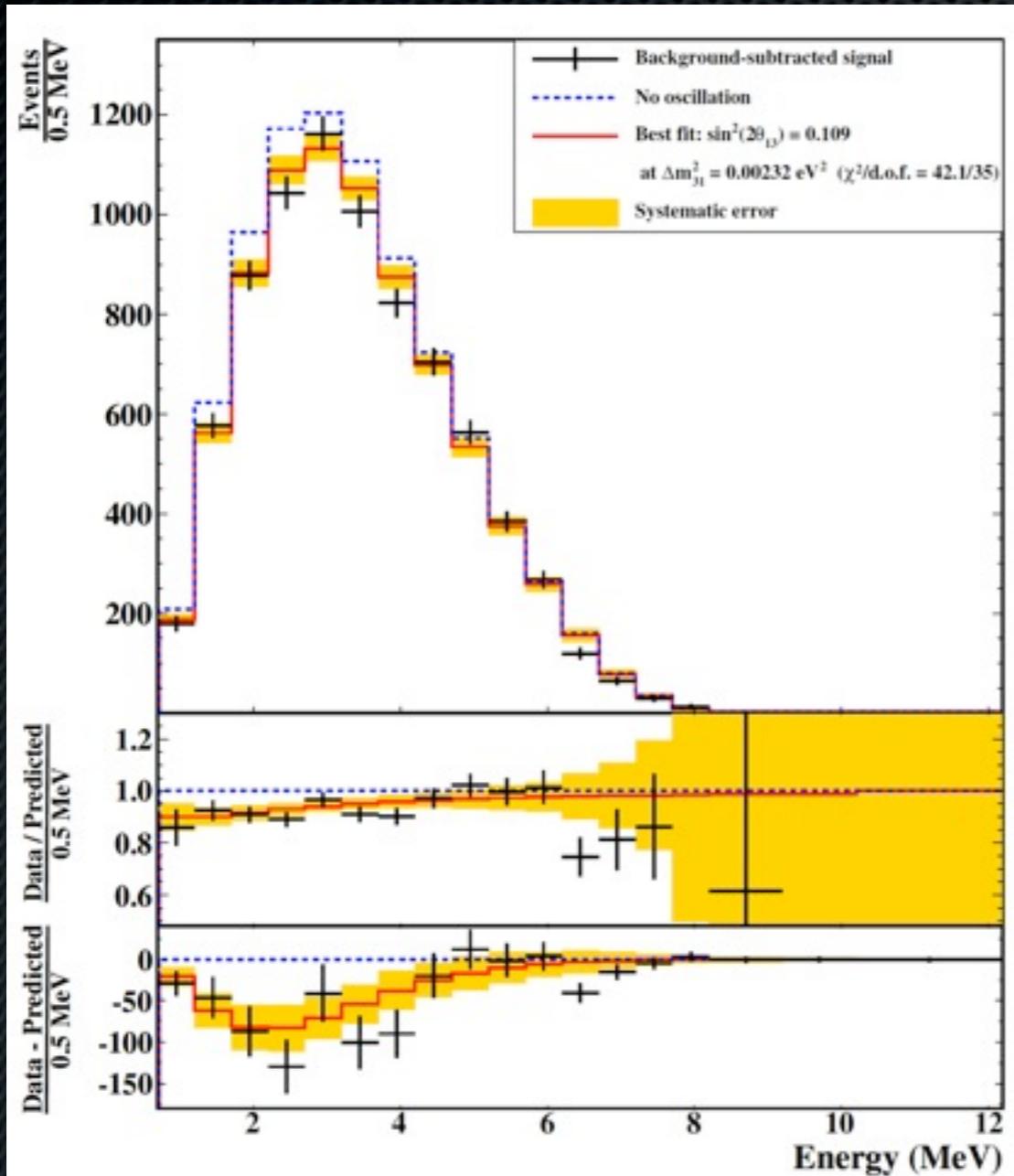


Pull terms on FN+SM rate,
Li rate, E scale and Δm^2

Rate + shape results

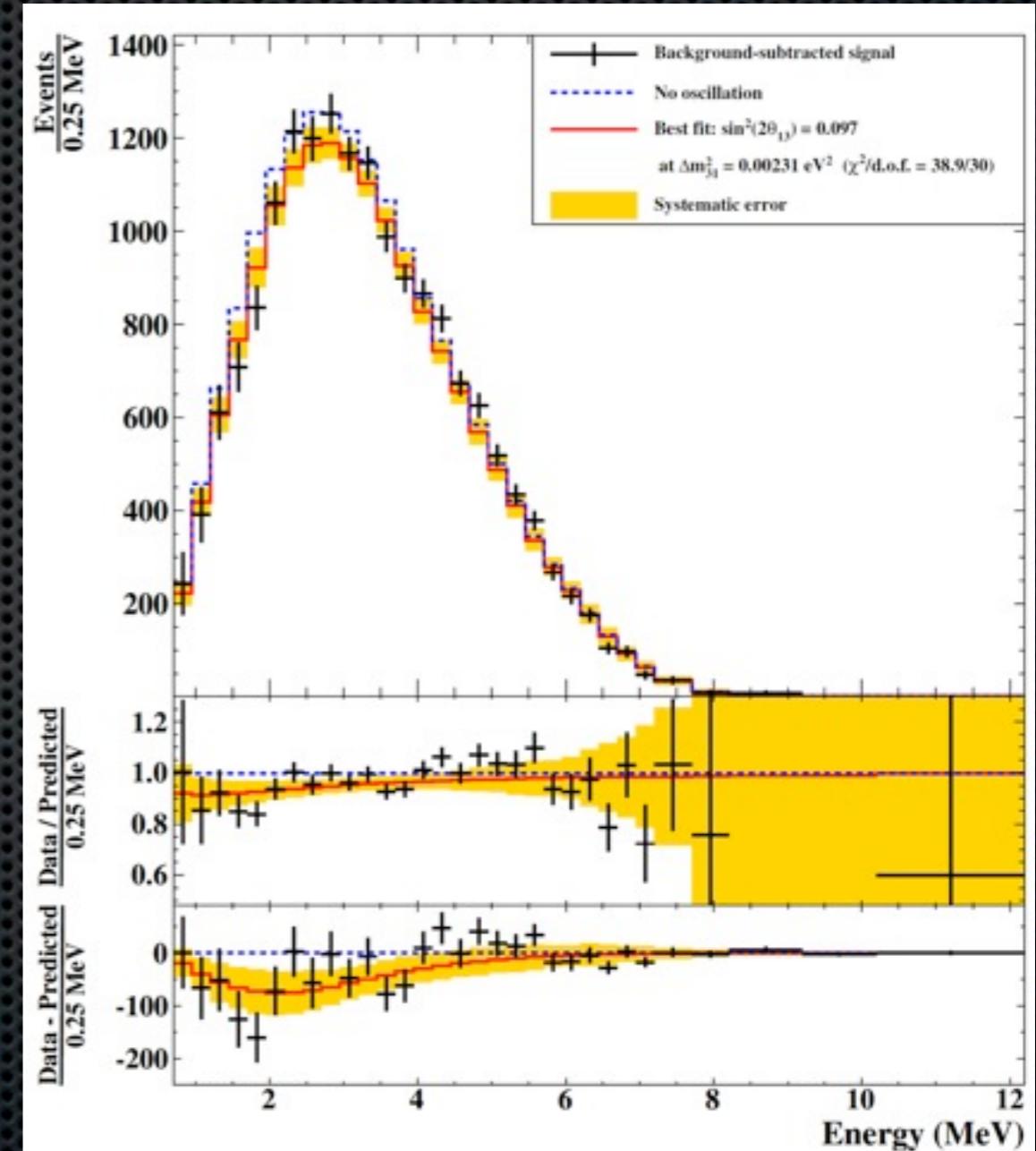
Gd analysis, June 2012

Phys. Rev. D86 (2012) 052008



H analysis, December 2012

Phys. Lett. B723 (2013) 66-70



$$\sin^2(2\theta_{13}) = \mathbf{0.109 \pm 0.039} [0.030^{\text{stat}} \pm 0.025^{\text{syst}}]$$

$$\sin^2(2\theta_{13}) = \mathbf{0.097 \pm 0.048} [0.034^{\text{stat}} \pm 0.034^{\text{syst}}]$$

Rate + shape constrains

- Background constrains from rate + shape fit:

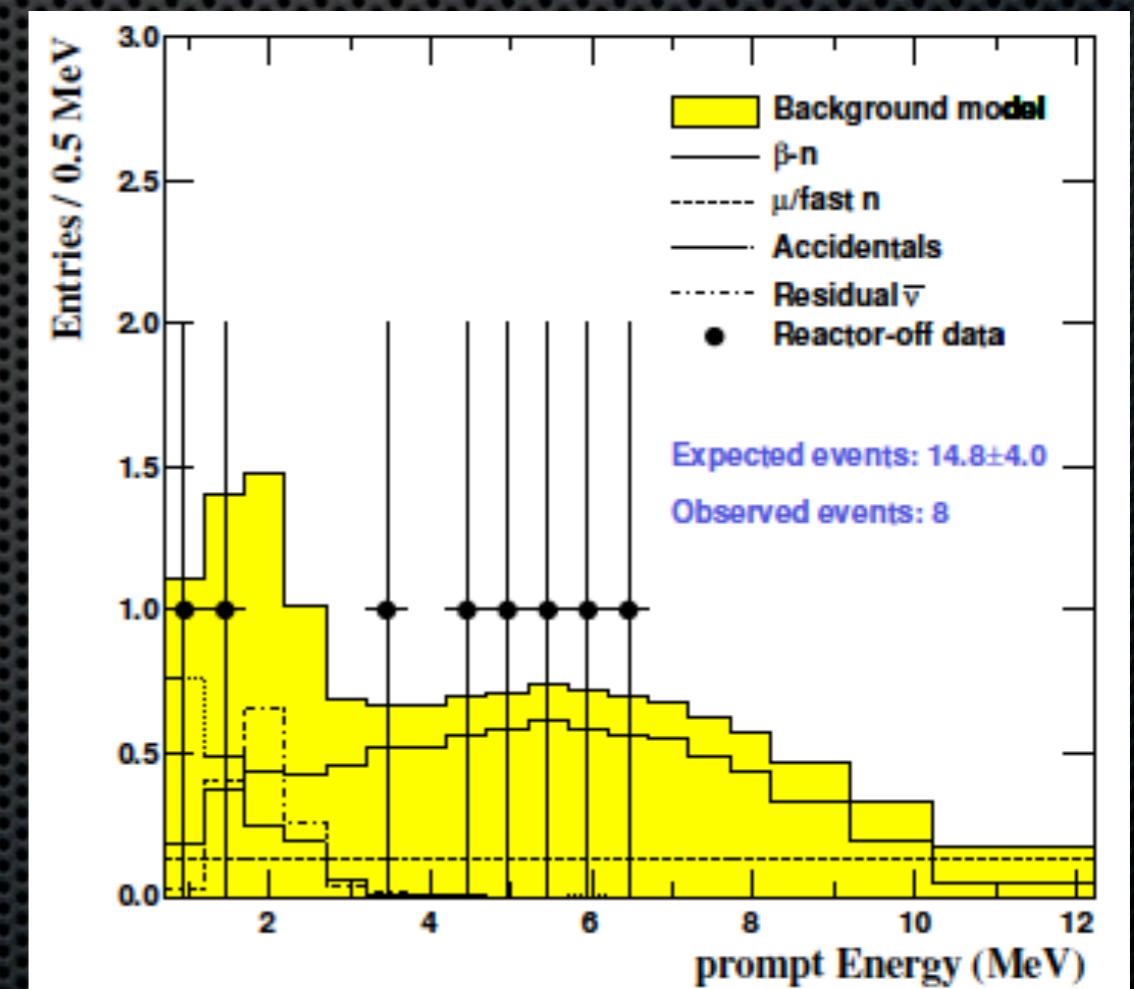
	Fit parameter	Initial value (rel. uncert.)	Final value (rel. uncert.)
Gd	${}^9\text{Li}$ backg.	$1.25 \pm 0.54 \text{ d}^{-1}$ (40%)	$1.00 \pm 0.29 \text{ d}^{-1}$ (30%)
	FN+SM backg.	$0.67 \pm 0.20 \text{ d}^{-1}$ (30%)	$0.64 \pm 0.13 \text{ d}^{-1}$ (20%)
H	${}^9\text{Li}$ backg.	$2.8 \pm 1.2 \text{ d}^{-1}$ (40%)	$3.9 \pm 0.6 \text{ d}^{-1}$ (15%)
	FN+SM backg.	$2.5 \pm 0.5 \text{ d}^{-1}$ (20%)	$2.6 \pm 0.4 \text{ d}^{-1}$ (15%)

- Energy scale and Δm^2 are also adjusted to reach best fit

Reactor off background measurements

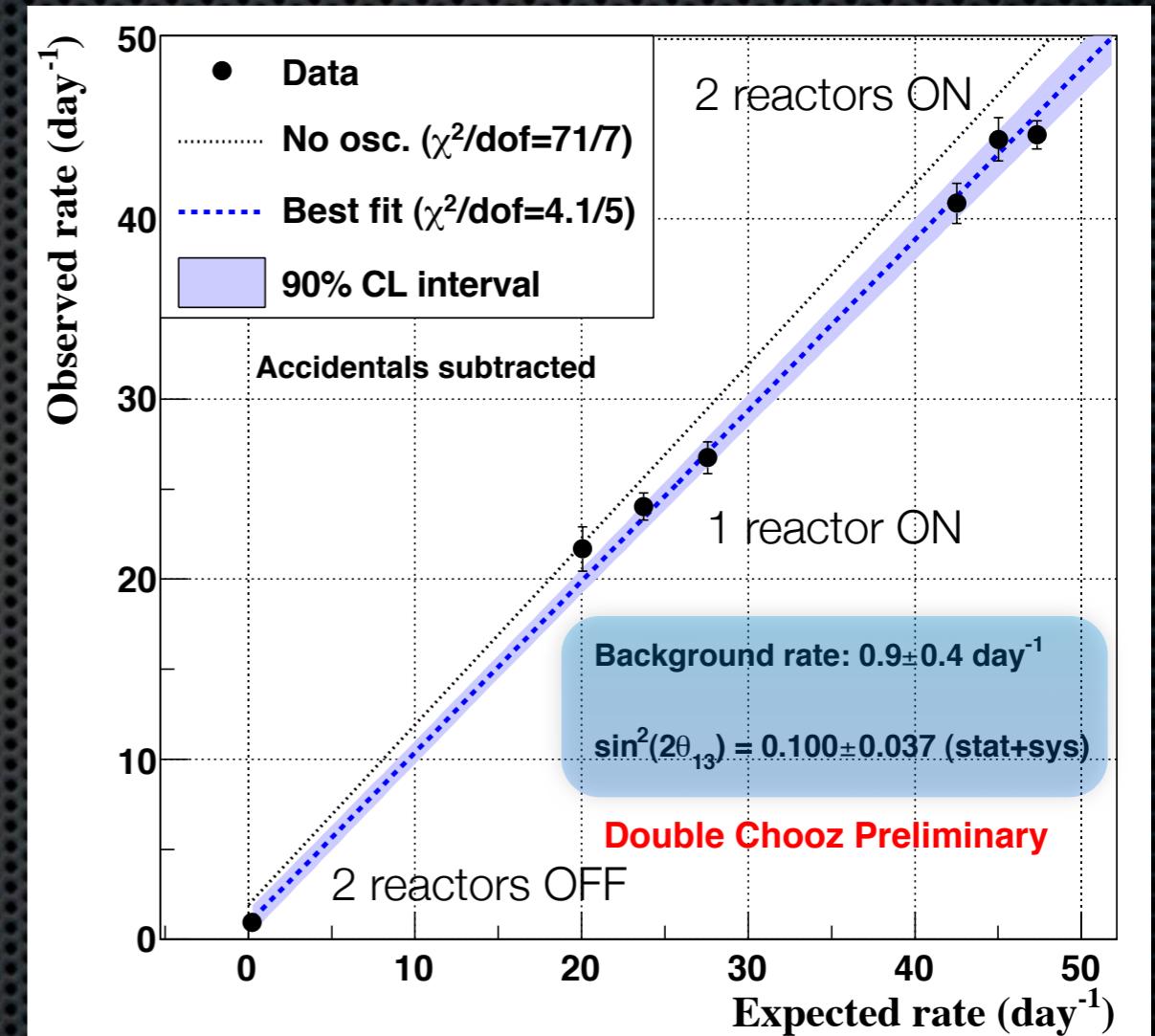
Phys. Rev. D87 (2013) 011102(R)

- 7.5 days of data with both reactors off
- Unique Double Chooz capability!
- Same selection than for Gd analysis
- Rate consistent with predictions
 - Observed: $1.0 \pm 0.4 \text{ d}^{-1}$
 - Predicted: $2.0 \pm 0.6 \text{ d}^{-1}$
- New constraint for oscillation fit



Reactor rate modulation (RRM) analysis

- Rate-only background-independent analysis
 - Observed vs expected $\bar{\nu}_e$ candidates rate using different reactor power
 - Fit provides $\sin^2 2\theta_{13}$ and the total background rate
- No background model assumed
- It includes the background reactors-off measurement



