PROSPECT: Precision Reactor Oscillation and Spectrum Experiment

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for the PROSPECT collaboration

BROOKHAVEN NATIONAL LABORATORY

Outline

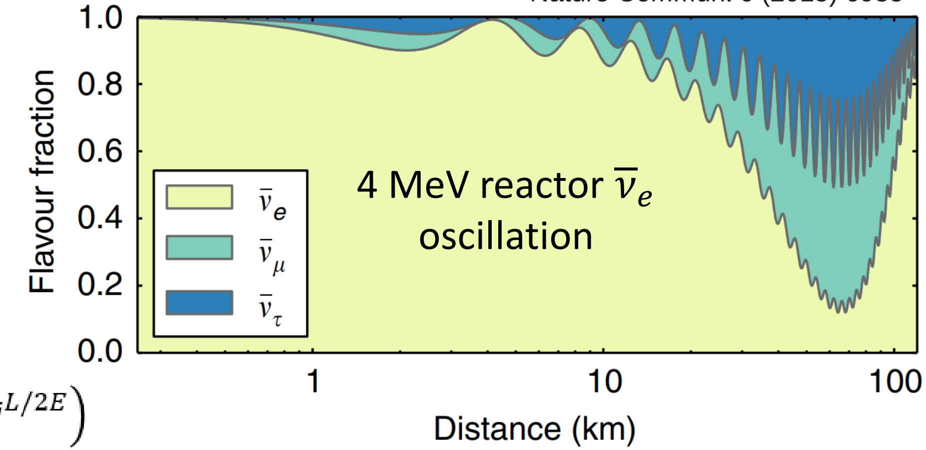
- Introduction
  - Neutrino oscillation and sterile neutrino
- PROPSECT: reactor model independent search for sterile neutrino
- PROSPECT: precision measurement of the ^{235}U antineutrino spectrum
- Summary

Neutrino Oscillation

Neutrino oscillation indicates:

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

Nature Commun. 6 (2015) 6935



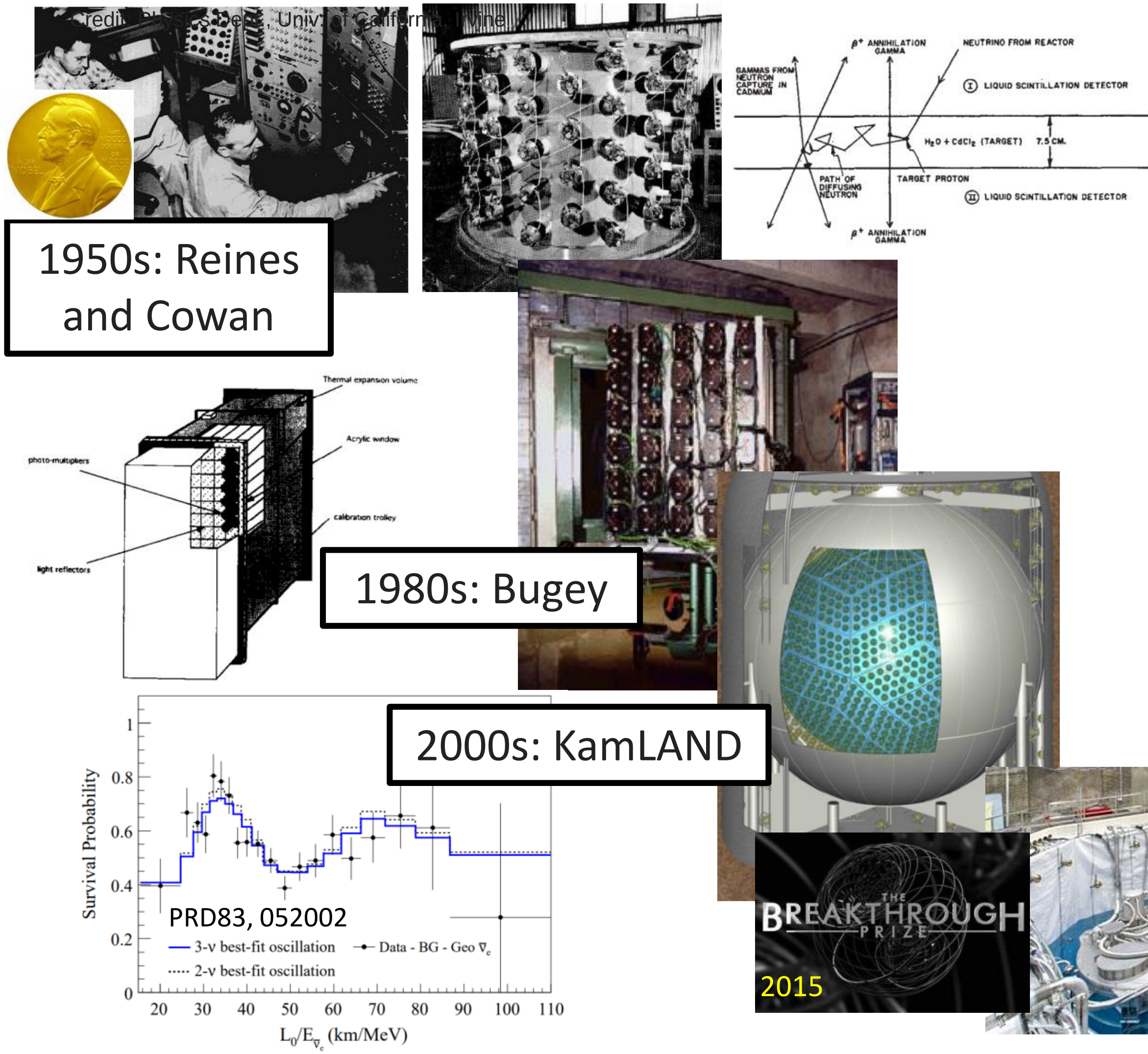
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 2\mathrm{Re}\sum_{j>i} U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}\left(1 - e^{i\Delta m^2_{ij}L/2E}\right)$$

Flavor eigenstates | Neutrino mixing matrix (U) | Mass eigenstates

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

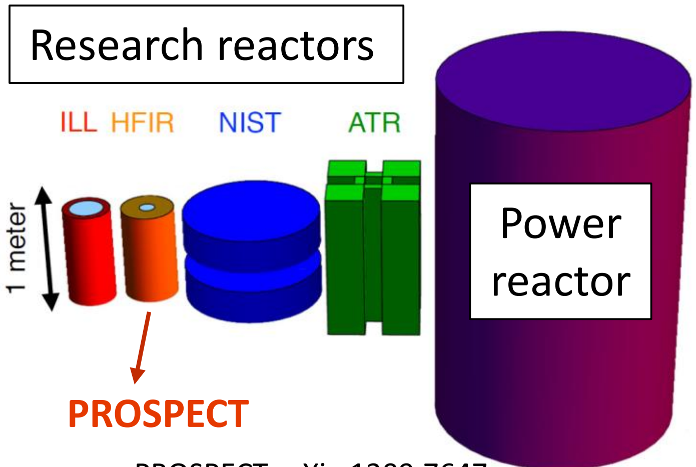
Atmospheric / Long baseline accelerator | Short baseline reactor / Long baseline accelerator | Solar / Long baseline reactor

Reactor Neutrino Experiments

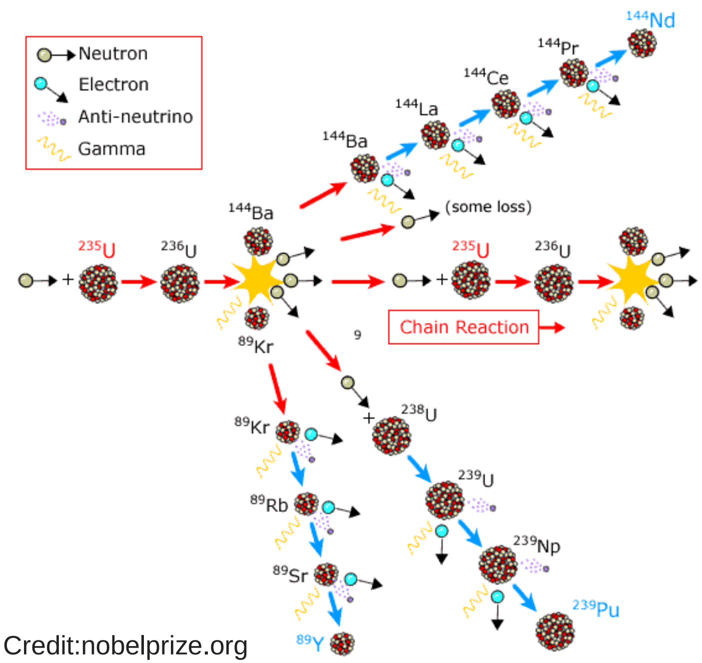


- Currently hold the best precision of
  - Δm^2_{21} (KamLAND)
  - θ_{13} (DayaBay)
- Comparable precision to accelerator-based exp.
  - $|\Delta m^2_{32}|$ (DayaBay)
- In the future JUNO will reach even better precision for
  - Δm^2_{21}, $|\Delta m^2_{32}|$, θ_{12}, Mass Hierarchy

Nuclear Reactor As Antineutrino Source



PROSPECT arXiv:1309.7647



Credit:nobelprize.org

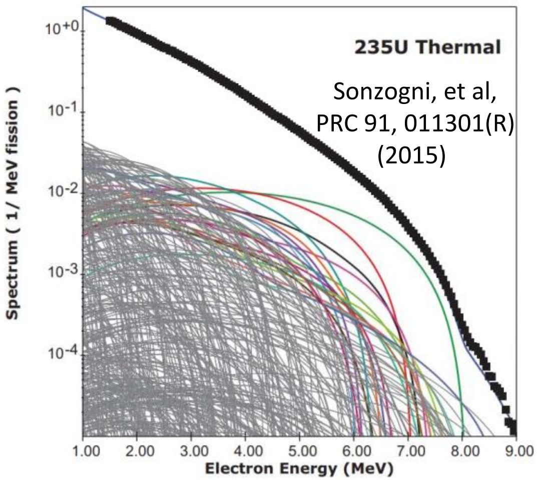
- Commercial reactors in Nuclear Power Plants have low-enriched uranium (LEU) cores
  - Mixture of fissions: $^{235}\mathrm{U}(\sim 55\%)$, $^{239}\mathrm{Pu}(\sim 30\%)$, $^{238}\mathrm{U}(\sim 10\%)$, $^{241}\mathrm{Pu}(\sim 5\%)$
  - Large power: $\sim$3 GW$_{\mathrm{th}}$
- Research reactors have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

- Nuclear reactors produce pure $\overline{\nu}_e$ from beta decays of fission daughters
  - Low energy: < 10 MeV
- $\sim$6 $\overline{\nu}_e$/fission
- $2 \times 10^7\ \overline{\nu}_e/\mathrm{MW_{th}}$ per second

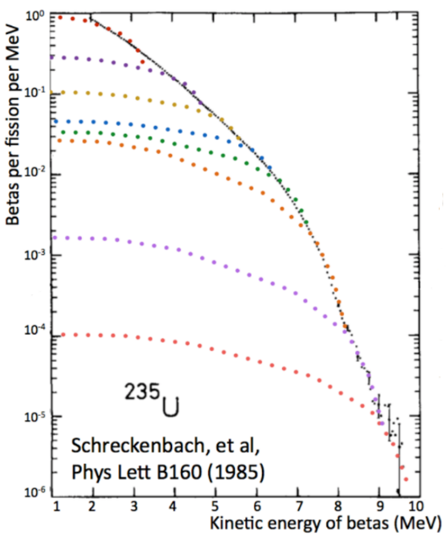
Methods to Predict Neutrino Flux/Spectra

Two main approaches:

- Ab initio method
  - Calculate the individual beta-decay spectra from 1000s of isotopes from database info
  - Sum according to cumulative yields
  - ~10% uncertainty due to missing data in the database and forbidden decays
- Conversion method
  - Measure total outgoing beta-decay electron spectrum of fission products
  - Predict corresponding anti-neutrino spectra with > 30 virtual branches
  - ~2.5% uncertainty



Example: Fit virtual beta branches



Prediction of neutrino flux has evolved upward over time

In the 1980s, two predictions became the standards for the field (ILL-Vogel model)

- Schreckenbach *et al*. converted their (ILL reactor) measured fission beta-spectra for ^{235}U, ^{239}Pu and ^{241}Pu into antineutrino spectra
- Vogel *et al*. used the nuclear databases to predict the spectrum for ^{238}U

