



International School on
Astroparticle Physics

13-24 June 2017
Arenzano (GE)
Europe/Rome timezone

Reactor ν Experiments

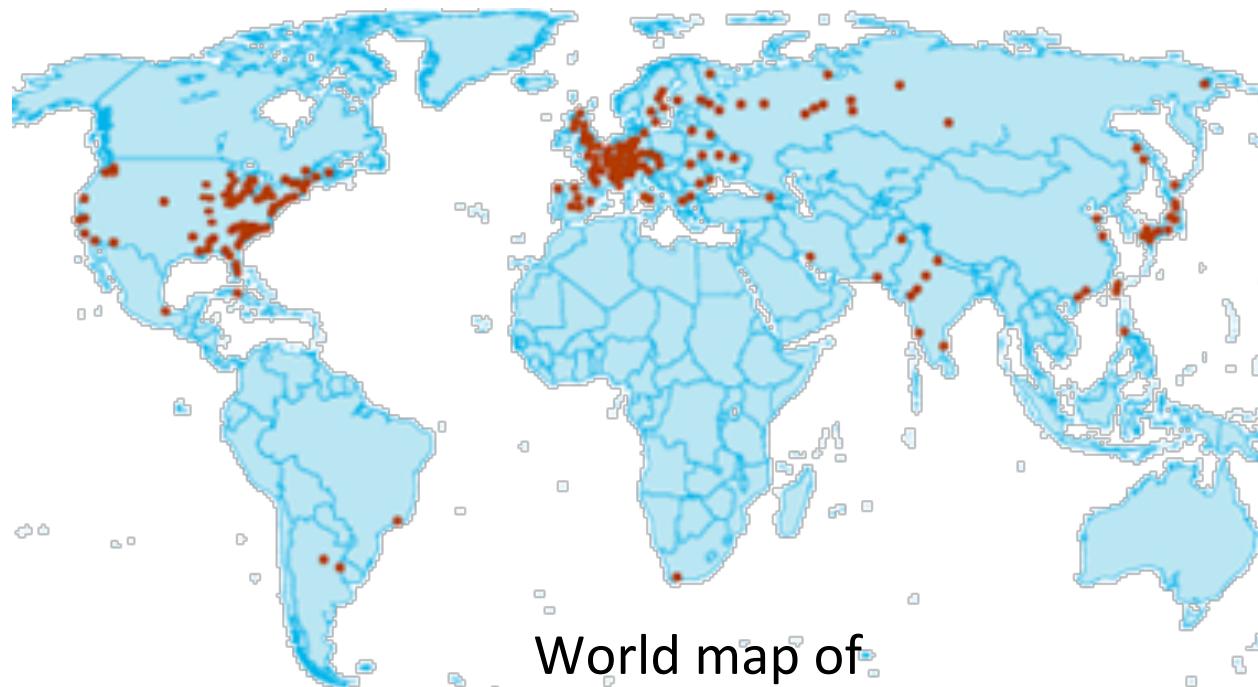
Sunny (Seon-Hee) Seo

Seoul National University

Outline

- Reactors: electron antineutrino source
- Reines-Cowan's experiment
 - discovery of (anti)neutrinos
- Neutrino oscillation experiments
 - solar Δm^2 : KAMLAND ← medium baseline \sim km
 - θ_{13} , atm. Δm^2 : Chooz, D-Chooz, RENO, Daya Bay ← short baseline $O(\sim 1 \text{ km})$
 - Mass ordering: JUNO, RENO-50 ← medium baseline $O(\sim 50 \text{ km})$
- Sterile neutrino search experiments
 - Very short baseline $O(1\text{m} \sim 10\text{m})$
 - DANSS, NEOS, Neutrino 4, Nucifer, NuLat, Poseidon, Prospect, Solid, Stereo etc.

World Nuclear Power Reactors I

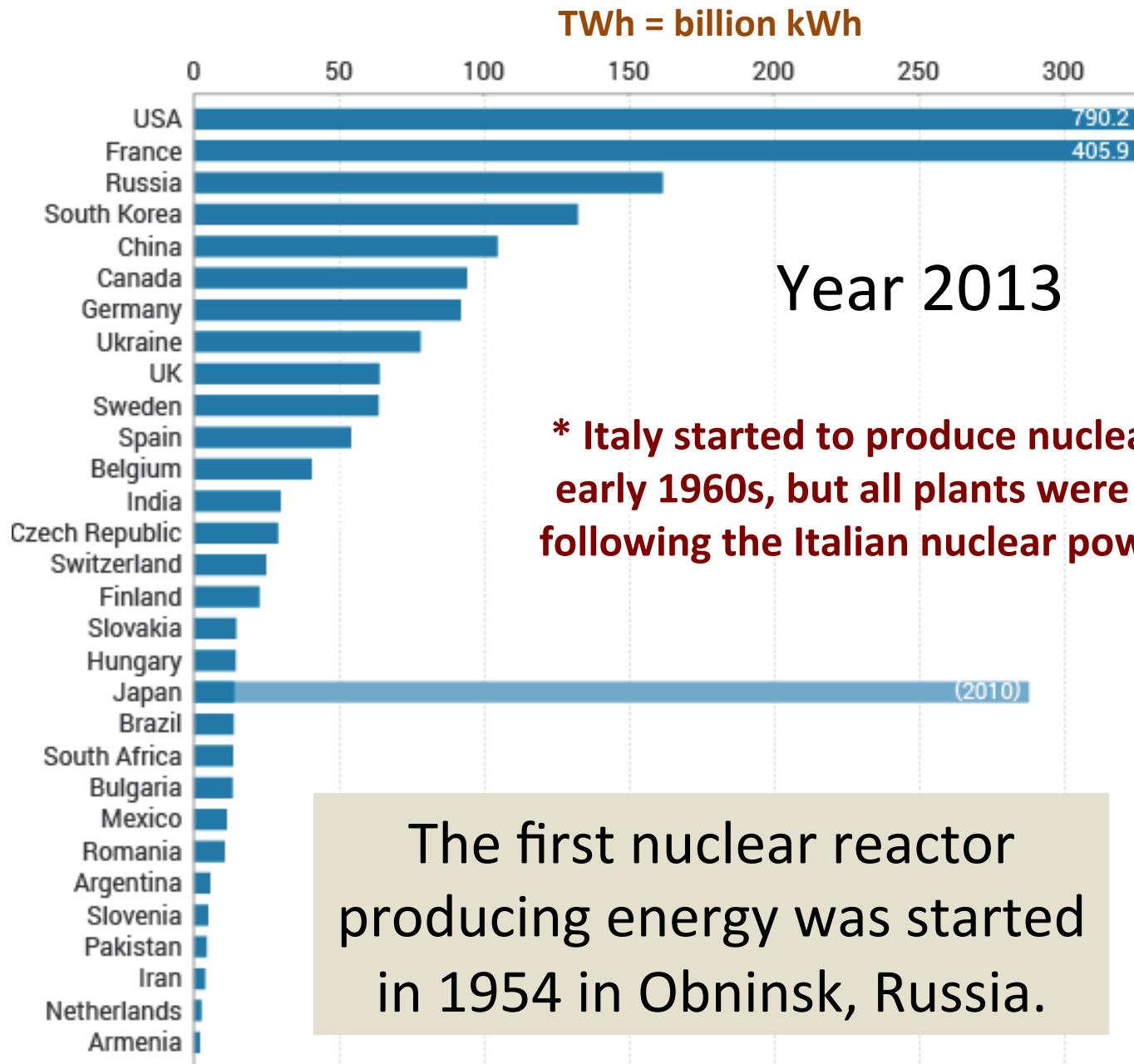


World map of
Nuclear power reactors

- 444 nuclear reactors for electricity generations + 63 under construction as of May 2016.
- ~ 12% of the world's electricity is produced from nuclear energy.

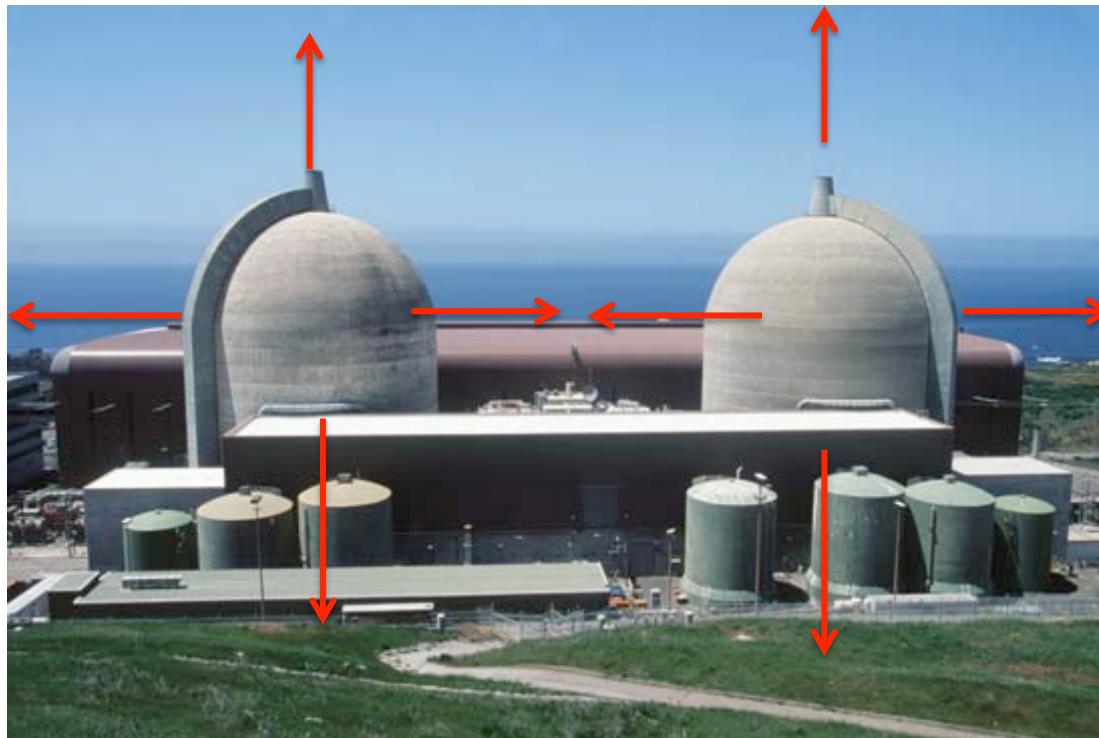
Reactor E fraction

France	76.3%
Ukraine	56.5%
Slovakia	55.9%
Hungary	52.7%
Slovenia	38.0%
Belgium	37.5%
Armenia	34.5%
Sweden	34.3%
Finland	33.7%
Switzerland	33.5%
Czech Republic	32.5%
South Korea	31.7%
Bulgaria	31.3%



Nuclear Reactors: source of $\bar{\nu}_e$

Nuclear reactors are copious & isotropic sources of $\bar{\nu}_e$.

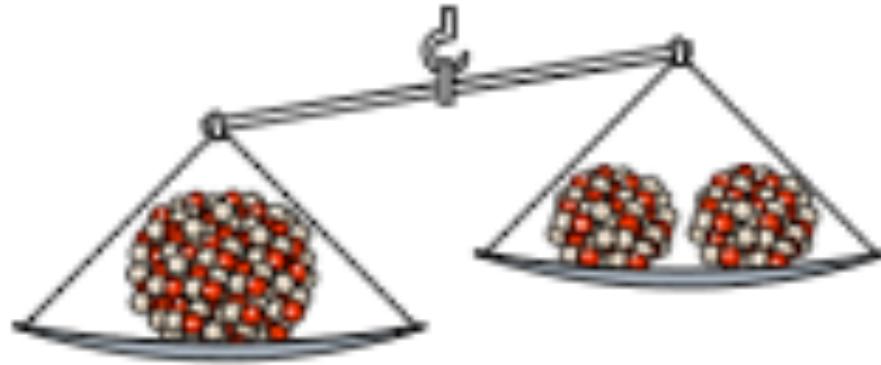


1 GW_{th} reactor
 $\rightarrow \sim 2 \times 10^{20} \bar{\nu}_e/\text{sec}$

The Diablo Canyon nuclear power plant
(~2.2 GW_{th}) in San Luis Obispo county, California.

(Exercise !)

What is Nuclear Fission ?



A heavy nucleus like uranium split in two parts:
the heavy nucleus has a larger mass.

The difference in masses, using the Einstein equation,
corresponds to an energy of about 200 MeV.

Discovery of Nuclear Fission

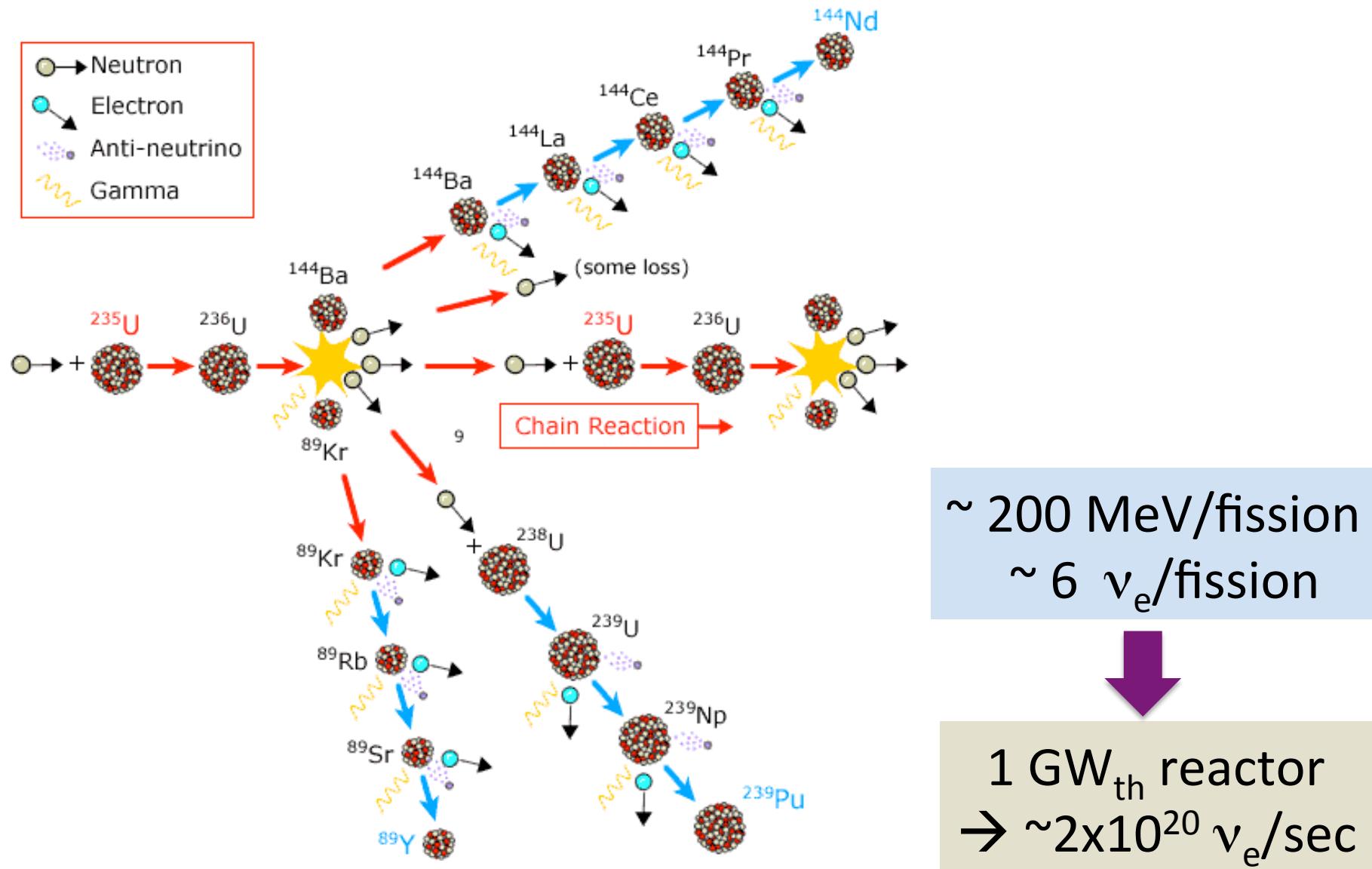
In 1938 by team of
L. Meitner, O. Hahn,
& F. Strassmann



Nobel Chemistry Prize in 1944

The Experimental Apparatus with which **the team of Otto Hahn, and Fritz Strassmann discovered Nuclear Fission in 1938**. The arrangement was originally in 3 separate rooms: irradiation, measurement, and chemistry at the Kaiser Wilhelm Institute for Chemistry in Berlin.

Nuclear Fission Process



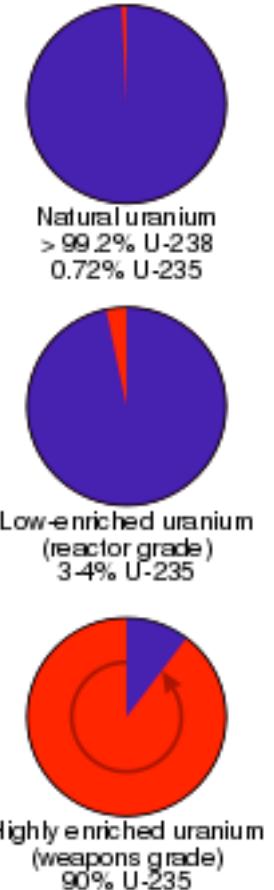
Breakdown of fission energy

	MeV
Kinetic energy of fission fragments	165 +/- 5
Instantaneous gamma rays	7 +/- 1
Kinetic energy of neutrons	5 +/- 0.5
Beta particles from product decay	7 +/- 1
Gamma rays from product decay	6 +/- 1
Neutrinos from product decay	10
TOTAL	200 +/- 6

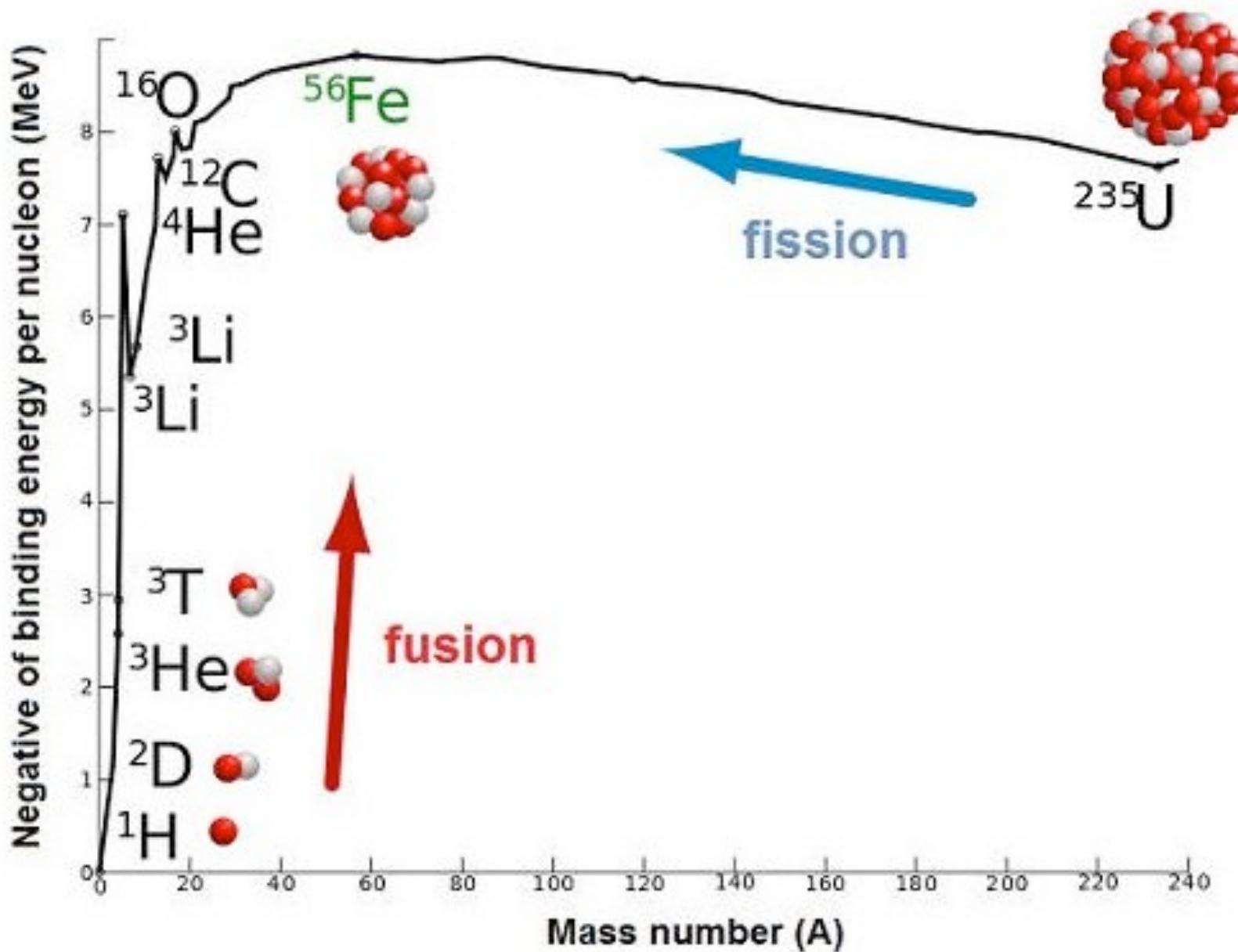
Uranium ore



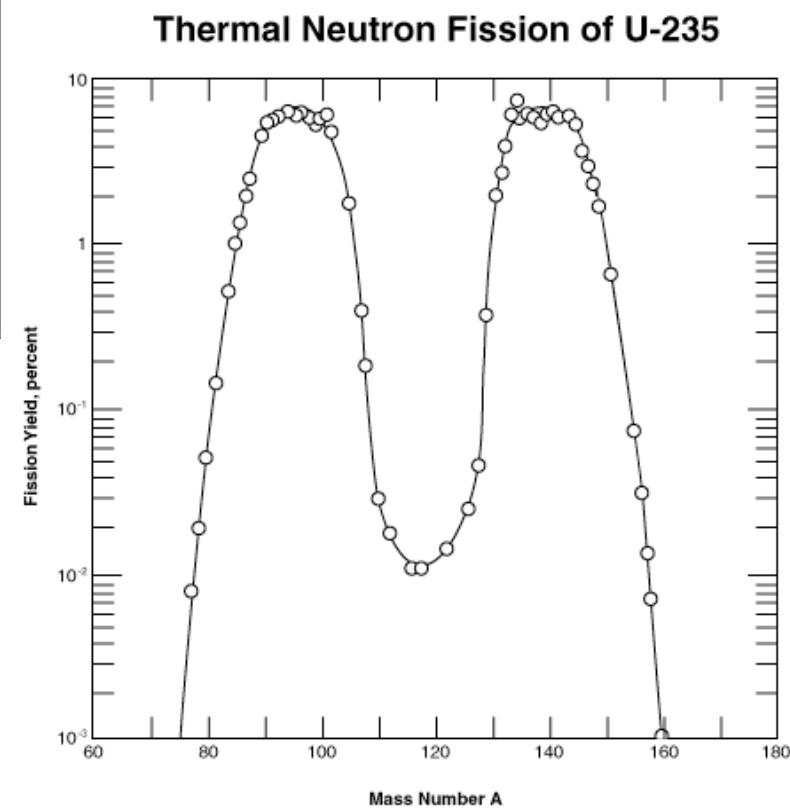
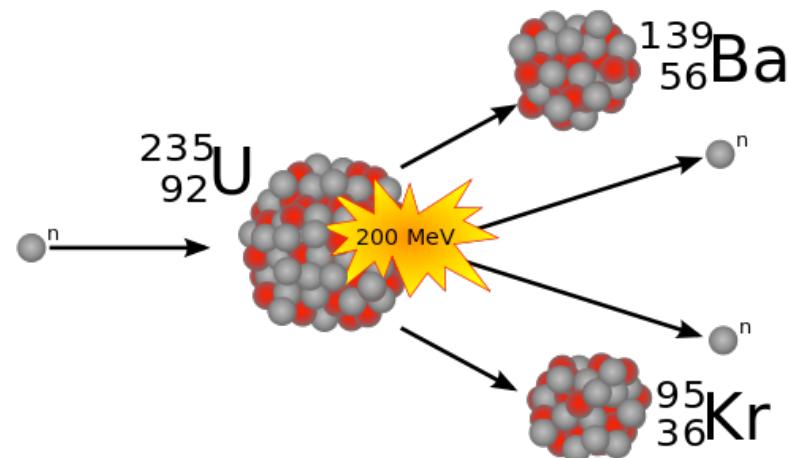
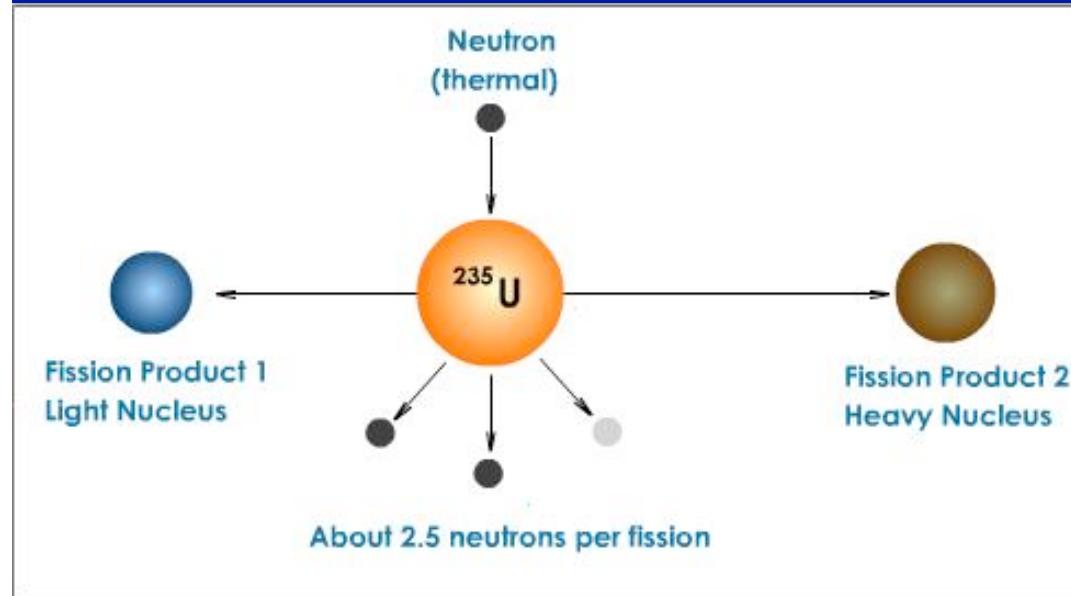
- U-235: 0.72 % fissile;
most widely used fuel in reactors
- U-238: 99.27 % fertile;
breeding Pu-239



Fission isotopes	Critical mass	production
U-233	16 kg	manufactured
U-235	54 kg	natural
Pu-239	10 kg	manufactured



Nuclear Fission Process



Why Some Isotopes are Unstable ?

n/p ratio

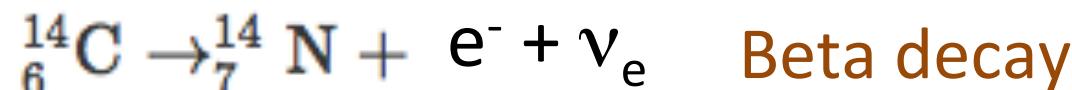
Example:

$$^{12}\text{C}: \text{n/p} = 6/6 = 1.0$$

$$^{13}\text{C}: \text{n/p} = 7/6 = 1.2$$

$$^{14}\text{C}: \text{n/p} = 8/6 = 1.3 \leftarrow \text{unstable}$$

^{14}C becomes stable by emitting beta, i.e., converting $\text{n} \rightarrow \text{p}$

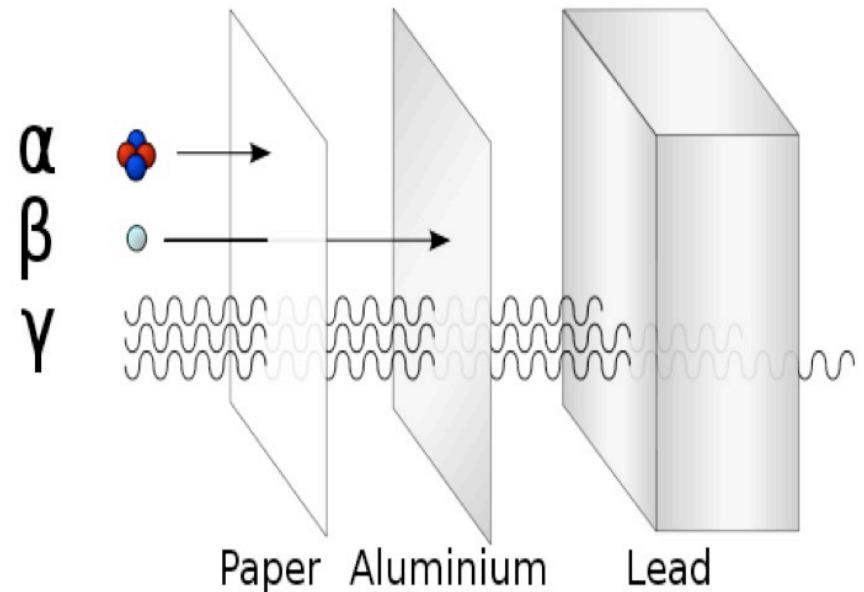
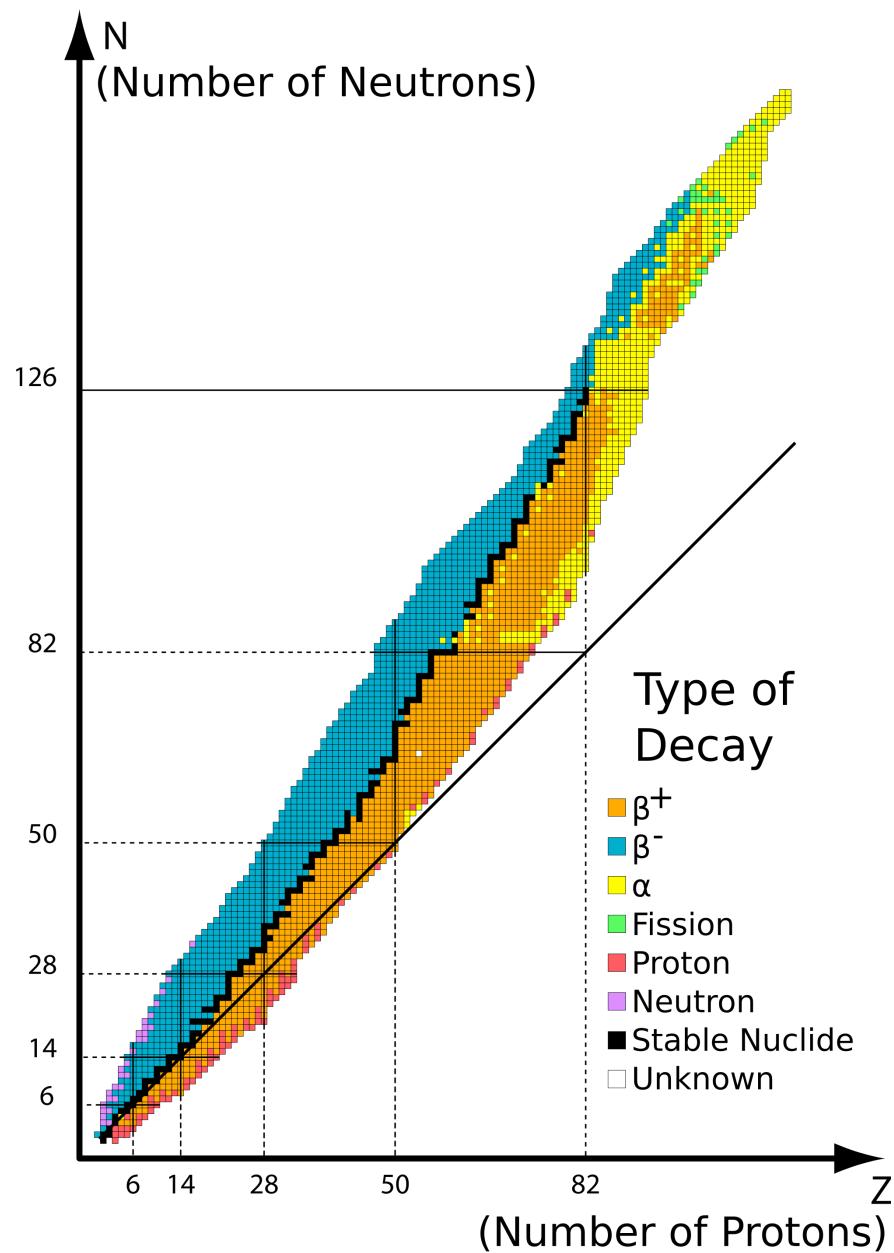


- All isotopes with $\text{n/p} < 1.0$ or > 1.5 are radioactive.
- All isotopes heavier than ${}^{209}\text{Bi}$ are radioactive.