**In agreement (~same precision)
with DC R+S results:**

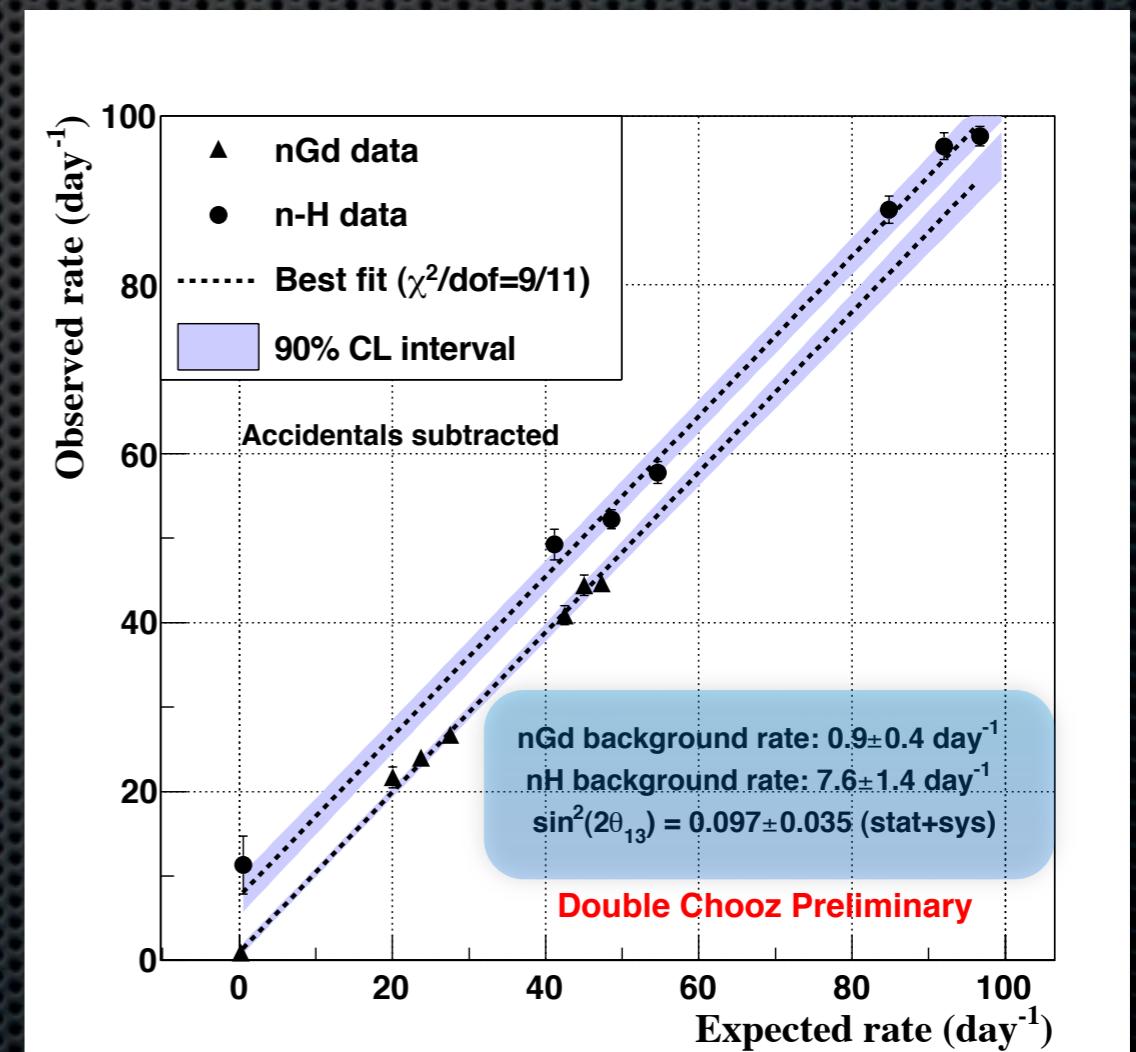
$$\sin^2(2\theta_{13}) = 0.109 \pm 0.039; \text{ Total BG: } 1.6 \pm 0.3 \text{ d}^{-1}$$

First combined Gd + H fit

- Combination of published Gd and H analyses

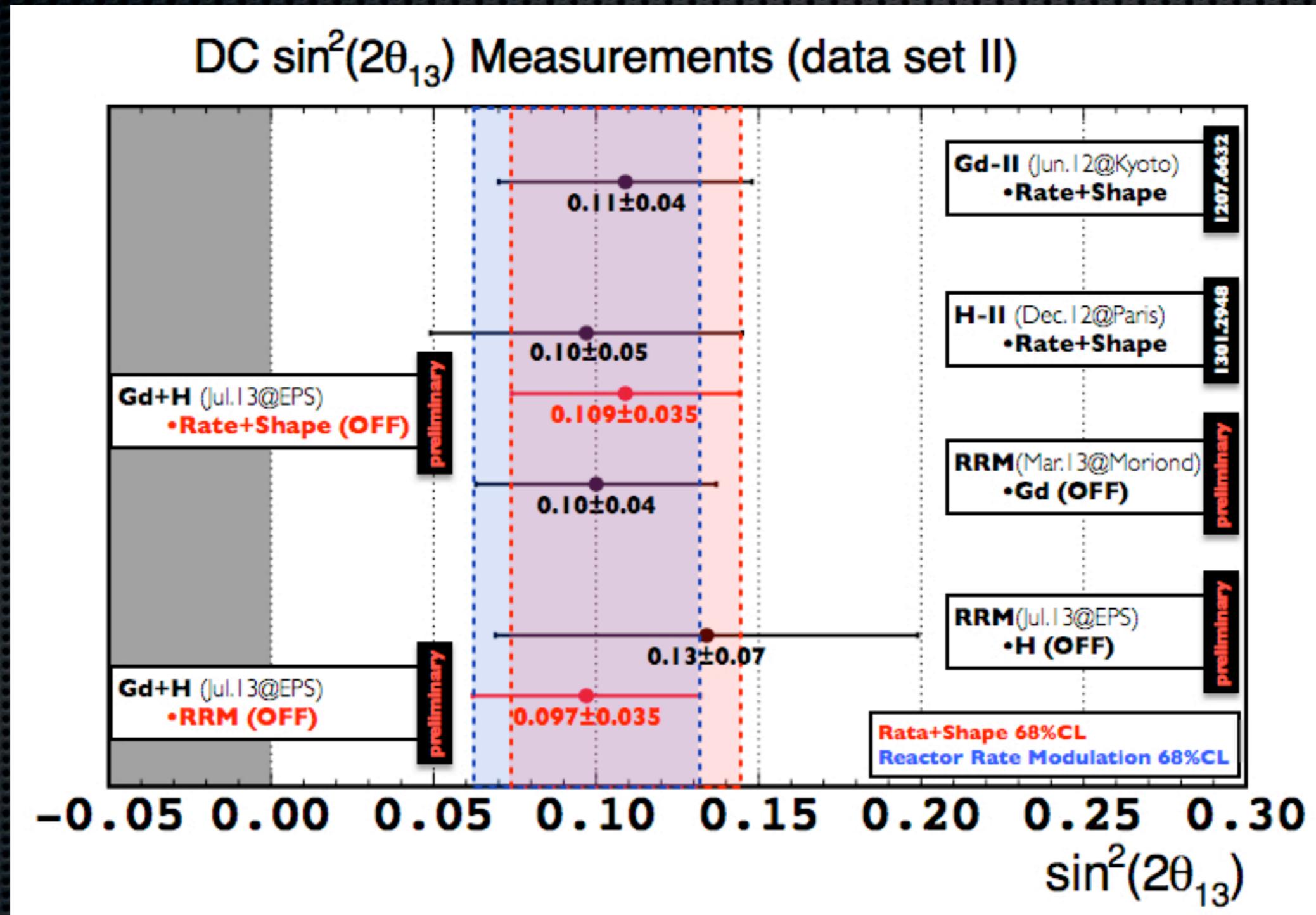
- April 2011 - March 2012
- Fit includes correlation of systematic errors
- Backgrounds constrained by reactor-off measurements
- Rate + shape preliminary result:
 - $\sin^2(2\theta_{13}) = 0.109 \pm 0.035$
- Rate only preliminary result:
 - $\sin^2(2\theta_{13}) = 0.107 \pm 0.045$

RRM analysis for Gd+H fit



Small impact on central values
Precision improvement

Summary of DC results



Near detector

- Construction ongoing
- Expected near detector data taking: spring 2014
- Projected final precision ~10%



Conclusions and prospects from Double Chooz

- ❖ Double Chooz has demonstrated the **robustness of its analyses**
 - ❖ Many independent background validations (estimation from sub-samples, R+S fit output, reactor-off measurement, RRM analysis)
 - ❖ Consistent θ_{13} results from independent analyses (R+S Gd, H, RRM, combined Gd+H...)
- ❖ Currently **finishing new improved analysis** including...
 - ❖ Statistics ($> 2x$)
 - ❖ Optimized selection: S/BG
 - ❖ Reduced systematics
- ❖ Near + Far detector analysis (mid. 2014)
 - ❖ Reactor flux uncertainty almost cancels!
 - ❖ Projected final precision $\sim 10\%$

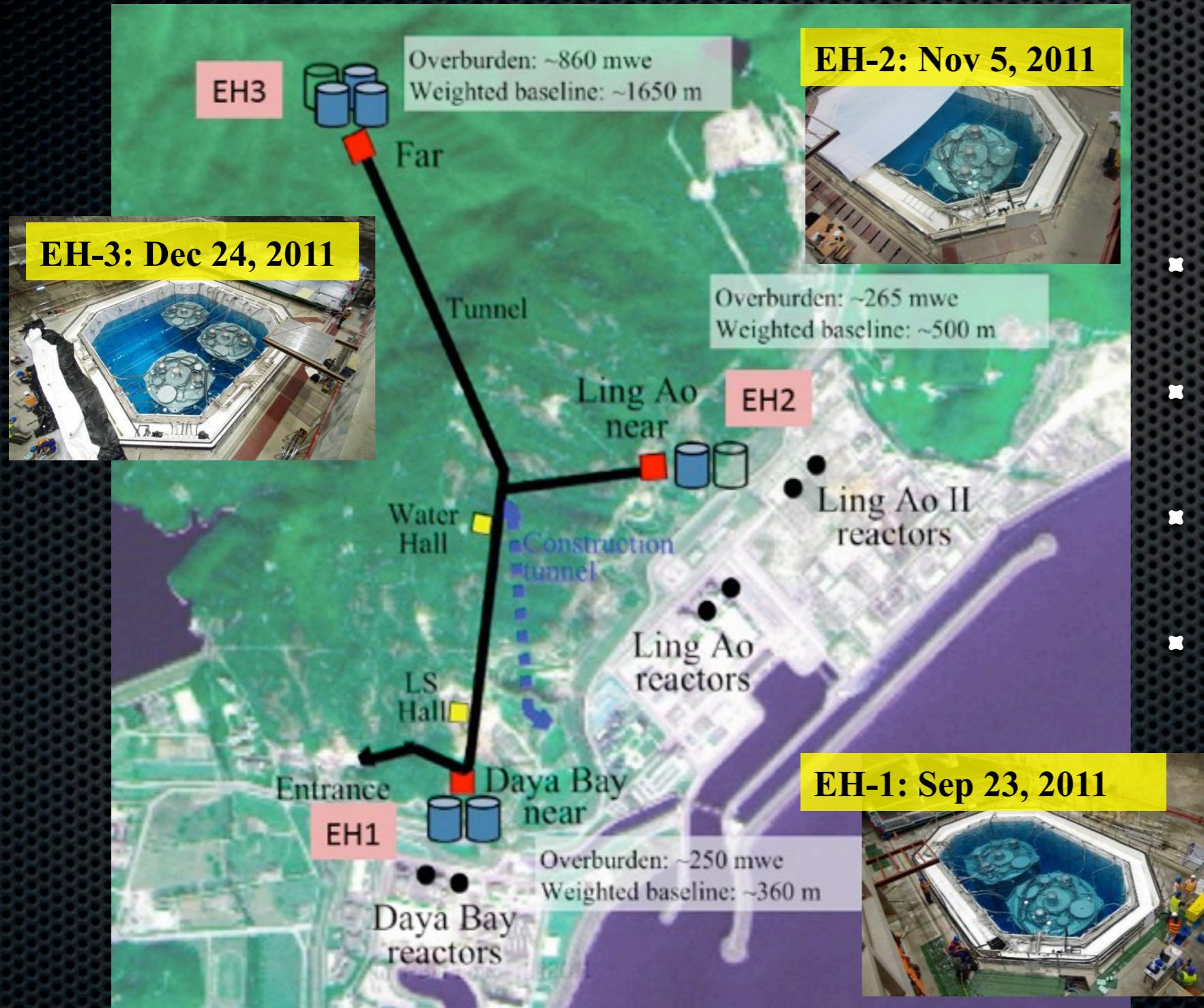
Daya Bay



Daya Bay collaboration



DB experimental layout



- 2 near and 1 far underground locations
- 8 detectors placed at different distances
- 6/8 detectors (20 ton each) are used for next results
- $6 \times 2.9 \text{ GW}_{\text{th}}$ reactor power

DB detectors

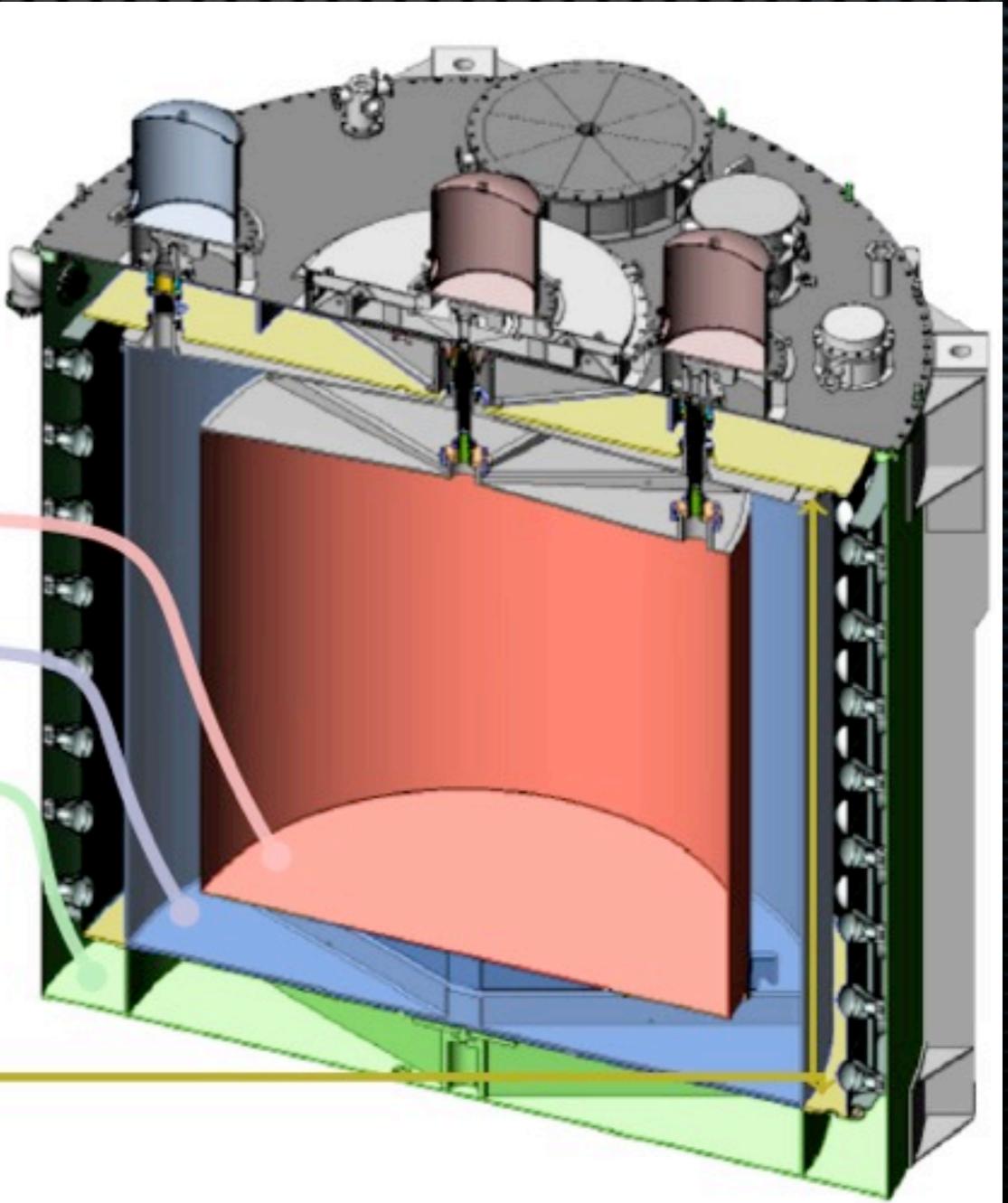
8 functionally identical detectors
reduce systematic uncertainties

3 zone cylindrical vessels

	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response



Daya Bay Calibration System

3 'robots' employed along 3 z-axes

- 1 Center of GdLS target volume
- 2 Edge of GdLS target volume
- 3 Middle of LS gamma catcher volume

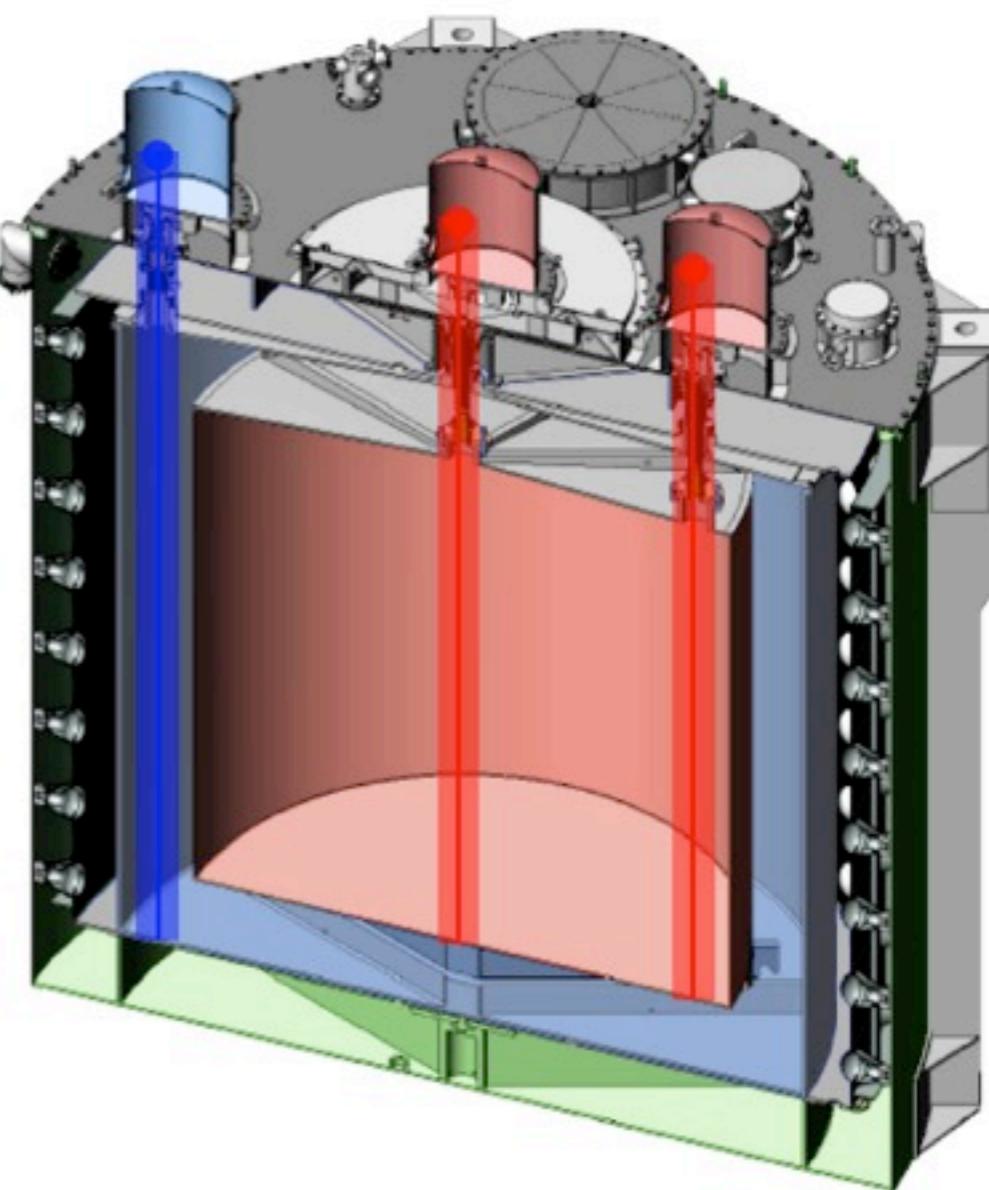
3 sources in each robot (employed weekly)

