PROSPECT: Precision Reactor Oscillation and Spectrum Experiment

Xiangpan JI

for the PROSPECT collaboration

BROOKHAVEN NATIONAL LABORATORY

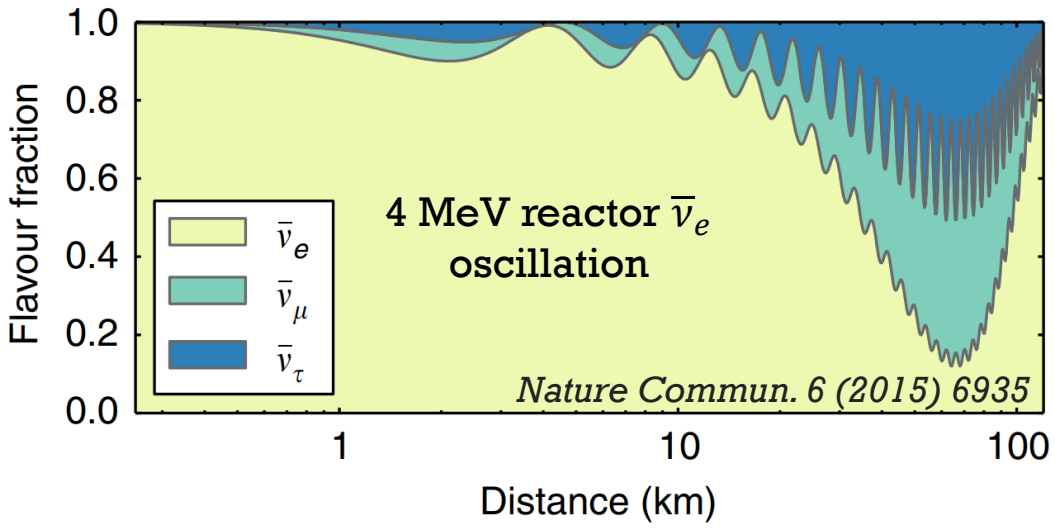
Brookhaven Forum 2019

Neutrino Oscillation

Neutrino oscillation indicates:

- Neutrinos have mass
- Neutrino flavor eigenstates are mixture of mass eigenstates

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 2\mathrm{Re}\sum_{j>i} U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}\left(1 - e^{i\Delta m^2_{ij}L/2E}\right)$$



Neutrino mixing matrix (U)

Flavor eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

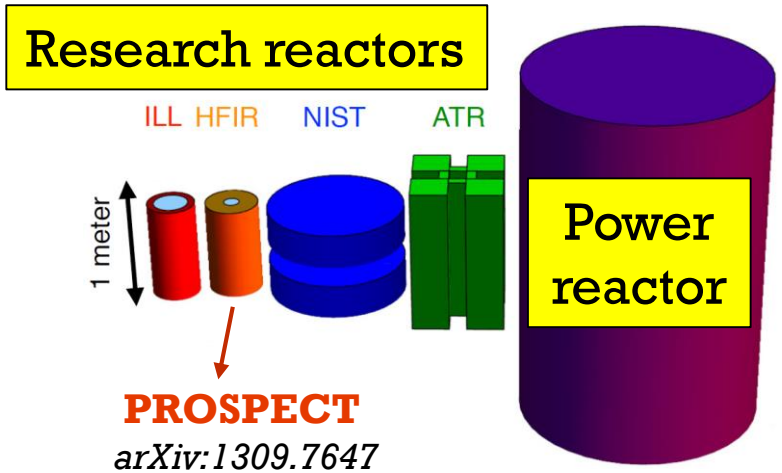
Mass eigenstates

Atmospheric/ Long baseline accelerator

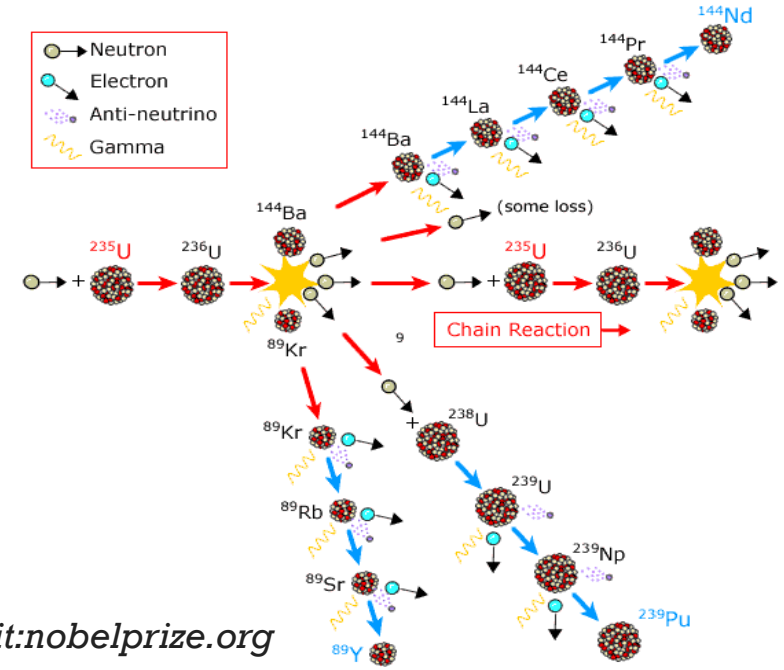
Short baseline reactor/ Long baseline accelerator

Solar/ Long baseline reactor

Nuclear Reactor As Antineutrino Source



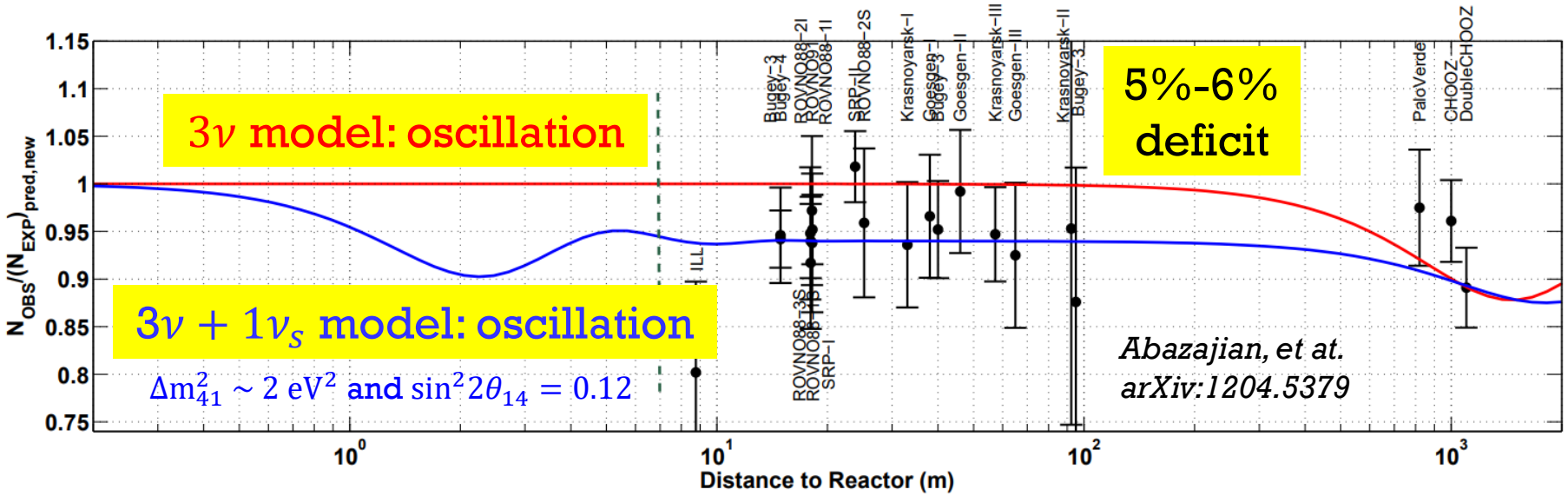
- Commercial reactors in Nuclear Power Plants have <u>low-enriched uranium</u> (LEU) cores
  - Mixture of fissions: $^{235}\mathrm{U}(\sim 55\%)$, $^{239}\mathrm{Pu}(\sim 30\%)$, $^{238}\mathrm{U}(\sim 10\%)$, $^{241}\mathrm{Pu}(\sim 5\%)$
  - Large power: ~ 3 $\mathrm{GW_{th}}$
- Research reactors have <u>highly-enriched uranium</u> (HEU) cores
  - <u>$^{235}\mathrm{U}$ fission fraction ~99%</u>
  - Lower power, few tens of $\mathrm{MW_{th}}$
  - Compact size