Types of Decays

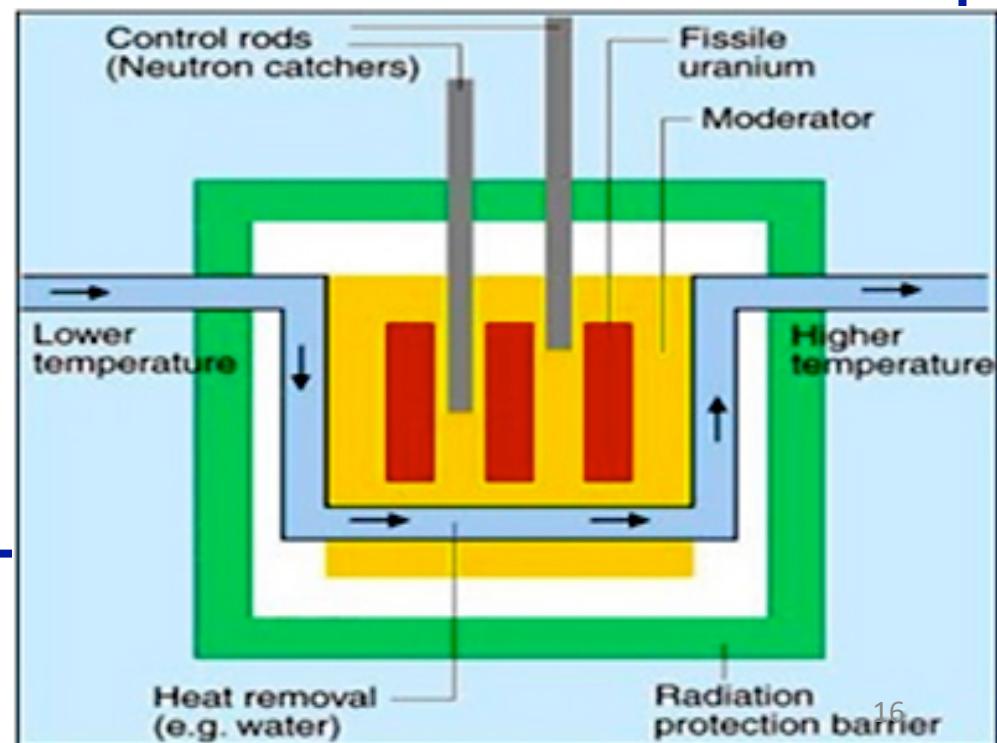
Type	Description	Change?	Example
Alpha	Nucleus releases a He atom. He atom is known as an alpha particle	A Helium atom is released. Remaining nucleus weighs 4 less and has 2 less protons	$^{238}_{92}U \rightarrow ^{234}_{90}Th + {}^4_2He$
Beta	Nucleus releases an electron and converts a neutron to a proton	Remaining atom has: •Same mass •One more proton, one less neutron	$^{231}_{53}I \rightarrow ^{231}_{54}Xe + {}^0_{-1}e$
Gamma	Nucleus goes from high energy state to a low energy state.	Nucleus remains same, but a gamma ray is released	$^{238}_{92}U \rightarrow ^{238}_{92}U + \gamma$
Positron	Nucleus releases a positively charged electron and converts a proton to a neutron	Remaining atom has: •Same mass •One more neutron, one less proton	$^{11}_6C \rightarrow ^{11}_5B + {}^0_1e$
Electron Capture	An electron from the electron cloud converts a proton into a neutron	Remaining atom has: •Same mass •One more neutron, one less proton	$^{201}_{80}Hg + {}^0_{-1}e \rightarrow ^{231}_{79}Au$

Types of Decays

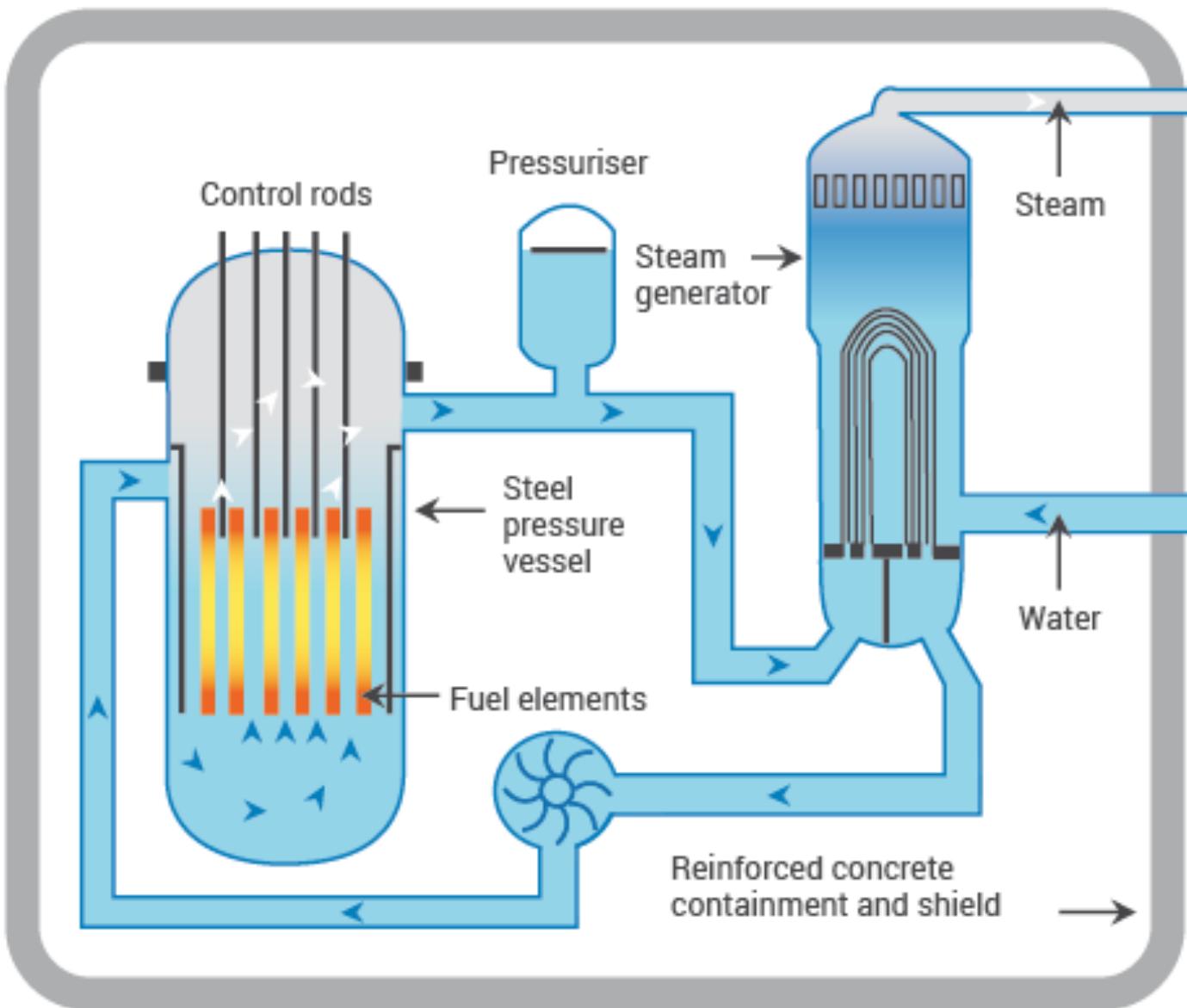


Basic Reactor Elements

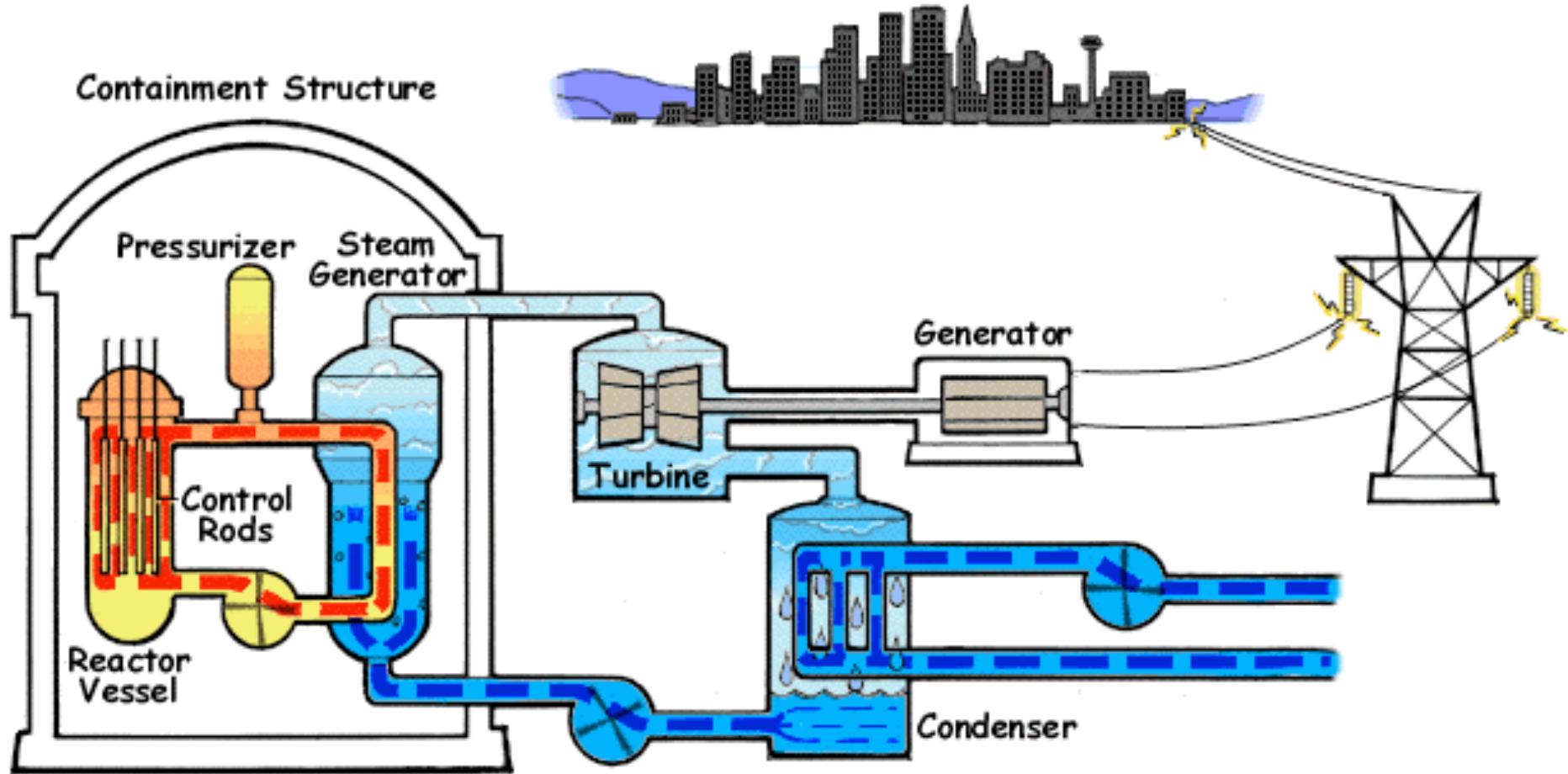
- **Reactor core**: for holding fission material or fuel
- **Moderator**: for slowing fast neutrons
- **Control rods**: holding neutron absorbers to control rate of fission
- **Monitoring system**: containing devices and indicators of operation
- **Energy transfer system**: to take the heat away



A Pressurized Water Reactor (PWR) ~ 63 % world reactors



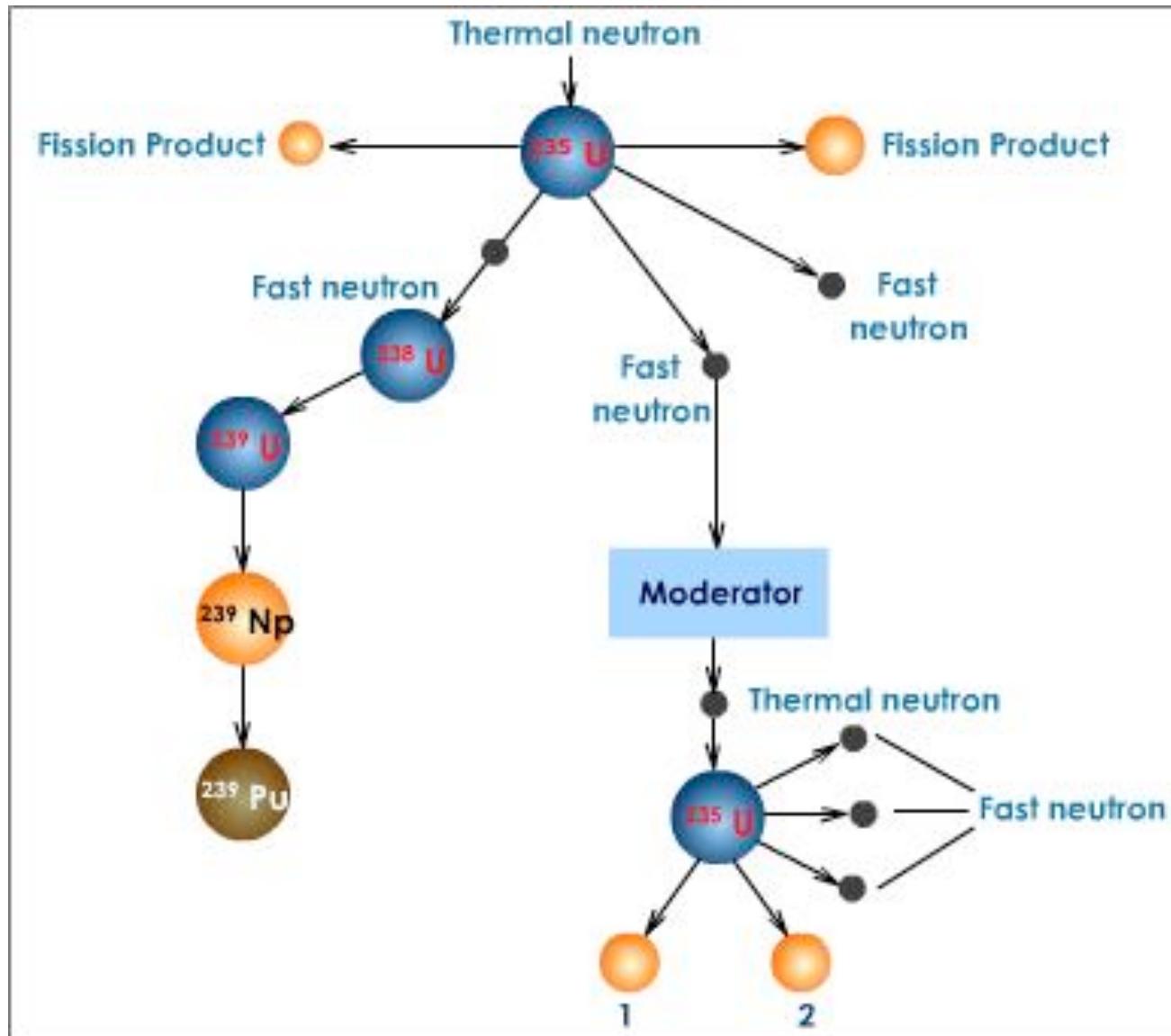
Pressurized Water Reactor



What is Nuclear Fission ?



Nuclear Fission Process



Thermal neutron:

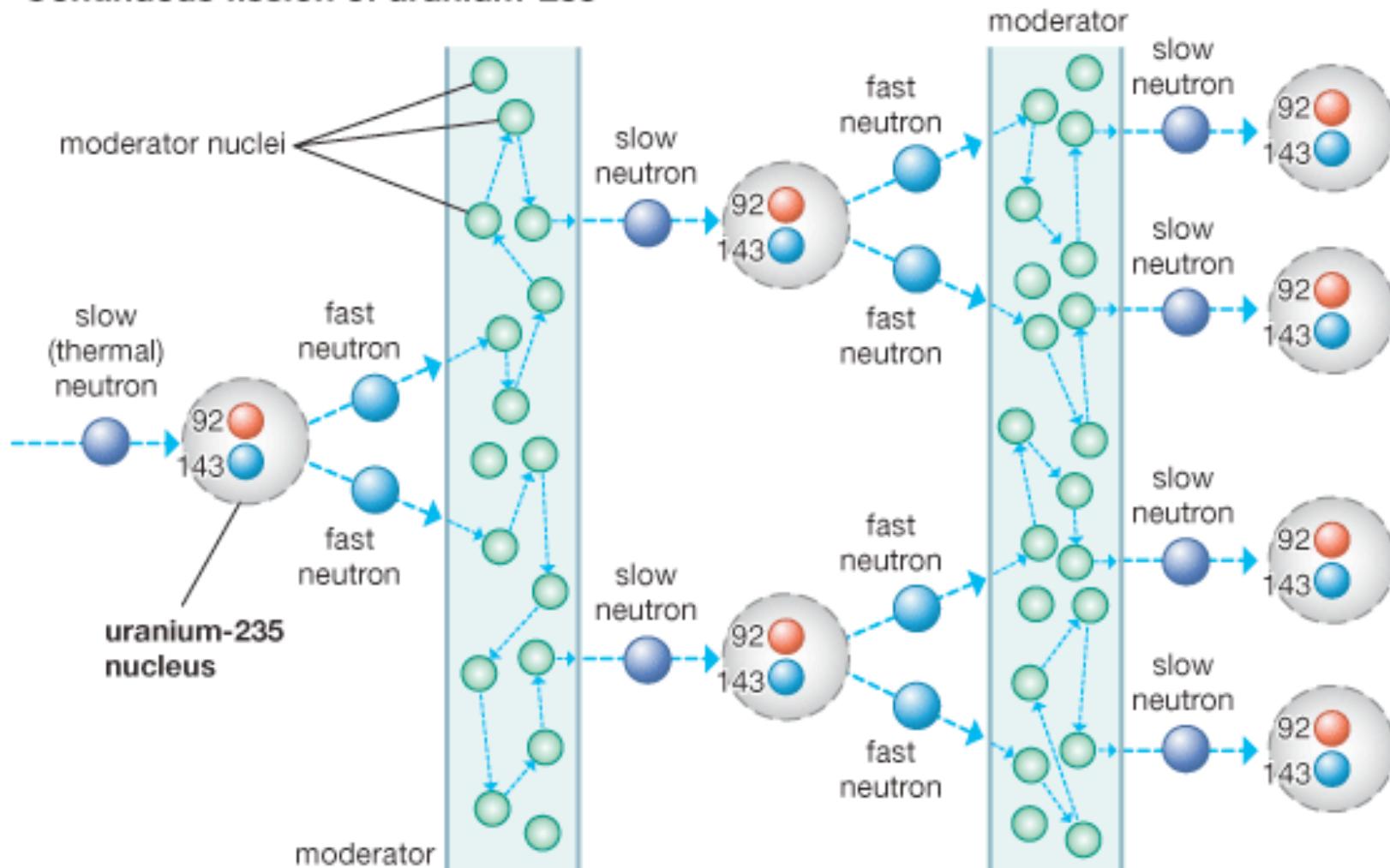
K.E = 25 meV
17 °C
(room temp.)
2.2 km/s

Fast neutron:

K.E = 1~20 MeV
14,000 km/s

Nuclear Chain Reaction

Continuous fission of uranium-235



Refueling Nuclear Power Reactor

Refueling:

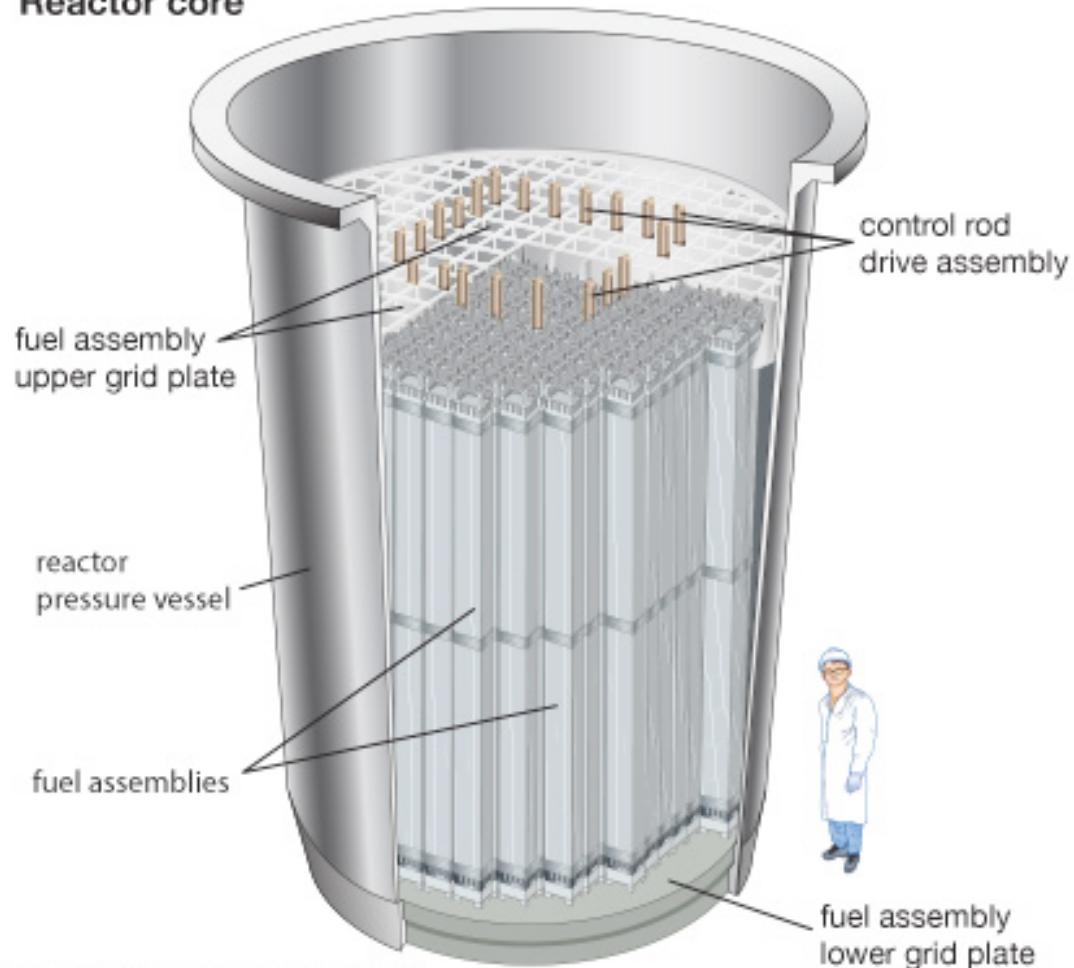
- Most of reactors needs to be shut down for refueling.
- Refueling interval: 1~2 years
- 1/4 ~ 1/3 fuels are replaced as new fuels.
- In most reactors the fuel is ceramic uranium oxide (UO_2 with a melting point of 2800°C)

Moderators:

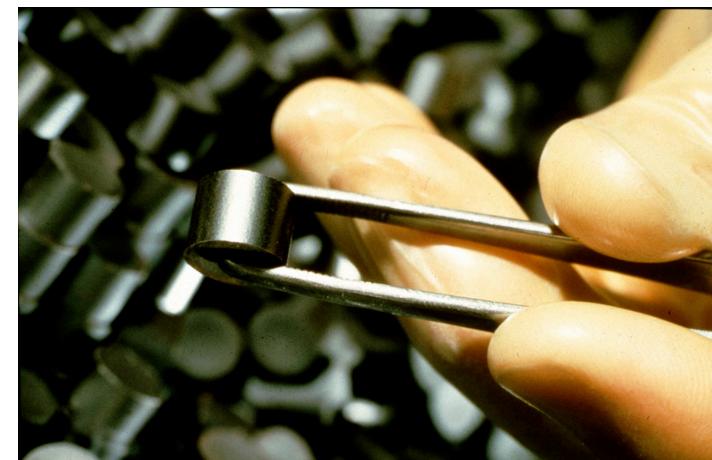
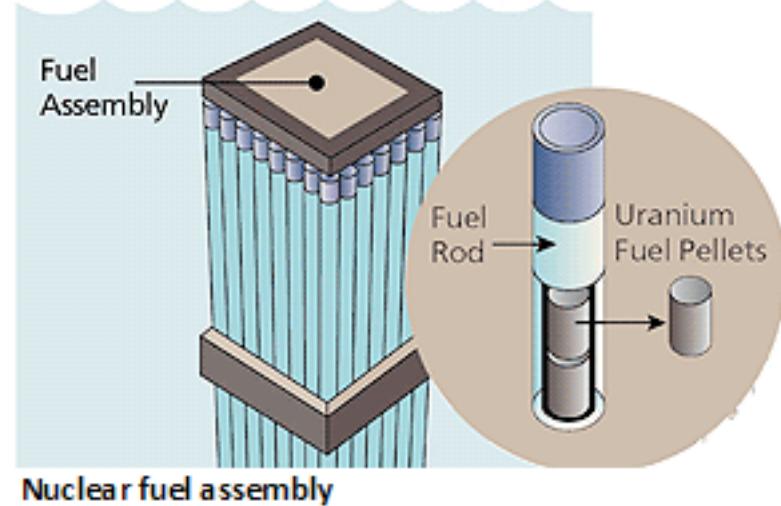
- Light water: enriched Uranium is used as fuel.
(3.5 ~ 5.0% U235)
- Graphite, heavy water: natural Uranium can be used
(0.7% U235, over 99.2% U238)

Reactor Core & Fuel

Reactor core

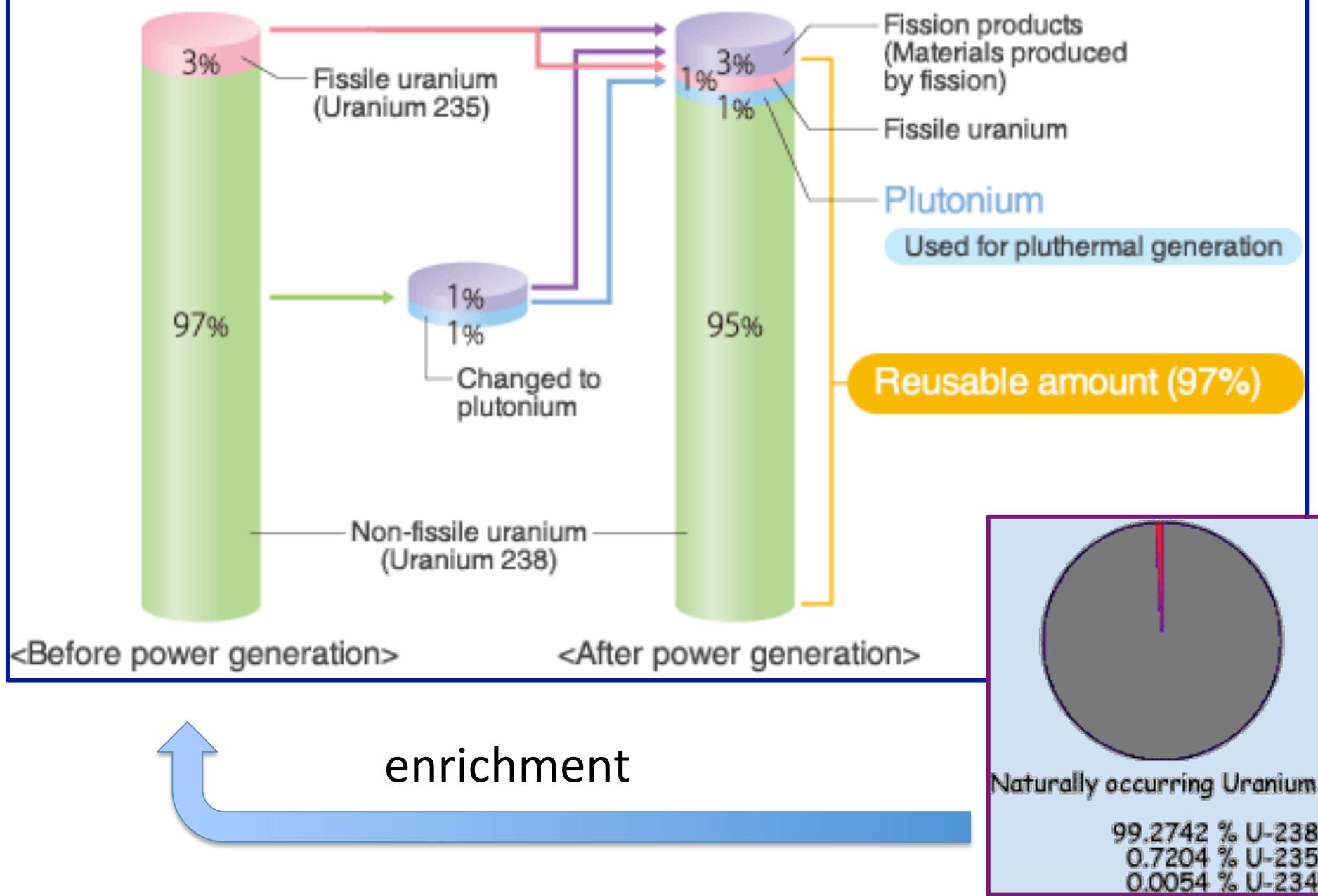


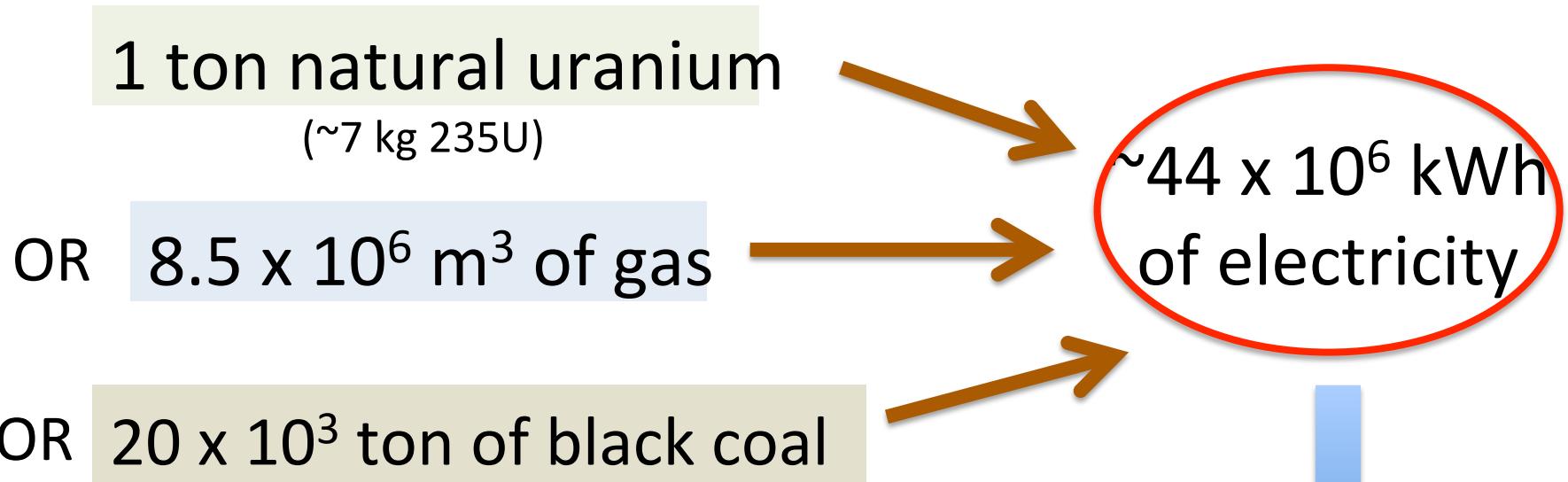
© 2012 Encyclopædia Britannica, Inc.



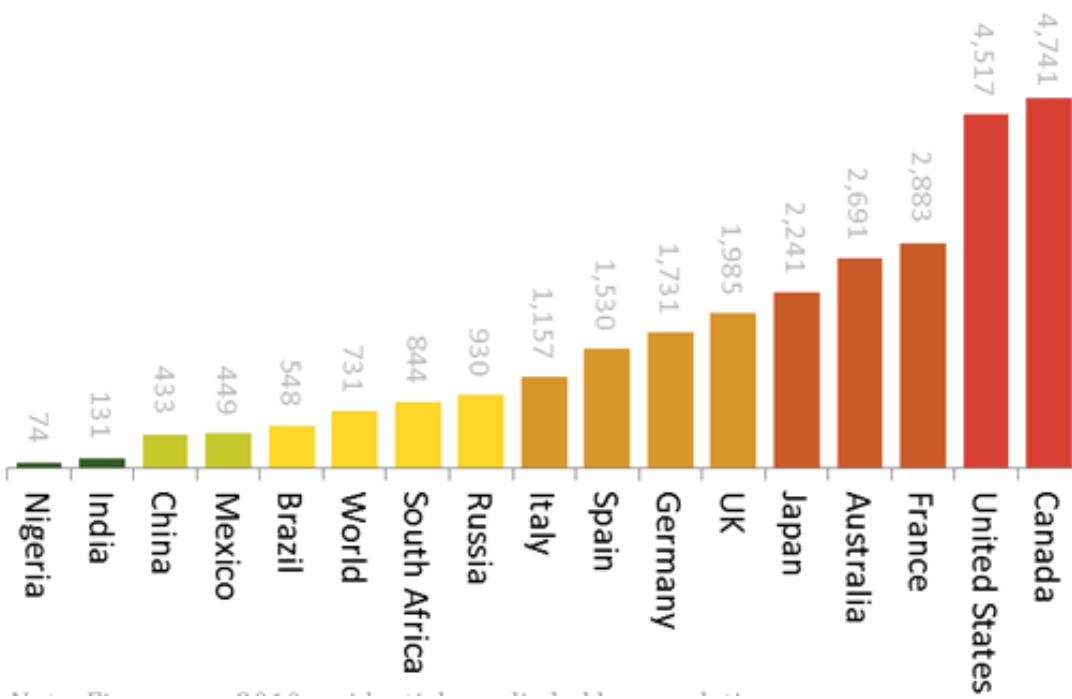
Uranium fuel pellet

Changes in the composition of uranium (Example)





Residential Electricity Use Per Capita (kWh/year)



Electricity that
~11,000 people
can use for 1 year
In Canada

> 99.9 % $\bar{\nu}_e$ are produced by ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu

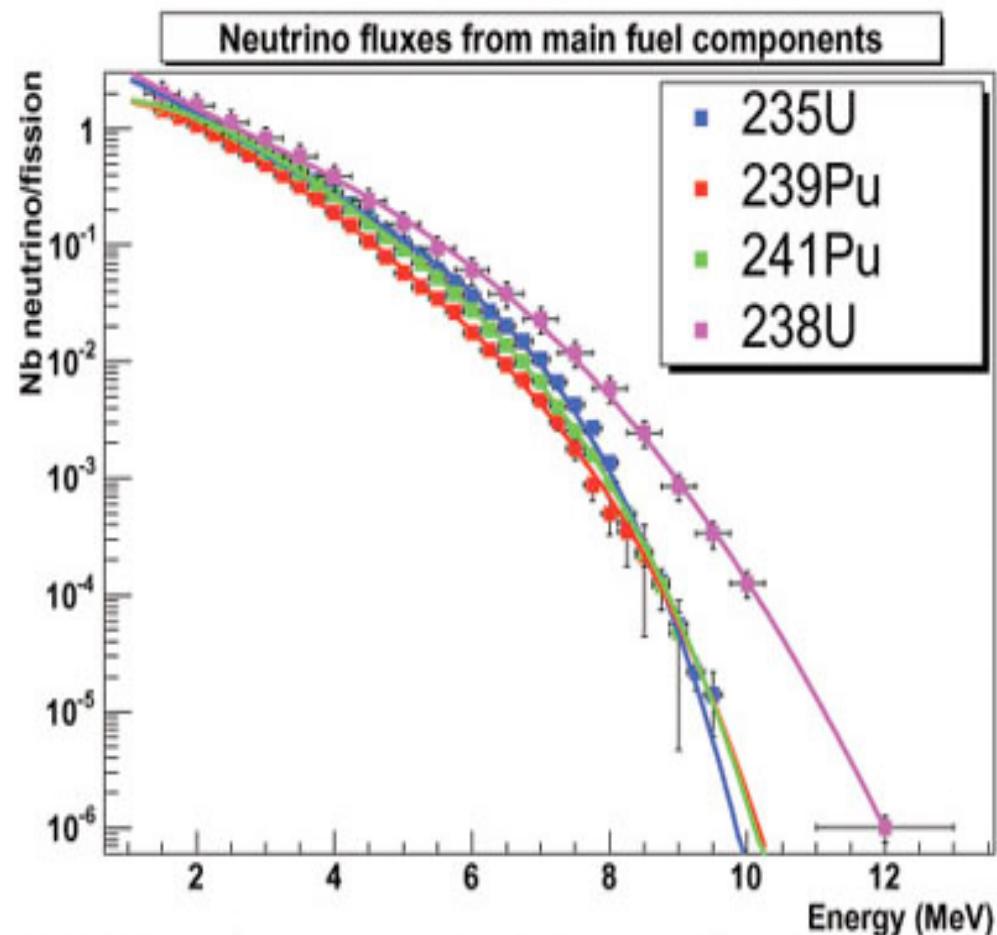
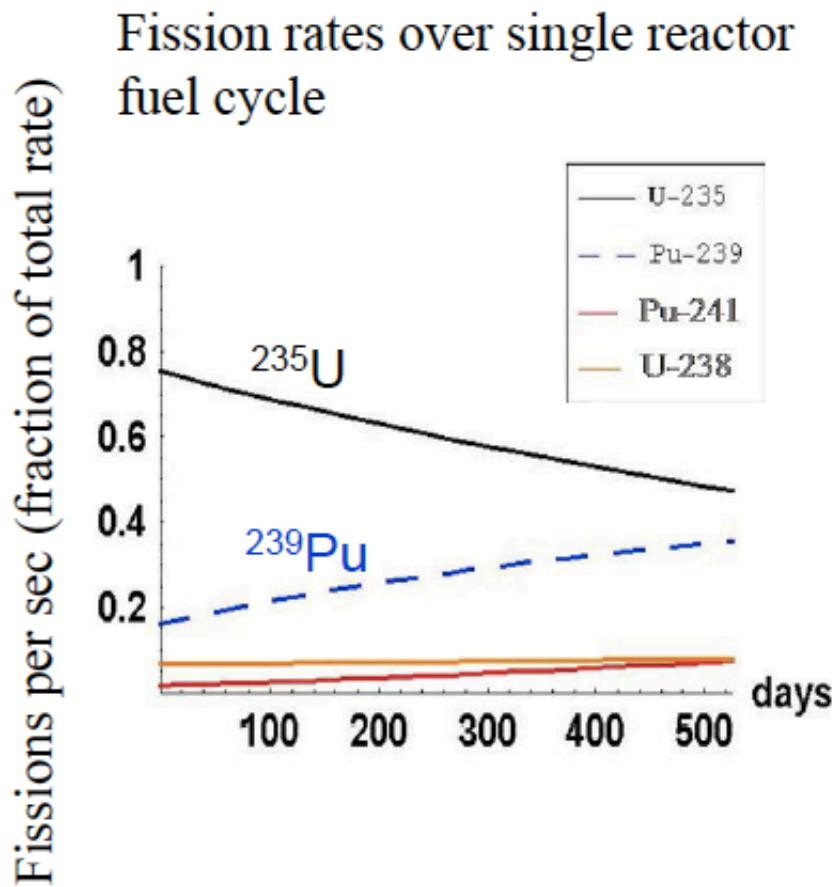


FIG. 7: Measured spectra of antineutrinos from the main components of the nuclear fuel. Taken from Ref. [20].