- 1 ^{68}Ge ($2 \times 511\text{ keV } \gamma$)
- 2 $^{241}\text{Am}^{13}\text{C}$ (n) + ^{60}Co ($1.17+1.33\text{ MeV } \gamma$)
- 3 LED diffuser ball

Additional temporary sources

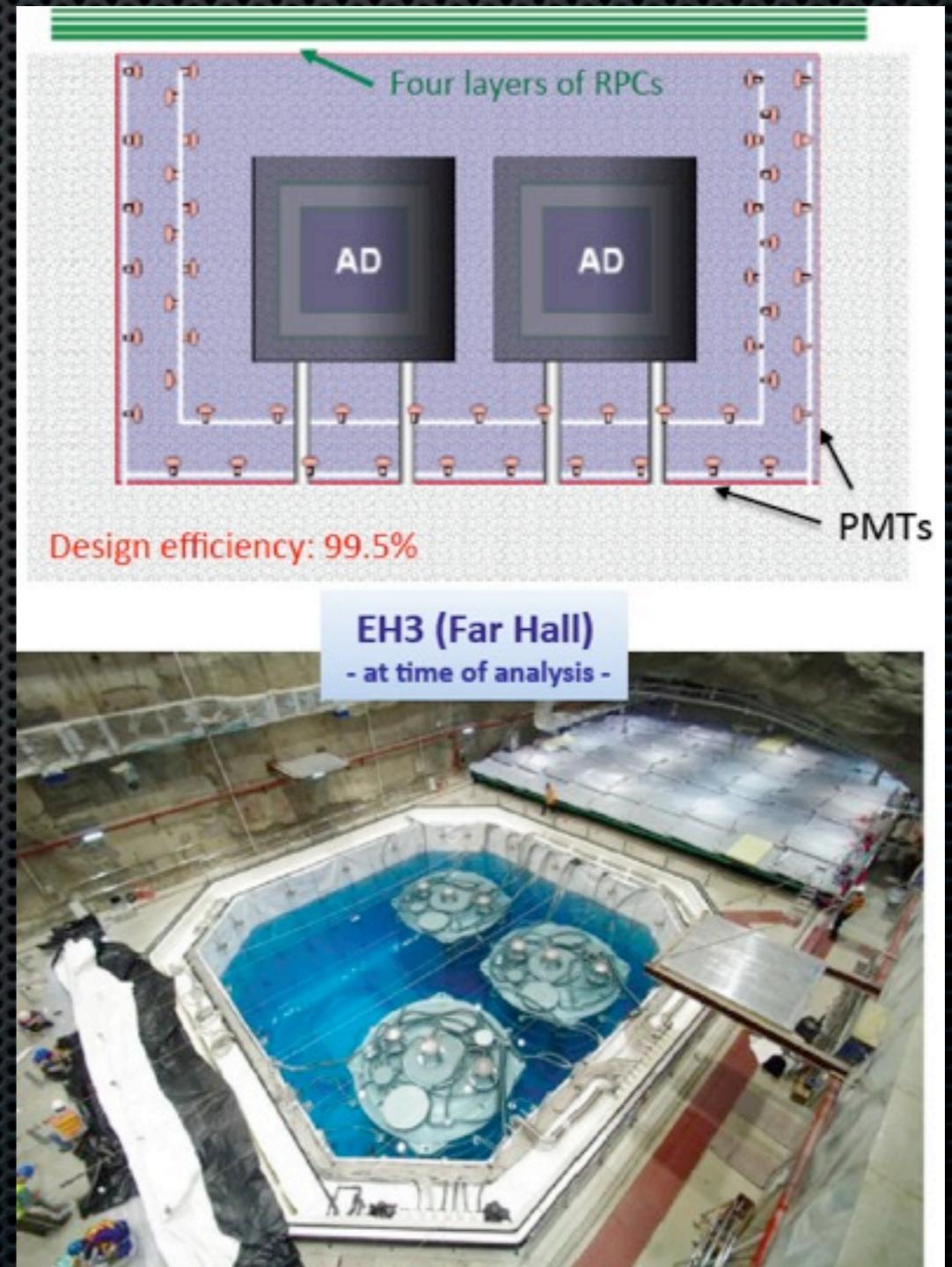
- 1 Gamma sources:
 - ▶ ^{137}Cs (0.662 MeV)
 - ▶ ^{54}Mn (0.835 MeV)
 - ▶ ^{40}K (1.461 MeV)
- 2 Neutron sources
 - ▶ ^{241}Am - ^9Be , ^{239}Pu - ^{13}C

$r = 1.775\text{ m}$ $r = 0$ $r = 1.35\text{ m}$



Muon veto systems

- Daya Bay detectors are immersed in an instrumented water pool
- Shield gammas from ambient radioactivity and neutrons produced by cosmic rays
- Serves as a Cerenkov detector to tag cosmic muons (reducing backgrounds)



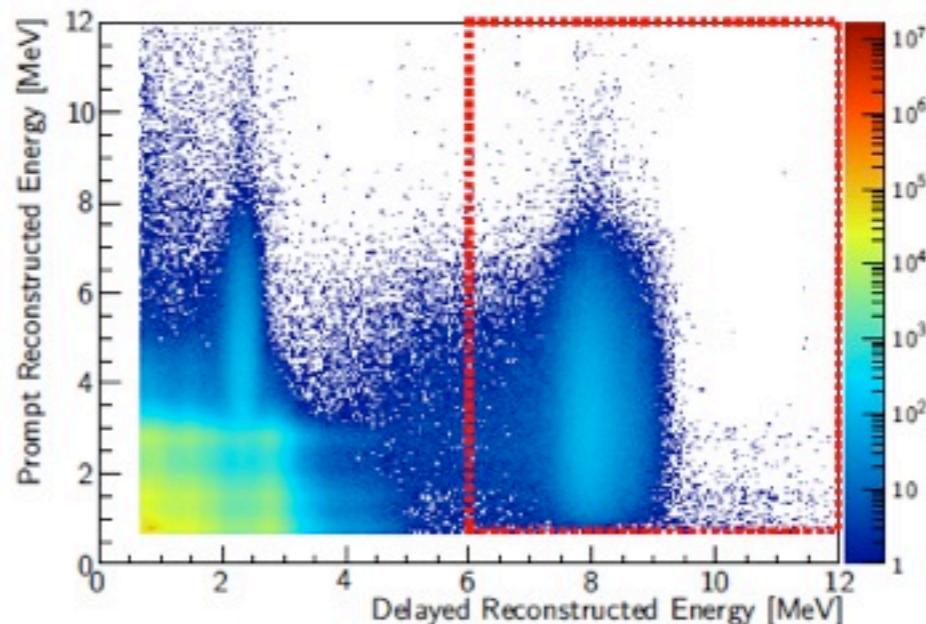
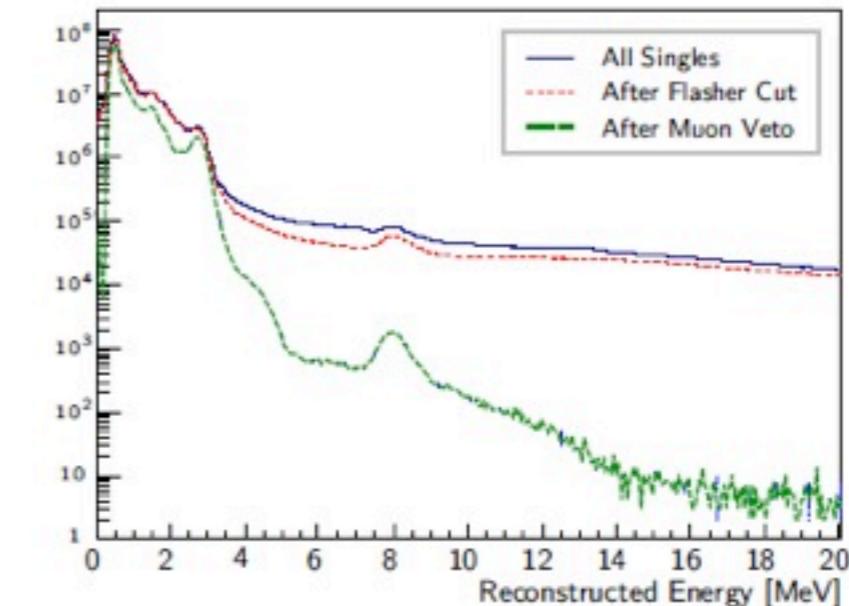
Daya Bay main results

- “Observation of electron-antineutrino disappearance at Daya Bay”,
Phys. Rev. Lett. 108 (2012) 171803
 - 55 days of data, 6 detectors N+F
 - $\sin^2(2\theta_{13}) = 0.092 \pm 0.016 \text{ (stat.)} \pm 0.005 \text{ (syst.)}$ (no-osc excluded at 5.2σ)
- “Improved measurement of electron antineutrino disappearance at Daya Bay”, *Chinese Phys. C*37 (2013) 011001
 - 139 days of data, 6 detectors N+F
 - $\sin^2(2\theta_{13}) = 0.089 \pm 0.010 \text{ (stat.)} \pm 0.005 \text{ (syst.)}$ (no-osc excluded at 7.7σ)
- Aug. 2013: First spectral analysis (*not published yet*)
 - 217 days, 6 detectors

Neutrino selection

Use IBD prompt+delayed coincidence signal

- 1 Reject spontaneous PMT light emission ("flashers")
- 2 Prompt positron:
 $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
- 3 Delayed neutron:
 $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
- 4 Neutron capture time:
 $1 \mu\text{s} < \Delta t < 200 \mu\text{s}$
- 5 Muon veto:
 - ▶ Water pool muon (>12 hit PMTs):
Reject $[-2\mu\text{s}, 600\mu\text{s}]$
 - ▶ AD muon ($>20 \text{ MeV}$):
Reject $[-2\mu\text{s}, 1400\mu\text{s}]$
 - ▶ AD shower muon ($>2.5 \text{ GeV}$):
Reject $[-2\mu\text{s}, 0.4\text{s}]$
- 6 Multiplicity:
 - ▶ No additional prompt-like signal
 $400\mu\text{s}$ before delayed neutron
 - ▶ No delayed-like signal
 $200\mu\text{s}$ after delayed neutron



Summary of signal and background events

	Near Halls			Far Hall		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (days)		191.001	189.645		189.779	
Efficiency $\epsilon_\mu \cdot \epsilon_m$	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (per day)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast-neutron (per day)*		0.92±0.46	0.62±0.31		0.04±0.02	
$^9\text{Li}/^8\text{He}$ (per day)*		2.40±0.86	1.2±0.63		0.22±0.06	
Am-C corr. (per day)*				0.26±0.12		
$^{13}\text{C}^{16}\text{O}$ backgr. (per day)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
IBD rate (per day)*	653.30±2.31	664.15±2.33	581.97±2.07	73.31±0.66	73.03±0.66	72.20± 0.66

* Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $\epsilon_\mu \cdot \epsilon_m$

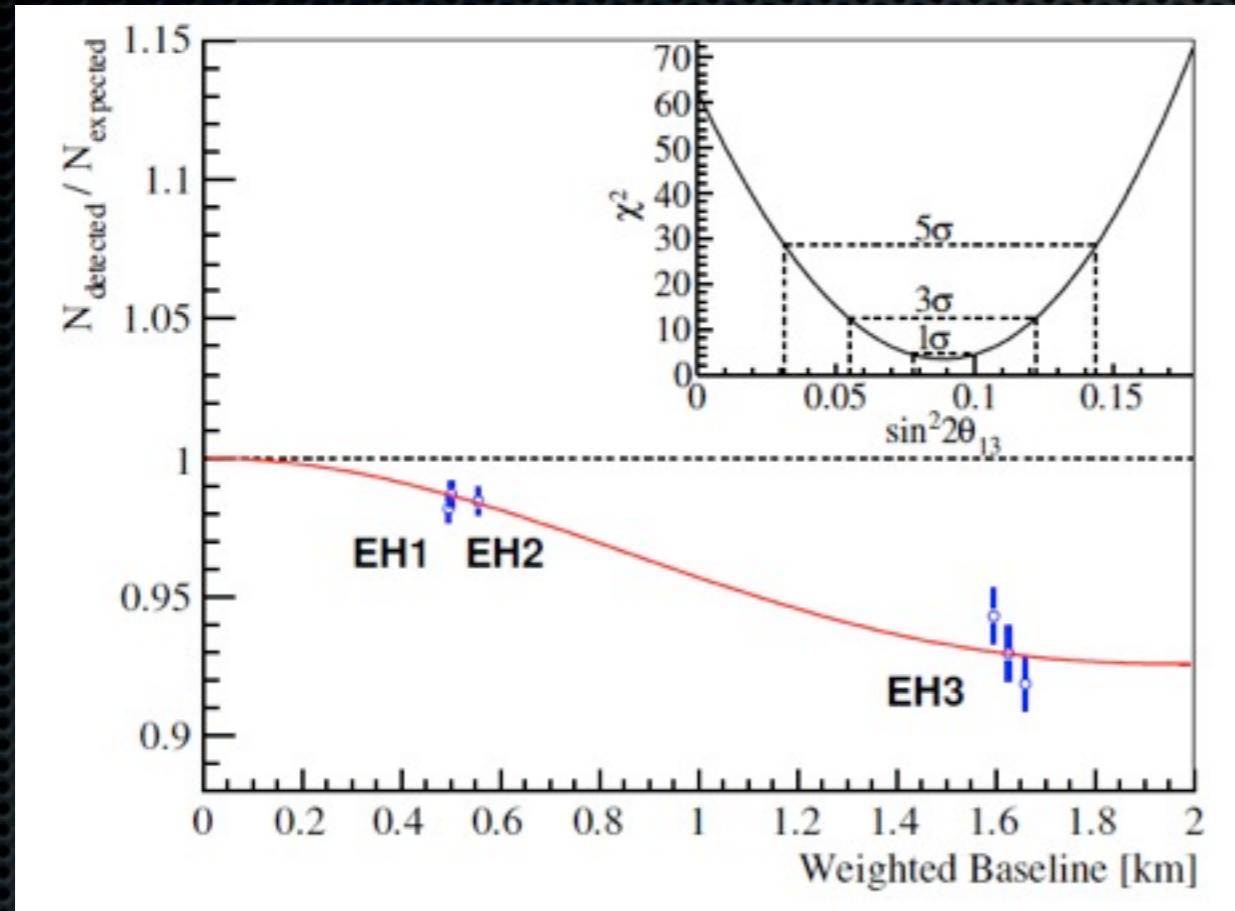
Uncertainties

	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%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

- Only uncorrelated uncertainties relevant to near/far oscillation analysis
- Largest systematics smaller than far site statistics (~1%)
- Impact of uncorrelated reactor systematics reduced by relative measurement

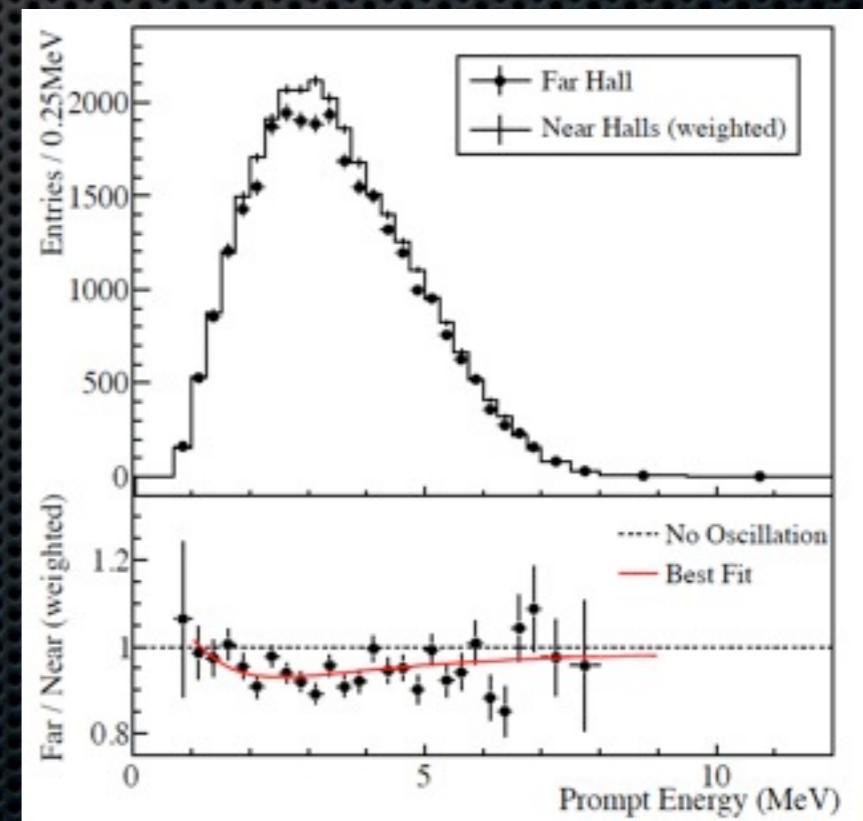
Rate oscillation fit



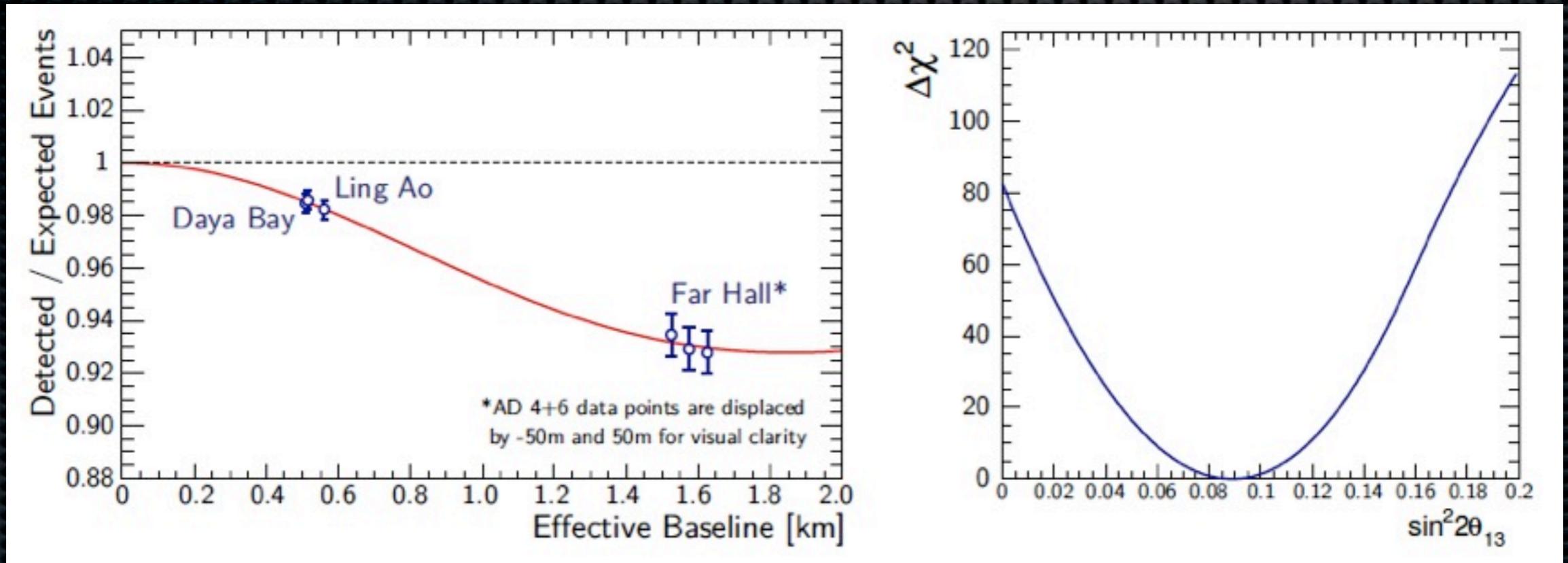
$R_{\text{obs/exp}} = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)}$
 (expected ratio 0.981 due to reactor core distance)

$$\begin{aligned} \chi^2 &= \sum_{d=1}^6 \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_d + B_d} \\ &+ \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^6 \left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2} \right) \end{aligned}$$

