Reactor antineutrino flux and spectrum measurement of Daya Bay Experiment

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On behalf of the Daya Bay collaboration

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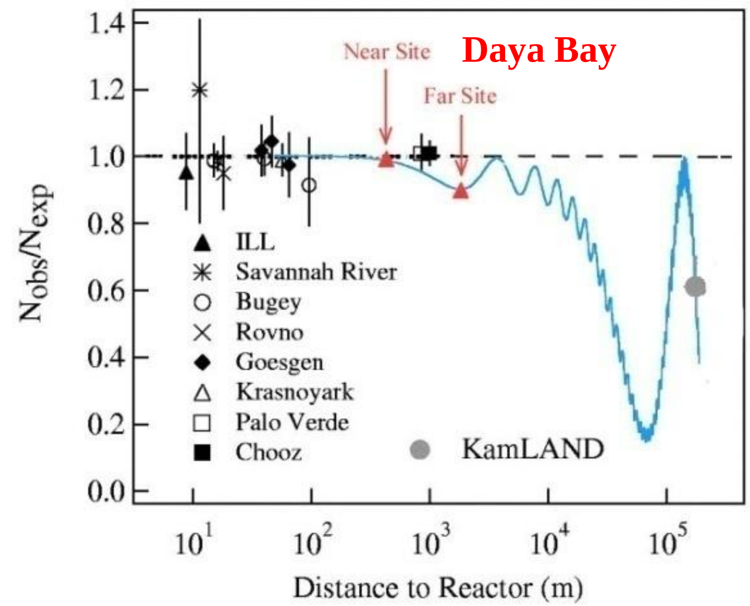
Daya Bay Experiment

- **DayaBay experiment**
  - In Shenzhen, southern China;
- **Key features of Daya Bay**
  - Large thermal power (6x2.9 GWth) and target mass (8x20 ton)
  - Near/far relative measurement to reduce reactor related errors
  - Identically designed multiple detectors to verify and reduce detector related errors
  - Good shielding and enough overburden to reduce backgrounds

Main Goals:

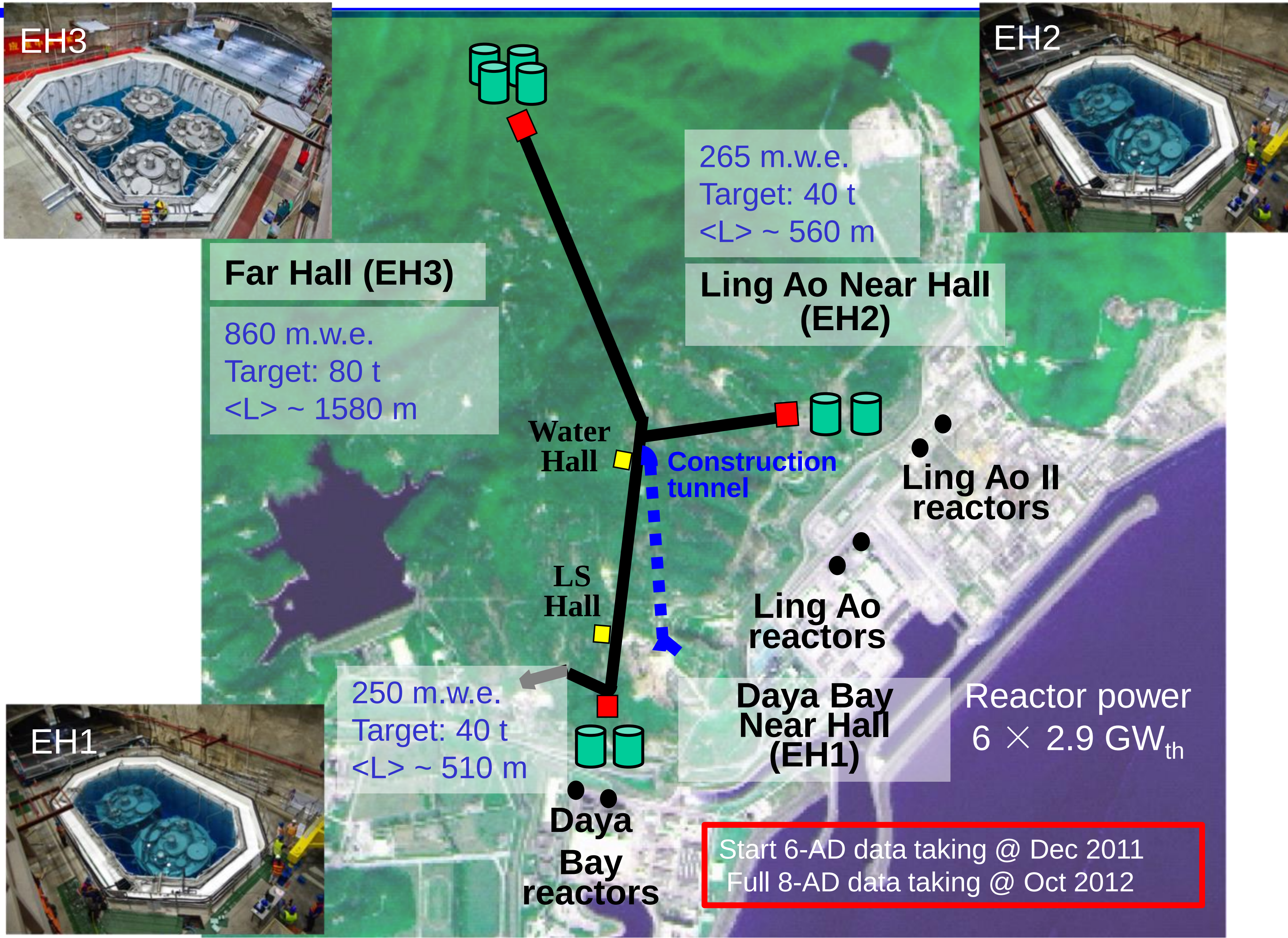
- World leading precision in measurement of θ_{13} and $|\Delta m^2_{ee}|$ oscillation parameters.
- Study the anti-neutrino flux and spectrum.
- Search for sterile neutrinos and other new physics



