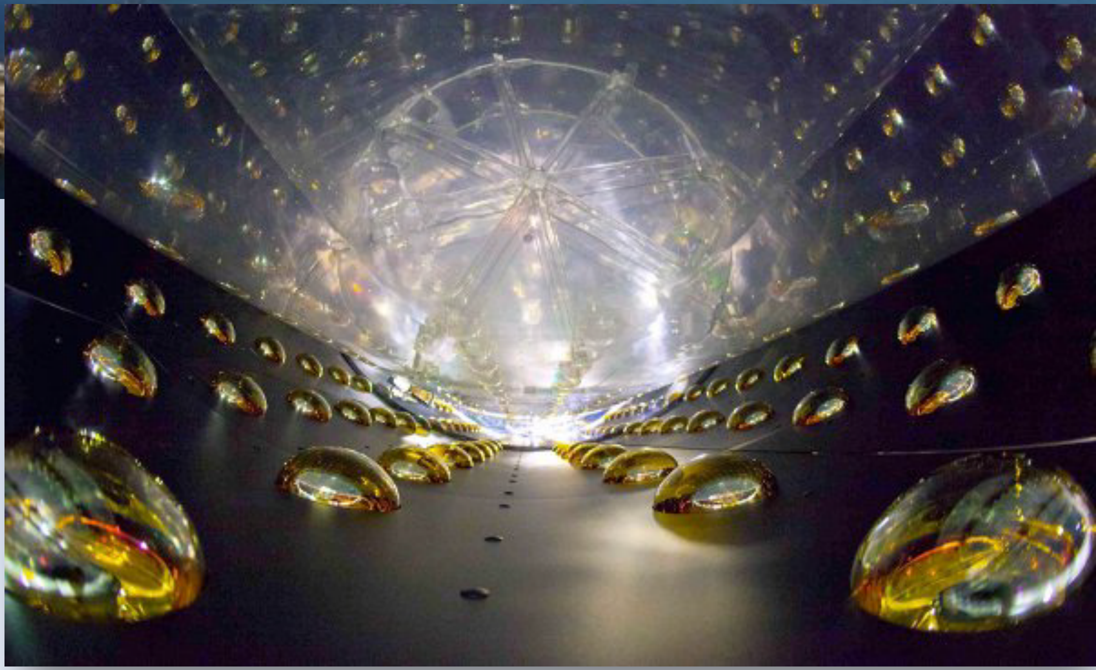
NEUTRINOS: *Masters of Surprise*



R. D. McKeown

UVa Physics Colloquium
Nov. 22, 2013

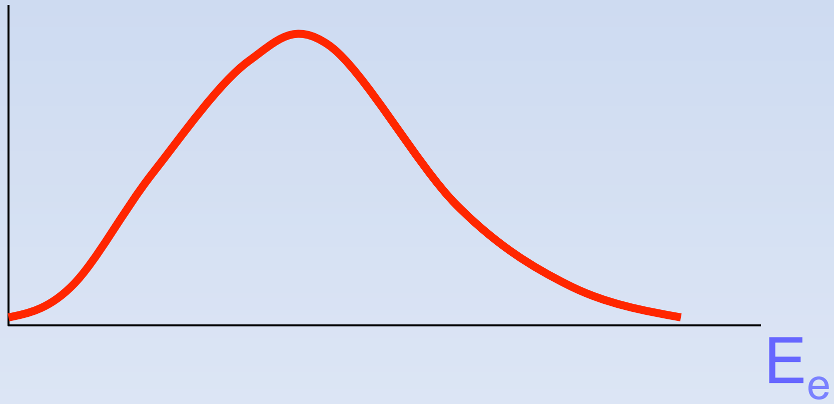
Outline

- Introduction to neutrinos and oscillations
- Reactor antineutrino experiments
- KamLAND
- Daya Bay
- Future experiments
- Conclusions

Nuclear Beta Decay

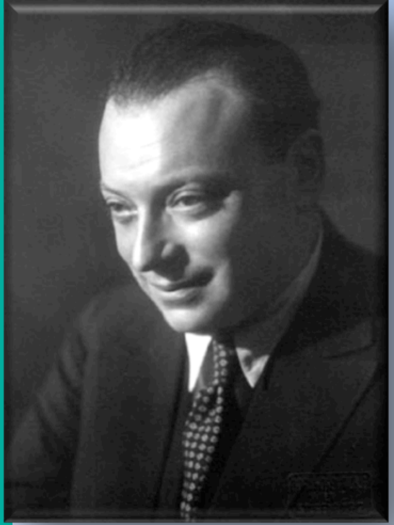
- Since 1920's physicists have observed beta decay (e.g. $^{14}C \rightarrow\ ^{14}N + e^-$)

- But the electron energy distribution is continuous:



- Where did the energy go??

Pauli's letter of the 4th of December 1930



Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li⁶ nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses> The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

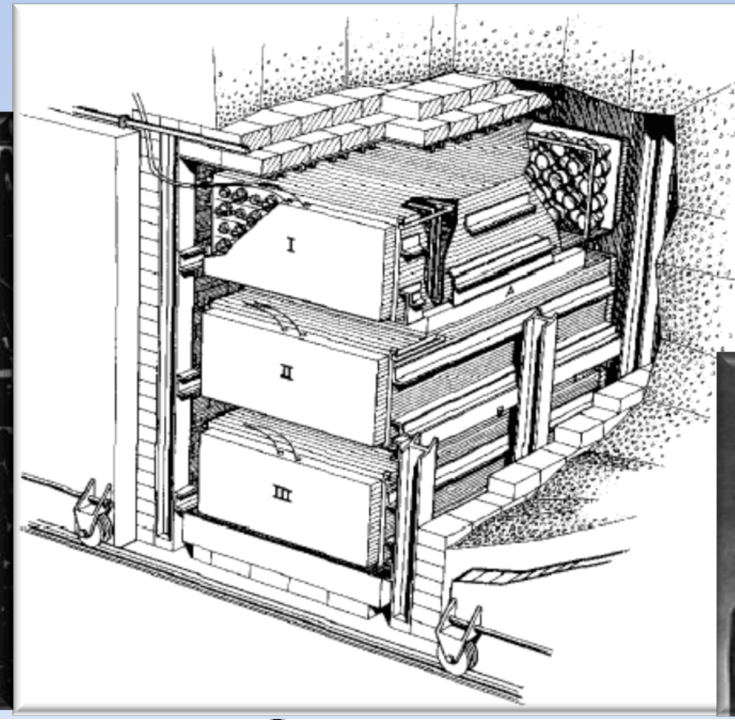
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

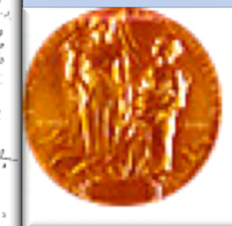
Your humble servant
. W. Pauli

"I have done a terrible thing, I have postulated a particle that cannot be detected."

Surprise: Detectable after all!

Discovery of the Neutrino – 1956
Reines and Cowan





Finally, we chose to look for the reaction $\bar{\nu}_e + p \rightarrow n + e^+$. If the free neutrino exists, this inverse beta decay reaction has to be there

F. Reines, Nobel Lecture, 1995

1967: Solar Neutrino Surprise

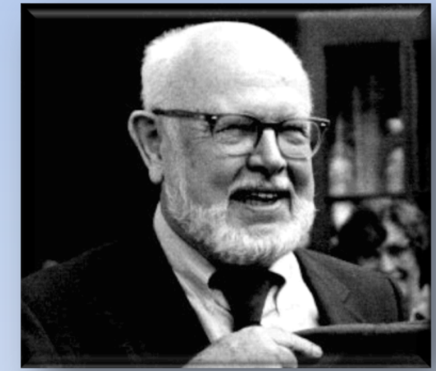
August 11, 1967

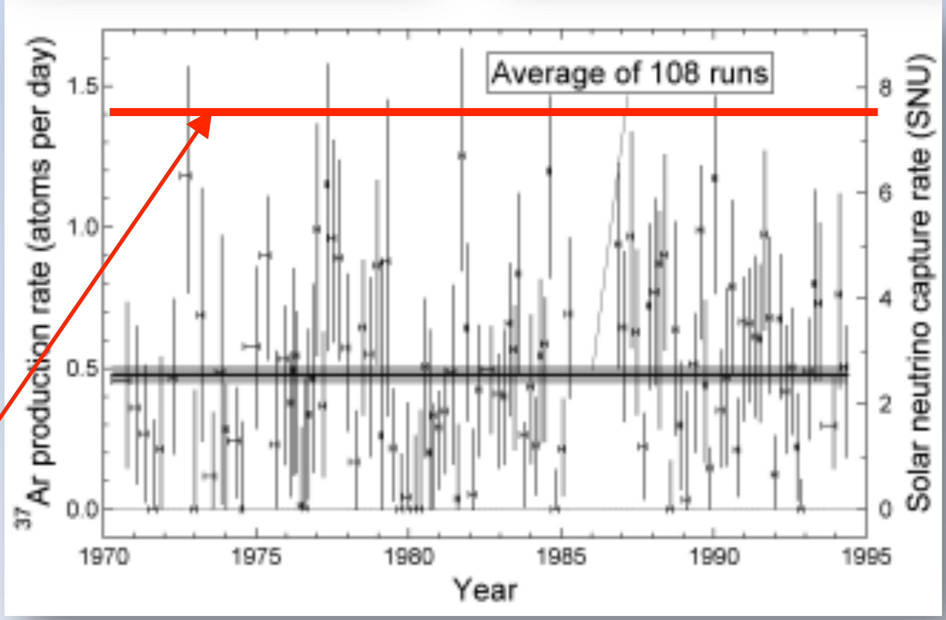
Dear Willy,

I do have a preliminary result from our first good run…

This limit is quite low…

Please regard these results as very preliminary. There are several points that must be checked before we are certain this is a bonafide observation. I will collect another sample in September–we are ready now, turn on the sun.





Standard Solar Model Calculation

Subsequent History

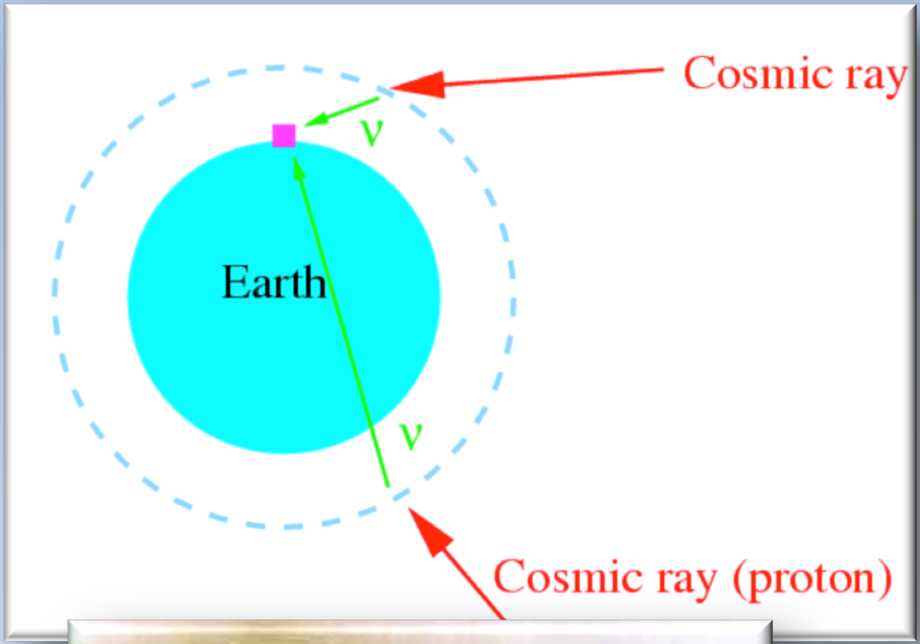
- 60's and 70's – n's studied in accelerator-based production:

  $n_e \neq n_m$

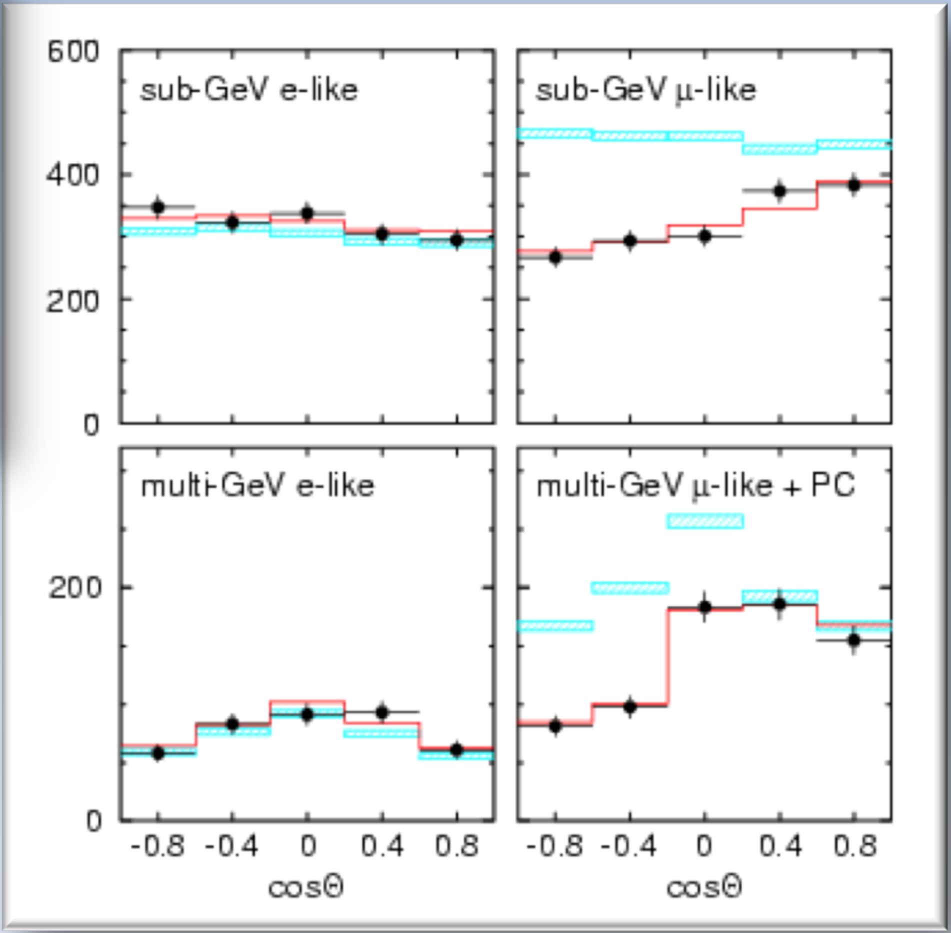
- 1980-present: the quest for neutrino mass and oscillations - n's as dark matter??

"All you have to do is imagine something that does practically nothing.
You can use your son-in-law as a prototype."

1998: Surprise!

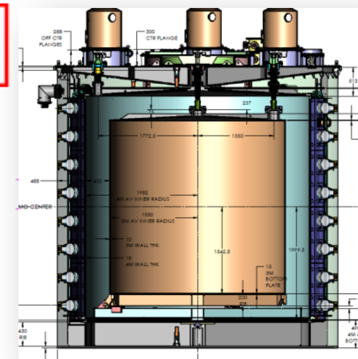


Super-Kamiokande reports first evidence for neutrino oscillations!



Neutrino Mass and Mixing

Two Generation Model



$$|\bar{\nu}_e\rangle \xrightarrow{\quad L \quad} A_e\,|\bar{\nu}_e\rangle + A_\mu\,|\bar{\nu}_\mu\rangle$$

$\bar{\nu}_1, \bar{\nu}_2$ mass eigenstates m_1, m_2

$$|\bar{\nu}_e\rangle = \cos\theta\,|\bar{\nu}_1\rangle + \sin\theta\,|\bar{\nu}_2\rangle$$

$$\Delta m^2 = m_1^2 - m_2^2$$

$$P_\mu = |A_\mu|^2 = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

$$P_e = |A_e|^2 = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

Requires:

- Neutrinos have nonzero mass
- Flavor mixing

Three Generations of Neutrinos

Pontecorvo Maki – Nakagawa – Sakata Matrix

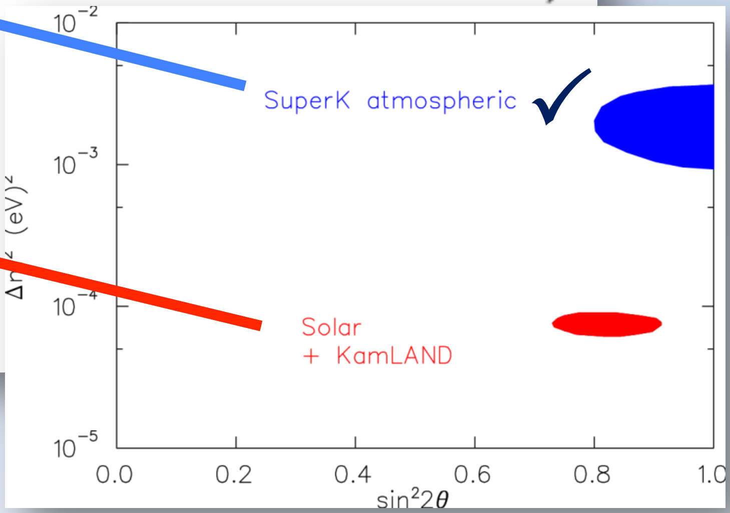
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

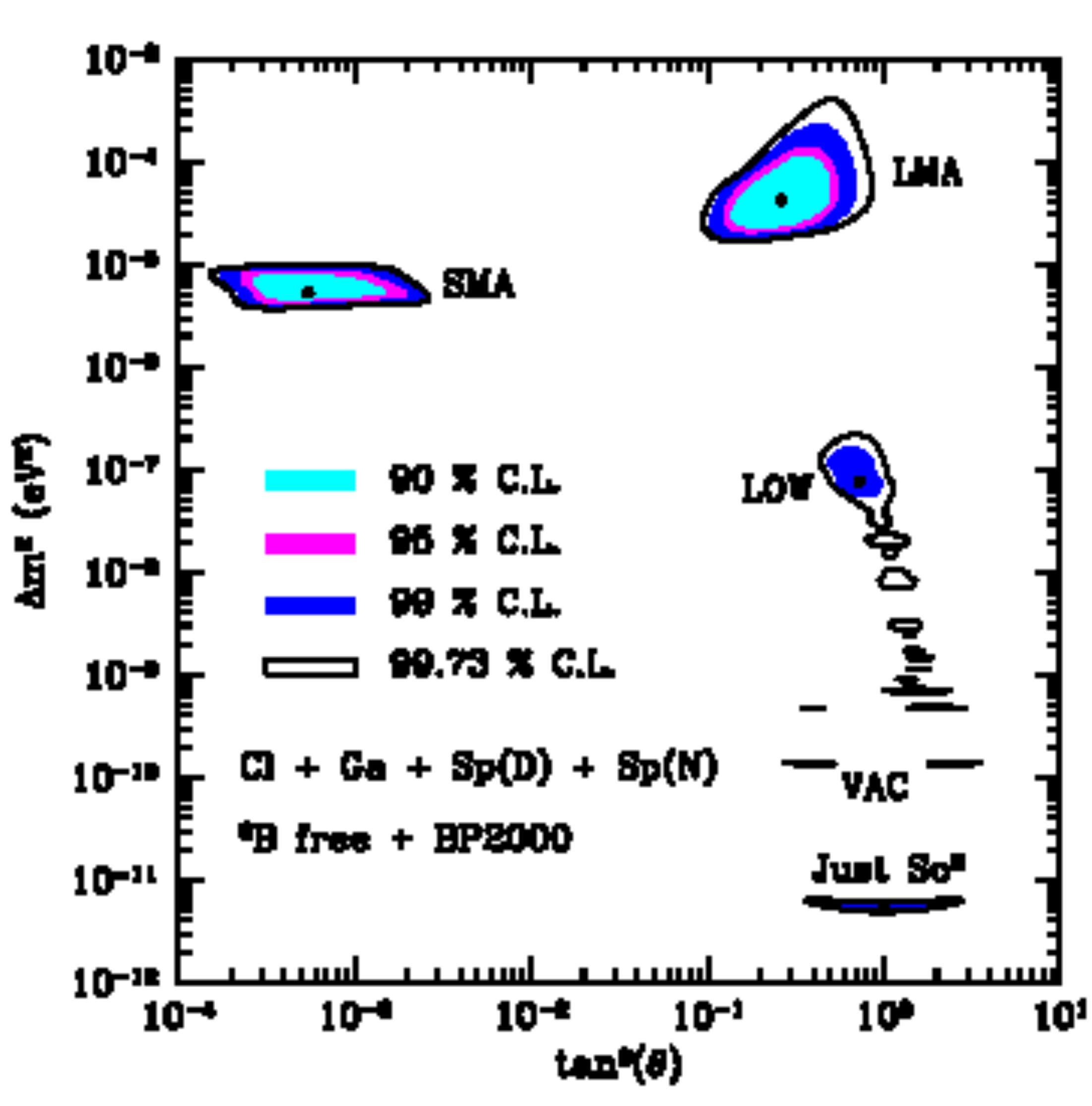
$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

3^{rd} mixing angle

CP violation

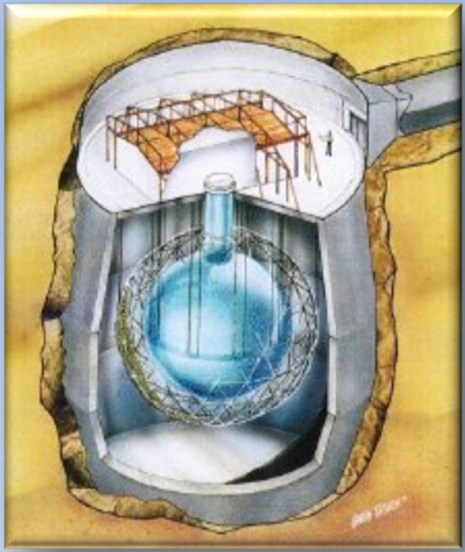


More Solar Neutrino Results



(Bahcall, Krastev and Smirnov, 2001)

<u>2002</u>: SNO finds missing solar neutrinos!!



