Recent results from Daya Bay

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On behalf of the Daya Bay collaboration

4th International Conference on New Frontiers in Physics (ICFNP2015)
August 24 – 30, 2015, Kolymbari, Crete, Greece

Recent results from Daya Bay

- *The Daya Bay Reactor Neutrino Experiment*
- *Recent oscillation results*
- *Absolute reactor anti-neutrino flux and spectrum*
- *Search for a light sterile neutrino*
- *More searches*

Neutrino Oscillations

- Each flavor state is a mixture of mass eigenstates
- described by a neutrino mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{cp}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{cp}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

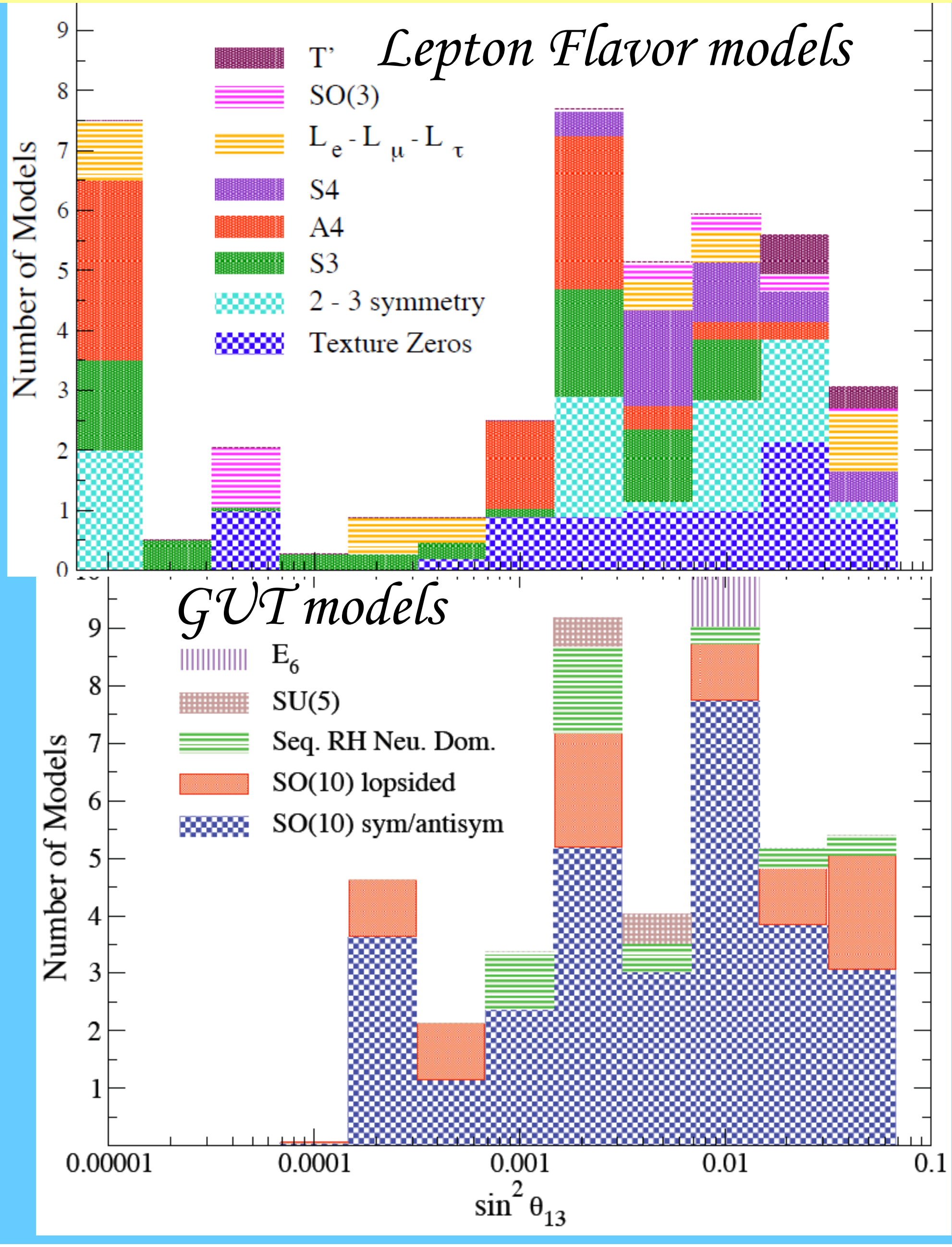
The Maki-Nakagawa-Sakata-Pontecorvo Matrix

- A freely propagating ν_e will oscillate into other types.

In general, $|\langle \nu_{\mu,\tau}(t)|\nu_e(0)\rangle|^2 \neq 0$;

$$|\langle \nu_e(t)\,|\,\nu_e(0)\rangle|^2 \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

θ_{13} selects Flavor/GUT models



Taken from C. Albright, arXiv: 0905.0146

Reactor expt.: a clean way to measure θ_{13}

$$P(\bar{\nu}_e \to x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- Reactor: abundant, free, pure source of $\bar{\nu}_e$

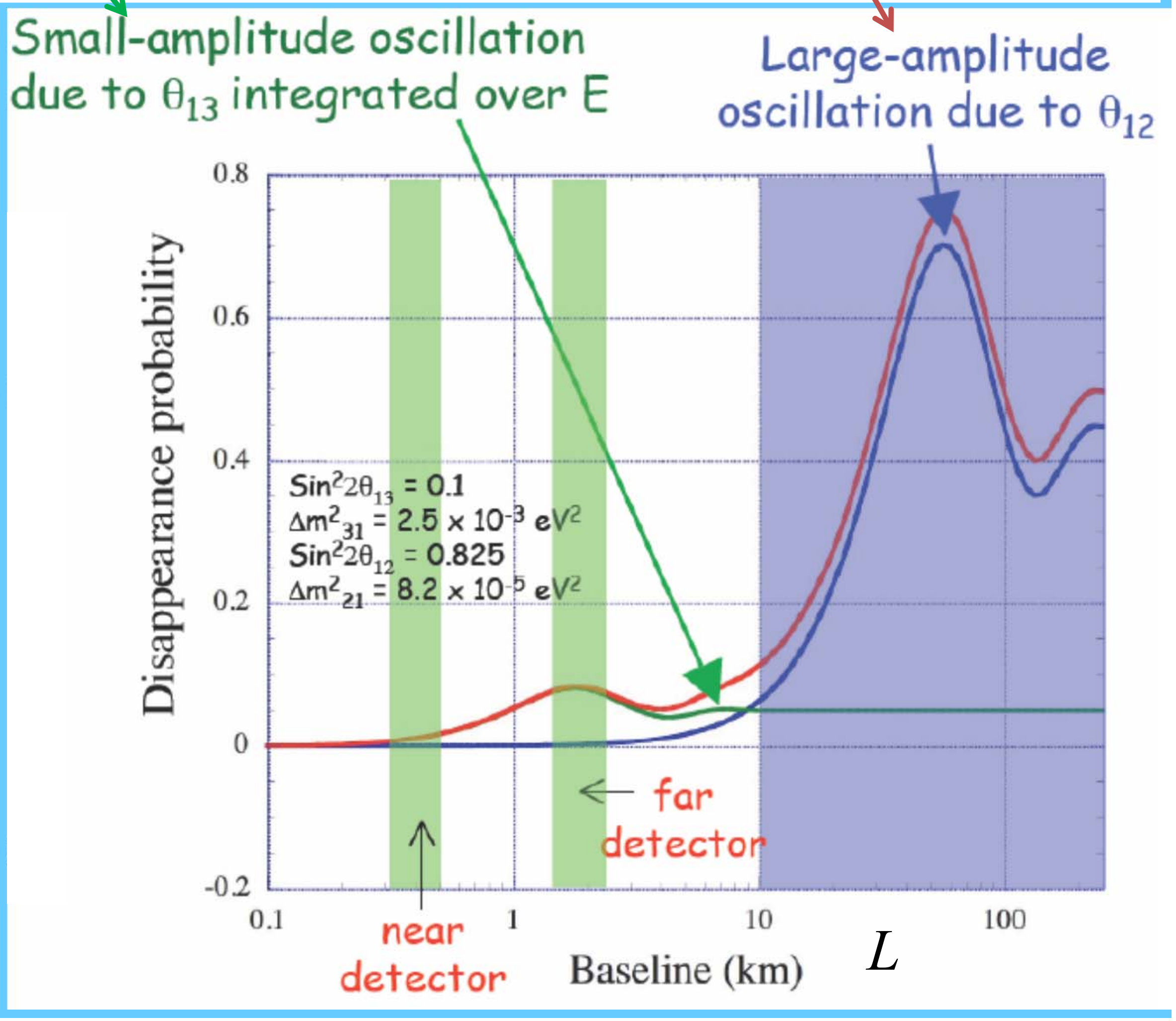
- disappearance of $\bar{\nu}_e$ *at small L depends only on* θ_{13}

Near-far configuration

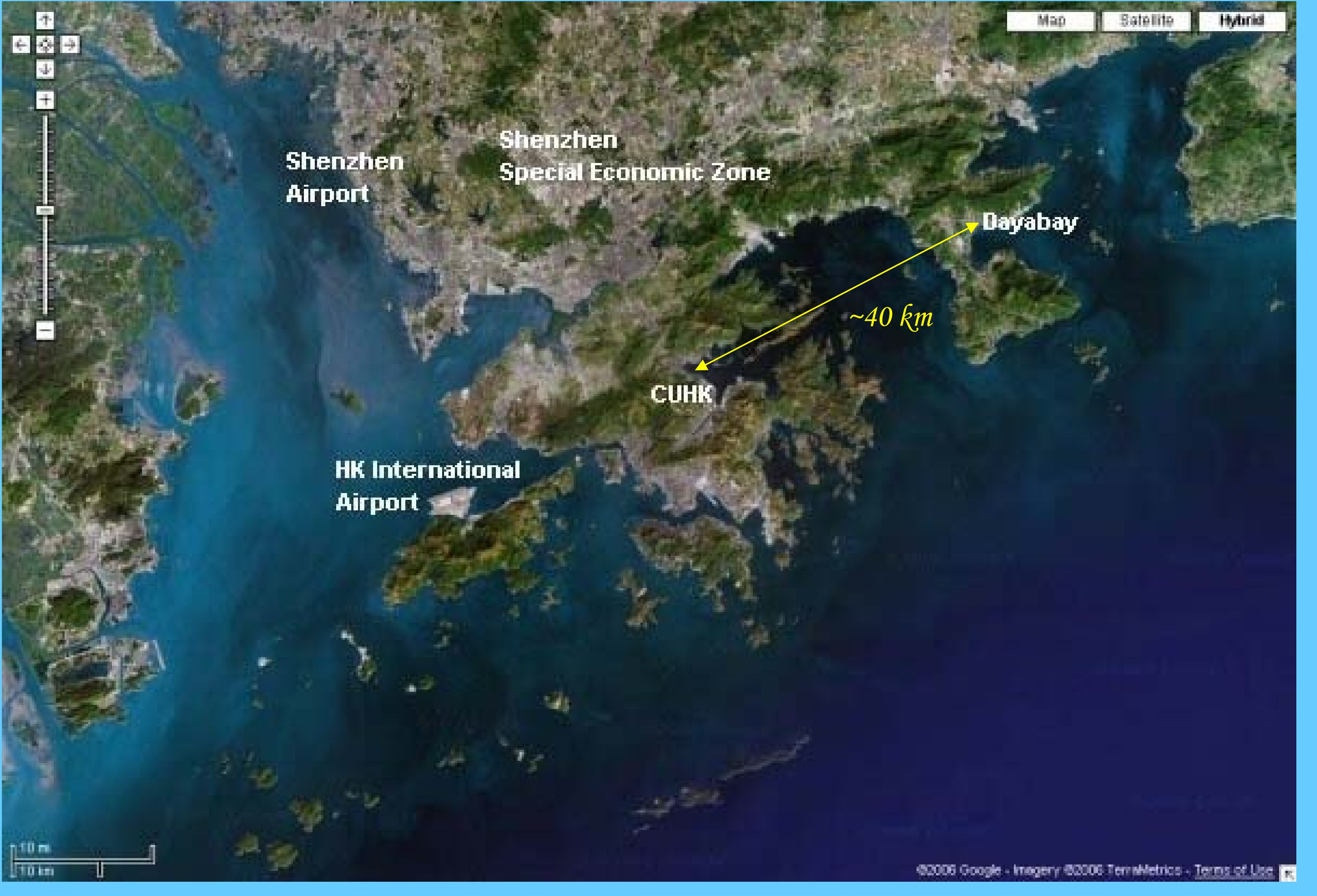
Near detectors: neutrino flux and spectrum for normalization