Plutonium breeding over fission cycle changes
 $\bar{\nu}_e$ rate by 5 ~ 10% and energy spectrum.

v Rate variation
from Palo Verde
3 core reactors

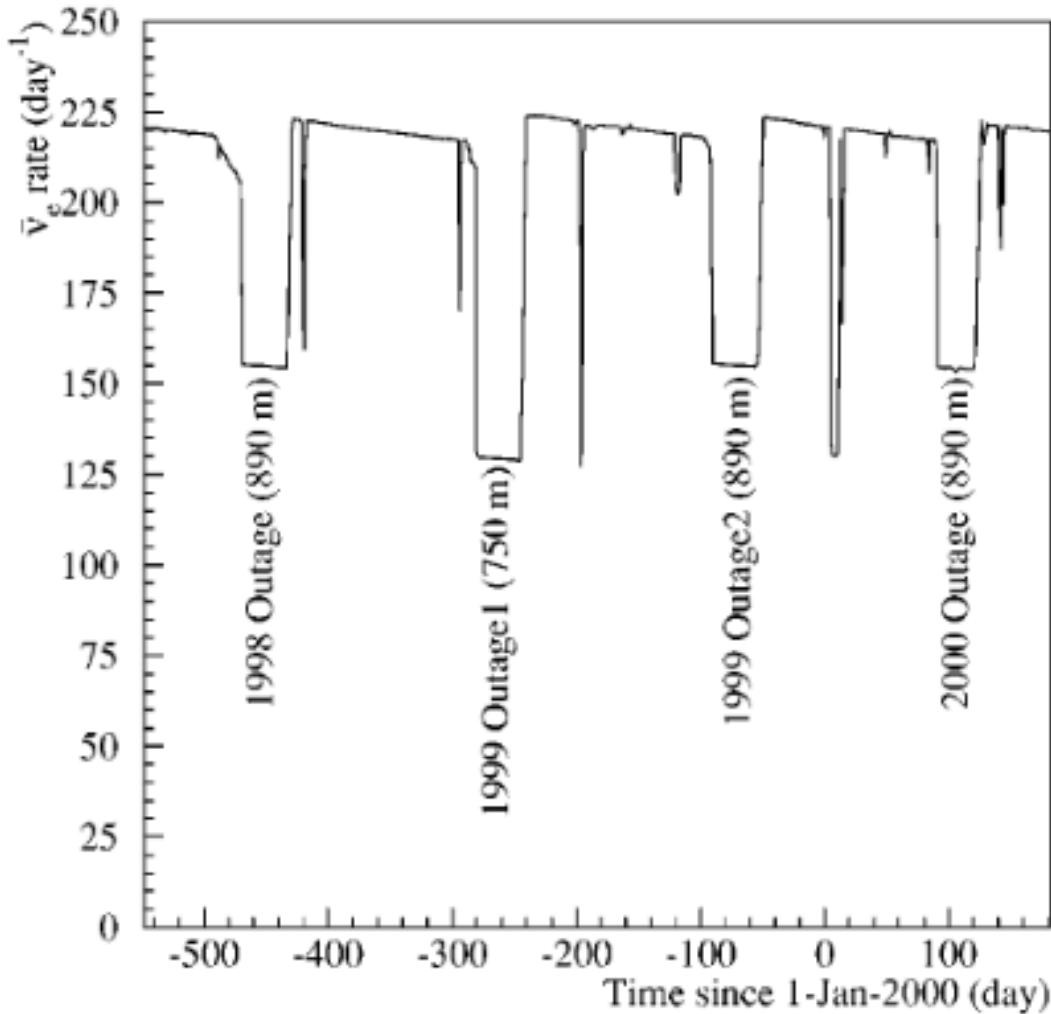


FIG. 1. The calculated $\bar{\nu}_e$ interaction rate in the detector target for the case of no oscillations. Four long periods of reduced flux from reactor refuelings were used for background subtraction. The decreasing rate during the full power operation is a result of the changing core composition as the reactor fuel is burned.

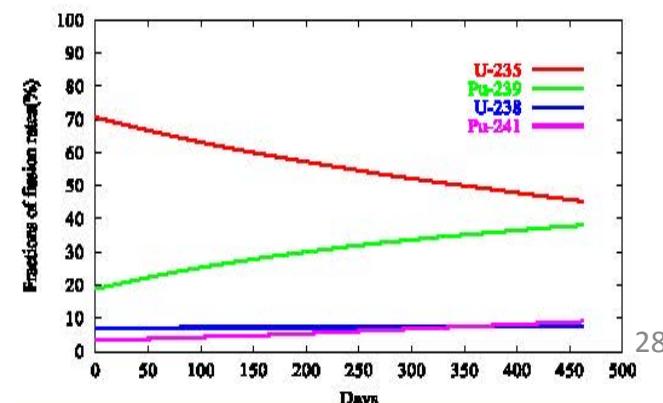
Expected Reactor Antineutrino Fluxes

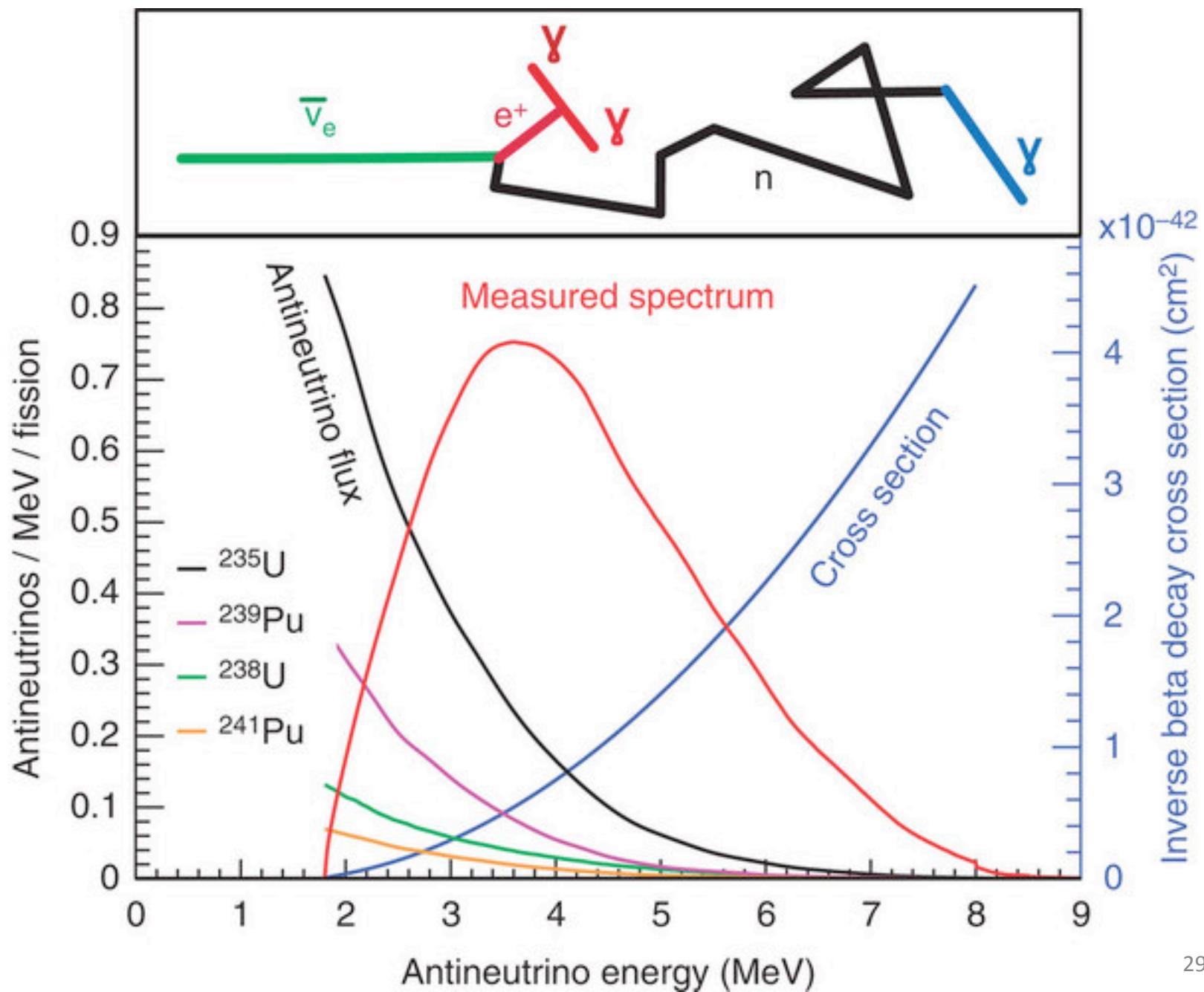
- Reactor neutrino flux

$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
 - [* P. Huber, Phys. Rev. C84, 024617 (2011)]
 - T. Mueller *et al.*, Phys. Rev. C83, 054615 (2011)]
- E_i : Energy released per fission
 - [* V. Kopeikin *et al.*, Phys. Atom. Nucl. 67, 1982 (2004)]

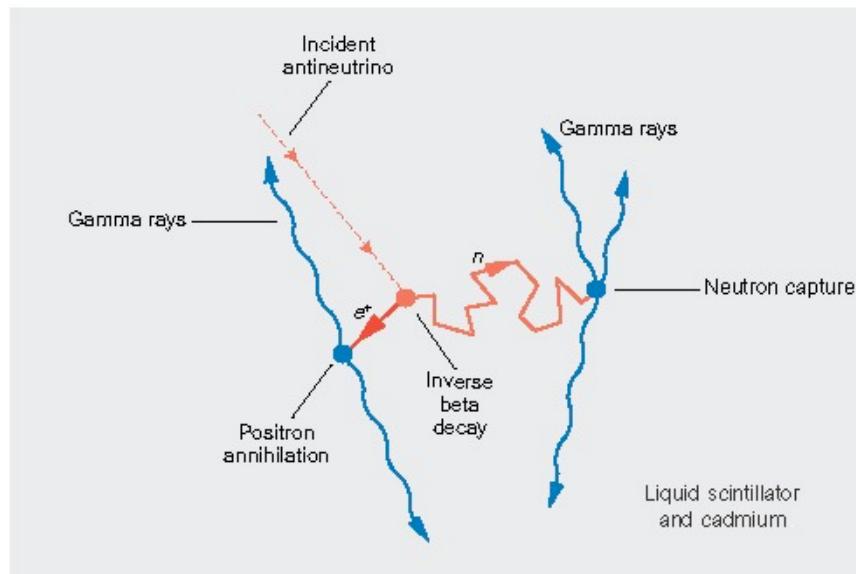
Isotopes	James	Kopeikin
^{235}U	201.7 ± 0.6	201.92 ± 0.46
^{238}U	205.0 ± 0.9	205.52 ± 0.96
^{239}Pu	210.0 ± 0.9	209.99 ± 0.60
^{241}Pu	212.4 ± 1.0	213.60 ± 0.65





Inverse Beta Decay & $\bar{\nu}_e$ detection

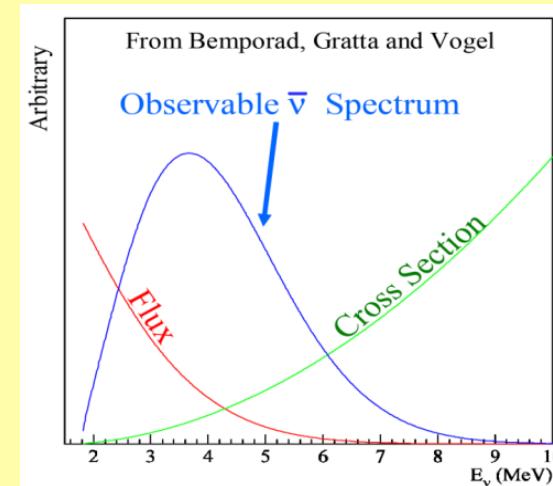
IBD process: $\bar{\nu}_e + p \rightarrow n + e^+$ possible for $E_{\bar{\nu}} > 1.8$ MeV



Neutrino energy measurement ↩

$$E_{\bar{\nu}} \approx T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

T_{e^+} $\underbrace{T_n + (M_n - M_p)}$ m_{e^+}
 $10-40 \text{ keV}$ 1.8 MeV



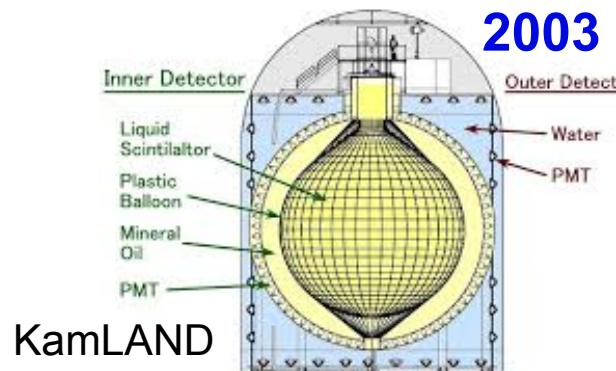
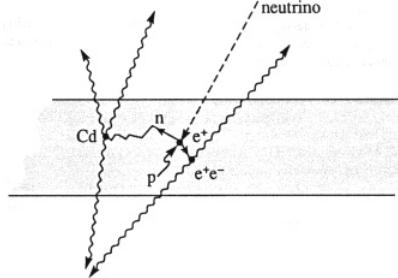
IBD signal pair:

- e^+ annihilation: prompt signal (S1)
- Neutron capture: delayed signal (S2)
(n-Gd, n-H, n-Li, n-Cd etc..)

Neutrino Physics with Reactor

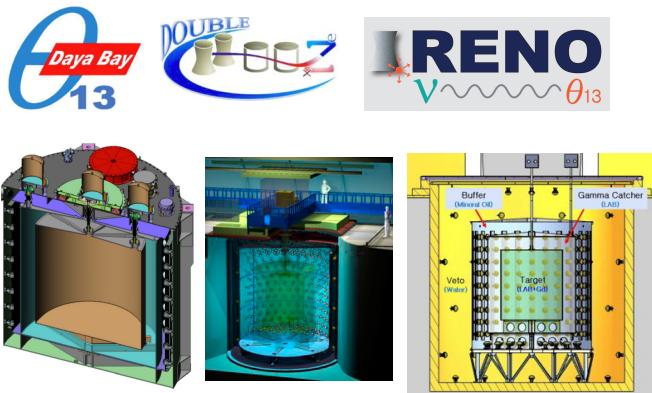
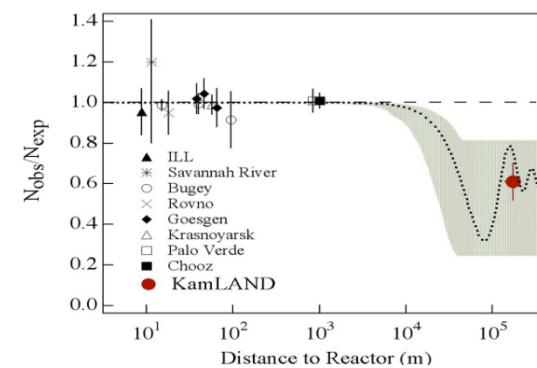
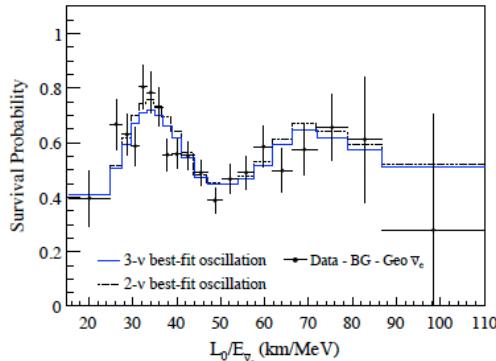


1956 Discovery of (anti)neutrino

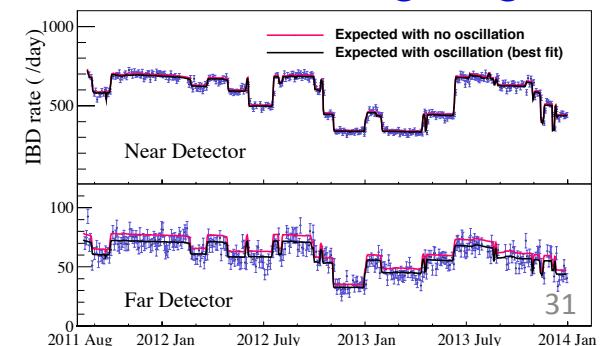
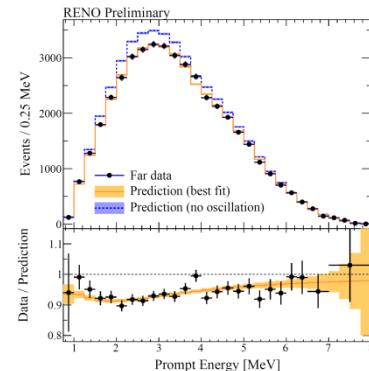


KamLAND

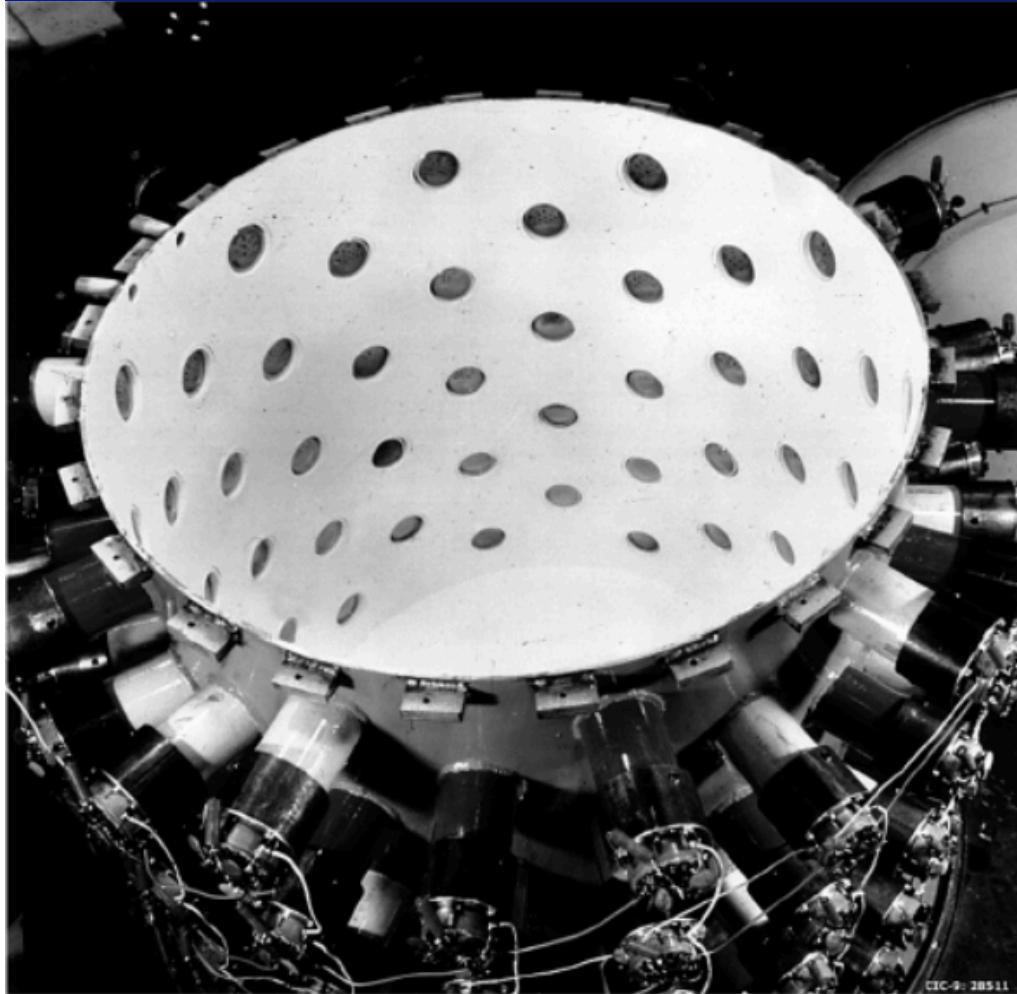
2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)



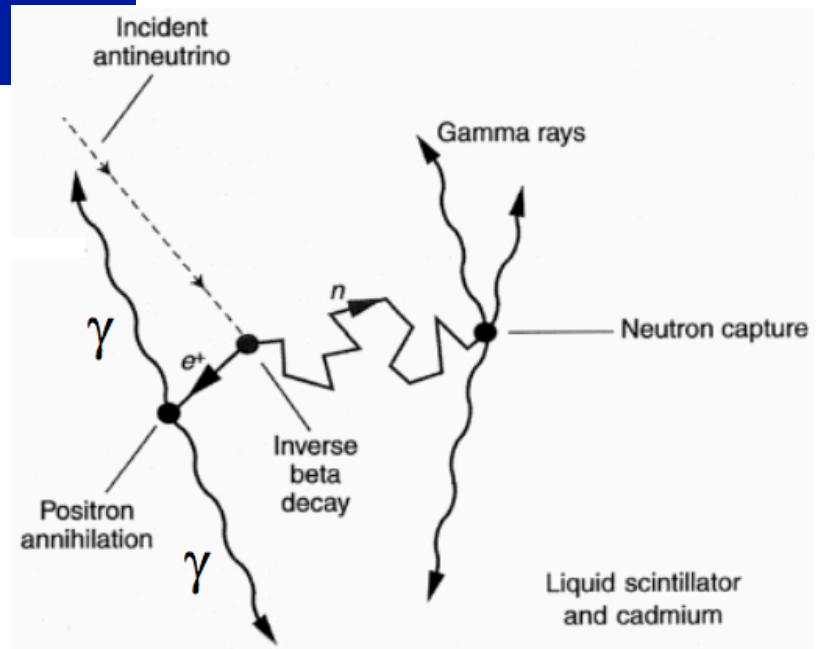
2012 Measurement of the smallest mixing angle θ_{13}



Detector of the Hanford experiment



Liquid scintillator w/ Cd doping:
300 liters



IBD signal pair:

- Prompt: $2 \sim 5$ MeV
- Delayed: $2 \sim 7$ MeV

Event rate: 590.4 ± 288 /day

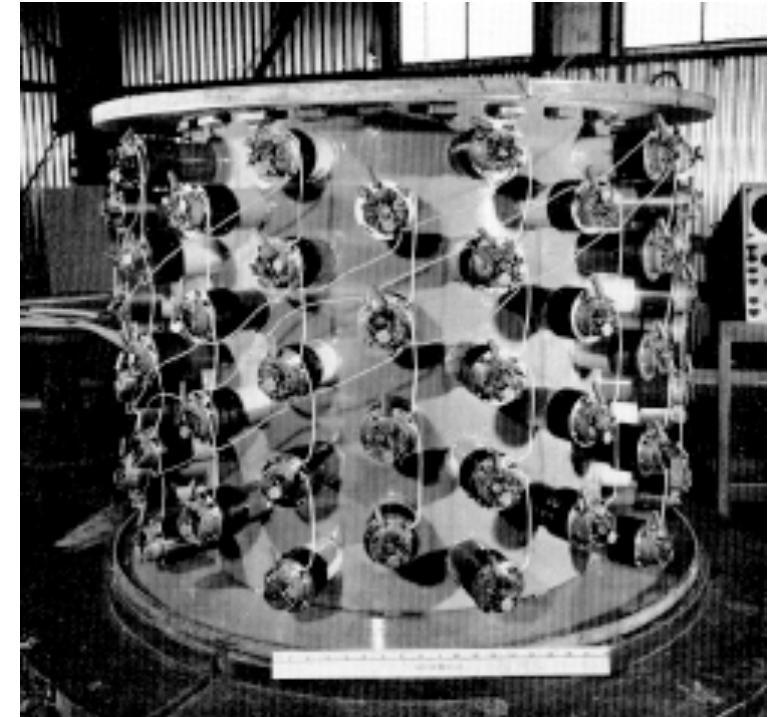
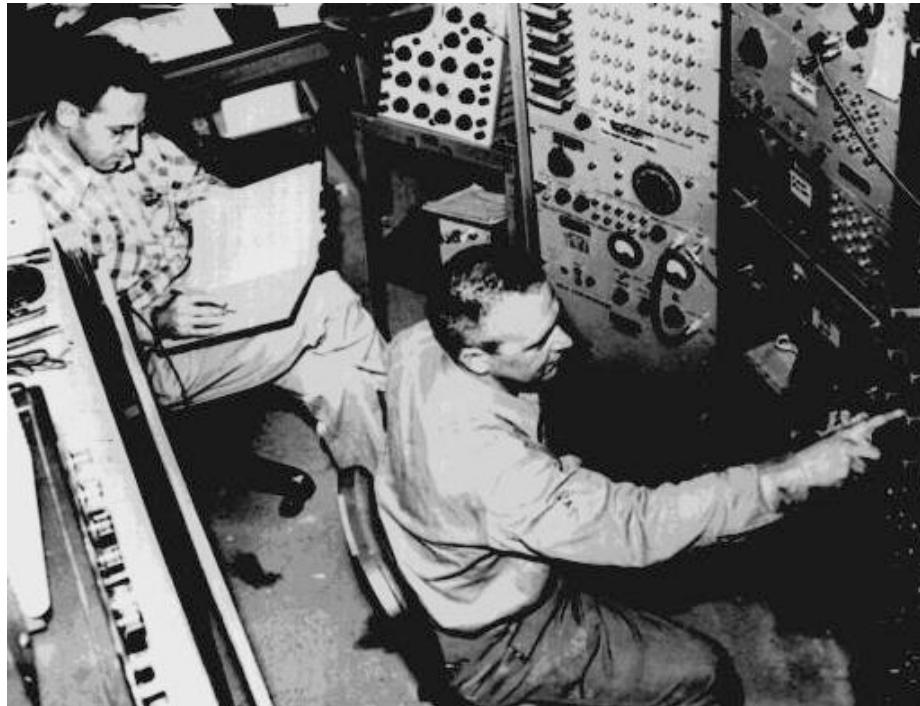
Signal/Noise: $\sim 1/20$

→ Inconclusive result

First discovery of neutrino is from reactor neutrinos !

Nobel Prize
in 1995

In 1956 @Savannah river, S. Carolina
By Reines and Cowan

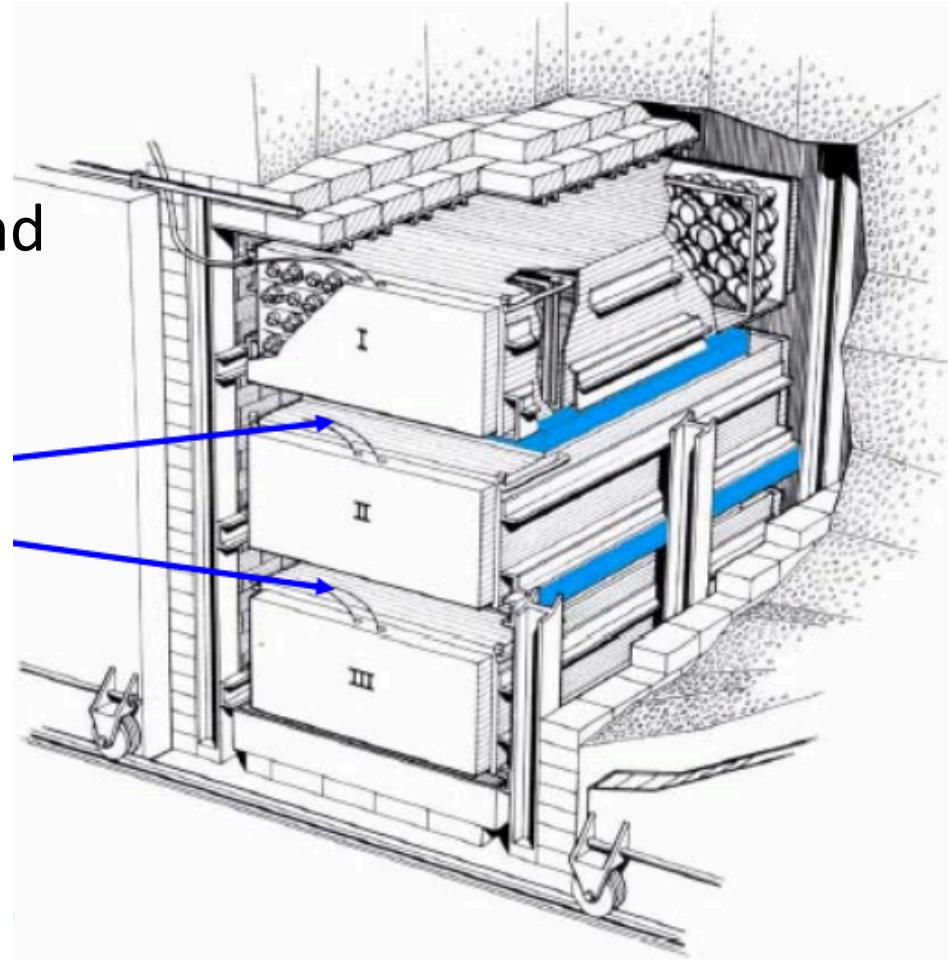


Savannah River Experiment in 1956

Tanks I, II, and III are filled with liquid scintillator and Instrumented with 5" PMTs

Target tanks (blue) are filled with water + CdCl_2

Two signals in neighboring tanks (I, II or II, III)



Signal/Background: ~ 3:1

Savannah River Experiment in 1956



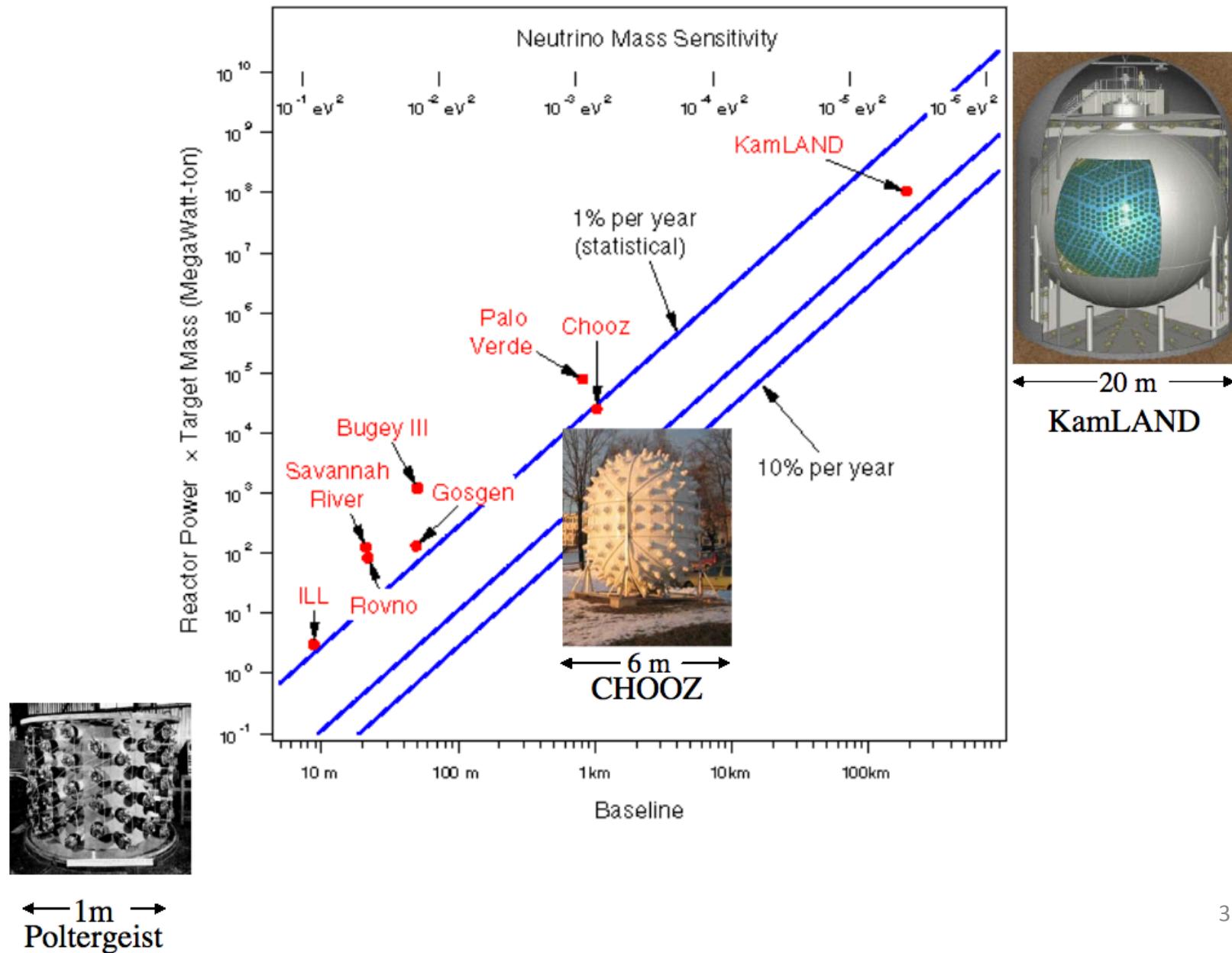
Electronics trailer

R.G.A. Arms “Detecting the Neutrino”,
Physics in Perspective, 3, 314 (2001)

Shielding: 4 ft of soaked sawdust



Past Reactor neutrino experiments



KamLAND

Kamioka Liquid-Scintillator Anti-Neutrino Detector

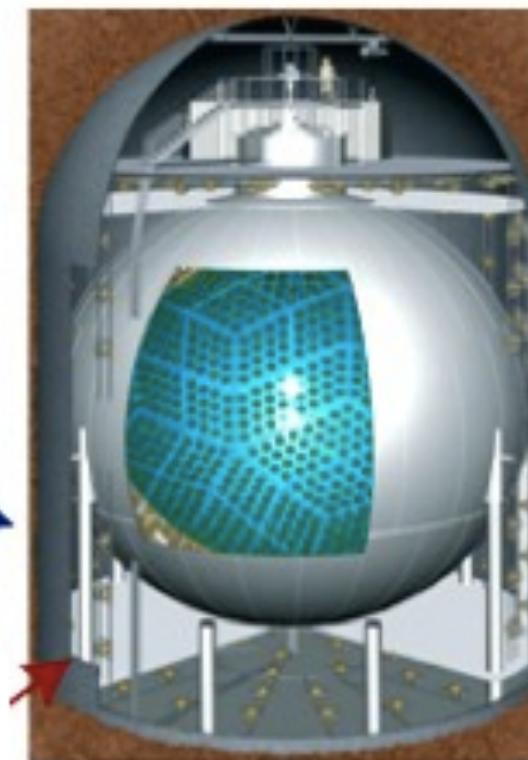


1 kton liquid scintillator detector

1st phase experiment

$$(E_{\text{th}} = 1.8 \text{ MeV})$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

