

# *Reactor electron anti-neutrino*

2012

## *Observation of electron anti-neutrino disappearance at Daya Bay*

- F.P. An et al., Daya Bay Coll., “A side-by-side comparison of Daya Bay anti-neutrino detectors”, [arXiv:1202.6181\[physics.ins-det\]](#), NIM A 685 (2012) 78-97
- F.P. An et al., Daya Bay Coll., “Observation of electron anti-neutrino disappearance at Daya Bay”, [arXiv:1203.1669\[hep-ex\]](#), submitted to PRL 108 (2012) 171803

# Neutrino mixing angles

## PMNS(\*) Lepton Mixing Matrix

flavour basis

mass basis

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

$$\begin{pmatrix} 0.7 & 0.7 & <0.2e^{i\delta} ? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$\delta$  gives  
CP violation

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & & & & & \\ & c_{23} & s_{23} & & & \\ & -s_{23} & c_{23} & & & \\ & & & c_{13} & & \\ & & & s_{13}e^{-i\delta} & & \\ & & & -s_{13}e^{i\delta} & & \\ & & & & 1 & \\ & & & & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & & 1 \end{pmatrix}$$

## CKM Quark Mixing Matrix

weak int. basis

strong int. basis

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

Is the lepton mixing matrix related to the quark mixing matrix?

(\*) Pontecorvo, Maki, Nakagawa, Sakata

# 3 flavor neutrino mixing

mixing matrix  $U_{MNSP}$  parametrized with 3 mixing angles  $\theta_{ij}$ , CP phase  $\delta$

+ 2 mass differences  $\Delta m^2_{\text{atm}}$ ,  $\Delta m^2_{\text{sol}}$

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

atmospheric  $\nu$   
+ K2K, MINOS

$$\Delta m^2_{\text{atm}} = 2.4 \cdot 10^{-3} \text{ eV}^2$$

$$\theta_{23} = (45 \pm 7)^\circ$$

reactor  $\nu$   
(CHOOZ)

$$\Delta m^2_{31} \approx \Delta m^2_{\text{atm}}$$

$$\theta_{13} < 13^\circ$$

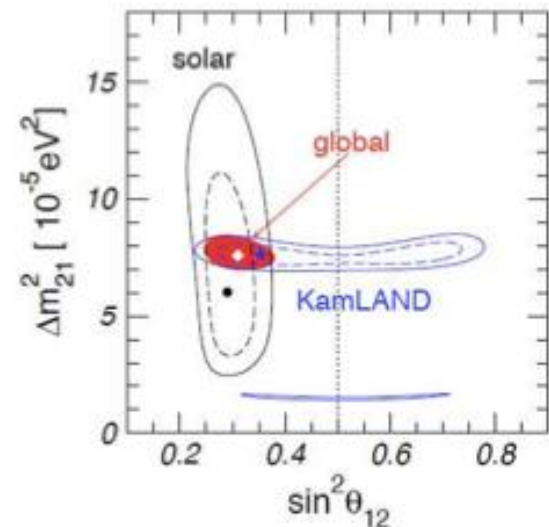
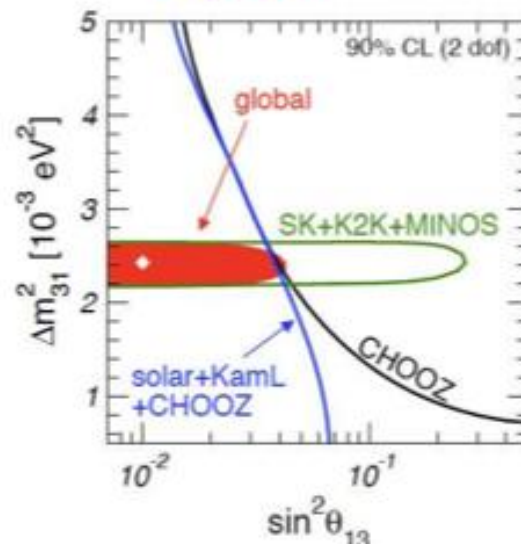
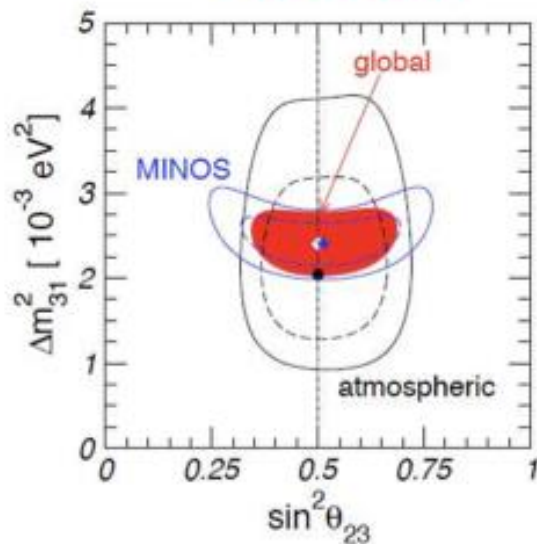
solar  $\nu$   
+ KamLAND

$$\Delta m^2_{\text{sol}} = 7.6 \cdot 10^{-5} \text{ eV}^2$$

$$\theta_{12} = (34 \pm 3)^\circ$$

$$s_{12} = \sin\theta_{12}$$

$$c_{12} = \cos\theta_{12}$$



# Neutrino oscillations

$$\begin{array}{c}
 \text{“atmospheric”} \\
 \Delta m^2_{23} = 2.4 \cdot 10^{-3} \text{ eV}^2 \\
 \theta_{23} = 45^\circ
 \end{array}
 \begin{array}{c}
 \text{“solar”} \\
 \Delta m^2_{12} = 7.6 \cdot 10^{-5} \text{ eV}^2 \\
 \theta_{12} = 34.4^\circ
 \end{array}
 \begin{array}{c}
 \text{long base line} \\
 \theta_{13} \text{ is smaller}
 \end{array}
 \begin{pmatrix}
 1 & 0 & 0 \\
 0 & c_{23} & s_{23} \\
 0 & -s_{23} & c_{23}
 \end{pmatrix}
 \begin{pmatrix}
 c_{12} & s_{12} & 0 \\
 -s_{12} & c_{12} & 0 \\
 0 & 0 & 1
 \end{pmatrix}
 \begin{pmatrix}
 c_{13} & 0 & s_{13}e^{-i\delta} \\
 0 & 1 & 0 \\
 -s_{13}e^{i\delta} & 0 & c_{13}
 \end{pmatrix}$$

- Key point: **the  $\Delta m^2$  are very different. Choosing L/E properly we can disentangle the effects of the different angles:**
  - **solar:** you need  $L/E \sim 10^5$ ; 100 km at 1 MeV (KamLand) or use MSW effect in the Sun
  - **atmospheric:**  $L/E \sim 10^3$ ; ~1000 km with a few GeV  $\nu_\mu$  beam;
  - **$\theta_{13}$ :** the  $\Delta m^2$  is the “atmospheric” one, but the effect is sub-dominant; you must choose L/E so that “solar” scale is not harmful and/or make a global analysis.
    - Accelerators with Long Base Line (possibly off-axis) OR reactors @ ~ 1 km



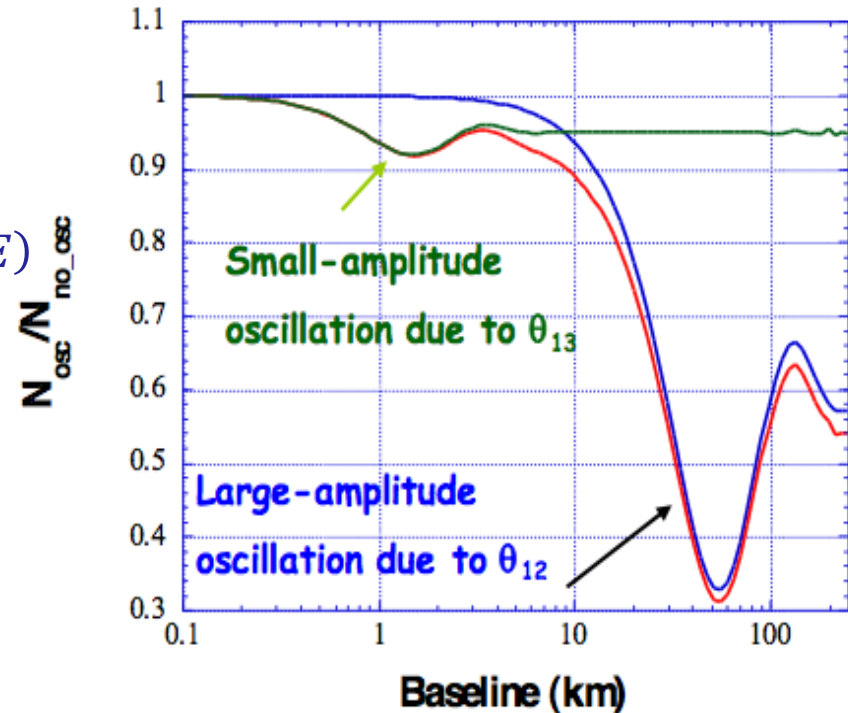
# Two ways to measure $\theta_{13}$

Reactor experiments:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{13}^2 L/E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 L/E)$$

Long baseline accelerator experiments:

$$P_{\mu e} \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{23}^2 L/E) + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 L/E) - A(\rho) \cos^2 \theta_{13} \sin \theta_{13} \sin \delta$$



At reactors:

- Clean signal, no cross talk with  $\delta$  and matter effects
- Relatively cheap compared to accelerator-based experiments
- They have provided the direction to the future of neutrino physics

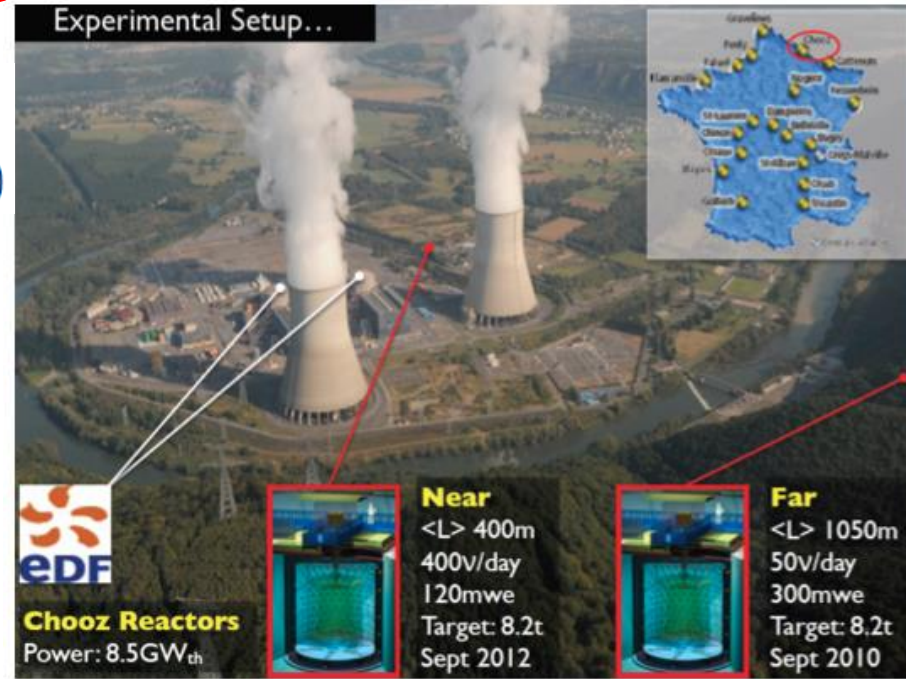
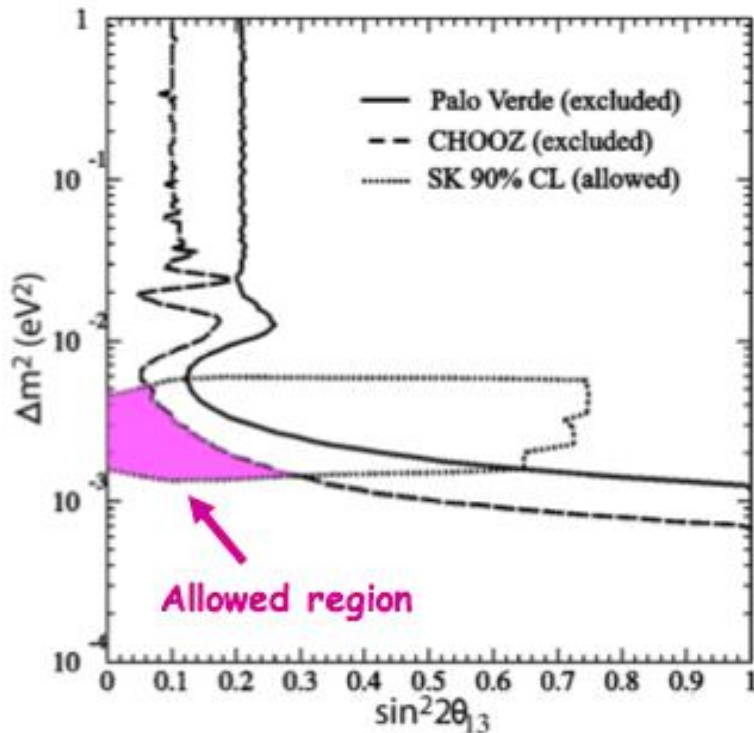
# Search for $\theta_{13}$ at reactors

Before 2012

$$1 - P_{ee} \simeq \sin^2(2\theta_{13})\sin^2(\Delta m_{13}^2 L/4E) + (\Delta m_{23}^2 L/4E)^2 \cos^4(\theta_{13})\sin^2(2\theta_{12})$$

Best result before 2012:

- **Chooz** (1999):  $\sin^2(2\theta_{13}) < 0.15$



- **Palo Verde** and **Chooz**: no signal  
 $\sin^2 2\theta_{13} < 0.15$  (90% CL) if  $\Delta m_{23}^2 = 0.0024 \text{ eV}^2$
- **T2K**:  $2.5\sigma$  over bckg  
 $0.03 < \sin^2 2\theta_{13} < 0.28$  (90% CL) for NH  
 $0.04 < \sin^2 2\theta_{13} < 0.34$  (90% CL) for IH
- **Minos**:  $1.7\sigma$  over bckg  
 $0 < \sin^2 2\theta_{13} < 0.12$  (90% CL) for NH  
 $0 < \sin^2 2\theta_{13} < 0.19$  (90% CL) for IH
- **Double Chooz**:  $1.7\sigma$   
 $\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$

# Best constraint on $\theta_{13}$ ...

.....from the Chooz experiment

M. Apollonio et. al.,  
Eur.Phys.J. C27 (2003) 331

Goal: test of  $\bar{\nu}_e \rightarrow \bar{\nu}_x$  oscillations for atmos.  $\Delta m^2$

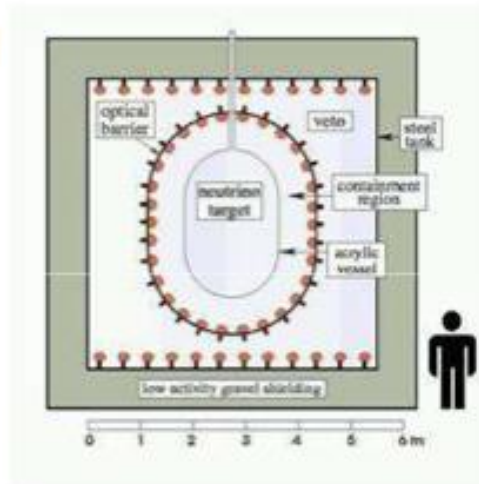
reactor experiment @ 1km

$P_{th} = 8.4 \text{ GW}_{th}$

5 t Gd loaded scintillator

overburden: 300 mwe

~ 2700 neutrino events

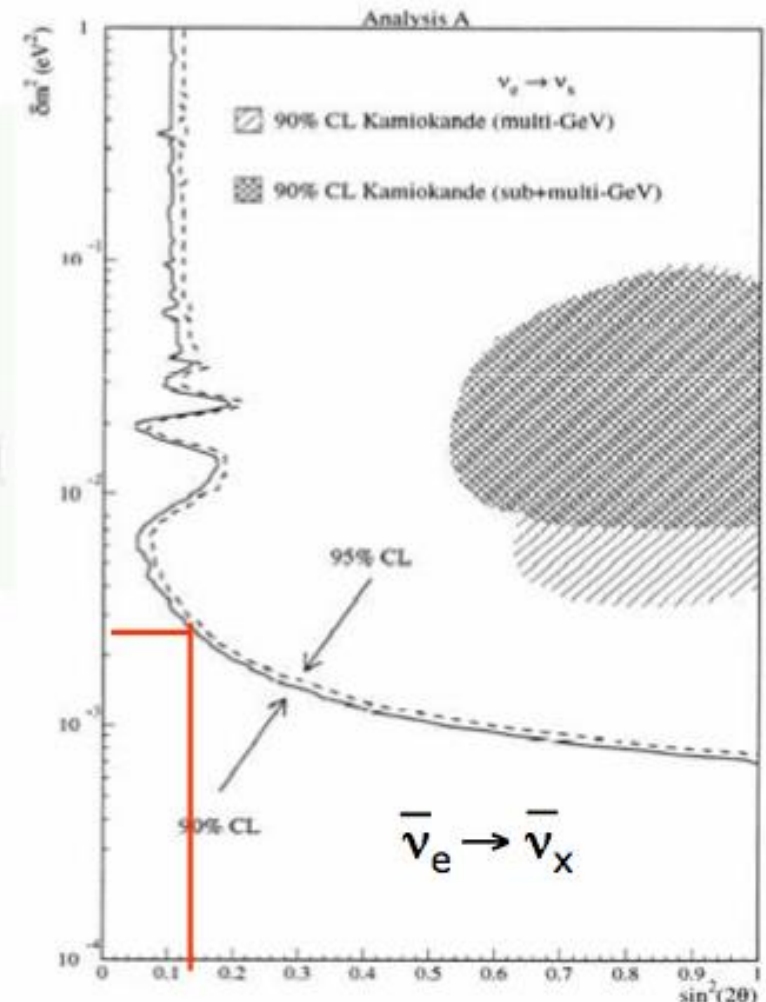


Result:

$$R(\text{data/MC}) = 1.01 \pm 0.028^{\text{stat}} \pm 0.027^{\text{syst}}$$

⇒ limit for  $\theta_{13}$ :  $\sin^2(2\theta_{13}) < 0.14$  (90%CL)

for  $\Delta m^2 = 2.4 \cdot 10^{-3} \text{ eV}^2$



# Nuclear reactor as neutrino source

neutron induced fission of fuel isotopes;  
subsequent fast beta decays of  
neutron-rich fission fragments

