A search for sterile neutrinos with PROSPECT

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FOR THE PROSPECT COLLABORATION

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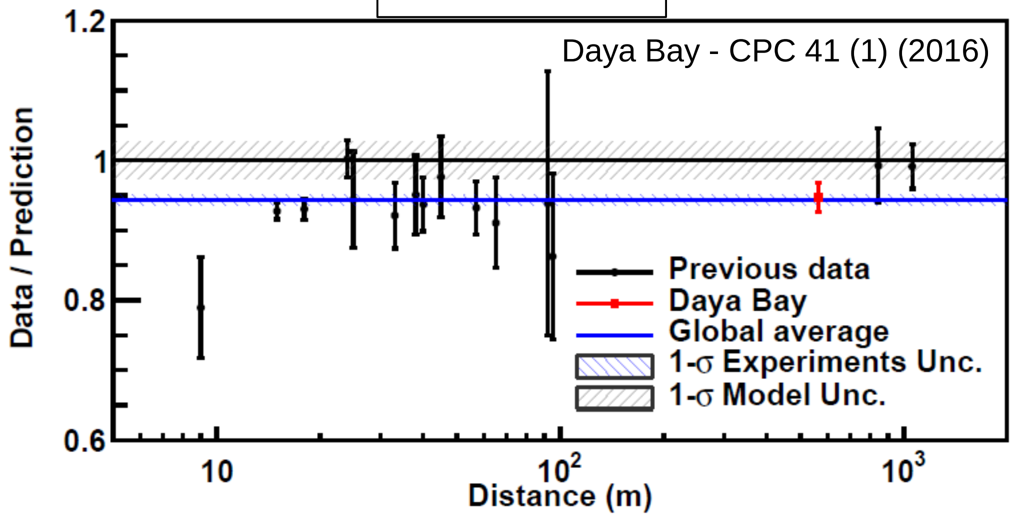
Motivation: Reactor Antineutrino Anomaly

Flux deficit



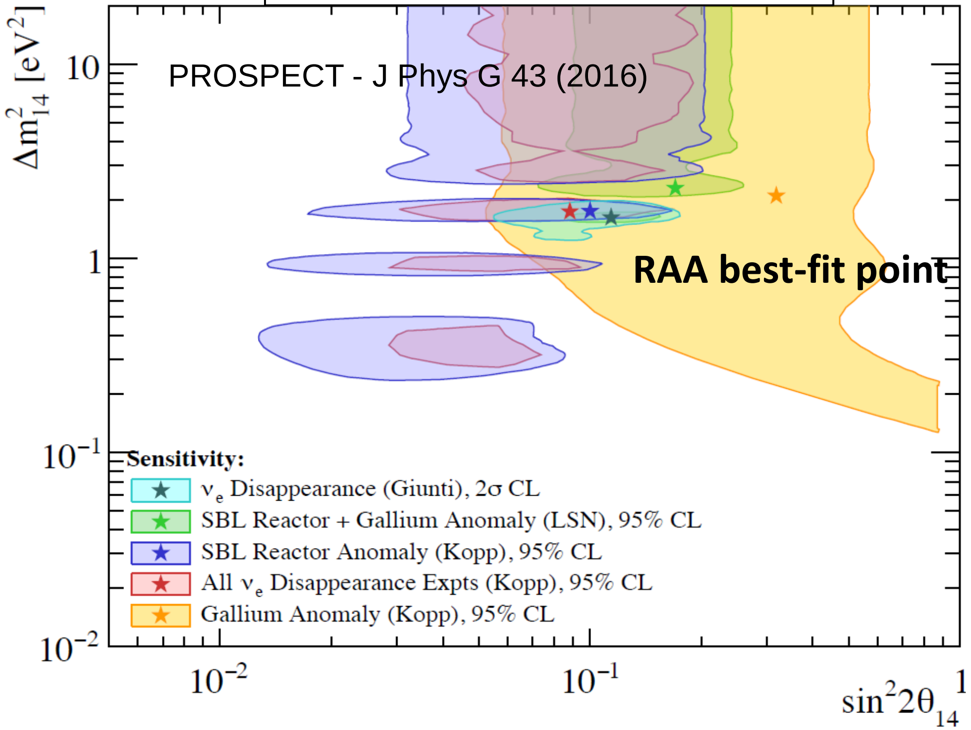
Anomaly:

- Observed flux shows 6% deficiency with respect to theoretical predictions

Possible explanations:

- Oscillations of $\bar{\nu}_e$ to sterile neutrinos, 1 eV^2-scale, **short-baseline**
- Flaws in the models/underlying nuclear data

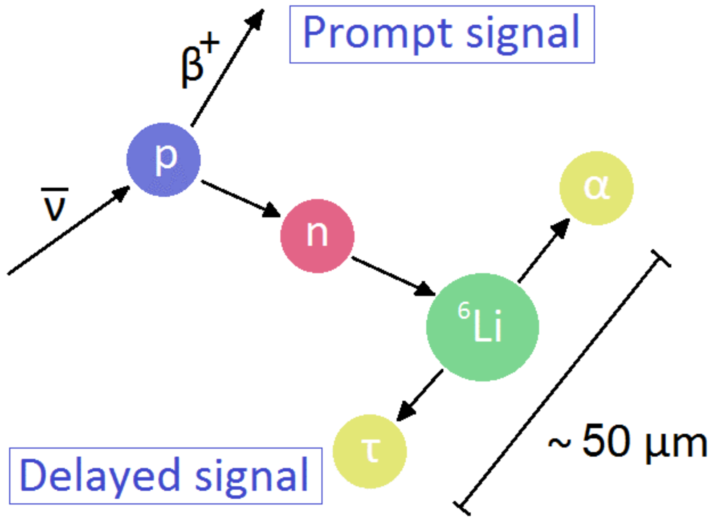
Sterile neutrino global fit



Global-fit: best-fit point at $sin^2 2\theta = 0.165, \Delta m^2 = 2.39$ eV^2 (RAA best-fit point)

PROSPECT performs search for short-baseline sterile neutrino oscillations

Experiment

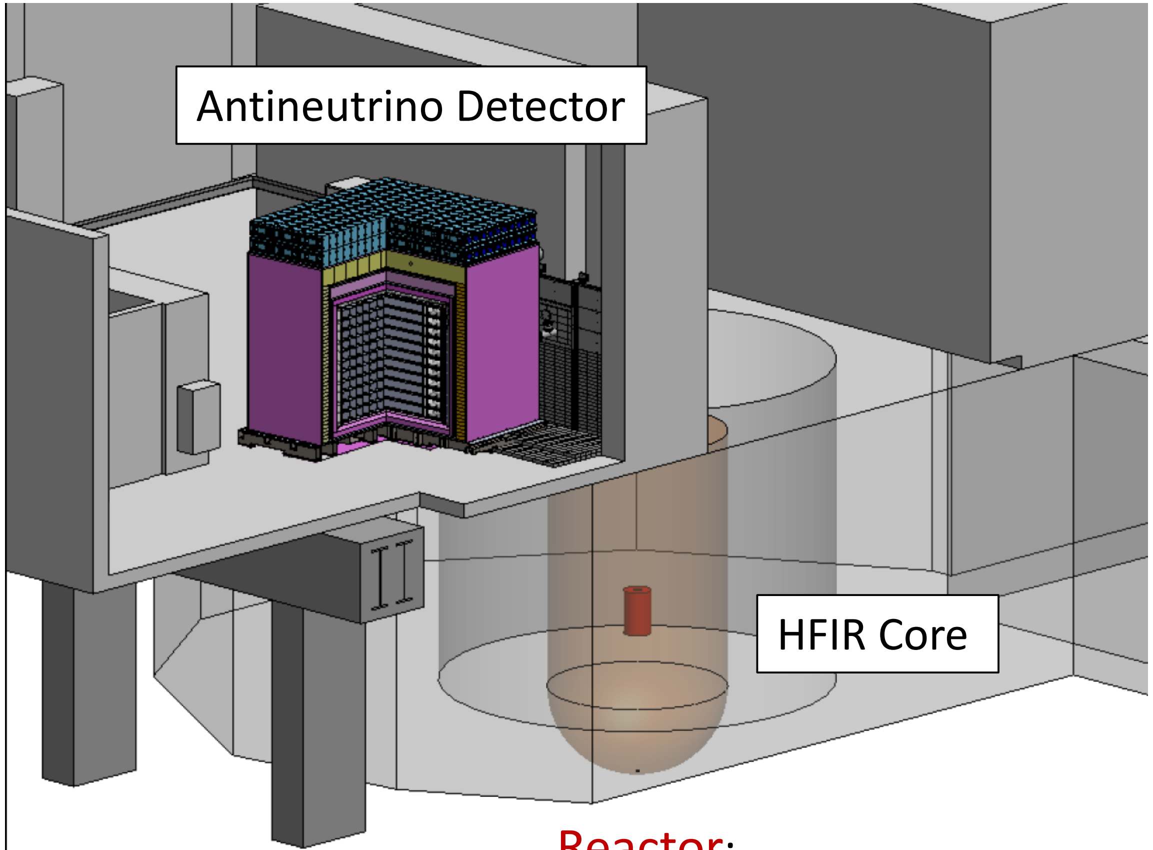


Inverse beta decay (IBD)

mechanism of detection of antineutrinos (^{6}Li-doped liquid scintillator EJ-309):