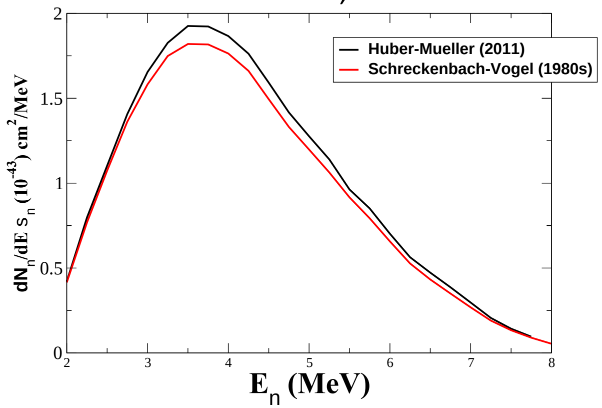
In 2011, both Huber and Muller et al. re-calculated the prediction (Huber-Mueller model), and the predicted antineutrino flux increase by 5-6%

Changes in Flux/Spectrum:

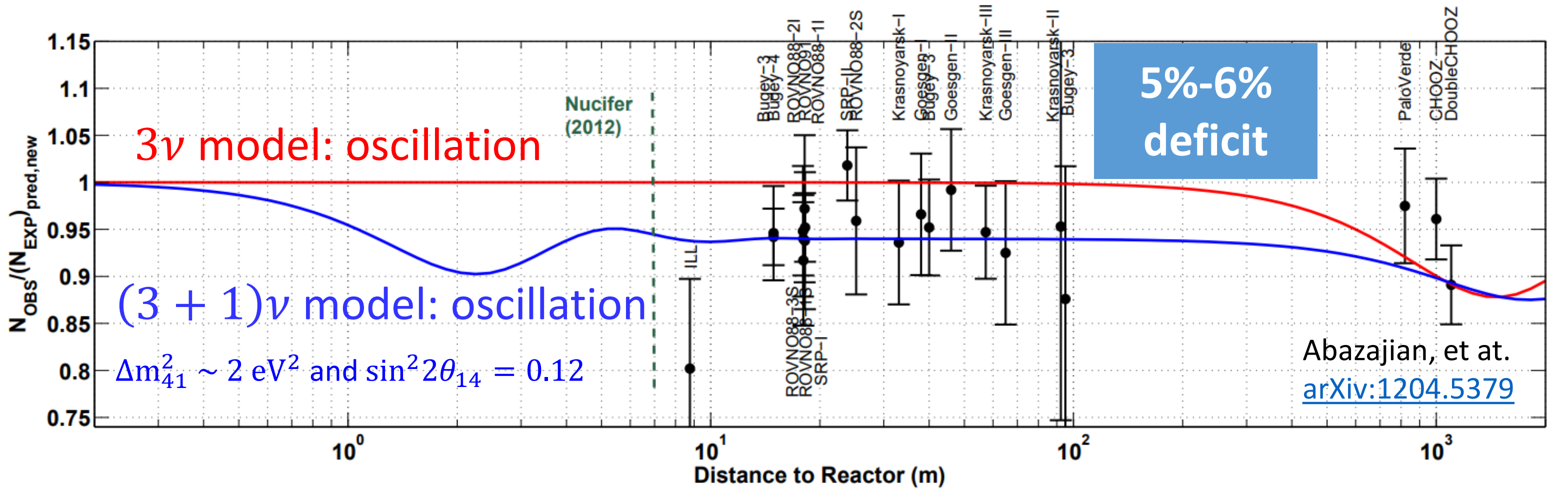
- Conversion: +3%
- Neutron lifetime: +1%
- Non-equilibrium isotopes: +1%

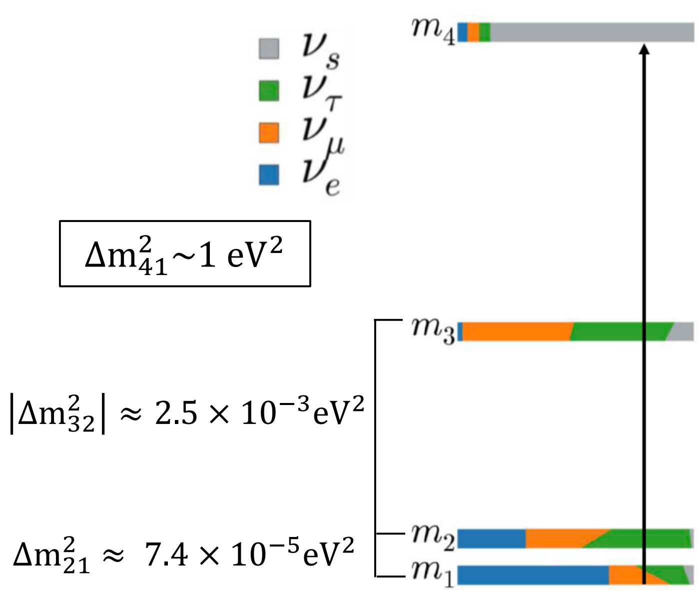
Phys.Rev. C24 (1981) 1543-1553
Phys.Lett. 118B (1982) 162-166
Phys.Lett. B218 (1989) 365-368

Danielson et at., Neutrino 2018



Reactor Antineutrino Anomaly: Flux Deficit





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

- Problems from reactor model predictions?
- New physics?

Sterile neutrino

- High frequency oscillation
- Mass splitting $\sim 1\ \mathrm{eV}^2$
- Baseline ~few meters

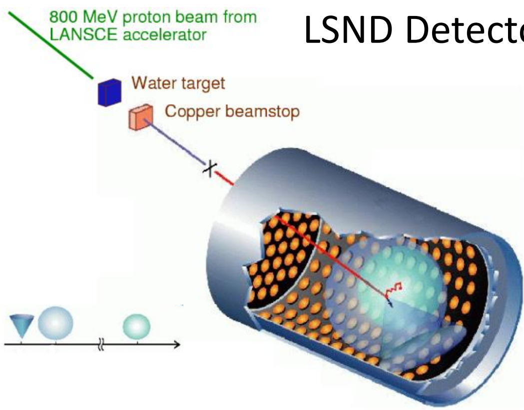
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{14} \sin^2\left(1.267\frac{\Delta m^2_{41} L}{E}\right) - \sin^2 2\theta_{13} \sin^2\left(1.267\frac{\Delta m^2_{31} L}{E}\right)$$

eV-scale Sterile Neutrino Hints

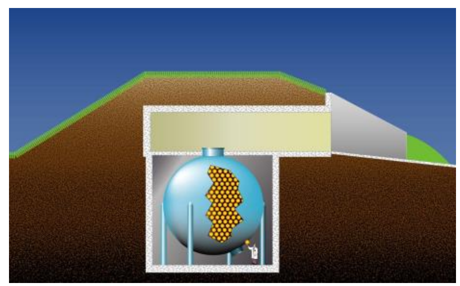
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance): $L/E \sim 30\text{m}/30\text{MeV}$
- MiniBooNE ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance): $L/E \sim 500\text{m}/500\text{MeV}$
- GALLEX/SAGE (ν_e disappearance): the gallium anomaly

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

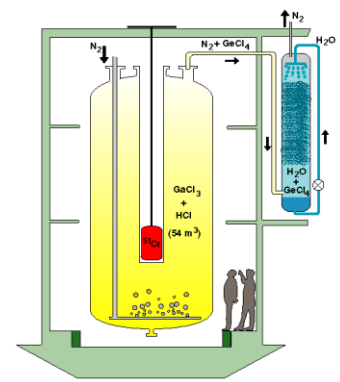
LSND Detector



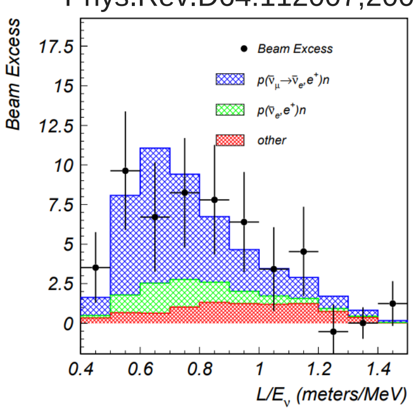
MiniBooNE
short baseline accelerator



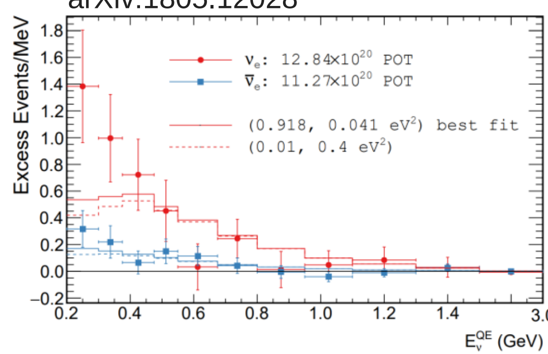
GALLEX/SAGE: Solar ν expts,
Calibrated $\boldsymbol{\nu_e}$ source: ^{51}Cr and ^{37}Ar

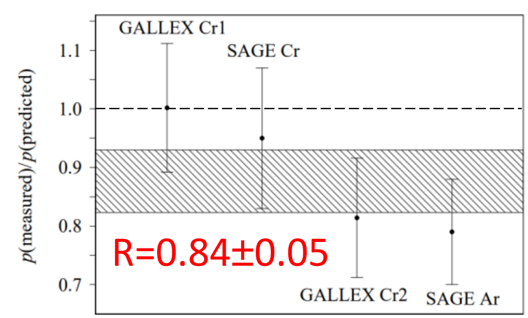


Phys.Rev.D64:112007,2001



arXiv:1805.12028

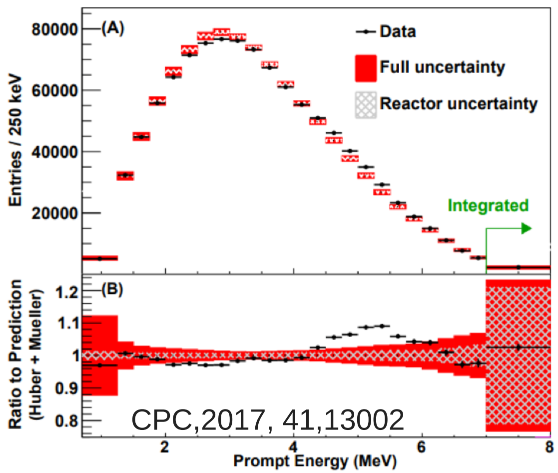




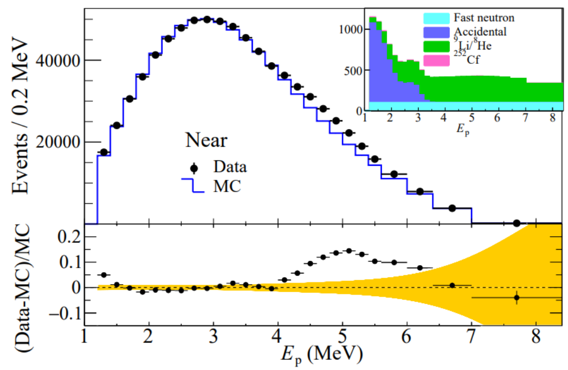
Phys.Rev.C73:045805,2006

Challenge to Reactor Model: Spectrum "Bump"

Daya Bay



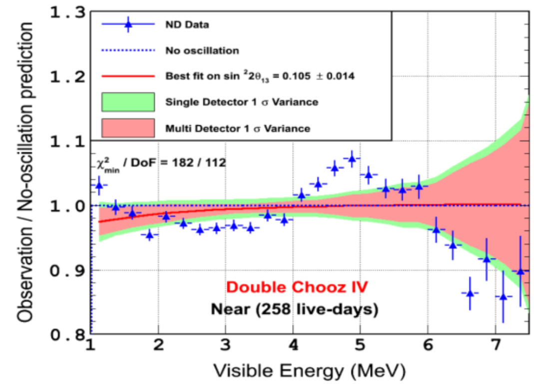
RENO



arXiv:1806.00248

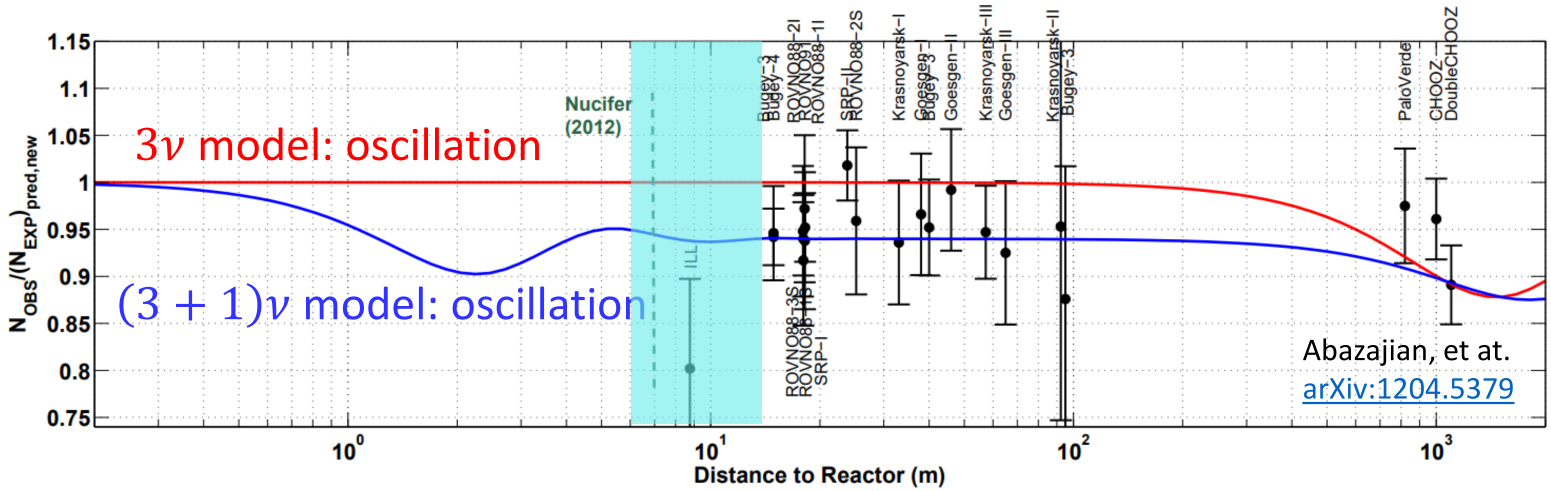
Double Chooz

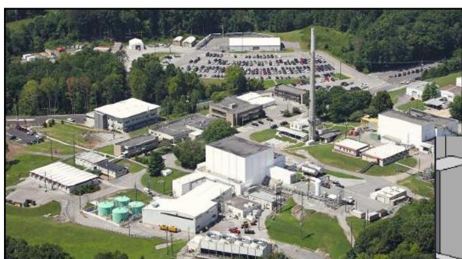
Neutrino 2018



- 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
- Indicates the reactor model uncertainty is under-estimated