⇒ emission of  $\sim 6 \bar{\nu}_e$  /fission  
( $\sim 2 \times 10^{20} \text{ s}^{-1}$  per  $\text{GW}_{\text{th}}$ )

continuous, isotropic neutrino flux 0 – 10 MeV

99.9% of  $\bar{\nu}_e$  are emitted by 4 isotopes

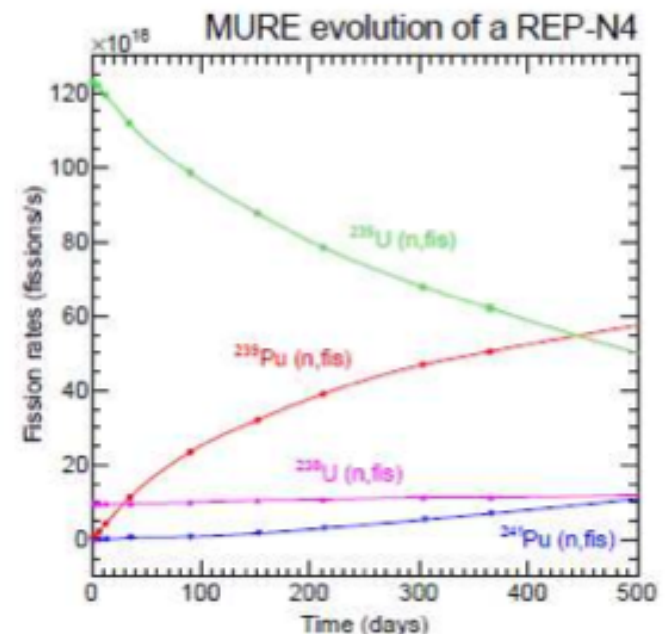
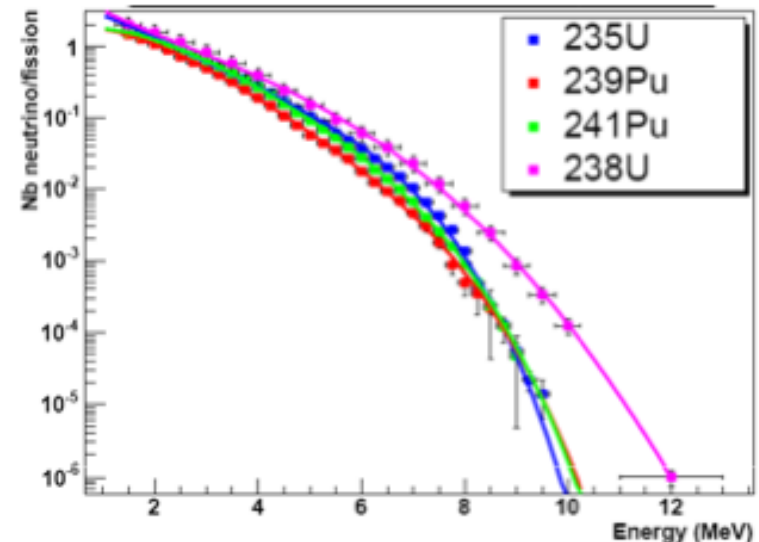
$^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$

neutrino flux and spectrum depend on

- reactor power
- composition of fuel elements
- burnup

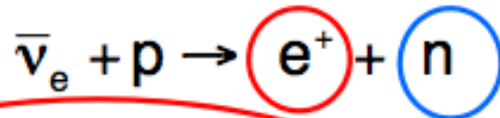
⇒  $\sim 2\%$  systematic uncertainty of predicted  $\bar{\nu}$  flux

Schreckenbach et al., Phys.Lett. B160 (1985)  
Hahn et al., Phys.Lett. B218 (1989)



# Antineutrino Detection

inverse beta decay:

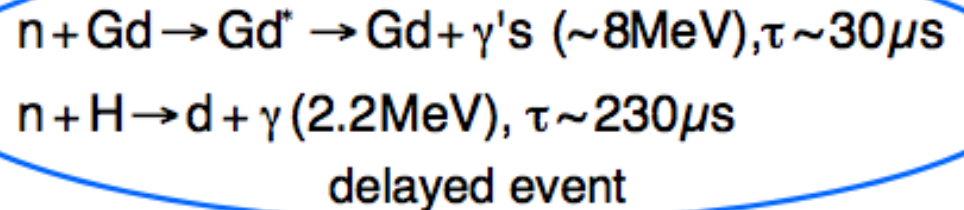


$$Q_{\text{thr}} = M_n + m_e - M_p \approx 1.8 \text{ MeV}$$

$$E_{\text{vis}} \approx E_\nu - E_n - 0.8 \text{ MeV}$$

$$\approx 1 - 8 \text{ MeV}$$

prompt event

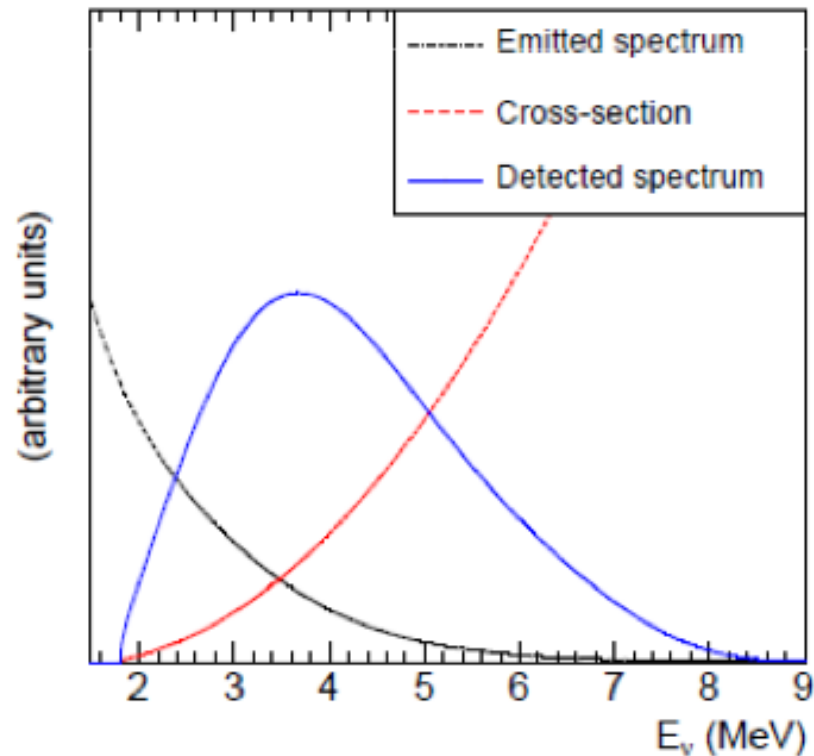


Detection in Gd-loaded liquid organic scintillator

$^{157}\text{Gd}$ ,  $^{155}\text{Gd}$  highest cross section for thermal n

release of total  $\sim 8 \text{ MeV}$   $\gamma$ s

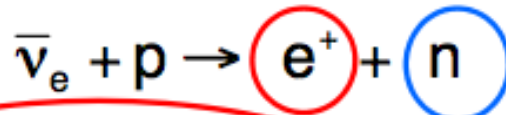
$\Rightarrow$  distinctive signature, well above radioactive background



# Antineutrino Signal

inverse beta decay:

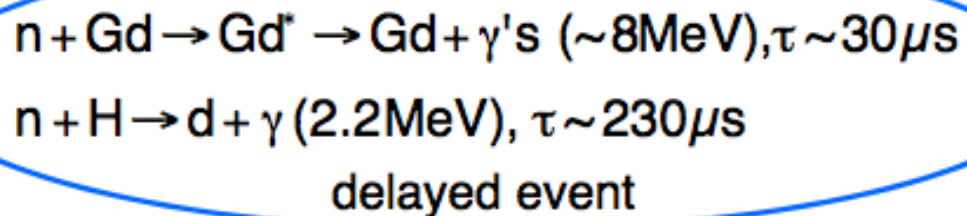
$$Q_{\text{thr}} = M_n + m_e - M_p \approx 1.8 \text{ MeV}$$



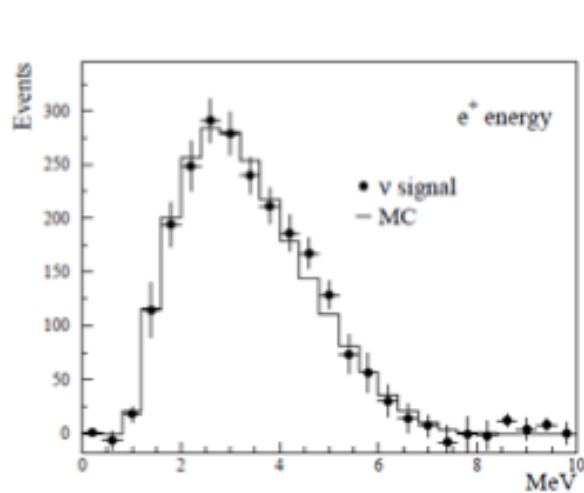
$$E_{\text{vis}} \cong E_\nu - E_n - 0.8 \text{ MeV}$$

$$\approx 1 - 8 \text{ MeV}$$

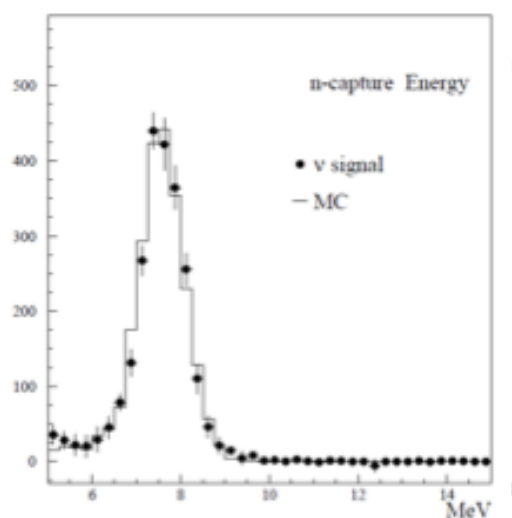
prompt event



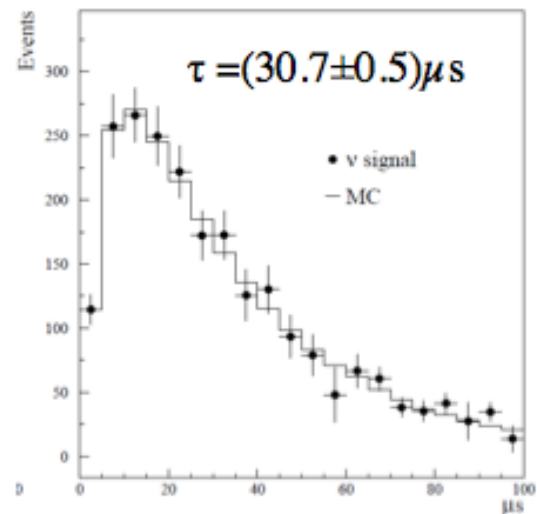
Detection in Gd-loaded liquid scintillator



$e^+$  energy



n capture energy



$e^+$ -n time delay

# Great success of reactor experiments in the past

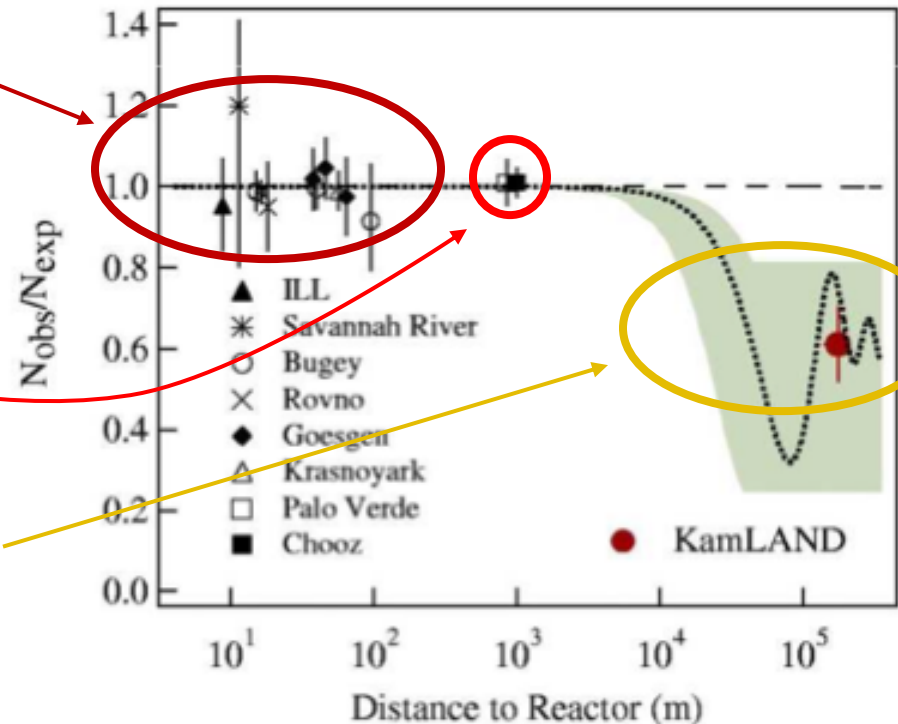
1956 first experimental neutrino detection  
by Cowan and Reines, Savannah River  
confirmation of Pauli's neutrino hypothesis  
⇒ Nobel Prize 1958



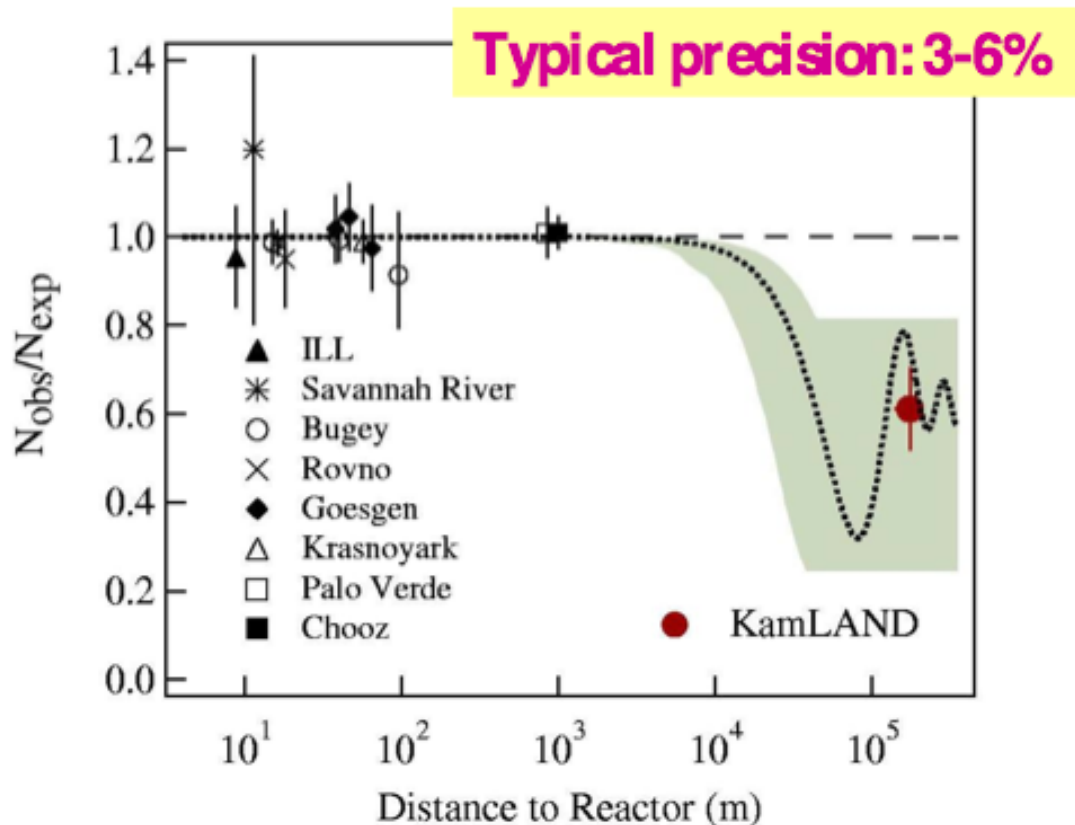
1980s measurement of reactor neutrino flux,  
search for neutrino oscillations  
at distances 10-100 m  
Goesgen, ILL, Bugey, Rovno, ...

