III. Reactor Neutrino Experiments

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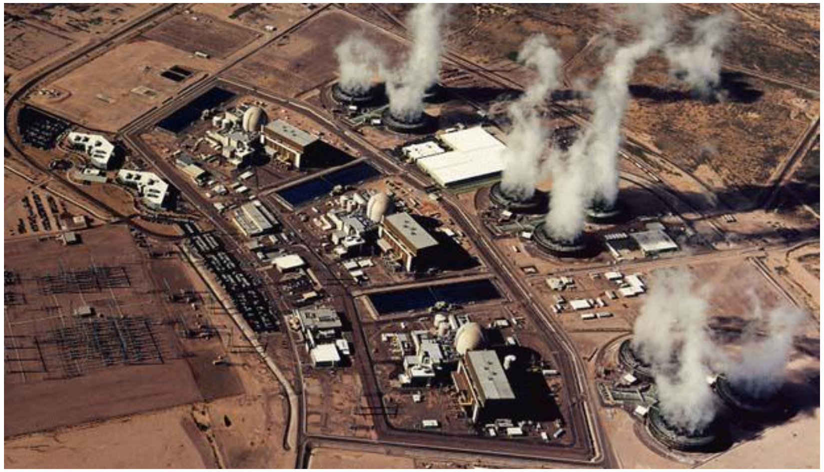
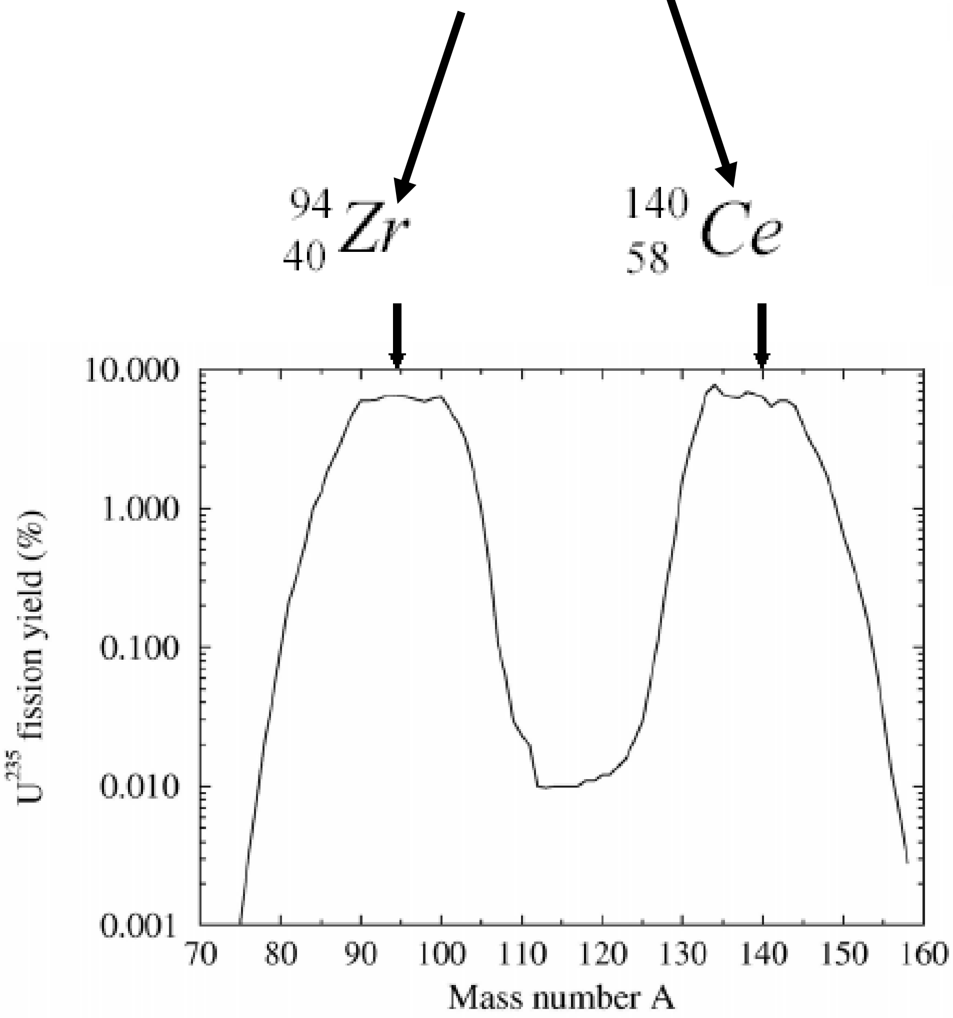
INSS 2014, St. Andrews

Neutrinos from Reactors



$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



The most likely fission products have a total of 98 protons and 136 neutrons, hence on average there are 6 n which will decay to 6p, producing 6 neutrinos

Neutrino flux of a commercial reactor with 3 $GW_{thermal}$: 6×10^{20} /s $\bar{\nu}$

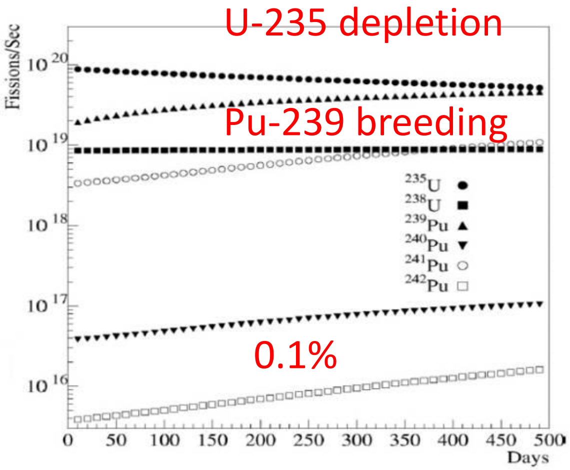
Reactor Neutrino Flux at a Glance

- Using PWR (Pressurized Water Reactor) as examples in the following.

U-235, U-238

Pu-239, Pu-241

Isotope evolvement, Palo Verde

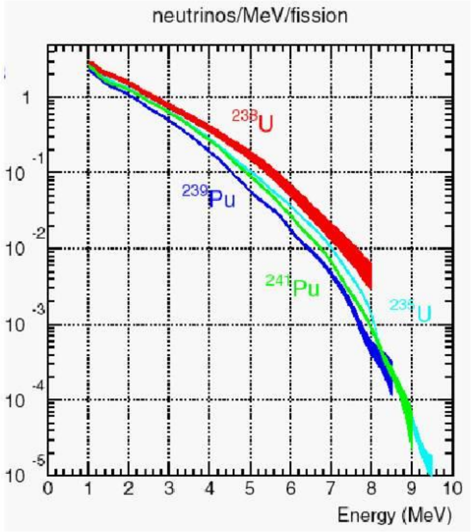


U-235 depletion

Pu-239 breeding

0.1%

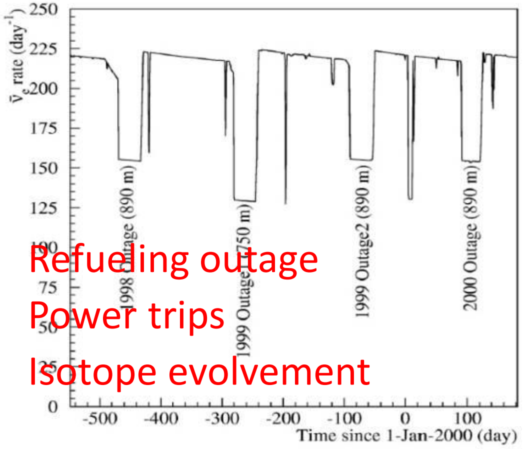
X



Neutrino spectra, ILL

More neutrinos from U-235 fission than Pu-239

Neutrino rate, Palo Verde



Refueling outage

Power trips

Isotope evolvement

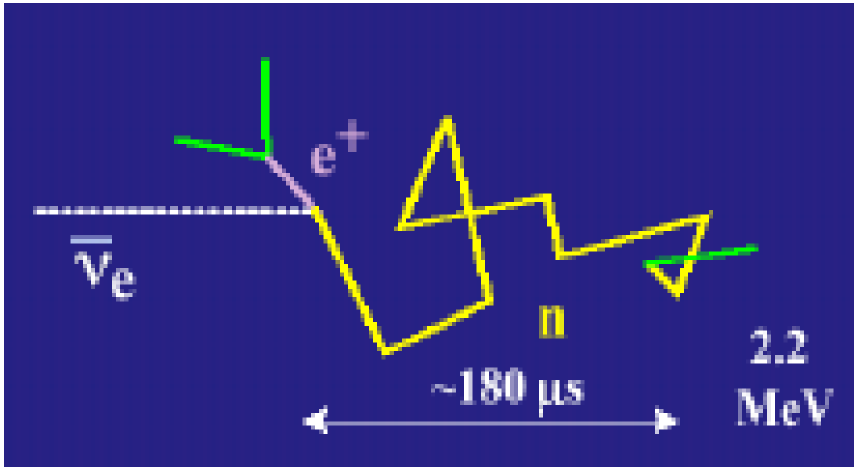
Neutrino Flux $S(E_\nu) = \sum_i^{istopes} f_i S_i(E_\nu)$

$$\boxed{S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)}$$

$$W_{th} = \sum_i f_i e_i \ , \qquad F = \sum_i f_i$$

Neutrino Detection:
Inverse-β Decays in Liquid Scintillator

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



τ ≈ 180 or 28 μs(0.1% Gd)

$$n + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$$
$$n + Gd \rightarrow Gd^* + \gamma\ (8\ \text{MeV})$$

Neutrino Event: coincidence in time, space and energy

Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p)}_{\text{1.8 MeV: Threshold}} + m_{e^+}$$

Why LS:

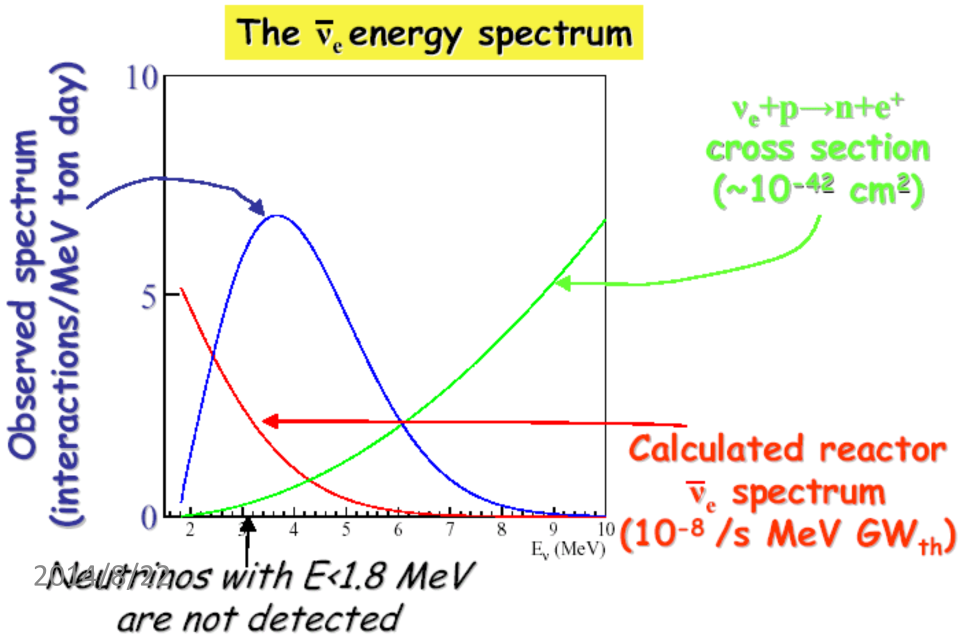
Being both the target and detector
Proton rich material
Good energy resolution
Easy handling for large volume
Relatively Cheap

Reactor Neutrino Spectrum

- **Three ways to obtain reactor neutrino spectrum:**
  - **Direct measurement**
  - **First principle calculation**
  - **Sum up neutrino spectra.**

^{235}U, ^{239}Pu, ^{241}Pu from their measured β spectra,

^{238}U from calculation (10%)

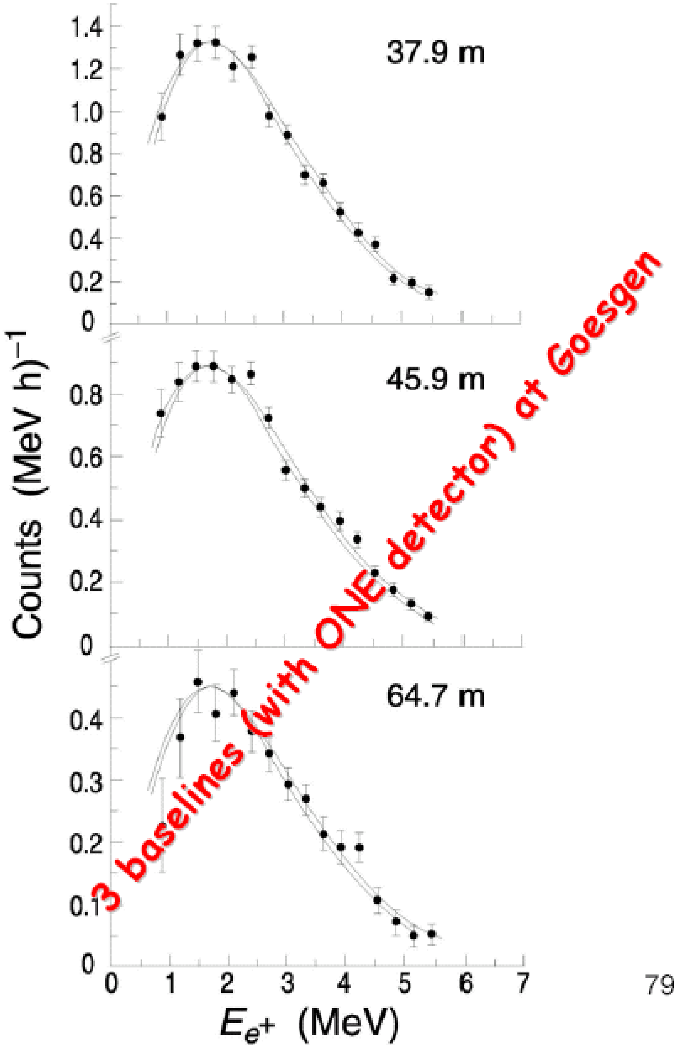


The $\bar{\nu}_e$ energy spectrum

ν_e+p→n+e$^+$ cross section (~10^{-42} cm^2)

Calculated reactor $\bar{\nu}_e$ spectrum (10^{-8} /s MeV GW$_{th}$)

Neutrinos with E<1.8 MeV are not detected

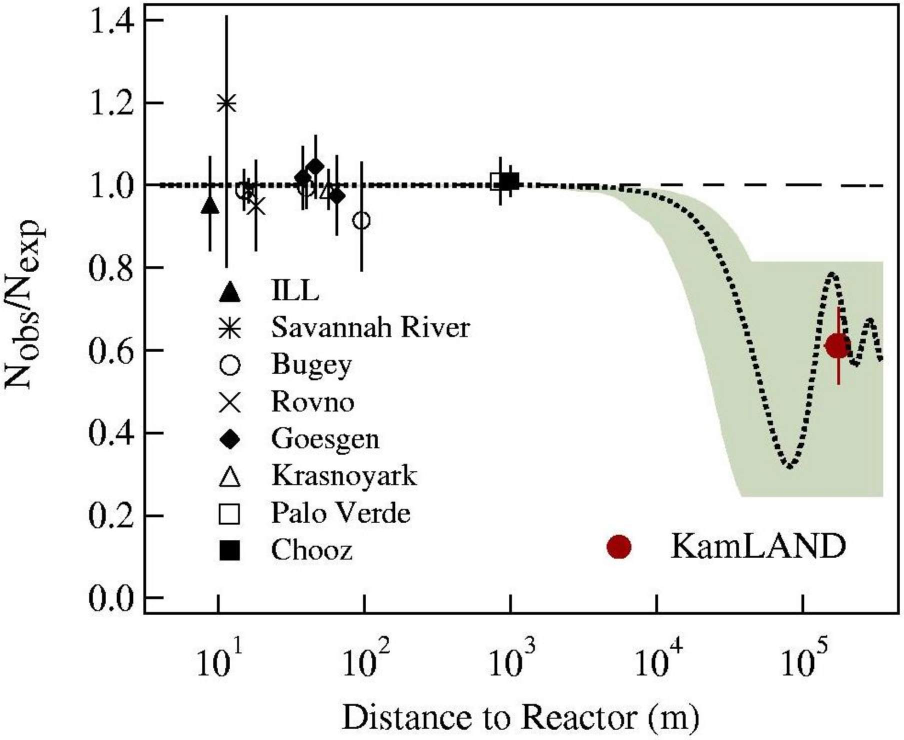


3 baselines (with ONE detector) at Goesgen

Reactor Neutrinos: a Brief History

- **Oscillation:**
  - **Early searches(70's-90's):**
    - ✓ **Reines, ILL, Bugey, … Palo Verde, Chooz**
  - **Determination of θ_{12}(90's-00's):**
    - ✓ **KamLAND**
  - **Discovery of θ_{13} (00's-10's):**
    - ✓ **Daya Bay, Double Chooz, RENO**
  - **Mass hierarchy(10's-20's):**
    - ✓ **JUNO, RENO-50**
- **Magnetic moments（90's-now)**
  - **Texono, MUNU, GEMMA, …**
- **Sterile neutrinos(10's):**
  - **Nucifer, Stereo, Solid …**

Oscillation signal:
$N_{obs}/N_{exp} < 1$



Savannah River experiment —

“Observation of neutrino oscillation”

- ^{3}He neutron detectors immersed in 268 kg D_2O tank placed 11.2m m from reactor :

$$\bar{\nu}_e + d \begin{array}{l} \nearrow n+n+e^{+} \quad (ccd) \\ \searrow n+p+\bar{\nu}_e \quad (ncd) \end{array}$$

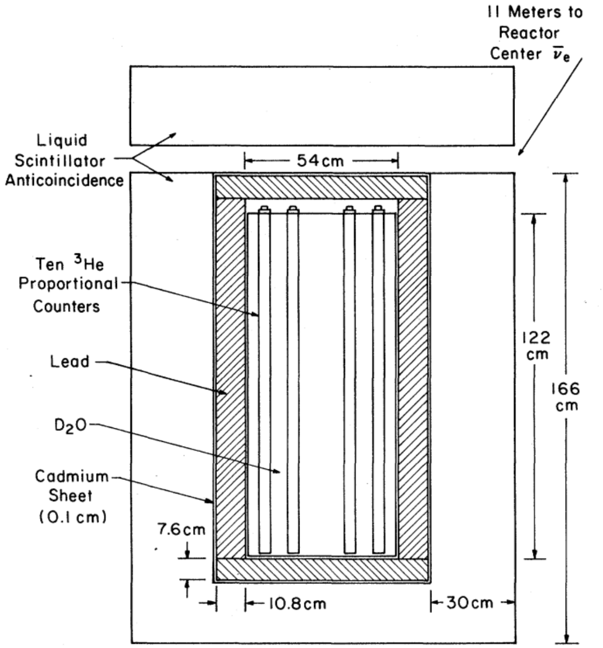
- Neutron signal:

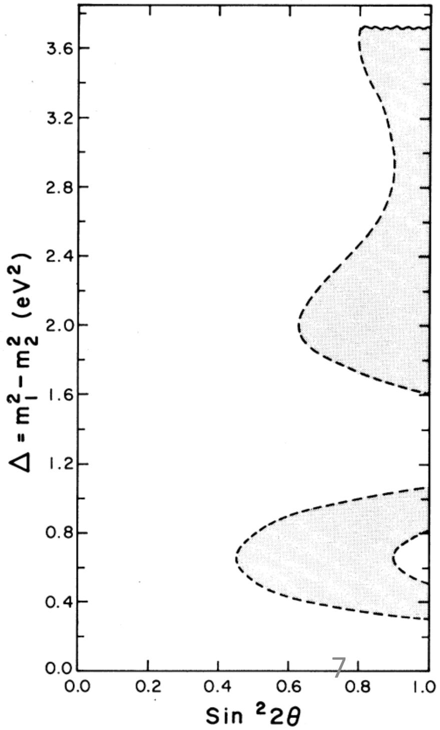
  $n + {}^3He \rightarrow p + {}^3H + 764$ keV

- Single/double neutron rate ➔ ccd/ncd
- Observed $R \equiv r^{exp}_{ccd/ncd} / r^{theo}_{ccd/ncd}$

  $= 0.40 \pm 0.22$

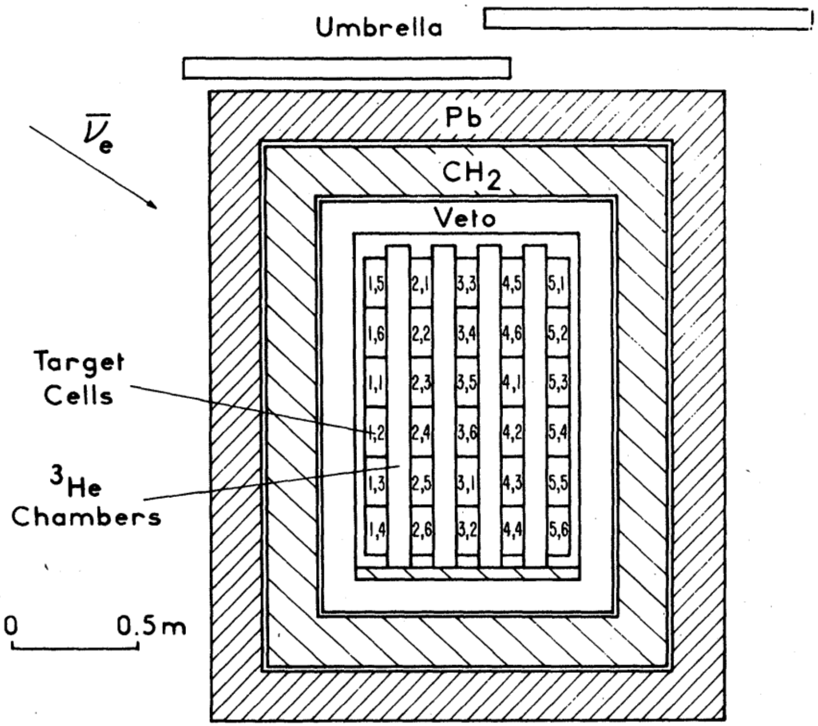
F. Reines et al., PRL 45(1980) 1307

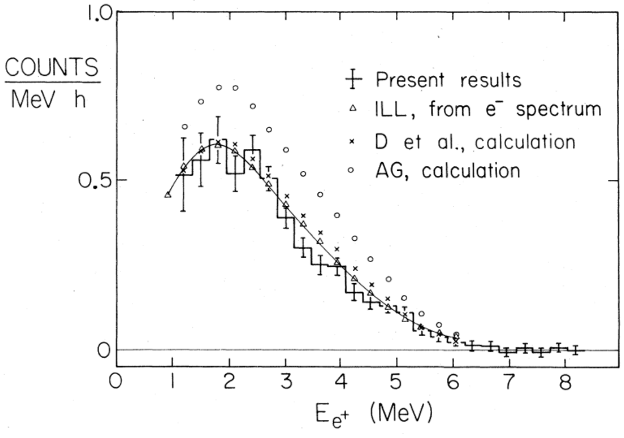


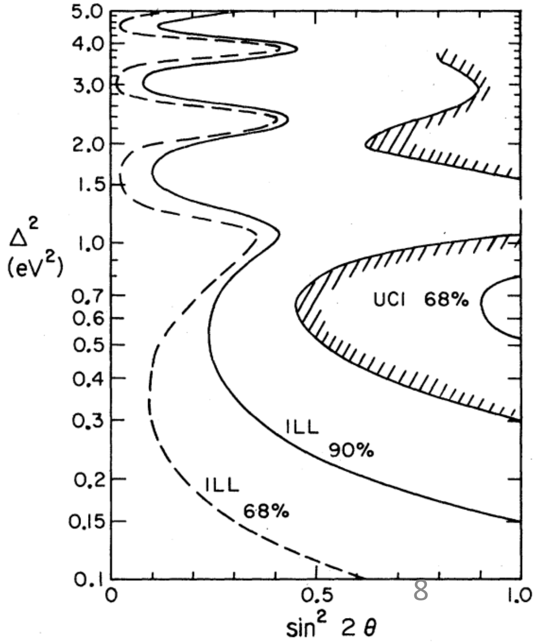


ILL： First Debate

- Baseline: 8.7 m
- 377 l Liquid scintillator detector
- Neutrons: by 4 ^{3}He planes in between LS cells(τ=150 μs)
- Techniques used until now: shielding, veto, background, on/off Comparison, efficiency, spectrum, stability, etc.
- Source: P. Vogel PRC19(1979)2259
- $N_{exp}/N_{theo.}$= 0.89± 0.04(stat.)± 0.14(syst.)