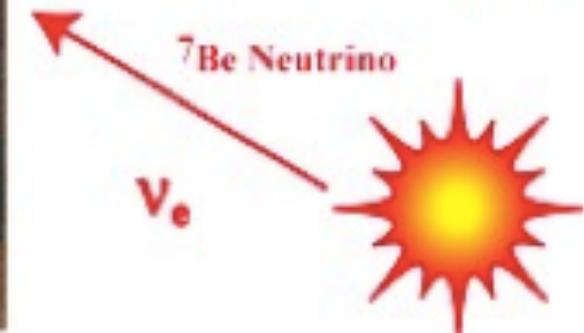
- Neutrino Oscillation Search by Reactor Anti-neutrinos



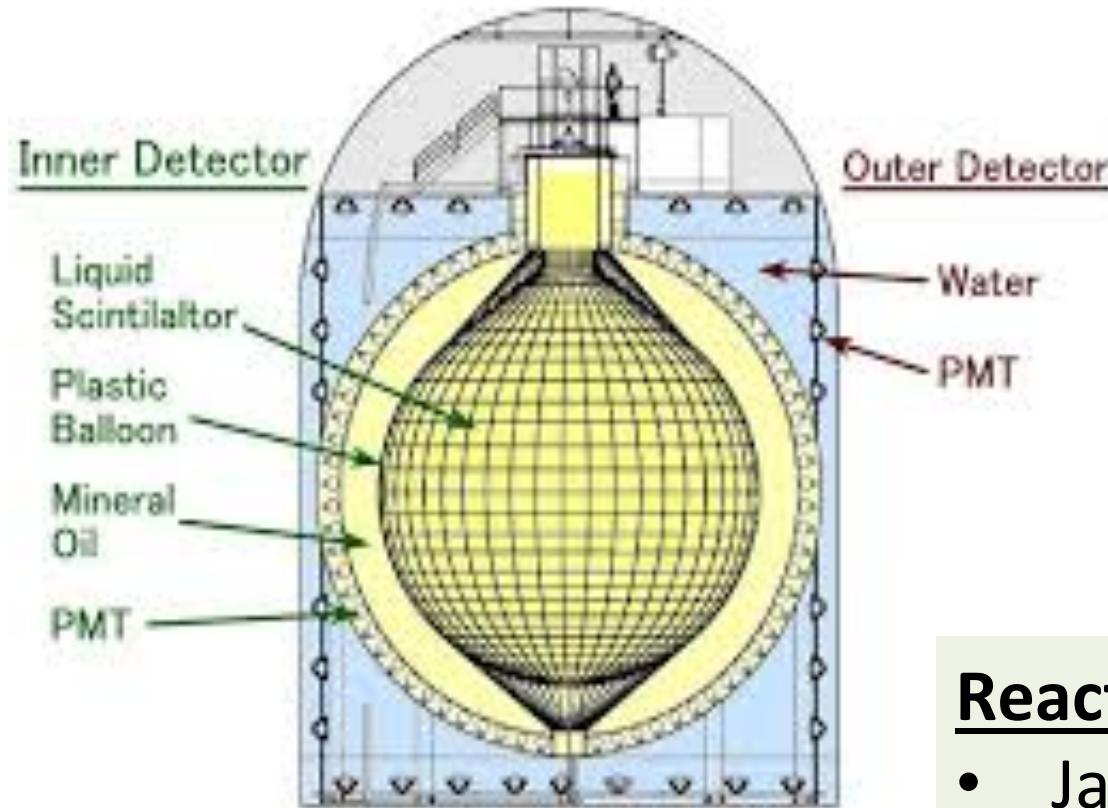
2nd phase experiment

$$(E_{\text{th}} = 200 \text{ keV})$$
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- Solar neutrino Detection



KamLAND Detector



Reactor neutrino flux:

- Japan: 95.5 % (53 reactors)
 - Korea: ~3 %
 - Taiwan: ~0.1 %
- $\langle L_{\text{eff}} \rangle = \sim 180 \text{ km}$

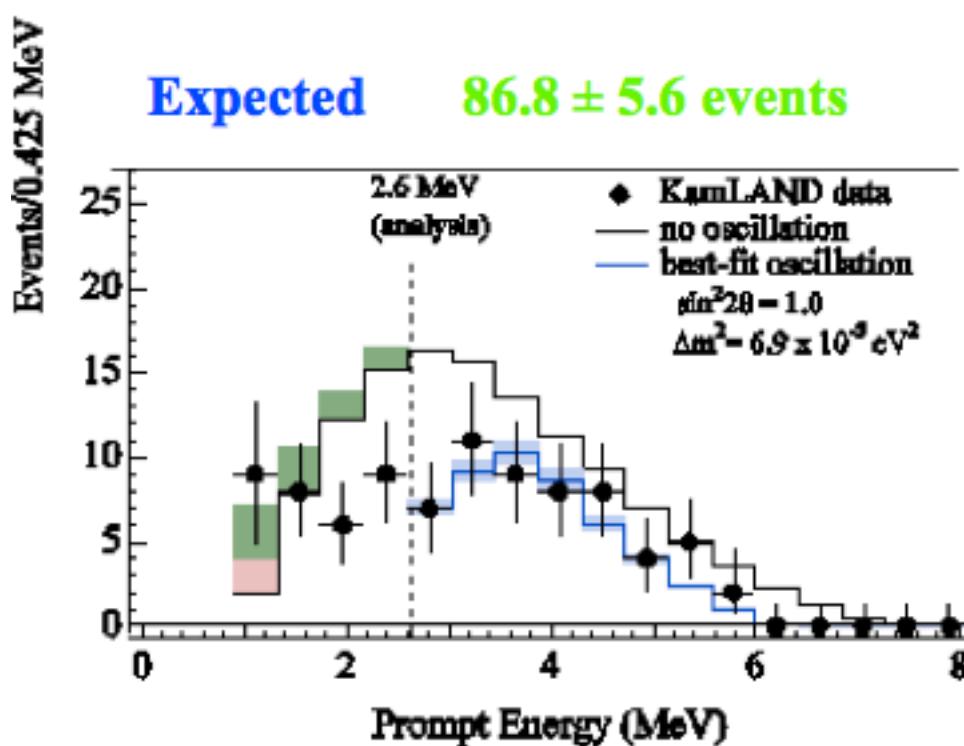
KamLAND result

Mar. 4 – Oct. 6, 2002
162 ton•yr (145.1 days)

Observed **54 events** ($E > 2.6 \text{ MeV}$)

Background **1 ± 1 events**

Expected **86.8 ± 5.6 events**

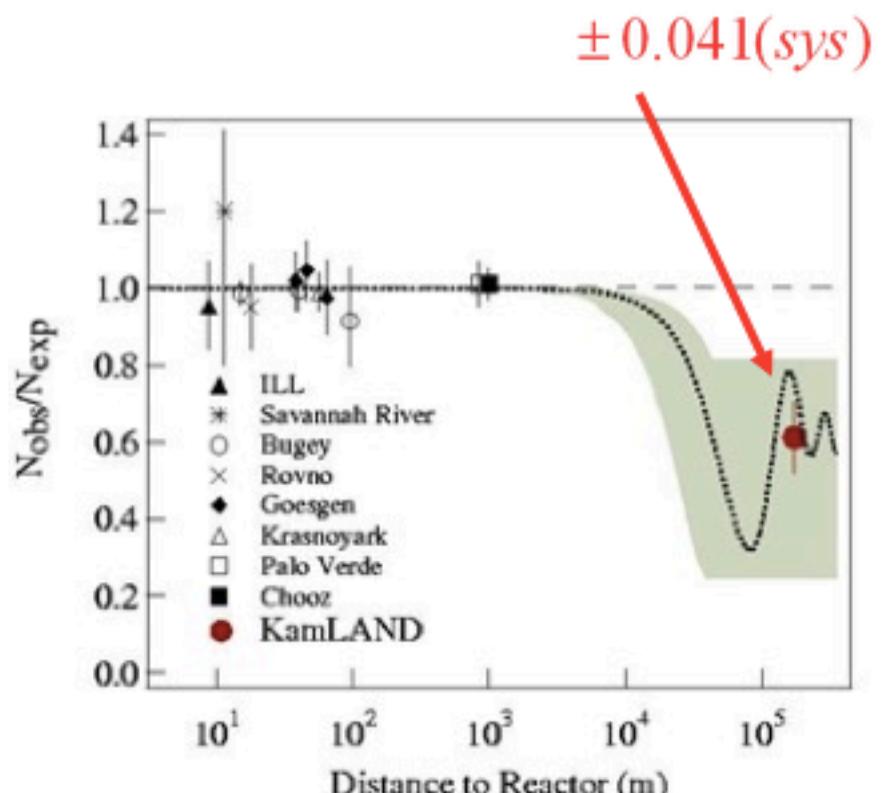


Geo Neutrino: 0 – 110 TW (95 % C.L.)

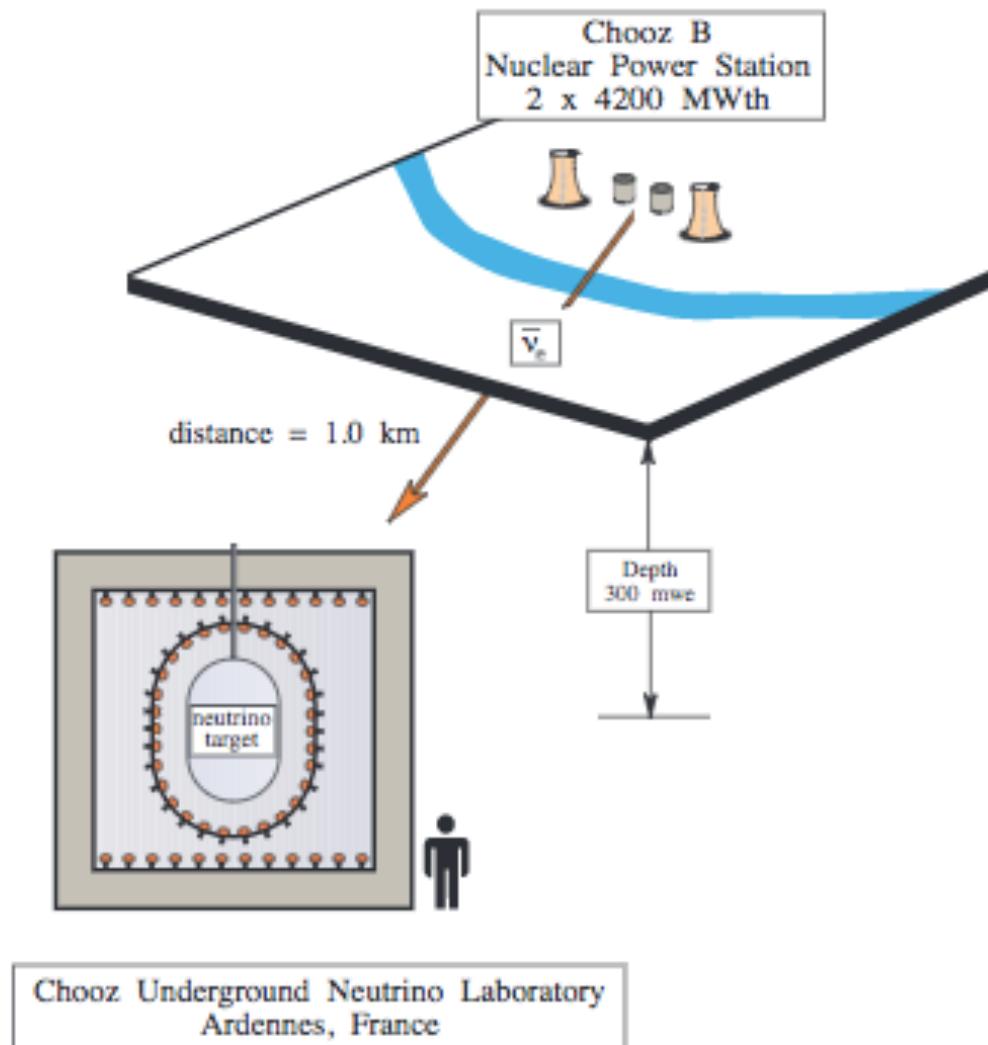
motoki@NDM03

$$\frac{N_{\text{obs}} - N_{\text{bg}}}{N_{\text{expected}}} = 0.611 \pm 0.085(\text{stat})$$

$\pm 0.041(\text{sys})$

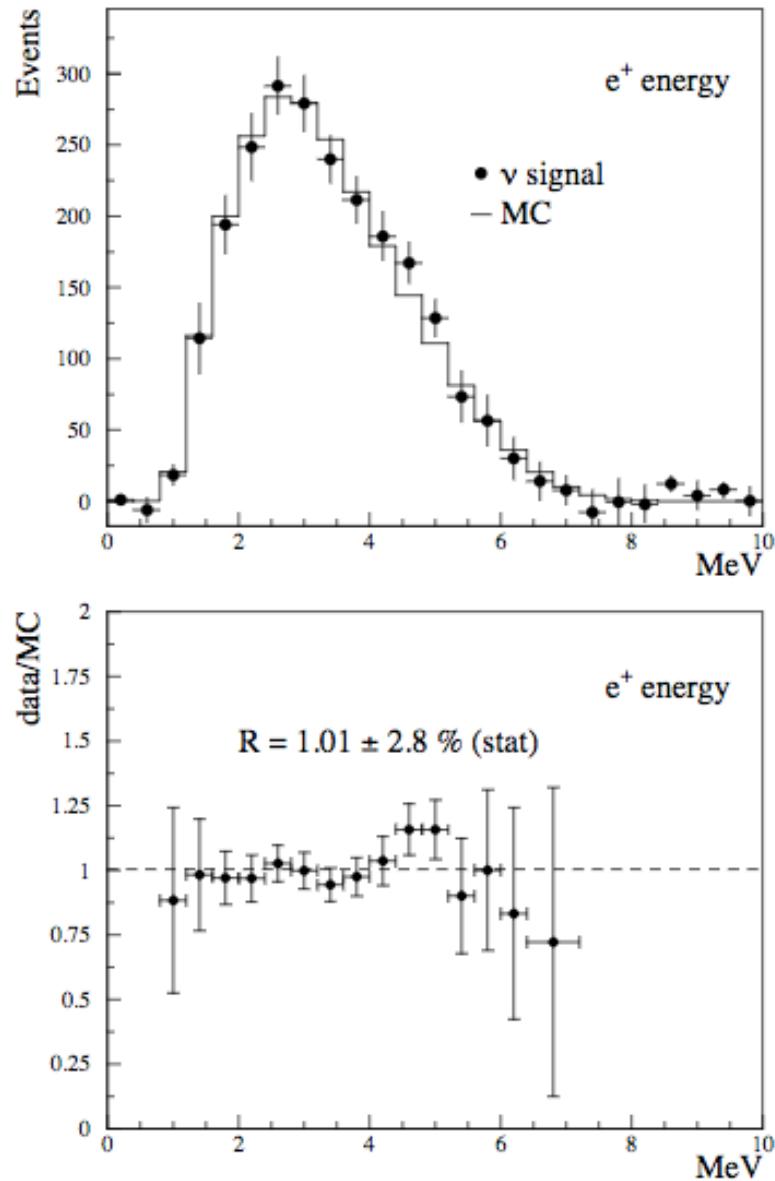


Chooz Experiment

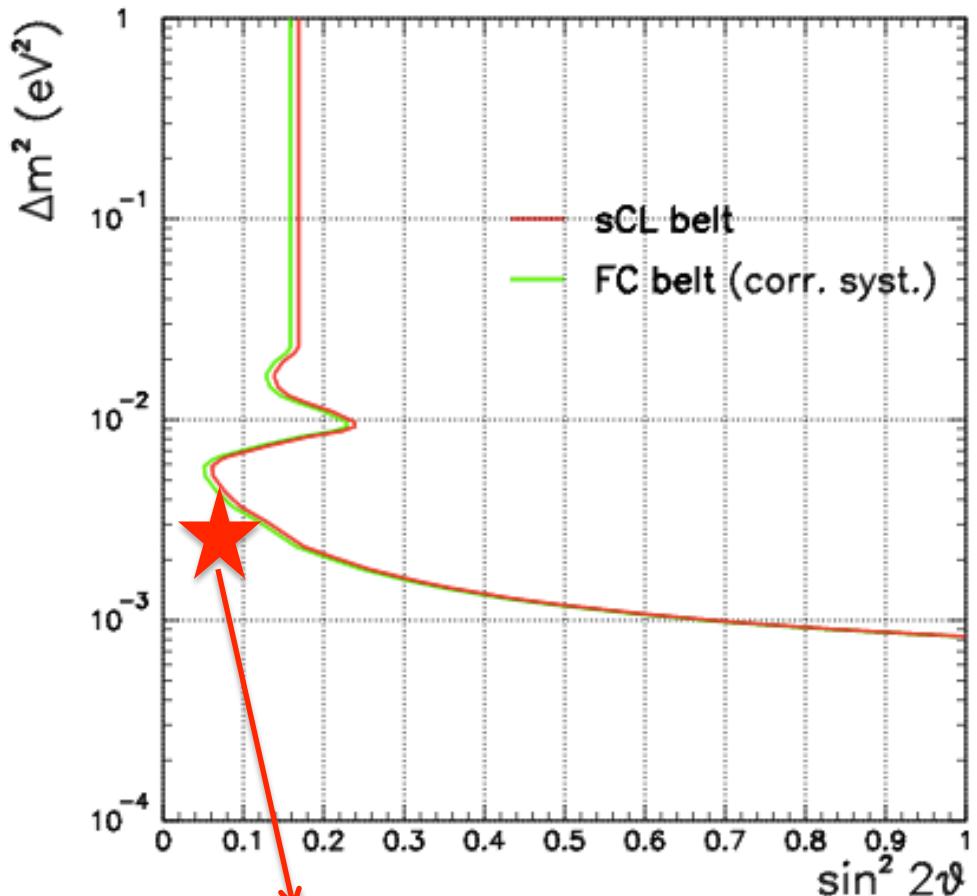


- 5 ton LS (0.09% Gd)
- took > 1 year data
(until July 1998)
- No oscillation observed
→ set limit
- Detector degradation

Chooz Results in 2003



Eur.Phys.J.C27:331-374,2003



2016 best fit

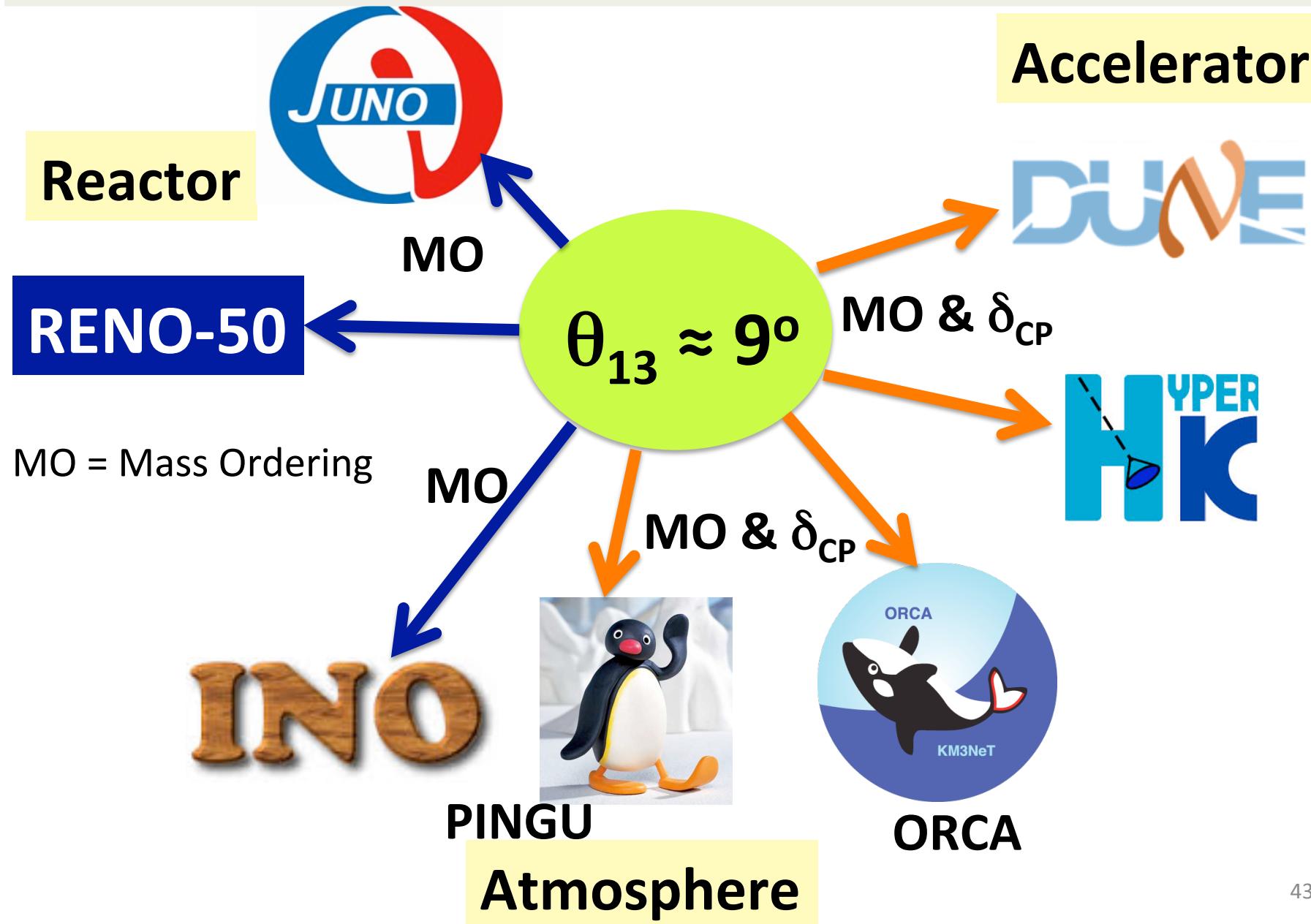
First θ_{13} measurements in 2012

~ 4 years ago

	Double Chooz	Daya Bay	RENO
Publication	PRL 108, 131801 (Mar. 30, 2012)	PRL 108, 171803 (Apr. 27, 2012)	PRL 108, 191802 (May 11, 2012)
$\sin^2(2\theta_{13})$	0.086	0.092	0.113
Stat. error	0.041 (101 days)	0.016 (49 days)	0.013 (220 days)
Syst. error	0.030 (flux uncert.)	0.005 (MC driven)	0.019 (data driven)
Significance	1.7 σ	5.2 σ	4.9 σ

The diagram illustrates the time scale of the measurements. Arrows point from the significance values to labels indicating the measurement duration: '1 month' under Double Chooz, '2 weeks' under Daya Bay, and '1 month' under RENO.

θ_{13} and Future Experiments



With Reactor Neutrinos

Short Baseline: $O(1\text{km})$

- To measure θ_{13} (finally measured in 2012 !)
- CP violation phase angle ?
(when combined with accelerator data)
- 4th family of neutrinos ?

} Current

Medium Baseline: $\sim 50 \text{ km}$

- To determine ν mass ordering (very challenging !)
- Very precise measurements on ν mixing parameters
- Super Nova ν , Solar ν , Geo ν
- Multi-purpose detector

} Future

PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

θ_{23}

θ_{13}

θ_{12}

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmos. ($\nu_\mu, \bar{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\bar{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\bar{\nu}_e$ deficit)

Neutrino Oscillation

Atmos. Neutrino
Oscillation

$$\theta_{23}$$

$\sim 45^\circ$ (1998)
Super-K; K2K



Solar Neutrino
Oscillation

$$\theta_{12}$$

34° (2001)
SNO, Super-K; KamLAND



Reactor Neutrino
Oscillation

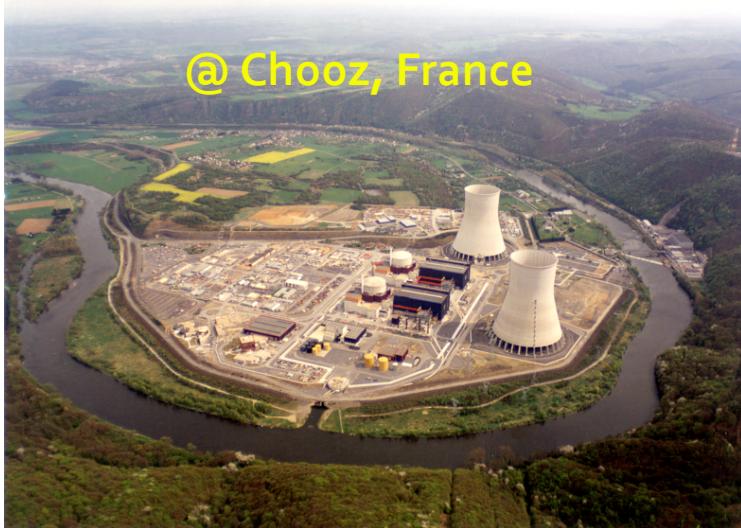
$$\theta_{13}$$

9° (2012)
Daya Bay, RENO,
Double Chooz

Reactor θ_{13} Experiments

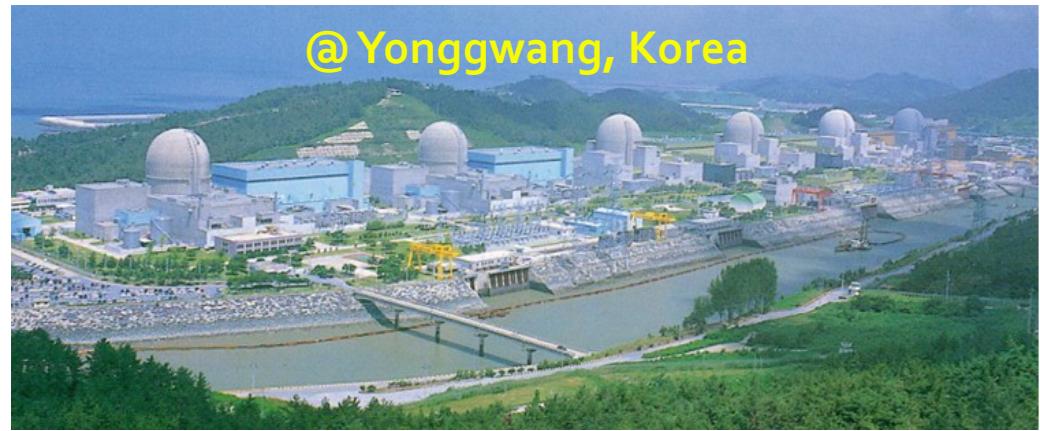
Double Chooz

@ Chooz, France



RENO

@ Yonggwang, Korea

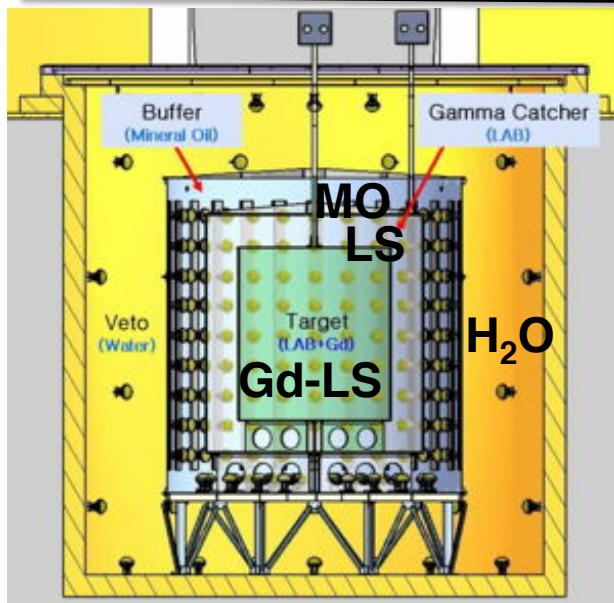
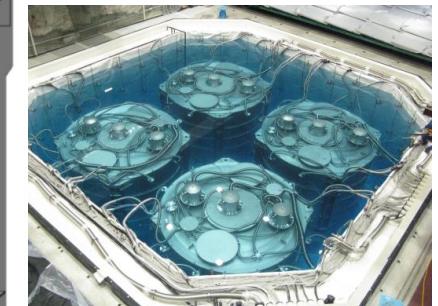
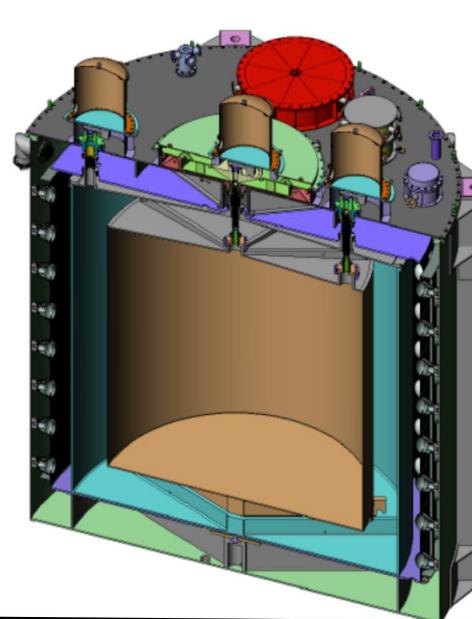
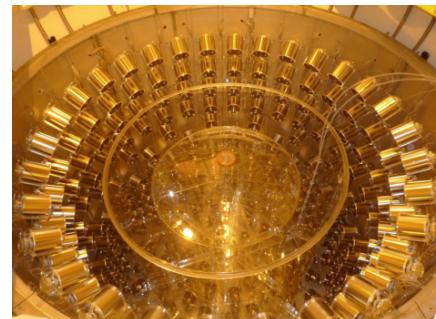
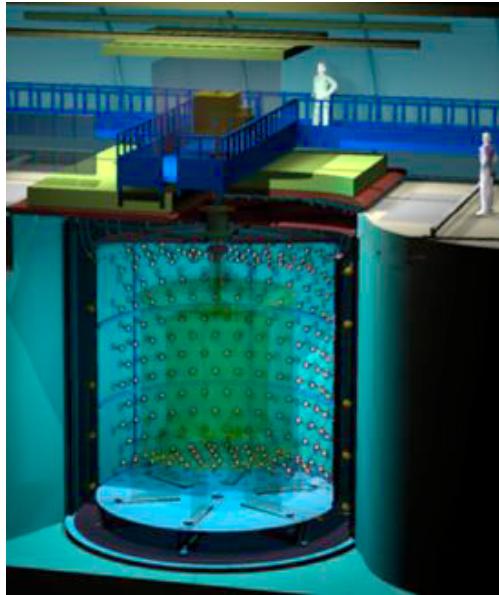


Daya Bay

@ Daya Bay, China

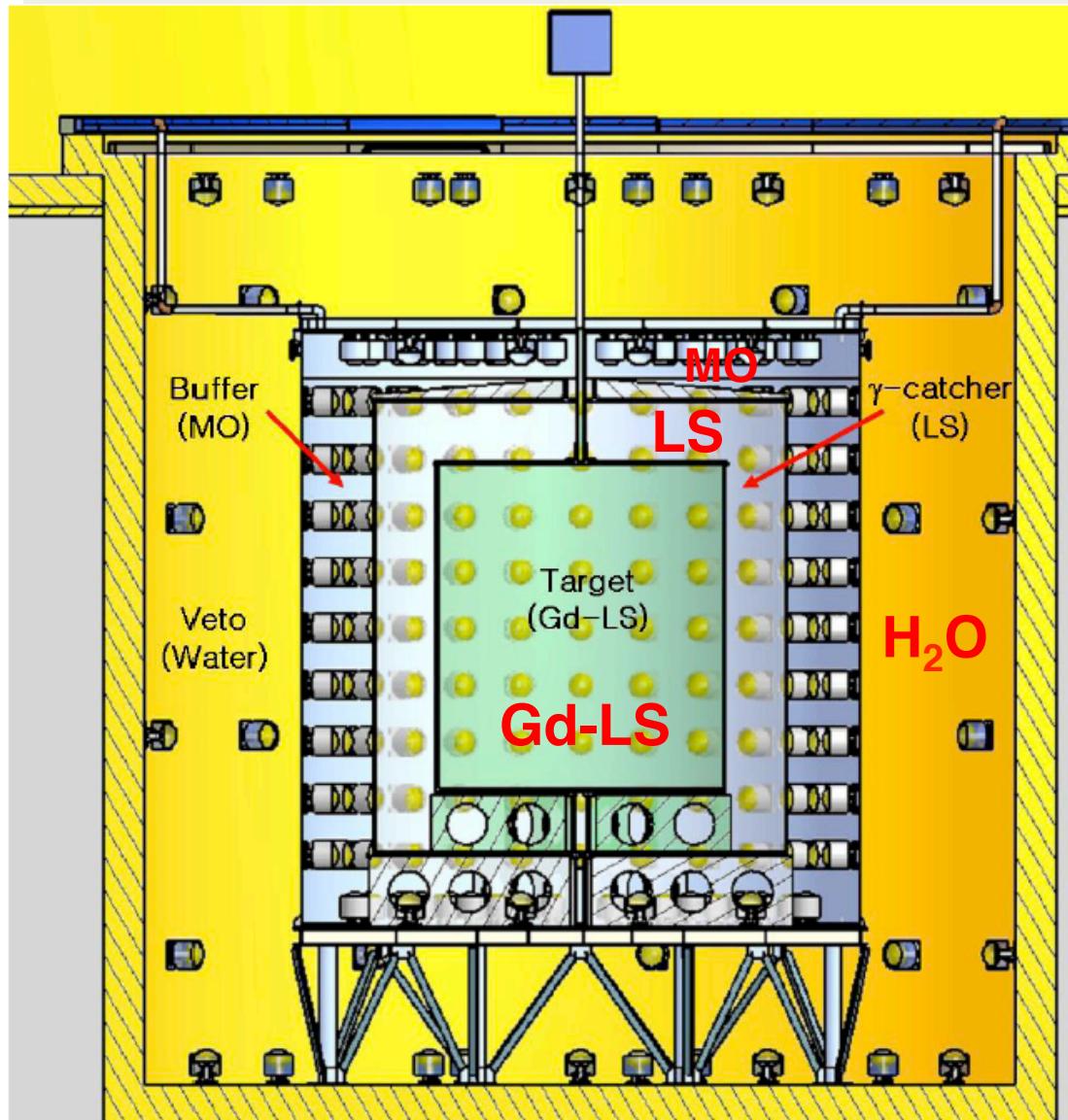


θ_{13} Reactor Neutrino Detectors



1. Cylindrical structure (four layers)
2. Neutrino Target: liquid scintillator with 0.1 % Gd doping

The RENO Detector



4 enclosed cylinders

▪ **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)

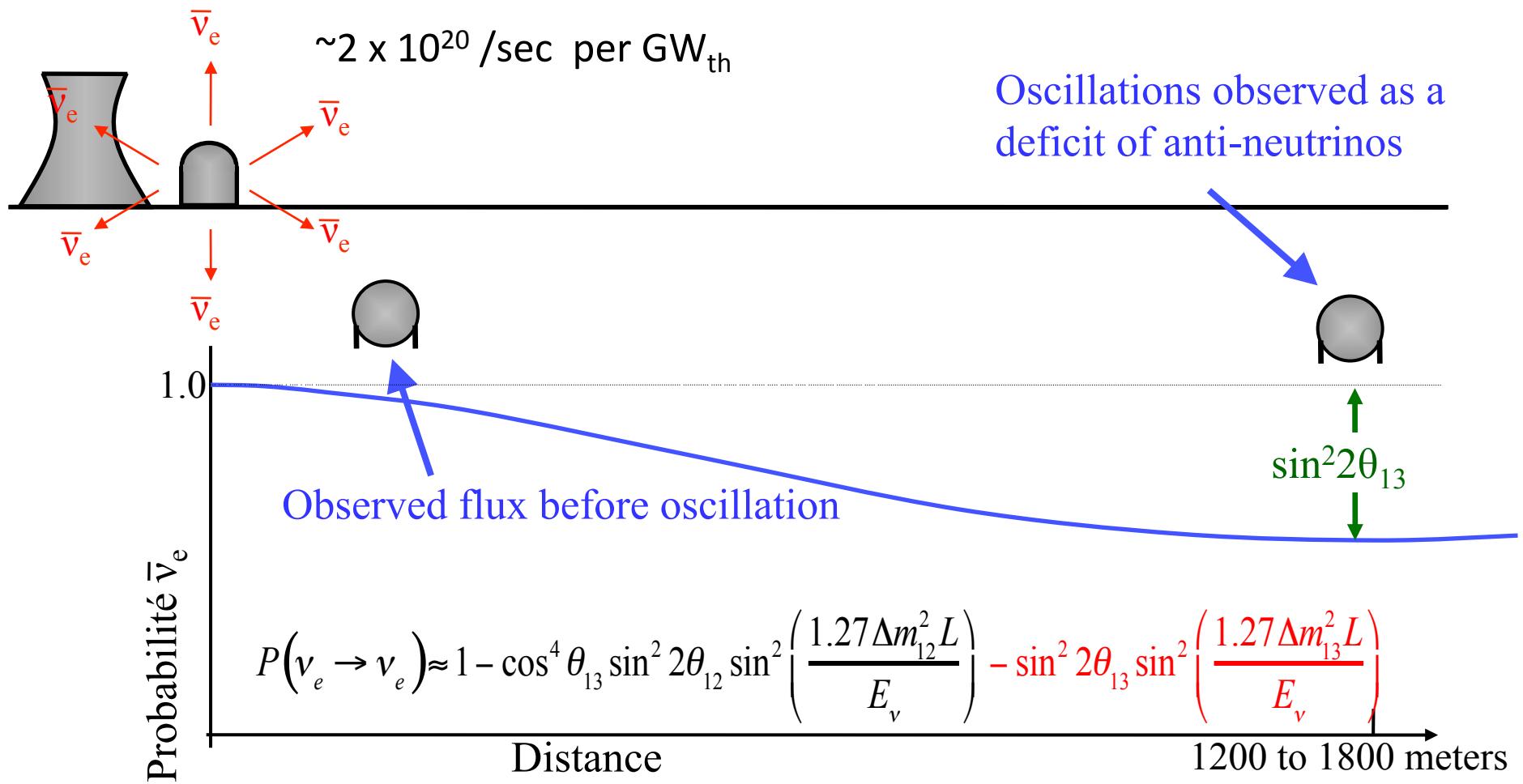
▪ **Veto : 350 ton water**

(R=4.2m, H=8.8m)

-- 354 ID 10 " PMTs

-- 67 OD 10" PMTs

How to measure θ_{13} ?