Far detectors: near oscillation maximum for best sensitivity

Relative measurement: cancel out most systematics

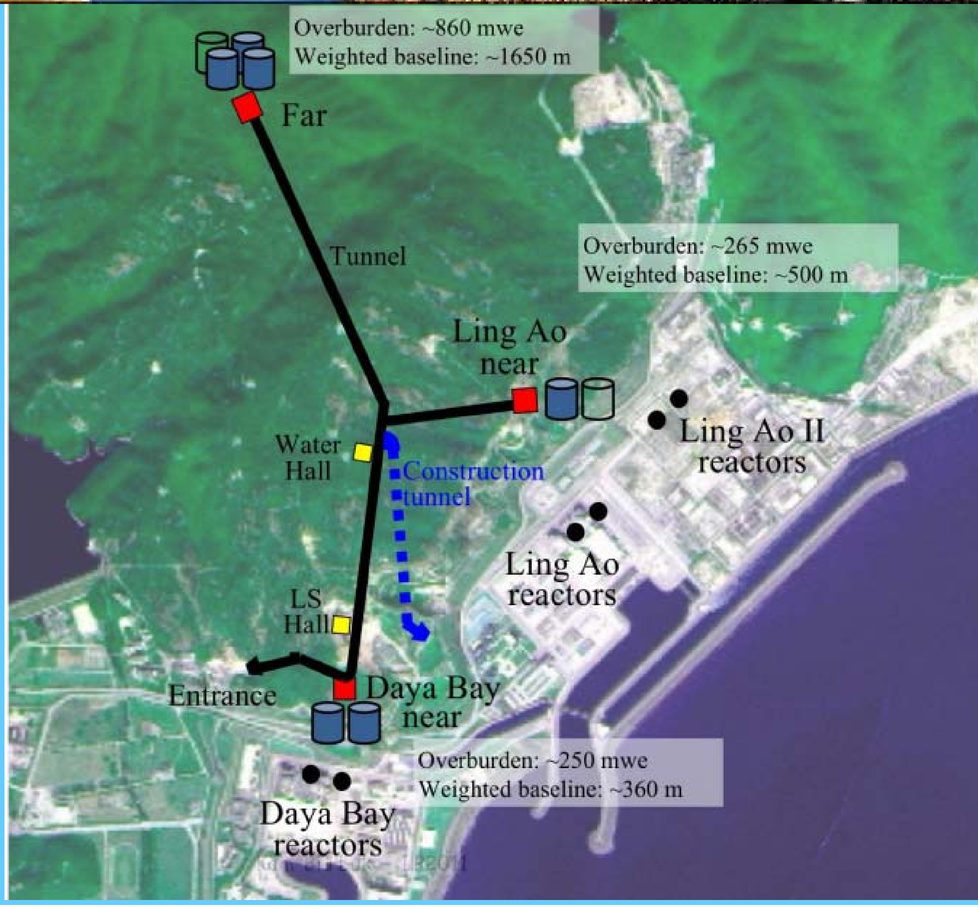


Daya Bay (China)

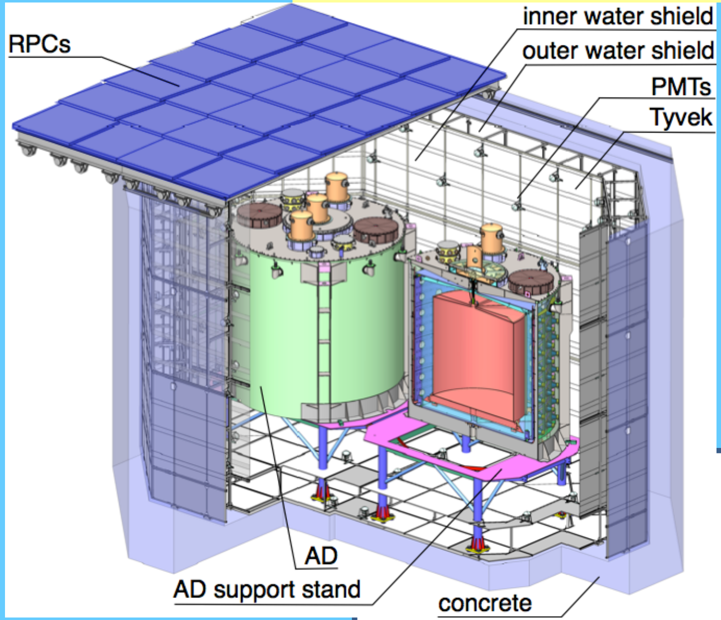


Daya Bay Reactor Neutrino Experiment

- *Top five most powerful nuclear plants* (17.4 GW_{th})
  → *large number of anti-neutrinos* (3x10^{21} $\bar{\nu}_e$ per s)
- *Adjacent mountains shield cosmic rays*



Daya Bay detectors

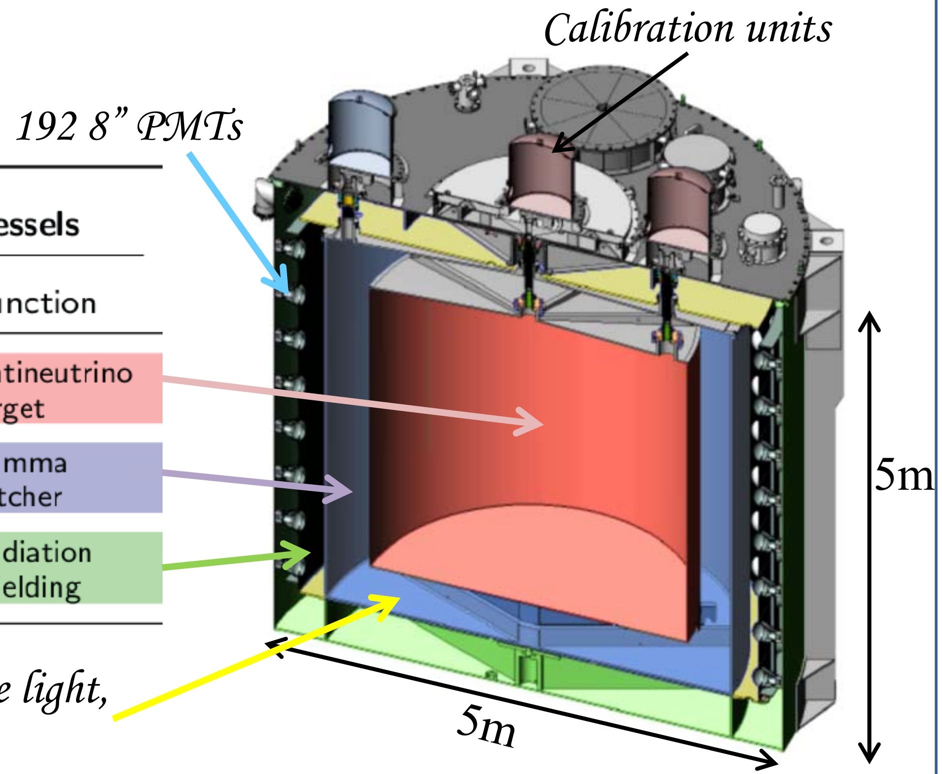


RPC : muon veto
Water pool: muon veto + shielding from environmental radiations (2.5m water)

8 functionally identical anti-neutrino detectors (AD) to suppress systematic uncertainties

3 zone cylindrical vessels

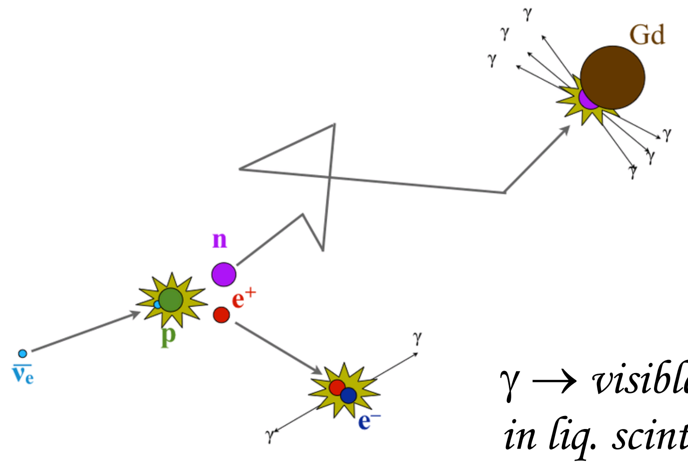
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding



Top and bottom reflectors: more light, more uniform detector response

Anti-neutrino detection

$\bar{\nu}_e$ *detected via inverse beta-decay (IBD):*



$\gamma \rightarrow$ *visible photons in liq. scintillator*

$\bar{\nu}_e + p \rightarrow e^+ + n$ *(prompt signal)*

~180μs → + p → D + γ (2.2 MeV)

→ + Gd → Gd*

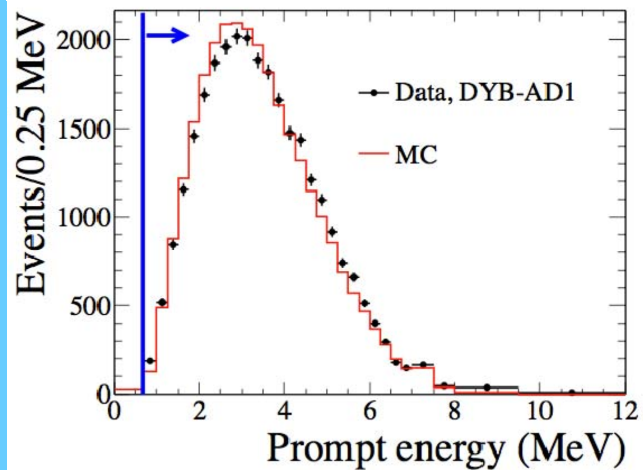
~30μs *for* 0.1% Gd → Gd + γ's (8 MeV)

(delayed signal)

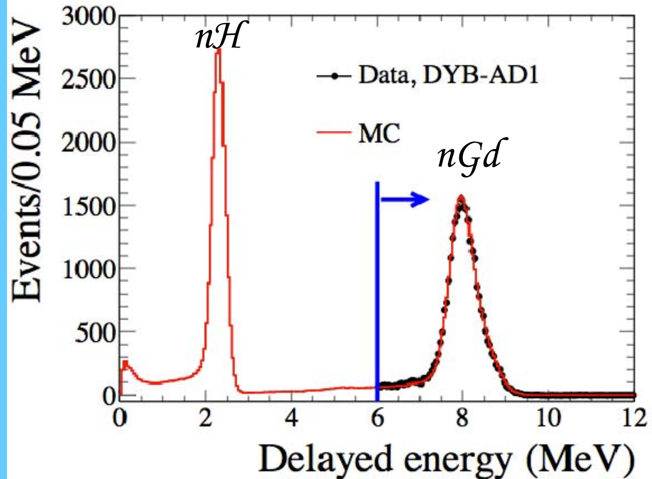
Powerful background rejection!

$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8$ MeV

Prompt Signal



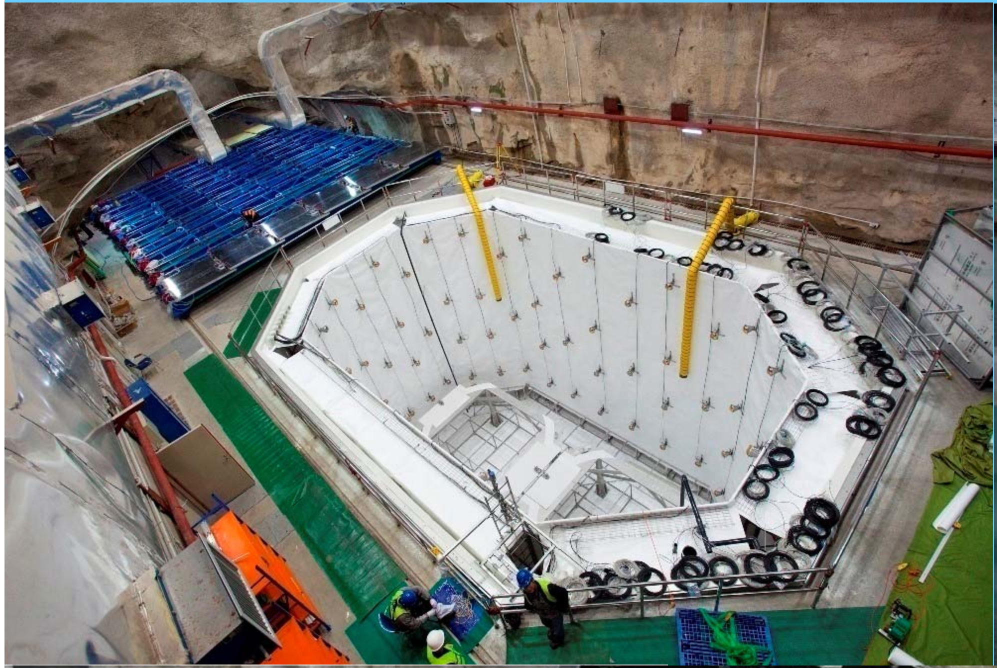
Delayed Signal

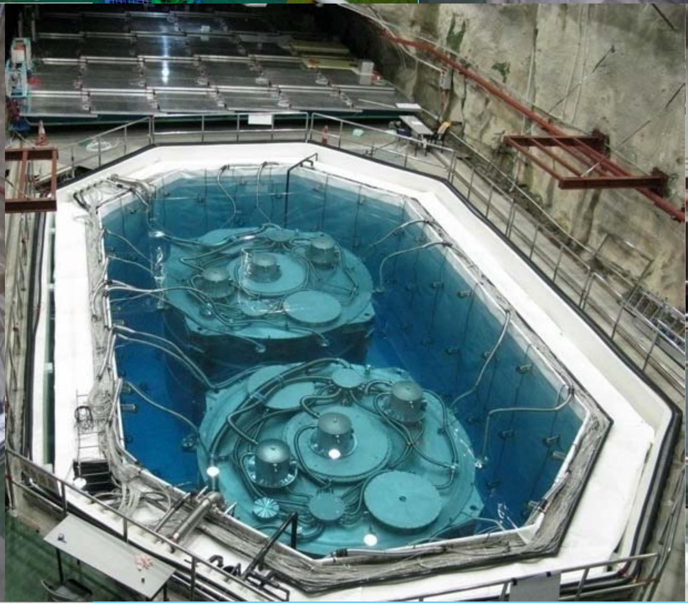


The Daya Bay Collaboration

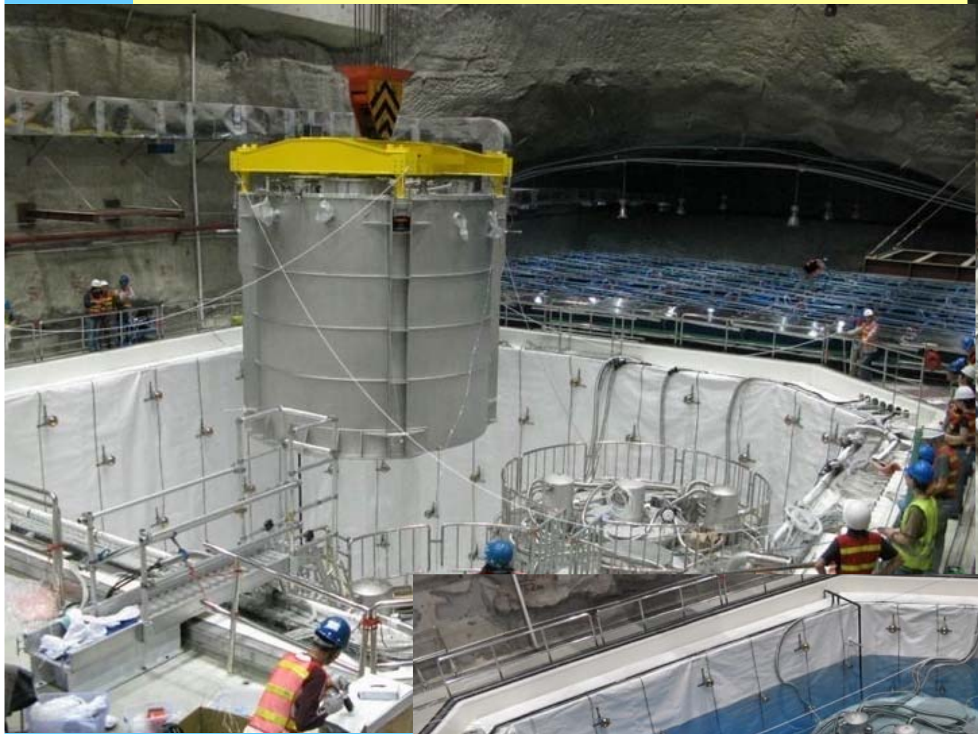
41 Institutes, ~ 230 collaborators from China, USA, Hong Kong, Taiwan, Chile, Czech Republic and Russia