1990s search for oscillations at  $d \sim 1$  km  
Chooz, Palo Verde  
best limit on  $\theta_{13}$

2001 proof of solar neutrino oscillations  
by KamLAND ( $d \sim 180$  km)  
most precise determination of  $\Delta m_{21}^2$



# Reactor Experiments: comparing observed/expected neutrinos



## Precision of past exp.

- ◆ Reactor power: ~ 1%
- ◆ Spectrum: ~ 0.3%
- ◆ Fission rate: 2%
- ◆ Backgrounds: ~1-3%
- ◆ Target mass: ~1-2%
- ◆ Efficiency: ~ 2-3%

To measure  $\theta_{13}$  a 0.4% precision is needed

# Terrestrial “Solar Neutrinos”

Can we convincingly verify oscillation with man-made neutrinos?

$$P_{surv} = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2 c^4 \text{ GeV } L}{\text{eV}^2 E_\nu \text{ km}} \right)$$

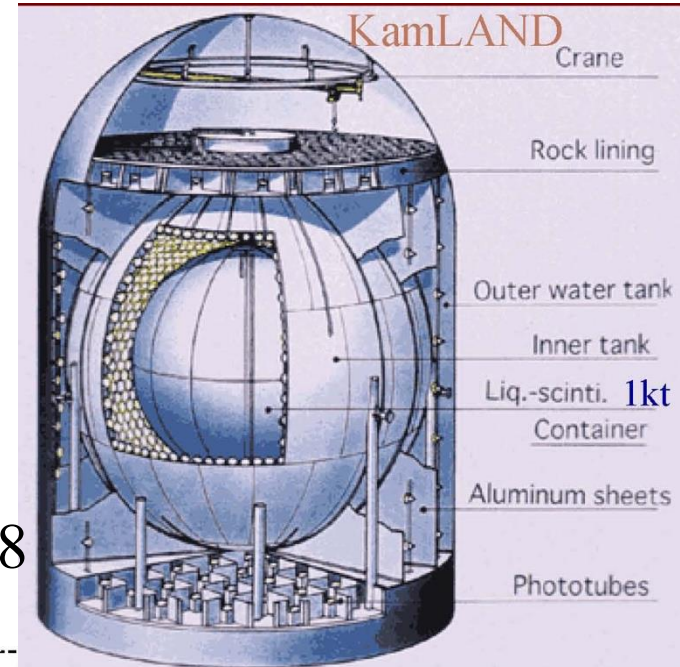
- Hard for low  $\Delta m^2$
- To probe LMA, need  $L \sim 100\text{km}$ ,  $1\text{kt}$
- Need low  $E_\nu$ , high  $\Phi_\nu$
- Use neutrinos from nuclear reactors

$$\Delta m^2 = 10^{-5} \text{ eV}^2$$

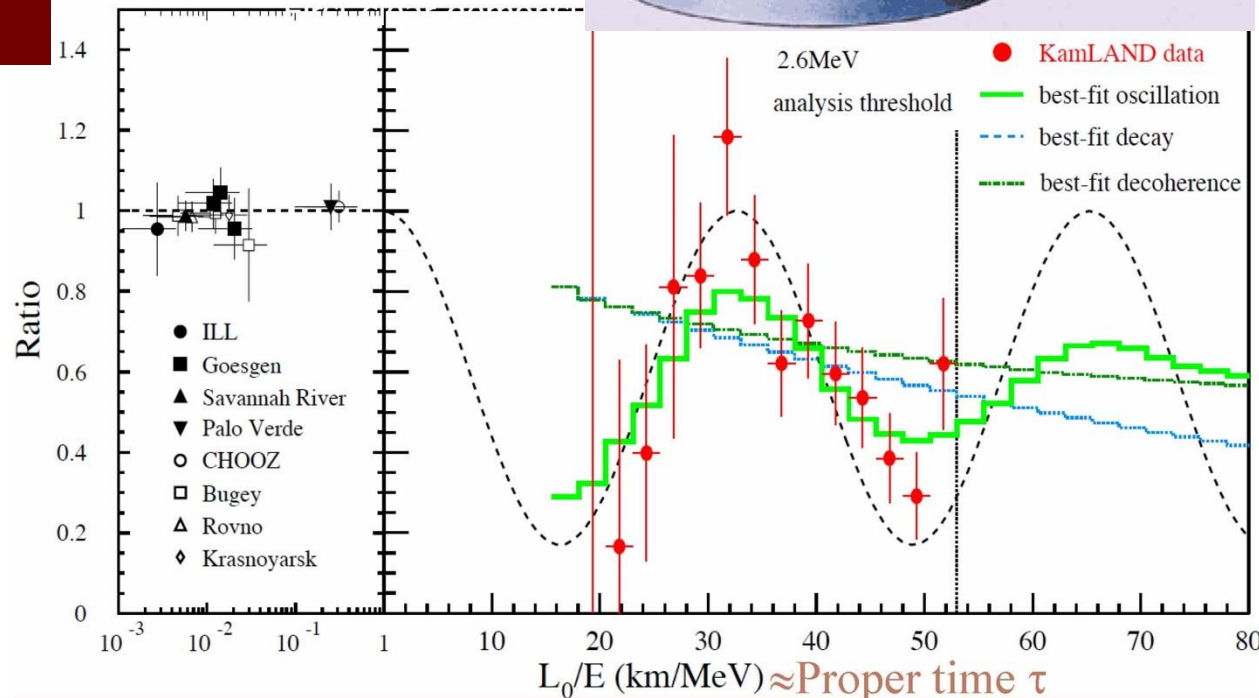
$$E_\nu = 3 \text{ MeV}$$

$$L = 180 \text{ km}$$

$$\rightarrow 1.27 \Delta m^2 L / E_\nu = 0.8$$



**KAMLAND: reactor anti-neutrino do oscillate!**



# Measuring $\theta_{13}$ with Reactor Experiments

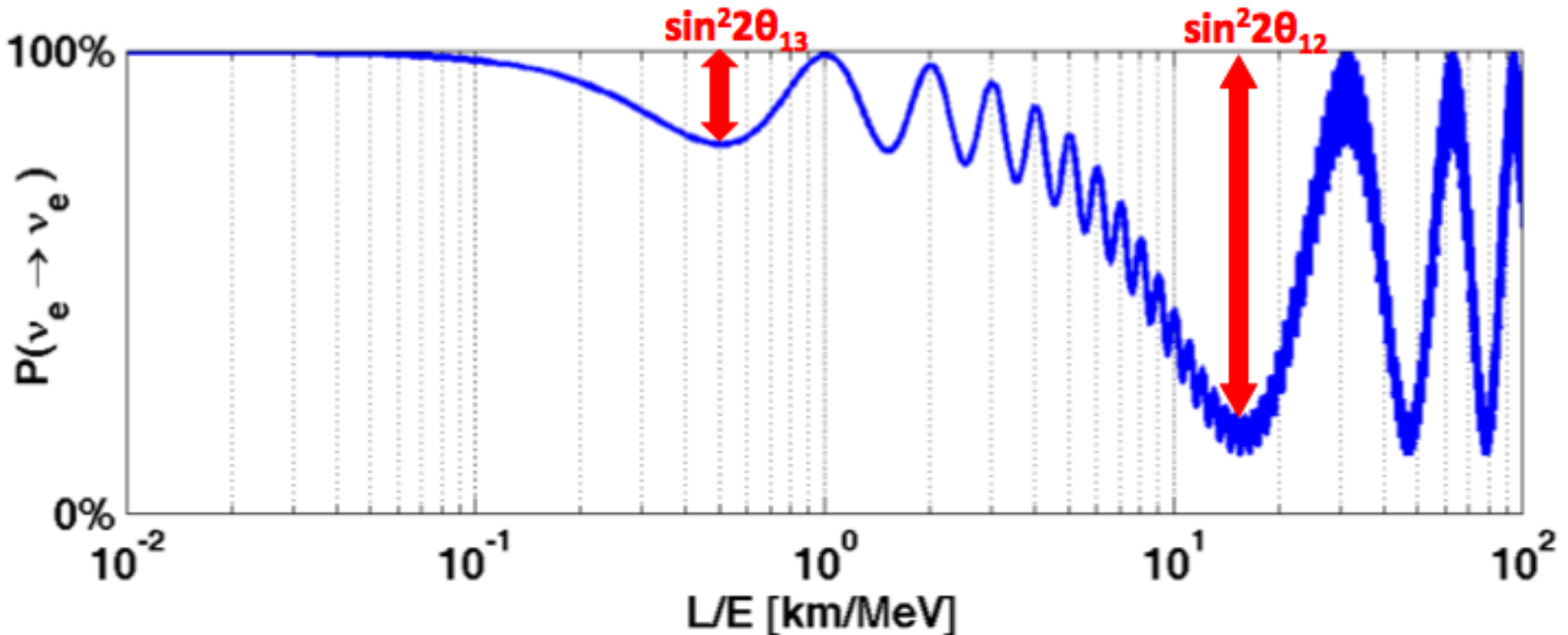
$\langle E_\nu \rangle \sim 4 \text{ MeV} \Rightarrow$  only disappearance experiments possible

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{\text{atm}}^2 L}{4E_\nu} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{\text{sol}}^2 L}{4E_\nu}$$

2 different length scales involved:

$$\Delta m_{\text{atm}}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \Rightarrow L \sim 1.8 \text{ km}$$

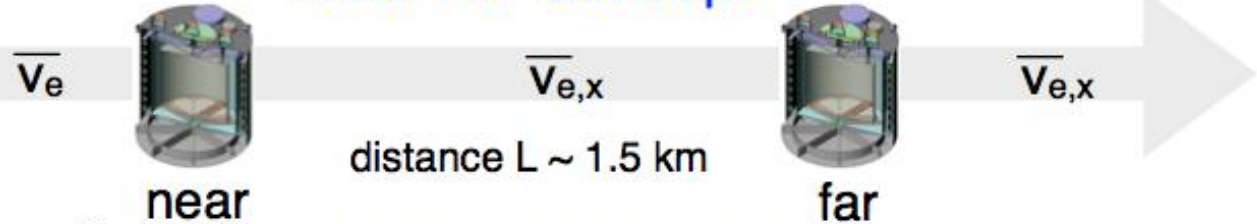
$$\Delta m_{\text{sol}}^2 = 8 \times 10^{-5} \text{ eV}^2 \Rightarrow L \sim 60 \text{ km}$$



# Measuring $\theta_{13}$ with Reactor Experiments

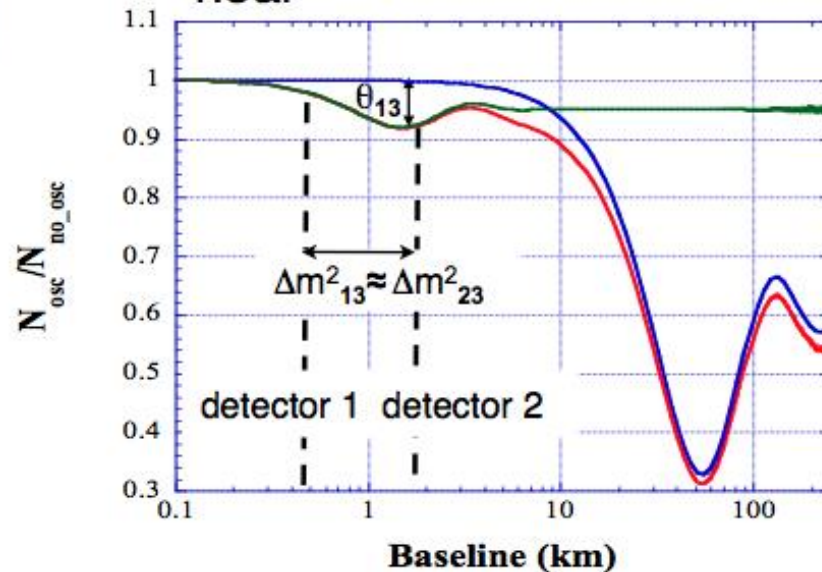


## Near-Far Concept



**Absolute Reactor Flux**  
Largest uncertainty in previous measurements

**Relative Measurement**  
Removes absolute uncertainties!



First proposed by L. A. Mikaelyan and V.V. Sinev,  
Phys. Atomic Nucl. 63 1002 (2000)

$$\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

far/near  $\bar{V}_e$  ratio

target mass

distances

efficiency

oscillation deficit

# Daya Bay

**Far site**  
1600 m from Ling Ao  
2000 m from Daya  
Overburden: 350 m

Empty detectors: moved to underground halls through access tunnel.  
Filled detectors: swapped between underground halls via horizontal tunnels.

**Ling Ao Near**  
500 m from Ling Ao  
Overburden: 98 m

**Mid site**  
~1000 m from Daya  
Overburden: 208 m

Ling Ao-II NPP  
(under const.)

Ling Ao NPP

**Daya Bay Near**  
360 m from Daya Bay  
Overburden: 97 m

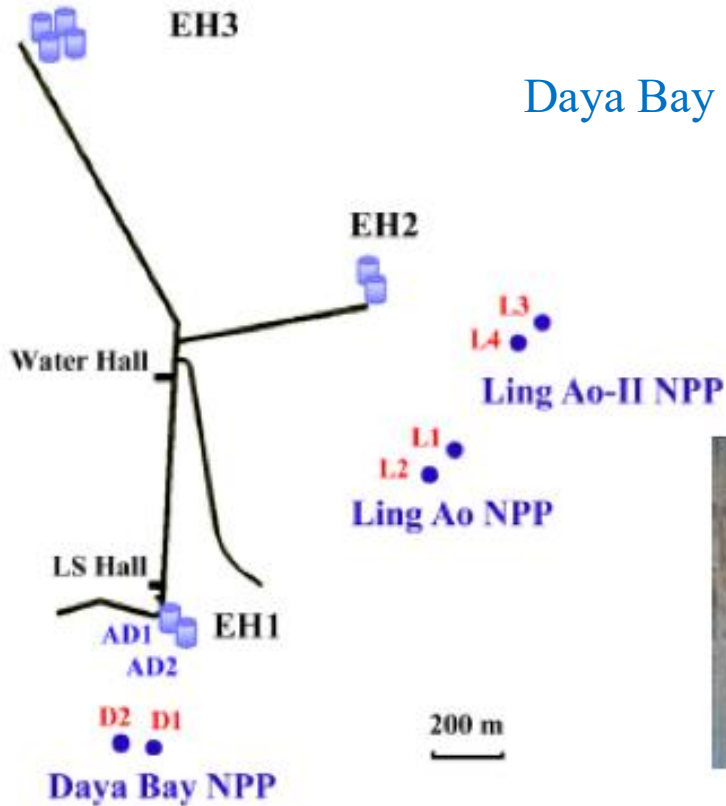
Daya Bay NPP



Total tunnel length: ~2700 m

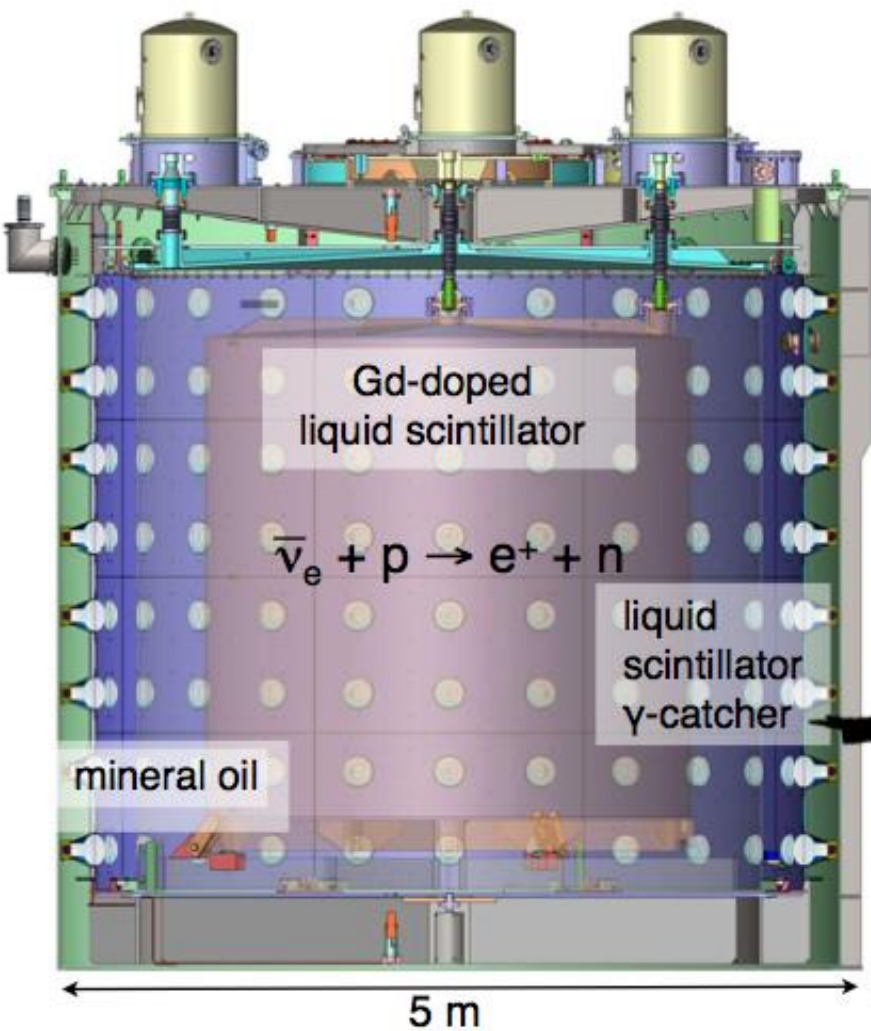
# Underground Labs

Daya Bay (China)



|     | Overburden<br>(MWE) | $R_{\mu}$<br>(Hz/m <sup>2</sup> ) | $E_{\mu}$<br>(GeV) | D1,2<br>(m) | L1,2<br>(m) | L3,4<br>(m) |
|-----|---------------------|-----------------------------------|--------------------|-------------|-------------|-------------|
| EH1 | 250                 | 1.27                              | 57                 | 364         | 857         | 1307        |
| EH2 | 265                 | 0.95                              | 58                 | 1348        | 480         | 528         |
| EH3 | 860                 | 0.056                             | 137                | 1912        | 1540        | 1548        |