$\sin^2(2\theta_{13}) = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)}$
 $(\chi^2/\text{dof} = 3.4/4)$ 12.6% precision measurement



Unpublished rate osc. fit

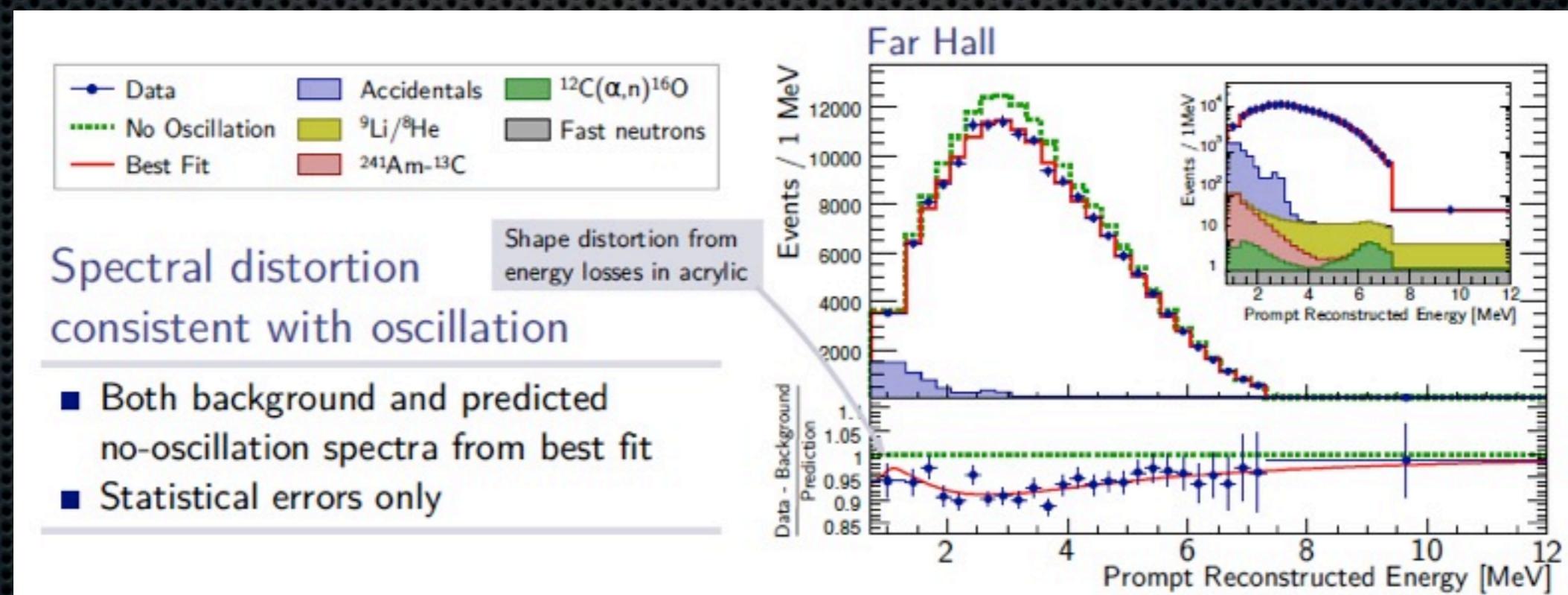
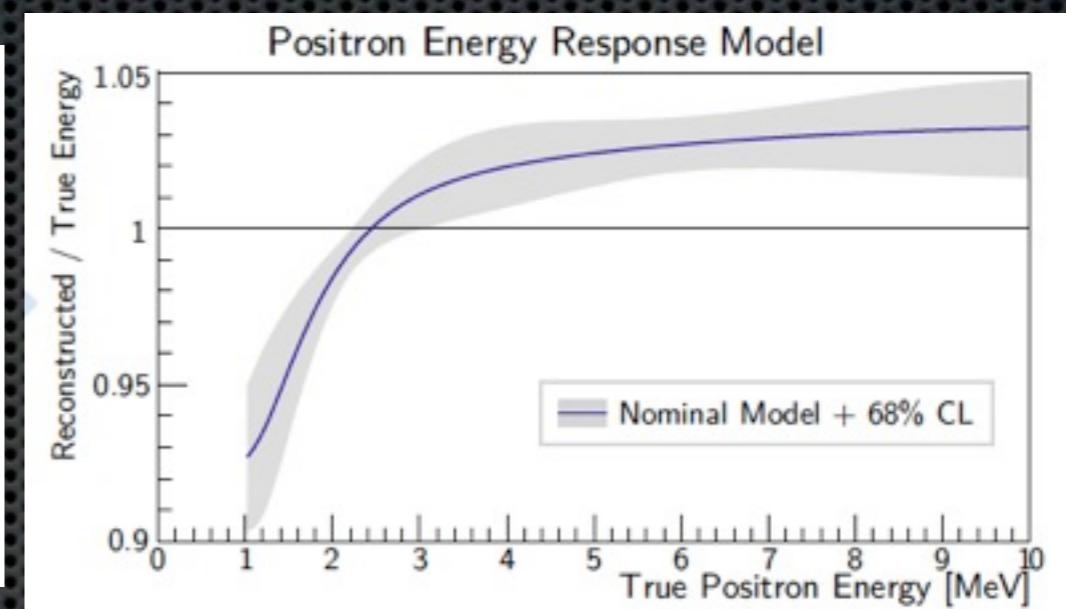
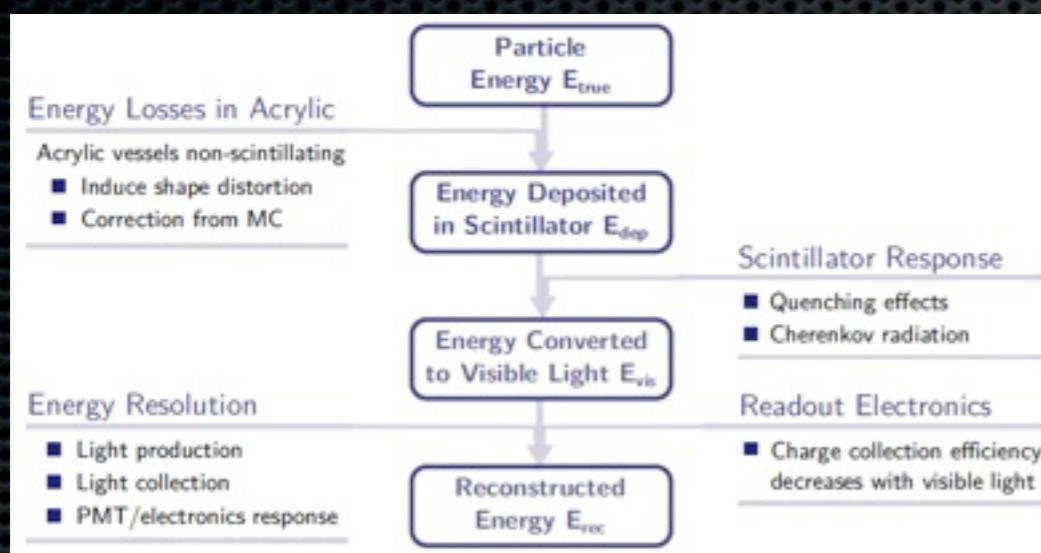


New result: $\sin^2(2\theta_{13}) = 0.089 \pm 0.009$

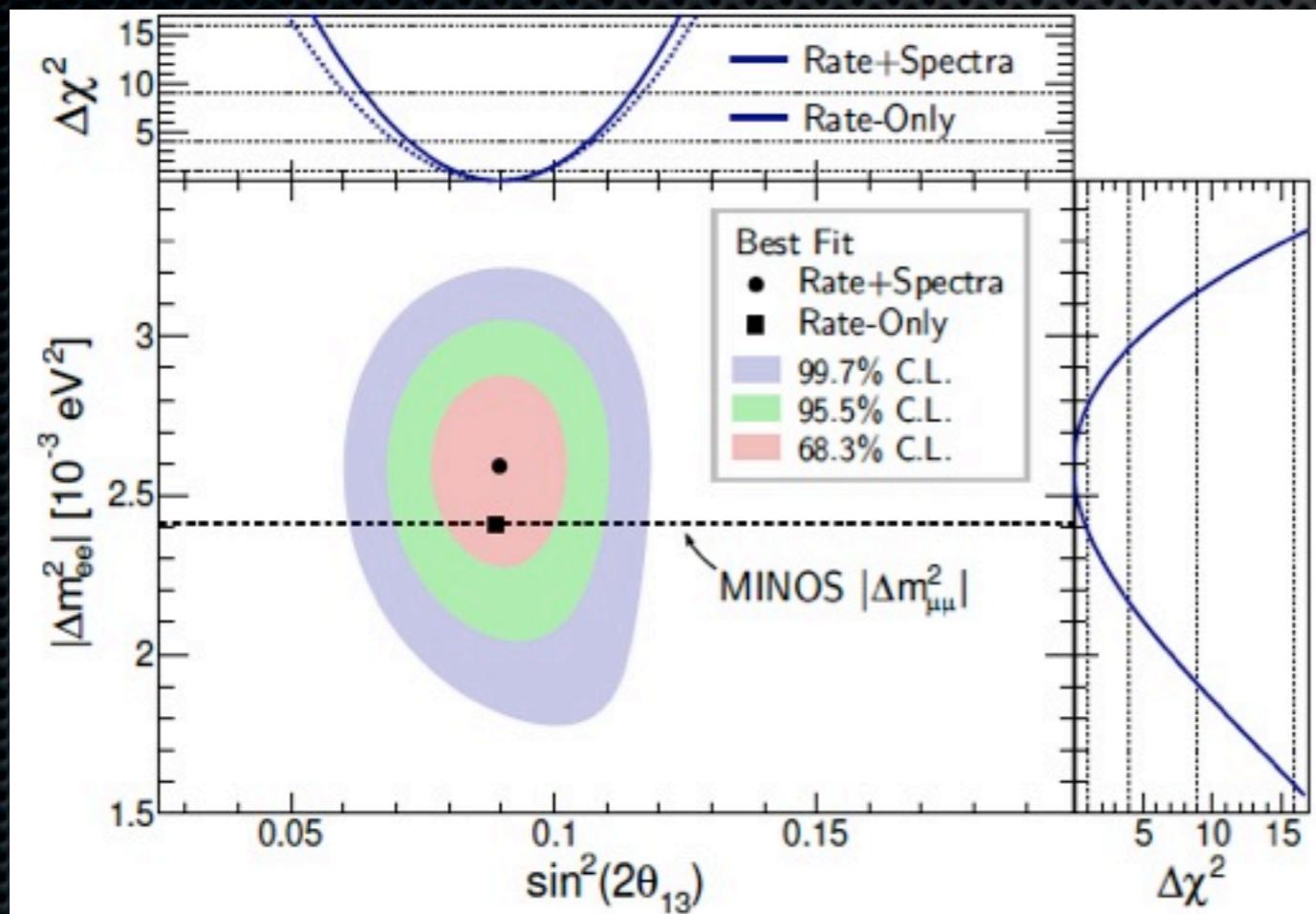
- Uncertainty reduced by statistics (217 days)
- Standard $\chi^2/\text{dof} = 0.48/4$

Energy response model

Complex energy conversion



Preliminary rate + shape fit



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

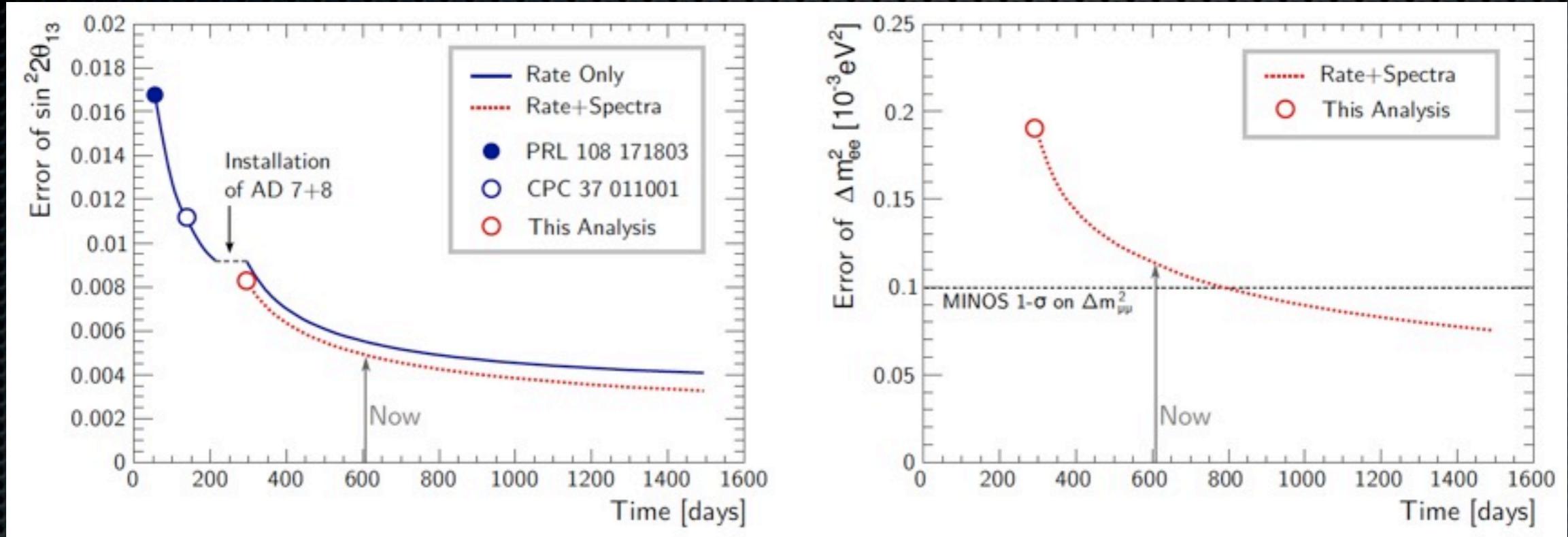
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3} \text{ eV}^2$$

$$\chi^2/N_{\text{DoF}} = 162.7/153$$

One effective oscillation frequency $|\Delta m^2_{ee}|$ is measured
Result consistent with MINOS

$$\begin{aligned} \sin^2(\Delta m^2_{ee} \frac{L}{4E}) \equiv & \cos^2 \theta_{12} \sin^2(\Delta m^2_{31} \frac{L}{4E}) \\ & + \sin^2 \theta_{12} \sin^2(\Delta m^2_{32} \frac{L}{4E}) \end{aligned}$$

Projected sensitivity



- Statistics contribute $\sim 73\% \sim 65\%$ to total uncertainty in $\sin^2\theta_{13}$ ($|\Delta m_{ee}^2|$)
- Precision of mass splitting measurement close to results from μ flavor sector

