Lastest Results from Daya Bay

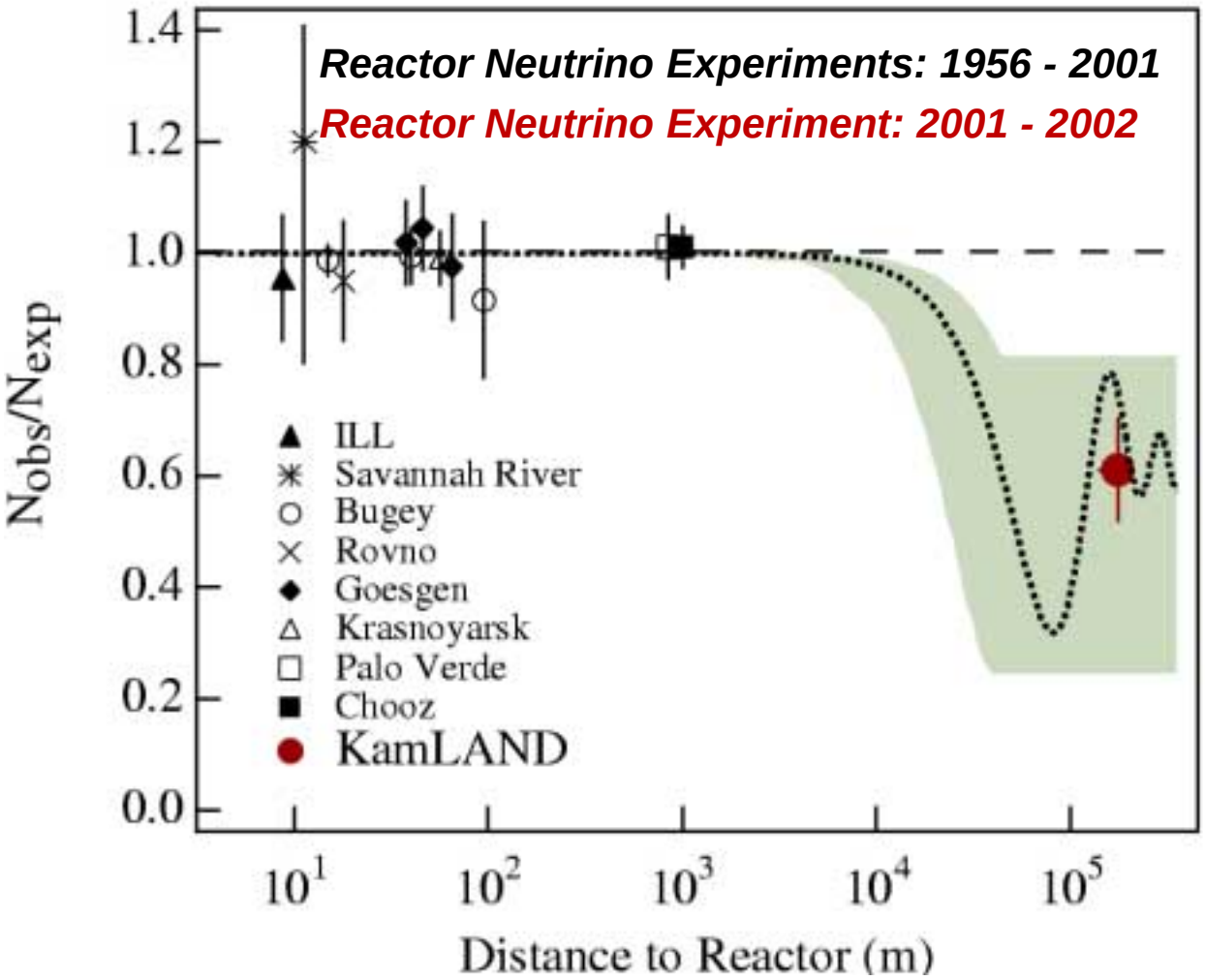
Wei Wang / 王為 (on behalf of Daya Bay), SYSU

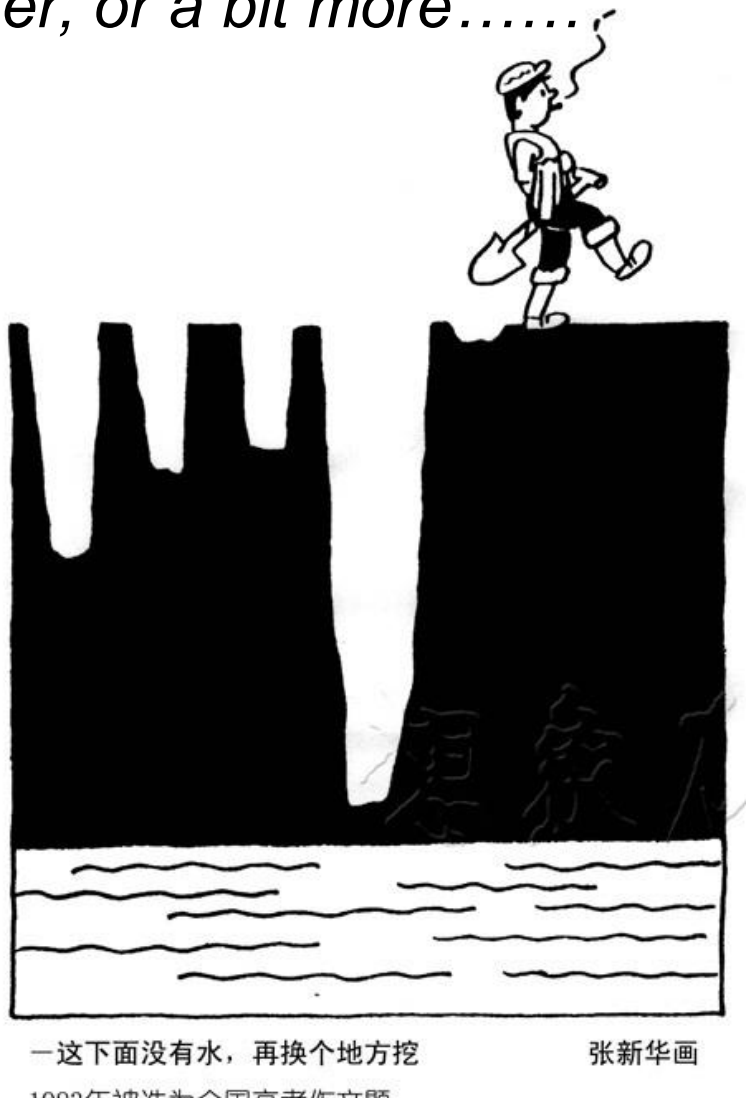
DISCRETE, Vienna, Nov 29, 2018

- ***The Daya Bay Experiment and Recent Improvements***
- ***Latest Oscillation Results***
- ***Reactor Antineutrino Flux Measurements***
- ***New Physics Searches***
- ***Summary***

Years between KamLAND and DYB+RENO+DC

Sometimes, we just need to push it a bit further, or a bit more……





We almost found it!

Reactor ν_e Disappearance Depends on θ_{13} (~km)

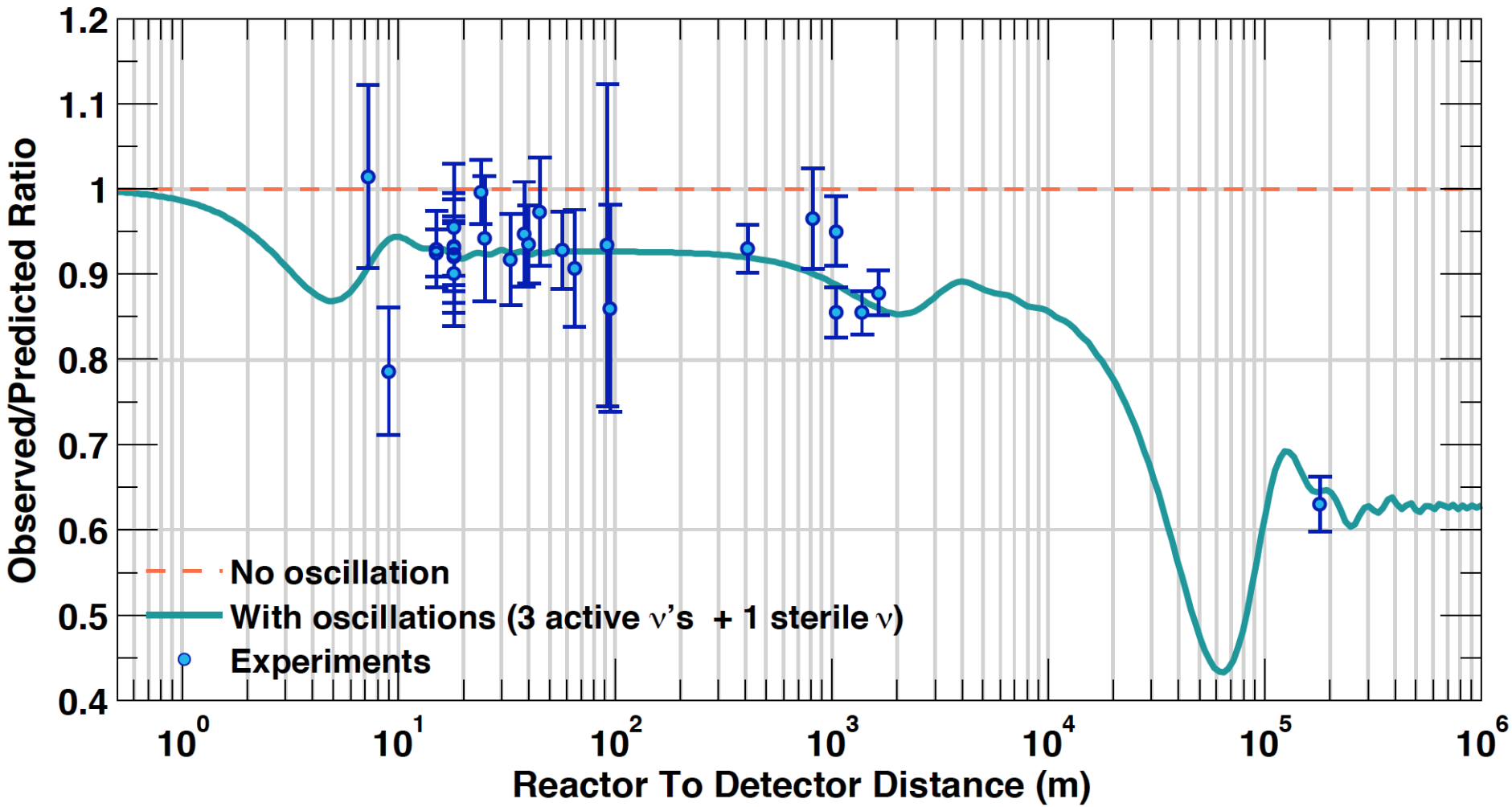
Photo by Kam-Biu Luk

Real meaning

Work Harder!

