The design and expanded physics reach of the PROSPECT-II detector upgrade

Snowmass CSS Meeting

July 23rd 2022

F. Sutanto for the PROSPECT Collaboration

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LLNL-PRES-837360

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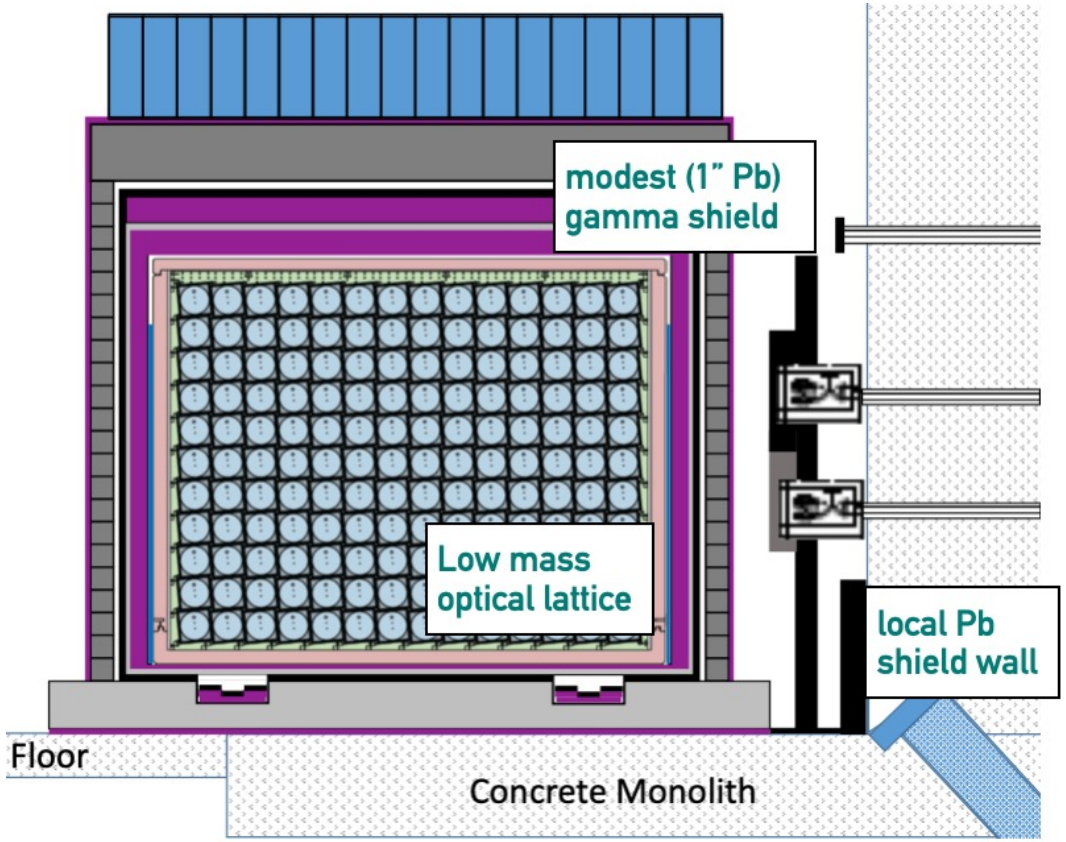
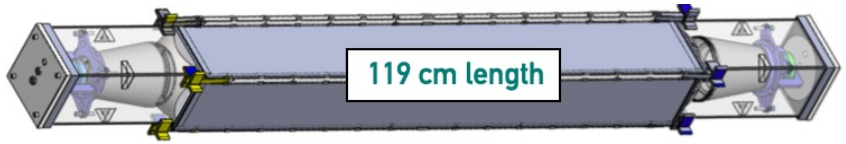
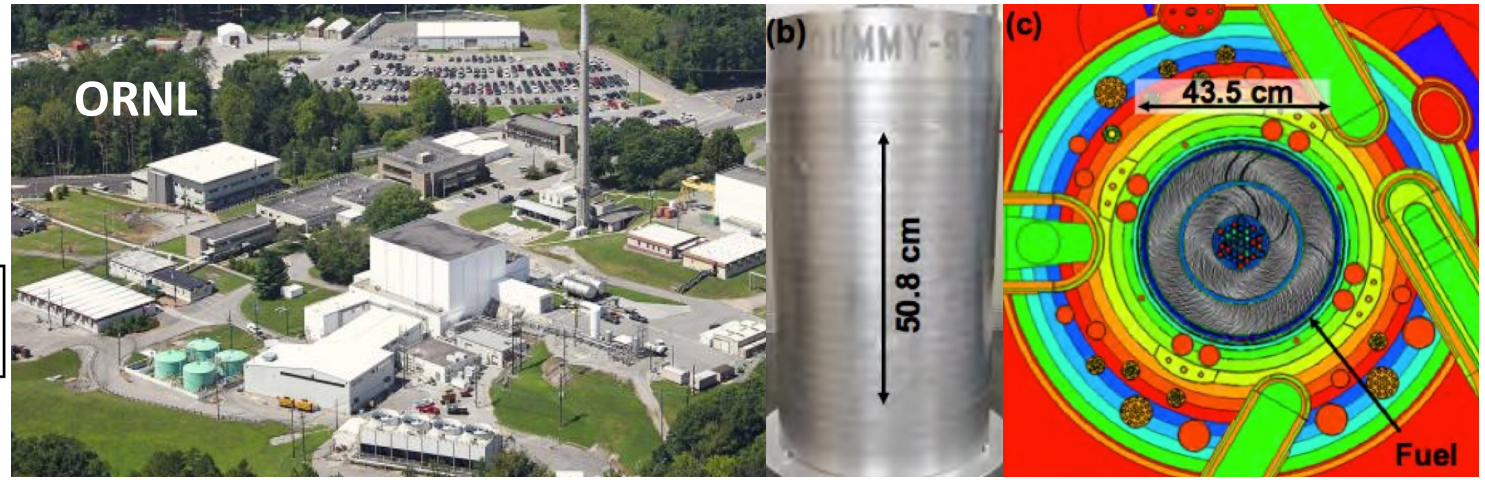
First phase of PROSPECT (P-I)





- 4 ton ^{6}Li-loaded fiducial volume
- 11 x 14 array of optically separated segments
- Double ended PMT readout, with light concentrators
- Good light collection and energy response ~4.5-5%√E energy resolution
- Full X, Y, Z event reconstruction
- On-surface deployment with minimal shielding

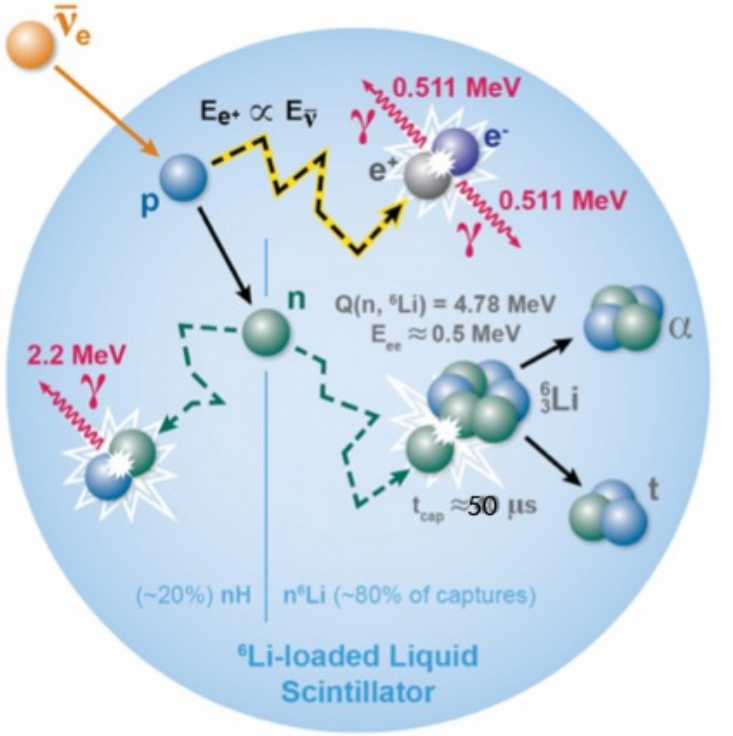


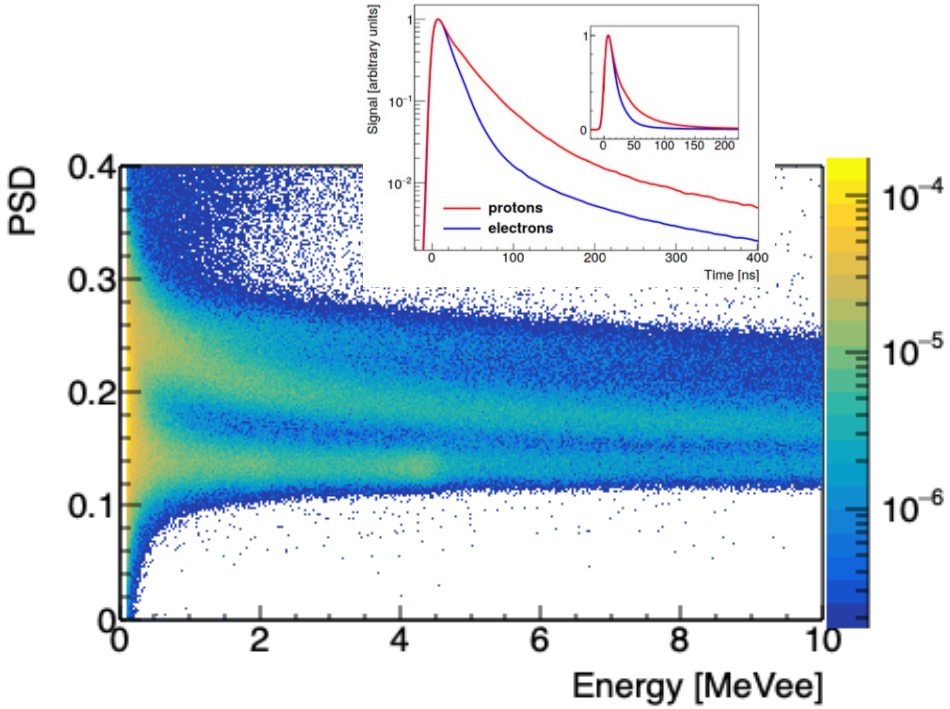
- >99% of antineutrino flux from ^{235}U fission (85 MW)
- Duty-cycle: 24 days cycle
- Compact core: height (0.5 m), diameter (0.4 m)
- Baseline: 7-9m → Can probe high Δm^2