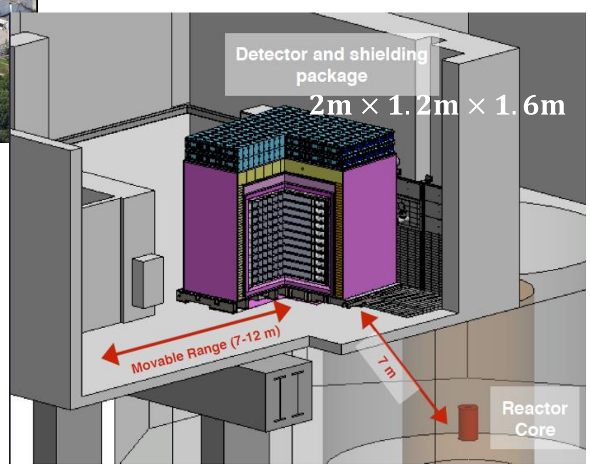
PROSPECT: Search for Sterile Neutrino





Reactor at Oak Ridge National Lab

PROSPECT Detector



Physics goals

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

PROSPECT Collaboration

High Flux Isotope Reactor (HFIR)

- 85MW highly-enriched uranium reactor
  - >99% ^{235}U fission fraction, effectively no isotopic evolution
- Compact core, 44 cm diameter and 51 cm tall
- 24 day cycles, 46% reactor up time

HFIR at Oak Ridge National Lab

44 cm

Reactor Core

Reactor Neutrino Detection through IBD Reaction

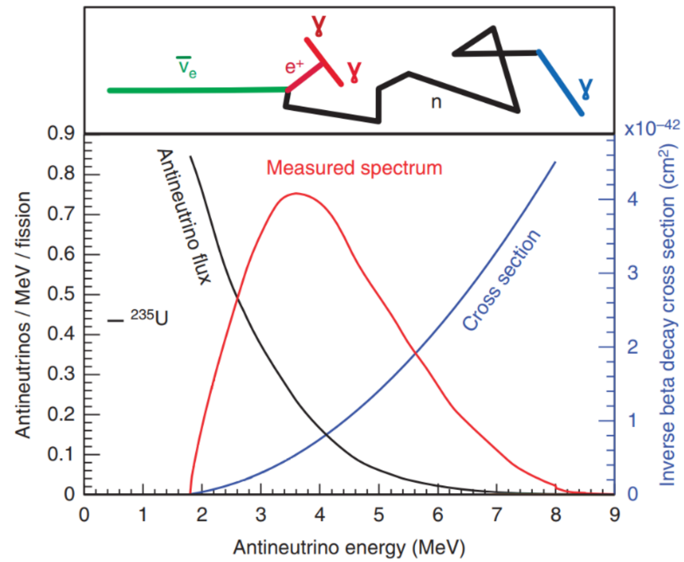
$$S(E_{\overline{\nu}}) = c \cdot f \cdot s(E_{\overline{\nu}}) \cdot \sigma(E_{\overline{\nu}})$$

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

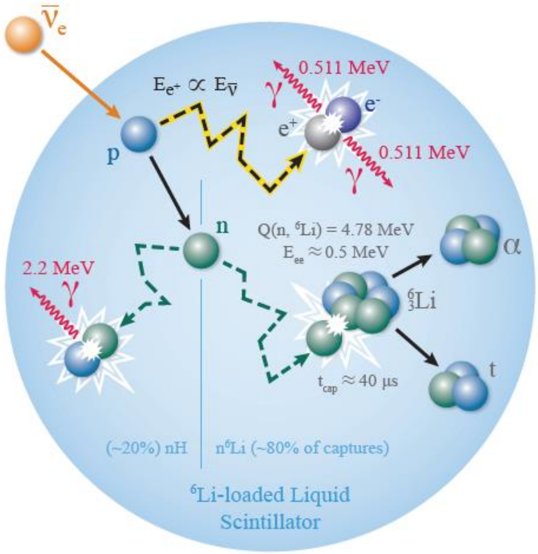
Inverse beta decay (IBD):

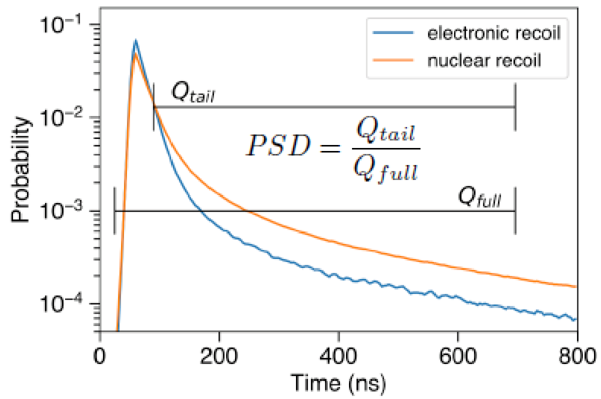
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

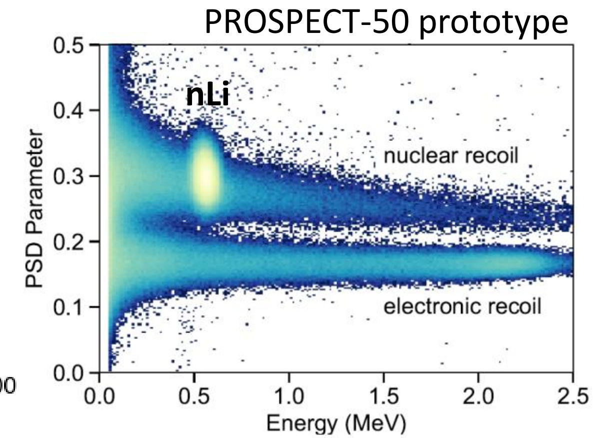
$$E_{\overline{\nu}} \approx T_{e^+} + 1.8\text{MeV}$$

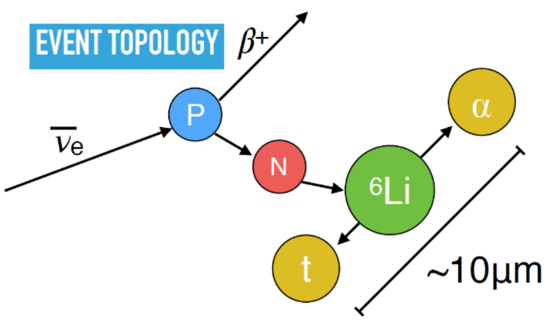


IBD Detection with ^{6}LiLS









- <u>Event Coincidence Signature</u>
  - e-like prompt signal, followed by a ~40μs delayed neutron capture
- <u>The Pulse Shape Discrimination (PSD)</u> of scintillator distinguishes the **β⁺-like** event (IBD signal) and ***n*-like** events (most significant background at HFIR).

Coincidence + PSD to reject of backgrounds

^{6}Li-Loaded Liquid Scintillator

LiLS Requirements:

- High light yield (>6000ph/MeV) for energy resolution
- Excellent pulse-shape discrimination (PSD)
- Non-toxic, high flashpoint
- Stable and affordable

LiLS based on EJ-309 meets all requirements

- 8200ph/MeV, excellent PSD
- **Safe to operate at a reactor**
- 95% ^{6}Li enrichment, 0.1% by mass

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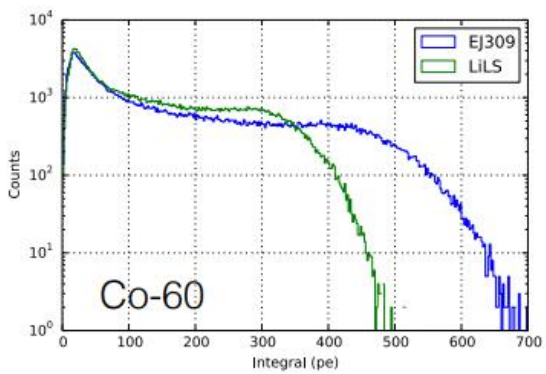
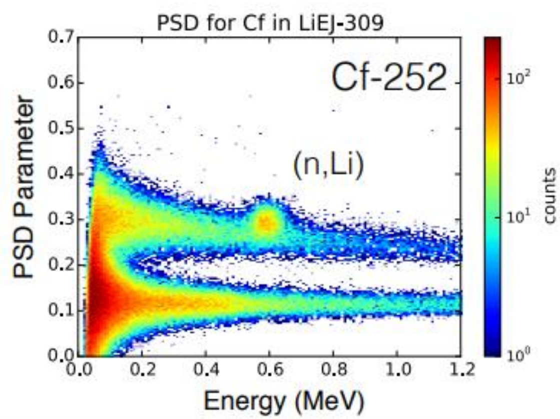
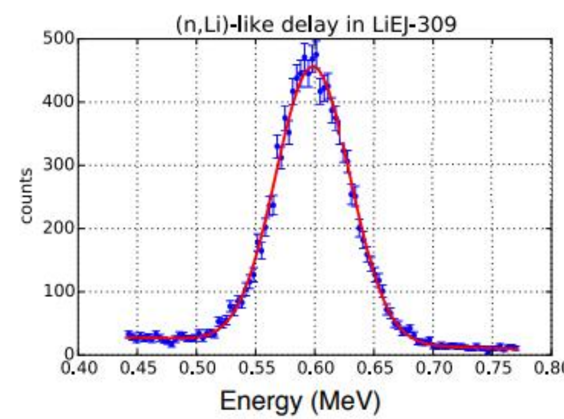


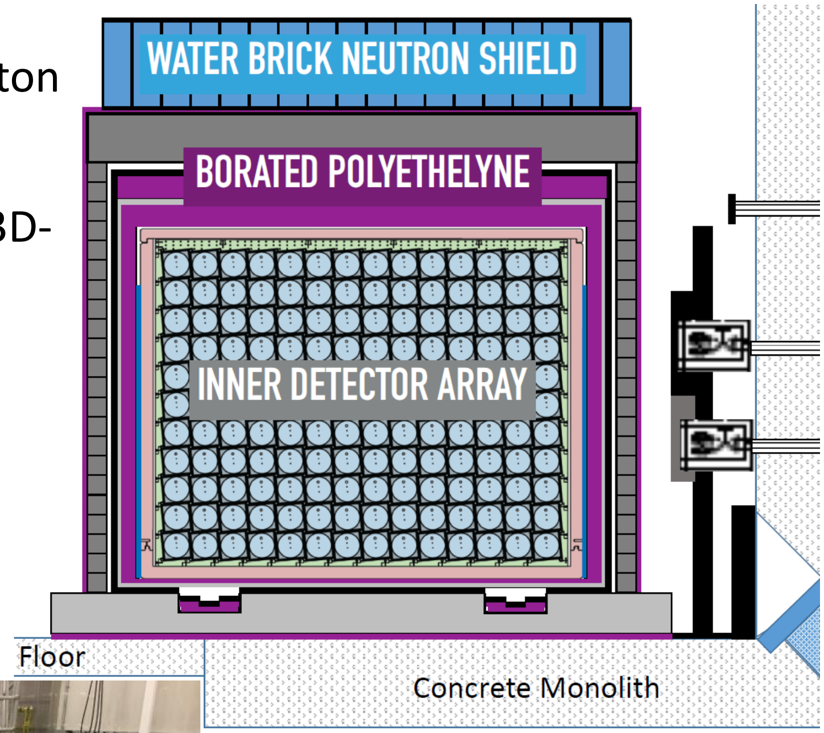




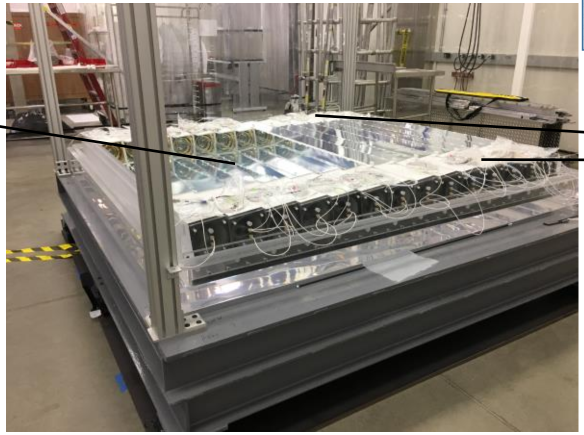
developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities

