Reactor electron anti-neutrino

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

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

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

δ gives CP violation

$$U_{MNS}=\begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\ U_{\mu1}&U_{\mu2}&U_{\mu3}\\ U_{\tau1}&U_{\tau2}&U_{\tau3}\end{pmatrix}$$

$$=\begin{pmatrix}1&&\\ &c_{23}&s_{23}\\ &-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&&s_{13}e^{-i\delta}\\ &1&\\ -s_{13}e^{i\delta}&&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&\\ -s_{12}&c_{12}&\\ &&1\end{pmatrix}$$

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 $\boldsymbol{U}_{MNSP}$ parametrized with 3 mixing angles θ_{ij}, CP phase δ

+ 2 mass differences Δm^2_{atm} , Δm^2_{sol}

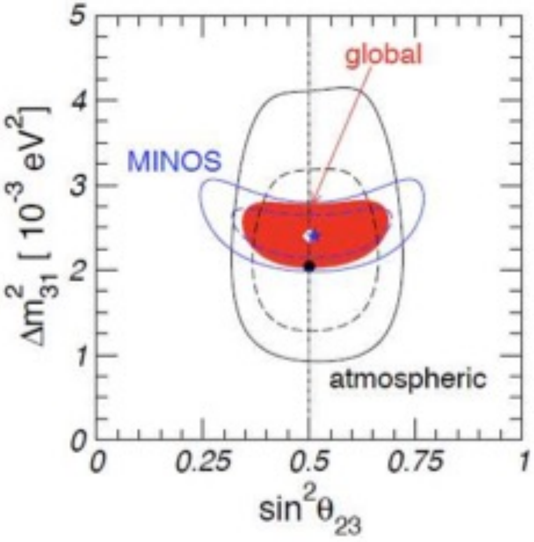
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}\,e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}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

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

atmospheric ν
+ K2K, MINOS

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

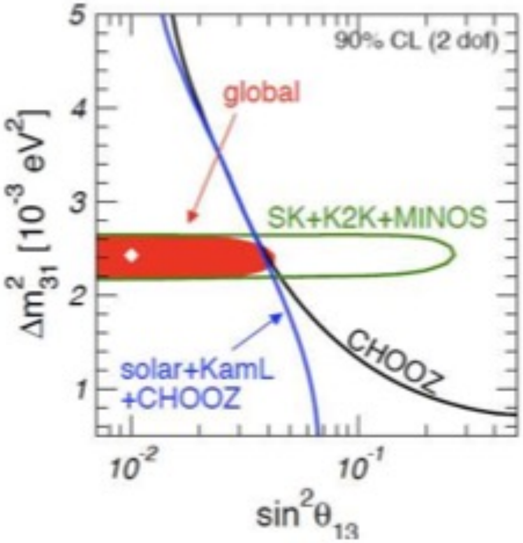
$\theta_{23} = (45 \pm 7)°$



reactor ν
(CHOOZ)

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

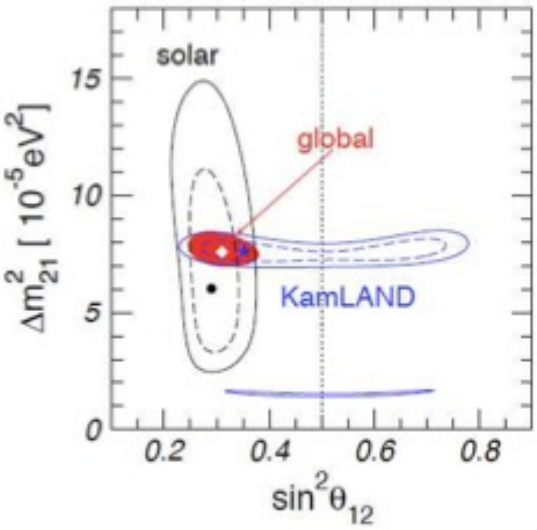
$\theta_{13} < 13$ °



solar ν
+ KamLAND

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

$\theta_{12} = (34 \pm 3)°$



Neutrino oscillations

"atmospheric"
$\Delta m^2_{23}=2.4\ 10^{-3}$ eV^2
$\theta_{23}=45°$

"solar"
$\Delta m^2_{12}=7.6\ 10^{-5}$ eV^2
$\theta_{12} = 34.4°$

long base line
θ_{13} is smaller

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

- Key point: **the Δm^2 are very different. Choosing L/E properly** we can disentangle the effects of the different angles:
  - **solar:** you need L/E ~ 10^5; 100 km at 1 MeV (KamLand) or use MSW effect in the Sun
  - **atmospheric:** L/E ~ 10^3; ~1000 km with a few GeV ν_μ beam;
  - **θ_{13}:** the Δm^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

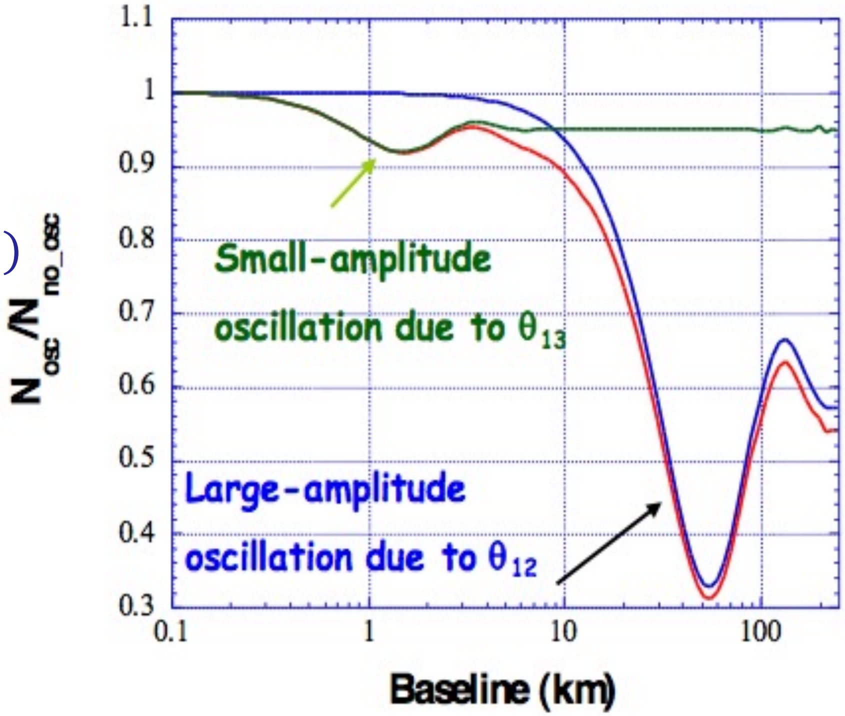
Two ways to measure θ_{13}

Reactor experiments:

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

Long baseline accelerator experiments:

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



At reactors:

- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compared to accelerator-based experiments
- Provides the direction to the future of neutrino physics

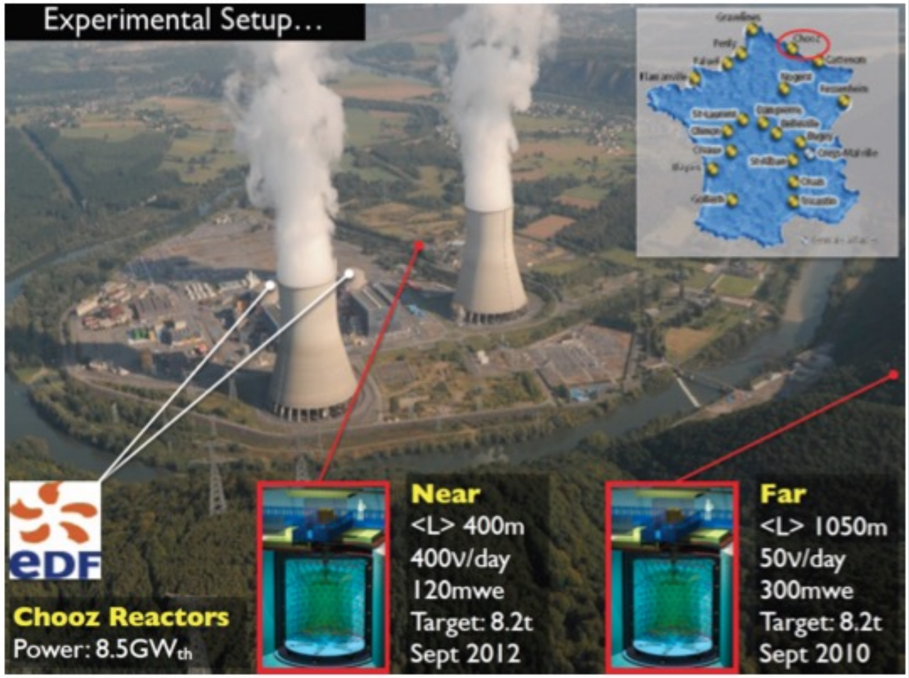
Search for θ_{13} at reactors

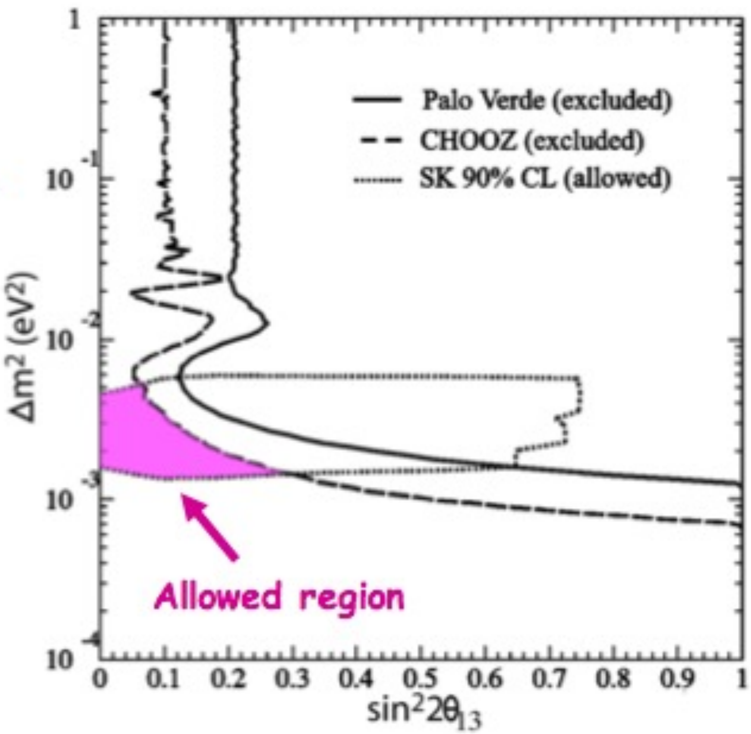
Before 2012

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

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 $\Delta m^2_{23} = 0.0024$ eV²
- ❑ T2K: 2.5σ 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: 1.7σ 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: 1.7σ
  $\sin^2 2\theta_{13} = 0.086 \pm 0.041(stat) \pm 0.030(syst)$

Best constraint on θ_{13}…

…..from the Chooz experiment

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

Goal: test of $\overline{\nu}_e \rightarrow \overline{\nu}_x$ oscillations for atmos. Δm^2

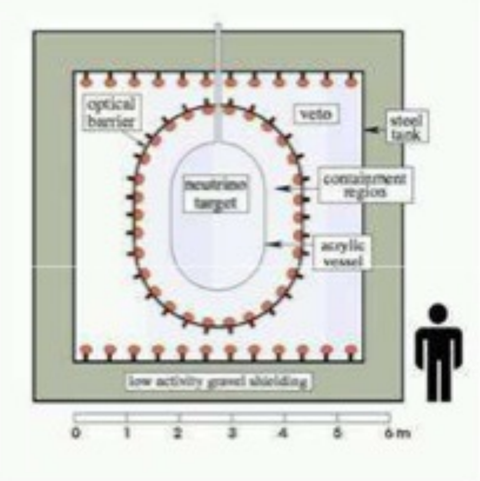
reactor experiment @ 1km

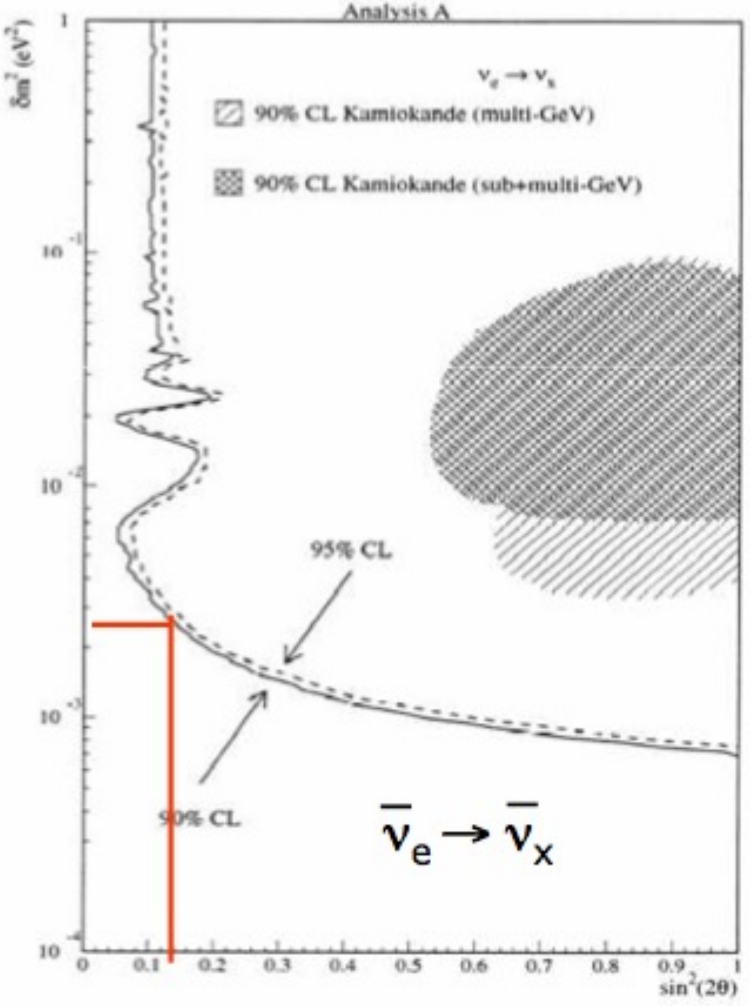
$P_{th} = 8.4\ GW_{th}$

5 t Gd loaded scintillator

overburden: 300 mwe

~ 2700 neutrino events





Result:

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

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

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

Nuclear reactor as neutrino source

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

$\Rightarrow$ emission of ~ 6 $\bar{\nu}_e$ /fission
(~ 2 x 10^{20} s^{-1} per GW_{th})

continuous, isotropic neutrino flux 0 – 10 MeV

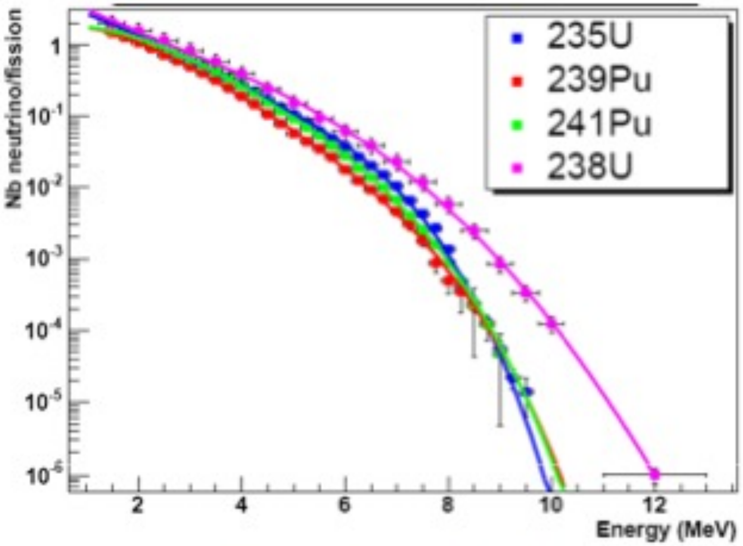
99.9% of ν_e are emitted by 4 isotopes
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