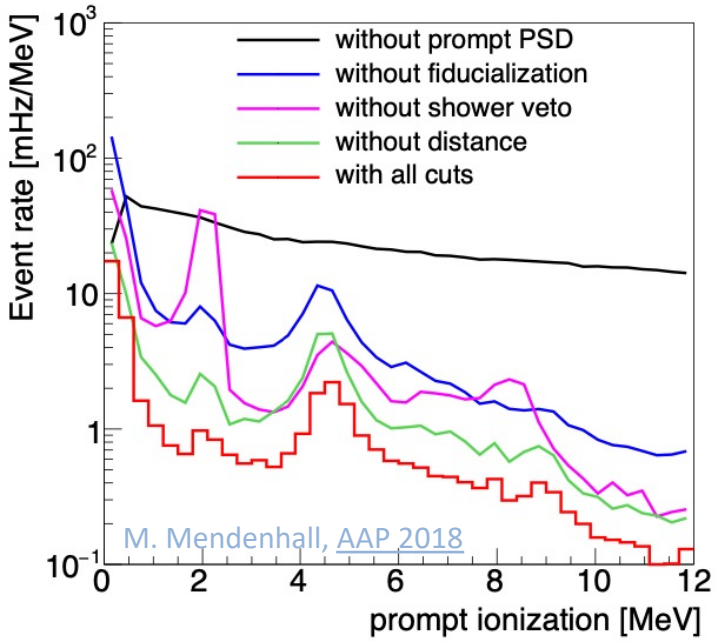
PROSPECT-I design feature

Inverse Beta Decay (IBD)

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

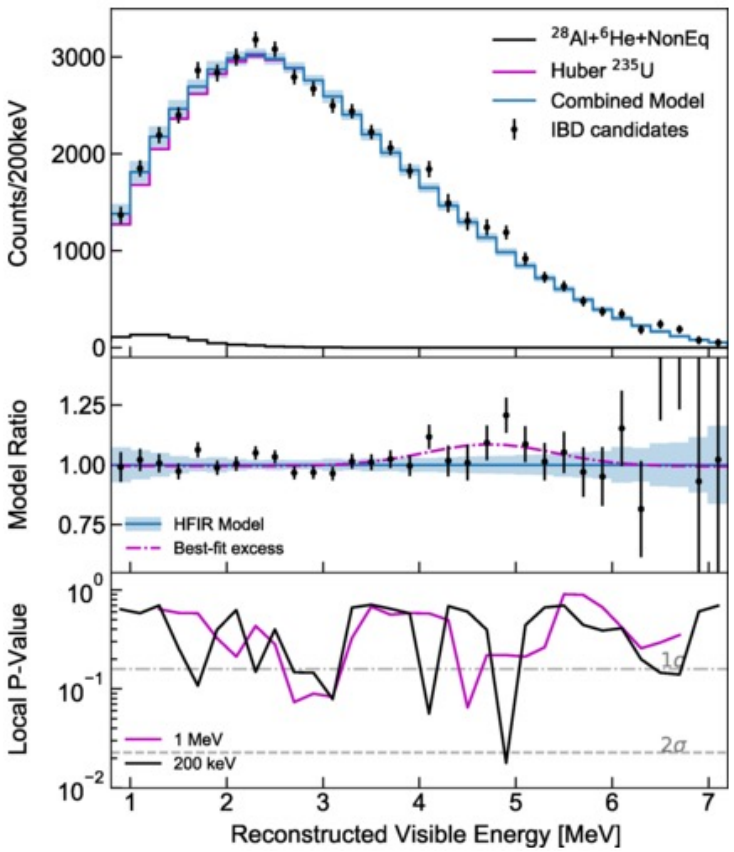


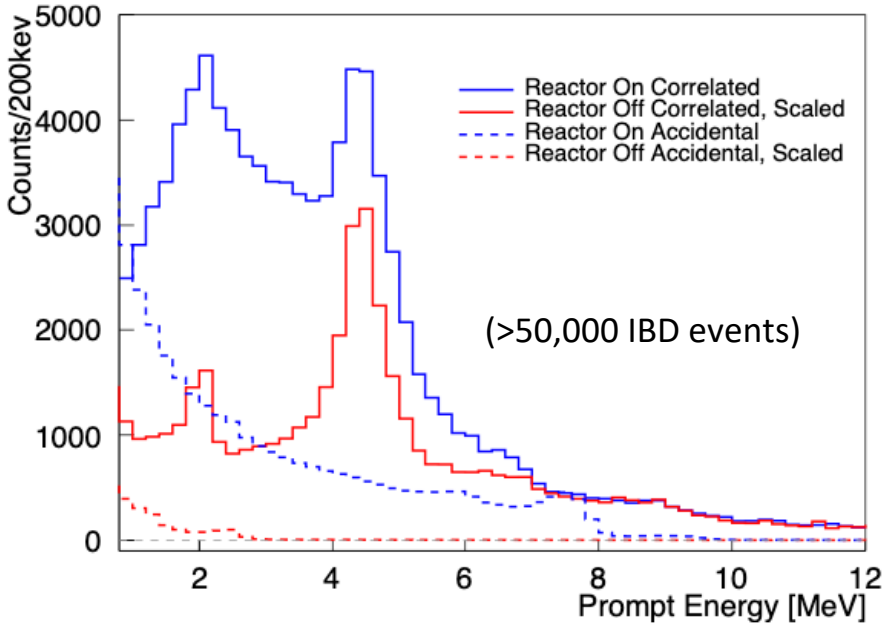




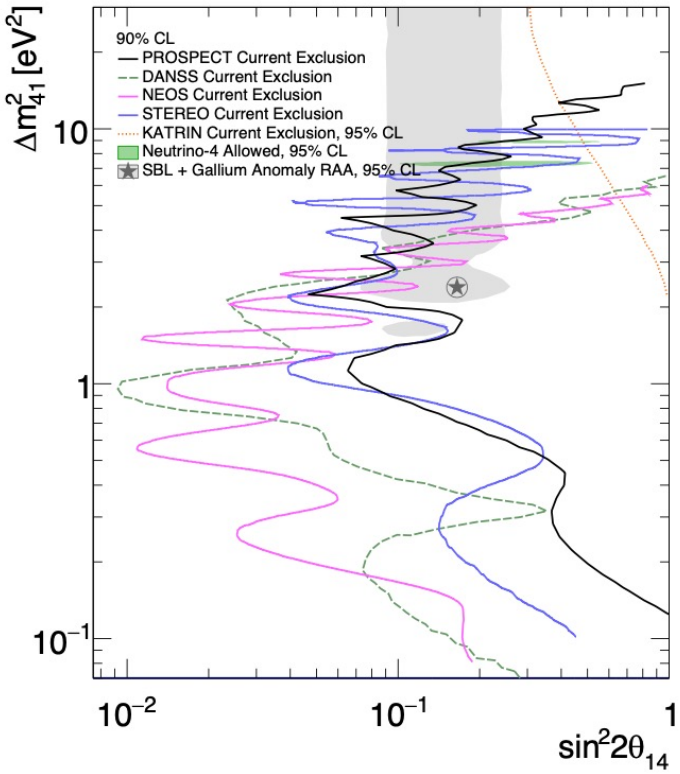
- Antineutrinos are detected via Inverse Beta Decay (IBD) interaction.
- The prompt energy gives an estimate of the antineutrino energy.
- The delayed n-Li capture is used for tagging the IBD candidates.
- Particle ID capability combined with good spatial resolution obtained via segmentation can remove a significant fraction of the backgrounds, enabling on-surface deployment with lightweight shielding.