Measured neutral current process:

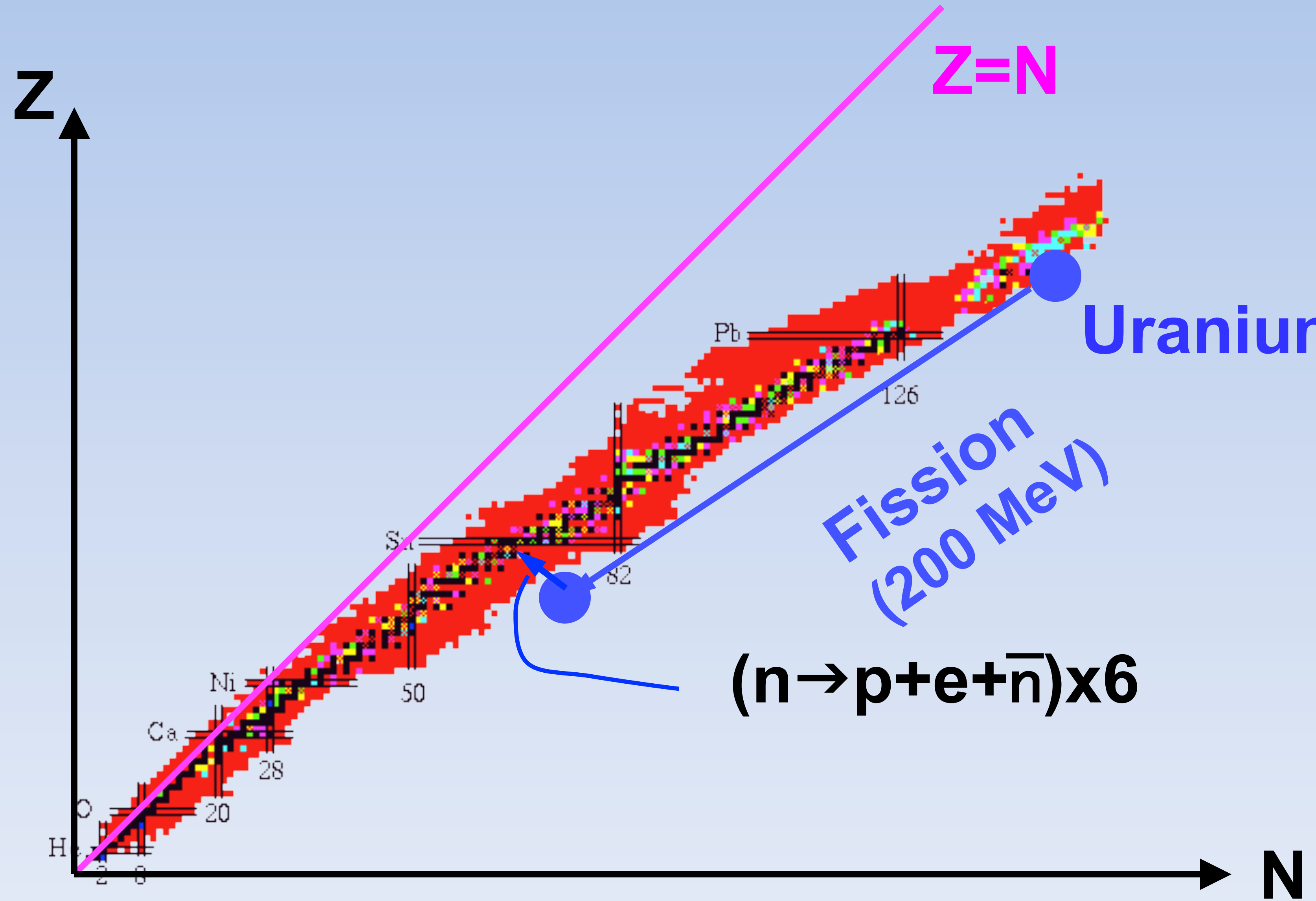
$$n_x + d \rightarrow n_x + p + n$$

$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst}) \times 10^6 \text{ /cm}^2\text{s}$$

$$f_{SSM} = 5.15 \times 10^6 \text{ /cm}^2\text{s}$$

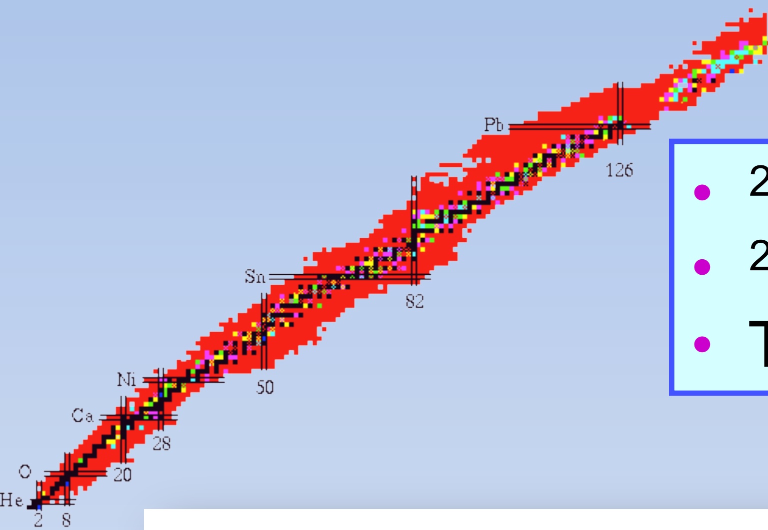
- $\overline{n}_e$ from n-rich fission products
- detection via inverse beta decay ($\overline{n}_e + p \rightarrow e^+ + n$)
- Measure flux and <u>energy spectrum</u>

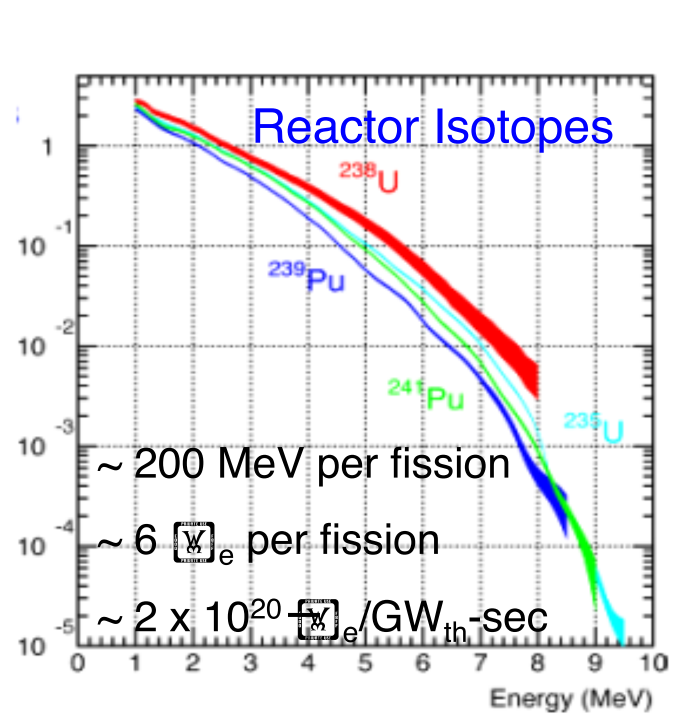
Nuclear Reactors make Antineutrinos



The Reactor Neutrino Flux and Spectrum

- ^{235}U, ^{239}Pu, ^{241}Pu from b measurements
- ^{238}U calculated
- Time dependence due to fuel cycle

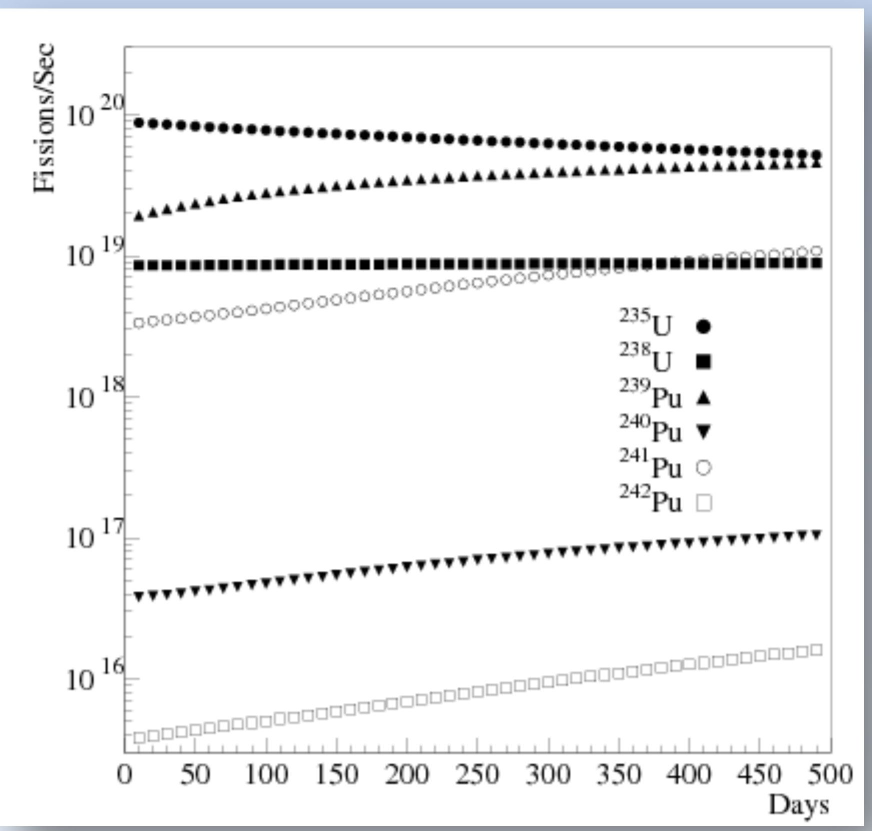




~ 200 MeV per fission

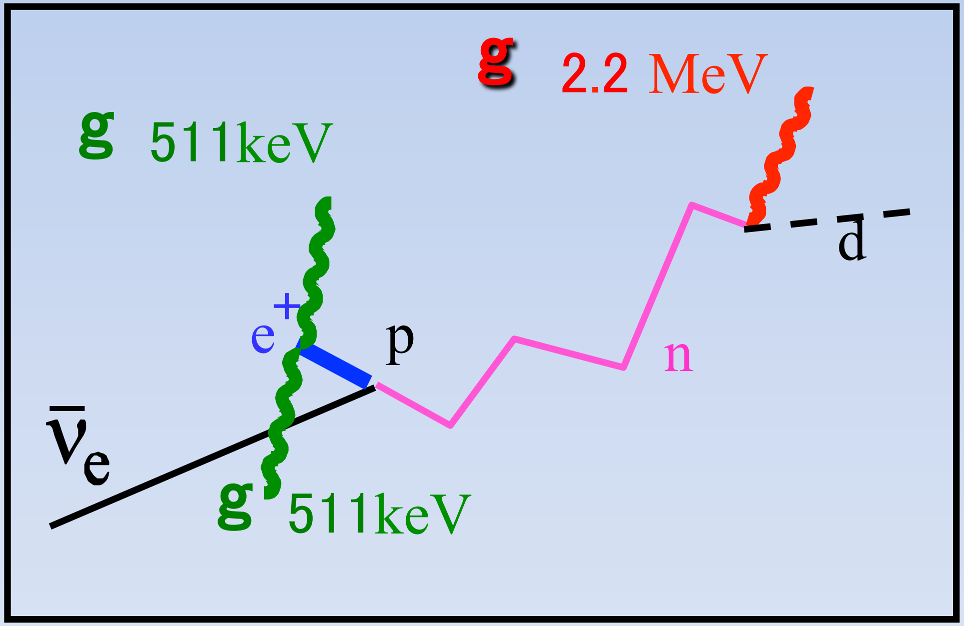
~ 6 $\bar{\nu}_e$ per fission

~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec



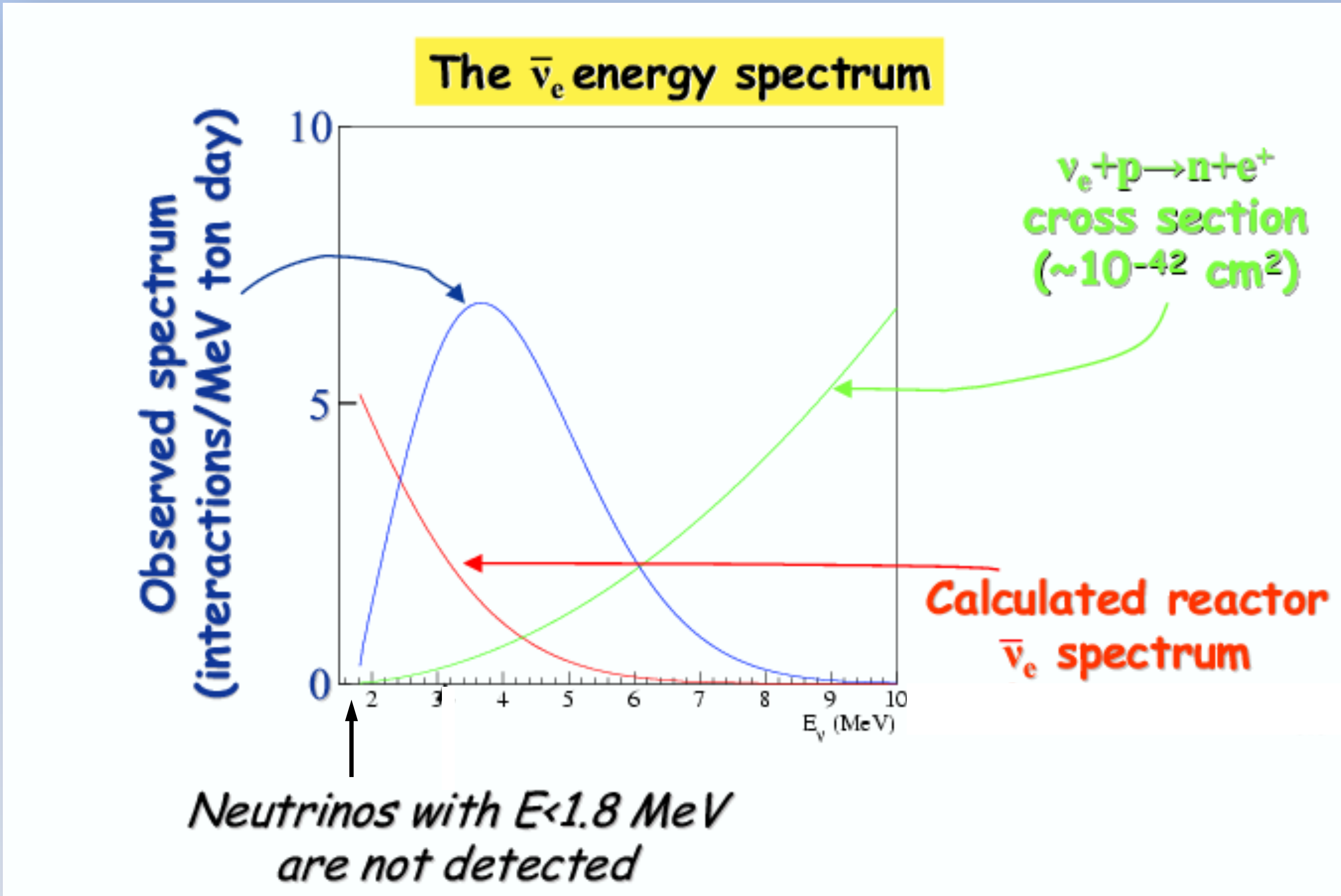
Detection Signal

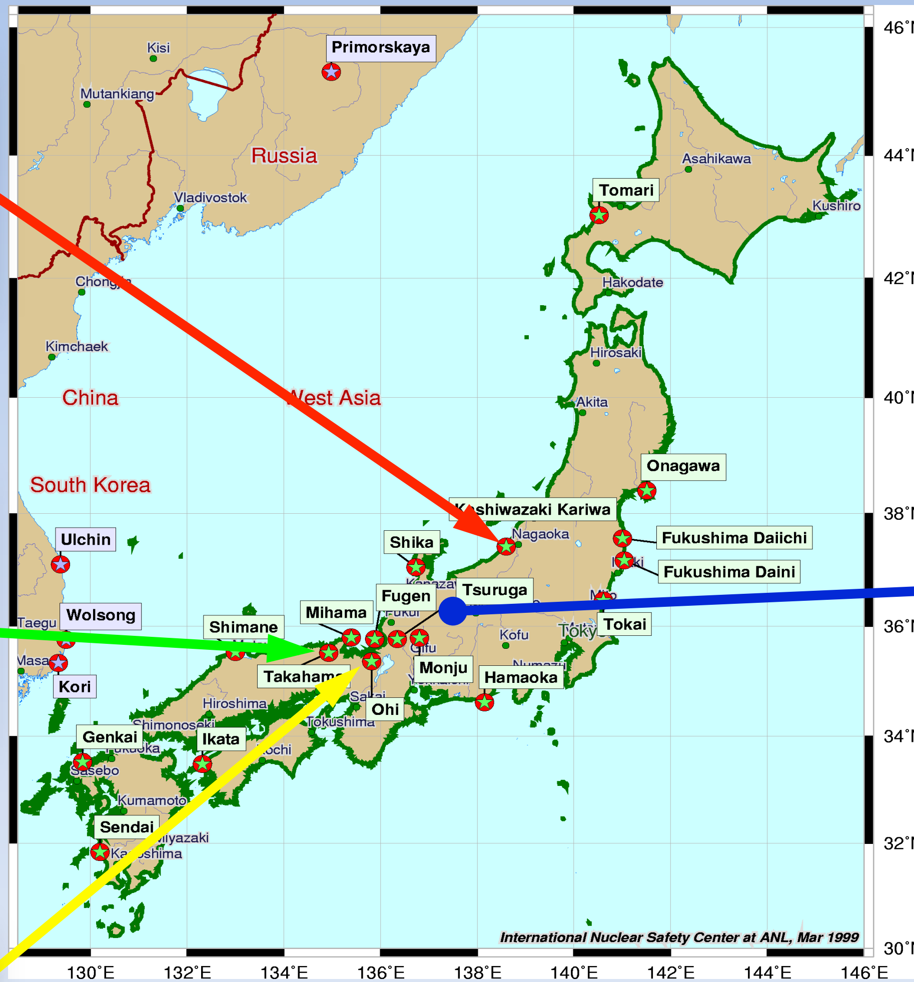
$$\overline{n} + p \rightarrow n + e^+$$



Coincidence signal:

- Prompt: e^+ annihilation → $E_n = E_{prompt} + \overline{E}_n + 0.8$ MeV
- Delayed: **n+p** 180 *m*s capture time, 2.2 MeV
  n+Gd 30 *m*s capture time, 8 MeV


The $\bar{\nu}_e$ energy spectrum
Observed spectrum (interactions/MeV ton day)
10
5
0
2
3
4
5
6
7
8
9
10
E_ν (MeV)
$\nu_e + p \rightarrow n + e^+$ cross section ($\sim 10^{-42}$ cm^2)
Calculated reactor $\bar{\nu}_e$ spectrum
Neutrinos with E<1.8 MeV are not detected