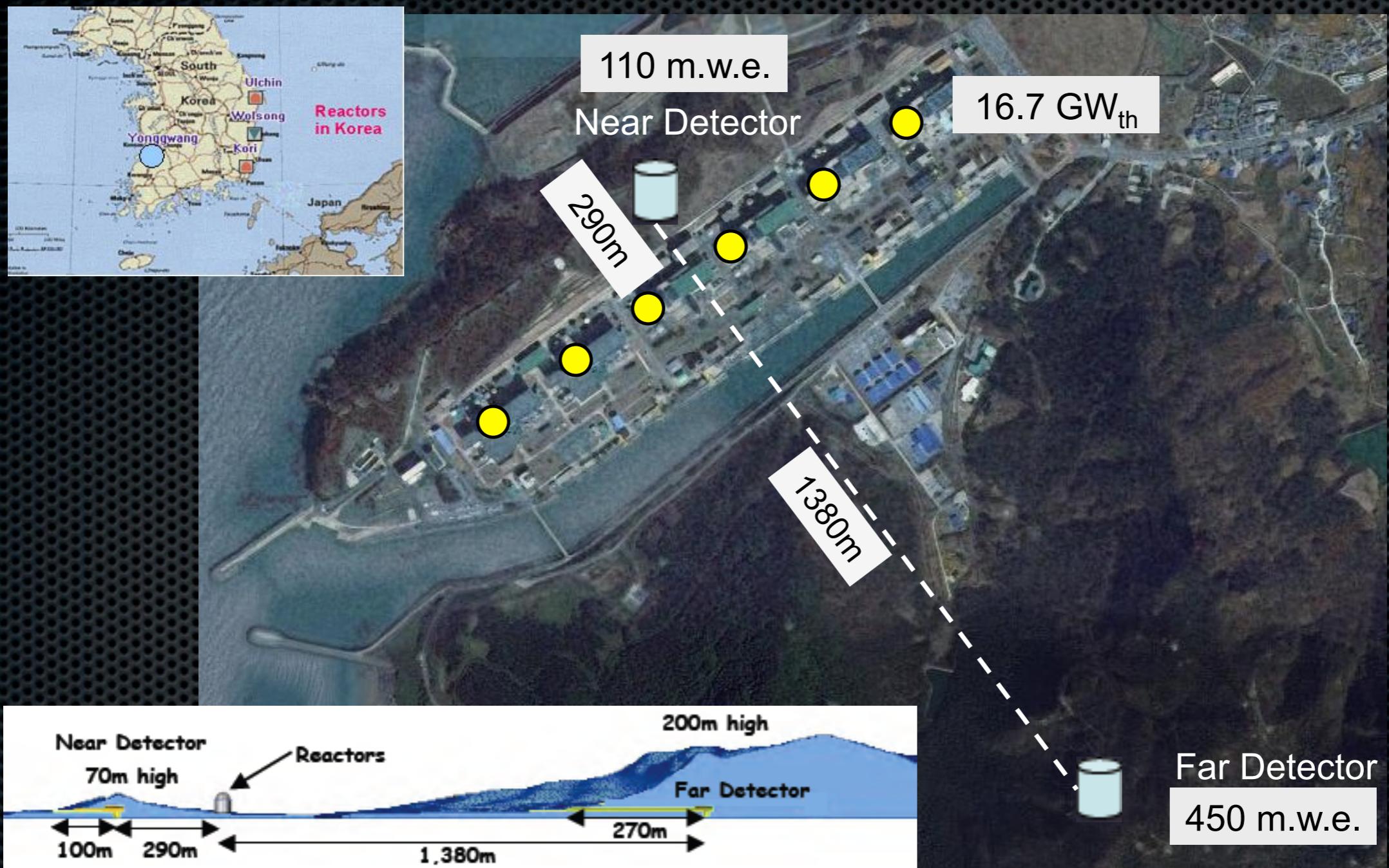
Daya Bay future goals

- Measure θ_{13} with high precision ($\sim 4\%$ in 3 years)
- Measure $|\Delta m^2_{ee}|$ complementary to accelerator-based experiments (final precision $< 0.1 \times 10^{-3} \text{ eV}^2$)
- Measure reactor flux/spectrum: resolve ambiguities in reactor predictions and anomaly
- Run for at least 3 years (~2015)

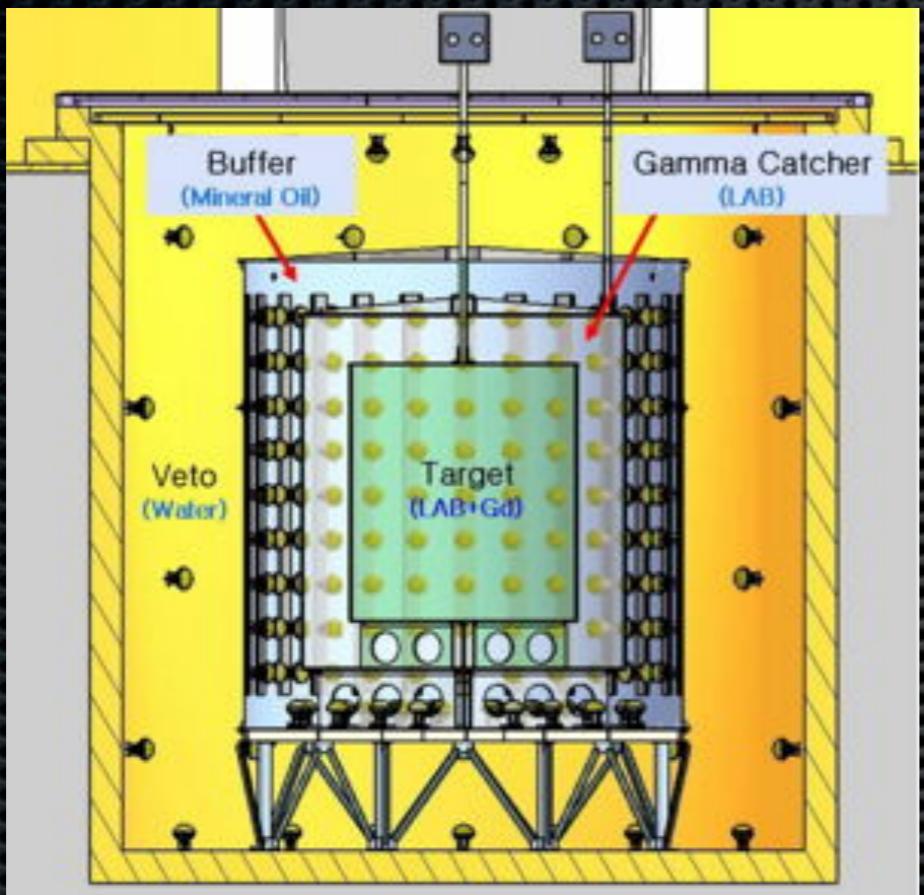
RENO



RENO experimental setup



RENO detectors



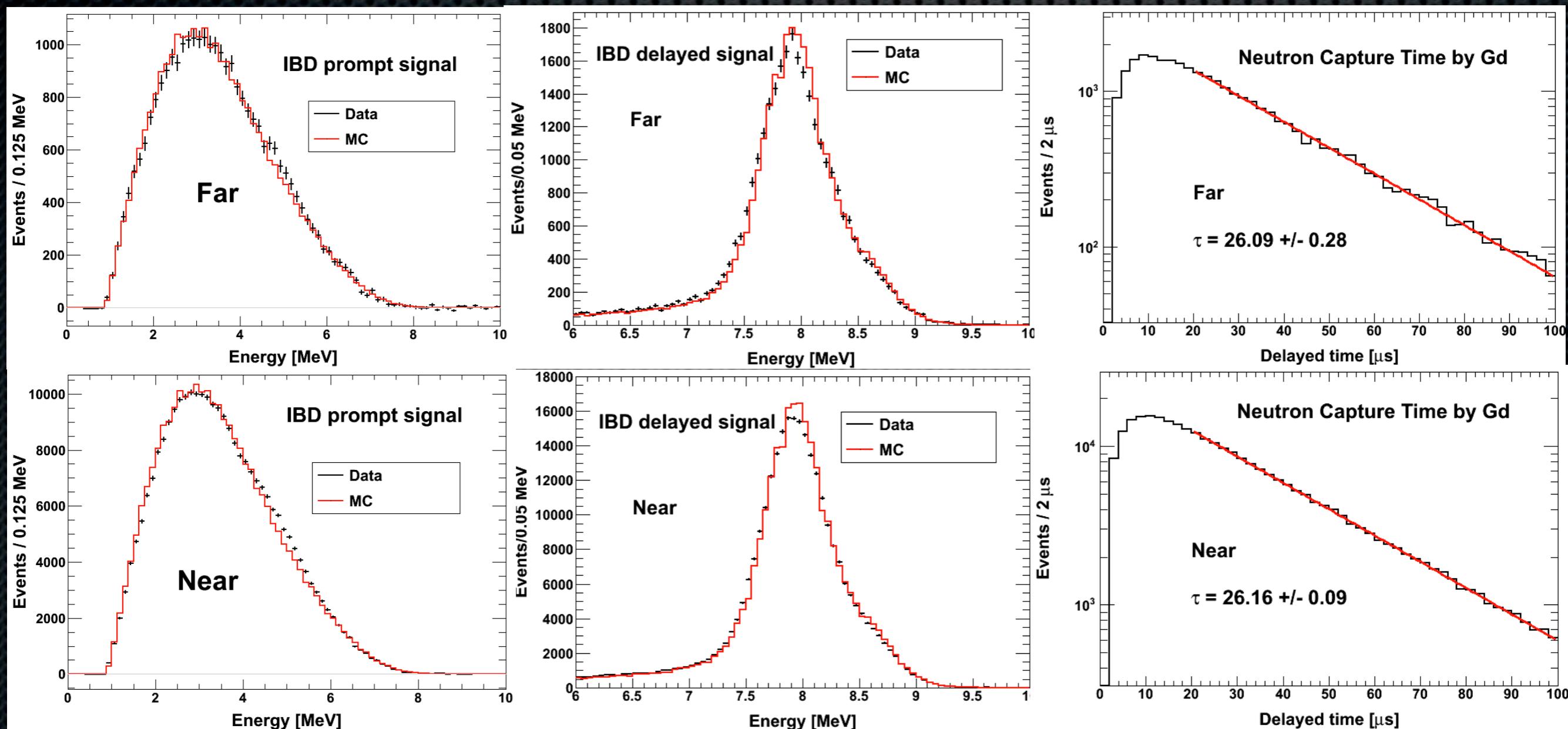
- 354 ID +67 OD 10" PMTs
- Target : 16.5 ton Gd-LS, R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS, R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil, R=2.7m, H=5.8m
- Veto : 350 ton water, R=4.2m, H=8.8m



RENO main results

- “Observation of reactor electron antineutrino disappearance in the RENO experiment”, *Phys. Rev. Lett.* 108 (2012) 19802
 - 220 days of data, 2 detectors N+F
 - $\sin^2(2\theta_{13}) = 0.113 \pm 0.013 \text{ (stat.)} \pm 0.019 \text{ (syst.)}$ (4.9σ significant signal)
- March 2013 (NuTel): Improved analysis with more statistics (*not published yet*)
 - 403 days of data, 2 detectors N+F
 - $\sin^2(2\theta_{13}) = 0.100 \pm 0.010 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$ (5.6σ significant signal)
- Sept 2013 (TAUP): Same statistics, reduced systematics (*not published yet*)
 - 403 days, 2 detectors
 - $\sin^2(2\theta_{13}) = 0.100 \pm 0.010 \text{ (stat.)} \pm 0.012 \text{ (syst.)}$ (6.3σ significant signal)

Neutrino selection



Summary of recent analysis

Signal and background events

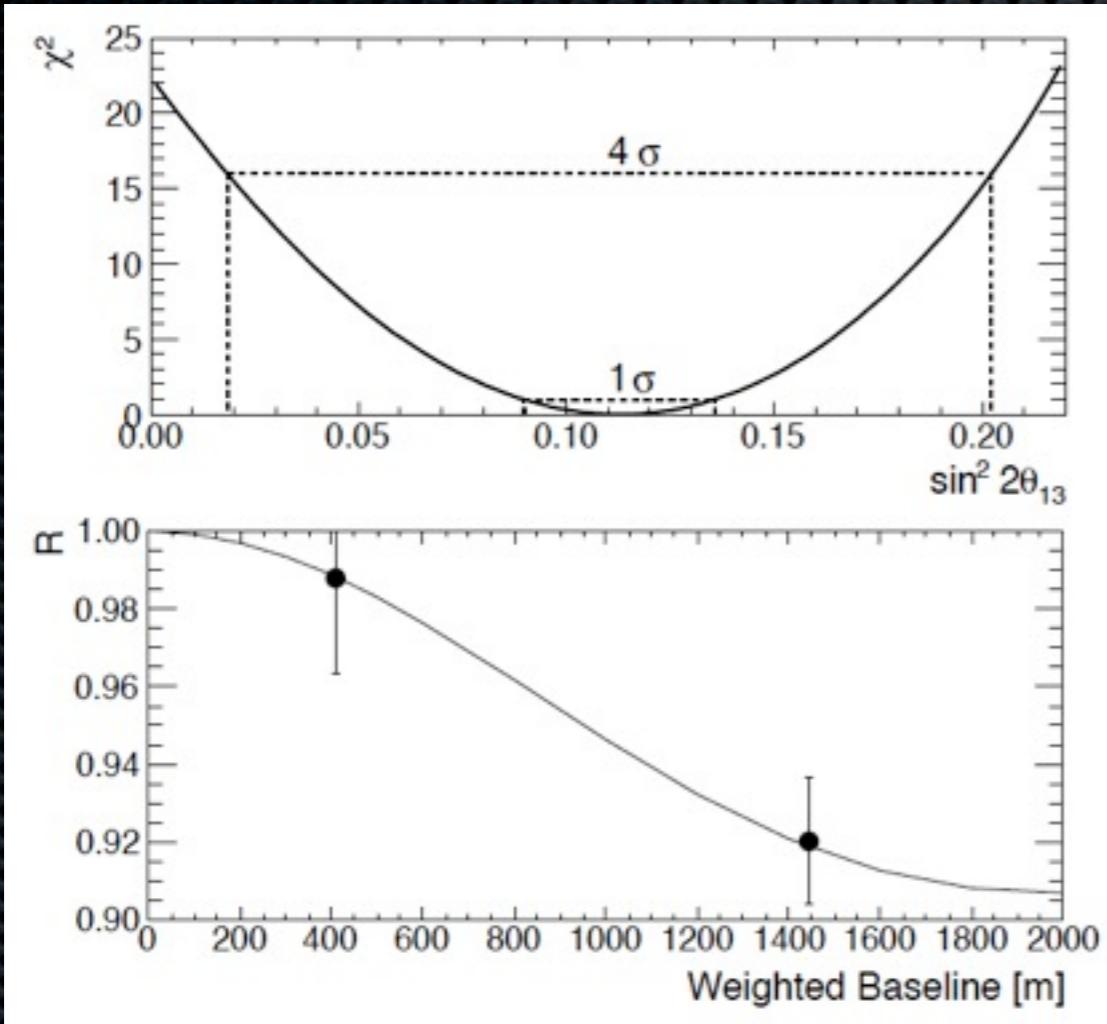
Detector	Near	Far
Selected events	279787	30211
Total background rate (per day)	21.17 ± 1.81	4.80 ± 0.46
IBD rate after background subtraction (per day)	737.00 ± 2.31	70.22 ± 0.64
DAQ Live time (days)	369.03	402.69
Detection efficiency (ϵ)	62.0 ± 0.014	71.4 ± 0.014
Accidental rate (per day)	3.61 ± 0.05	0.60 ± 0.03
$^9\text{Li}/^8\text{He}$ rate (per day)	13.97 ± 1.54	3.55 ± 0.45
Fast neutron rate (per day)	3.59 ± 0.95	0.65 ± 0.10

Uncertainties

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%

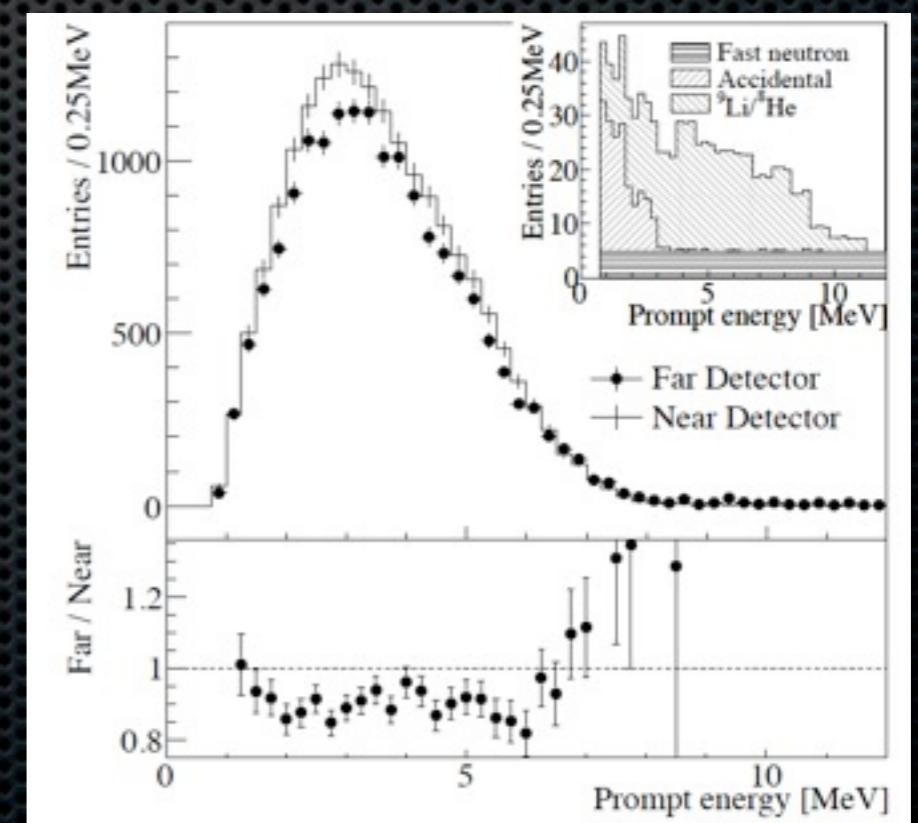
Rate oscillation fit



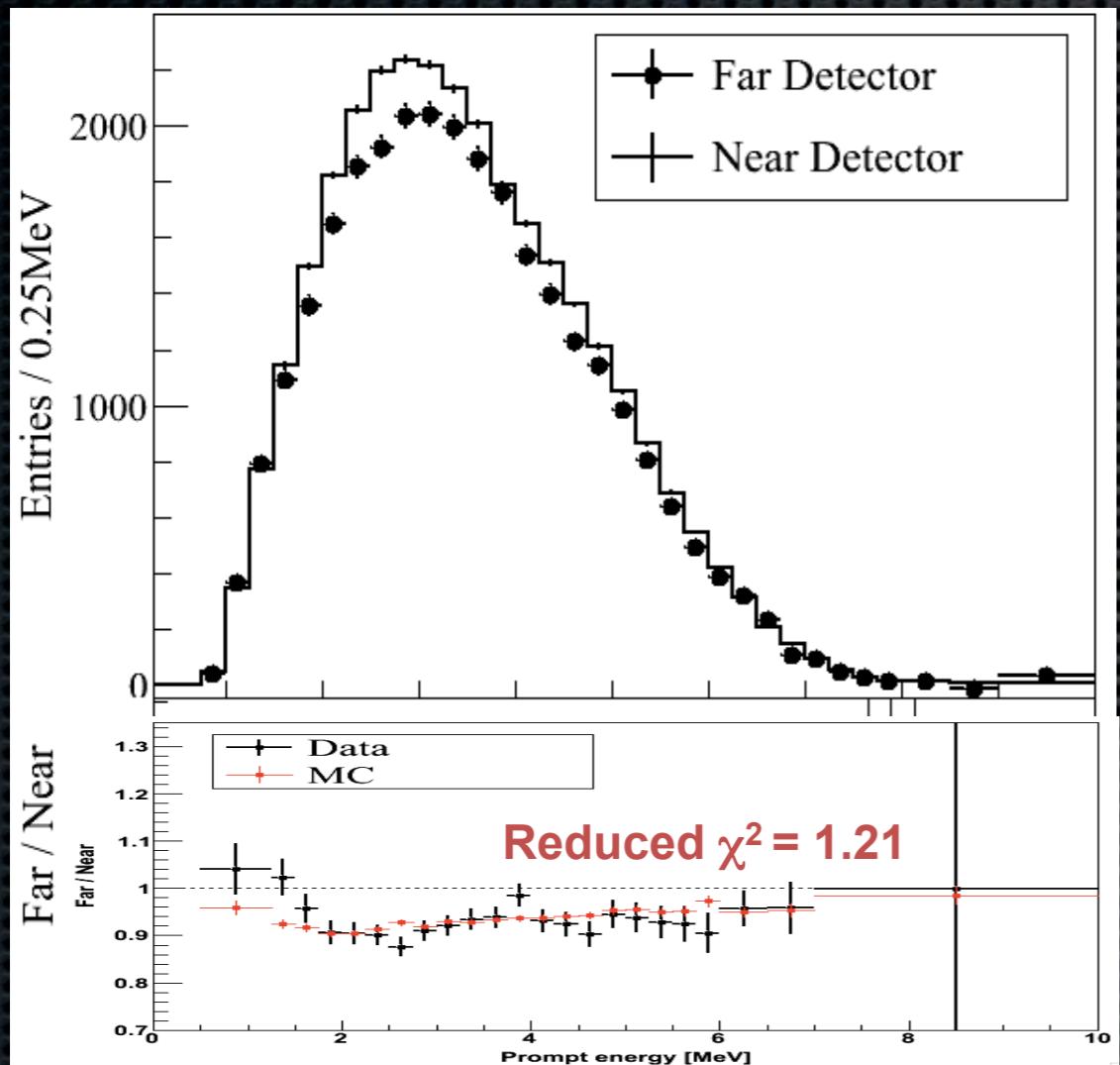
$$R_{\text{obs/exp}} = 0.920 \pm 0.009 \text{ (stat)} \pm 0.014 \text{ (syst)}$$