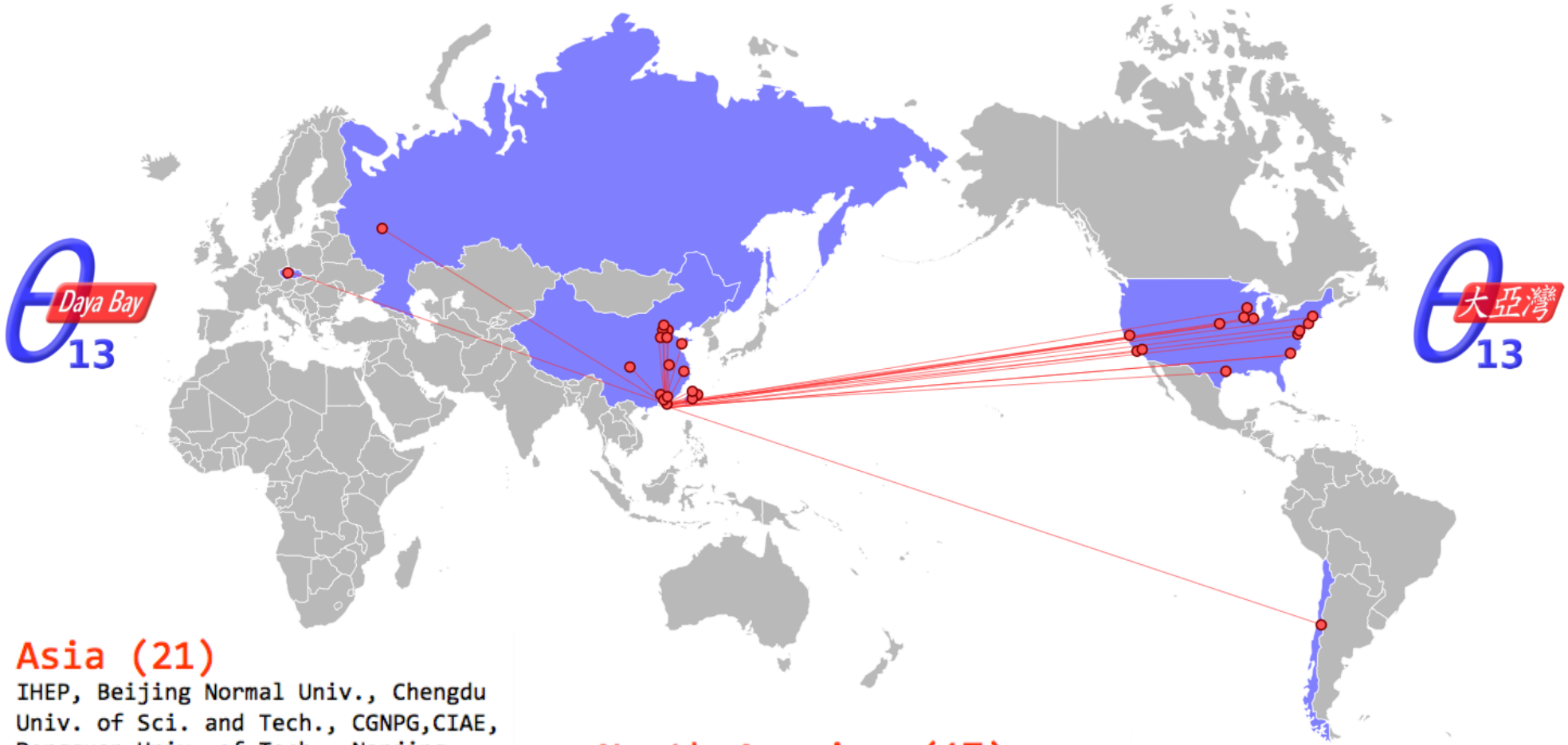
Reactor Neutrinos ***NOW***

This is what happens after working harder for 15 years ……



http://irfu.cea.fr/Spp/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=3045

The Daya Bay International Collaboration



Asia (21)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG,CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)

BNL, LBNL, Iowa State Univ., RPI, Illinois Inst. Tech., Princeton, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena, Temple Univ, Yale

Europe (2)

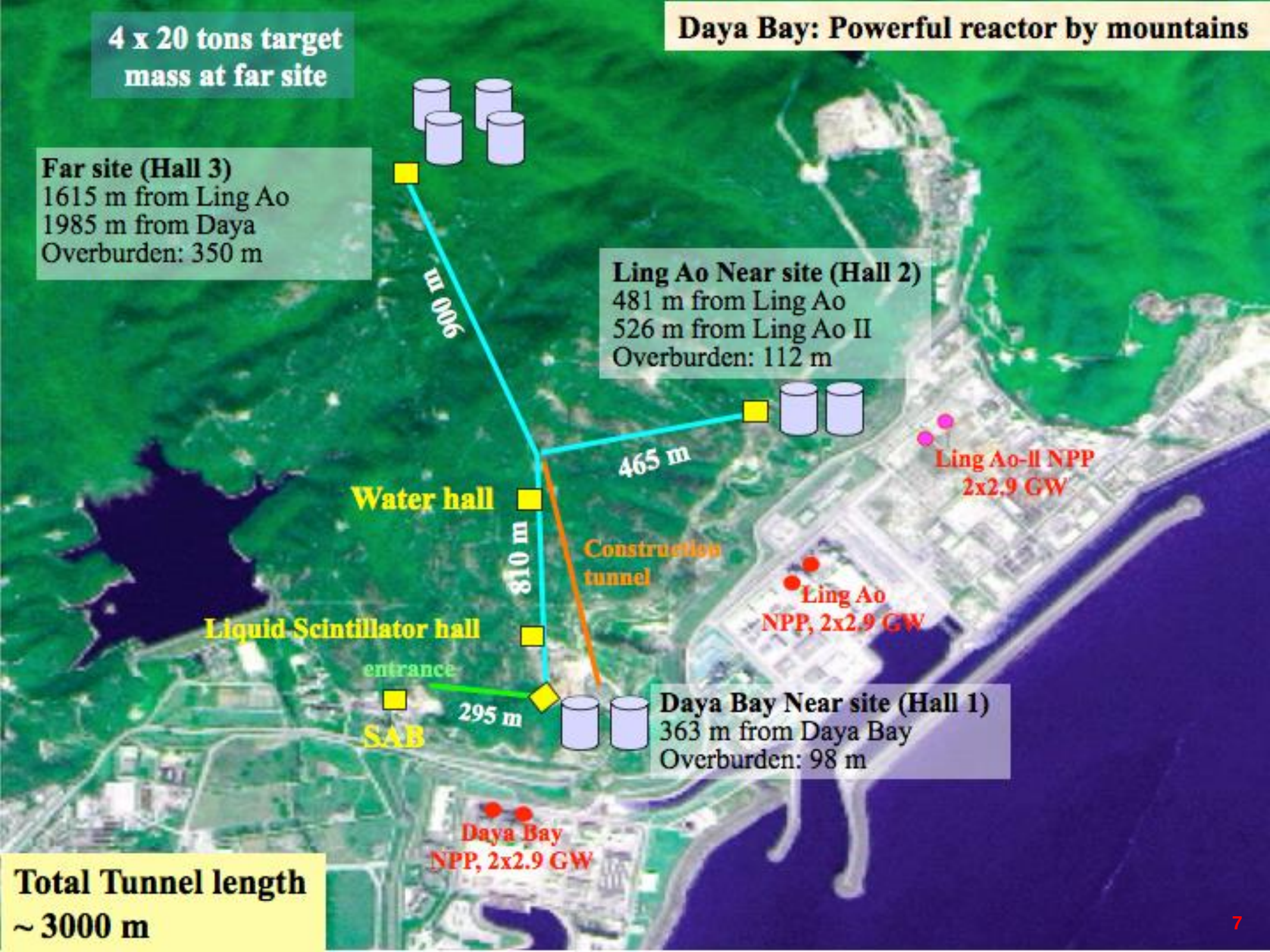
JINR, Dubna, Russia; Charles University, Czech Republic

South America (1)

Catholic Univ. of Chile

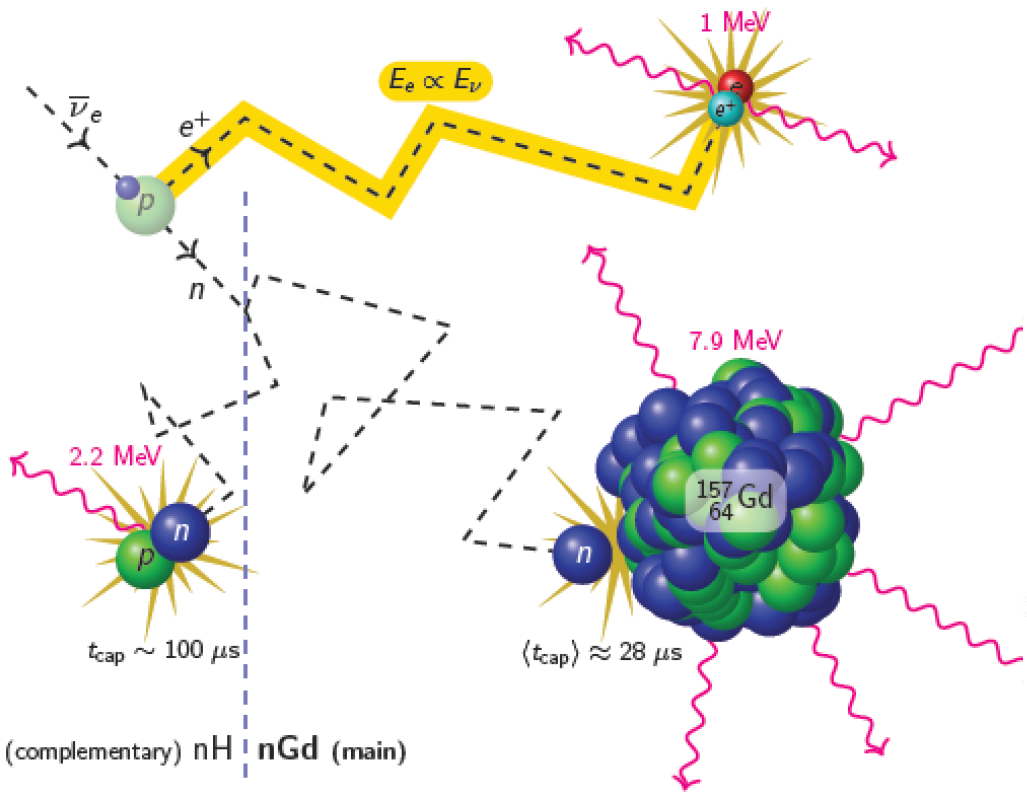
Daya Bay: A Powerful Neutrino Source at an Ideal Location

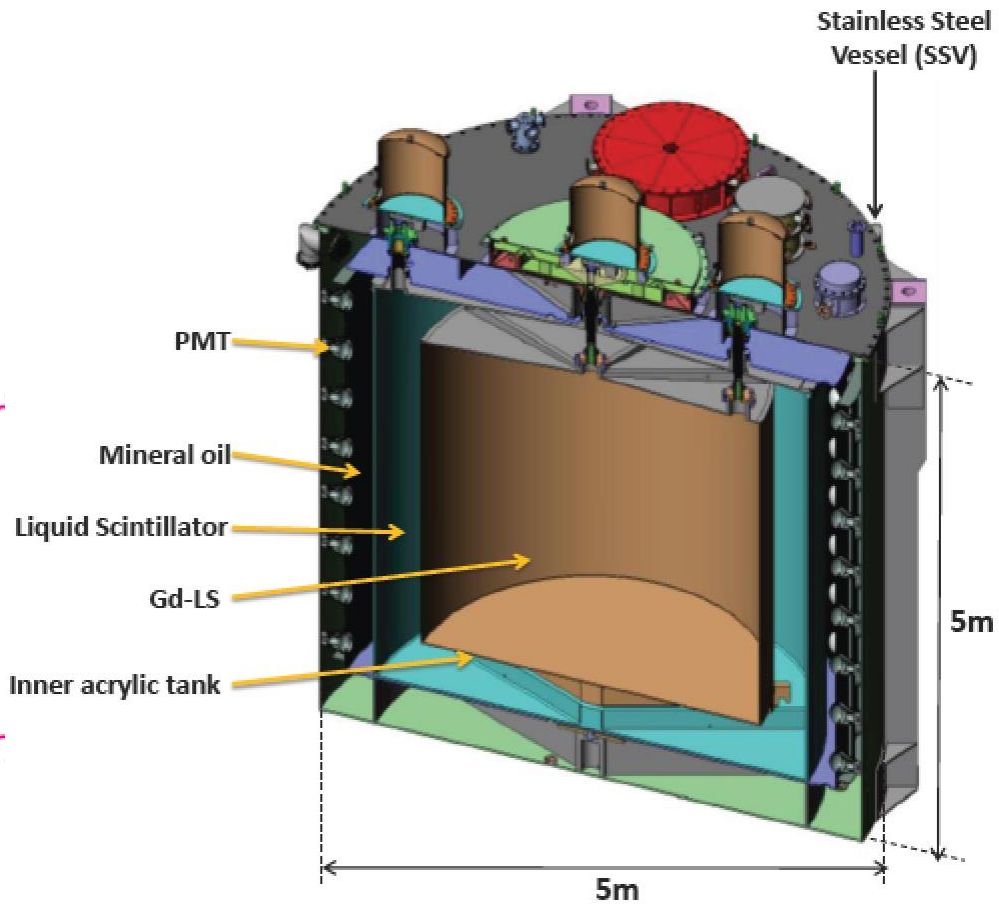
Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW_{th} power, 35×10^{20} neutrinos per second


Daya Bay: Powerful reactor by mountains
4 x 20 tons target mass at far site
Far site (Hall 3)
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
900 m
Ling Ao Near site (Hall 2)
481 m from Ling Ao
526 m from Ling Ao II
Overburden: 112 m
465 m
Ling Ao-II NPP
2x2.9 GW
Water hall
810 m
Construction tunnel
Ling Ao
NPP, 2x2.9 GW
Liquid Scintillator hall
entrance
295 m
SAB
Daya Bay Near site (Hall 1)
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP, 2x2.9 GW
Total Tunnel length
~ 3000 m