PROSPECT Detector Design

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

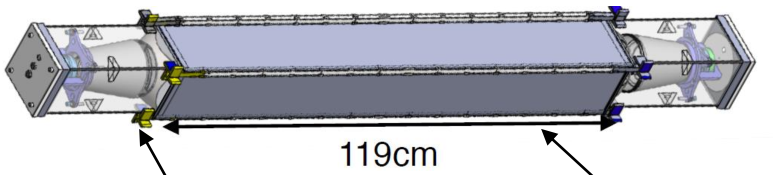


Reflector

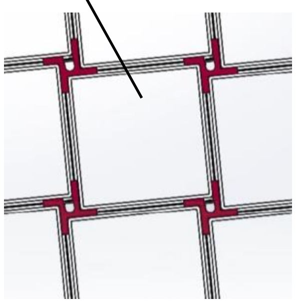


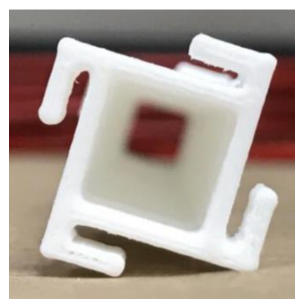
Double ended PMT readout for full (X,Y,Z) position reconstruction

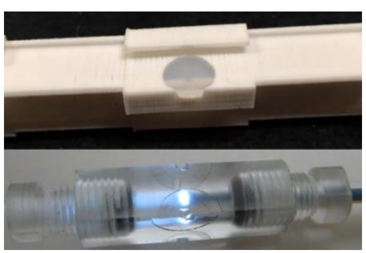
Detector Components



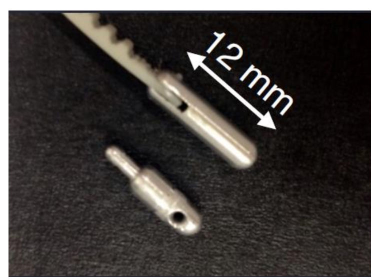
3D printed support rods
Tilted array for
calibration access



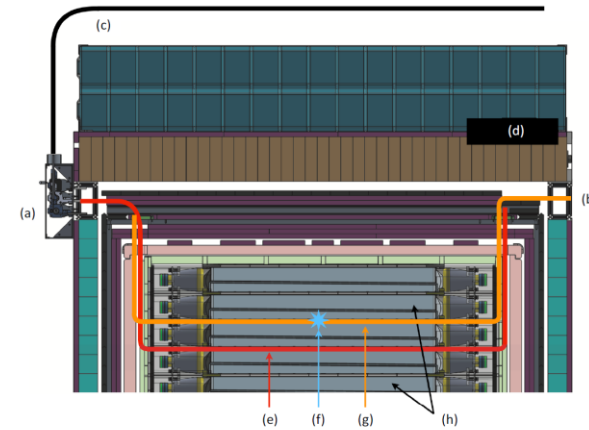


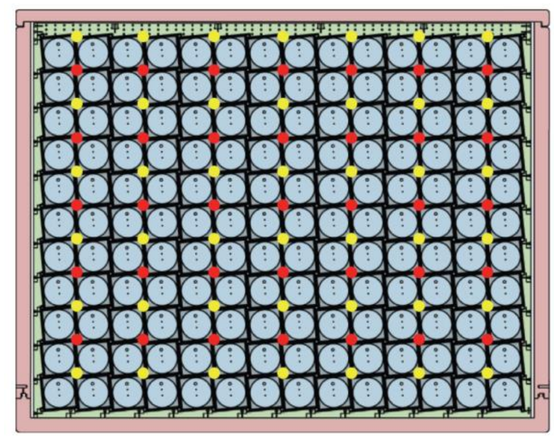


Optical diffuser



Radioactive source



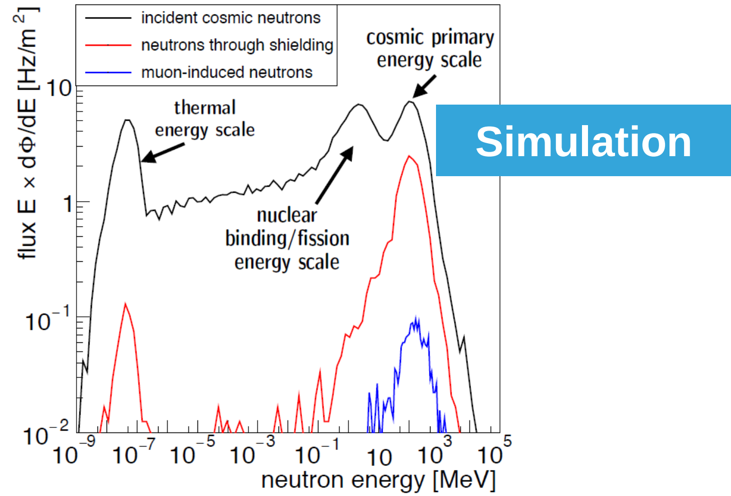


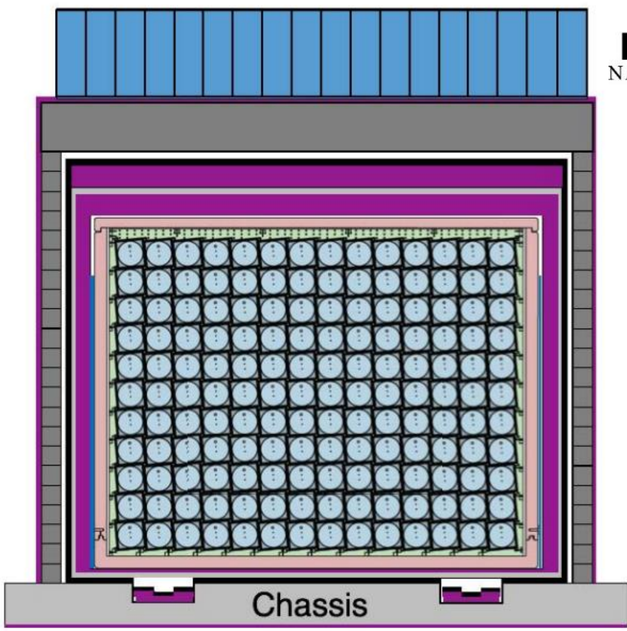
Locations of the radioactive source tube (35) and optical insert (42) positions in between the segments of the inner detector

Novel Shielding Design

- Detector operates at the surface < 1m overburden
  → cosmic-ray backgrounds
- Reactor-related bkgs (gammas and thermal n)

High energy neutrons main source of cosmogenic backgrounds





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- Water
- HDPE
- BPE
- 1" Lead

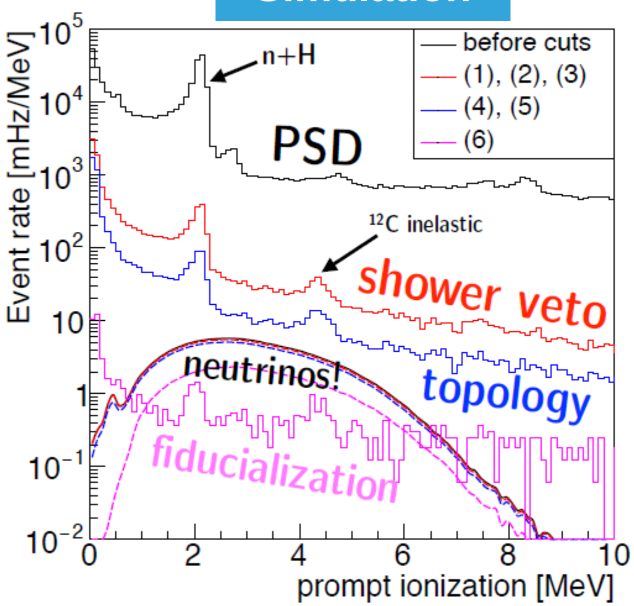
*HDPE: high density polyethylene
* BPE: borated polyethylene

Optimize space, weight, and total background suppression

- Main problem is ~100MeV neutrons
- create majority of IBD-like backgrounds (gamma-like prompt, neutron capture)
- Neutron spallation on high-Z shielding increases backgrounds
- *Need neutron shielding inside lead shielding*

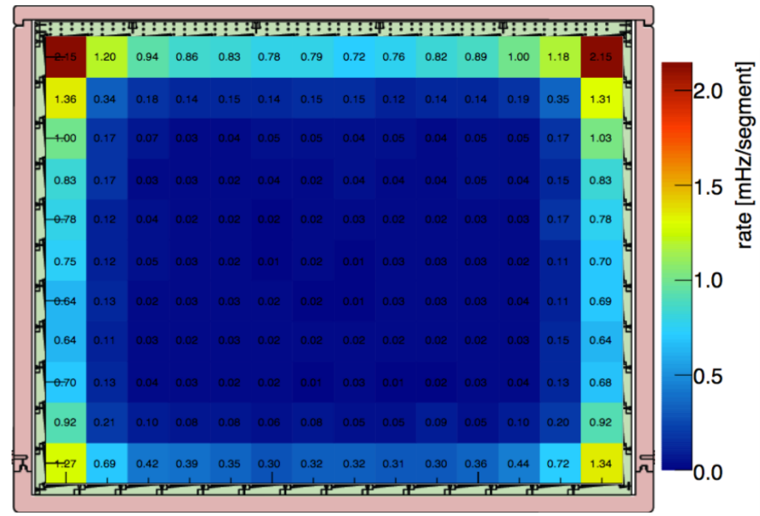
Active Background Suppression

Simulation



PROSPECT J.Phys. G43 (2016)

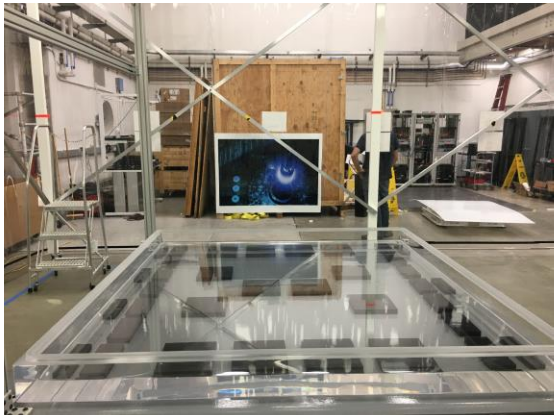
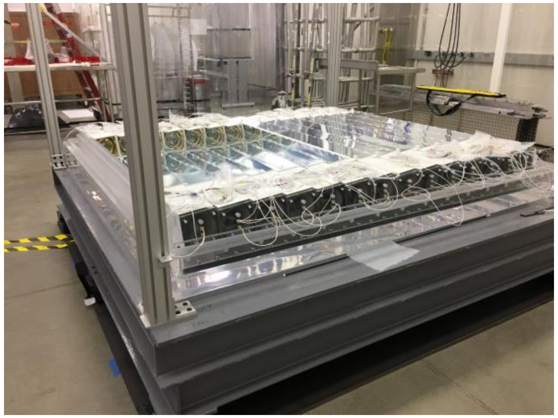
Simulation