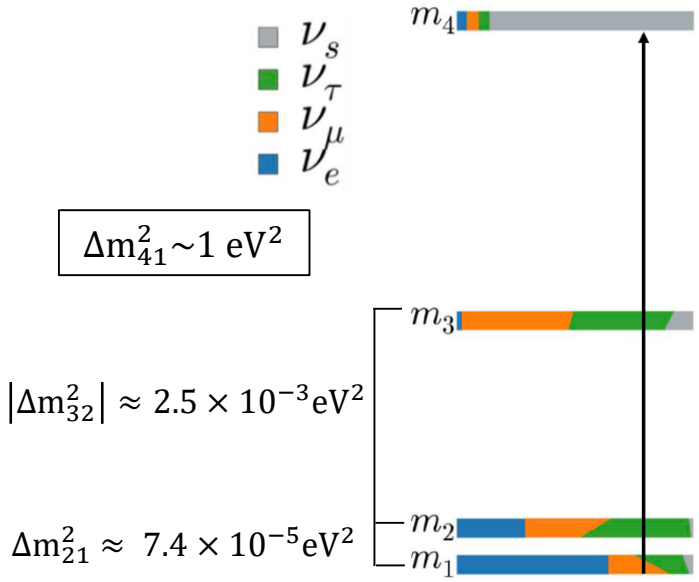


Credit:nobelprize.org

- Nuclear reactors produce pure $\bar{\nu}_e$ from beta decays of fission daughters
  - <u>Low energy</u>: < 10 MeV
  - ~ 6 $\bar{\nu}_e$/fission
  - 2×10^{17} $\bar{\nu}_e/\mathrm{MW_{th}}$ per second

Reactor Antineutrino Anomaly (RAA): Flux Deficit





What's the origin of the $\bar{\nu}_e$ flux deficit?

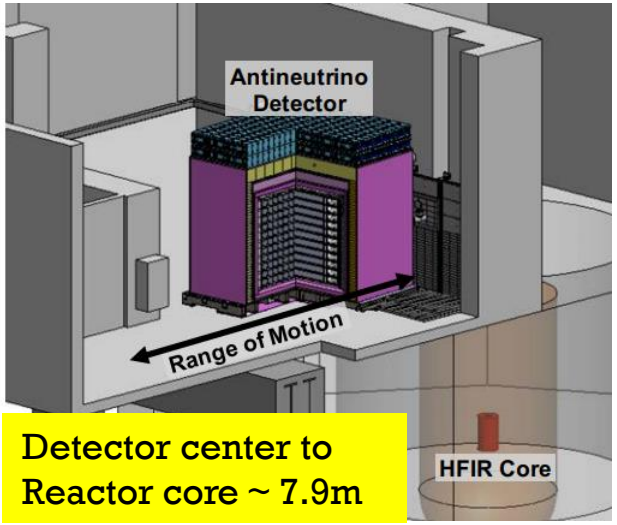
- Problems from reactor model predictions?
- New physics?

Sterile neutrino: doesn't interact in the SM

- High frequency oscillation
- Mass splitting ~1 eV^2
- Baseline ~few meters

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{14} \sin^2\left(1.267 \frac{\Delta m^2_{41} L}{E}\right) - \sin^2 2\theta_{13} \sin^2\left(1.267 \frac{\Delta m^2_{31} L}{E}\right)$$

PROSPECT Experiment Overview

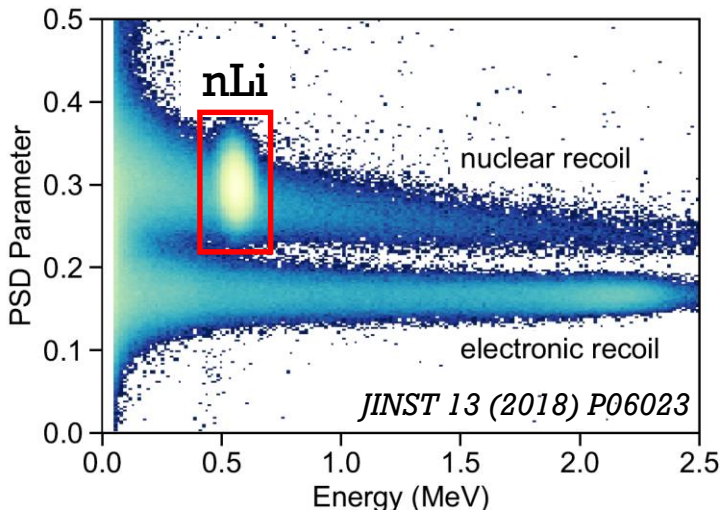


Detector center to Reactor core ~ 7.9m

Physics Objectives:

- Reactor model independent search for neutrino oscillations into eV-scale sterile states
- Precision measurement of the ^{235}U antineutrino spectrum

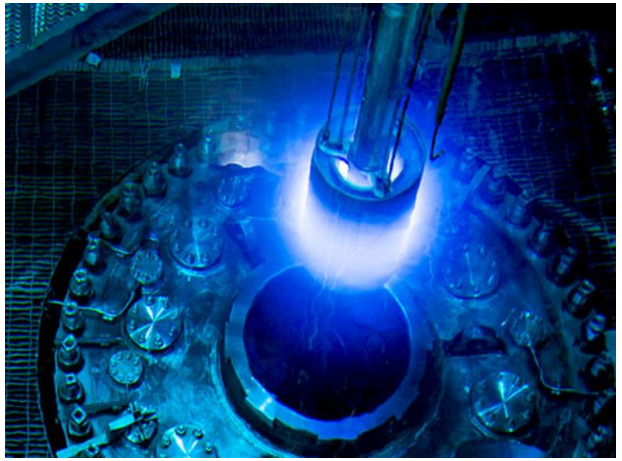
Segmented detector design using the pulse shape discrimination (PSD) capable ^{6}Li-doped liquid scintillator (LiLS) provides powerful near-surface background rejection

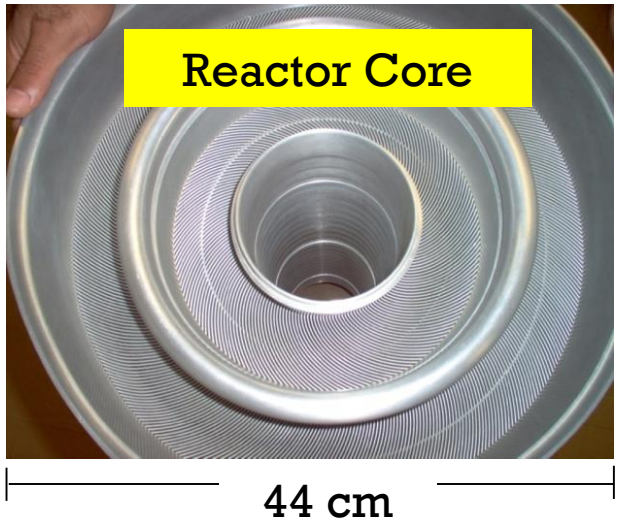


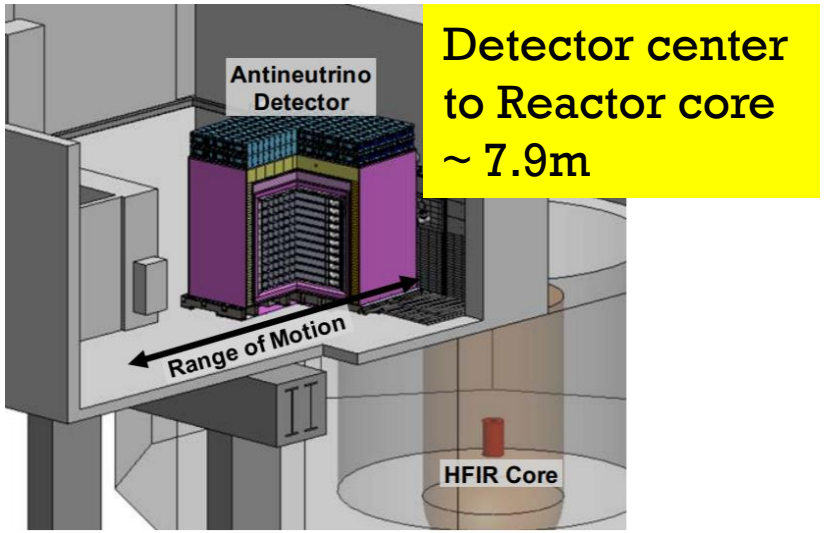
Experiment Site: HFIR

Power: 85 MW
Core shape: cylindrical
Size: h=0.5m, ϕ=0.44m
Duty-cycle:
46%, 7 cycles/yr, 24 days
Fuel:
highly-enriched uranium reactor, >99% ^{235}U fissions

Site Challenges:
detector near surface, little overburden
(<1m water equivalent)