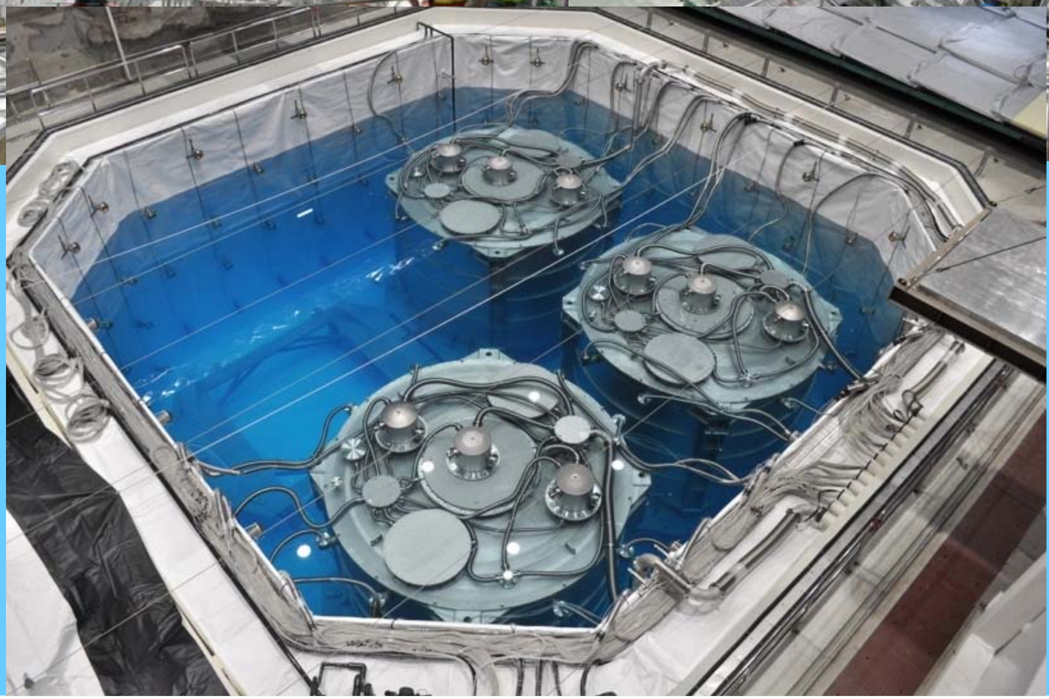
AD Installation - Near Hall





AD Installation - Far Hall





Signal and background summary

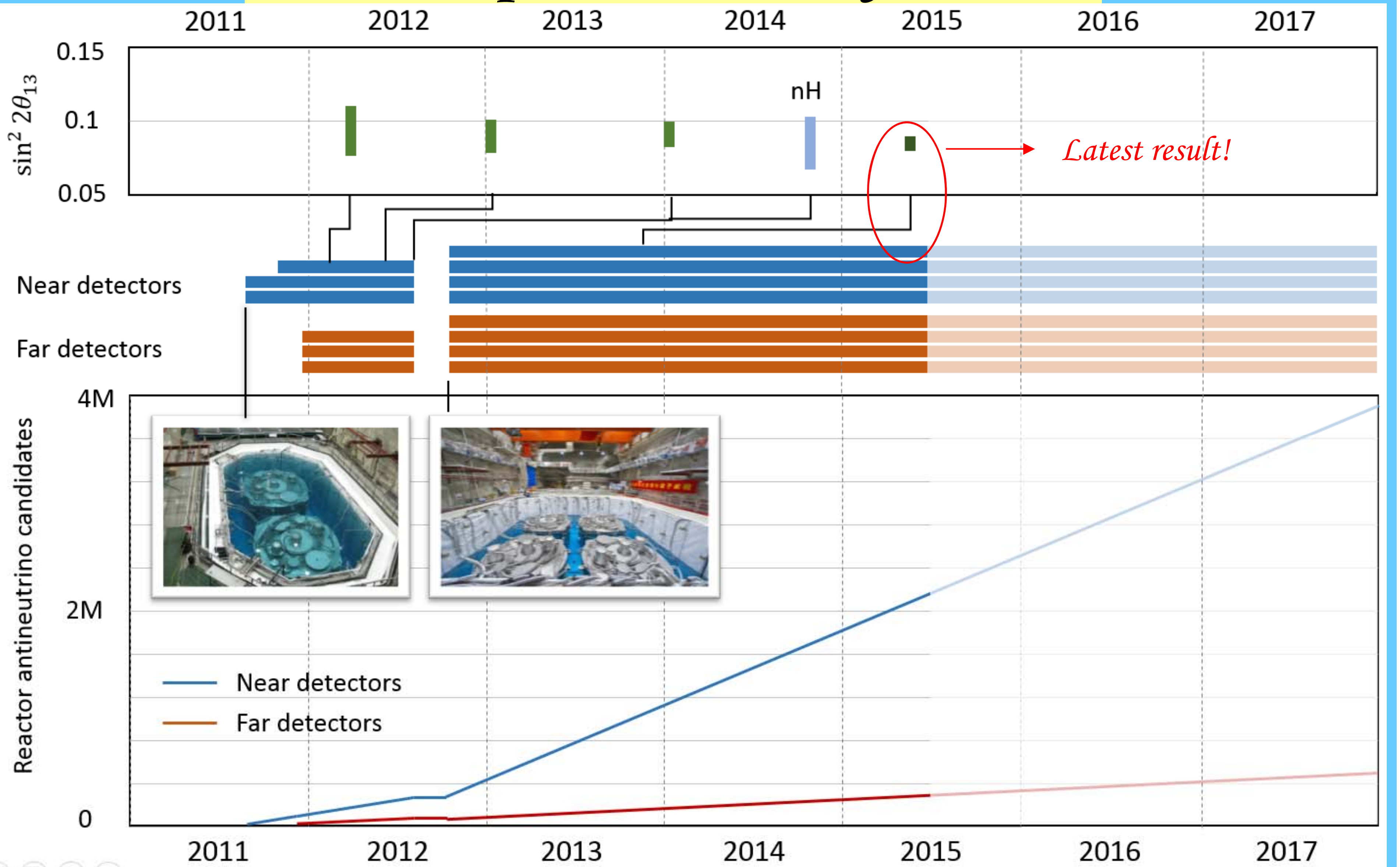
Starting with $3\text{x}10^{21}$ $\overline{\nu}_e$ *per s at the reactors*

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
IBD candidates	304459	309354	287098	190046	40956	41203	40677	27419
DAQ live time(days)	565.436	565.436	568.03	378.407	562.451	562.451	562.451	372.685
ε_μ	0.8248	0.8218	0.8575	0.8577	0.9811	0.9811	0.9808	0.9811
ε_m	0.9744	0.9748	0.9758	0.9756	0.9756	0.9754	0.9751	0.9758
Accidentals(per day)	8.92 ± 0.09	8.94 ± 0.09	6.76 ± 0.07	6.86 ± 0.07	1.70 ± 0.02	1.59 ± 0.02	1.57 ± 0.02	1.26 ± 0.01
Fast neutron(per AD per day)	0.78 ± 0.12		0.54 ± 0.19		0.05 ± 0.01			
^{9}Li/^{8}He(per AD per day)	2.8 ± 1.5		1.7 ± 0.9		0.27 ± 0.14			
Am-C correlated 6-AD(per day)	0.27 ± 0.12	0.25 ± 0.11	0.27 ± 0.12		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.09	
Am-C correlated 8-AD(per day)	0.20 ± 0.09	0.21 ± 0.10	0.18 ± 0.08	0.22 ± 0.10	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.07 ± 0.03
^{13}C(α, n)^{16}O(per day)	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
IBD rate(per day)	657.18 ± 1.94	670.14 ± 1.95	594.78 ± 1.46	590.81 ± 1.66	73.90 ± 0.41	74.49 ± 0.41	73.58 ± 0.40	75.15 ± 0.49

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of the IBD rates in AD1 and AD2 (AD3 and AD8 in the 8-AD period) was 0.981±0.004 (1.019±0.004) while the expected ratio was 0.982 (1.012).

F. P. An et al., Daya Bay Collaboration, arXiv: 1505.03456v1, 2015, cover paper of next PRL

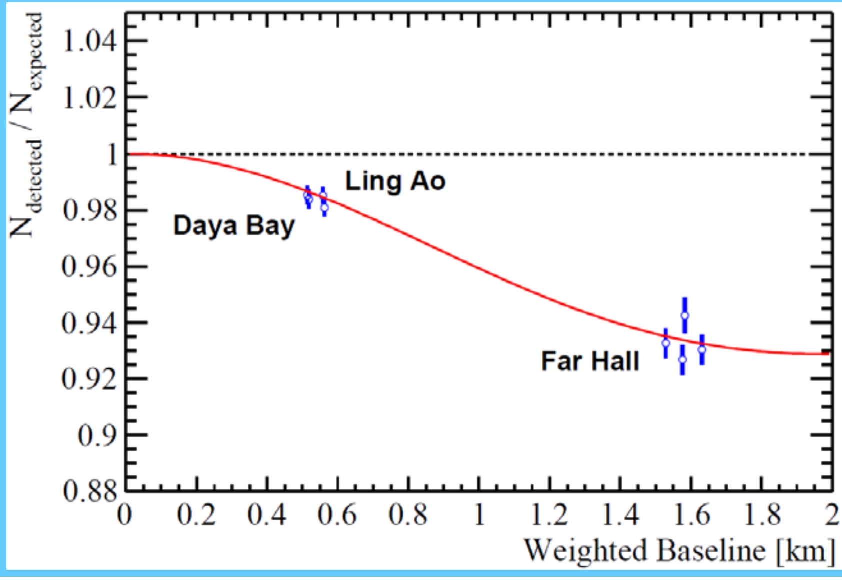
Operation history

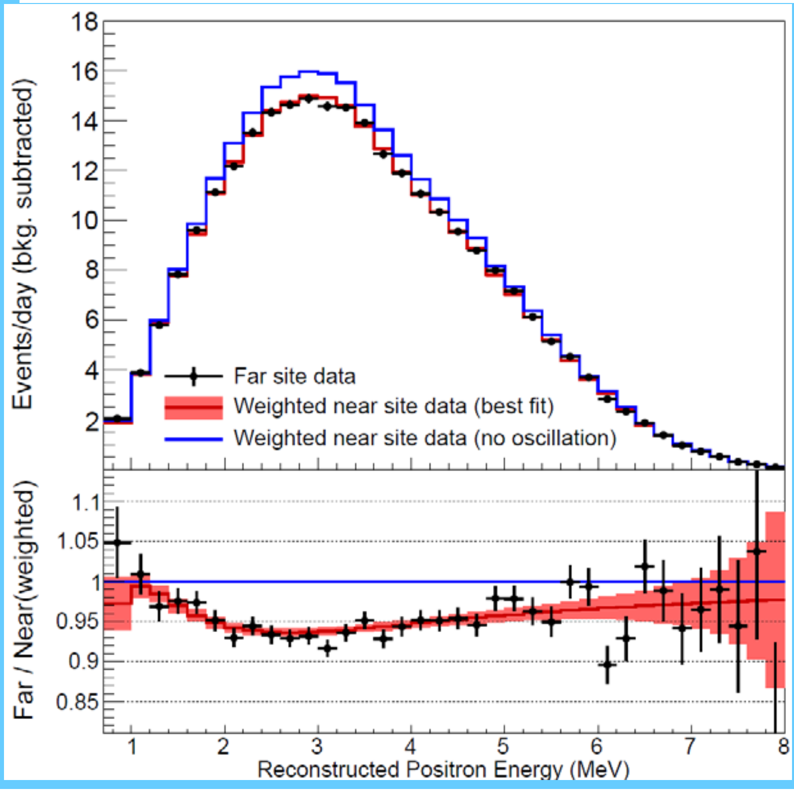


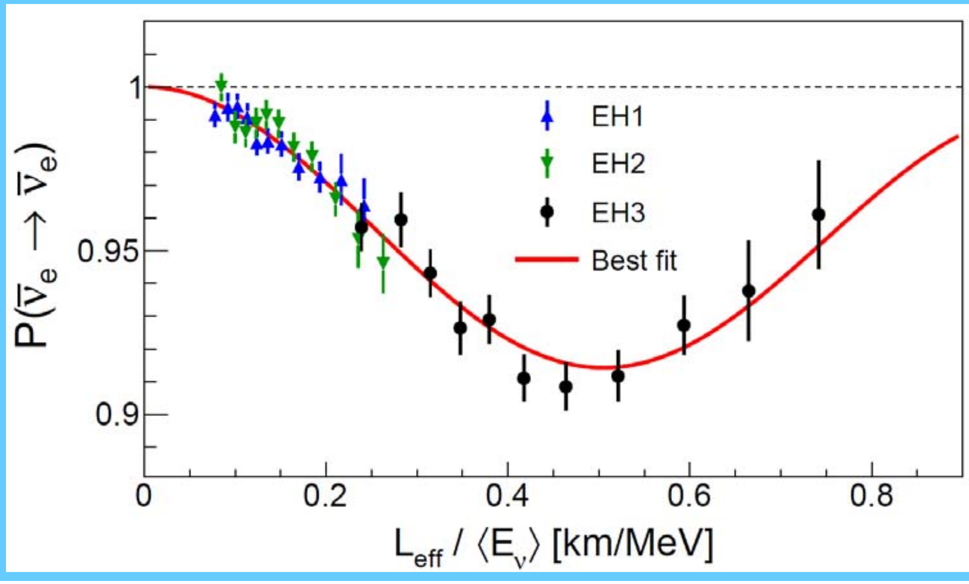
Oscillation results

$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{ee}^2 L/4E) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2(\Delta m_{21}^2 L/4E)$