PROSPECT-I achievements





- First on-surface detector to achieve S/B > 1 with minimal shielding
- First modern measurement of ^{235}U
- >2 sigma rejection of the "no-^{235}U" and "all-^{235}U" interpretation of the LEU bump

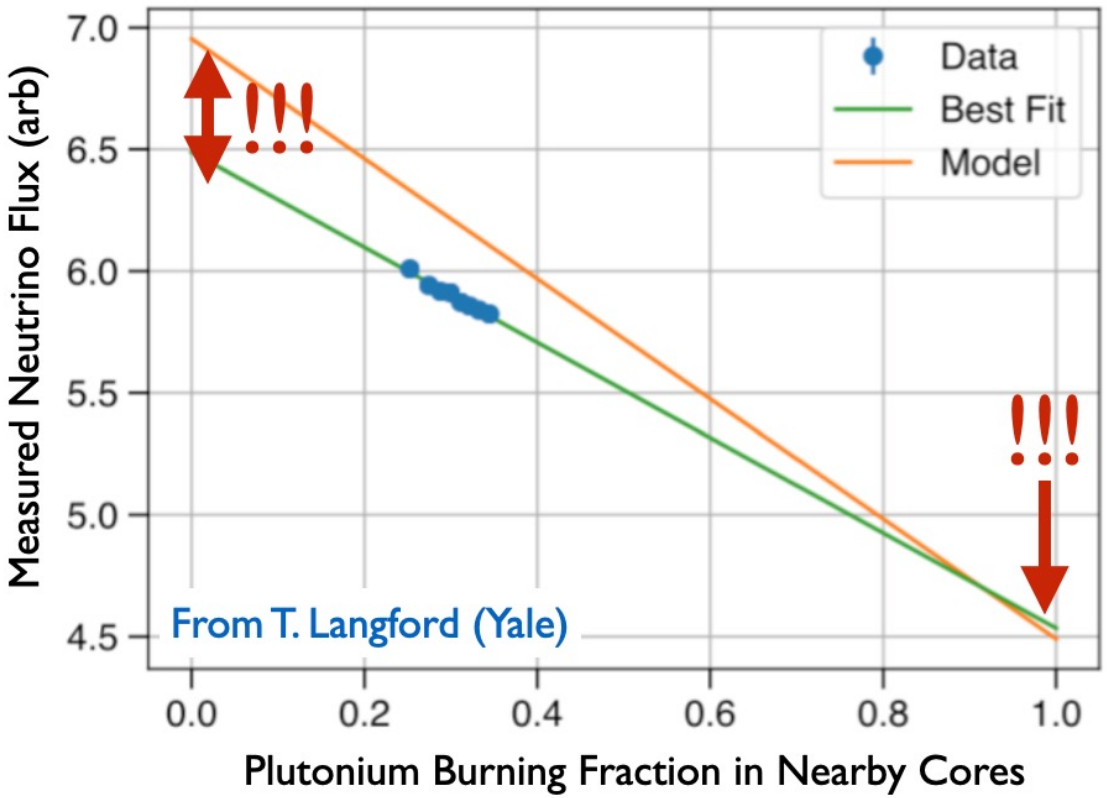


- Set new limits on eV-scale sterile neutrinos
- Cover a large region of the sterile neutrino parameter space

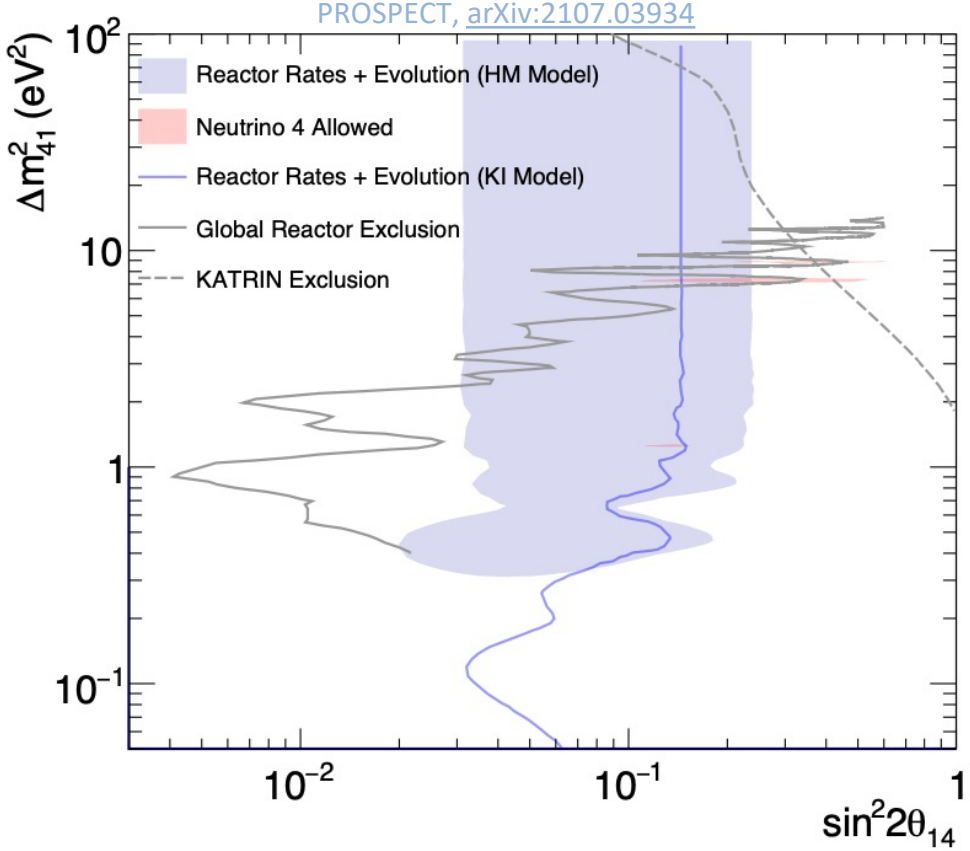
PROSPECT, PRD 103, 032001 (2021)

These results will further improve!
→ see Diego Venegas Vargas's talk

Physics context for P-II: What is the full explanation of RAA?



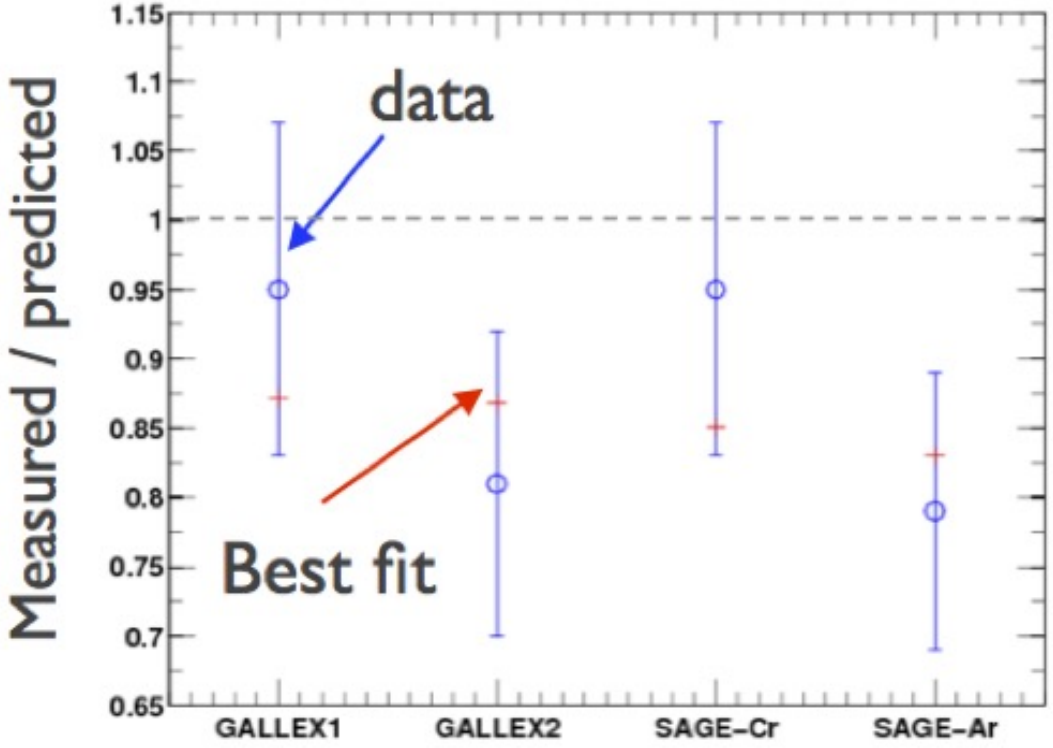
PROSPECT, arXiv:2107.03934



- Rate and flux-evolution measurements alone are not sufficient to unambiguously resolve the reactor anomaly.
- Relative spectral measurements are needed for a definitive resolution in the context of sterile neutrinos

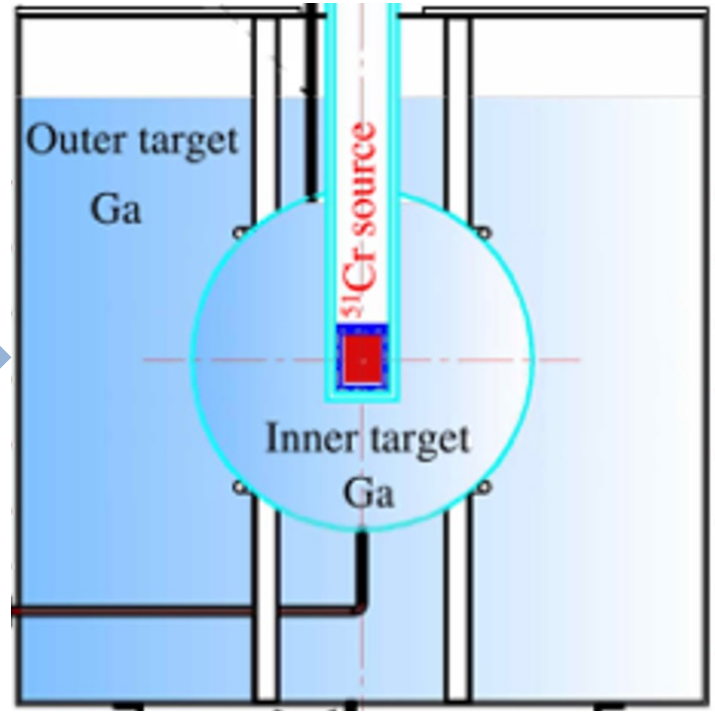
Physics context for P-II: Gallium Anomaly (GA)

Giunti and Laveder, PRC 83, 065504 (2011)



Confirmed!