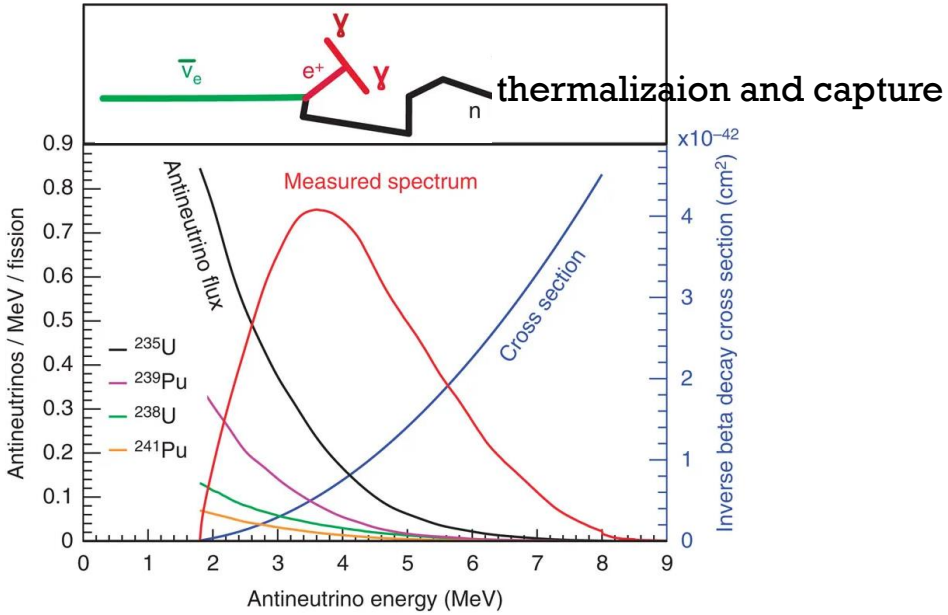
Reactor Neutrino Detection through IBD Reaction

Inverse beta decay (IBD):

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

$$E_{\bar{\nu}} \approx T_{e^+} + 1.8 \text{ MeV}$$

The positron carries most of the $\bar{\nu}_e$ energy



Credit: Nature Commun. 6 (2015) 6935

$$S(E_{\bar{\nu}}) = c \cdot f \cdot s(E_{\bar{\nu}}) \cdot \sigma(E_{\bar{\nu}})$$

- f: isotope fission fraction
- $s(E_{\bar{\nu}})$: isotope neutrino spectrum
- $\sigma(E_{\bar{\nu}})$: IBD cross section
- c: reactor thermal power, energy released per fission, baseline, target protons, detection efficiency, oscillation, etc.

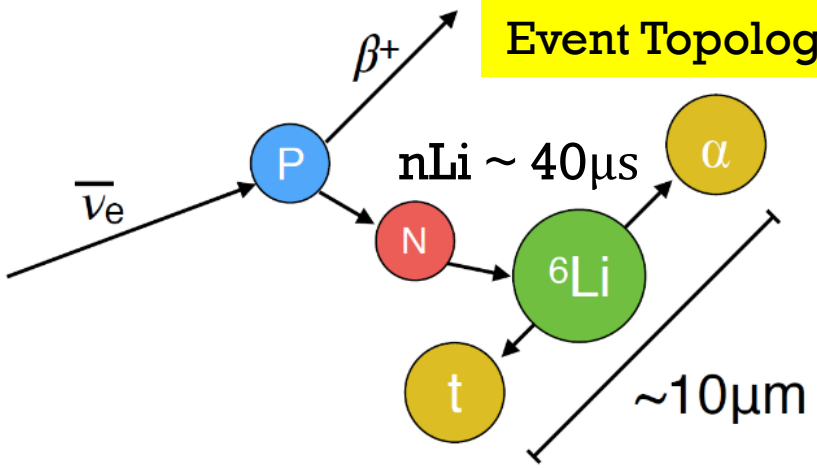
IBD Detection with LiLS

^{6}Li-loaded LS manufactured at BNL

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

$n + 6\text{Li} \rightarrow \alpha + t$

Event Topology



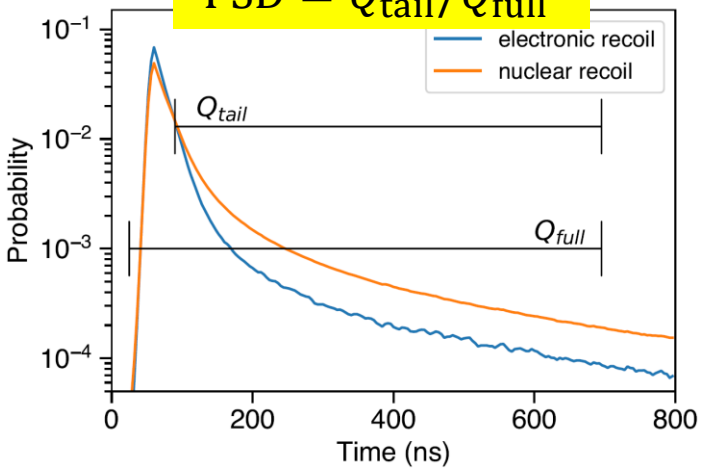
Event Signature:

- Prompt signal: positron from IBD
- Delayed signal: n capture on ^{6}Li

The two are time- and space- correlated

The Pulse Shape Discrimination (PSD) of scintillator distinguishes the $\boldsymbol{\beta^+}$**-like** event (IBD signal) and ***n*-like** event (most significant background at HFIR).

$\text{PSD} = Q_{\text{tail}}/Q_{\text{full}}$



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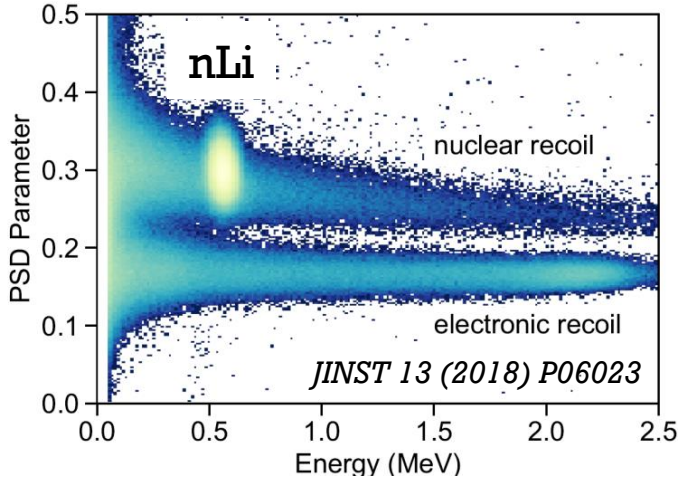


Xiangpan Ji, BNL

Correlation + PSD:

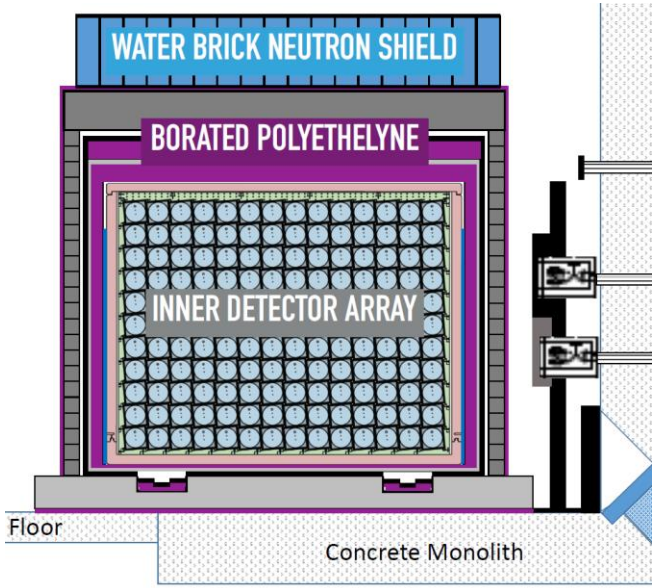
- Identify IBD signal
- Reject backgrounds

PROSPECT Detector Design

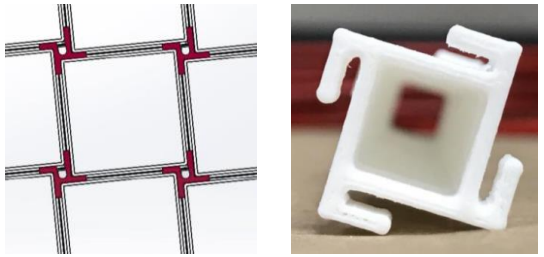
- 154 segments (14 x 11)
  - ~25 liters of LiLS per segment, total mass: 4ton
  - Segment: 119cm×15cm×15cm

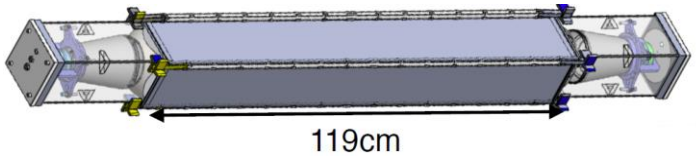
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods

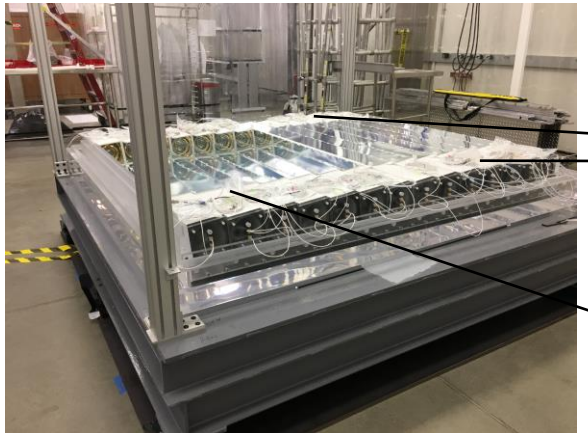
- Segmentation enables:
  1. Relative measurements
  2. Calibration access throughout volume
  3. Position reconstruction
  4. Event topology ID
  5. Fiducialization



Tilted array for calibration access







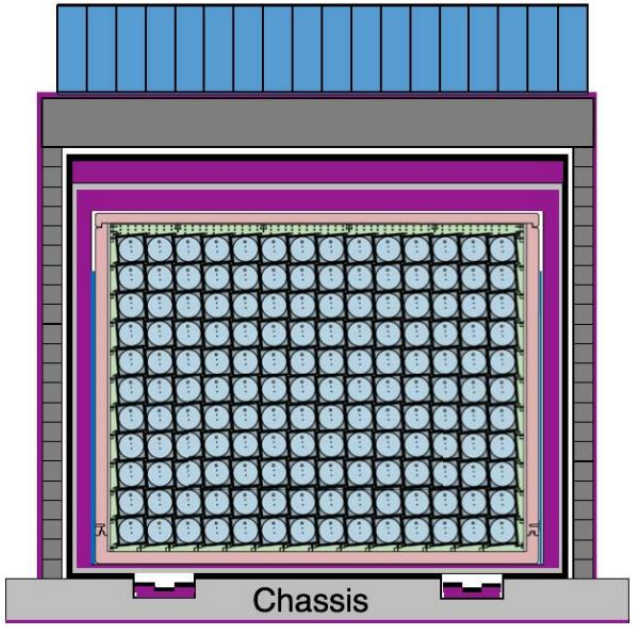
Double ended PMT readout for full (X,Y,Z) position reconstruction

Reflector

Background Rejection

Passive Shielding

- detector near surface,
- little overburden (<1m water equivalent)

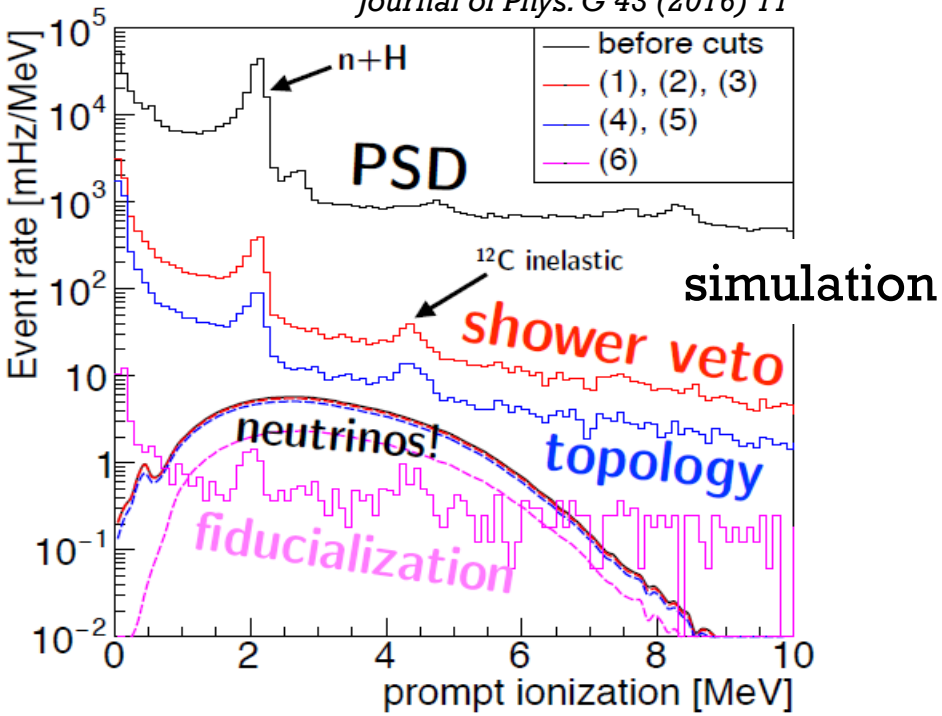


Water
HDPE
BPE
Lead

**HDPE:*
high density polyethylene
**BPE:*
borated polyethylene

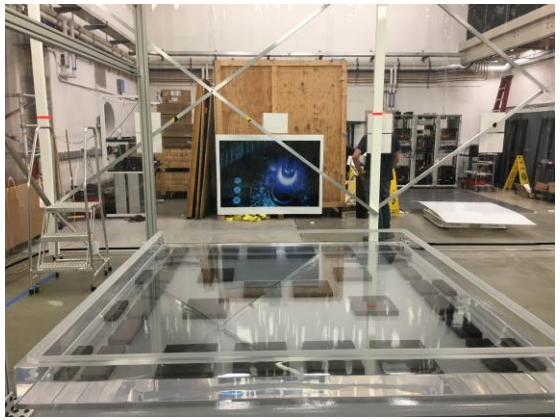
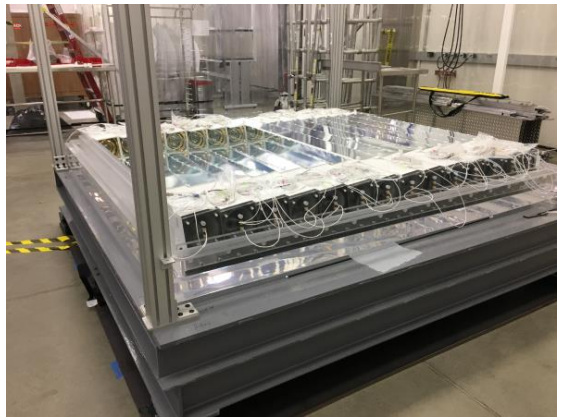
Active Suppression

Journal of Phys. G 43 (2016) 11



- Optimized detector design for background ID and suppression
- Combine PSD, shower veto, event topology, and fiducialization
- Active suppression of background > 10^4