# Daya Bay Antineutrino Detectors



automated calibration system

reflectors at top/ bottom of cylinder

photomultipliers

steel tank

radial shield

outer acrylic tank

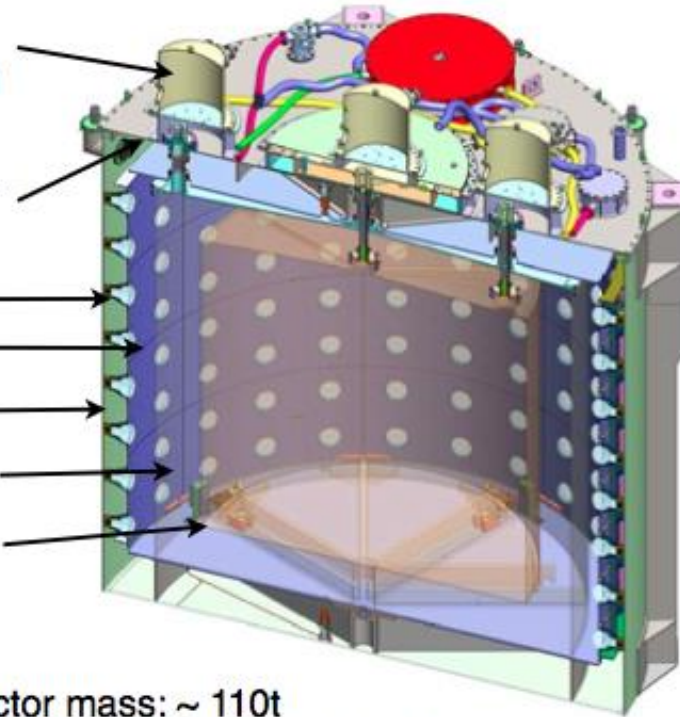
inner acrylic tank

Gd-doped liquid scintillator



liquid scintillator  $\gamma$ -catcher

mineral oil



total detector mass: ~ 110t

inner: 20 tons Gd-doped LS (d=3m)

mid: 20 tons LS (d=4m)

outer: 40 tons mineral oil buffer (d=5m)

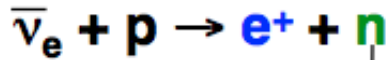
photosensors: 192 8"-PMTs

energy resolution:  $(7.5 / \sqrt{E} + 0.9)\%$

6 "functionally identical", 3-zone detectors reduces systematic uncertainties

$$\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

# Daya Bay Antineutrino Detection



0.3 b  $\rightarrow + p \rightarrow D + \gamma$  (2.2 MeV) (delayed)

49,000 b  $\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$ 's (8 MeV) (delayed)

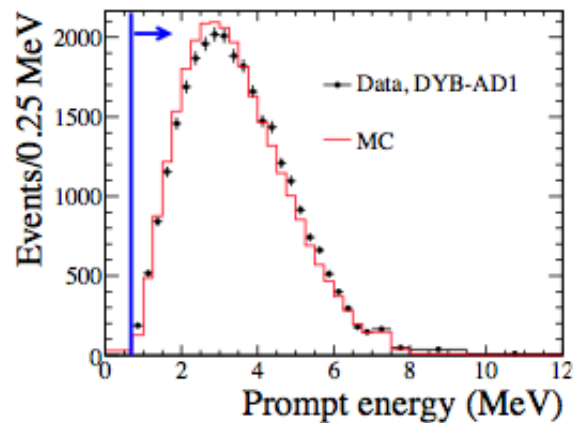
prompt+delayed coincidence provides distinctive signature

Prompt positron: carries antineutrino energy

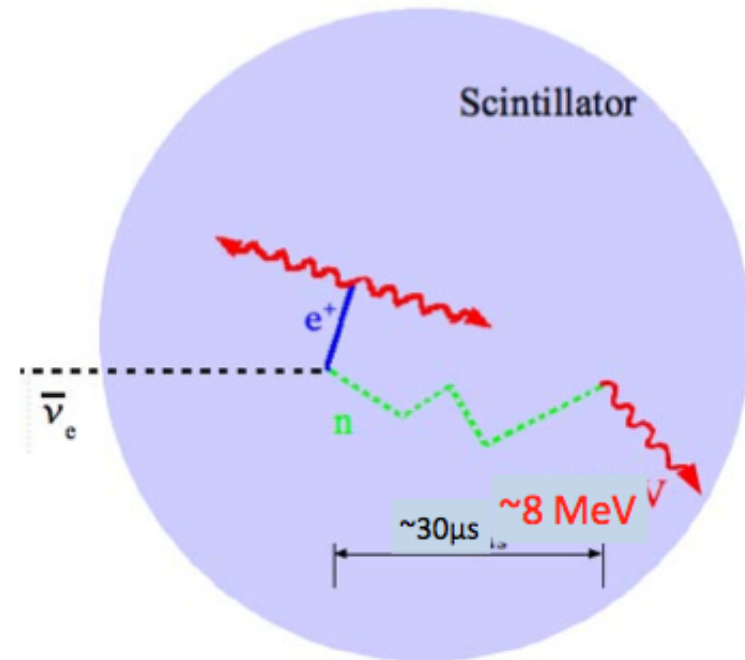
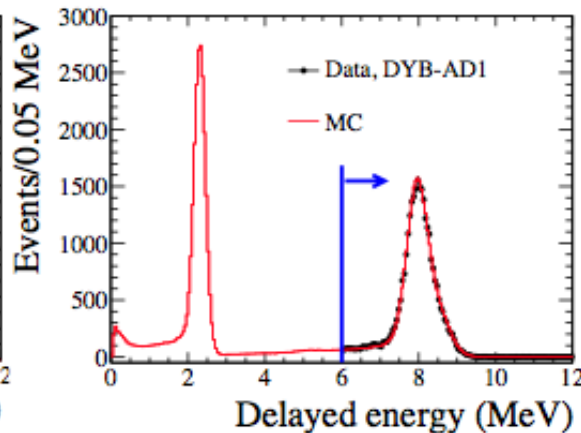
$$E_{e^+} \approx E_{\nu} - 0.8 \text{ MeV}$$

Delayed neutron capture: tags antineutrino signal

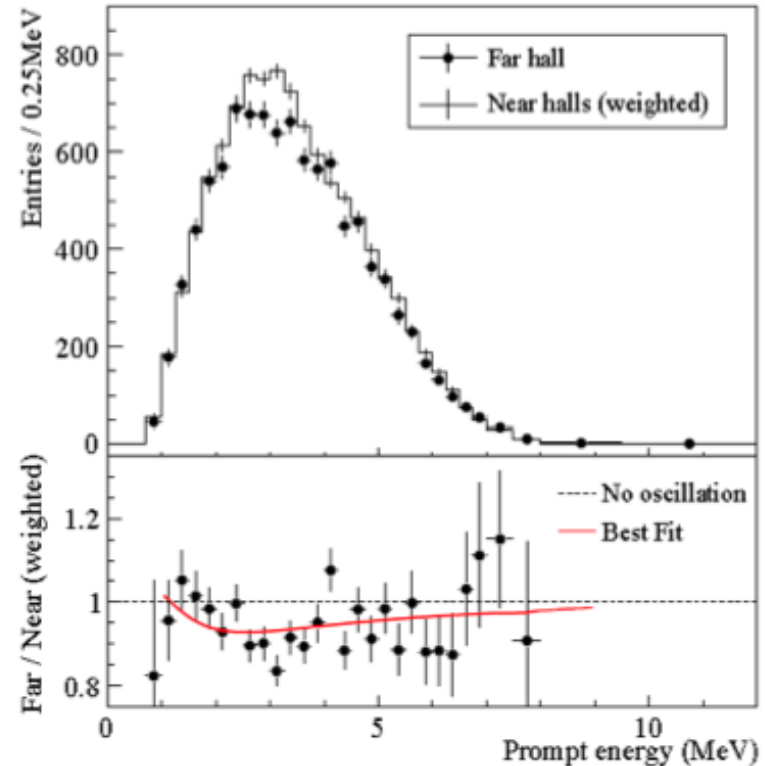
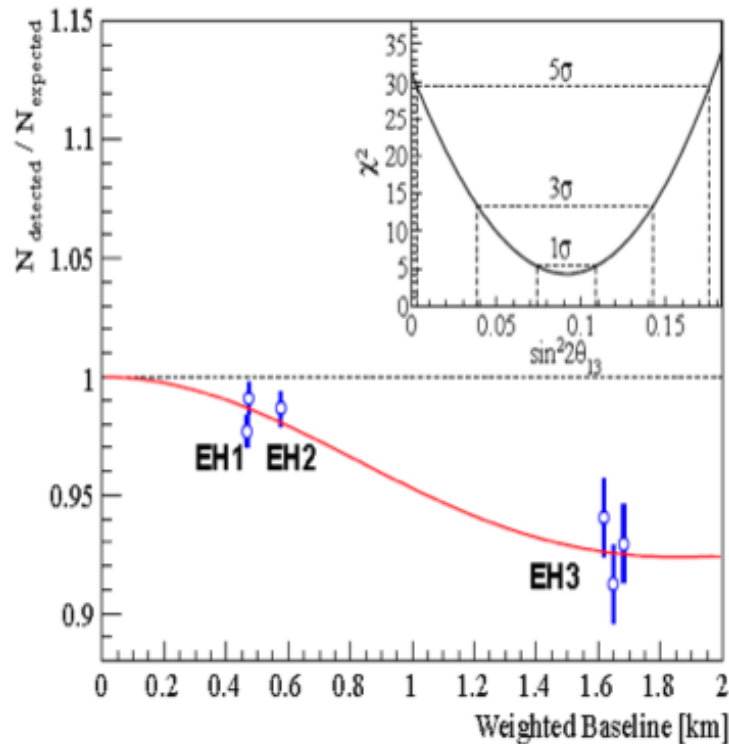
Prompt Energy Signal



Delayed Energy Signal



# March 8, 2012 : Daya Bay results



hall. Comparing with the prediction based on the near-hall measurements, a deficit of 6.0% was found. A rate-only analysis yielded  $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$ . The neutrino mixing angle  $\theta_{13}$  is non-zero with a significance of 5.2 standard deviations.

# Summary

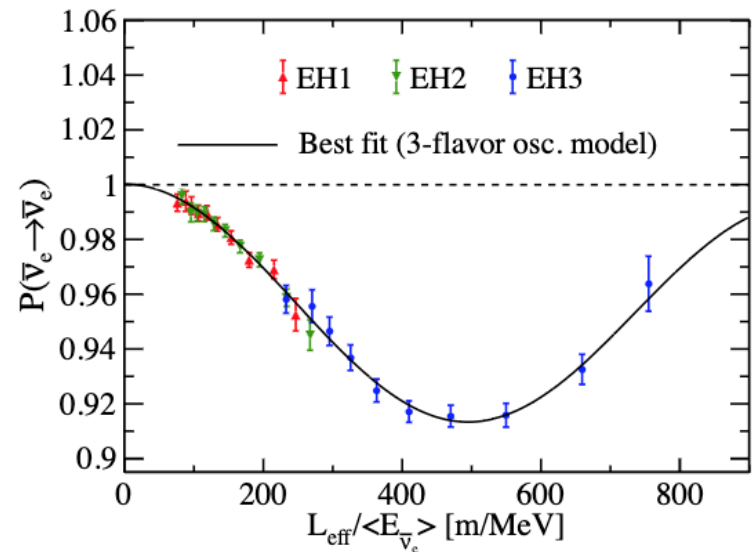
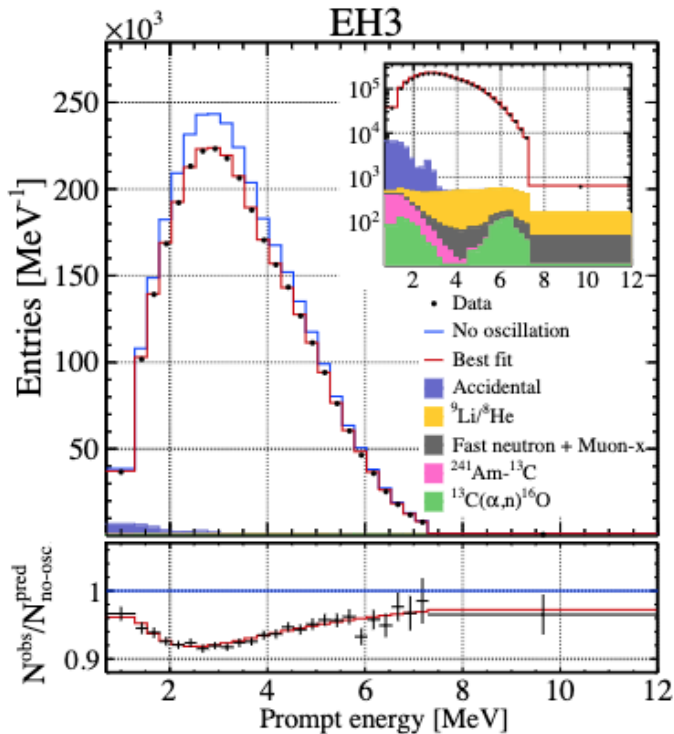
- Electron anti-neutrino disappearance is observed at Daya Bay:

$$R = 0.940 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$$

- The spectral distortion is observed too
- A new type of neutrino oscillation is thus discovered

- $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$   
( $\chi^2/\text{dof} = 4.26/4$ )
- $5.2 \sigma$  for non-zero  $\theta_{13}$

Final results on the full data set (2020)

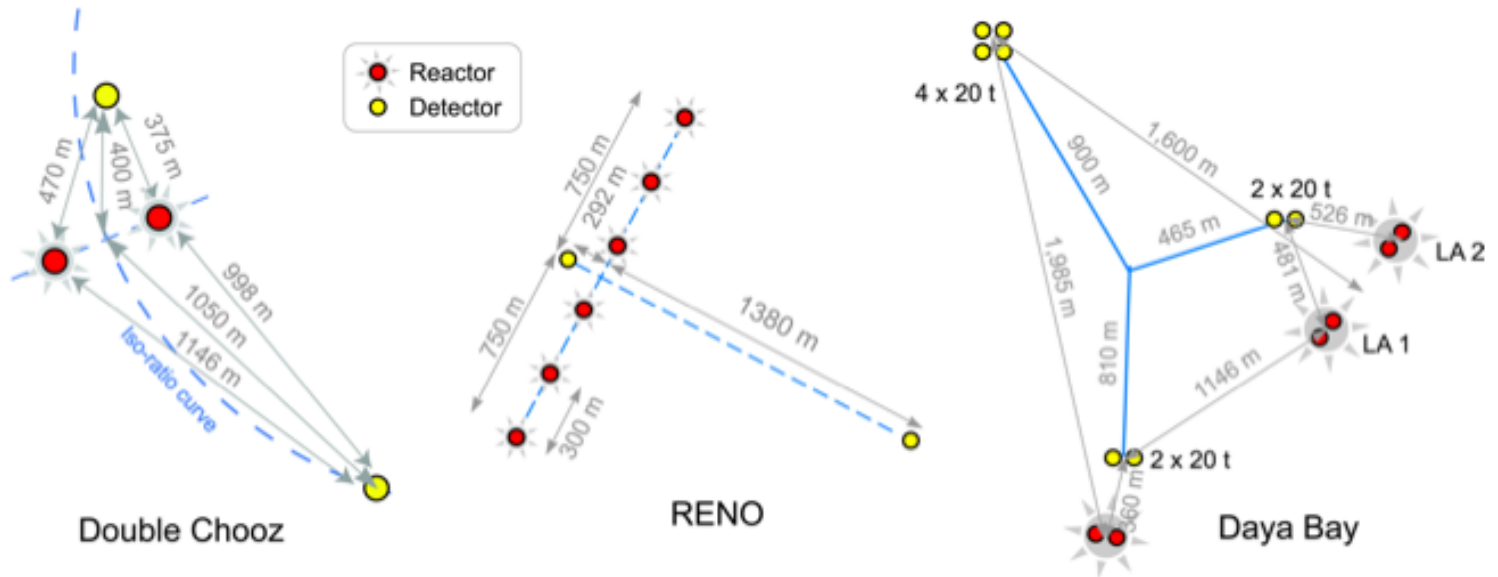


- $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$
- $\Delta m_{32}^2 = (2.466 \pm 0.060) \times 10^{-3} \text{ eV}^2$  for NO
- $\Delta m_{32}^2 = -(2.571 \pm 0.060) \times 10^{-3} \text{ eV}^2$  for IO