BEST, PRL 128, 232501 (2022)

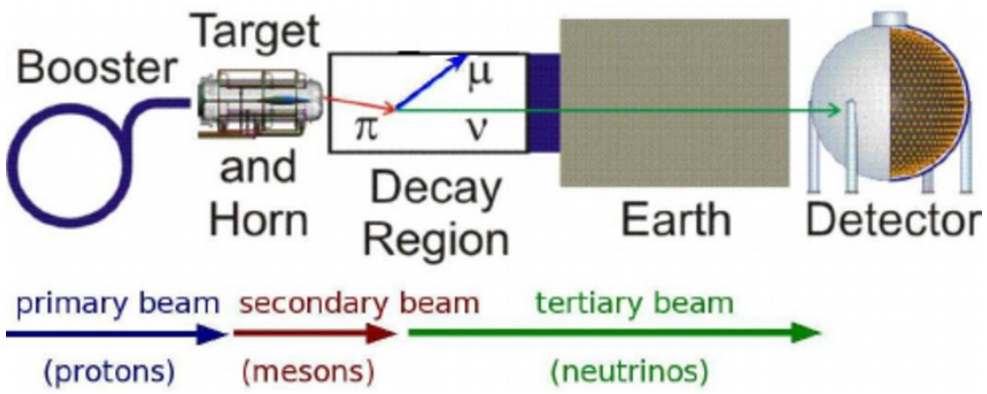


- Solar neutrino experiments with an intense radioactive source: $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- GA is recently confirmed by BEST experiment (~20% deficit in both inner and outer target volumes → sterile neutrino oscillation?)
- Gallium experiments so far cannot disambiguate between effects arising from oscillations or an unknown production effect.
- Relative reactor searches have the capability to directly search for the propagation effect induced by neutrino oscillations.

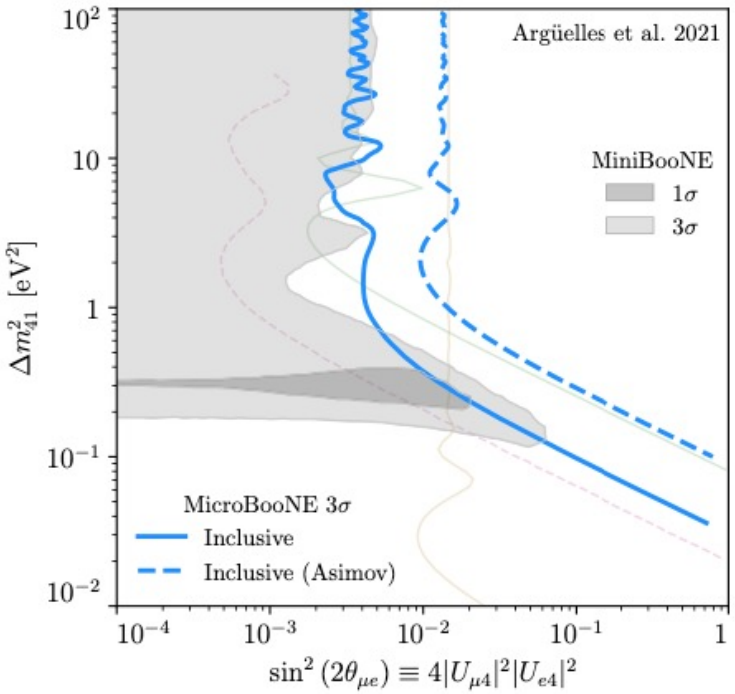
Physics context for P-II: LSND, MiniBooNE and MicroBooNE

- $\bar{\nu}_\mu$ (ν_μ) beam experiment
- Observe excess of $\bar{\nu}_e$ (ν_e)
- L/E is too small for standard oscillations

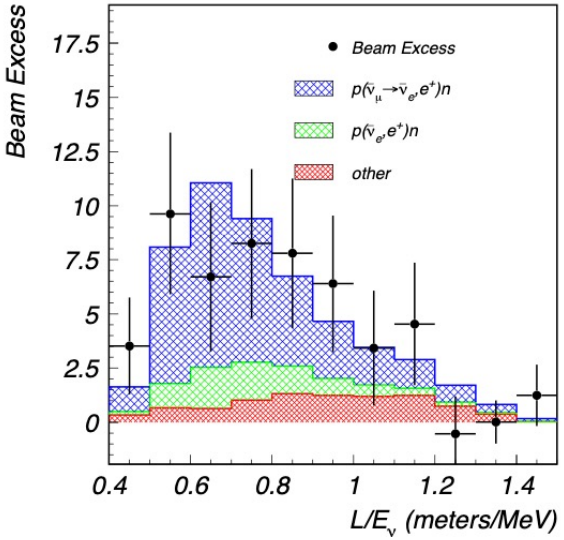
MiniBooNE, PRD 81, 092005 (2010)



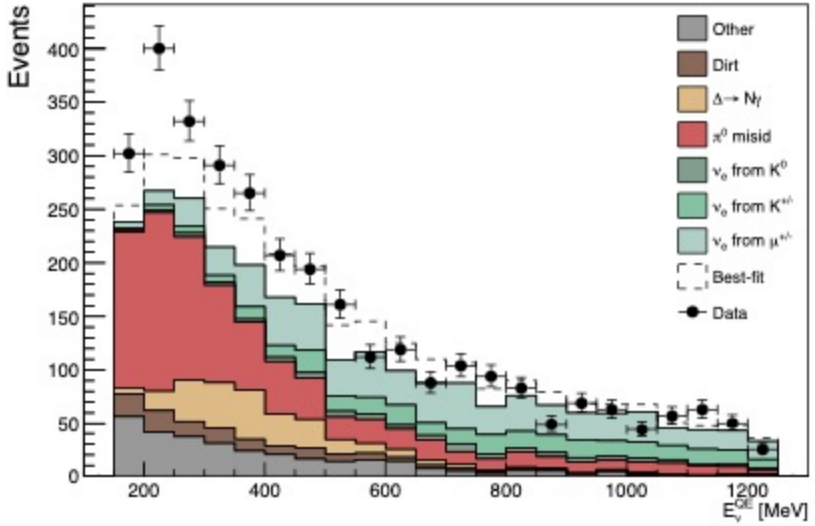
MicroBooNE, arXiv:2111.10359v2



LSND, PRD 64 112007 (2001)



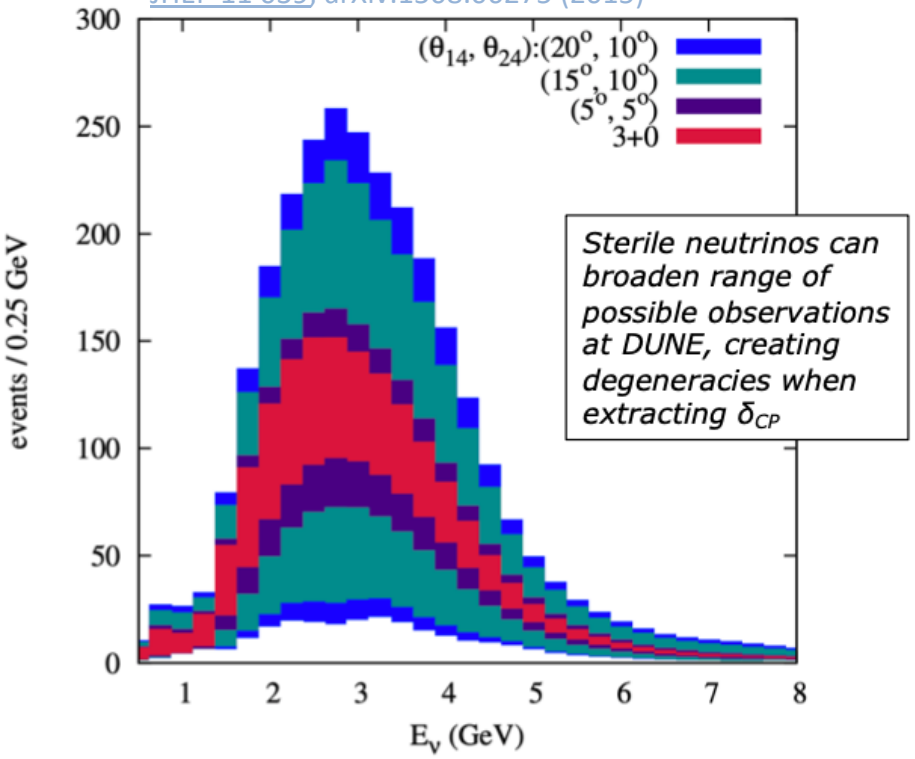
MiniBooNE, PRD 103 052002 (2021)