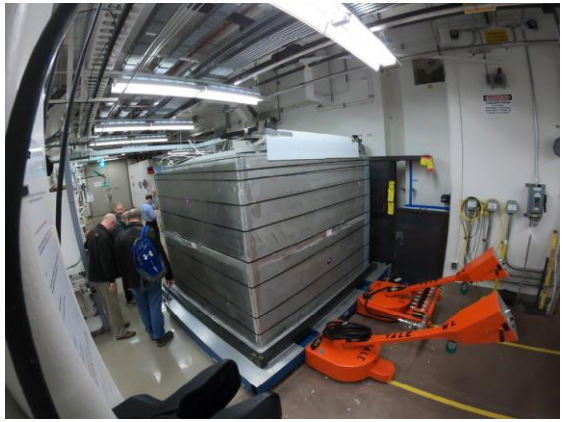
Construction and Installation

Oct 2017 – Jan 2018 at Yale Wright Lab

Arrival at Oak Ridge

At HFIR

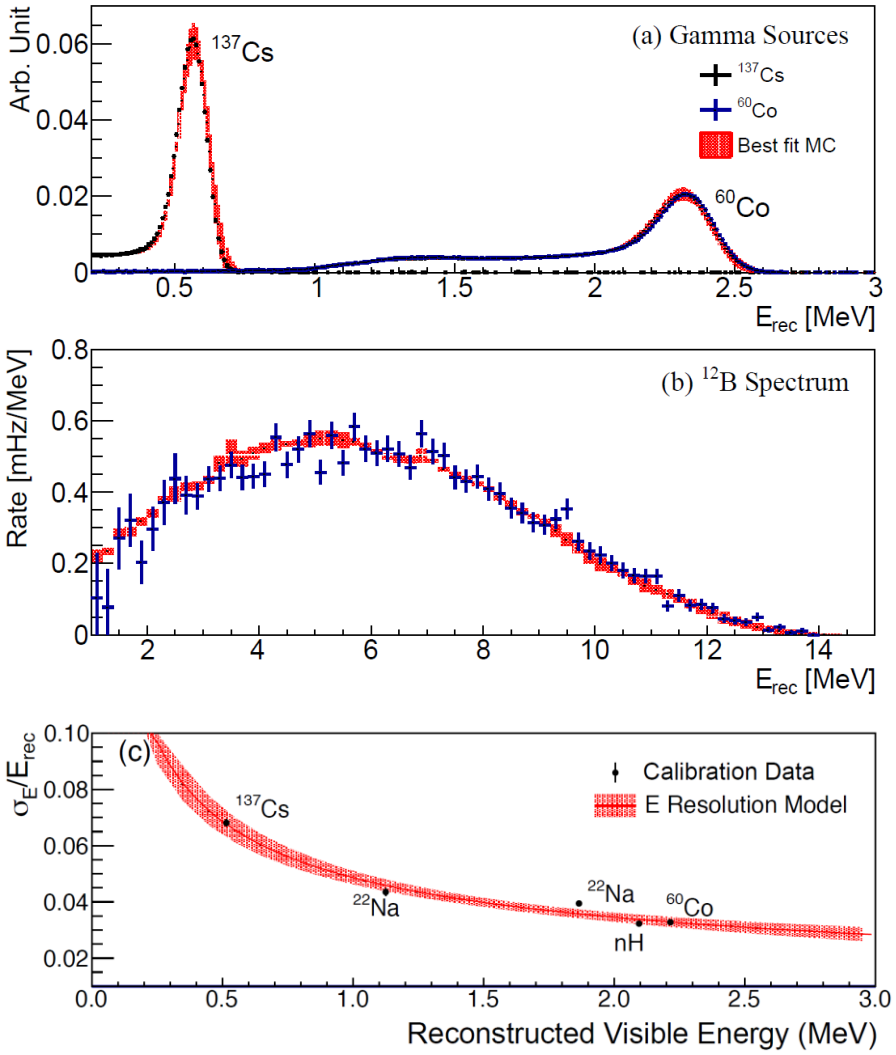


Filling LiLS from mixing tank

March 5, 2018
Began operation

Energy Reconstruction

- <u>High performance of energy reconstruction:</u> a key part for the precision measurement of neutrino oscillation and spectrum
- <u>Gammas sources</u>: ^{137}Cs, ^{60}Co deployed throughout detector, measure single segment response
- <u>High-energy beta spectrum</u>: Fast-neutron tagged ^{12}B
- **Full-detector E_{rec} within 1% of E_{true}**
- **High light collection: 795±15 PE/MeV**



Calibration spectra

Resolution vs. energy

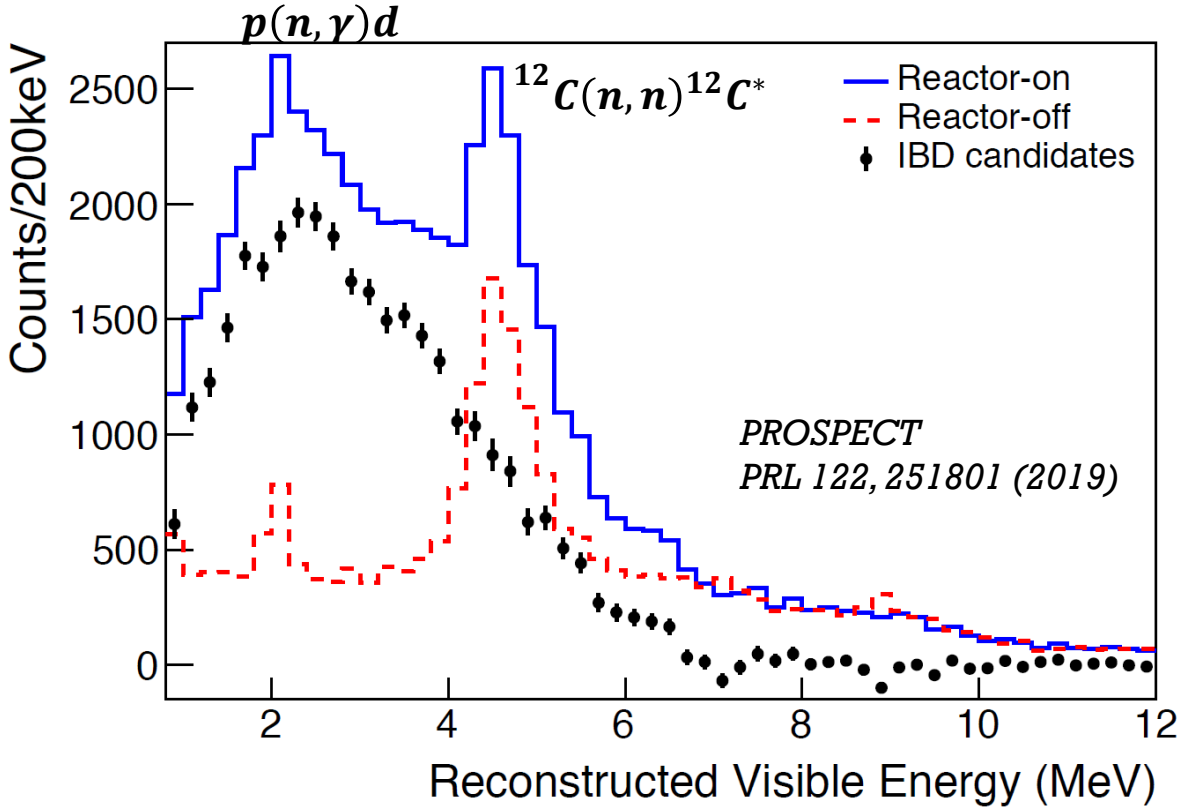
4.5%@1MeV

Phys. Rev. Lett. 121, 251802 (2018)
Phys. Rev. Lett. 122, 251801 (2019)

Measurement of ^{235}U Spectrum

- 40.3 days of reactor-on exposure
- 37.8 days of reactor-off exposure
- ~31000 IBD candidate events (reactor-off candidate events scaled to match exposure)
  ~6× greater statistics than ILL(1981)
- Measured spectrum with good S/B at surface 1.7/1 (0.8-7.2 MeV)

Prompt Energy Spectrum



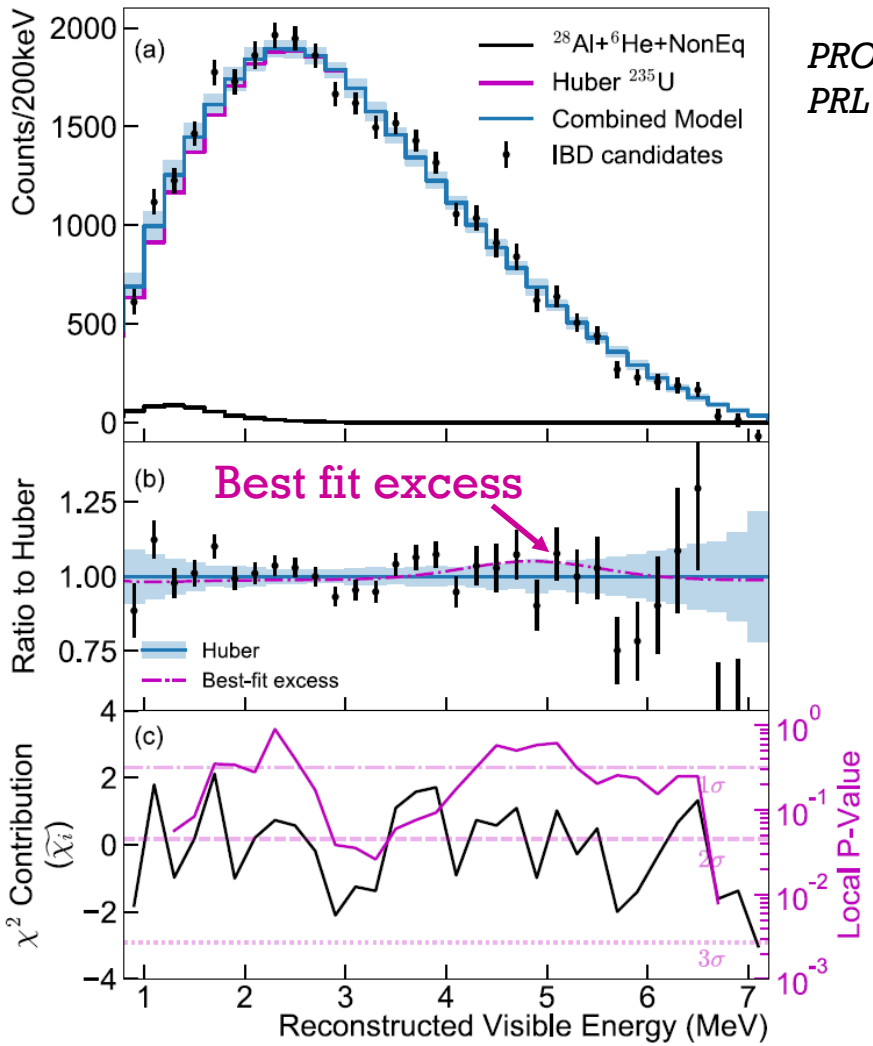
Interpretation of Prompt Energy Spectrum