F. Boehm et al., PLB97(1980)310
H.Kwon et al., PRD24(1981)1097

Bugey： a new claim

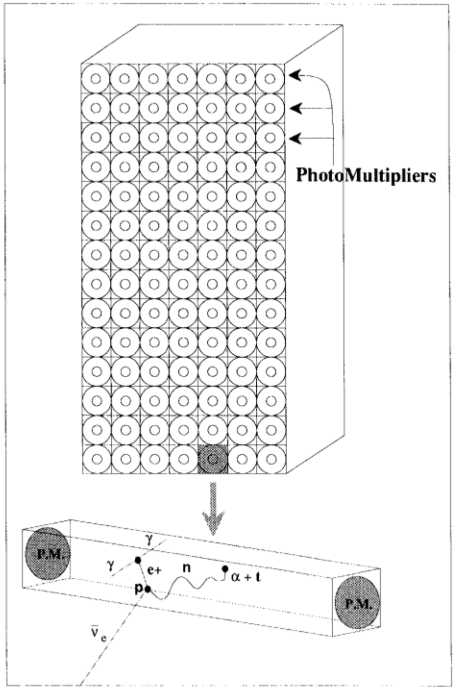
- Modules made of 98 SS cells, each of 0.85 m long, 8.5 cm ×8.5 cm in cross section, filled with PC based liquid scintillator doped with 0.15% ^{6}Li, and viewed by two PMTs at both ends
- Neutron signal (τ = 30 μs) :

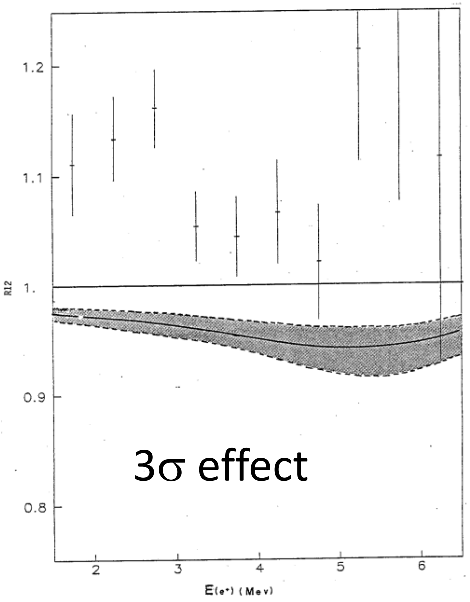
  $n+{}^{6}Li \rightarrow {}^{4}He+{}^{3}H+4.8MeV$

  E_{vis}= 0.53 MeV +

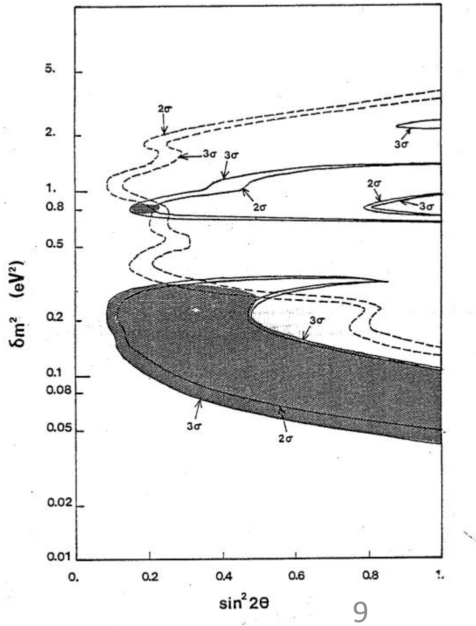
  PSD $Q_{delayed}/Q_{total}$
- Compare neutrino rate at

  14 and 18 m from reactors





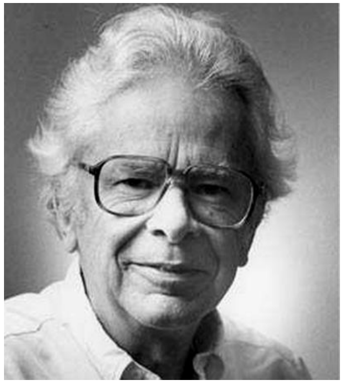
3σ effect

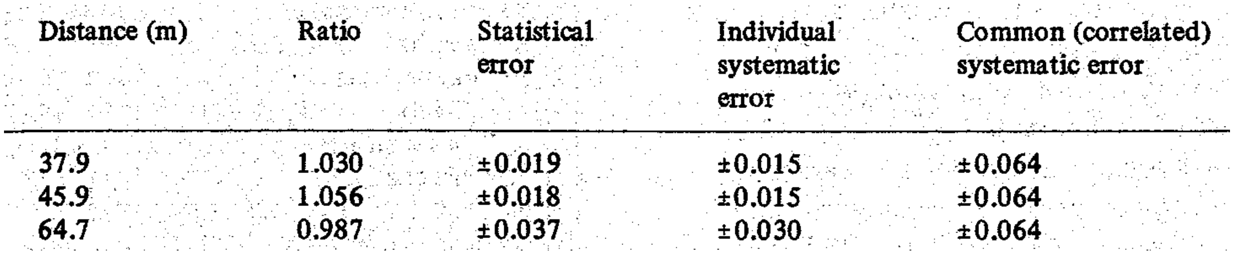


J.F. Cavaignac et al, Phys. Lett. B 148(1984)387

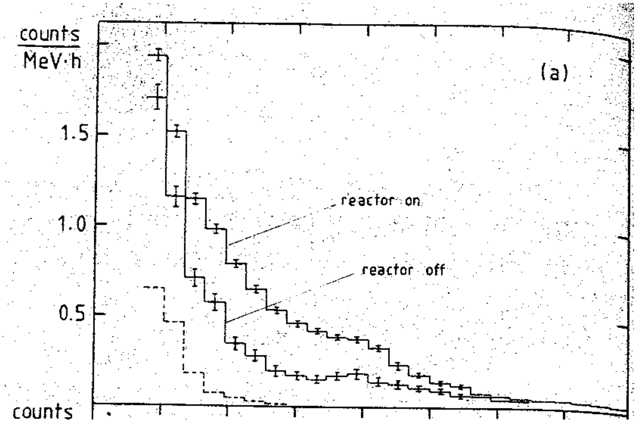
Disapproved Again by F. Boehm: Goesgen

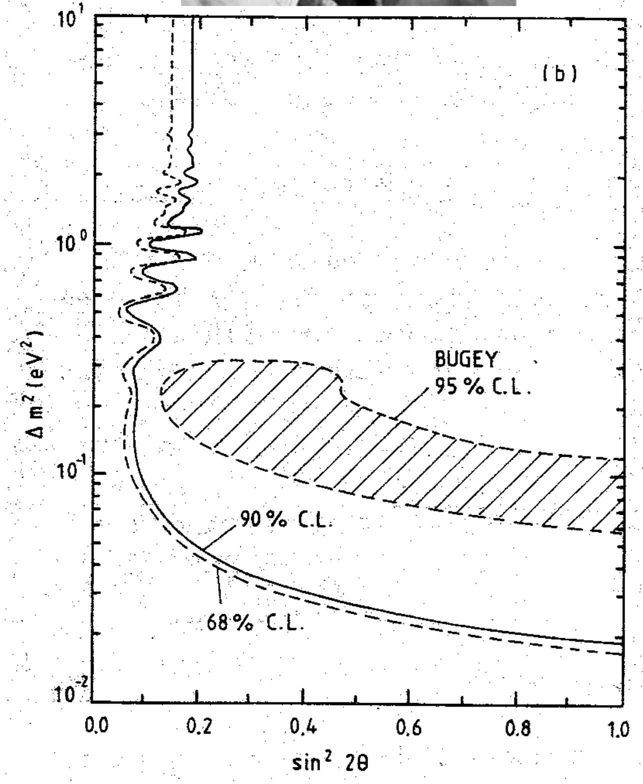
- Nearly the same Detector as ILL
- Baseline: 37.9, 45.9, 64.7
- Good agreement with expectation: rate and spectrum





Distance (m)	Ratio	Statistical error	Individual systematic error	Common (correlated) systematic error
37.9	1.030	±0.019	±0.015	±0.064
45.9	1.056	±0.018	±0.015	±0.064
64.7	0.987	±0.037	±0.030	±0.064





V. Zacek et al., PLB164(1985)193

A new era: Atmospheric neutrino anomaly

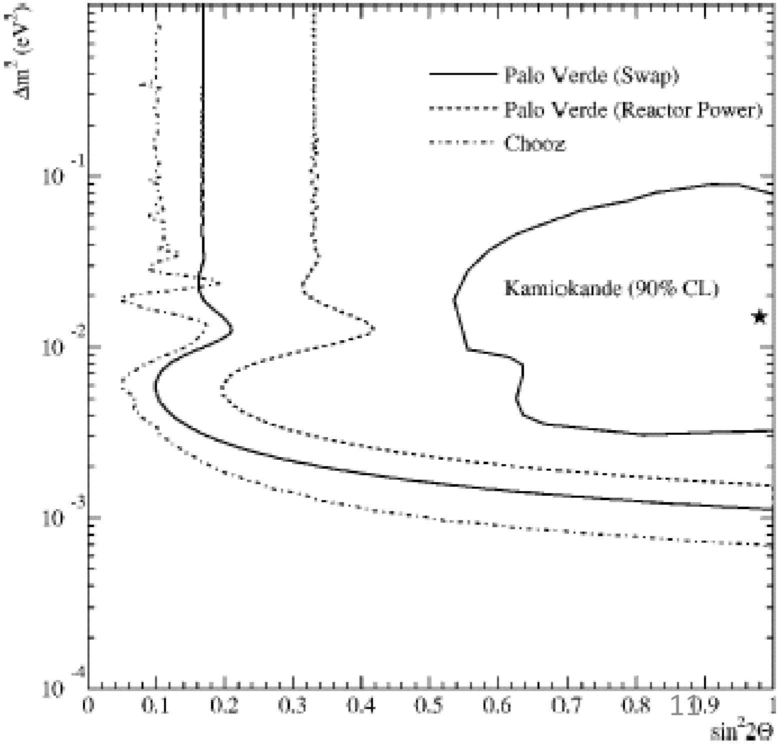
- Atmospheric neutrino results stimulate new experiments
  - If atmospheric $\nu_\mu \rightarrow \nu_e$
  - Baseline: ~1km
- F. Boehm: San Onofre ➔ Palo Verde (early 90's ➔ 00's)
  - From Goesgen
  - Difficult stories (California Gnatcatcher)
- Chooz (early 90's)
  - From Bugey+Russians
  - a successful story
- New techniques:

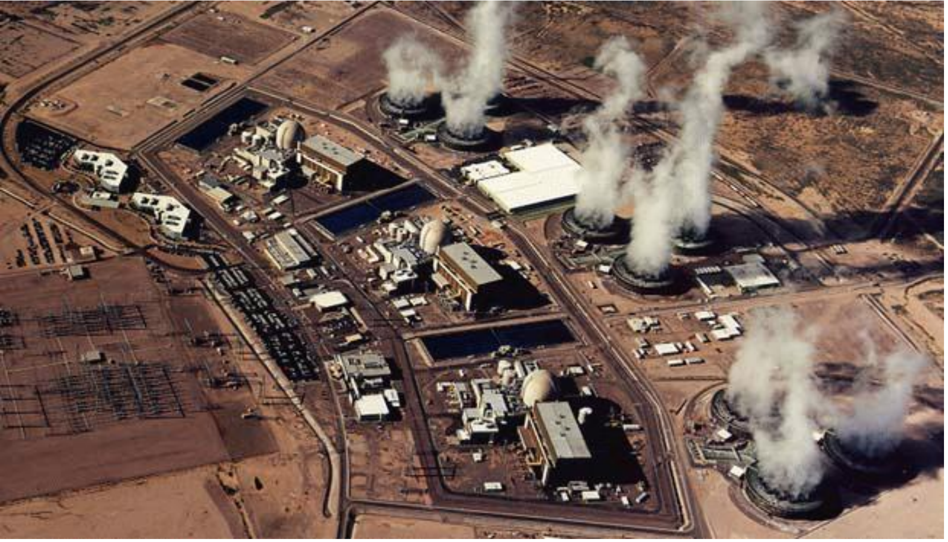
  larger detector,

  Gd-LS, MC,

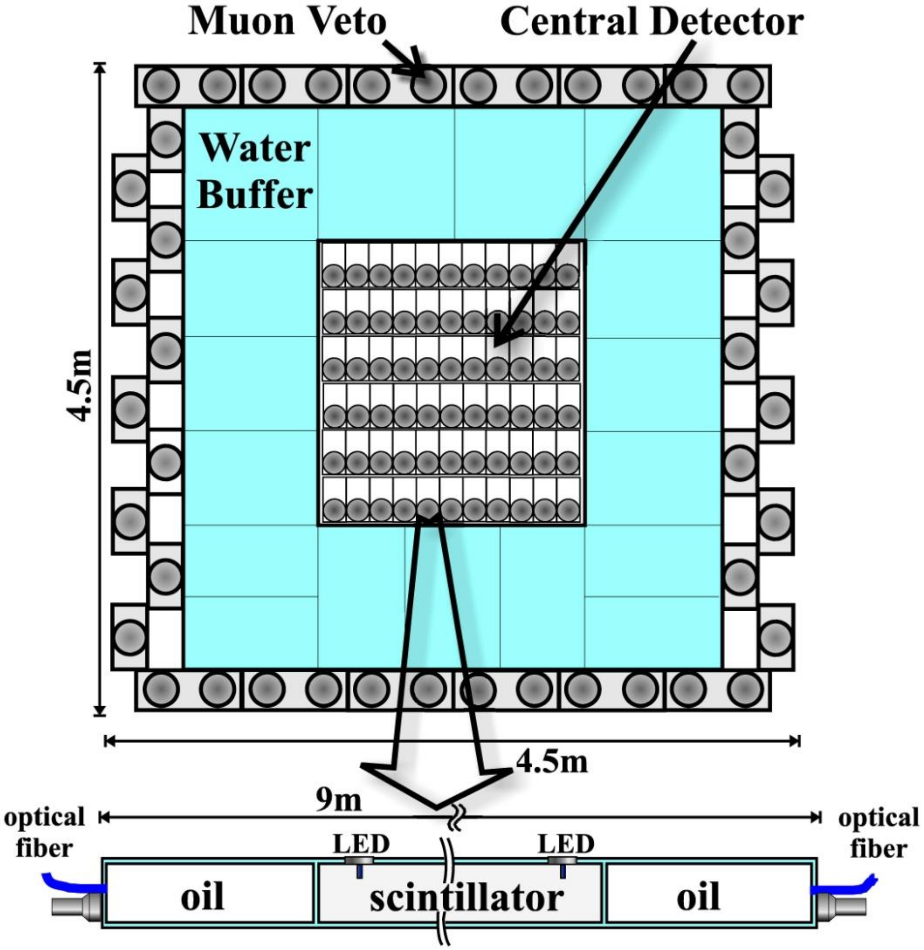
  HEP software &

  analysis method …





Palo Verde

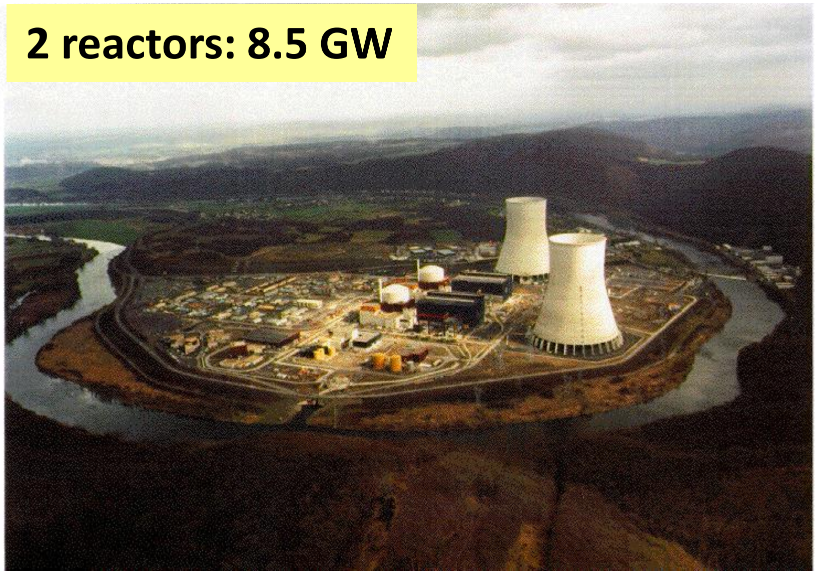


Palo Verde

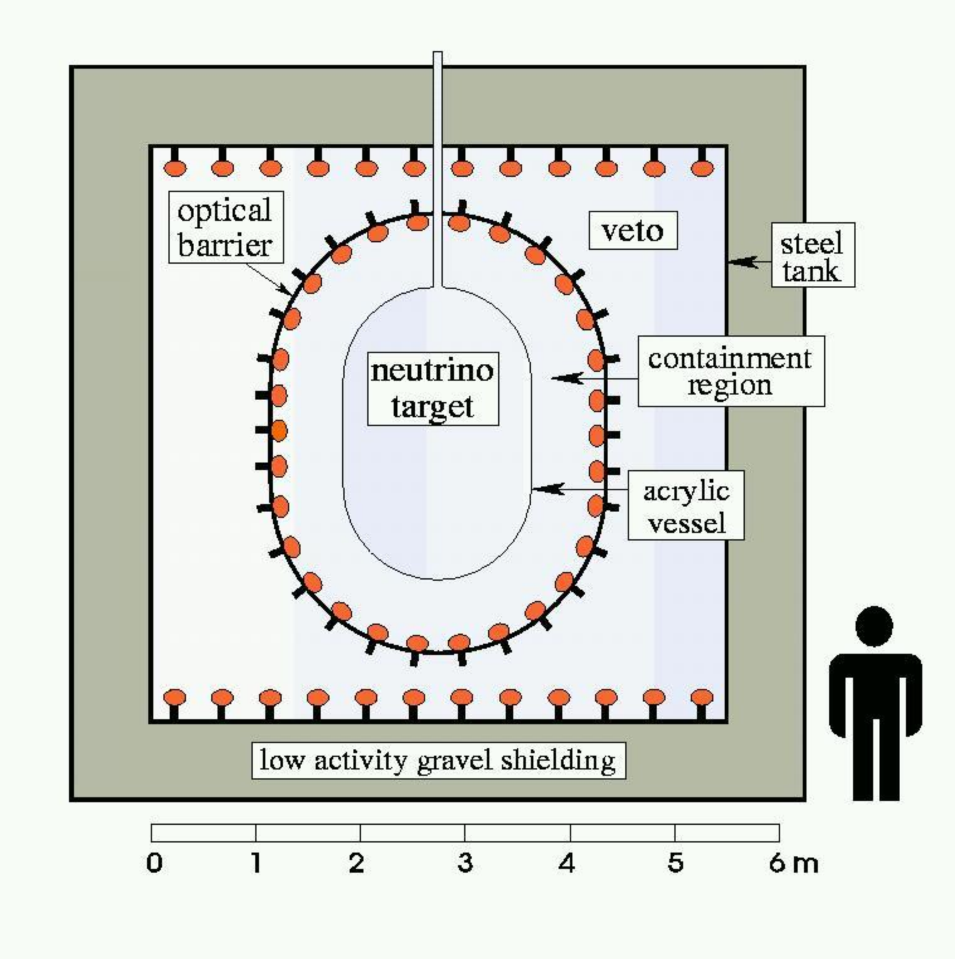
- 32 mwe shielding
- 12 ton, Gd loaded, scintillating target
- 3 reactors: 11.6 GW
- Baselines 890 m and 750 m
- Expected rate of ~20 evts/day
- Efficiency: ~ 10%
- Background: corr. ~ 15/day

  uncorr. ~ 7/day

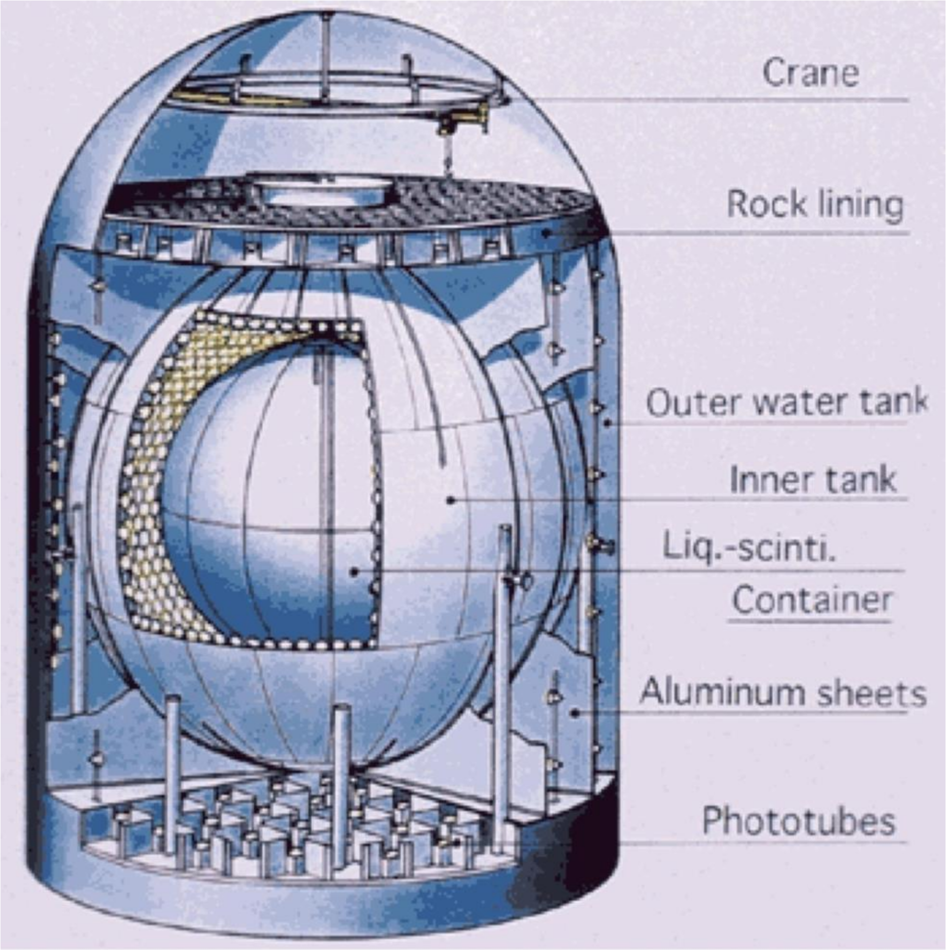
Chooz



- 5 ton, Gd loaded scintillator
- 300 mwe shielding
- Baselines 1115 m and 998 m
- Expected signal ~25 evts/day
- Efficiency: 70%
- Background: corr. 1/day
  uncorr. 0.5/day



KamLAND



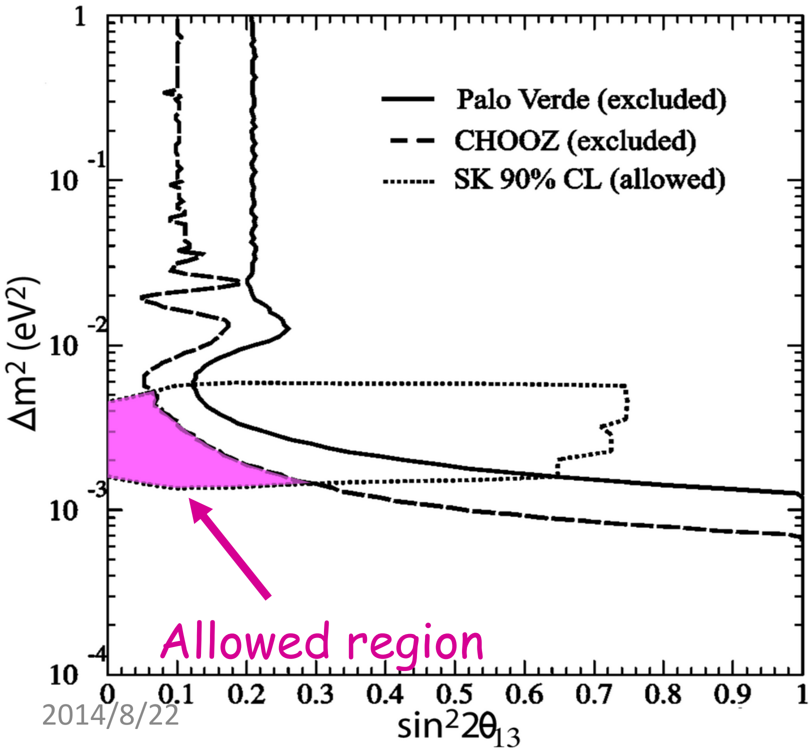
If solar neutrino problem is due to ν_e oscillation, reactor $\bar{\nu}_e$ can be used to look at it, if CPT is valid and if LMA solution is correct → a very brave move