Daya Bay Detectors

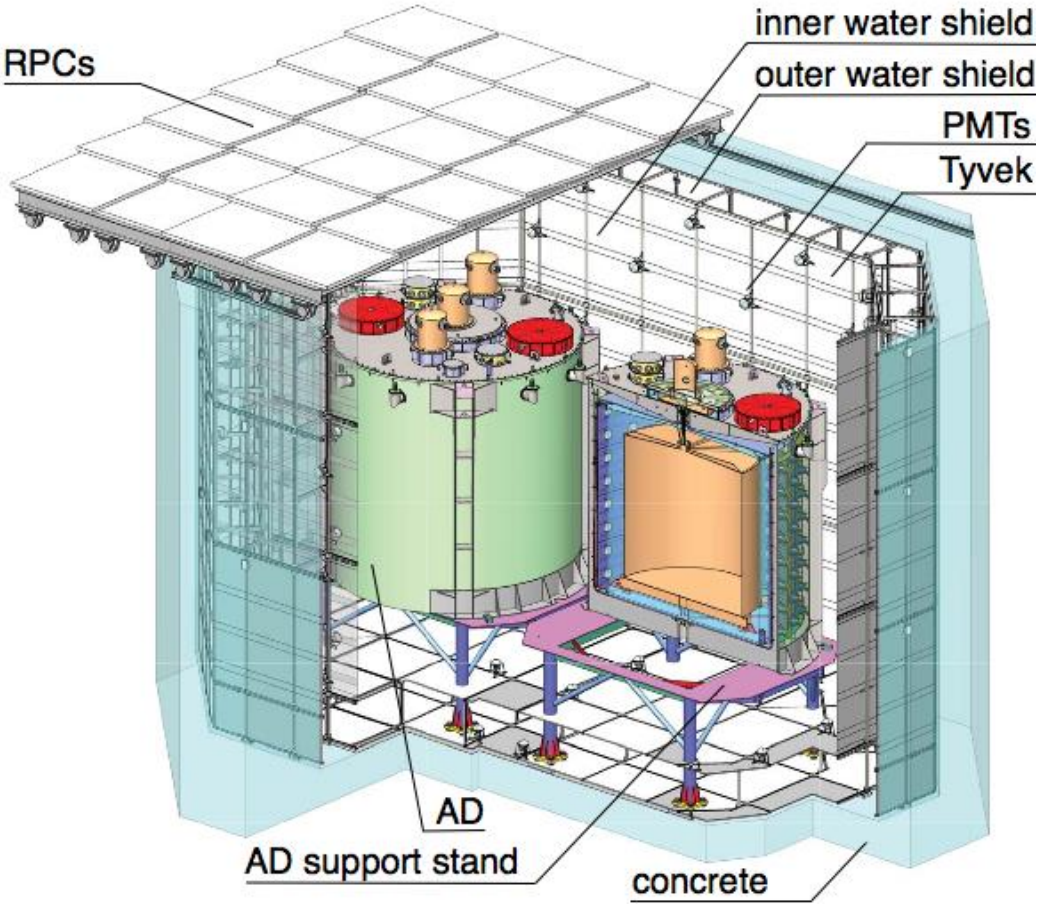
- The antineutrino detectors (ADs) are of a “3-zone” design
- Doped (Gd) LS as the target for inversed beta decays (IBDs)

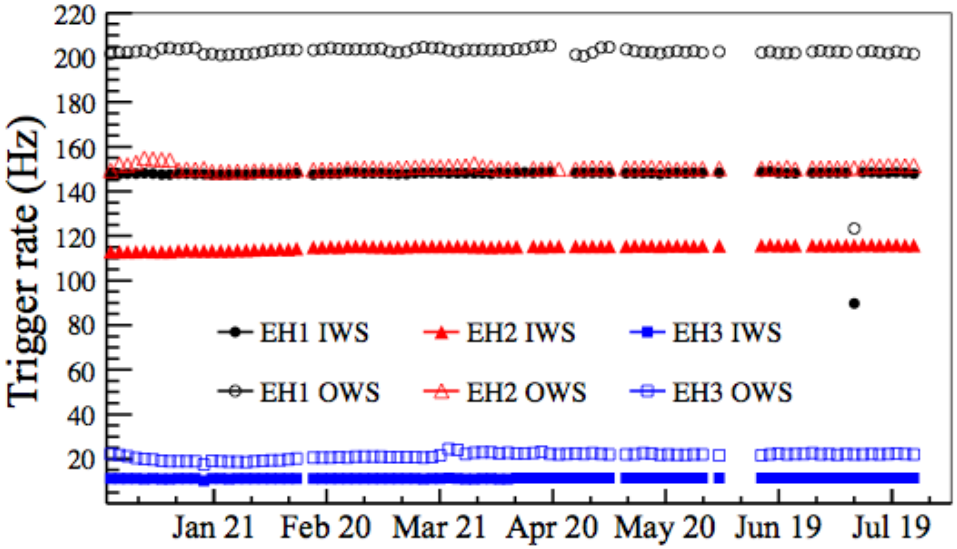


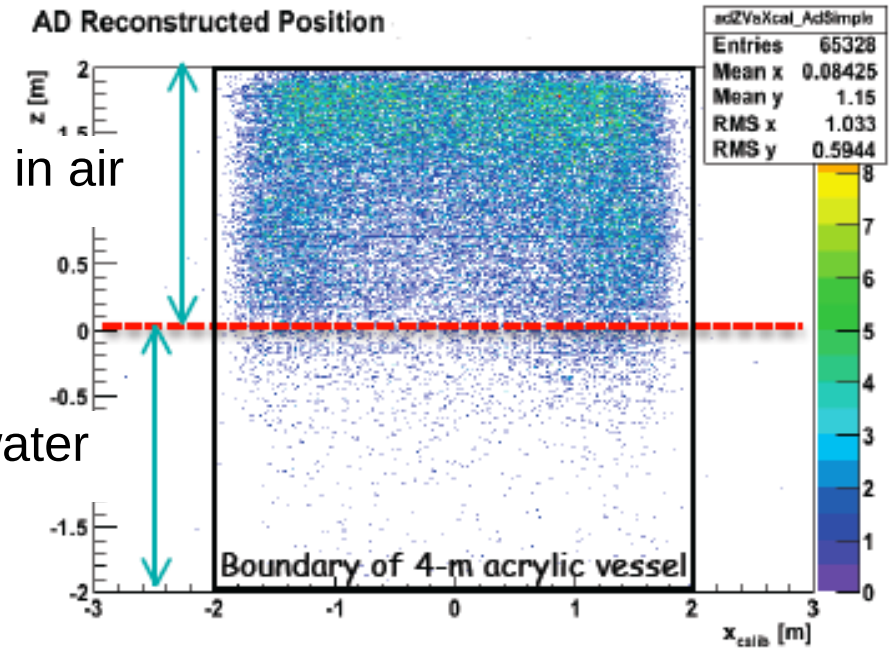


Energy Resolution: $\sigma_E/E \cong 8.5\%/\sqrt{E[MeV]}$

Daya Bay Detector System







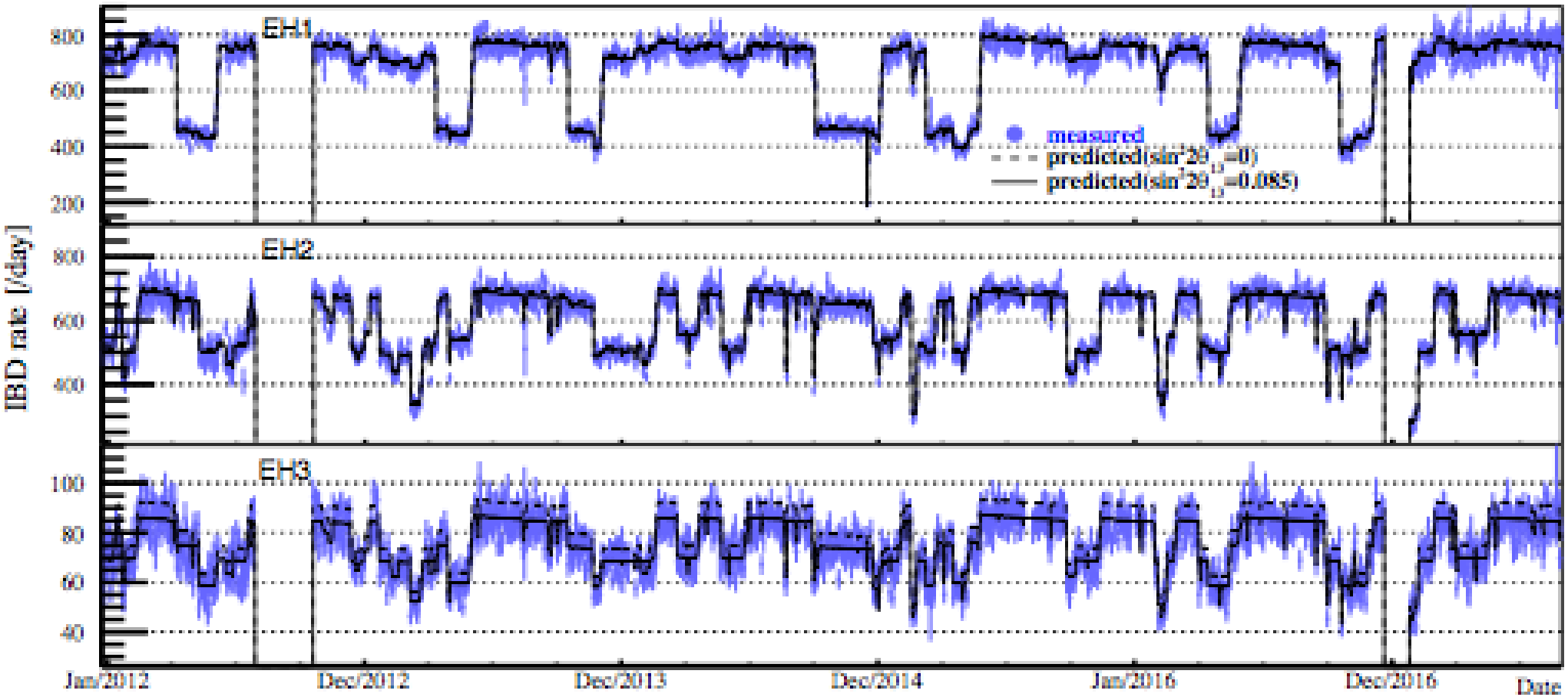
- ~100m-350m overburdens for 3 sites
- RPC + Water Cherenkov = inner (IWS) & outer (OWS) Water Cherenkov
  → 2.5 m thick water in each direction

From Assembly to Installation

A Small Big Science Project: Far Site

Daily IBD Event Rates per Detector per Day

- Since Christmas Eve of 2011, 1958 days of data made official



- 1230 days of data have been used for reactor antineutrino flux

The Latest Daya Bay Reactor Neutrino Data Set

- Summary of the 1958 days data sample:

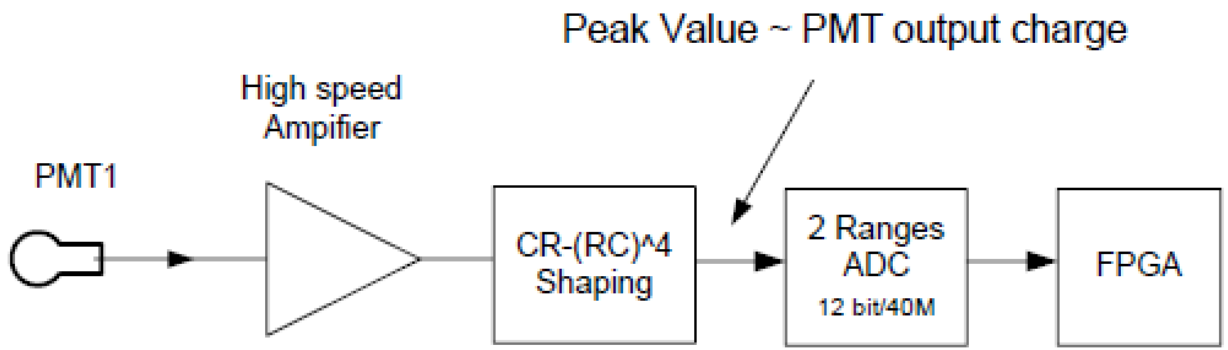
	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
ε_μ	0.8261	0.8221	0.8576	0.8568	0.9831	0.9831	0.9829	0.9833
ε_m	0.9744	0.9748	0.9758	0.9757	0.9761	0.9760	0.9758	0.9758
Accidentals (day^{-1})	8.27 ± 0.08	8.12 ± 0.08	6.00 ± 0.06	5.86 ± 0.06	1.06 ± 0.01	1.00 ± 0.01	1.03 ± 0.01	0.86 ± 0.01
Fast neutron (AD^{-1} day^{-1})	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
$^9Li/^8He$ (AD^{-1} day^{-1})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated 6-AD (day^{-1})	0.29 ± 0.13	0.27 ± 0.12	0.30 ± 0.14		0.24 ± 0.11	0.23 ± 0.10	0.23 ± 0.10	
Am-C correlated 8-AD (day^{-1})	0.15 ± 0.07	0.14 ± 0.06	0.12 ± 0.05	0.13 ± 0.06	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.02
$^{13}C(\alpha, n)^{16}O$ (day^{-1})	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
$\bar{\nu}_e$ rate (day^{-1})	659.36 ± 1.00	681.09 ± 0.98	601.83 ± 0.82	595.82 ± 0.85	74.75 ± 0.23	75.19 ± 0.23	74.56 ± 0.23	75.33 ± 0.24

