Reactor Neutrinos: Recent Results and Next Steps

Karsten M. Heeger
Yale University

KITP, October 4, 2014

Yale Wright Laboratory

Reactor Neutrinos: Recent Results and Next Steps

Recent Results (DayaBay)

Oscillation Measurements (active, sterile)

Absolute Reactor Antineutrino Flux
Absolute Reactor Spectrum
Predictions of the Reactor Spectrum

Future Efforts

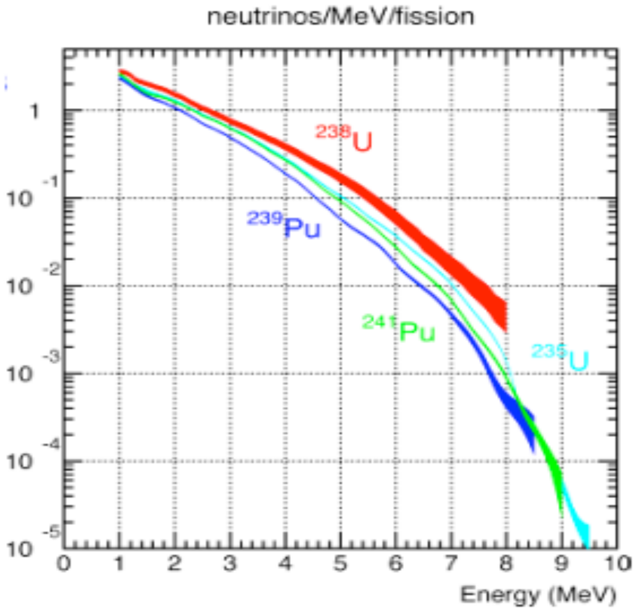
Short-baseline experiments (e.g. PROSPECT, NuLAT)
Mass Hierarchy (e.g. JUNO)

Reactor Antineutrino Flux and Spectrum

Source

$\bar{\nu}_e$ from β-decays

of n-rich fission products



pure $\bar{\nu}_e$ source

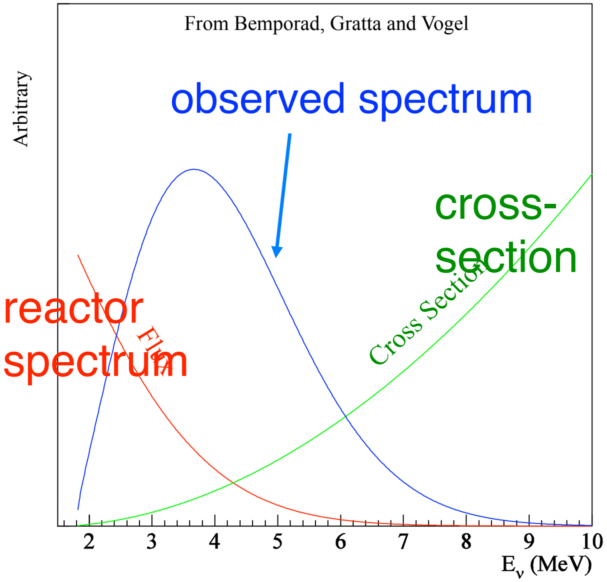
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

$$\frac{d^2N(E,t)}{dEdt} \equiv \sum_i \frac{W_{th}(t)}{\sum_j f_j(t)e_j} f_i(t)S_i(E)c_i^{ne}(E,t) + S_{SNF}(E,t) \quad (1)$$

Detection

inverse beta decay

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



observed spectrum

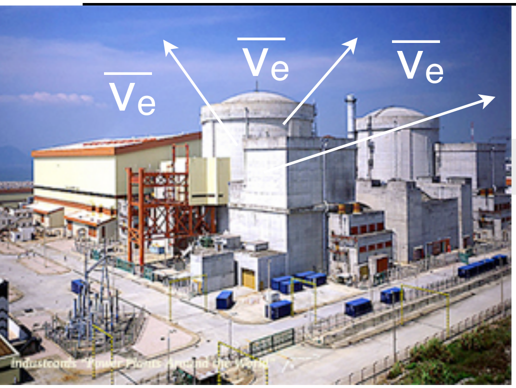
cross-section

reactor spectrum

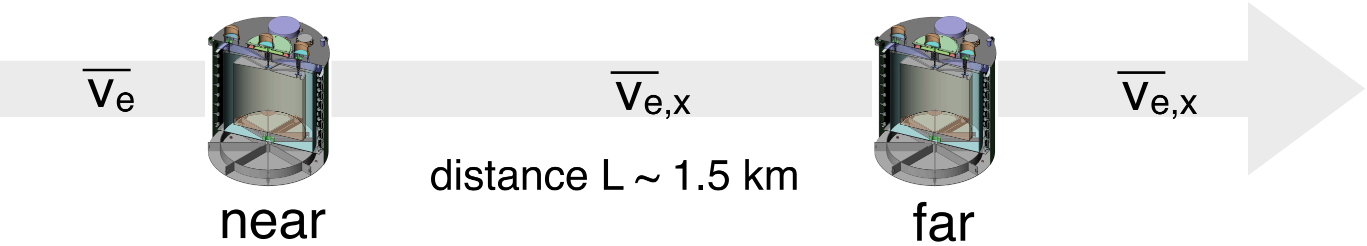
mean energy of $\bar{\nu}_e$: 3.6 MeV

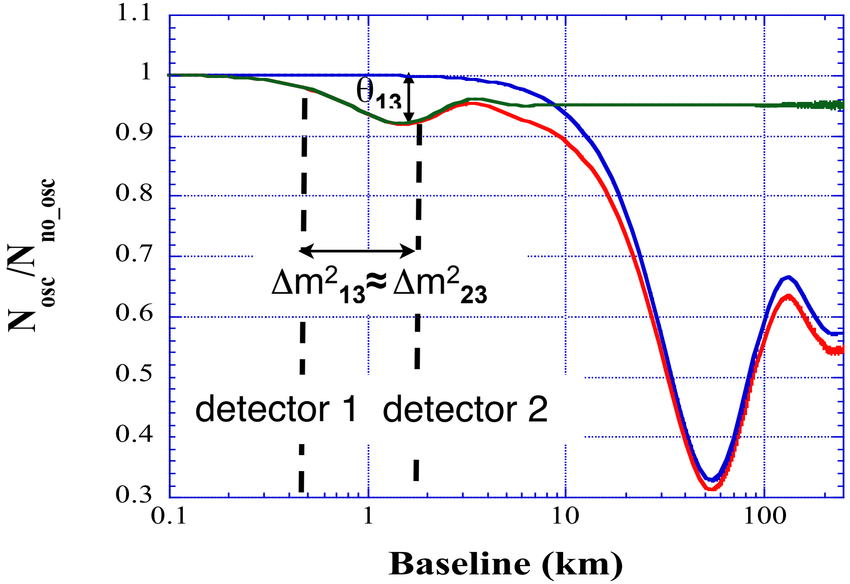
only disappearance experiments possible

Neutrino Oscillations in Reactor Experiments



Relative measurement between near and far detectors





Absolute Reactor Flux
Largest uncertainty in previous measurements

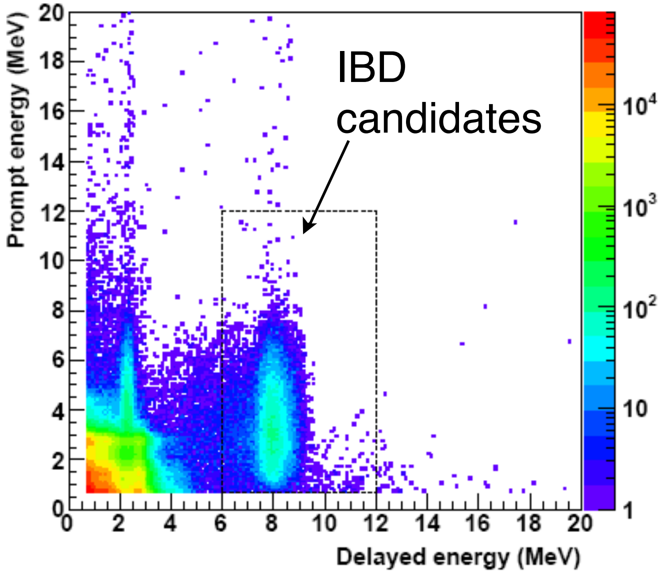
Relative Measurement
Removes absolute uncertainties!

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

far/near $\bar{\nu}_e$ target mass distances efficiency oscillation deficit

Antineutrino Candidates (Inverse Beta Decay)

Prompt + Delayed Coincidence

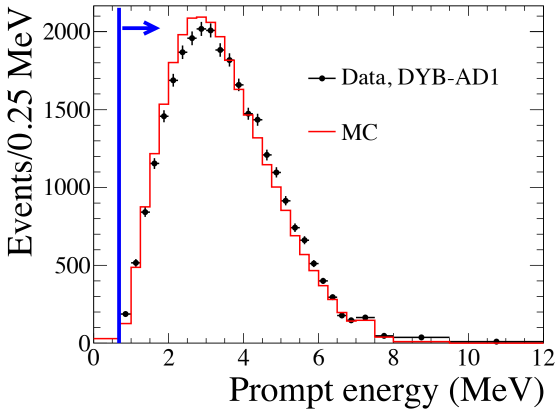


$$\overline{\nu}_e + p \rightarrow e^+ + n$$

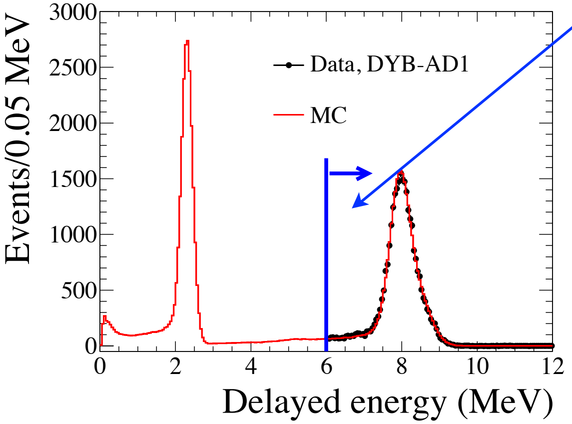
prompt event:
positron deposits energy and annihilates (~ns)