	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250

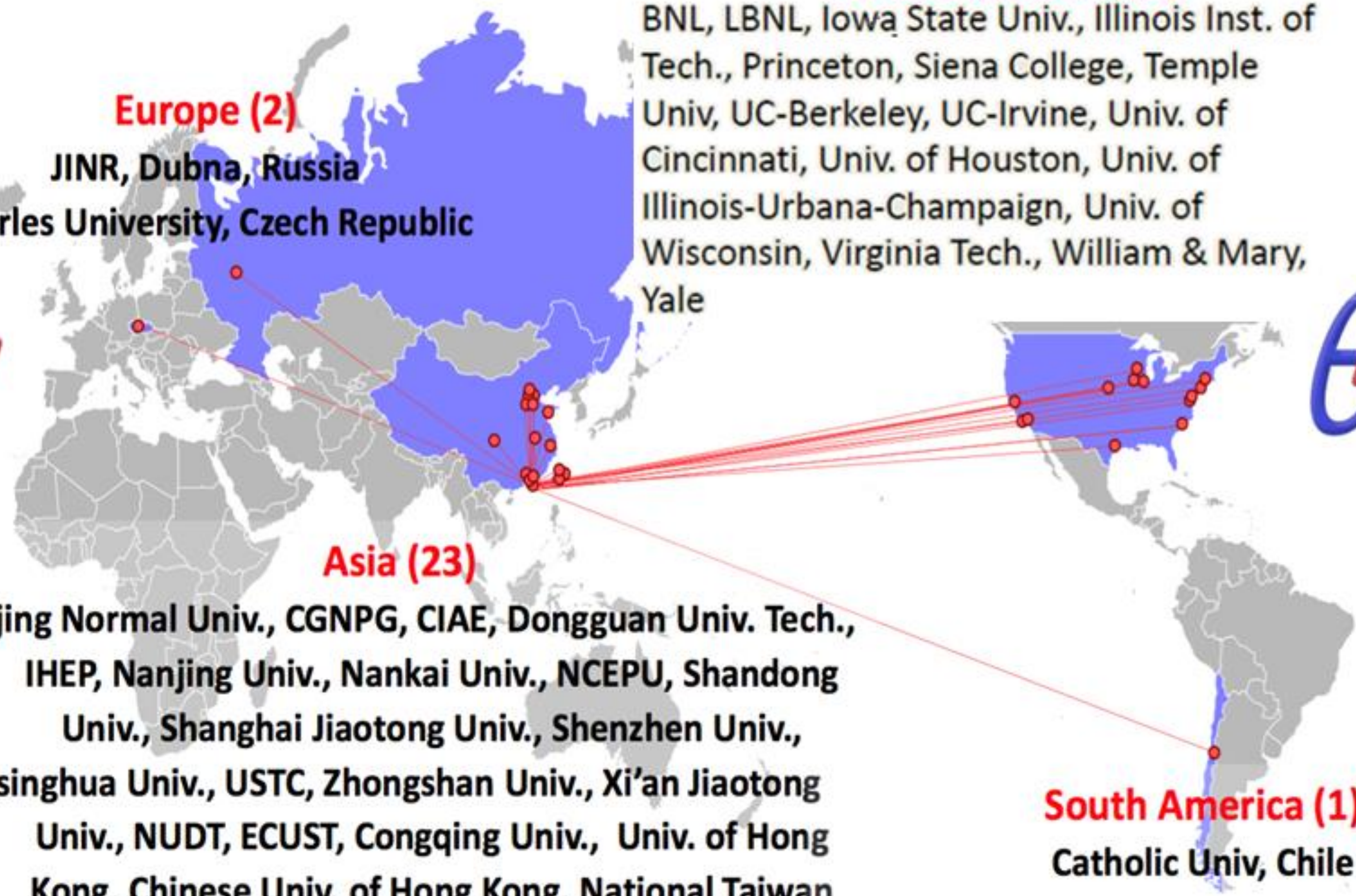
Large signal statistics and low background

Experimental setup



Daya Bay Collaboration

~200 collaborators



North America (16)

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

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

Asia (23)