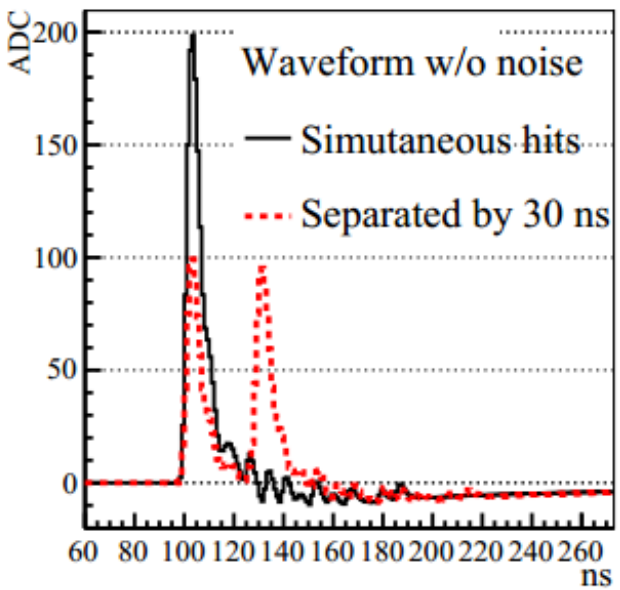
TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The measured ratio of IBD rates in AD1 and AD2 in the 6+8 AD period(AD3 and AD8 in the 8+7 AD period) is 0.981±0.002 (1.014±0.002) while the expected ratio is 0.982 (1.013).

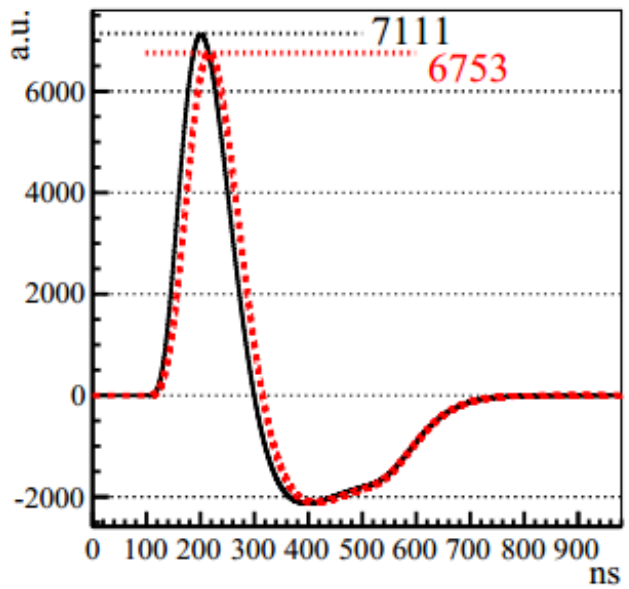
- Largest Reactor Neutrino Data Ever:
  - More than **3.9 million IBDs (0.5 million at far site)**
  - Statistical error in $\bar{\nu}_e$ rates: ~0.11% (near ADs), ~0.29% (far ADs)
  - Background uncertainty in $\bar{\nu}_e$ rates: ~0.12% (all ADs)

Nonlinearity in Energy Scale

- Scintillator's energy scale suffers from nonlinearity --- ***Common***
- Additional electronics nonlinearity for Daya Bay







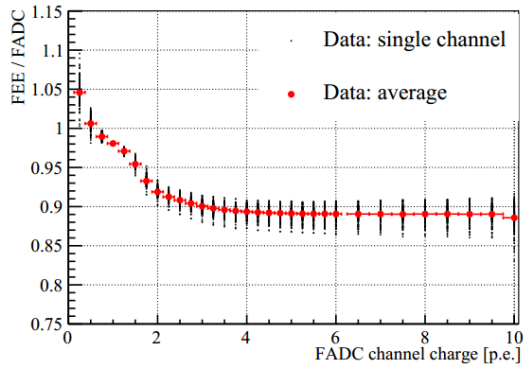
- Nonlinearity is primarily due to imperfect charge integration
- Loss of late hits (150 ns timing component in LS) also contributes

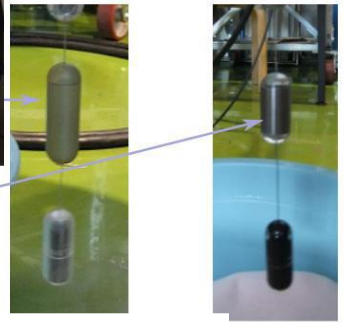
➢ More calibration

A Landmark Achievement for LS Detectors

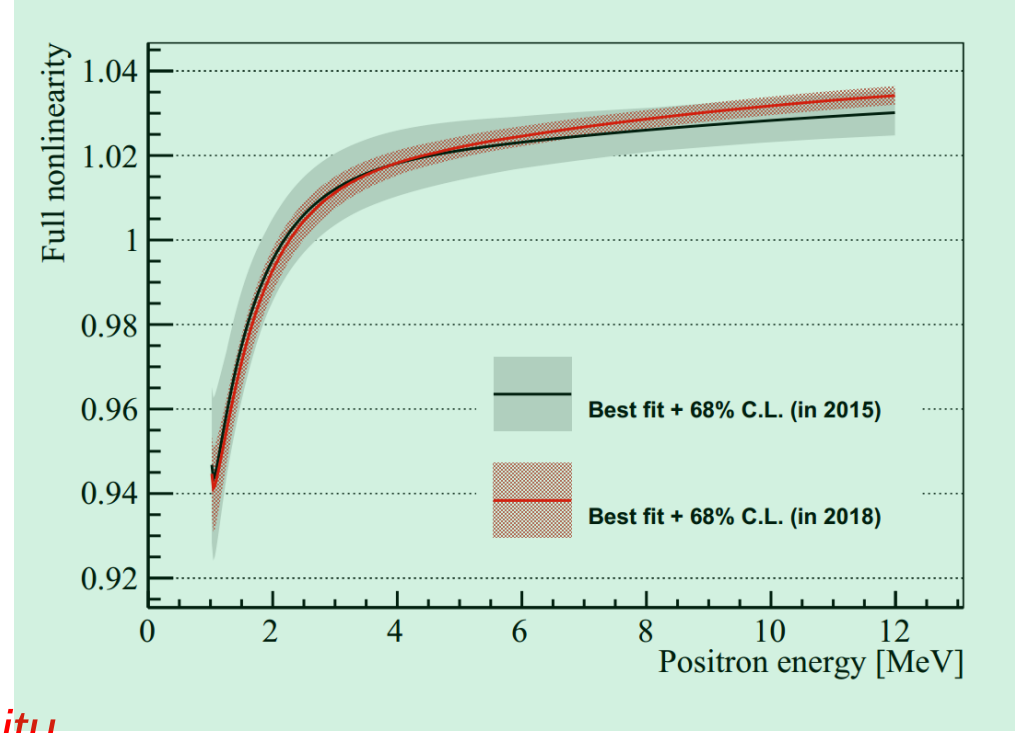
- ***0.5% uncertainty achieved!***

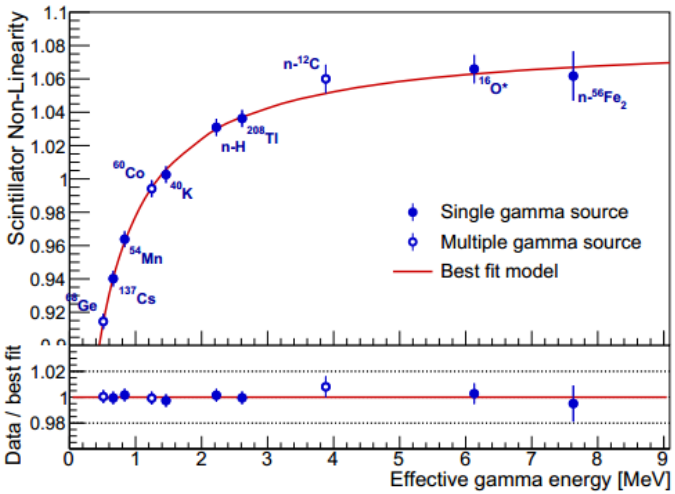
Two 10-bit FADC systems are installed side-by-side for AD1&2 *(Jan 2016)*