- Does MicroBooNE rule of the ν_e interpretation of the MiniBooNE excess?
- Does MicroBooNE disfavor the sterile neutrino explanation of the excess?
- A flavor-pure neutrino experiment may help to improve our understanding of the MiniBooNE anomaly

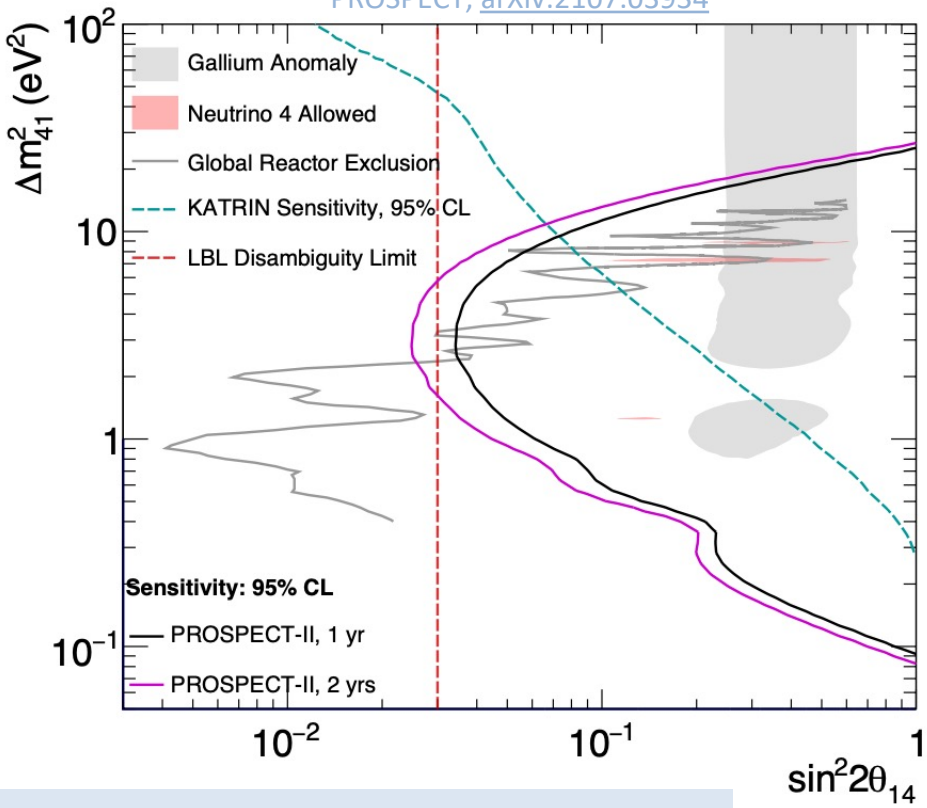
Physics context for P-II: Long-baseline experiment

R. Gandhi, B. Kayser, M. Masud and S. Prakash, JHEP 11 039, arXiv:1508.06275 (2015)



Sterile neutrinos can broaden range of possible observations at DUNE, creating degeneracies when extracting δ_{CP}

PROSPECT, arXiv:2107.03934

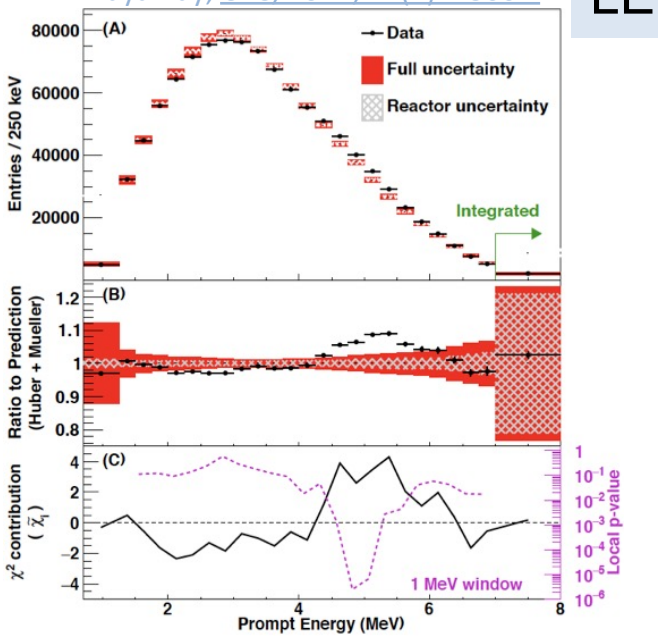


- Results from upcoming long baseline experiments designed to measure CPV remains ambiguous if sterile neutrinos are not fully excluded
- P-II in conjunction with the projected sensitivity from KATRIN can help to clear up the CP violation ambiguity

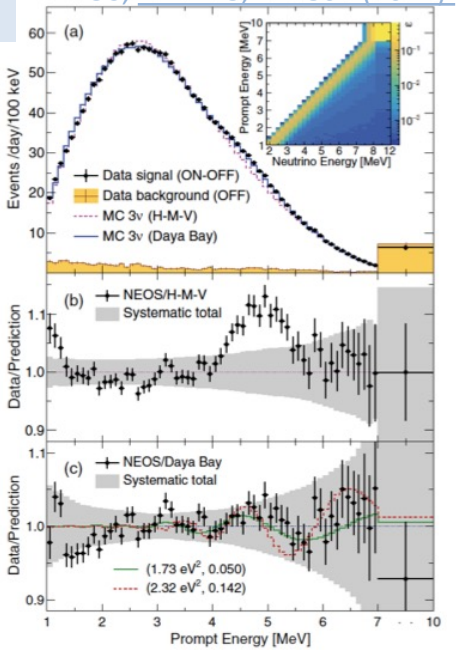
Physics context for P-II: Reactor spectrum anomaly

LEU

Daya Bay, CPC, 2017, 41(1): 13002

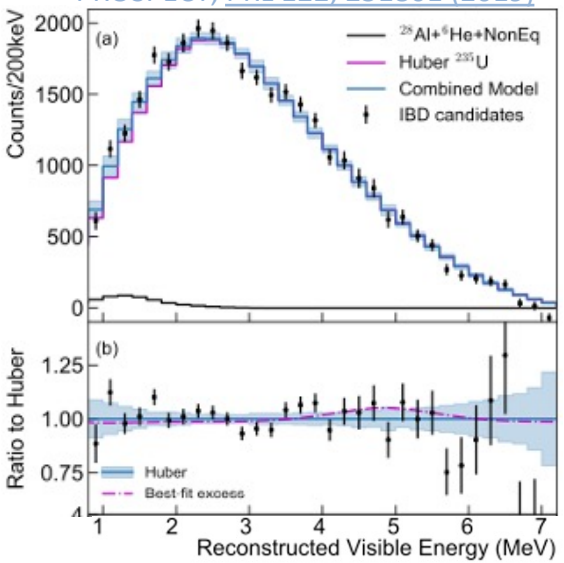


NEOS, PRL 118, 121802 (2017)

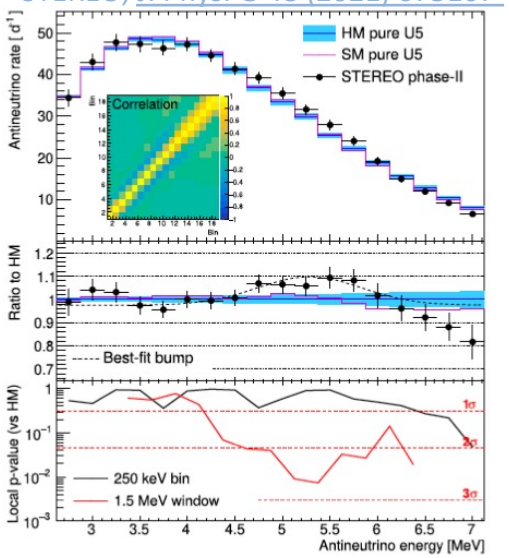


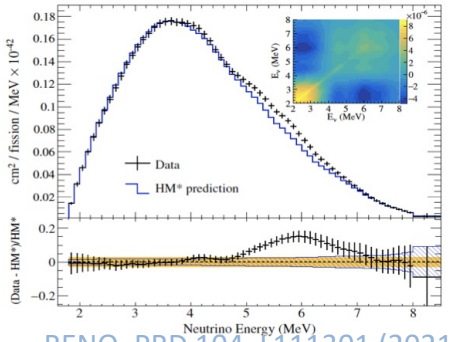
HEU

PROSPECT, PRL 122, 251801 (2019)

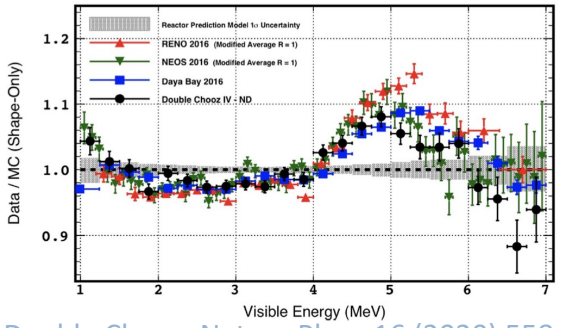


STEREO, J. Phys. G 48 (2021) 075107





RENO, PRD 104, L111301 (2021)