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

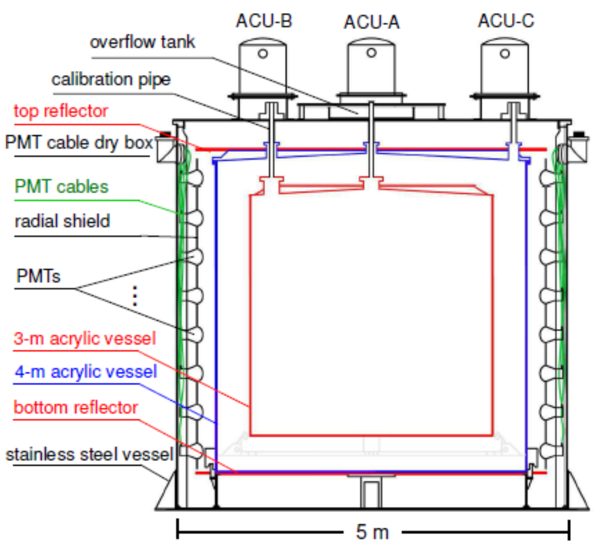
South America (1)

Catholic Univ, Chile

Detector design

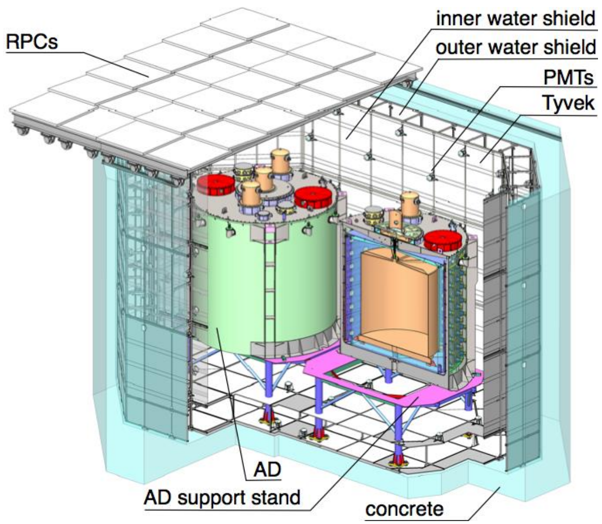
Daya Bay Antineutrino Detectors (AD)

- 8 functionally identical detectors to reduce the detector relative errors
- Three-zone modular structure
- Reflector at top and bottom:
  - Reflectors improve light collection and uniformity



Veto system

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8" PMTs in each near hall
  - 384 8" PMTs in Far Hall
- 4-layer RPC modules above pool
- Goal efficiency: > 99.5% with uncertainty <0.25%



➢ **Energy resolution: σ/E ~ 8.5 % /√E[MeV]**

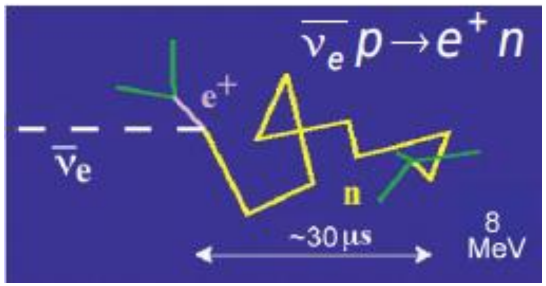
Neutrino detection and event selection

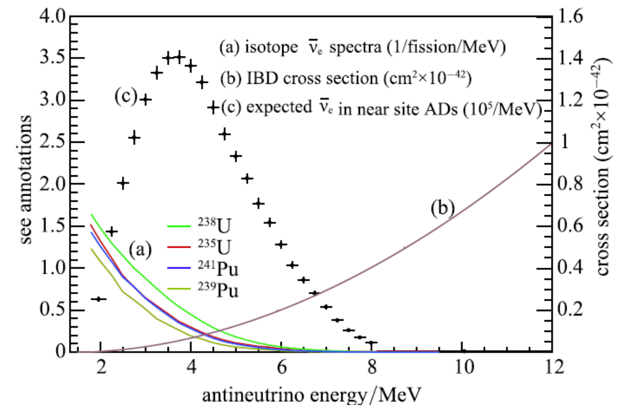
Inverse beta decay(IBD) in Gd-doped liquid scintillator

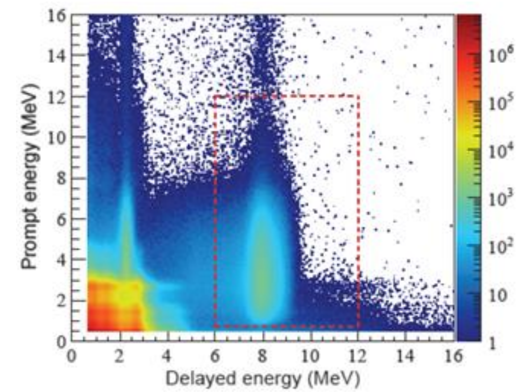
$$\overline{\nu_e} + p \rightarrow e^+ + n$$

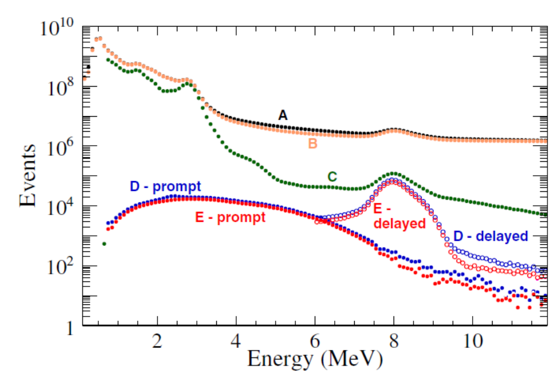
$\rightarrow$ + p $\rightarrow$ D + γ(2.2 MeV) (t~180 μs)