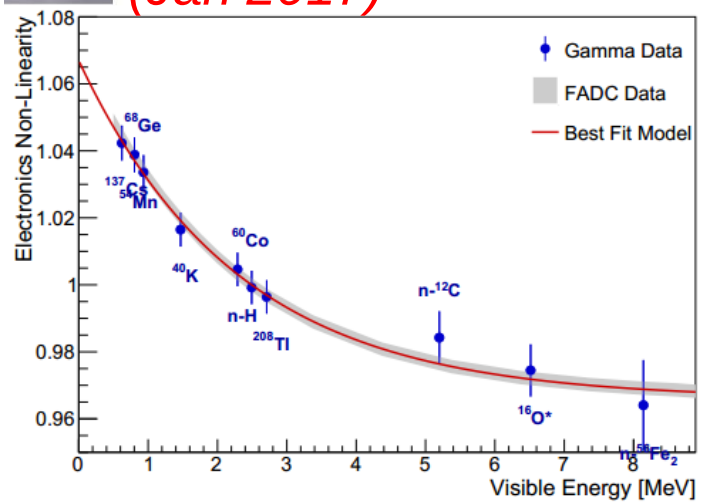


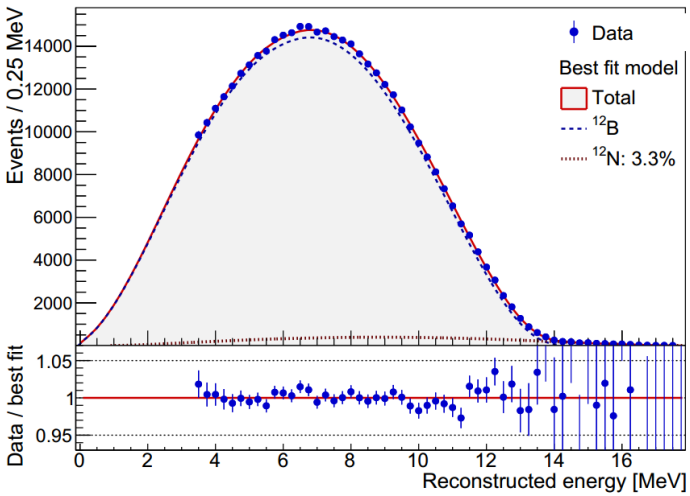


Calibration source effects studied *in-situ* *(Jan 2017)*



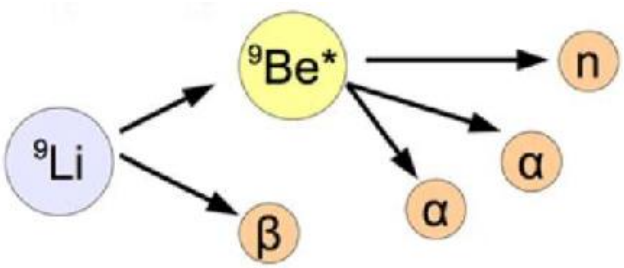




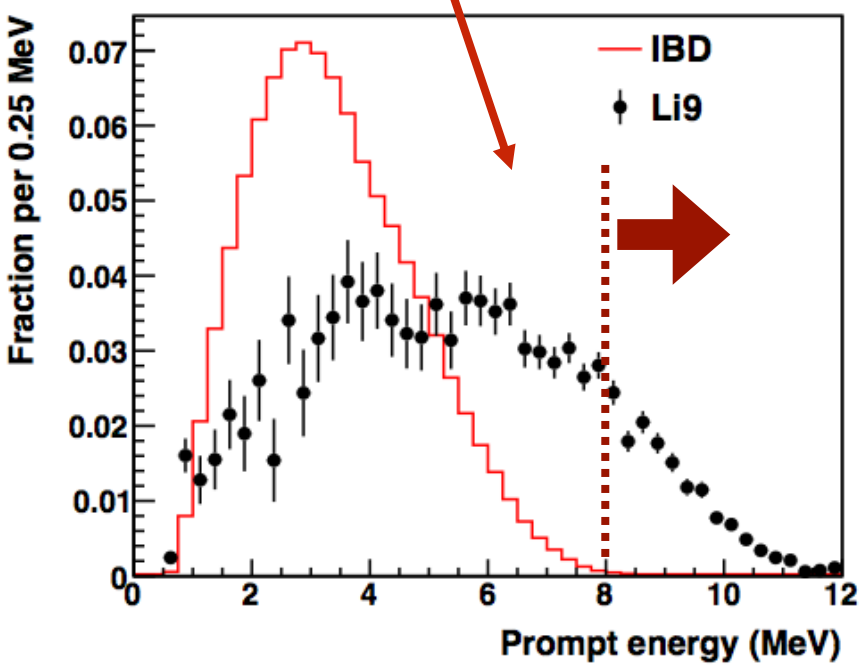


Improved ^{9}Li/^{8}He and Spent Fuel Backgrounds

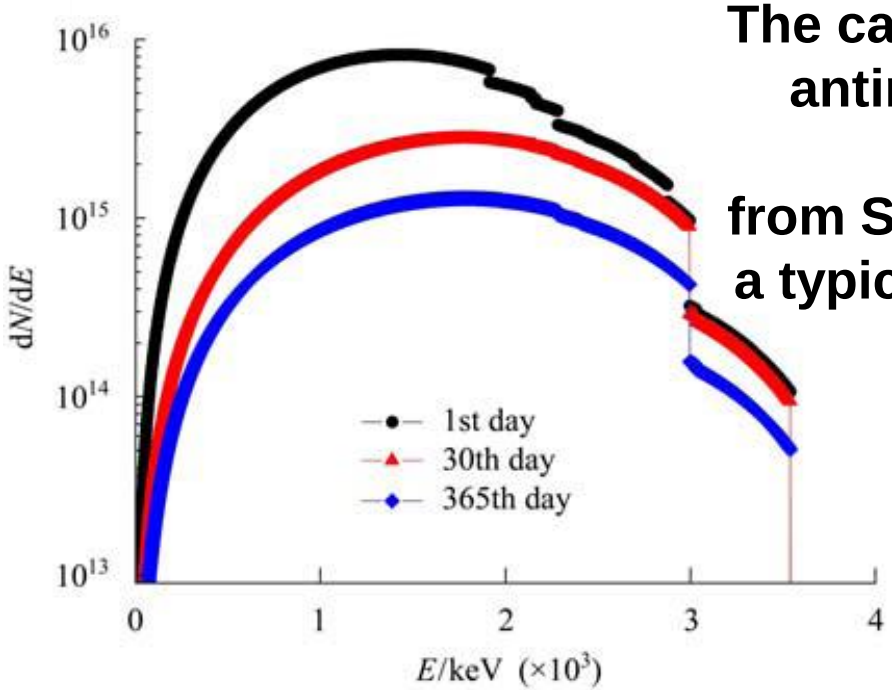
- Cosmogenic ^{9}Li/^{8}He β-n decays are indistinguishable from IBD events
- Taking advantage of very large statistics:



Apply a large E_{prompt} cut to enhance the ^{9}Li/^{8}He fraction:



^{9}Li/^{8}He uncertainty in near ADs reduced from 50% to 30%

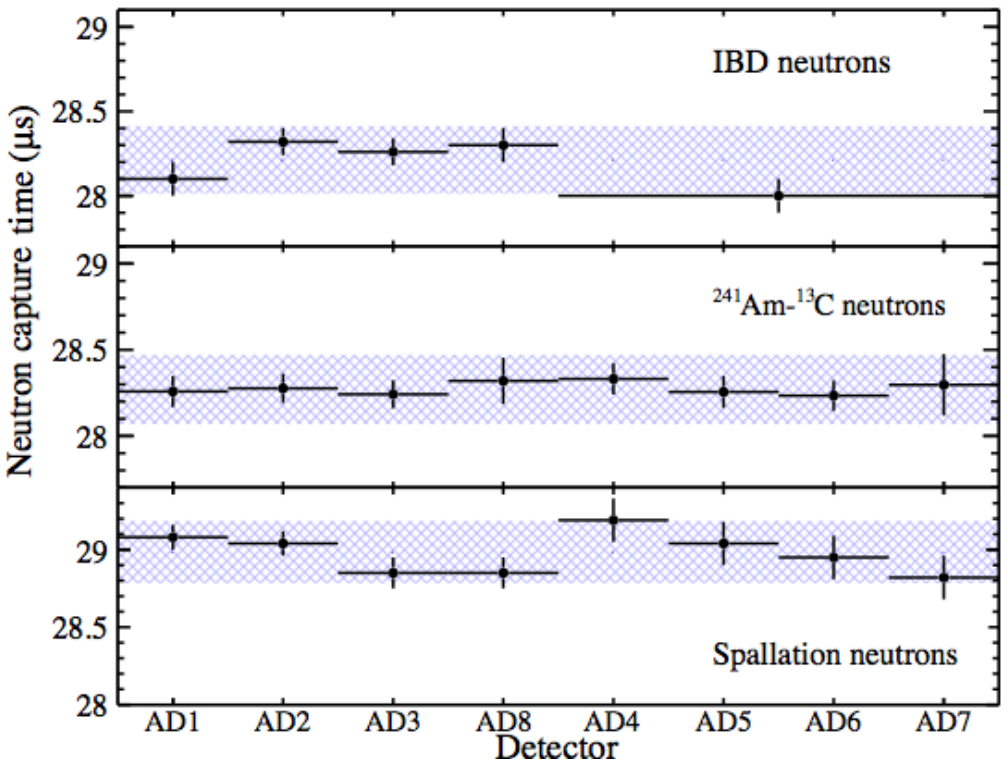


The calculated antineutrino spectra from SNF after a typical 1 GW reactor

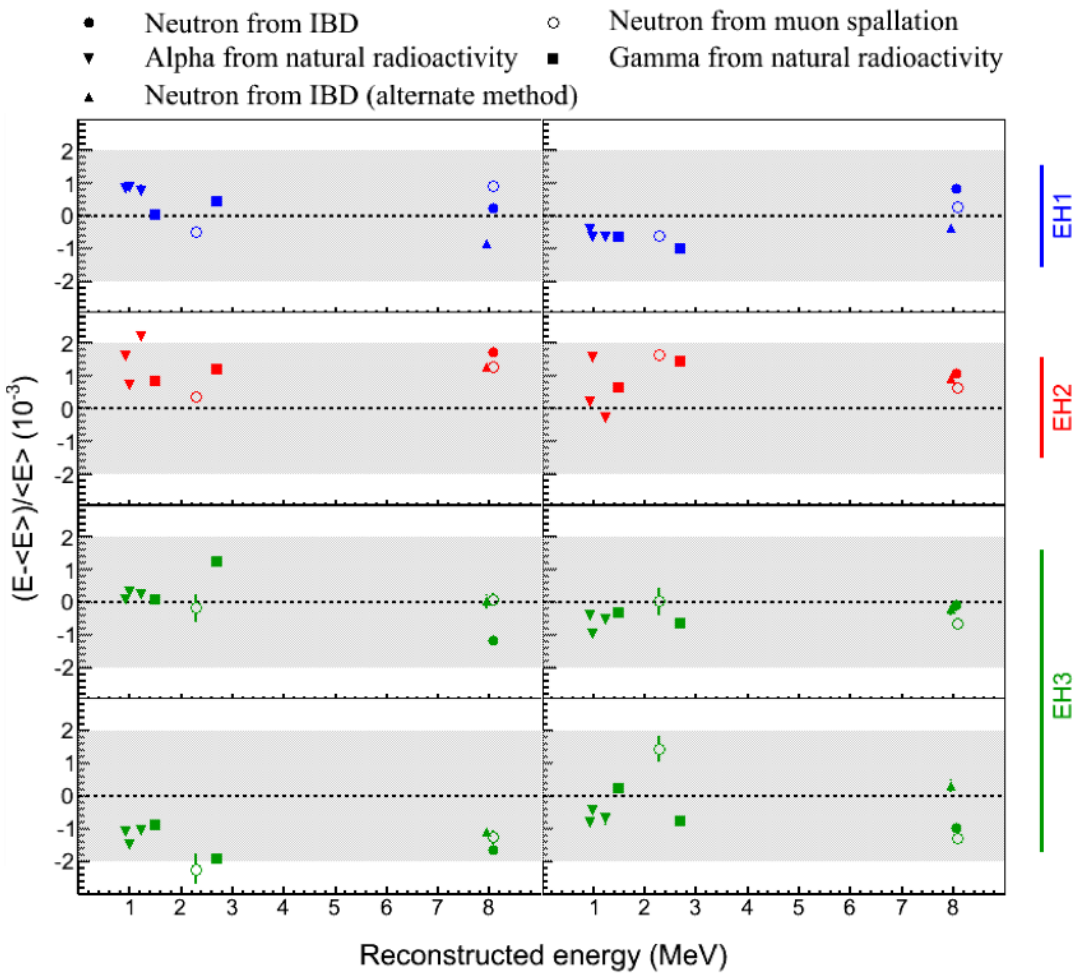
A more careful accounting of the spent nuclear fuel history reduced its uncertainty ***from 100% to 30% (SNF=0.3% of total rate)***

Relative Detection Efficiency

- The relative detection efficiency uncertainty and the relative energy scale uncertainty are the dominant systematics for θ_{13} and $|\Delta m^2_{ee}|$:



Relative Gd capture fraction uncertainty < 0.10%



Relative energy scale uncertainty < 0.2%

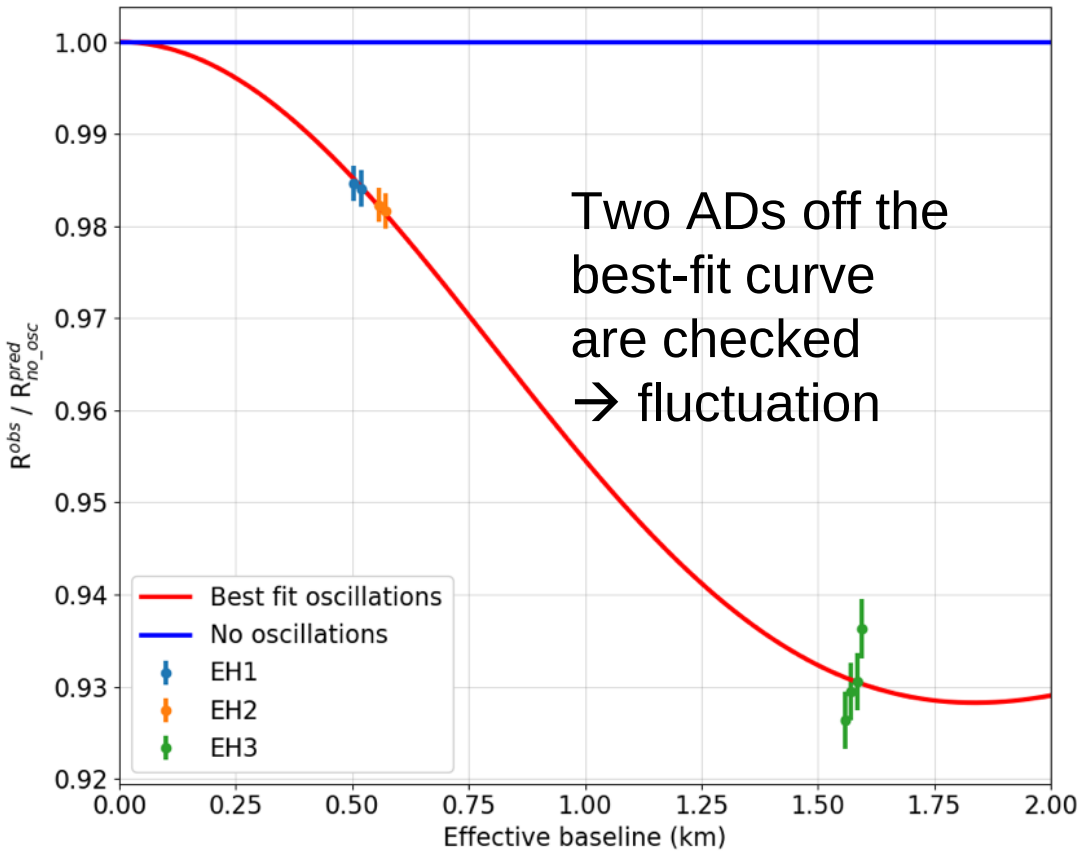
➢ ***Achieve a relative detection efficiency uncertainty of 0.13%***