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

- 1-10 MeV prompt signal – ionization and annihilation of positron
- ~0.5 MeV delayed signal – from neutron capture on ^{6}Li
- Distinctive tag – 50 μs delay in neutron capture
- Strong background rejection due to coincident signature



Reactor:

- 85 MW High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL)
- Burns highly enriched uranium fuel ^{235}U

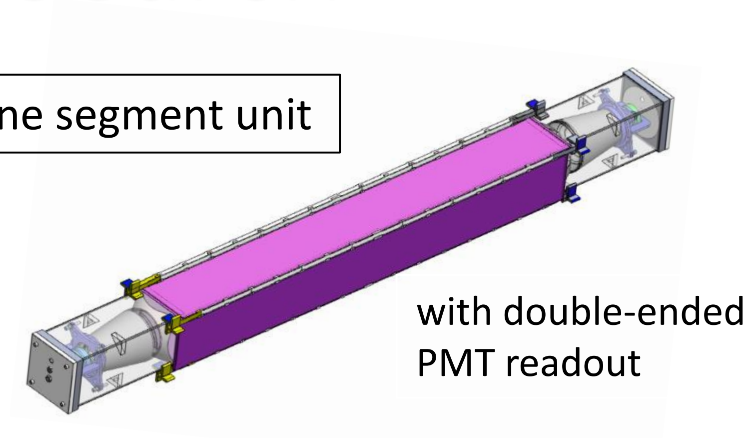
Detector:

- 11 x 14 (154) array of optically separated segments
- Distance from reactor – 7 m

Sterile Neutrino Oscillations Search

$$P_{ee} = 1 - sin^2 2\theta_{14} \cdot sin^2 \left(1.27 \cdot \Delta m_{41}^2 \frac{L}{E}\right)$$

L – baseline
E - energy



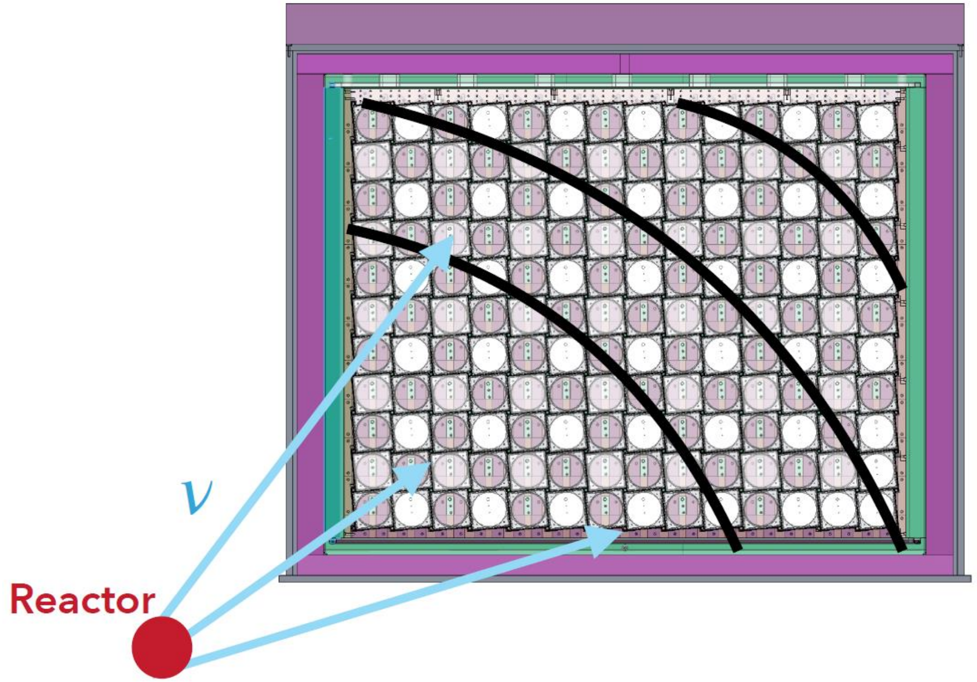
Segmented detector design:

- 154 segments = 154 individual-detectors within one full-volume detector
- Segments are at different baselines from the reactor

Relative spectral comparison:

- Compare measured energy spectrum for each baseline to the scaled full detector energy spectrum

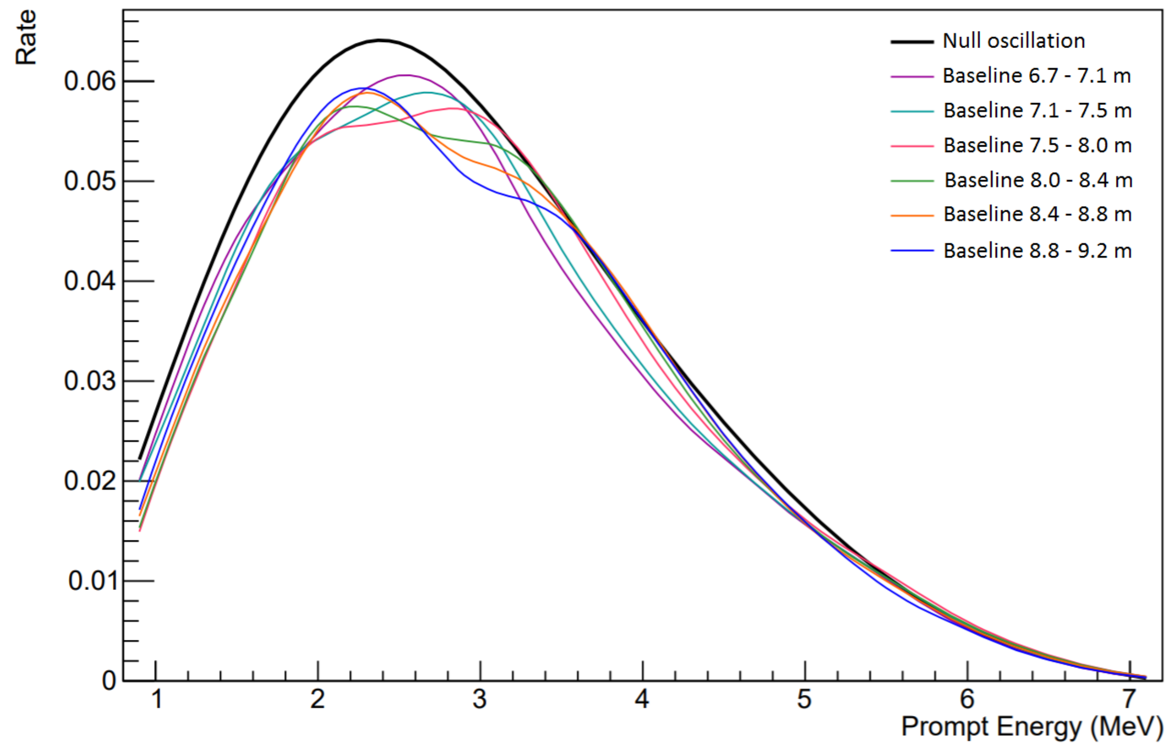
→ **Relative and reactor model-independent search for sterile neutrinos**