$\rightarrow$ + Gd $\rightarrow$ Gd* $\rightarrow$ Gd + γ's(8 MeV) (t~30 μs)







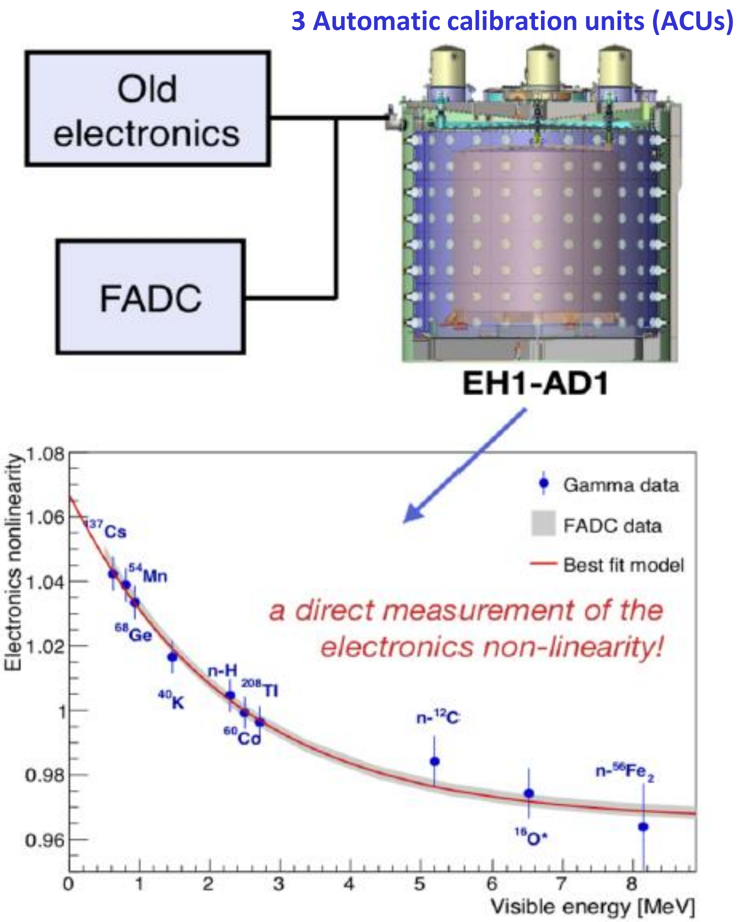


Event selection in data:

- All signal(A)
- Reject PMT flashers(B)
- Muon veto(C)
- Prompt positron:0.7MeV<Ep<12.0MeV
- Delayed neutron:6.0MeV<Ed<12.0MeV
- Neutron capture time: 1 μs < Δt < 200 μs
- Multiplicity: isolated candidate pairs (D)
- Shower muon veto(E)

Energy non-linearity calibration

Use different natural and artificial sources to calibrate the detector for energy scale, time-variation, non-uniformity and non-linearity.

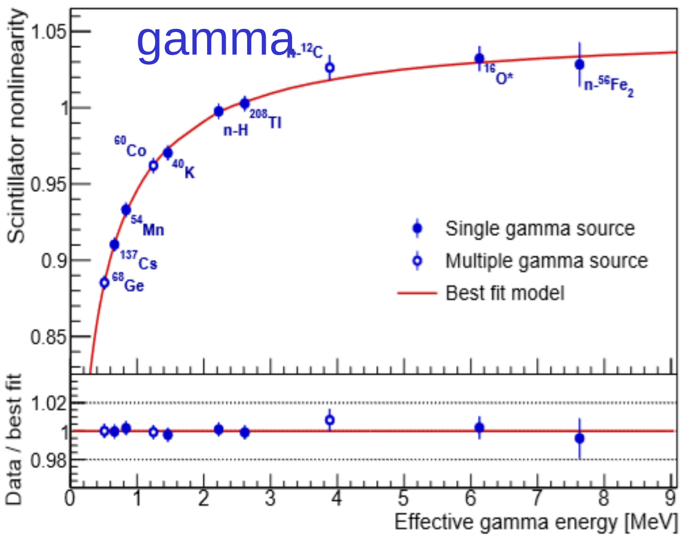


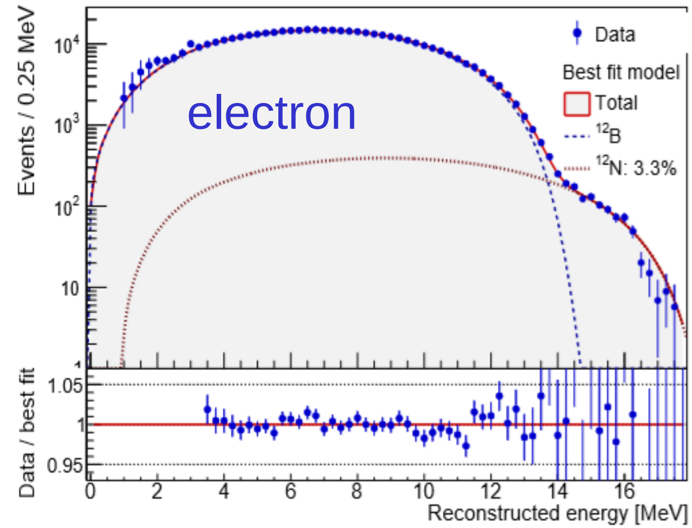
- **Two major sources of energy non-linearity:**
  - Scintillator response
  - Readout electronics response