Very long baseline → 100 km
Large detector → 1kt
Only possibility → re-use Kamiokande cavern

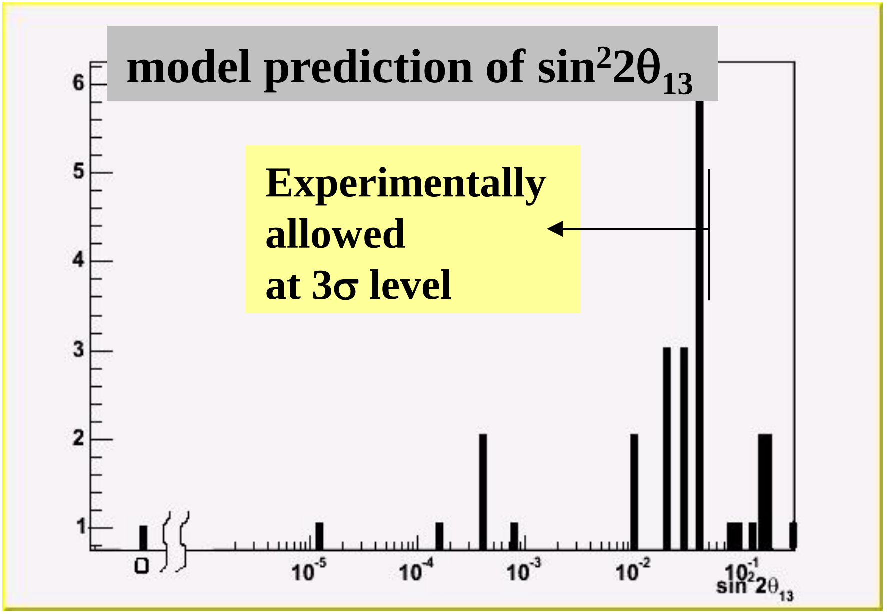
Very Lucky

Experiments for θ_{13}

- Once θ_{23} and θ_{12} established in 2003, interests mount on θ_{13}
- No good reason(symmetry) for $\sin^2 2\theta_{13} = 0$
- Even if $\sin^2 2\theta_{13} = 0$ at tree level, $\sin^2 2\theta_{13}$ will not vanish at low energies with radiative corrections
- Theoretical models predict $\sin^2 2\theta_{13}$ ~ 0.1-10 %



Allowed region



model prediction of $\sin^2 2\theta_{13}$

Experimentally allowed at 3σ level

An experiment with a precision for $\sin^2 2\theta_{13}$ less than 1% is desired

Why at reactors

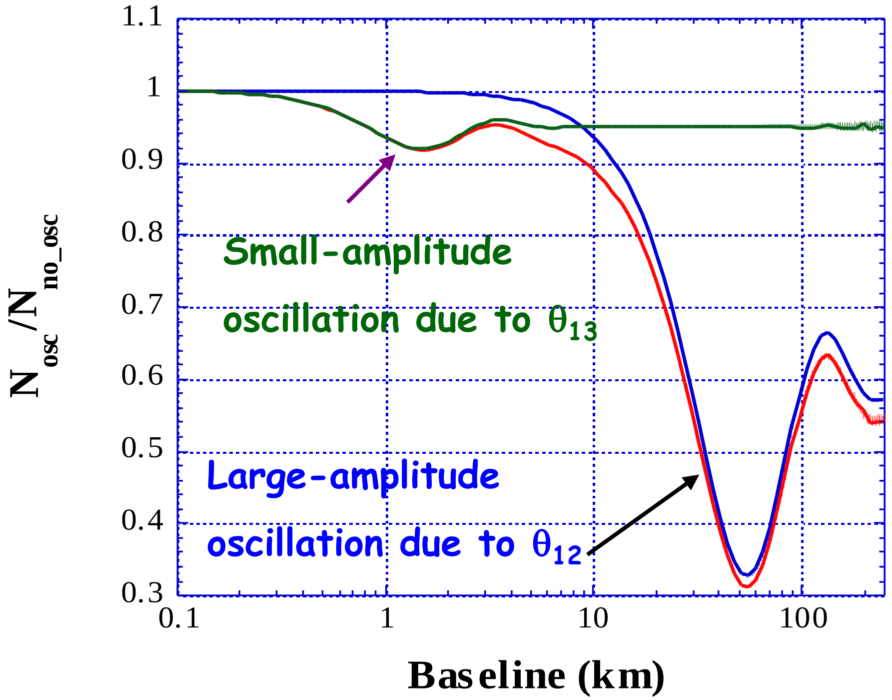
- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compare to accelerator based experiments
- Can be very quick

Reactor experiments:

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

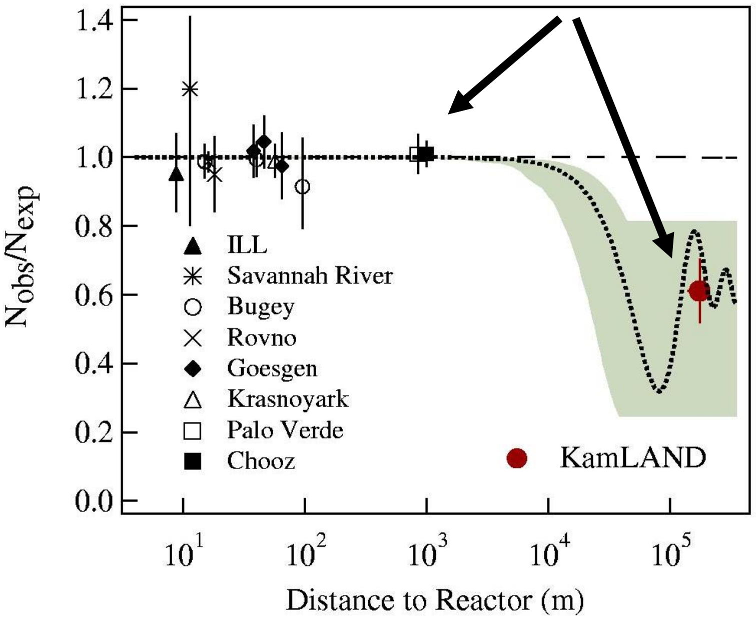
Long baseline accelerator experiments:

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



Reactor Experiment: comparing observed/expected neutrinos:

Typical precision: 3-6 %



Precision of past experiments:

- Reactor power： ~1%
- ν spectrum： ~0.3%
- Fission rate： ~ 2%

- Backgrounds： ~1-3%

- Target mass： ~1-2%
- Efficiency： ~2-3%

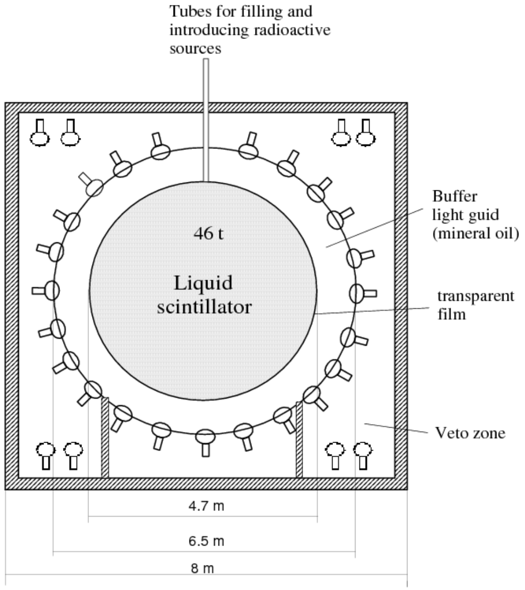
We need a precision of ~ 0.4%

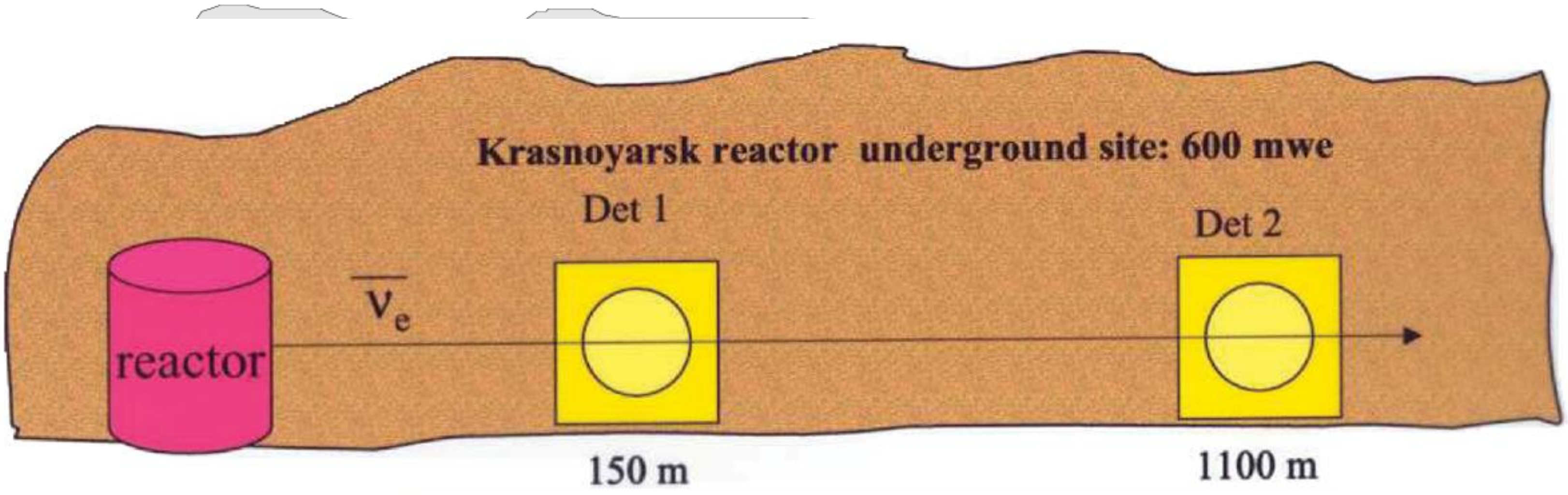
First idea: Kr2Det

- Krasnoyarsk underground reactor
- Near-far cancellation

L.A. Mikaelyan et al., hep-ex/9908047
V. Martemyanov et al., hep-ex/0211070

PMT type EMI 9350 Diameter - 8 inches
Coverage - 20%, PMT Number - 842

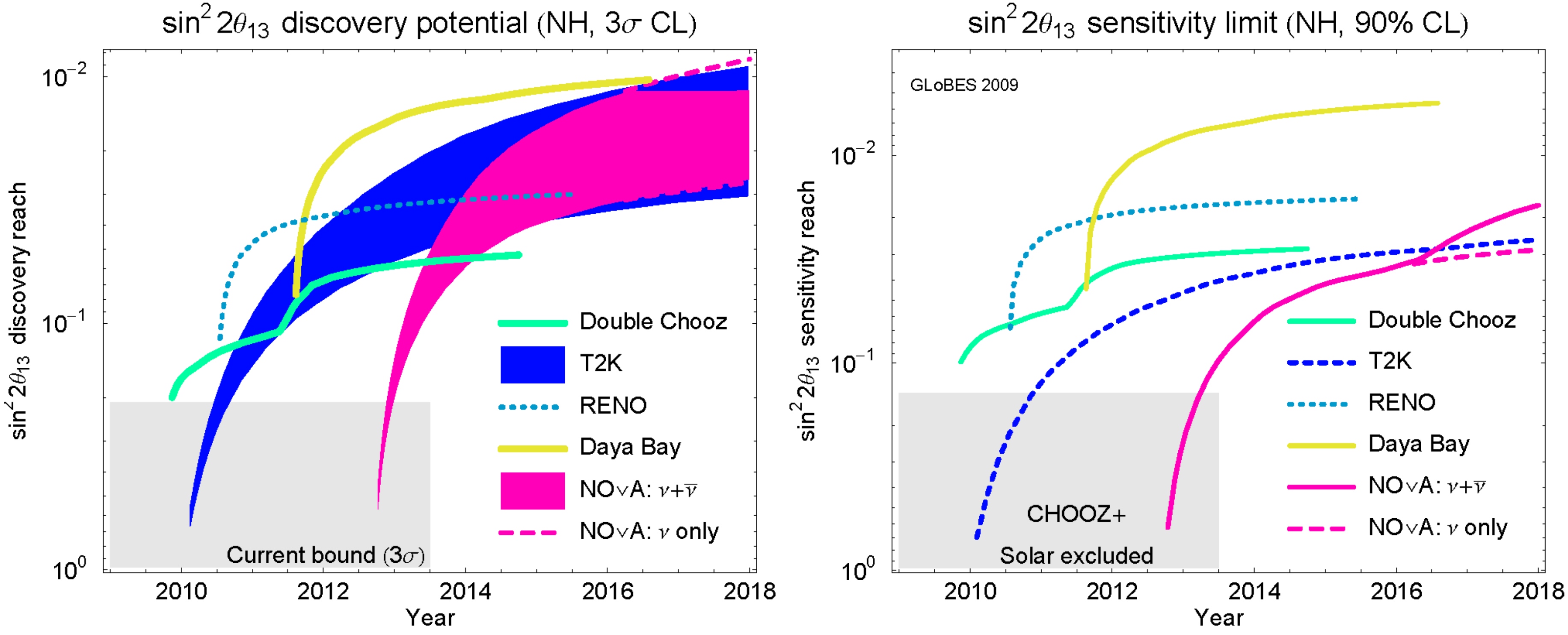




Target:	**50 m^3 oil+ppo**	**50 m^3**
Rate:	**2500/d**	**50/d**
S/B:	**>>1**	**~10:1**

Race to Measure θ_{13}

P. Huber et al., JHEP 0911:044,2009

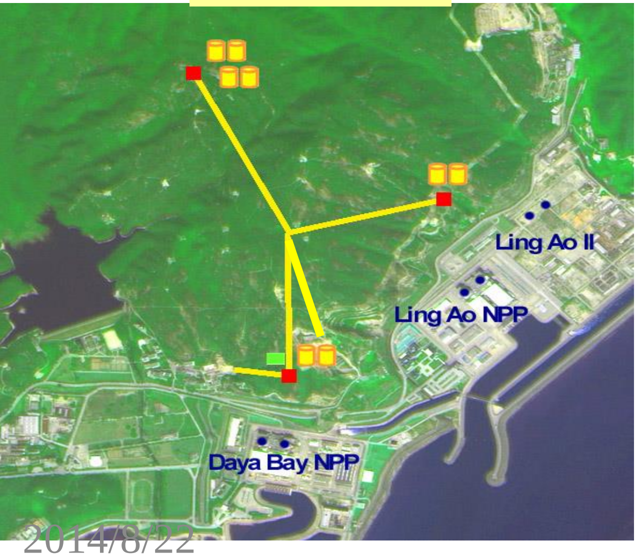


- Proposals from Russia, Japan, US and Brazil not approved

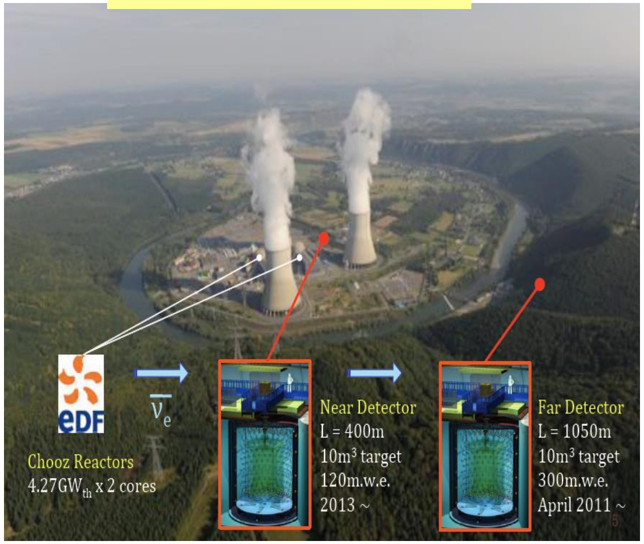
θ_{13}: Three on-going experiments

Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Reno	16.5	409/1444	16/16	120/450	~ 0.02

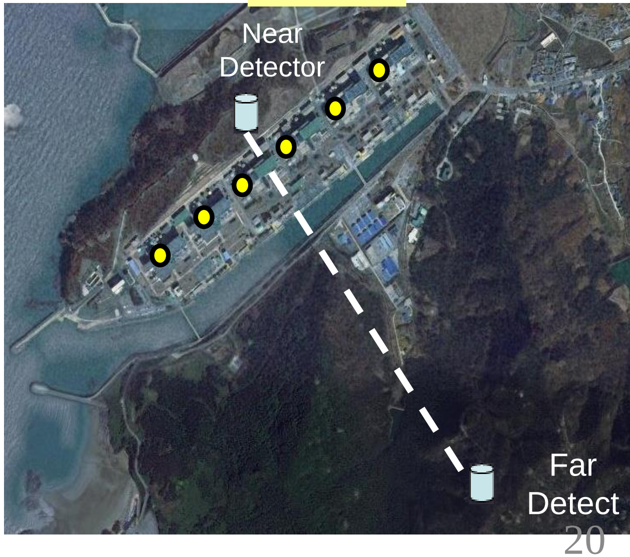
Daya Bay



Double Chooz



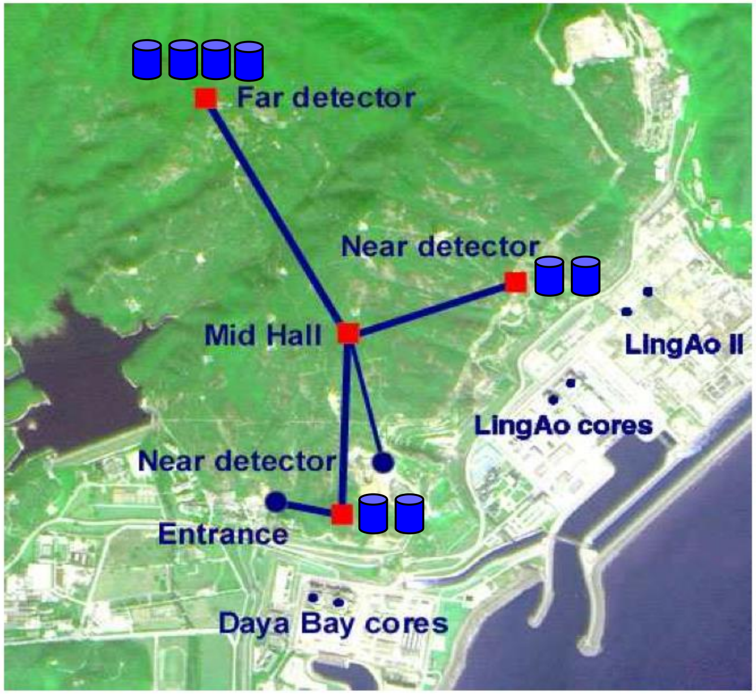
Reno

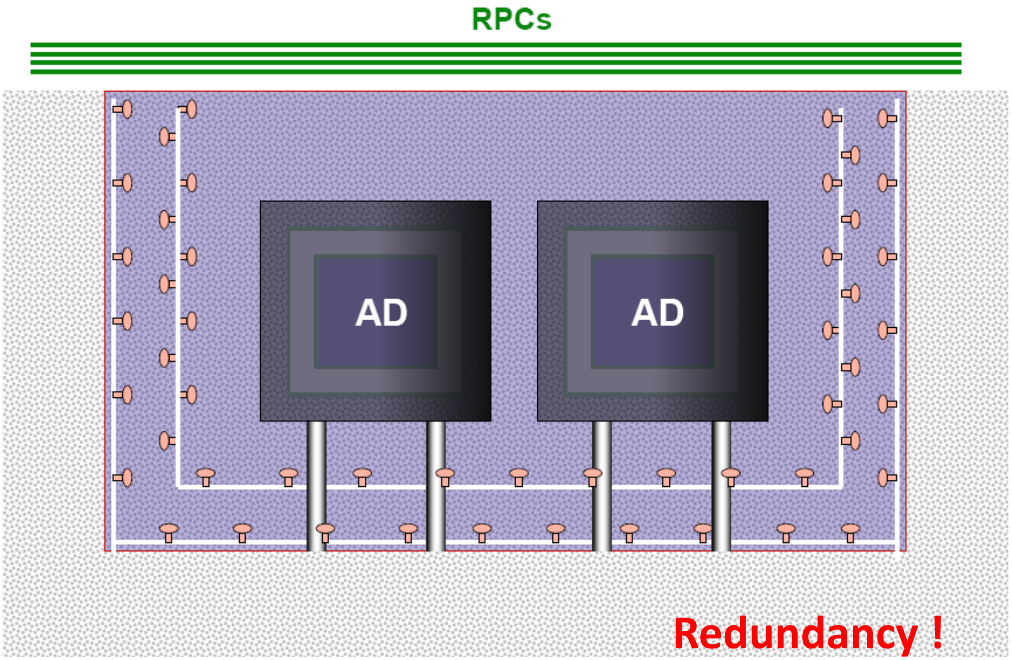


How Can Daya Bay Reach 0.5% Precision ?

- Increase statistics:
  - Powerful nuclear reactors(1 GW_{th}: 6 x 10^{20} $\bar{\nu}_e$/s)
  - Larger target mass
- Reduce systematic uncertainties:
  - Reactor-related:
    - Optimize baseline for the best sensitivity
    - Near and far detectors to minimize reactor-related errors
  - Detector-related:
    - Use "Identical" pairs of detectors to do *relative* measurement
    - Comprehensive programs for the detector calibration
    - Interchange near and far detectors (optional)
  - Background-related
    - Go deep to reduce cosmic-induced backgrounds
    - Enough active and passive shielding

Layout of Daya Bay Experiment



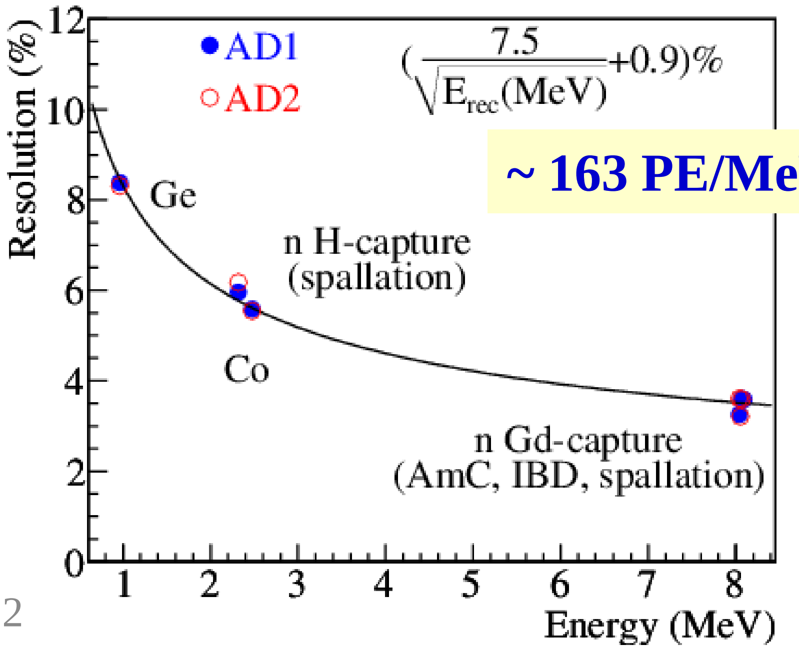


Redundancy !