Simulated background rate of cosmogenic neutron interactions

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

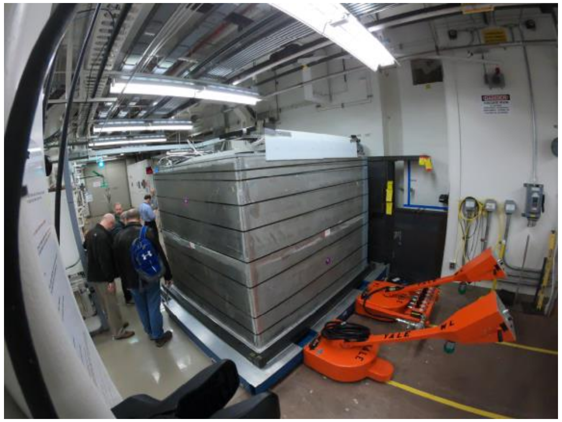
Construction and Installation

Oct 2017 – Jan 2018 at Yale Wright Lab

Arrive at Oak Ridge

At HFIR



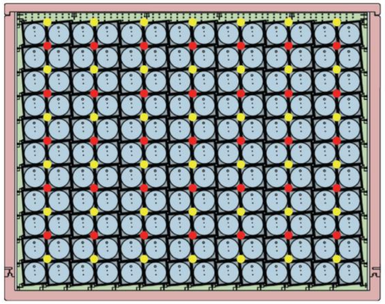
Filling LiLS from mixing tack

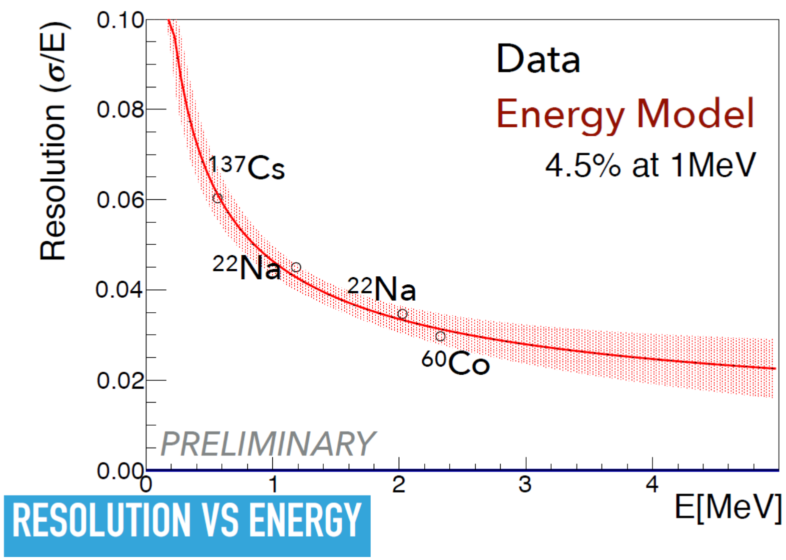
March 5, 2018 Began operation

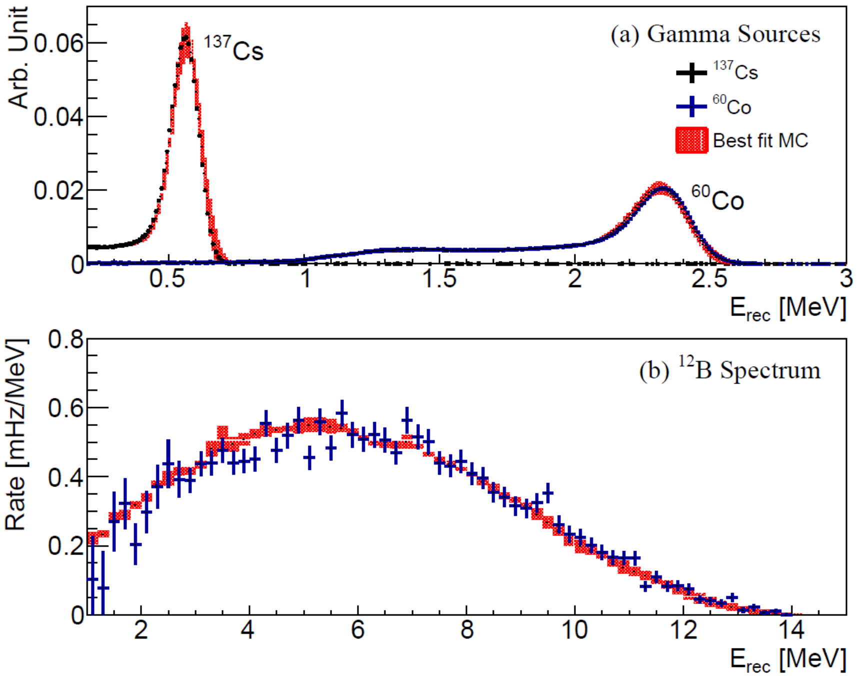
Detector Characterization

Energy Reconstruction

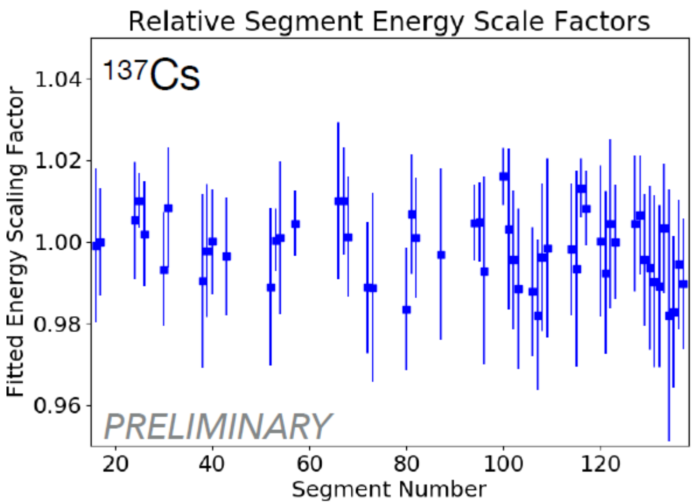
- Gammas sources (^{137}Cs, ^{60}Co) deployed throughout detector, measure single segment response
- Fast-neutron tagged ^{12}B
  - High-energy beta spectrum calibration
- Full-detector E_{rec} within 1% of E_{true}
- **High light collection: 795±15 PE/MeV**

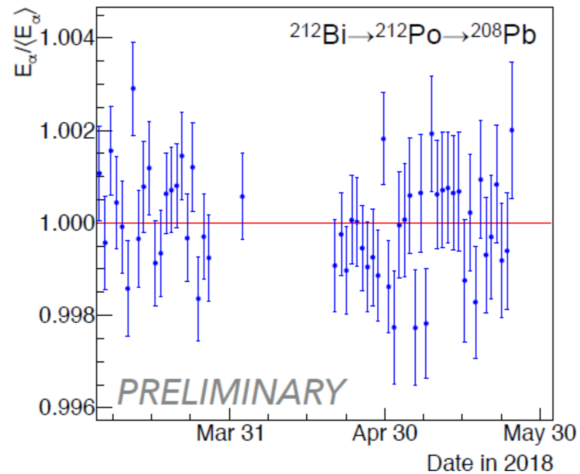


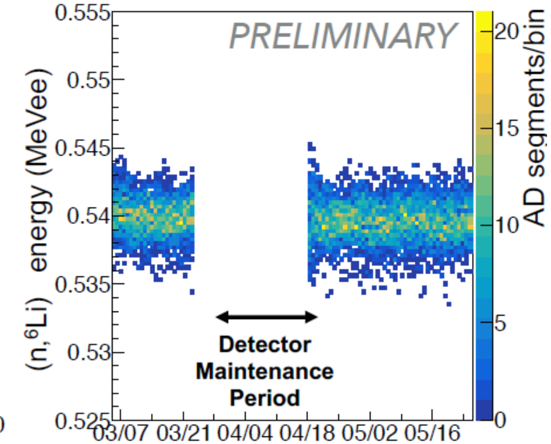


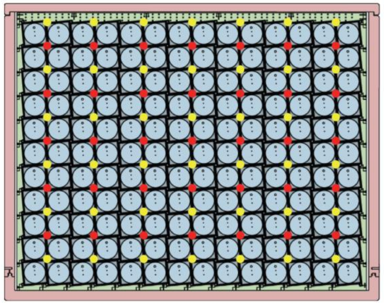


Detector Uniformity









Calibration Source Deployment:

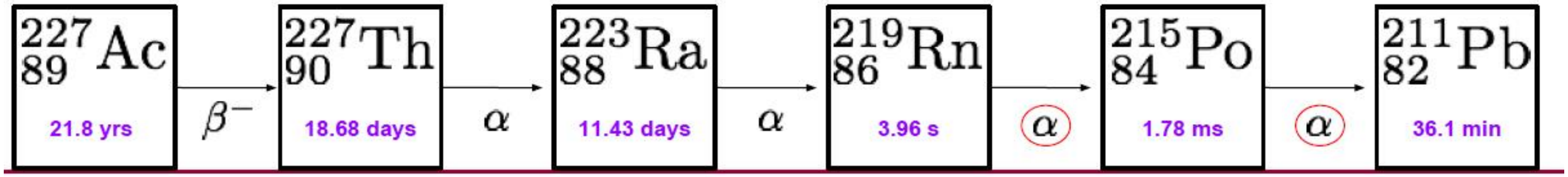
- 35 calibration source tubes throughout detector to map energy response
- Segment to segment uniformity ~1%
- ^{252}Cf source to study neutron capture efficiency

Intrinsic radioactive sources

- Track uniformity over time with distributed internal single-segment sources
- Alpha lines from ^{212}Bi→ ^{212}Po→^{208}Pb decays, nLi capture peak
- Reconstructed energy stability over time < 1%

^{227}Ac spike of ^{6}LiLS

note: not full U-235 decay chain



- **α,α** coincidence ^{219}Rn→^{215}Po→^{211}Pb (RnPo) provides localized, nearly mono-energetic deposits
- If ^{227}Ac uniformly dissolved in ^{6}LiLS, then relative RnPo rate per cell gives the relative mass per cell: Essential for oscillation measurement
- R&D at BNL determined no significant ^{227}Ac adsorption on detector materials
- ~0.8 Bq ^{227}Ac added to ~4500 L total ^{6}LiLS

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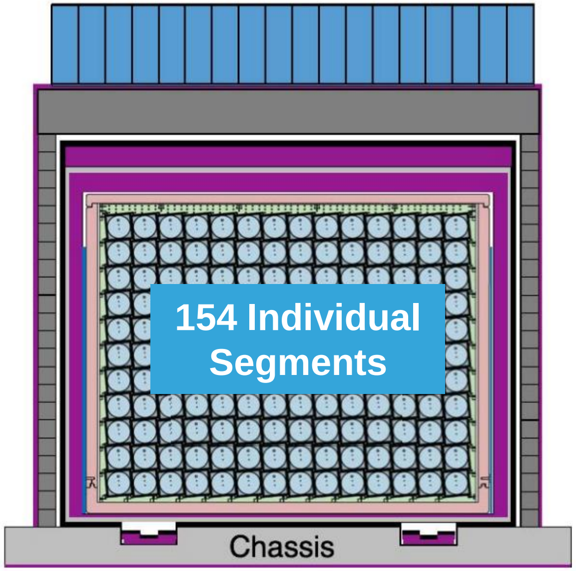
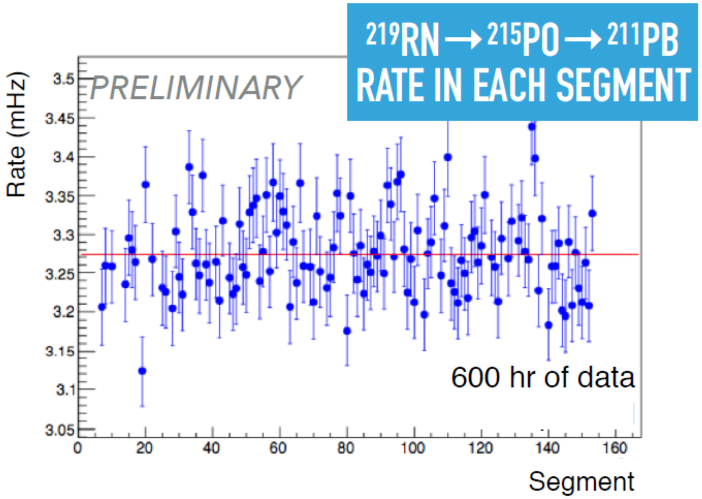
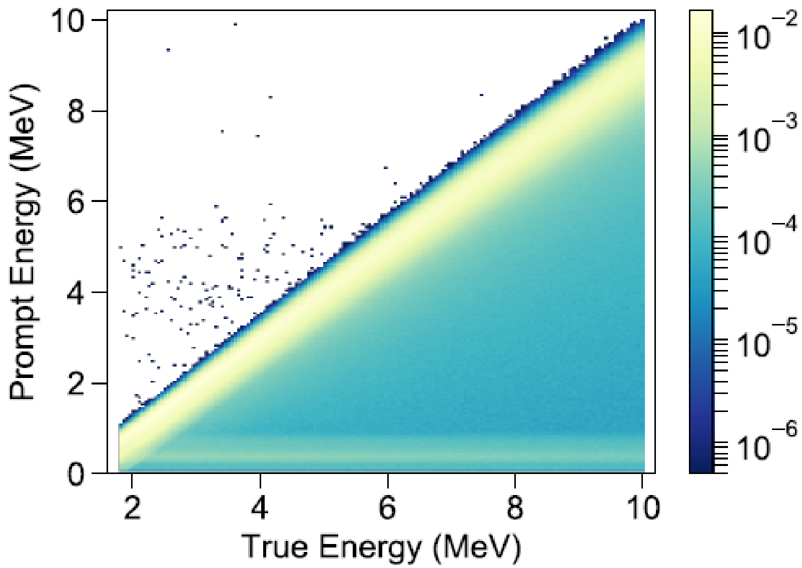
Relative Mass Measurement of Segment