Improve energy nonlinearity:

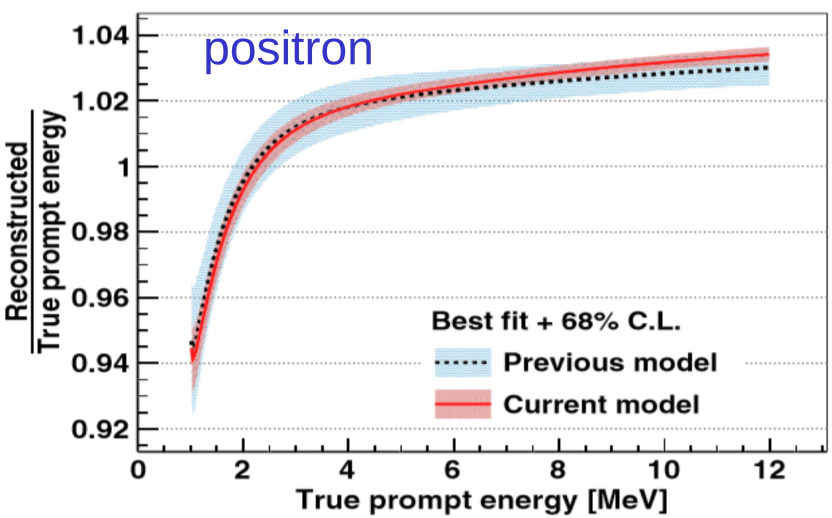
- End of 2015: installation of a full FADC readout system in EH1-AD1, taking data simultaneously with standard electronics
- Special calibration in 2017: ^{60}Co sources with different enclosures to constrain the optical shadowing effect

Energy non-linearity calibration





arXiv:1902.08241(2019)



The energy model is needed to convert the positron energy to antineutrino energy.

Nominal energy model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum

Uncertainty reduced to ~0.5% since 2018
(~1% previously)

Reactor antineutrino flux measurement

source	Previous value	Previous rel. err.	This work value	This work 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%
$\varepsilon_{\rm IBD}$				
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\rm other}$	98.49%	0.16%	98.49%	0.16%
total	-	2.1%	-	1.5%

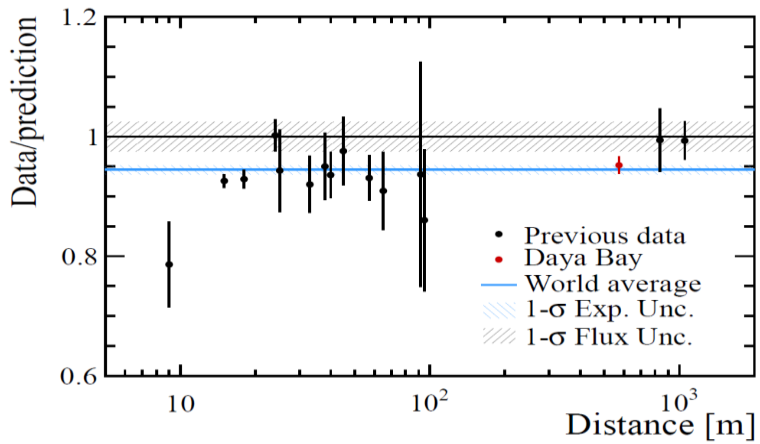
arXiv:1808.10836(2018)

1230 days of data

- Reactor antineutrino flux:
  - Data/Prediction (Huber+Mueller) :
    - $0.952 \pm 0.014(\text{exp.}) \pm 0.023$ (model)
  - Data/Prediction (ILL+Vogel):
    - $1.001 \pm 0.015(\text{exp.}) \pm 0.027$ (model)

The neutron detection efficiency uncertainty is significantly improved.

- New neutron calibration data(Calibration campaign late 2016/early 2017)
- Detailed MC and data comparison to constrain the uncertainty.



IBD yield

$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43} cm^2/fission$$

Measurement consistent with the global average of the previous short baseline experiments

Data sets for antineutrino spectrum measurement

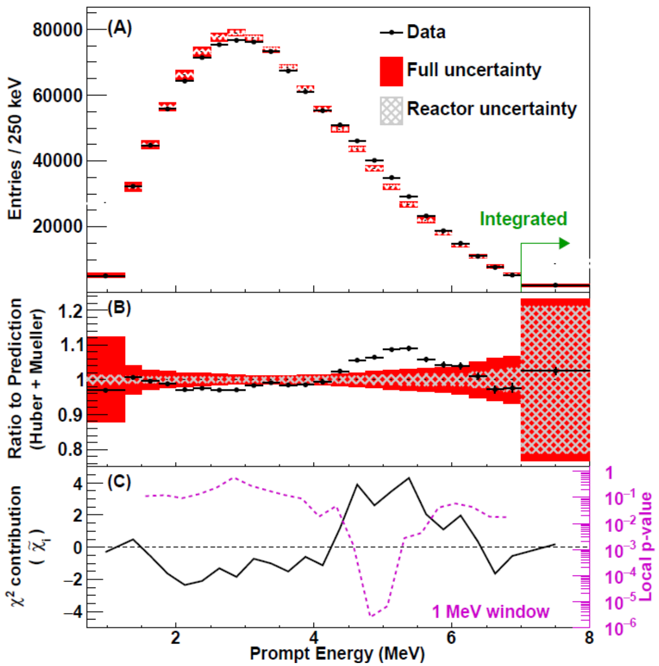
Three results released for reactor antineutrino spectrum measurement.