IO

# The three reactor experiments

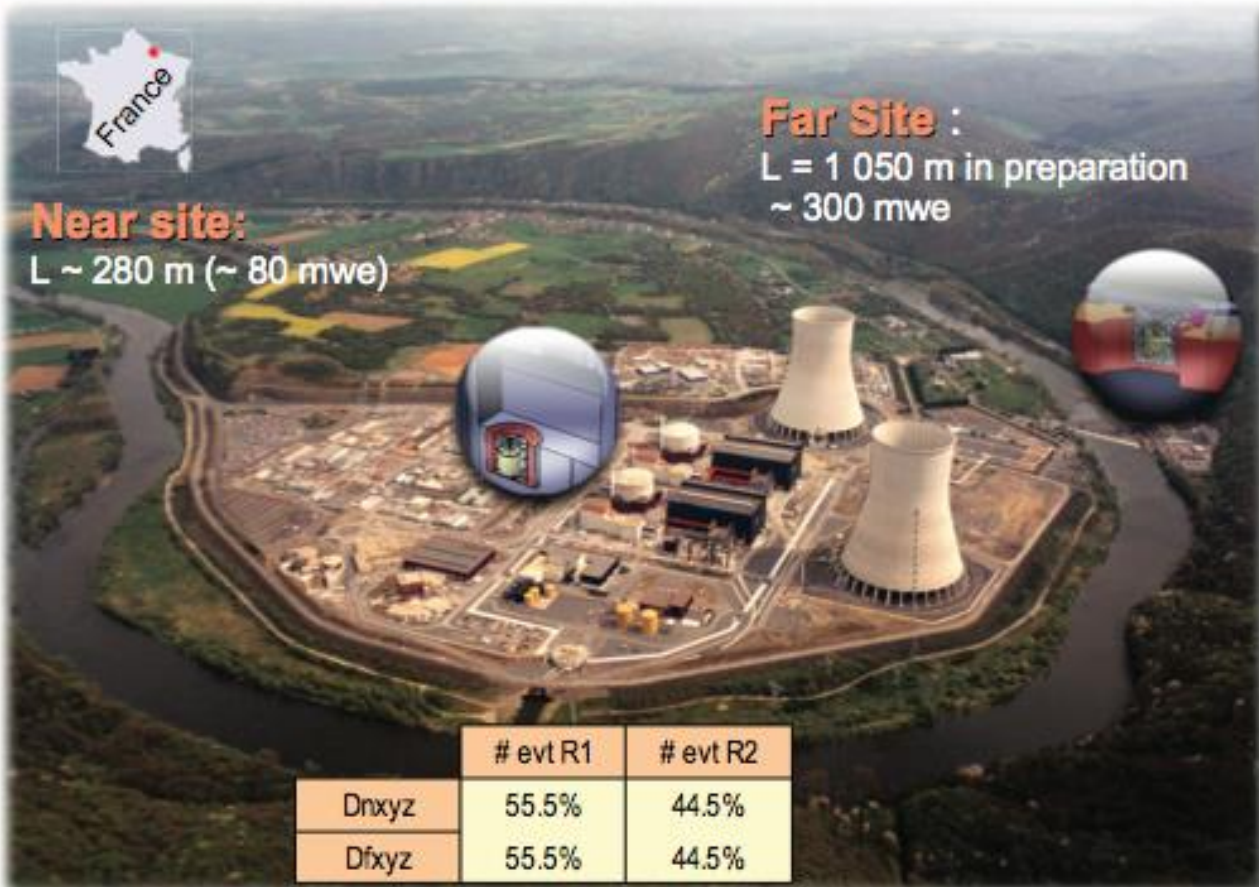
| Setup        | $P_{Th}$ [GW] | $L$ [m] | $m_{Det}$ [t] | Events/year      | Backgrounds/day |
|--------------|---------------|---------|---------------|------------------|-----------------|
| Daya Bay     | 17.4          | 1700    | 80            | $10 \cdot 10^4$  | 0.4             |
| Double Chooz | 8.6           | 1050    | 8.3           | $1.5 \cdot 10^4$ | 3.6             |
| RENO         | 16.4          | 1400    | 15.4          | $3 \cdot 10^4$   | 2.6             |





# Double Chooz

Talk by J. Dawson



**Near site:**  
L ~ 280 m (~ 80 mwe)

**Far Site :**  
L = 1 050 m in preparation  
~ 300 mwe

|       | # evt R1 | # evt R2 |
|-------|----------|----------|
| Dnxyz | 55.5%    | 44.5%    |
| Dfxyz | 55.5%    | 44.5%    |

**2 cores – 1 site – 8.5 GW<sub>th</sub>**

**1 near position, 1 far**

- target: 2 x 8.3 t

**Civil engineering**

- 1 near lab ~ Depth 40 m, Ø 6 m

- 1 available lab

**Statistics (including  $\epsilon$ )**

- far: ~ 40 evts/day

- near: ~ 460 evts/day

**Systematics**

- reactor : ~ 0.2%

- detector : ~ 0.5%

**Backgrounds**

-  $\sigma_{b2b}$  at far site: ~ 1%

-  $\sigma_{b2b}$  at near site: ~ 0.5%

**Planning**

1. Far detector only

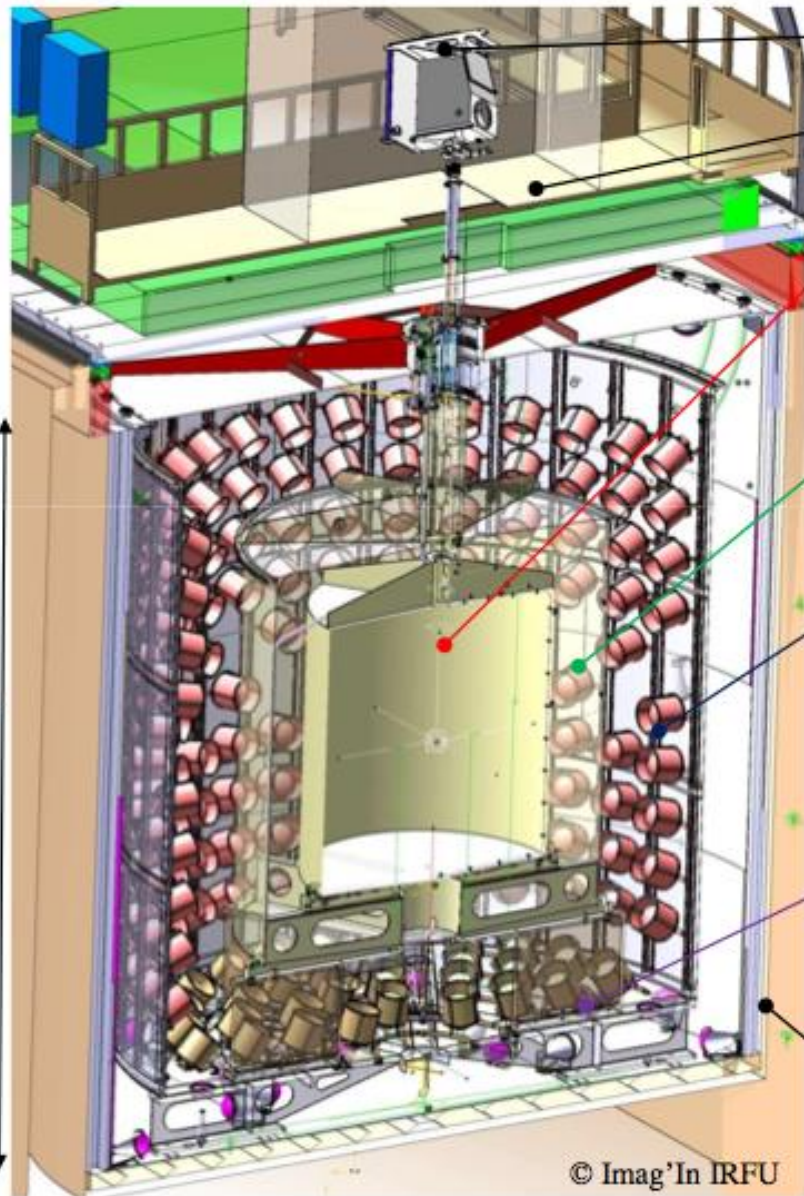
- Sensitivity (1.5 ans) ~ 0.06

2. Far + Near sites

- available from 2010

- Sensitivity (3 years) ~ 0.025

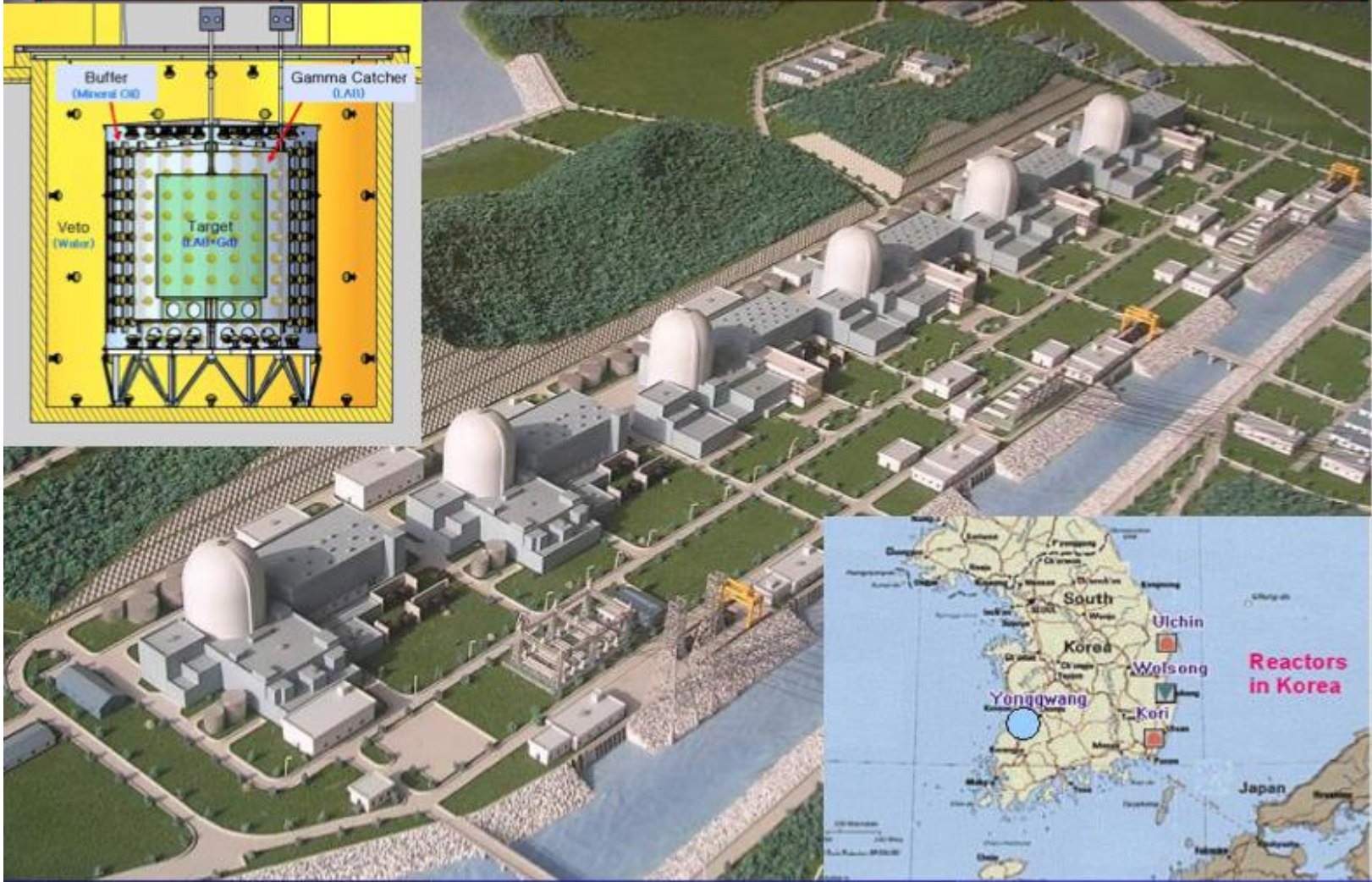
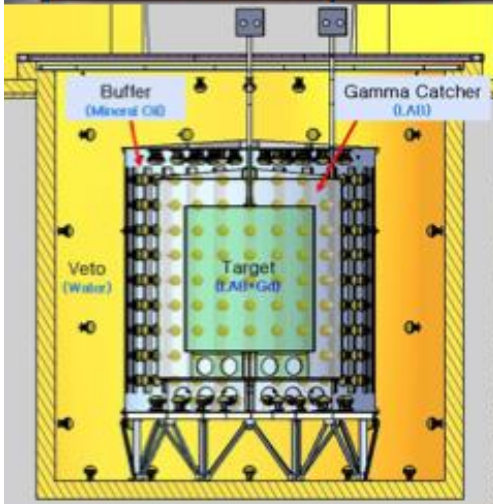
# Detector Design



- calibration glove box
- external muon veto plastic scintillator strips
- **target: 10.3 m<sup>3</sup> Gd-loaded scintillator 0.1%**  
in acrylic vessel (r=1.15m, h=2.5m)
- **γ-catcher: 22.4 m<sup>3</sup> unloaded scintillator**  
in acrylic vessel (r=1.7m, h=3.6m)
- non-scintillating **buffer: 100 m<sup>3</sup> mineral oil**  
in stainl. steel vessel (r=2.8m, h=5.7m)  
390 PMTs (10'')
- **inner muon veto: 90 m<sup>3</sup> liquid scintillator**  
in steel vessel (r=3.3m, h=7m)  
78 8'' PMTs
- 15 cm **steel shielding** against external γ's

# RENO

|      | Location | Thermal Power | Distances Near/Far (m) | Depth (mwe) | Target Mass (tons) | Cost   |
|------|----------|---------------|------------------------|-------------|--------------------|--------|
| RENO | Korea    | 17.3 GW       | 290/1380               | 120/450     | 16/16 ton          | ~10M\$ |



# Experimental Results at that time (2012)

**T2K ( $\theta_{13} > 0 @ 2.5\sigma$ )**

Expected events: 1.5, Detected 6

$\nu_e$  appearance  
on  $\nu_\mu$  beam

**Double Chooz ( $1.3\sigma$ )**

Expected events: 4344, Detected 4101  
 $R_{DC} = 0.944 \pm 0.016(\text{stat}) \pm 0.040(\text{syst})$

**Daya Bay ( $5.2\sigma$ )**

Expected events: 85506, Detected 80376  
 $R_{DB} = 0.940 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$

$\bar{\nu}_e$  disappearance  
on  $\bar{\nu}_e$  from reactors

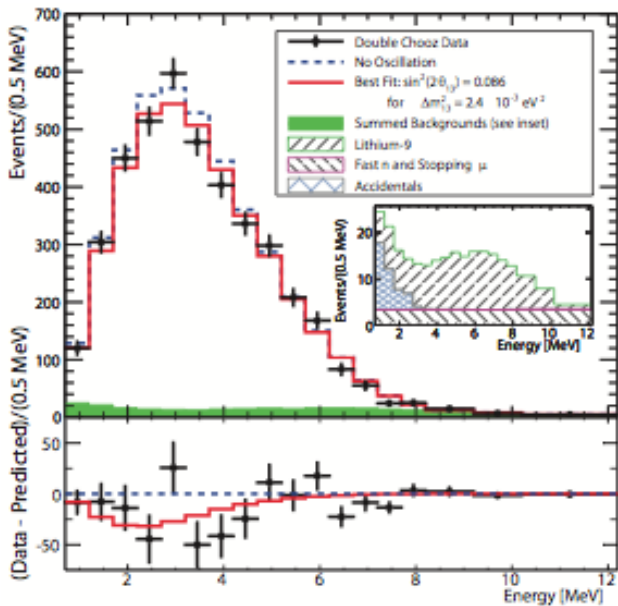
**RENO ( $4.9\sigma$ )**

Expected events: 149905, Detected 137912  
 $R_R = 0.920 \pm 0.009(\text{stat.}) \pm 0.014(\text{syst.})$