- *Far/near relative measurement*
- *Oscillation parameters measured with rate + spectral distortion*
- *Both consistent with neutrino oscillation interpretation*







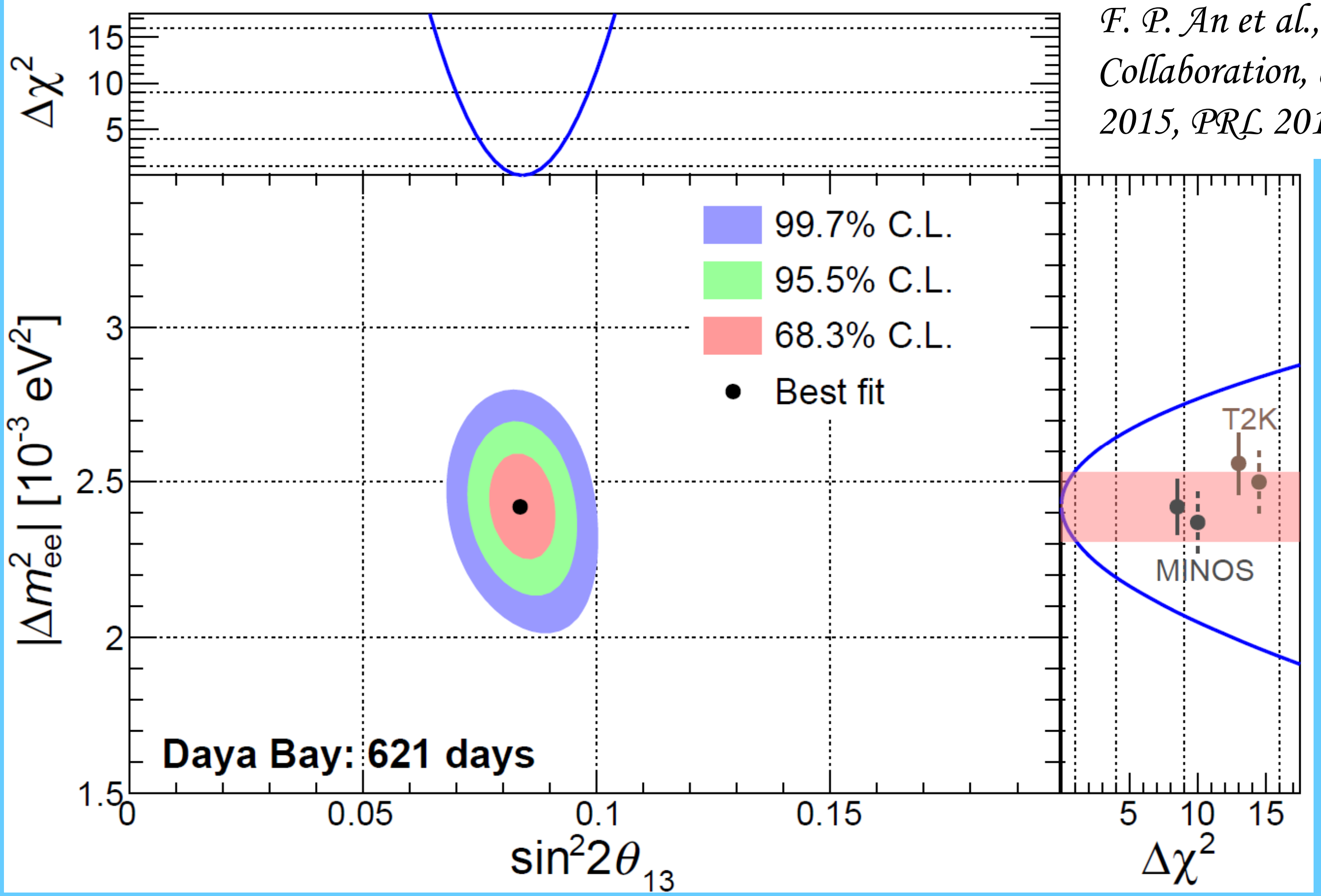
Oscillation results

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$
$$\left|\Delta m^2_{ee}\right| = \left(2.42 \pm 0.11\right) \times 10^{-3}\,\text{eV}^2$$
$$\chi^2/\text{NDF} = 134.6/146$$

- Unprecedented precision: ~6%

- Consistent with muon disappearance expt., with comparable precision

F. P. An et al., Daya Bay Collaboration, arXiv: 1505.03456v1, 2015, PRL 2015



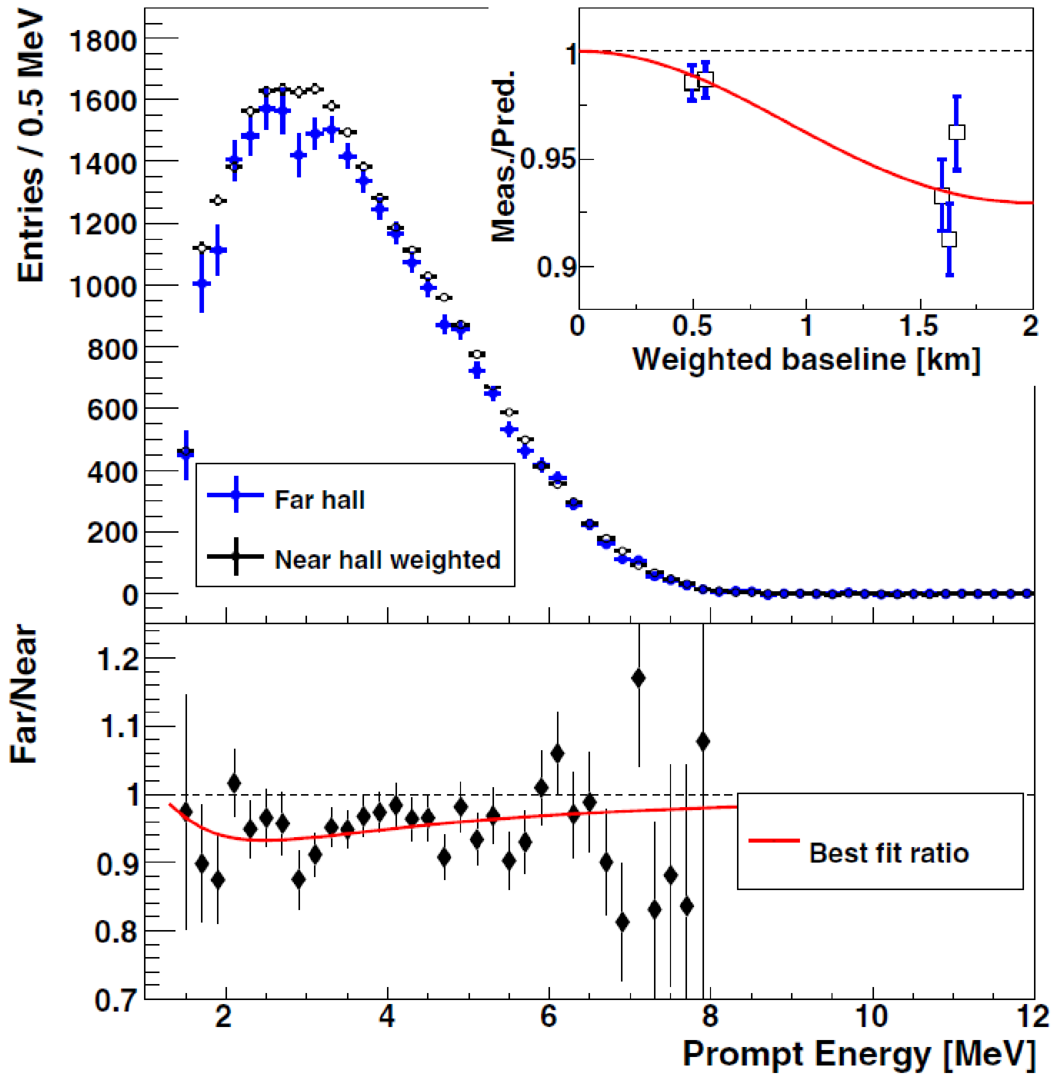
Independent θ_{13} measurement with nH

- *Independent measurement, different systematics*
- *Longer capture time, lower delayed energy* (2.2 MeV) $\rightarrow$ *high accidental background*
- $\rightarrow$ *higher prompt energy cut* (> 1.5 MeV) + *prompt-to-delay distance cut* (< 0.5 m)
- *rate deficit with 217 days of 6AD data:*

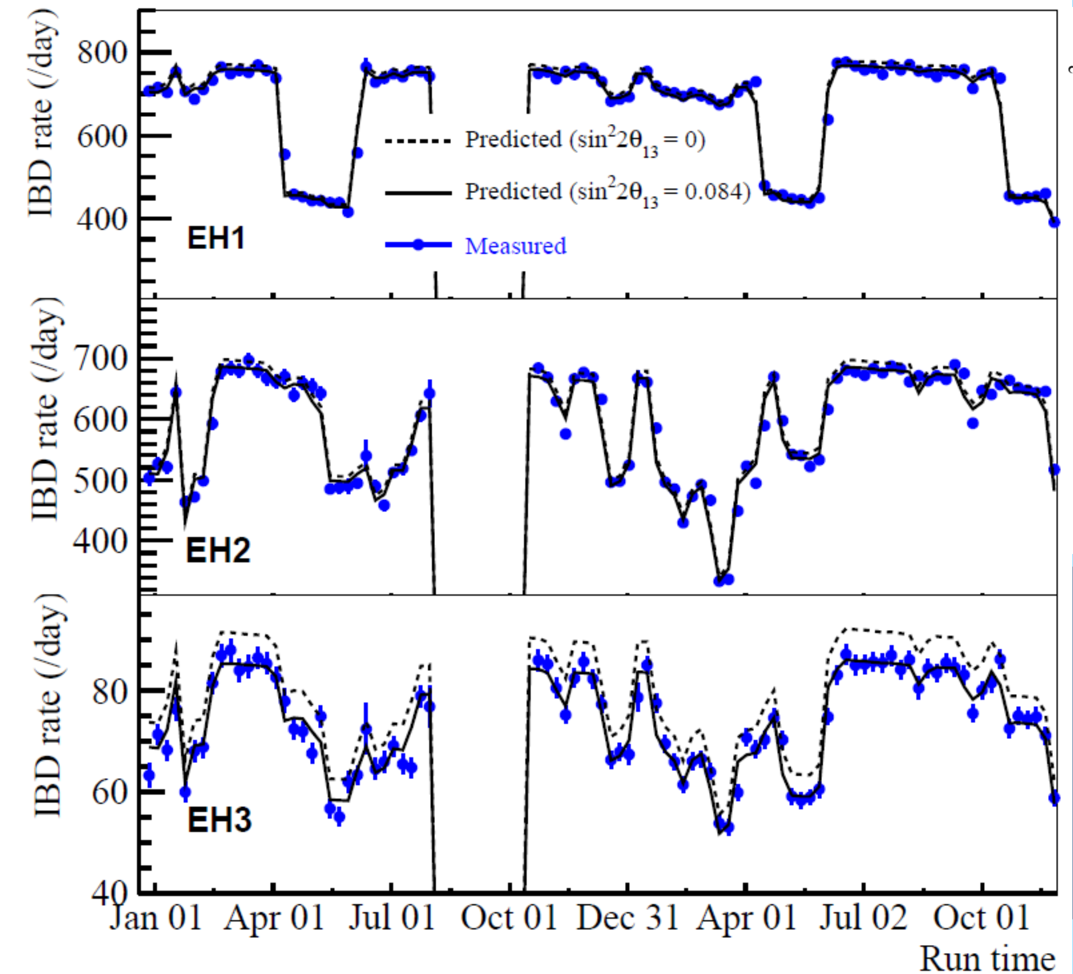
$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