$$\begin{aligned} \chi^2 = & \sum_{d=N,F} \frac{\left[N_{\text{obs}}^d + b_d - (1 + a + \xi_d) \sum_{r=1}^6 (1 + f_r) N_{\text{exp}}^{d,r} \right]^2}{N_{\text{obs}}^d} \\ & + \sum_{d=N,F} \left(\frac{\xi_d^2}{\sigma_d^{\xi^2}} + \frac{b_d^2}{\sigma_d^{b^2}} \right) + \sum_{r=1}^6 \left(\frac{f_r}{\sigma_r} \right)^2 \end{aligned}$$

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



Unpublished rate osc. fit

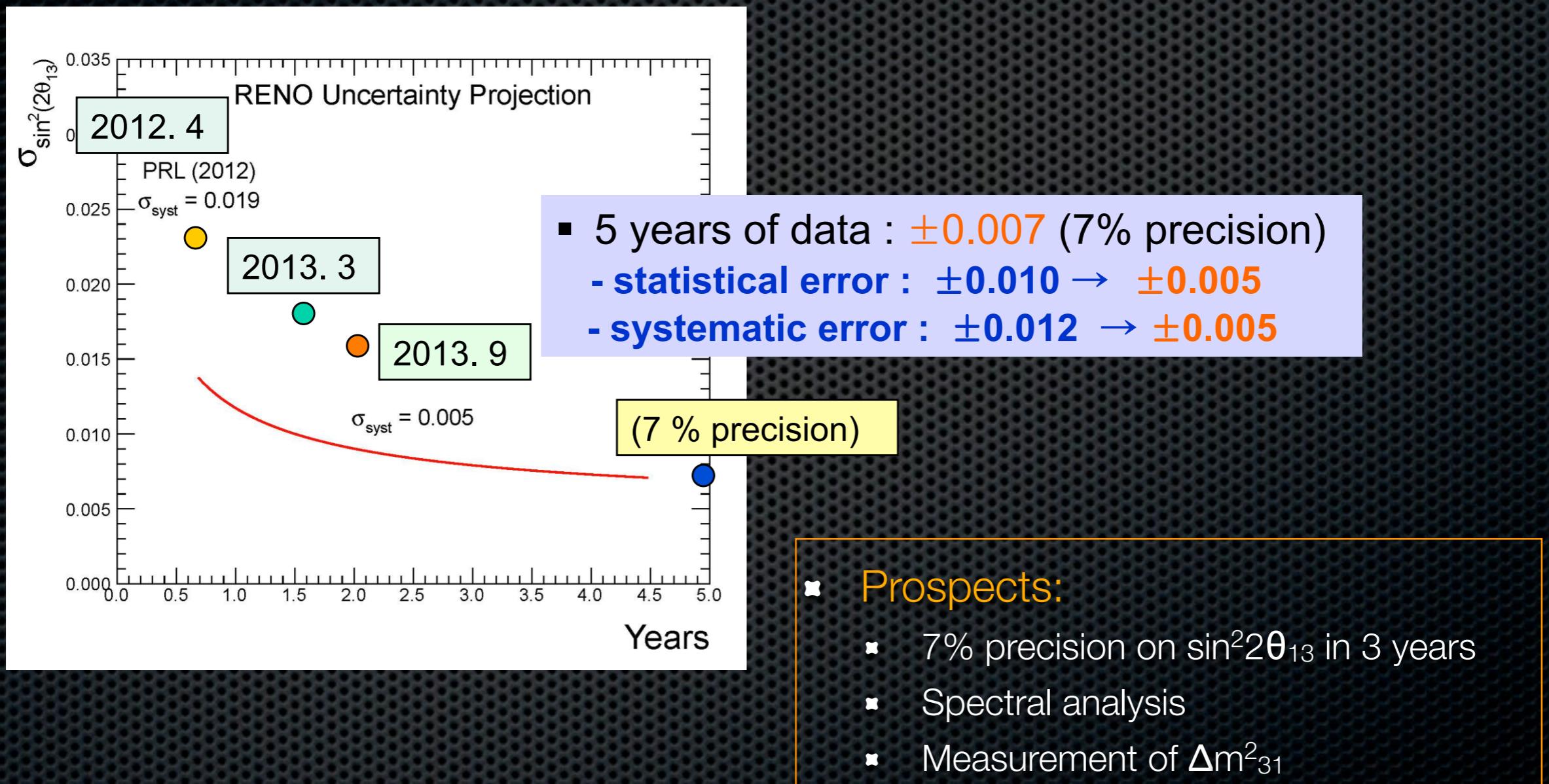


New result:

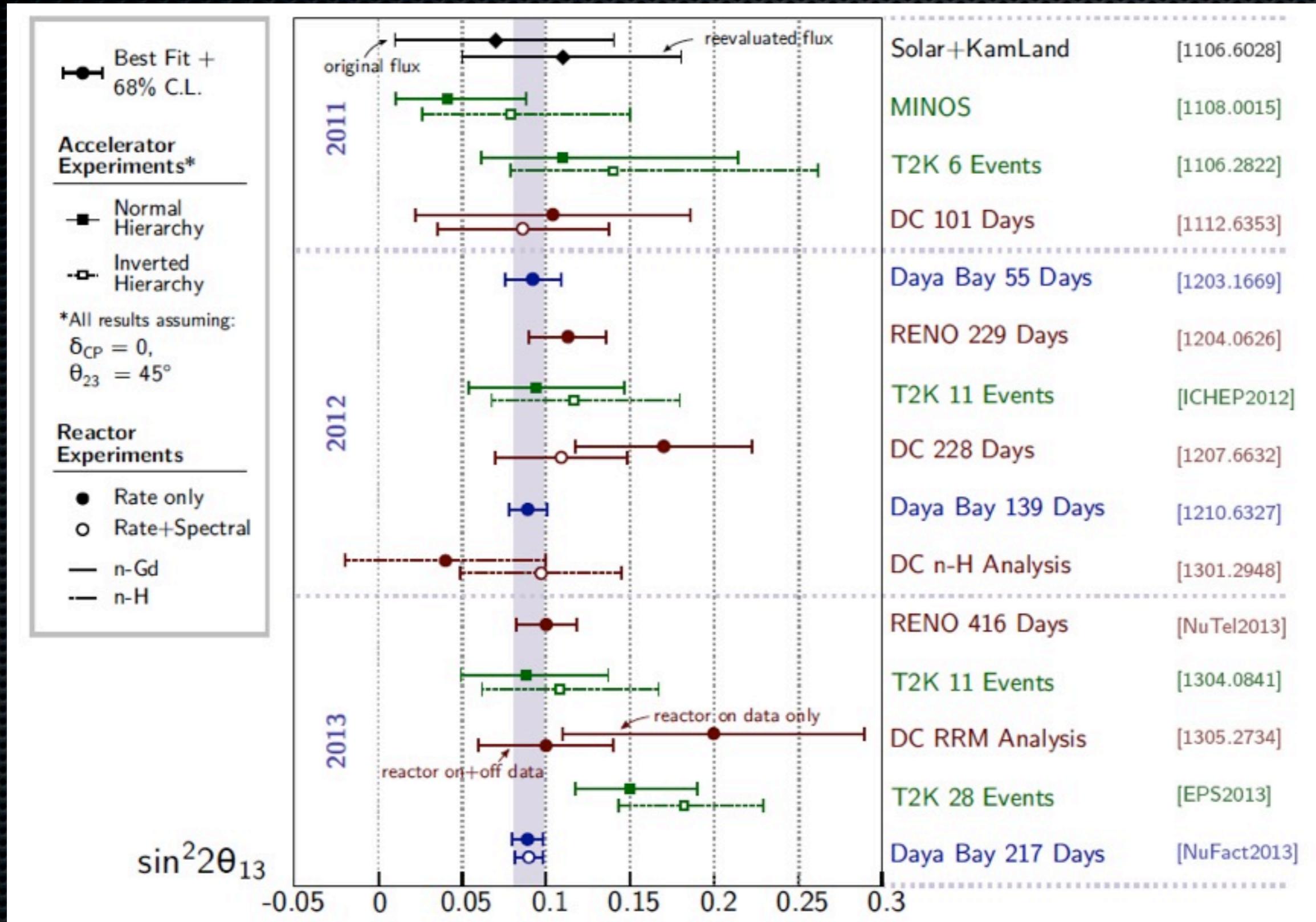
$$R_{\text{obs/exp}} = 0.929 \pm 0.006 \text{ (stat)} \pm 0.007 \text{ (syst)}$$

$$\sin^2(2\theta_{13}) = 0.100 \pm 0.010 \text{ (stat)} \pm 0.012 \text{ (syst)}$$

Projected sensitivity



Summary of global results

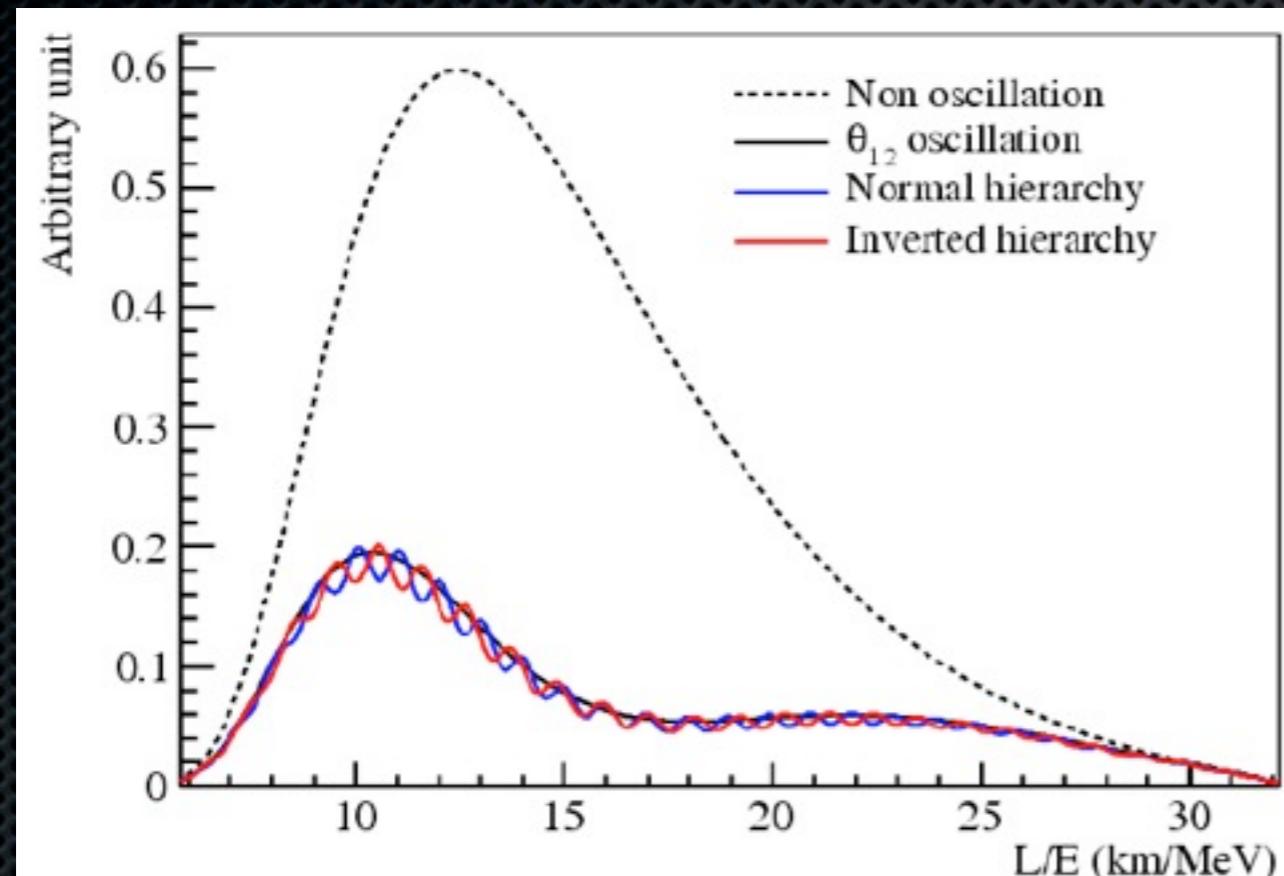


Reactor results on θ_{13}

- ✿ Clear success of reactor experiments in measuring θ_{13}
- ✿ θ_{13} reactor measurement will dominate for long...
- ✿ Idea of final combination among the three experiments once defining correlated errors between experiments and estimation of errors in a unified way

III. Future experimental reactor prospects

Mass hierarchy by reactor experiments



$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

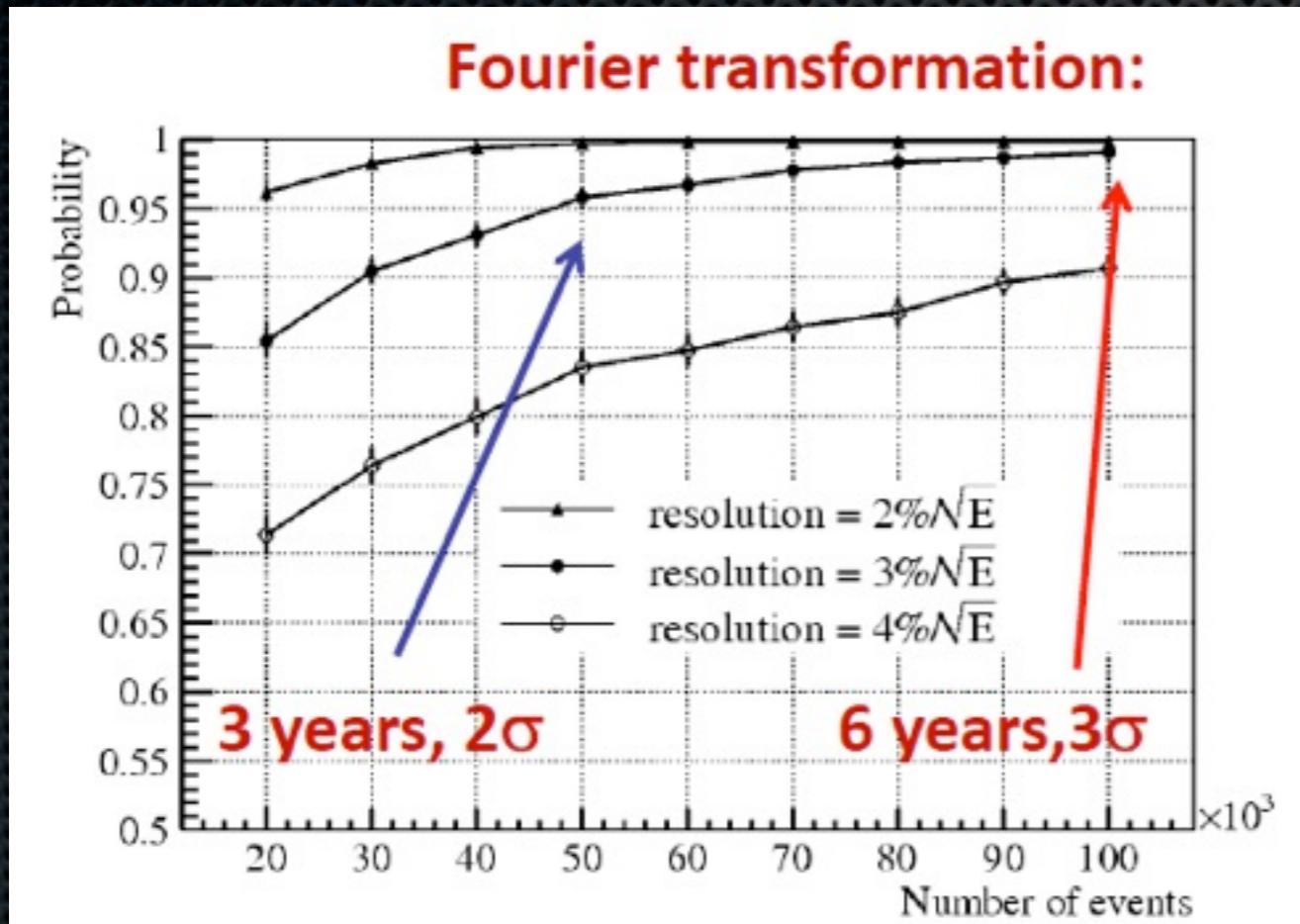
$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

$$\Delta_{21} \ll \Delta_{31} \approx \Delta_{32}$$

S.T.Petcov et al., PLB533 (2002) 94
S. Choubey et al., PRD68 (2003) 113006
J. Learned et al., hep-ex/0612022
L. Zhan et al., PRD78 (2008) 111103
L. Zhan et al., PRD79 (2009) 073007