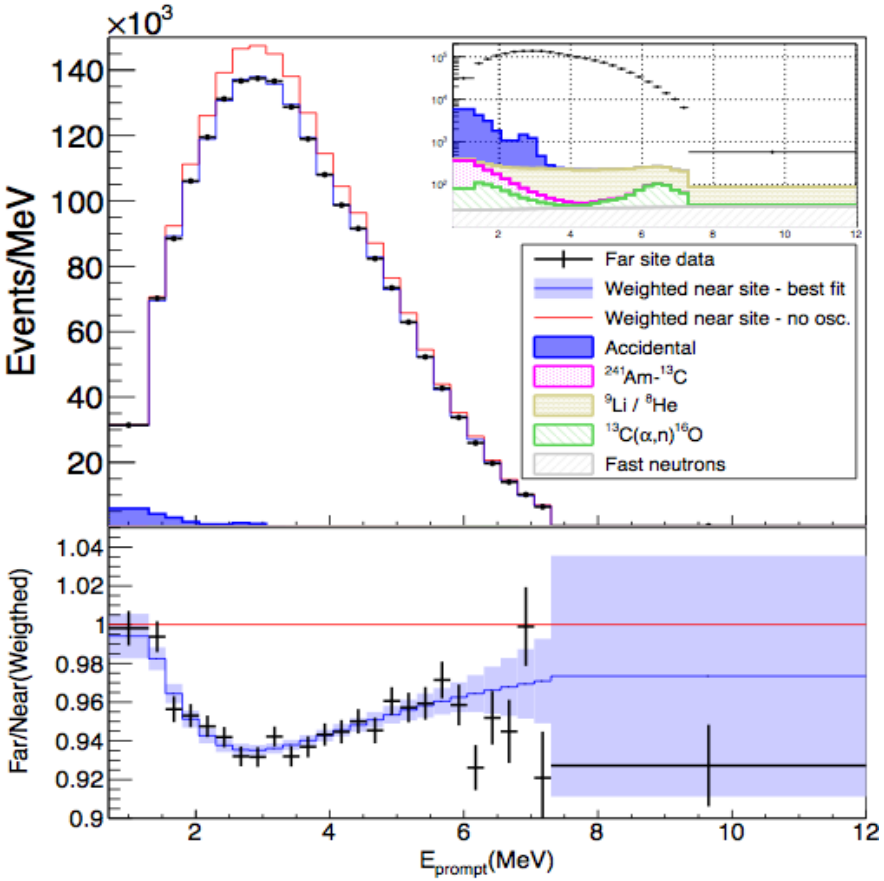
Oscillation Results of 1958 Days

Rate-only
χ^2/ndf=8.8/6 (p-value=0.19)

arXiv:1809.02261

Rate + Shape
χ^2/ndf=148.0/154





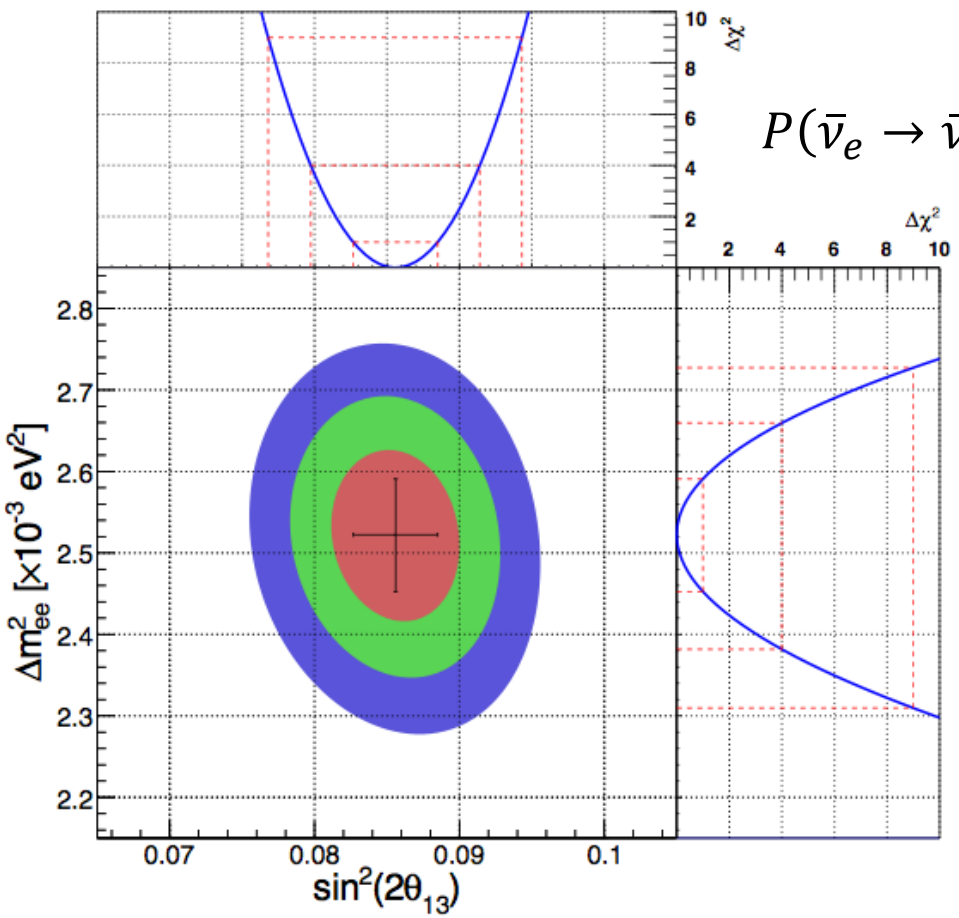
Old news: data fits in the 3-neutrino oscillation paradigm nicely

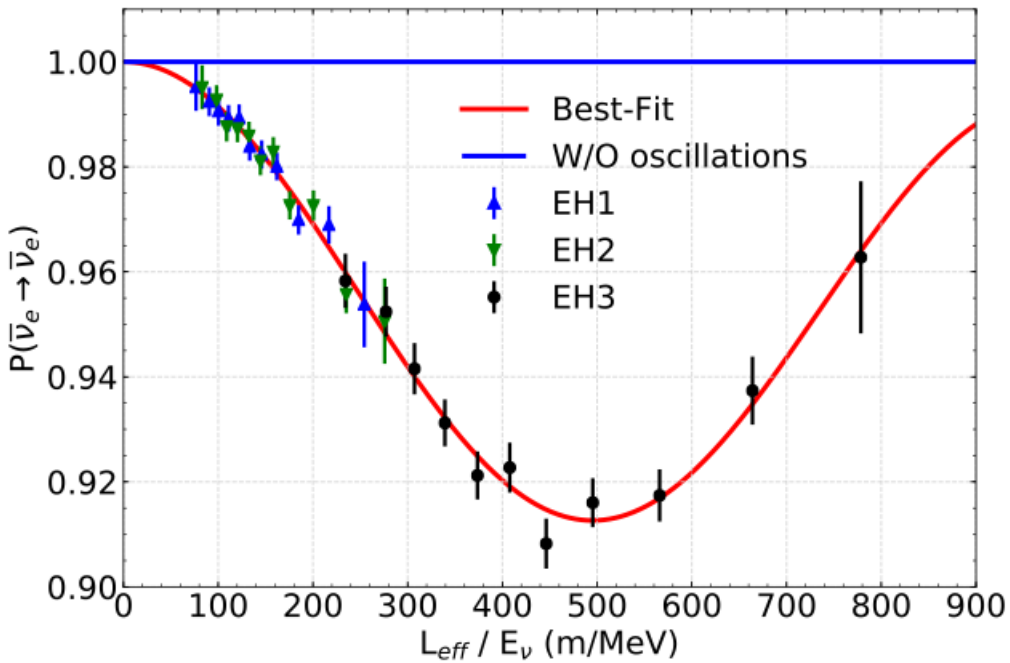
Oscillation Results of 1958 Days

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively

effective mass splitting

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{solar term}$$





$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

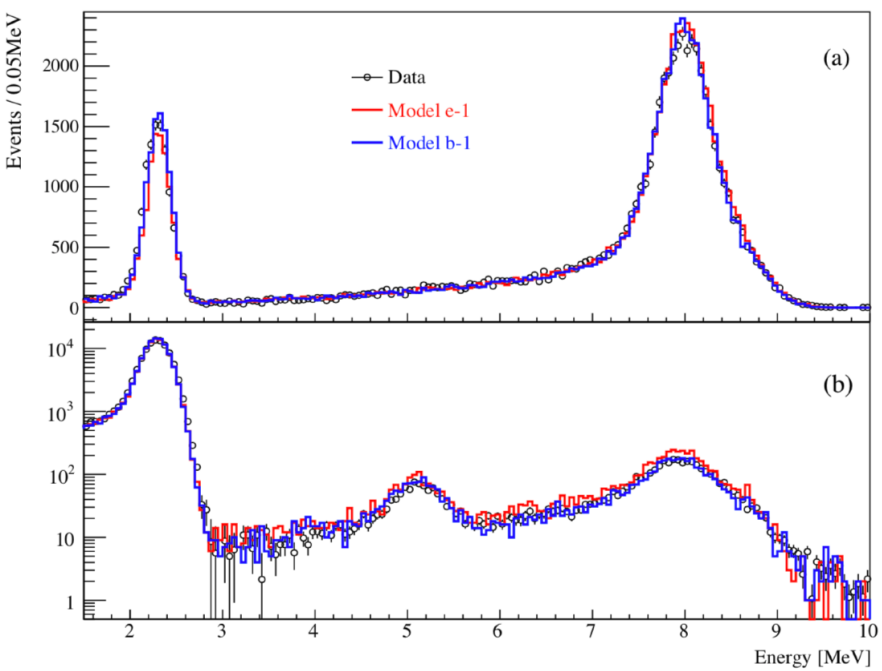
The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

Reactor Neutrino Flux Measurements (1230 Days)

arXiv:1808.10836

- Dominated systematic is the neutron detection efficiency
- New neutron calibration data
  - ^{241}Am-^{13}C and ^{241}Am-^{9}Be sources
  - Deployed along 3 axes

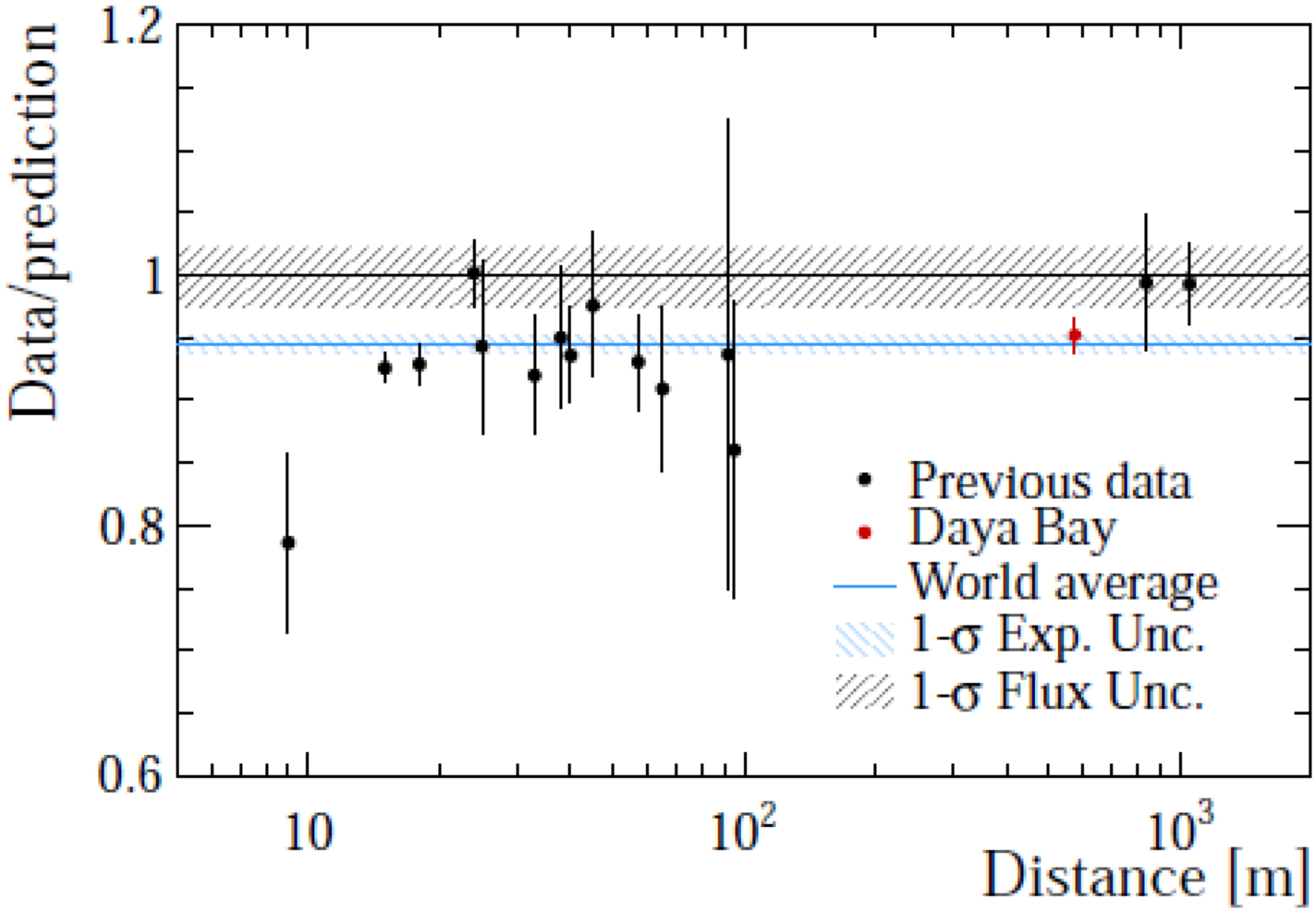
	Previous		This work	
source	value	rel. err.	value	rel. err.
statistic	-	0.1%	-	0.1%
oscillation	-	0.1%	-	0.1%
target proton	-	0.92%	-	0.92%
reactor				
power	-	0.5%	-	0.5%
energy/fission	-	0.2%	-	0.2%
IBD cross section	-	0.12%	-	0.12%
fission fraction	-	0.6%	-	0.6%
spent fuel	-	0.3%	-	0.3%
non-equilibrium	-	0.2%	-	0.2%
$\varepsilon_{\mathrm{IBD}}$				
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\mathrm{other}}$	98.49%	0.16%	98.49%	0.16%
total	-	2.1%	-	1.5%