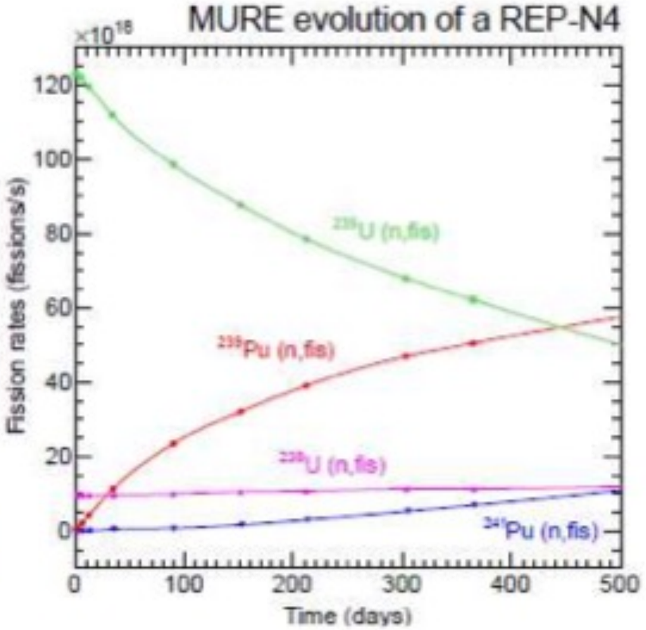
neutrino flux and spectrum depend on

- reactor power
- composition of fuel elements
- burnup

$\Rightarrow$ ~ 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:

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

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

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

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

prompt event

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s } (\sim 8\text{MeV}), \tau \sim 30\mu s$$

$$n + H \rightarrow d + \gamma\,(2.2\text{MeV}),\ \tau \sim 230\mu s$$

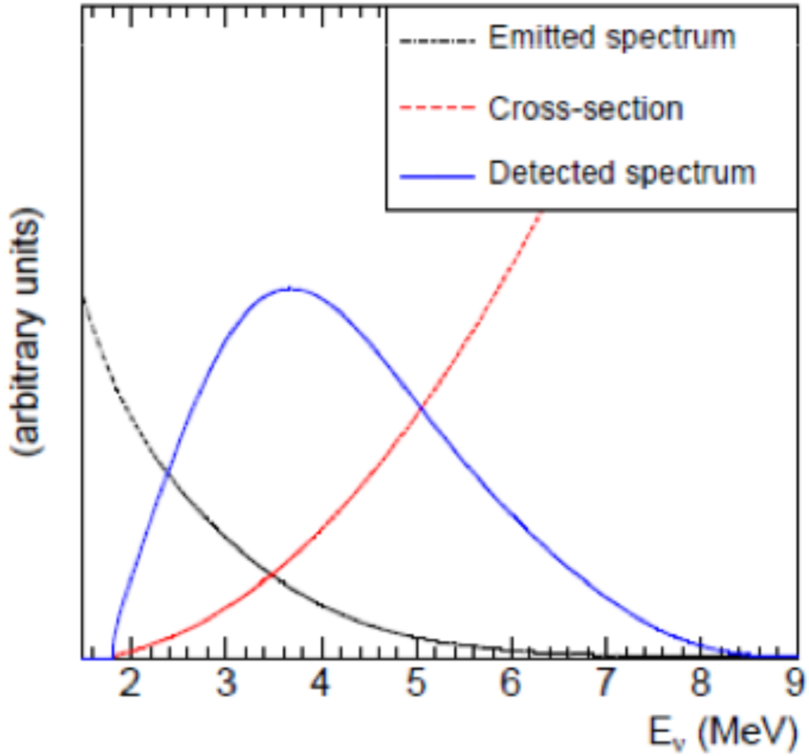
delayed event

Detection in Gd-loaded liquid organic scintillator

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

release of total ~8 MeV γs

⇒ distinctive signature, well above radioactive background



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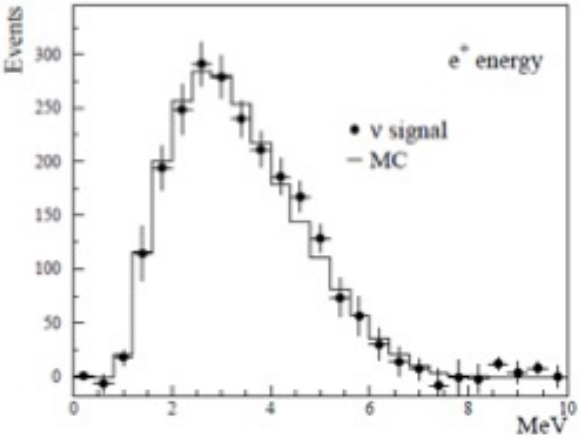
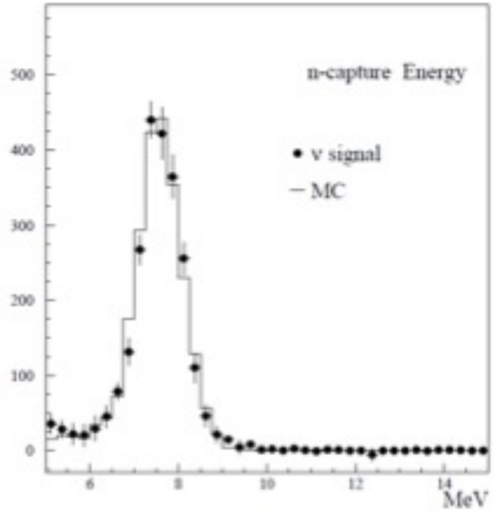
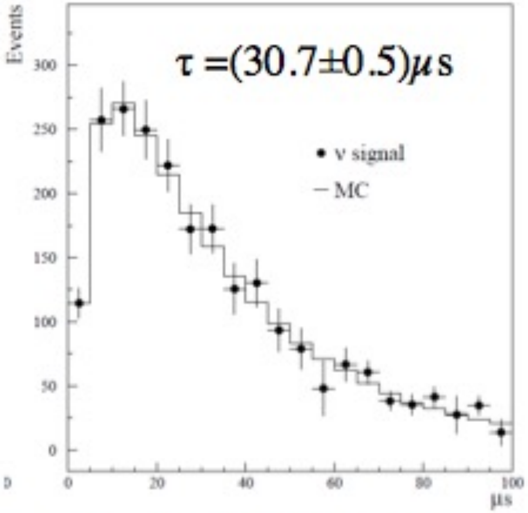


e^+ energy



n capture energy

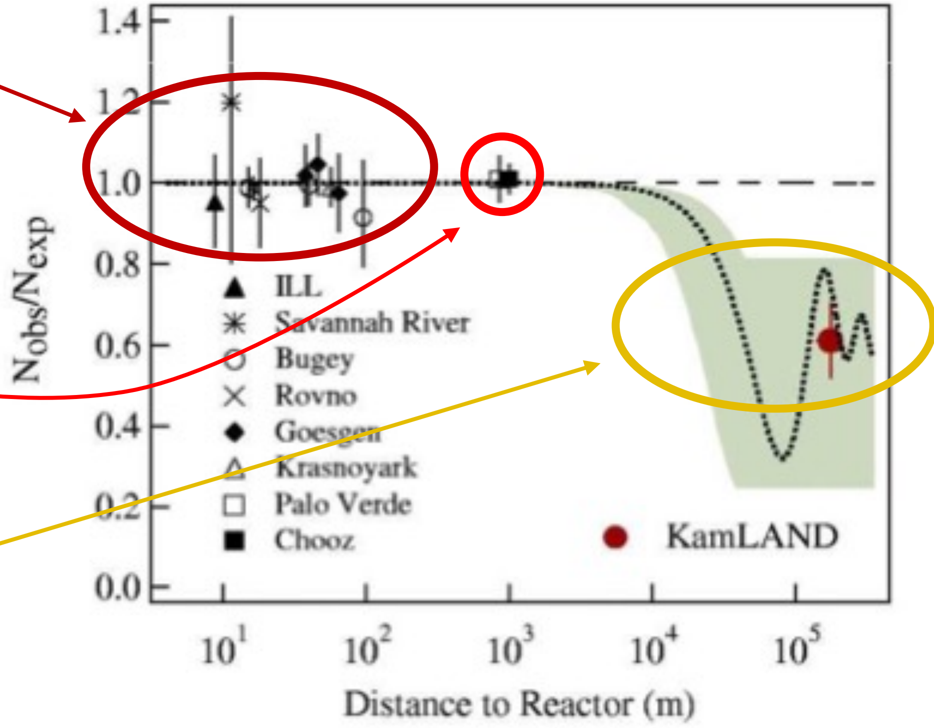


e^+-n time delay

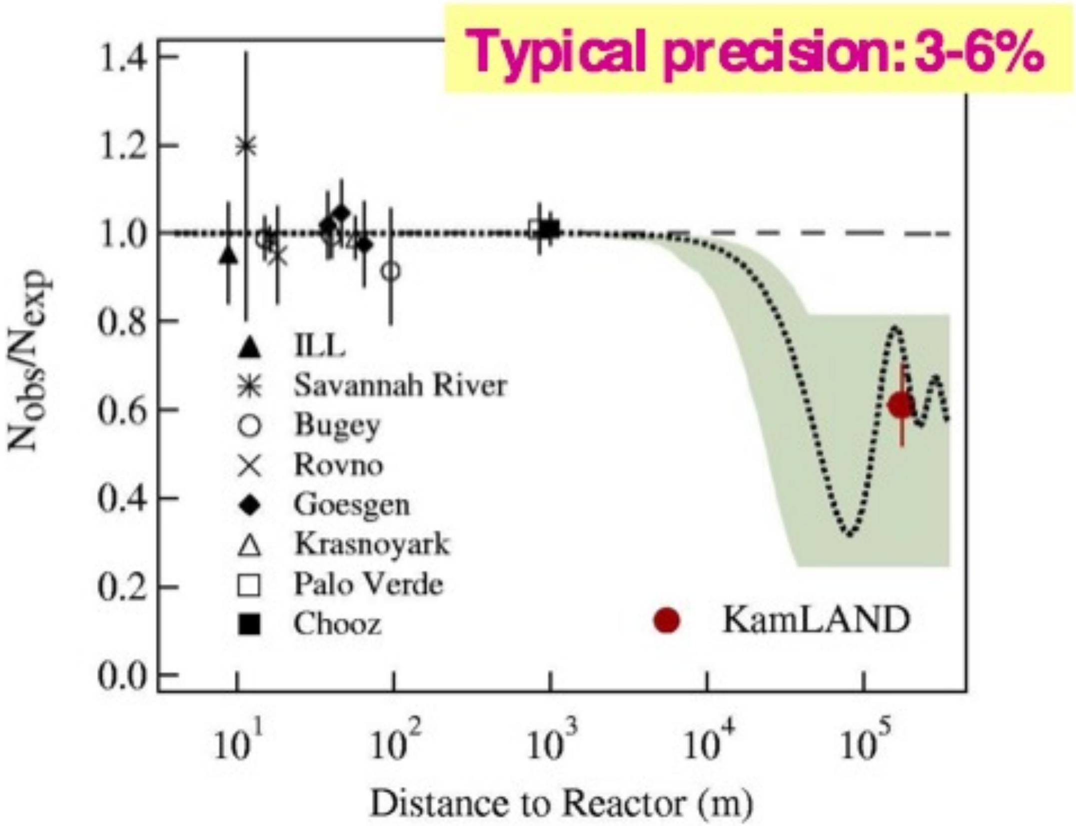
Apollonio et al. (2003)

Great success of reactor experiments in the past

1956	first experimental neutrino detection by Cowan and Reines, Savannah River confirmation of Paulis neutrino hypothesis ⇒ Nobel Prize 1995
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~1km Chooz, Palo Verde best limit on θ_{13}
2001	proof of solar neutrino oscillations by KamLAND (d~ 180 km) most precise determination of Δm_{21}^2



Reactor Experiments: comparing observed/expected neutrinos



Typical precision: 3-6%

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 θ_{13} a 0.4% precision is needed

Terrestrial "Solar Neutrinos"

Can we convincingly verify oscillation with man-made neutrinos?

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

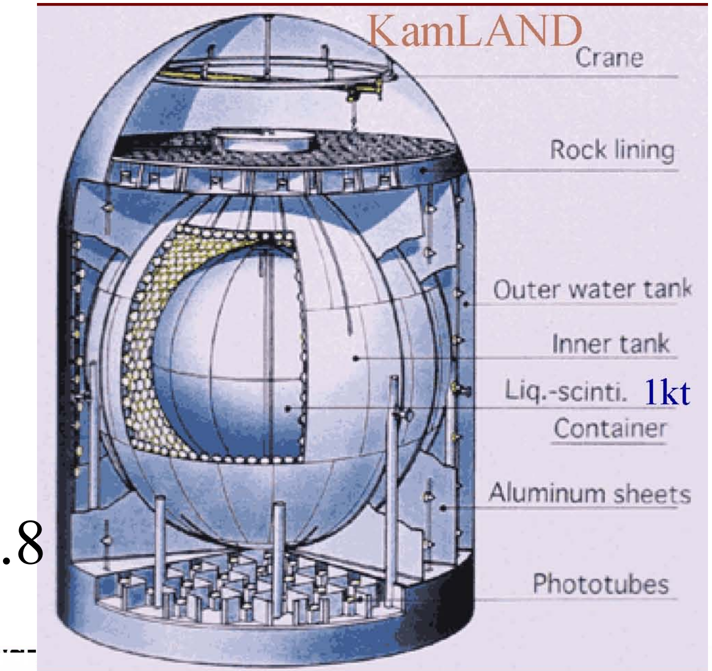
- Hard for low Δm^2
- To probe LMA, need L~100km, 1kt
- Need low E_ν, high Φ_ν
- Use neutrinos from nuclear reactors

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

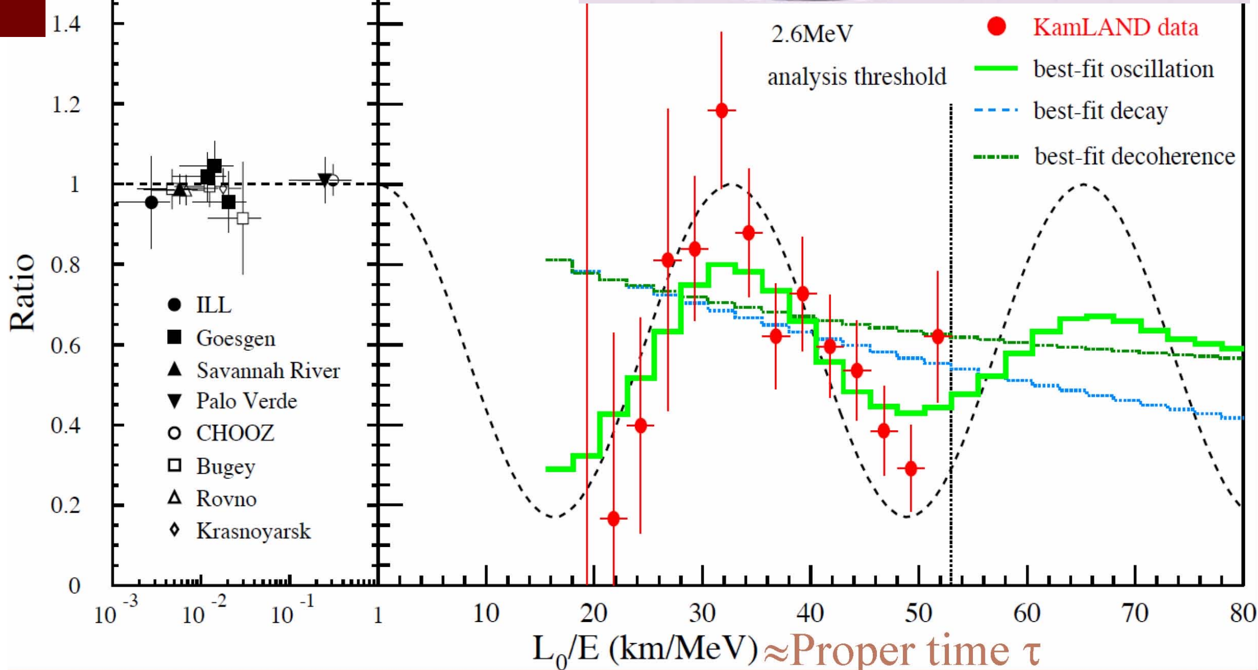
$E_\nu = 3$ MeV

$L = 180$ km

→ $1.27\Delta m^2 L/E_\nu = 0.8$



KAMLAND: reactor anti-neutrino do oscillate!