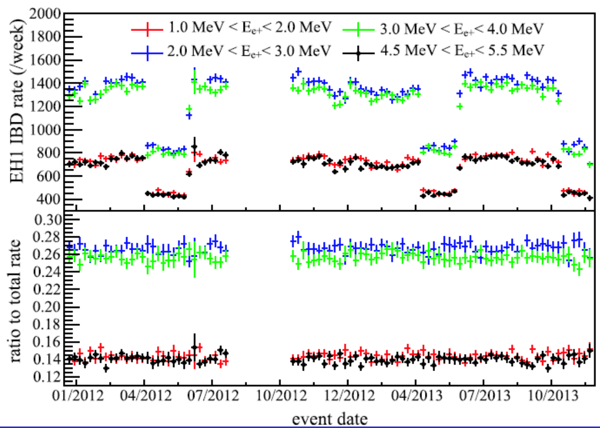
	Days of data	Statistics	Energy scale uncertainty
RPL116,061801(2016)	217	0.3 million	1%
CPC41,013002	621	1.1million	1%
arXiv:1904.07812	1958	3.5million	0.5%

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ 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			
^{9}Li/^{8}He (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
$\overline{\nu}_e$ 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

1958 days of data

Reactor antineutrino spectrum measurement



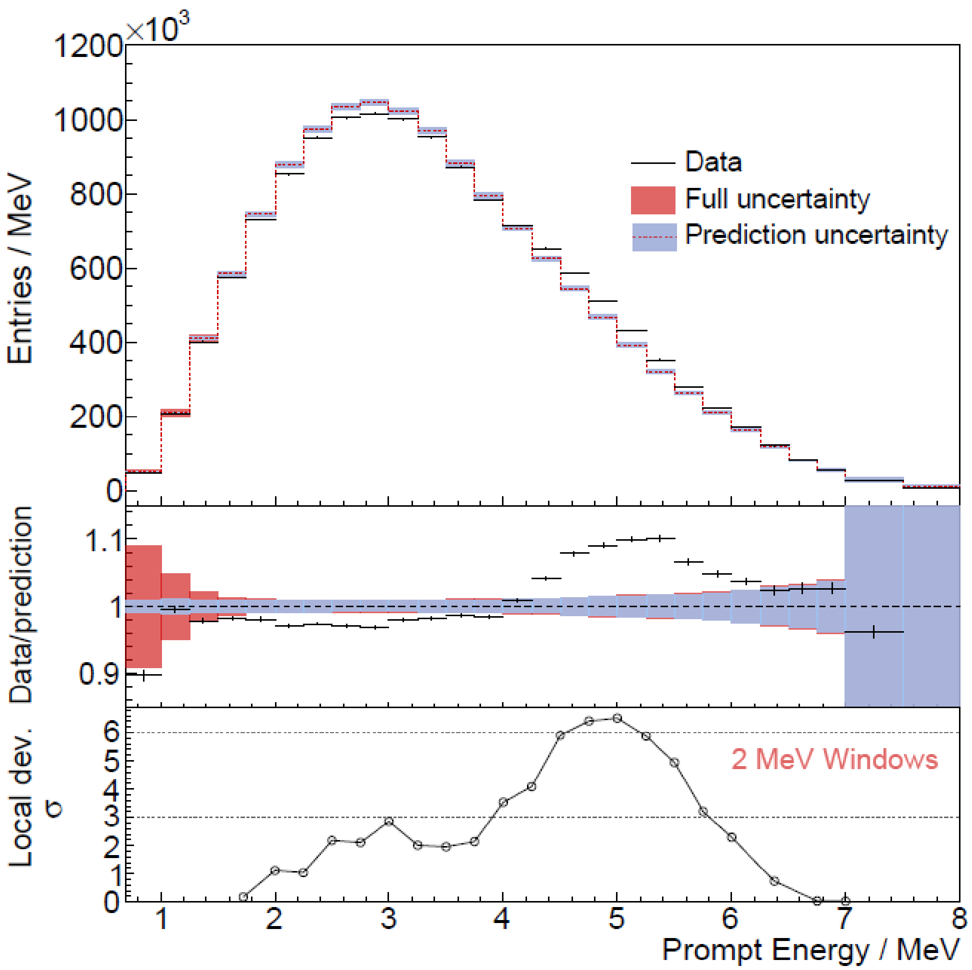


Chinese Physics C, 2017, 41(1): 13002-013002

- 621 days data with more than 1.2 million IBD candidates
  - high-statistics reactor antineutrino spectrum measurement
- A 2.9 σ global deviation compared to Huber+Mueller model prediction;
- Event excess in 4~6 MeV region(4.4 σ)
  - Excess events characteristics are same as IBD events, correlated with reactor power but time independent
  - Ruled out detector effects
    - There are no event excess for the spallation ^{12}B beta spectra at same energy range

Antineutrino spectrum update

- High-statistics measurement of the spectral shape of reactor anti-neutrinos with 1958 days of data(3.5million).



arXiv:1904.07812(2019)

Spectrum shape compared with Huber+Mueller model

- Global discrepancy with the prediction at 5.3 σ
- Local deviation in 4-6 MeV region: 6.3 σ

Reactor antineutrino flux evolution

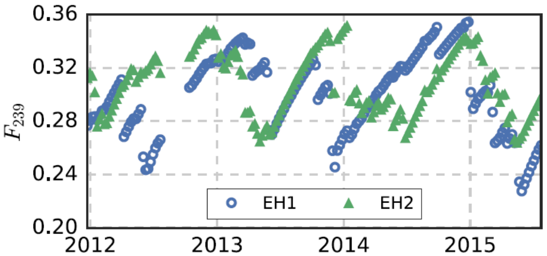
Analysis of dependence of IBD yield/fission σ_i for each fission isotope (i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) on effective fission fraction.