Is PROSPECT consistent with Huber ^{235}U model?
$\chi^2/\mathrm{ndf} = 51.4/31$, p-value = 0.01

Huber model broadly agrees with spectrum but exhibits large χ^2/ndf with respect to measured spectrum, not a good fit

Shape of measured ^{235}U spectrum is consistent with deviation relative to prediction observed at LEU reactors (e.g. Daya Bay)

<u>PROSPECT current measurement is statistics limited. Expect improvement as more data are collected.</u>



PROSPECT
PRL 122, 251801 (2019)

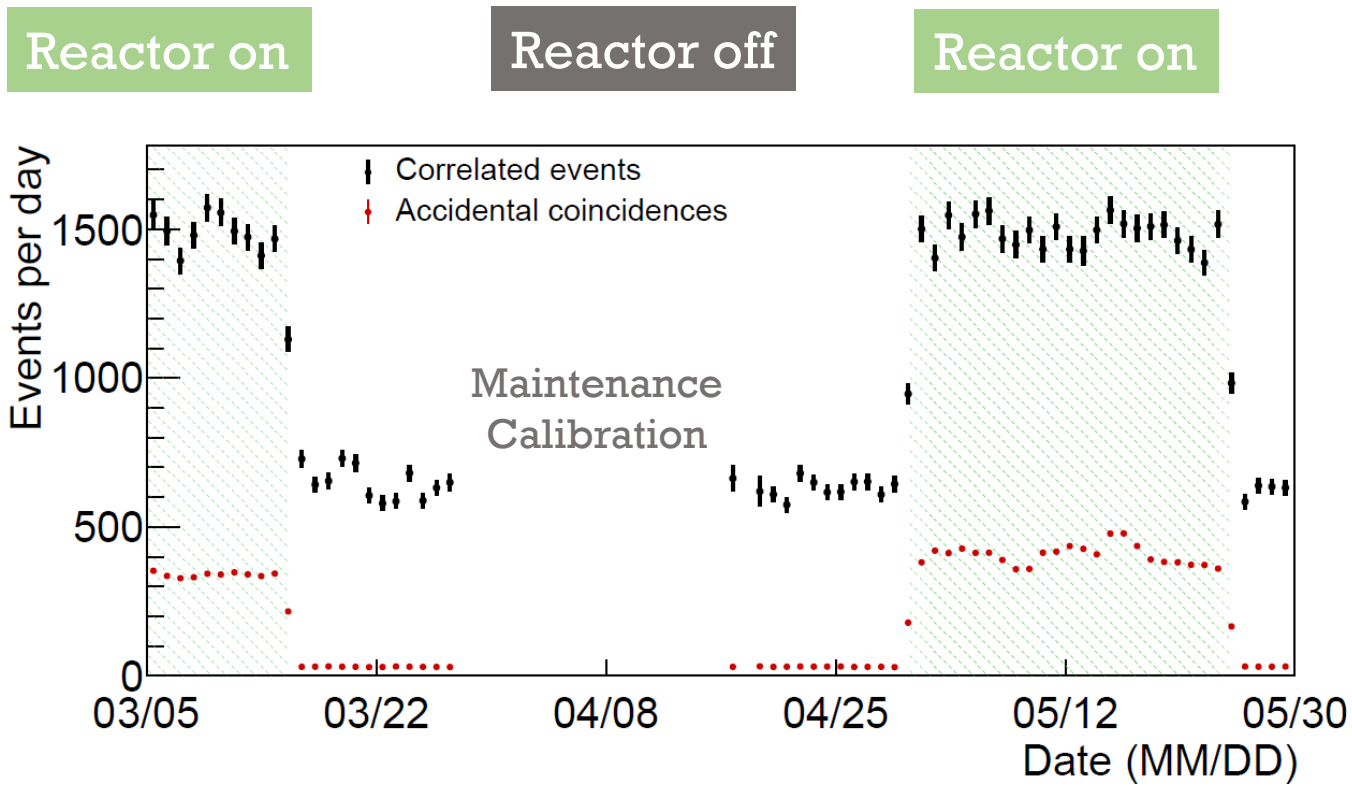
First Oscillation Analysis Data Set

33 days of reactor-on exposure
28 days of reactor-off exposure

25461±283 IBDs detected
Average of 771 IBDs/day

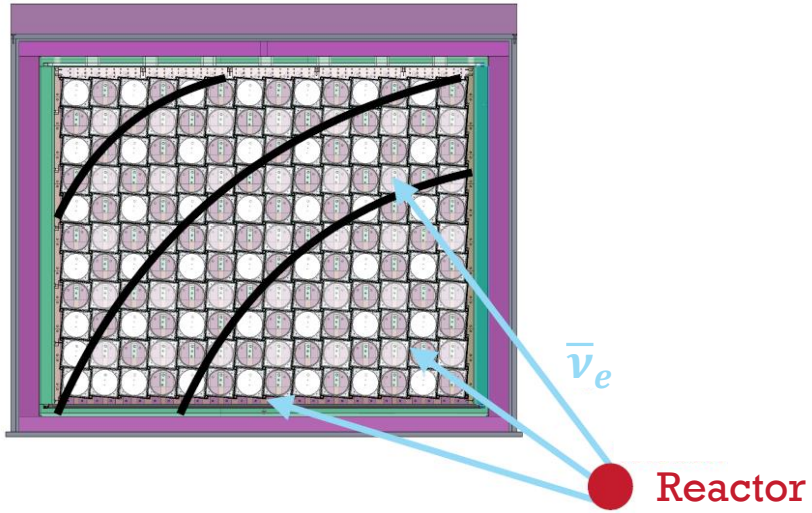
S/correlated background = 1.32
S/accidental background = 2.2

IBD event selection defined and frozen on 3 days of data

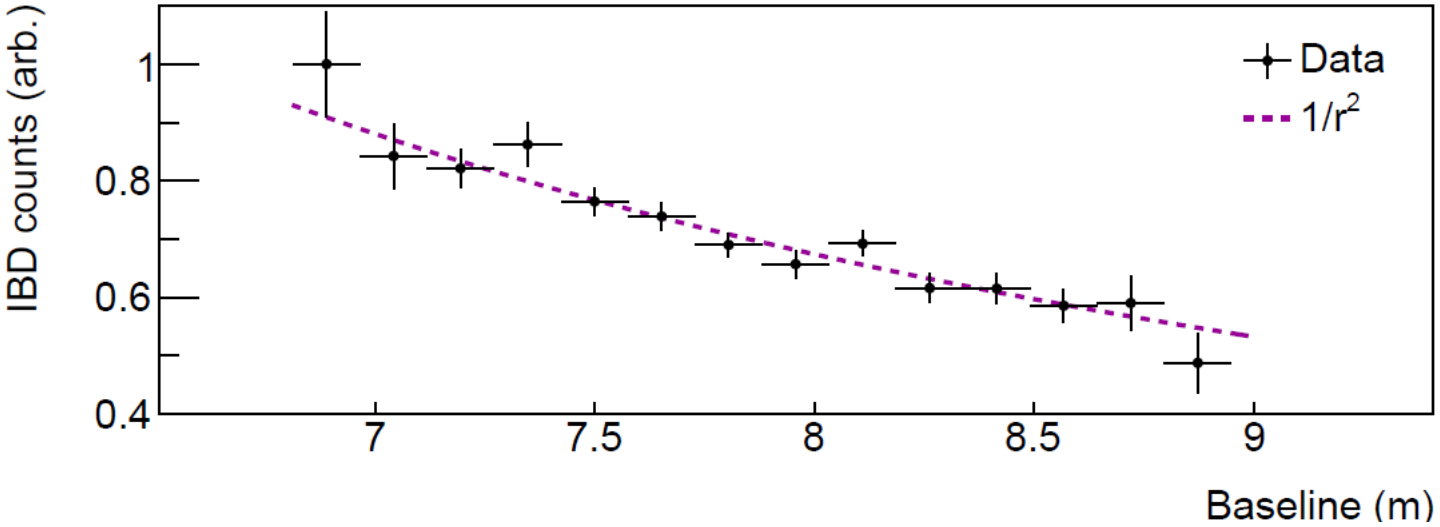


PROSPECT, Phys. Rev. Lett. 121, 251802 (2018)

Neutrino Rate vs. Baseline



PROSPECT, Phys. Rev. Lett. 121, 251802 (2018)