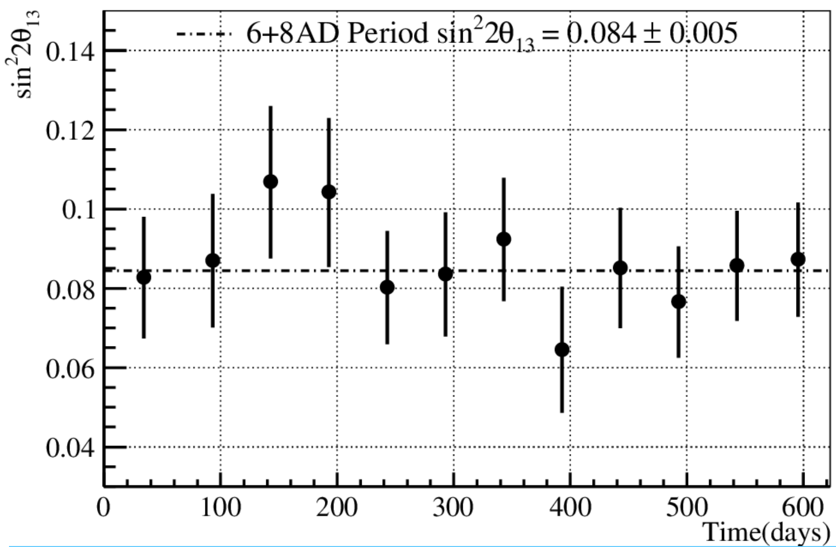
- *Spectral analysis in progress*

F. P. An et al., Daya Bay Collaboration, PRD ***90****, 071101 (2014).*



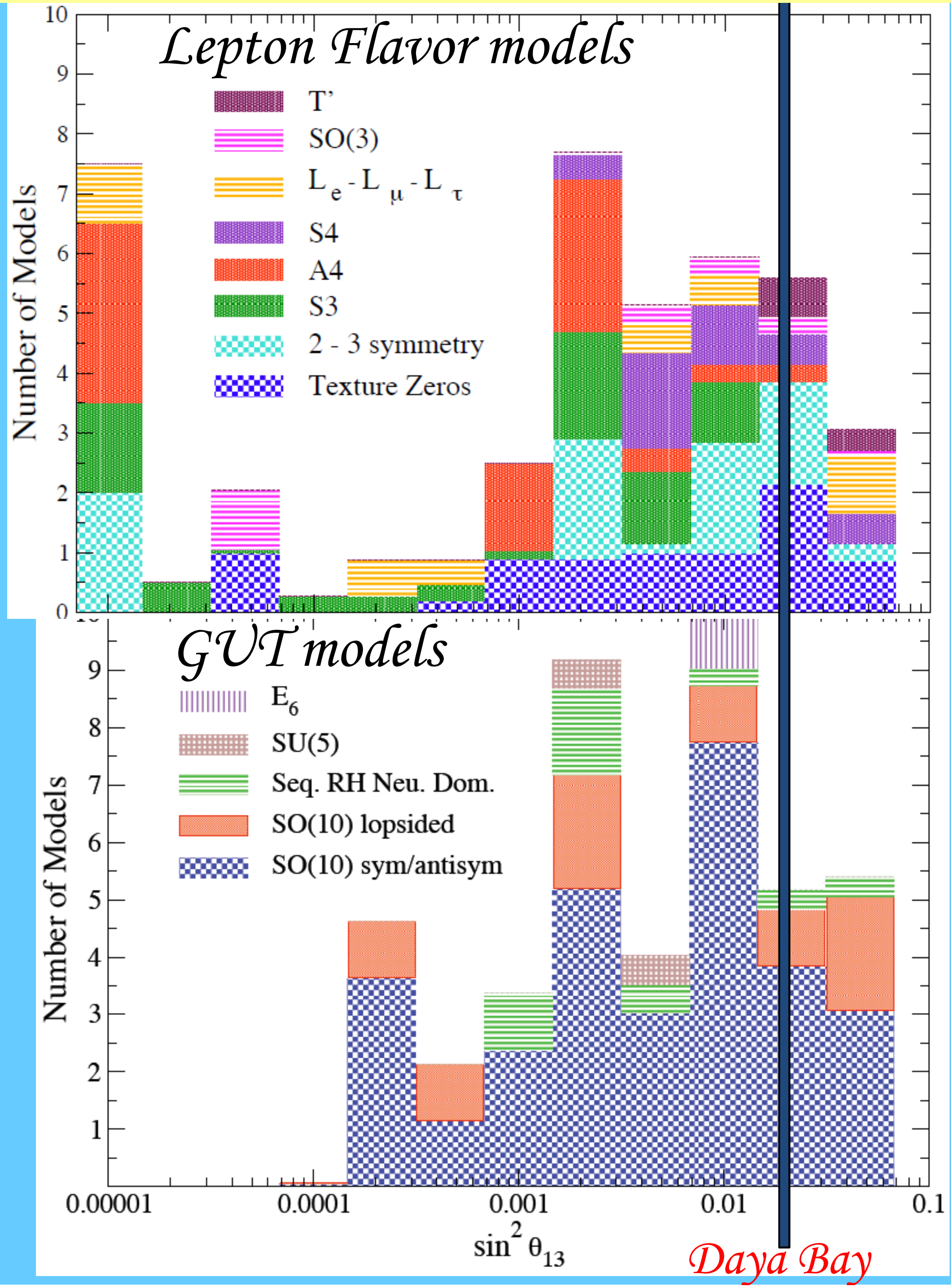
Reactor anti-neutrino rate deficit





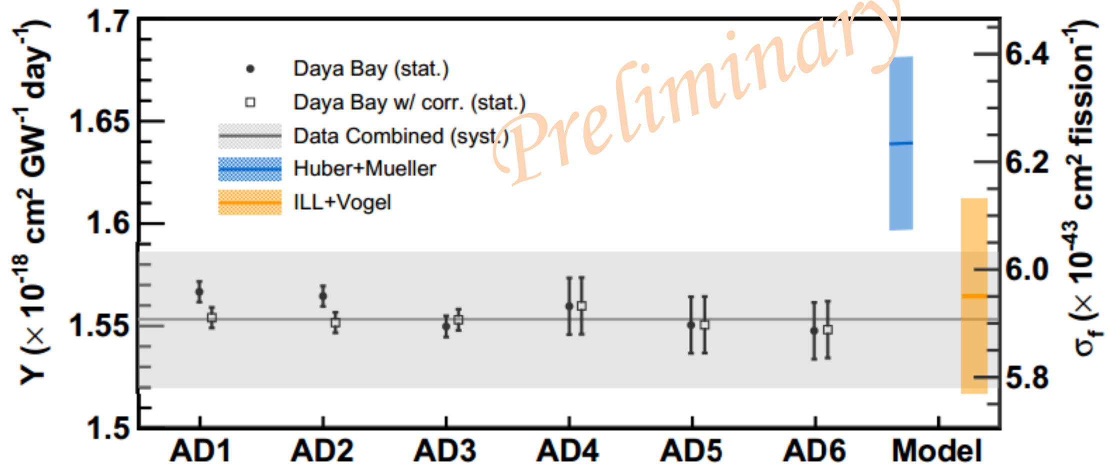
- *Measured* $\bar{\nu}_e$ *rate highly correlated with reactor prediction*
- *Consistent rate deficit* (= $\sin^2 2\theta_{13}$) *vs. time*

θ_{13} selects Flavor/GUT models

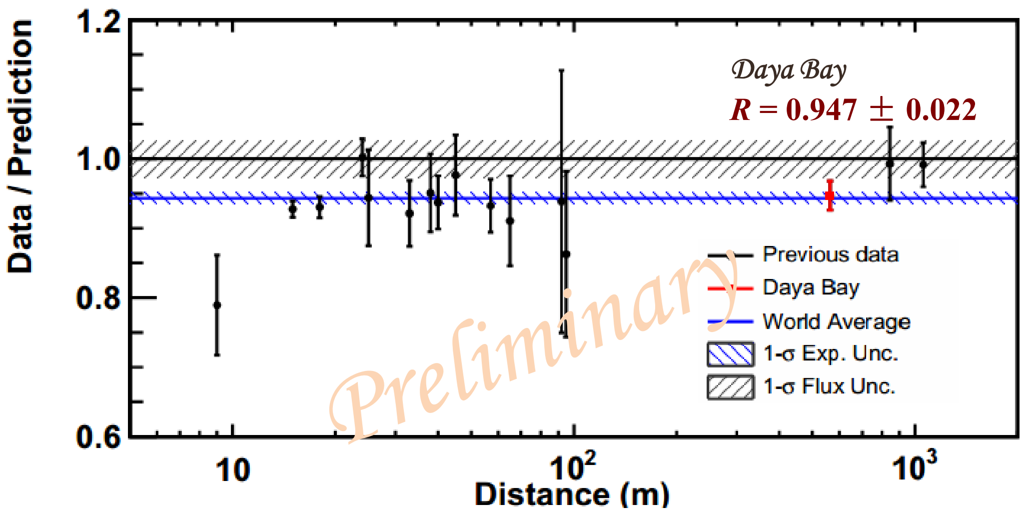


Taken from C. Albright, arXiv: 0905.0146

Reactor antineutrino flux



Measured IBD events (background subtracted) in each detector are normalized to cm²/GW/day (Y_0) and cm²/fission (σ_f).



Global comparison of measurement and prediction (Huber+Mueller)

Daya Bay's reactor antineutrino flux measurement is consistent with previous short baseline experiments.

3-AD (near sites) measurement

$Y_0 = 1.553 \times 10^{-18}$

$\sigma_f = 5.934 \times 10^{-43}$

Compare to flux model

Data/Prediction (Huber+Mueller)

0.947 ± 0.022

Data/Prediction (ILL+Vogel)

0.992 ± 0.023

Effective baseline (near sites)

$L_{eff} = 573\text{m}$

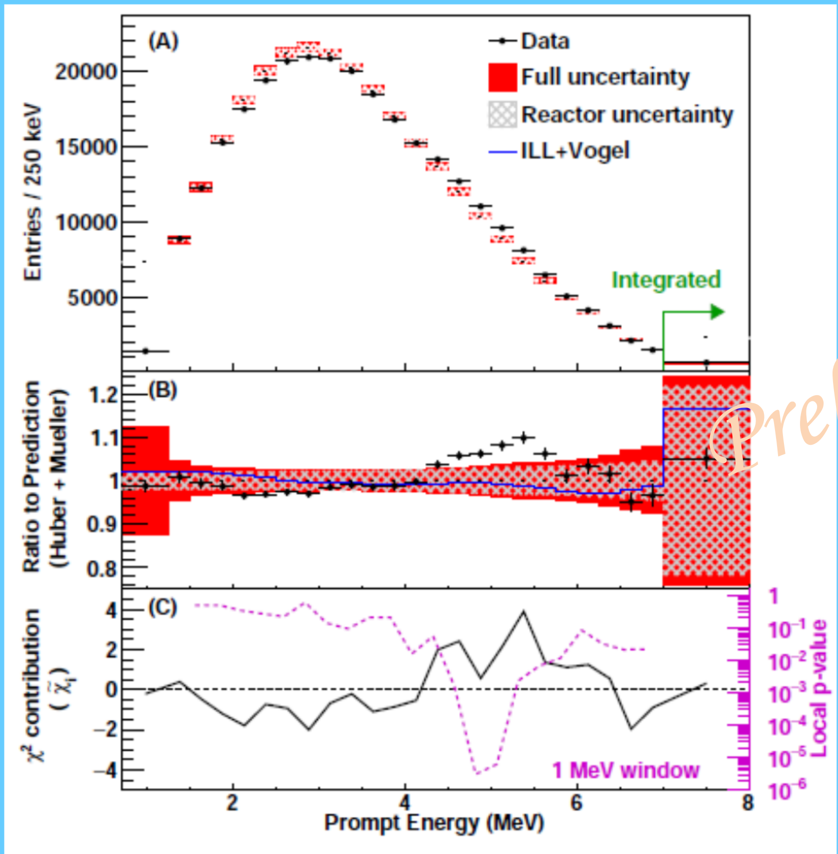
Effective fission fractions α_k

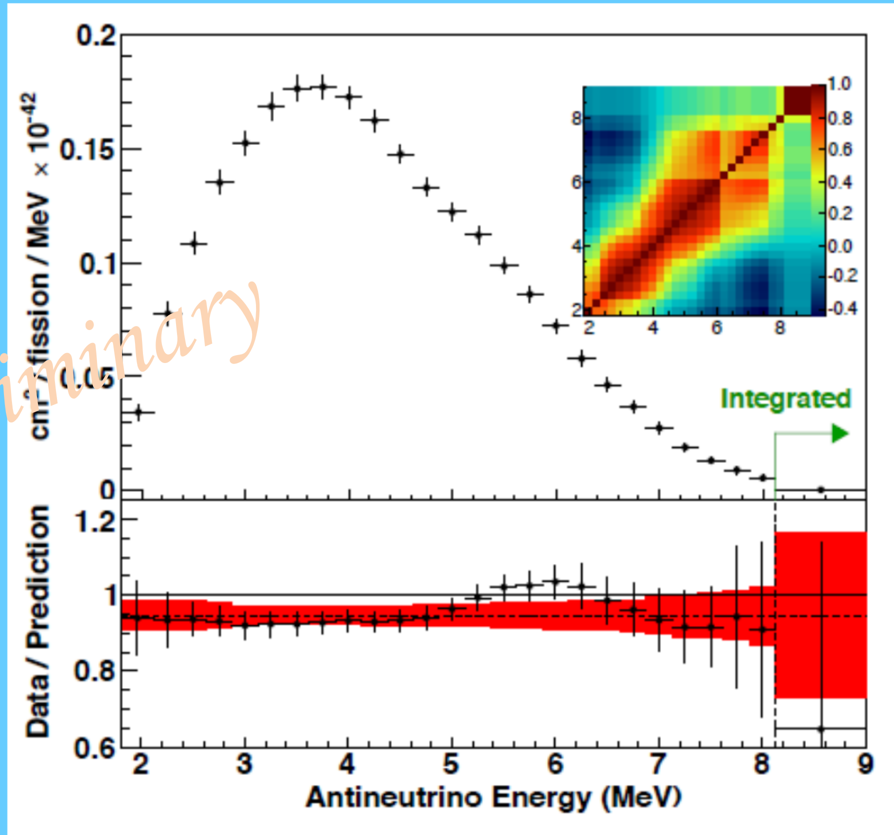
^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.586	0.076	0.288	0.050

Reactor antineutrino spectrum

- *Absolute positron spectral shape is NOT consistent with the prediction. A bump is observed in* 4-6 MeV.