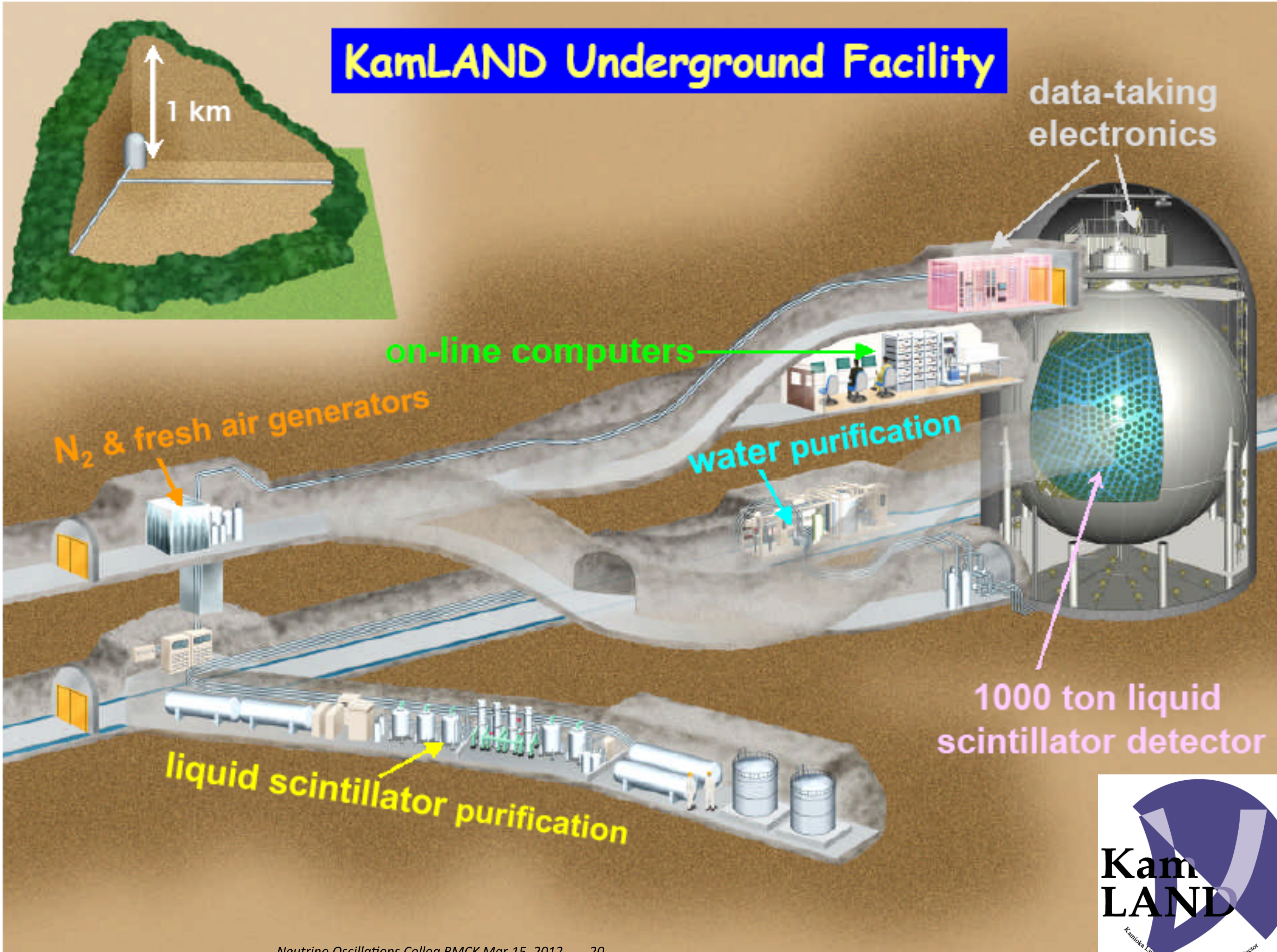


KamLAND used the entire Japanese nuclear power industry as a long-baseline neutrino source

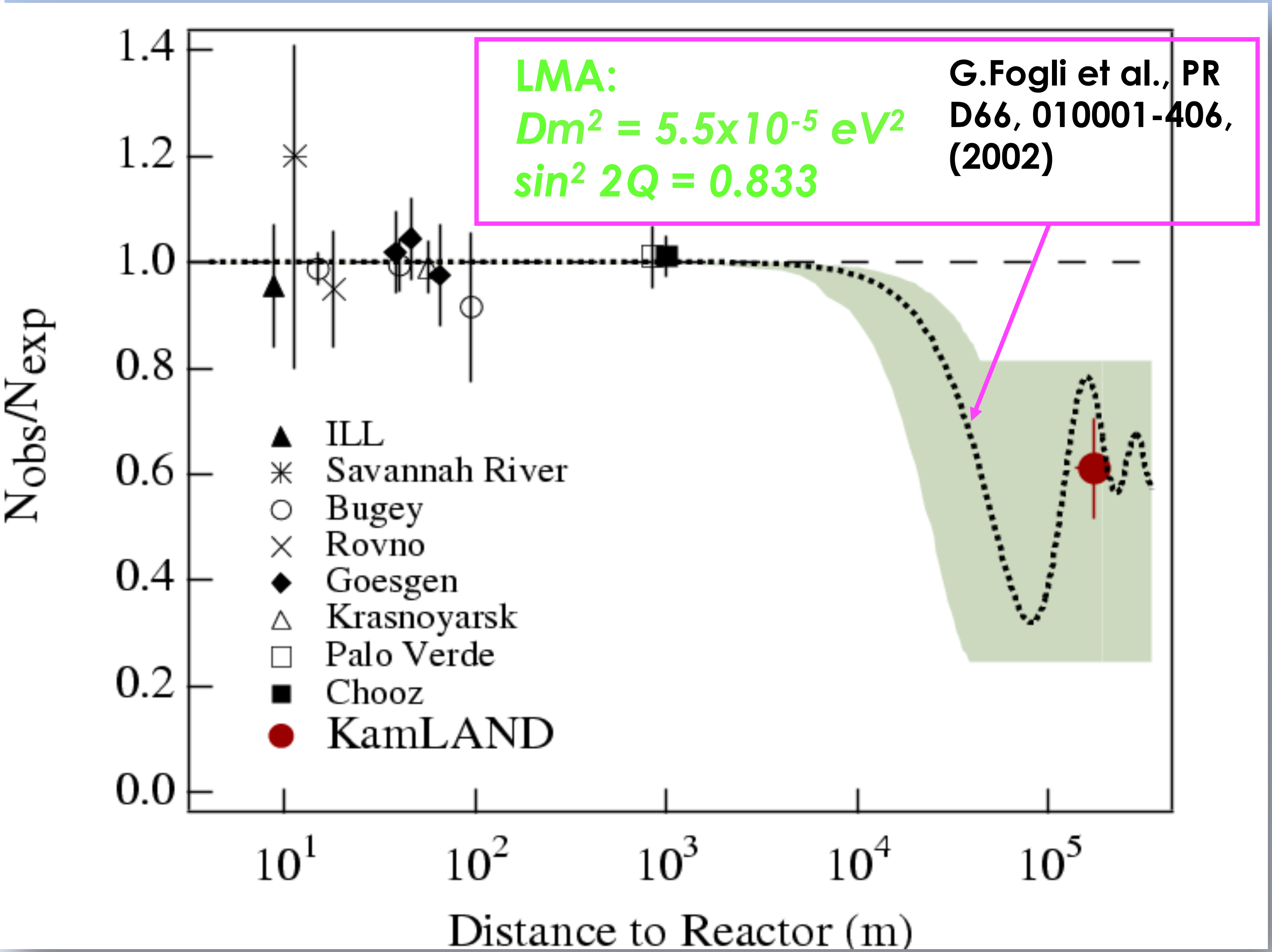
KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

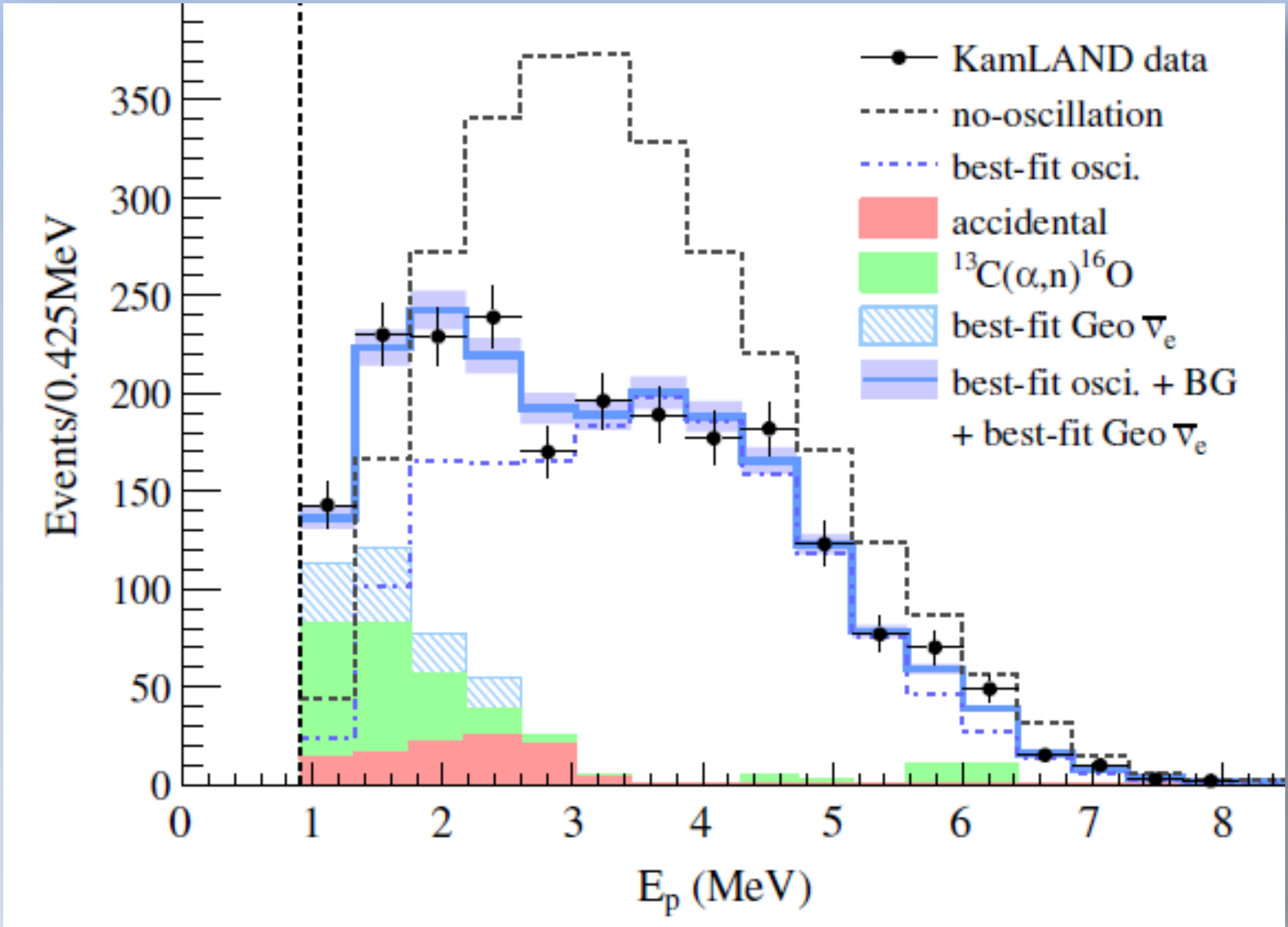
Neutrinos were "free of charge"


KamLAND Underground Facility
1 km
data-taking
electronics
on-line computers
N_2 & fresh air generators
water purification
1000 ton liquid
scintillator detector
liquid scintillator purification
Kam
LAND

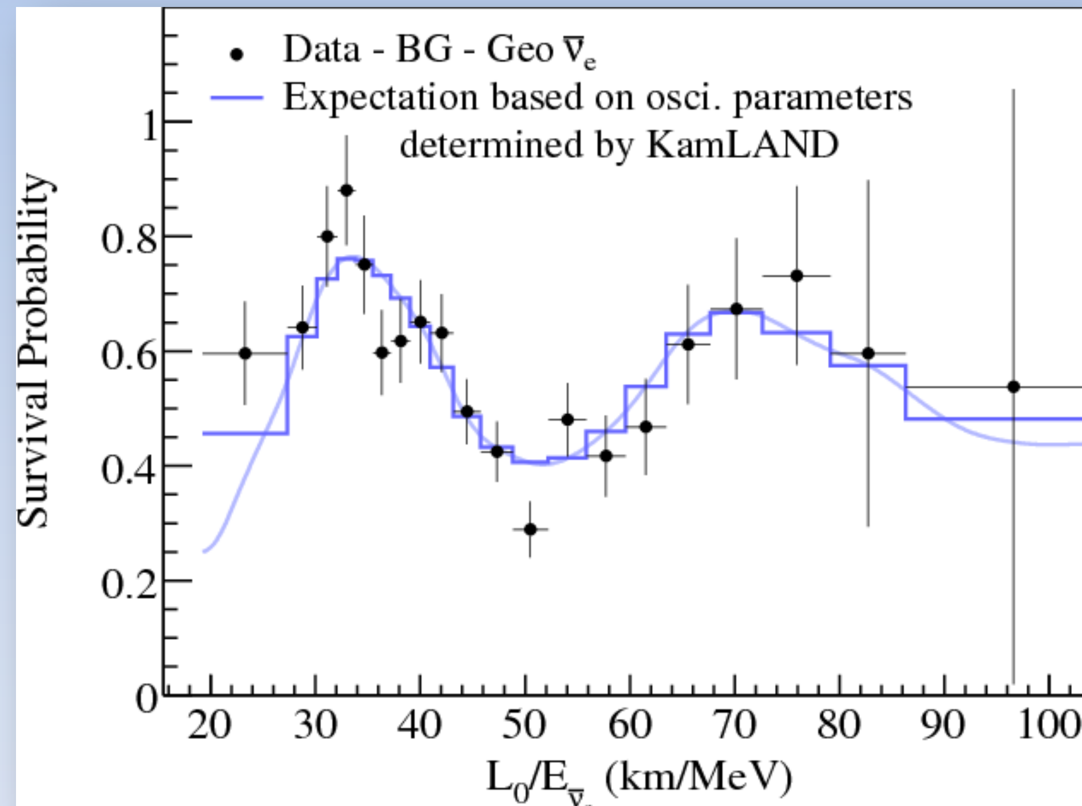
2003: KamLAND Surprise

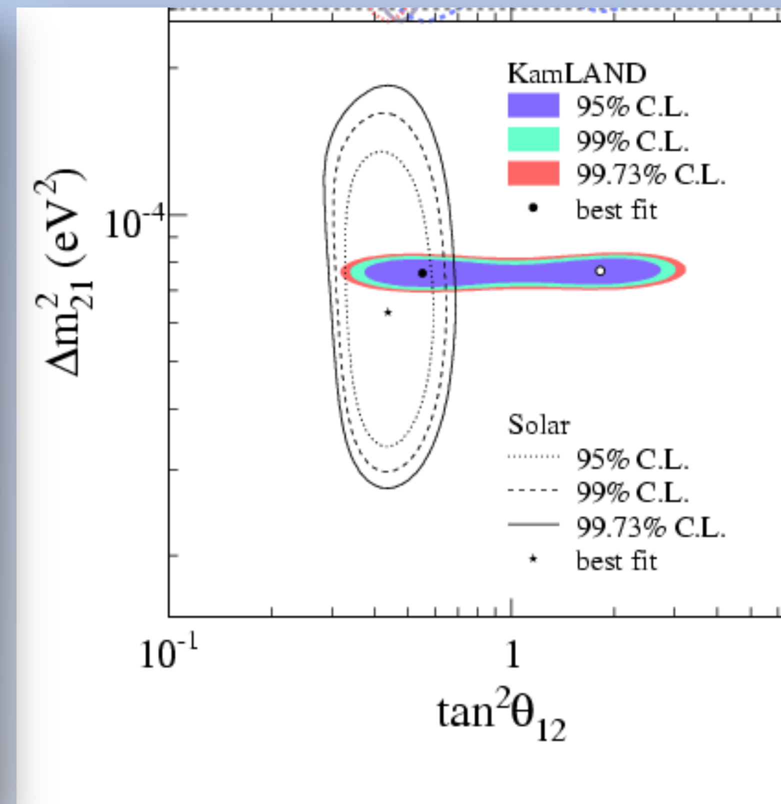


KamLAND Energy Spectrum (2007)



KamLAND Result (2008)





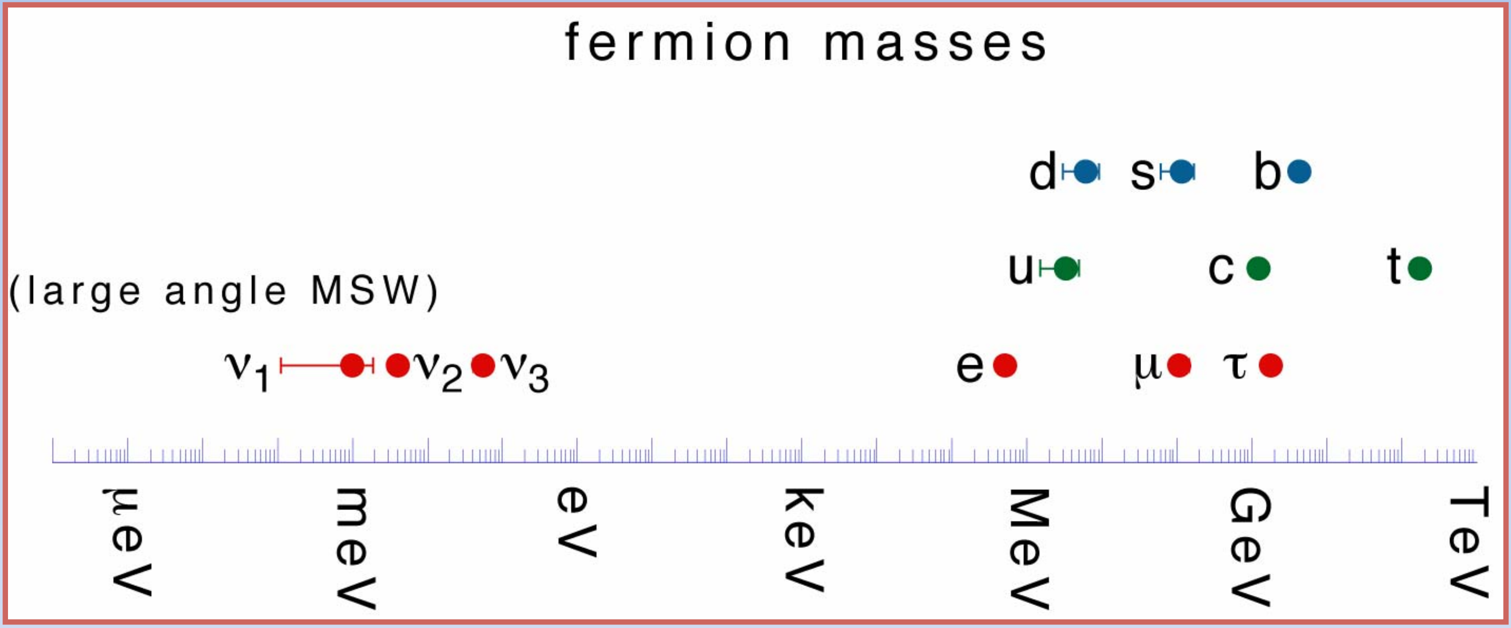
PRL 100, 221803 (2008)

Best combined fit values:

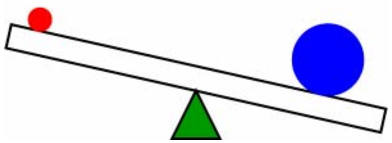
$Dm^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}$ eV^2

$tan^2q = 0.47^{+0.06}_{-0.05}$

The Mass Puzzle

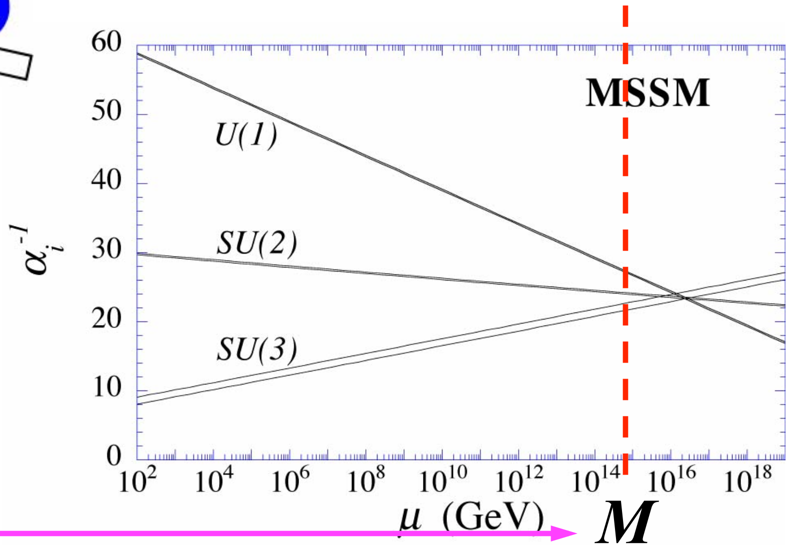


"Seesaw mechanism"



$$(\nu_L \quad \nu_R)\begin{pmatrix} & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$m_\nu = \frac{m_D^2}{M} << m_D$$



Pontecorvo Maki – Nakagawa – Sakata Matrix

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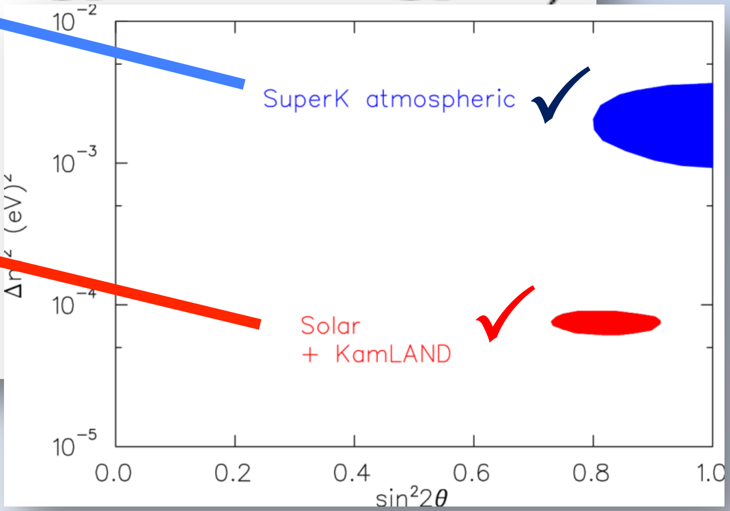
Gateway to CP Violation!