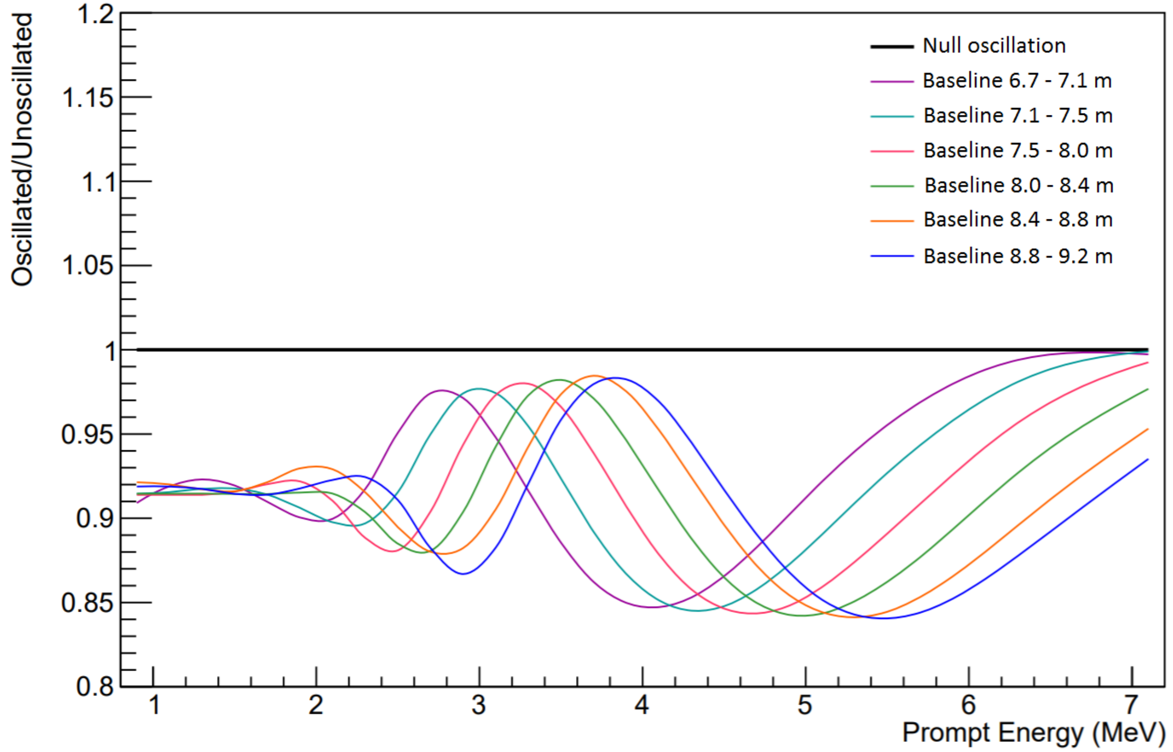
Oscillations Baseline Dependence

$$P_{ee} = 1 - sin^2 2\theta_{14} \cdot sin^2\left(1.27 \cdot \Delta m^2_{41} \frac{L}{E}\right)$$

MC-generated oscillated spectra for different baselines for RAA best-fit point ($sin^2 2\theta_{14} = 0.165, \Delta m^2_{41} = 2.39$ eV²)