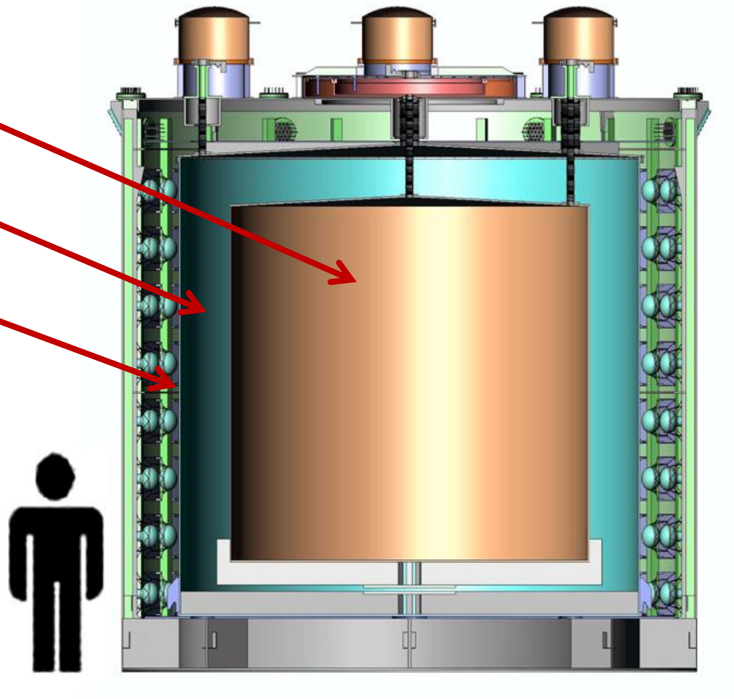
- Near-Far relative mea. to cancel correlated syst. err.
  - 2 near + 1 far
- Multiple modules per site to reduce uncorrelated syst. err. and cross check each other (1/sqrt(N))
  - 2 at each near site and 4 at far site
- Multiple muon veto detectors at each site to reach highest possible eff. for reducing syst. err. due to backgrounds
  - 4 layer of RPC + 2 layer of Cerenkov detector

Anti-neutrino Detector (AD)

- **Three zones modular structure:**
  - **I. target: Gd-loaded scintillator**
  - **II. γ-catcher: normal scintillator**
  - **III. buffer shielding: oil**
- **192 8” PMTs/module**
- **Two optical reflectors at the top and the bottom, Photocathode coverage increased from 5.6% to 12%**



~ 163 PE/MeV



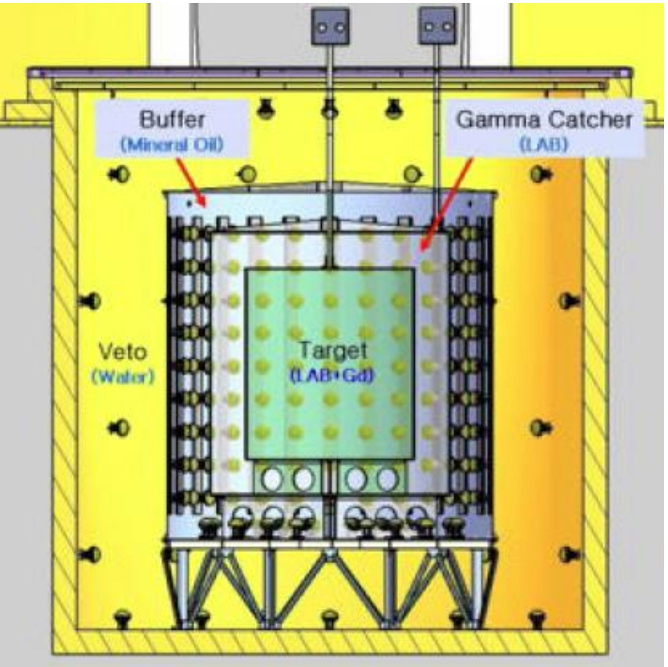
Target: 20 t, 1.6m

γ-catcher: 20t, 45cm

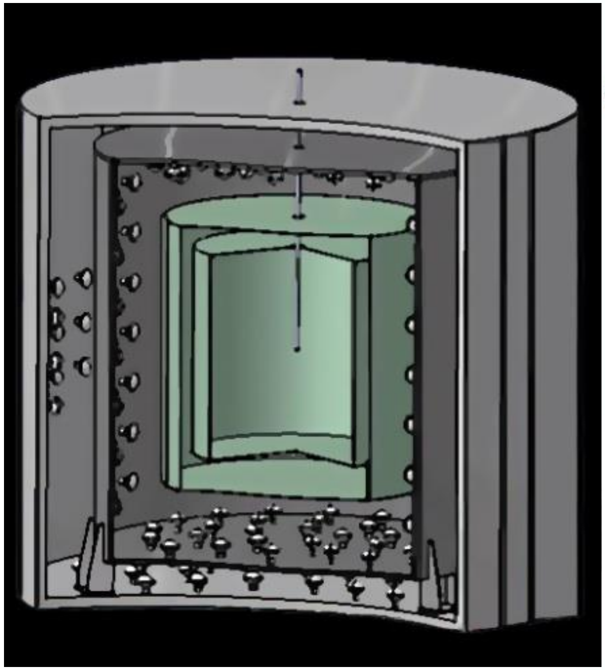
Buffer: 40t, 45cm

Total weight: ~110 t

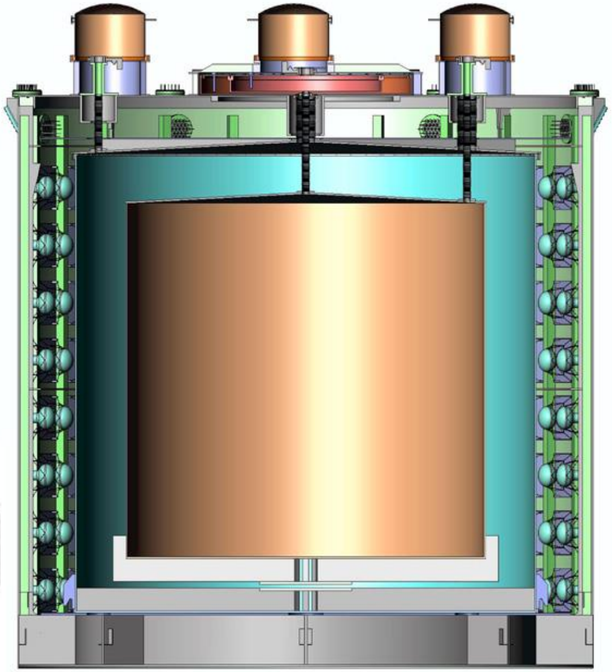
Comprision with other detectors



RENO



Double Chooz



Daya Bay

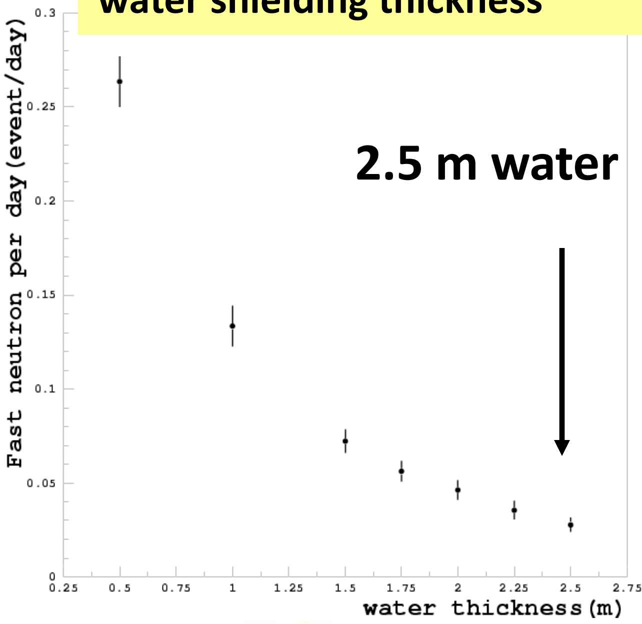
	PMT	Coverage	pe yield	MO	Acc. Bkg.	ΔB/B
Daya Bay	192 8"	~6%	163 pe/MeV	50 cm	1.4%/4.0%	1.0%/1.4%
RENO	354 10"	~15%	230 pe/MeV	70 cm	0.56%/0.93%	1.4%/4.4%
Double Chooz	390 10"	~16%	200 pe/MeV	105 cm	0.6%	0.8%

Water Buffer & VETO

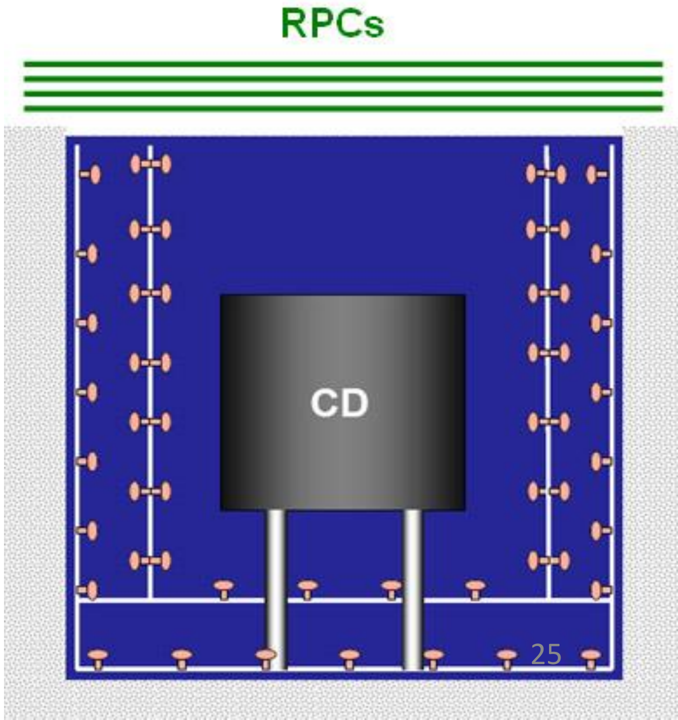
- **2.5 m water buffer to shield backgrounds from neutrons and γ's from lab walls**
- **Cosmic-muon VETO Requirement:**
  - **Inefficiency < 0.5%**
  - **known to <0.25%**
- **Solution: multiple detectors**
  - **cross check each other to control uncertainties**
- **Design:**
  - **4 layers of RPC at TOP +**
  - **2 layers of water detector**

RPC over scintillator: insensitive to γ backgrounds

Neutron background vs water shielding thickness



2.5 m water



Background Estimate

- **Uncorrelated backgrounds: U/Th/K/Rn/neutron**

  Single gamma rate @ 0.9MeV < 50Hz

  Single neutron rate < 1000/day

  2m water + 50 cm oil shielding

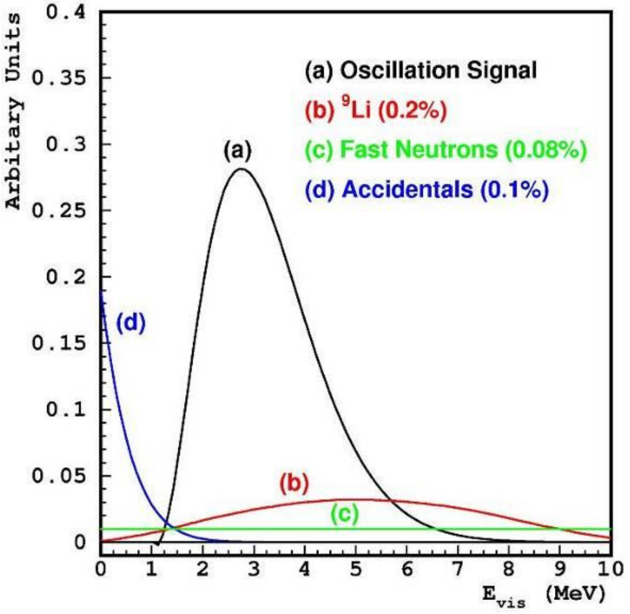
- **Correlated backgrounds:** **n ∝ $E_\mu^{0.75}$**

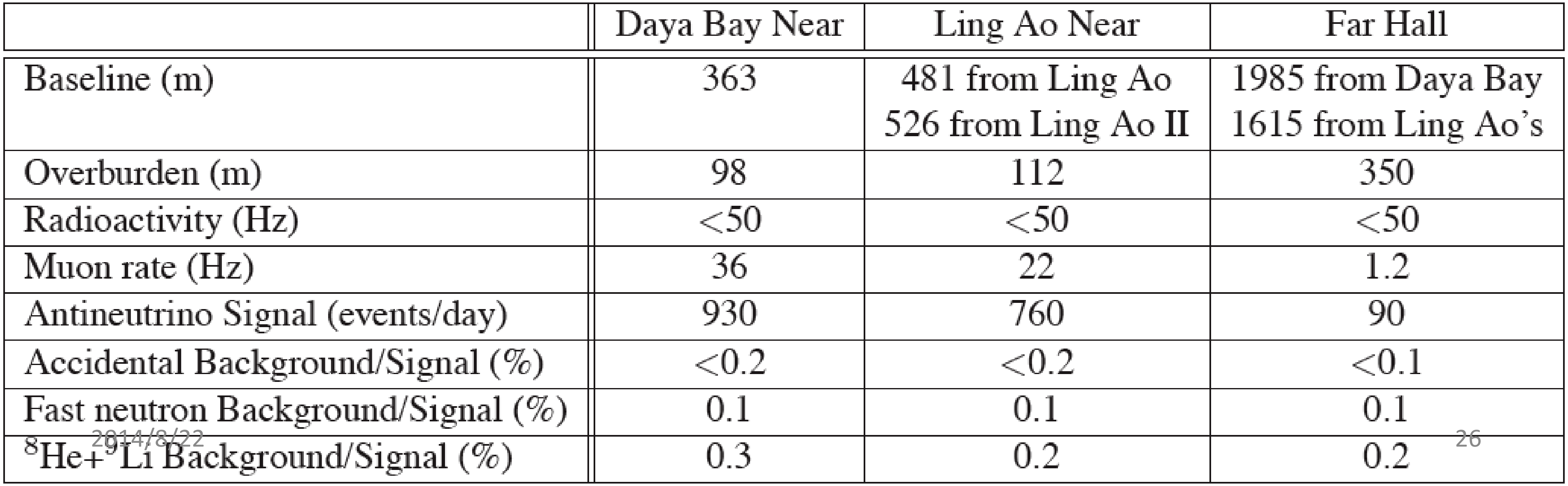
  Neutrons: >100 MWE + 2m water

  Y.F. Wang et al., PRD64(2001)0013012

  ^{8}He/^{9}Li: > 250 MWE(near), >1000 MWE(far)

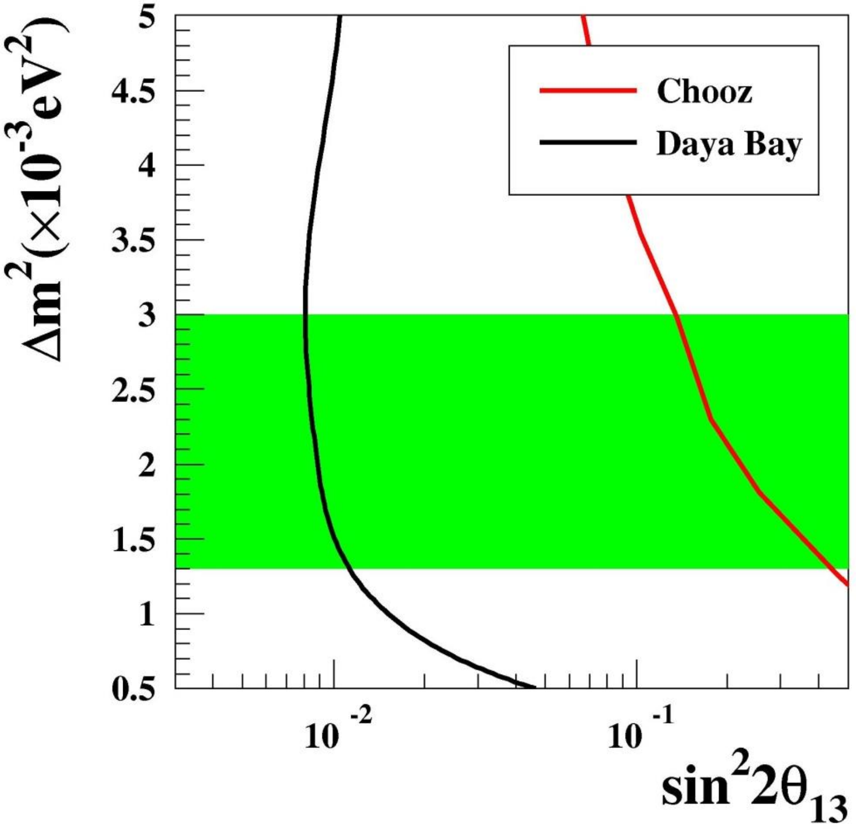
  T. Hagner et al., Astroparticle. Phys. 14(2000) 33





	Daya Bay Near	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao's
Overburden (m)	98	112	350
Radioactivity (Hz)	<50	<50	<50
Muon rate (Hz)	36	22	1.2
Antineutrino Signal (events/day)	930	760	90
Accidental Background/Signal (%)	<0.2	<0.2	<0.1
Fast neutron Background/Signal (%)	0.1	0.1	0.1
^{8}He+^{9}Li Background/Signal (%)	0.3	0.2	0.2

Sensitivity to $\mathrm{Sin}^2 2\theta_{13}$



sources	Uncertainty
Reactors	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

$$\chi^2 = \min_{\alpha's} \sum_{i=1}^{Nbin} \sum_{A=1,3} \frac{\left[M_i^A - T_i^A\left(1+\alpha_D+\alpha_c+\alpha_d^A+c_i+\sum_r \frac{T_i^{rA}}{T_i^A}\alpha_r\right) - b^A B_i^A \right]^2}{T_i^A + T_i^{A2}\sigma_b^2 + B_i^A}$$

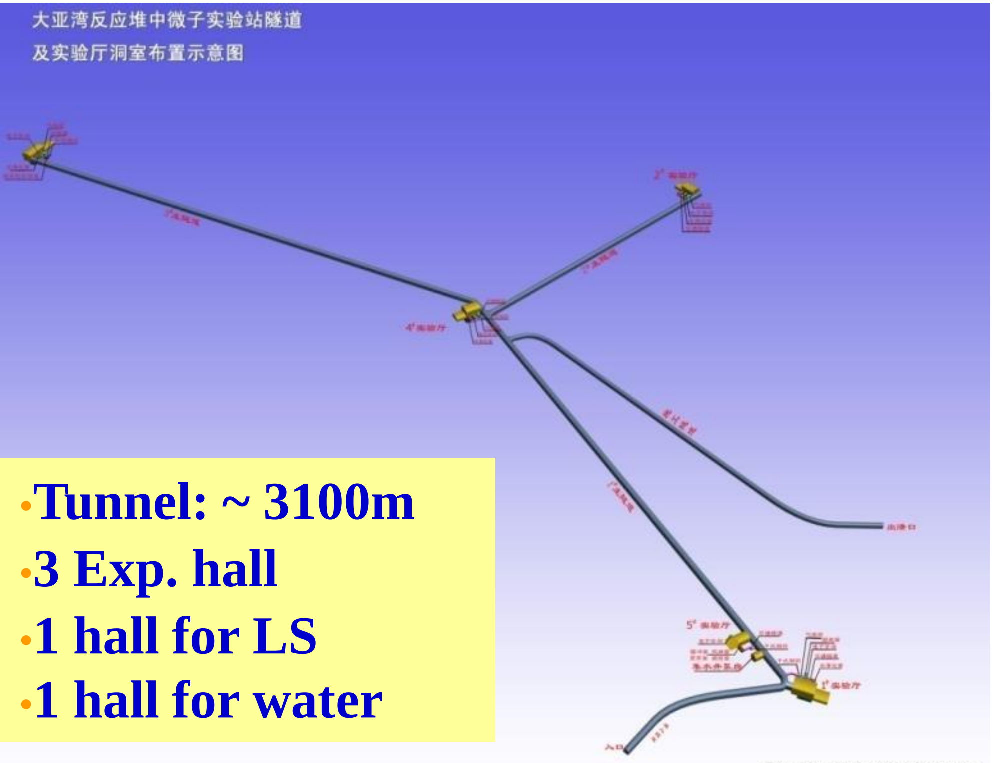
$$+\frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{Nbin} \frac{c_i^2}{\sigma_{shape}^2} + \sum_{A=1,3}\left(\frac{\alpha_d^{A2}}{\sigma_d^2} + \frac{b^{A2}}{\sigma_B^2} \right)$$

Timeline of the Experiment

- **Aug. 2003: Experimental plan and the detector design is proposed**
- **2006: Project approved in China, and afterwards in other countries**
- **Oct. 2007: Civil construction started**
- **Dec.2010: All the blasting for the tunnel and underground hall completed**
- **2008-2011: Detector construction, assembly and installation**
- **Aug. 2011: Near detector data taking started**
- **Dec. 2011: Far detector data taking started ➔ full detector data taking**

Opening ceremony： Oct. 2007

Tunnel and Underground Lab

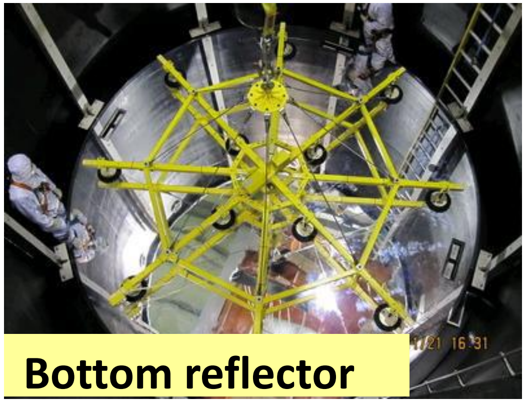


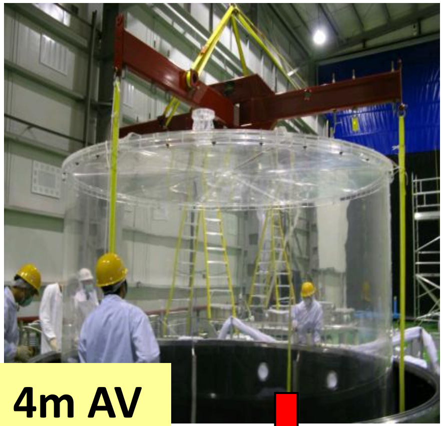
- Tunnel: ~ 3100m
- 3 Exp. hall
- 1 hall for LS
- 1 hall for water

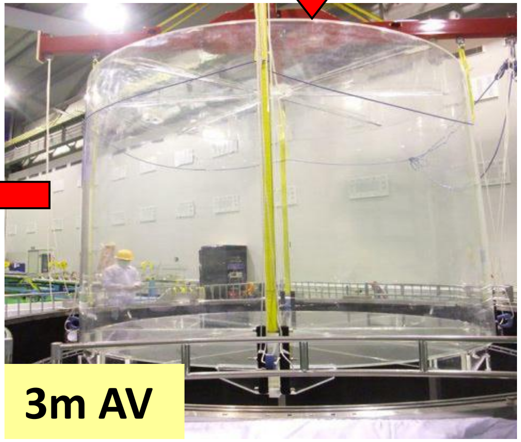
A total of ~ 3000 blasting right next reactors. No one exceeds safety limit set by National Nuclear Safety Agency（0.007g）