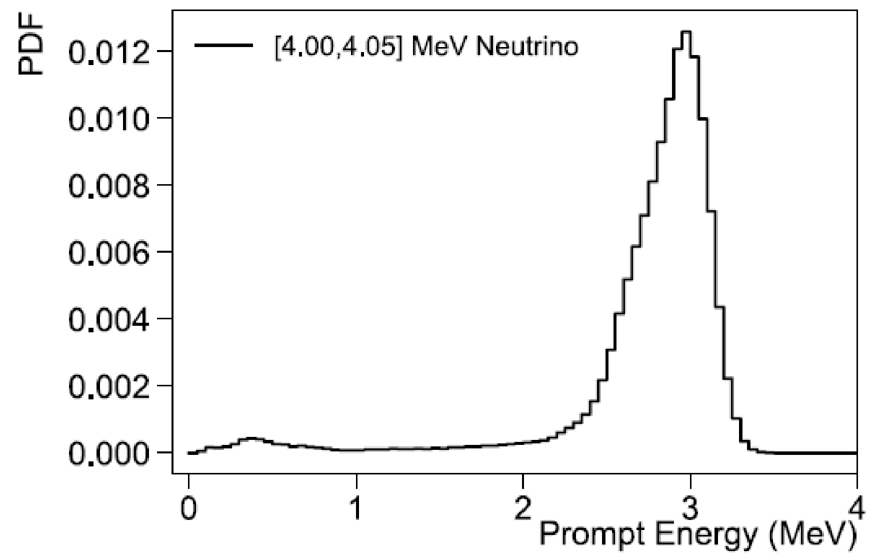
- Relative mass vital for oscillation search
- <u>Survey during construction: < 1% variation</u>
- ^{227}Ac added to LS prior to filling
- Double alpha decay ($^{219}Rn \rightarrow ^{215}Po \rightarrow ^{211}Pb$), highly localized, easy to ID, 1.78ms lifetime
- <u>Direct measurement of relative target mass in each segment</u>
- Through it, also measured absolute z-position resolution of < 5cm



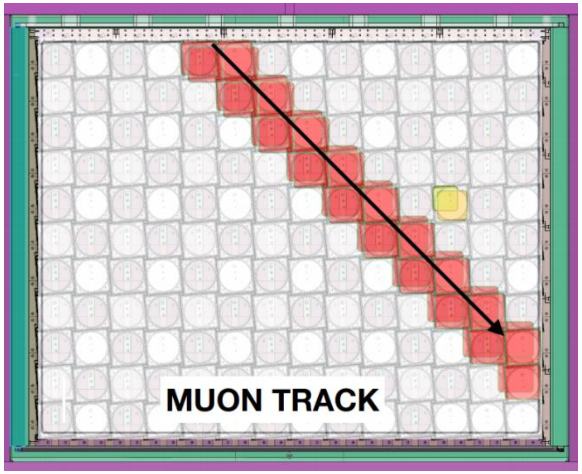


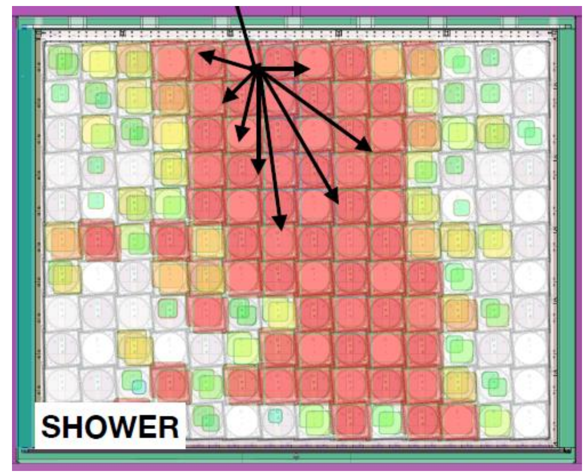
Detector Response

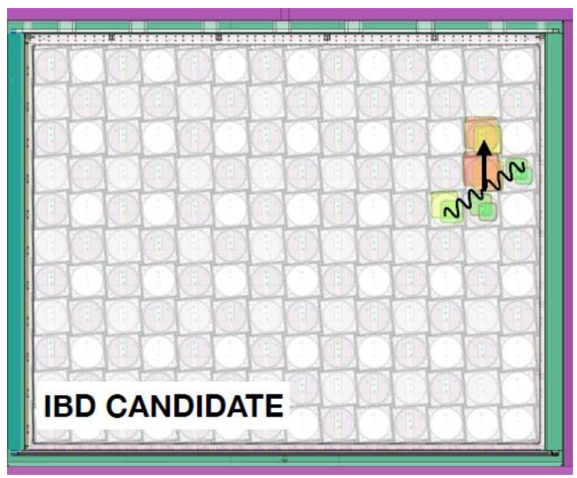




- Segmented detectors have much more complicated response than large monolithic detectors
- Detailed Monte Carlo model of the detector incorporates all known characteristics
- Covariance matrices built through variation of parameters in MC, used for comparison between measured spectrum and model predictions

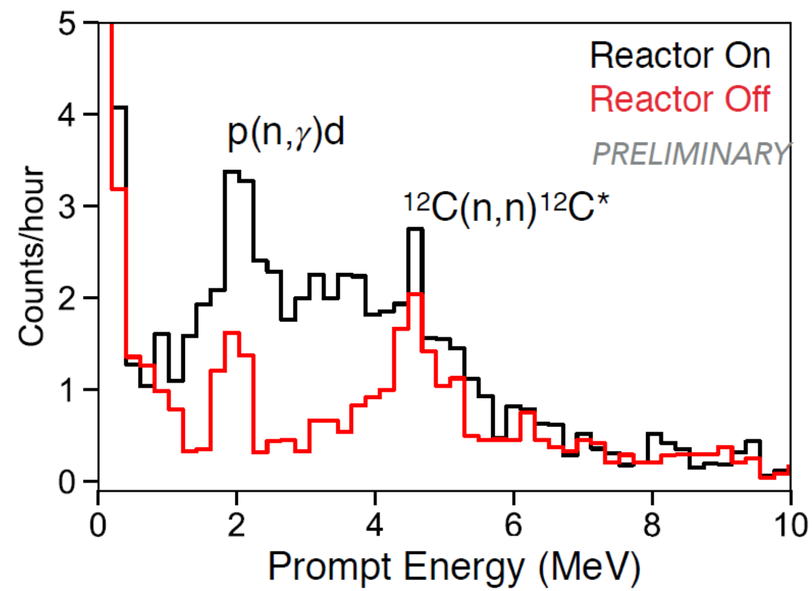

MUON TRACK


SHOWER


IBD CANDIDATE

First 24Hours of Detector Operation

- **March 5, 2018:** Fully assembled detector began operation
- **Reactor On:** 1254±30 correlated events between [0.8, 7.2MeV]
- **Reactor Off:** 614±20 correlated events (first off day March 16)
  - Clear peaks in background from neutron interactions with H and ^{12}C
- **Time to 5σ detection at earth's surface: < 2hrs**

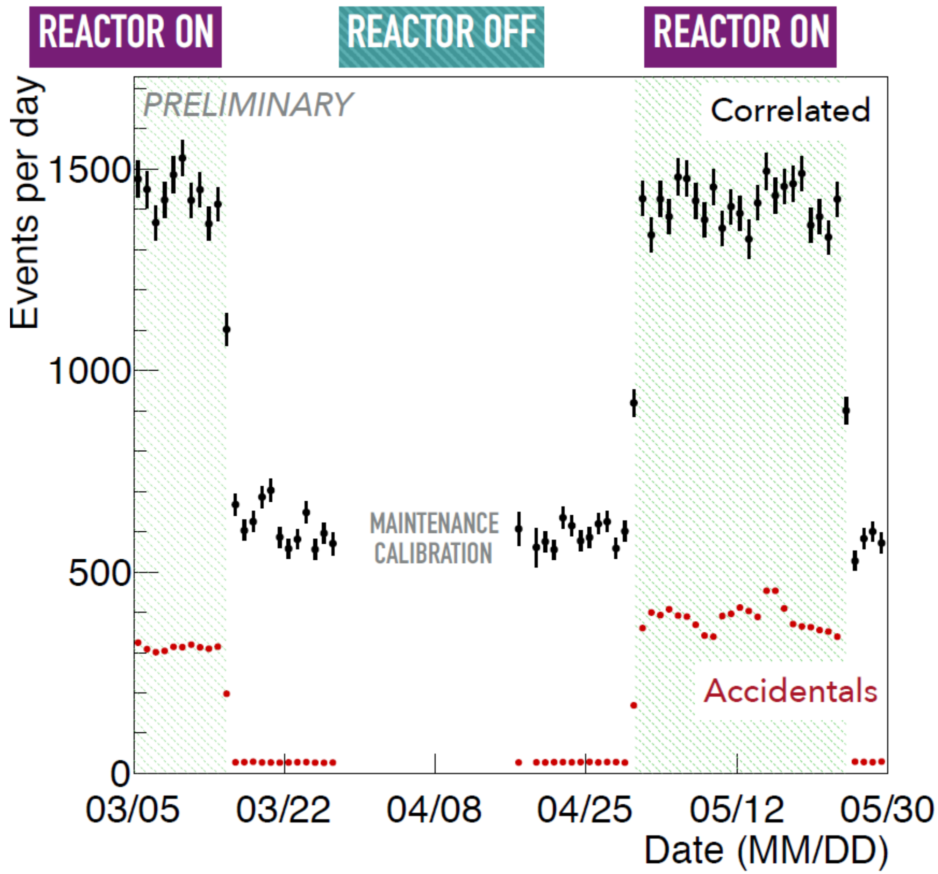


PROSPECT is measuring the ^{235}U antineutrino spectrum

Search for Sterile Neutrino

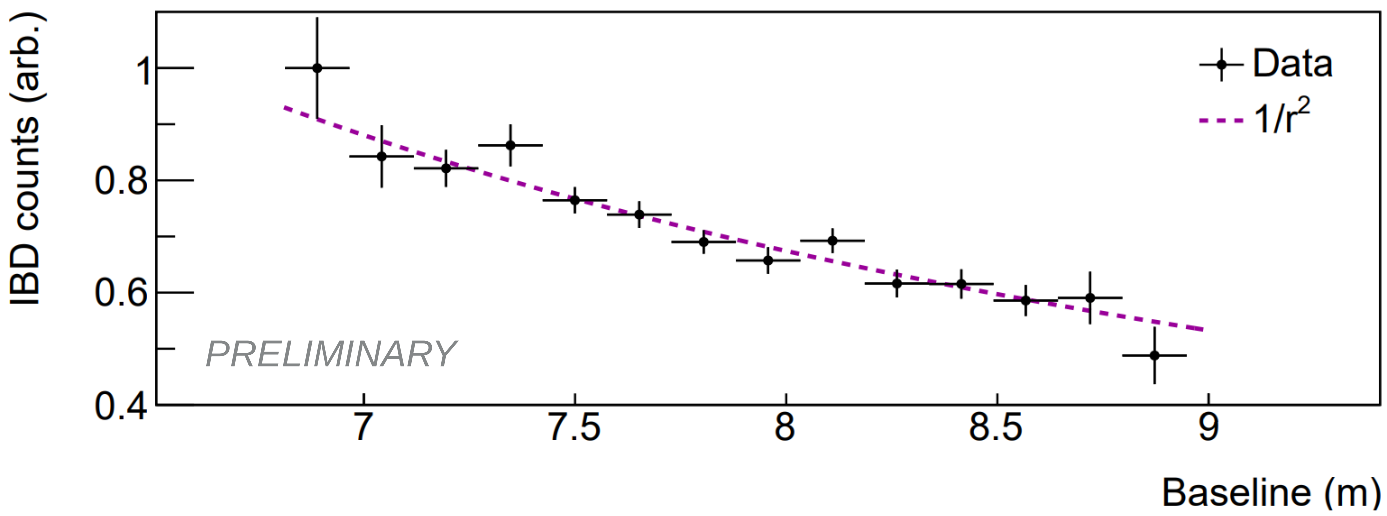
Oscillation Data Set

- 33 days of Reactor On
- 28 days of Reactor Off
- S/Correlated B = 1.32
- S/Accidental B = 2.20
- **25,461 IBDs detected**
- Average of ~770 IBDs/day
- IBD event selection defined and frozen on 3 days of data