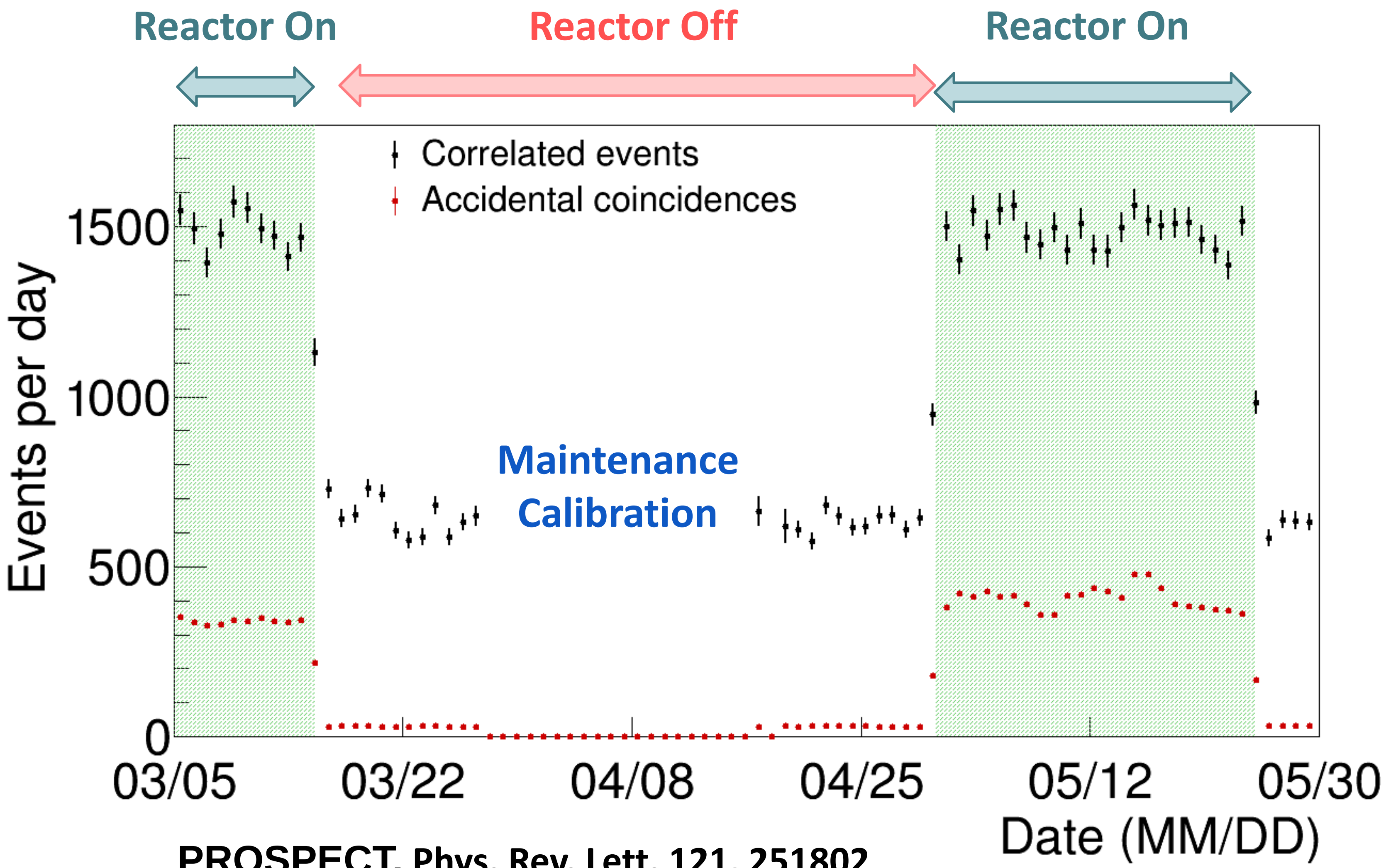


Before spectral shape relativization



After spectral shape relativization

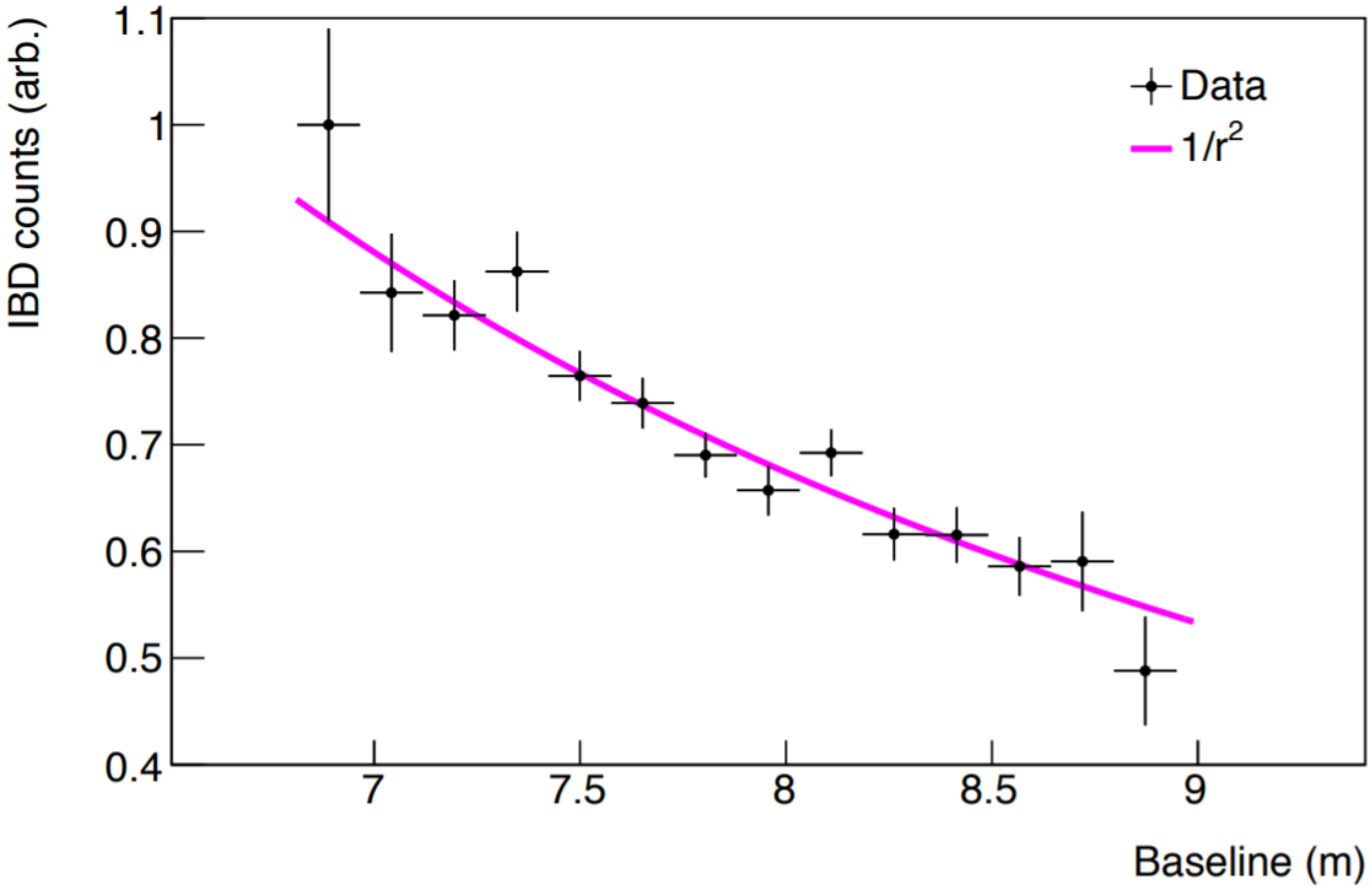
Reactor Neutrino Analysis Dataset



PROSPECT, Phys. Rev. Lett. 121, 251802

- 33 days of Reactor On
- 28 days of Reactor Off
- 24,461 IBDs detected (0.8-7.2 MeV)
- Average of ~771 IBDs/day
  - Correlated S:B = 1.32
  - Accidental S:B = 2.20
- Best demonstrated S:B for an on-surface reactor experiment

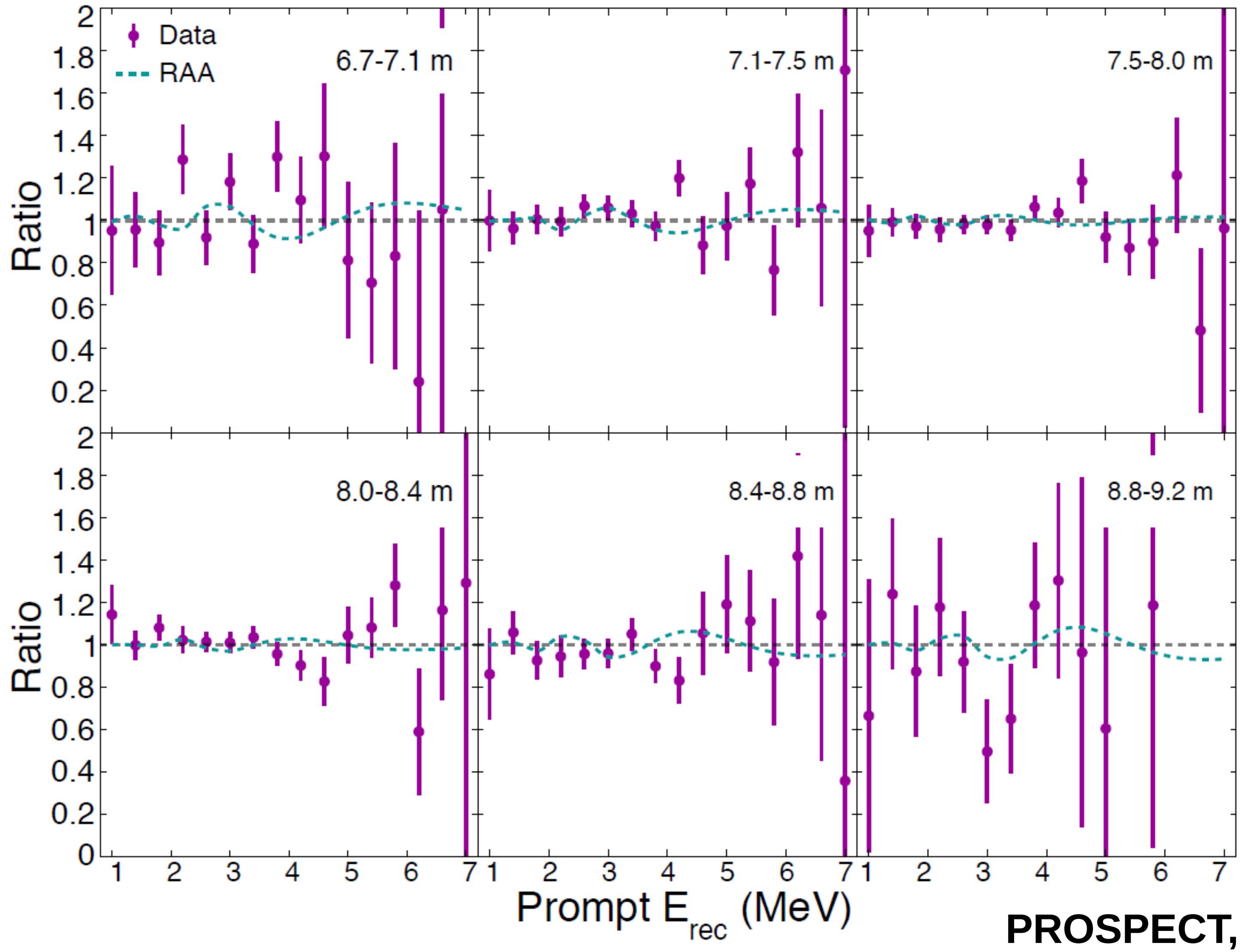
IBD Rate vs Baseline



PROSPECT, Phys. Rev. Lett. 121, 251802

- Events from 108 fiducial segments binned into 14 baseline bins
- Flux follows $1/r^2$ behavior throughout detector volume
- 40% flux decrease from front of detector to back as expected
- The experiment covers range of different baselines

IBD Spectrum vs Baseline



- 33 days of reactor on regime, 28 days of reactor off
- 6 baselines
- Ratio = $\frac{\text{Spectrum at Baseline}}{\text{Full detector spectrum}}$
- Data are compared to spectrum for modeled oscillations for RAA-best fit value (green dashed line)
- Flat dashed line: null oscillations
- Comparing to RAA best-fit point simulation, data do not follow oscillatory pattern