- Find disappearance of $\bar{\nu}_e$ fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

θ_{13} & $|\Delta m^2_{ee}|$ measurements

Survival prob.

$$\begin{aligned} 1 - P &= \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) \\ &\quad + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\ &\approx \sin^2 2\theta_{13} \sin^2 \Delta_{ee} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}, \quad (1) \end{aligned}$$

Where,

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \quad (i,j = 1,2,3)$$

$$\Delta_{ee} \equiv \frac{\Delta m_{ee}^2 L}{4E}$$

"Approx. Osc. Prob.
accurate to
1 part in 10^4 "

$$\Delta m_{ee}^2 \equiv \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

Parke
arXiv:1601.07464

→ Find minimum χ^2 by varying θ_{13} & $|\Delta m^2_{ee}|$

Parameter estimation

What is Δm_{ee}^2 ?

$$\Delta m_{ee}^2 \equiv \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

Parke
arXiv:1601.07464

- ν_e weighted average of Δm_{31}^2 and Δm_{32}^2 Exercise
- L/E independent (see next page !)
- Mass ordering independent
- Weakly dependent on solar parameters

$$\left. \begin{aligned} |\Delta m_{31}^2| &= |\Delta m_{ee}^2| \pm \sin^2 \theta_{12} \Delta m_{21}^2 \\ |\Delta m_{32}^2| &= |\Delta m_{ee}^2| \mp \cos^2 \theta_{12} \Delta m_{21}^2 \end{aligned} \right\} \quad \begin{matrix} \rightarrow \\ \text{More dependent on} \\ \text{Solar parameters} \end{matrix}$$



How Does Daya Bay Define Δm_{EE}^2 ?

$$\sin^2 \Delta_{EE} \equiv c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}$$

$$\Rightarrow \Delta m_{EE}^2 = \left(\frac{4E}{L} \right) \arcsin \left[\sqrt{(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32})} \right]$$

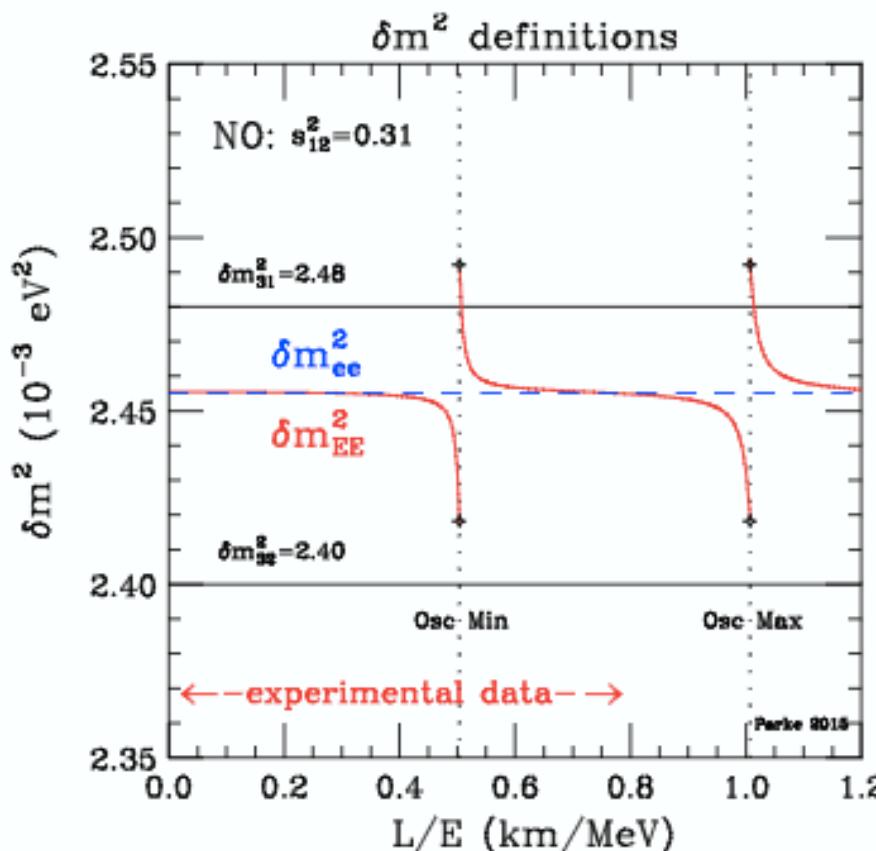
Maladies:

- L/E dependent
- no simple physical meaning !
- Discontinuous at Osc. Max./Min.
($L/E \approx 0.5, 1.0, \dots \text{ km/MeV}$)
3% jump

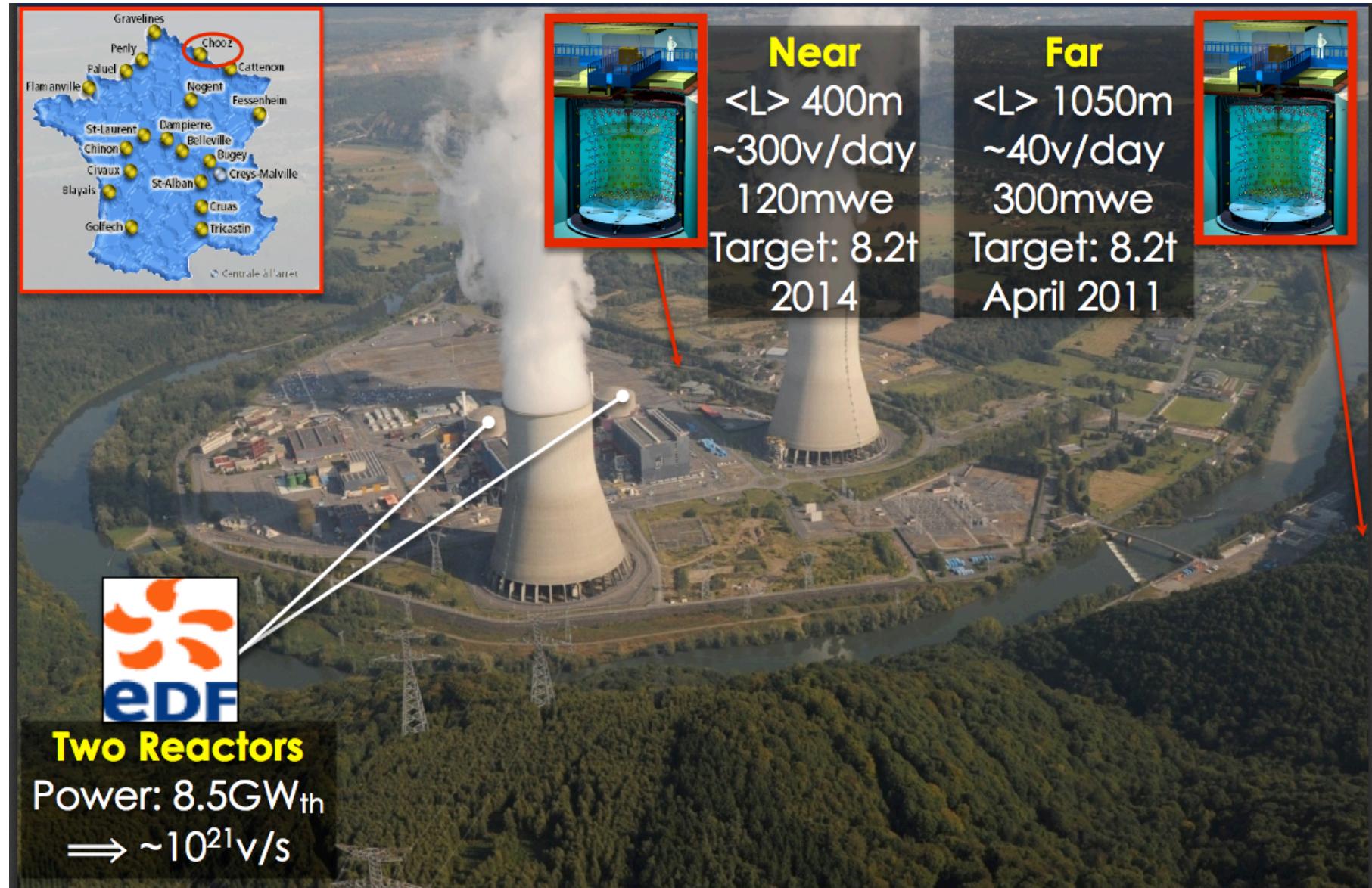
Why???

RHS (1) never gets exactly to 1,
or back to 0
whereas LHS does !

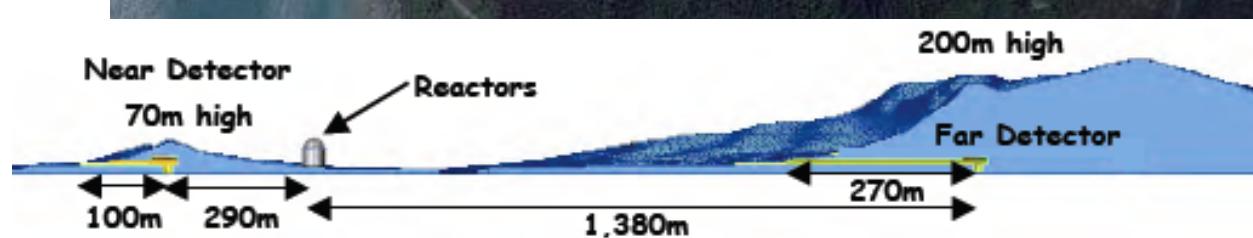
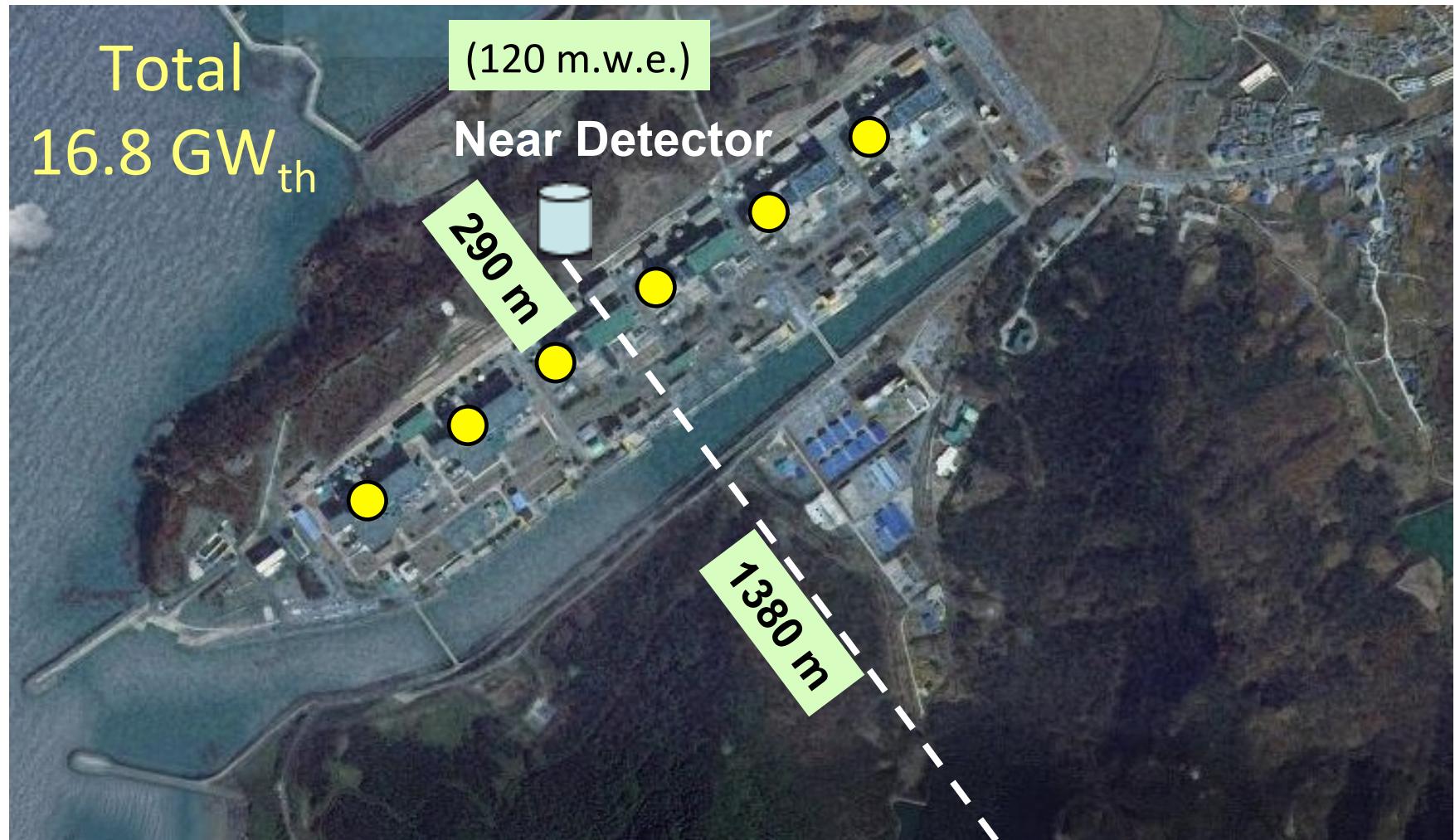
eg $\sin^2(\frac{\pi}{2} \mp \epsilon) = 1 - \epsilon^2 + \mathcal{O}(\epsilon^4)$
with $\epsilon = s_{12}c_{12}\Delta_{21}$



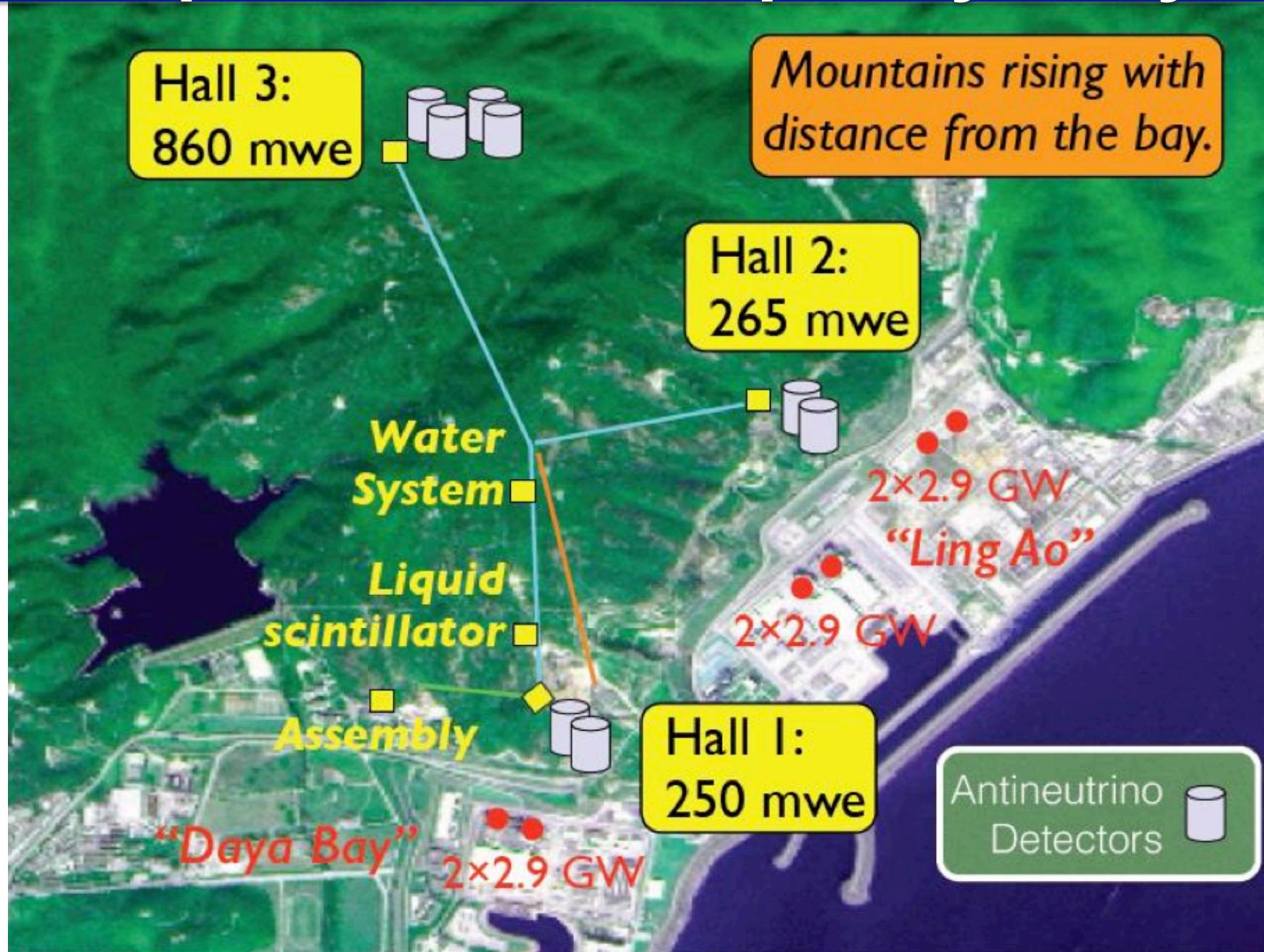
Experimental Setup: Double Chooz



Experimental Setup: RENO



Experimental Setup: Daya Bay



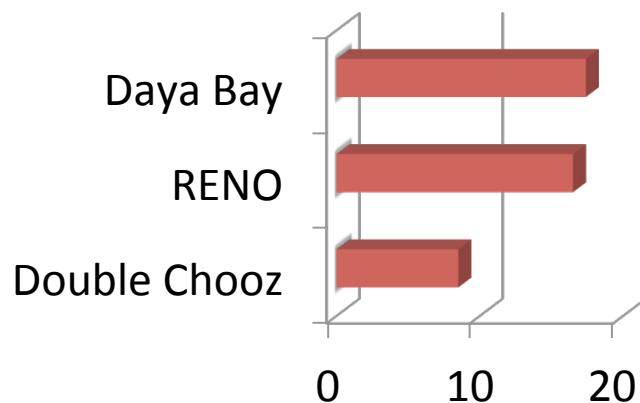
Reactor v Experiments

Experiment (location)	$\sin^2 2\theta_{13}$ Sensitivity	Thermal Power (GW)	Distance Near/Far (m)	Depth Near/Far (mwe)	Target mass (ton)	Cost (US \$)	# of physicists
Double Chooz (France)	> 0.03	8.5	400/1050	120/300	10/10	?	> 160
RENO (Korea)	> 0.02	16.8	290/1380	120/450	16/16	~10 M	40
Daya Bay (China)	> 0.01	17.4	360(500)/ 1985(1613)	260/860	40x2/80	?	~ 230

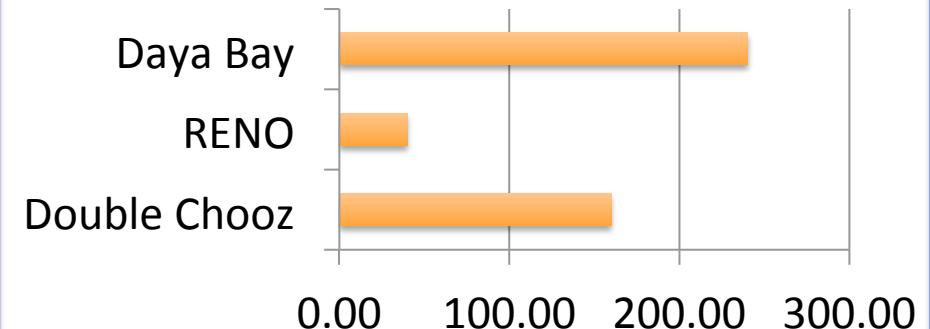
- RENO was the 1st reactor experiment to take data using both near & far detectors.

Comparisons

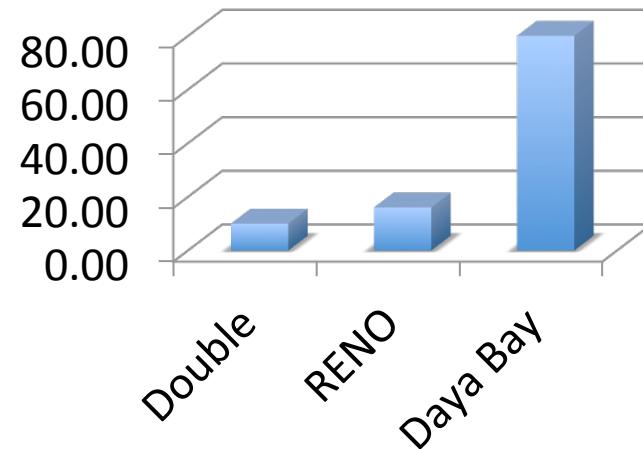
Reactor Thermal Power (GW_{th})



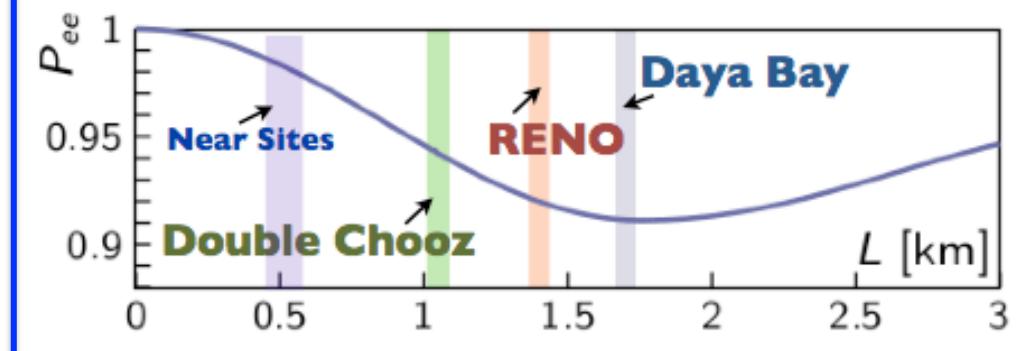
Manpower



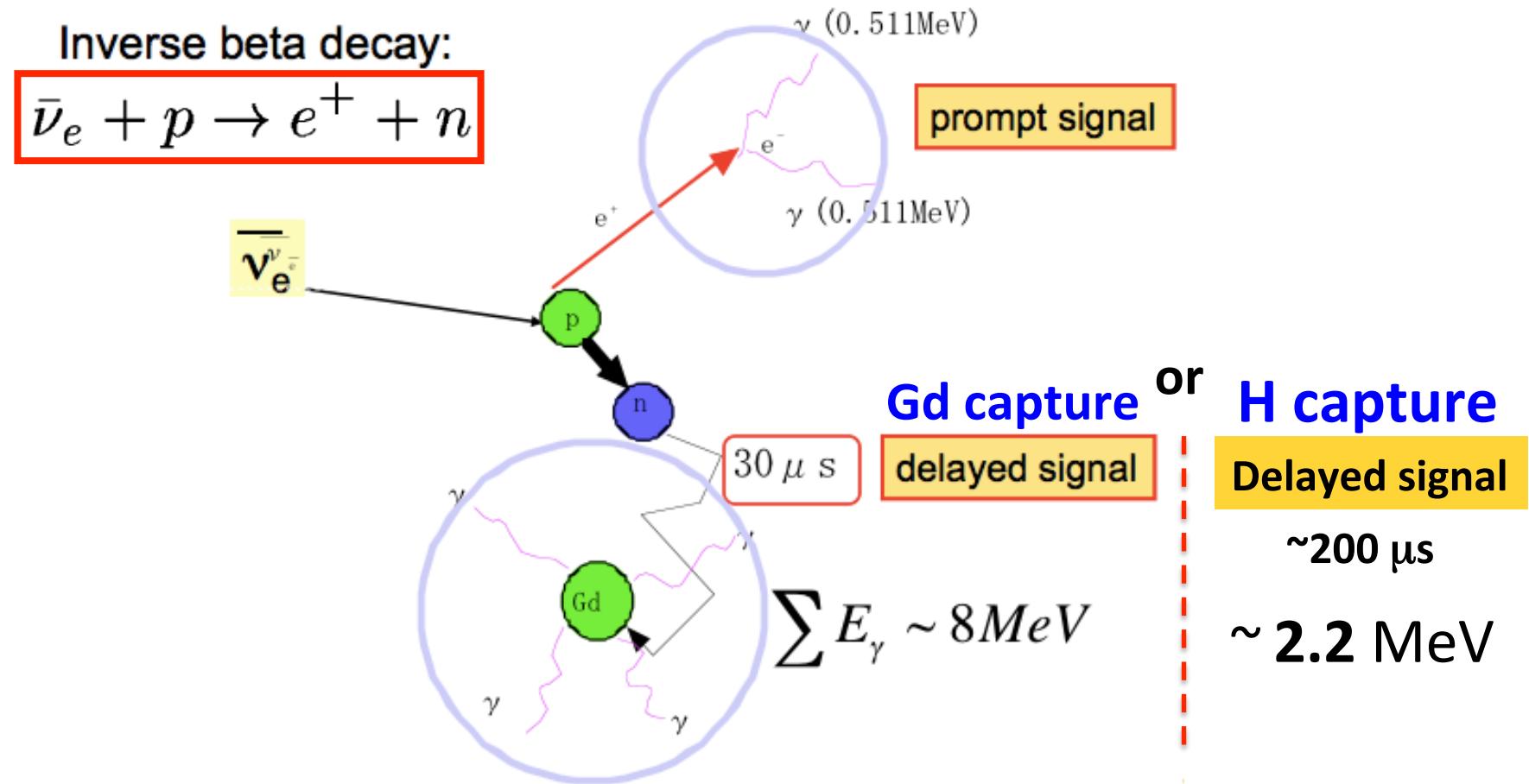
Target (ton)



Baselines



Detection Principle of Reactor Neutrinos

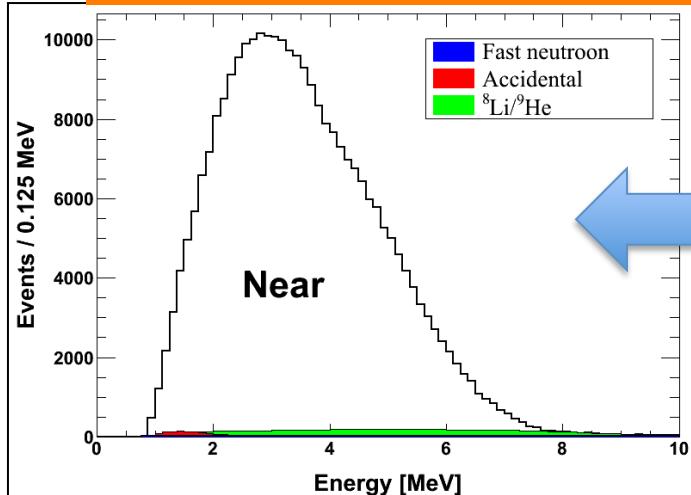


- Prompt signal (e^+) : 1 MeV 2γ 's + e^+ kinetic energy ($E = 1\sim 10 MeV$)
- Delayed signal (n) : 8 MeV γ 's from neutron's capture by **Gd** or **H**
 $\sim 30 \mu s$ or $\sim 200 \mu s$

Signal: IBD Pair

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

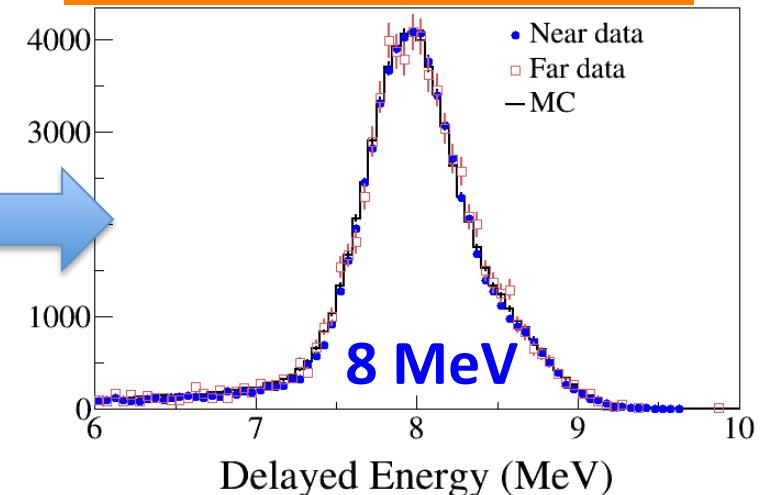
Prompt signal (S1)



n-Gd IBD

$\sim 30 \mu\text{s}$

Delayed signal (S2)



S1

n-H IBD

$\sim 200 \mu\text{s}$

S2

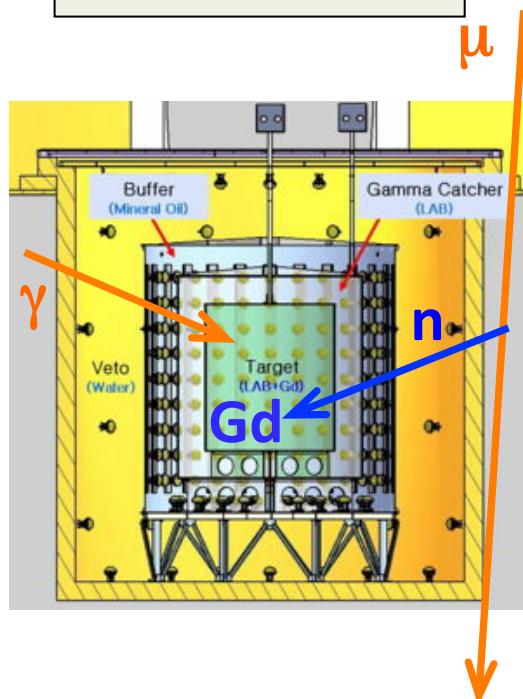
2.2 MeV

Suppresses background a lot !

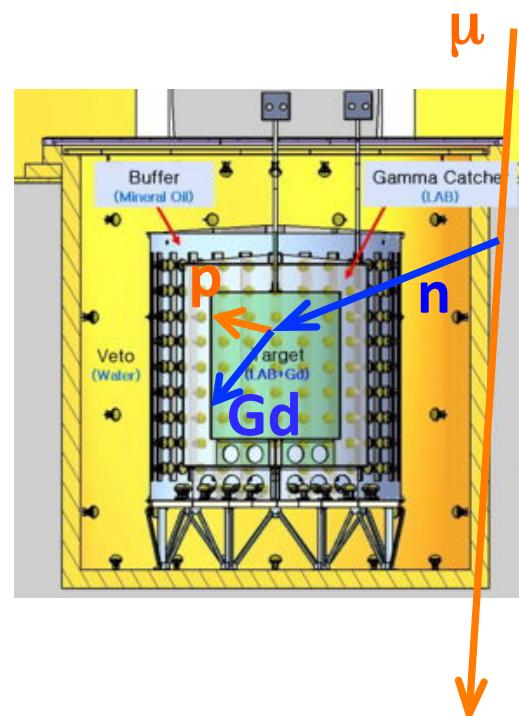
Backgrounds

- Accidental coincidence between prompt and delayed signals
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)
- ${}^9\text{Li}/{}^8\text{He}$ β -n followers produced by cosmic muon spallation

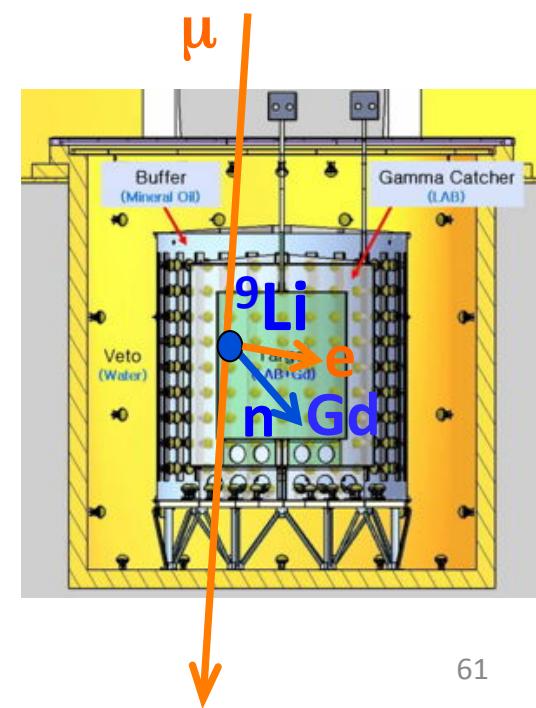
Accidentals



Fast neutrons



${}^9\text{Li}/{}^8\text{He}$ β -n followers



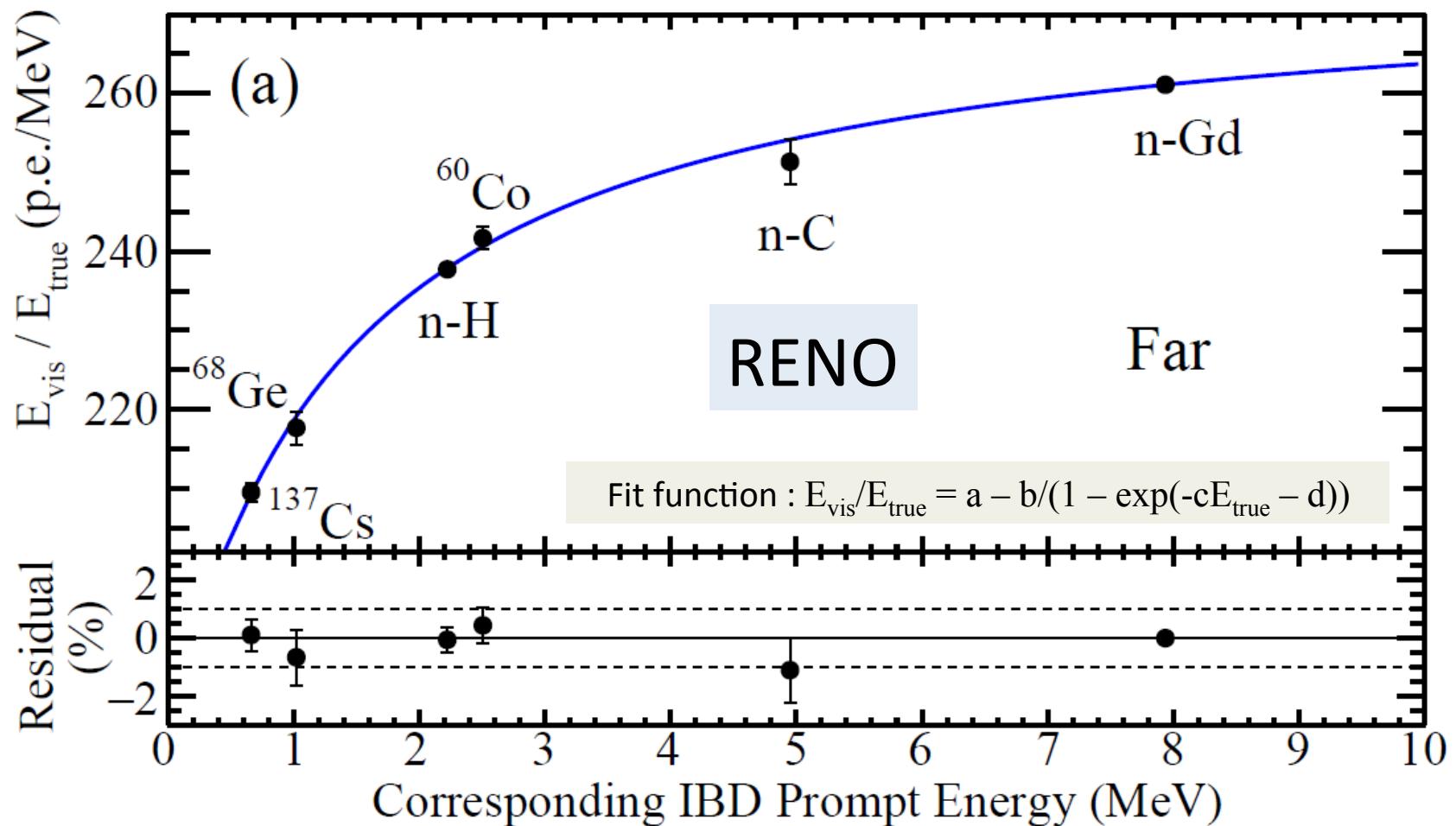
Why Precise θ_{13} ?