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

CP violation

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$



Neutrino vs. Quark Mixing

Leptons

$$U_\ell = \begin{pmatrix} 0.85 & 0.52 & \sin q_{13} \\ -0.33 & 0.62 & -0.72 \\ -0.40 & 0.59 & 0.70 \end{pmatrix}$$

Why so different???

Quarks

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.003 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

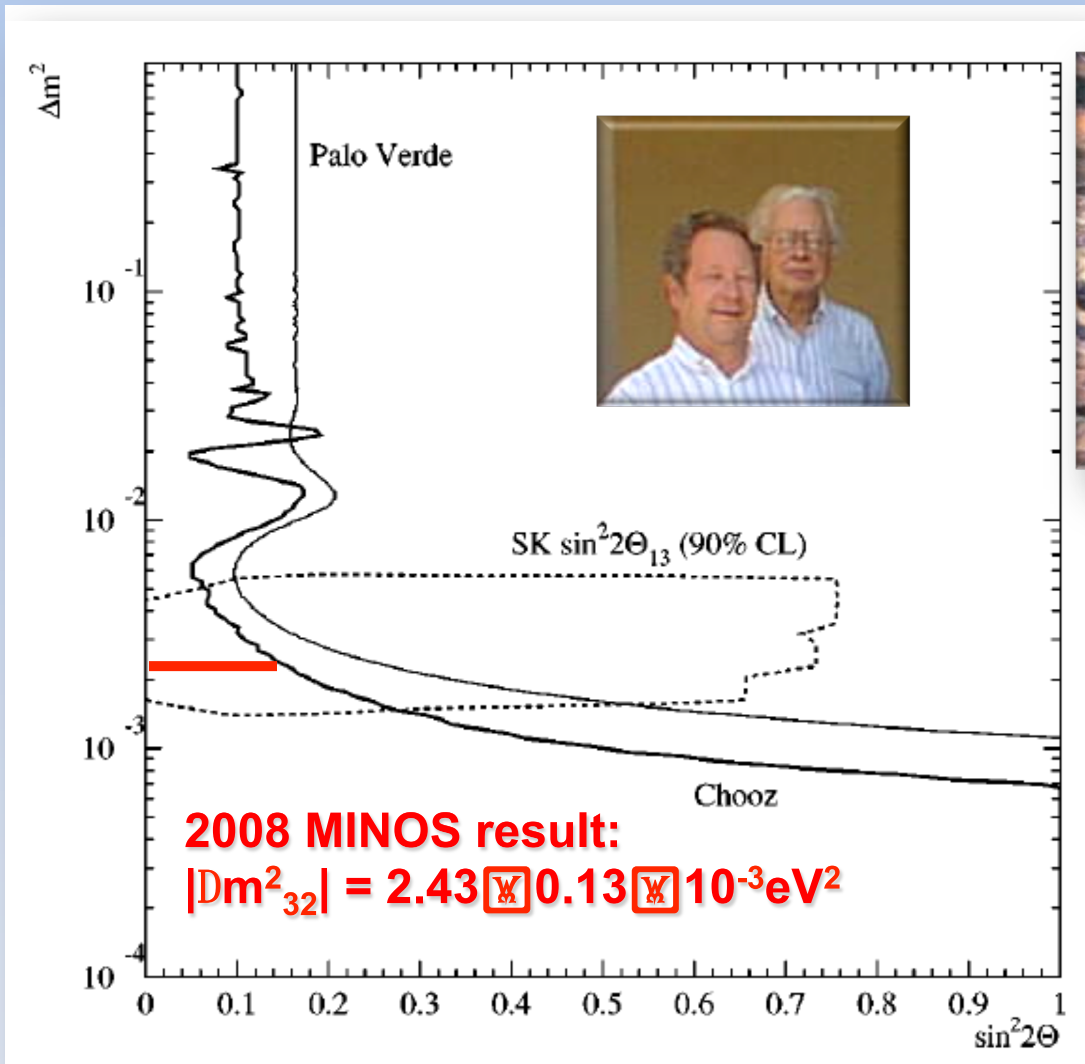
Tri-bimaximal neutrino mixing:

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

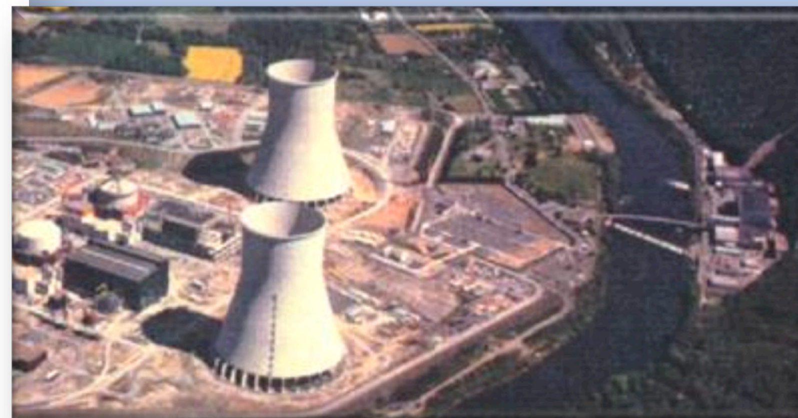
(Harrison, Perkins, Scott 1999)

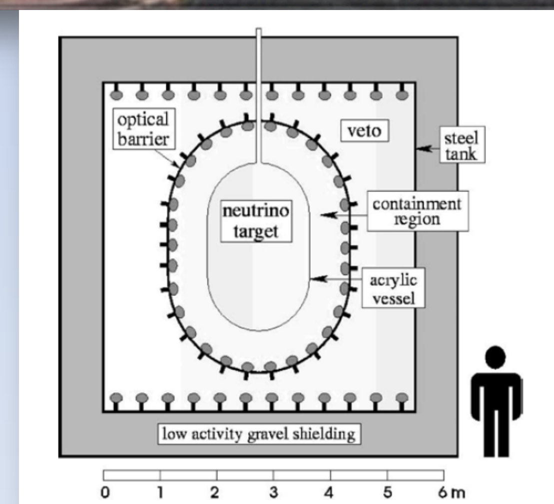
CHOOZ/Palo Verde limits for θ_{13}

(2001-3)



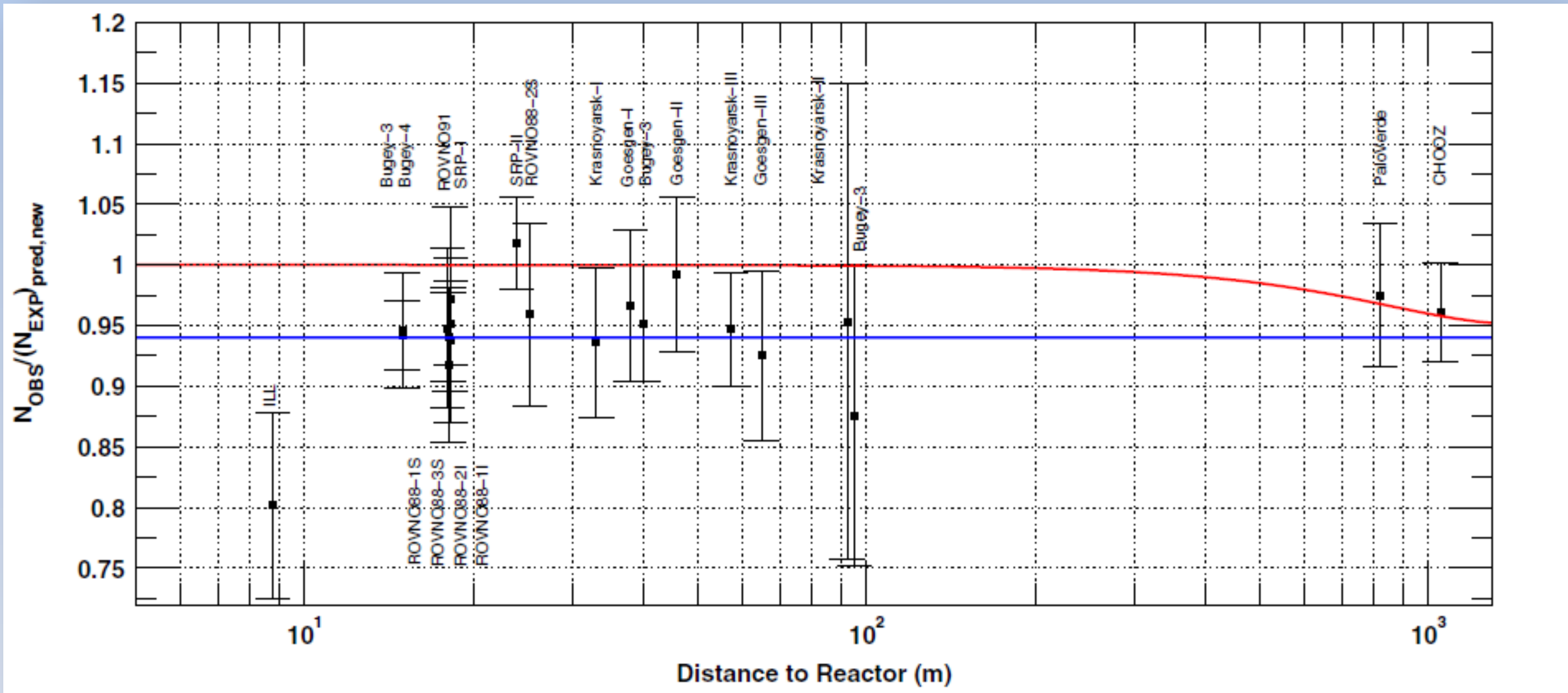
2008 MINOS result:
$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} eV^2$





$\sin^2 2\theta_{ee} < 0.15$ (90% CL)

Recent Reactor Flux Analysis (2011)



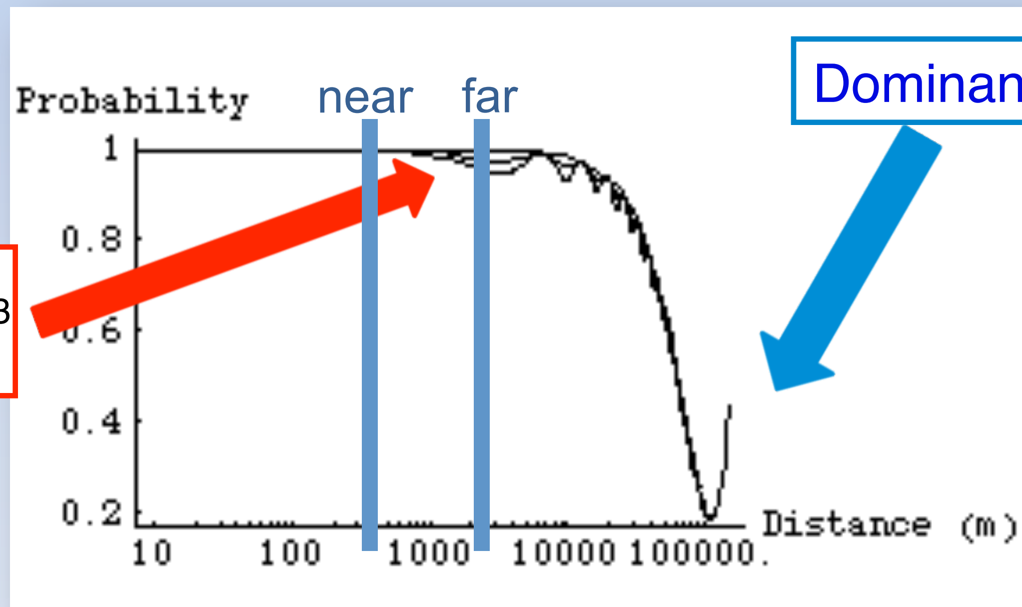
- PRD 83, 073006 (2011)
- 0.943 +- 0.023

$\bar{n}_e$ Survival Probability (3 generations)

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\Delta m^2_{ee} \cdot \frac{L}{E}\right) - \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\Delta m^2_{21} \cdot \frac{L}{E}\right)$$

$$|\Delta m^2_{ee}| \sim |\Delta m^2_{32}| \approx |\Delta m^2_{31}| >> |\Delta m^2_{21}|$$

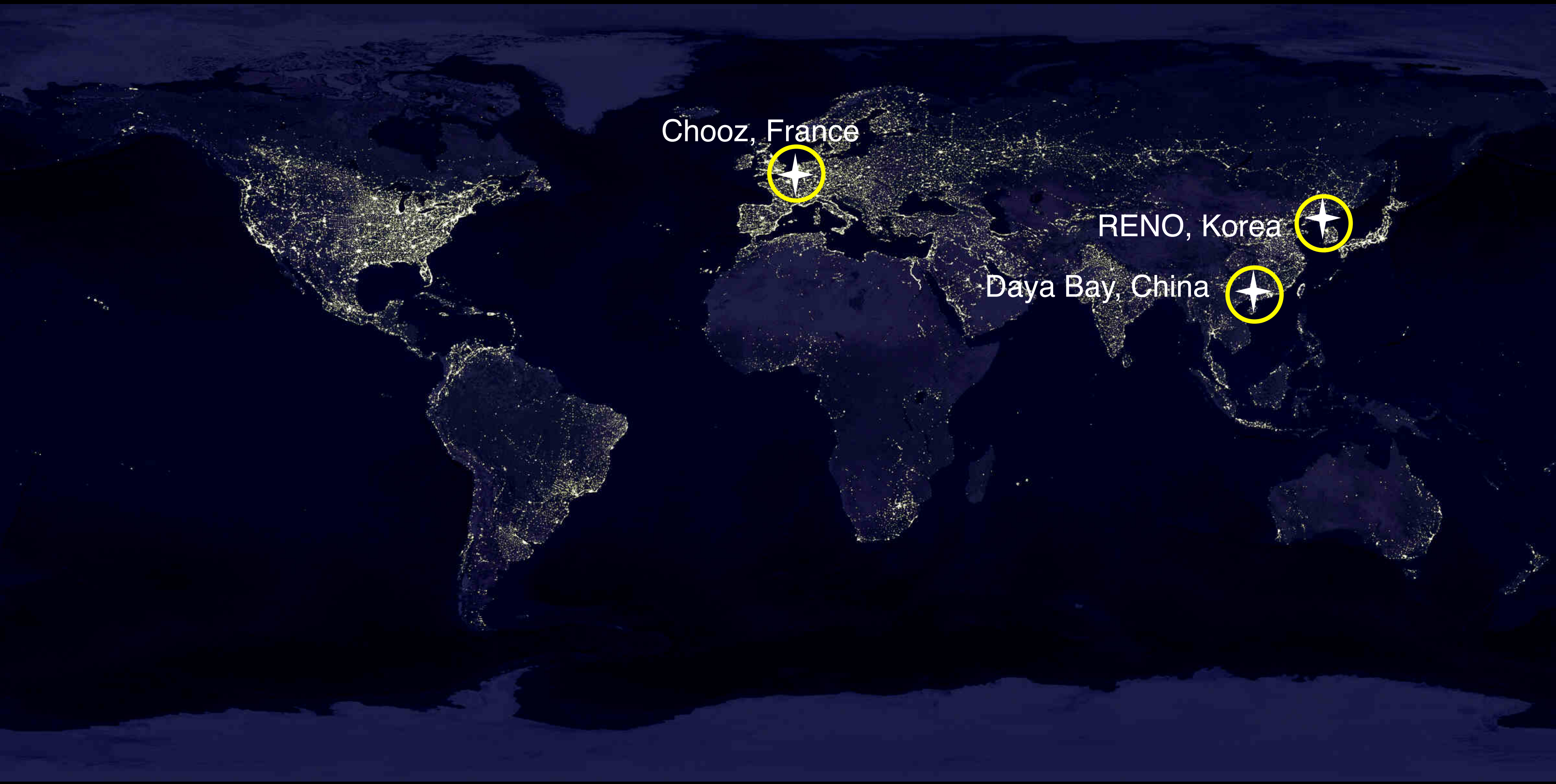
Subdominant θ_{13} Oscillation



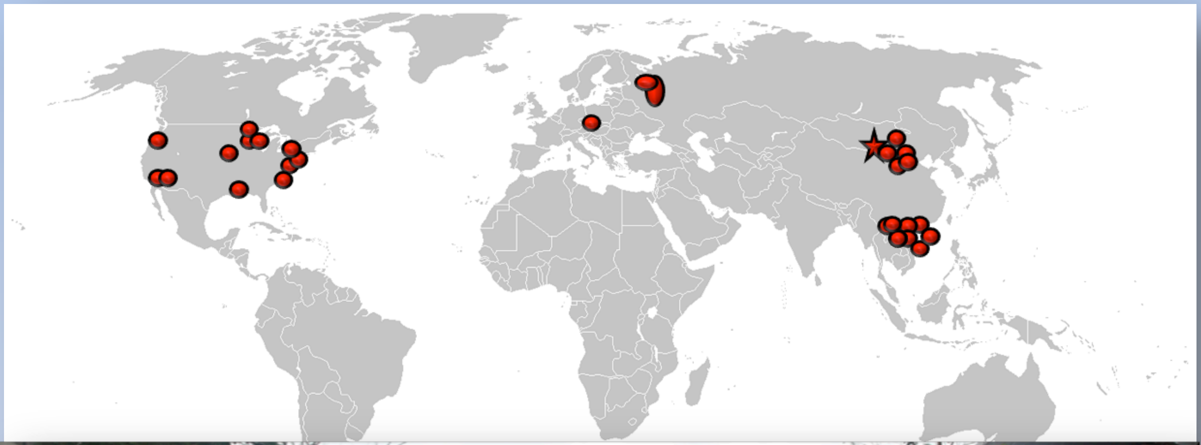
Dominant θ_{12} Oscillation

- "Clean" measurements of q, Dm^2
- Far/near ratio to cancel uncertainty in reactor flux

New Reactor θ_{13} Neutrino Experiments



Daya Bay Collaboration
An International Effort



Asia (20)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)
Brookhaven Natl' Lab, Caltech, Cincinnati, Houston, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl' Lab, Princeton, Rensselaer Polytech, UC Berkeley, UCLA, Wisconsin, William & Mary, Virginia Tech, Illinois, Siena College

Europe (3)
Charles Univ,. Dubna, Kurchatov Inst.