PROSPECT, Phys. Rev. Lett. 121, 251802

Building χ^2

Compare obtained spectrum (O) with predicted spectrum (E, expected) for different baselines (l) and energies (e)

$$\chi^2 = \Delta^T V_{tot}^{-1} \Delta \qquad \Delta_{l,e} = O_{l,e} - O_e \frac{E_{l,e}}{E_e} \qquad O_e = \sum_{l=1}^{6} O_{l,e}, \quad E_e = \sum_{l=1}^{6} E_{l,e}$$

total covariance matrix

scaling to remove dependence on shape of spectrum

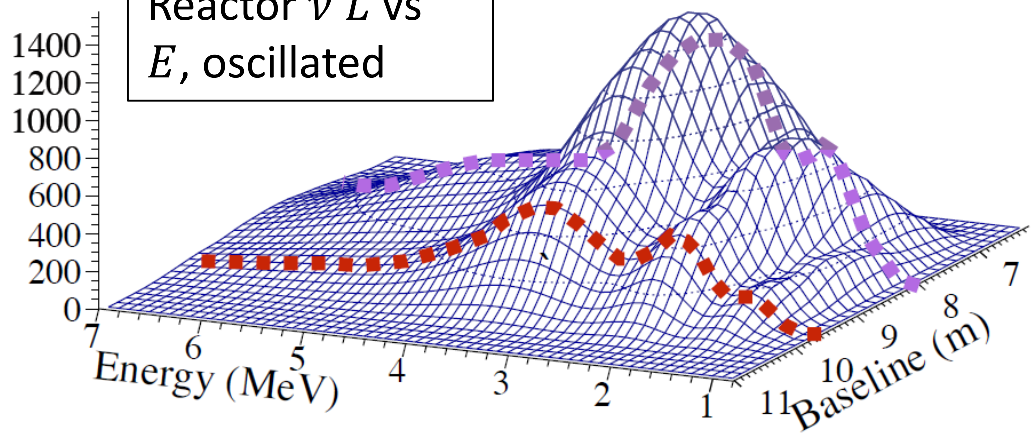
sum over all 6 baselines

Predicted spectrum:

$$E_{l,e} = E_{l,e}^{null} \cdot \left(1 - sin^2 2\theta_{14} \cdot sin^2\left(1.27 \cdot \Delta m_{41}^2 \frac{L}{E_\nu}\right)\right)$$

6 baseline bins
16 energy bins

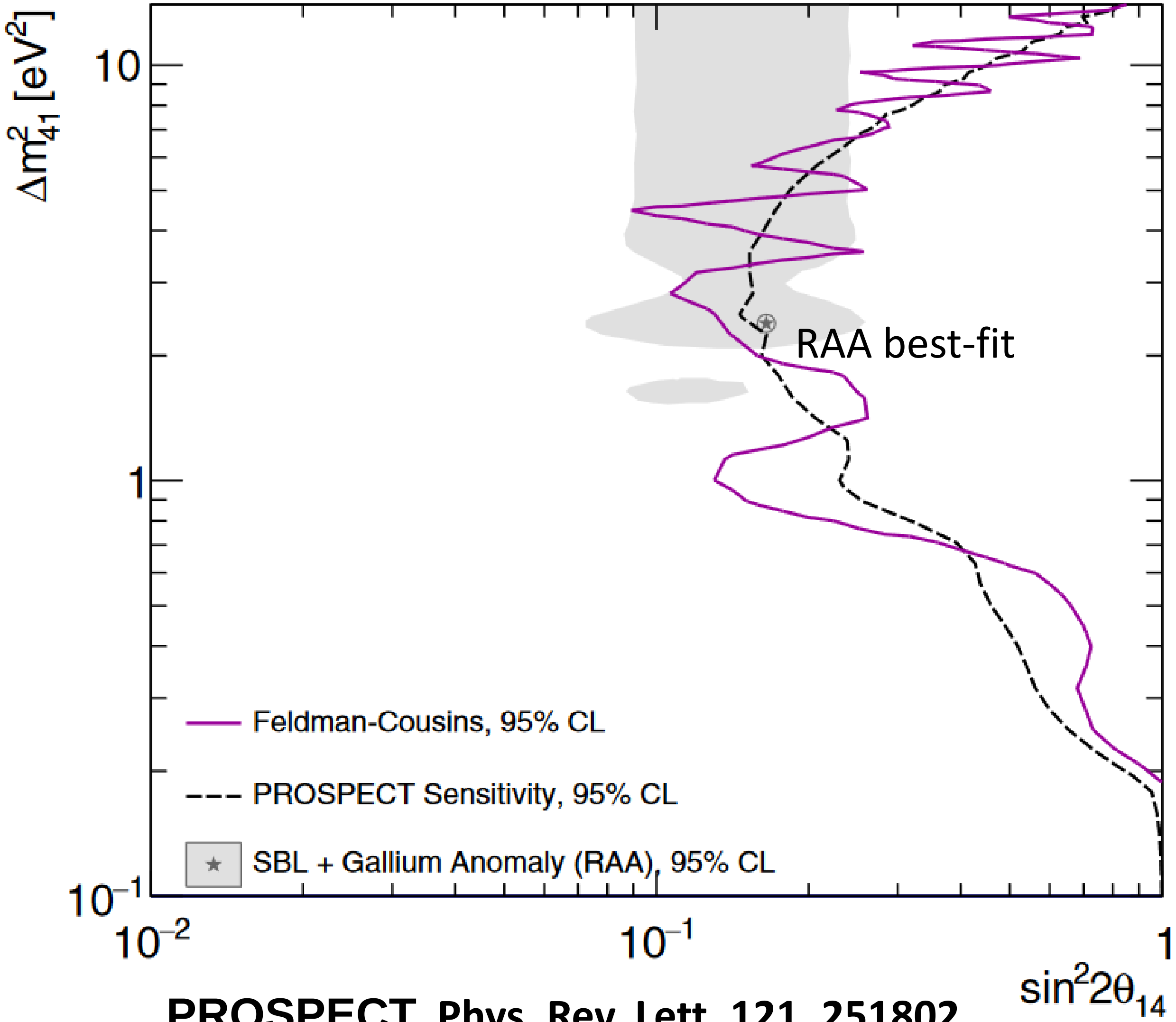
Reactor $\bar{\nu}$ L vs E, oscillated



Covariance matrix V_{tot}:

- Sum of all covariance matrices V_x produced for each systematic uncertainty and signal and background statistical uncertainties
- Takes into account their correlation between energy and baseline bins

Confidence Interval



PROSPECT, Phys. Rev. Lett. 121, 251802

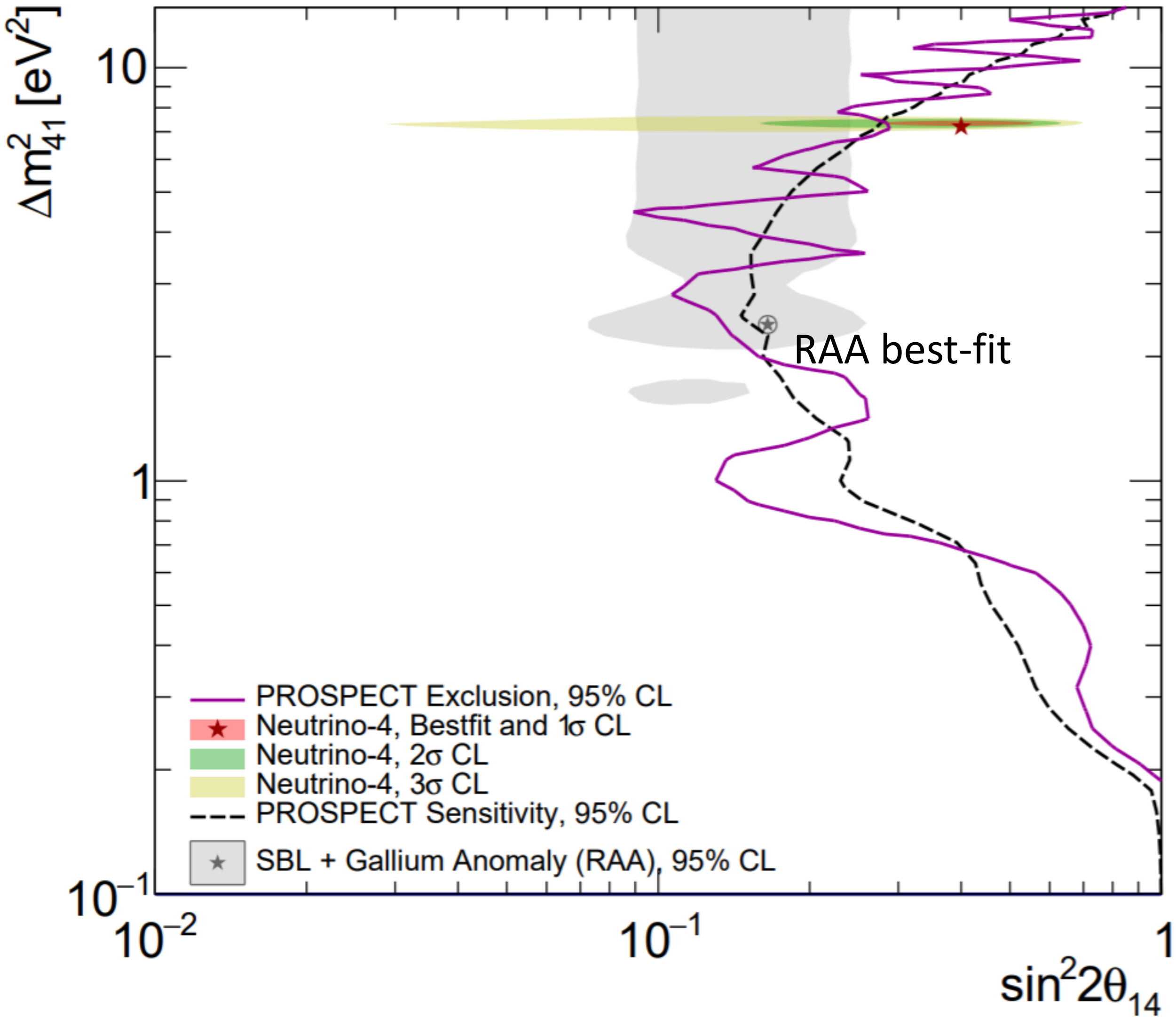
- χ^2 is calculated by comparing measured spectra to predicted spectra at each baseline
- Was calculated with Feldman-Cousins approach
- Covariance matrices reflect uncertainties and energy/baseline correlations
- 95% exclusion curve based on 33 days Reactor On operation