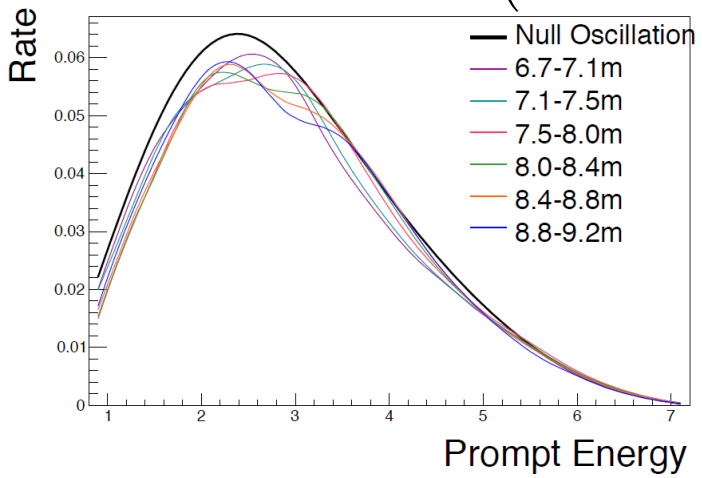


- Observation of $1/r^2$ behavior throughout detector volume
- Cover a wide relative baseline range
- 40% flux decrease from front of detector to back as expected

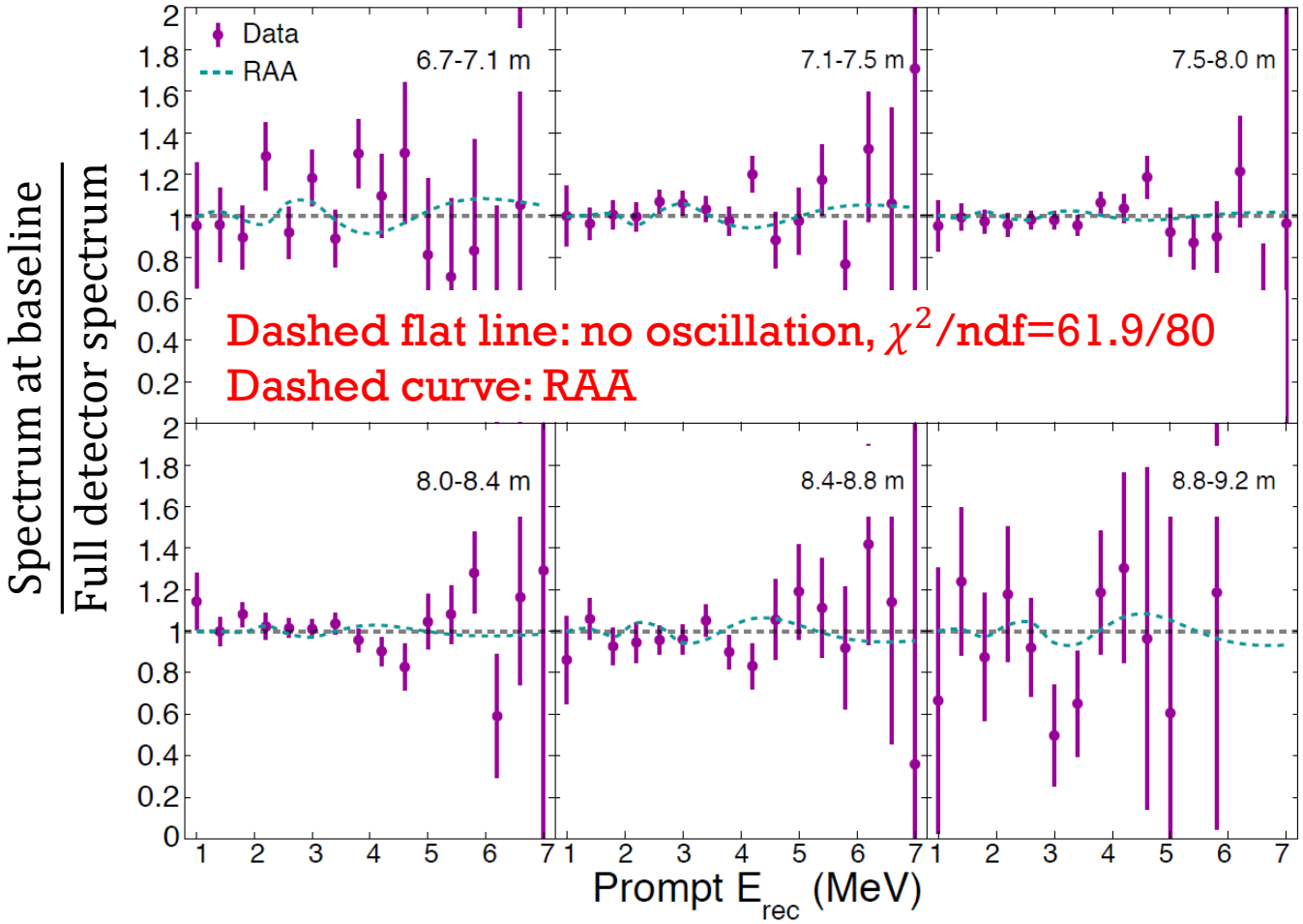
Neutrino Spectrum vs. Baseline

Illustration of Spectral Distortion vs. Baseline

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2\left(1.267 \frac{\Delta m^2_{41} L}{E}\right)$$



PROSPECT, Phys. Rev. Lett. 121, 251802 (2018)



Dashed flat line: no oscillation, χ^2/ndf=61.9/80

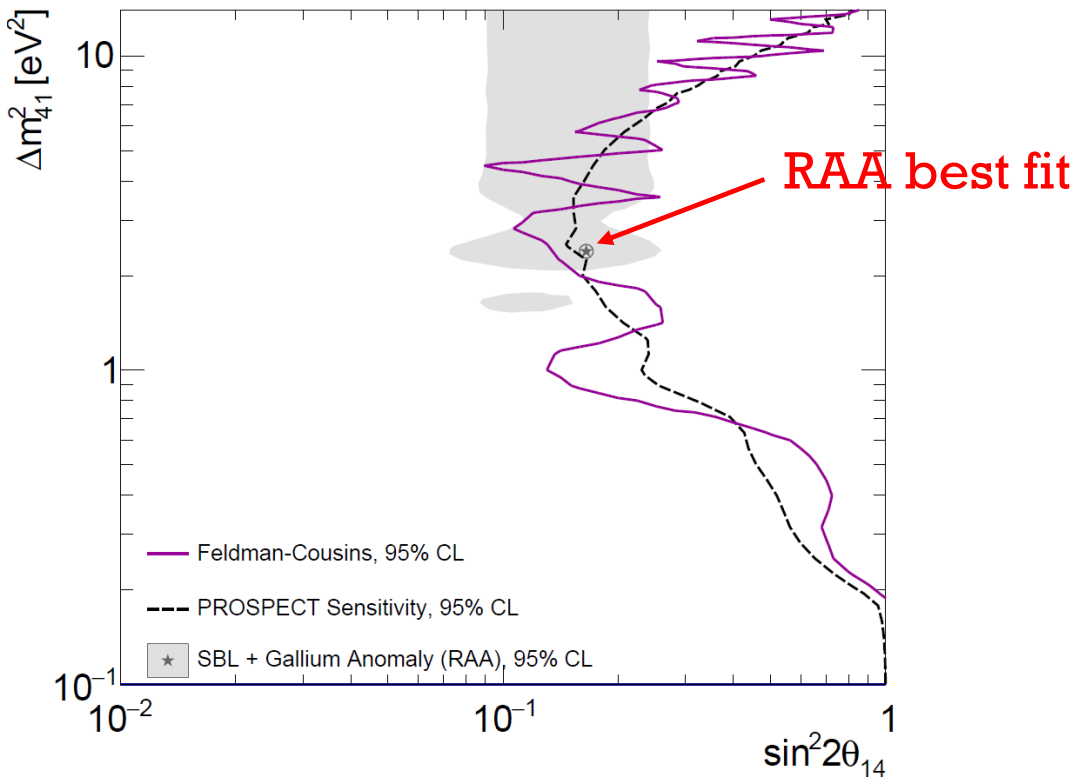
Dashed curve: RAA

- Compare spectra from 6 baselines to measured full-detector spectrum
- Good agreement between the data and the no-oscillation hypothesis
- Direct ratio search for oscillations, reactor model independent

Oscillation Search Results

- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/baseline correlations
- Critical χ^2 map generated from toy MC using full covariance matrix
- 95% C.L. exclusion curve based on 33 days of reactor on operation
- Cross checked with an independent analysis using Gaussian CLs method (NIMA 827 (2016) 63-78)

PROSPECT, Phys. Rev. Lett. 121, 251802 (2018)



Direct test of the Reactor Antineutrino Anomaly
Disfavors RAA best-fit point at >95% (2.2σ)

Summary

- PROSPECT started taking data in March, 2018
- Background rejection and energy resolution meet expectation and match Monte Carlo
- World-leading signal-to-background for a surface-based detector (< 1mwe overburden). Observed antineutrinos from HFIR with good signal/background.
- First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.2σ.
- Performed a modern high-statistics ^{235}U spectrum measurement using a surface-based detector; currently statistics limited
- More data has been collected and analysis is ongoing