delayed event:
neutron thermalizes and captures on **Gd**

Prompt Energy Signal

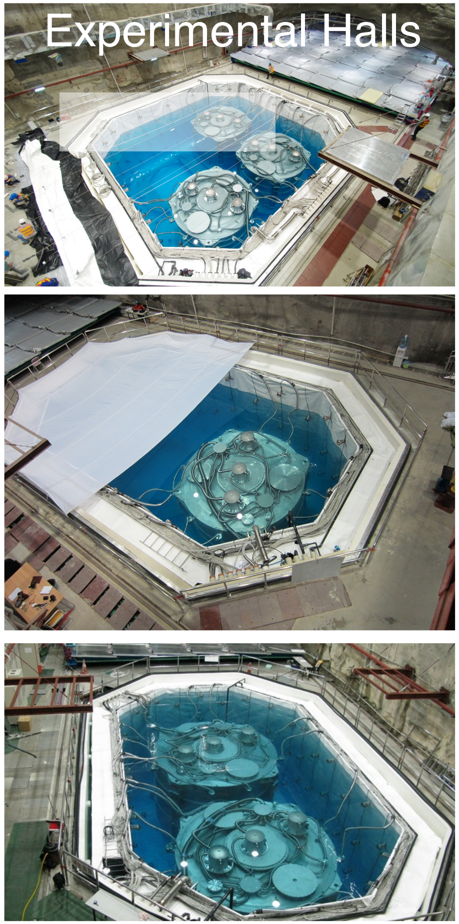


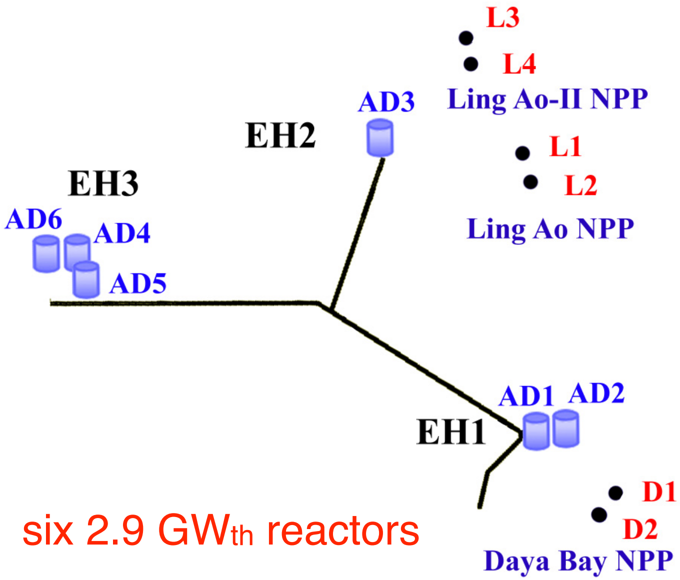
Delayed Energy Signal



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

Daya Bay Reactor Experiment



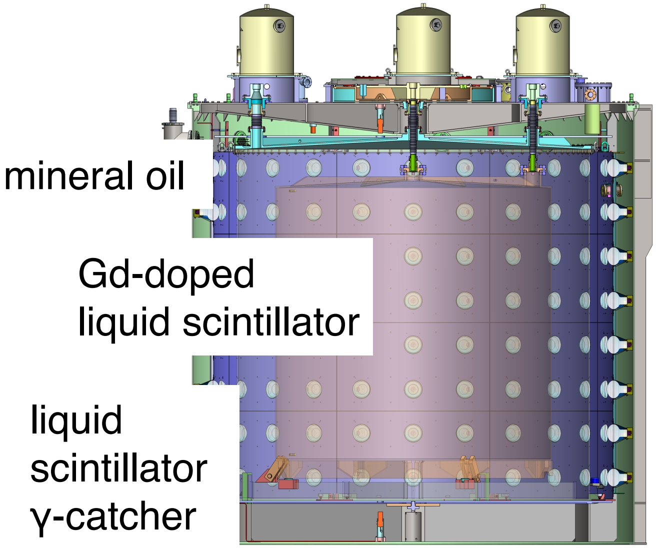


six 2.9 GW_{th} reactors

6 detectors, Dec 2011- Jul 2012
217 days

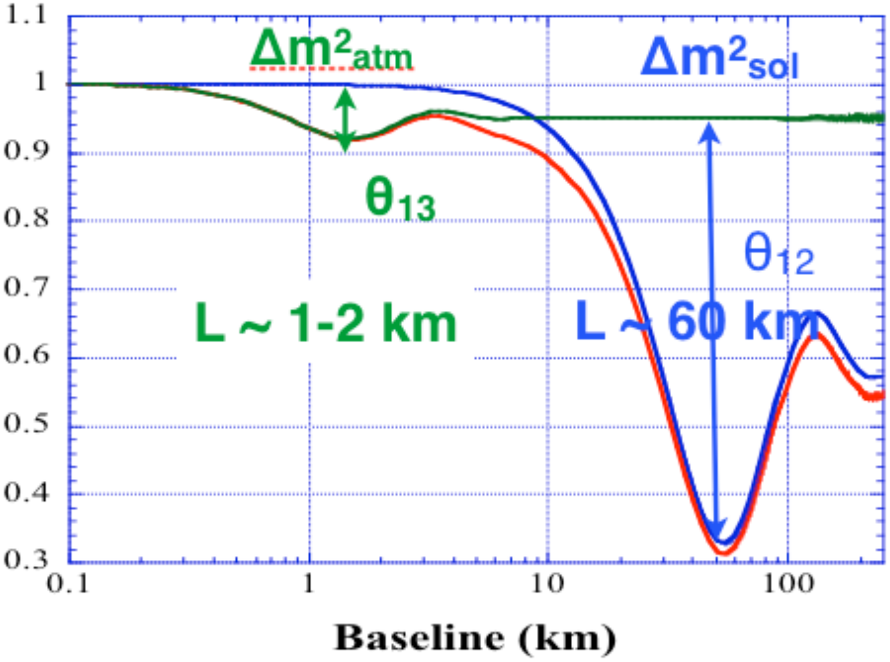
now running with 8 detectors

Antineutrino Detector



target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: (7.5 / √E + 0.9)%

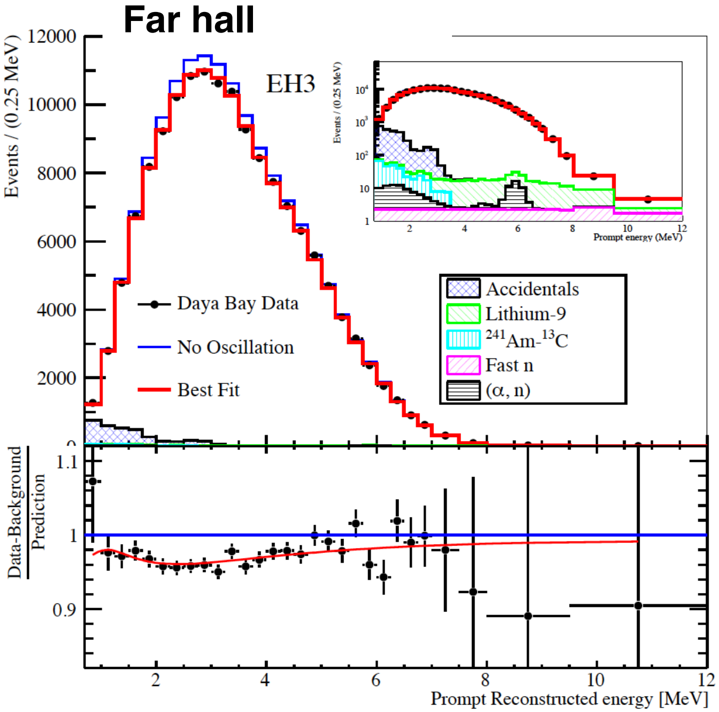
Oscillation Measurements



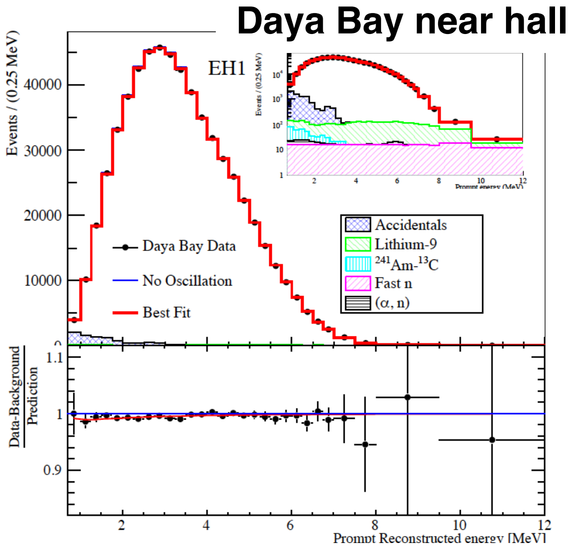
Energy Spectra

Prompt positron spectra measured in near, far detector halls

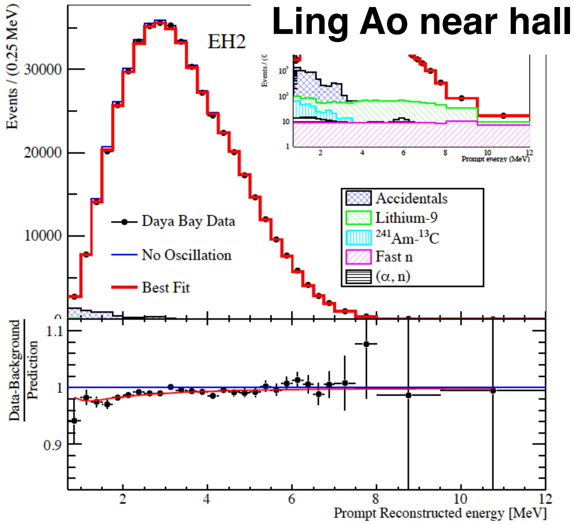
Far hall

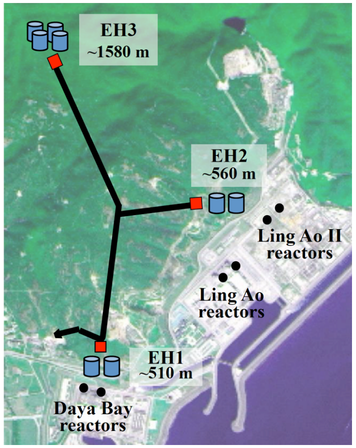


Daya Bay near hall



Ling Ao near hall

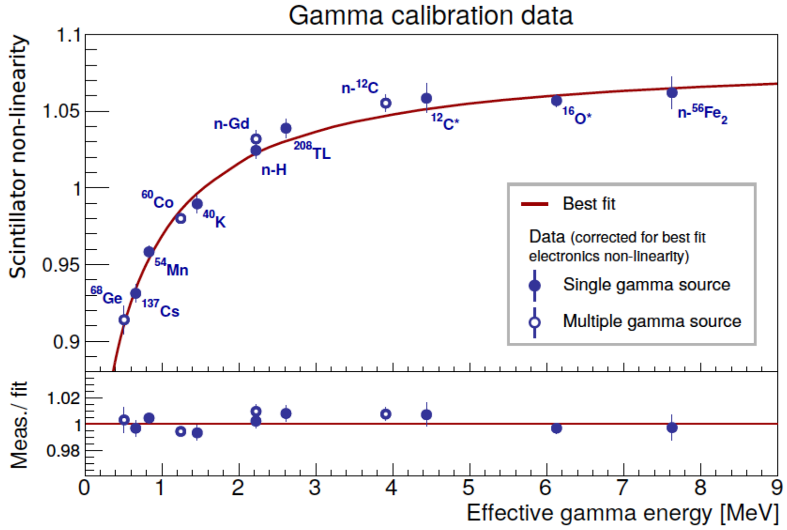


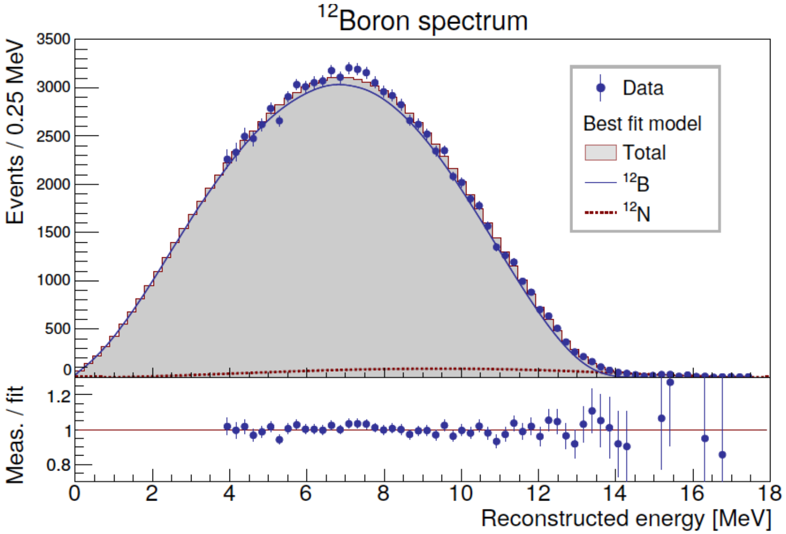


~300,000 inverse beta decay (IBD) events in near detectors

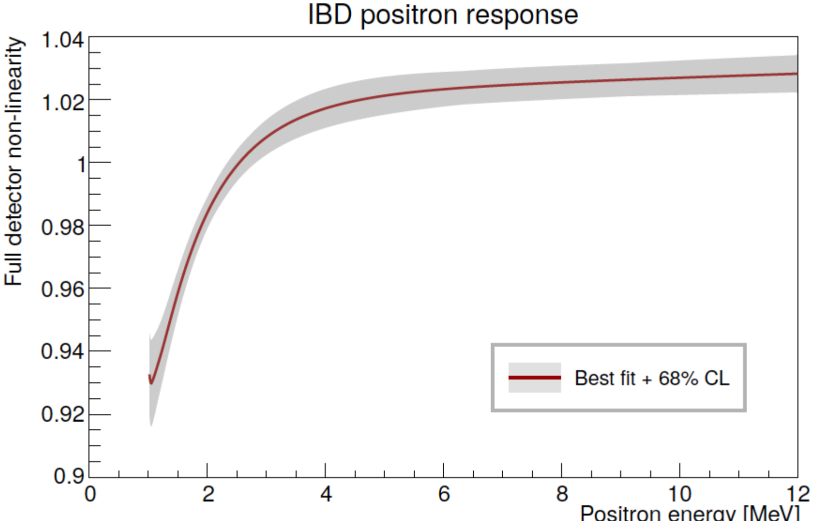
~42,000 IBD in far detector, spectral distortions consistent with neutrino oscillations

Energy Non-Linearity Calibration





- Two major sources of non-linearity
  - **scintillator response:** modeled with Birks formula and Cherenkov fraction
  - **electronics:** modeled with MC and single channel FADC measurement
- Combined fit with mono-energetic gamma peaks and ^{12}B beta-decay spectrum
- Cross-validated with ^{214}Bi, ^{208}Tl beta-decay spectrum, Michel electron spectrum and standalone bench-top Compton scattering measurement.

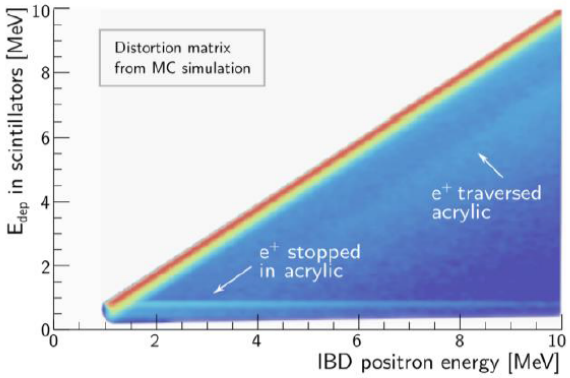


< 1% uncertainty (correlated among all detectors)

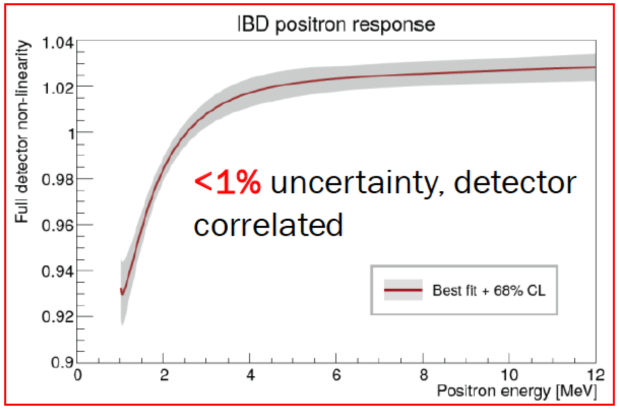
Daya Bay Detector Response and Efficiency

Detector Response

Energy losses in acrylic vessels

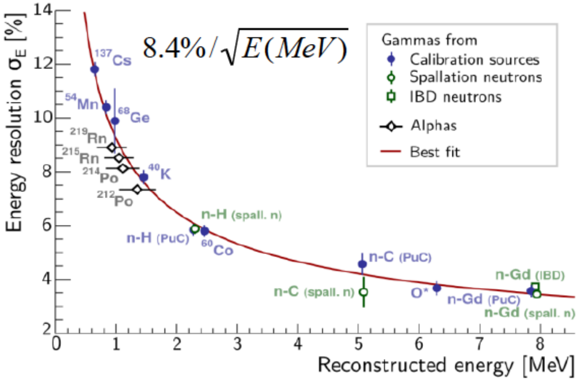


Nonlinear energy response



<1% uncertainty, detector correlated

Energy resolution



Detection Efficiency

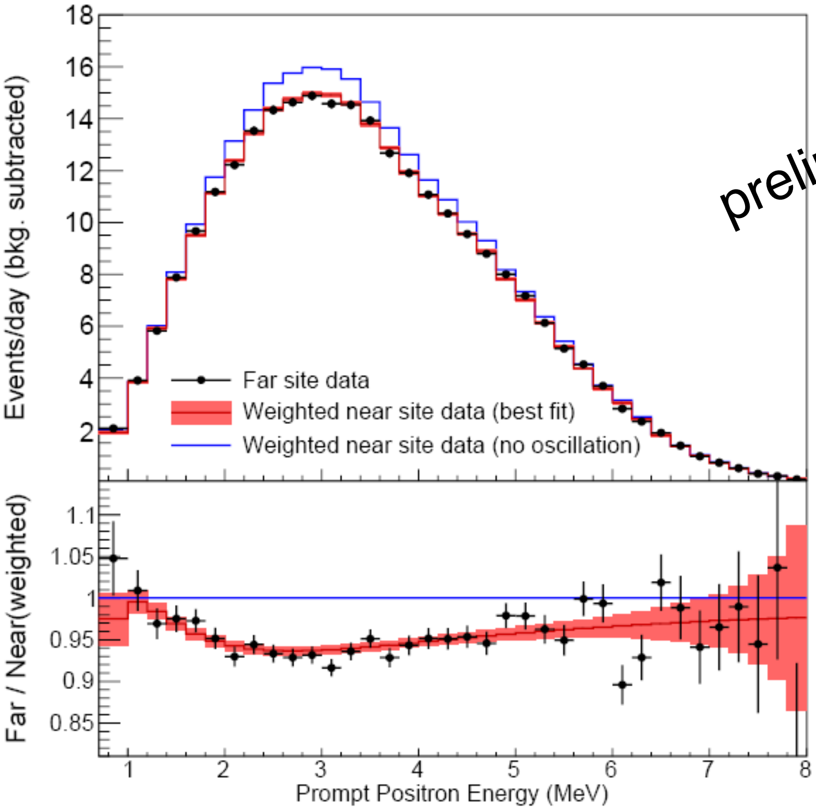
	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

Detector efficiency is obtained from full detector MC simulation which is tuned with data.

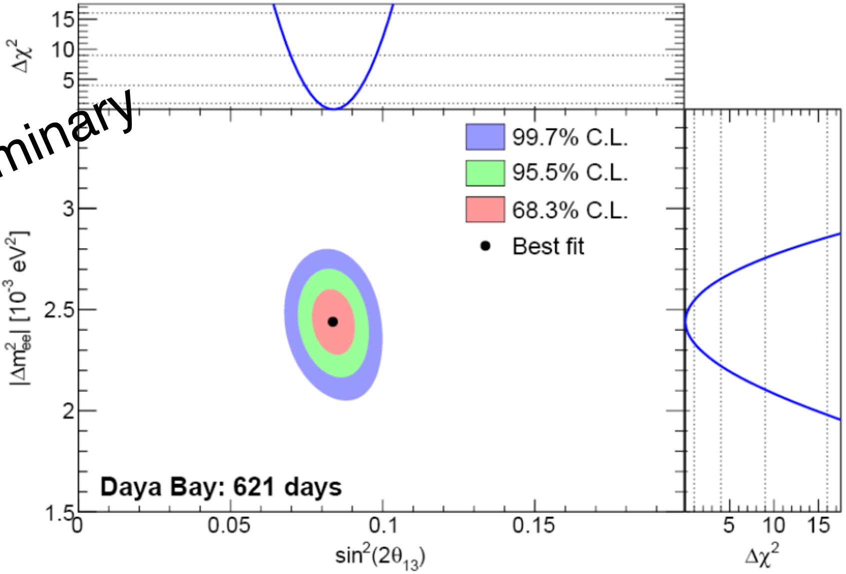
Correlated uncertainties from comparison of MC and data.

Latest Daya Bay Results

621 days of data, n+Gd



preliminary



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

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

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

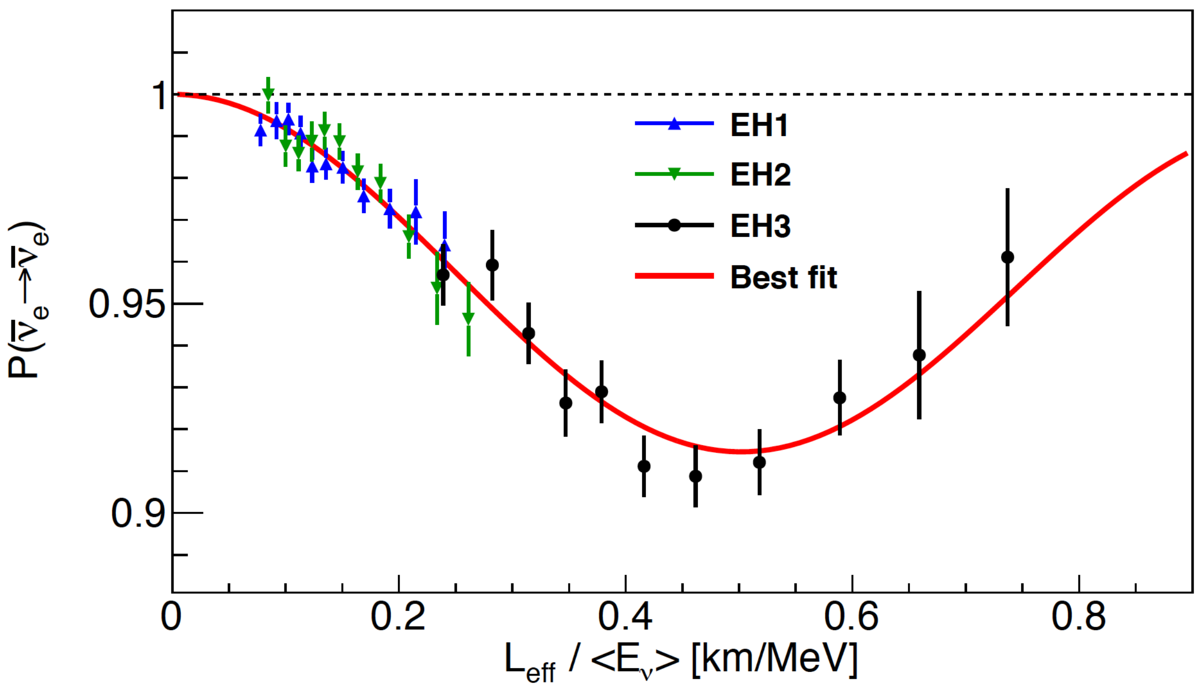
- far site expected spectra based on near-site observed spectra
- current analysis is designed to be (almost) independent of any reactor flux models

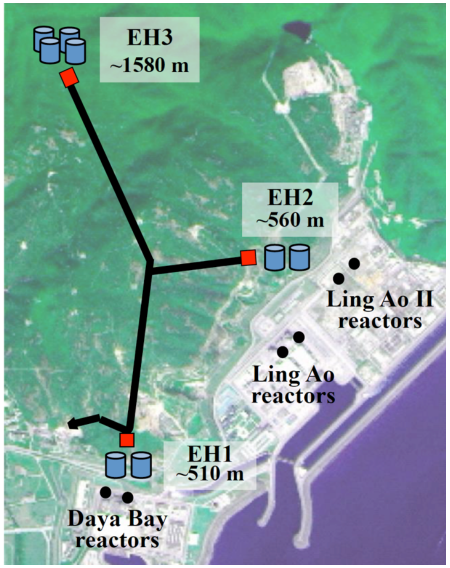
consistent results from nH analysis

Daya Bay Neutrino Oscillation

Neutrino oscillation is energy and baseline dependent

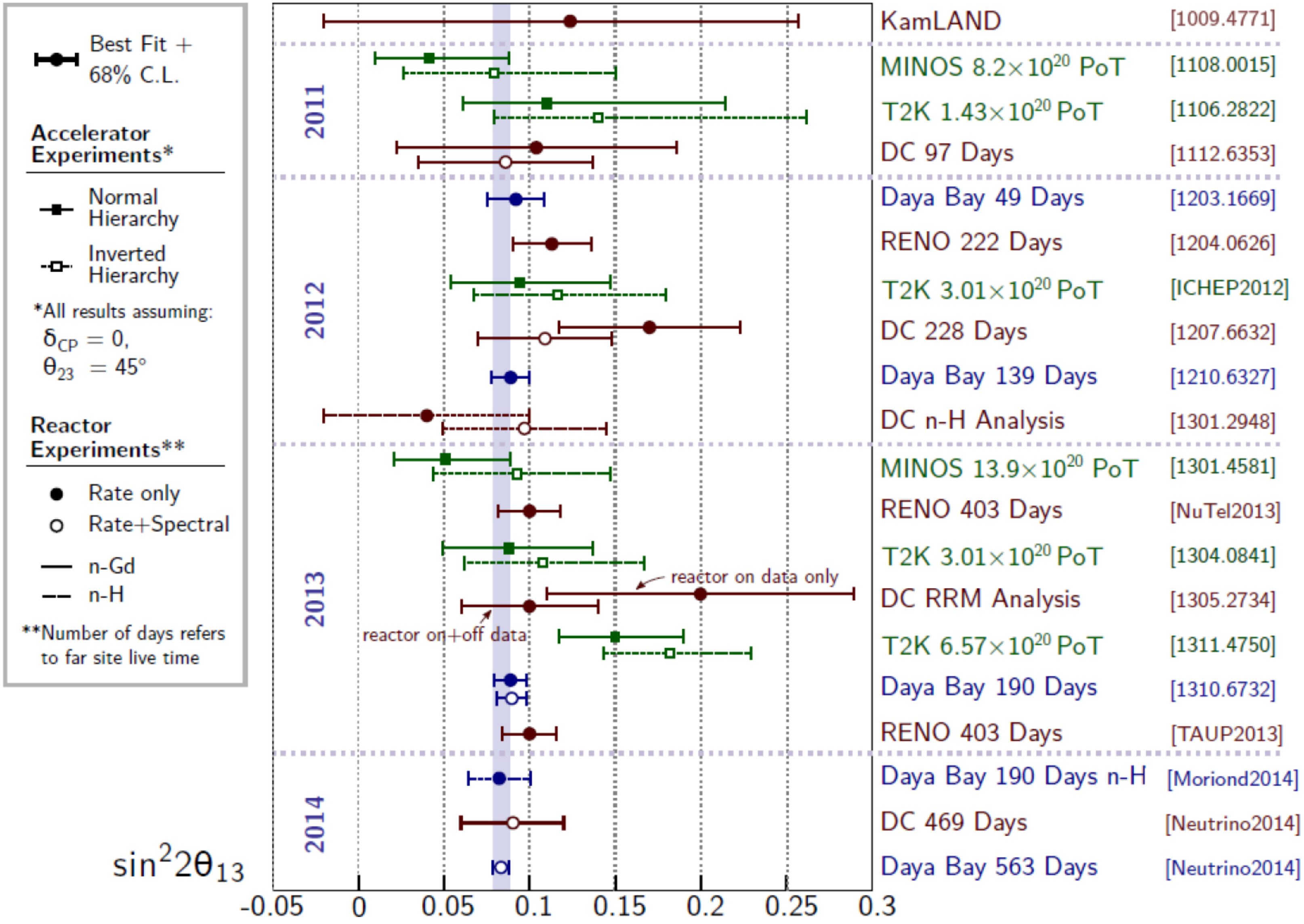
$$P_{i\to j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$