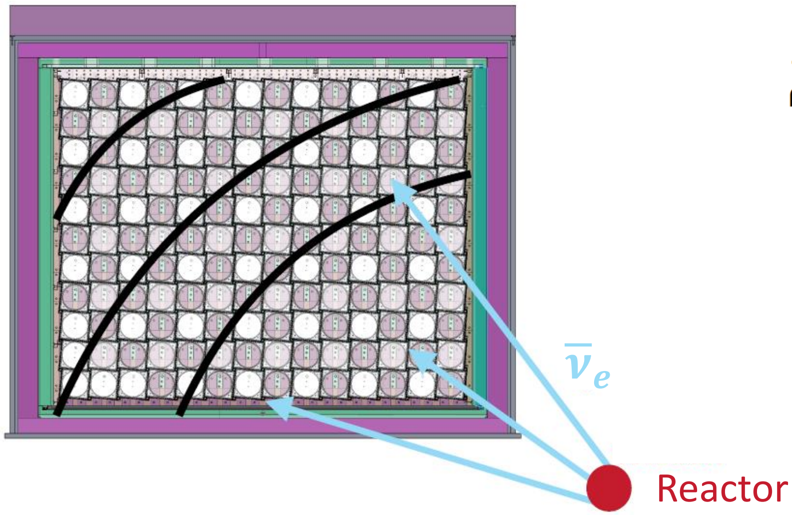
arxiv:1806.02784, accepted by the PRL

Neutrino Rate vs Baseline

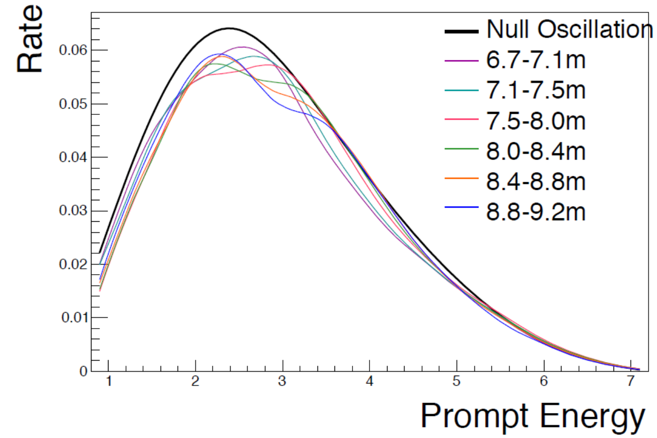


- **Observation of $1/r^2$ behavior throughout detector volume**
- Bin events from 108 fiducial segments into 14 baseline bins
- *40% flux decrease from front of detector to back*

Spectrum Distortion from Oscillation



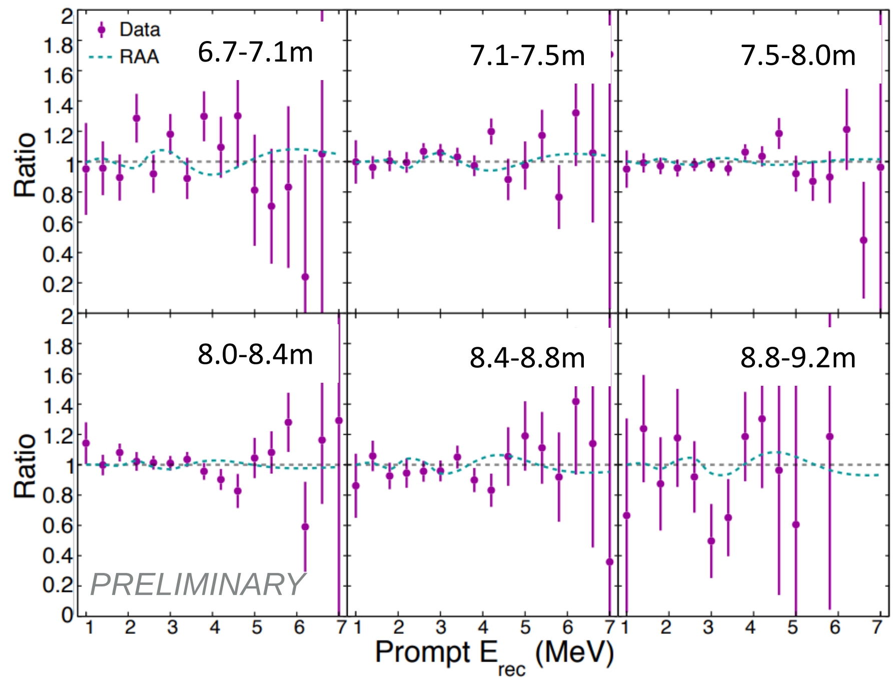
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{14} \sin^2\left(1.267 \frac{\Delta m^2_{41} L}{E}\right)$$



$\Delta m^2_{41} \sim 2\ \mathrm{eV}^2$ and $\sin^2 2\theta_{14} = 0.12$

- Neutrino oscillations modify the neutrino spectrum as a function of baseline
- Segmentation provides coverage of a range of baselines without moving
- Measure neutrino spectrum for each baseline and compare shape to the detected full-volume
- ***Reactor model-independent search for sterile neutrinos***

Neutrino Spectrum vs Baseline

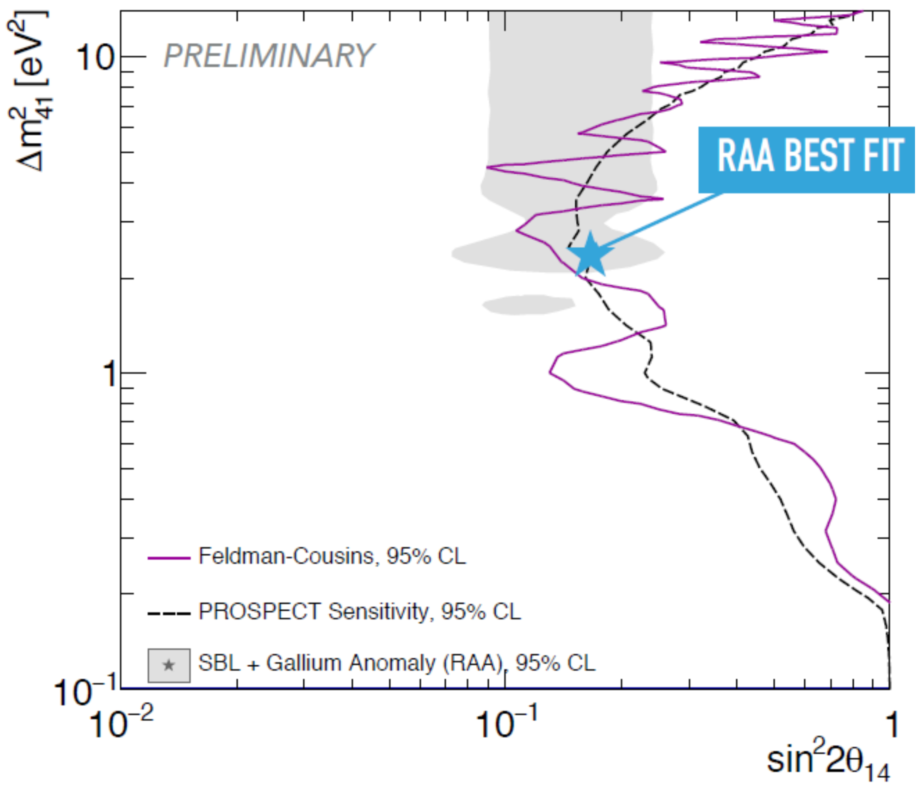


$\Delta m^2_{41} \sim 2\ \mathrm{eV}^2$ and $\sin^2 2\theta_{14} = 0.12$

- Compare spectra from 6 baselines to measured full-detector spectrum
- Null-oscillation would yield a flat ratio for all baselines
- **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 Reactor On operation
- Cross checked with an independent analysis using Gaussian CLs method (NIMA 827 (2016) 63-78).
- *Direct test of the Reactor Antineutrino Anomaly*

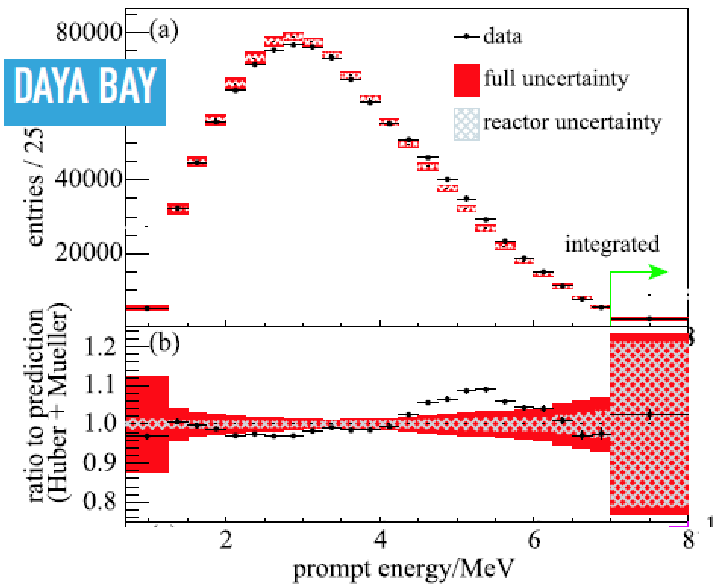


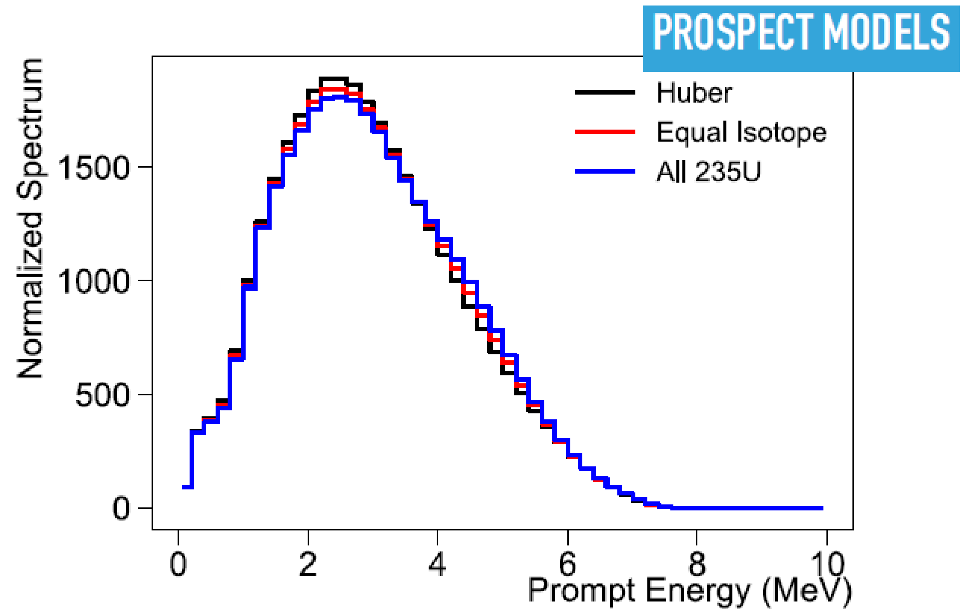
Disfavors RAA best-fit point at >95% C.L. (2.2σ)