1. θ_{13} affects θ_{12} (θ_{23}) and δ_{CP} measurements.
2. θ_{13} is best measured in short (1~2 km) baseline reactor ν experiments. → legacy measurement

Thus, we need to measure it
as precise as possible
with the currently operating detectors.

Energy Calibration from γ -ray Sources

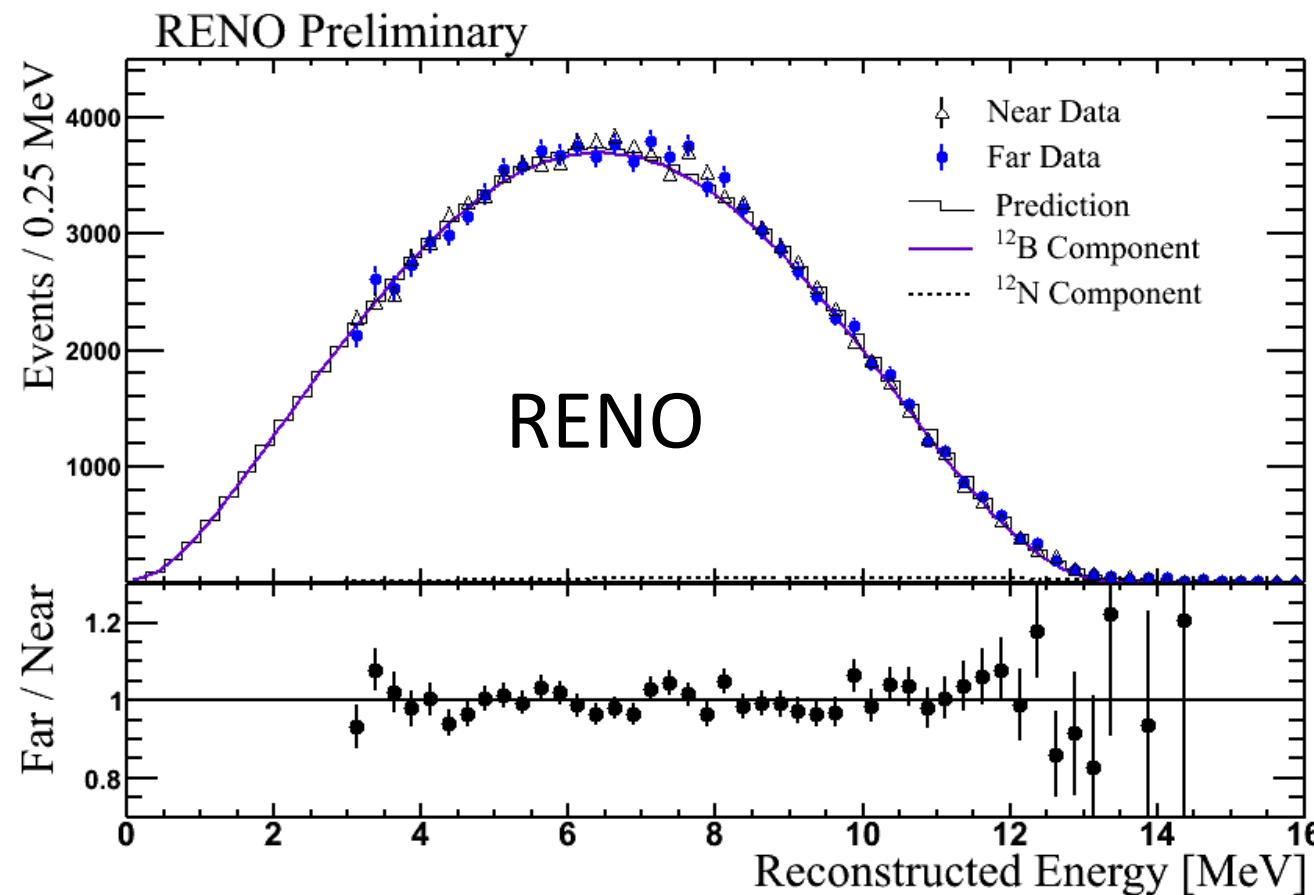
Non-linear response of the scintillation energy is calibrated with γ -ray source



Deviation of all calibration data points with respect to the best-fit is within $\sim 1\%$.

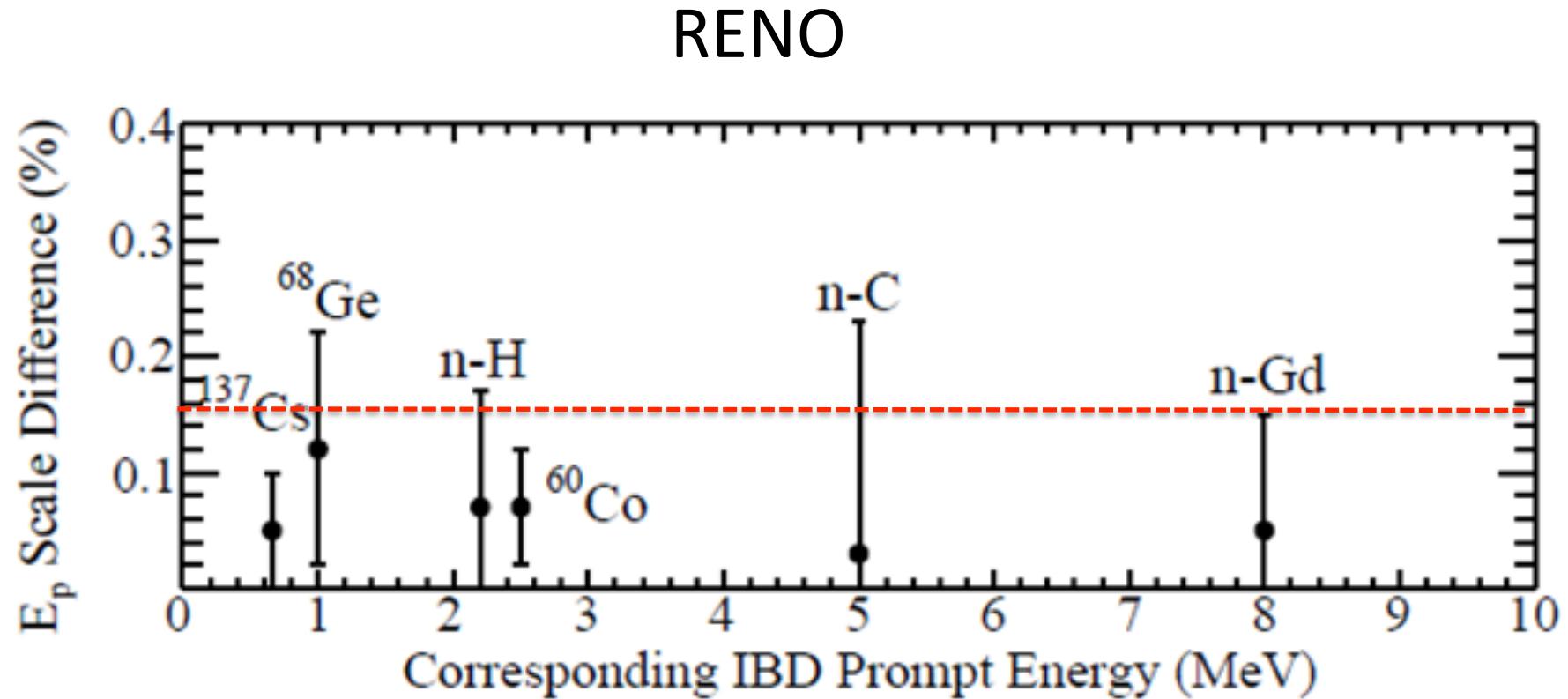
^{12}B Energy Spectrum (Near & Far)

- Electron energy spectrum from β -decays from ^{12}B and ^{12}N , which are produced by cosmic-muon interactions



Good agreement between data and MC spectrum!

Energy Scale Difference between Near & Far

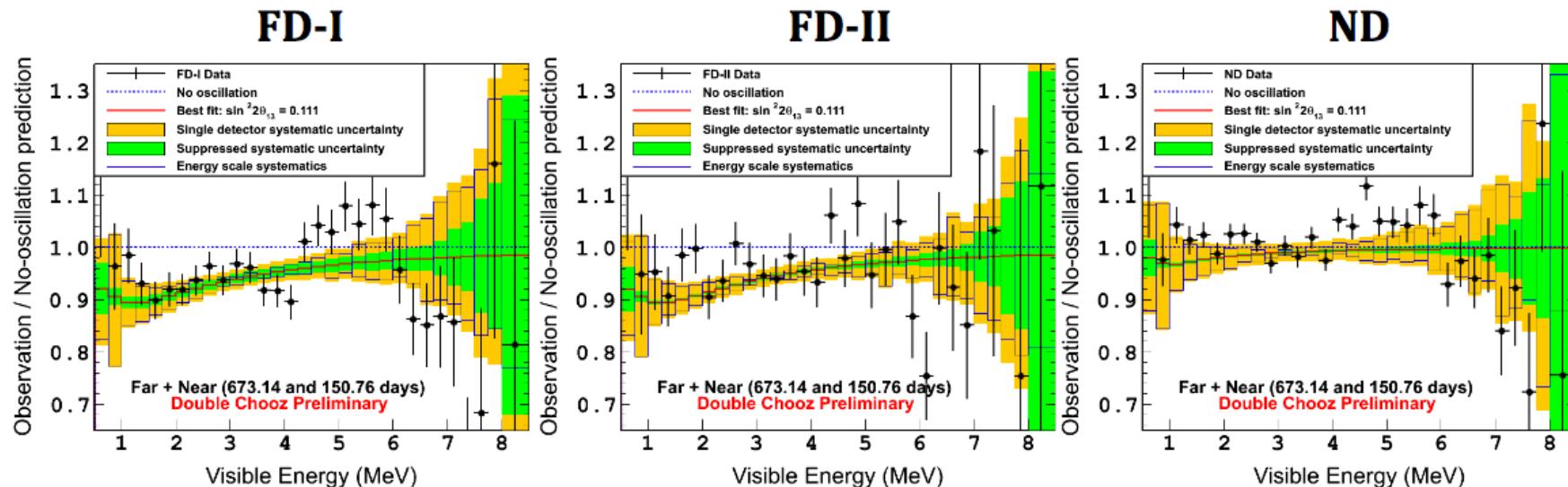


Energy scale difference $< 0.15\%$ for $E_p = 1 \sim 8$ MeV

θ_{13} : Double Chooz

Fit results

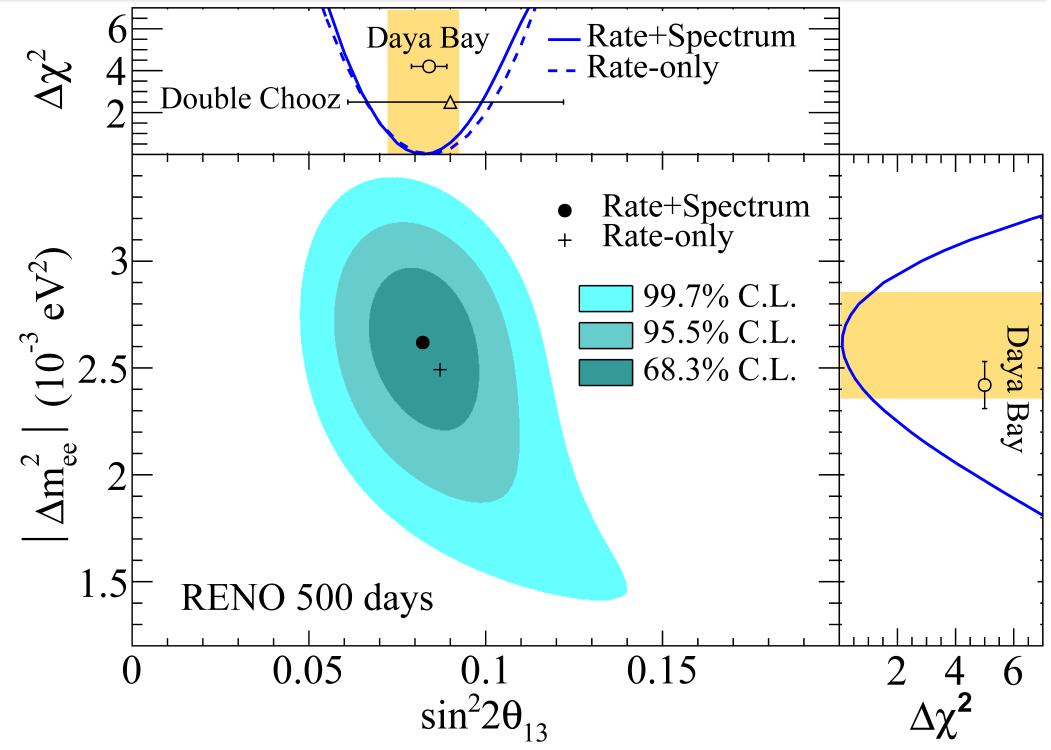
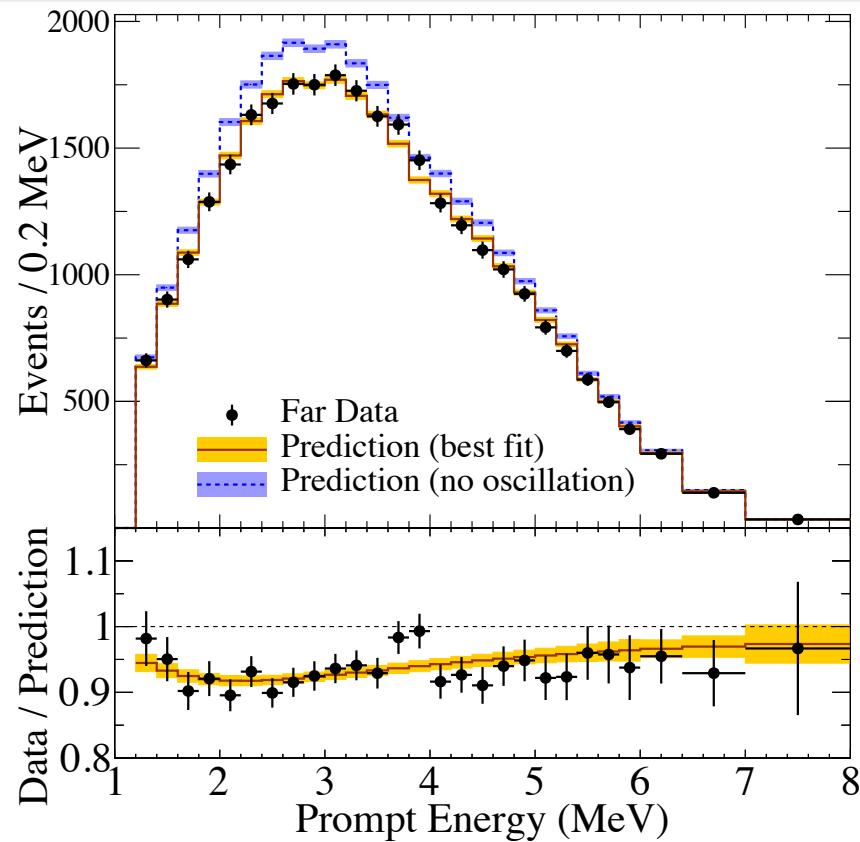
@ Moriond 2016



- Best-fit: $\sin^2 2\theta_{13} = 0.111 \pm 0.018$ (stat.+syst.) ($\chi^2/\text{dof} = 128.8/120$)
 - Non-zero θ_{13} observation at 5.8σ C.L.
 - Cosmogenic ${}^9\text{Li}$ BG: $0.75 \pm 0.14 \text{ d}^{-1}$ (FD), $4.89 \pm 0.78 \text{ d}^{-1}$ (ND)
 - Fast-n+stop- μ BG: $0.535 \pm 0.035 \text{ d}^{-1}$ (FD), $3.53 \pm 0.16 \text{ d}^{-1}$ (ND)
 - Energy non-linearity: consistent across data sets and with calibration

Double Chooz Preliminary

θ_{13} & $|\Delta m^2_{ee}|$ in RENO



PRL 116, 211801, 2016

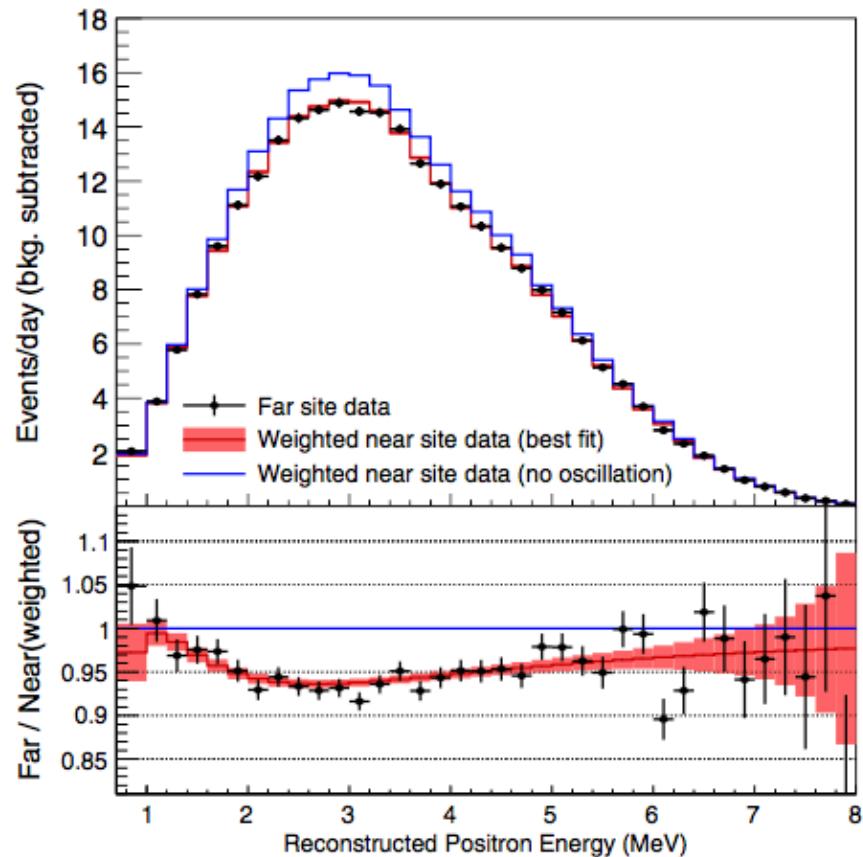
500 days

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat}) \pm 0.006(\text{syst})$$

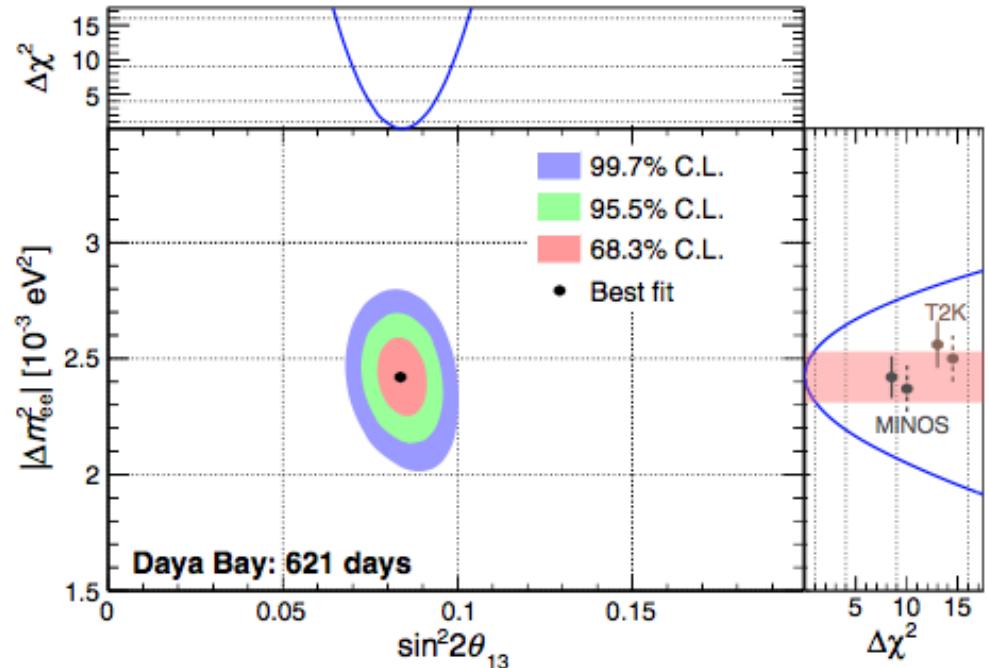
RENO's 1st $|\Delta m^2_{ee}|$ measurement!

$$|\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.}) (\times 10^{-3} \text{ eV}^2)$$

θ_{13} & $|\Delta m^2_{ee}|$ in Daya Bay



621 days

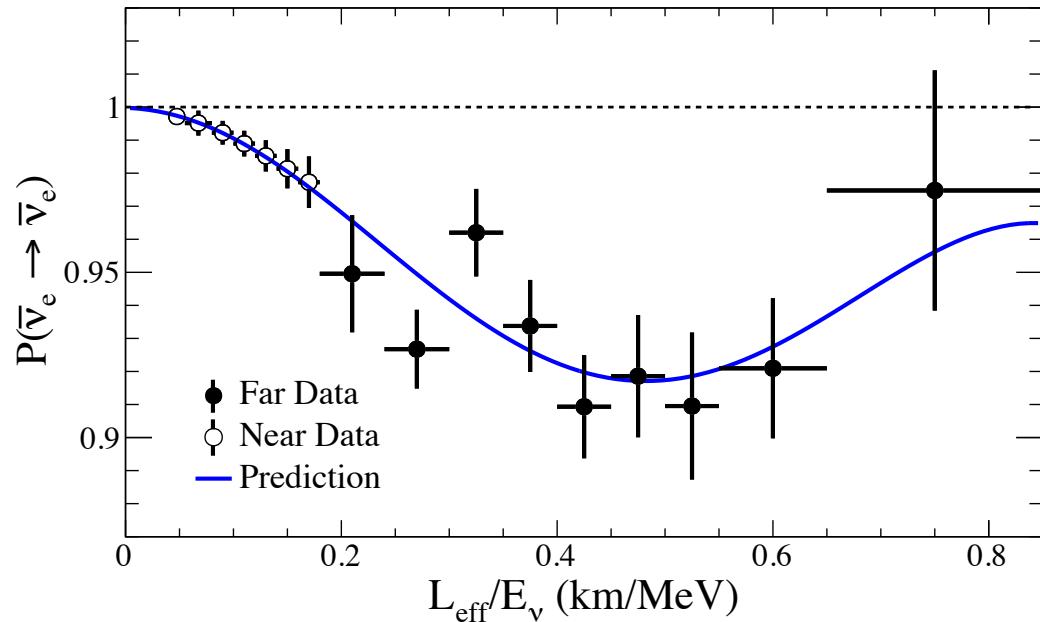


PRL 115, 111802 (2015)

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \text{ eV}^2$$

Reactor Neutrino Disappearance on L/E

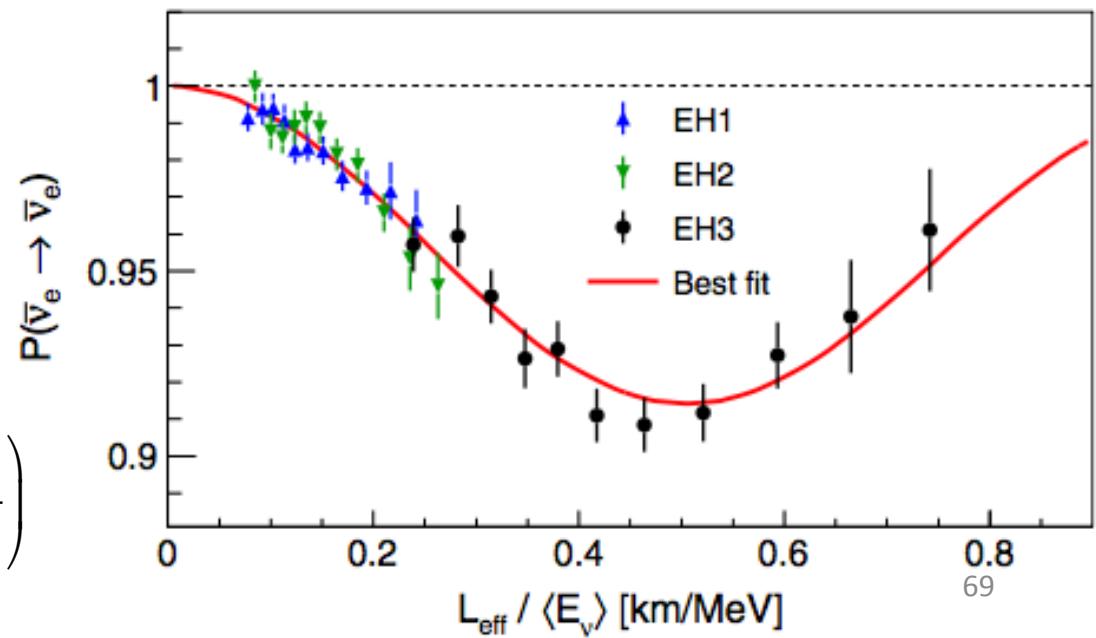


RENO

PRL 116, 211801, 2016

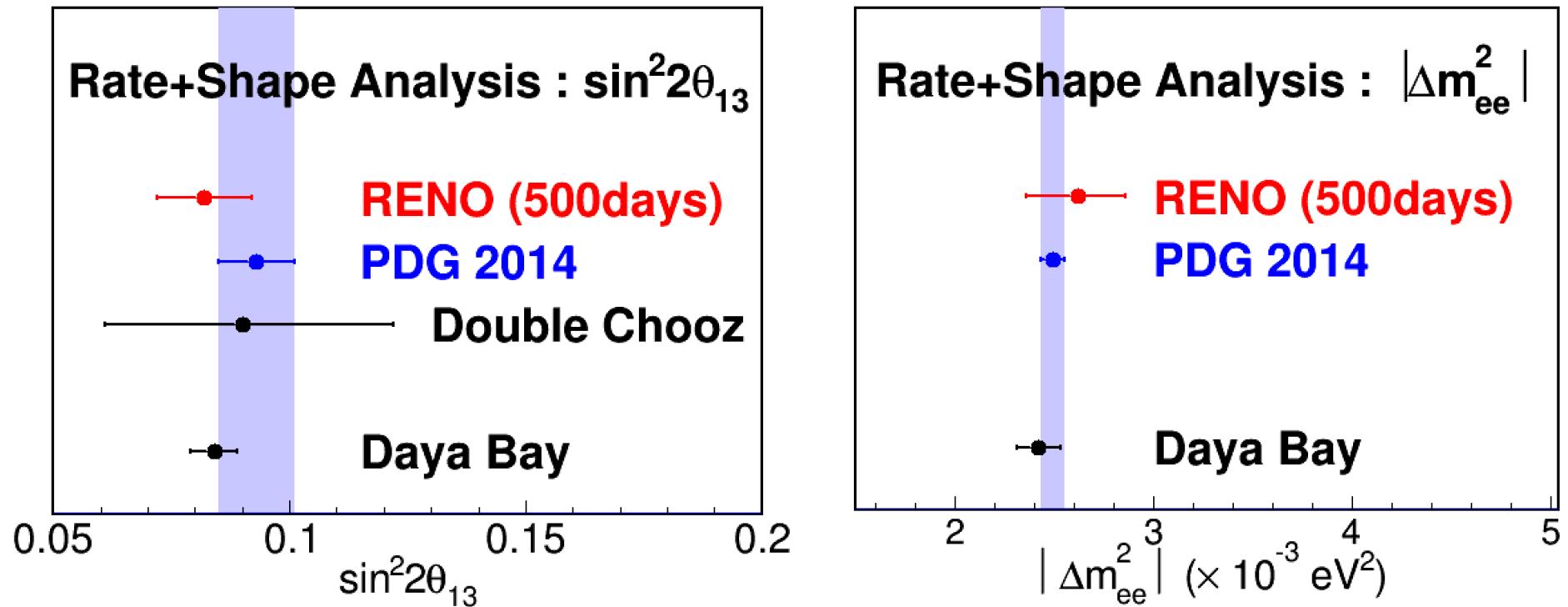
Daya Bay

PRL 115, 111802 (2015)



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\Delta m_{ee}^2 \frac{L}{4E_\nu} \right)$$

Summary: Recent n-Gd Results

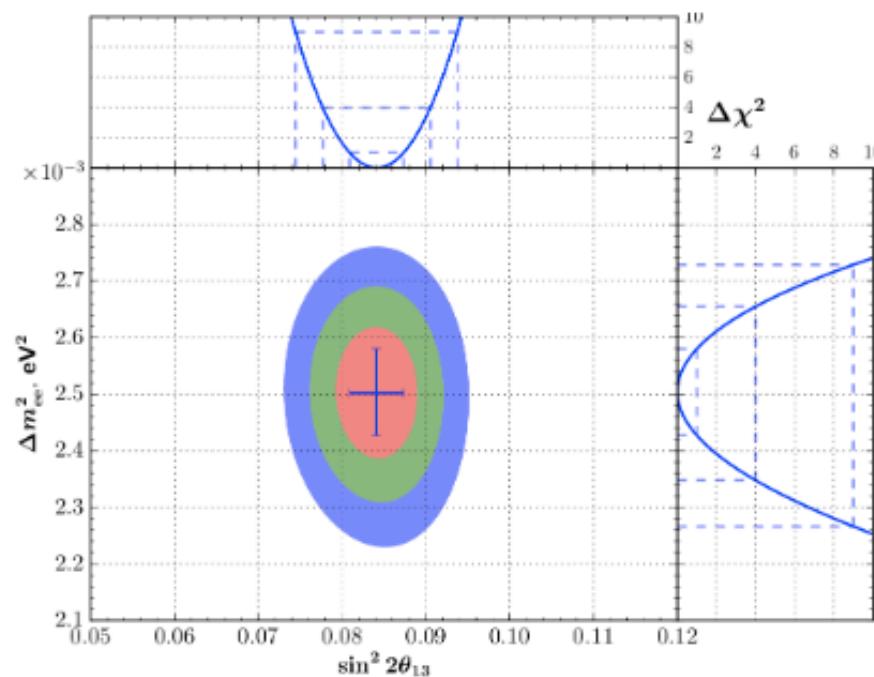


Rate + Shape [χ^2/NDF]	$\sin^2 2\theta_{13} \pm \text{Total Error}$	$ \Delta m_{ee}^2 ^2 (\times 10^3 \text{ eV}^2) \pm \text{Total Error}$
RENO [58.9 / 66]	0.082 ± 0.010	$2.62^{+0.24}_{-0.26}$
Daya Bay [134.6/146]	0.084 ± 0.005	2.42 ± 0.11
Double Chooz [52.2/40]	$0.090^{+0.032}_{-0.029}$	---

θ_{13} & $|\Delta m^2_{ee}|$ in Daya Bay 2016

Poster Id: P2.063 by Maxim Gonchar

Oscillation results



$$P = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.267 \Delta m_{21}^2 L}{E} - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m_{ee}^2 L}{E}.$$

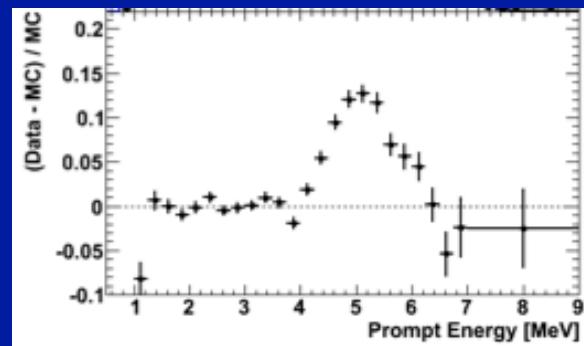
$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$
 $|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3} \text{ eV}^2$
 $\chi^2/\text{NDF} = 232.6/263$

Last publication:
P. R. L. 115, 111802 (2015)

$\sin^2 2\theta_{13} = [8.4 \pm 0.5] \times 10^{-2}$
 $|\Delta m^2_{ee}| = [2.42 \pm 0.11] \times 10^{-3} \text{ eV}^2$

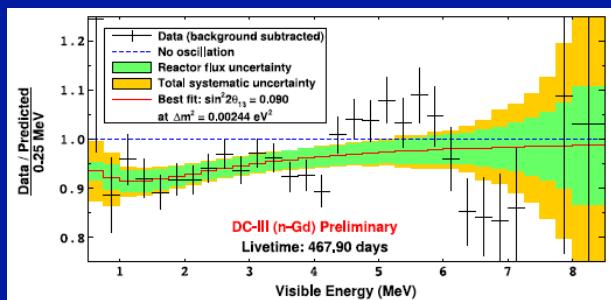
The 5 MeV Excess in 2014

RENO



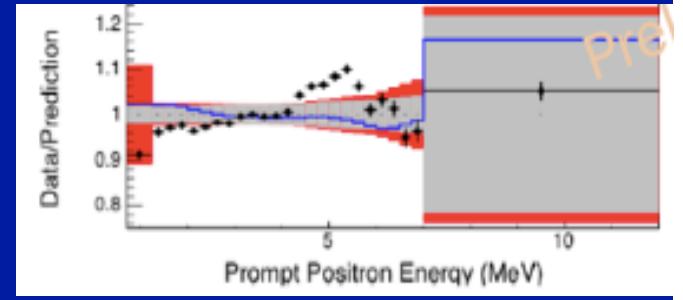
(In Neutrino 2014)

Double Chooz



(In Neutrino 2014)

Daya Bay



(In ICHEP 2014)

In 2012

- RENO: excess ($? \sigma$) in $[3, 8]$ MeV region
 - (1) new background ?
 - (2) energy scale issue ?
 - (3) reactor v model issue ?