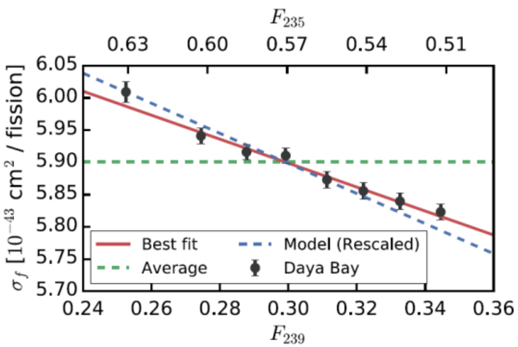
Effective fission fraction (F_i): Weighted by power (*W*), *survival* probability (*p*), *baseline (L) over 6* reactor cores

Phys. Rev. Lett. 118.251801

1230 days, near detectors

$$F_i(t) = \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r f_{i,r}(t)}{L_r^2 \bar{E}_r(t)} \Big/ \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r}{L_r^2 \bar{E}_r(t)}$$

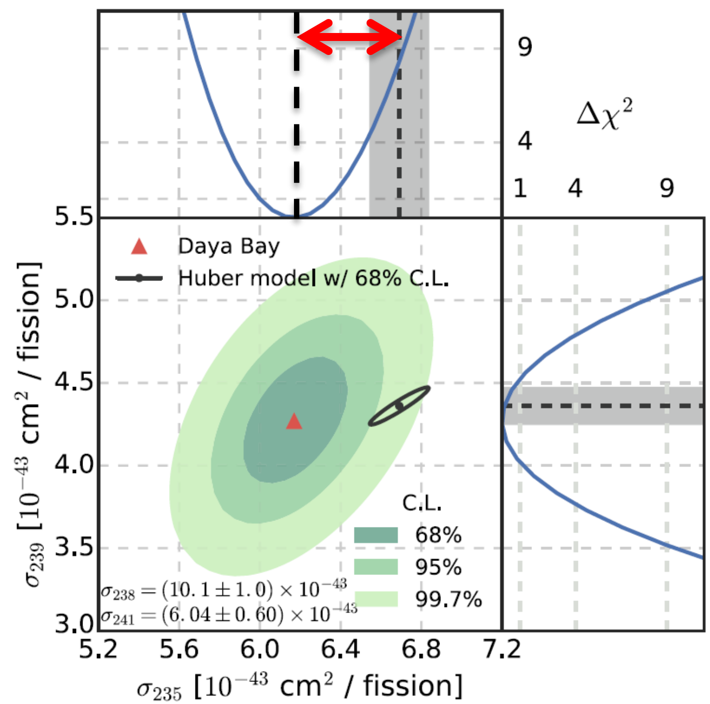




$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \bar{F}_{239})$$

Unit $(\times 10^{-43} cm^2 / fission)$	$d\sigma_f / dF_{239}$
Daya Bay	-1.86±0.18
Huber-Mueller Model	-2.46±0.06

7.8% deficit for ^{235}U



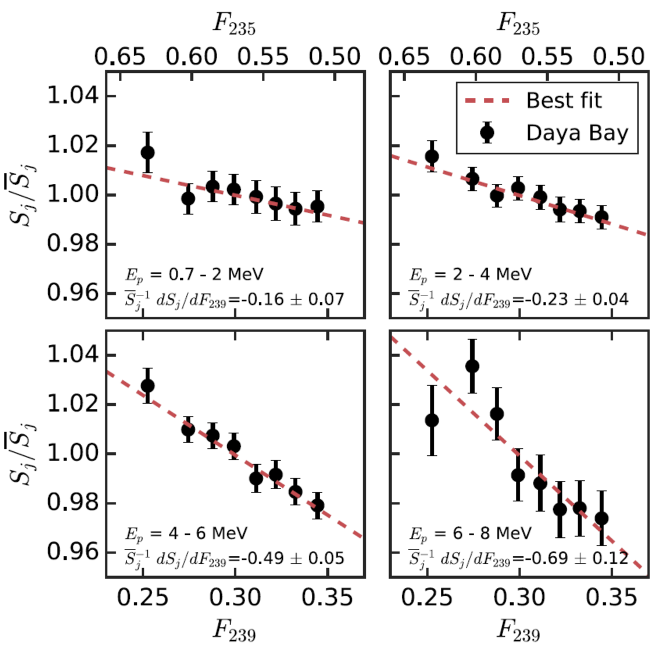
^{235}U could be the primary contributor to the reactor anti-neutrino anomaly.