Exclude RAA best-fit point at >95% CL (2.2σ)

Short-baseline reactor experiment Neutrino-4: *observation of sterile neutrino oscillations at* $sin^2 2\theta = 0.4, \Delta m^2 = 7.2\ eV^2$ *best-fit point*

Neutrino-4 best fit also disfavored at >95% CL

Confidence Interval



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Feldman-Cousins Approach

- Standard (incorrect) method does not handle boundary features such as bounded nature of $sin^2 2\theta$ (0,1) or cases when oscillation frequency approaches energy bin size. Feldman-Cousins method solves those problems
- Comparing p-values for Feldman-Cousins and standard (incorrect) methods:

P-values	3ν-oscillation hypothesis
Feldman-Cousins	0.58
Standard (incorrect) confidence intervals assignment	0.14

- If standard (incorrect) confidence levels used instead of Feldman-Cousins:
  - We say 3ν is less compatible with data than it actually is
- Illustrates an importance of using Feldman-Cousins

Feldman-Cousins Approach

- ❝ The construction of the test statistic probability distribution through Monte Carlo techniques is hence mandatory in order to ensure accurate results. The Monte Carlo construction is computationally demanding, but it is feasible as proved by the experiments that are already performing it. Indeed, the proposed analysis procedure is very similar to the what is used by e.g. MiniBooNE and **PROSPECT**. ❞

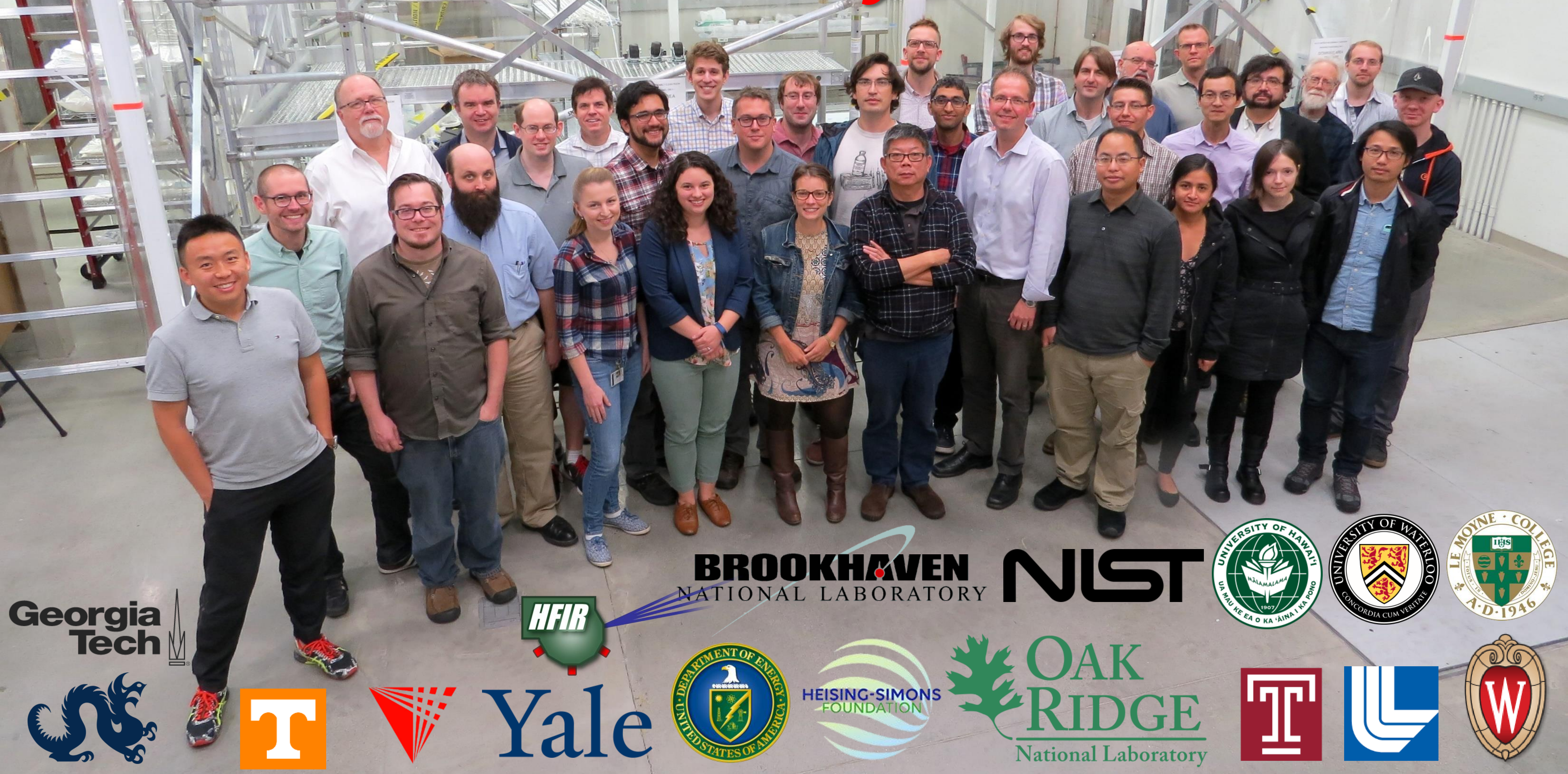
"Statistical Methods for the Search of Sterile Neutrinos", Matteo Agostini, Birgit Neumair

arXiv: 1906.11854

Conclusion

- PROSPECT performs search for short-baseline sterile neutrino oscillations from highly-enriched ^{235}U reactor
- Segmented detector design and relative spectral comparison used in the analysis allow relative and reactor model-independent study
- With 33 days of data, PROSPECT disfavored RAA sterile neutrino best fit point at 95% C.L. (2.2σ)
- Feldman-Cousins method is necessary to assign correct confidence intervals

Thank you!