Measuring θ_{13} with Reactor Experiments

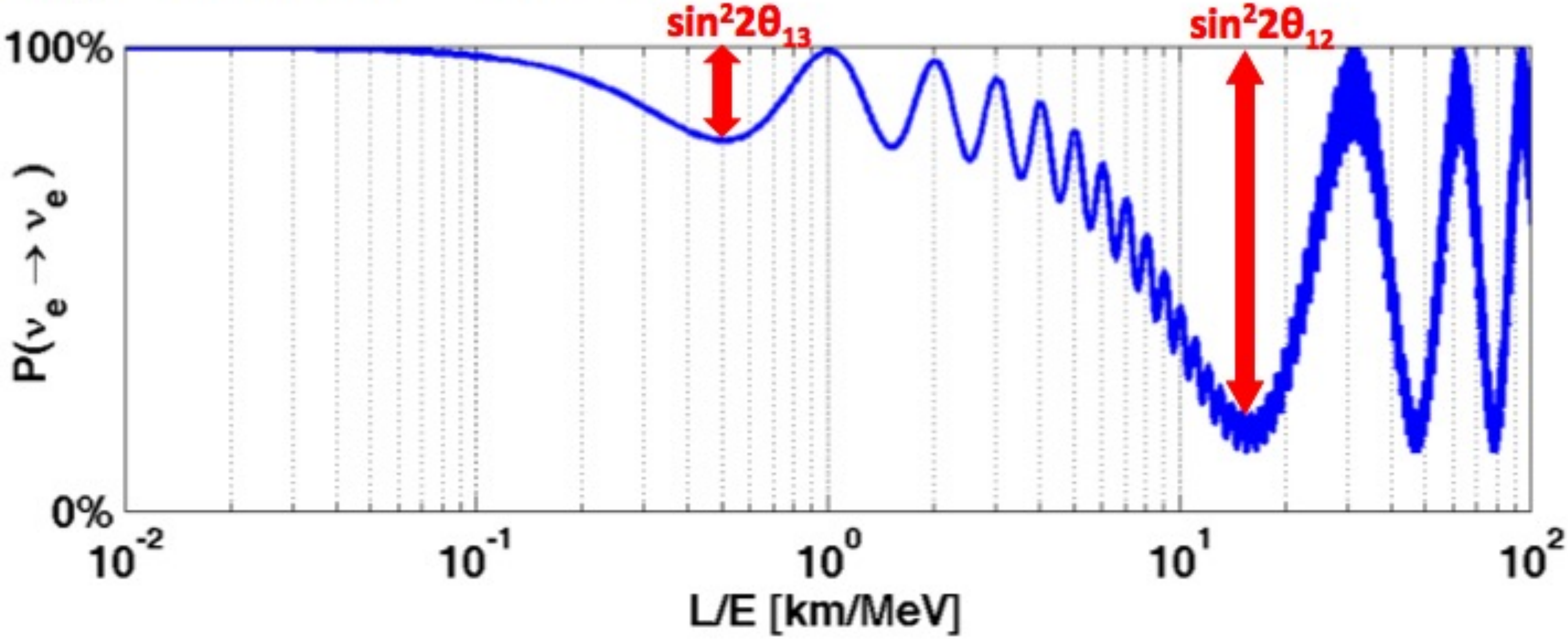
$<E_\nu> \sim 4$ MeV ⇒ only disappearance experiments possible

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{atm} L}{4E_{\bar{\nu}}} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{sol} L}{4E_{\bar{\nu}}}$$

2 different length scales involved:

$\Delta m_{atm}{}^2 = 2.5 \times 10^{-3}$ eV^2 ⇒ L ~ 1.8 km

$\Delta m_{sol}{}^2 = 8 \times 10^{-5}$ eV^2 ⇒ L ~ 60 km



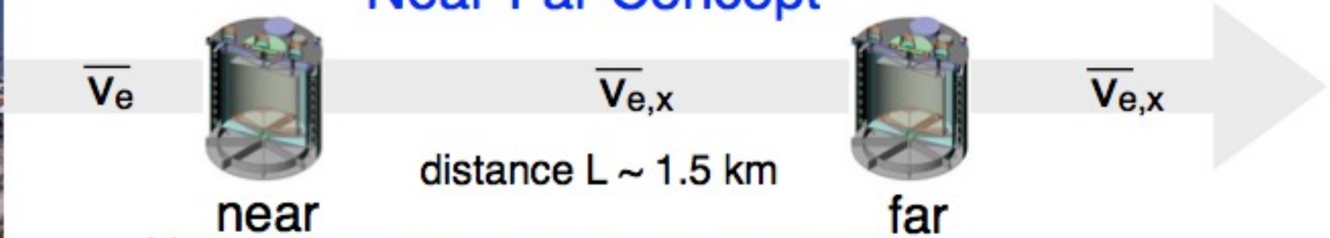
Measuring θ_{13} with Reactor Experiments

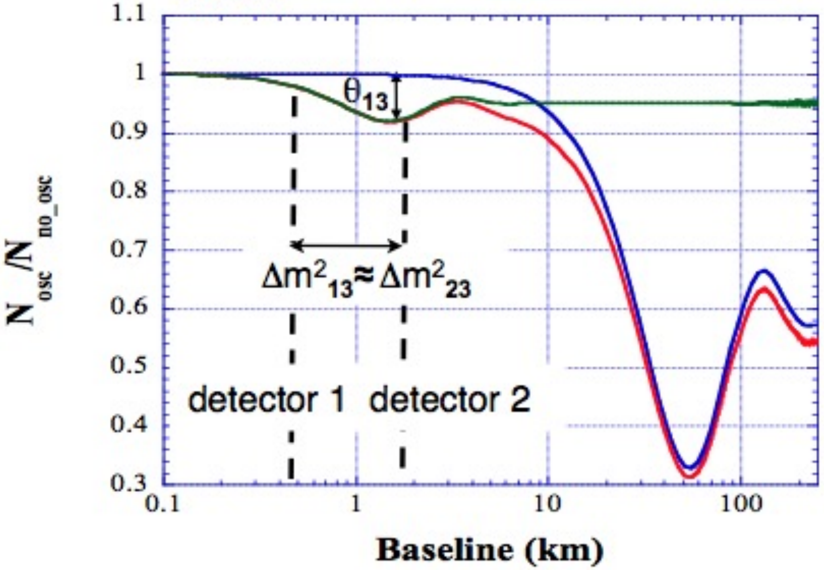
Absolute Reactor Flux
Largest uncertainty in
previous measurements

Relative Measurement
Removes absolute
uncertainties!

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

Near-Far Concept

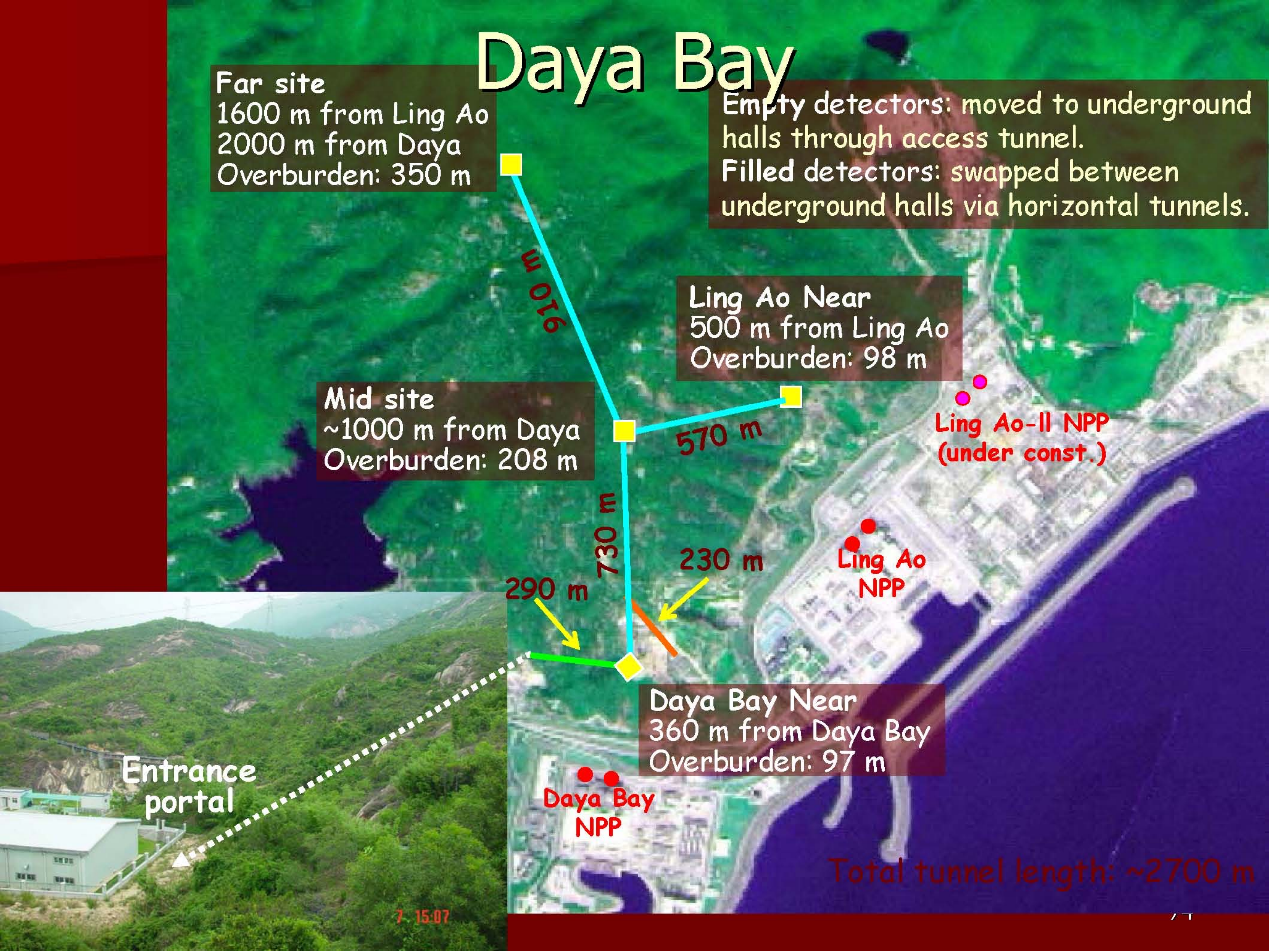




$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

far/near $\overline{\nu}_e$ ratio — target mass — distances — efficiency — oscillation deficit

Daya Bay



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

Mid site
~1000 m from Daya
Overburden: 208 m

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

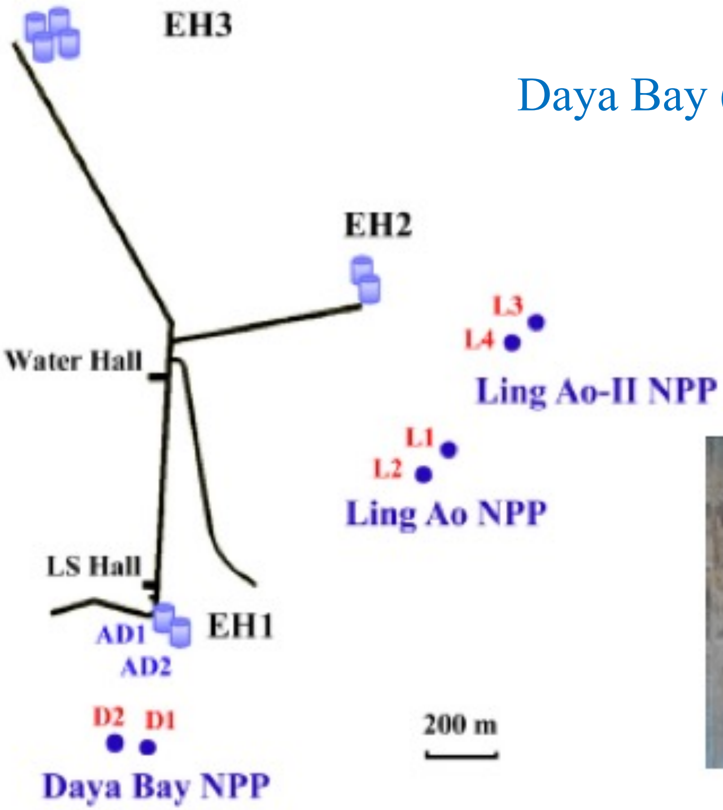
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

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

Total tunnel length: ~2700 m

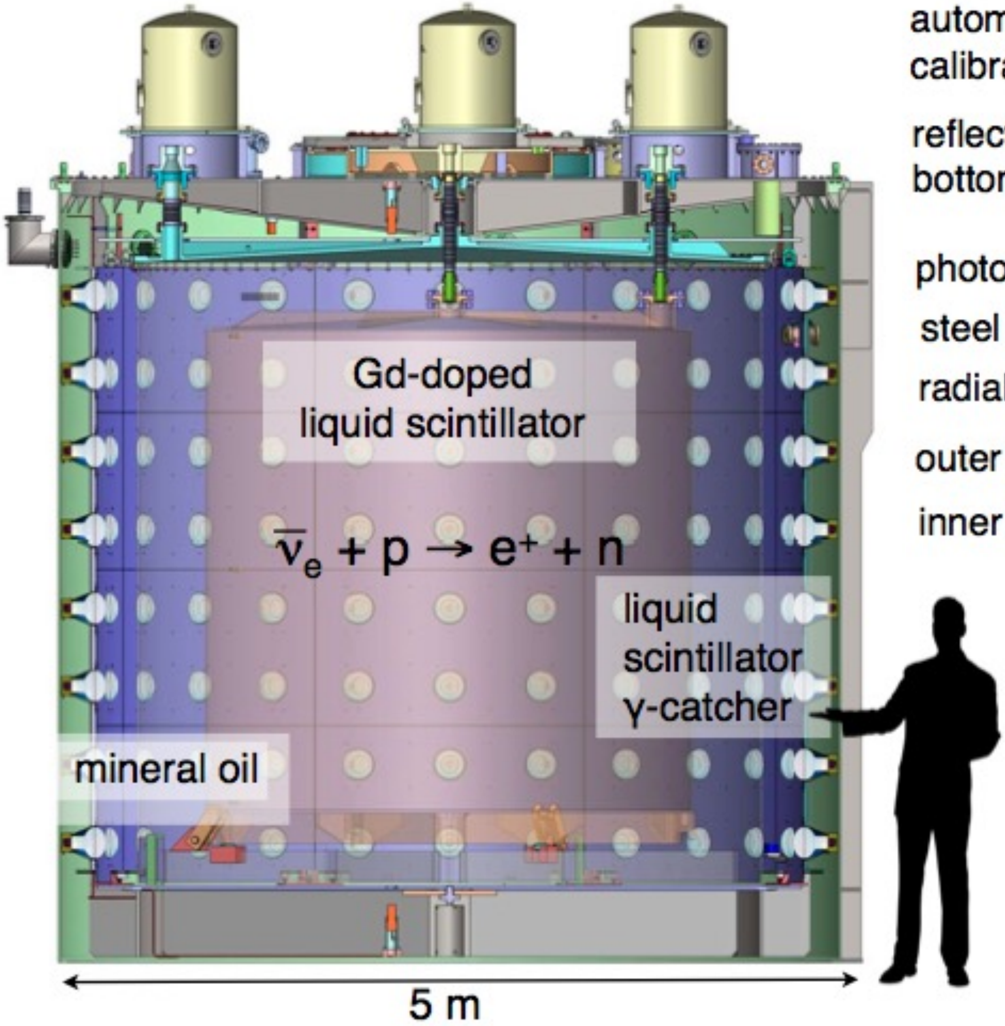
Underground Labs

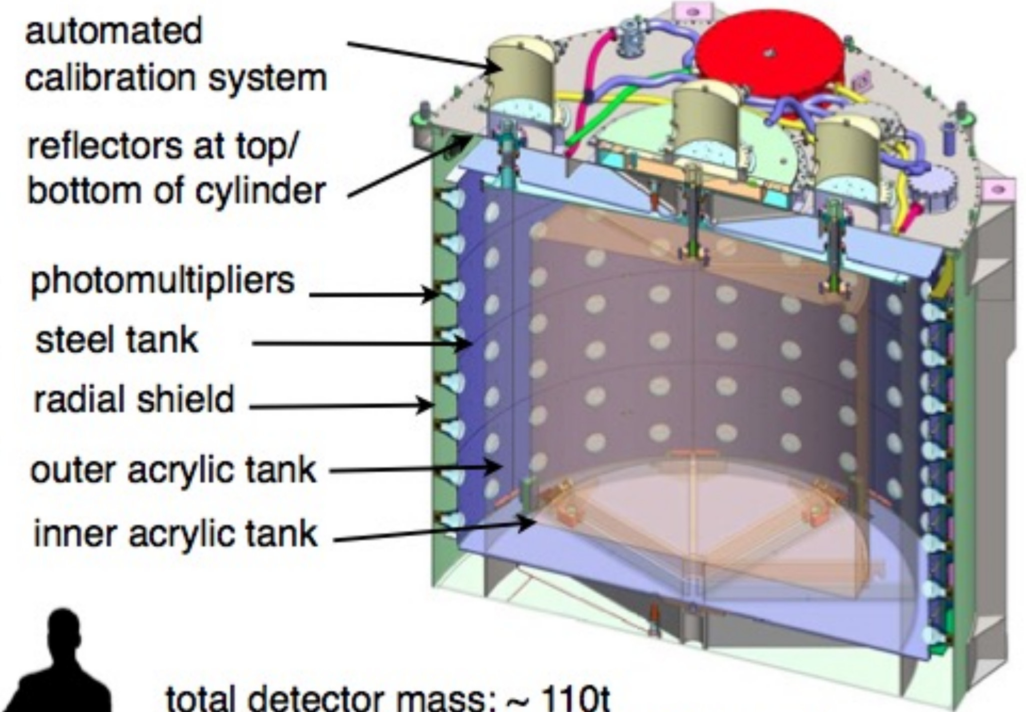
Daya Bay (China)