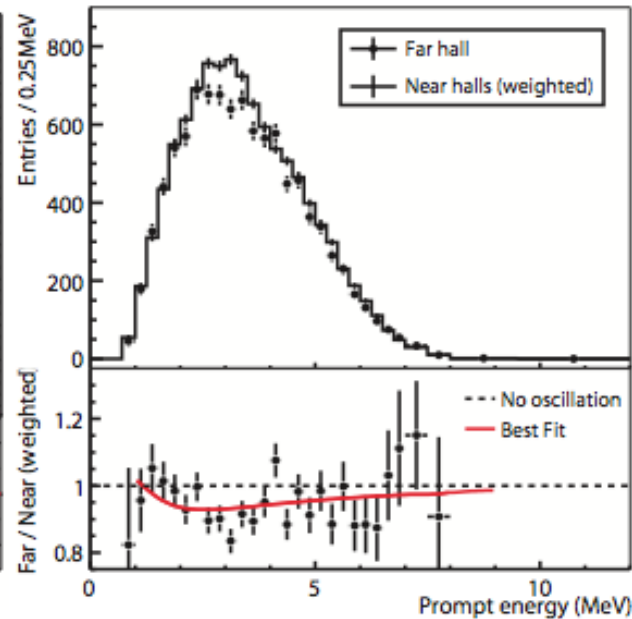
# Spectral information

Not used in the fit

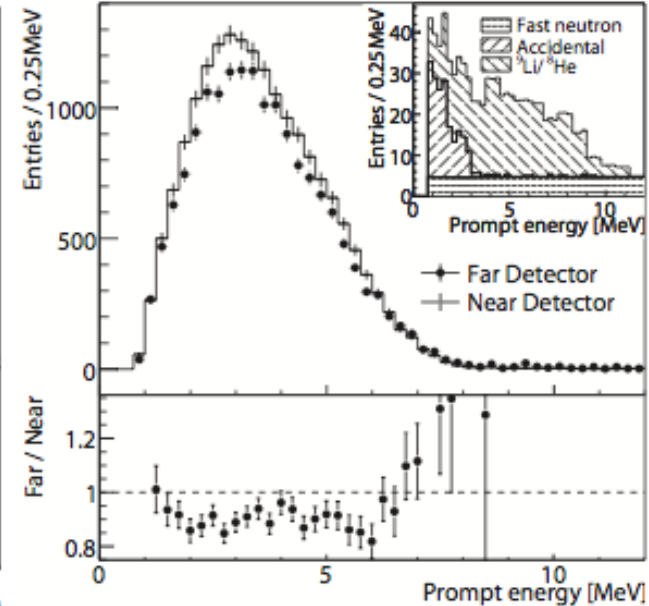
Double Chooz



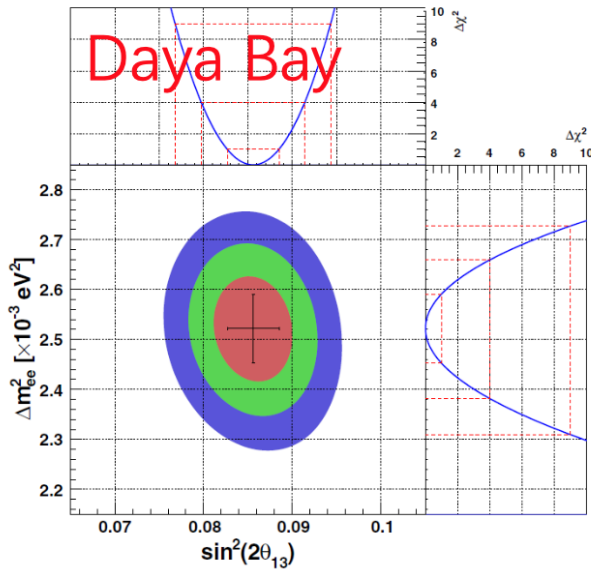
Daya Bay



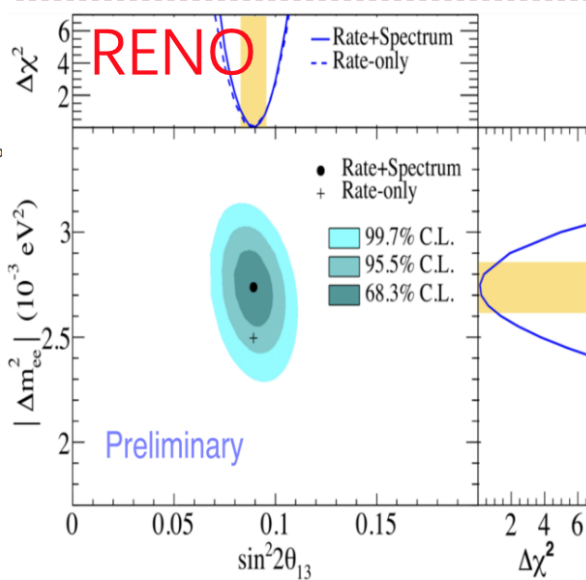
RENO



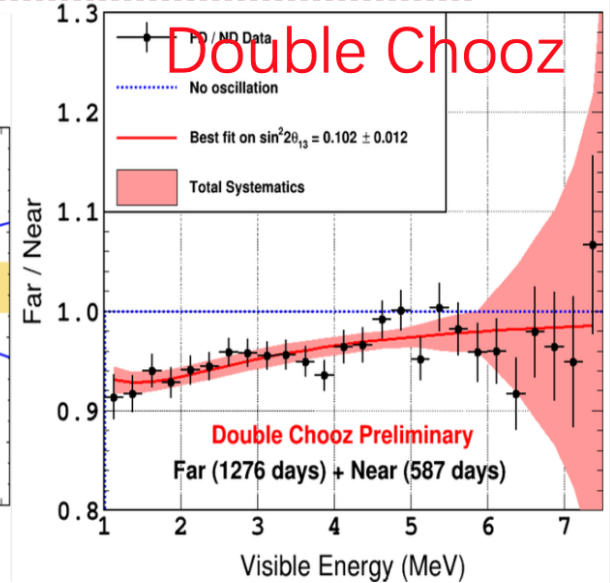
# Recent $\theta_{13}$ and $|\Delta m_{ee}^2|$ Results (2020)



Daya Bay



RENO



Double Chooz

Gd-capture

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

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

PRL 121 241805 (2018)

H-capture

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

PRD 93 072011 (2016)

Gd-capture

$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(\text{stat.}) \pm 0.0045(\text{sys.})$$

$$|\Delta m_{ee}^2| = 2.74 \pm 0.10(\text{stat.}) \pm 0.06(\text{sys.})(\times 10^{-3} \text{ eV}^2)$$

@ICHEP 2020

H-capture

$$\sin^2 2\theta_{13} = 0.086 \pm 0.008(\text{stat.}) \pm 0.014(\text{sys.})$$

JHEP 04 (2020) 029

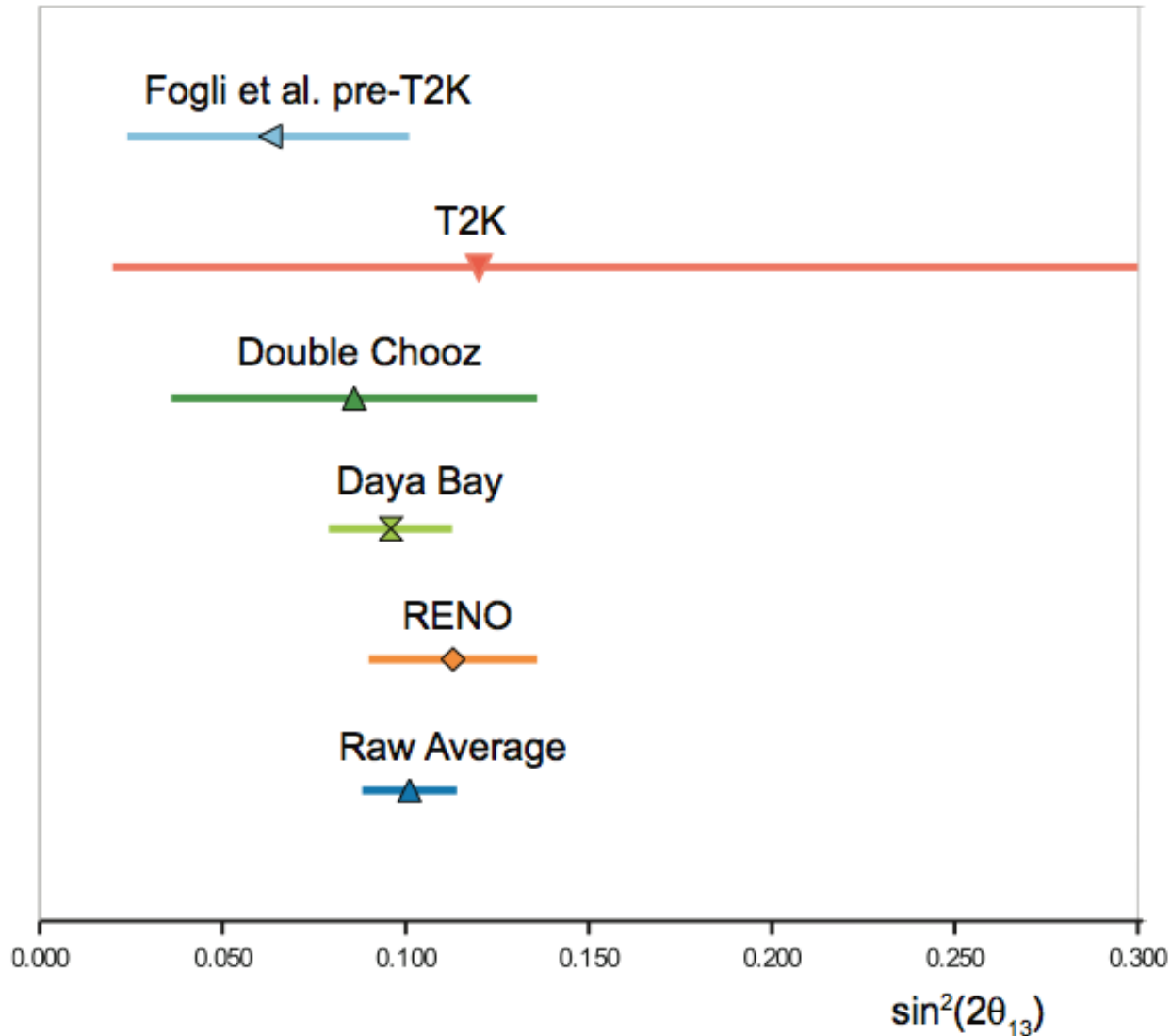
Total-capture

$$\sin^2 2\theta_{13} = 0.102 \pm 0.011(\text{syst.}) \pm 0.004(\text{stat.})$$

@Neutrino 2020

# Summary of $\theta_{13}$ results

Computed for  $\Delta m_{23}^2 = 2.4 \cdot 10^{-3} \text{ eV}^2$

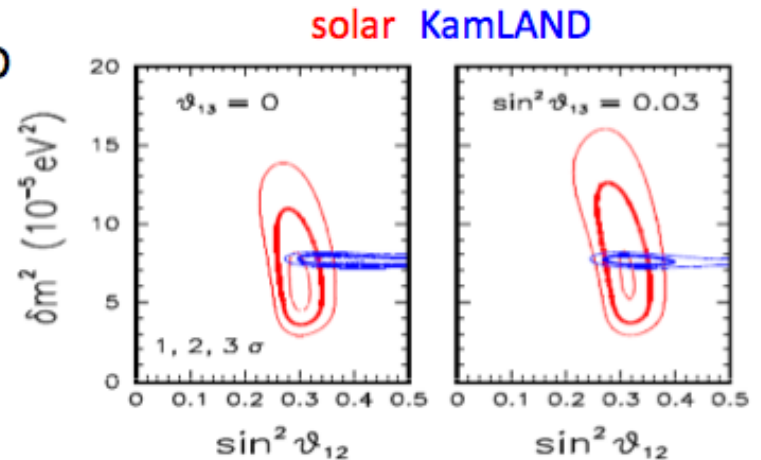


# Before 2011: hints about a non null $\theta_{13}$

## Global fits to oscillation data

Imperfect agreement between KamLAND and solar fits: for  $\theta_{13}=0$ , solar expts. and KamLAND prefer different values of  $\theta_{12}$   
 $\Rightarrow$  weak preference for  $\theta_{13}>0$

e.g. Fogli, Lisi et al., 0905.3549 (2009)  
Mezzetto, Schwetz, J.Phys.G37, 103001 (2010)  
Gonzales-Garcia et al., 1001.4524 (2010)

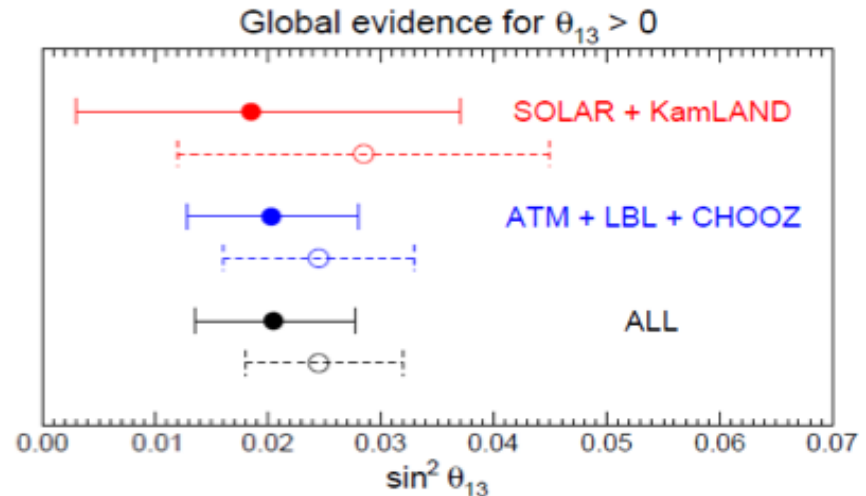


Including recent T2K result

best fit:  $\sin^2 2\theta_{13} = 0.08 \pm 0.03$

3  $\sigma$  evidence for  $\theta_{13} > 0$

Fogli et al., arXiv:1106.6028v1



# *Results on $\theta_{13}$ by neutrino beams*

## 2 experimental approaches to determine $\theta_{13}$

### • Accelerator experiments ( $\nu_\mu$ -beam)

- appearance experiment:  $\nu_\mu \rightarrow \nu_e$  (and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ )

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \approx 0.03$$

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\Delta_{31}$$

$$- \alpha \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \cos(\delta) \Delta_{31} \cos\Delta_{31} \sin\Delta_{31}$$

$$- \alpha \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin(\delta) \Delta_{31} \sin^2\Delta_{31}$$

$$+ \alpha^2 \dots$$

- long baseline ( $10^2 - 10^3$  km)  $\Rightarrow$  matter effects,  $\text{sgn}(\Delta m_{31}^2)$
- multiple correlations and degeneracies

### T2K, NoVa, ...

### • nuclear reactors

- $\bar{\nu}_e, \langle E_\nu \rangle$  few MeV  $\Rightarrow$  disappearance experiment

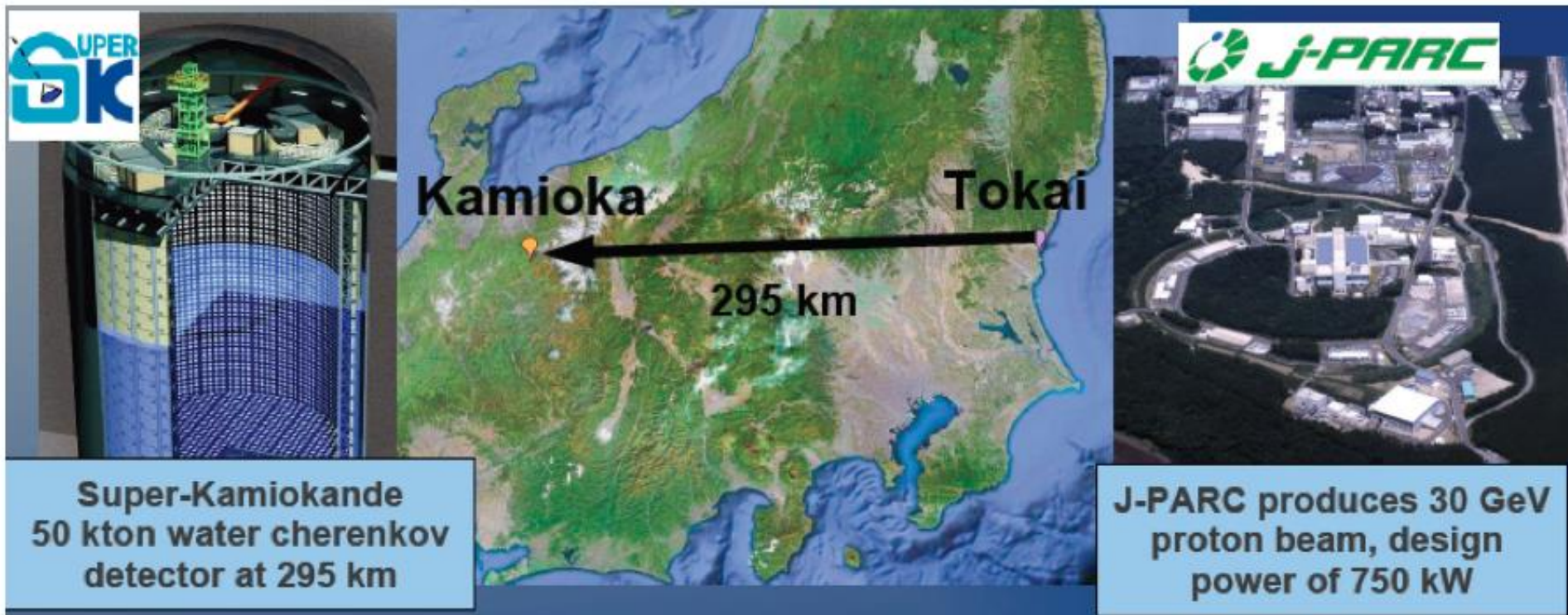
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

- look for rate deviation from  $1/r^2$  and spectral distortions
- clean measurement of  $\theta_{13}$ , independent of  $\delta$ -CP, weak dependence on  $\Delta m_{21}^2$
- small distance (1 - 2 km)  $\Rightarrow$  matter effects negligible

### Double Chooz, Daya Bay, RENO

# T2K: $\nu_e$ appearance to search for $\theta_{13}$

- The **T2K** experiment is designed to **measure  $\theta_{13}$  mixing angle** by means of a  **$\nu_\mu$  beam** produced at J-PARC and sent to the already existing and well understood **Super-Kamiokande detector** (295 km away)