Daya Bay demonstrates L/E oscillation

A Precision Measurement of θ_{13}



2011

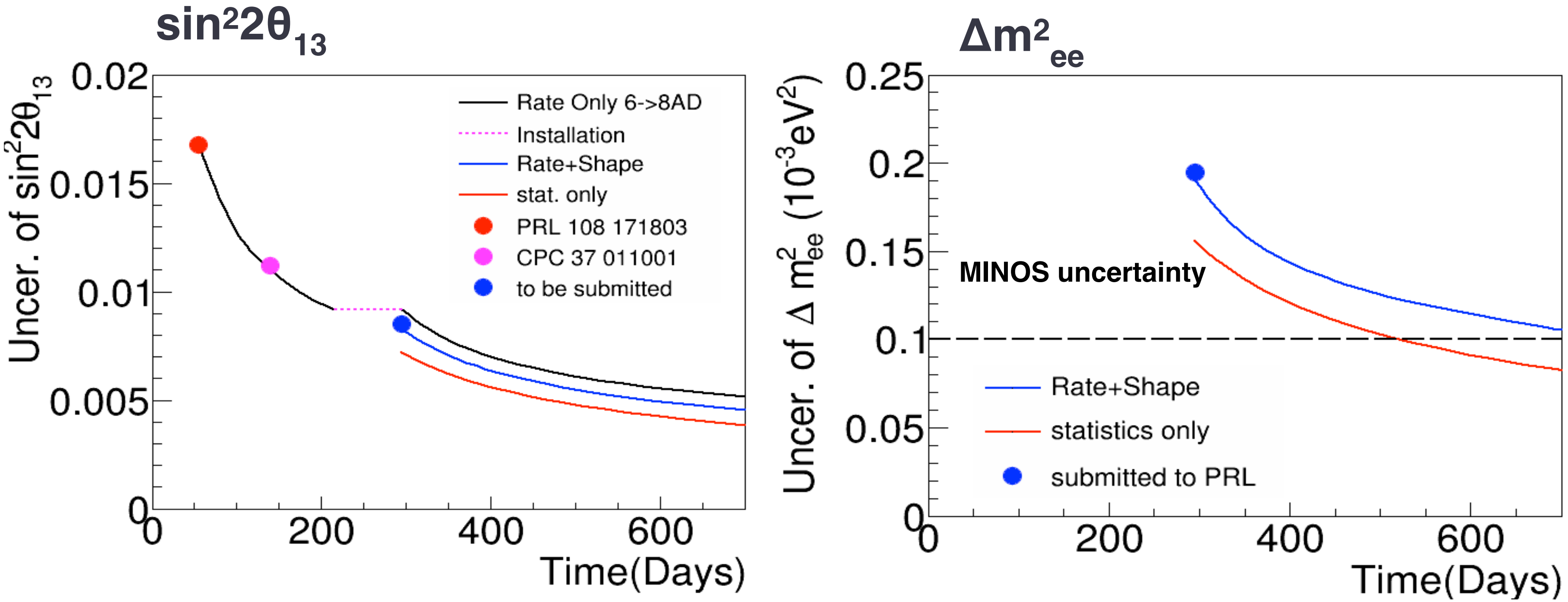
2012

2013

2014

Daya Bay Sensitivity Projections

Precision Measurements in $\sin^2 2\theta_{13}$ and Δm^2_{ee}



Daya Bay remains statistically limited through 2015

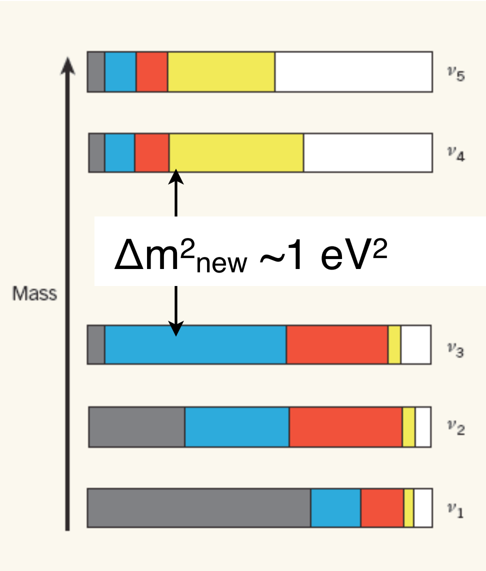
Major systematics:

θ_{13}: Relative + absolute energy, and relative efficiencies

$|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds

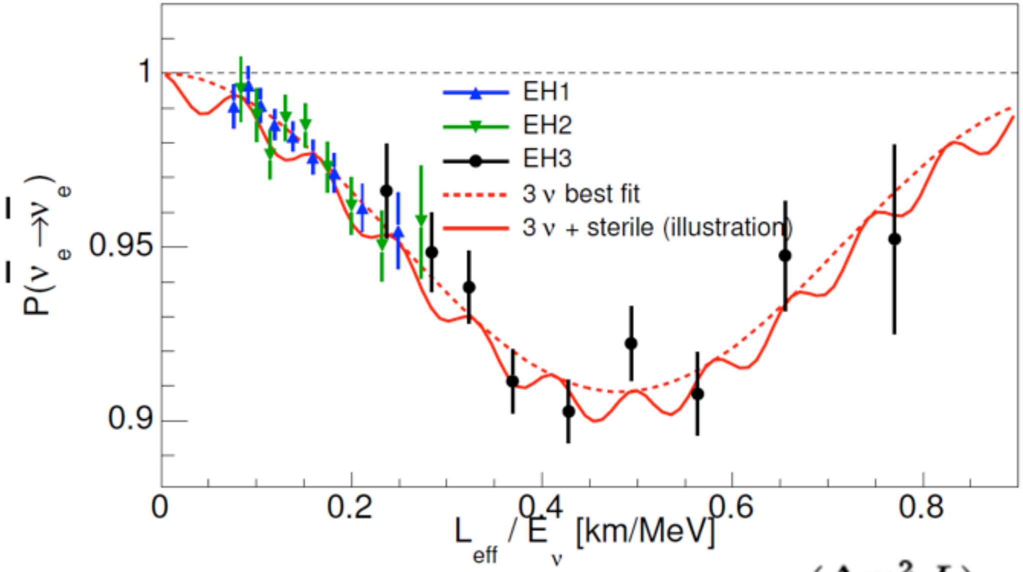
Daya Bay can also improve systematics.

Beyond 3 Neutrinos?



$\Delta m^2_{new} \sim 1\ \mathrm{eV}^2$

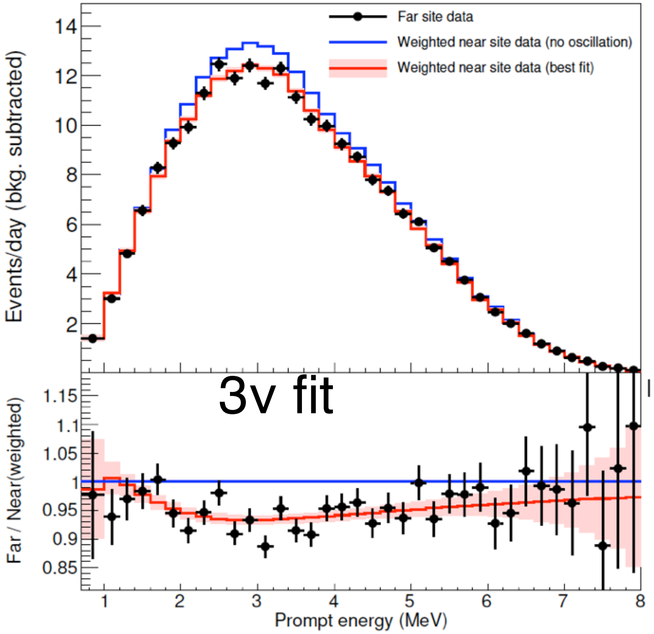
Search for Sterile Neutrinos at Daya Bay



$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

sterile neutrinos would appear as additional spectral distortion and overall rate deficit

look for additional spectral distortions and rate deficit



3ν fit

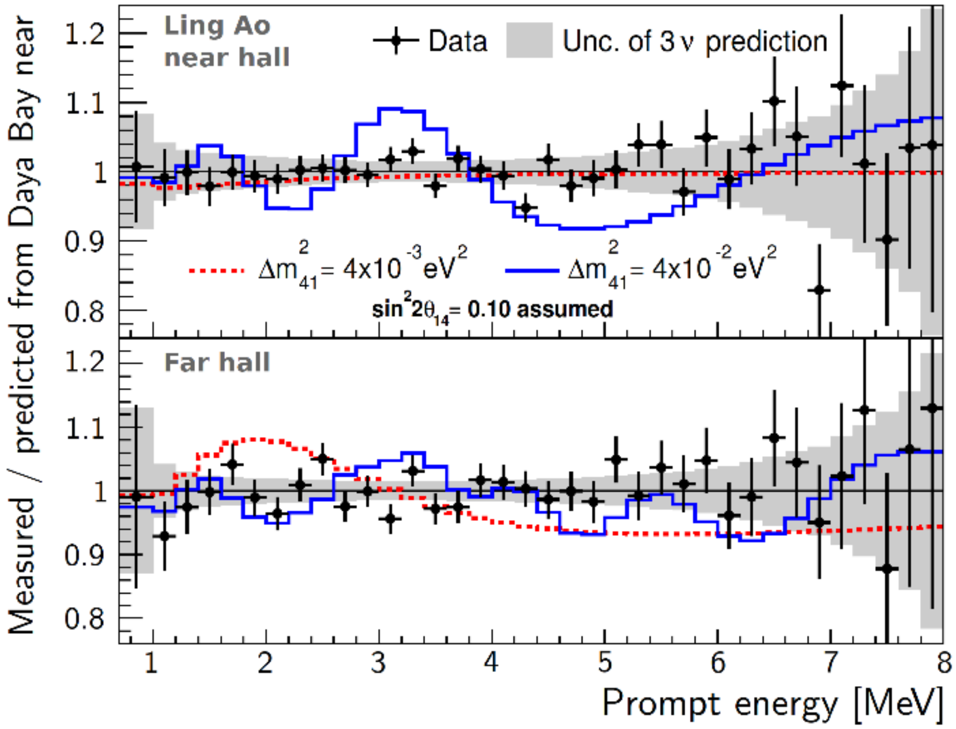
expand to 3+1ν fit

relative rate+shape comparison

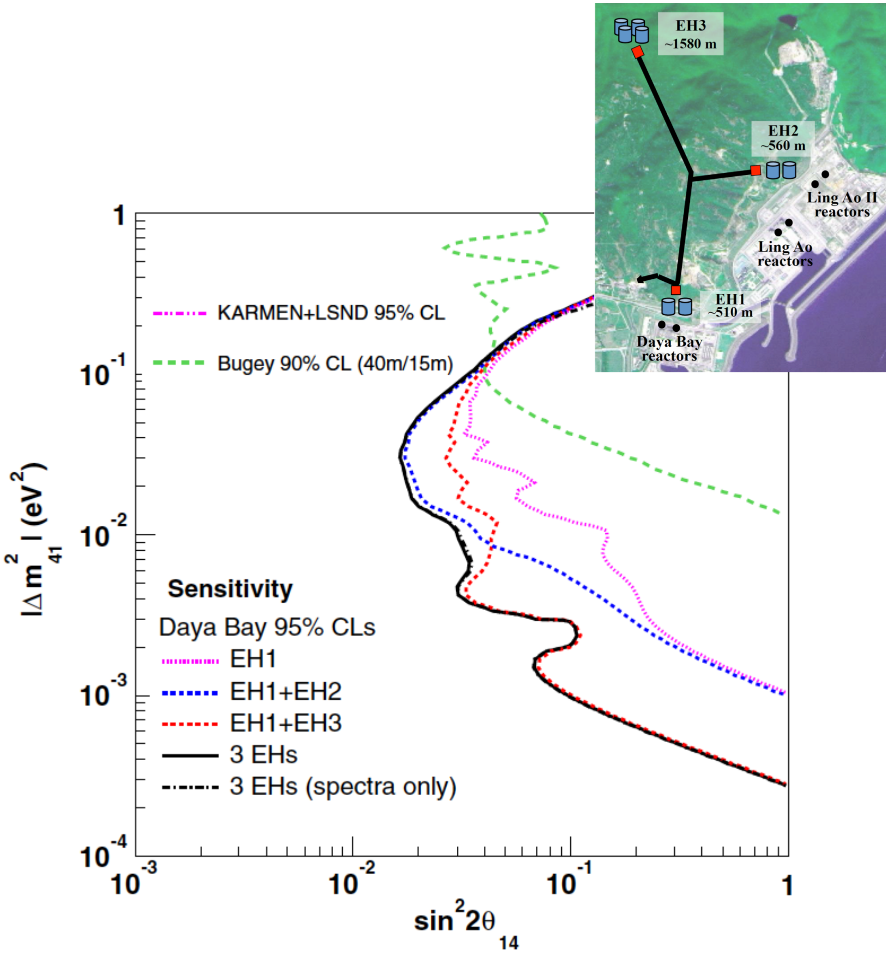
- independent of reactor model, loss of sensitivity at high Δm^2

Probe largely unexplored region at $\Delta m^2_{41} < 0.1$ eV^2

Probing ν Oscillations at Different Baselines



Daya Bay collaboration
PRL 113 (2014) 141802



Experimental halls have different baselines which make them sensitive to different mass ranges of sterile neutrinos.

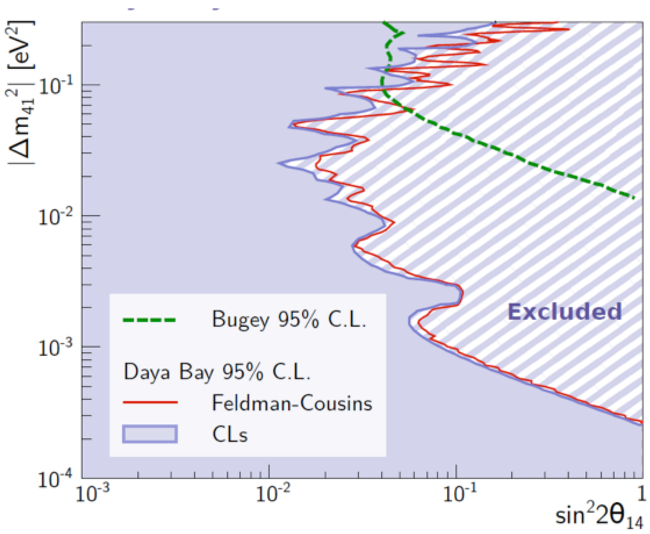
Daya Bay Sterile ν Results

Daya Bay sets new limits in region of $\Delta m^2_{41} < 0.1\ \mathrm{eV}^2$

Daya Bay consistent with standard 3-flavor neutrino model

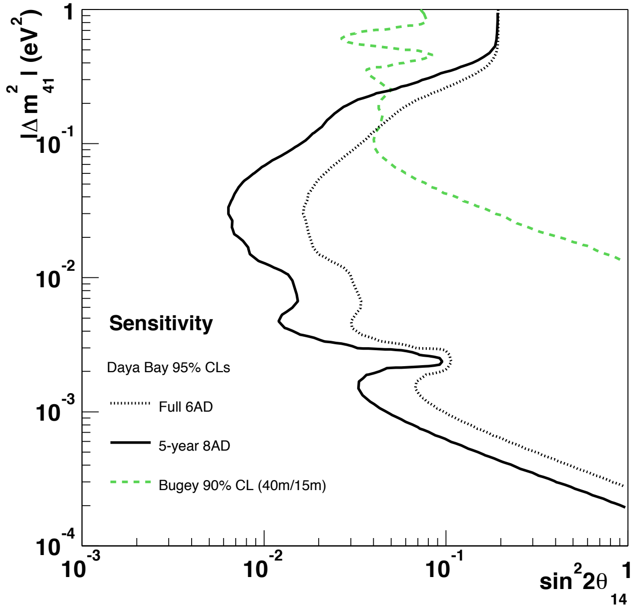
Recent Results

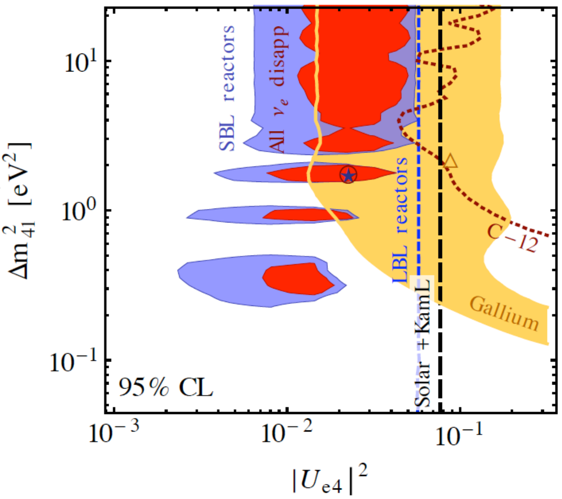
6 detectors



Future Sensitivity

8 detectors



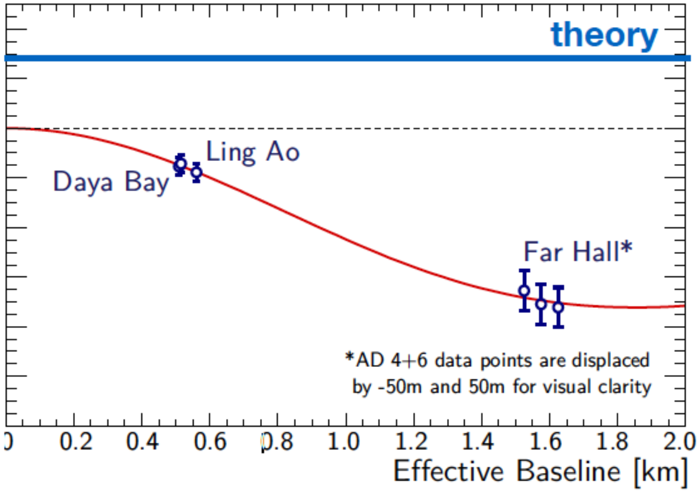


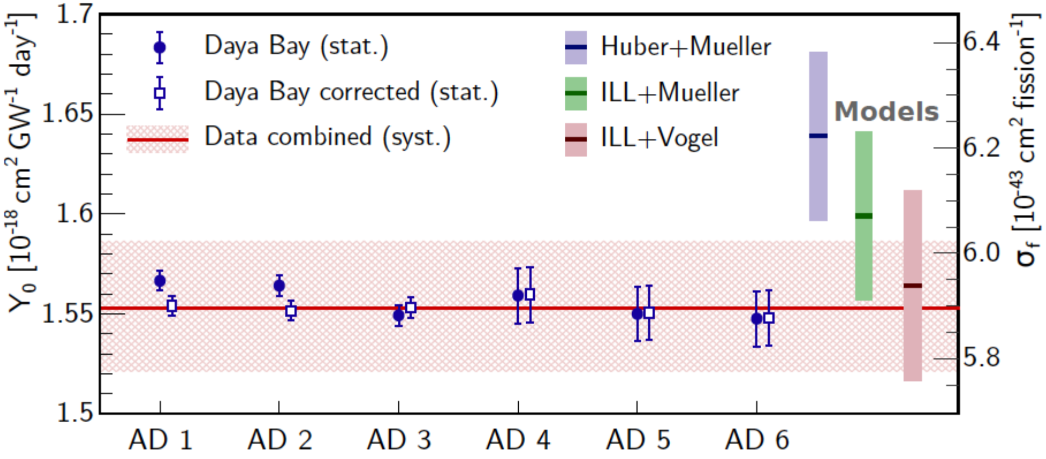
best fit regions

Current results are limited by statistics. Expect improvement with the full 5-year data set.

Daya Bay Flux Normalization

Measurement of Reactor Neutrino Flux in Every Antineutrino Detector





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

	Uncertainty
statistics	0.2%
$\sin^2 2\theta_{13}$	0.2%
reactor	0.9%
detector efficiency	2.1%
combined	**2.3%**

3-AD (near sites) measurement:

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

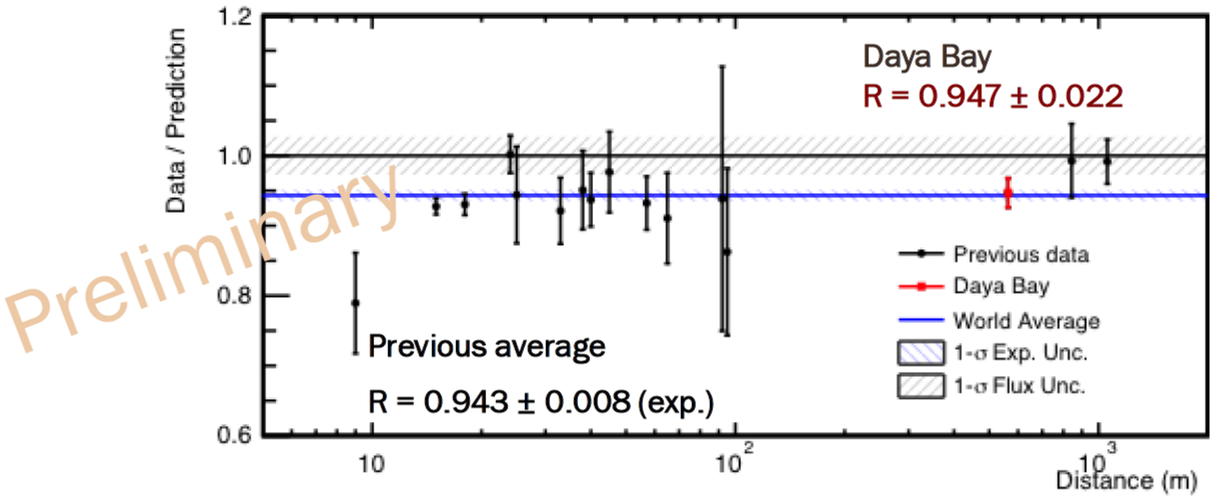
$\sigma_f = 5.934 \times 10^{-43}$

Data/Prediction (Huber+Mueller)
0.947 ± 0.022

Data/Prediction (ILL+Vogel)
0.992 ± 0.023

Daya Bay Flux Normalization

Global comparison of measurement and prediction (Huber+Mueller)



Results based on 3 near site Antineutrino Detectors (ADs)

Effective baseline of Daya Bay: $L_{eff} = 573$m

- Flux weighted detector-reactor distances of 3 ADs in near sites only.