	Overburden （MWE）	R_μ （$\mathrm{Hz/m^2}$）	E_μ （GeV）	D1,2 (m)	L1,2 (m)	L3,4 (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

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

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \boxed{\left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)}\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\boxed{\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)}\left[\frac{P_\mathrm{sur}(E, L_\mathrm{f})}{P_\mathrm{sur}(E, L_\mathrm{n})}\right]$$

Daya Bay Antineutrino Detection

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

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)

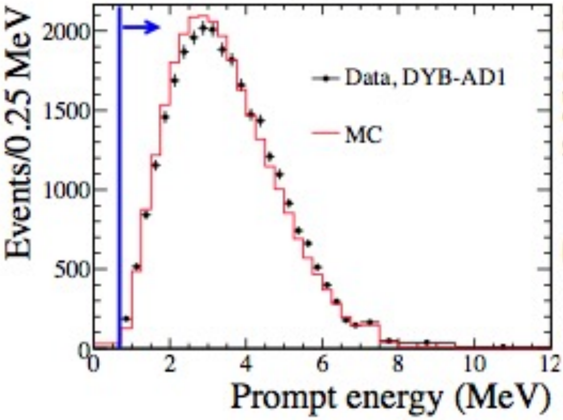
prompt+delayed coincidence provides distinctive signature

Prompt positron: carries antineutrino energy

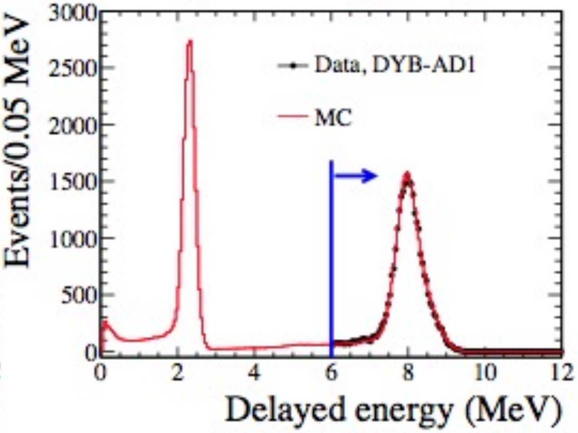
$E_{e+} \approx E_{\nu} - 0.8$ MeV

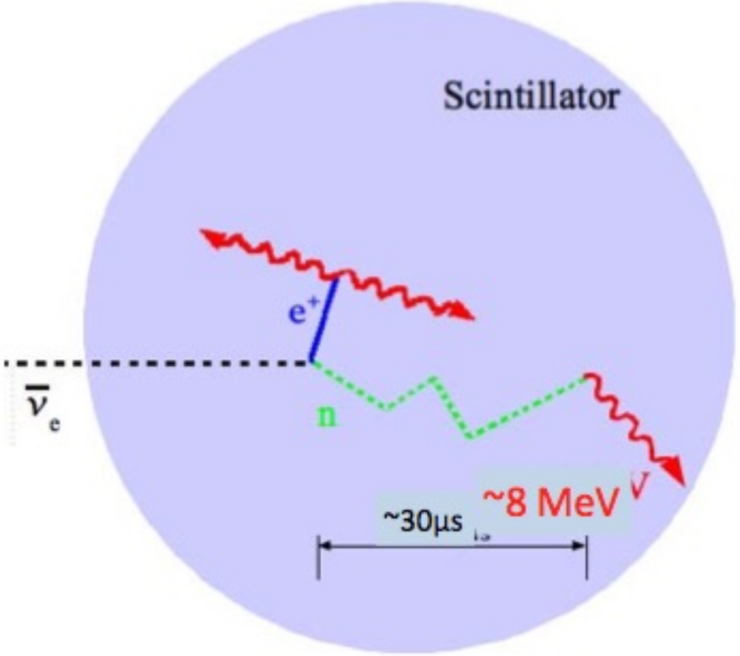
Delayed neutron capture: tags antineutrino signal

Prompt Energy Signal

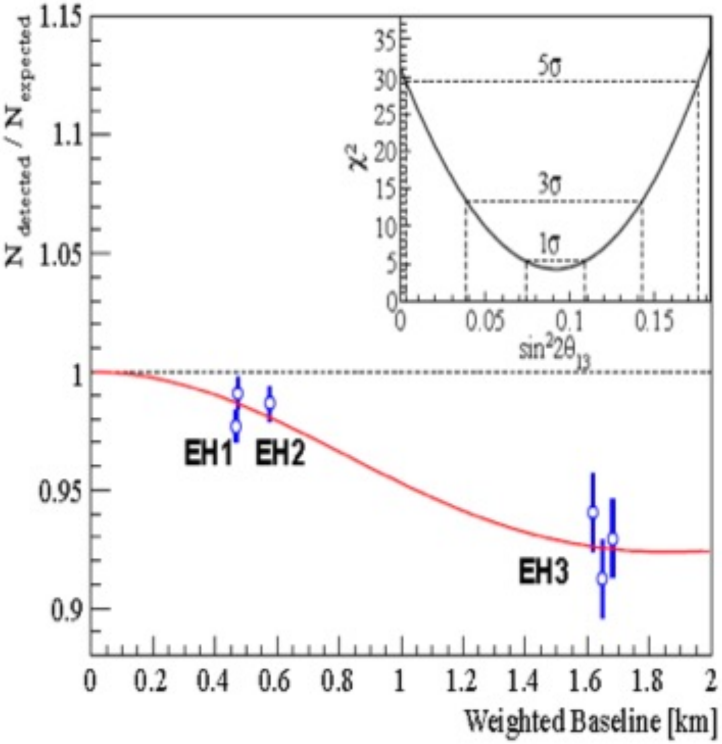


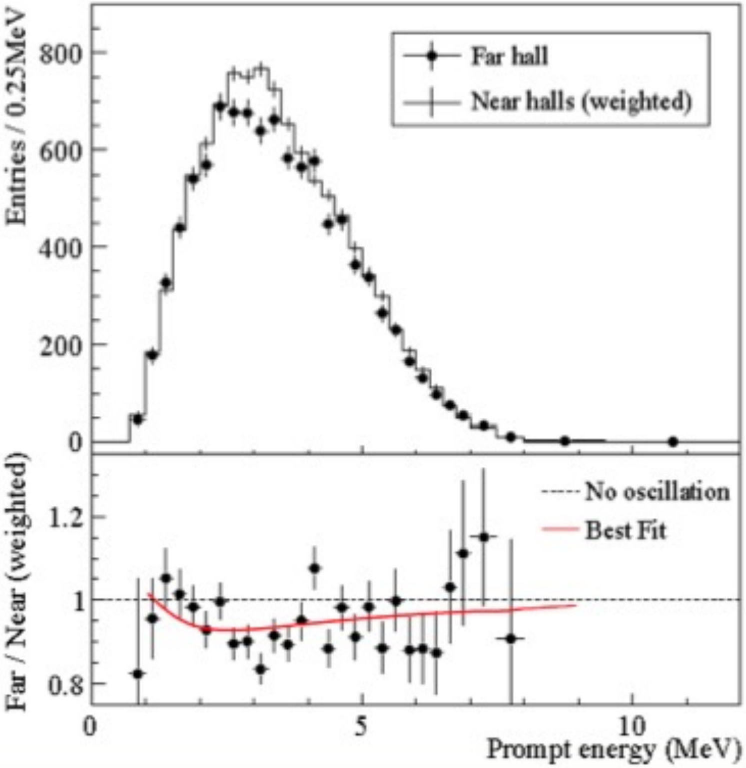
Delayed Energy Signal





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 $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$. The neutrino mixing angle θ_{13} is non-zero with a significance of 5.2 standard deviations.

Summary

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

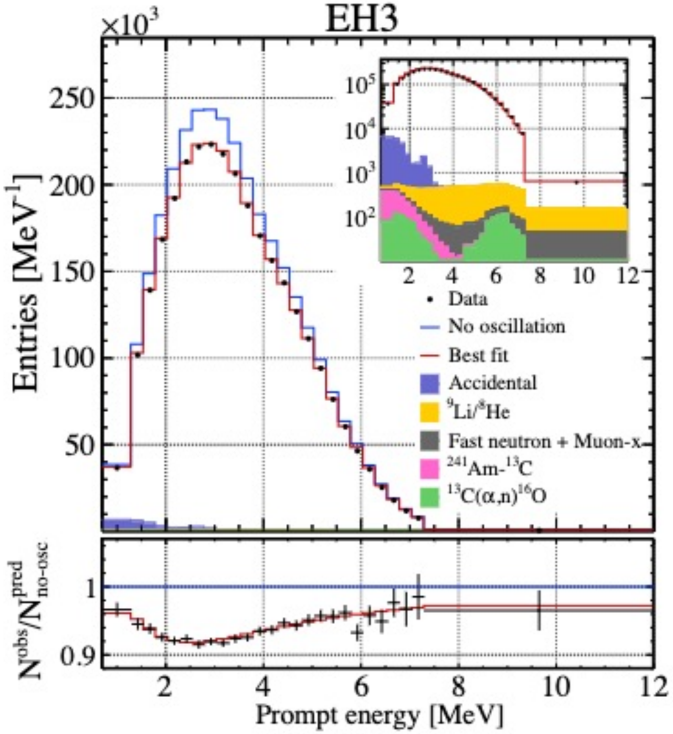
$$R = 0.940 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$$

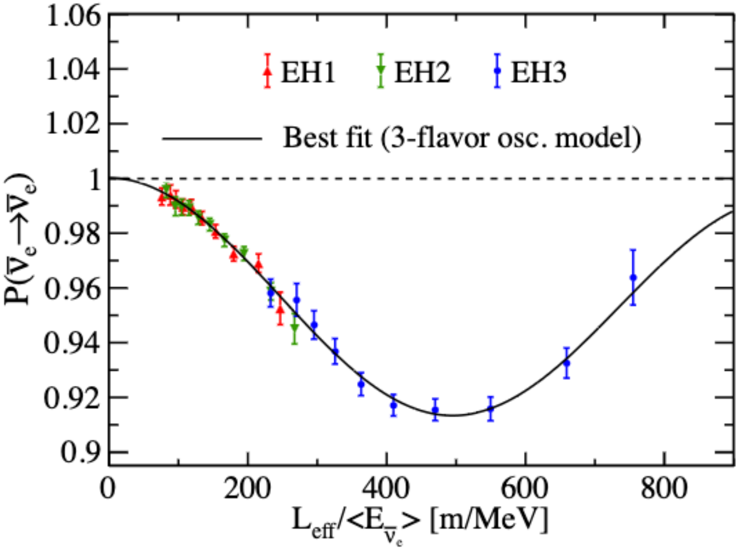
- The spectral distortion is observed too
- A new type of neutrino oscillation is thus discovered

➢ $\sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst)$ $(\chi^2/dof = 4.26/4)$

➢ 5.2 σ for non-zero θ_{13}

Final results on the full data set (2020)





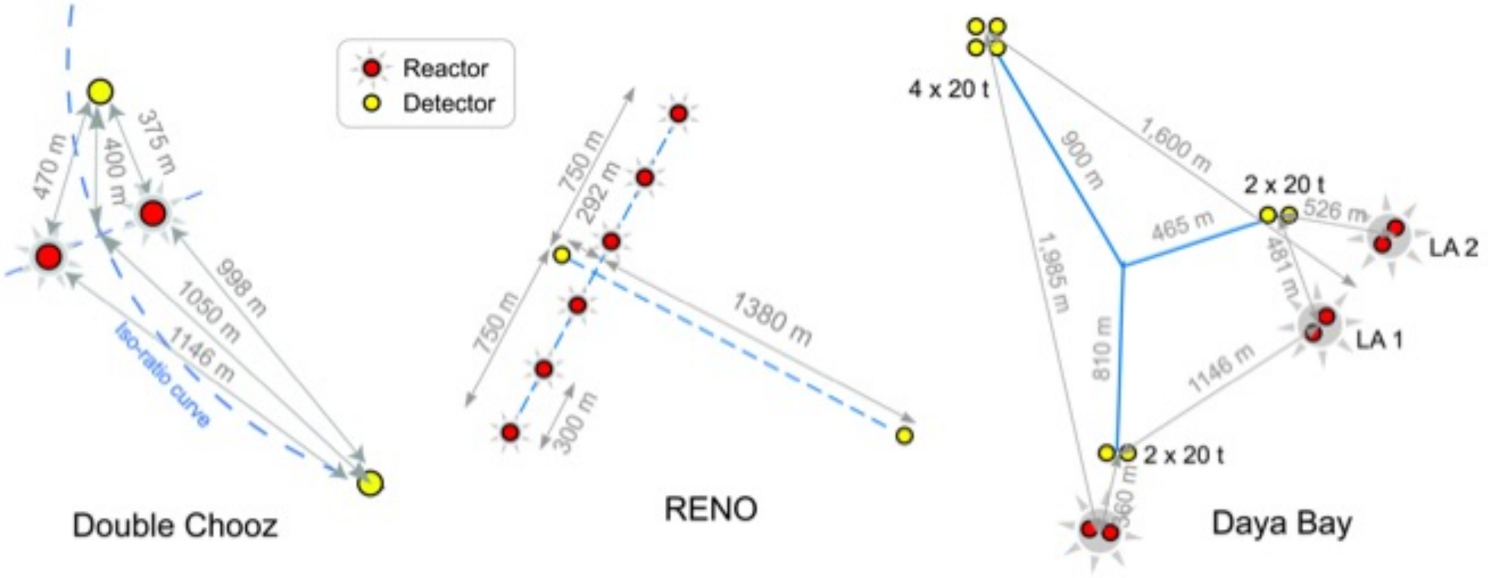
➢ $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