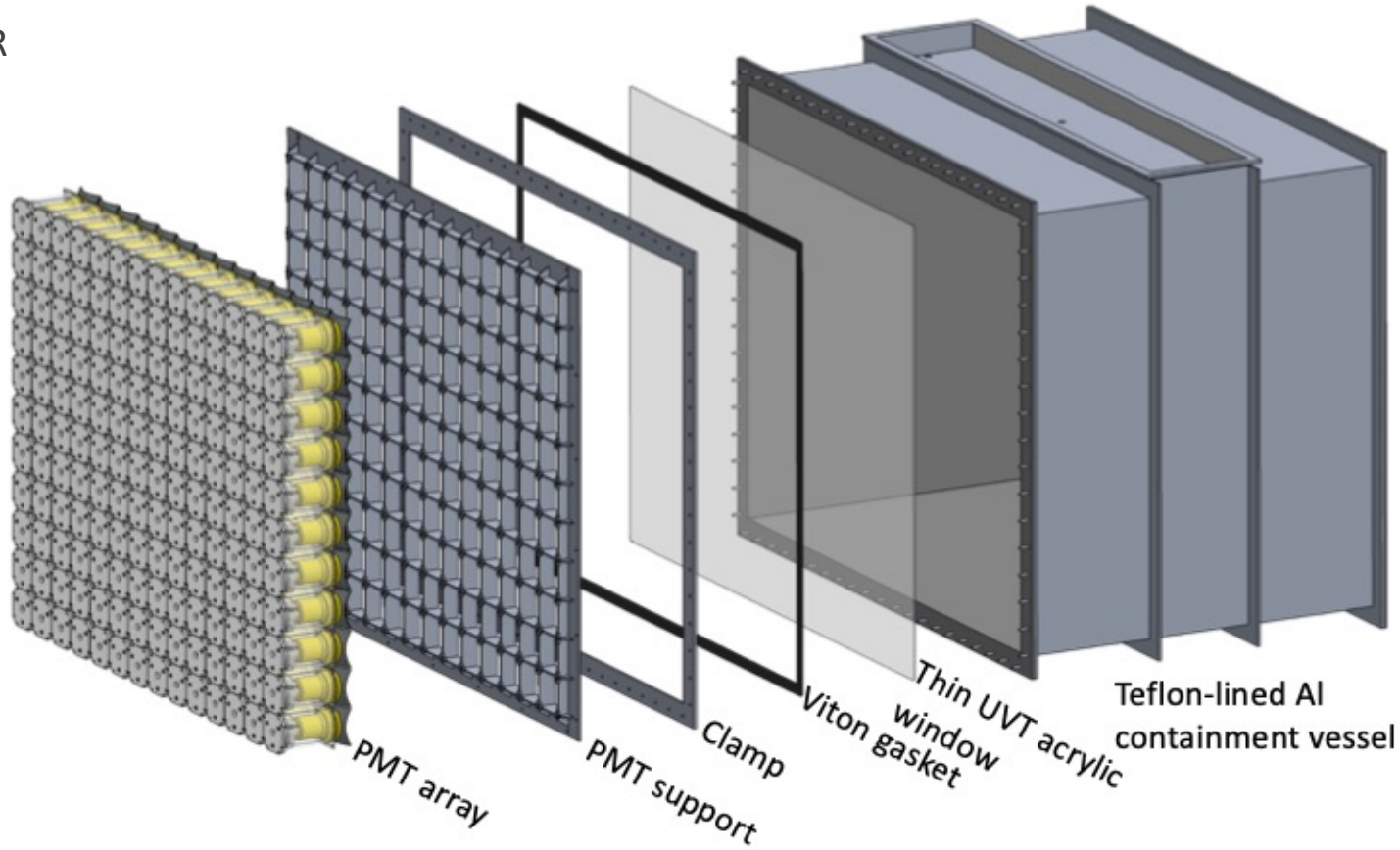


Double Chooz, Nature Phys. 16 (2020) 558

- The 4-6 MeV bump is consistent across LEU experiments
- P-I and STEREO results suggest that spectrum anomaly is not solely due to ^{235}U → P-II can further improve the precision of the world-leading P-I measurement of U-235 ν_e energy spectrum
- P-II and Daya Bay joint analysis would produce purely data-driven reactor ν_e spectrum models → high-priority nuclear data need

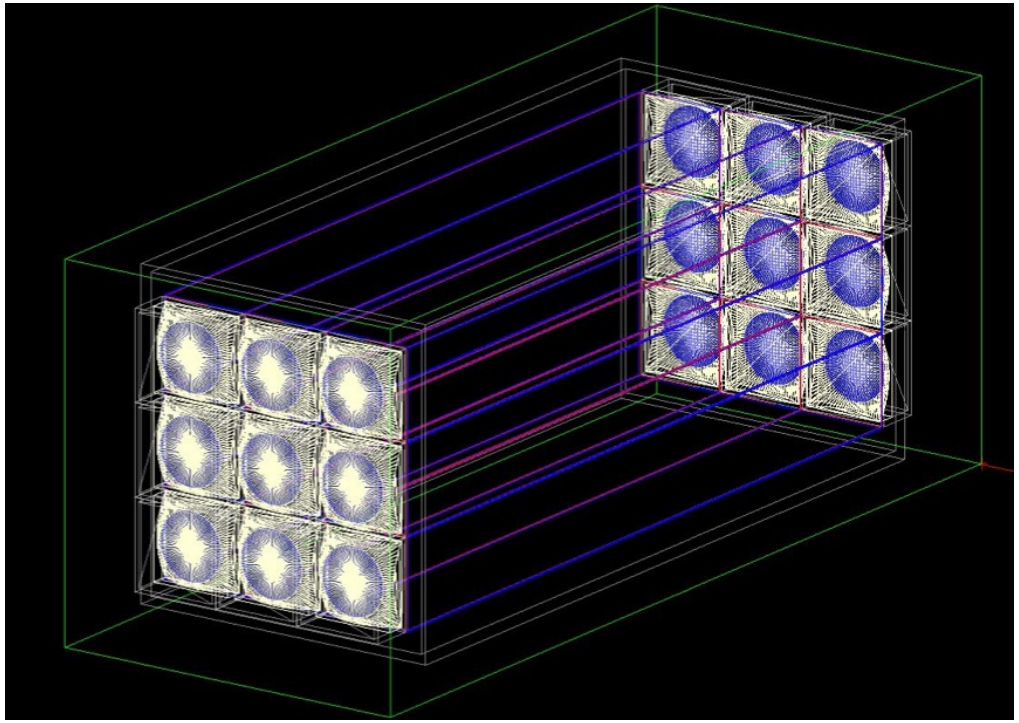
PROSPECT-II design

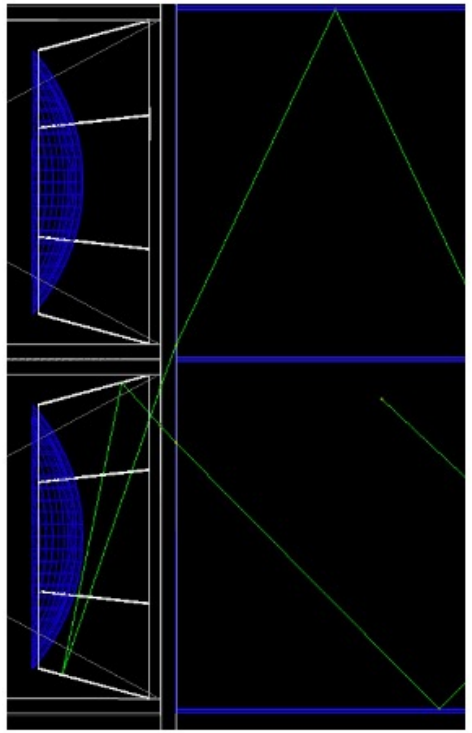
- Retains successful elements of PROSPECT-I: 14x11 optically segmented ^{6}Li-doped liquid scintillator with minimal shielding, located 7-9m from HEU core of HFIR (+ possible LEU site)
- Moves PMTs out of liquid scintillator volume to avoid contacts with other materials
- Increases signal collection capacity with 20% longer segments, 20% increased ^{6}Li loading, longer data-taking period → 10x effective statistics at HFIR
- Designed to facilitate deployment at multiple sites
- Can be built in a relatively fast timeframe (1 year) and only needs a small funding mechanism
- Uses external calibration system instead of calibration tubes inside active volume