- *Extract a generic observable reactor antineutrino spectrum by removing the detector response*



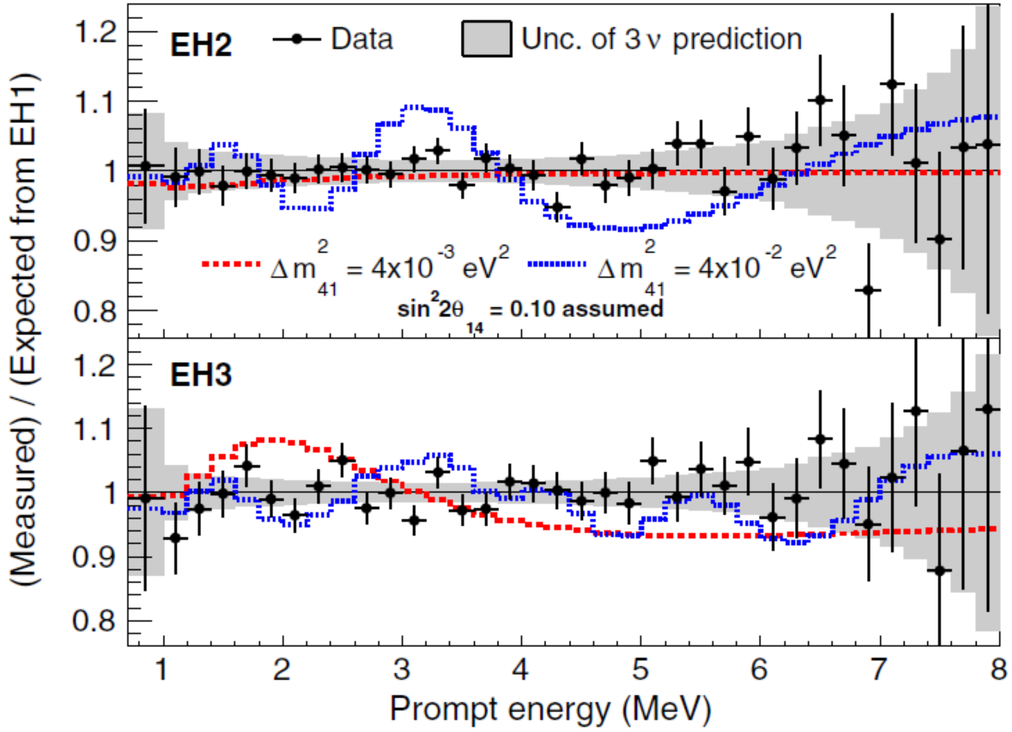


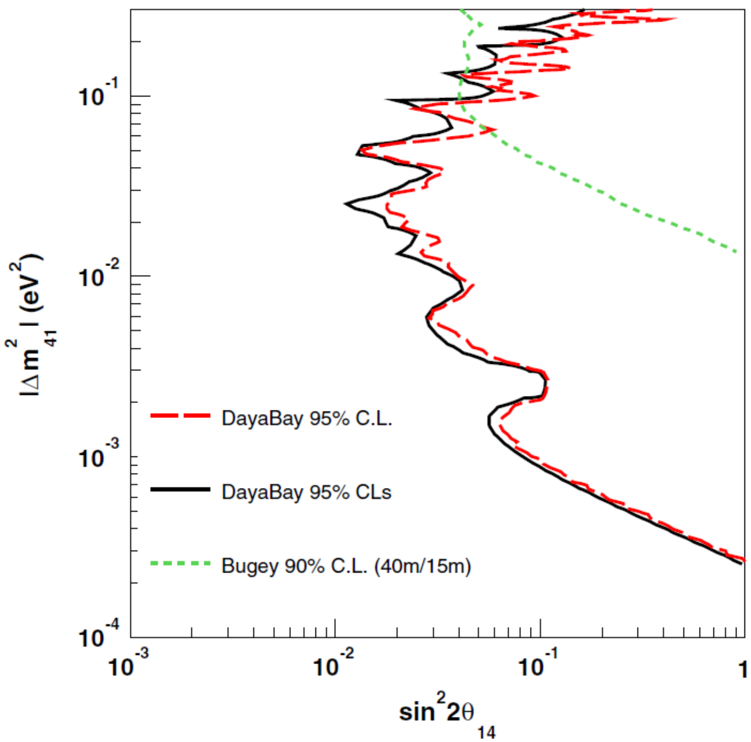
Submitted to PRL, 2015.

Search for a light sterile neutrino

- *Sterile neutrino: additional oscillation mode* θ_{14}
- *3 expt. halls* → *multiple baselines*
  - *Relative measurement at EH1* (~350m), *EH2* (~500m), *EH3* (~1600m)
  - *Unique sensitivity, most stringent limit on* $\sin^2 2\theta_{14}$ *at* 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2

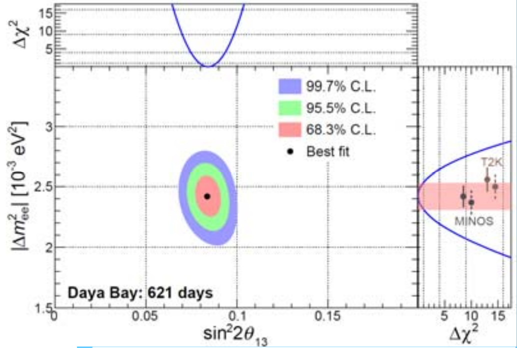
F. P. An et al., Daya Bay Collaboration, PRL ***113****, 141802 (2014)*

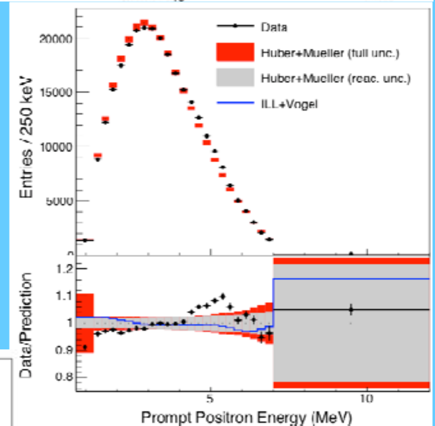


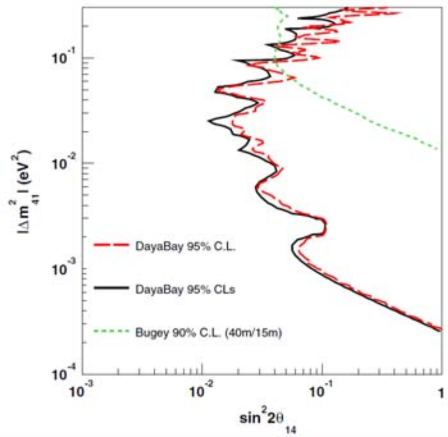


Summary

- *Daya Bay* ***full 8-AD configuration***
  - *Most precision measurement of* $\sin^2 2\theta_{13}$: **6%**
  - *Most precision measurement of* $|\Delta m^2_{ee}|$ *in the* $\bar{\nu}_e$ *disappearance channel:* **4%**
  - *Oscillation results confirmed with independent nH rate measurement*
- *reactor antineutrino flux and spectrum*
  - ***Flux*** *: consistent with previous short baseline experiments*
  - ***Spectrum:* 4σ *deviation*** *from prediction in* [4, 6] MeV e^+ energy
- *Set* ***new limit*** *to light sterile neutrinos*







More searches

- Precision measurement of spectral distortion:
  - neutrino decoherence
  - sterile neutrino mixing
  - CPT violation/NSI
  - mass-varying neutrinos
- Precision measurement of neutrino rate:
  - sidereal modulation (CPT violation, …)
  - supernova neutrinos
- High energy events:
  - neutron-anti-neutron oscillation

Recent results from Daya Bay

Ming-chung Chu

The Chinese University of Hong Kong, Hong Kong

On behalf of the Daya Bay collaboration

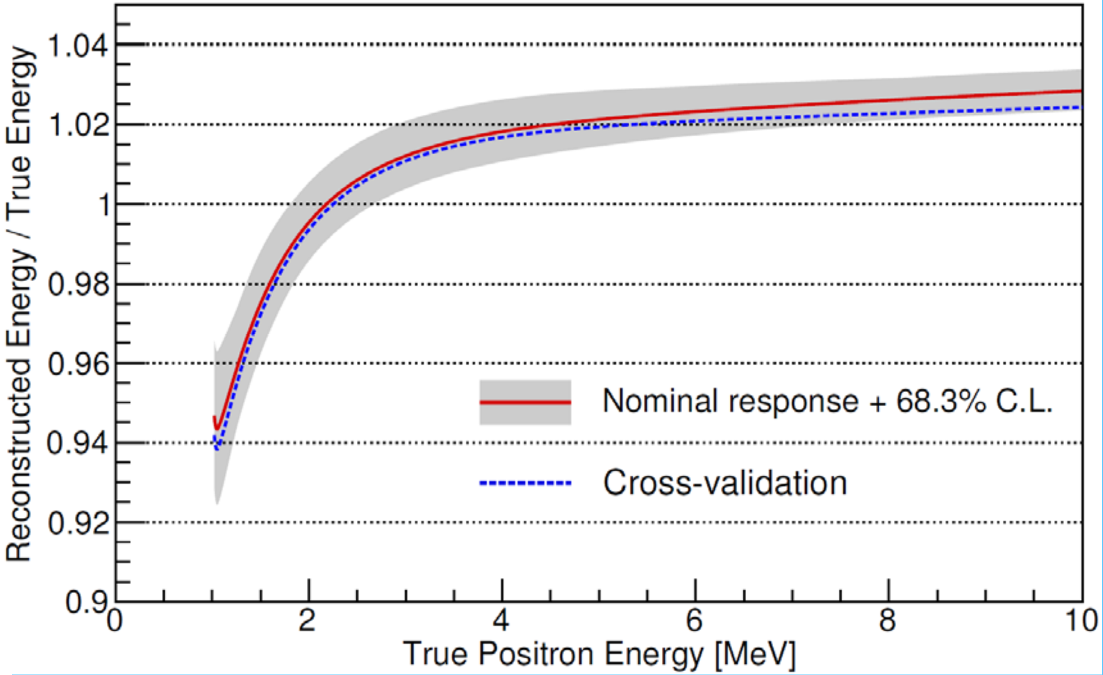
4th International Conference on New Frontiers in Physics (ICFNP2015)

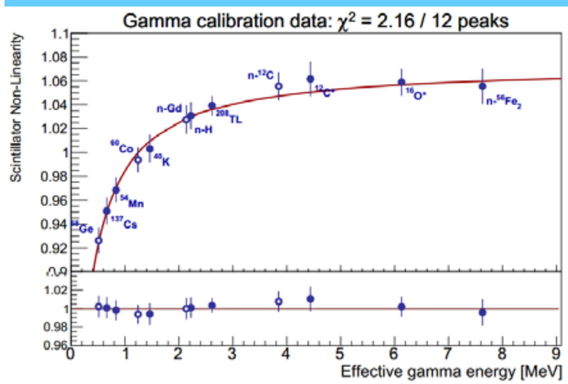
August 24 – 30, 2015, Kolymbari, Crete, Greece

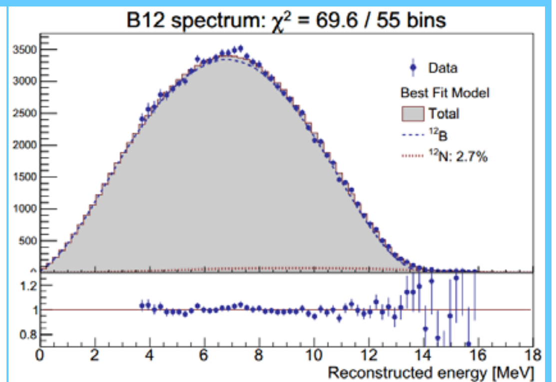
backup

Detector energy response model

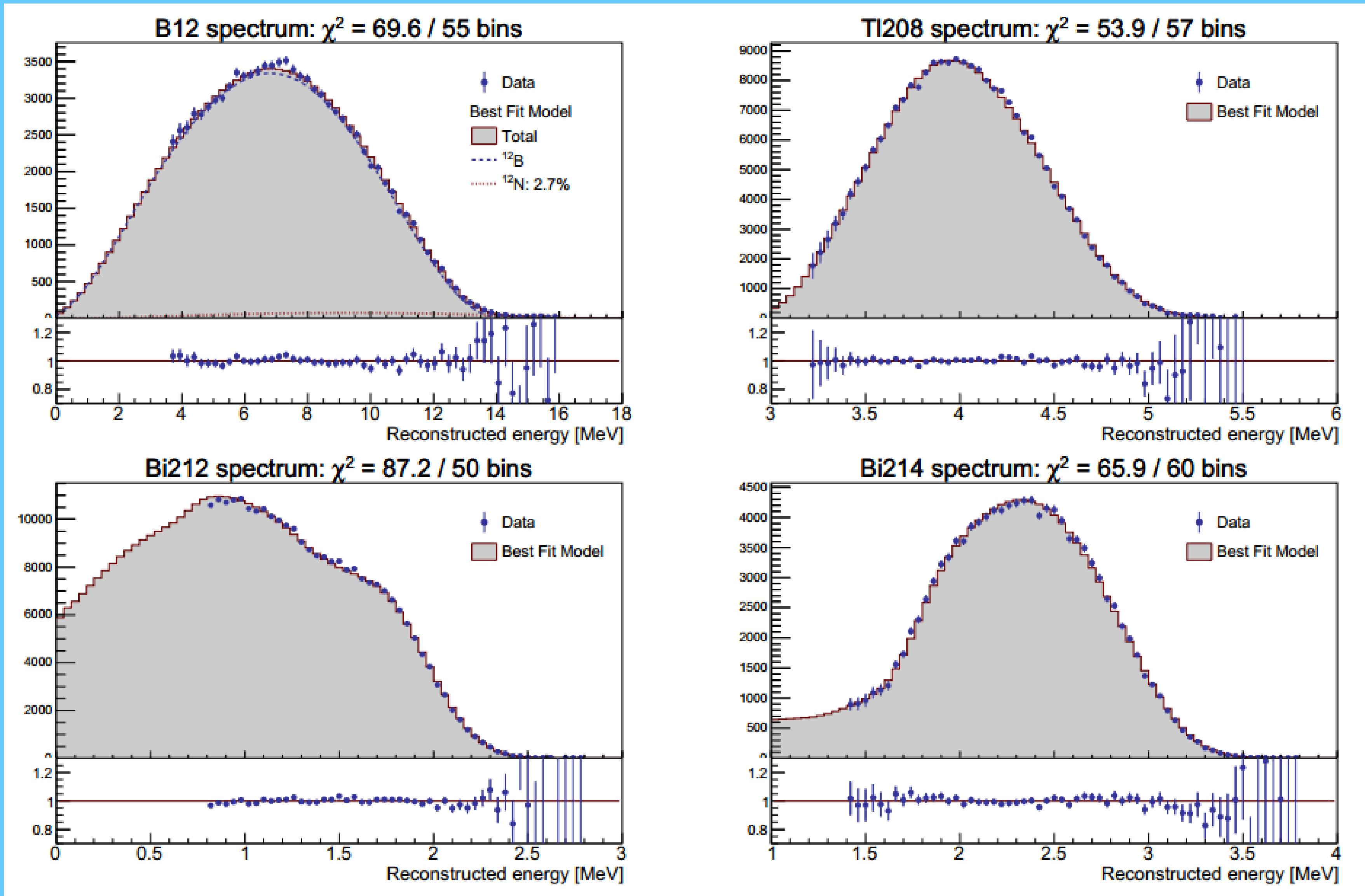
- *Particle-dependent scintillator nonlinearity: modeled with Birks' law and Cherenkov fraction*
- *Charge-dependent electronics nonlinearity: modeled with MC and single channel FADC measurement*
- *Nominal model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum*
- *Cross-validation model: fit to ^{208}Th, ^{212}Bi, ^{214}Bi beta-decay spectrum, Michel electron*
- *Uncertainty* $< 1\%$ *above* 2 MeV