- **Was: ε_n = *(81.83 +/- 1.38)%***
- **Now: ε_n = *(81.48 +/- 0.60)%***

Flux Measurement (RAA) Updates

- Reactor antineutrino yield: f = (5.91+/-0.09)x10^{-43} cm^2/fission



ILL+Vogel	Huber+Mueller
R = 1.001+/-0:015+/-0.0026	R = 0.952+/-0.014+/- 0.023
(exp) (model)	(exp) (model)

Search for Time-Varying Antineutrino Signal

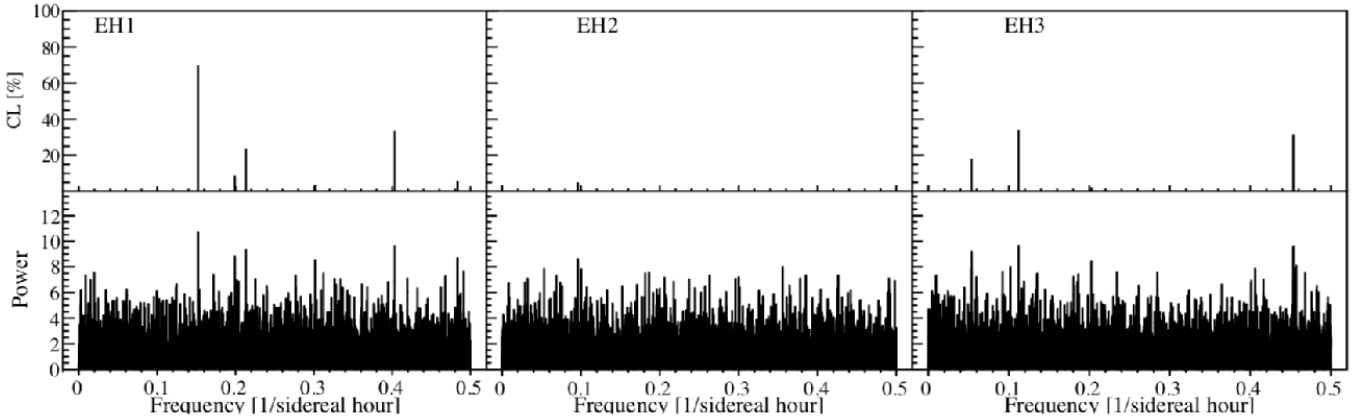
Phys.Rev. D98 (2018) no.9, 092013

- We performed a search for a time-varying $\bar{\nu}_e$ signal over 704 calendar days
  - ***Motivated by models with ultralight dark matter coupling to neutrinos, as well as Lorentz and CPT violation.***

- Search for any periodicity with a Lomb-Scargle (LS) periodogram:

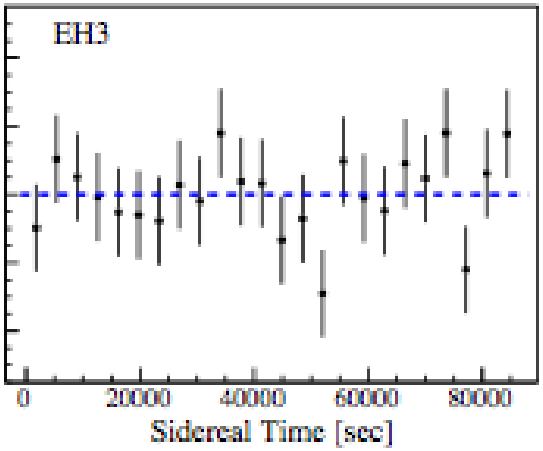
Highest LS powers in each hall

Hall	Frequency	Period	Confidence Level
EH1	0.15 hr^{-1}	6.6 hr	69.8%
EH2	0.10 hr^{-1}	10.4 hr	5.1%
EH3	0.11 hr^{-1}	8.9 hr	33.9%



No signal was found

- Also search for a sidereal modulation in the context of the Standard Model Extension (SME):
  - The multiple directions and high-statistics can disentangle the complex relationship between sidereal amplitudes and individual SME coefficients



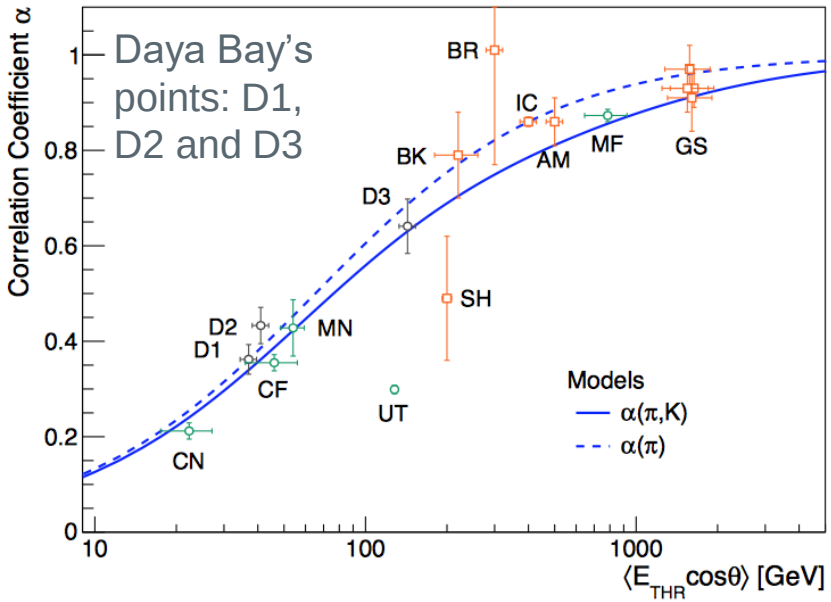
Other Recent Results

- Two cosmic-ray results from Daya Bay were released recently:

Seasonal Variation of the Underground Cosmic Muon Flux

Observe a clear correlation between atmospheric temperature and variations in muon flux

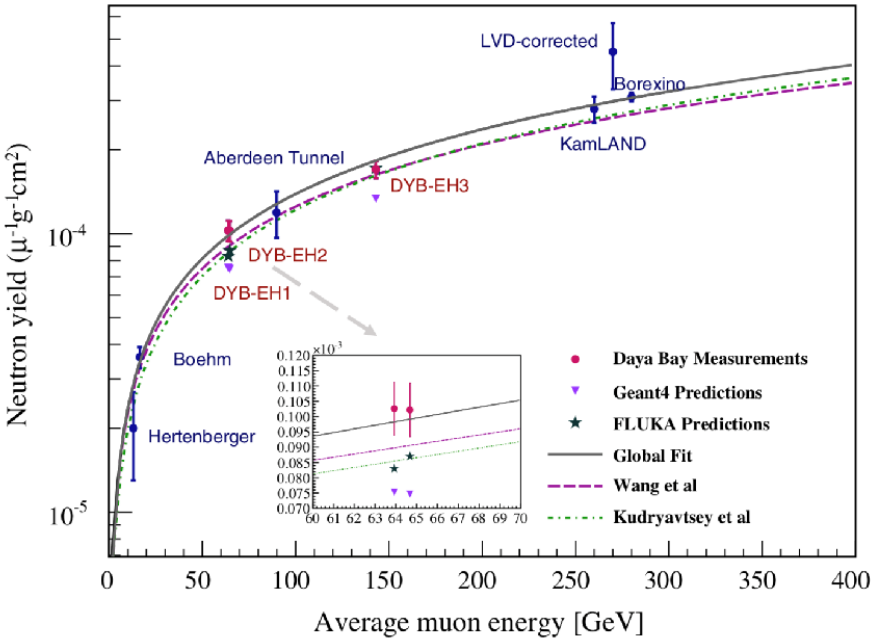
JCAP 1801 no1 (2018)



Cosmogenic neutron production at Daya Bay

Measurement of neutron yield in LS. Important input for underground experiments.

Phys. Rev. D97, 052009 (2018)



Outlook & News

- Daya Bay will run until 2020: achieve < 3% precision in $\sin^2 2\theta_{13}$

- After the special calibration campaign in early 2017, EH1-AD1 was taken down permanently and its Gd-LS replaced with JUNO LS

  - Loss of this detector will only impact $\sin^2 2\theta_{13}$ precision by < 0.05%

  - Carrying out measurements on LS R&D in conjunction with subset of JUNO collaboration

    - Evaluating performance of purification methods and of different LS recipes, among others

- Also working on improving our other results:

  - A single-channel non-linearity correction derived from the FADC data will improve our absolute reactor antineutrino shape measurement

  - New sterile neutrino, nH and fuel evolution results are already well advanced

Summary

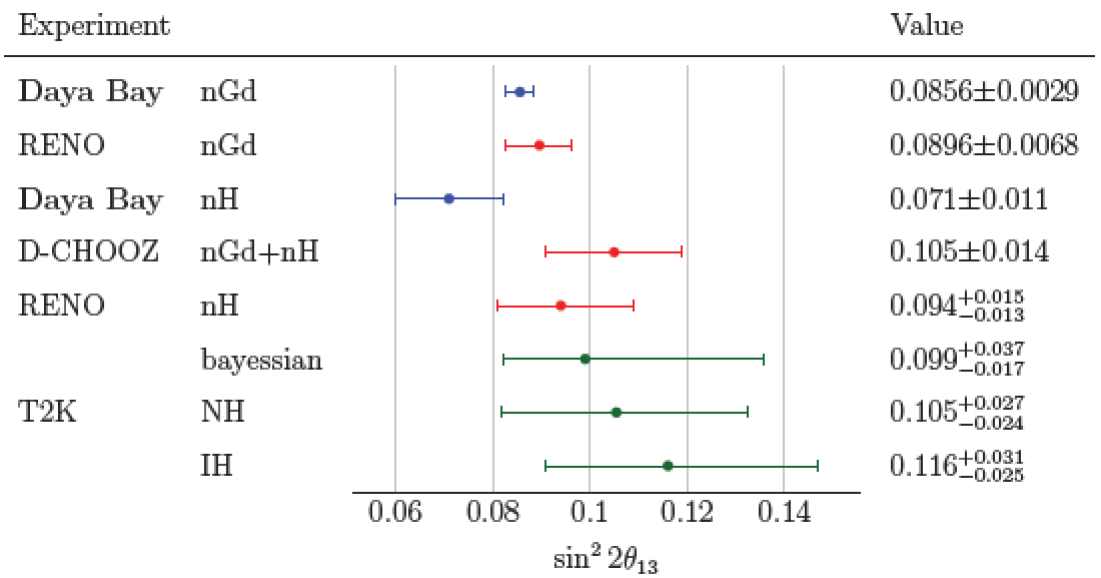
- **With the increased statistics (1958 days) and improved systematics, Daya Bay delivers the most precise θ_{13} measurement and the 2nd best Δm^2_{atm}**
  - **The value of theta13 has enabled the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments**
- **"RAA" and the "bump" stay (1230 days)**