Effective fission fractions α_k of Daya Bay ^{235}U: ^{238}U: ^{239}Pu: ^{241}Pu = 0.586: 0.076: 0.288: 0.050

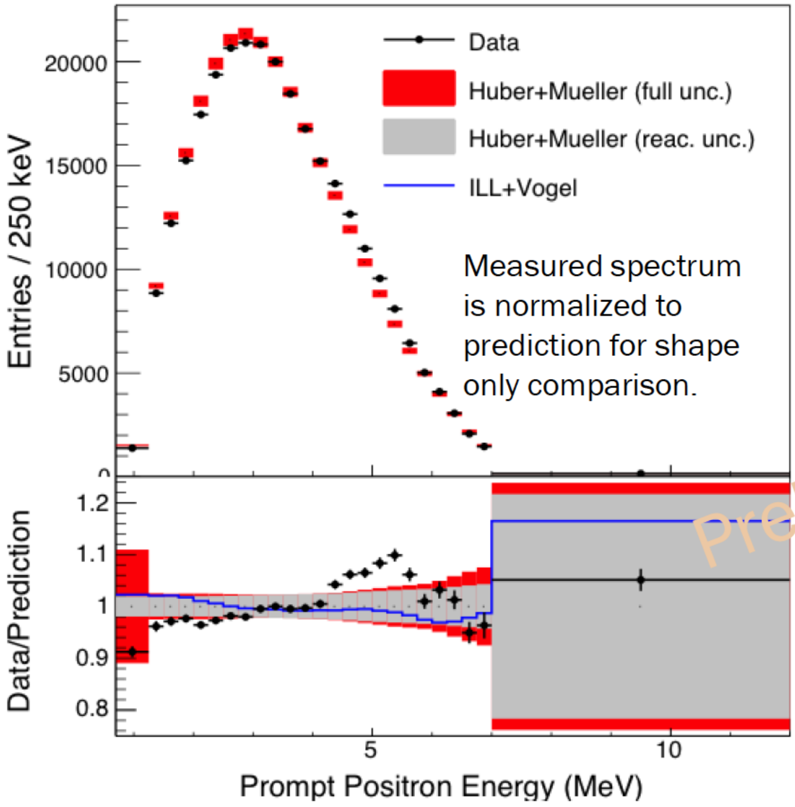
- Mean fission fractions from 3 ADs in near sites only.

Daya Bay reactor flux measurement consistent with previous results

Daya Bay Spectrum

Comparison of Data and Prediction

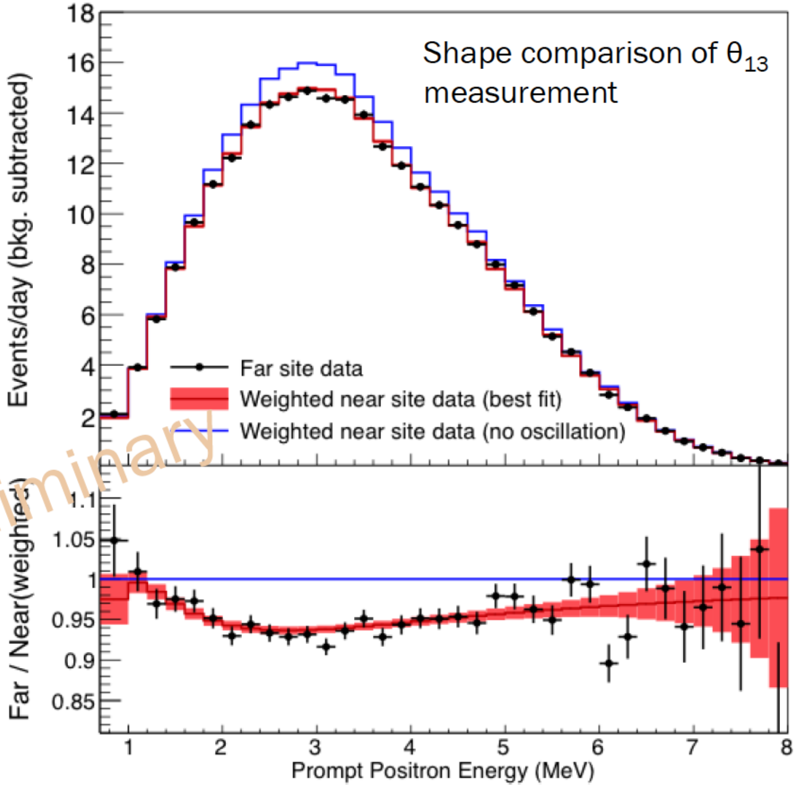
- Absolute shape comparison of data and prediction: $\chi^2/\mathrm{ndf} = 41.8/21$



Measured spectrum is normalized to prediction for shape only comparison.

Shape Comparison Between Near and Far Detectors

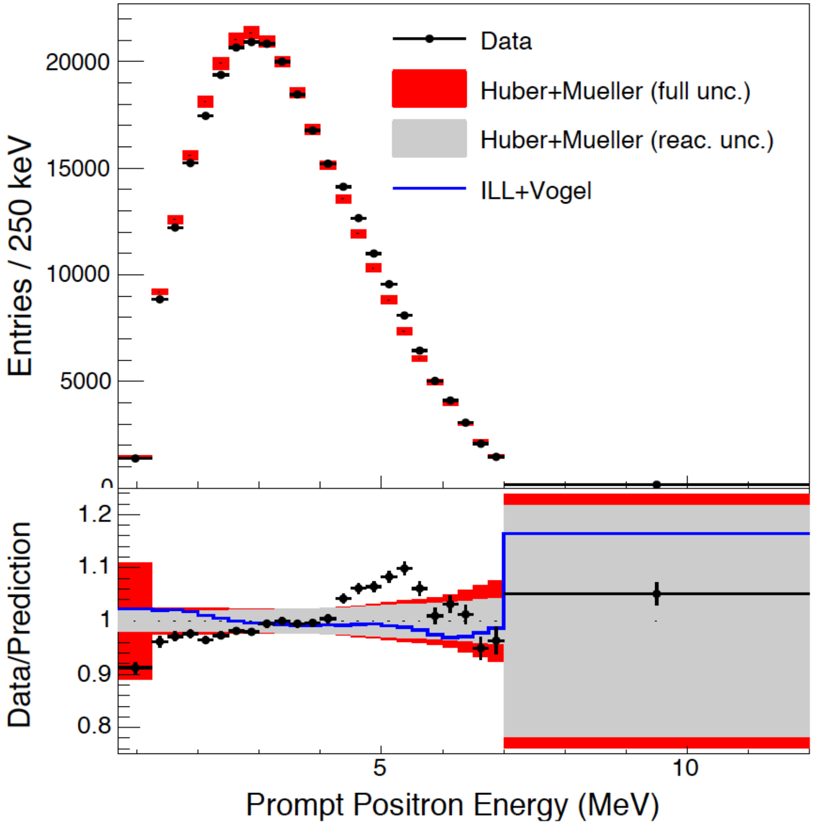
- Primarily relative shape comparison among detectors: $\chi^2/\mathrm{ndf} = 134.7/146$



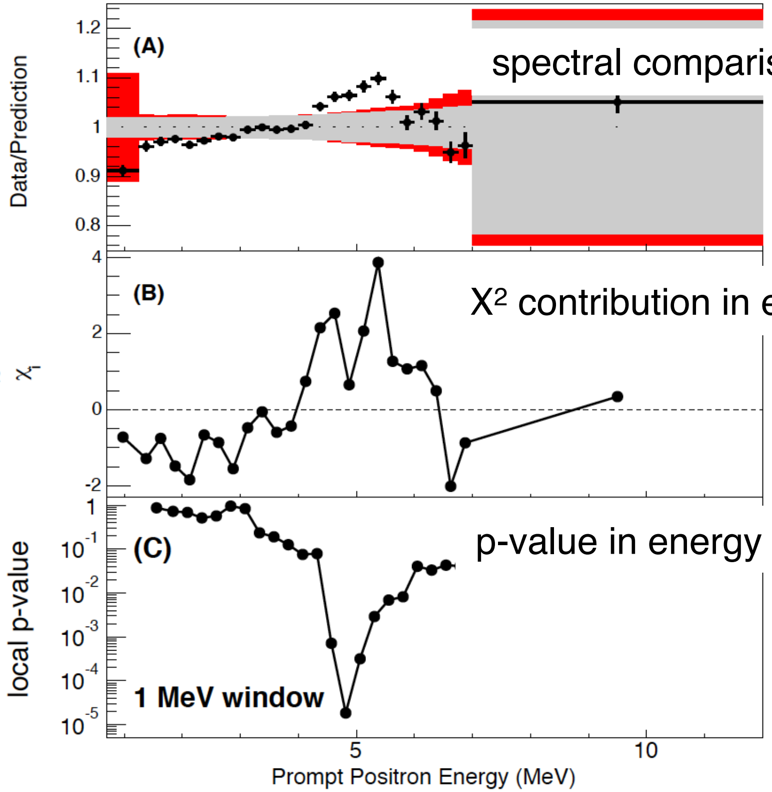
Shape comparison of θ_{13} measurement

Daya Bay Absolute Spectrum

Data/prediction shows deviation in 4-6 MeV region



Significance of Deviations



spectral comparison

X^2 contribution in each bin

p-value in energy window

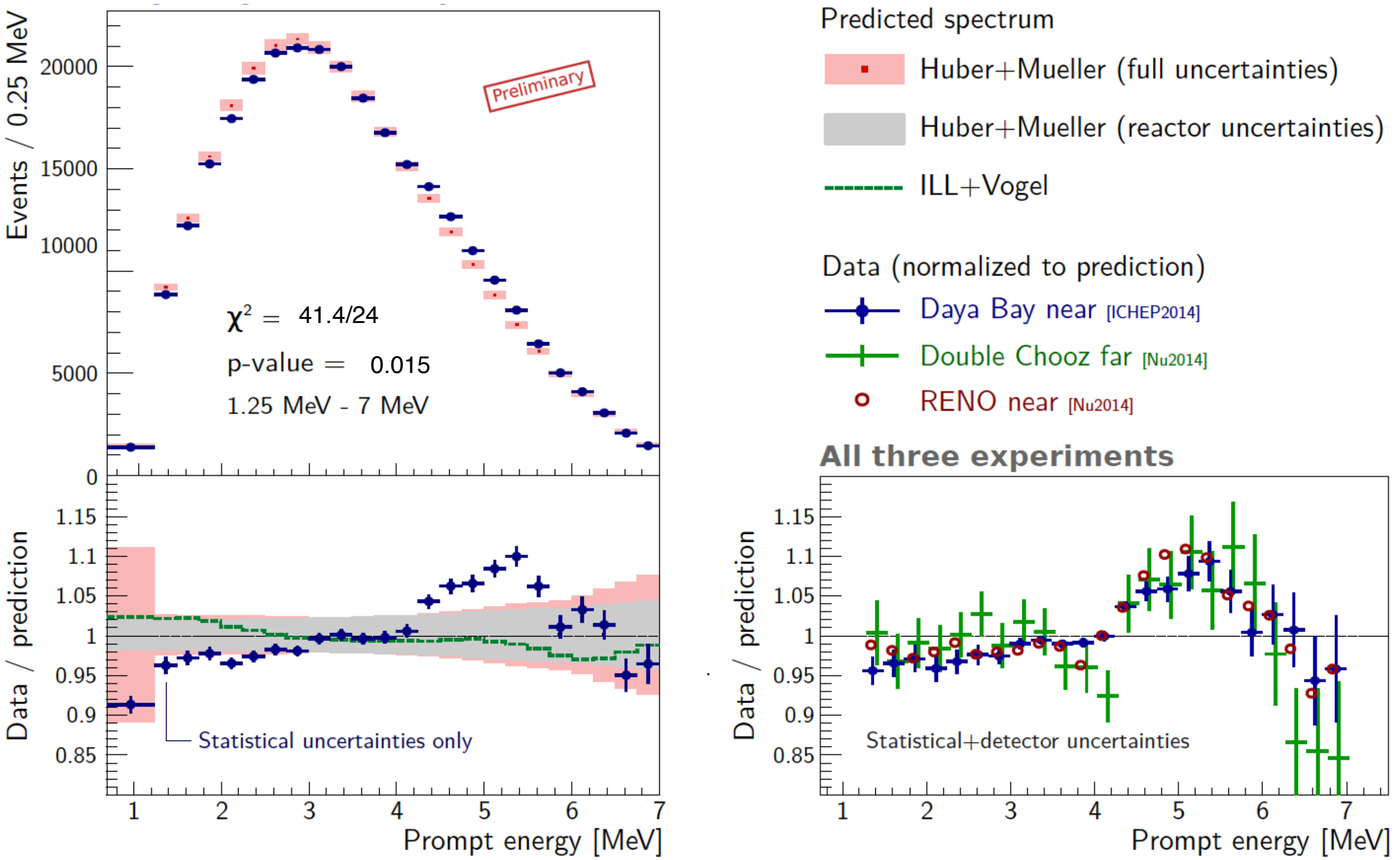
Recent ab-initio calculation provides a possible explanation involving decays from prominent fission daughter isotopes.

Dwyer, Langford
arXiv:1407.1281

Daya Bay Spectrum

Data/prediction shows deviation in 4-6 MeV region.

Spectral feature seen by Daya Bay, Double Chooz, and Reno



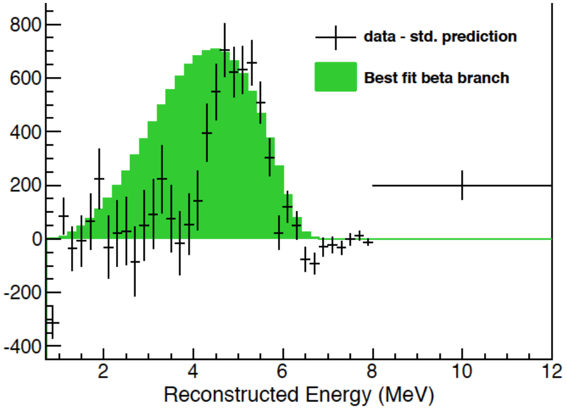
Excess events around 5 MeV reactor power correlated & time independent, match IBD events

Discrepancy ~2σ over entire energy range, ~4σ locally

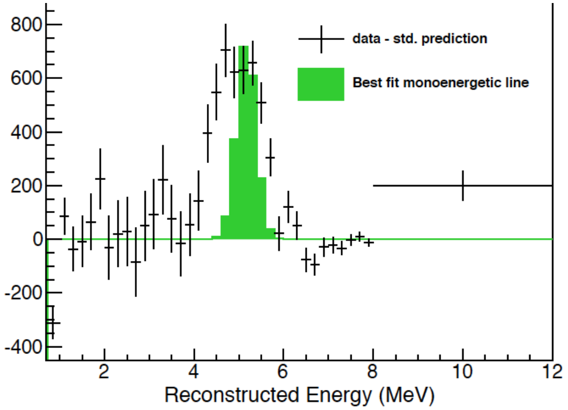
Daya Bay Absolute Spectrum

Investigation of Spectral Feature

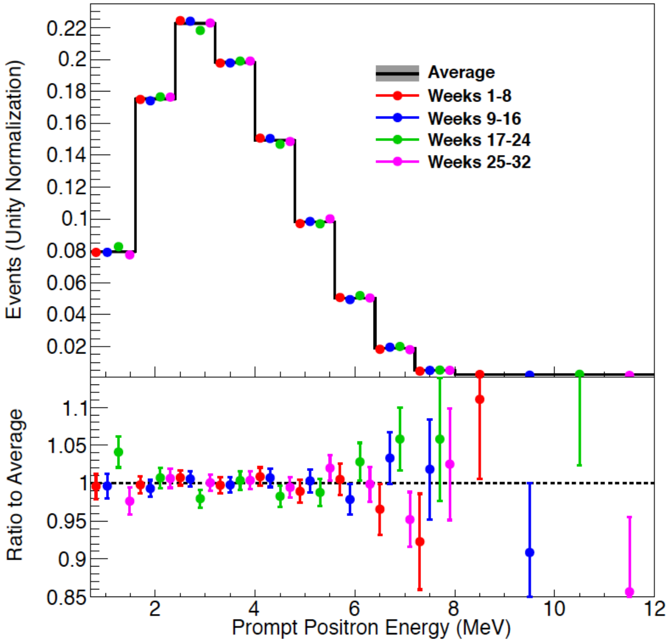
Not a beta-branch



Not a delta function



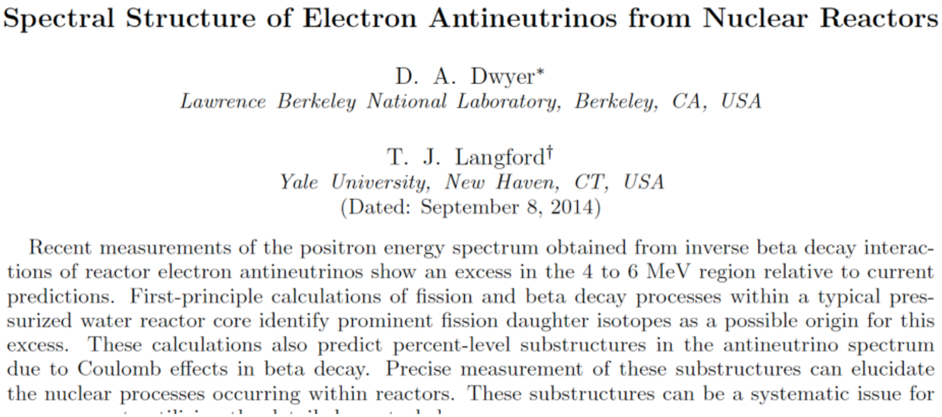
No time-dependence



^{12}B spectrum does not have local structure at [4,6] MeV

Disfavors instrumental effects
(electronics and non-linear energy model distortion)

Predicting the Reactor Spectrum

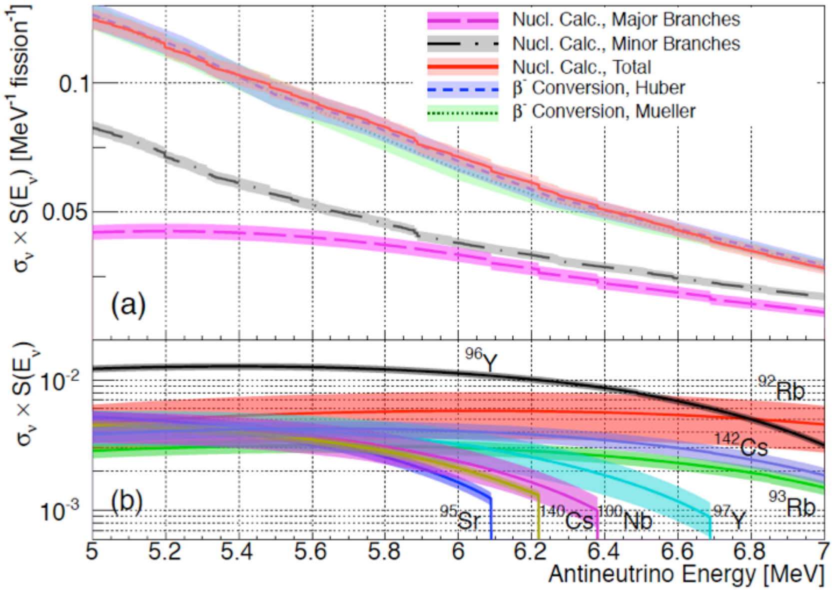


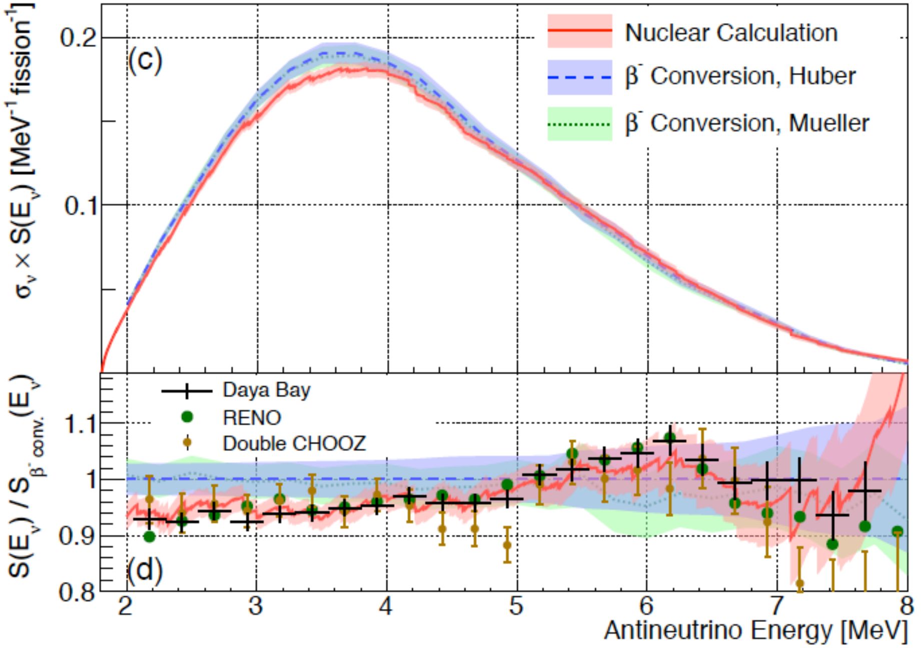
Spectral Structure of Electron Antineutrinos from Nuclear Reactors