(In Neutrino 2012)

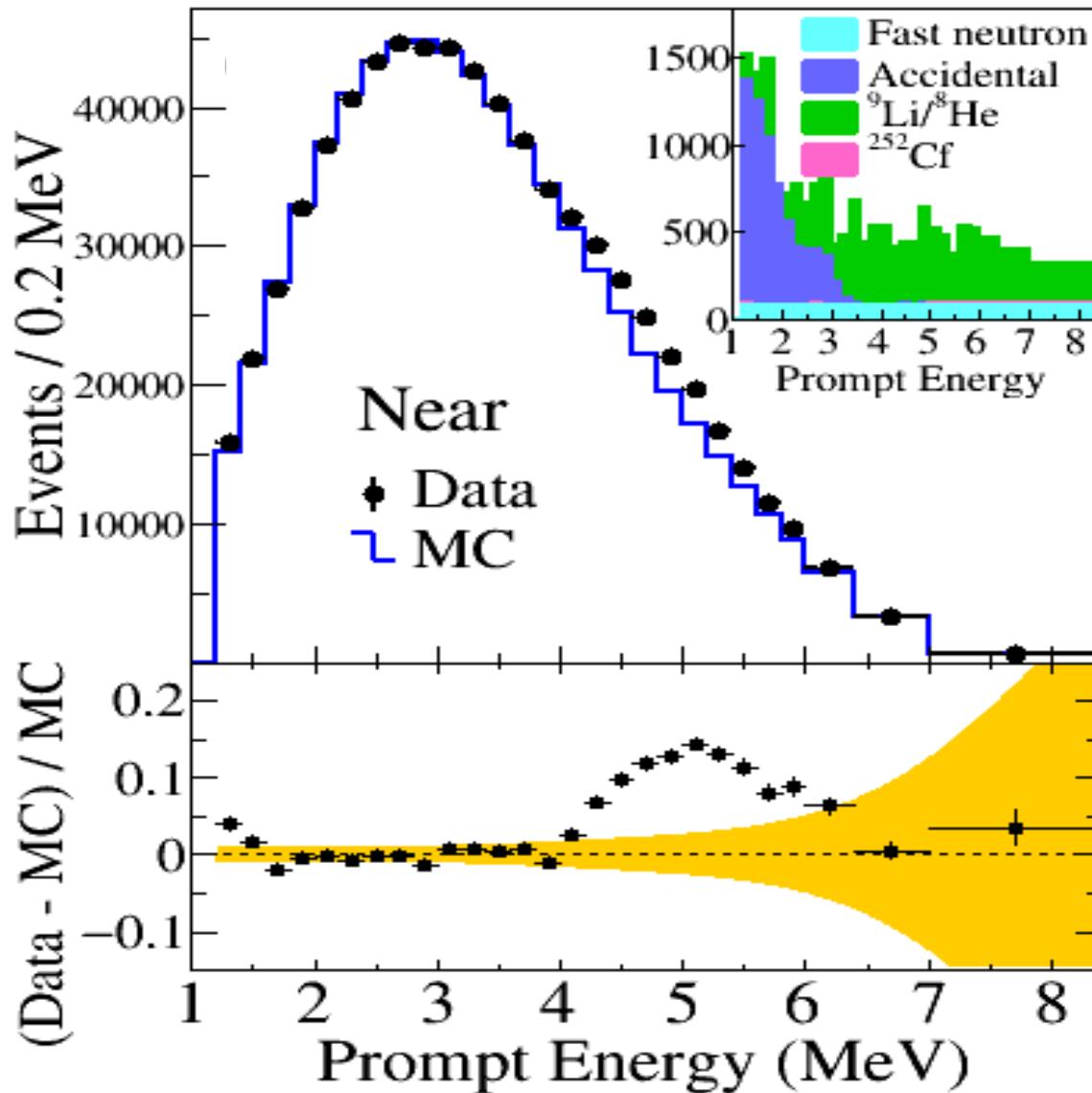
In 2014

- RENO: 5 MeV excess (3.5σ) correlation w/ reactor P_{th} .
- DC: 5 MeV excess ($? \sigma$) correlation w/ reactor P_{th} .
- DB: 5 MeV excess ($? \sigma$) $\rightarrow 4 \sigma$ in 2016

Observation of an excess at 5 MeV

1400 days of data (Aug. 2011 – Sep 2015)

(Preliminary)

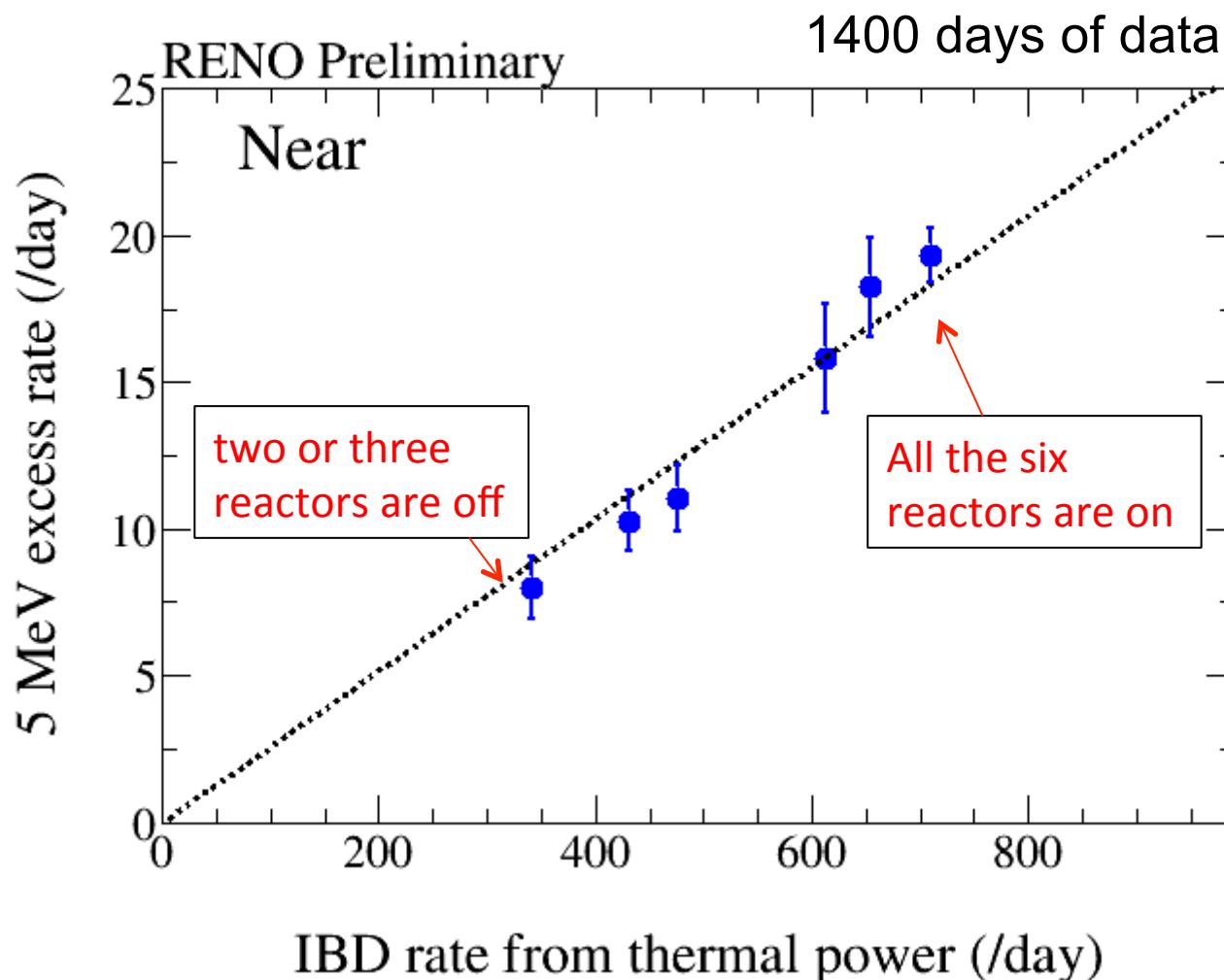


The measured near spectrum is compared with prediction using χ^2 test.

Fraction of
5 MeV excess:
 2.50 ± 0.21 (%)

Significance of the 5 MeV
excess: **12σ**

Correlation of 5 MeV Excess with Reactor Power



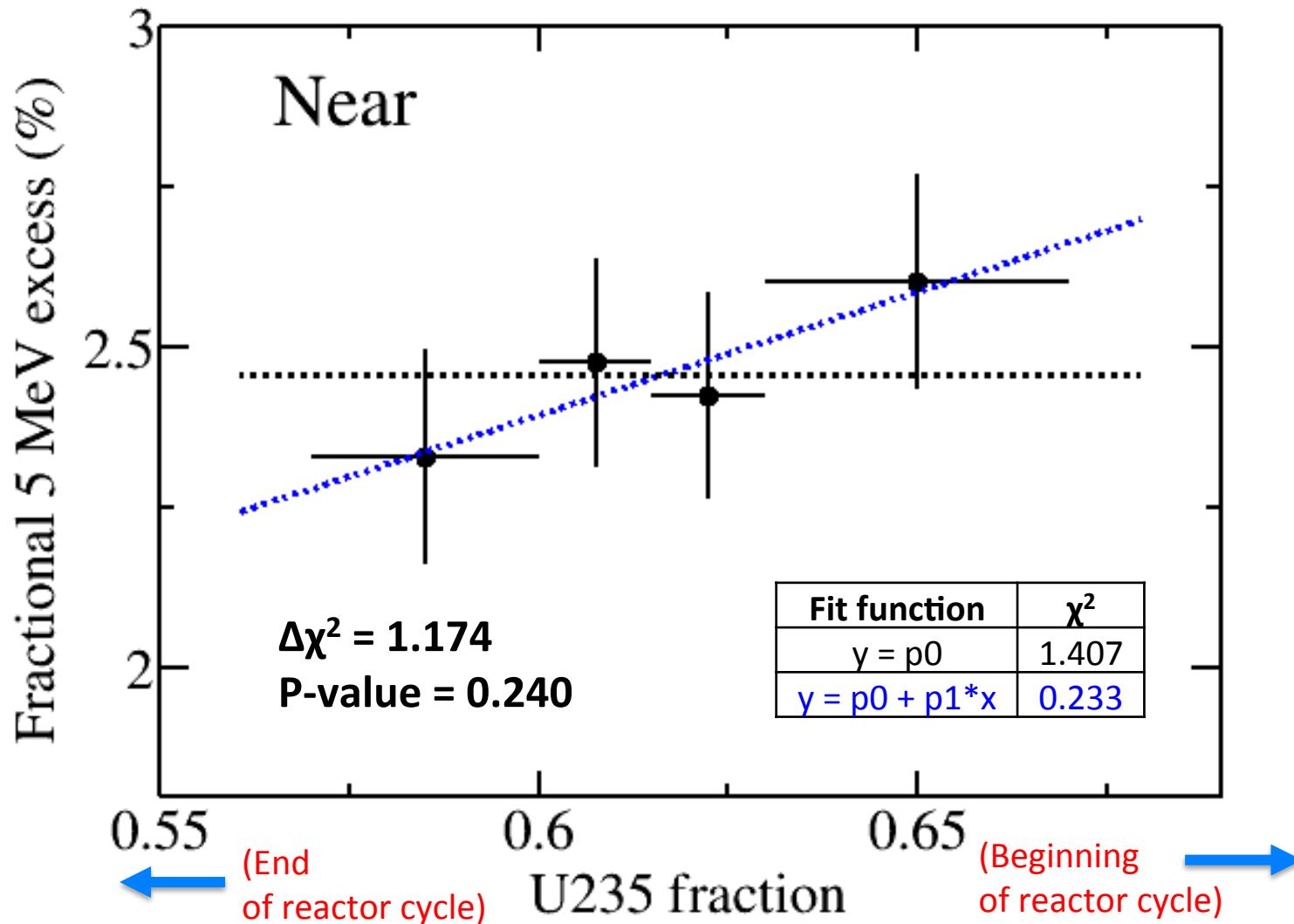
5 MeV excess has a clear correlation with reactor thermal power !

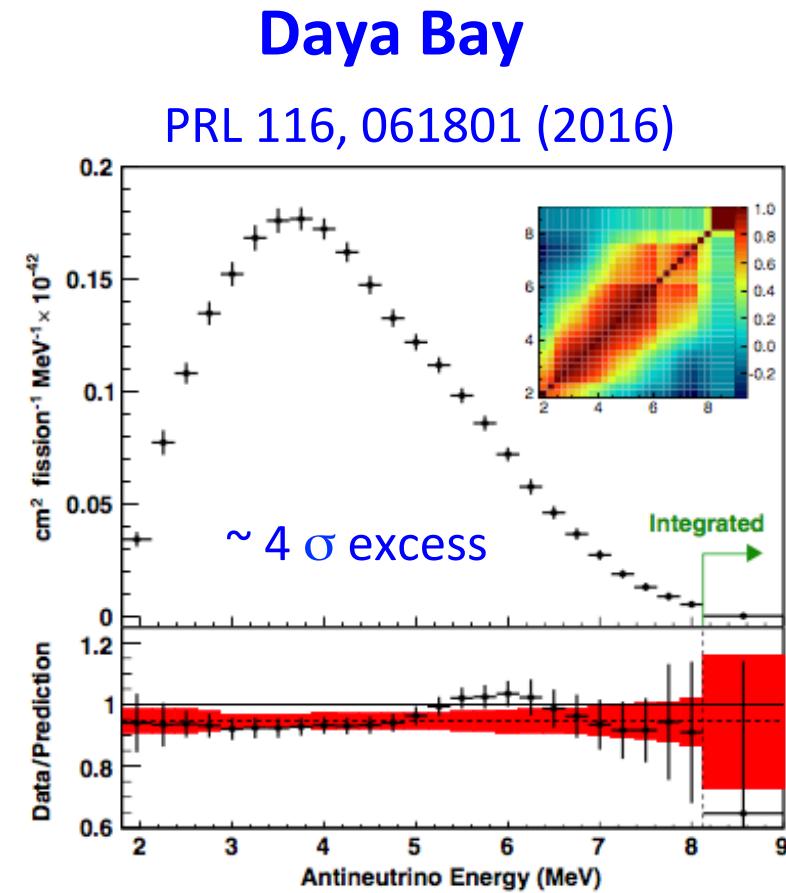
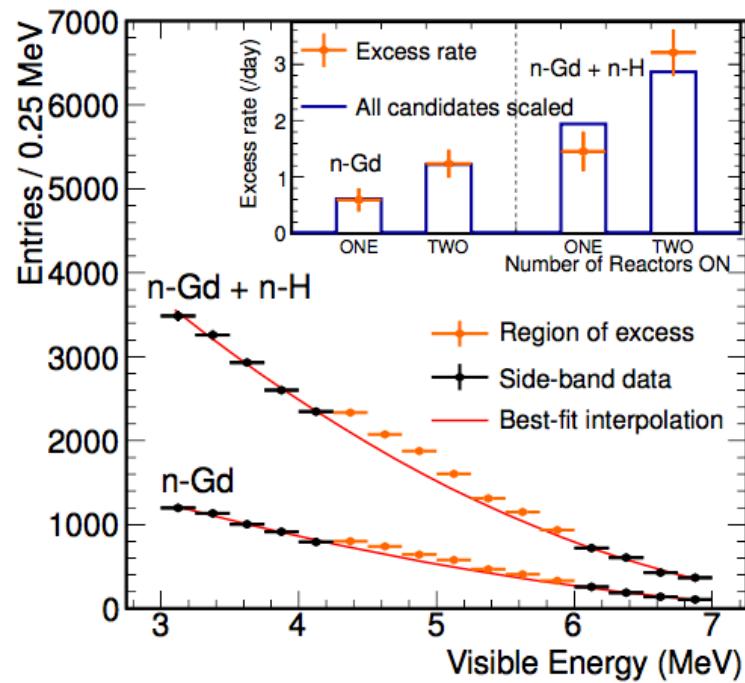
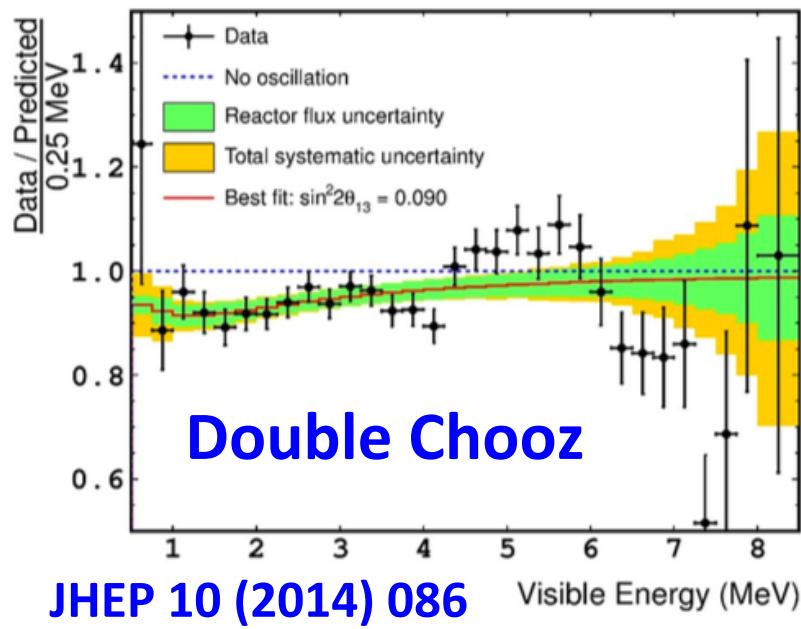
The 5 MeV excess comes from reactors!

Correlation of 5 MeV Excess with ^{235}U

(Preliminary)

^{235}U fraction corresponds to freshness of reactor fuel





Determination of normalization factor, R

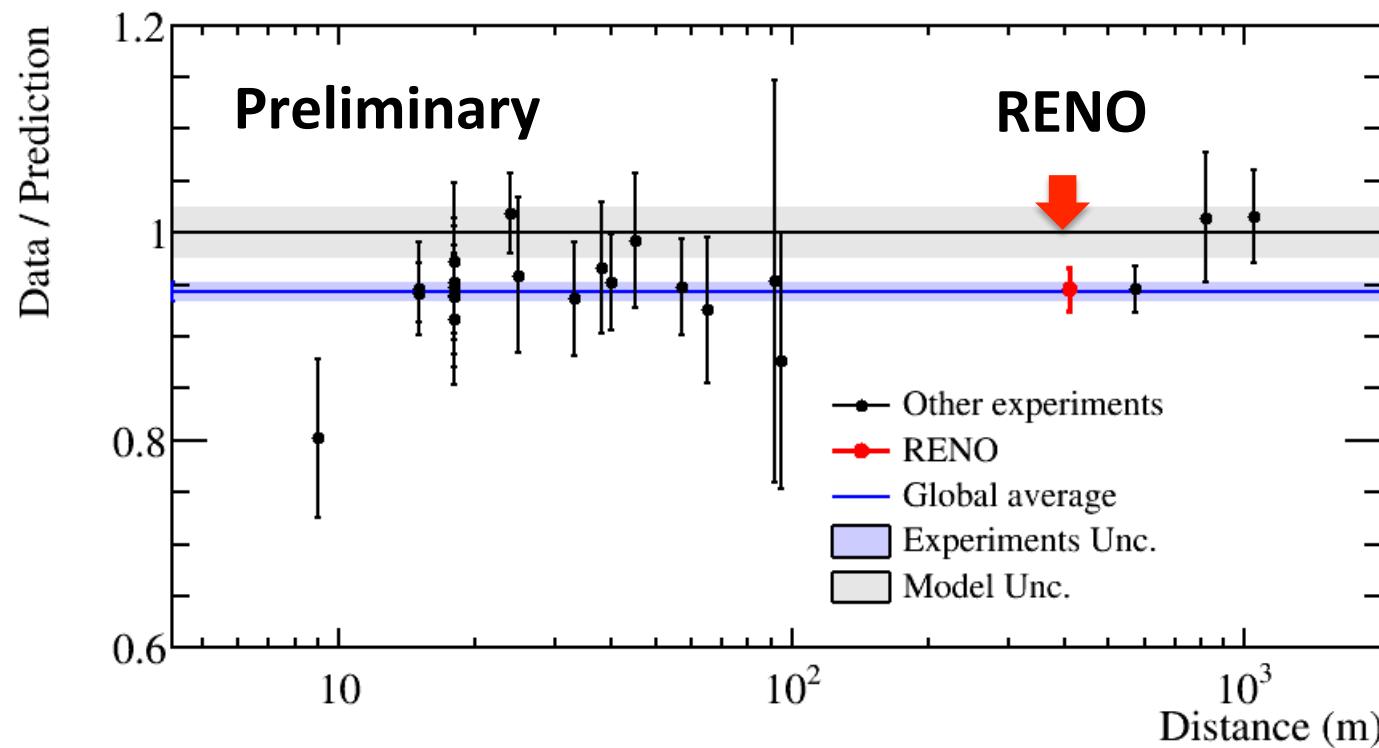
$R(\text{data/prediction}) = 0.946 \pm 0.021 \text{ (RENO)}$

Preliminary

$R(\text{data/prediction}) = 0.95 \pm 0.02 \text{ (DYB)}$

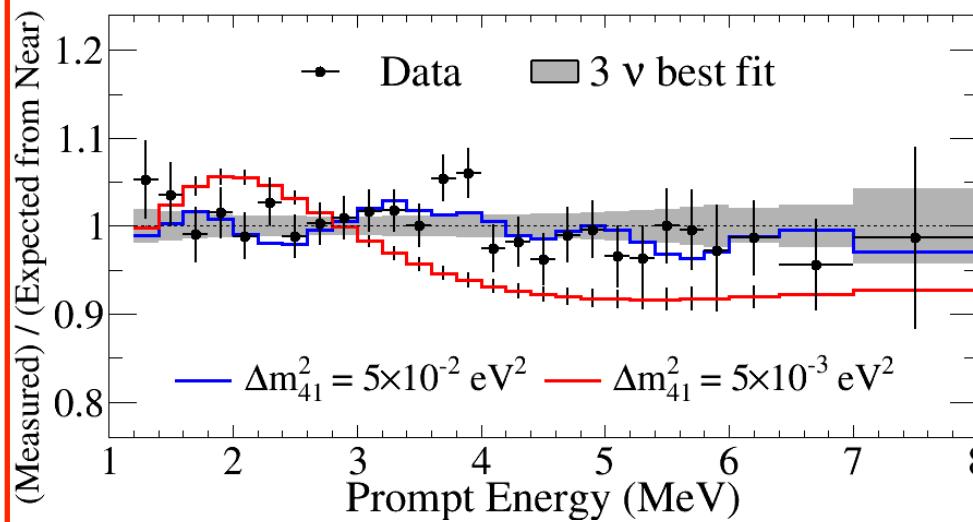
- The flux prediction is with Huber + Mueller model
- Flux weighted baseline at near : 411 m (RENO)

Comparison with other experiments



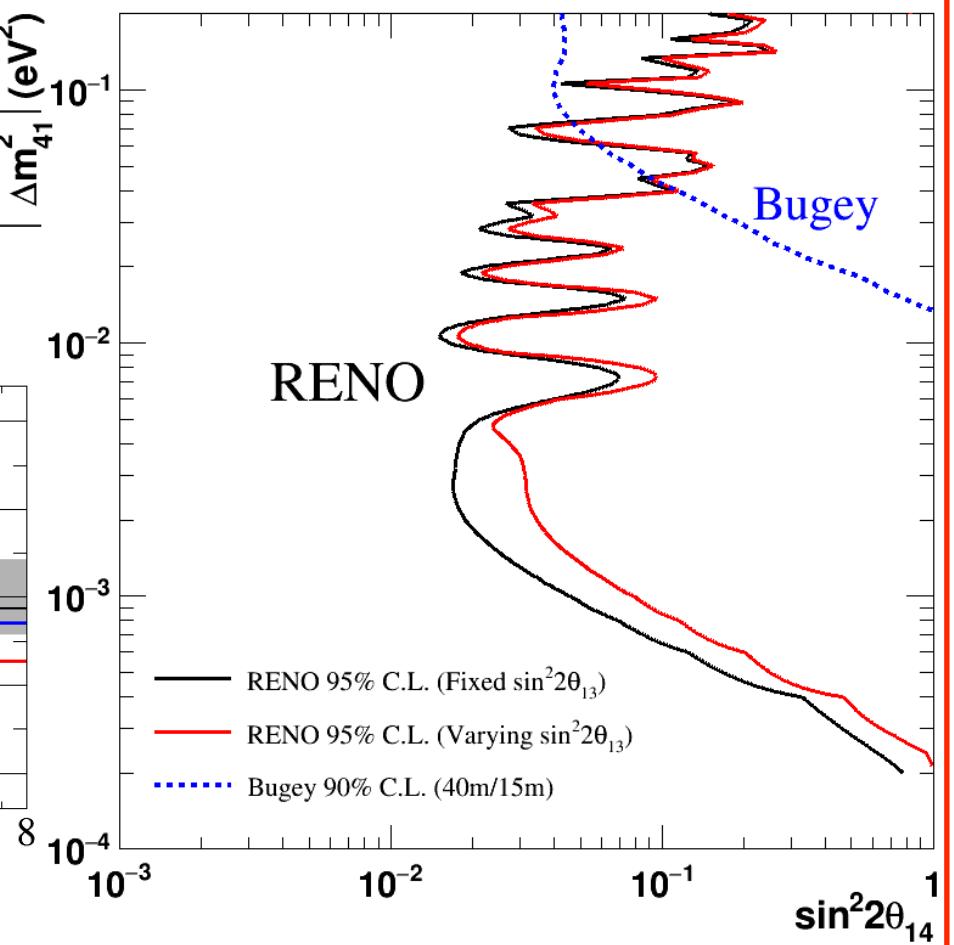
Light Sterile Neutrino Search Results

- All 500 days of RENO data
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region $10^{-3} \text{ eV}^2 < \Delta m_{41}^2 < 0.1 \text{ eV}^2$



full curves assumes $\sin^2 2\theta_{14} = 0.1$

Paper in preparation

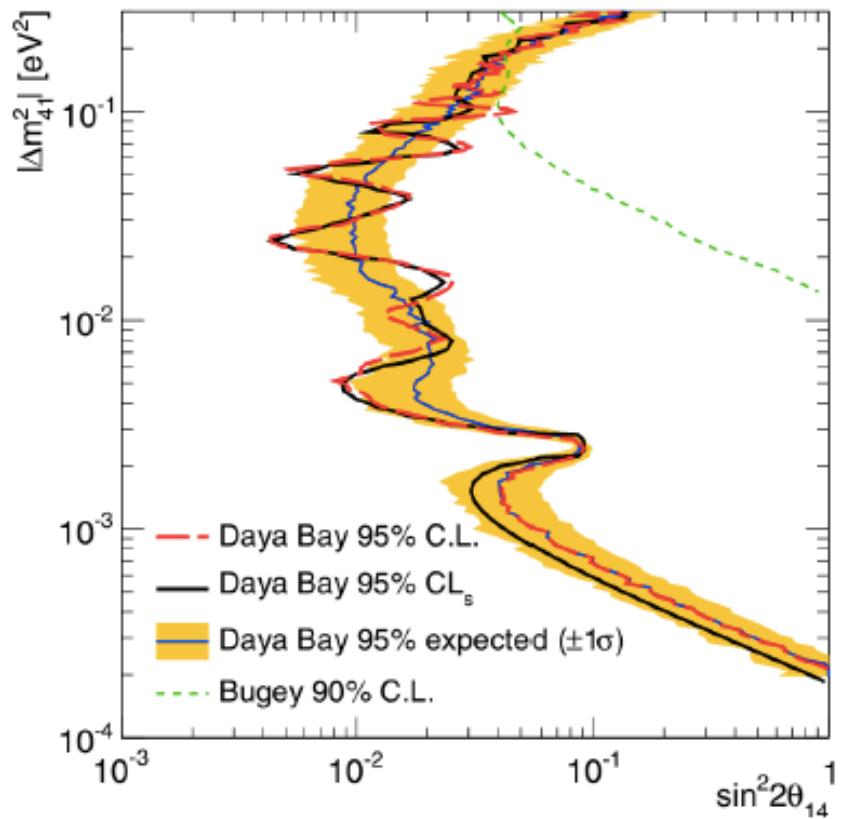
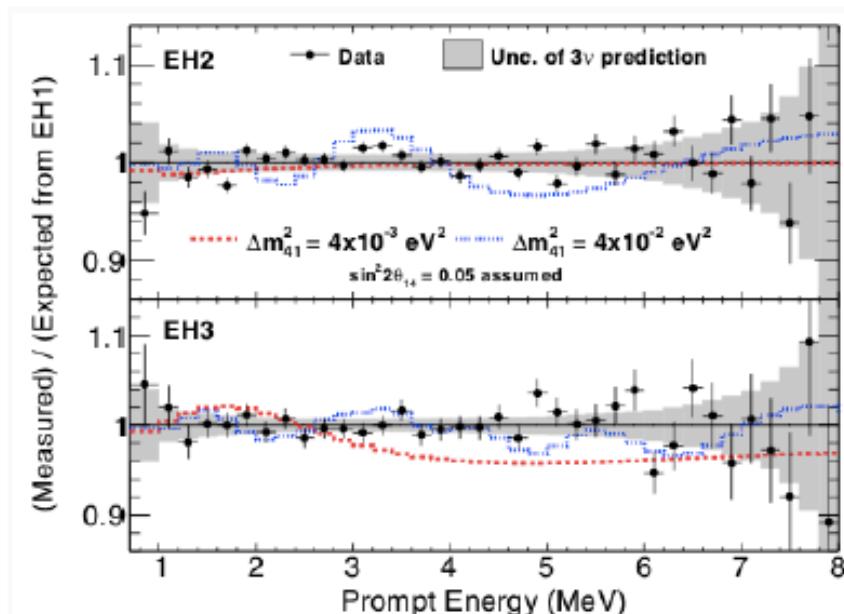


Light sterile ν search

621 days data



- Relative comparison of energy spectra at three EHs
- No evidence of a light sterile neutrino
- Sensitivity at $<0.1\text{eV}^2$ region improved by **2 times** with respect to Phys. Rev. Lett. **113**, 141802



Most stringent limits on $\sin^2 2\theta_{14}$ for the $\Delta m_{41}^2 2 \times 10^{-4} \text{ eV}^2 \sim 0.2 \text{ eV}^2$ region!

θ_{13} & $|\Delta m^2_{ee}|$ measurements

This is a “Parameter estimation”.

→ Find minimum χ^2 by varying θ_{13} & $|\Delta m^2_{ee}|$

χ^2 Fit Methods

- Covariance matrix method:  Daya Bay
 - more traditional in HEP in the past
 - could be more difficult when # of sys. error increases.
- Pull method:  Stump et al, PRD65, 014012 (2002)
 - reduces error
 - easier to code up RENO

The two methods are exactly identical mathematically. Fogli et al, PRD66, 053010 (2002)

General χ^2 Fit with Pull Method

Fogli et al, PRD 66, 053010 (2002)

$$\chi_{\text{pull}}^2 = \min_{\{\xi_k\}} \left[\sum_{n=1}^N \left(\frac{R_n^{\text{expt}} - R_n^{\text{theor}} - \sum_{k=1}^K \xi_k c_n^k}{u_n} \right)^2 + \sum_{k=1}^K \xi_k^2 \right]$$

Correlated
error

Pull parameters

Uncorrelated
Error

Red arrows point to the ξ_k term in the equation and the ξ_k^2 term in the error term.

Pull method is more practical when
 K (#. sys. error sources) $\ll N$ (#. observables)

RENO: χ^2 fit

$$\chi^2 = \sum_{i=1}^{N_{bins}} \frac{(O_i^{F/N} - T_i^{F/N})^2}{U_i^{F/N}} + \sum_{d=N,F} \left(\frac{b^d}{\sigma_{bkg}^d} \right)^2 + \sum_{r=1}^6 \left(\frac{f_r}{\sigma_{flux}^r} \right)^2 + \left(\frac{\epsilon}{\sigma_{eff}} \right)^2 + \left(\frac{e}{\sigma_{scale}} \right)^2$$

PRL 116, 211801 (2016)

(Pull method)

$$T_i^{F/N} = T_i^{F/N}(b^d, f_r, \epsilon, e; \theta_{13}, |\Delta m_{ee}^2|)$$

- ❖ Expected events term ($T_i^{F/N}$) contains energy dependent BKG uncertainties.