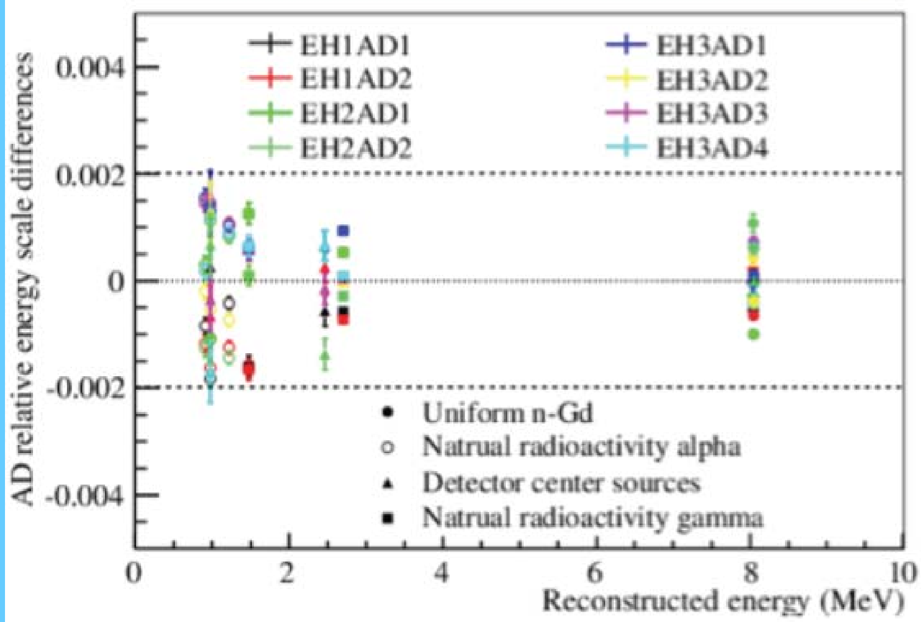


Detector energy response model

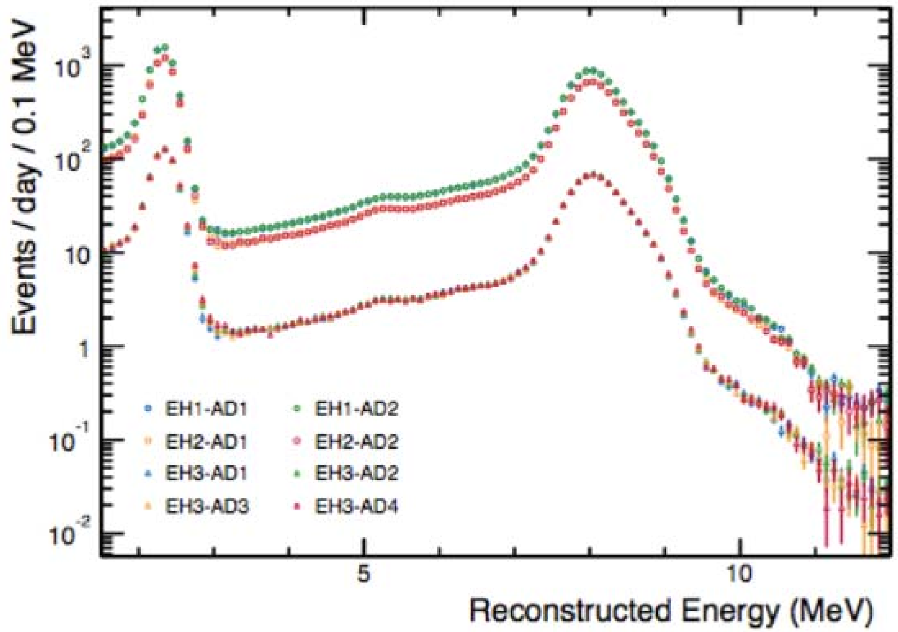


AD Calibration

ACU: ^{60}Co, ^{68}Ge, AmC
Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{215}Po



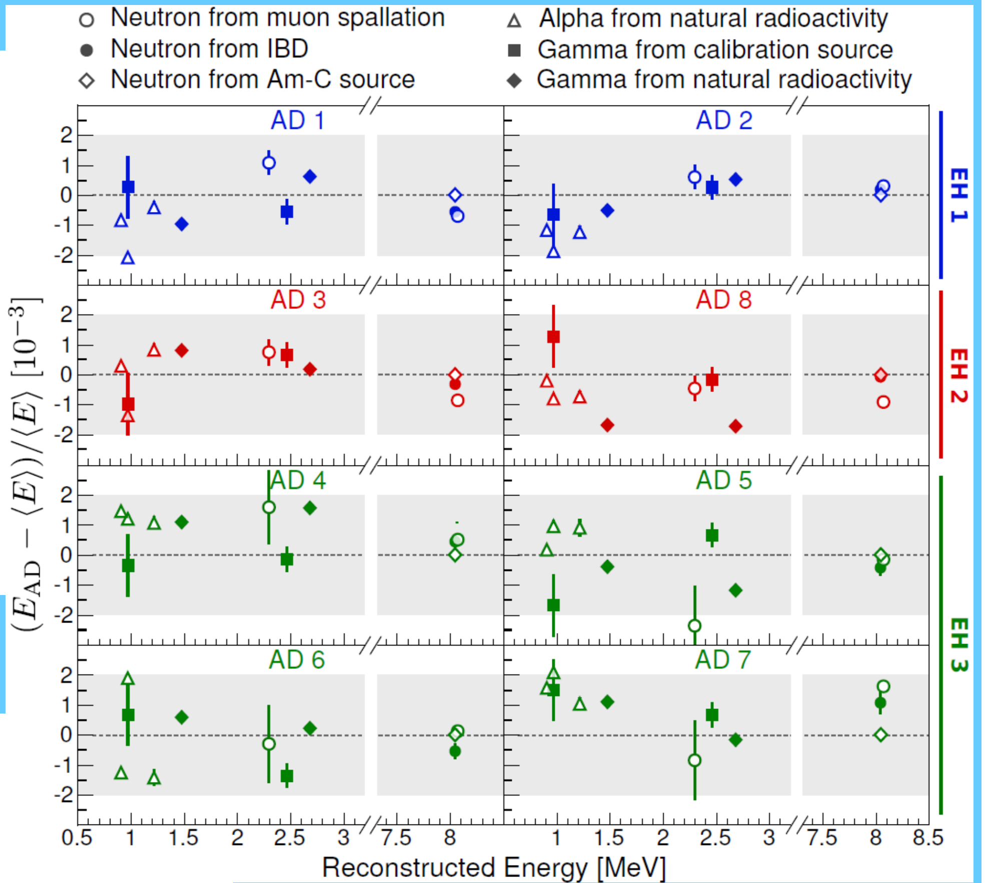
spallation neutron capture spectrum



Less than 0.2% variation in reconstructed energy between detectors.

Energy calibration

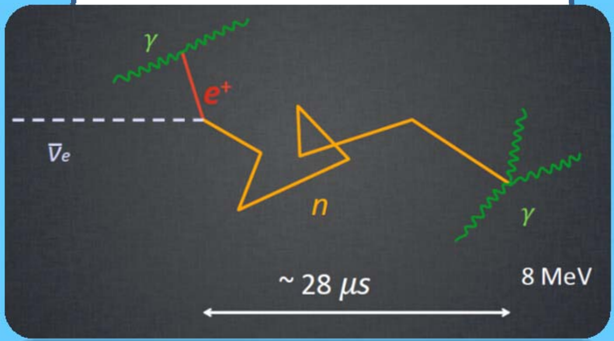
- PMT gain: Single electrons from photocathode
- Absolute energy scale: AmC at AD center
- Time variation: ^{60}Co at AD center
- Non-uniformity: ^{60}Co at different positions
- Alternative calibration: spallation neutrons

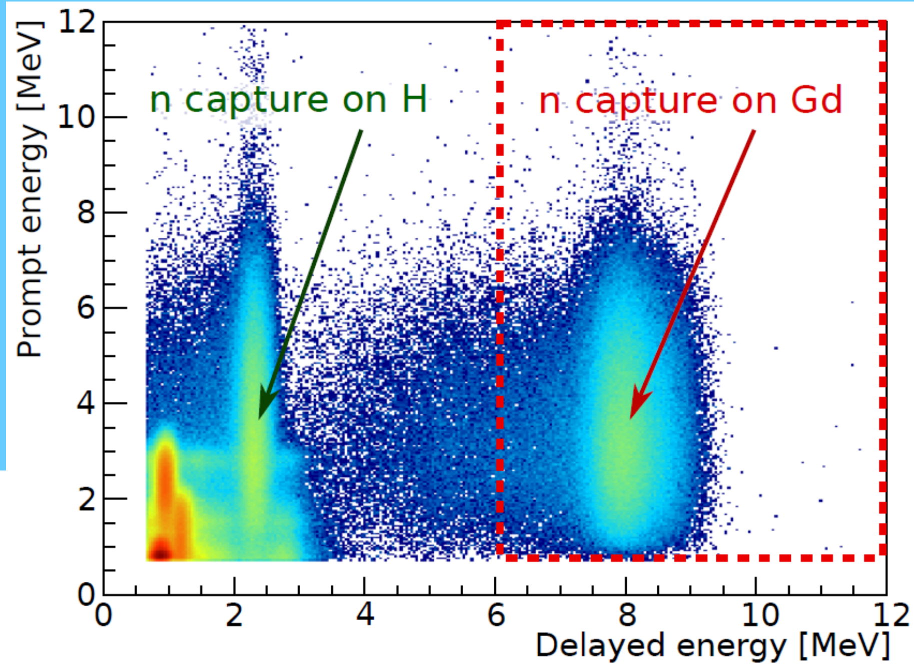


- Relative energy scale uncertainty: 0.2%
  - ^{68}Ge, ^{60}Co, AmC: detector center
  - nGd from IBD and muon spallation: Gd-LS region
  - α from polonium decay: Gd-LS vertex cut
  - ^{40}K, ^{208}Tl, nH: 1m vertex cut