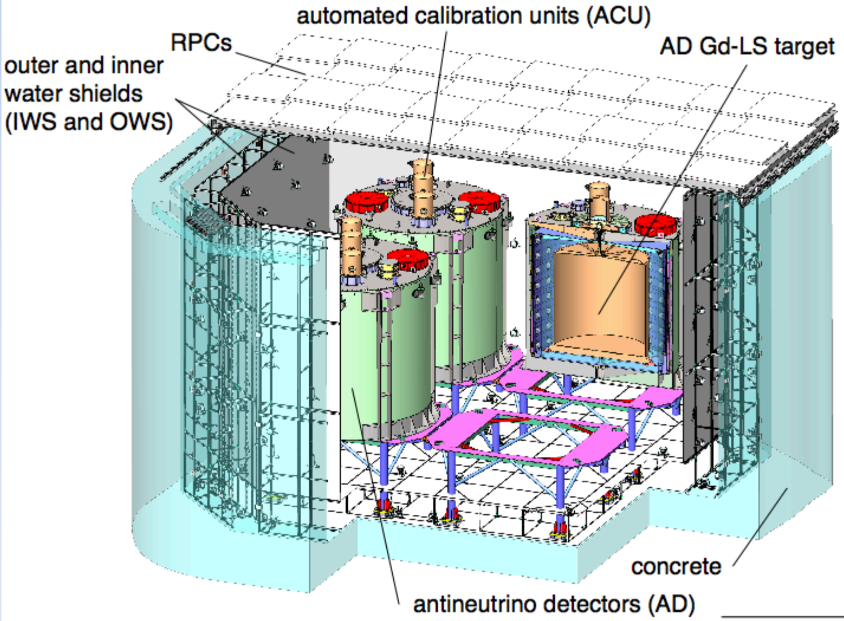
~240 collaborators

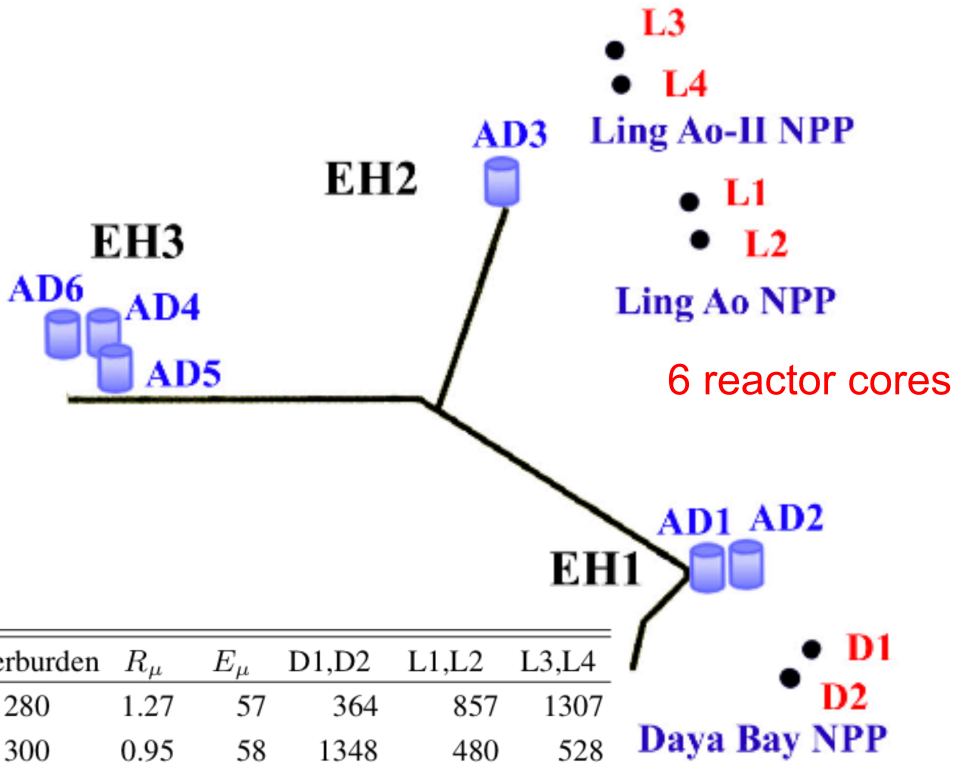
Daya Bay - A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW$_{th}$ (6 x 2.95 GW$_{th}$)
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce ~2×10^{20} antineutrinos/sec/GW

Daya Bay Experiment Layout

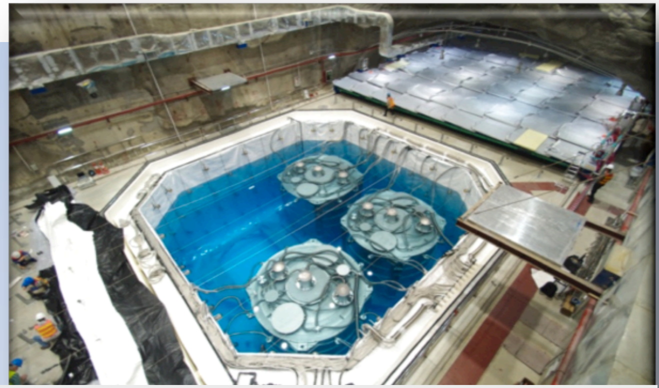




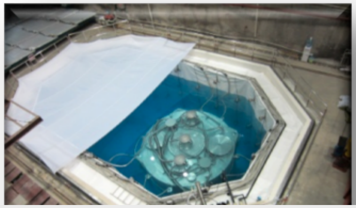
6 antineutrino detectors in 3 underground experimental halls

	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

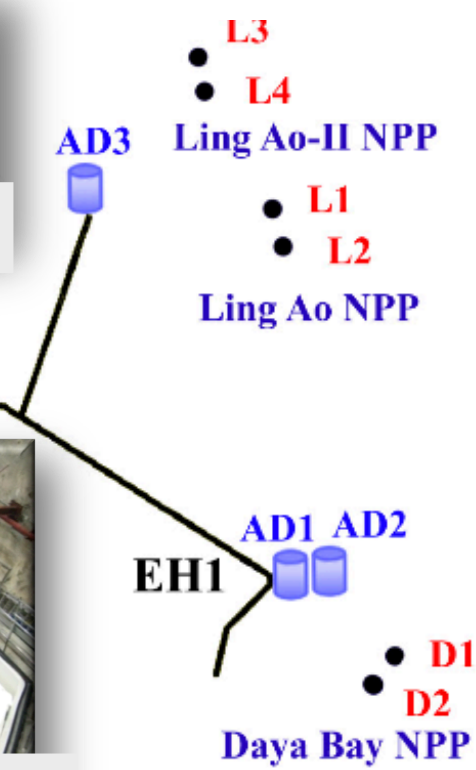
Daya Bay Experiment Layout

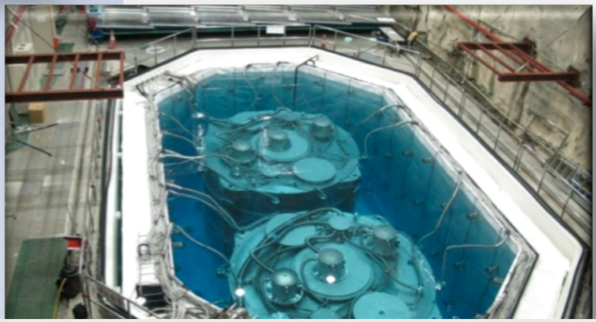


Hall 3: began 3AD operation on Dec. 24, 2011



Hall 2: began 1 AD operation on Nov. 5, 2011





Hall 1: began 2AD operation on Sep. 23, 2011

Antineutrino Detectors

6 'functionally identical' detectors:

Reduce systematic uncertainties

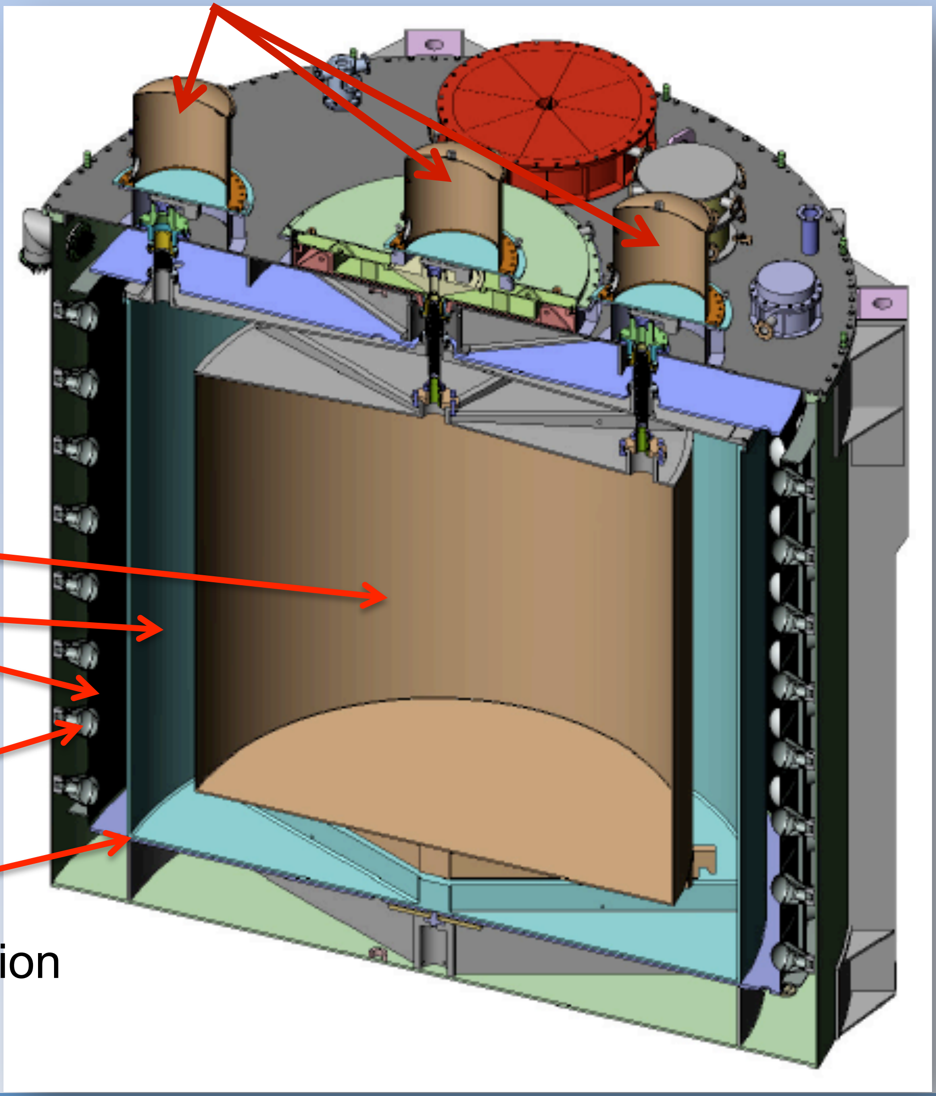
$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

3 nested cylinders:

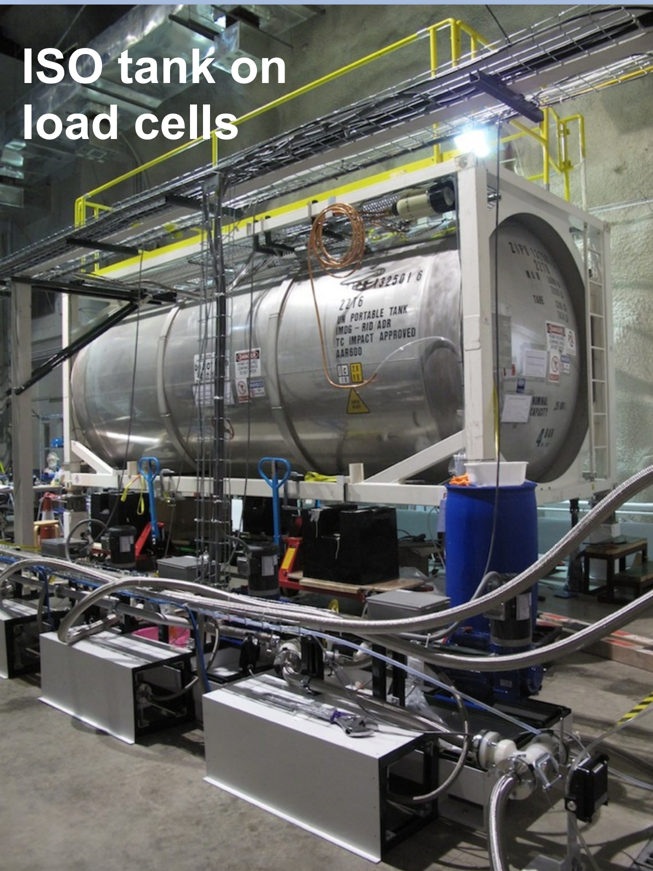
Inner: 20 tons Gd-doped LS (d=3.1m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

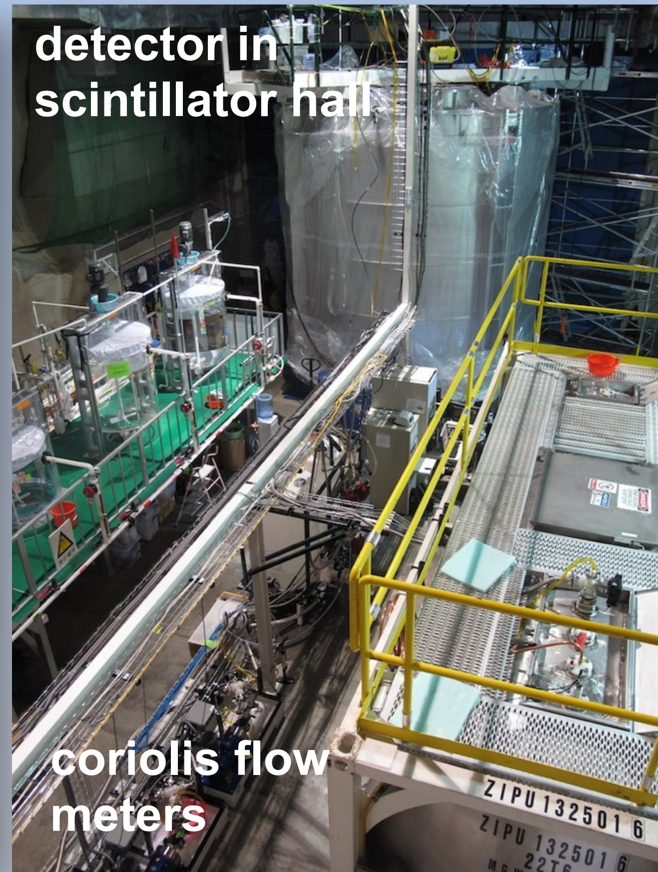
Each detector:

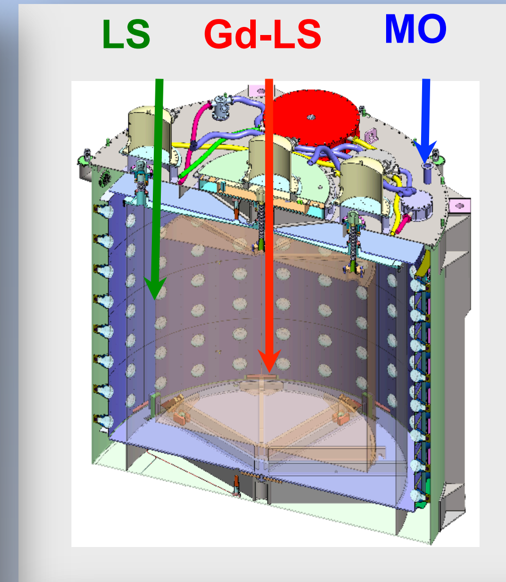
192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / √E + 0.9)% energy resolution



Detector Filling and Target Mass Measurement







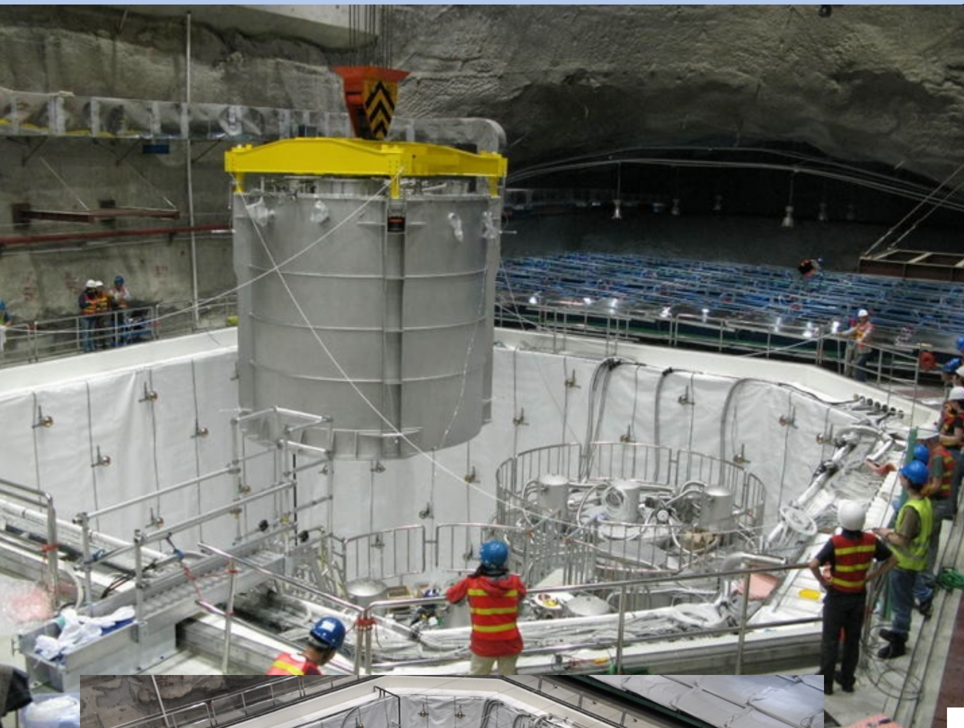
Quantity	Relative	Absolute
protons/kg	neg.	0.47%
Density (kg/L)	neg.	neg.
Total mass	0.015%	0.015%
Overflow tank geometry	0.0066%	0.0066%
Overflow sensor calibration	0.0043%	0.0043%
Bellows Capacity	0.0025%	0.0025%
Target mass	0.017%	0.017%
Target protons	0.017%	0.47%

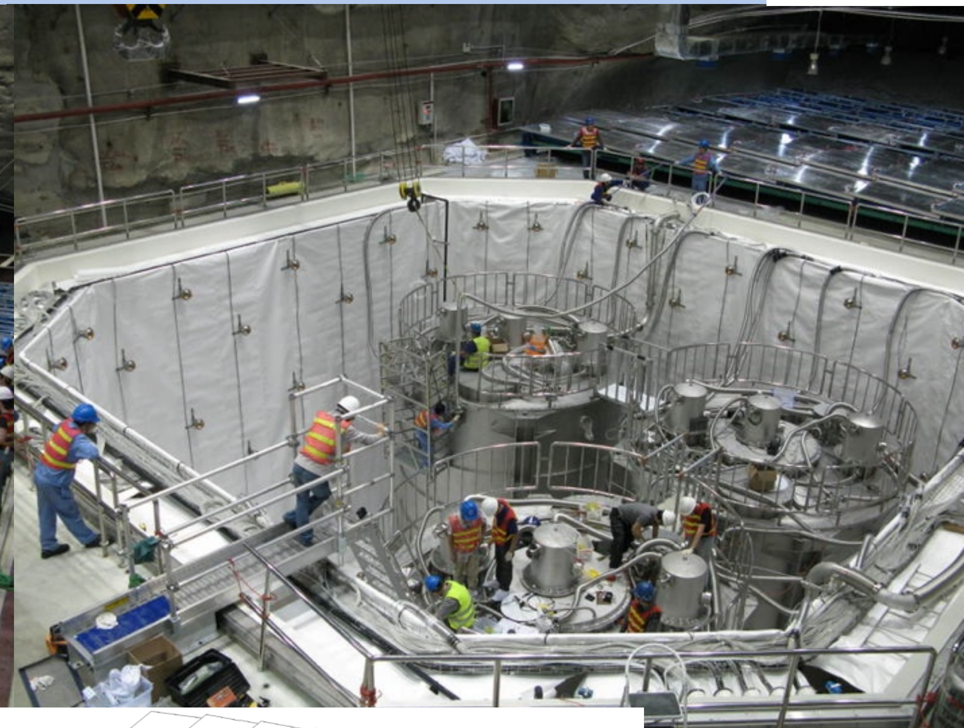
Target mass determination error ± 3kg out of 20,000

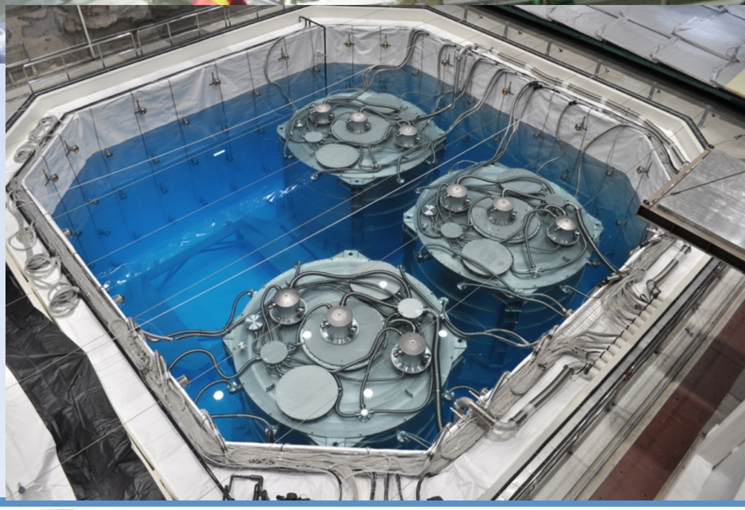
<0.03% during data taking period

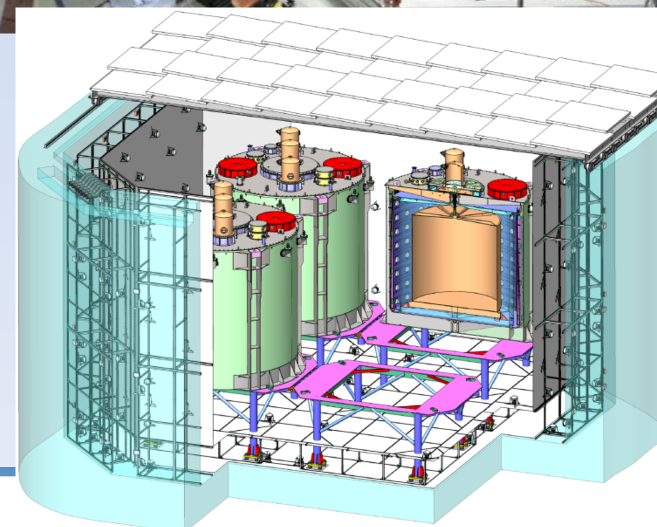
Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.