➢ $\Delta m^2_{32} = (2.466 \pm 0.060)\times 10^{-3}$ eV² for NO

➢ $\Delta m^2_{32} = -(2.571 \pm 0.060)\times 10^{-3}$ eV² for IO

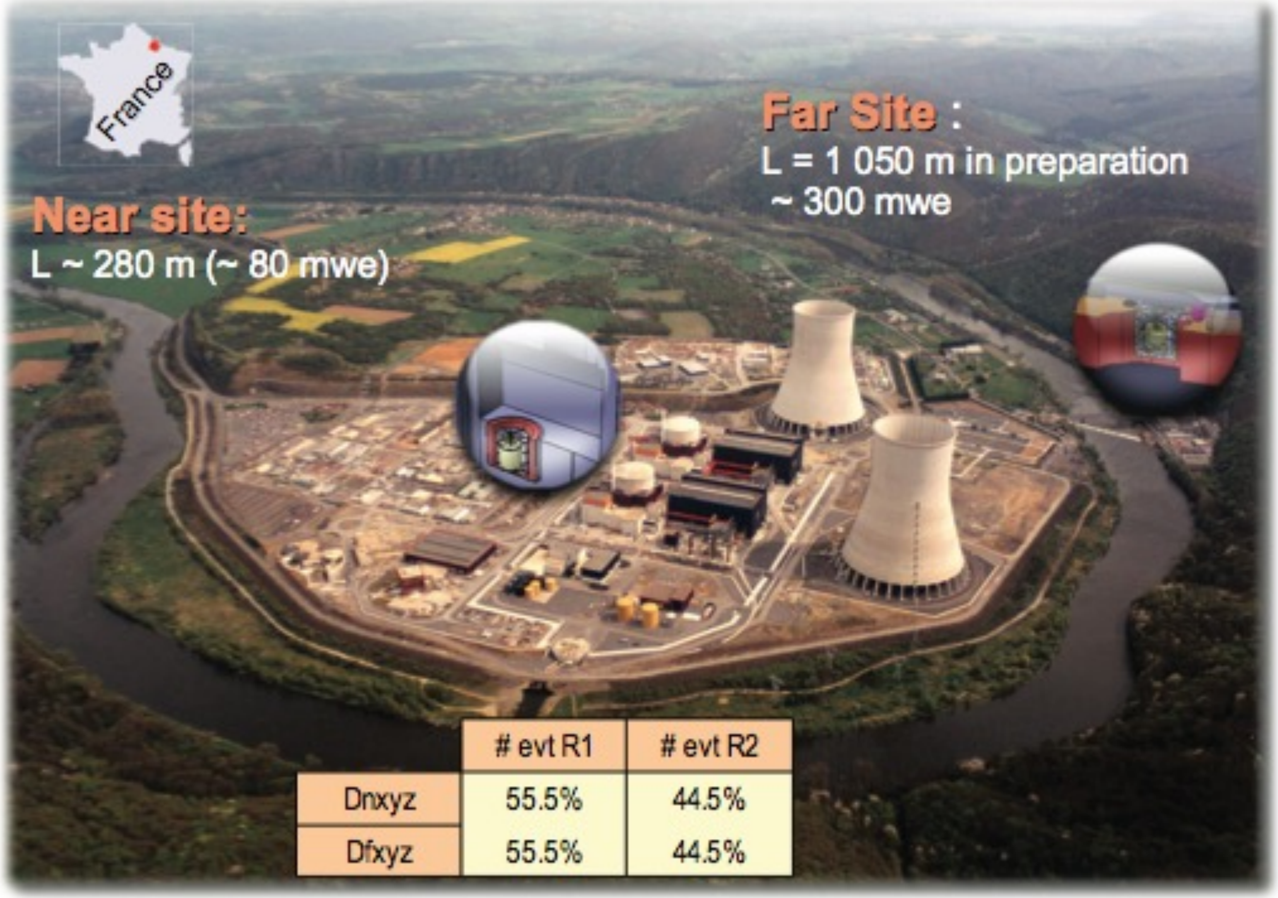
The three reactor experiments

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



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

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

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

2 cores – 1 site – 8.5 GW_{th}

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 ε)

- far: ~ 40 evts/day
- near: ~ 460 evts/day

Systematics

- reactor : ~ 0.2%
- detector : ~ 0.5%

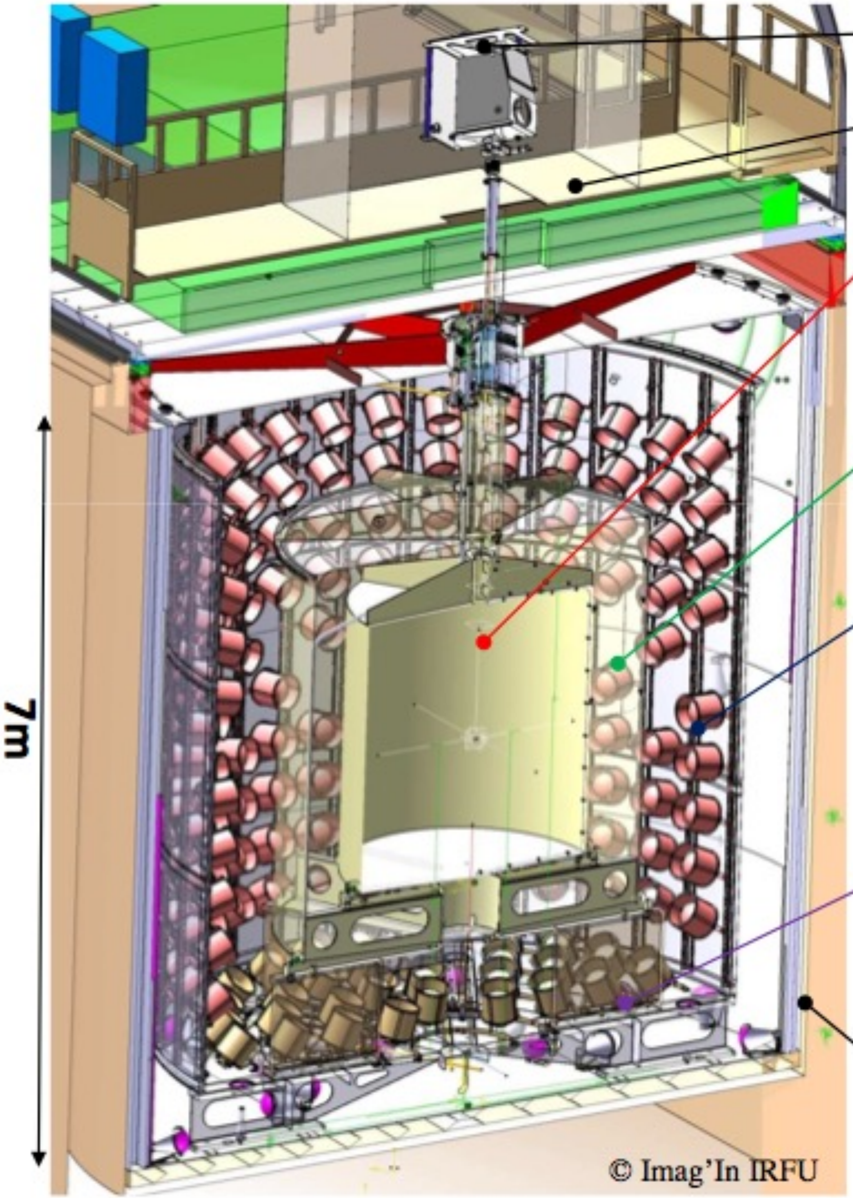
Backgrounds

- σ_{b2b} at far site: ~ 1%
- σ_{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

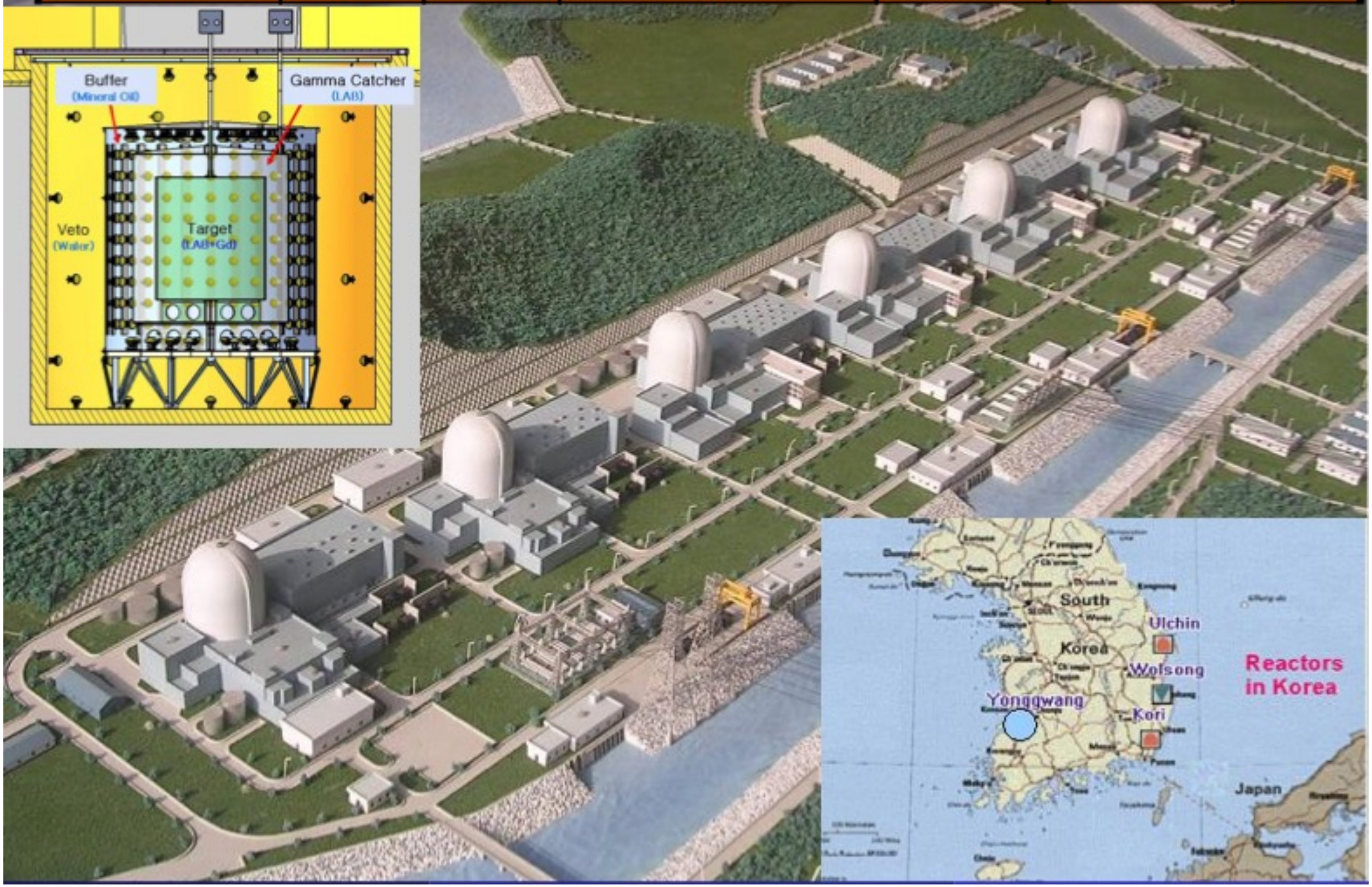


© Imag'In IRFU

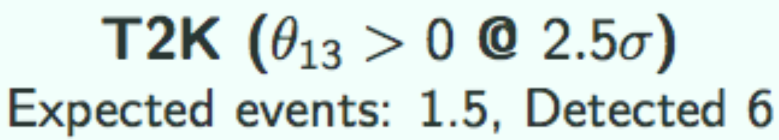
- **calibration glove box**
- **external muon veto** plastic scintillator strips
- **target**: 10.3 m^3 Gd-loaded scintillator 0.1%
  in acrylic vessel (r=1.15m, h=2.5m)
- **γ-catcher**: 22.4 m^3 unloaded scintillator
  in acrylic vesssel (r=1.7m, h=3.6m)
- non-scintillating **buffer**: 100 m^3 mineral oil
  in stainl. steel vessel (r=2.8m, h=5.7m)
  390 PMTs (10´´)
- inner **muon veto**: 90 m^3 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$



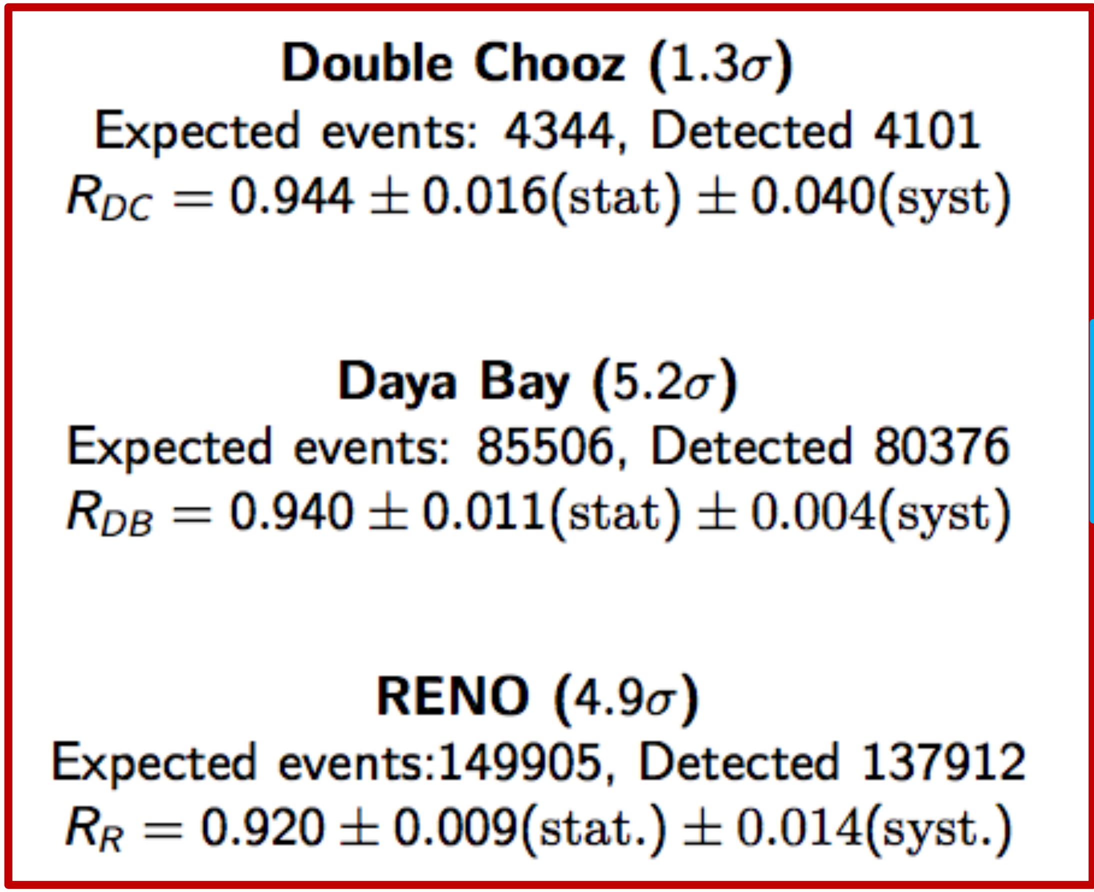
Experimental Results at that time (2012)



T2K ($\theta_{13} > 0$ @ 2.5σ)

Expected events: 1.5, Detected 6

ν_e appearance
on ν_μ beam



Double Chooz (1.3σ)

Expected events: 4344, Detected 4101

$R_{DC} = 0.944 \pm 0.016(\mathrm{stat}) \pm 0.040(\mathrm{syst})$

Daya Bay (5.2σ)

Expected events: 85506, Detected 80376

$R_{DB} = 0.940 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst})$

RENO (4.9σ)

Expected events:149905, Detected 137912

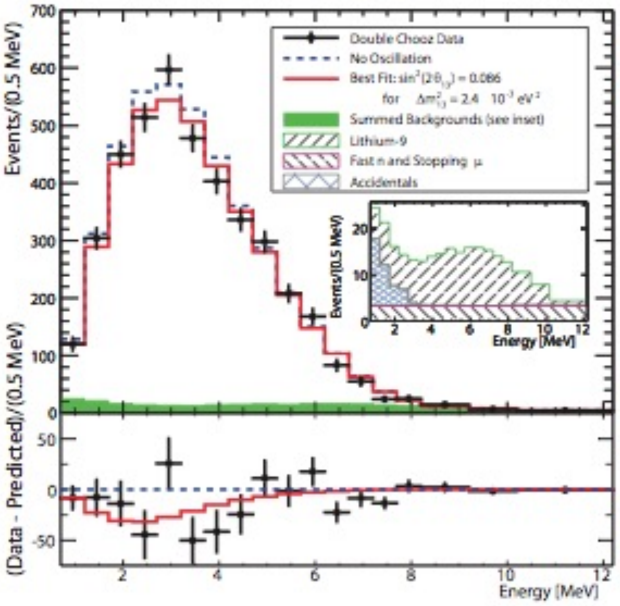
$R_R = 0.920 \pm 0.009(\mathrm{stat.}) \pm 0.014(\mathrm{syst.})$