- **OFF-AXIS beam to have a narrow energy distribution.**

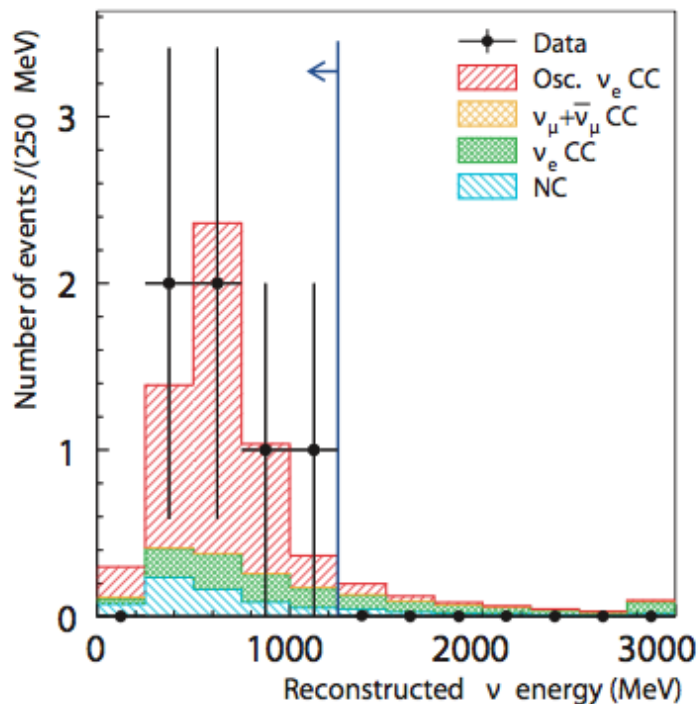
$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \left( \frac{\Delta m_{13}^2 L}{4E} \right) \left[ 1 \pm \frac{2a}{\Delta m_{13}^2} (1 - 2s_{13}^2) \right]$$

# T2K result

PRL 107 (2011) 041801

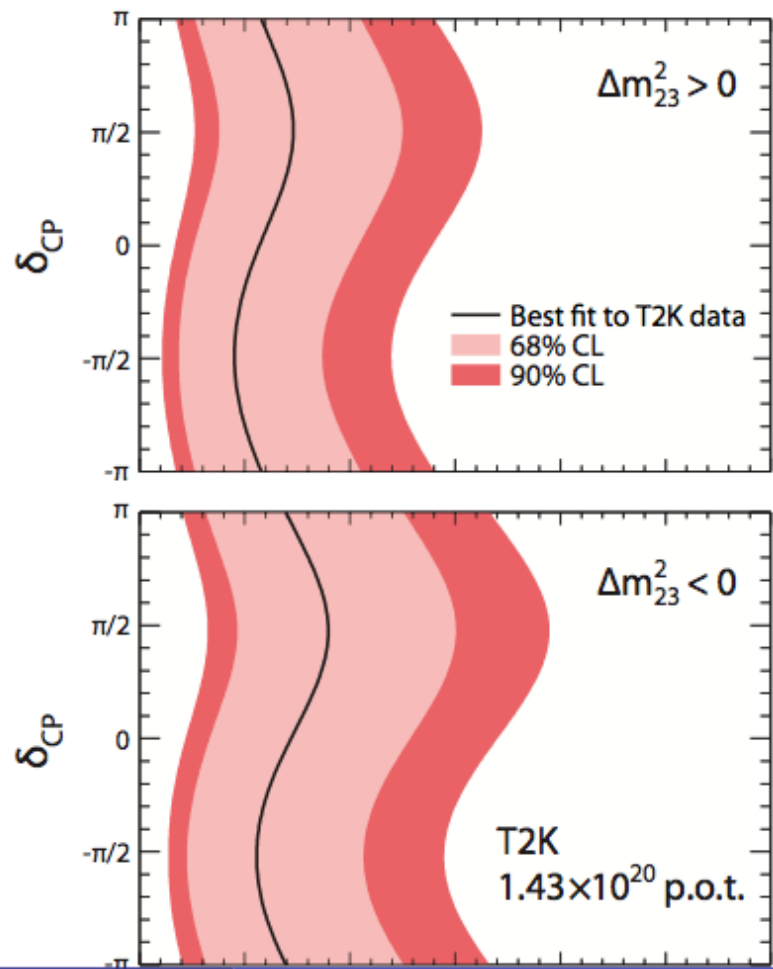
Results on 2013: measured 28 events (bck:  $4.64 \pm 0.53$ )

Expected:  $1.5 \pm 0.3$   
Measured: 6



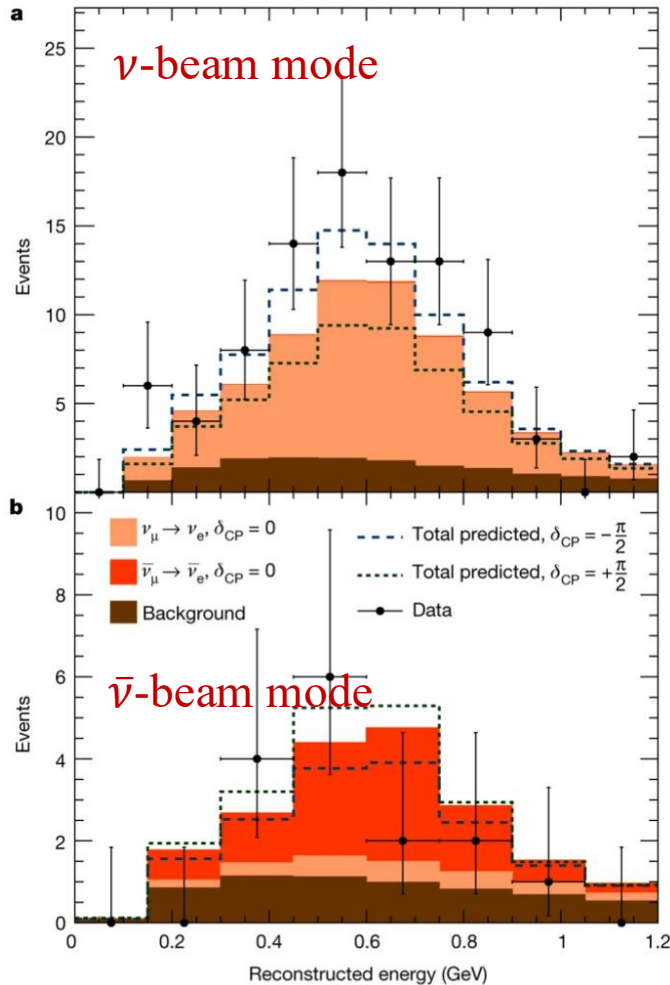
## Systematic errors

| Source                   | $\sin^2 2\theta_{13} = 0$ | $\sin^2 2\theta_{13} = 0.1$ |
|--------------------------|---------------------------|-----------------------------|
| (1) neutrino flux        | $\pm 8.5\%$               | $\pm 8.5\%$                 |
| (2) near detector        | $+5.6\%$<br>$-5.2\%$      | $+5.6\%$<br>$-5.2\%$        |
| (3) near det. statistics | $\pm 2.7\%$               | $\pm 2.7\%$                 |
| (4) cross section        | $\pm 14.0\%$              | $\pm 10.5\%$                |
| (5) far detector         | $\pm 14.7\%$              | $\pm 9.4\%$                 |

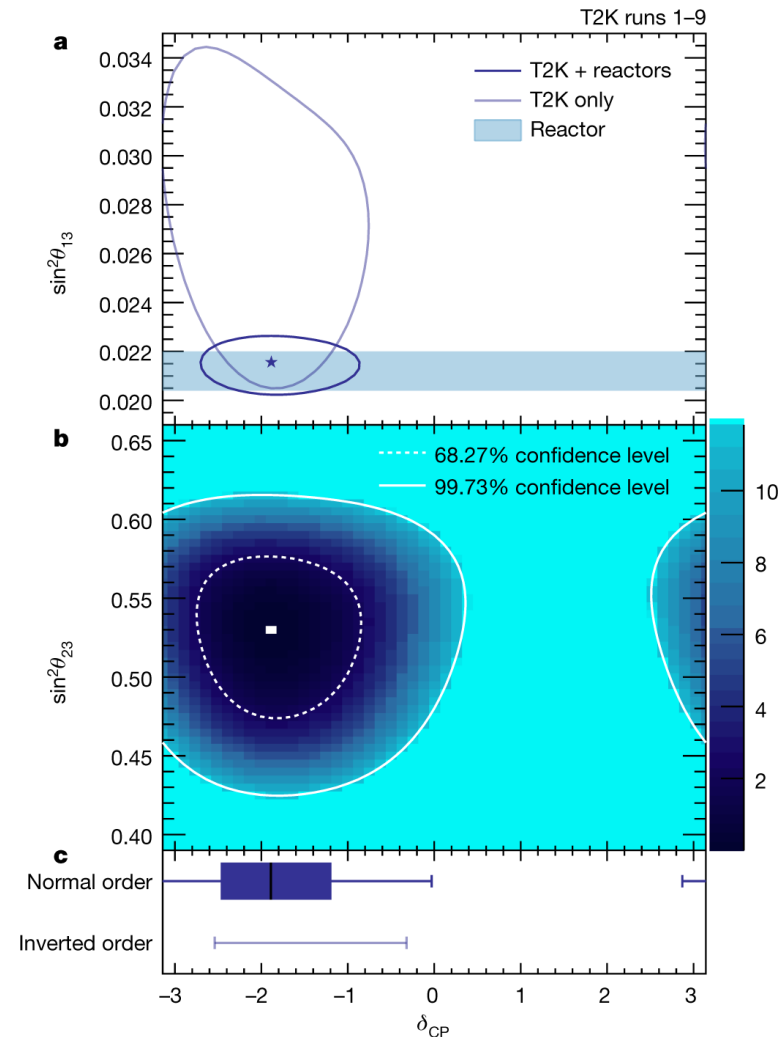


# The latest T2K results (2020)

- Two-dimensional confidence intervals at the 68.27% confidence level for  $\delta_{CP}$  versus  $\sin^2\theta_{13}$  in the preferred normal ordering.
- The T2K intervals indicate the measurement obtained without using the external constraint on  $\sin^2\theta_{13}$
- T2K + reactor intervals do use the external constraint.



- We note that there are no values in the inverted ordering inside the 68.27% interval.



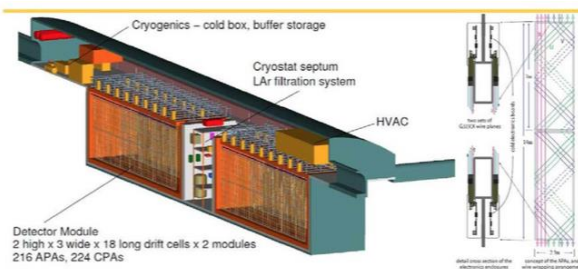
# Critical Questions for Future Neutrino Physics Program

- 1) Are neutrinos their own anti-particles? Dirac or Majorana neutrinos ( $0\nu\beta\beta$ )
- 2) What are the scale of neutrino masses and the hierarchy of the neutrino mass ordering? (Oscillations indicate  $\Delta m^2 \neq 0$ , but unable to determine  $m_\nu$ ).

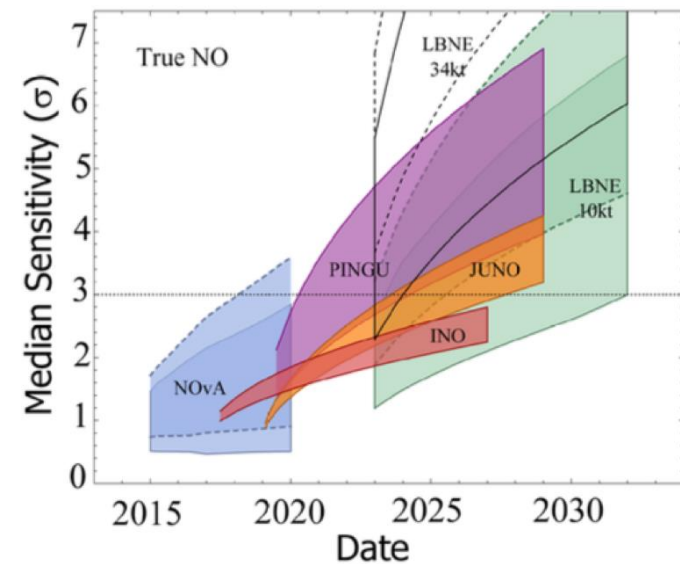
- Pure oscillation effects in  $\nu_e$  disappearance: **Juno**
- Matter effects in  $\nu_\mu$  disappearance: **INO, Pingu, Orca, HyperKamiokande**
- Matter effects in  $\nu_e$  appearance: **NOvA, Dune, T2HK**

- 3) Do neutrinos violate the CP symmetry and contribute to the matter-antimatter asymmetry?

Mainly two players: Dune and HyperKamiokande



Blennow et al., JHEP 1403 (2014)028



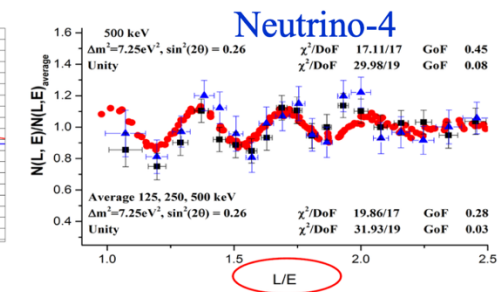
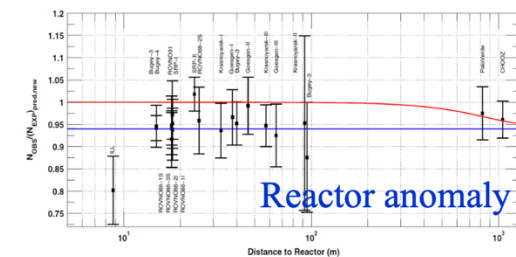
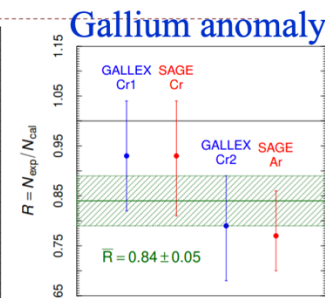
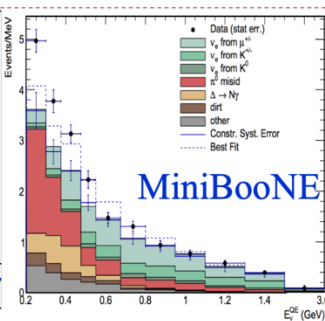
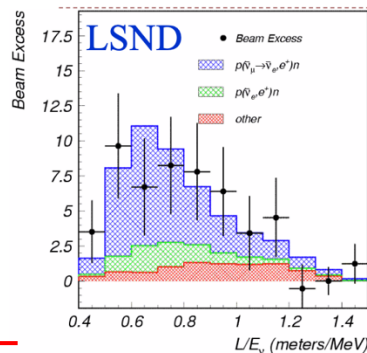
# Is all discovered?

✓ A few experiments show (weak/not-strong) **deviations** (*anomalies*) from the 3 flavor  $\nu$ -osc paradigm:

- **LSND** at Los Alamos observed excess of  $\bar{\nu}_e$  events in the  $\bar{\nu}_\mu$  beam
- **Mini-Boone** confirmed anomaly at low energy in anti-neutrino mode but not in neutrino mode
- **Gallium anomalies**: events from calibration sources in GALLEX and SAGE are less than expected ( $2.8\sigma$ )
- **Reactor anomalies**: reanalysis of reactor expts show a (small) deficit of  $\nu_e$
- **Neutrino-4**: antineutrinos from reactor; pattern of L/E oscillation

✓ It is too early to claim new physics. The only picture consistent with all data is the existence of sterile neutrinos.