D. A. Dwyer*
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

T. J. Langford†
Yale University, New Haven, CT, USA
(Dated: September 8, 2014)

Recent measurements of the positron energy spectrum obtained from inverse beta decay interactions of reactor electron antineutrinos show an excess in the 4 to 6 MeV region relative to current predictions. First-principle calculations of fission and beta decay processes within a typical pressurized water reactor core identify prominent fission daughter isotopes as a possible origin for this excess. These calculations also predict percent-level substructures in the antineutrino spectrum due to Coulomb effects in beta decay. Precise measurement of these substructures can elucidate the nuclear processes occurring within reactors. These substructures can be a systematic issue for



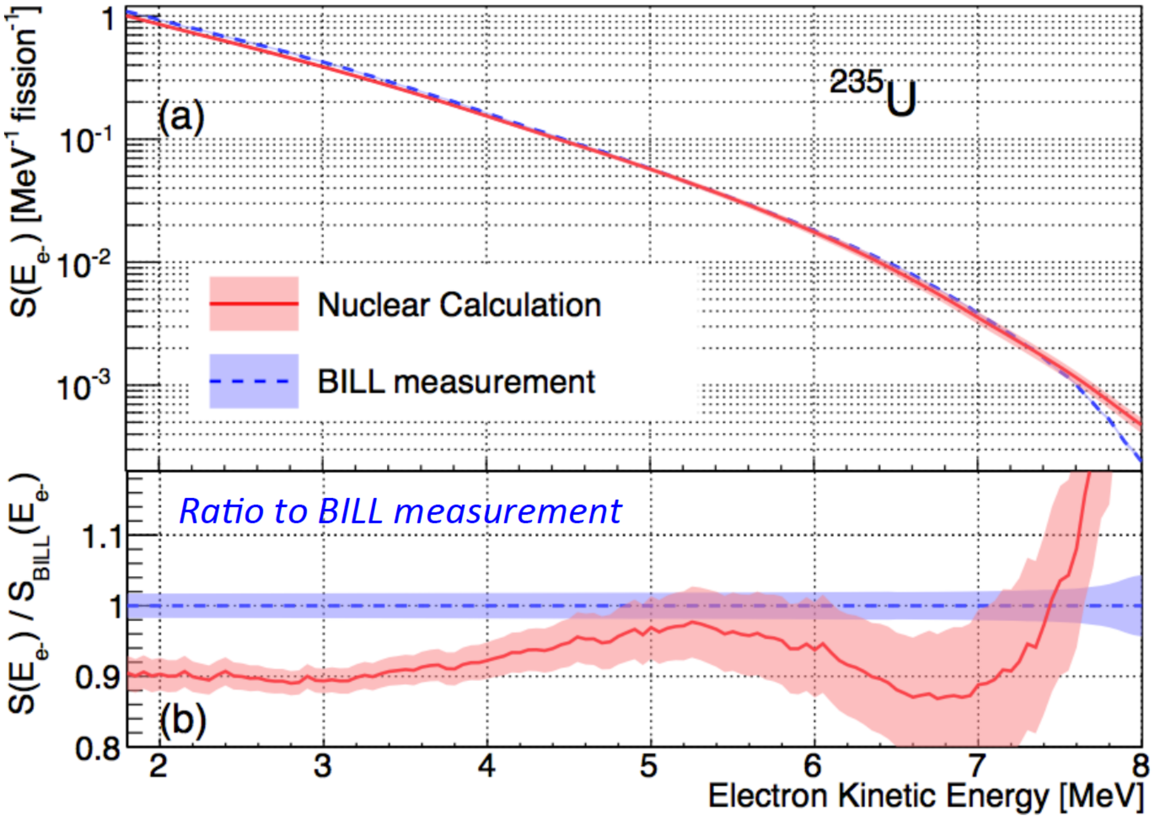


Do we understand predictions and models of reactor spectrum?

From Dwyer, Langford
arXiv:1407.1281

Predicting the Reactor Spectrum

Direct calculation of ^{235}U β^- spectrum disagrees with BILL measurement



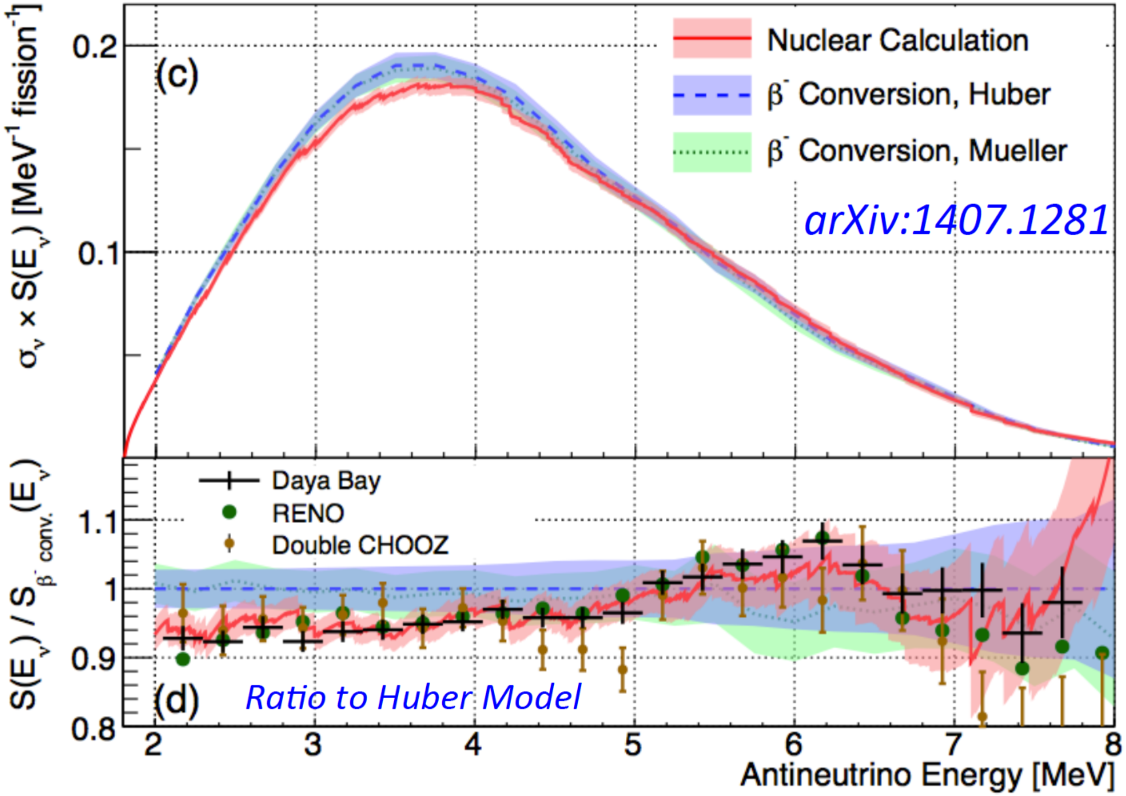
Note:
Uncertainty band for calc. is a lower bound.

Only includes tabulated yield+branch uncertainties

From Dwyer, Langford
arXiv:1407.1281

Predicting the Reactor Spectrum

Direct calculation appears to agree with preliminary measurements from recent reactor experiments



arXiv:1407.1281

Ratio to Huber Model

Note:
Preliminary data compared using approx. $E_\nu \approx E_{e+} + 0.8$ MeV

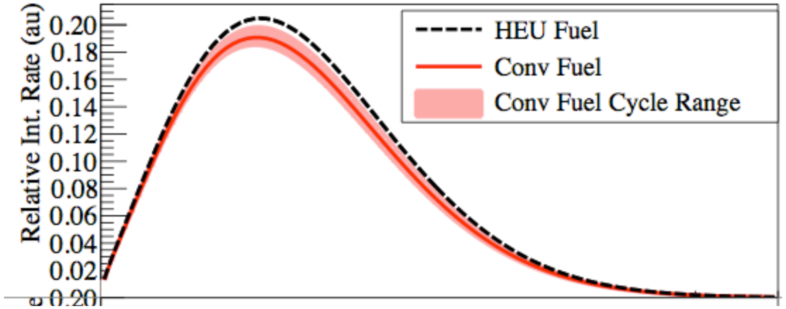
Data normalization adjusted to accurately compare shape.

Experimental data needed to understand spectrum and constrain reactor models

From Dwyer, Langford
arXiv:1407.1281

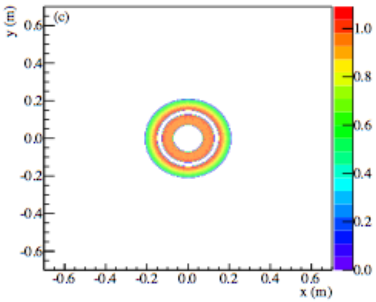
A Reactor Experiment At Short Baselines

Measurement of Reactor Spectrum



HEU core provides static spectrum
Measure at short baselines (<10m)

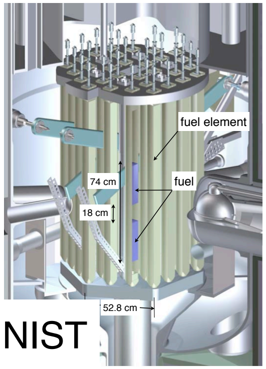
At Short Distance From a Point Source



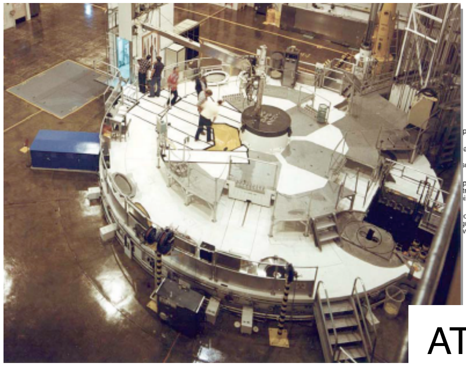
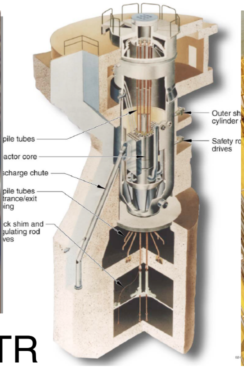
compact core (< 1m)

Precision study of the reactor spectra at short baselines

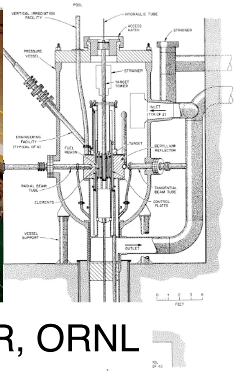
US operates high-powered research reactors

NBSR, NIST

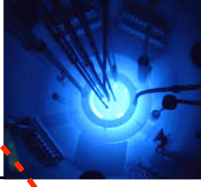



ATR

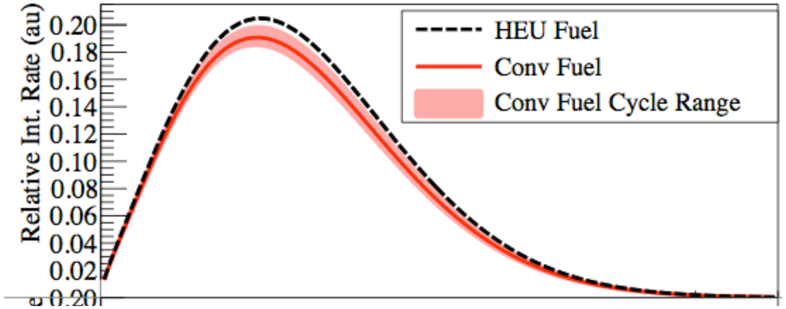
HFIR, ORNL

A Reactor Experiment At Short Baselines

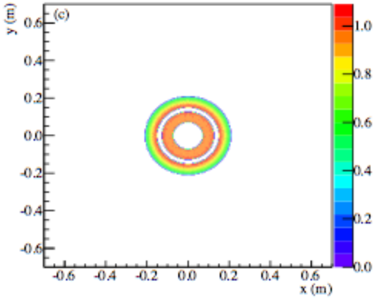


Measurement of Reactor Spectrum

At Short Distance From a Point Source



commercial core

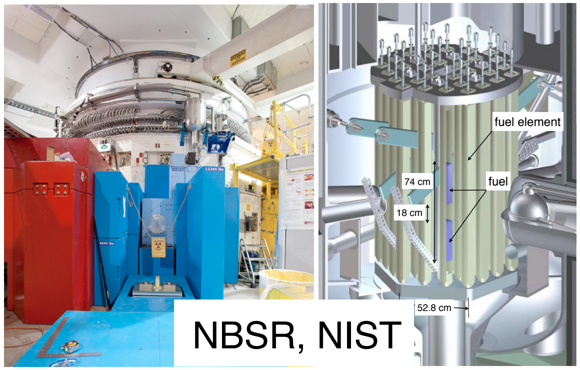


HEU core provides static spectrum
Measure at short baselines (<10m)

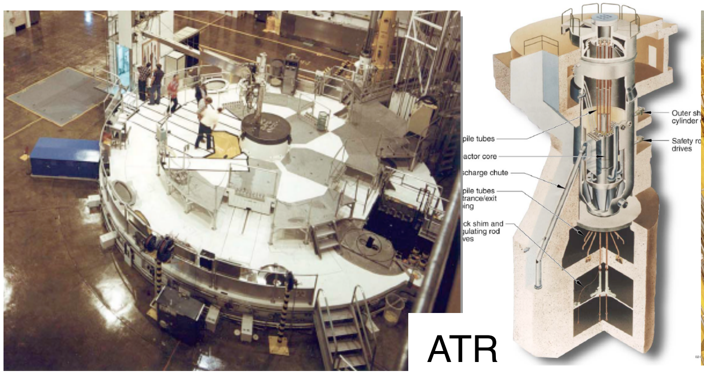
compact core (< 1m)

Precision study of the reactor spectra at short baselines

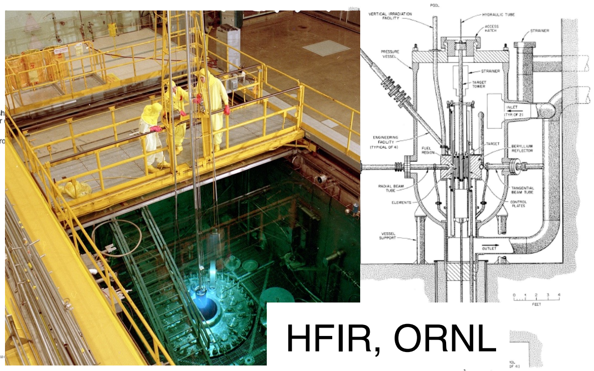
US operates high-powered research reactors



NBSR, NIST

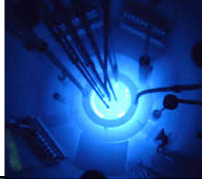


ATR

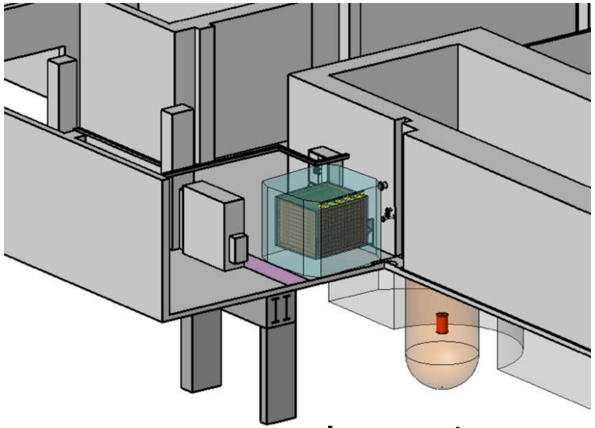


HFIR, ORNL

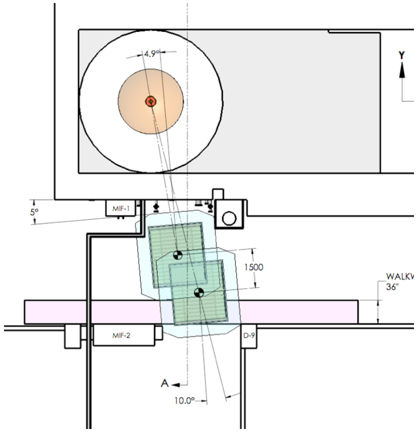
PROSPECT



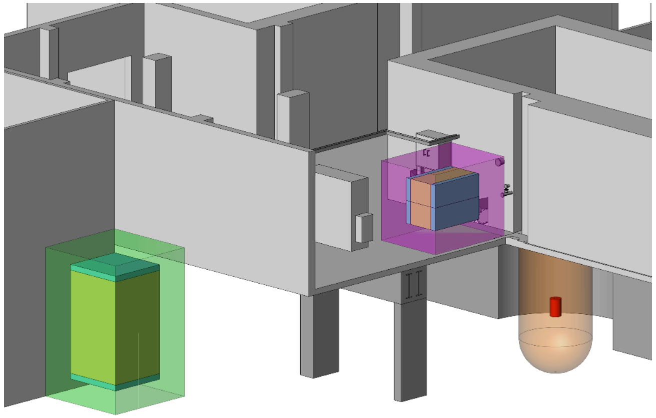
A Precision Oscillation and Spectrum Experiment



phase 1



phase 1+

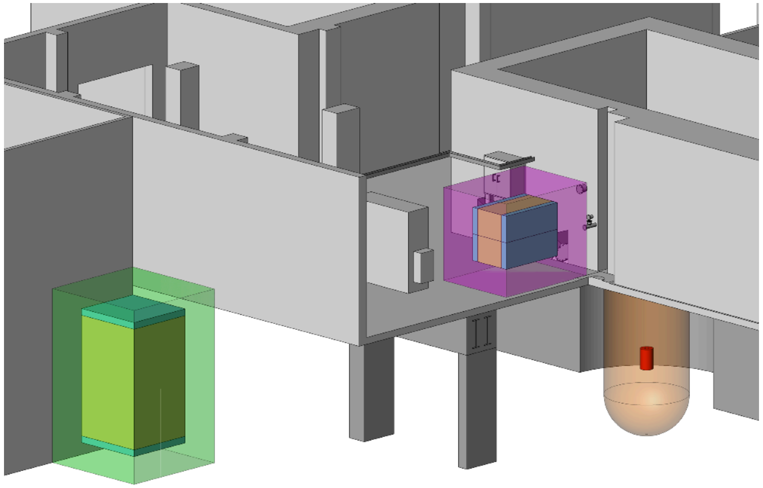


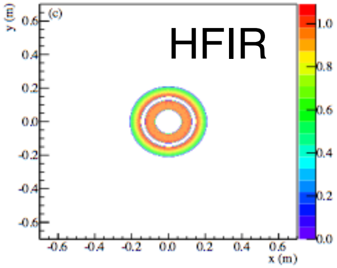
phase 2

PROSPECT Physics

A Precision Oscillation and Spectrum Experiment

2 Detectors

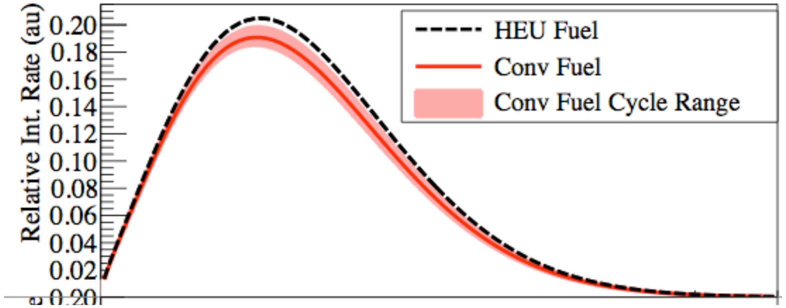




Primary Physics Objectives

1. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards

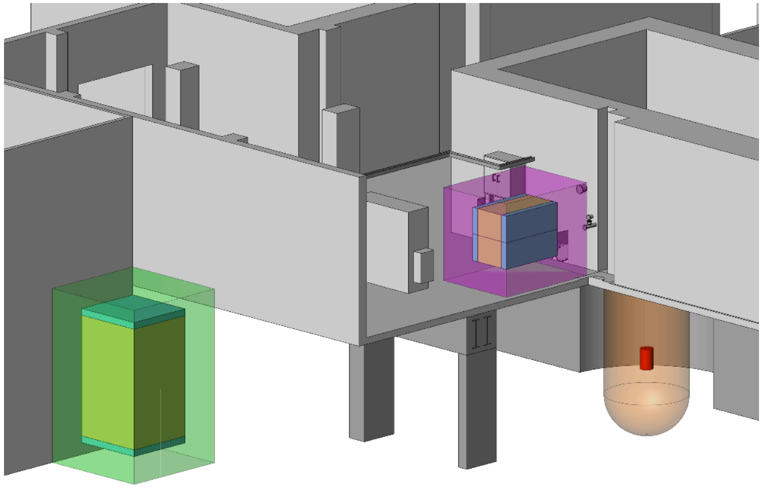
2. Search fort short-baseline oscillation within near detector and between near and far detector