Evolution of the reactor antineutrino spectrum

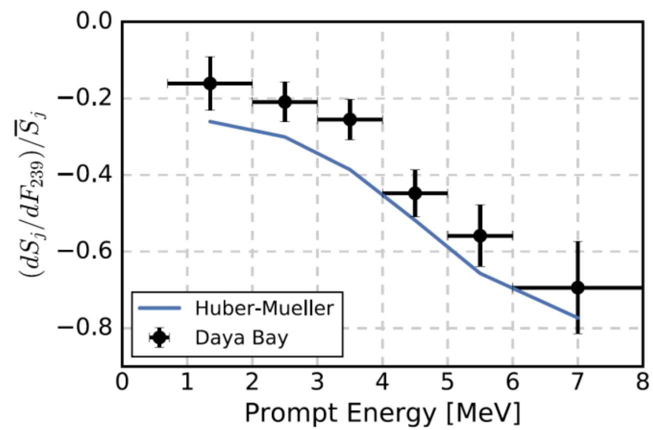
Observed IBD spectra per fission, S, $\sigma_f = \sum_j S_j$ the sum of IBD yields in all prompt energy bins.
$\overline{S}_j$: F_{239}-averaged IBD yield per fission value. Y axis is the ratio of $S_j / \overline{S}_j$.

$$S_j(F_{239}) = \bar{S}_j + \frac{dS_j}{dF_{239}}(F_{239} - \bar{F}_{239})$$

Relative IBD yield per fission vs F_{235} or F_{239}



Fractional variations in IBD yield for different prompt energy range



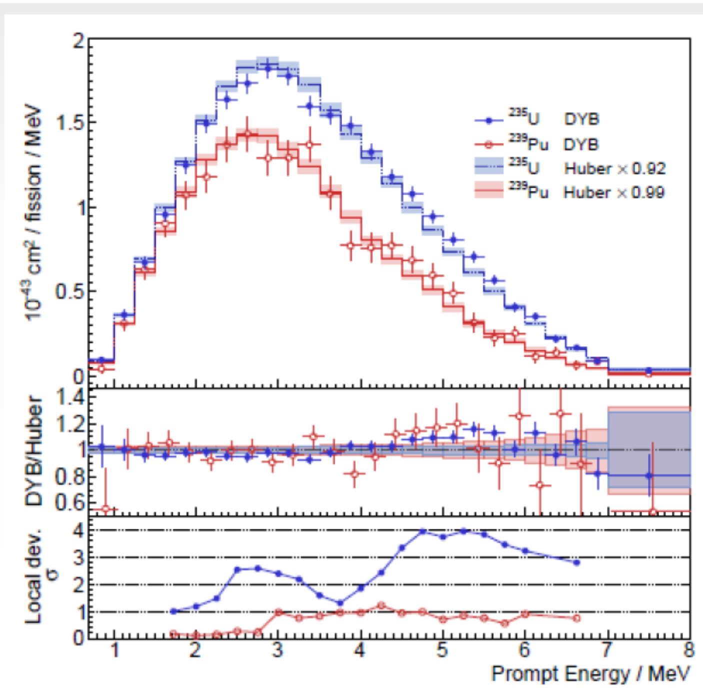
The trend is generally consistent with prediction

4 different energy bins for the analysis

- Energy-dependent evolution is observed.
- Change in spectral shape as fuel composition evolves.

Extract ^{235}U and ^{239}Pu Spectrum

- Extract ^{235}U and ^{239}Pu spectra based on the spectrum evolution
  - Data set: 1958 days
  - Ordered by ^{239}Pu fission fraction into 20 data groups
  - Fit the ^{235}U and ^{239}Pu spectra, as two dominant components
  - Not sensitive to ^{238}U and ^{241}Pu
    - Assign >10% uncertainties both on rate and shape as prior inputs.



arXiv:1904.07812(2019)

- First measurement of ^{235}U spectrum and ^{239}Pu spectrum in commercial reactors
- Compare spectral shape with model after normalizing to area
  - Similar bump excess in 4—6 MeV for ^{235}U and ^{239}Pu
  - Significance of local deviations:
    - 4σ for ^{235}U
    - 1.2σ for ^{239}Pu(larger uncertainty)

IBD yield comparison

^{235}U: data/prediction = 0.92 ±0.023(exp.)±0.021(model)

^{239}Pu: data/prediction = 0.99 ±0.057(exp.) ±0.025(model)

Summary

- **Energy non-linearity calibration**
  – Uncertainty improved from 1% to 0.5%.
- **A new measurement of reactor antineutrino prompt energy spectrum with 1958 days data.**
  - Global discrepancy with the prediction at 5.3 σ
  - Local deviation in 4-6 MeV region: 6.3 σ
- **First measurement of ^{235}U and ^{239}Pu spectra in commercial reactors.**
  – Similar deviation compared with model predictions.
  – ^{235}U: data/prediction = 0.92 ±0.023(exp.) ±0.021(model).
  – ^{235}U spectral shape local deviation significance: 4σ (4-6MeV)
- **The experiment is expected to continue running until 2020.**
  – Expect to get uncertainty in oscillation parameters to below 3%
- **Posters of Daya Bay:**
  – Daya Bay neutrino oscillation results(Vit Vorobel)
  – Improved Measurement of the Reactor Antineutrino Flux at Daya Bay(Ming-Chu Chu)

Thanks