Measurement of the ^{235}U Spectrum

Bump-Origin Hypotheses

Daya Bay: commercial reactors

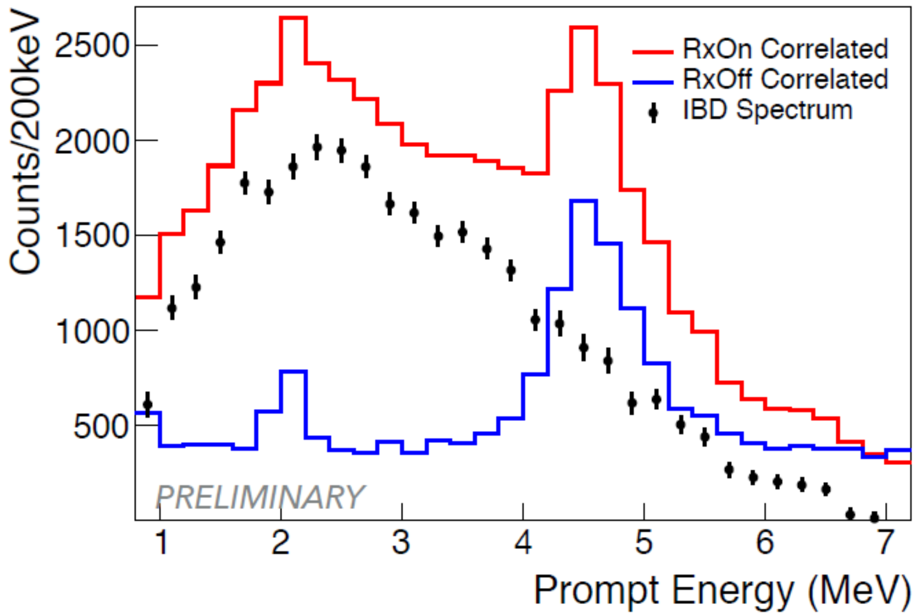




Use the Daya Bay ratio to Huber/Mueller model to modify Huber ^{235}U spectrum

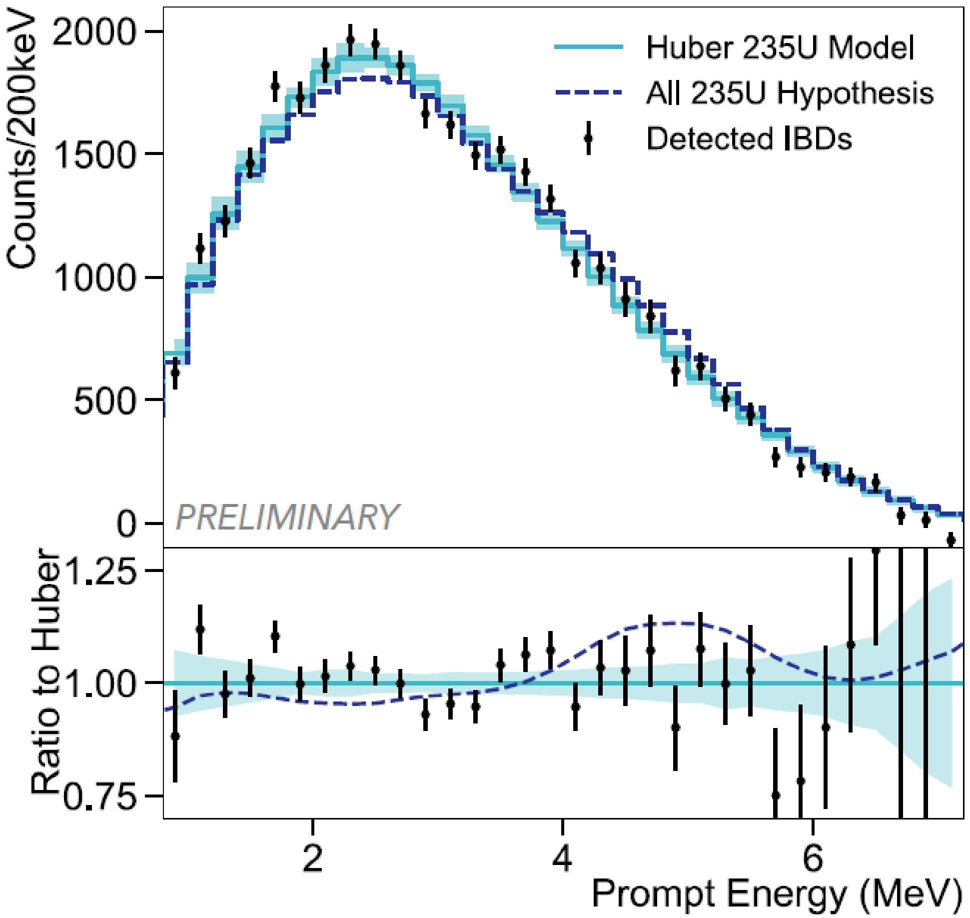
- **Hypothesis 1:** Deviation contained in other isotopes (Huber ^{235}U is correct)
- **Hypothesis 2:** Deviation shared equally by 4 parent isotopes
- **Hypothesis 3:** All deviation from ^{235}U (maximal change to Huber ^{235}U)

Measurement of spectrum



- 40.2 days reactor-on, 37.8 days reactor-off exposure
- ~31,000 IBDs detected, >700 IBDs/live-day
- Signal-to-background = 1.7

Comparison to Models



- Is PROSPECT consistent with Huber ^{235}U model?
  - $\chi 2$/ndf = 52.7/31
  - Not great, but "standard" comparison
- Frequentist comparison to ad-hoc models:
  1. No strong preference between Huber and Equal Isotope
  2. **Disfavor All 235U hypothesis at 3σ**

Spectral Interpretation

- Our measured ^{235}U spectrum cannot fully explain the Daya Bay, Double Chooz, and RENO spectral deviations
  - Implies that some fraction of the bump must come from other fissioning isotopes
- We do not yet have the sensitivity to discriminate between the unmodified Huber model and the Equal Isotope Hypothesis
- ***Statistics limited result, stay tuned for more!***

Conclusion and Outlook

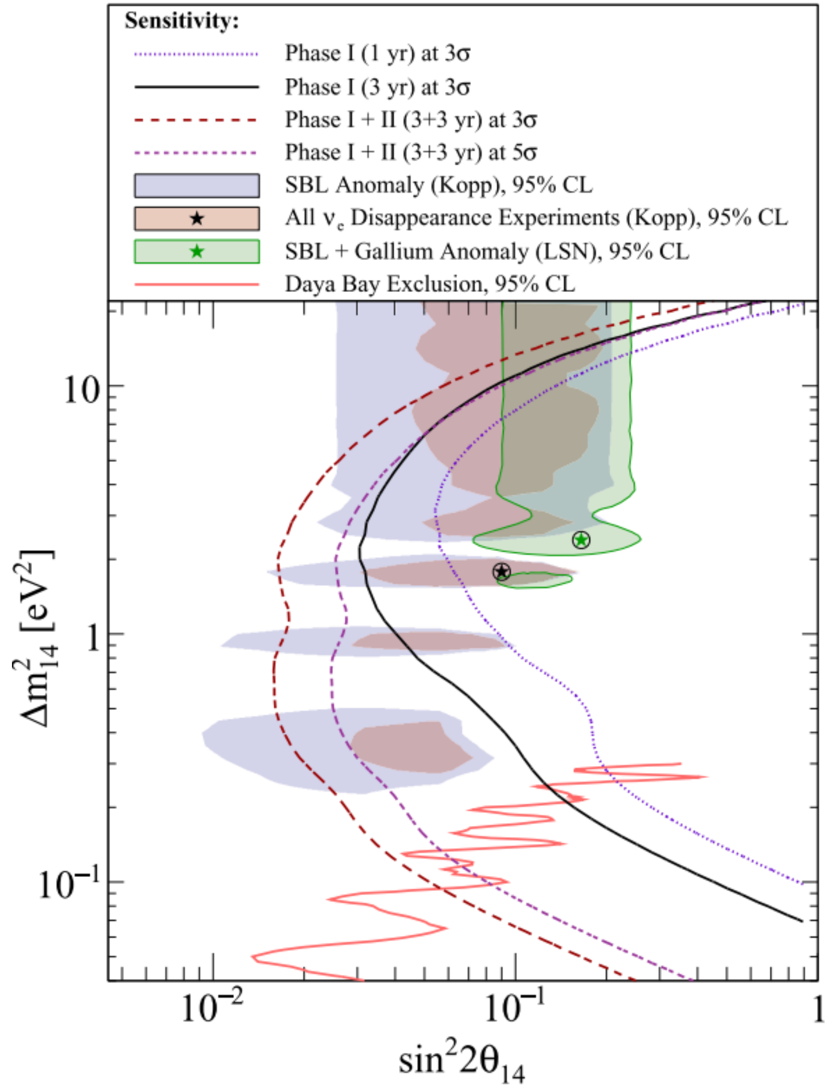
- PROSPECT started collecting data on March 5, 2018
- **World-leading signal-to-background achieved for surface-based detector**
- **First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.2σ (arXiv: 1806.02784, accepted by PRL)**
- **First high-statistics measurement of the 235U IBD spectrum disfavors "All ^{235}U" hypothesis at 3σ**
- ***Statistics limited, and continuing to collect data***

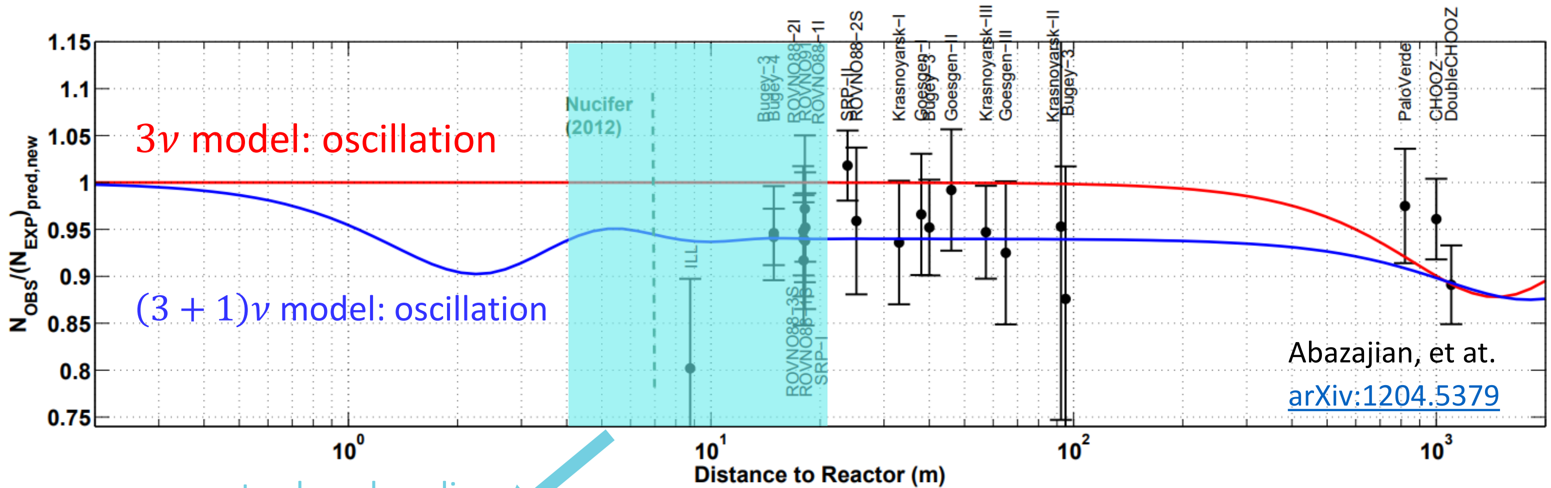
Thank you!

Backup

PROSPECT Sensitivities

- Probe the RAA best-fit point at 4σ after 1 year of data taking
- Have >3σ reach of the favored parameter space after 3 years





meter-long baseline

Finished phase I | Taking data | Planned

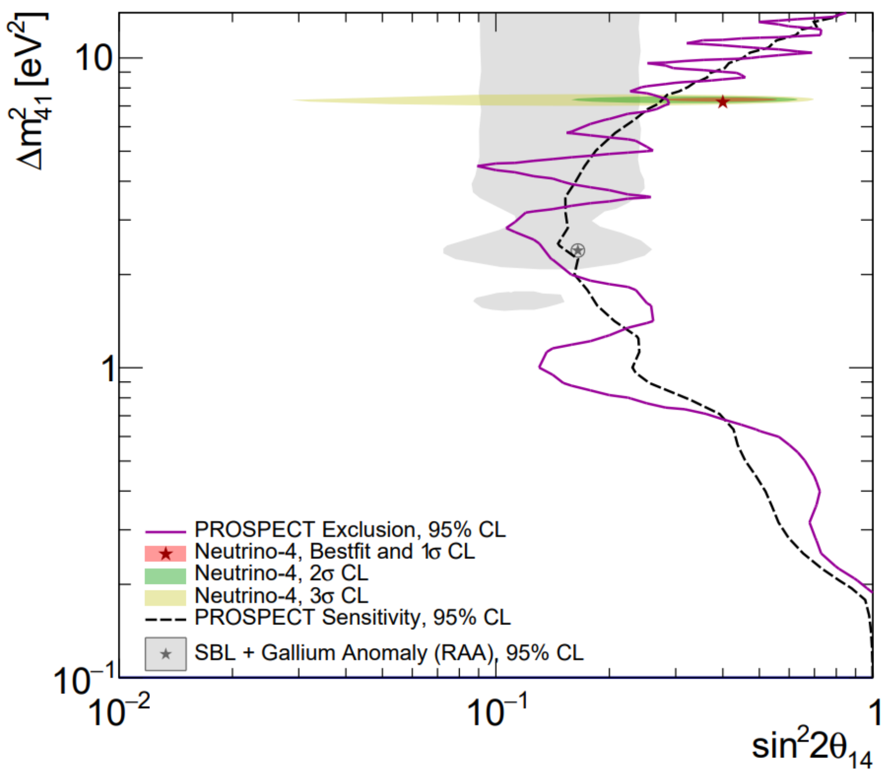
C.Zhang, NuFact 2018

Experiment	Reactor	Baseline (m)	Overburden (m.w.e)	Mass (ton)	Segmentation	Energy res. (@ 1 MeV)
NEOS (South Korea)	LEU 2.8 GW	23.7	~20	1.0	none	5%
Nucifer (France)	HEU 70 MW	7.2	~12	0.6	none	10%
NEUTRINO4 (Russia)	HEU 100 MW	6 - 12	~10	0.3	2D	
DANSS (Russia)	LEU 3.1 GW	10.7 - 12.7	~50	1.1	2D	17%
STEREO (France)	HEU 58 MW	9 – 11	~15	1.6	1D 25 cm	8%
PROSPECT (USA)	HEU 85 MW	7 - 12	< 1	1.5	2D 15cm	4.5%
SoLid (UK Fr Bel US)	HEU 70 MW	6 - 9	~10	1.6	3D 5cm	14%
CHANDLER (USA)	HEU 75 MW	5.5 - 10	~10	1.0	3D 5cm	6%
NuLAT (USA)	HEU 20 MW	4	few	1	3D 5cm	4%

Reactor short baseline experiments

- Search for the sterile neutrino
- Measure the reactor neutrino spectrum

✓ The best energy resolution at present



Neutrino-4, 480 days of reactor-on (arxiv:1809.10561)

PROSPECT, 33 days of reactor on