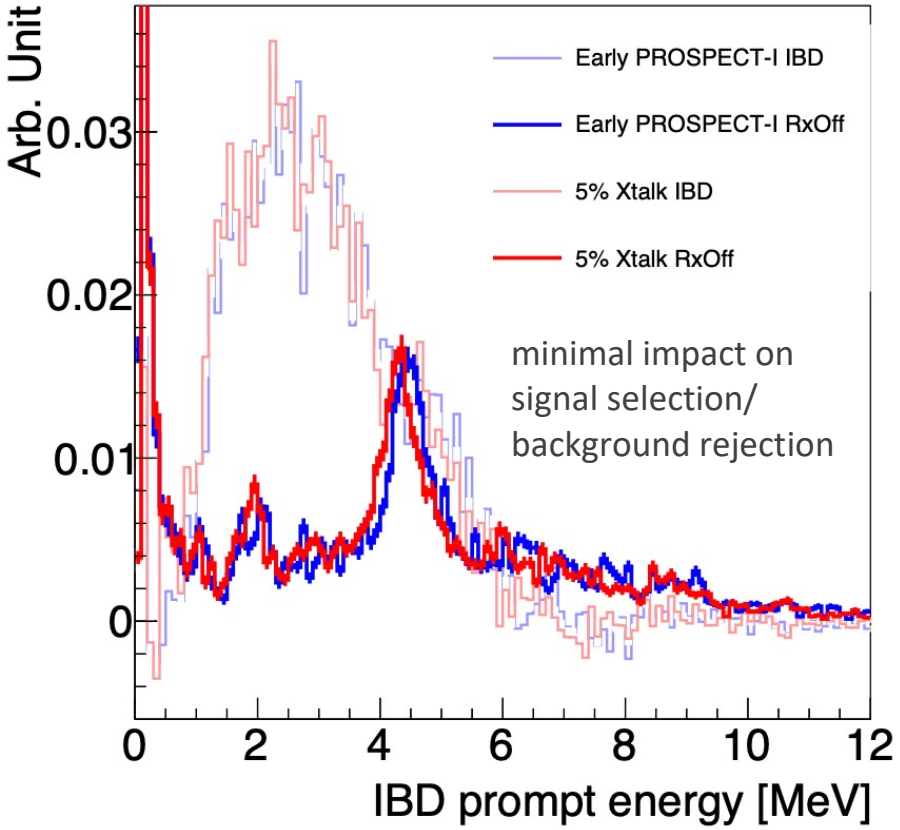
PROSPECT, arXiv:2107.03934

Validation of redesigned PMT interface





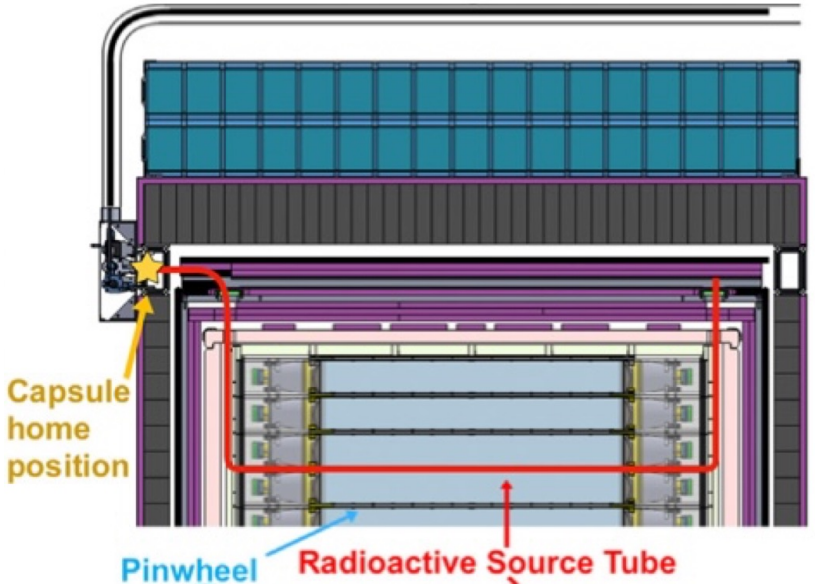
<5% cross-talk target

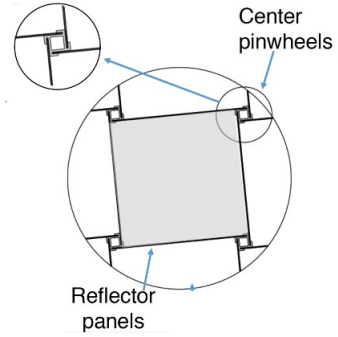


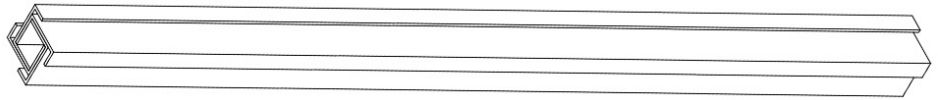
- Acrylic windows allow for light leakage from one segment to neighboring segments
- Optical model was benchmarked by matching the light curve measured on the PROSPECT-I prototype
- Data-driven simulation validates that moving PMTs out of the scintillator introduces minimal cross-talk between segments (5% target is achievable!)

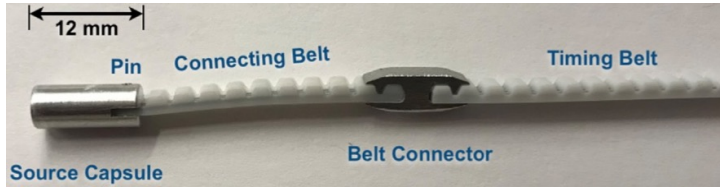
PROSPECT-II conceptual calibration design