- MH identification by Fourier transform to L/E spectrum
- Precision energy spectrum measurement: looking for interference between P_{31} and P_{32}

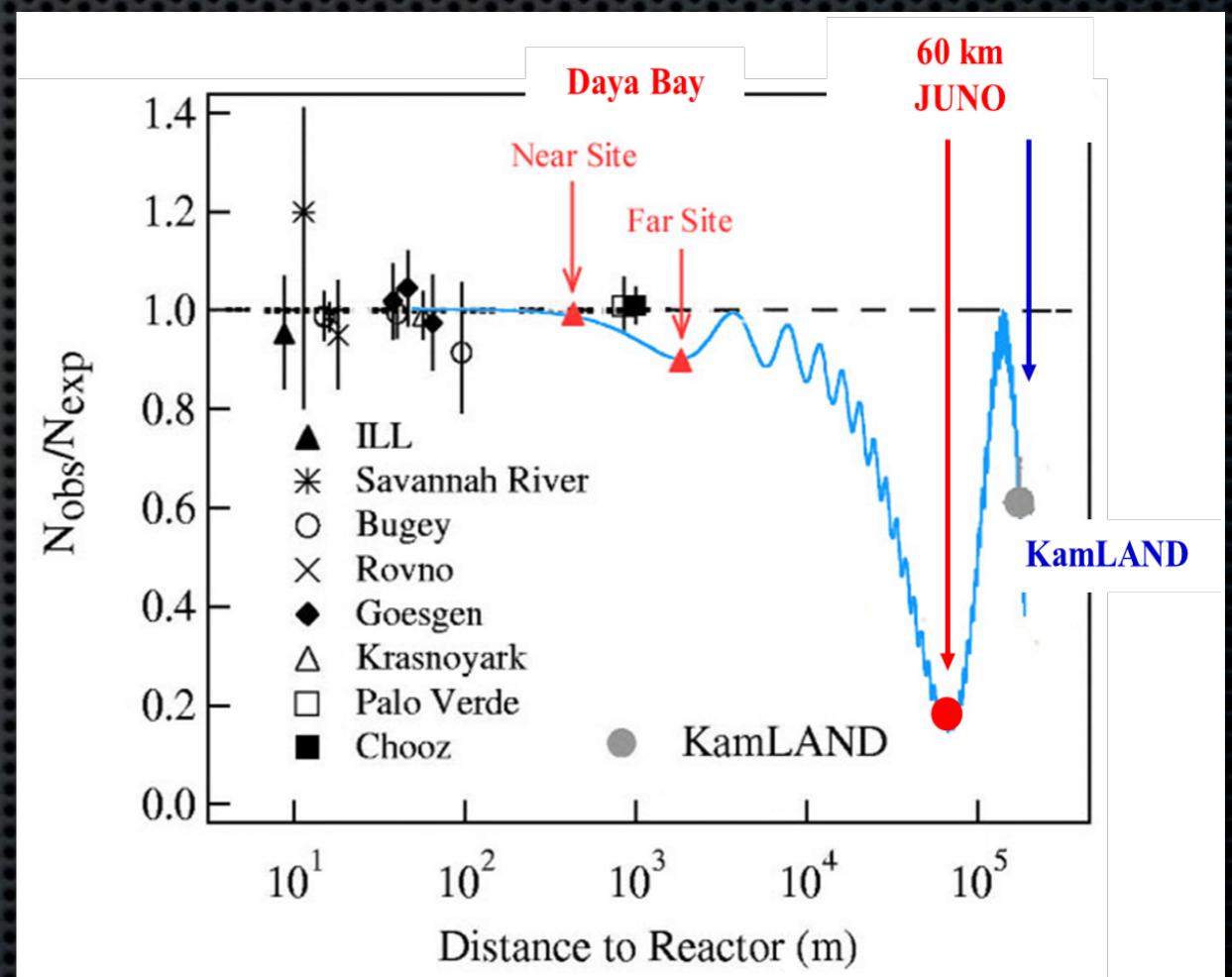
Mass hierarchy sensitivity



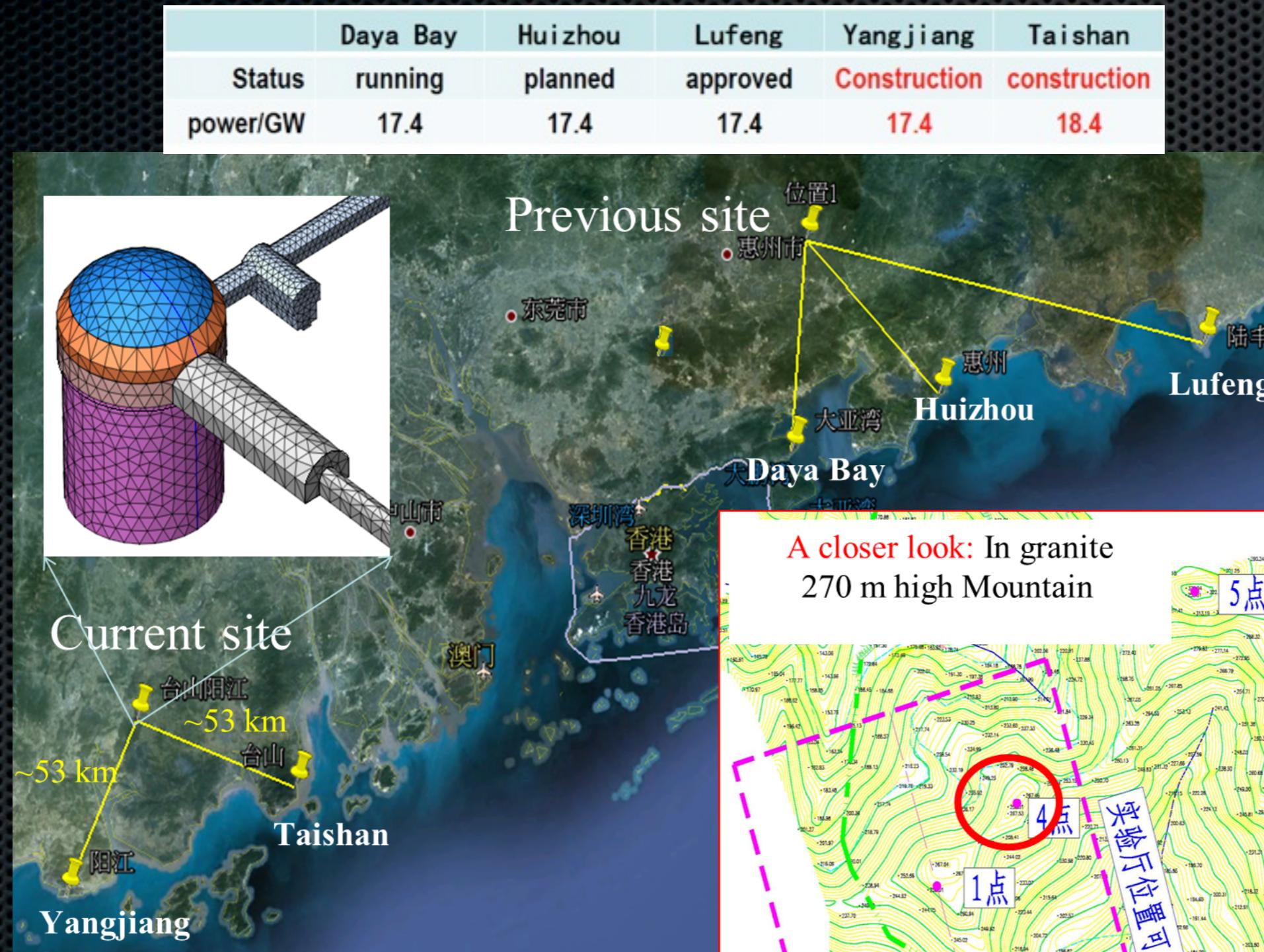
- Detector size: 20 kton
- Energy resolution: $3\%/\sqrt{E}$
- Thermal power: 36 GW
- Baseline: 58 km

Jiangmen Underground Neutrino Observatory (JUNO)

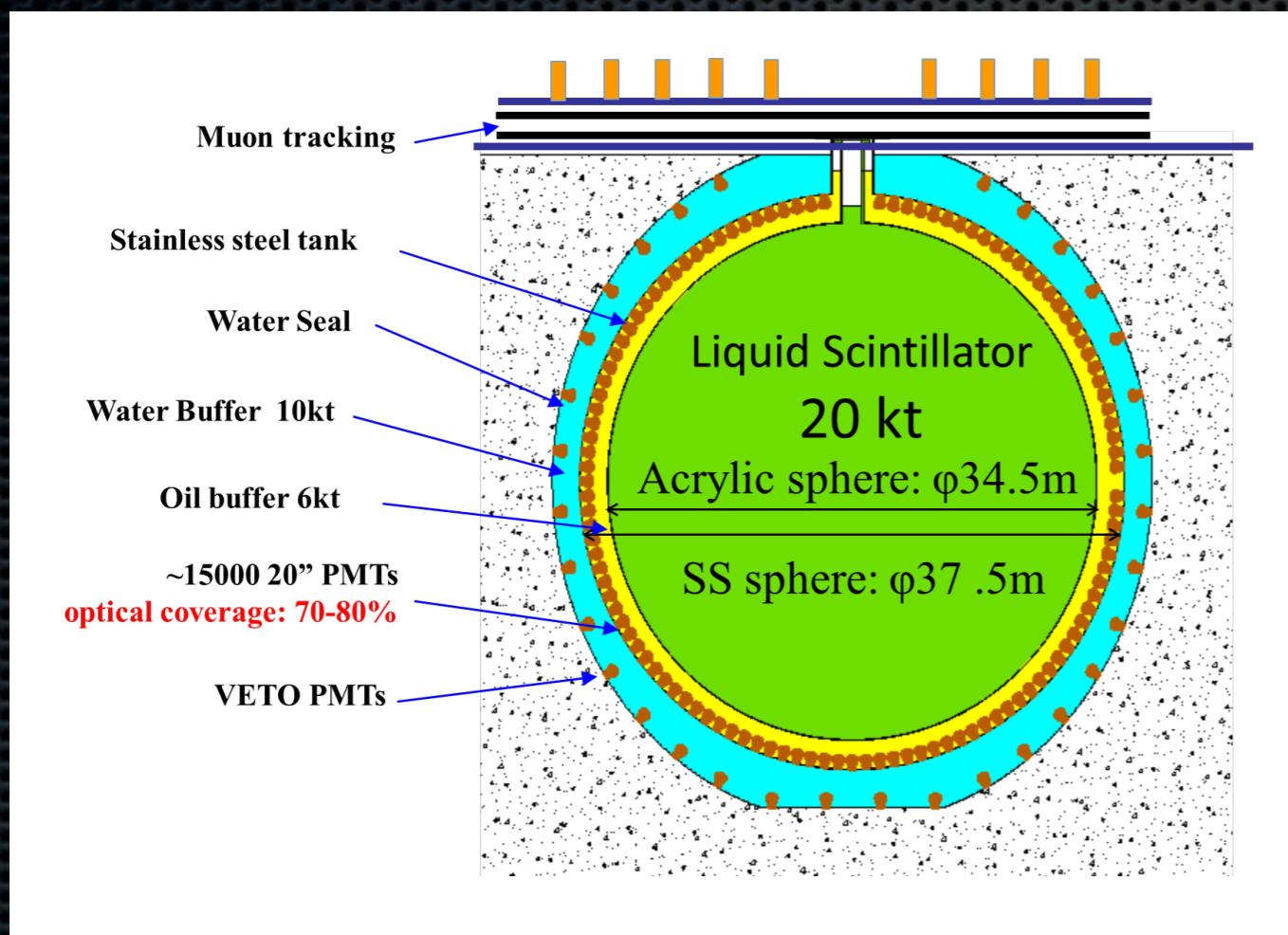
- Statistical sensitivity to mass hierarchy
- Major project in China (already funded)
- Very challenging measurements:
 - Requires major improvements in detector technology
 - Energy resolution and scale are of paramount importance
 - Improves with percent-level precision on Δm^2_{23}



JUNO experimental site



JUNO detector

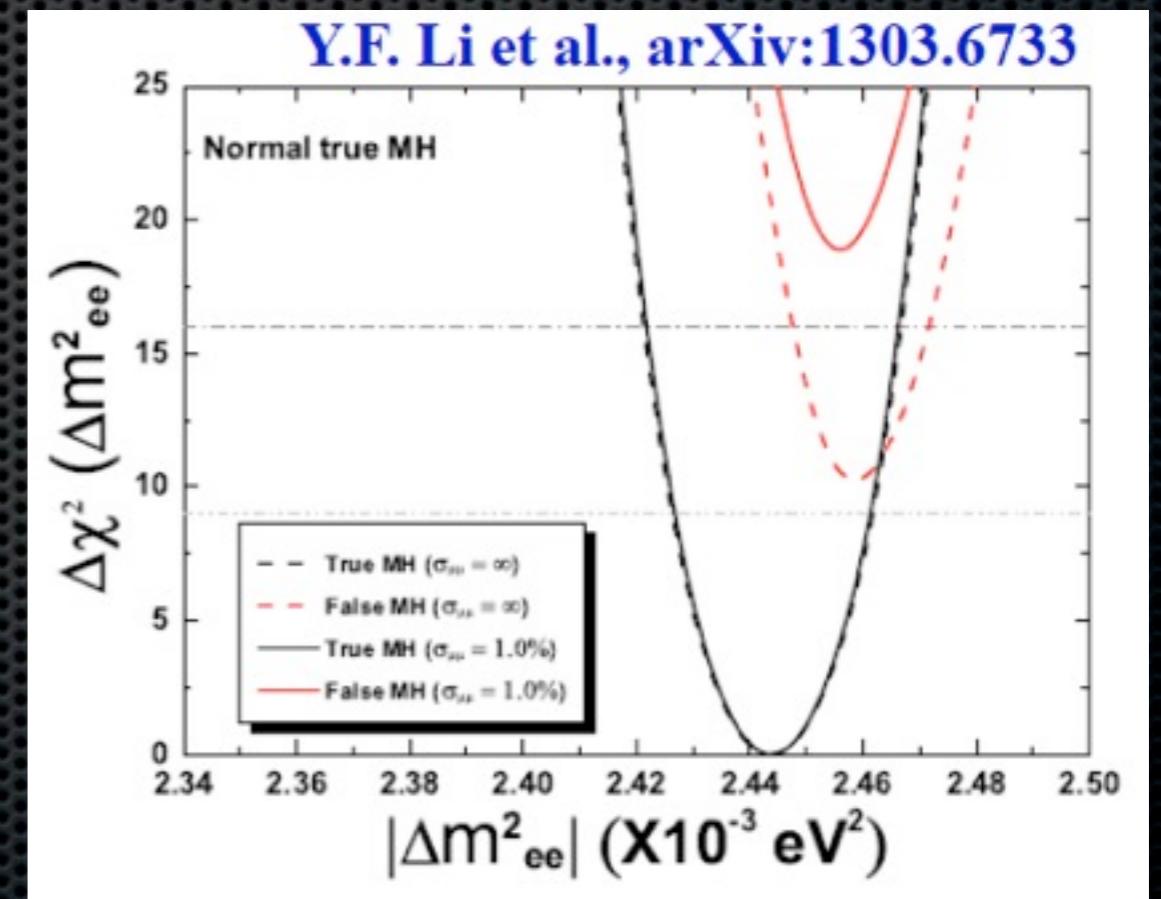


- Site determined
- Detailed civil design underway
- Detector design underway
- R&D started:
 - Detector prototyping
 - LAB-based liquid scintillator
 - Photodetectors
 - Readout electronics
- Schedule:
 - Construction: 2013-2019
 - Filling & data taking: 2020

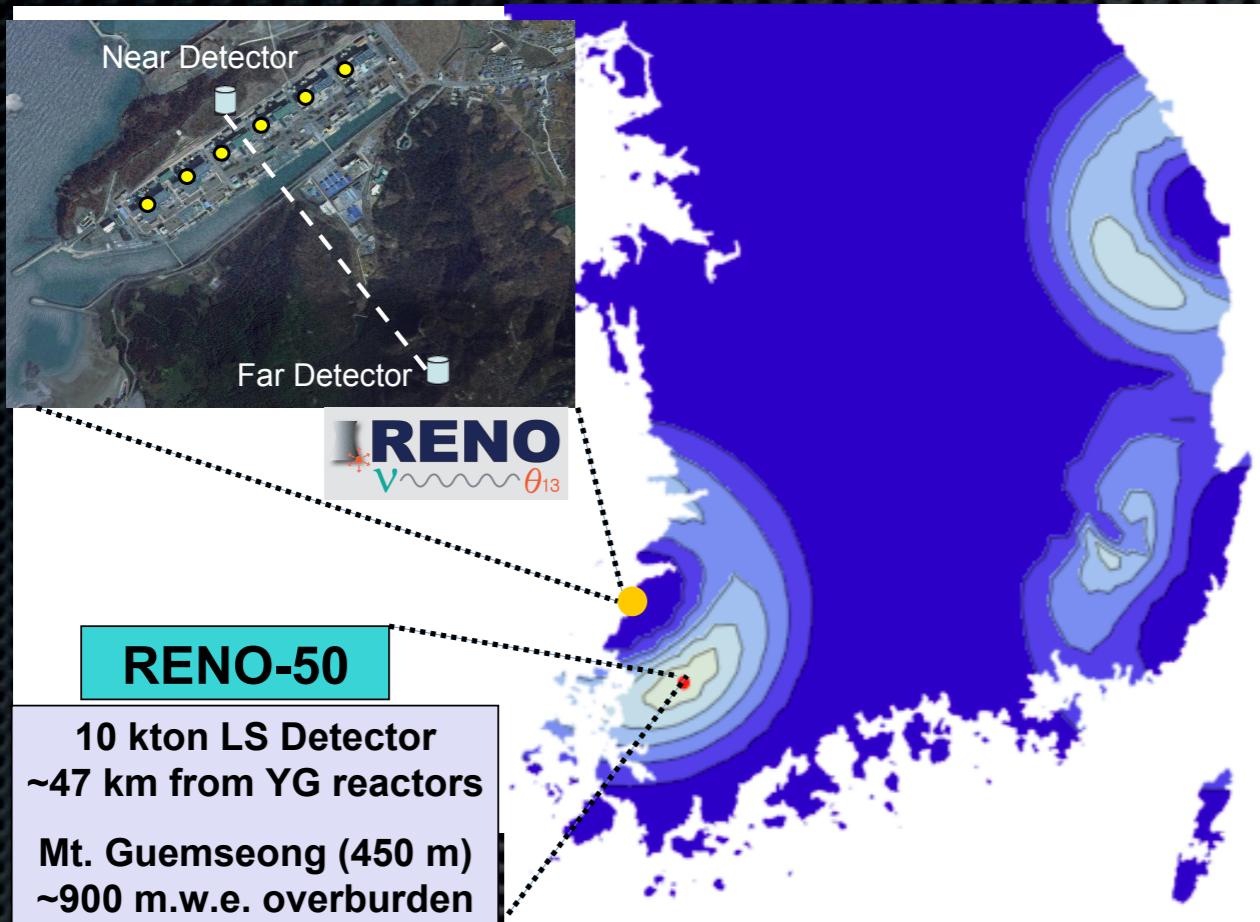
Physics potential

- Mass hierarchy sensitivity
 - MH can be determined at 3.7σ (4.4σ) in 6 years for $\Delta m^2_{\mu\mu}$ uncertainty of 1.5% (1.0%)
- Precise determination of oscillation parameters (<1%)
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos

Detector size: 20 kton
Energy resolution: $3\%/\sqrt{E}$
Thermal power: 36 GW
Baseline: 58 km



RENO-50



Underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit (Yonggwang) nuclear power plant

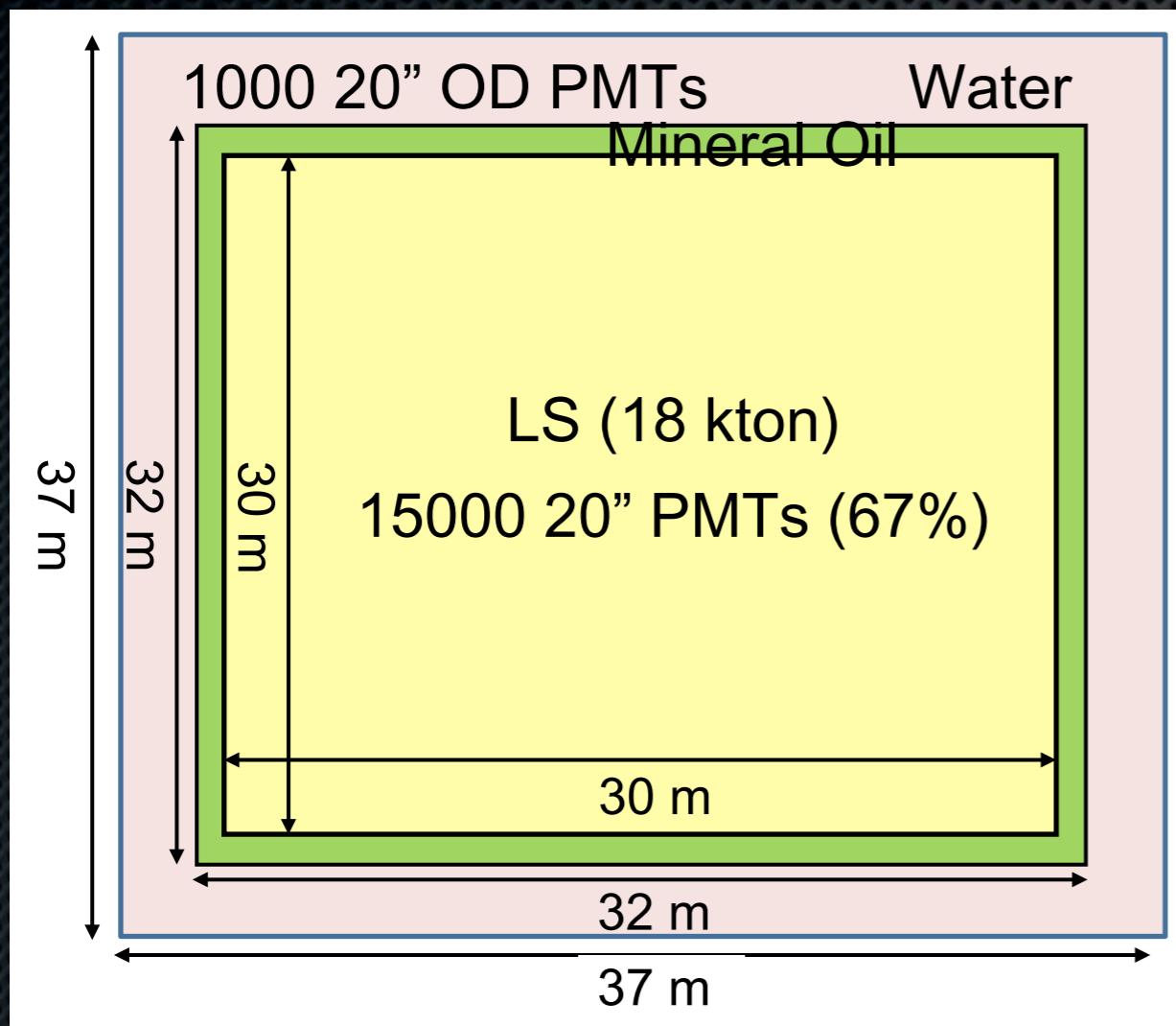
Schedule:

2013-2018: Facility and detector construction
~2019: Operation and experiment

Goals:

- High precision measurement of θ_{12} , Δm^2_{12} and Δm^2_{13} (< 1% precision)
- Determination of neutrino mass hierarchy (challenging: requires extremely good energy resolution)
- Study neutrinos from reactors, the Sun, the Earth, supernova and any possible stellar objects

Conceptual design of RENO-50



	KamLAND	RENO-50
LS mass	~1 kton	18 kton
E resolution	6%/ \sqrt{E}	3%/ \sqrt{E}
Light yield	250 p.e./MeV	>1000 p.e./MeV

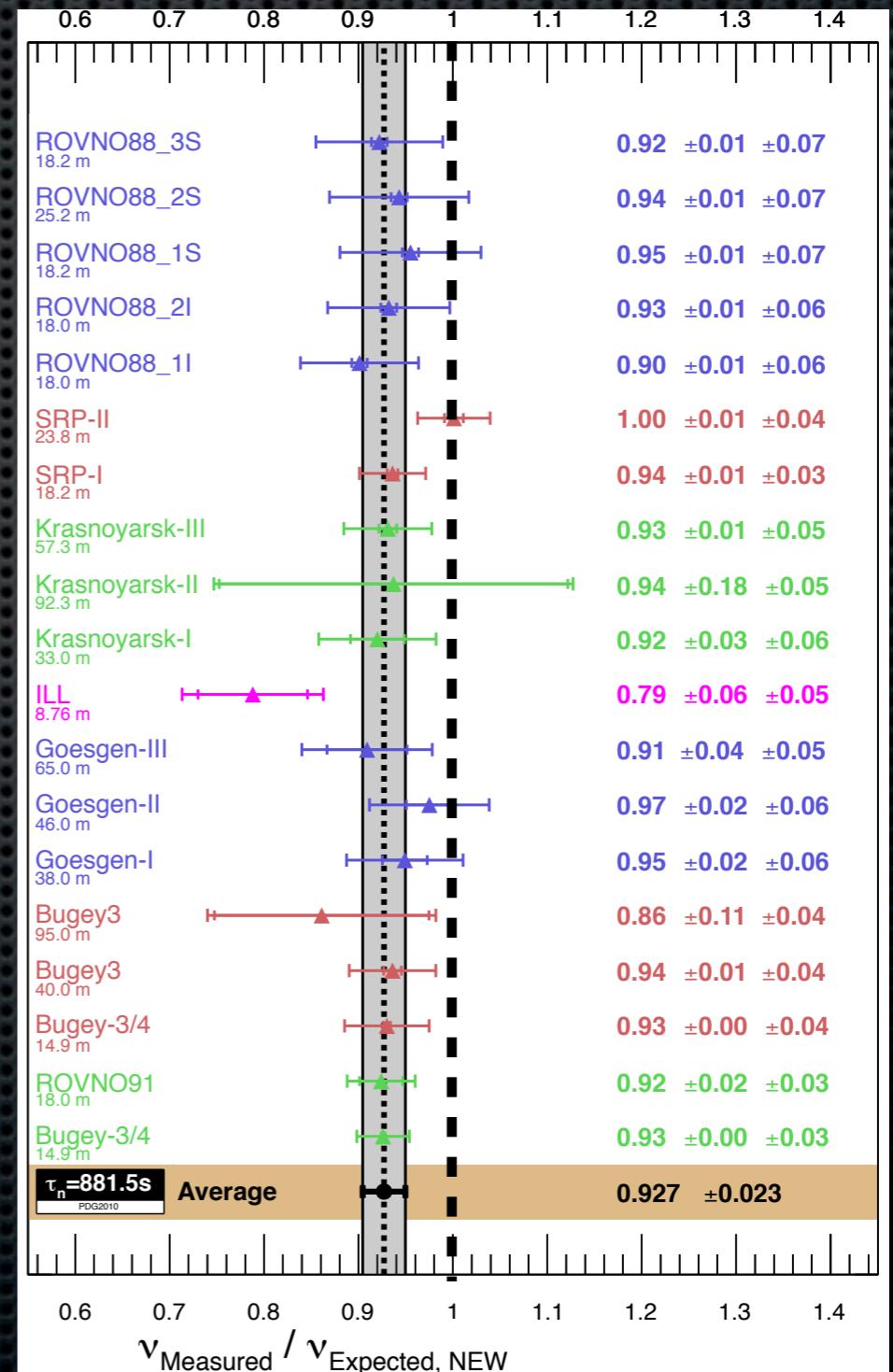
- Energy resolution challenge:
 - High transparency LS: 15m → 25m (purification and better PPO)
 - Large photocathode coverage: 34% → 67% (15000 20" PMTs)
 - High QE PMT: 20% → 35% (Hamamatsu 20" HQE PMT)
 - High light yield LS: x1.5 (1.5 g/l PPO → 5 g/l PPO)

Sterile neutrinos

- New fission antineutrino flux calculations suggest that all SBL reactor experiments are observing a deficit:
 - For $\Delta m^2 \geq 1 \text{ eV}^2$ (no compatible with 3v osc. scenario)
- There are other hints for sterile neutrinos (LNSD, MiniBooNE, ...)
 - Not all of them are compatible!
- Global fit of all hints: severe tensions

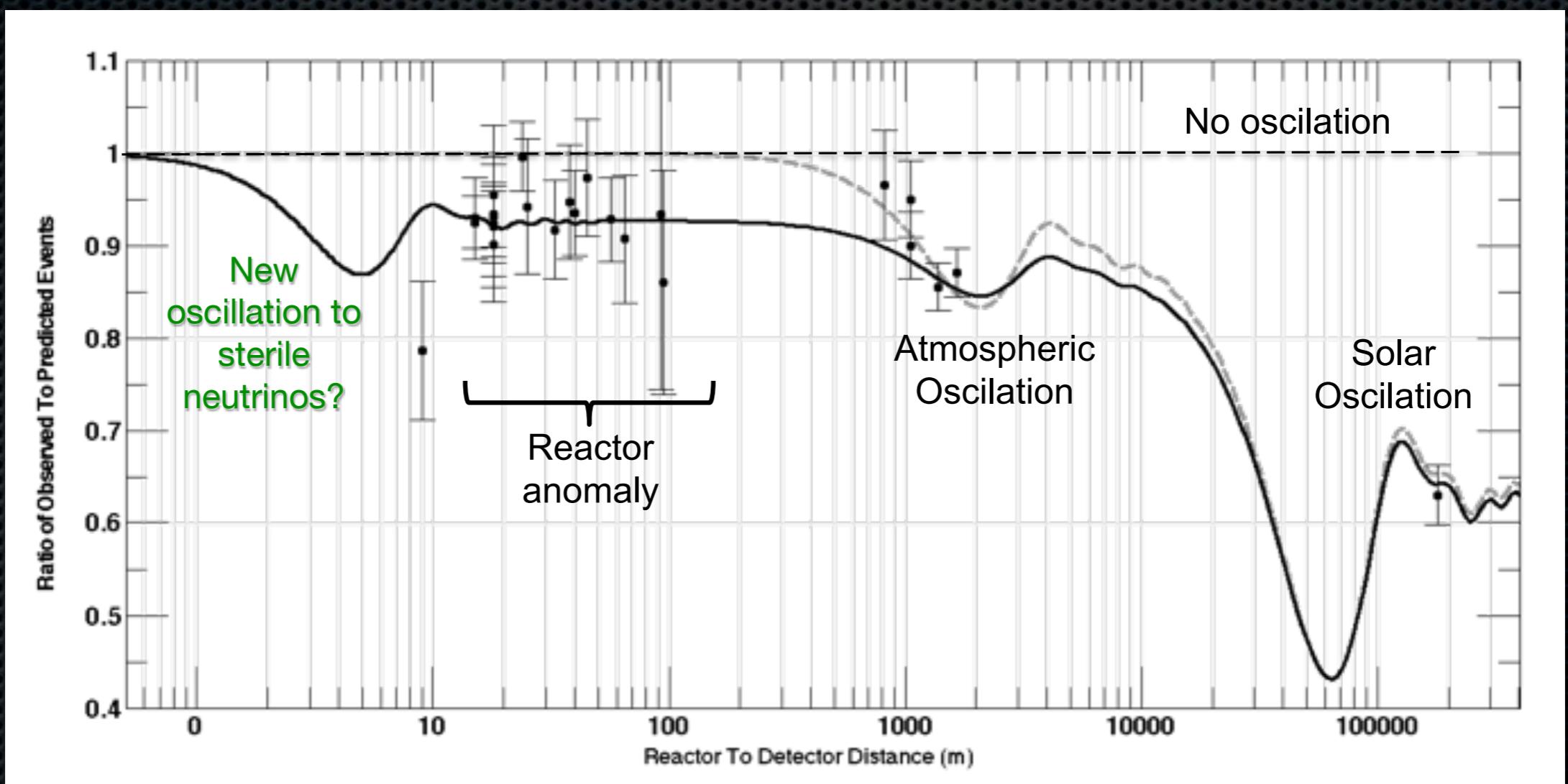
Reanalysis of reactor short baseline experiments

G. Mention et al., Phys. Rev. D83 (2011) 073006



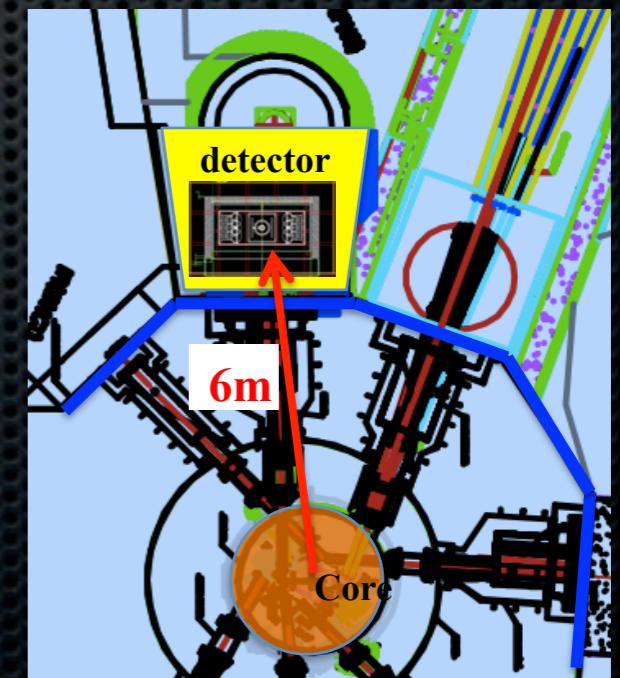
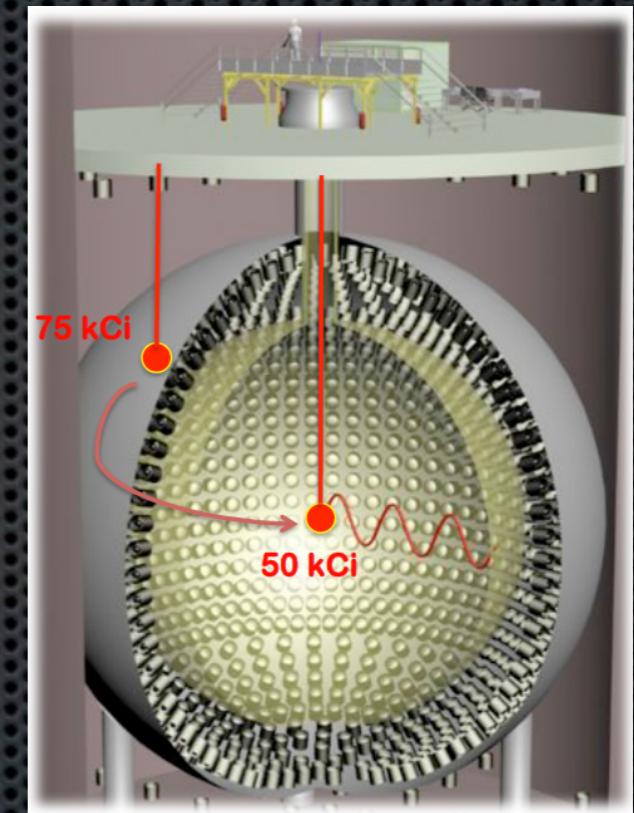
The reactor anomaly

Observed/predicted averaged event ratio: $R=0.935\pm0.024$ (2.7σ)



Experiments to test the 4th neutrino hypothesis

- Radioactive source experiments: CeLAND (^{144}Ce in KamLAND), SOX (^{51}Cr in Borexino)
 - Low background measurements
 - Challenge of production and transportation of intense source
- Accelerator beams: IsoDAR, ICARUS/NESSiE, nuSTORM...
- Reactors: NUCIFER, Stereo, Hanaro, Neutrino-4, Solid...
 - Background reduction is challenging
 - Synergies with reactor monitor experiments



Conclusions

- Reactor neutrino oscillation experiments at $\sim 1\text{ km}$ baseline have demonstrated electron antineutrino disappearance driven by θ_{13}
 - Ongoing reactor experiments try to measure $\sin^2 2\theta_{13}$ to $< 4\%$ precision
- Next generation of reactor neutrino experiments focus on mass hierarchy determination and precision measurements of oscillation parameters → technical challenges
 - JUNO in China already approved
 - RENO-50 in Korea
 - Data taking will start ~ 2020
- Sterile neutrinos will be explored by reactors (and source & accelerator experiments)