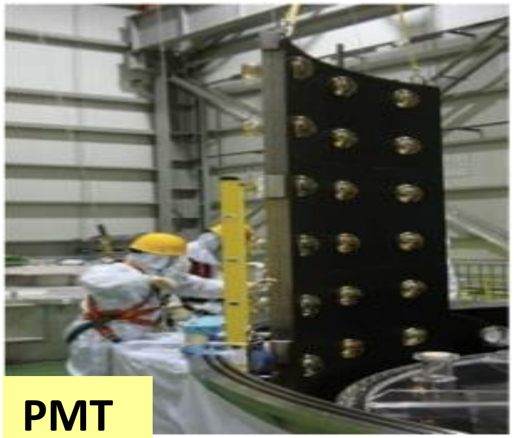
AD Assembly

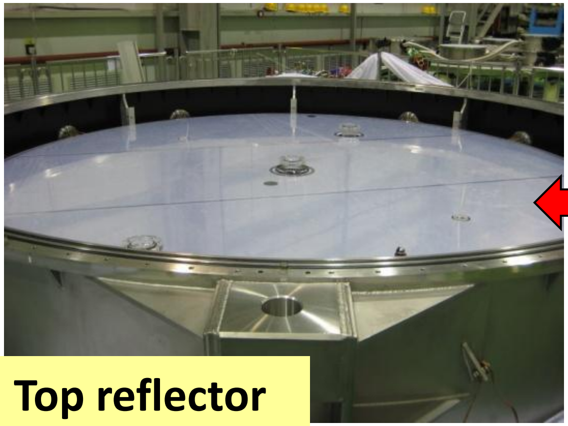

SSV


Bottom reflector

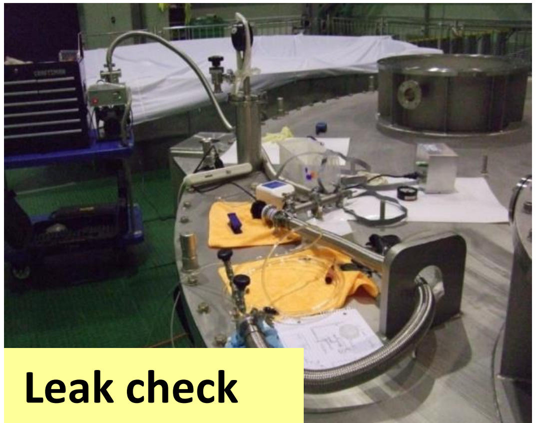

4m AV


3m AV


PMT


Top reflector


SSV lid


Leak check


ACU

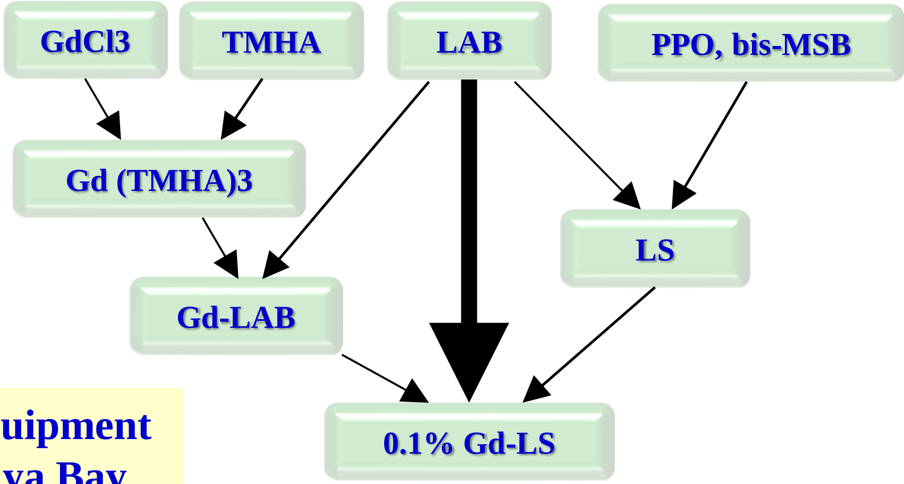
Gd-Loaded Liquid Scintillator: a challenge

- Issue: transparency, aging, …

Currently produced Gd-loaded liquid scintillators

Groups	Solvent	Complexant for Gd compound	Quantity(t)
Chooz	IPB	alcohol	5
Palo Verde	PC+MO	EHA	12
Double Chooz	PXE+dodecane	Beta-Dikotonates	8
Reno	LAB	TMHA	40
Daya Bay	LAB	TMHA	185

Gd-LS production Equipment and the process by Daya Bay



GdCl3

TMHA

LAB

PPO, bis-MSB

Gd (TMHA)3

LS

Gd-LAB

0.1% Gd-LS

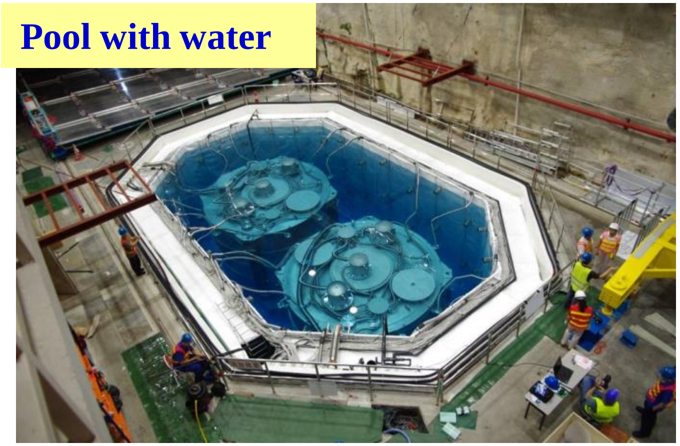
Water Cerenkov Detector Installation

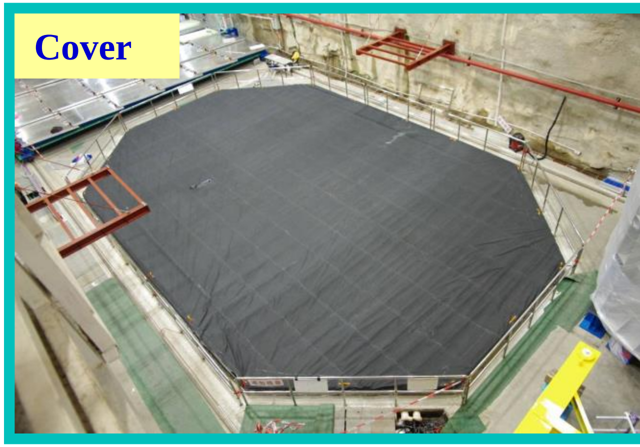

PermaFlex painting


PMT frame & Tyvek

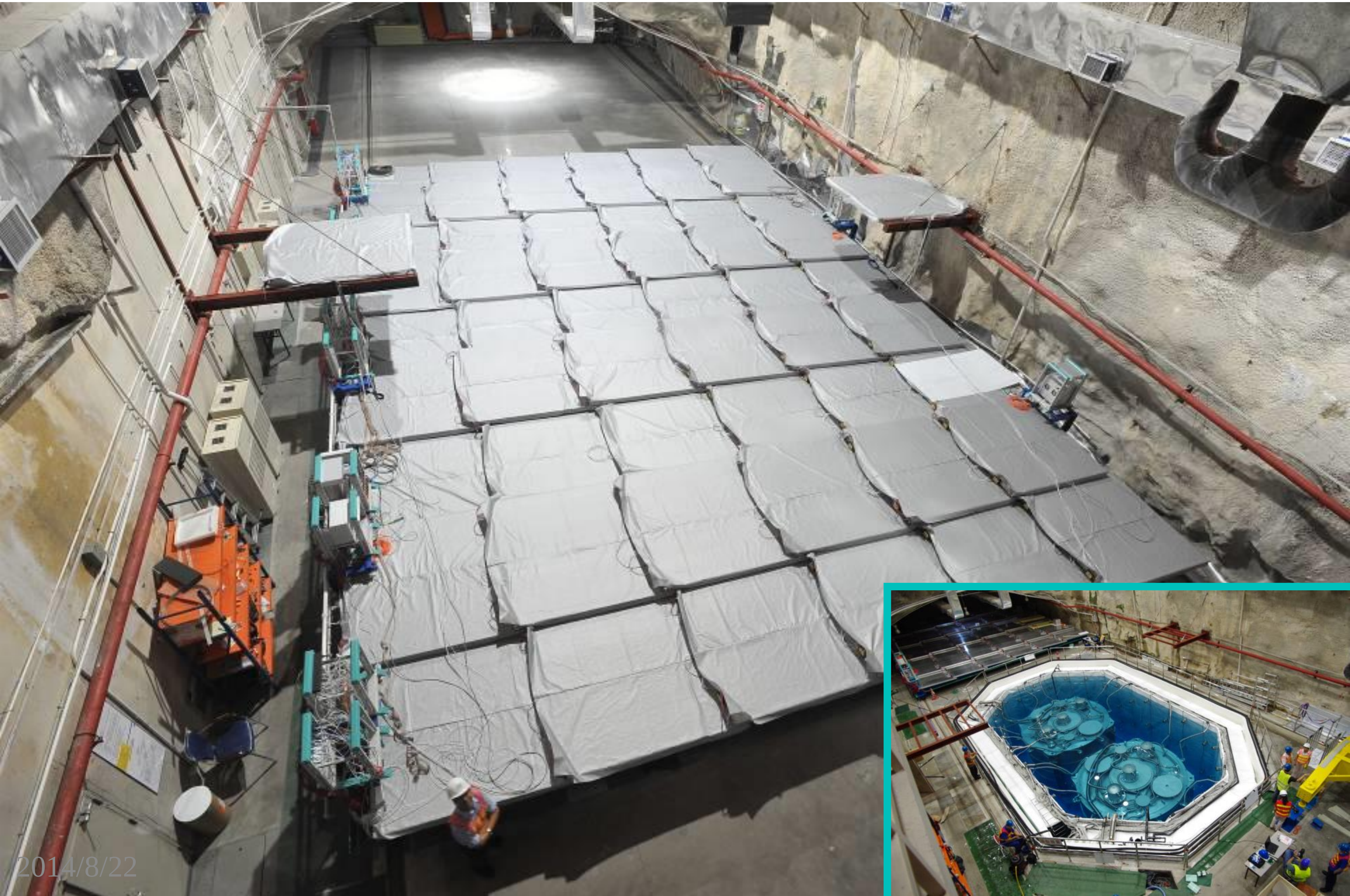

Completed pool


Install AD


Pool with water


Cover

Hall 1(two ADs) Started Operation on Aug. 15, 2011



Daya Bay: Data Taking & Analysis Status

Two detector comparison NIM A685 (2012)78

- 90 days of data, Daya Bay near only

First oscillation analysis PRL 108(2012)171803

- 55 days of data, 6 ADs near+far
- 5.2 σ, ~ 20% precision

Improved results CPC 37 (2013)011001

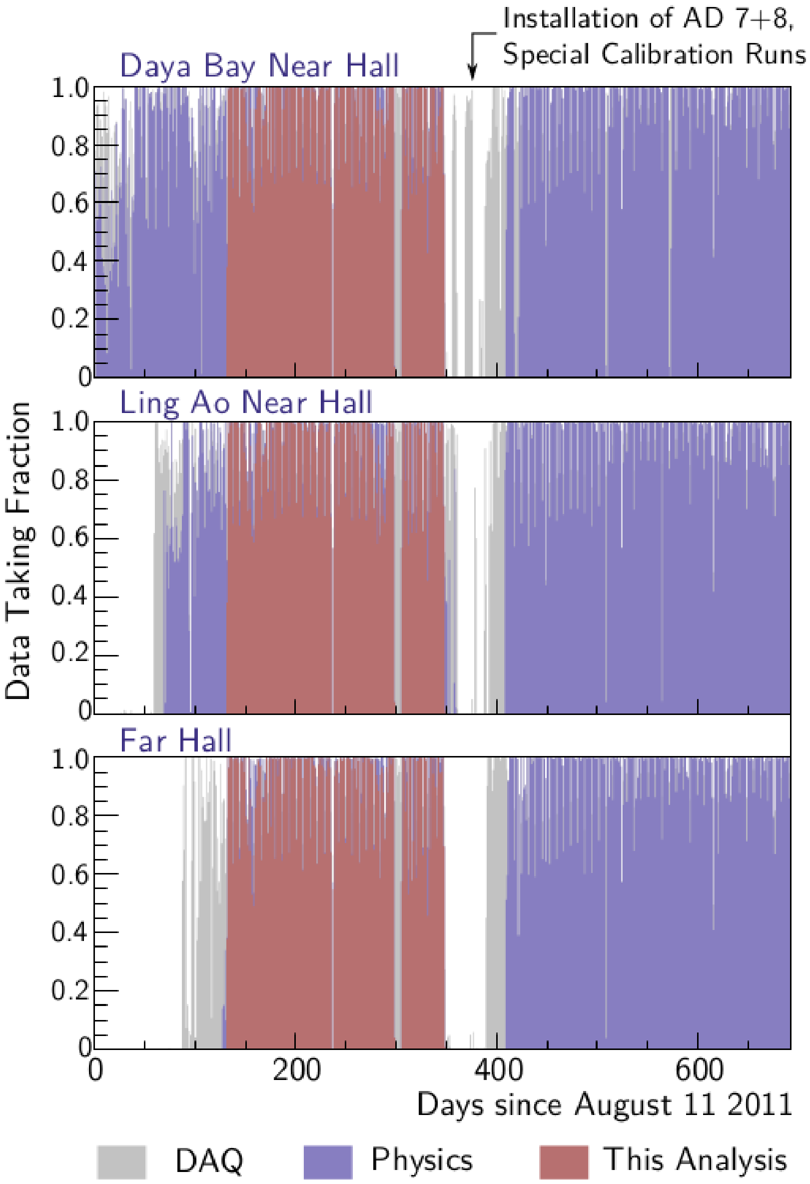
- 139 days of data, 6 ADs near+far
- ~ 7 σ, ~ 15% precision

Spectral Analysis PRL 112(2014)061801

- 217 days complete 6 AD period
- ~ 10 σ, ~10% precision

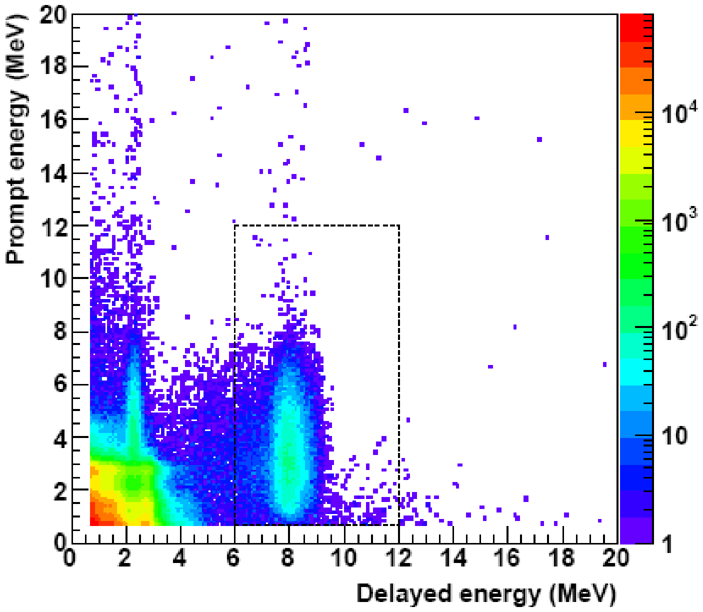
Latest results Announced at Neutrino 2014

- 217 days 6 AD + 404 days 8 AD
- ~ 17 σ, ~6% precision

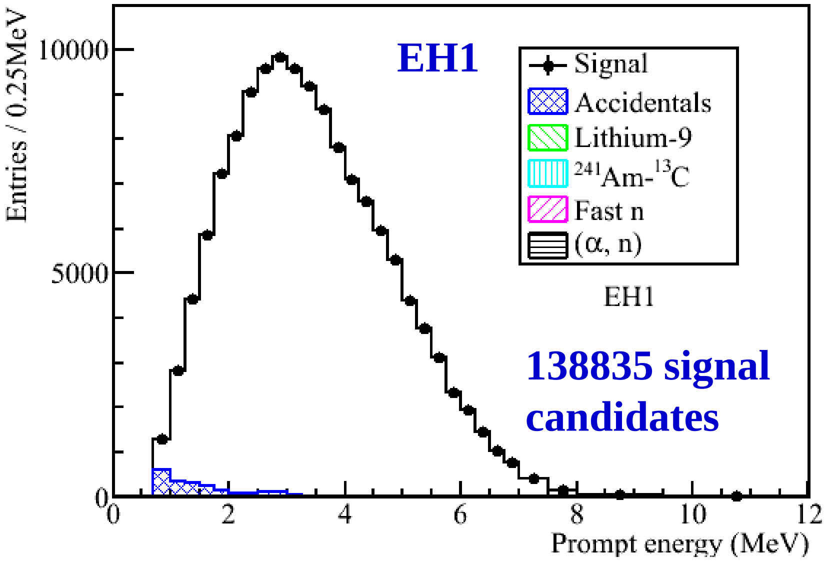


Neutrino Event Selection

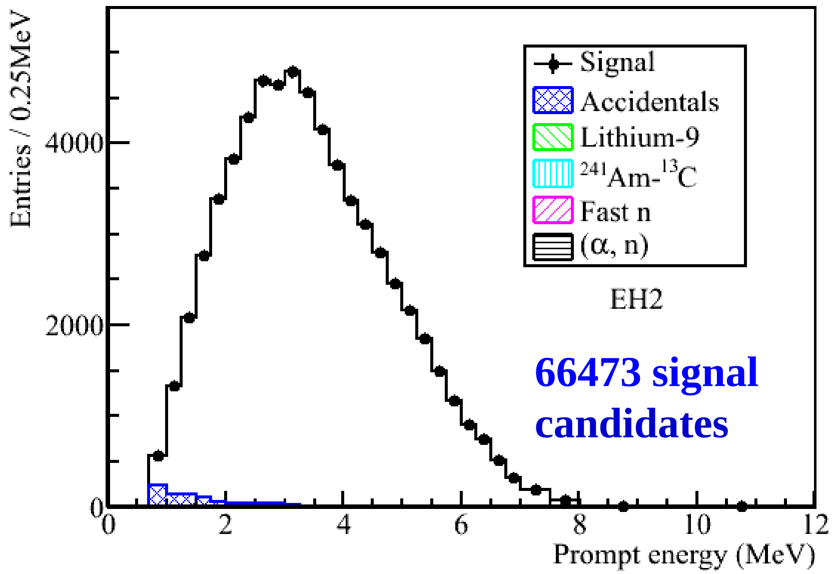
- **Pre-selection**
  - **Reject Flashers**
  - **Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon**
- **Neutrino event selection**
  - **Multiplicity cut**
    - ✓ Prompt-delayed pairs within a time interval of 200 μs
    - ✓ No triggers(E > 0.7MeV) before the prompt signal and after the delayed signal by 200 μs
  - **Muon veto**
    - ✓ *1s* after an AD shower muon
    - ✓ *1ms* after an AD muon
    - ✓ *0.6ms* after an WP muon
  - **$0.7\text{MeV} < E_{\text{prompt}} < 12.0\text{MeV}$**
  - **$6.0\text{MeV} < E_{\text{delayed}} < 12.0\text{MeV}$**
  - **$1\mu\text{s} < \Delta t_{e^+\text{-}n} < 200\mu\text{s}$**



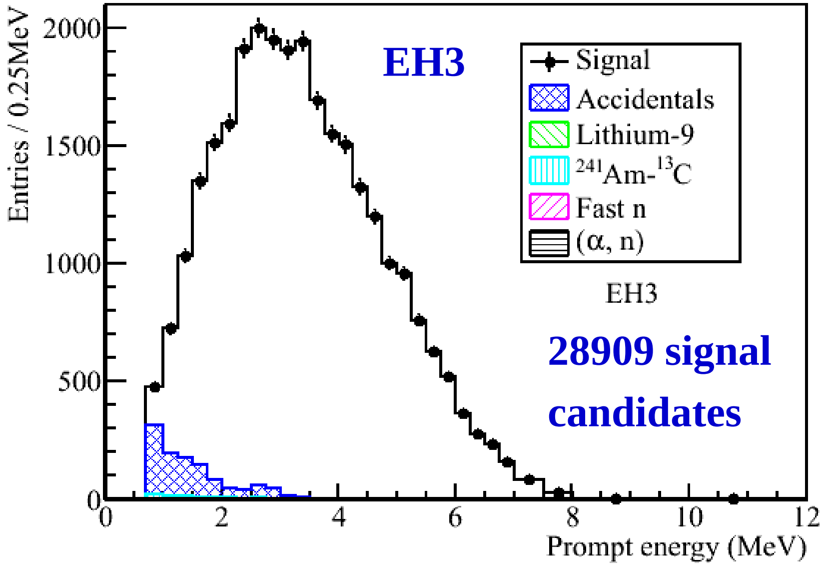
Signal+Backgound Spectrum



138835 signal candidates



66473 signal candidates

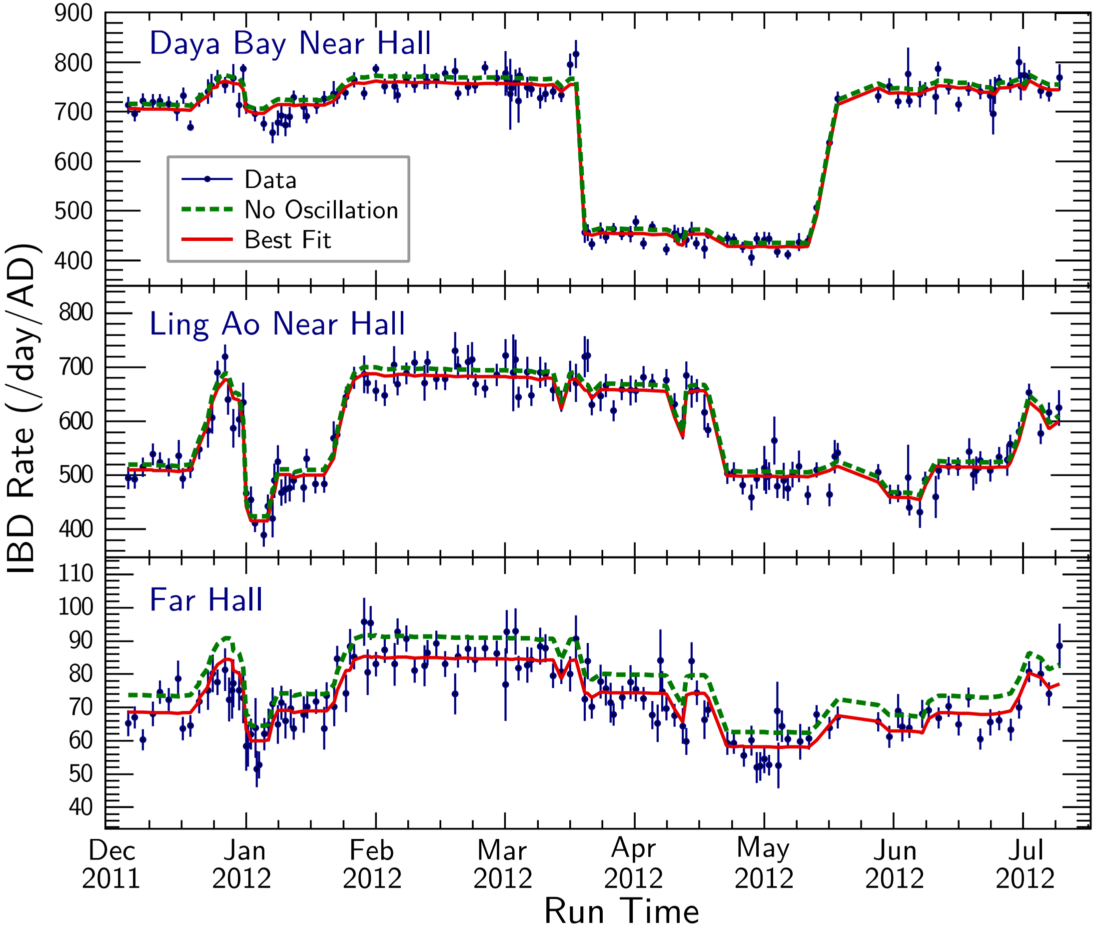


28909 signal candidates

	B/S @EH1/2	B/S @EH3
Accidentals	~1.4%	~4.5%
Fast neutrons	~0.1%	~0.06%
^{8}He/^{9}Li	~0.4%	~0.2%
Am-C	~0.03%	~0.3%
α-n	~0.01%	~0.04%
Sum	~2%	~5%

Daily Neutrino Rate

- **Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties**
- **Rate changes reflect the reactor on/off.**



Prediction:

- **Baseline（ 3.5cm，~0.002%）**
- **Target mass（3kg，0.015%）**
- **Reactor neutrino flux**