Antineutrino Detector Installation - Far Hall



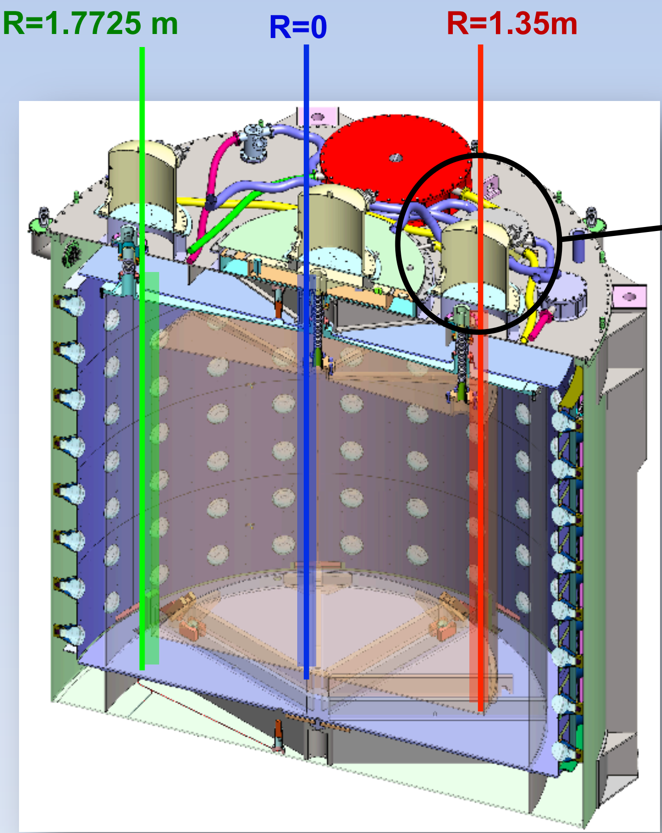






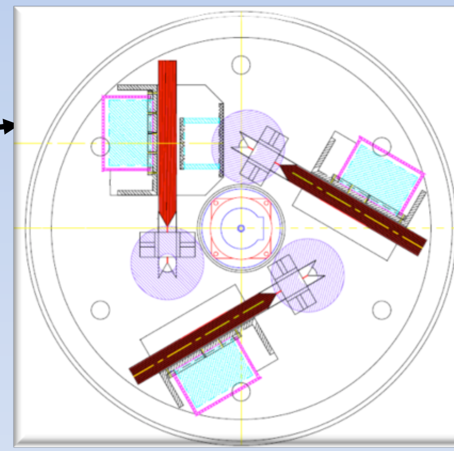
Automated Calibration System

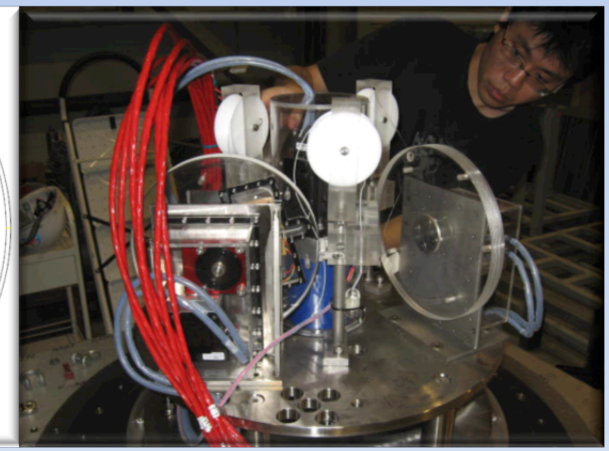
3 Automatic calibration units (ACUs)
on each detector



Three axes: center, edge of target, middle of gamma catcher

Top view





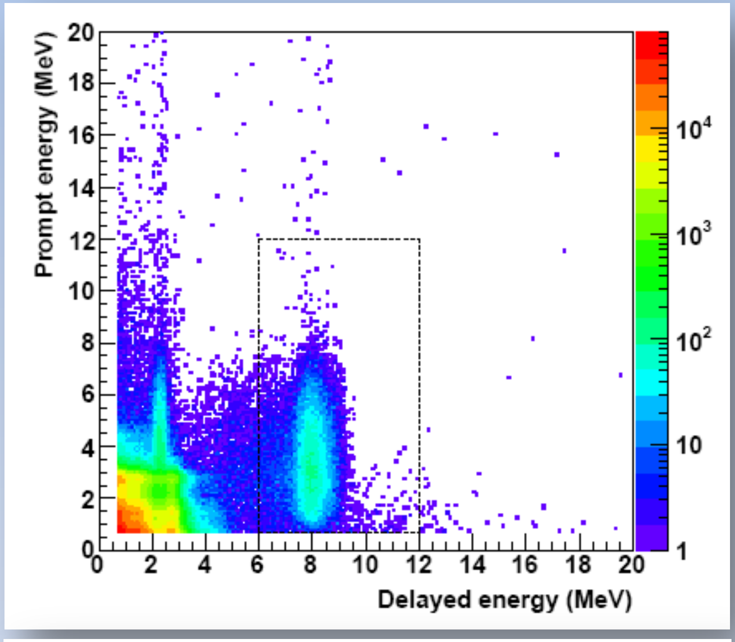
3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for T_0 and gain

Antineutrino (IBD) Selection

Selection of Prompt + Delayed

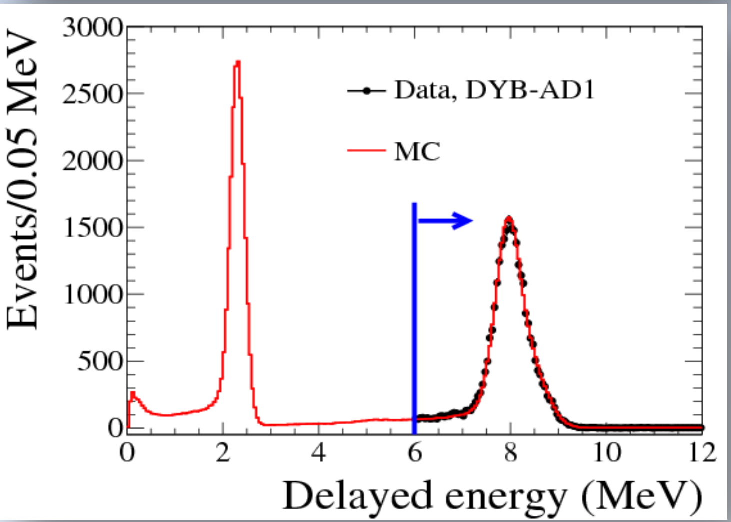
- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.



Selection driven by uncertainty in relative detector efficiency

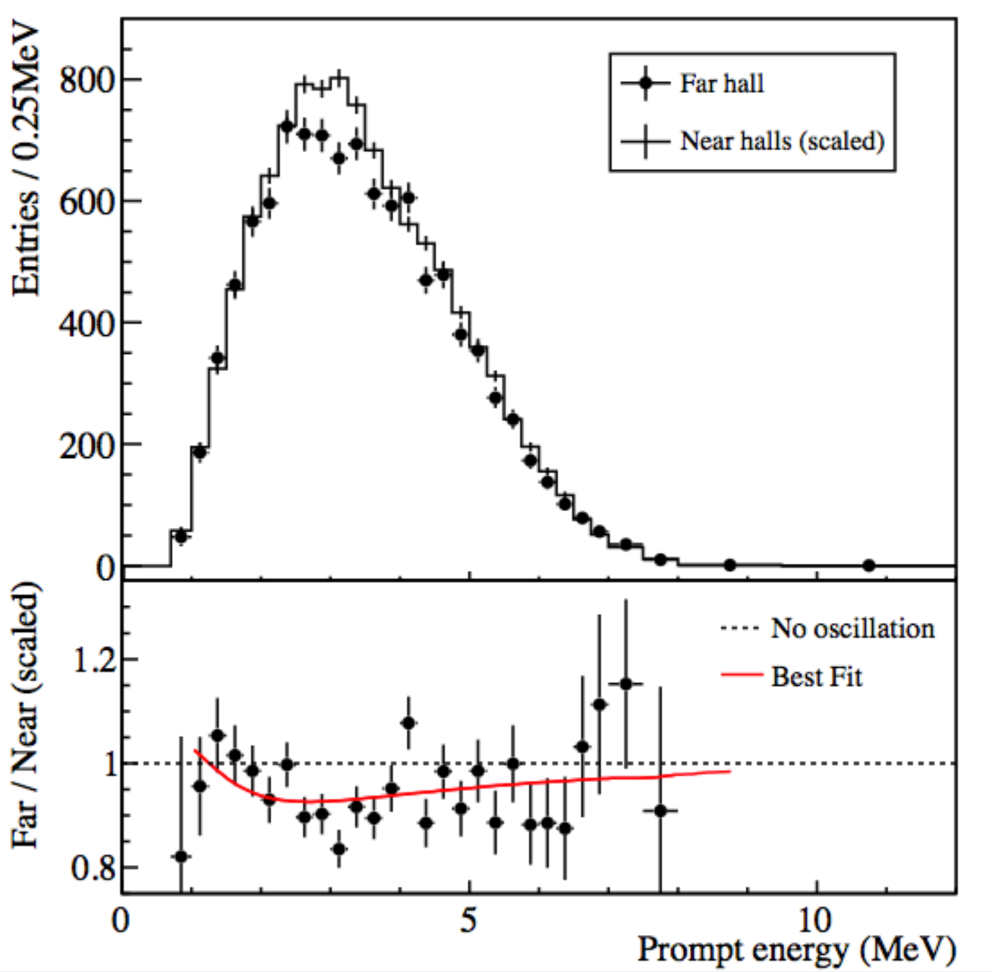
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.



March 2012: θ_{13} Surprise!

Compare measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

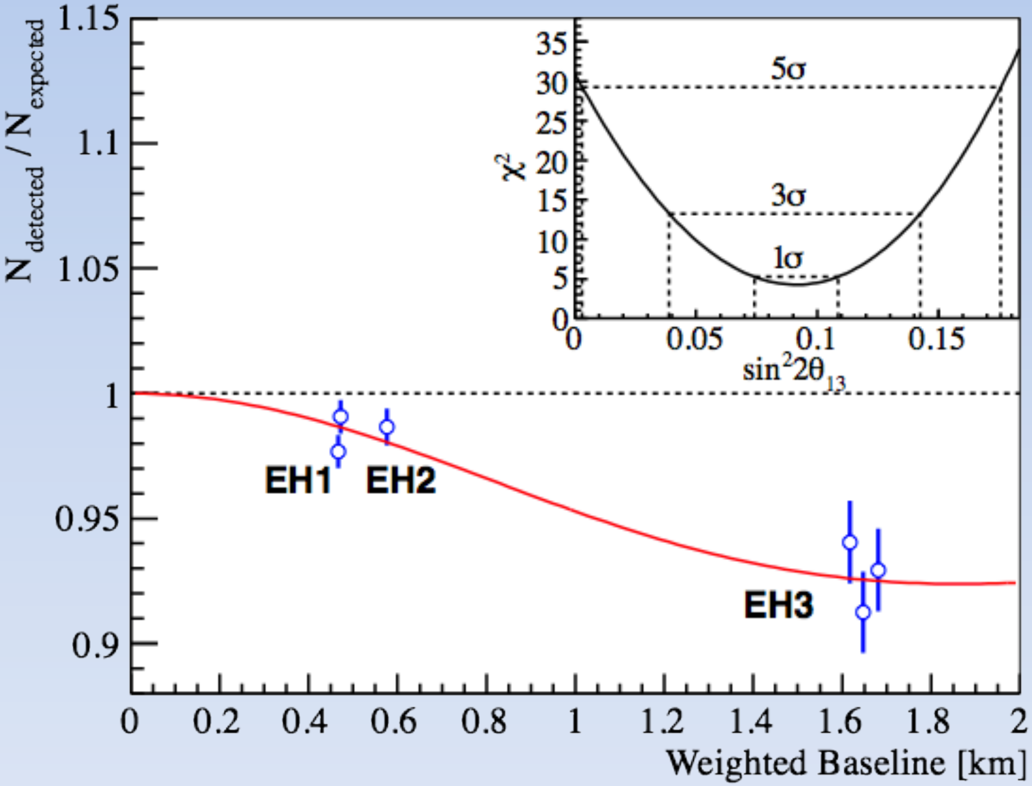
R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

Clear observation of far site deficit!

Spectral distortion consistent with oscillation.

March 2012 Rate Analysis

Estimate θ_{13} using measured rates in each detector.



Uses standard χ^2 approach.

Far vs. near relative measurement. [Absolute rate is not constrained.]

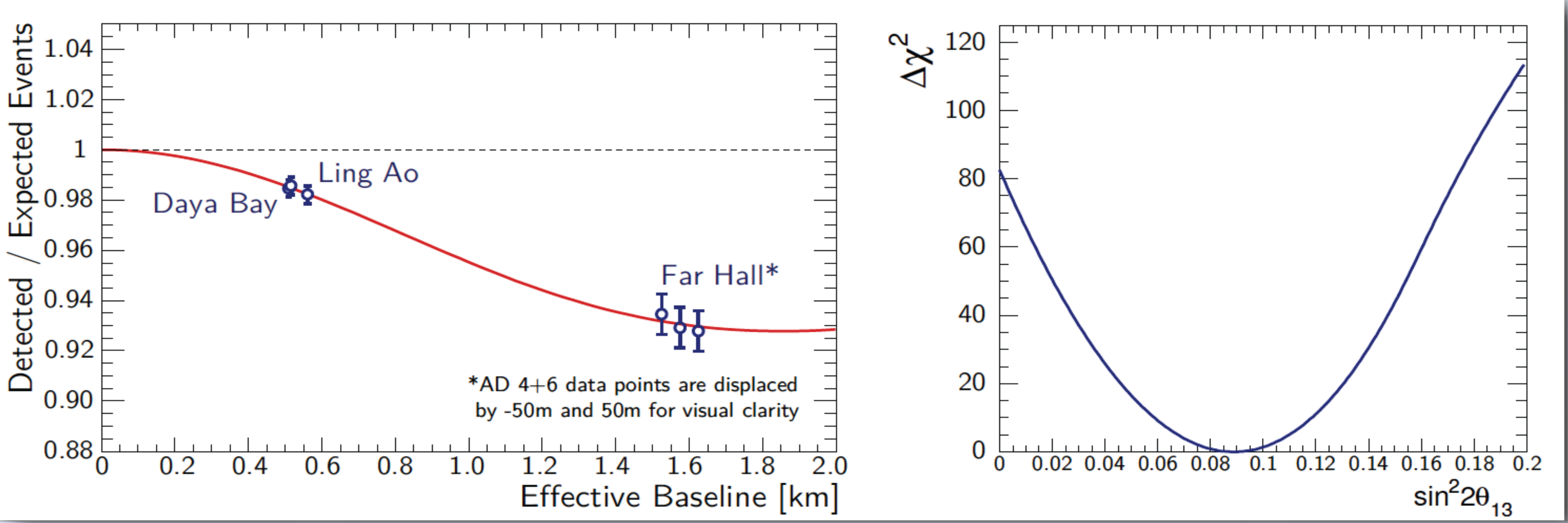
Consistent results obtained by independent analyses, different reactor flux models.

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

$\sin^2 2\theta_{13} = 0$ excluded at 5.2σ

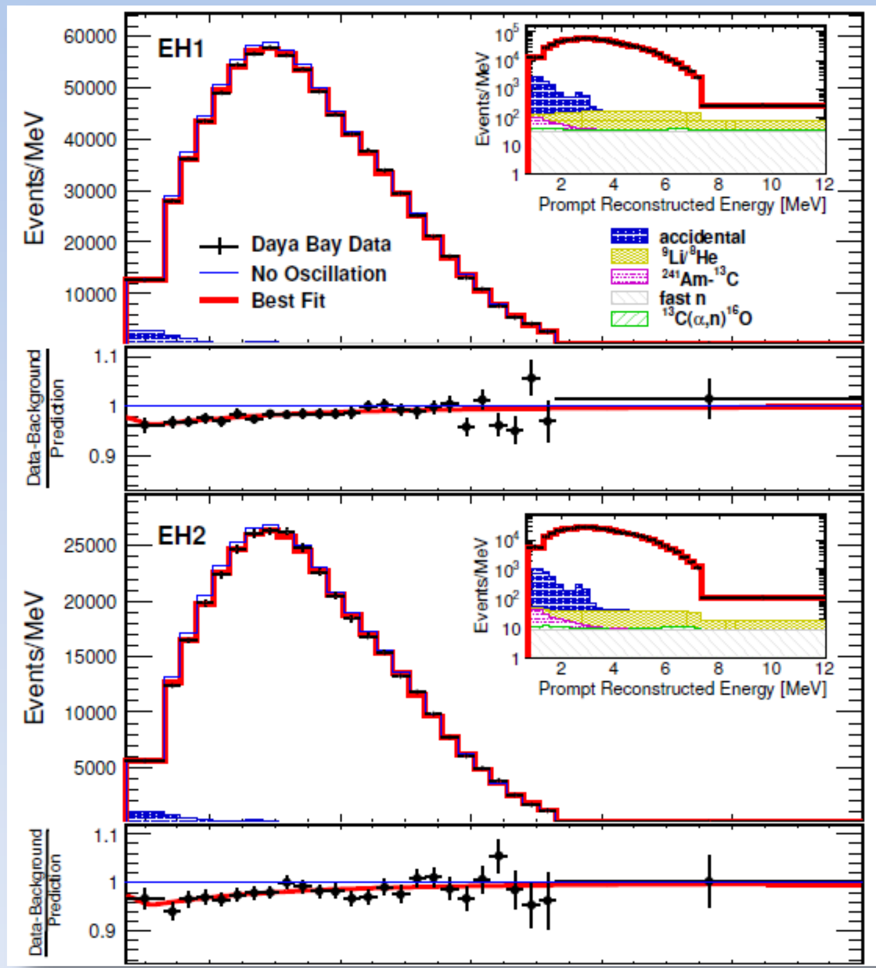
July 2013: Updated result

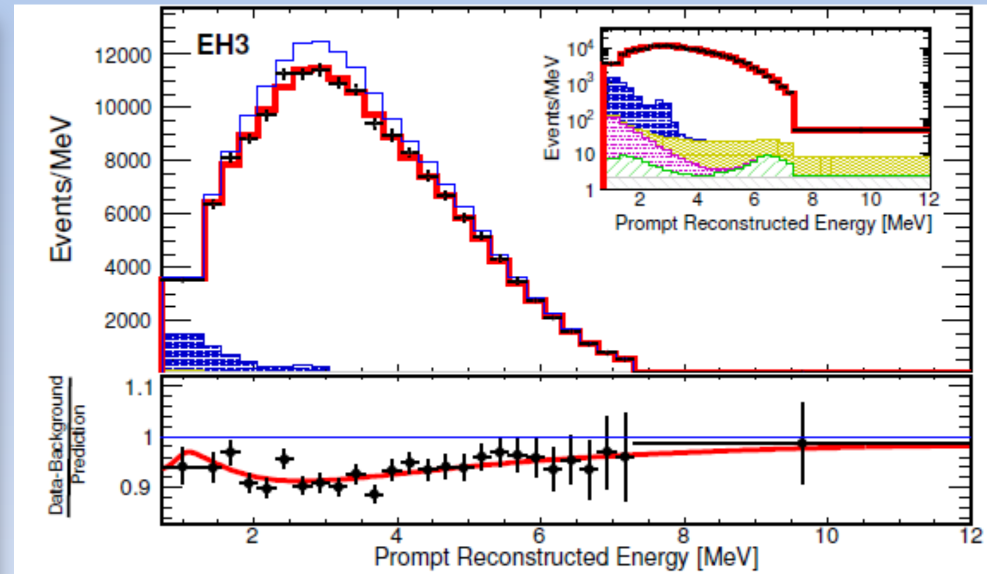
Rate only analysis:



$\sin^2 2q_{13} = 0.089 \pm 0.009$

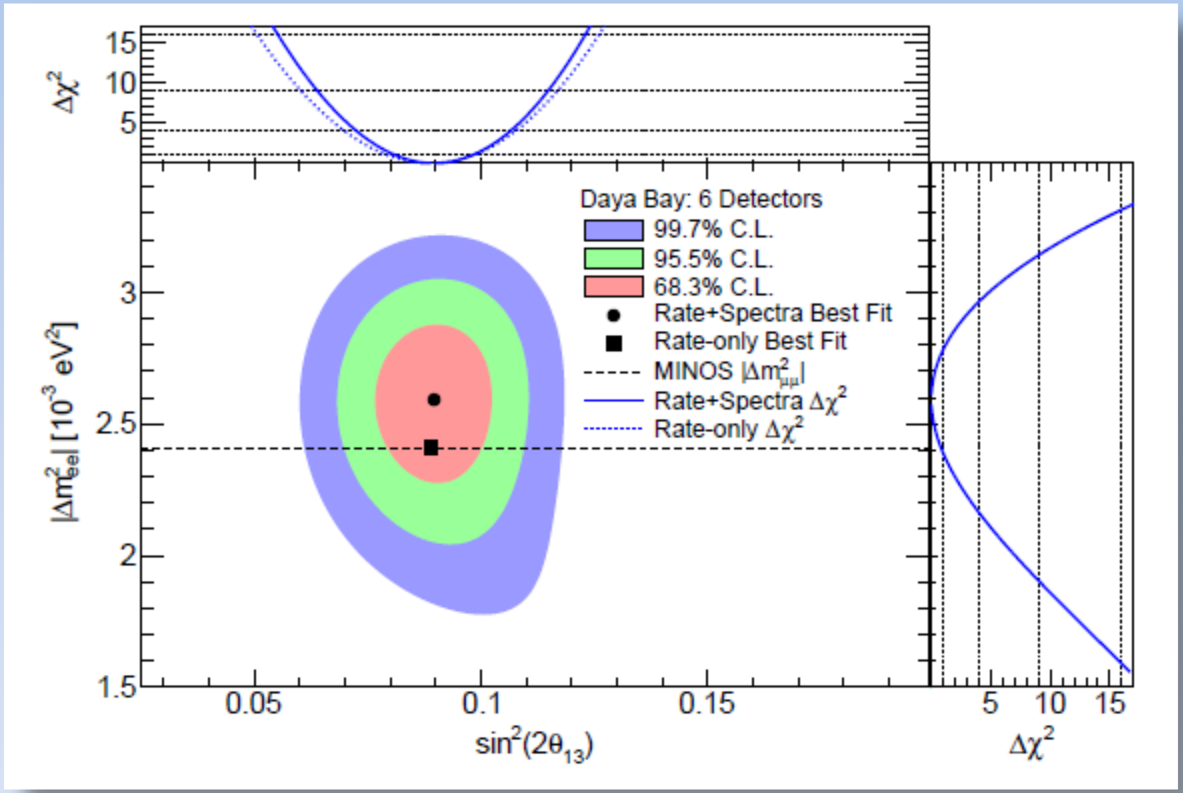
Energy Spectrum Distortion





- Clear difference at far site
- Consistent with oscillations

Rate + Shape Analysis

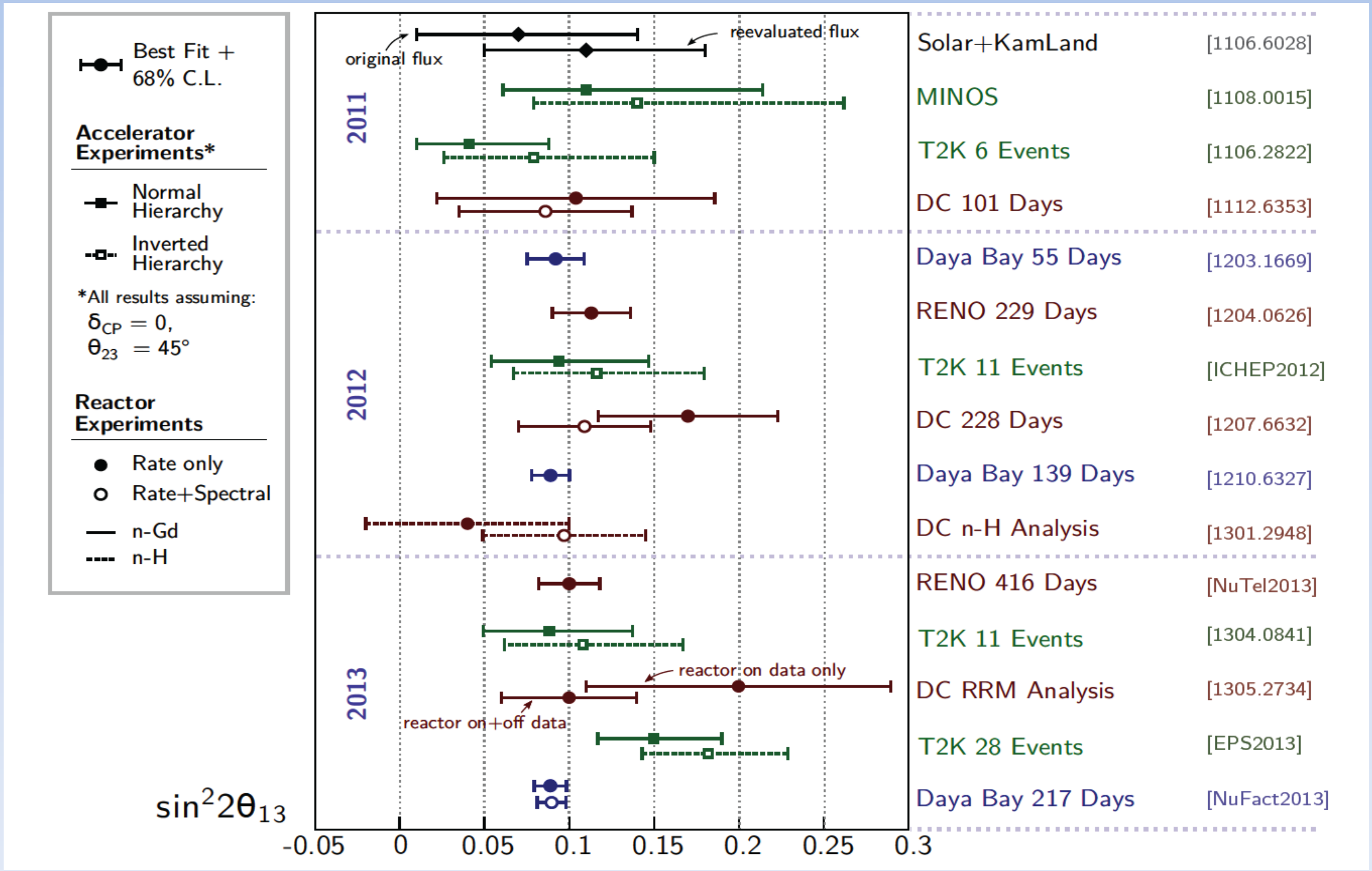


$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

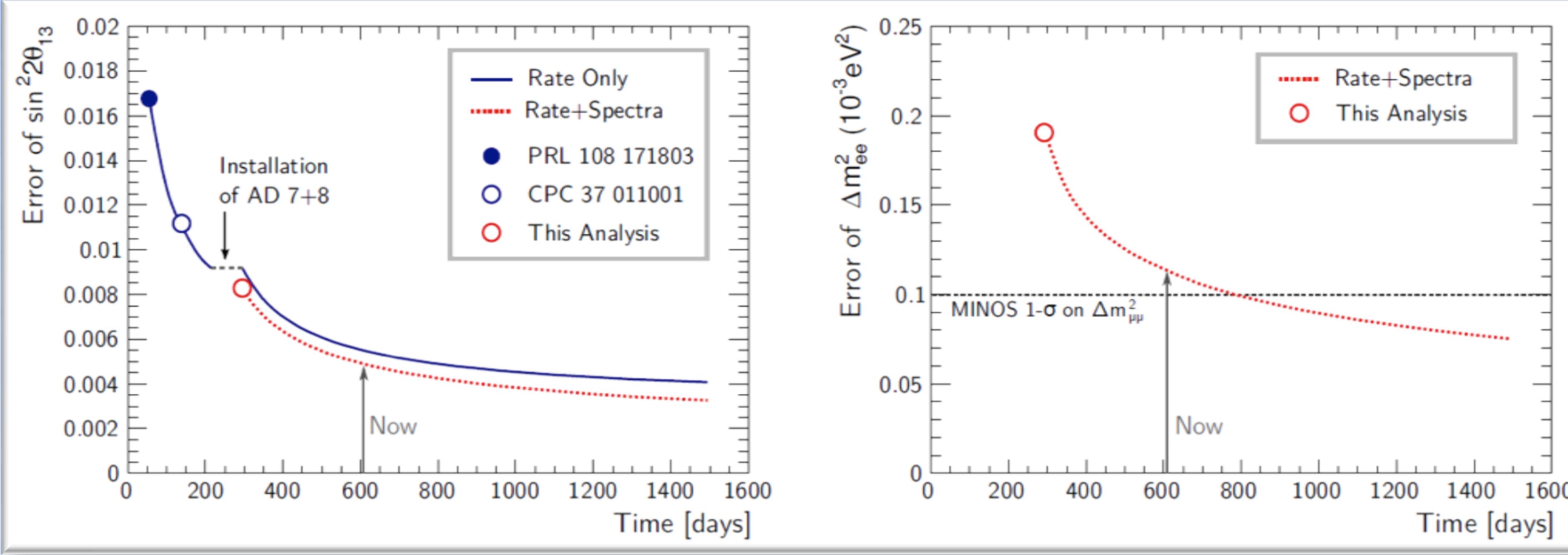
$$\chi^2/N_{\mathrm{DOF}} = 162.7/153$$

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

Global Comparison



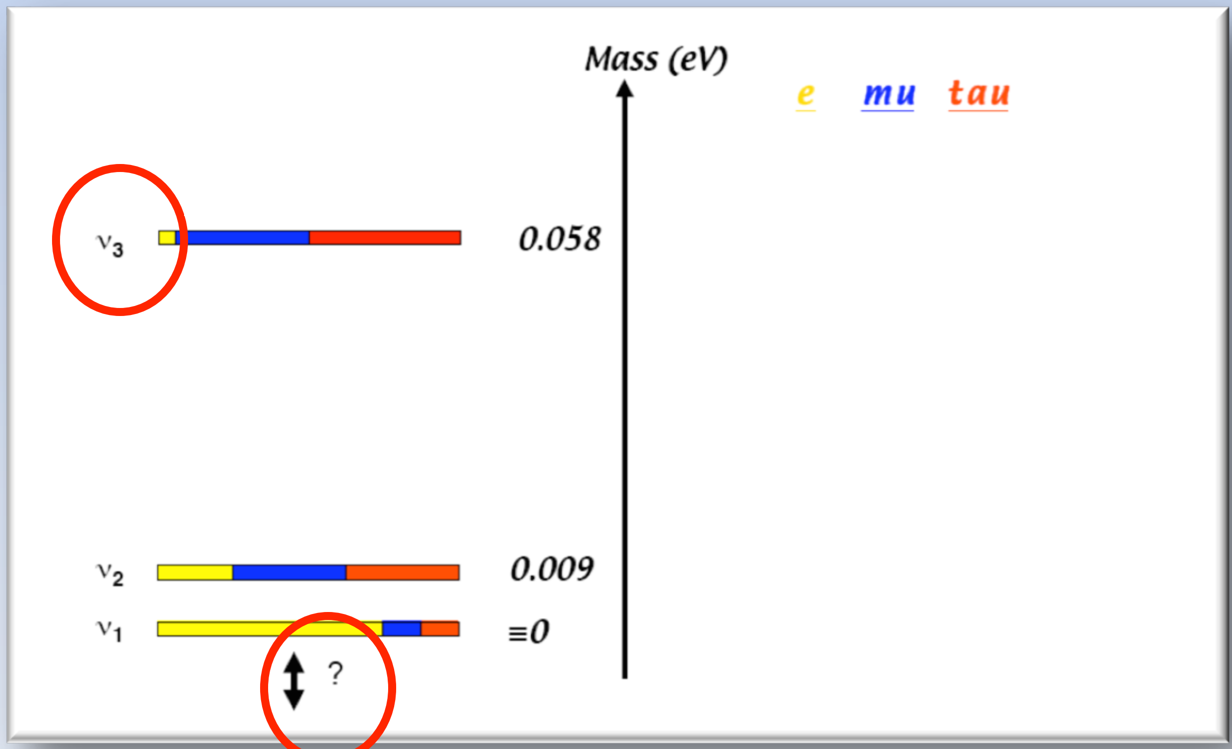
Future Sensitivity



- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - θ13: Relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
- Precision of mass splitting measurement closing in on results from μ flavor sector

Neutrinos: Completing the Picture

- q_{13} – the last mixing angle (reactor – now have it!!)
- Mass hierarchy (→ accelerator, reactor?)
- CP violation – "leptogenesis" (→ accelerator)
- Absolute mass scale (→ Tritium b endpoint, cosmology…)
- Antineutrino=neutrino (Majorana → double b decay)?

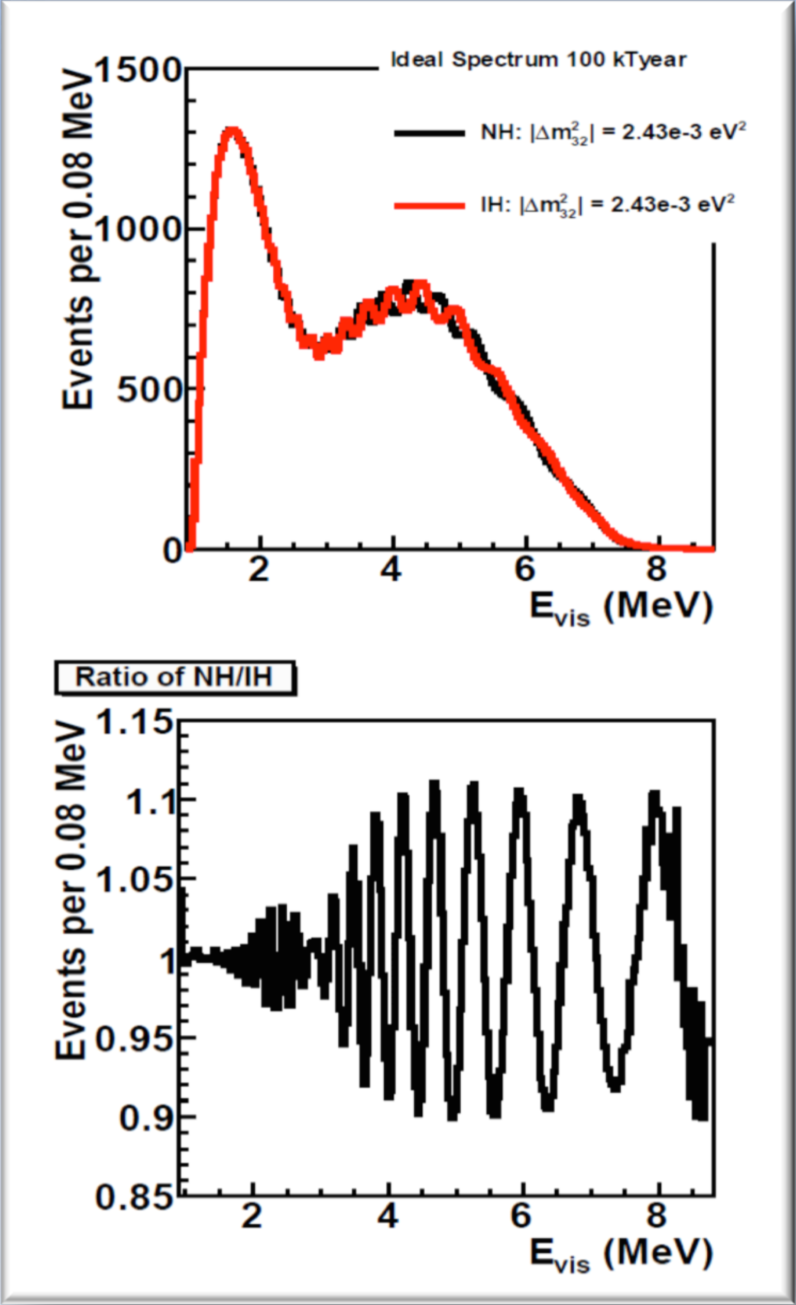


Mass Hierarchy using Reactor Antineutrinos

- 60 km baseline
- E resolution ~DB/3

Choubey, Petcov, and Piai PRD68,113006 (2003)
Learned et al. PRD78, 071302R, (2008)
Zhan et al. PRD78, 111103R (2008)
Zhan et al. PRD79, 073007 (2009)
Qian et al. PRD, 87, 033005 (2013)

Requires ~ 0.2% absolute energy scale

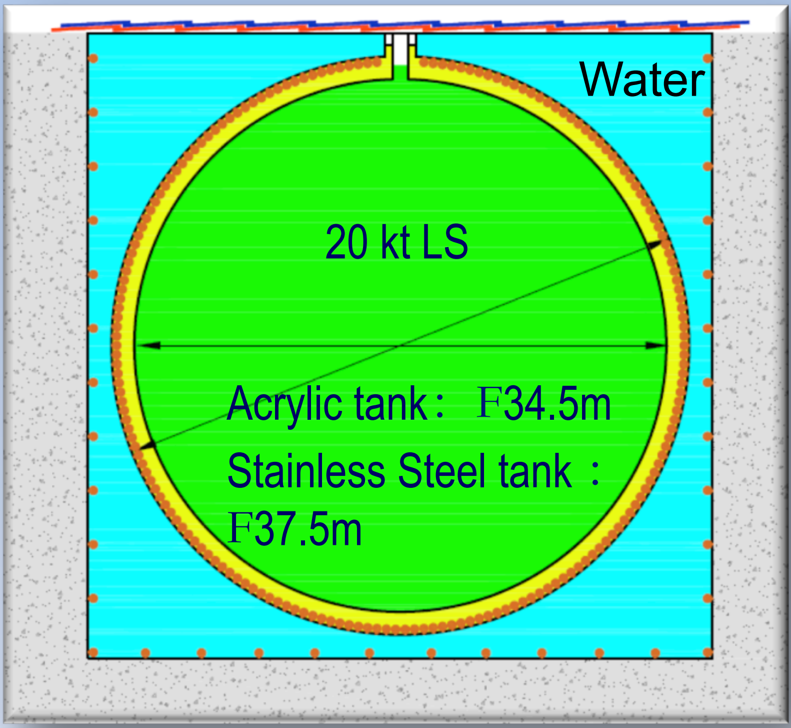


"JUNO" (~ 300 M$)

- **20 kT F.V. liquid scintillator detector at 55-60 km**
- ~ 40 GW_{th} power
- ~700 m underground
- **< 3% resolution @ 1 MeV**
- **Sub 1% energy calibration**