Antineutrino candidates selection

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

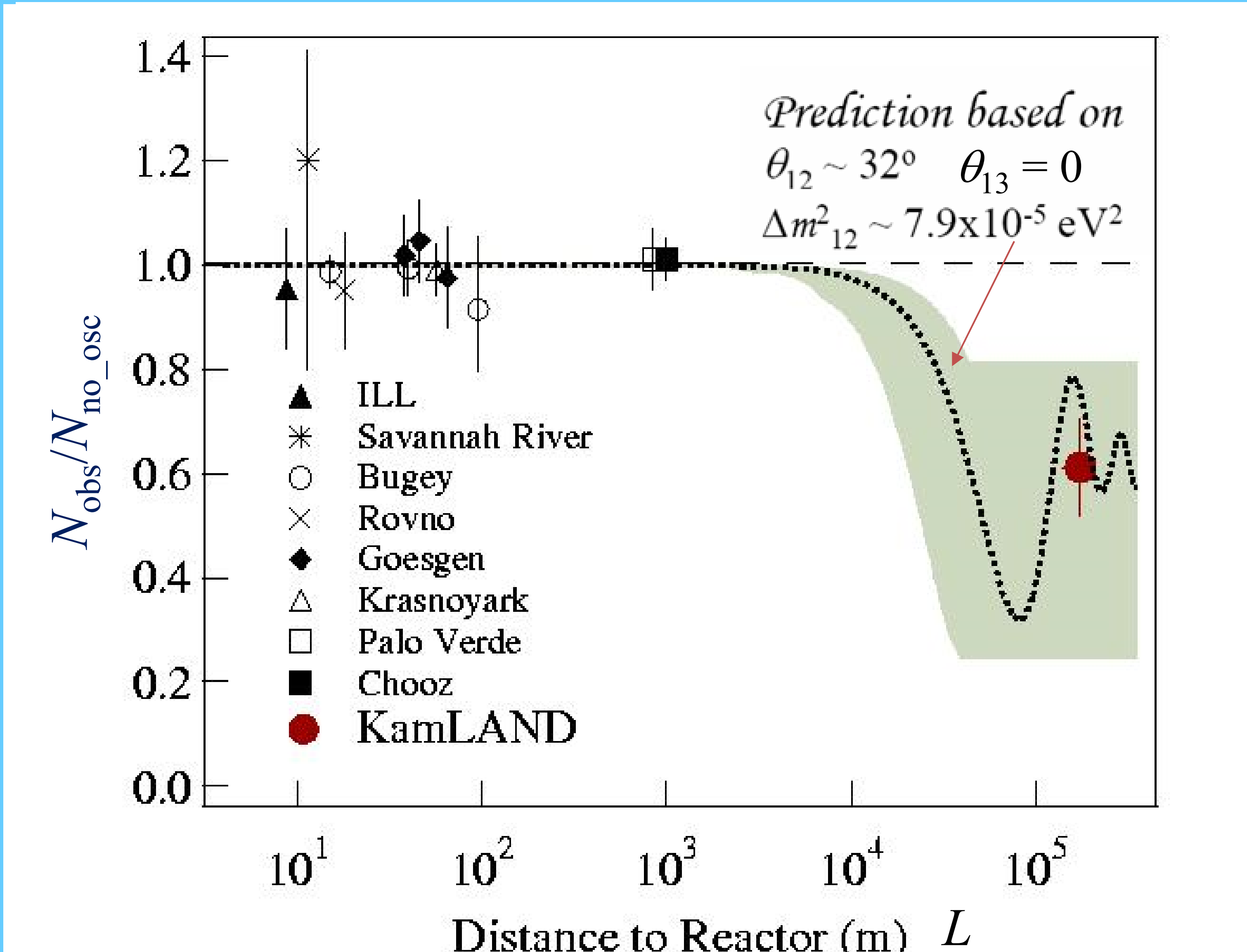




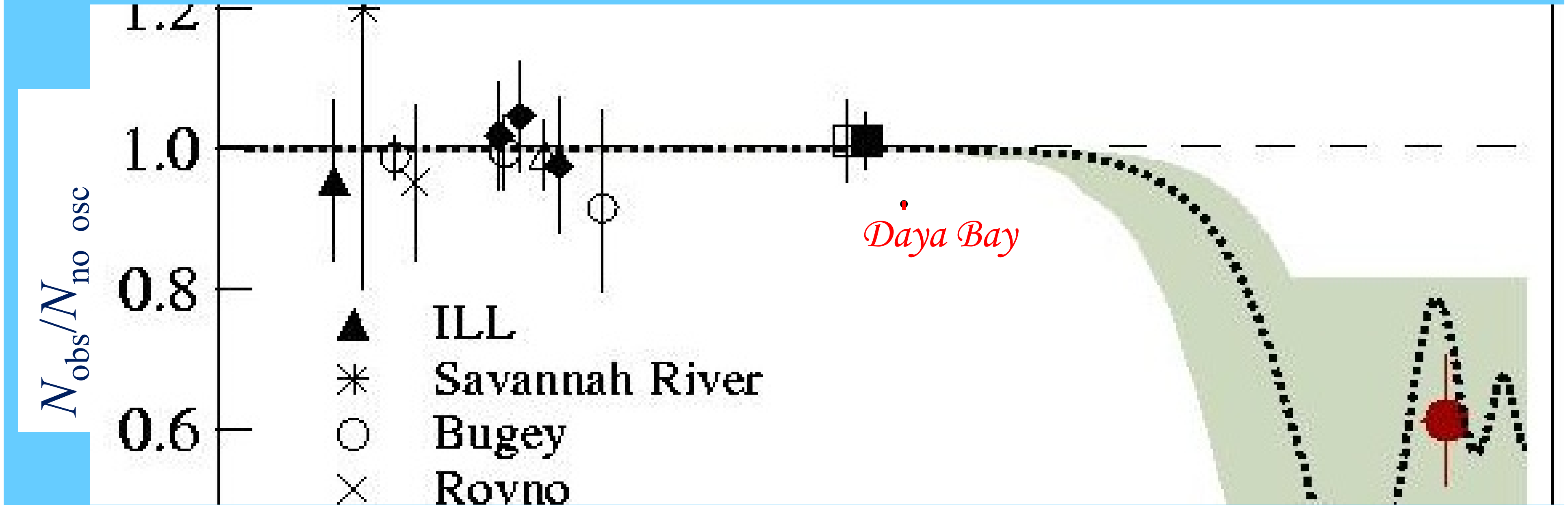
- *Reject PMT flashers*
- ***Coincidence** in energy and time with multiplicity = 2*
  - ***Energy:*** 0.7 MeV < E_p < 12.0 MeV, 6.0 MeV < E_d < 12.0 MeV
  - ***Time:*** 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
- *Muon **anticoincidence***
  - *Water pool muon: reject* 0.6 ms
  - *AD muon* (>20 MeV): *reject* 1 ms
  - *AD shower muon* (>2.5 GeV): *reject* 1 s

	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 fraction	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%

Precisely measuring θ_{13}



Precisely measuring θ_{13}



An order of magnitude improvement in precision!

A new era of precision neutrino experiments!

Near/far Configuration

Minimize systematic uncertainties:

reactor-related: cancelled by near-far ratio

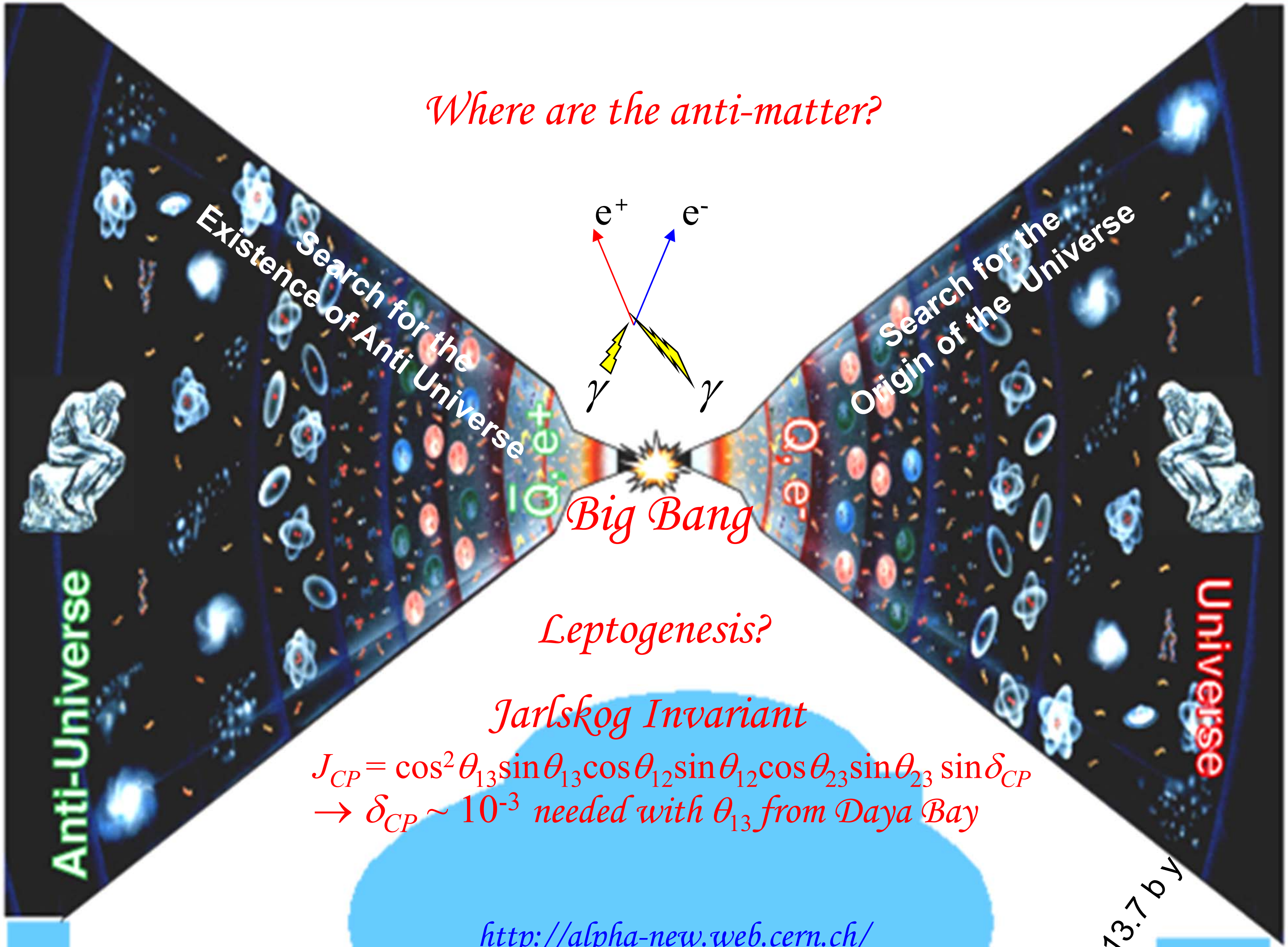
detector-related: use 'identical' detectors, careful calibration

$$\frac{R_{\text{Far}}}{R_{\text{Near}}} = \left(\frac{L_{\text{Near}}}{L_{\text{Far}}}\right)^2 \frac{N_{\text{Far}}}{N_{\text{Near}}} \frac{\varepsilon_{\text{Far}}}{\varepsilon_{\text{Near}}} \left(\frac{P_{\text{surv}}(L_{\text{Far}})}{P_{\text{surv}}(L_{\text{Near}})}\right)$$

$\bar{\nu}_e$ *detection ratio* — $1/r^2$ — *number of protons* — *detector efficiency* — *Survival prob.* → $\sin^2(2\theta_{13})$

Parameter	*CHOOZ error*	*Near/far configuration*
Reaction cross section	1.9 %	*Cancelled out*
Number of protons	0.8 %	*Reduced to* ~ 0.03%
Detection efficiency	1.5 %	*Reduced to* ~ 0.2%
Reactor power	0.7 %	*Reduced to* ~ 0.04%
Energy released per fission	0.6 %	*Cancelled out*
CHOOZ Combined	2.7 %	~ 0.21%

Leptogenesis?



Where are the anti-matter?

Big Bang

Leptogenesis?

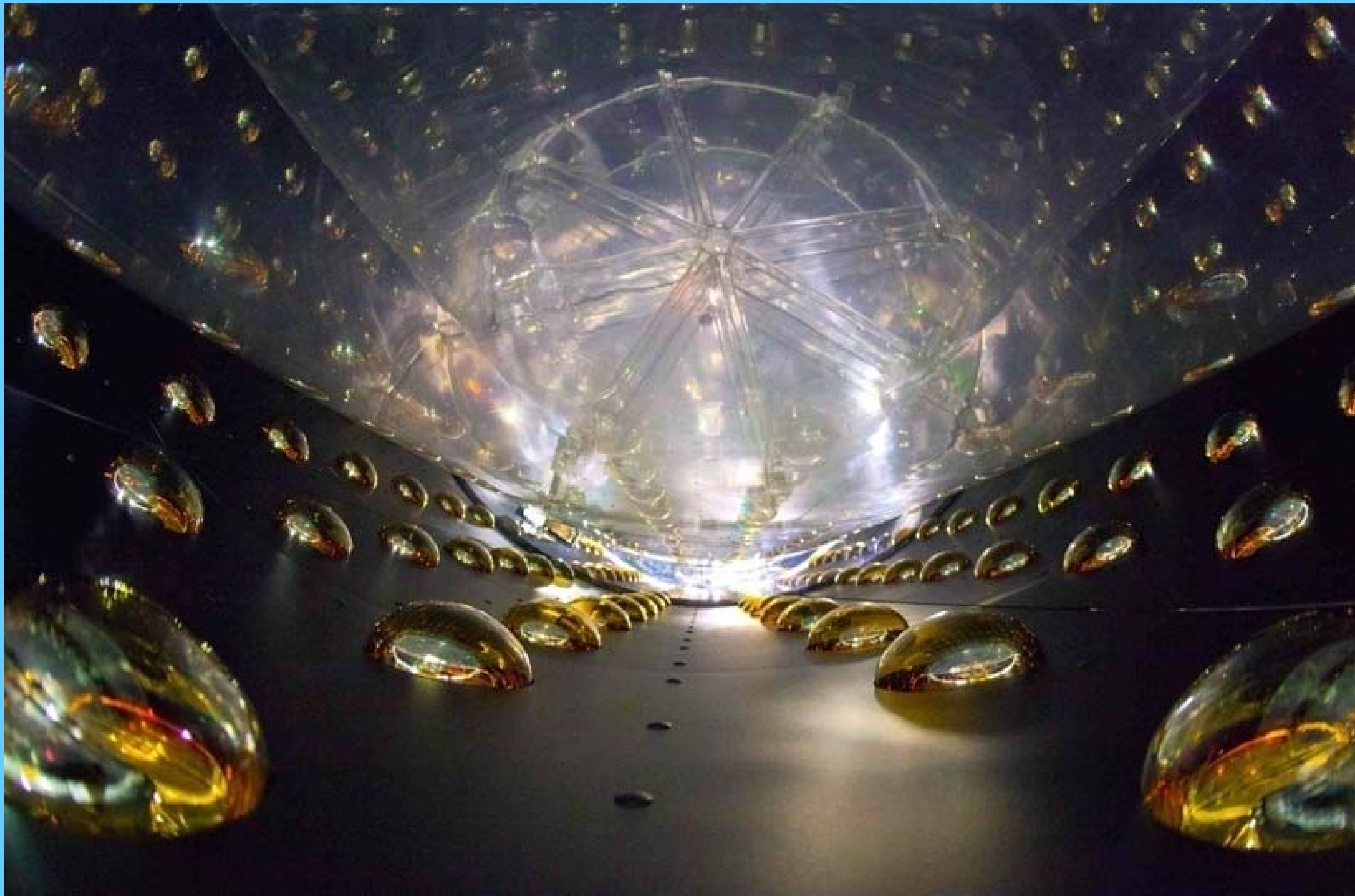
Jarlskog Invariant

$J_{CP} = \cos^2\theta_{13}\sin\theta_{13}\cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$

$\rightarrow \delta_{CP} \sim 10^{-3}$ *needed with* θ_{13} *from Daya Bay*

http://alpha-new.web.cern.ch/

Interior of an AD



Background

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Extend to larger data set
$^{9}Li/^{8}He$	0.4%	0.4%	~50%	Measured with after-muon events	Extend to larger data set
Fast neutron	0.1%	0.1%	~30%	Measured from RPC+OWS tagged muon events	Model independent measurement
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source	Two sources are taken out in Far site ADs
α-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Reassess systematics