✓ A short-term program includes ~~MCI~~ ~~neutrino sources (sources in~~  ~~$\nu$  expts?)~~; SBL (short-baseline) expt probing GeV  $\nu_e$  appearance at short distances (100m – 1 km)



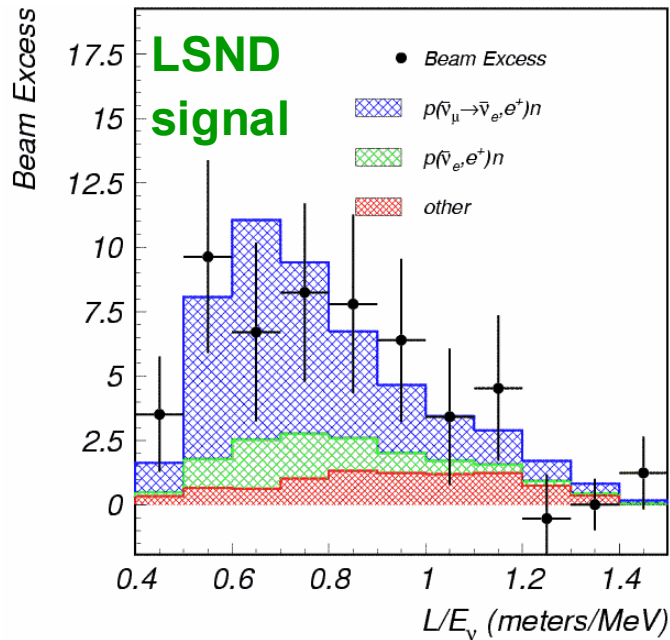
# LSND experiment

LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

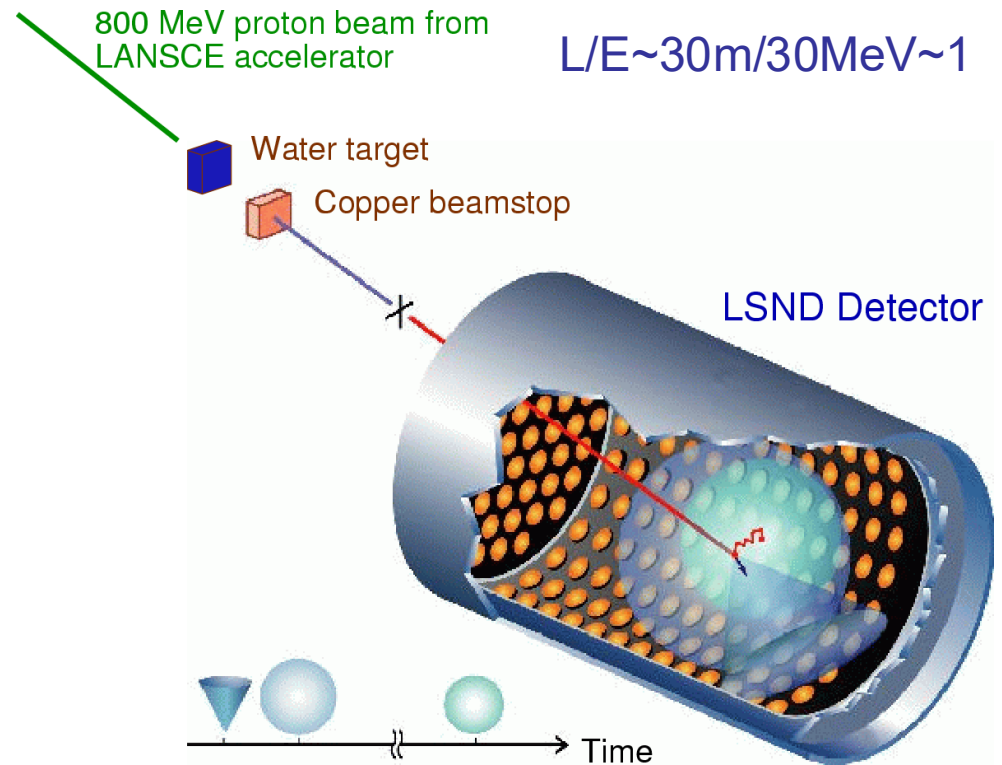
$$\bar{\nu}_{\mu} \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

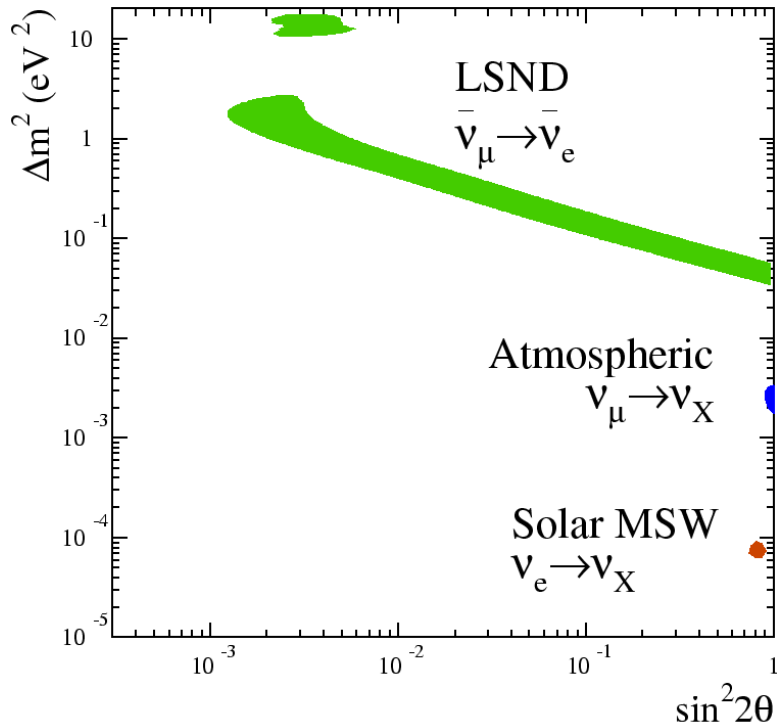
$87.9 \pm 22.4 \pm 6.0$  (3.8 $\sigma$ )



LSND Collaboration,  
PRD 64, 112007



# LSND experiment



3 types of neutrino oscillations are found:

LSND neutrino oscillation:  $\Delta m^2 \sim 1 \text{ eV}^2$   
 Atmospheric neutrino oscillation:  $\Delta m^2 \sim 10^{-3} \text{ eV}^2$   
 Solar neutrino oscillation:  $\Delta m^2 \sim 10^{-5} \text{ eV}^2$

But we cannot have so many  $\Delta m^2$ !

$$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$$

New physics?

- sterile neutrino
- Lorentz violation
- CPT violation
- extra dimension
- etc

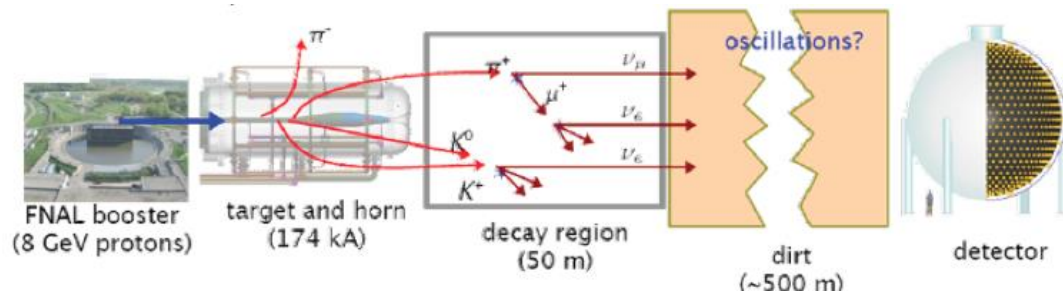
We need to test LSND signal!

MiniBooNE experiment is designed to have same  $L/E \sim 500\text{m}/500\text{MeV} \sim 1$  to test LSND  $\Delta m^2 \sim 1 \text{ eV}^2$

# Mini-Boone

PRL 102 (2009) 101802

PRL 105 (2010) 181801



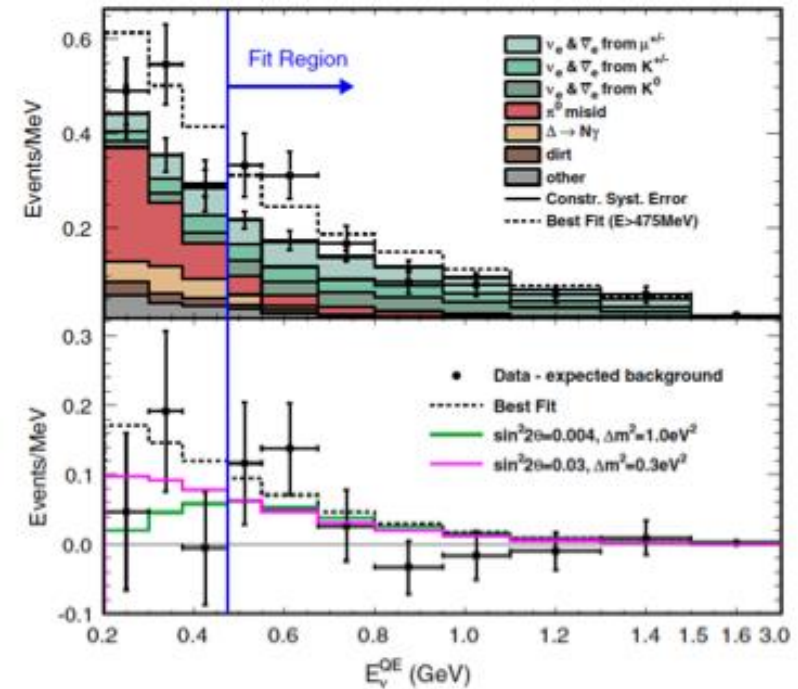
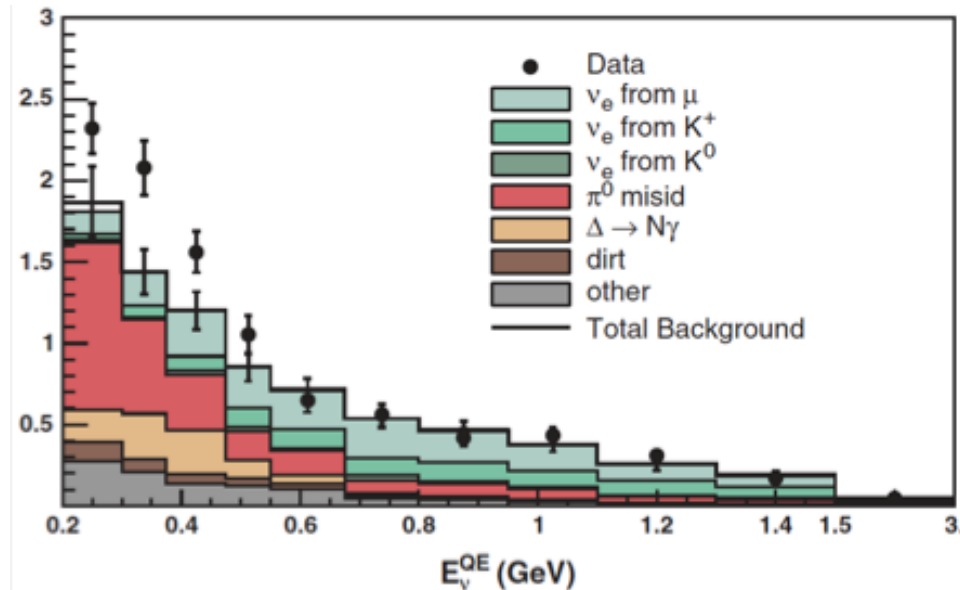
- Liquid mineral oil detector (scintillation and Cerenkov) used to detect  $\nu_e$  ( $\bar{\nu}_e$ ) in a predominantly  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) beam.
- Designed and built to check the LSND result

## • Neutrino mode

- LSND ruled out if CP is assumed
  - No deviation with  $E > 475$  MeV
- A different excess at low energy
  - Inconsistent with LSND
  - Statistically large ( $>6\sigma$ )

## • Anti-Neutrino mode

- Anomaly confirmed at low energy
  - $E < 475$  MeV
- Consistent with LSND
  - $\sim 2\sigma$  effect



# The Gallium data

- In the 90's 2 experiments (Gallex and SAGE) have measured the solar neutrino flux with an energy threshold of  $\sim 200$  keV

- Radiochemical experiments

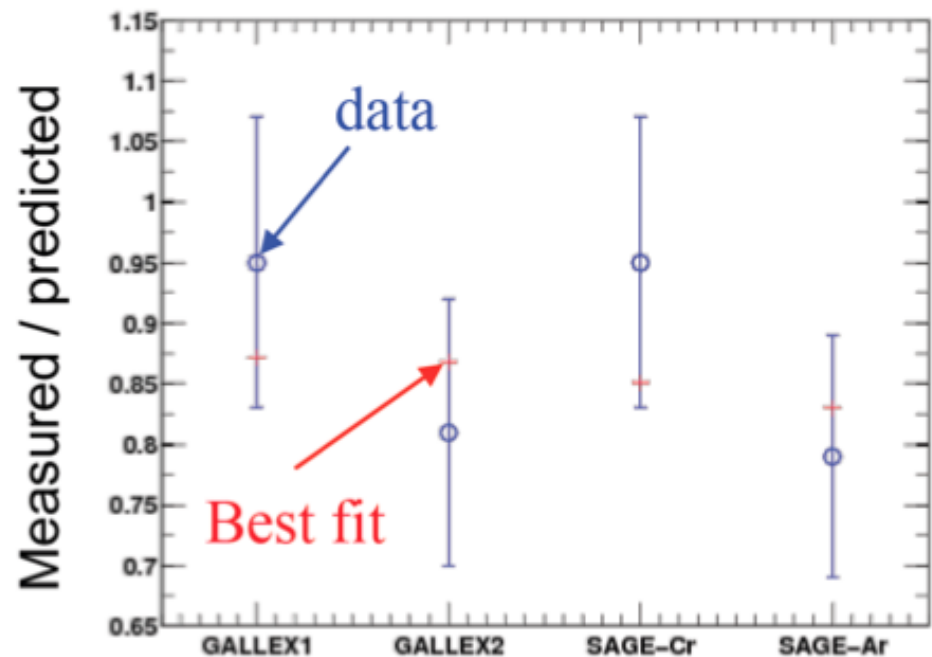
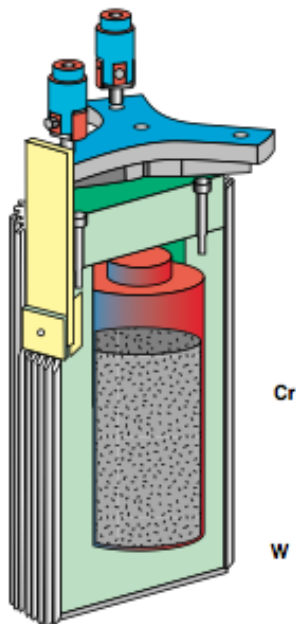
- For calibration purposes, they built and operated powerful **radioactive neutrino sources**

- $^{51}\text{Cr}$  source ( $\sim 2$  MCi, a few  $10^{16}$   $\nu/s$  !)

- $^{37}\text{Ar}$  source (SAGE only, 0.2 MCi)

$$R_B^{\text{Ga}} = 0.86_{-0.05}^{+0.05} \quad \text{Giunti-Laveder} \\ \text{hep/ph: 1006.3244}$$

Data is lower than expected @  $2.8\sigma$



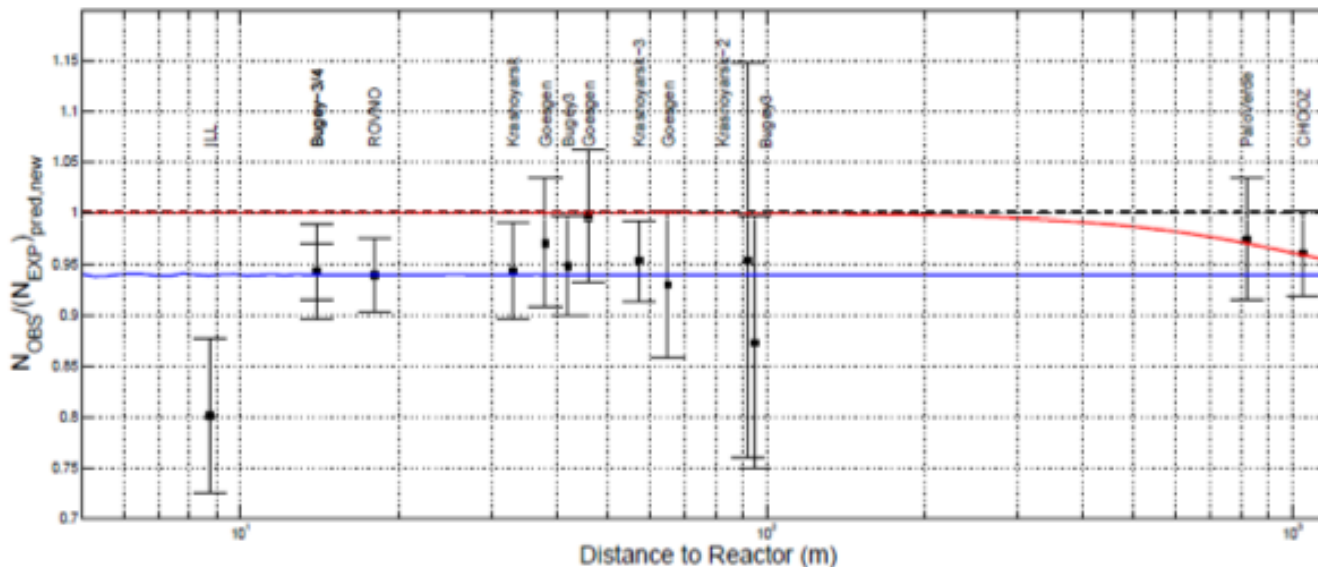
# Reactor antineutrino anomaly

Phys. Rev. D83 (2011) 073006

Reanalysis of reactor experiments with new flux predictions & new cross sections

⇒ short baseline experiments < 100 m from a reactor observed a deficit of  $\nu_e$

$$N_{\text{OBS}}/N_{\text{EXP}} = 0.937 \pm 0.027 \quad \Leftrightarrow \quad 98.4 \% \text{ CL.}$$



Black dotted:  
no osc.

Red line:  
 $\sin^2(2\Theta_{13}) = 0.06$

Blue line:  
 $|\Delta m_{\text{new}}^2| = 1.5 \text{ eV}^2$   
 $\sin^2(2\Theta_{\text{new}}) = 0.1$

Possible explanations:

- Calculations are wrong: ILL data are unchanged w.r.t old prediction...
- Bias in all short-baseline experiments near reactors: unlikely...
- Oscillation towards a 4<sup>th</sup> sterile  $\nu$ ?