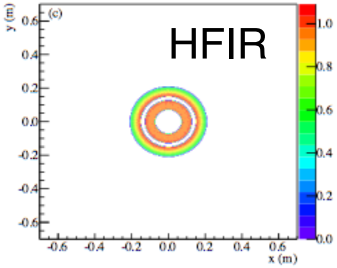


PROSPECT Physics

A Precision Oscillation and Spectrum Experiment

2 Detectors

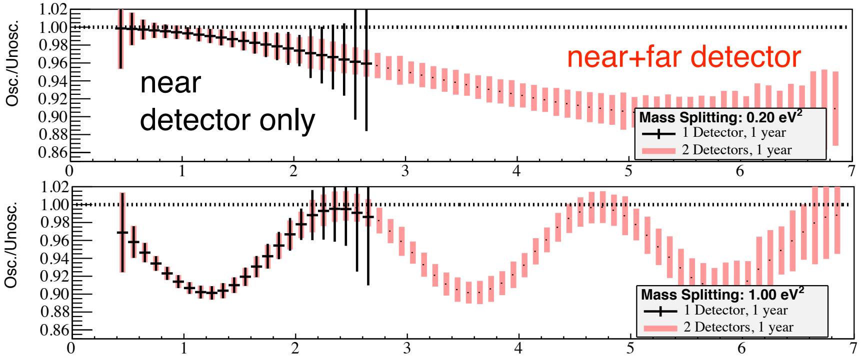




Primary Physics Objectives

1. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards

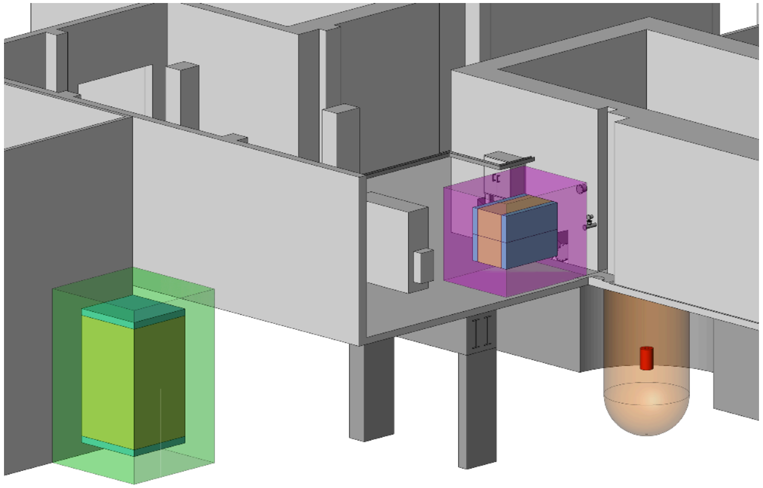
2. Search fort short-baseline oscillation within near detector and between near and far detector

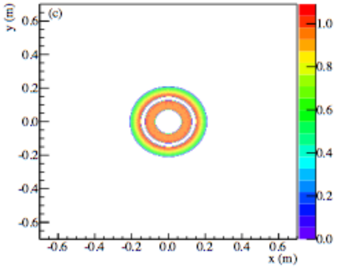


PROSPECT Physics

A Precision Oscillation and Spectrum Experiment

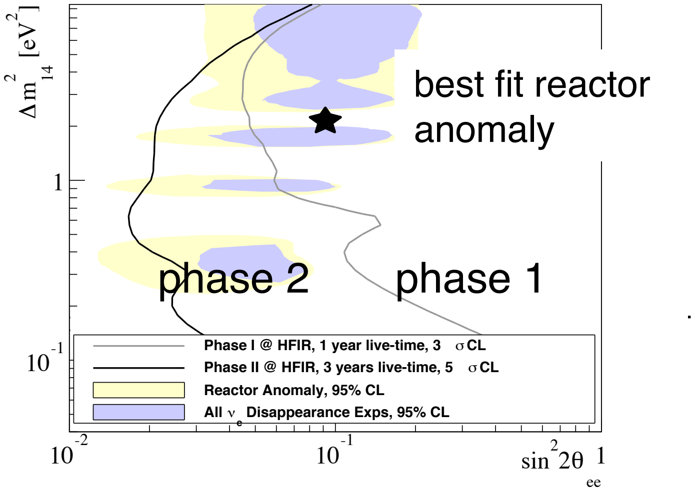
2 Detectors



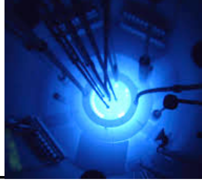


Primary Physics Objectives

1. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum for physics and safeguards
2. Search fort short-baseline oscillation within near detector and between near and far detector

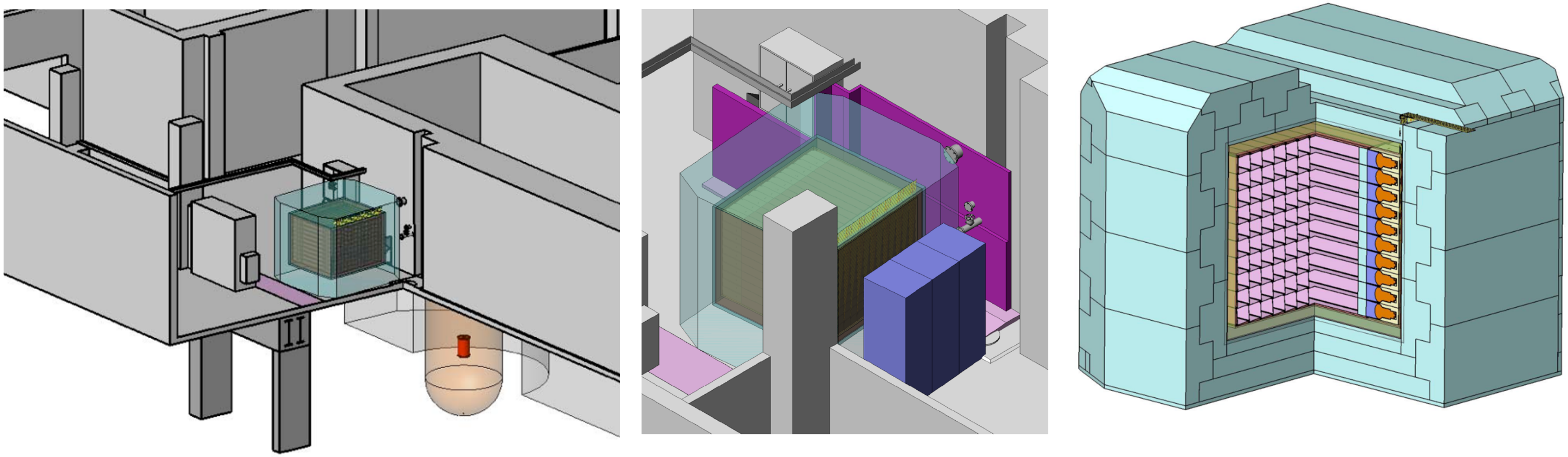


PROSPECT Detector



A Phased Approach

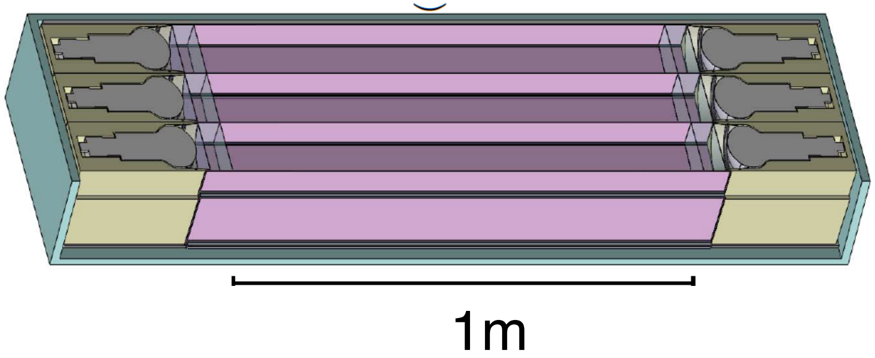
Near Detector - Phase I



2.5 ton active volume of LiLS

~ O(150) optical segments, thin wall separation

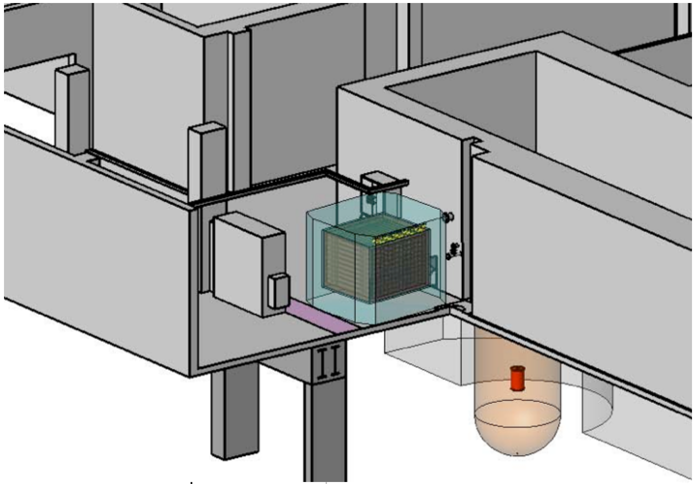
double-ended readout

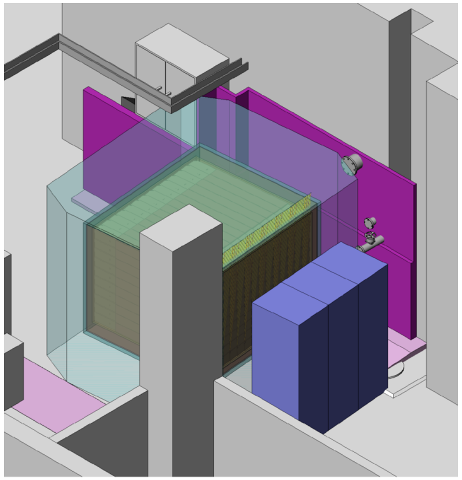


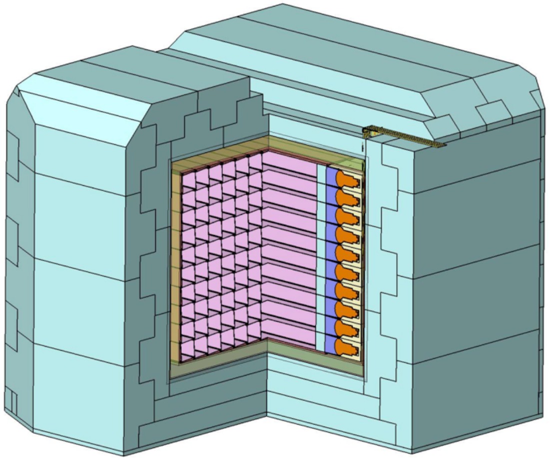
PROSPECT Detector

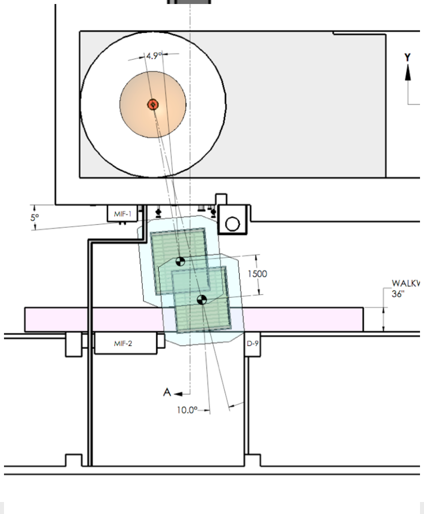
A Phased Approach

Near Detector - Phase I





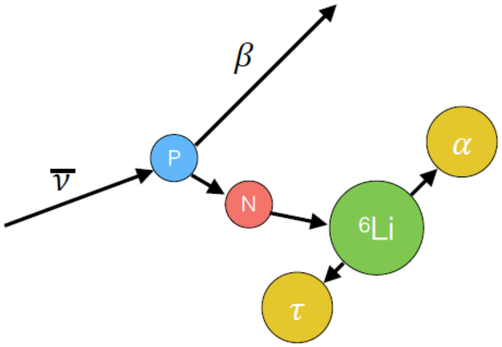




Systematic check by moving near detector by ~1/2 detector length

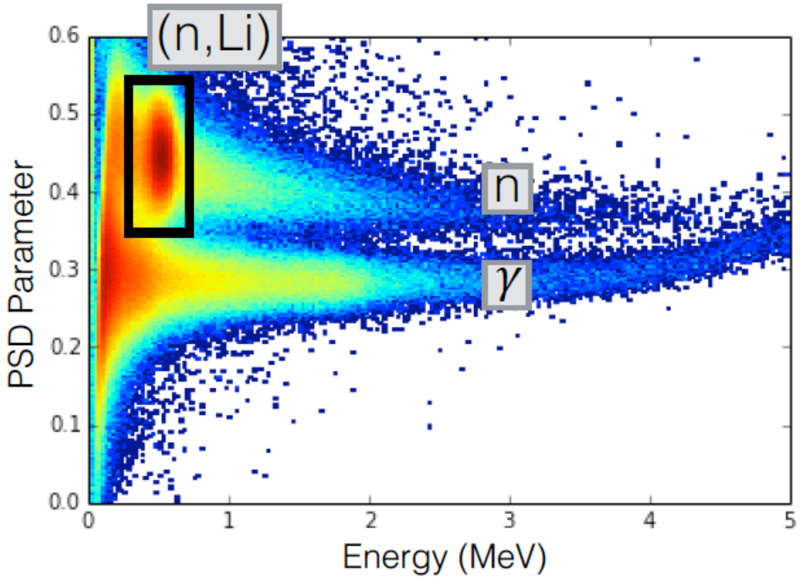
PROSPECT Detector

Event Identification



Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li



inverse beta decay

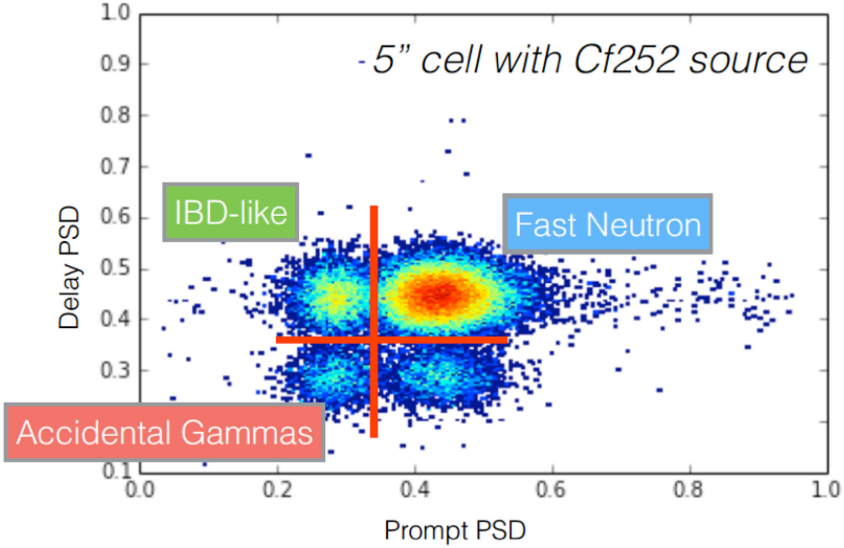
γ-like prompt, n-like delay

fast neutron

n-like prompt, n-like delay

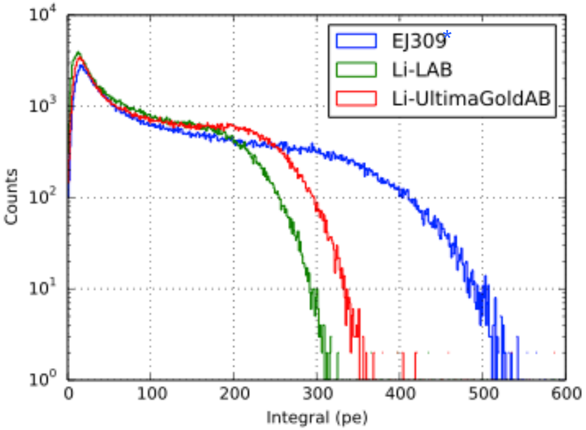
accidental gamma

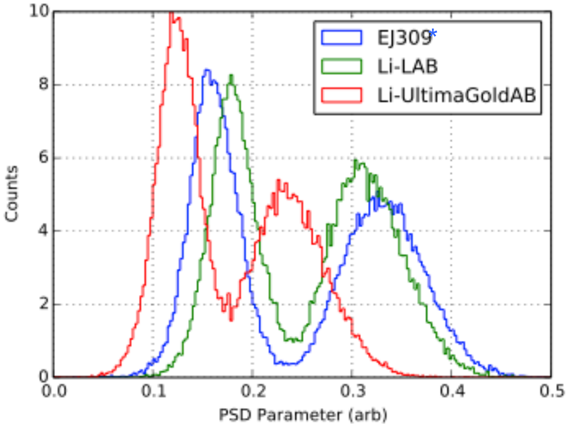
γ-like prompt, γ-like delay



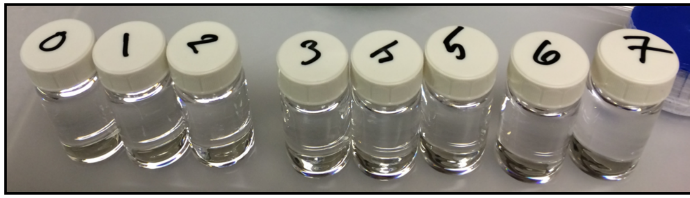
PROSPECT - LiLS

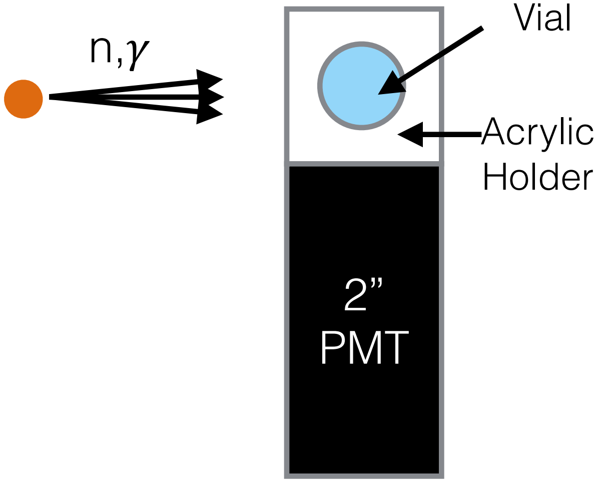
Liquid Scintillator Target





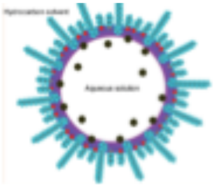
* PSD benchmark





- Samples produced by Brookhaven and NIST
- Sent to Yale for testing with radioactive sources
- - ^{252}Cf and ^{60}Co
- Characterize Light Yield and PSD performance in small vials, feed results back to NIST/BNL
- Use larger cells to determine geometric effects on performance