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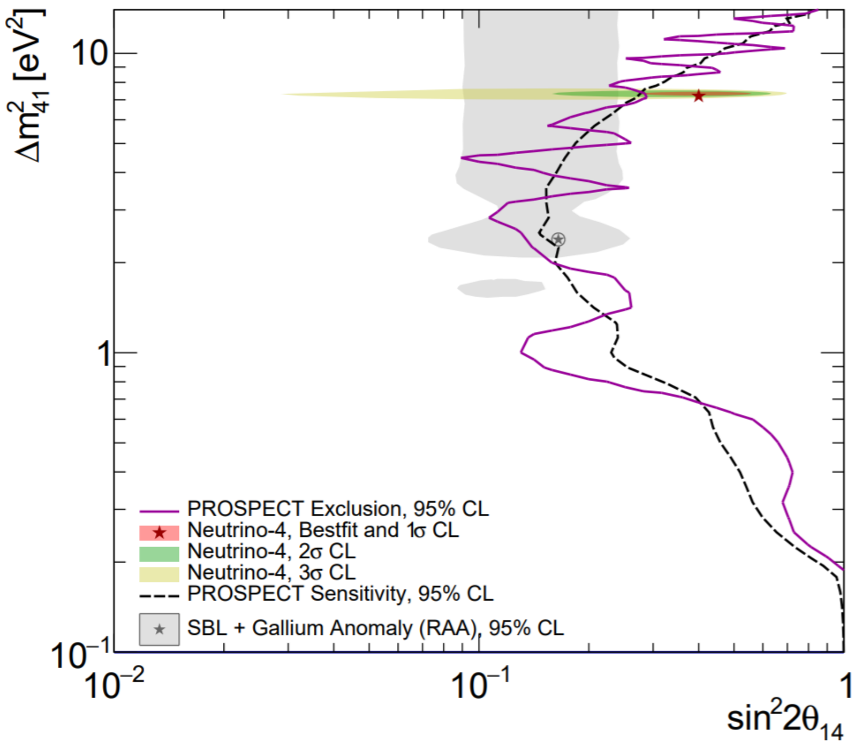
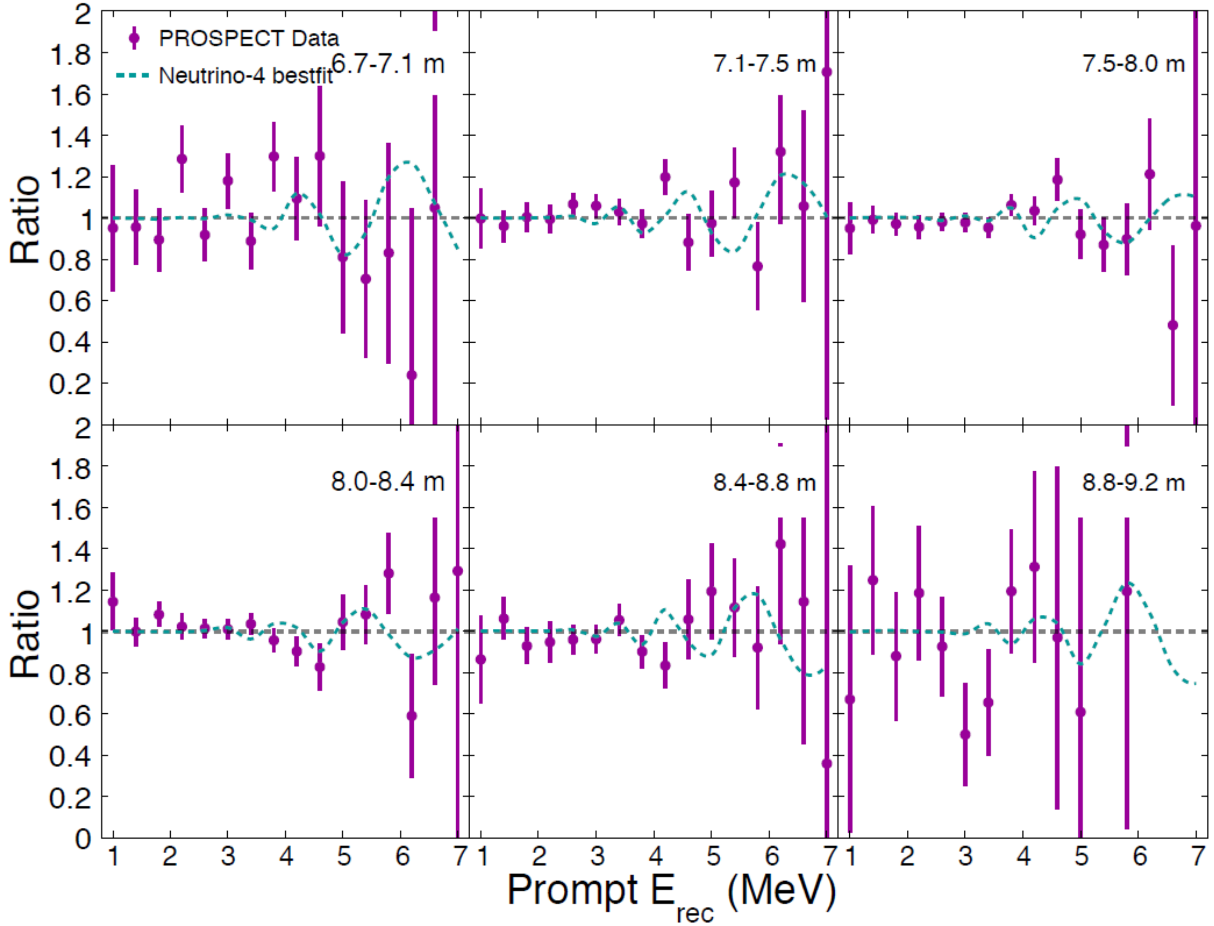
Backup Slides

Comparison to Neutrino-4 Results

PROSPECT already covers Neutrino-4 best-fit point and 1σ at 95% CL

Neutrino-4,arXiv:1809.10561 "The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino"





Short-baseline reactor experiment Neutrino-4: *observation of sterile neutrino oscillations at* $\sin^2 2\theta = 0.4, \Delta m^2 = 7.2\ eV^2$ *best-fit point*

Comparison to Neutrino-4 Results

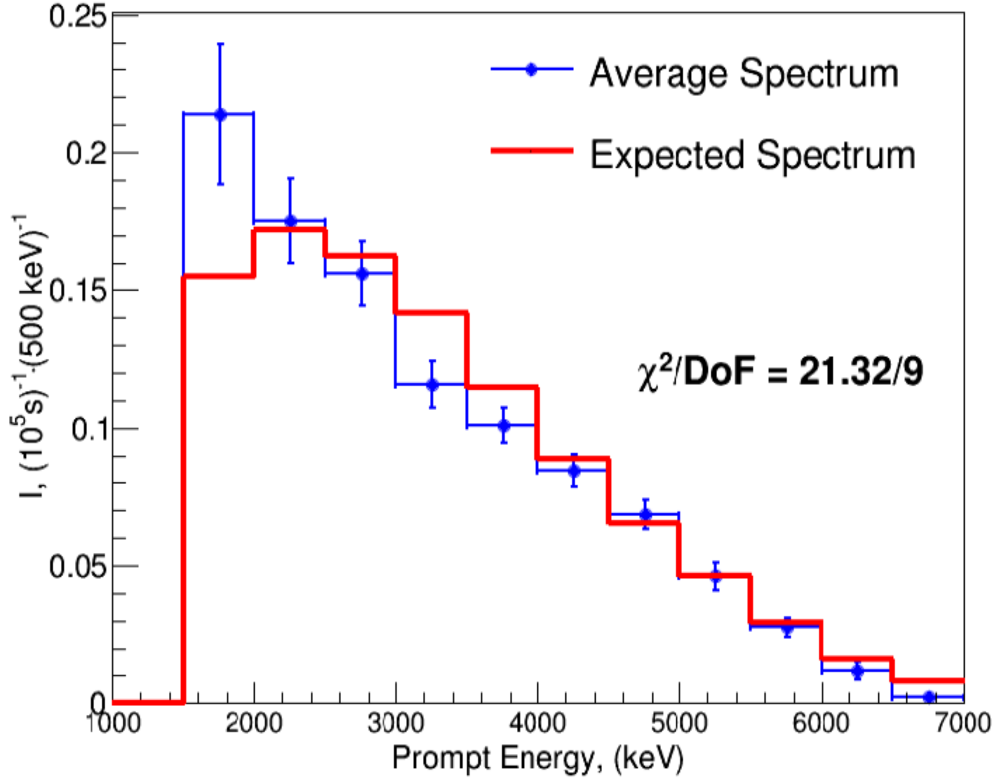
Neutrino-4:

- Use “standard” method of constructing confidence intervals

$$\Delta\chi^2(\sin^2(2\theta_{14}),\Delta m^2_{14}) = \chi^2 - \chi^2_{min} < A,$$
$$(A = 2.30(1\sigma), A = 6.18(2\sigma), A = 11.83(3\sigma))$$