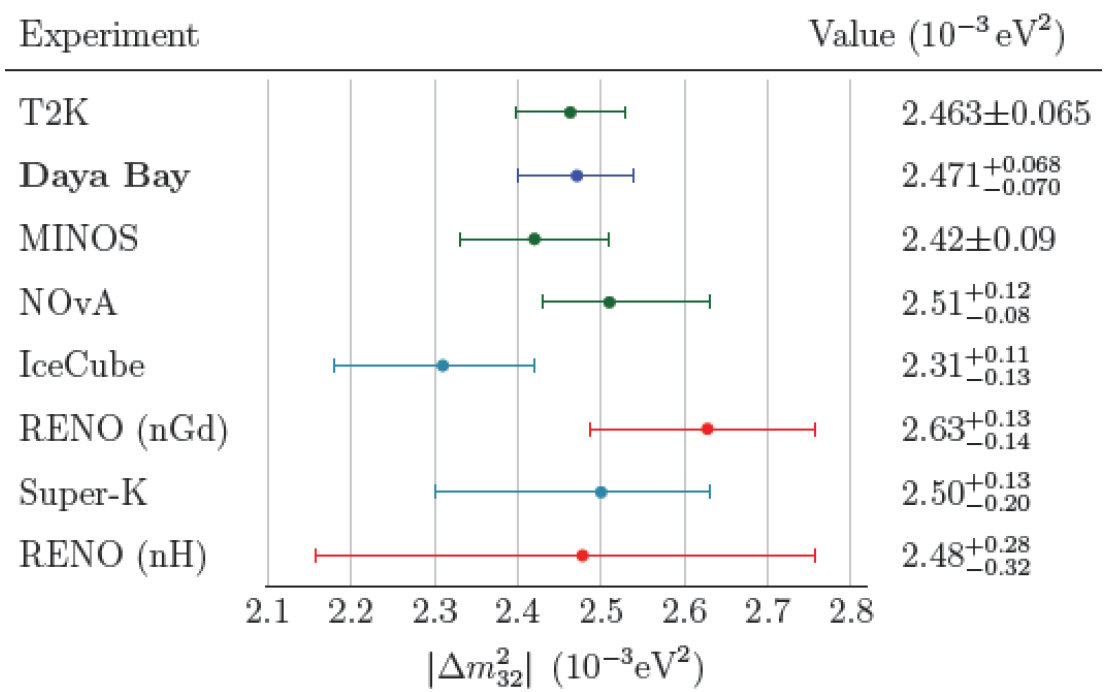
➢ **Daya Bay will keep taking data till 2020, while improving statistics and updating all analyses; Helping other experiments like JUNO; Joint analysis with VSBL experiment…**

Global Measurements of θ_{13} and Δm^2_{atm}

- The most precise $\sin^2 2\theta_{13}$
- Once most precise now the 2nd place Δm^2_{atm}

➢ Painting a better and better global picture





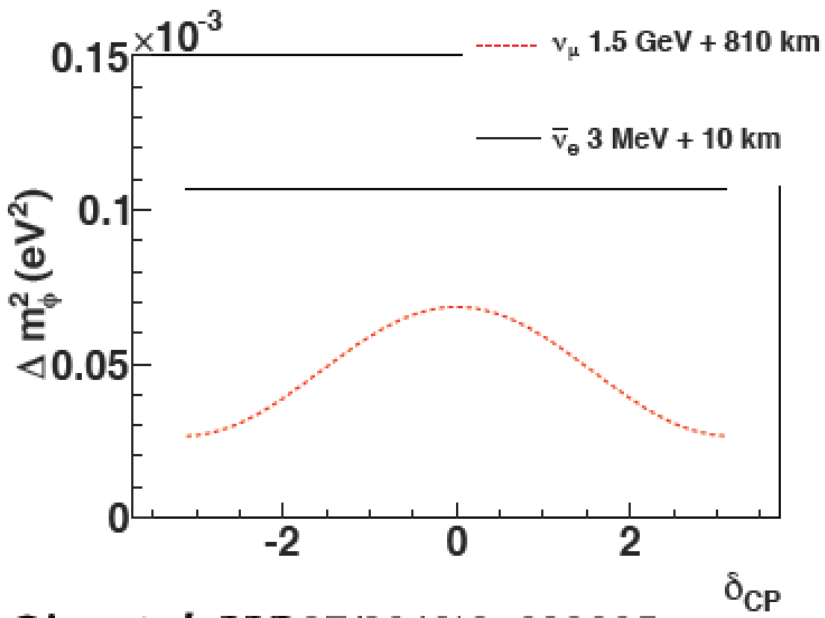
Daya Bay


Take home message: ~ 6 ν's / fission
Neutron
Electron
Anti-neutrino
Gamma
235U
236U
144Ba
89Kr
(some loss)
Chain Reaction
144Ba
144La
144Ce
144Pr
144Nd
238U
239U
239Np
239Pu
89Kr
89Rb
89Sr
89Y

e-Flavor and μ-Flavor Feels MH Effect Differently

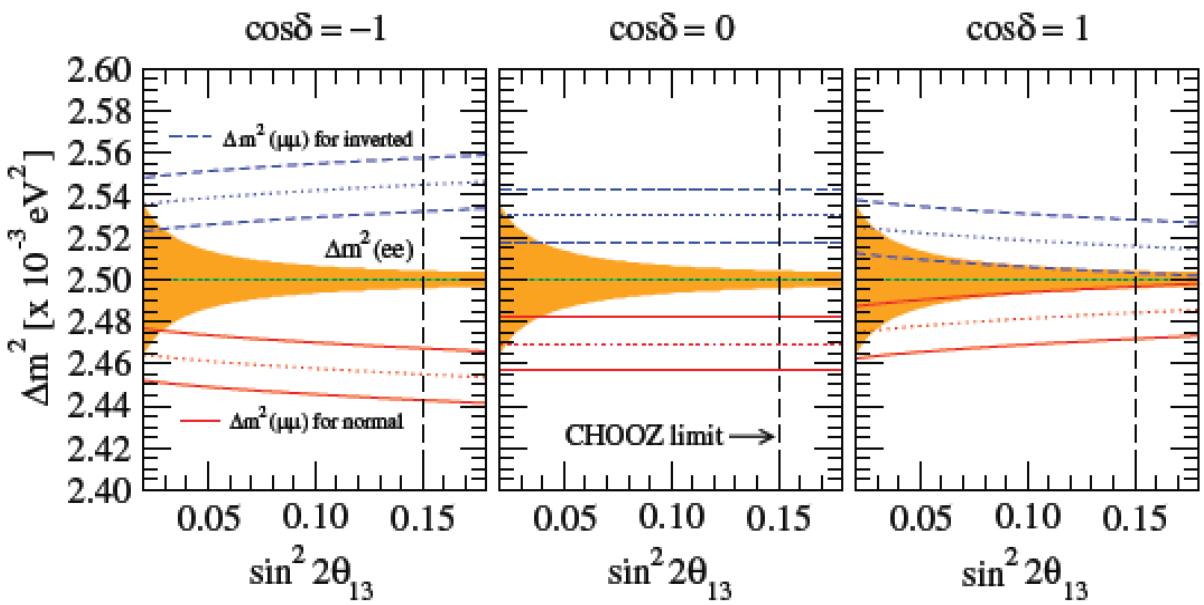
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1 - 4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$



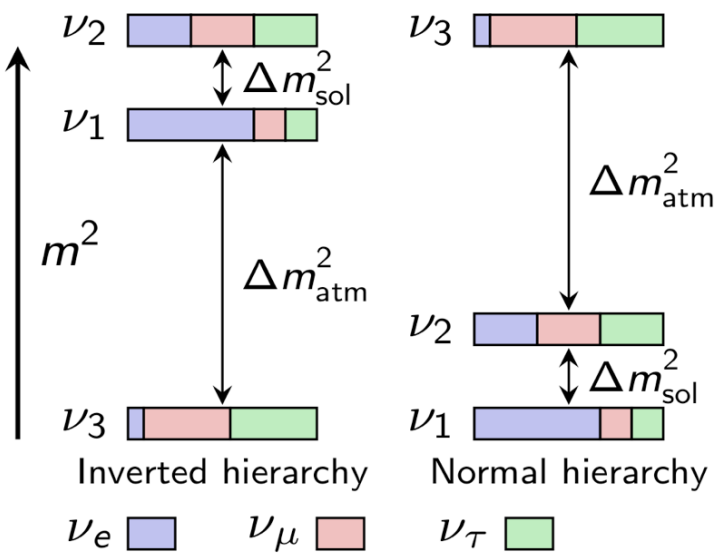
Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



Minakata and Parke et al PRD74(2006), 053008

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors



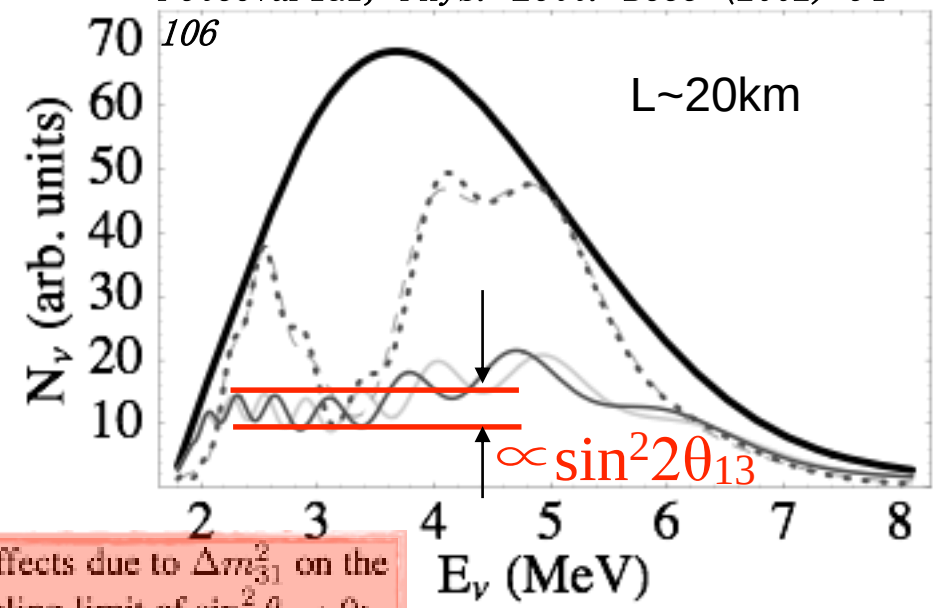
- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale

✓ Both scales can be studied by observing the spectrum of reactor neutrino flux

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

✓ Mass hierarchy is reflected in the spectrum
✓ Signal independent of the unknown CP phase

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}$ – driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

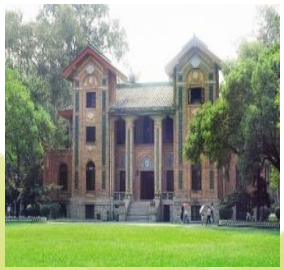
Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302

Three Cities, Five Campuses

北校园
Guangzhou North Campus

南校园
Guangzhou South Campus

东校园
Guangzhou East Campus



广州校区 Guangzhou Campuses
文、理、医传统优势学科 Liberal arts, Sciences and Medical Sciences

珠海校区
Zhuhai Campus
深海、深空、深地
Deep Sea, Deep Space, Deep Earth

深圳校区
Shenzhen Campus
医科和新型工科
Medical Sciences and New Engineering

The 5-Campus system of SYSU is attracting, training and keeping top-level talents for the Greater Bay Area (Guangdong - Hong Kong - Macao); SYSU in return enjoys resources and opportunities for developments and talent cultivation.

Campuses		Schools/Departments
Guangzhou Campuses	South Campus	33
	East Campus	
	North Campus	
Zhuhai Campus		16
Shenzhen Campus		8
In total		57

School of Physics: Facts and Vision

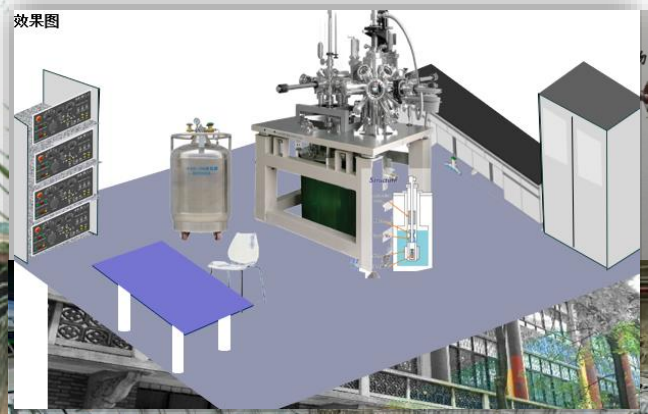
中山大學 SUN YAT-SEN UNIVERSITY

Currently: ~85 Faculties

ESI Top 1%; Top 10 in China

Goal: ~150 Faculties

First Class in the World



Traditionally Established

- ☐ Theoretical Physics
- ☐ Condensed Matter
- ☐ Optics

Newly Developed

- ☐ Energy Physics
- ☐ Soft Condensed Matter

New Research Platforms

- ☐ Neutron Science Center
- ☐ Ultrafast Laser Platform
- ☐ Center for Particle Physics