PerkinElmer

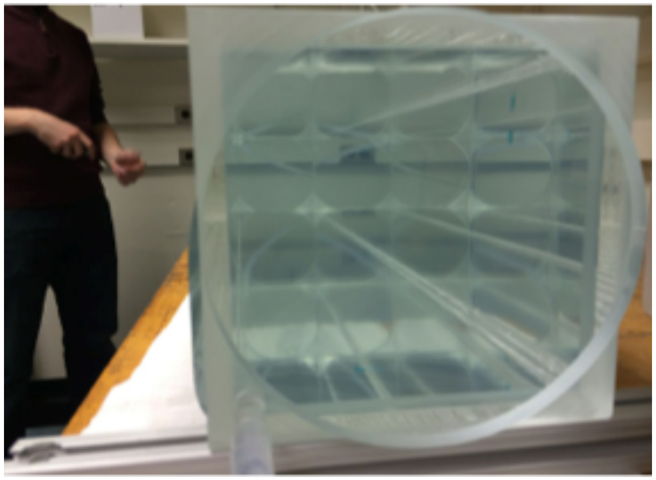


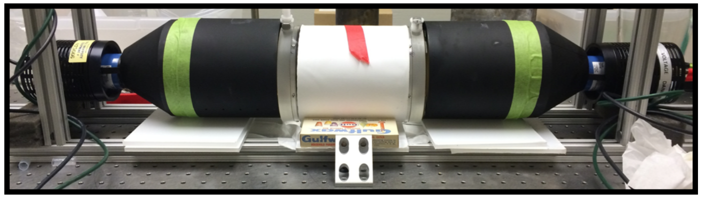
Ultima-Gold doped with NIST ^{6}Li micro-emulsion

PSD enhanced LAB-LS doped with BNL ^{6}Li chemistry

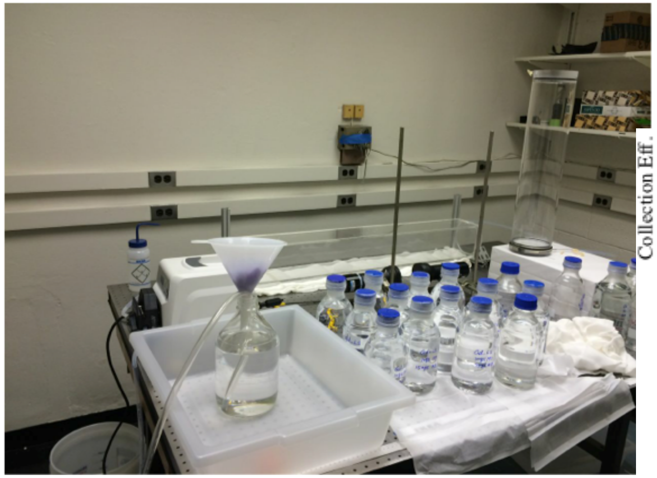
PROSPECT - Scintillator Tests

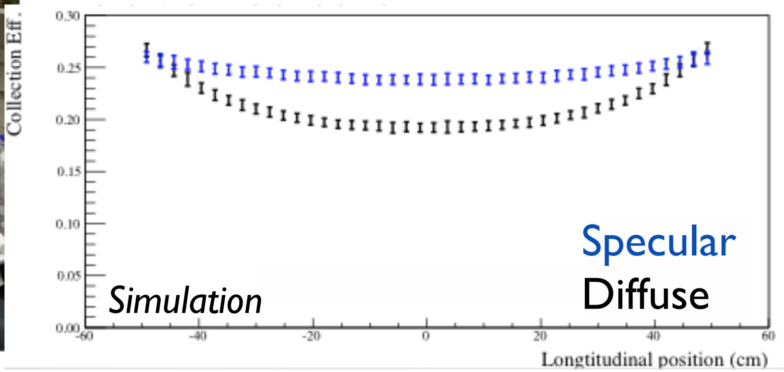
Liquid Scintillator Testing

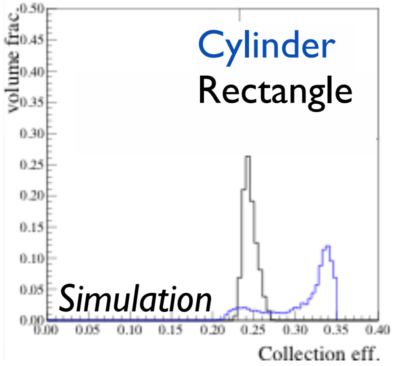




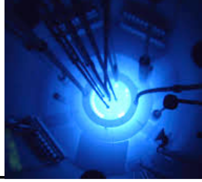
- ~20 liter cells have been constructed
- Mockup of one PROSPECT segment, study PSD and light collection in real-world conditions
- Test various reflector materials (ESR, Mylar, Tyvek, etc) to compare to simulations
- To be deployed at reactor site in late 2014 to test background mitigation techniques







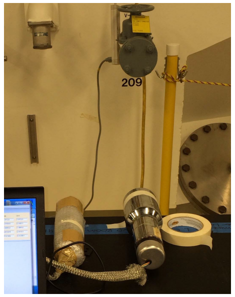
Background Measurements at HFIR



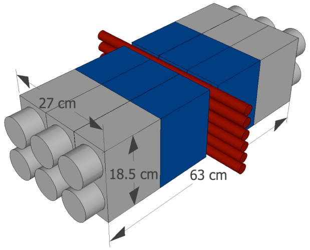
Measurement Techniques

REM

HPGe

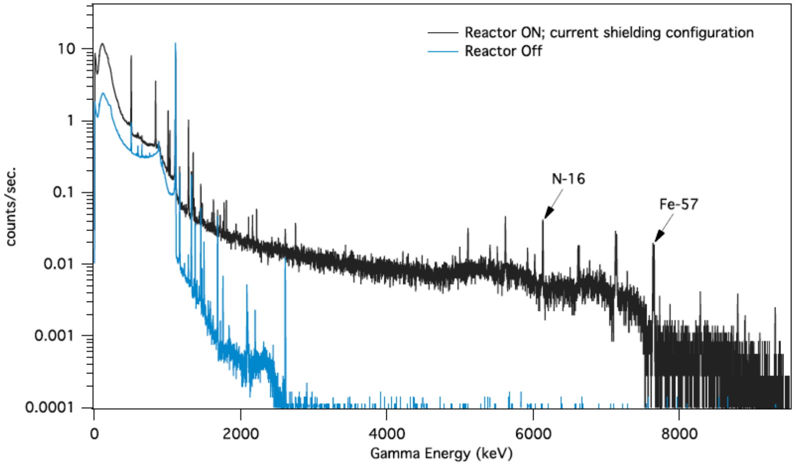


NaI



Neutron

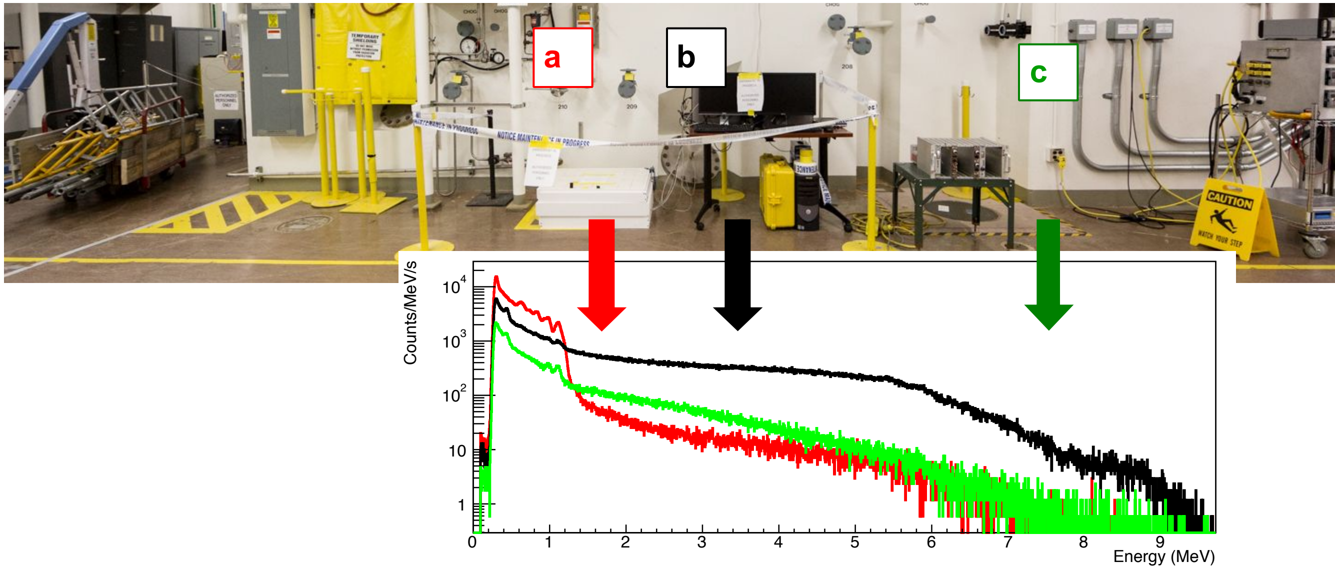
Reactor on/off Backgrounds



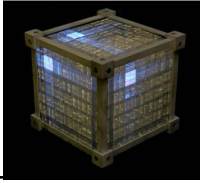
Localized Backgrounds

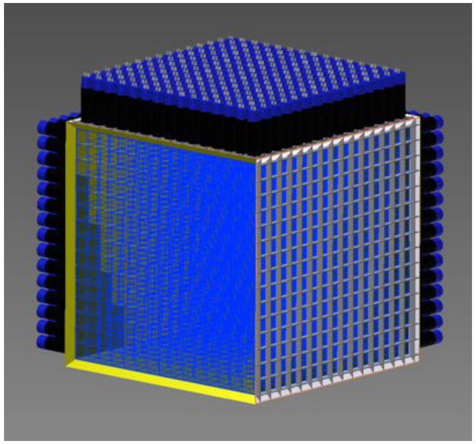
Several features of the HFIR near location result in localized gamma ray emissions.

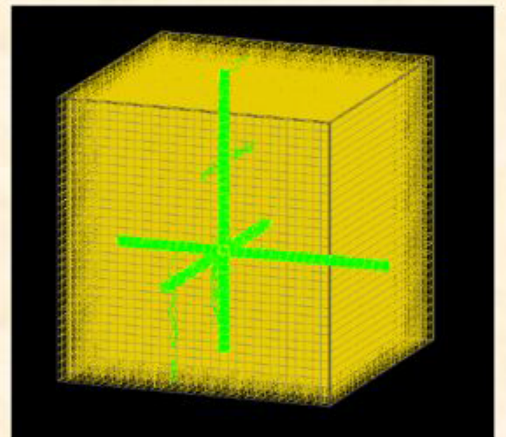
local shielding

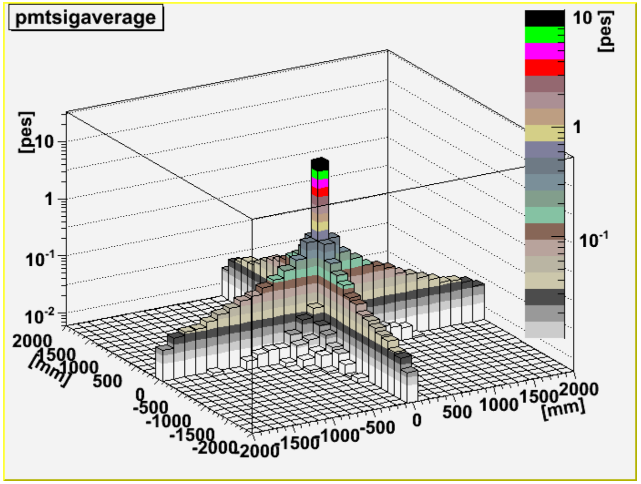


NuLAT - Neutrino Detection on a Lattice



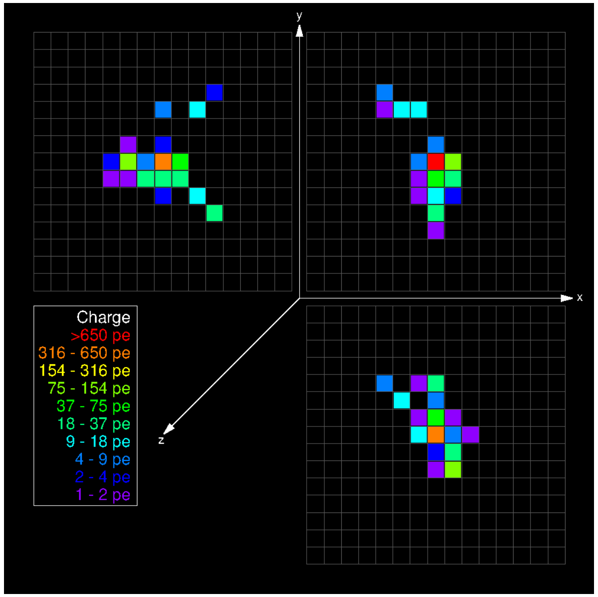






<u>NuLat:</u>
15^3 = 3375 voxels
Cubes 2.25” each
Boron Doped PVT scintillator
0.005” air gap between cells
6 *15^2 = 1350 of 2” PMTs

<u>Compact version:</u>
Mirrors on 3 faces
675 PMTs
Fits in mTC cave at NIST for test



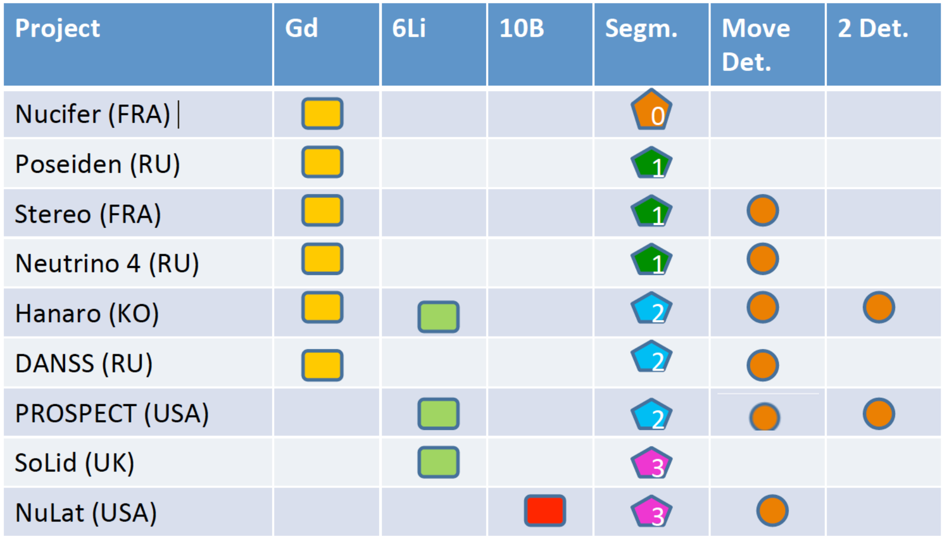
- Positron energy in red cell
- One sees the light from annihilation gammas in neighbor cells

Learned, Vogelaar

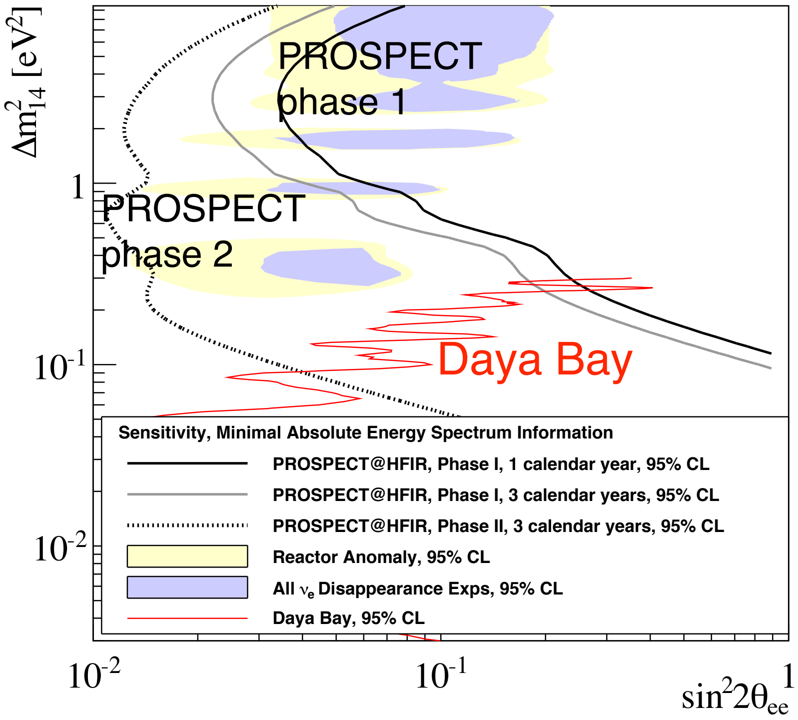
Worldwide Short-Baseline Reactor Experiments

Short-baseline reactor experiments

Variety of approaches worldwide to address experimental challenges (background rejection)



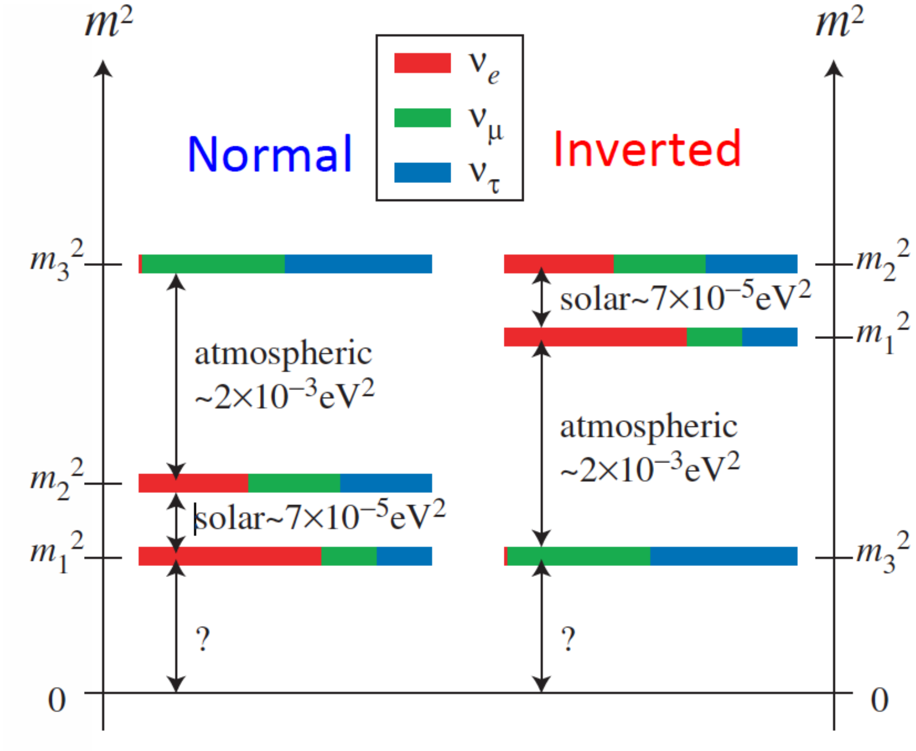
Project	Gd	6Li	10B	Segm.	Move Det.	2 Det.
Nucifer (FRA)	🟨			0		
Poseiden (RU)	🟨			1		
Stereo (FRA)	🟨			1	●	
Neutrino 4 (RU)	🟨			1	●	
Hanaro (KO)	🟨	🟩		2	●	●
DANSS (RU)	🟨			2	●	
PROSPECT (USA)		🟩		2	●	●
SoLid (UK)		🟩		3		
NuLat (USA)			🟥	3	●	