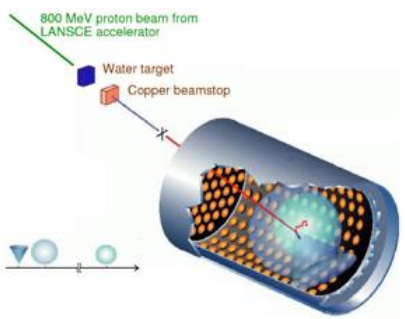
PROSPECT Collaboration

Backup

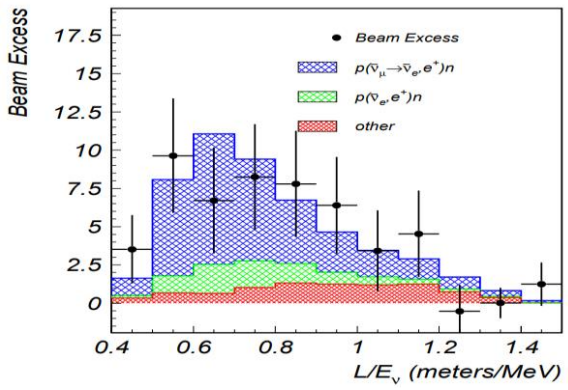
eV-scale Sterile Neutrino Hints

LSND

- $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
- $L/E \sim 30\text{m}/30\text{MeV}$



Phys.Rev.D64:112007,2001



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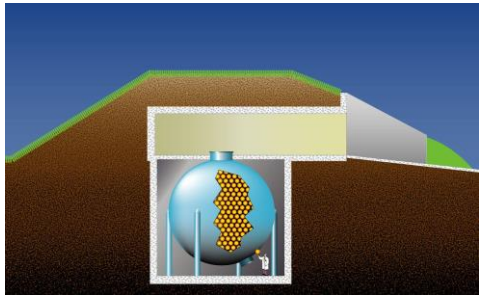
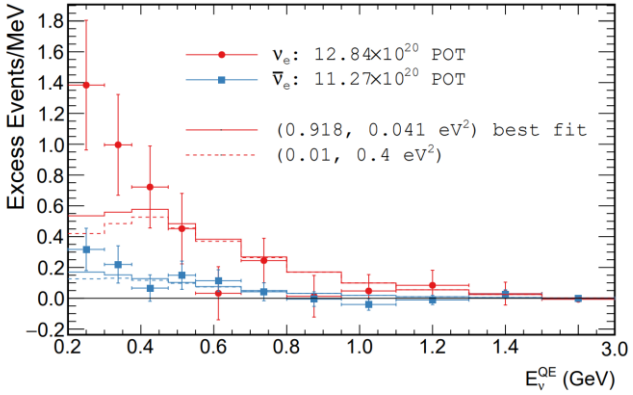
MiniBooNE

- $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
- $L/E \sim 500\text{m}/500\text{MeV}$



Phys. Rev. Lett. 121, 221801



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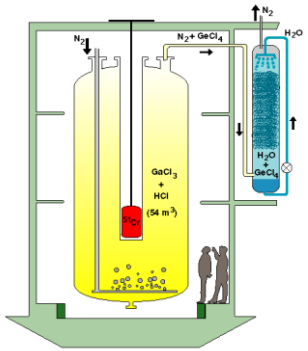
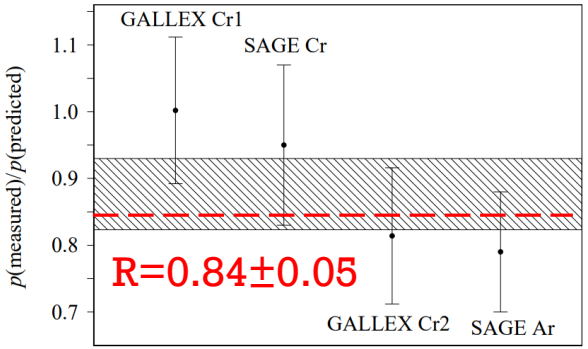
GALLEX/SAGE: Solar ν expts, Calibrated ν_e source: ^{51}Cr and ^{37}Ar

- ν_e disappearance

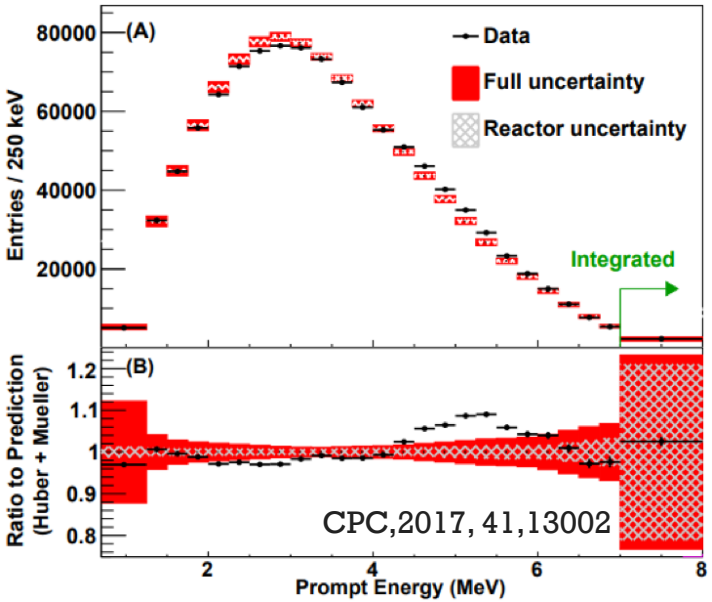


Phys.Rev.C73:045805,2006

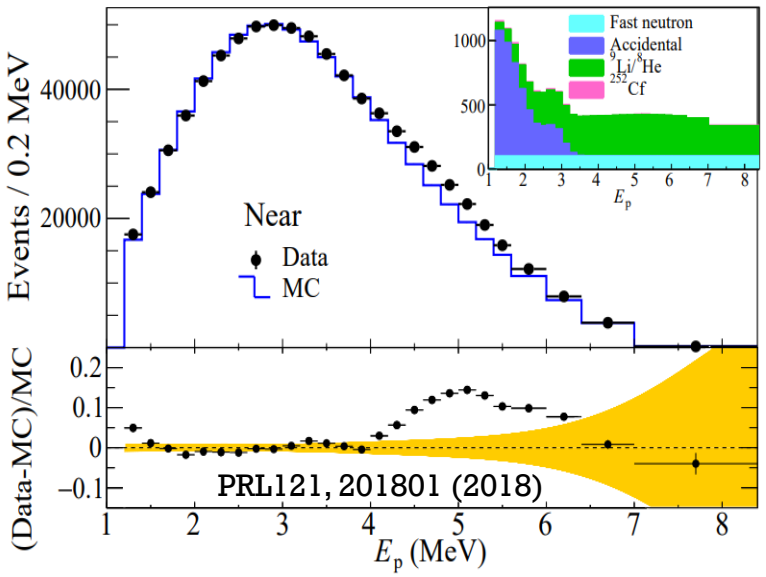


Reactor Antineutrino Spectral Anomaly: the "Bump"

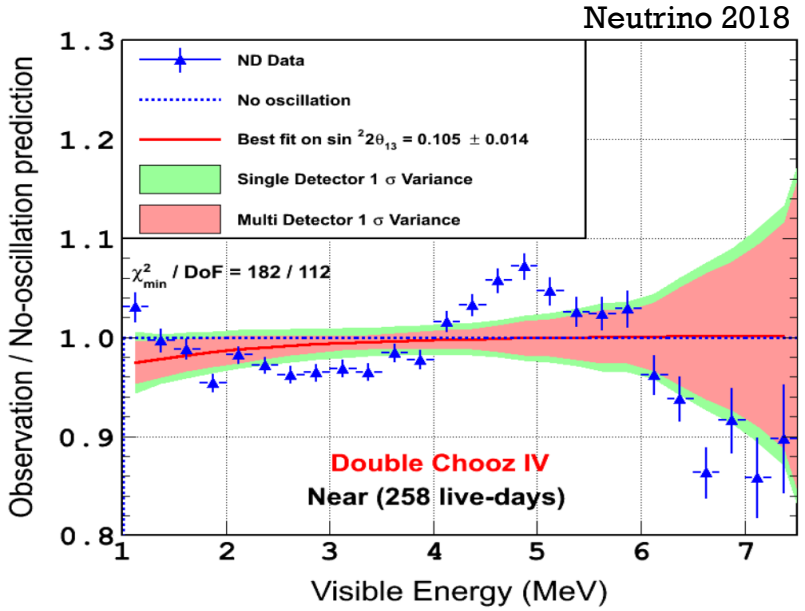
Daya Bay



RENO



Double Chooz



- Bump in 4-6 MeV prompt energy (5-7 MeV neutrino energy) observed in 2014 by three θ_{13} experiments
- Cannot be explained by detector effects such as energy response
- Problems from reactor model predictions?