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

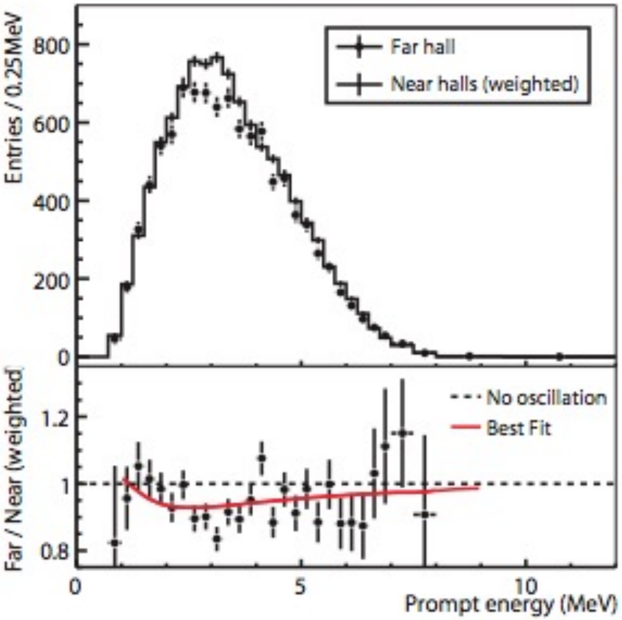
Spectral information

Not used in the fit

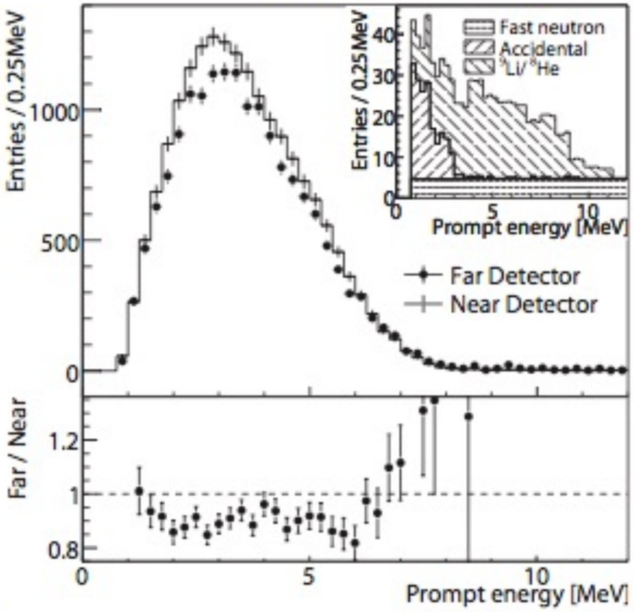
Double Chooz



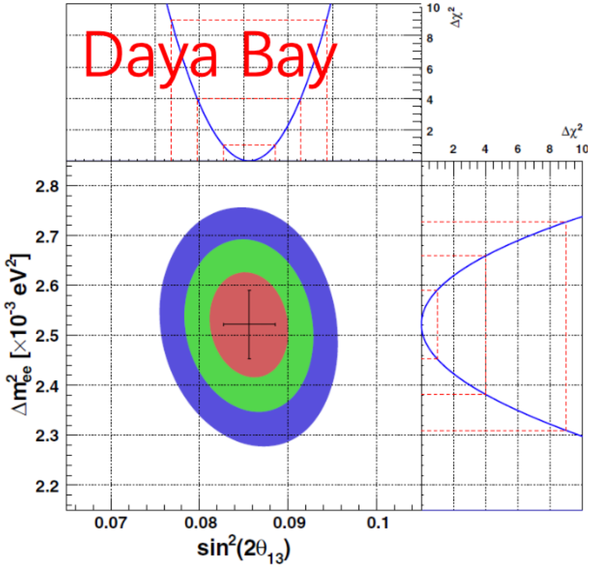
Daya Bay



RENO



Recent θ_{13} and $|\Delta m^2_{ee}|$ Results (2020)



Gd-capture

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

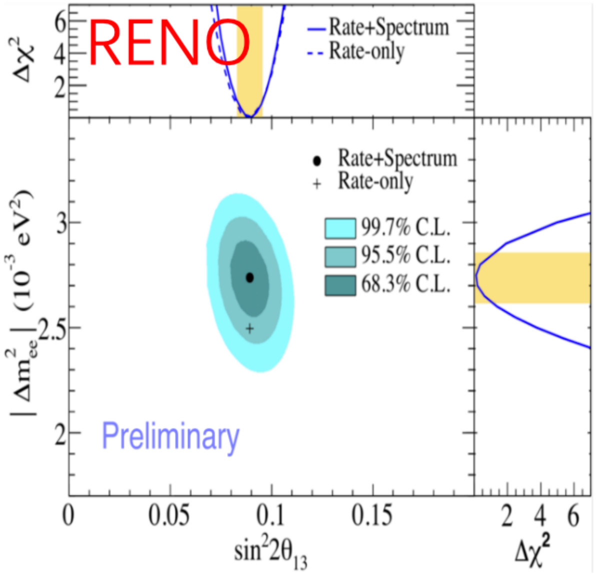
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

*PRL **121** 241805 (2018)*

H-capture

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

*PRD **93** 072011 (2016)*



Gd-capture

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

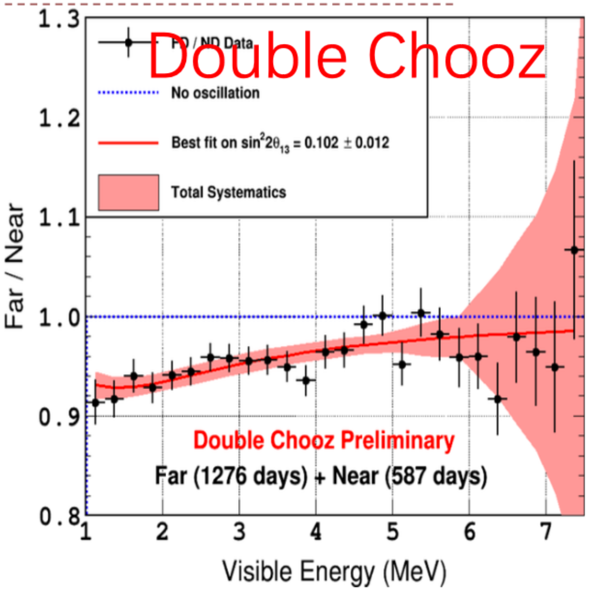
$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\text{eV}^2)$$

@ICHEP 2020

H-capture

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

JHEP 04 (2020) 029



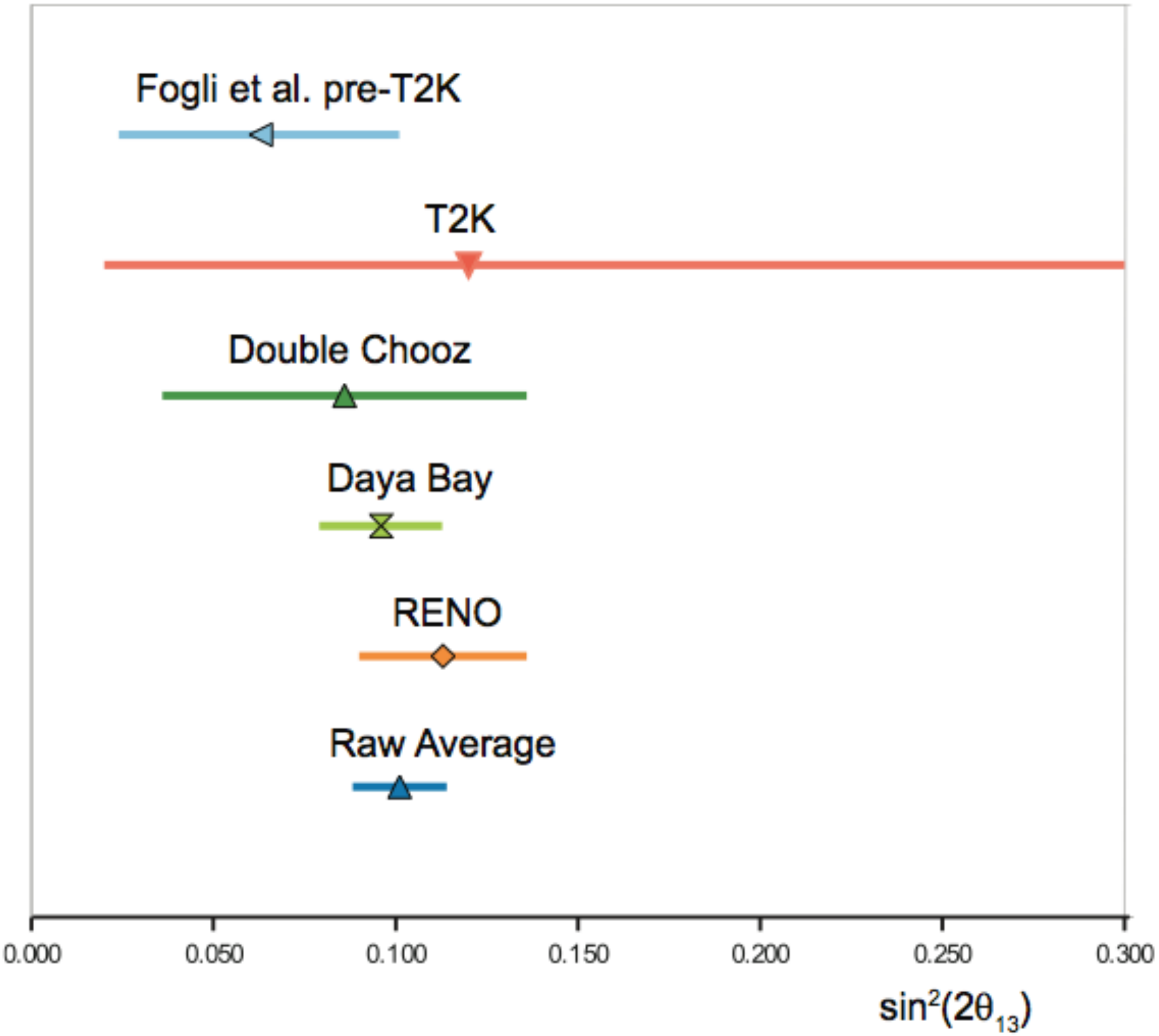
Total-capture

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

@Neutrino 2020

Summary of θ_{13} results

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



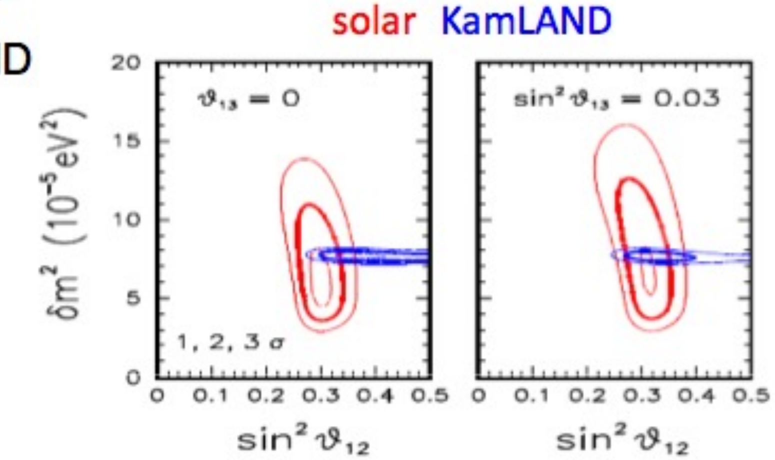
Before 2011: hints about a non null θ_{13}

Global fits to oscillation data

Imperfect agreement between KamLAND and solar fits: for $\theta_{13}=0$, solar expts. and KamLAND prefer different values of θ_{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)

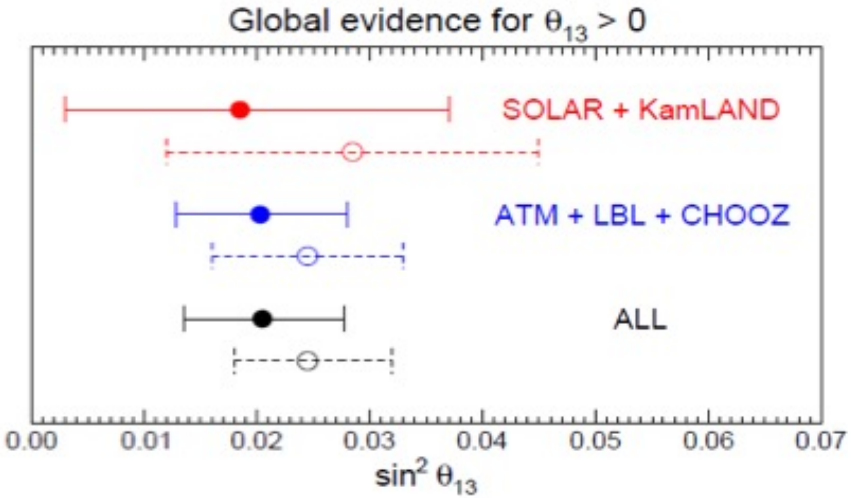


Including recent T2K result

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

3 σ evidence for $\theta_{13}>0$

Fogli et al., arXiv:1106.6028v1



Results on θ_{13} by neutrino beams

2 experimental approaches to determine θ_{13}

- **Accelerator experiments** (ν_μ-beam)
  - appearance experiment: $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

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

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \sim\ & \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\Delta_{31} \\ & - \alpha \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \cos(\delta) \Delta_{31} \cos\Delta_{31} \sin\Delta_{31} \\ & - \alpha \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin(\delta) \Delta_{31} \sin^2\Delta_{31} \\ & + \alpha^2 \ldots \end{aligned}$$

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

T2K, NoVa, ...

- **nuclear reactors**
  - $\bar{\nu}_e$, $<E_\nu>$ few MeV ⇒ disappearance experiment

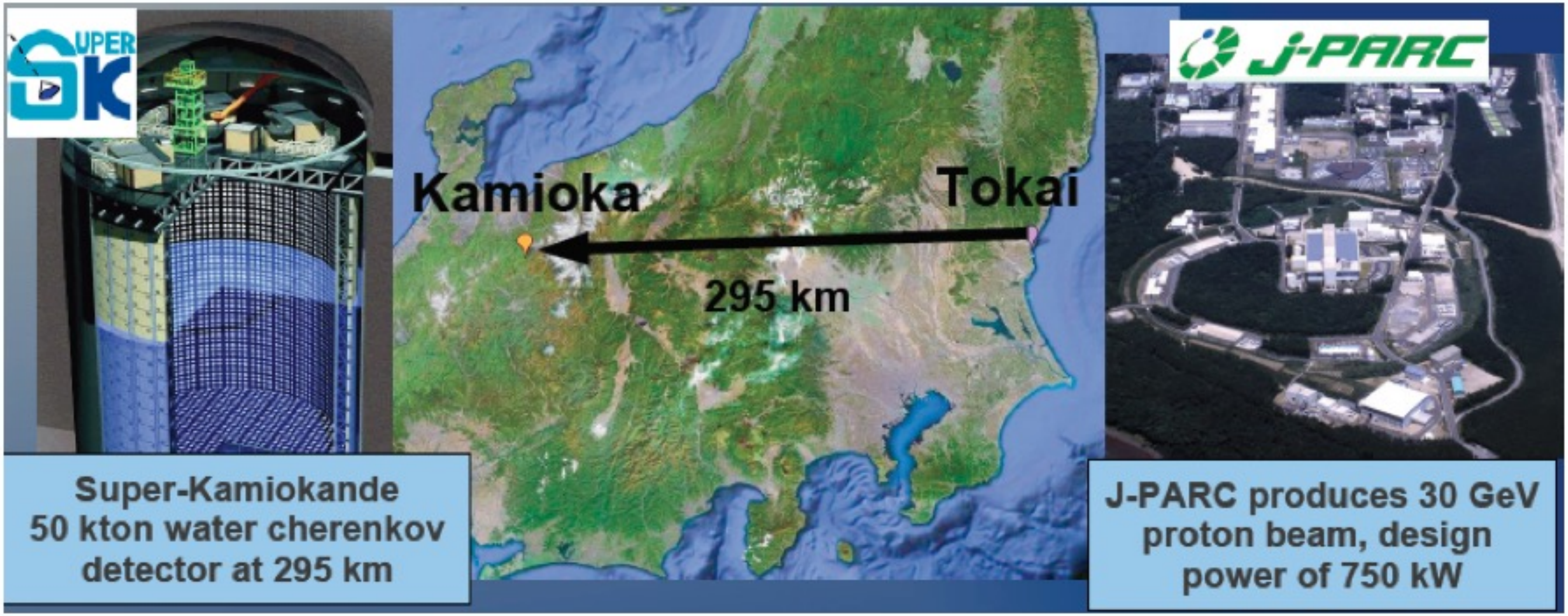
$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