Physics Reach to 3+1 Oscillations

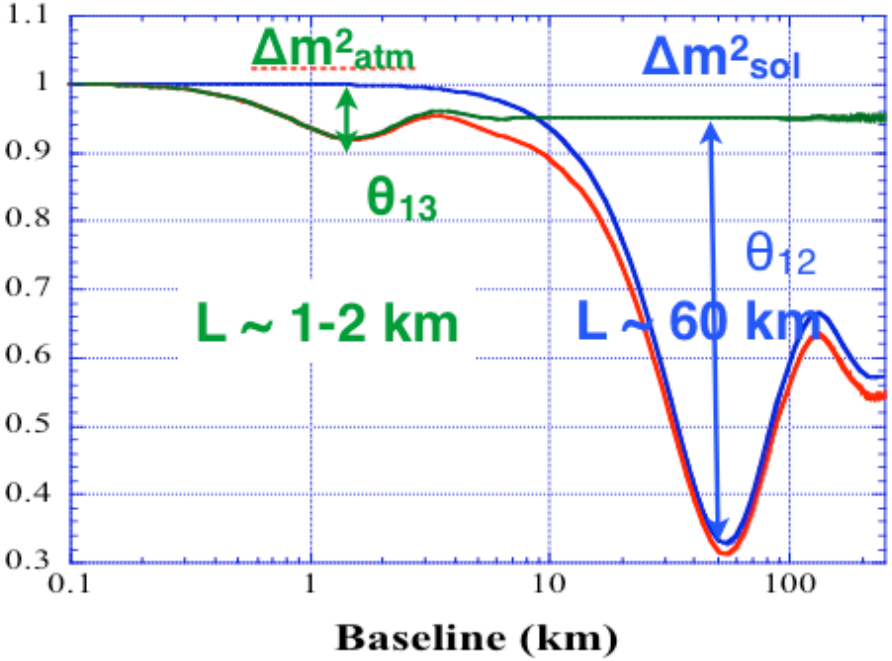
Short and intermediate reactor experiments (e.g. Daya Bay and PROSPECT) probe relevant parameter space

Mass Hierarchy



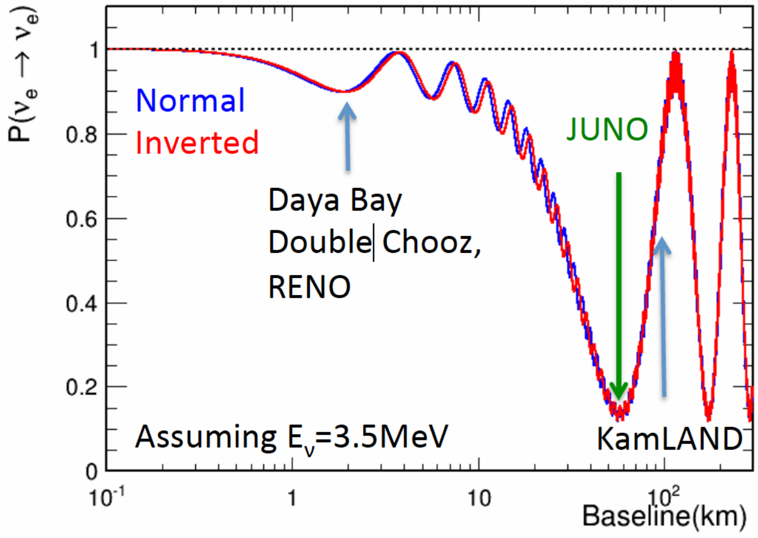
Mass Hierarchy and Reactor Neutrinos

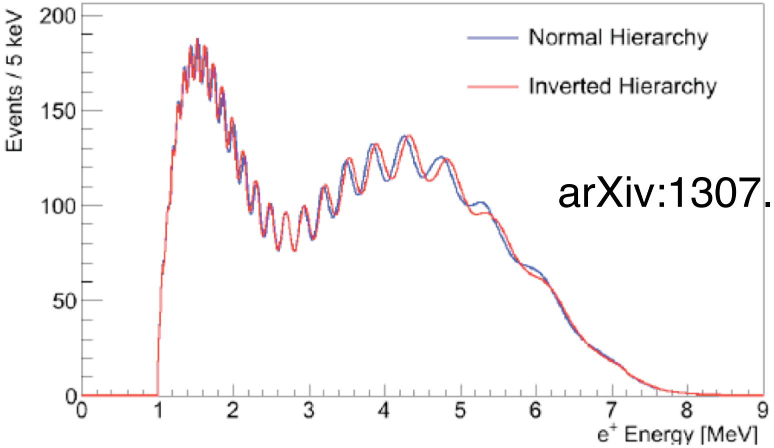
Precision Measurement at ~ 58km



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

Δm^2_{21} is only 3% of $|\Delta m^2_{32}|$



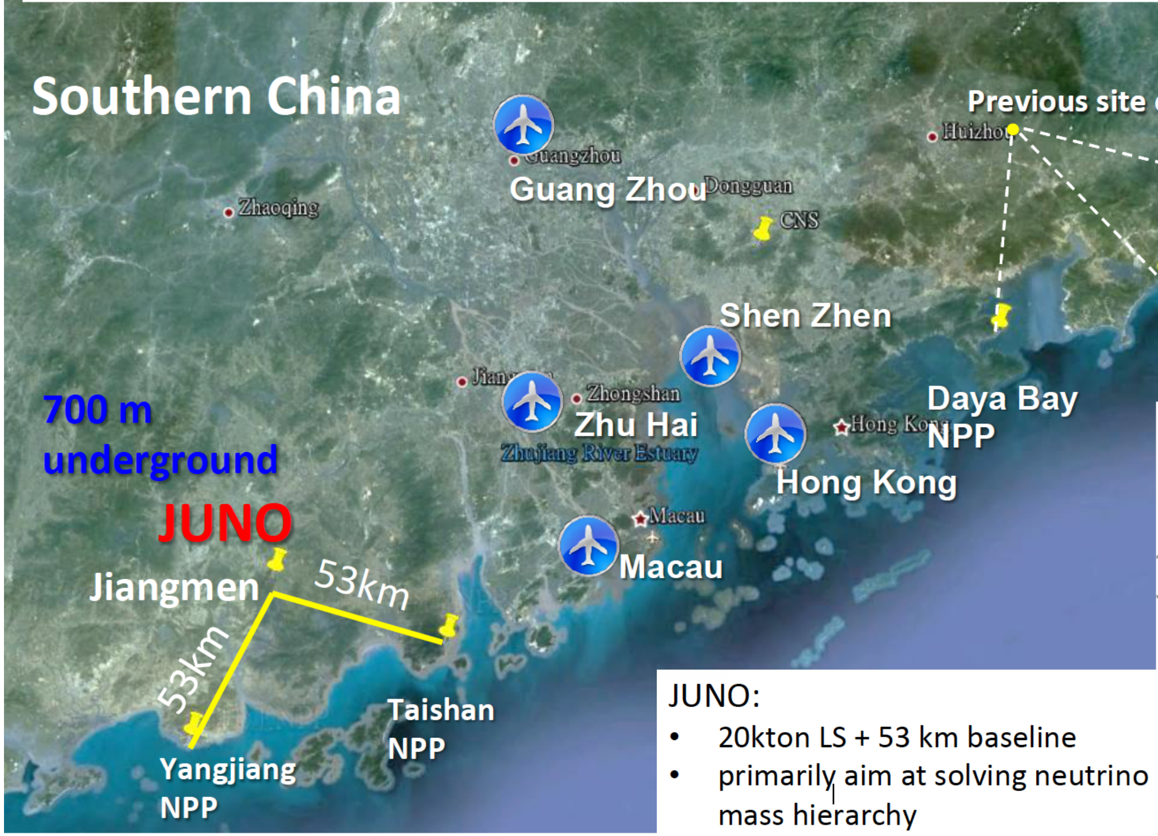


arXiv:1307.5487

mass hierarchy is contained in the spectrum independent of the unknown CP phase

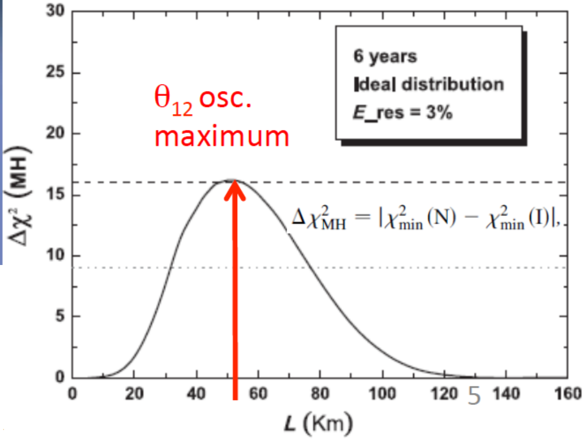
Jiangmen Underground Neutrino Observatory (JUNO)

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



JUNO:

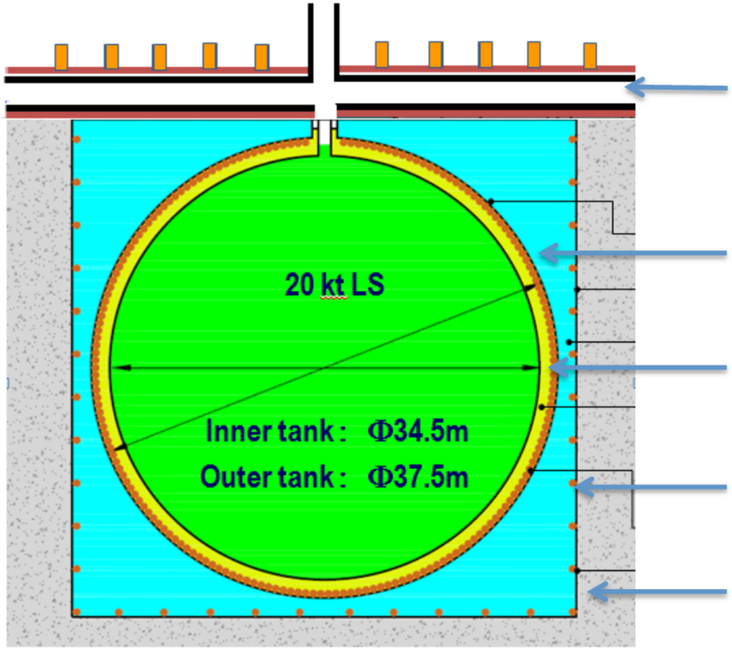
- 20kton LS + 53 km baseline
- primarily aim at solving neutrino mass hierarchy



Jiangmen Underground Neutrino Observatory (JUNO)

	KamLAND	JUNO
LS mass	1kt	20kt
Energy resolution	6%/√E	3%/√E
Light yield	250 P.E./MeV	1200 P.E./MeV
PMT coverage	34%	80%

Default option:
Acrylic Tank + Stainless steel structure



Muon veto
(Opera target tracker)

Water System

15000 20” PMT

2000 20” Veto PMT

Magnet shielding

Backup option:
Stainless Steel Tank + Balloon

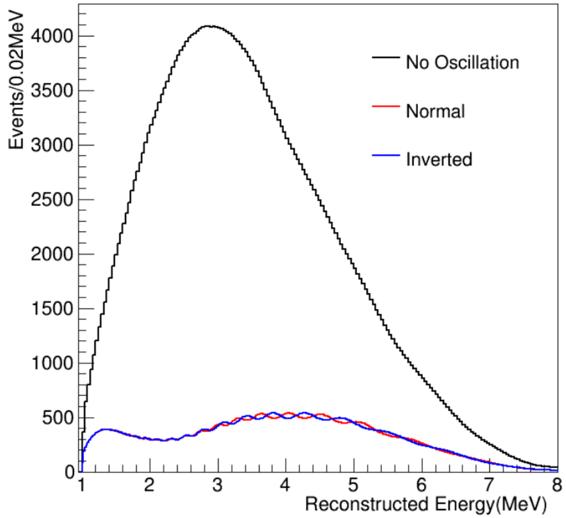
7

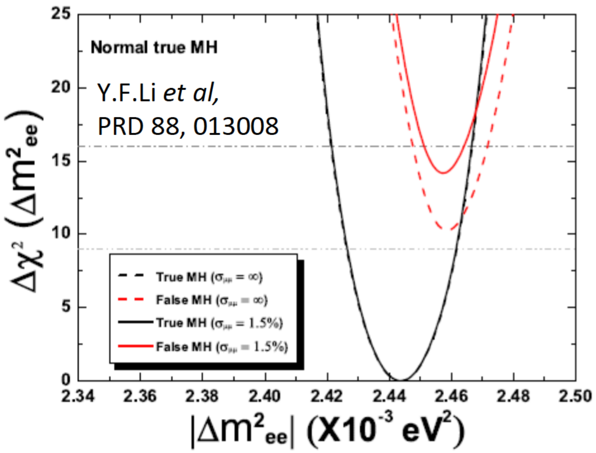
groundbreaking in 2015, filling and data taking in 2020

JUNO Physics

Sensitivity to Mass Hierarchy

10^5 events with 5-6 years of data-taking





Y.F.Li *et al*,
PRD 88, 013008

Precision 3-ν Oscillation Physics

	Current	**JUNO**
Δm	3%	0.6%
Δm	5%	0.6%
sin	6%	0.7%
sin	20%	N/A
sin	10% (~4% in 3 yrs)	15%

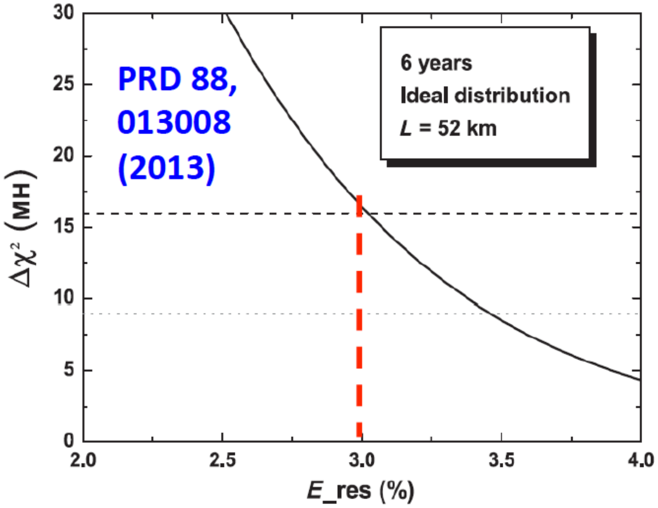
with 6 years of data taking assuming 3% energy resolution and 1% energy non-linearity, JUNO MH sensitivity is $\Delta\chi^2$=9-10 (~3σ)

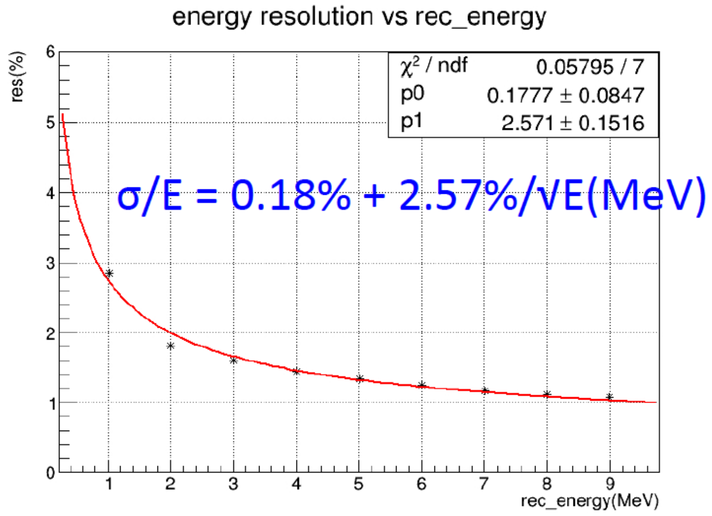
adding external T2K/NovA $\Delta m_{\mu\mu}$ of 1.5% constraint, JUNO cam achieve MH sensitivity with $\Delta\chi^2$=14 (~4σ)

JUNO - Experimental Challenges

Energy Resolution

- 3%/√E energy resolution
- JUNO preliminary Monte Carlo,
    - based on Daya Bay Monte Carlo
    - JUNO Geometry: 77% PMT coverage
    - High QE Efficiency: 25% -> 35%
    - LS attenuation length (1m-tube measurement @430nm)
        - From: 15m (= absorption 30m + Rayleigh scattering 30m)
        - To: 20m (= absorption 60m + Rayleigh scattering 30m)


PRD 88, 013008 (2013)


energy resolution vs rec_energy

$\sigma/E = 0.18\% + 2.57\%/\sqrt{E(\mathrm{MeV})}$

Other Challenges

- liquid scintillator
- detector calibration
- PMTs

Summary & Outlook

Reactor neutrinos are a tool for discovery.
Reactors are flavor pure sources of $\overline{\nu}_e$

Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$, and **reactor antineutrino flux and spectra**. Daya Bay flux measurement is consistent with previous short-baseline measurements (~5% deficit). Positron spectrum appears inconsistent with current predictions in 4-6 MeV region.

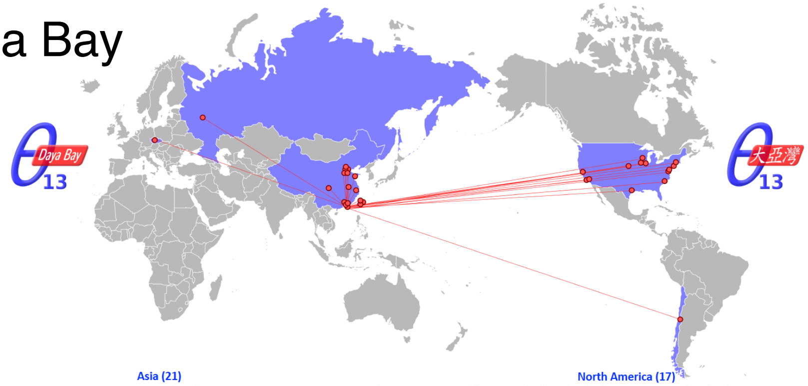
Medium-baseline experiments **(L~60km)** (e.g JUNO, RENO-50) are technically demanding but may offer <1% **precision oscillation physics and a window to the mass hierarchy.**

Short-baseline **(L~10m)** experiments (e.g. PROSPECT, NuLAT) offer opportunities for **precision studies of reactor spectrum** and a definitive search for **short-baseline oscillation** and **sterile neutrinos**.

Acknowledgements

Thanks to Daya Bay, JUNO, PROSPECT, and NuLAT collaborators for materials

Daya Bay



Asia (21)
Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

North America (17)
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton,, Siena College, Temple University, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Europe (2)
Charles University, JINR Dubna

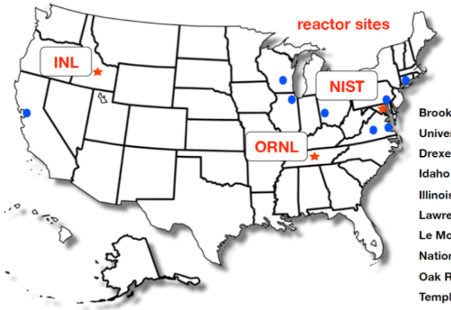
South America (1)
Catholic Univ. of Chile

NuLAT

J. Blackmon, R. Dorrill, M.Duvall, C.Lane, P.Huber, J.G.Learned, V.Li, D.Markov, J.Maricic, R.Milincic, H.P.Mumm, S.Negrashov, M.Rosen, M.L.Pitt, C.Rasco, S.D.Rountree, S.M.Usman, G.Varner, R.B.Vogelaar, T.Wright, Z.Yokley,

Drexel, Johns Hopkins, LSU, NIST Gaithersburg, North Carolina Central, U. Hawaii, Virginia Tech

PROSPECT



58 collaborators
11 universities
5 national laboratories

- Brookhaven National Laboratory
- University of Chicago
- Drexel University
- Idaho National Laboratory
- Illinois Institute of Technology
- Lawrence Livermore National Laboratory
- Le Moyne College
- National Institute of Standards and Technology
- Oak Ridge National Laboratory
- Temple University
- University of Tennessee
- Virginia Tech University
- University of Waterloo
- University of Wisconsin
- College of William and Mary
- Yale University

JUNO Collaboration

US*
BNL, UIUC, Houston
Observers on behalf of US institutions

Europe (20)*
APC Paris
Charles U.
CPPM Marseille
FZ Julich
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Padova
INFN-Perugia
INFN-Roma 3
U. libre de Bruxelles (Observer)
IPHC Strasbourg
JINR
LLR Paris
RWTH Aachen U.
Subatech Nantes
TUM
U.Hamburg
U.Mainz
U.Oulu
U.Tuebingen

Asia (25)
Beijing Normal U.
CAGS,
CIAE
DGUT
ECUST
Guangxi U.
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Pekin U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.