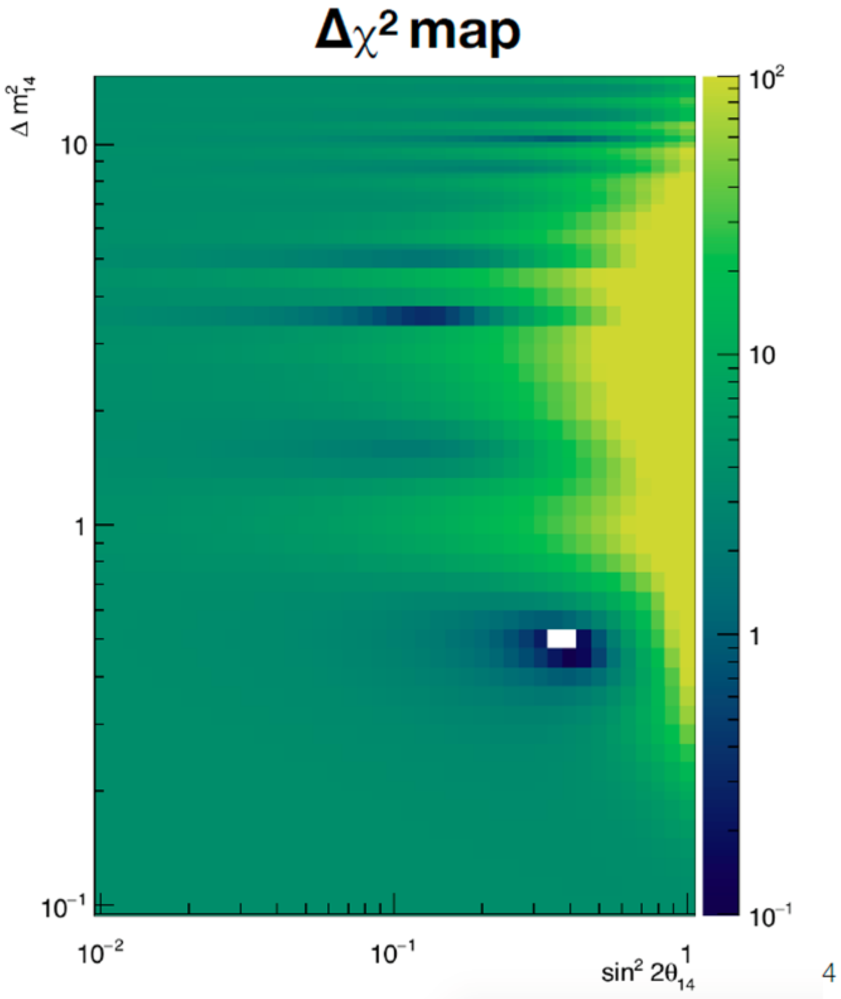
- Poor agreement between measured and predicted spectrum
- Non-linear effects of detector response are not taken into account

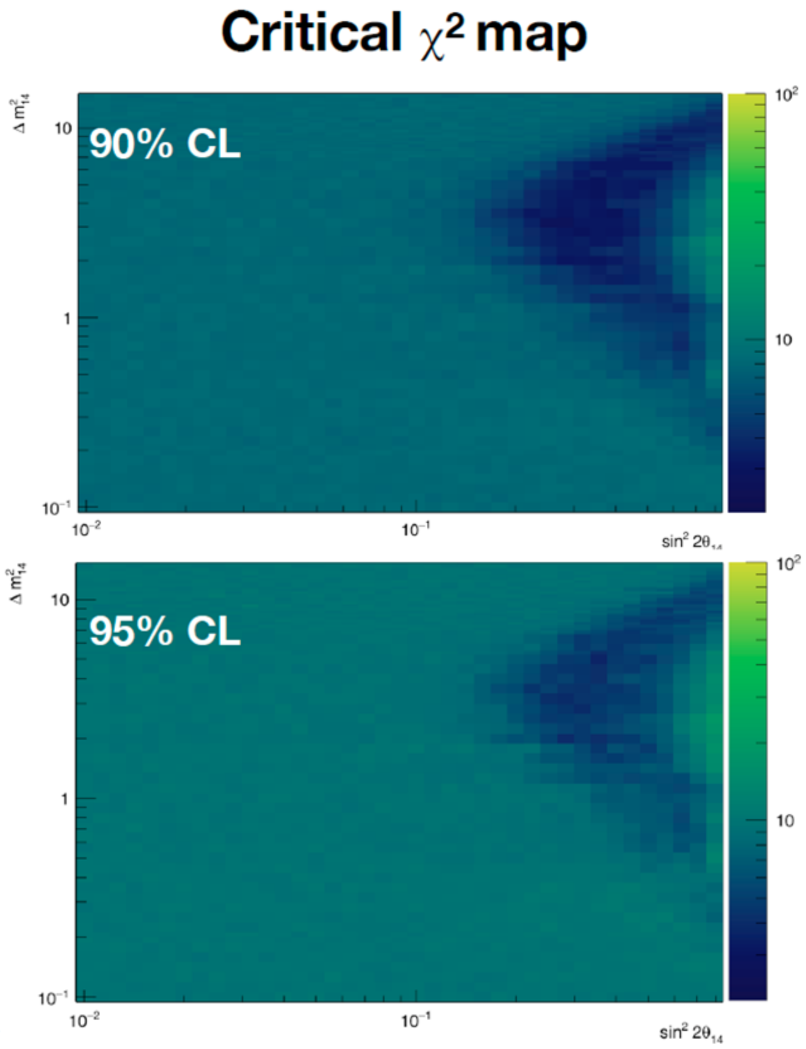
Neutrino-4,arXiv:1809.10561 “The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino”



Prompt signal spectrum (blue) vs MC-simulated spectrum for U-s sera35 (red)

$\Delta\chi^2$ and critical χ^2 maps





https://arxiv.org/abs/1806.02784

Confidence Intervals

- For each set $(\Delta m_{14}^2, sin^2 2\theta_{14})$ 1000 oscillated MC toy datasets are generated
- Fluctuations in the toys are determined by statistical and systematic uncertainties
- For each toy dataset and every point in $(\Delta m^2, \theta)$-grid, χ_{min}^2 is calculated $\Delta\chi^2$:

$$\Delta\chi^2 = \chi_{min,true}^2 - \chi_{min,best-fit}^2$$

$$\chi^2 = \boldsymbol{\Delta}^{\mathrm{T}} \mathrm{V}_{\mathrm{tot}}^{-1} \boldsymbol{\Delta},$$

$$\boldsymbol{\Delta}_{l,e} = O_{l,e} - O_e \frac{E_{l,e}}{E_e}$$

- $\chi_{min,true}^2$ is χ_{min}^2 for true oscillation parameters used in generation of the particular toy; $\chi_{min,best-fit}^2$ is χ_{min}^2 for best-fit oscillation parameters for this particular toy
- $\chi_C^2(\alpha)$ is defined for each point in $(\Delta m^2, \theta)$-grid such that

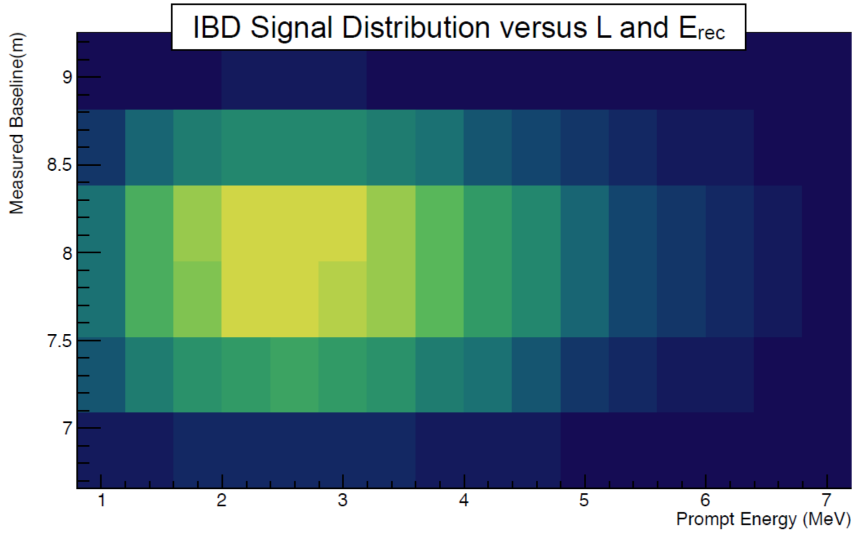
$$\frac{\sum_0^{\Delta\chi_C^2} P(\Delta\chi^2)}{\sum_0^{\infty} P(\Delta\chi^2)} = \alpha$$

where $P(\Delta\chi^2)$ – probability density distribution (PDF) of $\Delta\chi^2$

- Point in oscillation parameter grid is excluded at α confidence interval, if

$$\Delta\chi_{data}^2 > \Delta\chi_C^2$$

Toy datasets are compared with predicted oscillated spectrum



Example of a toy L-E distribution