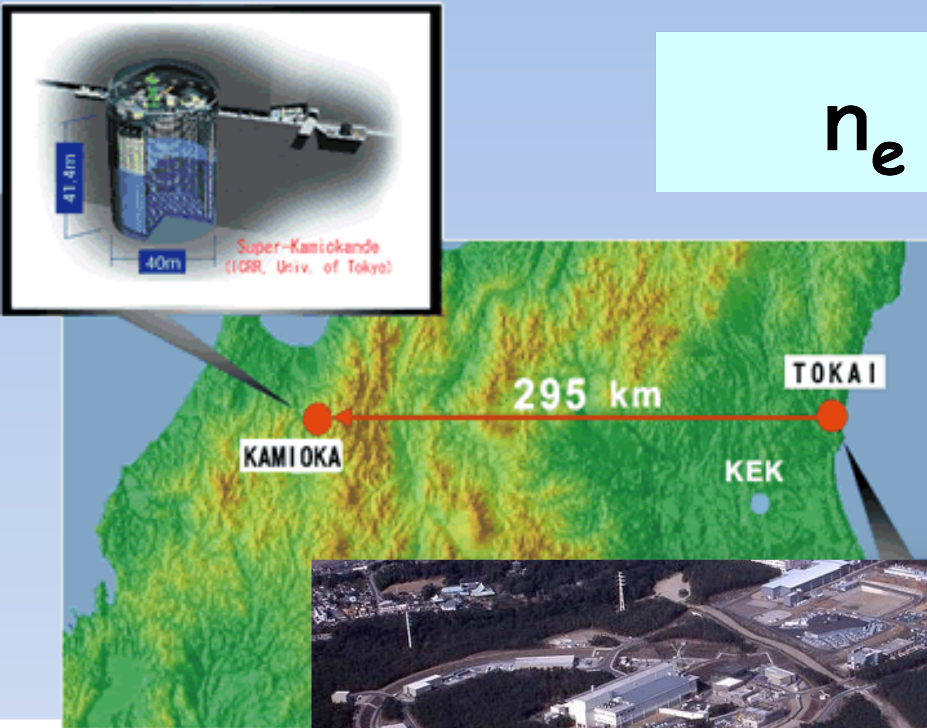
	Current	Daya Bay II
Dm^2_{12}	3%	0.6%
Dm^2_{23}	5%	0.6%
sin^2q_{12}	6%	0.7%
sin^2q_{23}	20%	N/A
sin^2q_{13}	14%→ 4%	~ 15%

From Y. F. Wang



MH can be determined to $\Delta\chi^2$>25 in 6 years

n_e Appearance



T2K- From Tokai To Kamioka

Mass hierarchy (+/-)

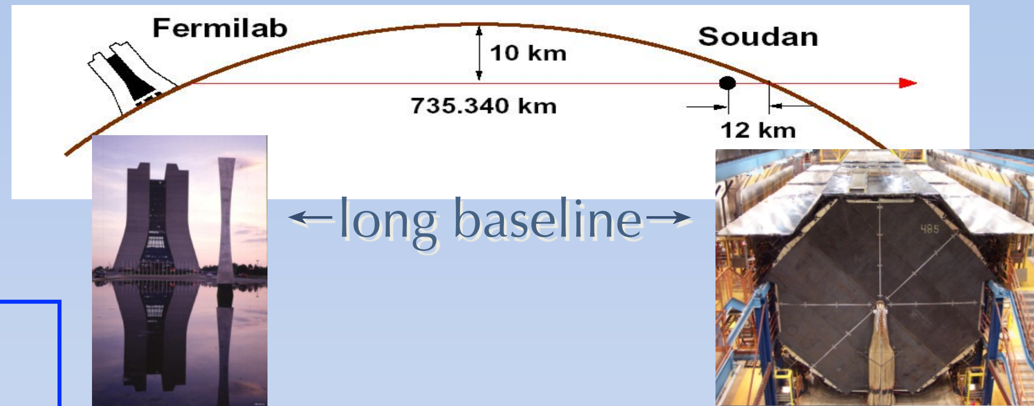
CP violation

matter

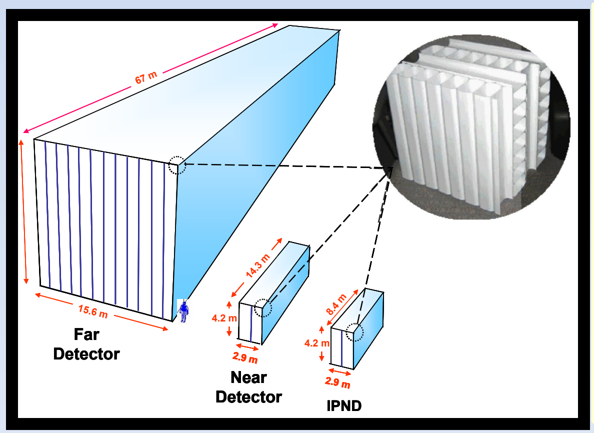
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
& + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right] .
\end{aligned}
$$

Current US (Fermilab) Program

MINOS

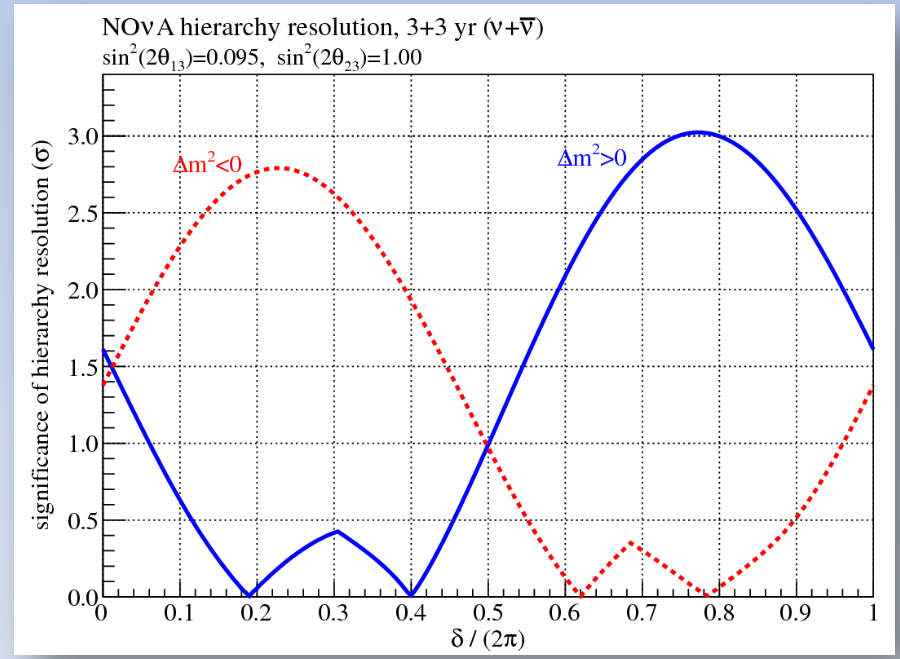


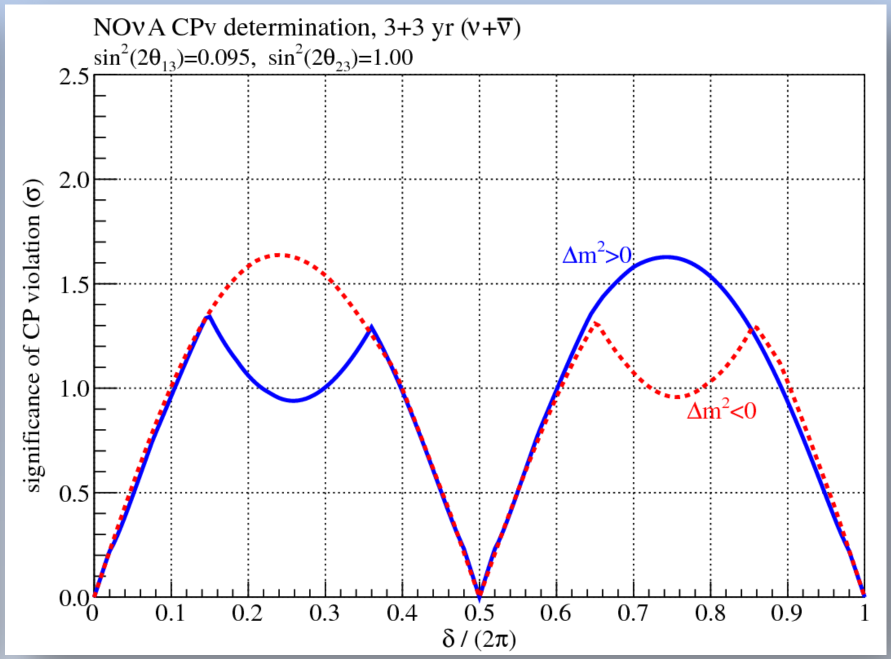
n_m disappearance:
$Dm_{23}^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2



$n_m \longrightarrow n_e$

NOVA Sensitivity (2019)

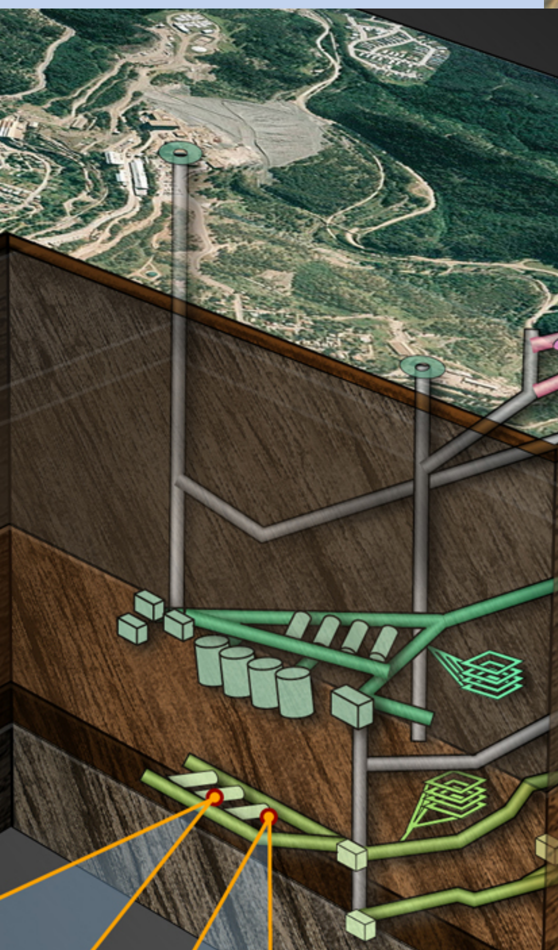




(R. Patterson, NuFACT 2012)

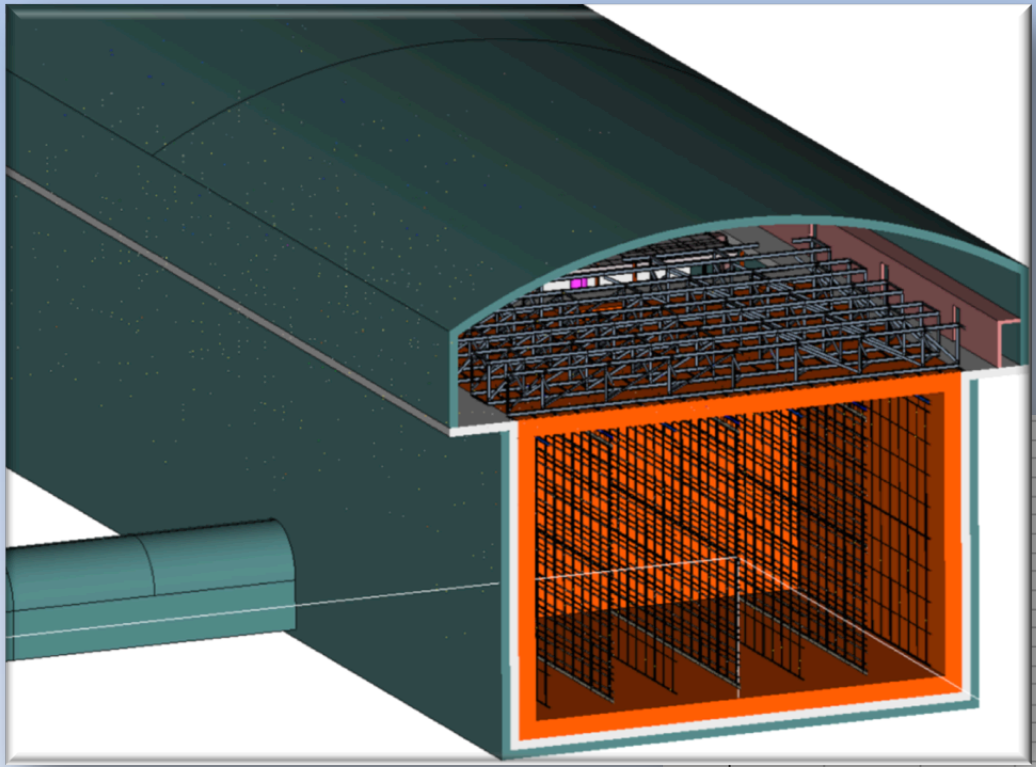
- **For Mass Hierarchy, 37% of d range covered**
- **Slight improvement from combining with T2K**

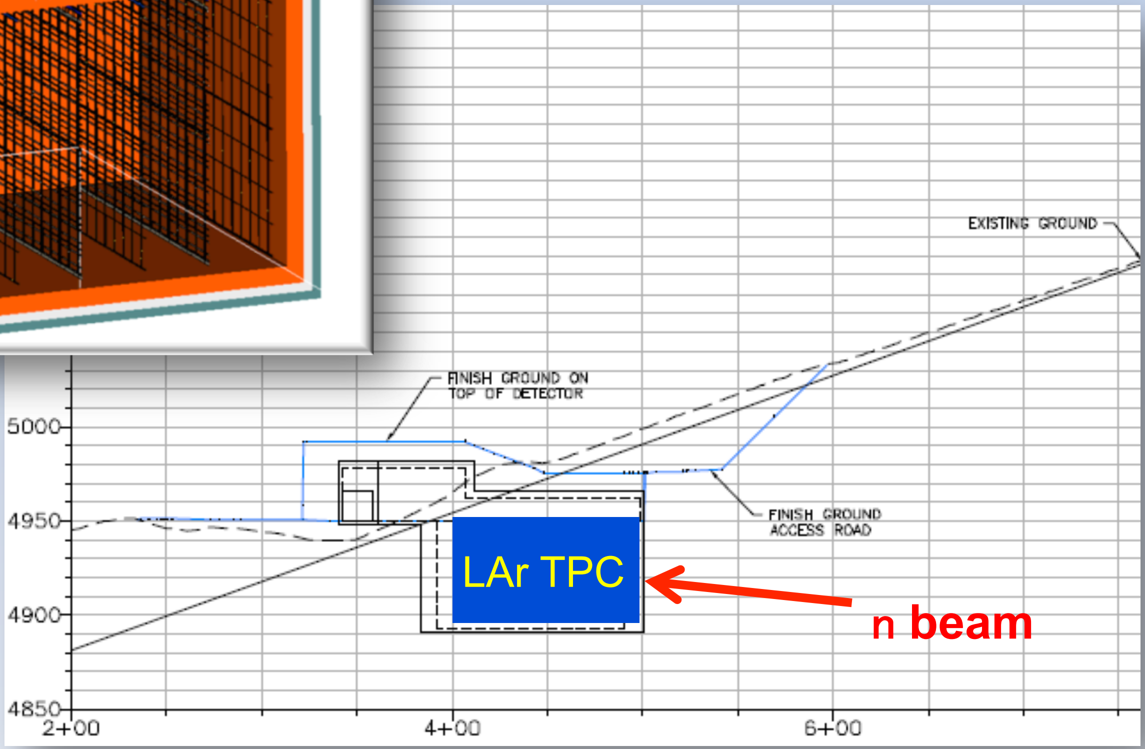

LBNE
N
Ontario
North Dakota
Minnesota
Lead, SD
South Dakota
1289 km
Wisconsin
Michigan
Milwaukee
Iowa
Nebraska
Chicago
Illinois



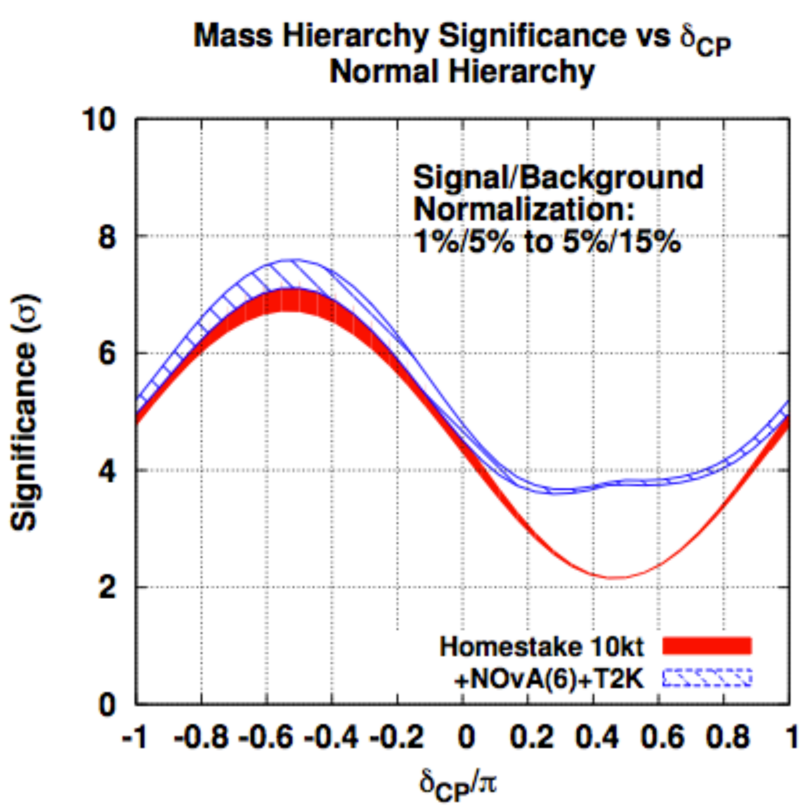
Far Detector :LAr TPC Detector

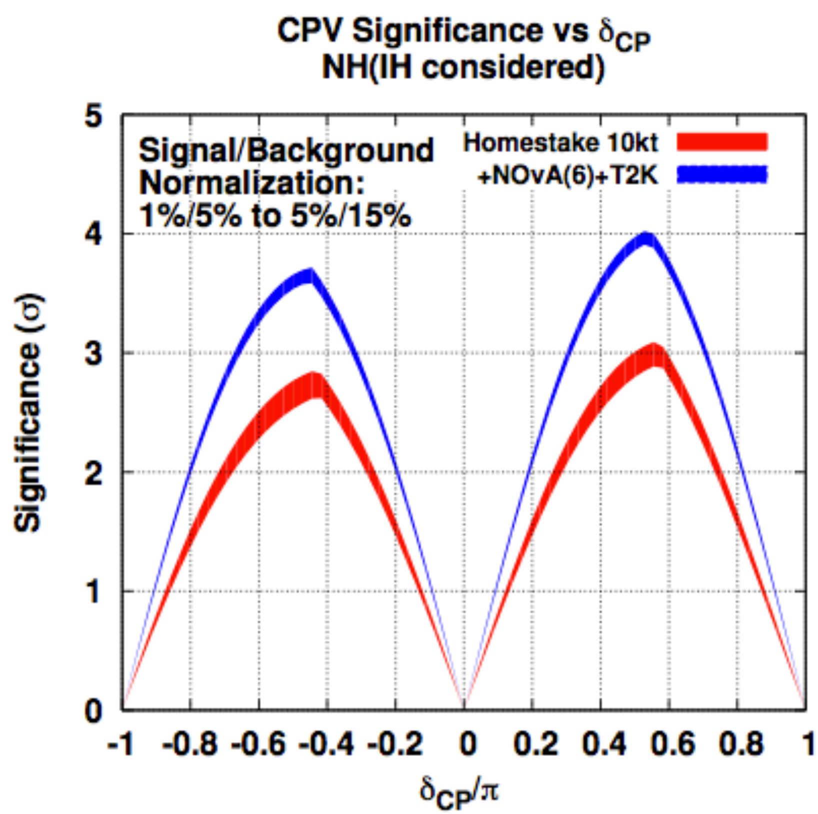
- 10 kt fiducial mass
- TPC design:
  - 3.7 m drift length
  - 5 mm wire spacing
  - three stereo views





LBNE Sensitivity





(Caveat: MH significance is not Gaussian statistics
see Qian, et al., Phys.Rev. D86 (2012) 113011)

Summary

- Many surprising discoveries in neutrino physics in the last decades
- We now have determined q_{13} !
  - -large value facilitates future measurements
- Future experiments are being planned to study mass hierarchy, CP violation, supernova neutrinos …

Perhaps the best is yet to come!


Stay Tuned !!