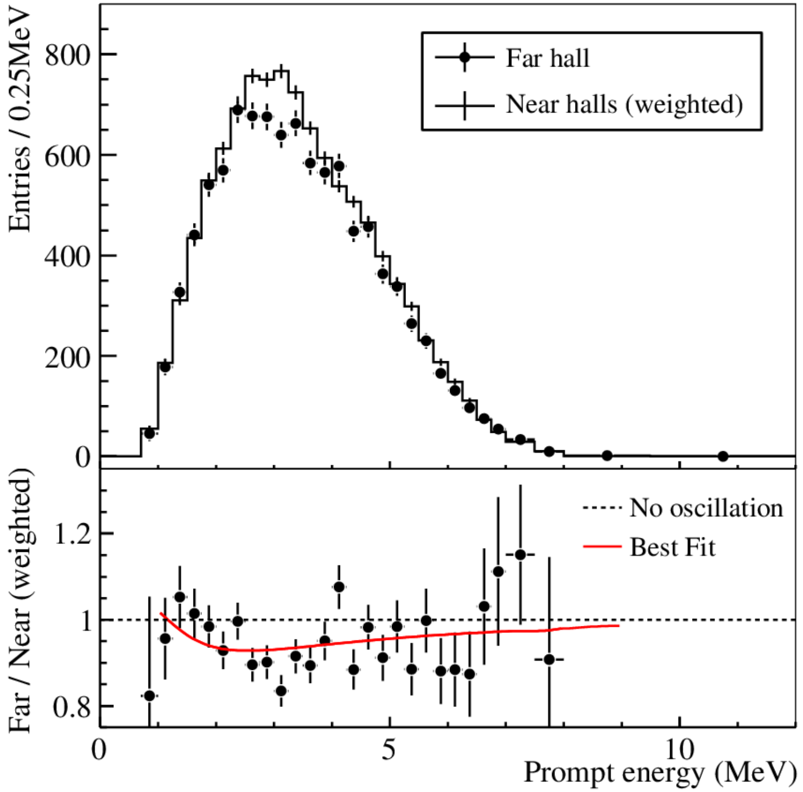
Predictions are absolute, multiplied by a normalization factor from the fitting

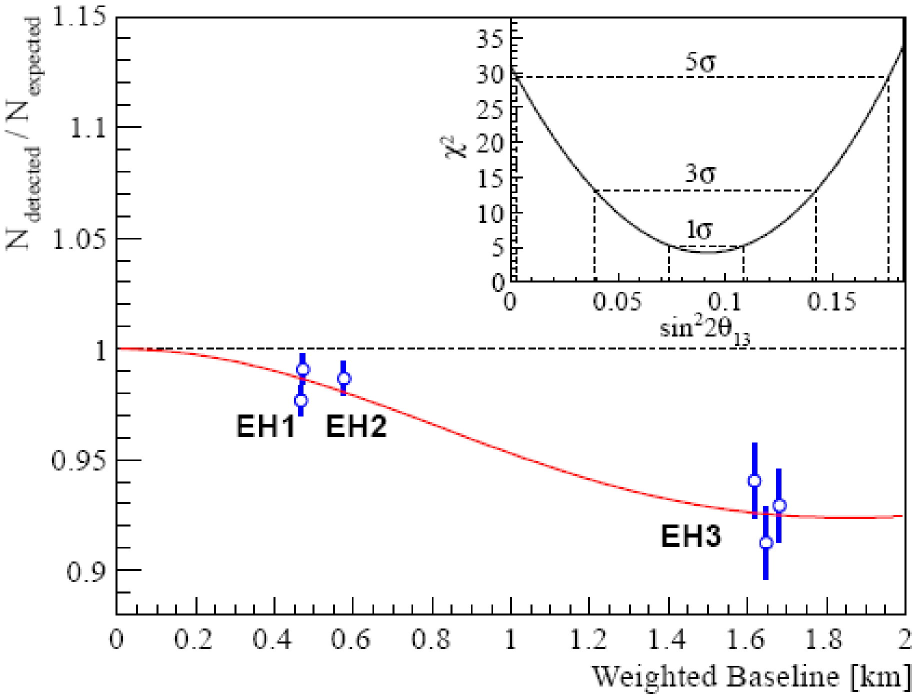
A New Type of Oscillation Discovered

- **Electron anti-neutrino disappearance:**

R = 0.940 ±0.011 (stat) ±0.004 (syst)

announced on Mar. 8, 2012



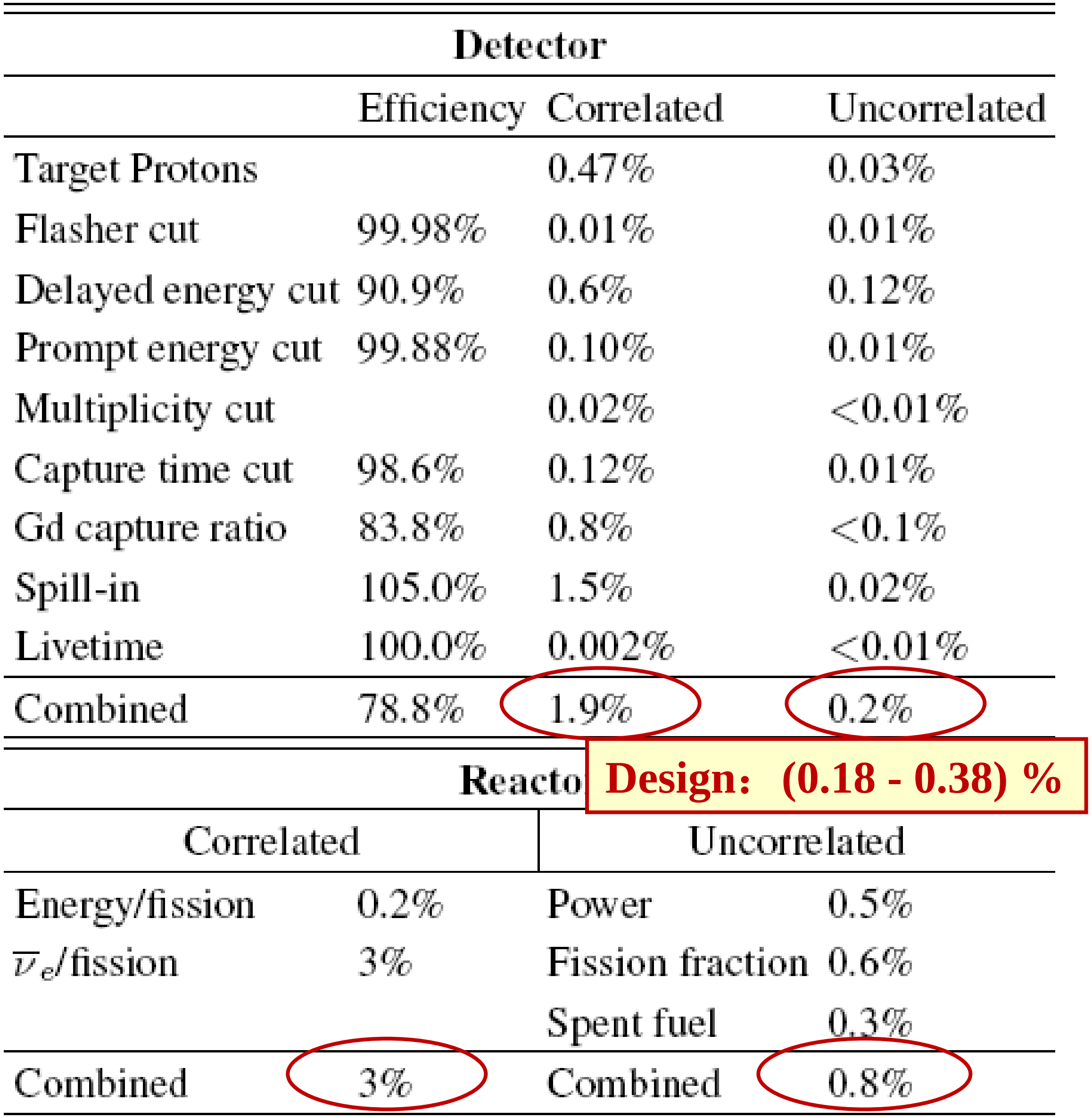


$\sin^2 2\theta_{13}$ = 0.092 ± 0.016(stat) ± 0.005(syst)

χ^2/NDF = 4.26/4, 5.2 σ for non-zero θ_{13}

F.P. An et al., Phys. Rev. Lett. 108, (2012) 171803; citation > 880

The Most Precise Neutrino Experiment

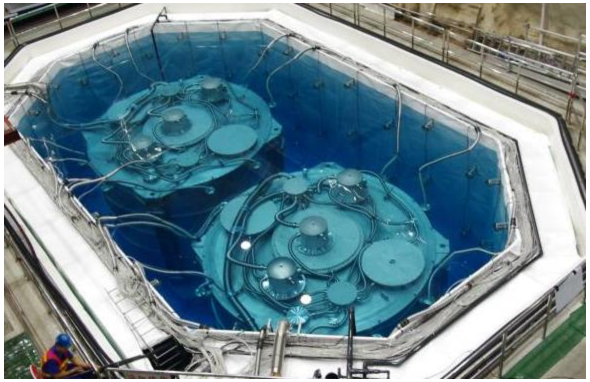


Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reacto			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Design: (0.18 - 0.38) %

Side-by-side Comparison



Expectation:

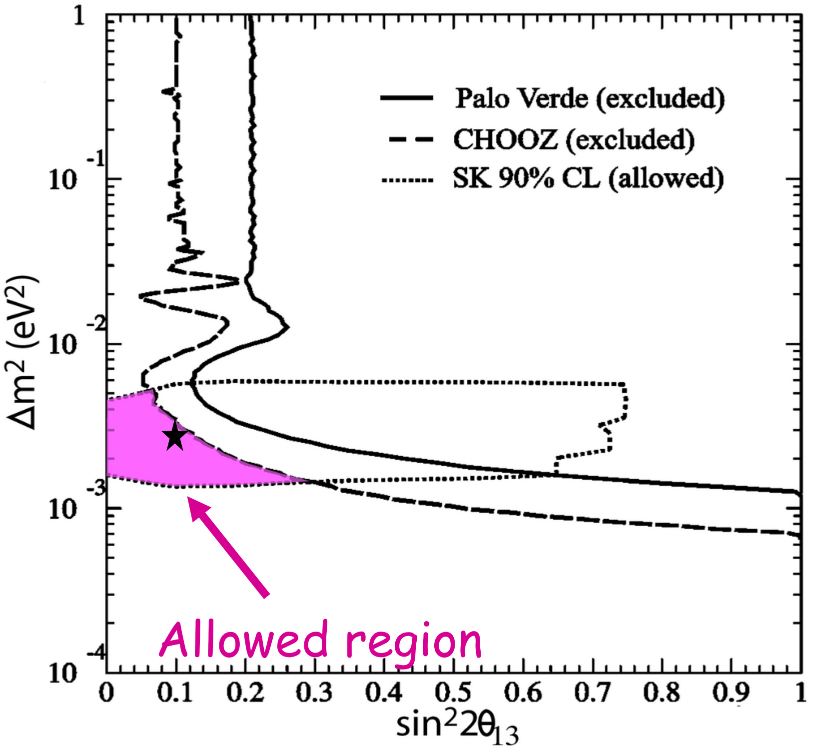
R(AD1/AD2) = 0.982

Measurement:

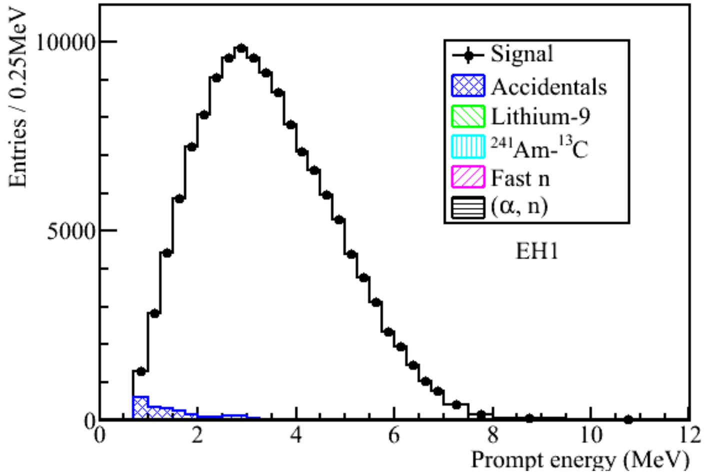
0.981 ± 0.004

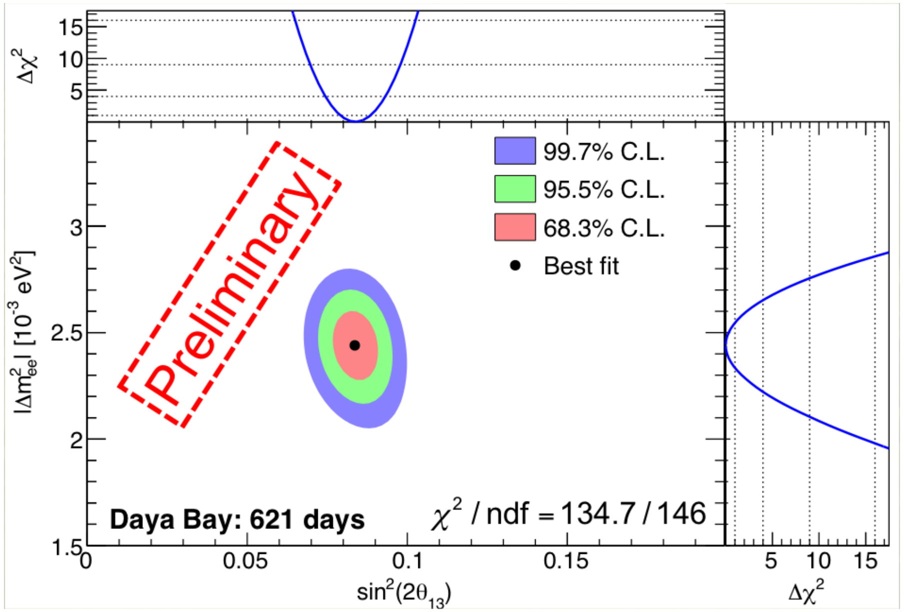
Another Lucky Story

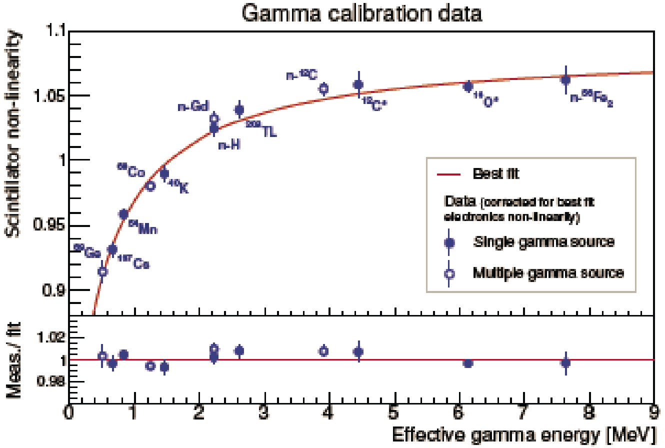
- It is big !
- Everybody can see it
- Easy for future experiments: mass hierarchy, CP phase, etc.



New Results：Spectral Analysis







$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

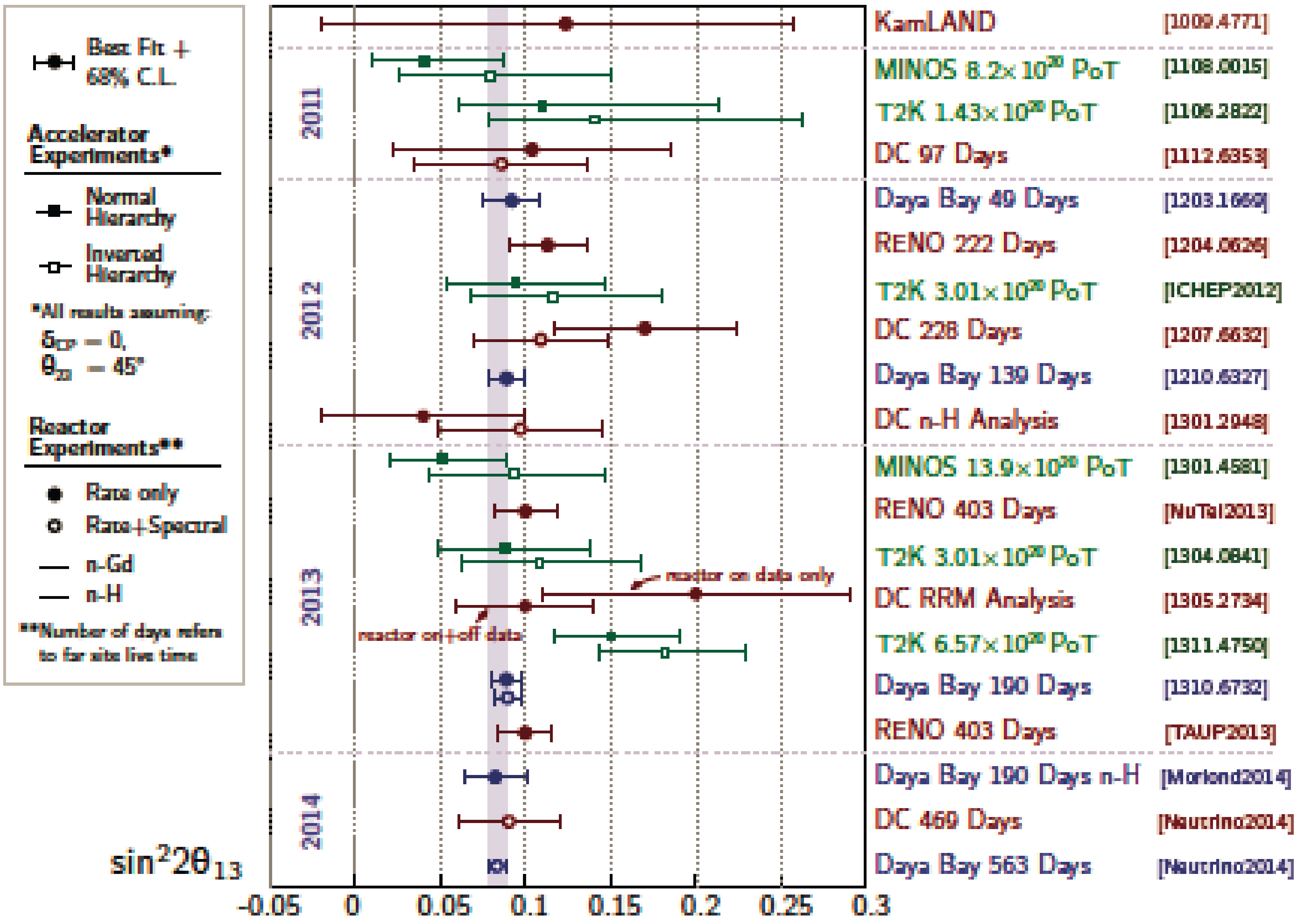
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

- ◆ **Each bin is an oscillation measurement**
- ◆ **Energy non-linearity calibration by various sources: Uncertainty < 1%**

Zhang's talk @Neutrino 2014

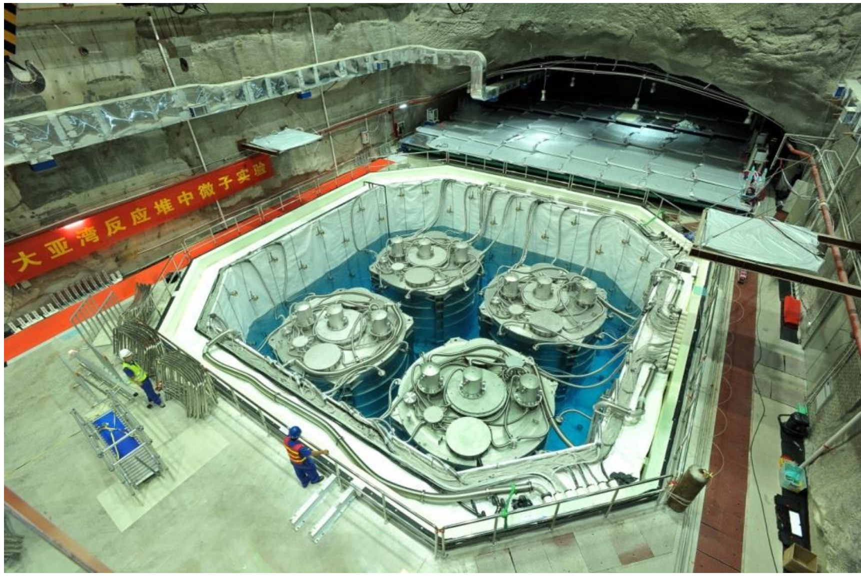
Comparison of θ_{13} Measurements

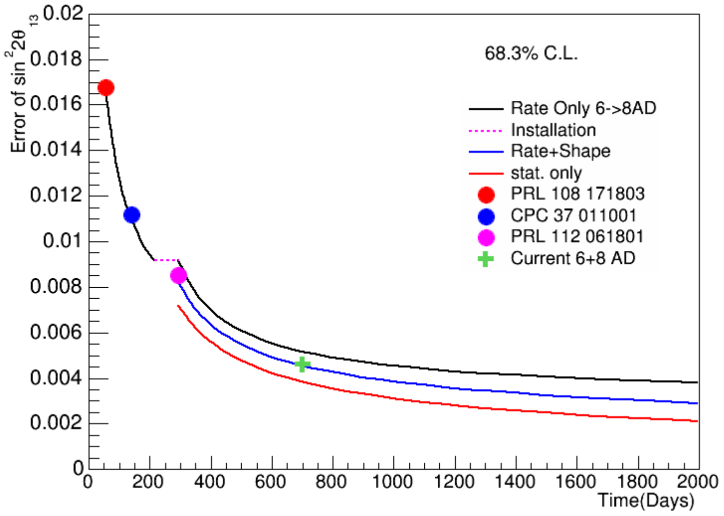


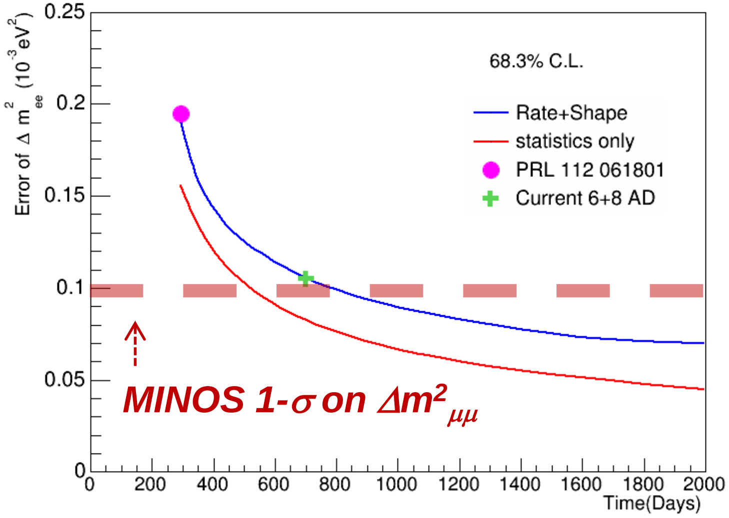
Current Status and Future Plan

- **Completed all detector installation**
- **Completed special automatic & manual calibration**
- **Data taking until 2017**
- **Precision can reach:**

  $\Delta(\sin^2 2\theta_{13}) \sim 3\%$







Still a Lot of Unknowns

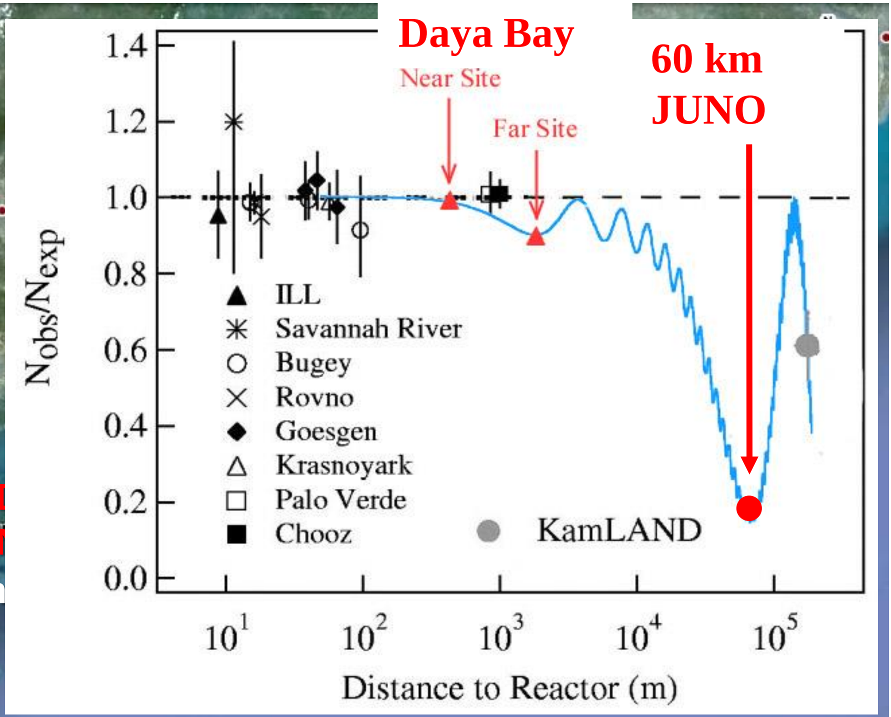
- Neutrino oscillation:
  - Neutrino mass hierarchy ?
  - Unitarity of neutrino mixing matrix ？
  - Θ_{23} is maximized ?
  - CP violation in the neutrino mixing matrix as in the case of quarks ? Large enough for the matter-antimatter asymmetry in the Universe ?
- What is the absolute neutrino mass ?
- Neutrinos are Dirac or Majorana ?
- Are there sterile neutrinos？
- Do neutrinos have magnetic moments ？
- Can we detect relic neutrinos ?
- ……