  - look for rate deviation from $1/r^2$ and spectral distortions
  - clean measurement of θ_{13}, independent of δ-CP, weak dependence on Δm^2_{21}
  - small distance (1 – 2 km) ⇒ matter effects negligible

Double Chooz, Daya Bay, RENO

T2K: ν_e appearance to search for θ_{13}

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



Super-Kamiokande 50 kton water cherenkov detector at 295 km

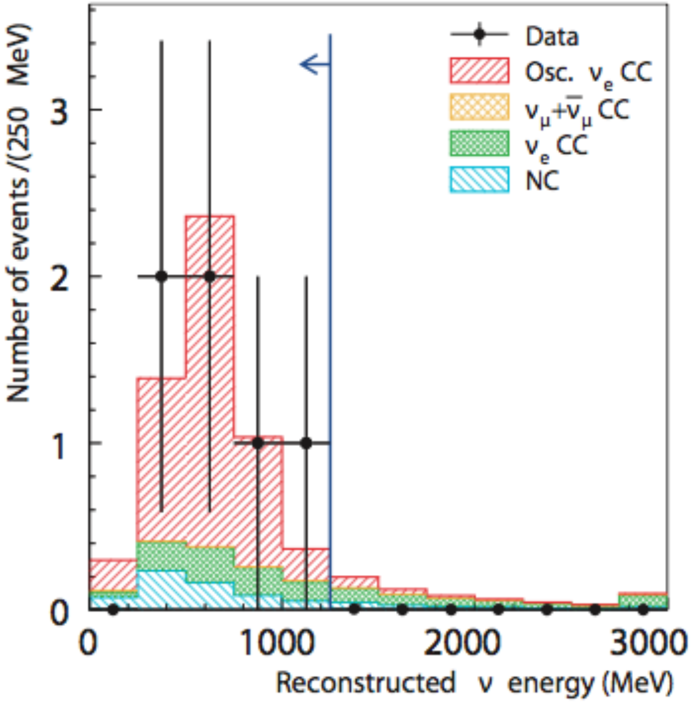
J-PARC produces 30 GeV proton beam, design power of 750 kW

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

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

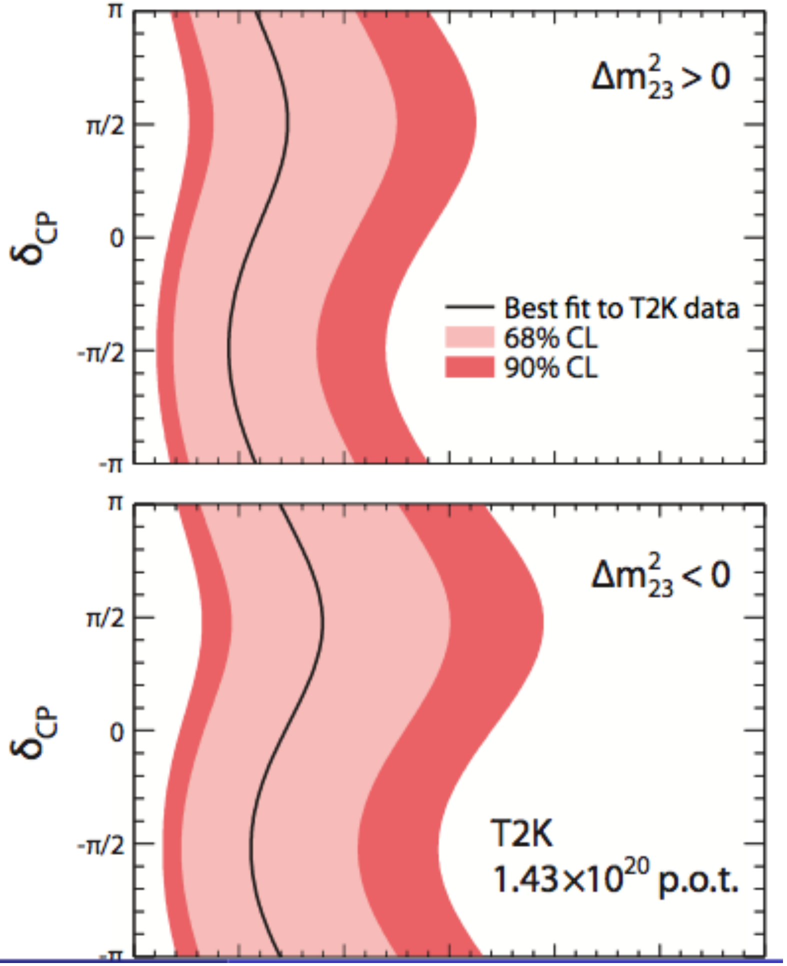
T2K result

PRL 107 (2011) 041801

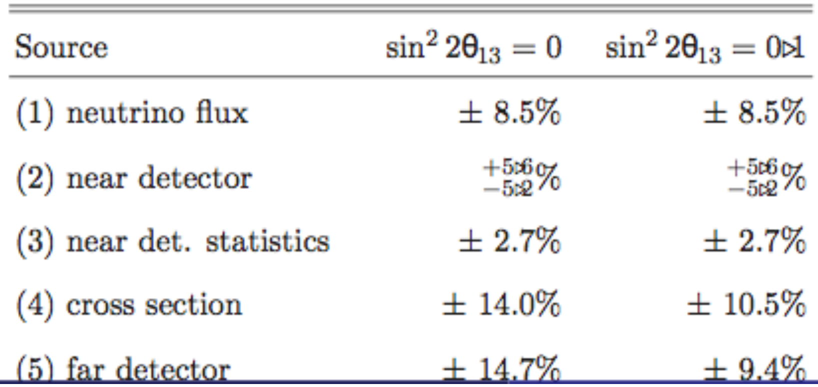


Expected: 1.5 +/- 0.3
Measured: 6

Results on 2013: measured 28 events (bck:4.64±0.53)



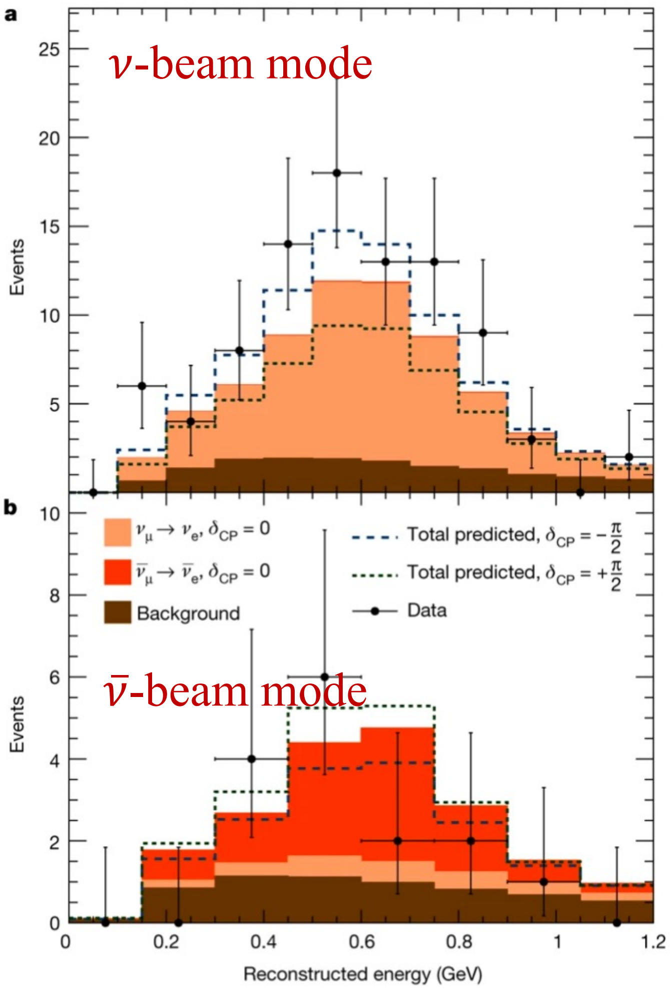
Systematic errors

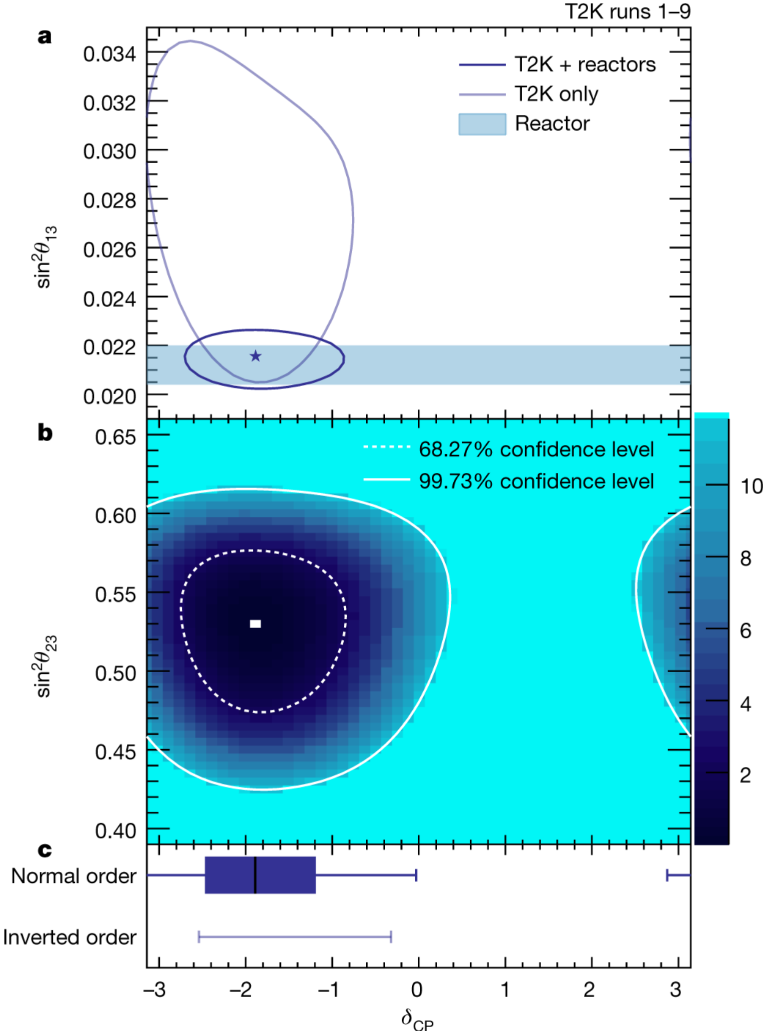


Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	± 8.5%	± 8.5%
(2) near detector	$^{+5.6}_{-5.2}$%	$^{+5.6}_{-5.2}$%
(3) near det. statistics	± 2.7%	± 2.7%
(4) cross section	± 14.0%	± 10.5%
(5) far detector	± 14.7%	± 9.4%

The latest T2K results (2020)

- Two-dimensional confidence intervals at the 68.27% confidence level for δ_{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.

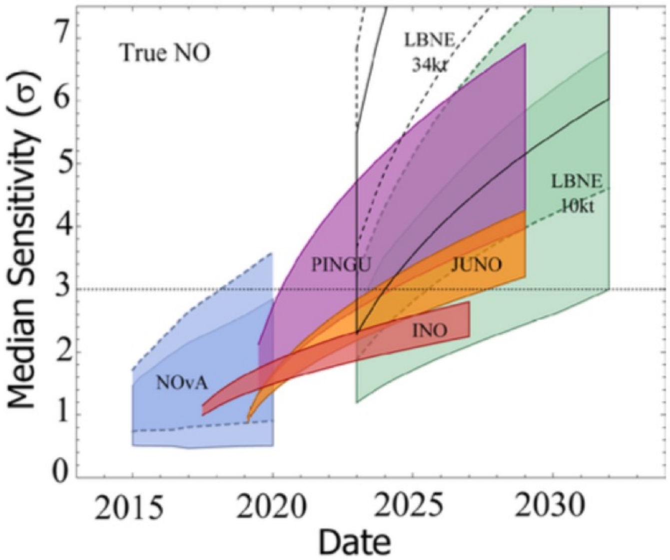
Critical Questions for Future Neutrino Physics Program

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_ν).

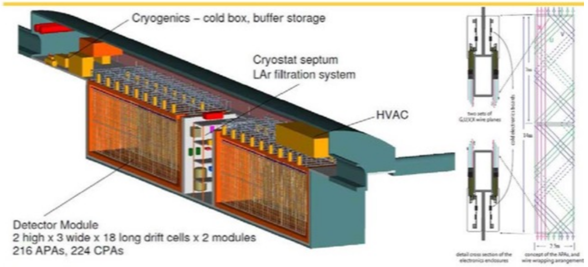
- Pure oscillation effects in ν_e disappearance: **Juno**
- Matter effects in ν_μ disappearance: **INO, Pingu, Orca, HyperKamiokande**
- Matter effects in ν_e appearance: **NOvA, Dune, T2HK**

Blennow et al., JHEP 1403 (2014)028



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

Mainly two players: Dune and HyperKamiokande



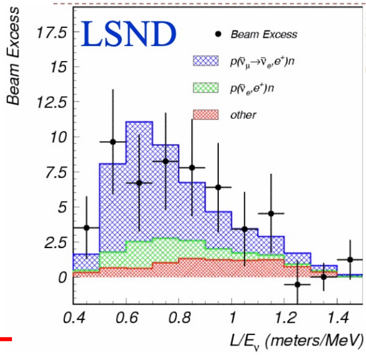
Is all discovered?

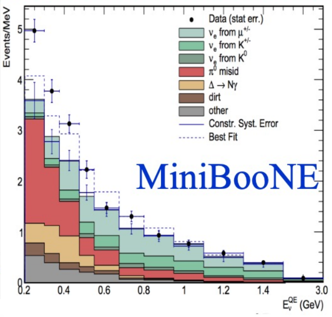
✓ A few experiments show (weak/not-strong) **deviations** (***anomalies***) from the 3 flavor ν-osc paradigma:

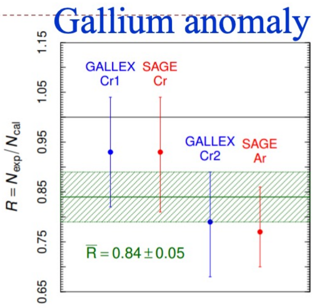
- **LSND** at Los Alamos observed excess of $\bar{\nu}_e$ events in the $\bar{\nu}_\mu$ beam
- **Mini-Boone** confirmed anomaly at low energy in anti-neutrino mode but not in neutrino mode
- **Gallium anomalies**: events from calibration sources in GALLEX and SAGE are less than expected (2.8σ)
- **Reactor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

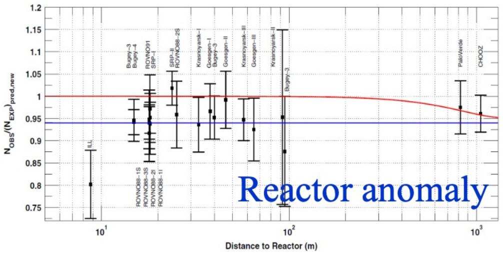
✓ It is too early to claim new physics. The only picture consistent with all data is the existence of sterile neutrinos.