68 bins = 34 energy bins \times 2 periods

Daya Bay: χ^2 fit

(Covariance Matrix method)

PRL 115, 111802 (2015)

$$\chi^2 = \sum_{i,j} (N_j^f - w_j N_j^n)(V^{-1})_{ij}(N_i^f - w_i N_i^n)$$

Weight

$$w_i = \frac{N_i^f}{N_i^n} = \left(\frac{T^f}{T^n}\right) \left(\frac{\epsilon^f}{\epsilon^n}\right) \sum_j \mathcal{P}(E_j^{\text{true}} | E_i^{\text{rec}}) r_j$$

Extrapolation factor

$$r_j = \frac{\sum_k^{\text{cores}} P(E_j^{\text{true}}, L_k^f) \phi_{jk} / (L_k^f)^2}{\sum_k^{\text{cores}} P(E_j^{\text{true}}, L_k^n) \phi_{jk} / (L_k^n)^2}$$

Cov. Matrix element

$$V_{ij} = \frac{1}{N} \sum_i^N (S_i^f - w_i S_i^n)(S_j^f - w_j S_j^n)$$

148 bins = 37 energy bins $\times 2$ N-F pair $\times 2$ periods

Double Chooz: χ^2 fit

$$\chi^2 = \sum_{i=1}^{40} \sum_{j=1}^{40} (N_i^{\text{obs}} - N_i^{\text{exp}}) M_{ij}^{-1} (N_j^{\text{obs}} - N_j^{\text{exp}}) + \sum_{k=1}^5 \frac{\epsilon_k^2}{\sigma_k^2} \quad (\text{Hybrid method})$$

$$+ (\epsilon_a, \epsilon_b, \epsilon_c) \begin{pmatrix} \sigma_a^2 & \rho_{ab}\sigma_a\sigma_b & \rho_{ac}\sigma_a\sigma_c \\ \rho_{ab}\sigma_a\sigma_b & \sigma_b^2 & \rho_{bc}\sigma_b\sigma_c \\ \rho_{ac}\sigma_a\sigma_c & \rho_{bc}\sigma_b\sigma_c & \sigma_c^2 \end{pmatrix}^{-1} \begin{pmatrix} \epsilon_a \\ \epsilon_b \\ \epsilon_c \end{pmatrix} + 2 \left[N_{\text{off}}^{\text{obs}} \cdot \ln \left(\frac{N_{\text{off}}^{\text{obs}}}{N_{\text{off}}^{\text{exp}}} \right) + N_{\text{off}}^{\text{exp}} - N_{\text{off}}^{\text{obs}} \right]$$

Cov. Matrix element

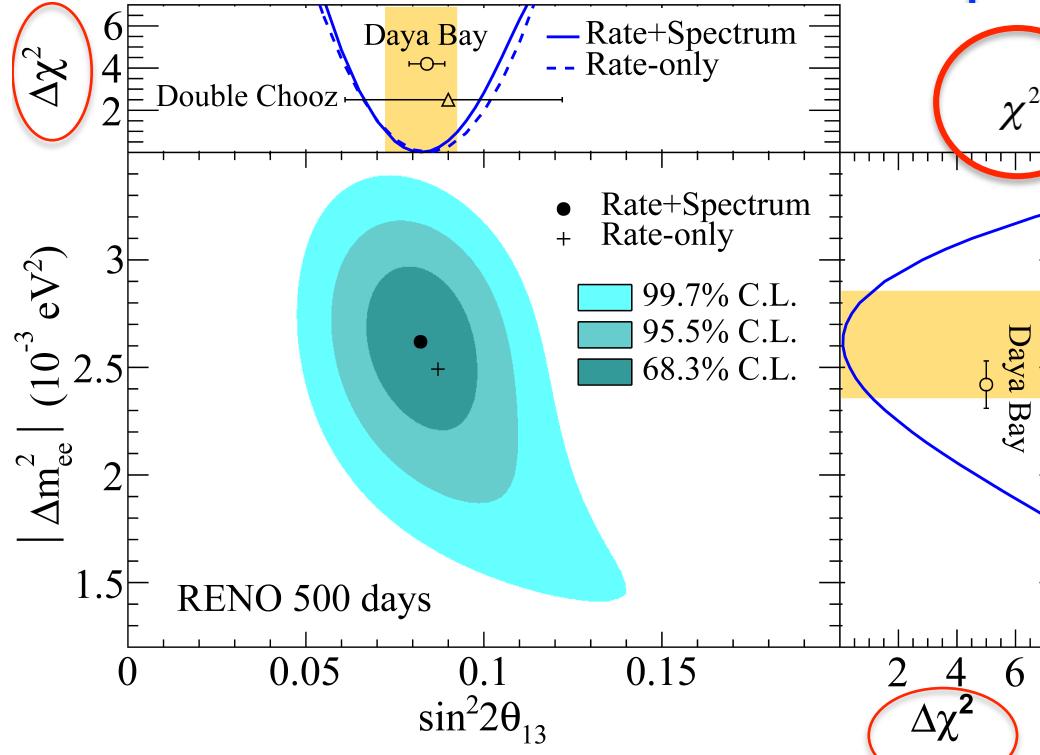
JHEP 10, 086 (2014)

$$M_{ij} = M_{ij}^{\text{stat}} + M_{ij}^{\text{flux}} + M_{ij}^{\text{eff}} + M_{ij}^{\text{Li/He(shape)}} + M_{ij}^{\text{acc(stat)}}$$

Source	Uncertainty (%)
Reactor flux	1.7
Detection efficiency	0.6
${}^9\text{Li} + {}^8\text{He}$ BG	+1.1 / -0.4
Fast-n and stop- μ BG	0.1
Statistics	0.8
Total	+2.3 / -2.0

Fit Parameter	Input Value	Best-Fit Value
Li+He bkg. (d^{-1})	$0.97^{+0.41}_{-0.16}$	0.74 ± 0.13
Fast-n + stop- μ bkg. (d^{-1})	0.604 ± 0.051	$0.568^{+0.038}_{-0.037}$
Accidental bkg. (d^{-1})	0.0701 ± 0.0026	0.0703 ± 0.0026
Residual $\bar{\nu}_e$	1.57 ± 0.47	1.48 ± 0.47
Δm^2 (10^{-3} eV^2)	$2.44^{+0.09}_{-0.10}$	$2.44^{+0.09}_{-0.10}$
E-scale ϵ_a	0 ± 0.006	$0.001^{+0.006}_{-0.005}$
E-scale ϵ_b	0 ± 0.008	$-0.001^{+0.004}_{-0.006}$
E-scale ϵ_c	0 ± 0.0006	$-0.0005^{+0.0007}_{-0.0005}$

θ_{13} & $|\Delta m^2_{ee}|$ uncertainties



PRL 116, 211801 (2016)

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat}) \pm 0.006(\text{syst})$$

$$|\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.}) (\times 10^{-3} eV^2)$$

$$\chi^2 = \sum_{P=\text{before,After}} \left\{ \sum_{i=1 \sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{\left(U_i \right)^2} \right\} + \text{Pull_Terms}$$

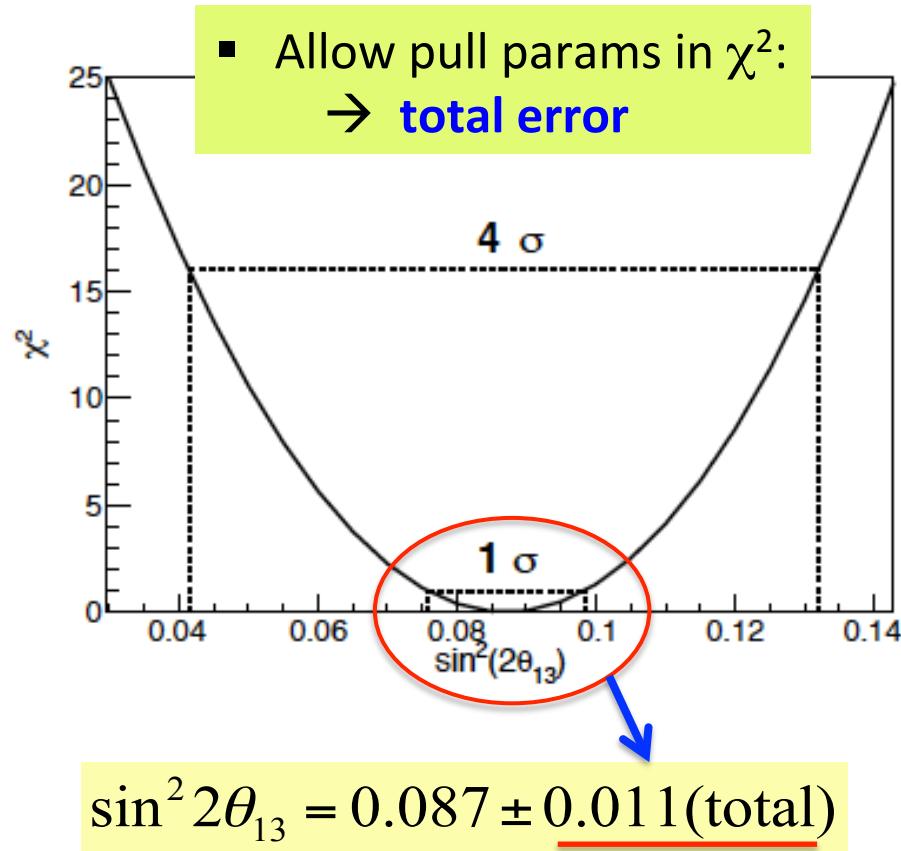
$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

$$\Delta\chi^2 = \chi^2 - \chi^2_{\min}$$

1 σ uncertainty:
 $\Delta\chi^2 = 1$

- Allow pull params in χ^2 :
 \rightarrow **total error**
- Remove pull params in χ^2 :
 \rightarrow **stat. error**

Example: Rate-only Analysis



$$\chi^2 = \sum_{P=SetA, SetB} \left\{ \frac{\frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} - \frac{N_{exp}^{F,P}}{N_{exp}^{N,P}}}{U^P} \right\}^2 + \chi_{penalty}^2$$

where

$$N_{exp}^{F,P} = \sum_{r=1}^6 [(1 + \xi + \xi_{SetB}^{SetB} + f_r) \cdot N_{exp}^{F,P,r}] - b_F^P - \beta_F^P \cdot S_{LH}^F$$

$$N_{exp}^{N,P} = \sum_{r=1}^6 [(1 + \xi_N^{SetB} + f_r) \cdot N_{exp}^{N,P,r}] - b_N^P - \beta_N^P \cdot S_{LH}^N$$

$$U^P = \frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} \sqrt{\frac{N_{obs}^{F,P} + N_{bkg}^{F,P}}{\left(N_{obs}^{F,P}\right)^2} + \frac{N_{obs}^{N,P} + N_{bkg}^{N,P}}{\left(N_{obs}^{N,P}\right)^2}}$$

and

$$\begin{aligned} \chi_{penalty}^2 &= \left(\frac{\xi}{\sigma_\xi} \right)^2 + \sum_{d=F,N} \left(\frac{\xi_d^{SetB}}{\sigma_{\xi_d}} \right)^2 \\ &\quad + \sum_{r=1}^6 \left(\frac{f_r}{\sigma_{f_r}} \right)^2 + \sum_{P,d} \left(\frac{b_d^P}{\sigma_{b_d}^P} \right)^2 + \sum_d \left(\frac{S_{LH}^d}{\sigma_{LH}^d} \right)^2 \end{aligned}$$

Example: Rate-only Analysis

$$\chi^2 = \sum_{P=SetA, SetB} \left\{ \frac{\frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} - \frac{N_{exp}^{F,P}}{N_{exp}^{N,P}}}{U^P} \right\}^2 + \chi^2_{penalty}$$

where

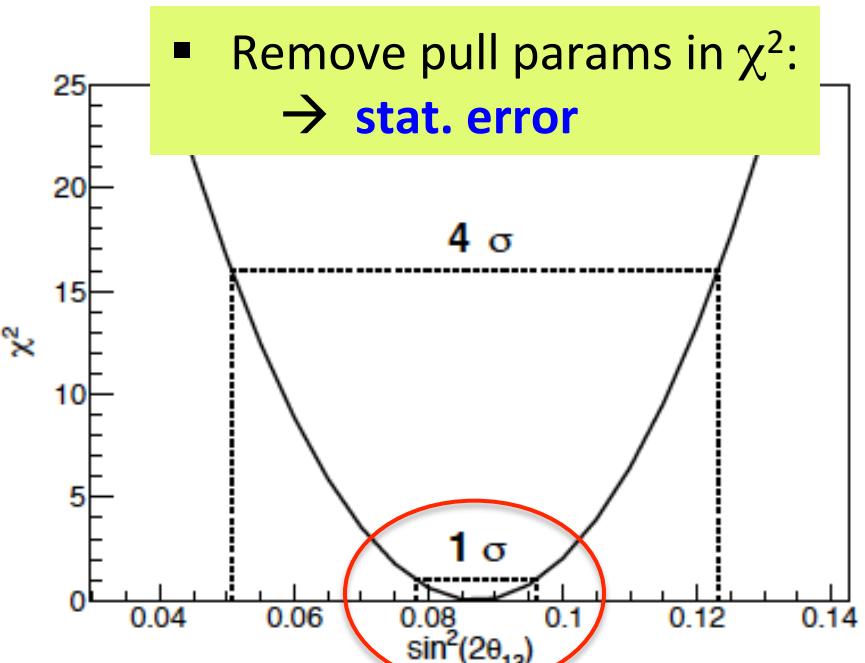
$$N_{exp}^{F,P} = \sum_{r=1}^6 [(1 + \xi + \xi_{SetB}^{SetB} + f_r) \cdot N_{exp}^{F,P,r}] - b_F^P - \beta_F^P \cdot S_{LH}^F$$

$$N_{exp}^{N,P} = \sum_{r=1}^6 [(1 + \xi_{SetB}^{SetB} + f_r) \cdot N_{exp}^{N,P,r}] - b_N^P - \beta_N^P \cdot S_{LH}^N$$

$$U^P = \frac{N_{obs}^{F,P}}{N_{obs}^{N,P}} \sqrt{\frac{N_{obs}^{F,P} + N_{bkg}^{F,P}}{(N_{obs}^{F,P})^2} + \frac{N_{obs}^{N,P} + N_{bkg}^{N,P}}{(N_{obs}^{N,P})^2}}$$

and

$$\begin{aligned} \chi^2_{penalty} &= \left(\frac{\xi}{\sigma_\xi} \right)^2 + \sum_{d=F,N} \left(\frac{\xi_d^{SetB}}{\sigma_{\xi_d}} \right)^2 \\ &= \sum_{r=1}^6 \left(\frac{f_r}{\sigma_{f_r}} \right)^2 + \sum_{P,d} \left(\frac{b_d^P}{\sigma_{b_d}^P} \right)^2 + \sum_d \left(\frac{S_{LH}^d}{\sigma_{LH}^d} \right)^2 \end{aligned}$$

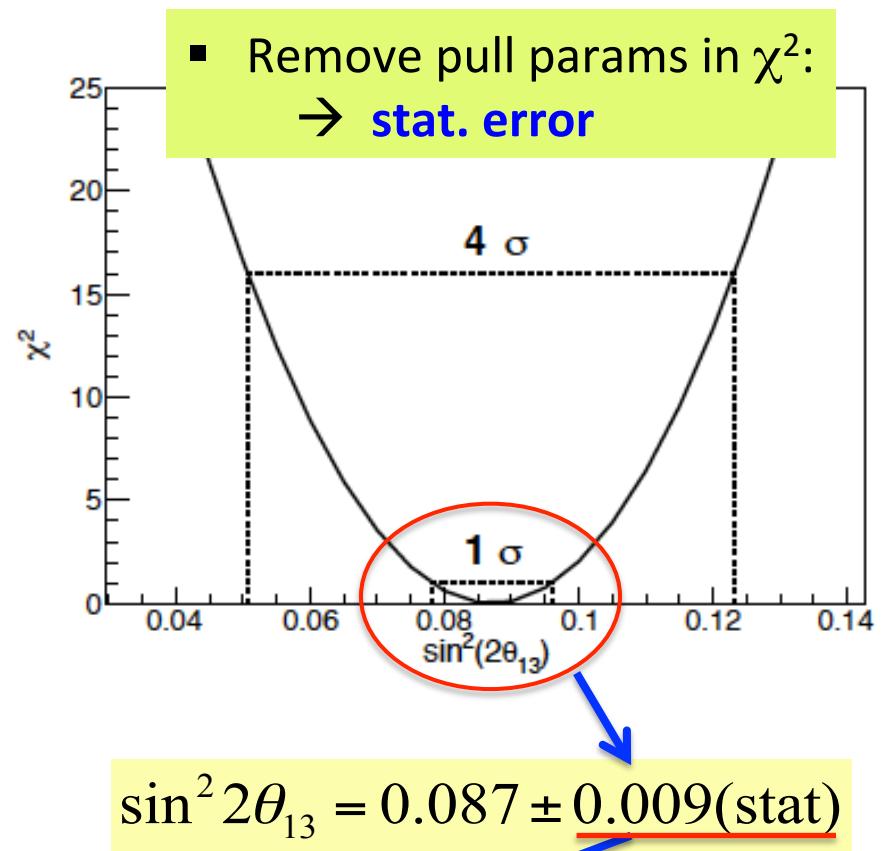
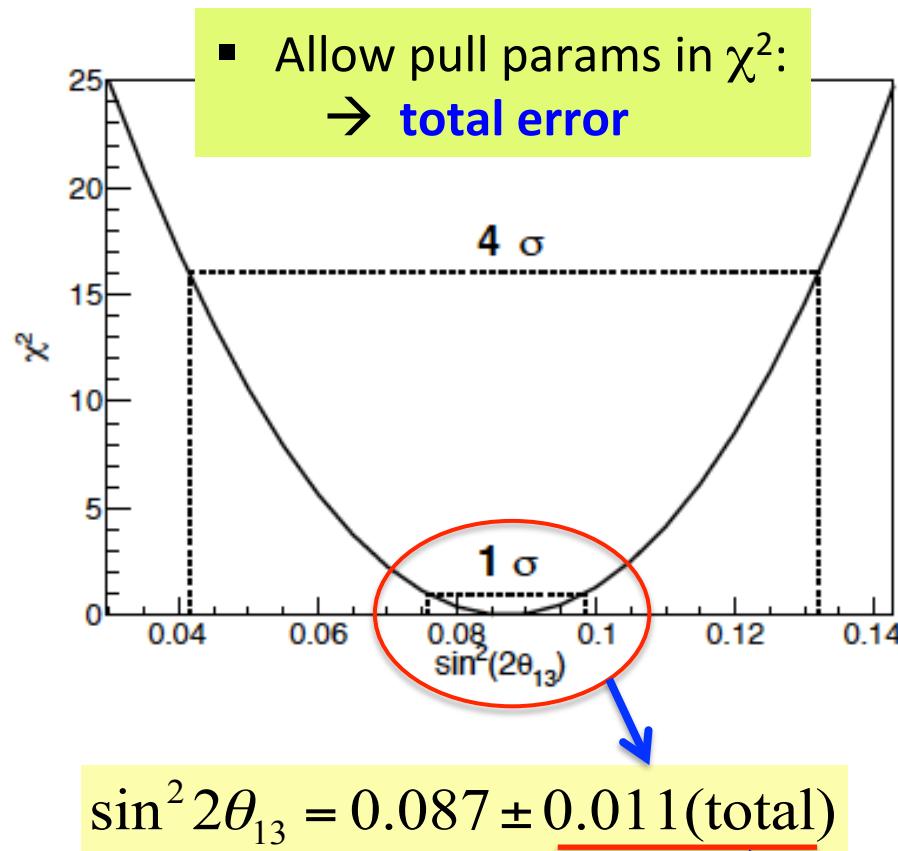


$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat})$$

$$\delta_{syst.}^2 = \delta_{total}^2 - \delta_{stat.}^2$$

$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat}) \pm 0.007(\text{syst})$$

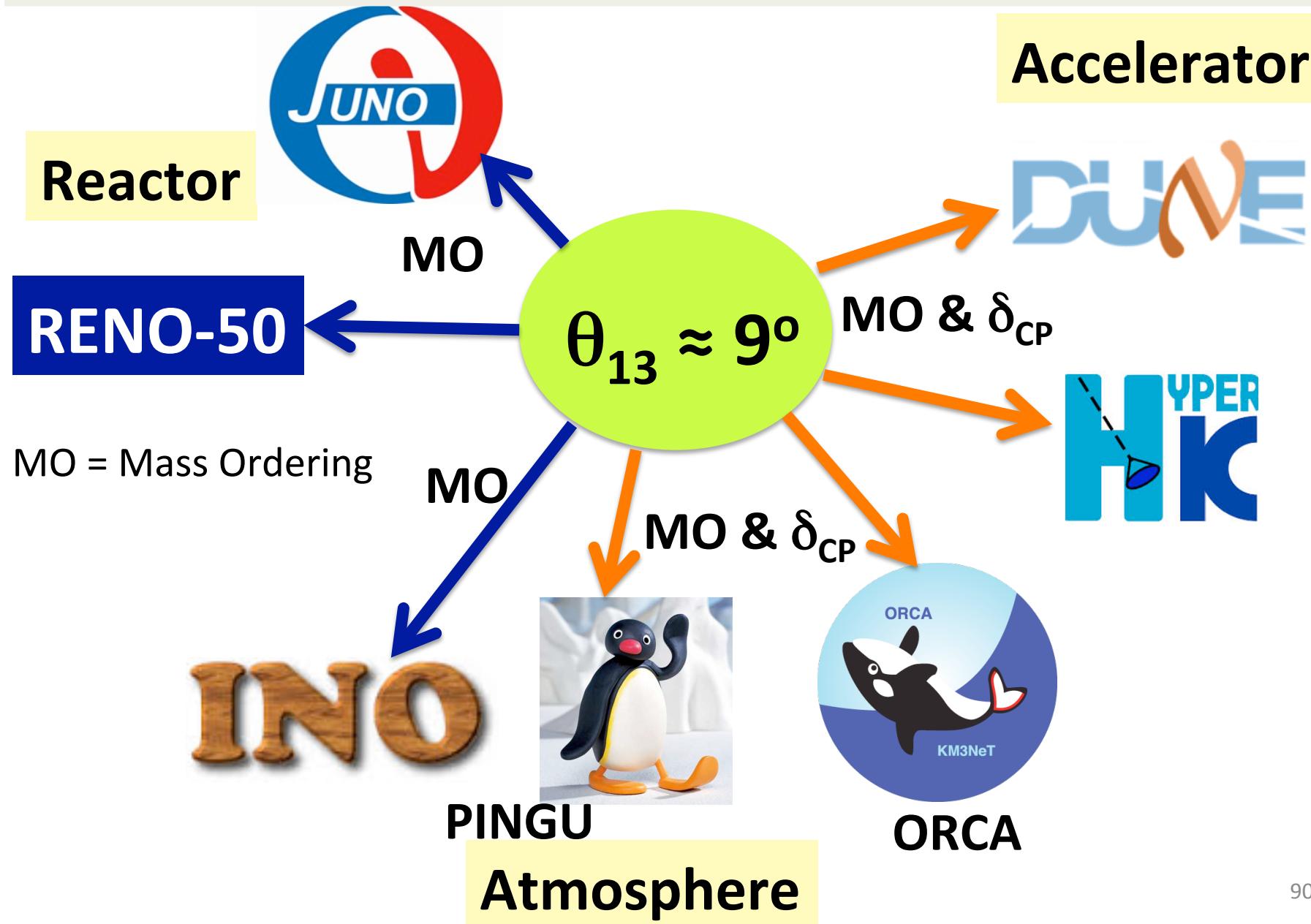
Example: Rate-only Analysis



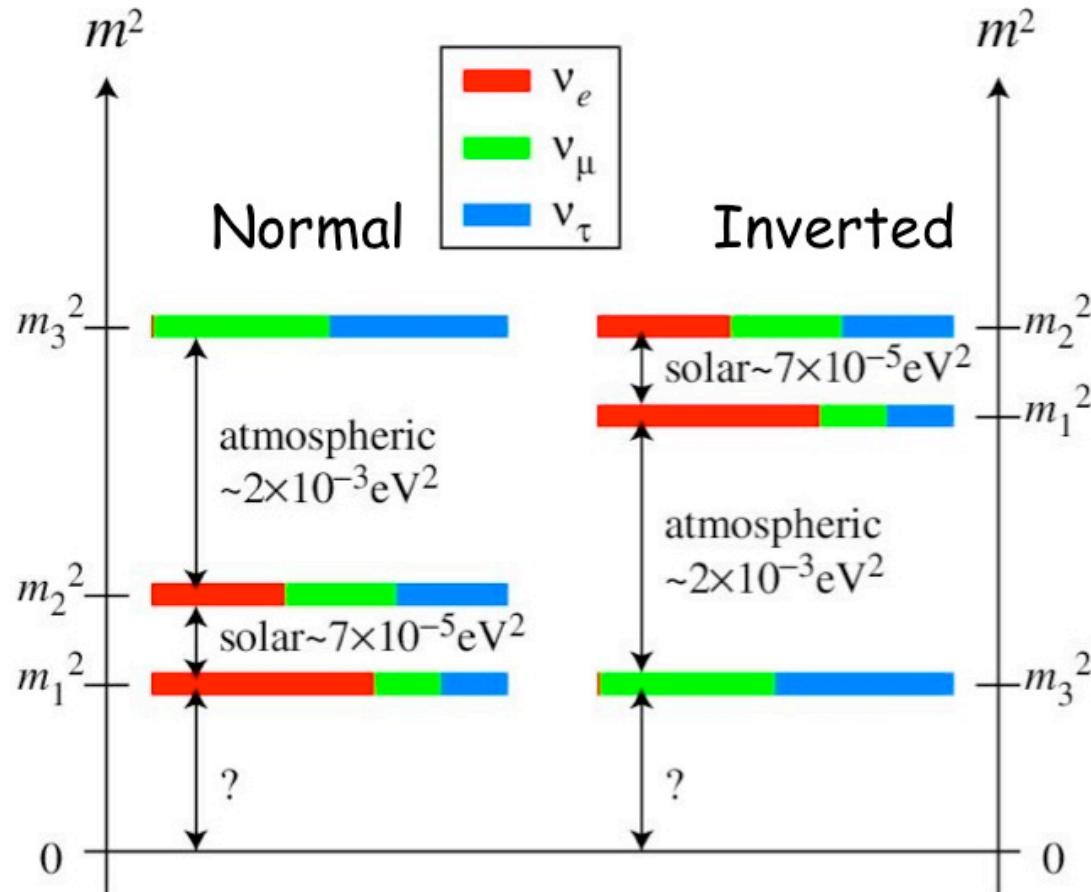
$$\delta_{\text{syst.}}^2 = \delta_{\text{total}}^2 - \delta_{\text{stat.}}^2$$

RENO
Rate-only → $\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat}) \pm 0.007(\text{syst})$
result

θ_{13} and Future Experiments



Neutrino Mass Ordering w/ Reactors: JUNO & RENO-50



MO determination
w/ reactor neutrinos

- **No δ_{CP} dependence**
- **No matter effect**

Mass Ordering Term in P_{ee}

$$P_{ee} = \left| \sum_{i=1}^3 U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$

ν_e Survival probability

$$= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta_{21})$$

Exercise

$$- \sin^2 2\theta_{13} \sin^2 (|\Delta_{31}|)$$

$$- \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 (\Delta_{21}) \cos (2|\Delta_{31}|)$$

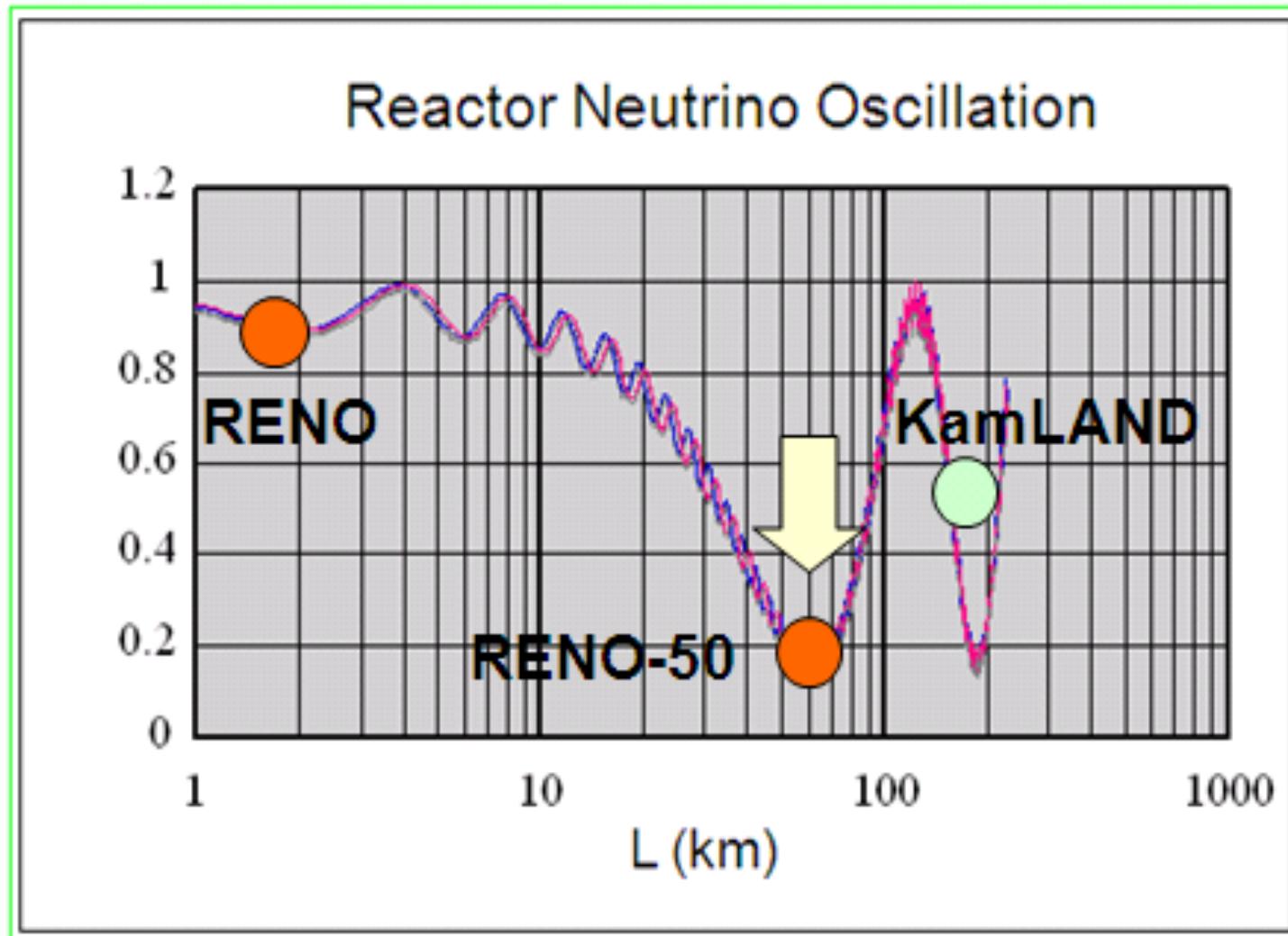
$$\pm \frac{\sin^2 \theta_{12}}{2} \sin^2 2\theta_{13} \sin (2\Delta_{21}) \sin (2|\Delta_{31}|)$$



Mass Hierarchy
difference

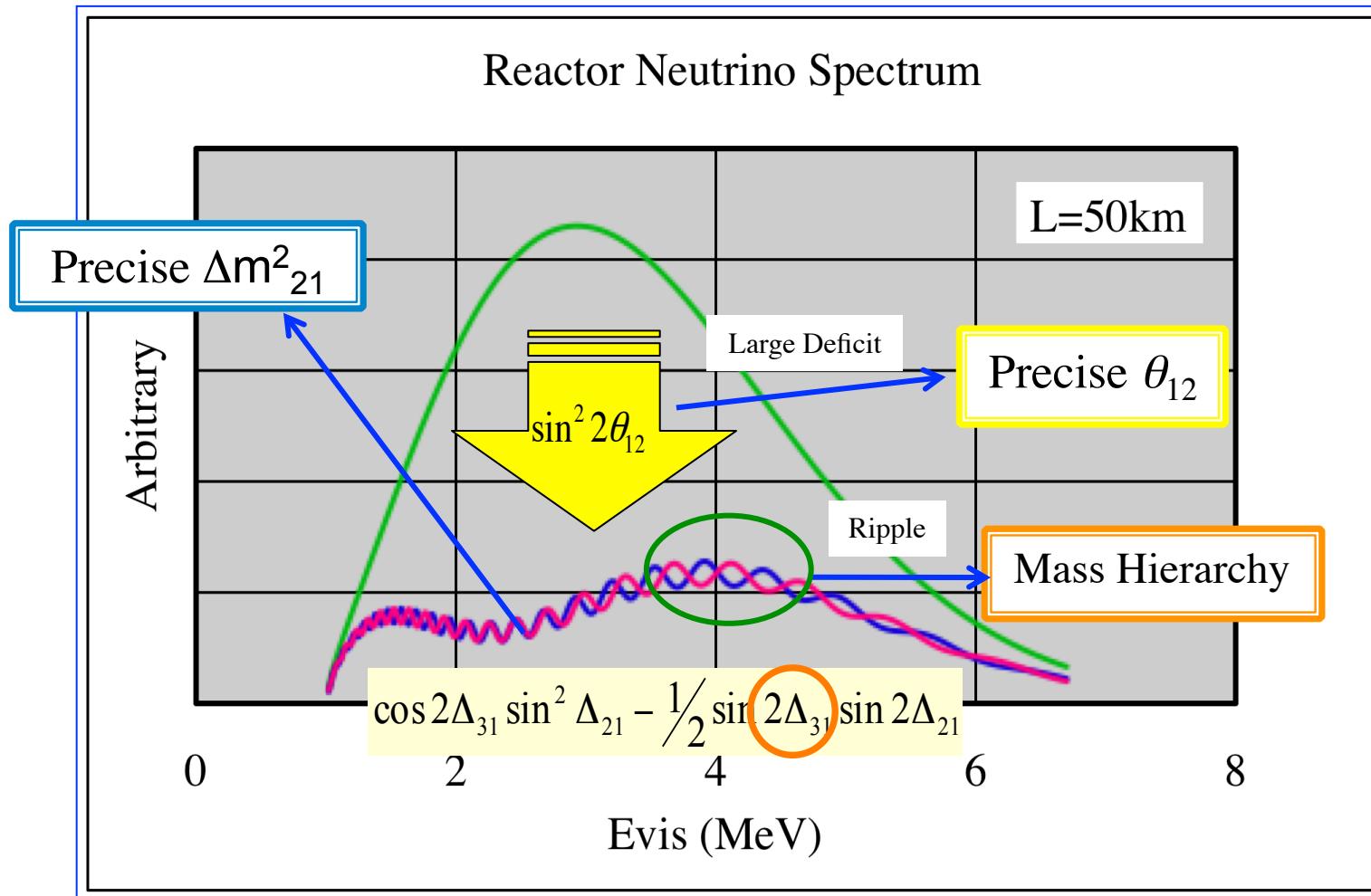
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2),$$

Reactor Neutrino Oscillations at 50-60 km



Reactor Neutrino Oscillations at 50-60 km

$$P_R(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \left\{ \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} + \sin^2 2\theta_{13} \sin^2 \Delta_{31} \right. \\ \left. + \sin^2 2\theta_{13} \sin^2 \theta_{12} \left(\cos 2\Delta_{31} \sin^2 \Delta_{21} - \frac{1}{2} \sin 2\Delta_{31} \sin 2\Delta_{21} \right) \right\}$$



Important Factors for MO Determination w/ reactors

- Energy resolution
- Absolute energy scale
- Energy non-linearity

Energy Resolution

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

Stochastic term “a”:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_{N_{pe}}}{N_{pe}} \approx \frac{1}{\sqrt{N_{pe}}}$$

- “a” is determined by p.e. statistics
- better light yield leads to better ...

Constant term “b”:

- Stability of calibration (T, radiation,..)
- Loss of energy (leakage, dead material)
- etc...

Noise term “c”:

- caused by random processes, such as, PMT, thermal, and electronic noises

To achieve better σ_E/E

- Increasing PMT coverage

$\sim 34\% \rightarrow \sim 70 \text{ to } 80\%$

- Increasing PMT QE

$\sim 20\% \rightarrow \sim 35\%$

- Increasing attenuation length

$\sim 12 \text{ m} \rightarrow 20 \text{ m}$

- High Light Yield LS

$\times 1.5 (1.5 \text{ g/l PPO} \rightarrow 5 \text{ g/l PPO})$

Savannah river experiment observed reactor-dependent signal (Apr. 1956).

Signal/Background: ~ 3:1

In June of 1956, they sent a telegram to Pauli:

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.²²

- A Science article reported that the observed cross section was within 5% of the $6.3 \times 10^{-44} \text{ cm}^2$ expected (although the predicted cross section has a 25% uncertainty).
- In 1959, following the discovery of parity violation in 1956, the theoretical cross section was increased by $\times 2$ to $(10 \pm 1.7) \times 10^{-44} \text{ cm}^2$
- In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma = (12^{+7}_{-4}) \times 10^{-44} \text{ cm}^2$

Spallation Produced Radio-Isotopes in Liquid Scintillator

	Isotope	t _{1/2}	E _{max} (MeV)	Background
β^-	¹² B	0.02 s	13.4	Uncorrelated
	¹¹ Be	13.80 s	11.5	Uncorrelated
	¹¹ Li	0.09 s	20.8	Correlated
	⁹ Li	0.18 s	13.6	Correlated
	⁸ Li	0.84 s	16.0	Uncorrelated
	⁸ He	0.12 s	10.6	Correlated
	⁶ He	0.81 s	3.5	Uncorrelated
β^+, EC	¹¹ C	20.38 m	0.96	Uncorrelated
	¹⁰ C	19.30 s	1.9	Uncorrelated
	⁹ C	0.13 s	16.0	Uncorrelated
	⁸ B	0.77 s	13.7	Uncorrelated
	⁷ Be	53.3 d	0.48	Uncorrelated

World Nuclear Power Reactors II

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia, China	277	257	enriched UO ₂	water	water
Boiling water reactor (BWR)	US, Japan, Sweden	80	75	enriched UO ₂	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	25	natural UO ₂	heavy water	heavy water
Gas-cooled reactor (AGR & Magnox)	UK	15	8	natural U (metal), enriched UO ₂	CO ₂	graphite
Light water graphite reactor (RBMK & EGP)	Russia	11 + 4	10.2	enriched UO ₂	water	graphite
Fast neutron reactor (FBR)	Russia	2	0.6	PuO ₂ and UO ₂	liquid sodium	none
TOTAL		438	376			

IAEA data, end of 2014. GWe = capacity in thousands of megawatts (gross)

Source: *Nuclear Engineering International Handbook 2011*, updated to 1/1/12