The JUNO Experiment

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Overburden ~ 700 m

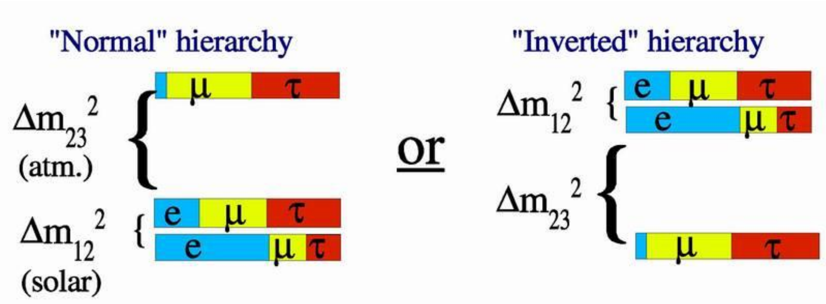
Kaiping,
Jiang Men city,
Guangdong Province



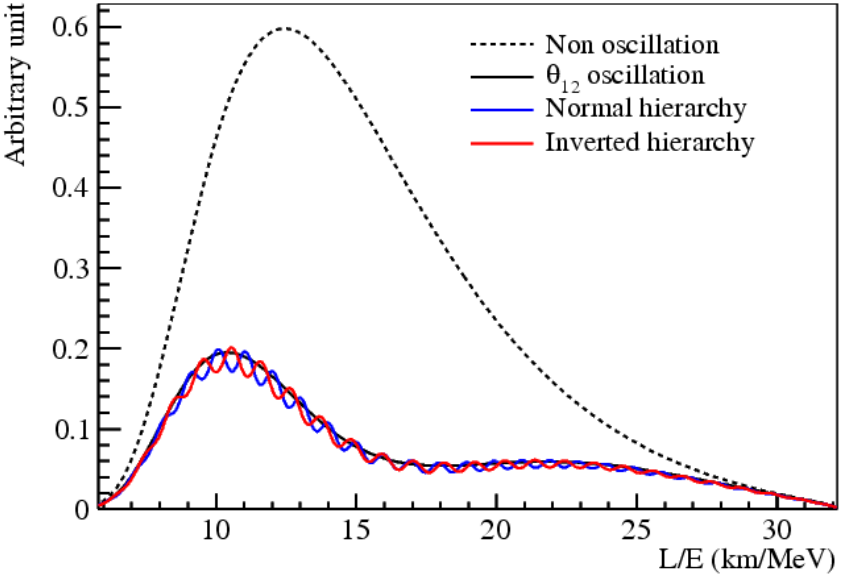
Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;

Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

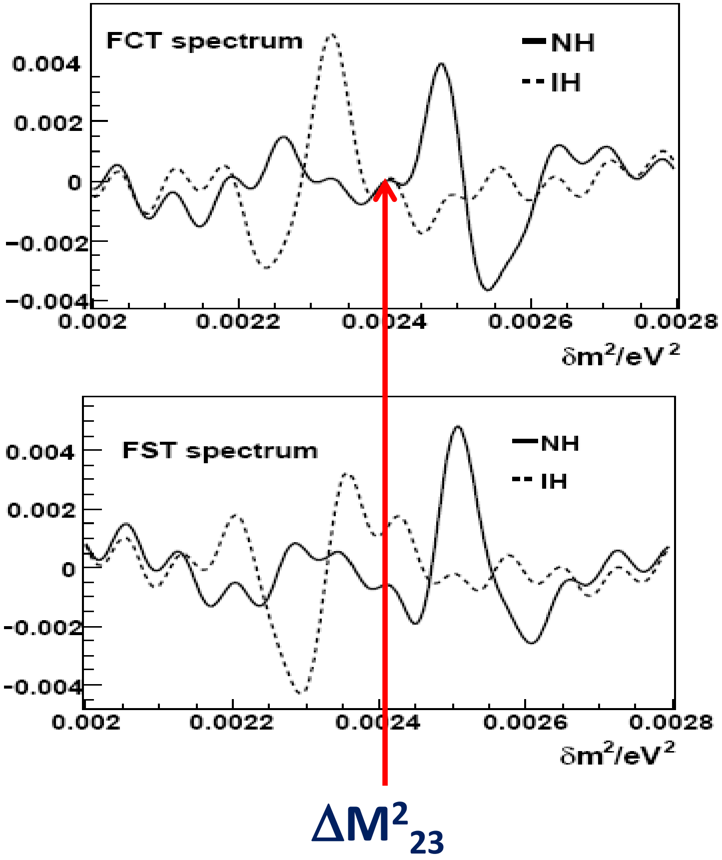
Mass Hierarchy at Reactors



$$
\begin{aligned}
& \Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \; & |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \; & |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$



$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

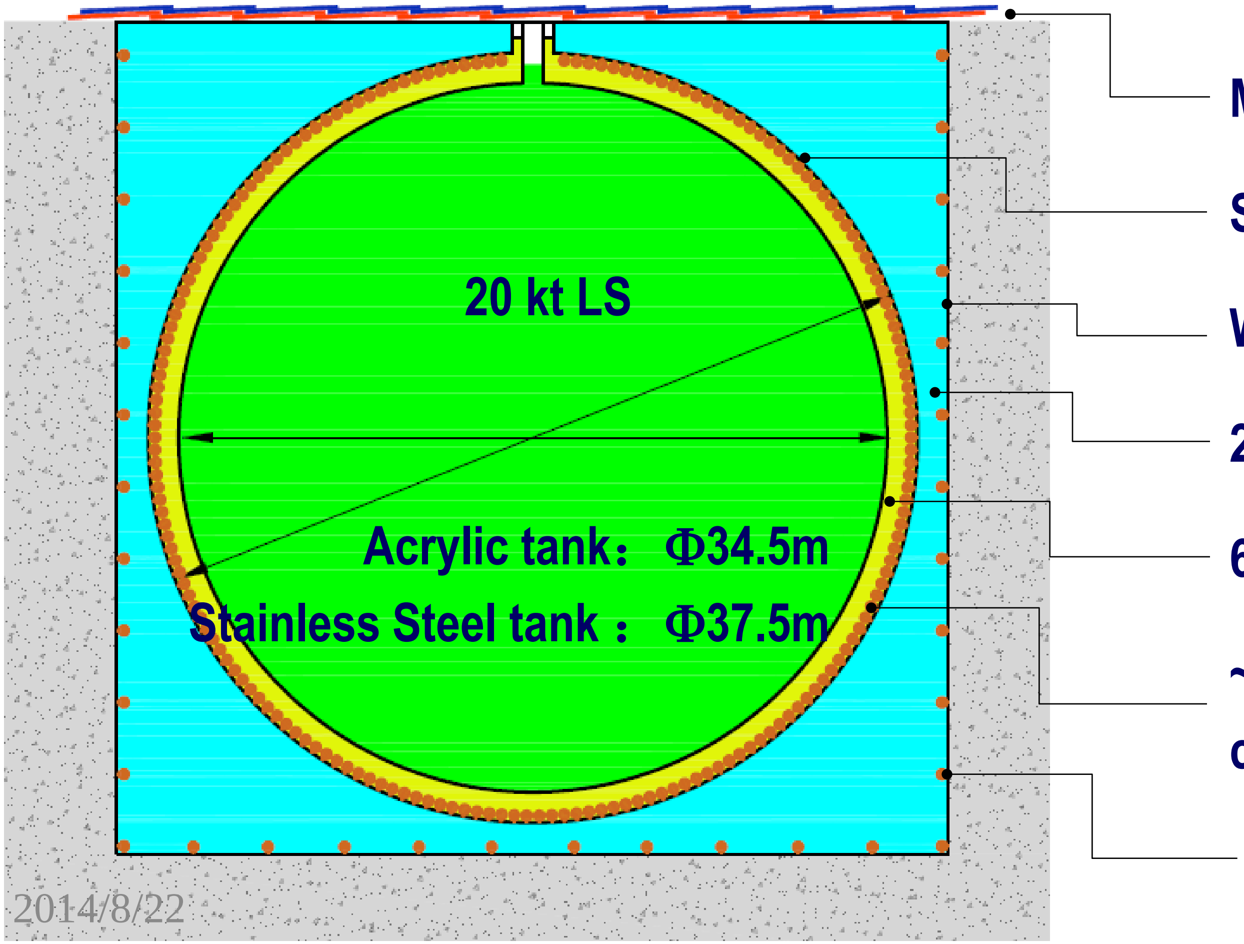


L. Zhan et al., PRD78:111103,2008; PRD79:073007,2009

The Plan: a Large LS Detector

- LS volume: × 20 ➔ for more statistics (40 events/day)
- light(PE) × 5 ➔ for better resolution ($\Delta M^2_{12}/\ \Delta M^2_{23}$ ~ 3%)

40 events/day



20 kt LS

Acrylic tank： Φ34.5m

Stainless Steel tank： Φ37.5m

Muon detector

Steel Tank

Water seal

20kt water

6kt MO

~15000 20” PMTs

coverage: ~80%

1500 20” VETO PMTs

Physics Reach

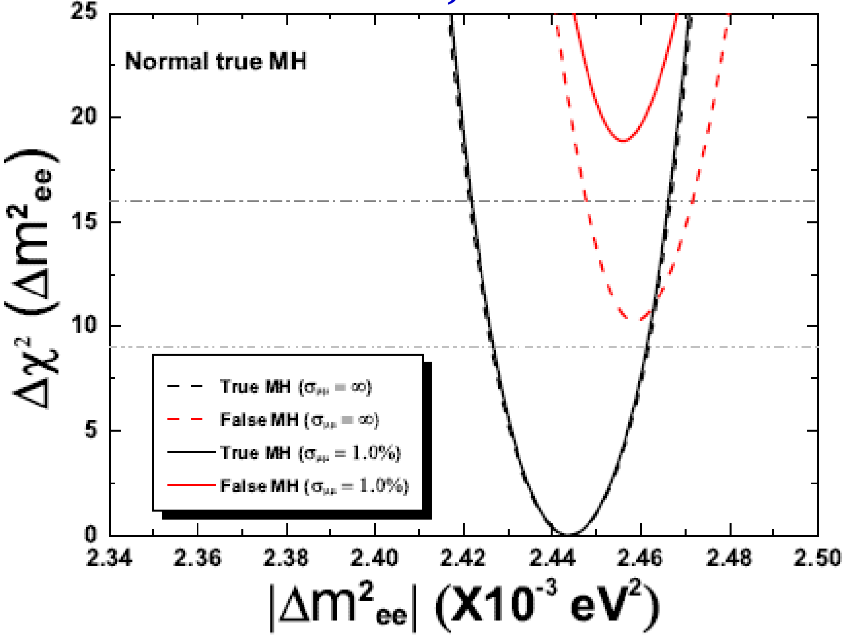
Thanks to a large θ_{13}

- **Mass hierarchy**
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- ……

	Current	Daya Bay II
Δm^2_{12}	4%	0.6%
Δm^2_{23}	4%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	10%	N/A
$\sin^2\theta_{13}$	6% ➔ 4%	~ 15%

Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW

Y.F. Li et al., arXiv:1303.6733



For 6 years, mass hierarchy cab be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

Signals & Backgrounds

- **Estimated IBD signal event rate: ~40/day**
- **LS without Gd-loading for**
  - ⇨ Better attenuation length ➔ better resolution
  - ⇨ Lower irreducible accidental backgrounds from LS, important for a larger detector:
    - ✓ With Gd: ~ 10^{-12} g/g ➔ 50,000 Hz
    - ✓ Without Gd: ~ 10^{-16} g/g ➔ 5 Hz

τ ~ 200 μs

- **Backgrounds**

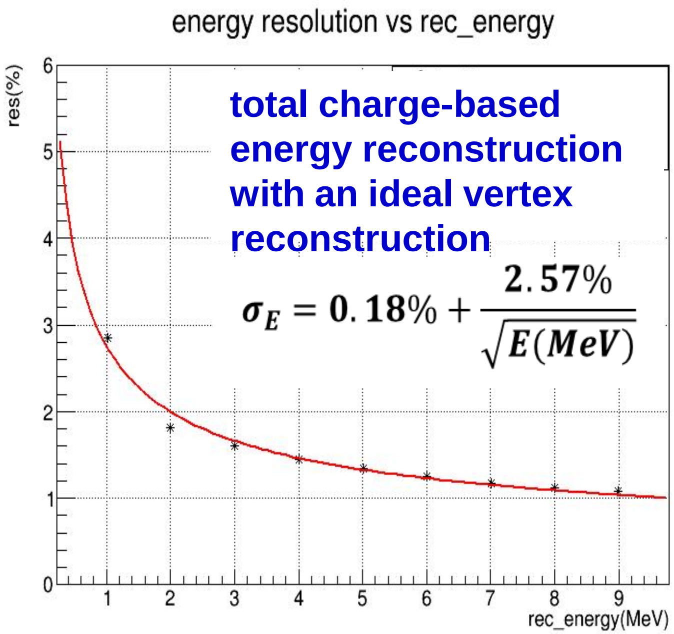
Overburden 700m:
E_μ ~ 211 GeV, R_μ ~ 3.8 Hz
Single rates:
5 Hz by LS and 5Hz by PMT
Good muon tracking
muon efficiency ~ 99.5%

	B/S @ DYB EH1	B/S @ JUNO	Techniques to be used by JUNO
Accidentals	~1.4%	~10%	Low PMT radioactivity; LS purification; prompt-delayed distance cut
Fast neutron	~0.1%	~0.4%	High muon detection efficiency (similar as DYB)
^{9}Li/^{8}He	~0.4%	~0.8%	Muon tracking; If good track, distance to muon track <5m and veto 2s; If shower muon, full volume veto 2s

MC Study：Energy Scale & Resolution

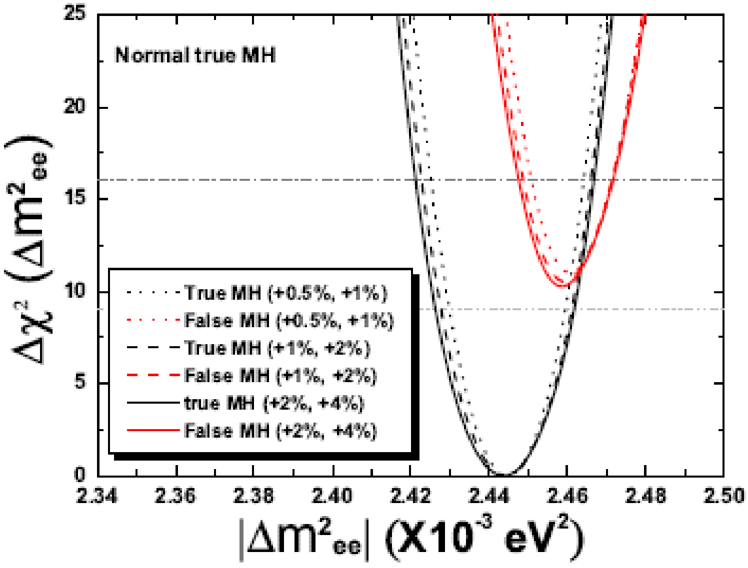
- **Resolution: based on DYB with:**
  - **JUNO Geometry**
  - **80% photocathode coverage**
  - **PMT QE from 25% ➔ 35%**
  - **Attenuation length of 20 m ➔**
    - ✓ **abs. 60 m + Rayleigh scatt. 30m**
- **Energy scale**
  - **By introduce a self-calibration (based on ΔM^2_{ee} periodic peaks), effects can be corrected and sensitivity is un-affected**

    Y.F. Li et al., arXiv:1303.6733
  - **Application of this method:** **Relatively insensitive to continuous backgrounds, non-periodic structures**



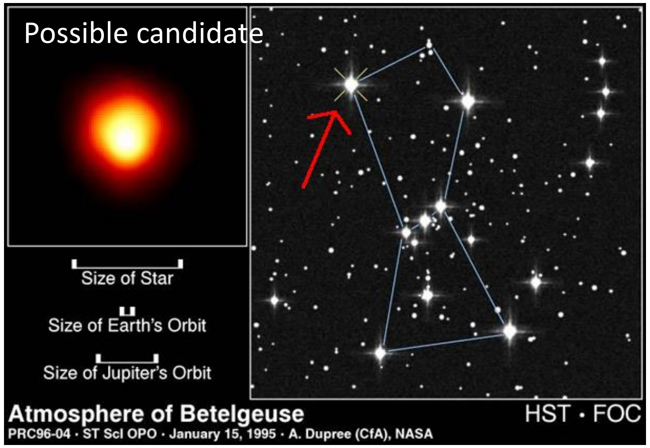
total charge-based energy reconstruction with an ideal vertex reconstruction

$$\sigma_E = 0.18\% + \frac{2.57\%}{\sqrt{E(MeV)}}$$



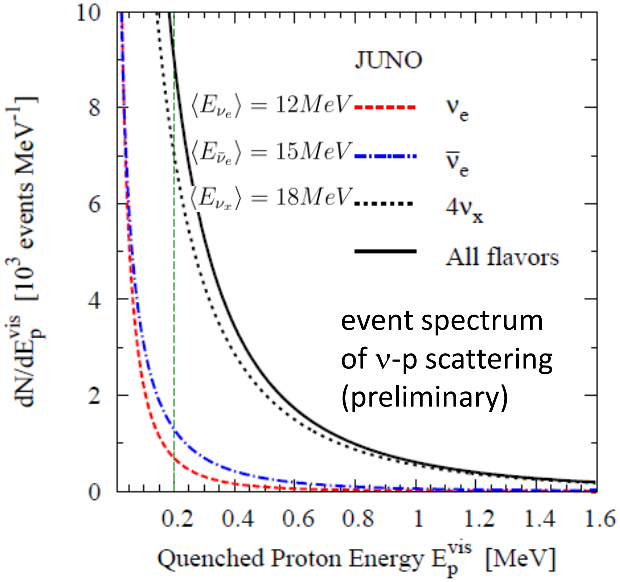
Supernova neutrinos

- **Less than 20 events observed so far**
- **Assumptions:**
  - **Distance: 10 kpc (our Galaxy center)**
  - **Energy: 3×10^{53} erg**
  - **L_ν the same for all types**


Possible candidate

Atmosphere of Betelgeuse

PRC96-04 · ST ScI OPO · January 15, 1995 · A. Dupree (CfA), NASA


event spectrum of ν-p scattering (preliminary)

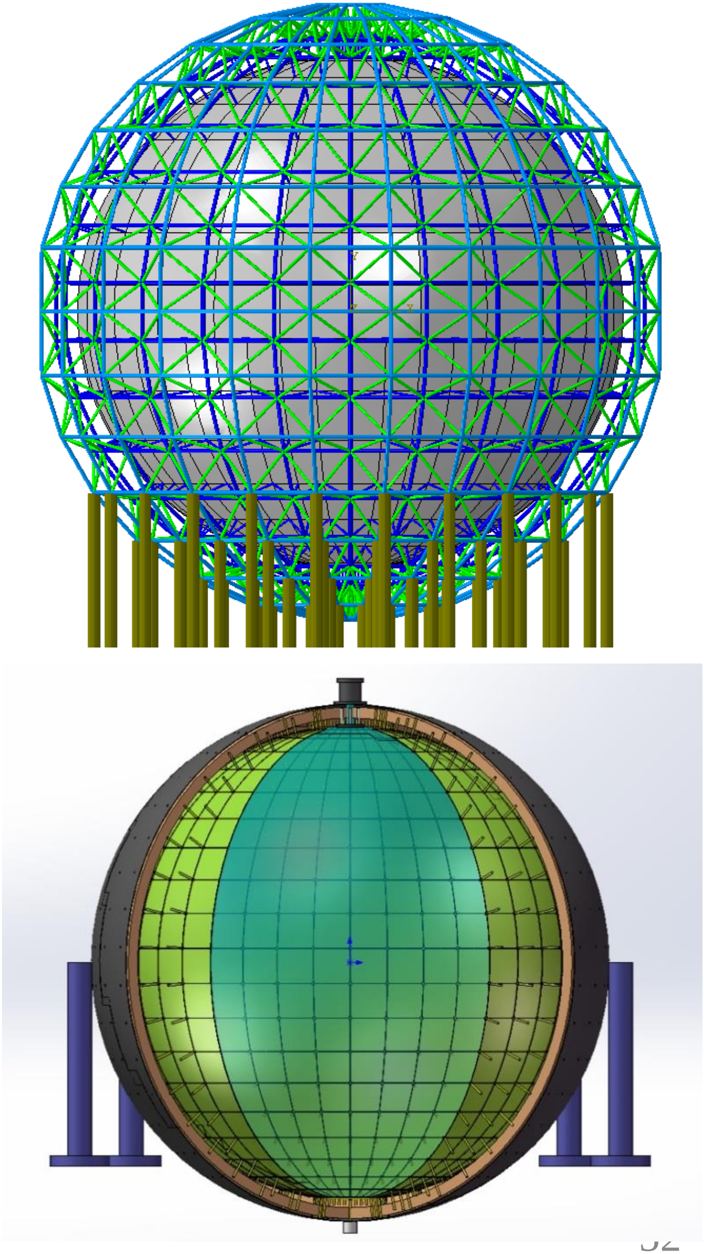
Estimated numbers of neutrino events in JUNO (preliminary)

Channel	Type	Events for different $\langle E_\nu\rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

**LS detector vs. Water Cerenkov detectors:
much better detection to these correlated events**

→ Measure energy spectra & fluxes of almost all types of neutrinos

Challenge I: Large Detector Structure

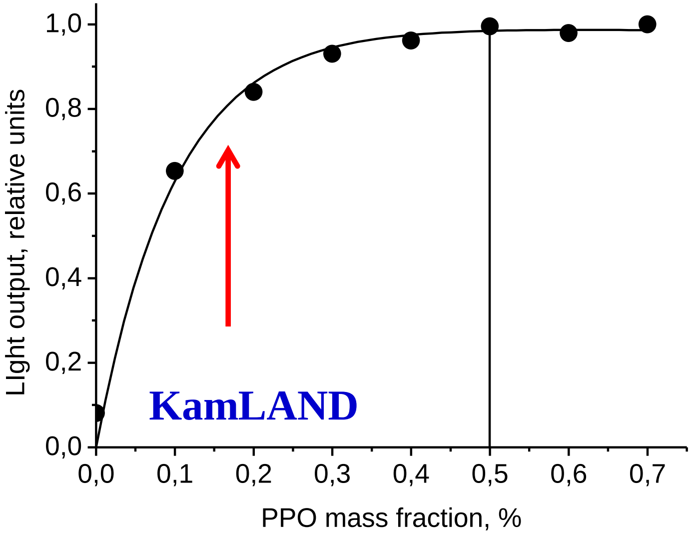


- **A D~35m detector in the water pool:**
  - **Mechanics，optics, chemistry, …**
  - **How to keep it clean during and after the assembly ?**
  - **Possibility of assembly within 2 years**
- **Current design:**
  - **Default: acrylic tank(D~35m) + SS structure**
    - ✓ **Acrylic bonding, creeping，stress, steel support at acrylic, deformation, event reconstruction with total refection, …**
  - **Backup: SS tank(D~38m) + acrylic panel + balloon**
    - ✓ **Balloon materials, cleanness, leaks, deployment, …**
- **R&D and prototyping underway**