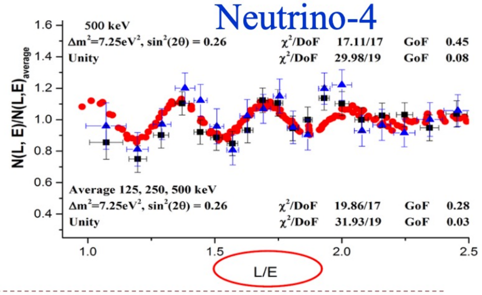
✓ A short-term program includes ~~MCi neutrino sources (sources in ν expts?)~~; SBL (short-baseline) expt probing GeV ν_e appearance at short distances (100m – 1 km)











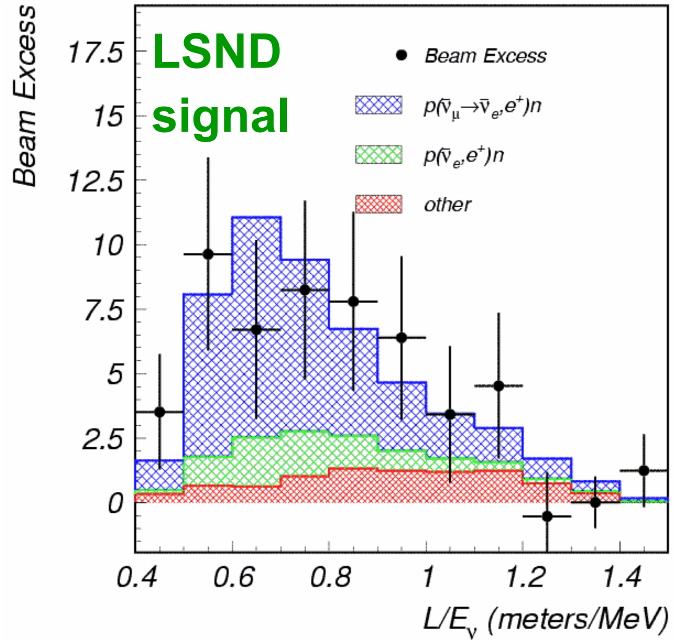
LSND experiment

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

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

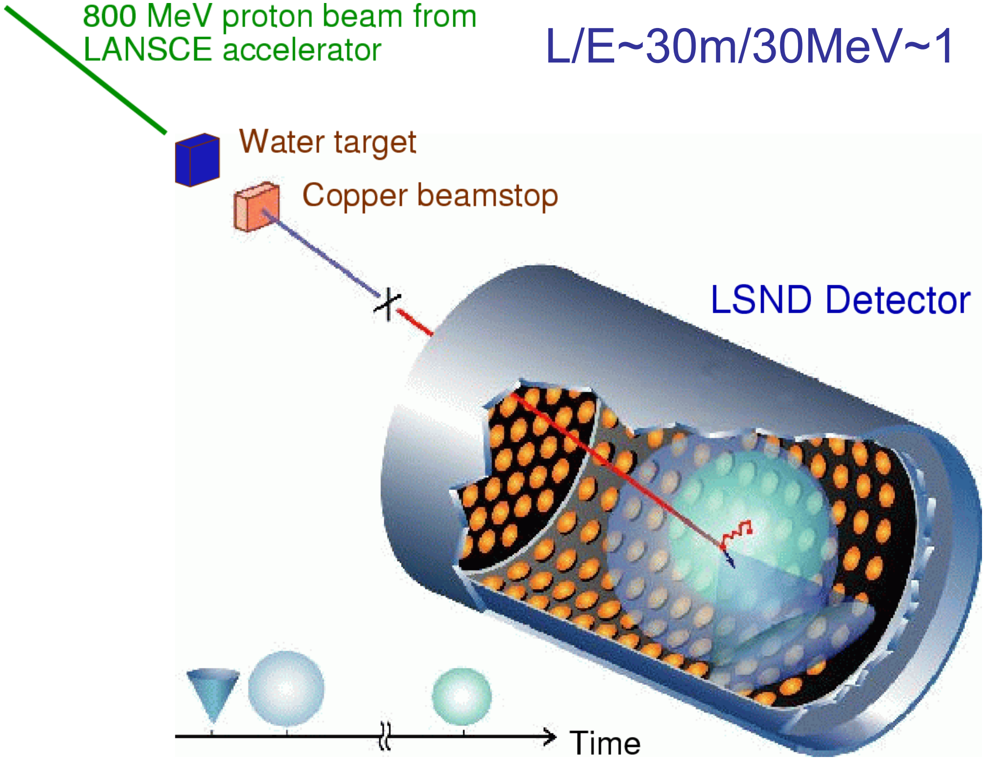
$$n + p \to d + \gamma$$

87.9 ± 22.4 ± 6.0 (3.8σ)

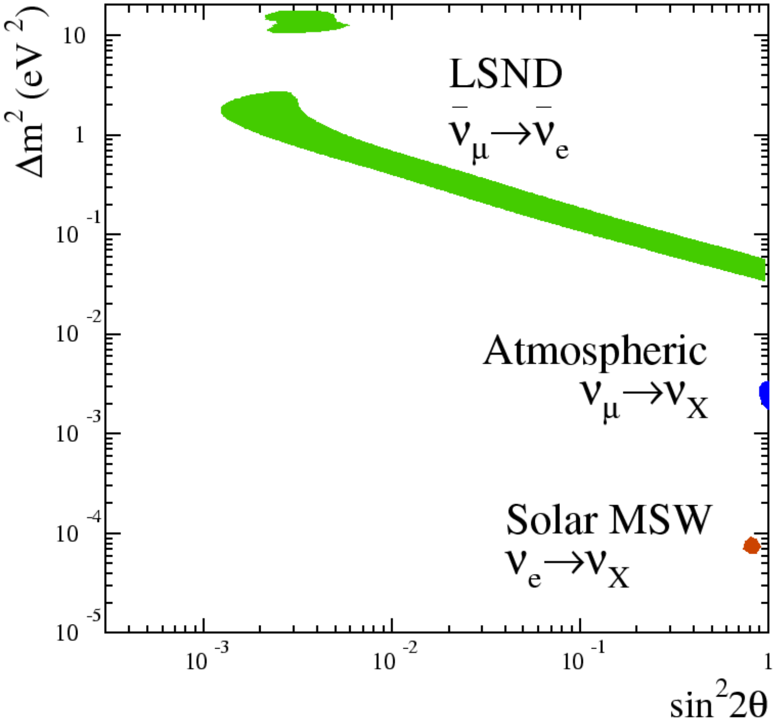


LSND Collaboration,
PRD 64, 112007

L/E~30m/30MeV~1



LSND experiment



3 types of neutrino oscillations are found:

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

But we cannot have so many Δm^2!

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

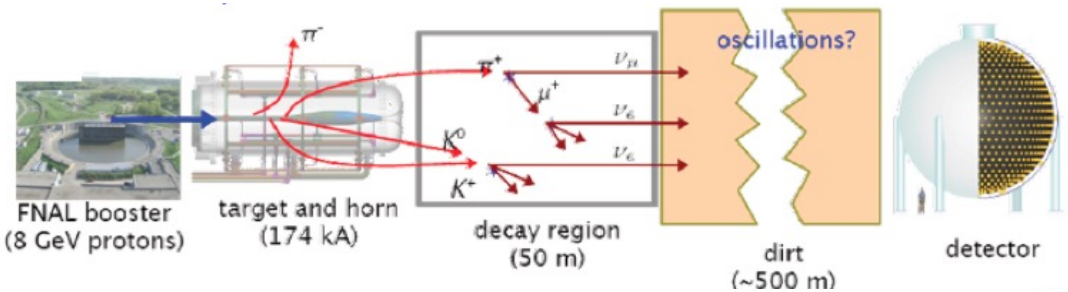
New physics?
- sterile neutrino
- Lorentz violation
- CPT violation
- extra dimension
- etc

We need to test LSND signal!

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

Mini-Boone

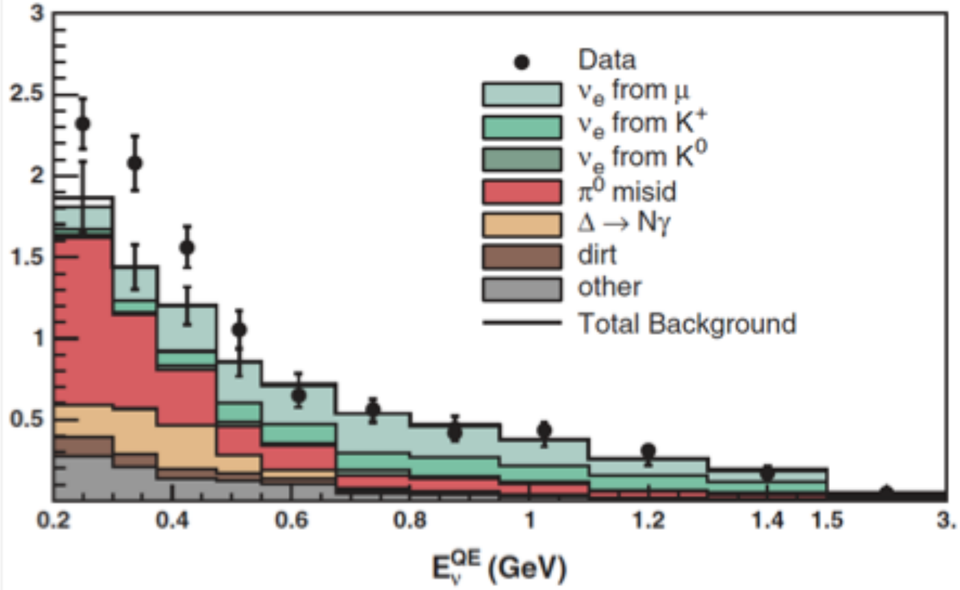
PRL 102 (2009) 101802
PRL 105 (2010) 181801

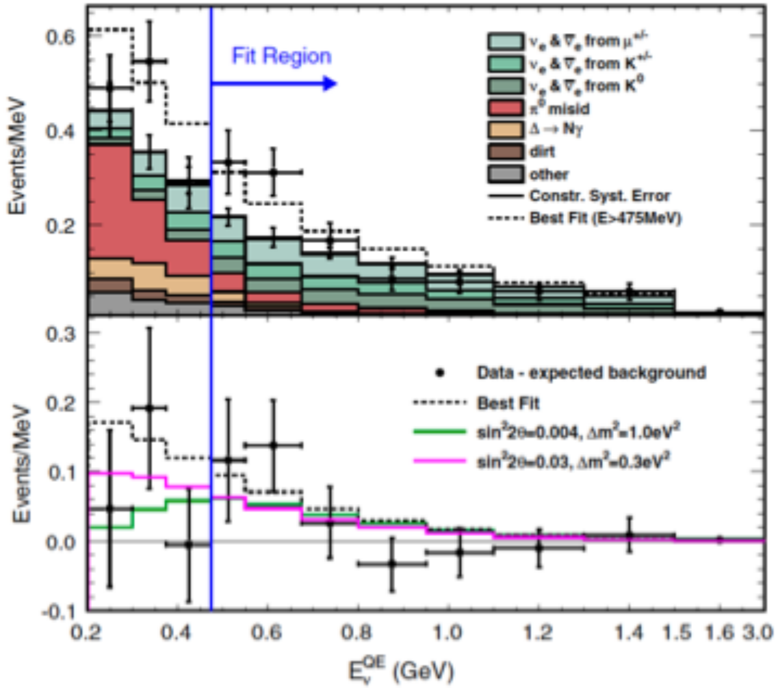


- Liquid mineral oil detector (scintillation and Cerenkov) used to detect ν_e ($\bar{\nu}_e$) in a predominantly ν_μ ($\bar{\nu}_\mu$) beam.
- Designed and built to check the LSND result

- 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 (>6σ)

- Anti-Neutrino mode
  - Anomaly confirmed at low energy
    - E < 475 MeV
  - Consistent with LSND
    - ~2σ effect

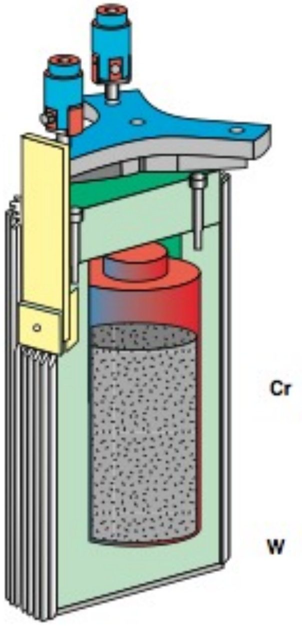




The Gallium data

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

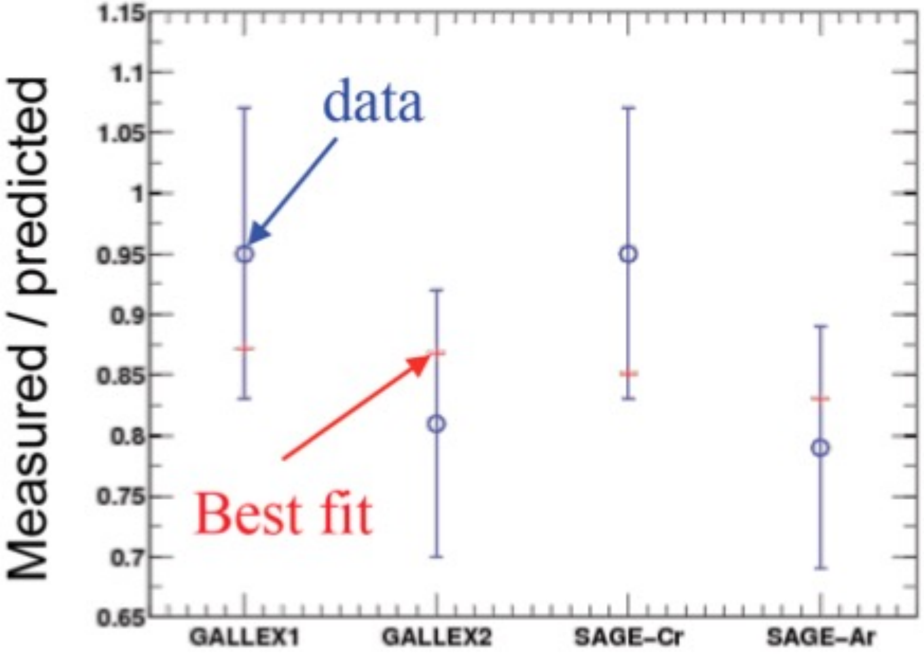
- For calibration purposes, they built and operated powerful **radioactive neutrino sources**
  - ^{51}**Cr** source **(~ 2 MCi, a few 10^{16} ν/s !)**
  - ^{37}**Ar** source (SAGE only, 0.2 MCi)



$$R_{\mathrm{B}}^{\mathrm{Ga}} = 0.86^{+0.05}_{-0.05}$$

Giunti-Laveder
hep/ph: 1006.3244

Data is lower than expected @ 2.8σ



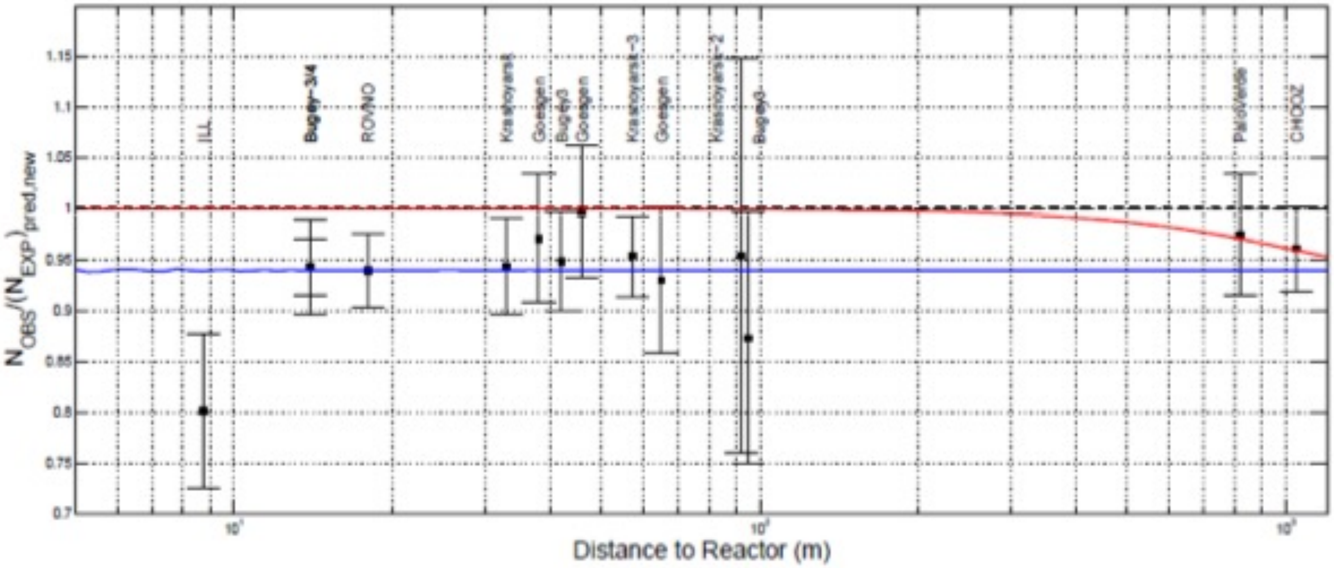
Reactor antineutrino anomaly

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 ν_e

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



Black dotted:
no osc.

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

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

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 4th sterile ν?