Challenge II: Transparent Liquid Scintillator

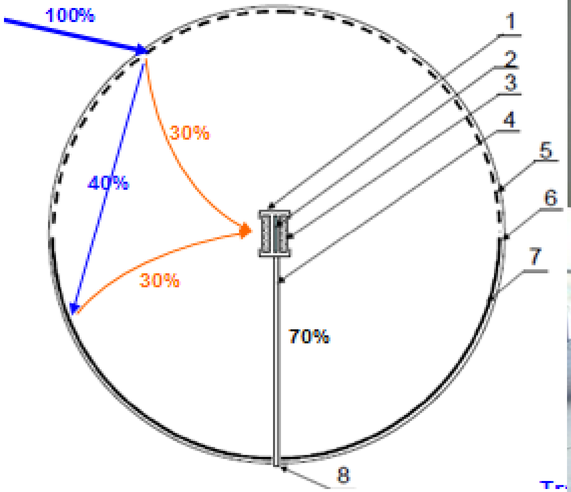
- **Our choice: LAB+PPO+BisMSB**
  - **At Daya Bay: 15m**
  - **Our target: 30 m**
- **R&D efforts:**
  - **Improve raw materials**
  - **Improve the production process**
  - **Purification**
    - **Distillation, Filtration, Water extraction, Nitrogen stripping…**
  - **Optimization of fluor concentration**
- **Other works：**
  - **Rayleigh scattering measurement**
  - **Energy non-linearity study**
  - **Aging study**
  - **Material selection: BKG & purity issues**
  - **Engineering issues for 20kt**
    - **Equipment, logistics, safety, …**

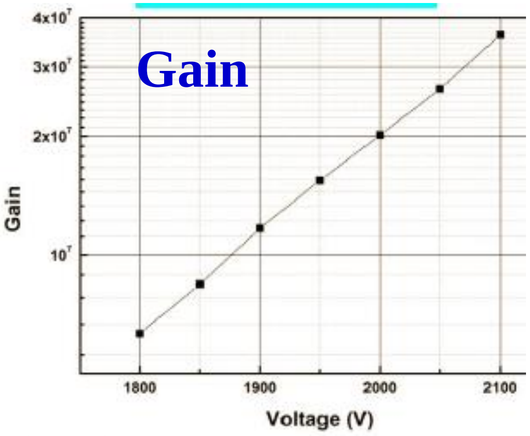
Linear Alky Benzene	Atte. L(m) @ 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 coloum	18.6
Al_2O_3 coloum	22.3
LAB from Nanjing, Raw	20
Al_2O_3 coloum	25

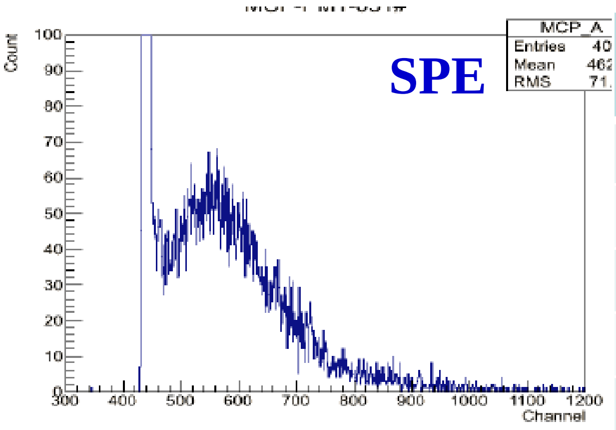


Challenge III: High QE PMT

- Three types of high QE 20” PMTs under development:
  - A new type of MCP-PMT: 4π collection
  - Hammamatzu R5912-100 with SBA photocathode
  - Photonics-type PMT
- MCP-PMT development:
  - Technical issues mostly resolved
  - Successful 8” prototypes
  - A few 20” prototypes







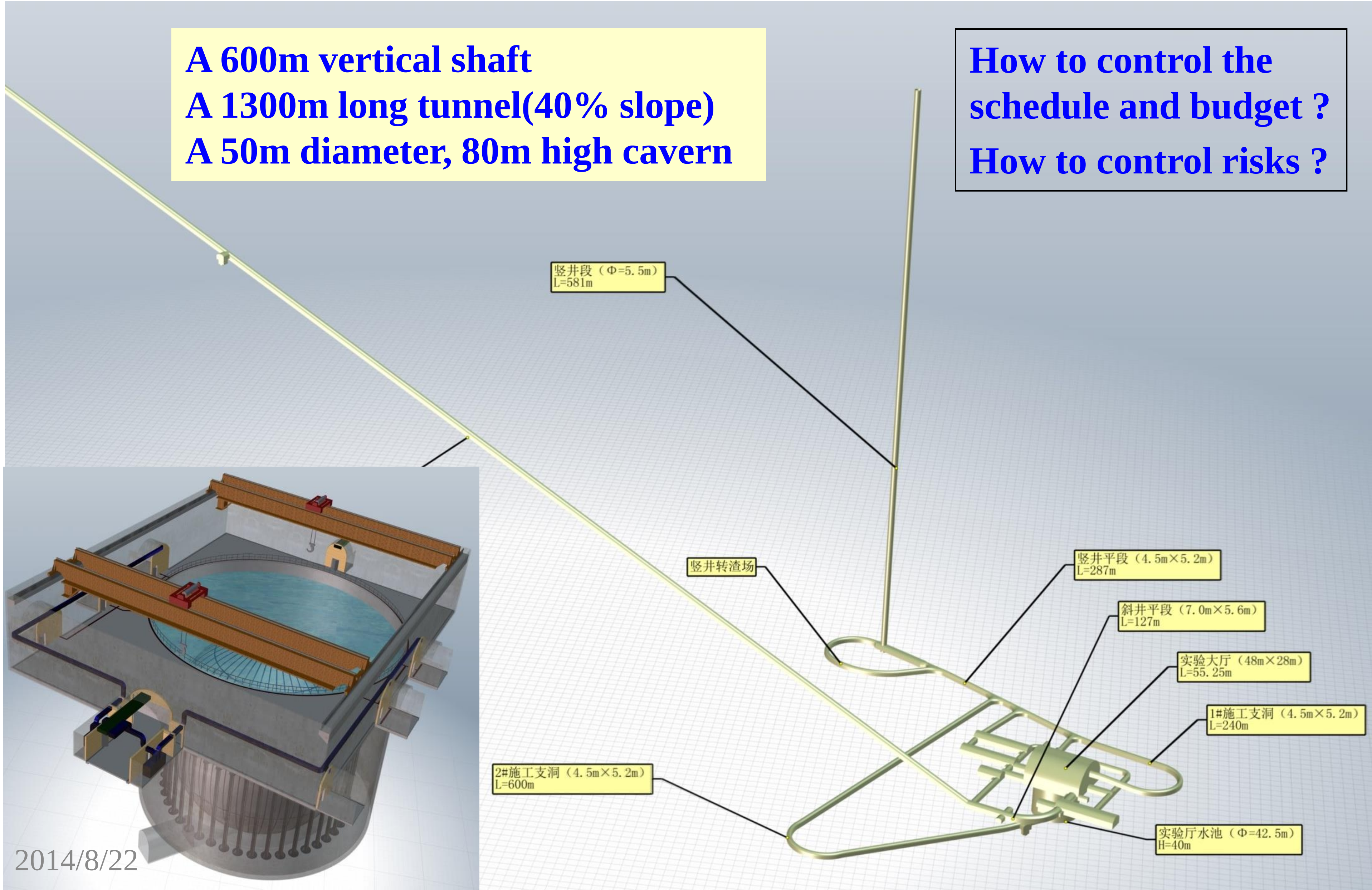
	R5912	R5912 -100	MCP-PMT
QE@410nm	25%	>30%	25-30%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	~ 2
TTS	5.5ns	1.5 ns	3.5 ns

Challenge IV: Civil Construction

A 600m vertical shaft
A 1300m long tunnel(40% slope)
A 50m diameter, 80m high cavern

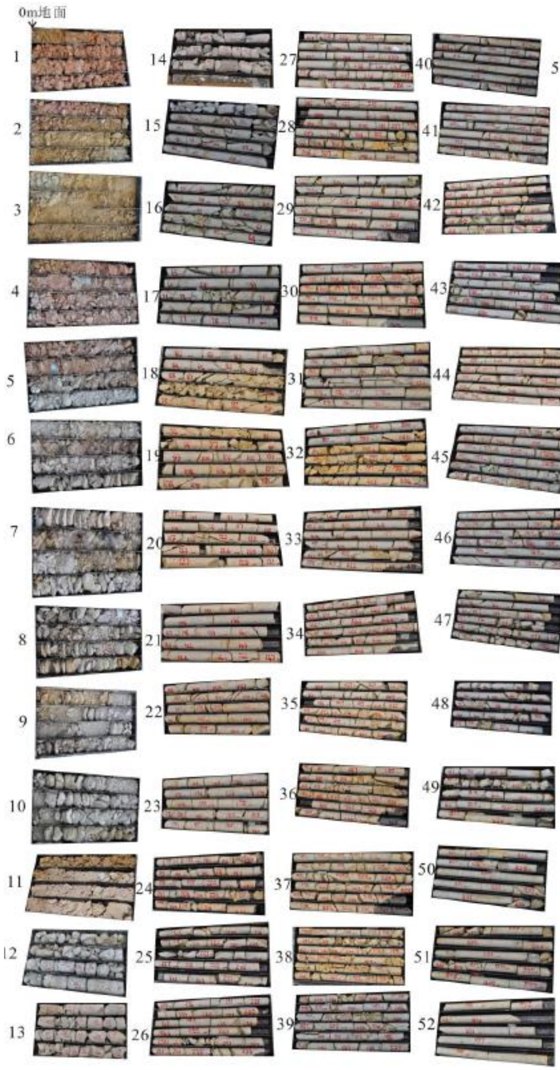
How to control the schedule and budget ?

How to control risks ?



Current Status & Brief Schedule

- Project approved by CAS for R&D and design
- Geological survey completed
  - Granite rock, tem. ~ 31 ^{o}C, little water
- EPC contract signed:
  - Engineering design by July
  - Construction work by Nov.
- Paper work towards the construction:
  - Land, environment, safety, …



Schedule:

Civil preparation： 2013-2014

Civil construction： 2014-2017

Detector component production： 2016-2017

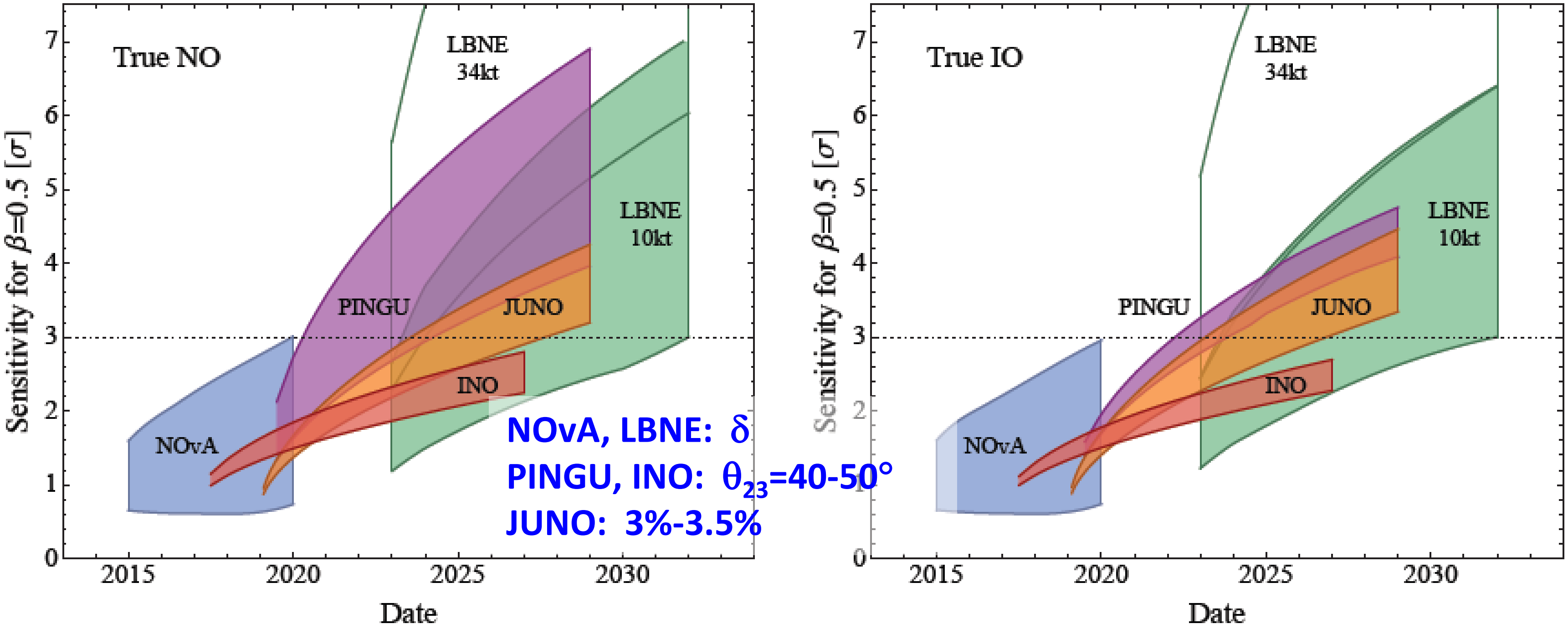
PMT production： 2016-2019

Detector assembly & installation： 2018-2019

Filling & data taking： 2020

Race for the Mass Hierarchy

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, LBNE: δ

PINGU, INO: θ_{23}=40-50°

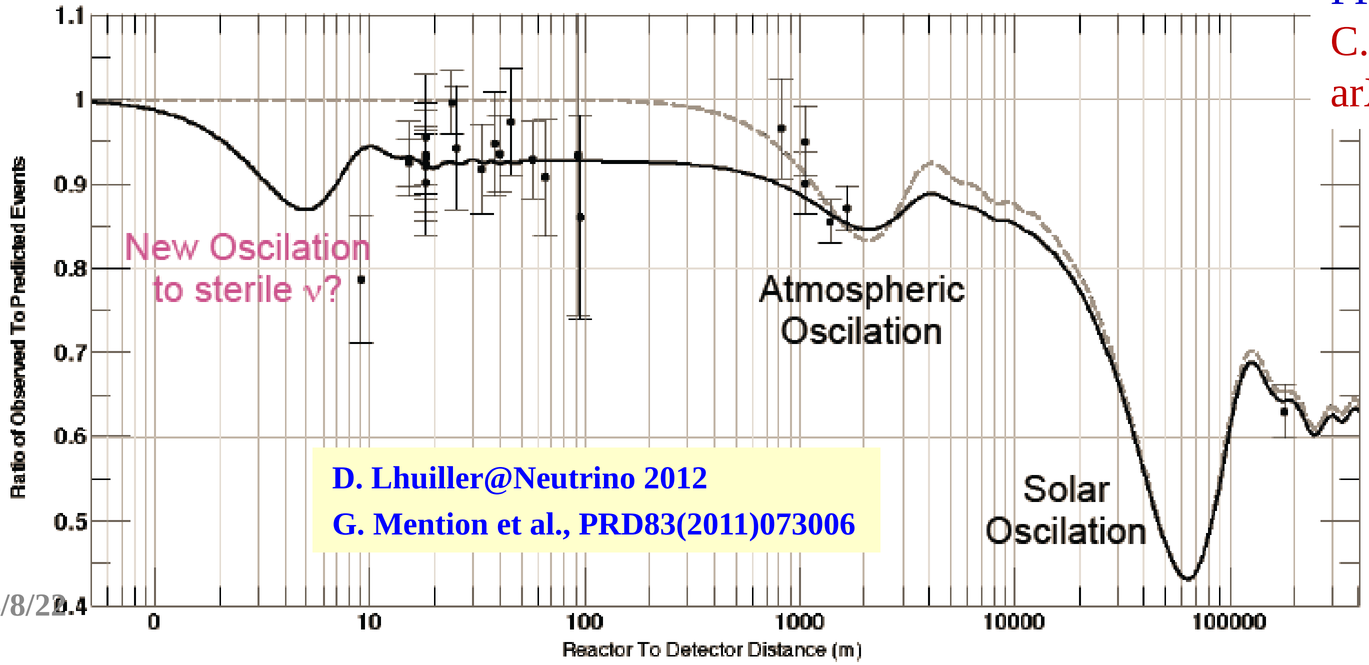
JUNO: 3%-3.5%

- **JUNO is competitive for measuring MH using reactor neutrinos**
  - **Independent of the yet-unknown CP phase, matter effects and θ_{23}**
- **Many other science goals:**
  - **Precision measurement of Δm_{31}^2, θ_{12}, Δm_{21}^2**
  - **Geo-, solar, supernova, …, neutrinos**

Reactor Neutrino Anomaly

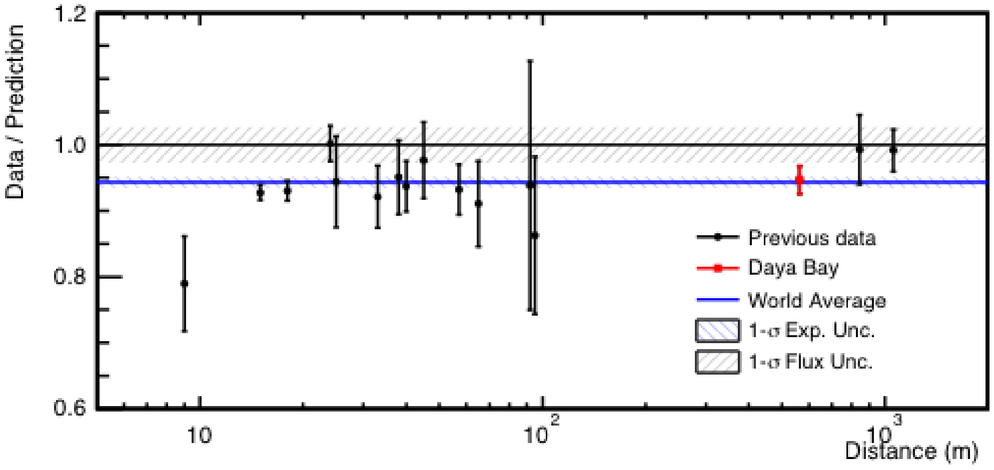
- **By a new flux calculation, there may exist a reactor neutrino flux deficit: 0.943±0.023. A 3σ effect ?**
- **Later confirm by other calculations**
- **Oscillation with sterile neutrinos ?**
  - **Other experimental “hints”: LSND, MiniBooNE, Gallex…**
  - **Global fit of all “hints”: severe tensions**
  - **Cosmological bounds: not so favored**

T.A. Mueller et al.,
PRC83:054615,2011
P. Huber et al.,
PRC84:024617,2011.
C. Zhang et al.,
arXiv: 1303.0900



D. Lhuiller@Neutrino 2012
G. Mention et al., PRD83(2011)073006

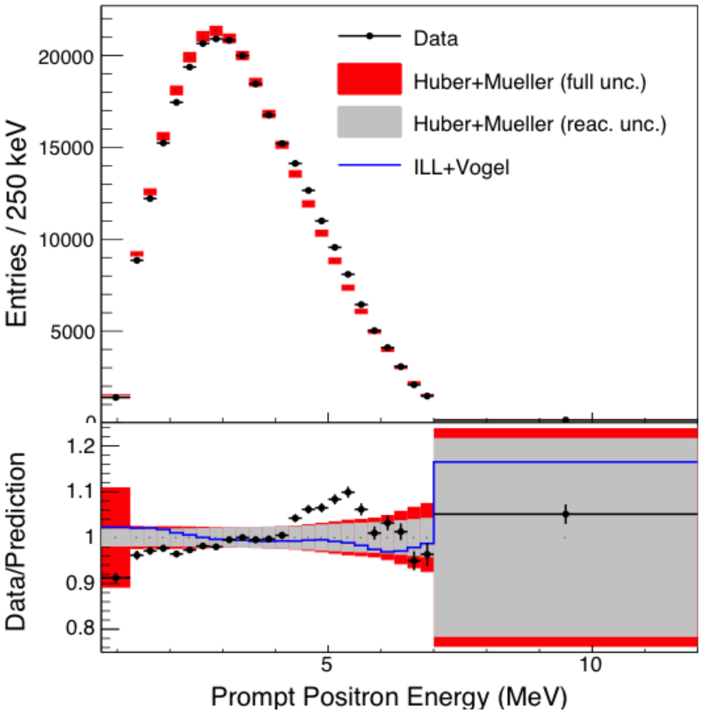
Latest Results from Daya Bay



- **Flux**
  - **Data/Prediction (Huber+Mueller)**

    0.947 ± 0.022
  - **Data/Prediction (ILL+Vogel)**

    0.992 ± 0.023
  - **Consistent with previous measurement**
- **Spectrum**
  - **After non-linearity correction**
  - **Deviation in [4, 6] MeV is ~4σ.**
  - **Events are reactor power correlated & time independent, similar to IBD event and disfavors unexpected backgrounds**
  - **An absolute spectrum is extracted by using an un-folding method**

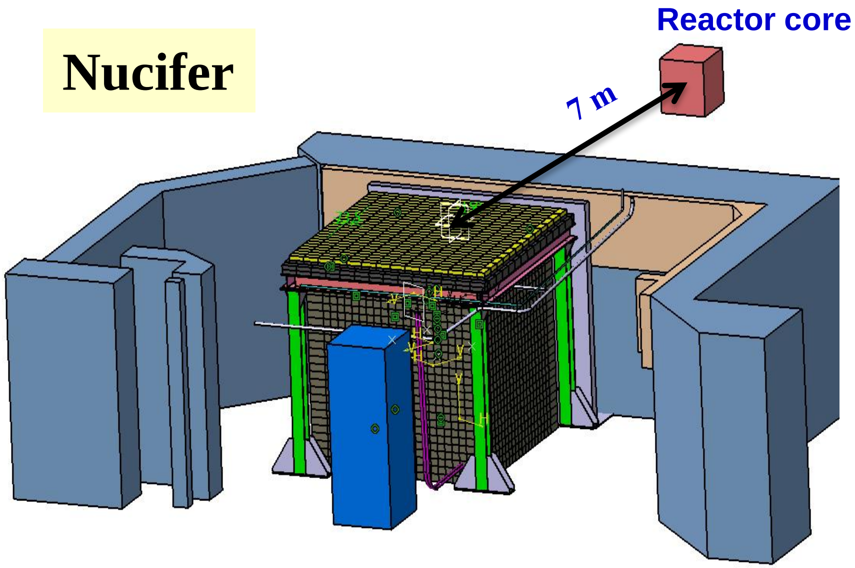


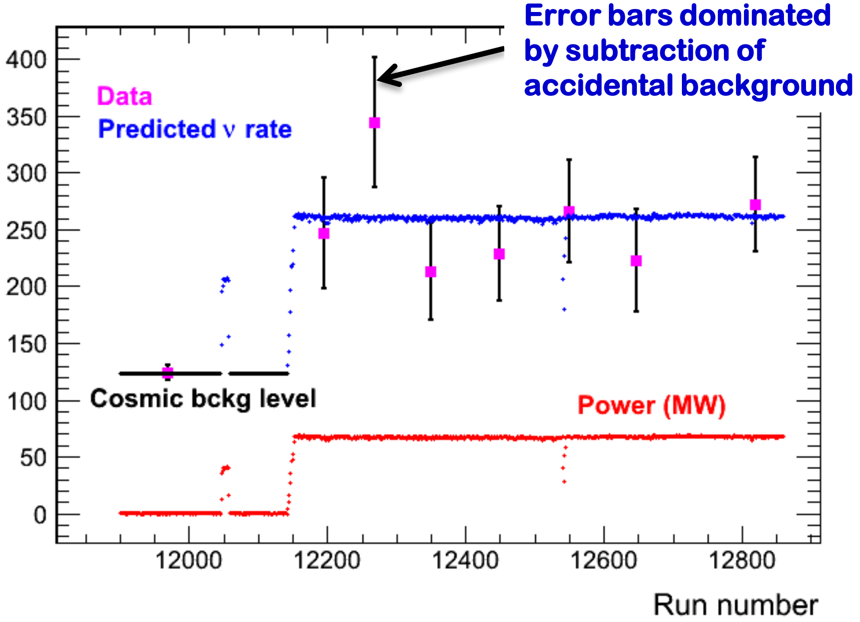
arXiv:1407.1281

Solution: Experiments

- **Radioactive sources: CeLAND(^{144}Ce in KamLAND), SoX(^{51}Cr in Borexino),…**
- **Accelerator beams: IsoDAR, Icarus/Nessie, nuSTORM…**
- **Reactors: Nucifer, Stereo, Solid, Prospect, SCARR, …**
  - ⇨ **Backgrounds near by reactors**
  - ⇨ **Precision better than 1%**

Nucifer





Error bars dominated by subtraction of accidental background

Figures from T. Lasserre

Will be upgraded to reduce backgrounds

Summary

- Reactor is a powerful man-made source: a free neutrino factory
  - If not too far, more powerful than solar, atmospheric, and accelerator neutrinos
- Great achievements: θ_{12}, θ_{13}
- Great future:
  - mass hierarchy
  - "All" mixing parameters