PROSPECT-I in-situ internal calibration

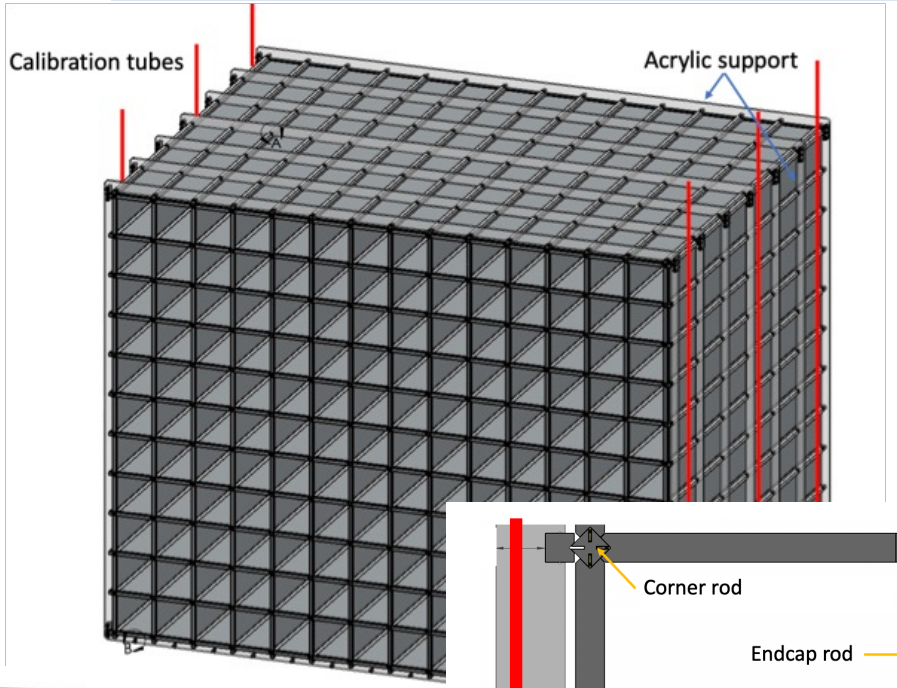


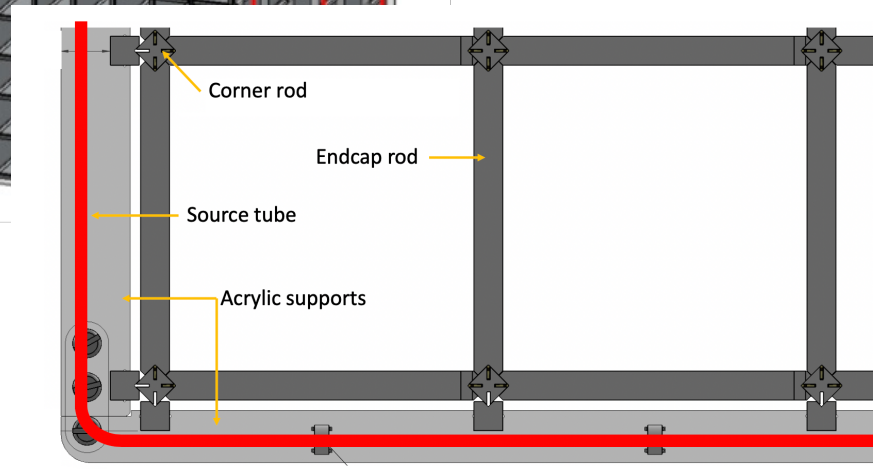




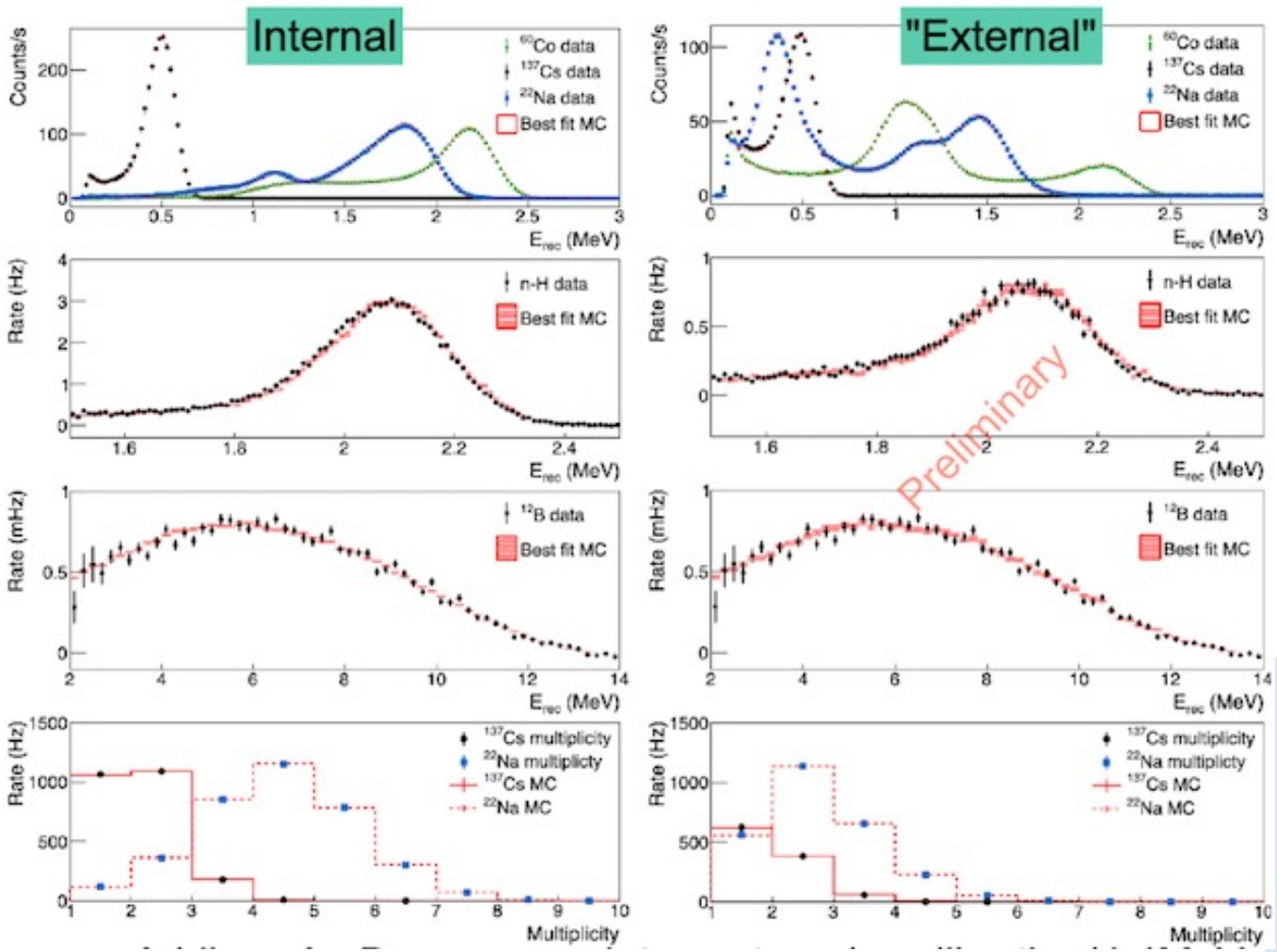


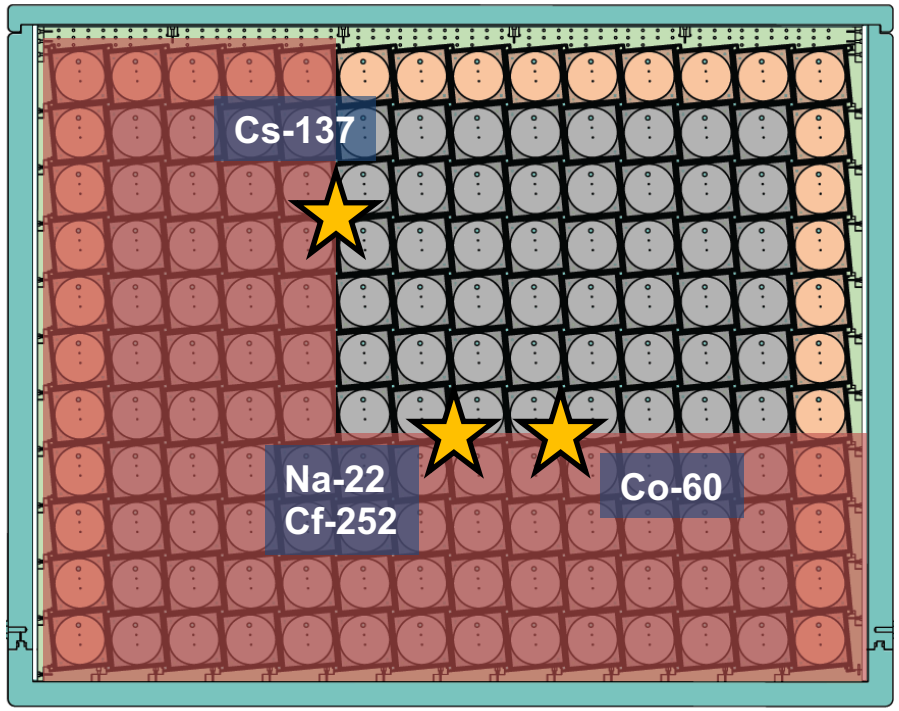
PROSPECT-II external calibration design





Validation of external calibration approach

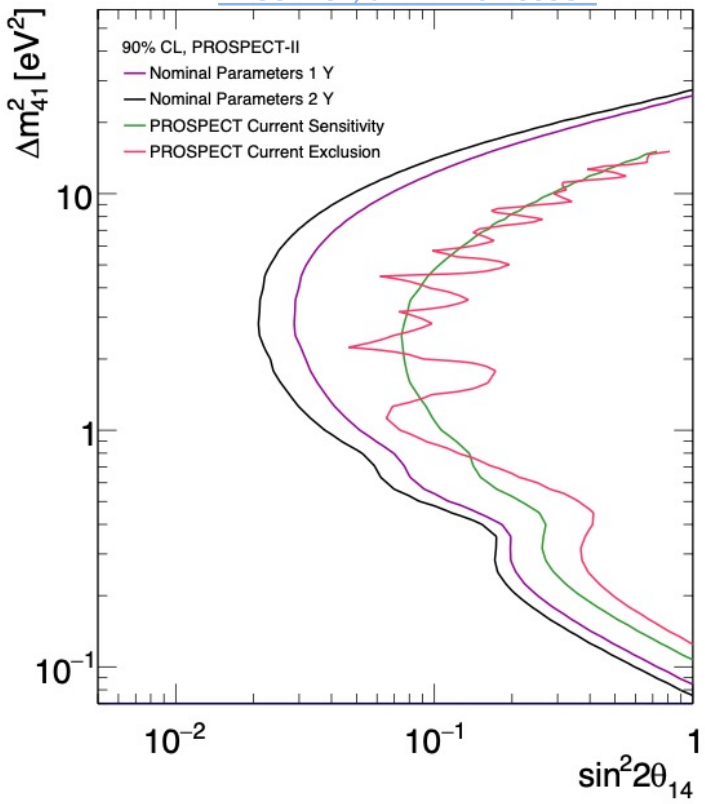




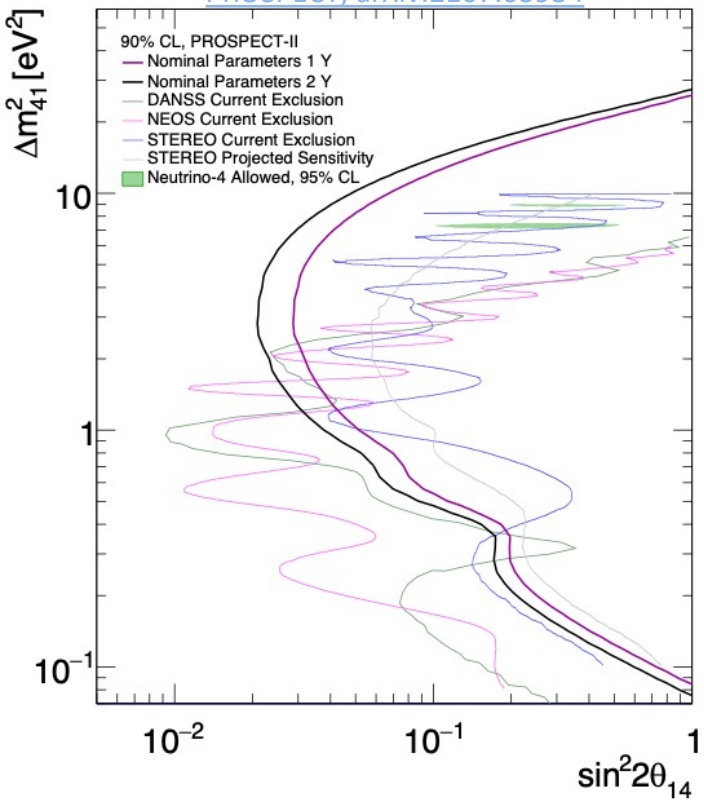
- We can use PROSPECT-I data to simulate external source deployment.
- Good agreement in energy and segment multiplicity responses is observed.
- Performance of external calibration is comparable to internal calibration (stay tuned for our upcoming publication!)

PROSPECT-II projected oscillation sensitivity

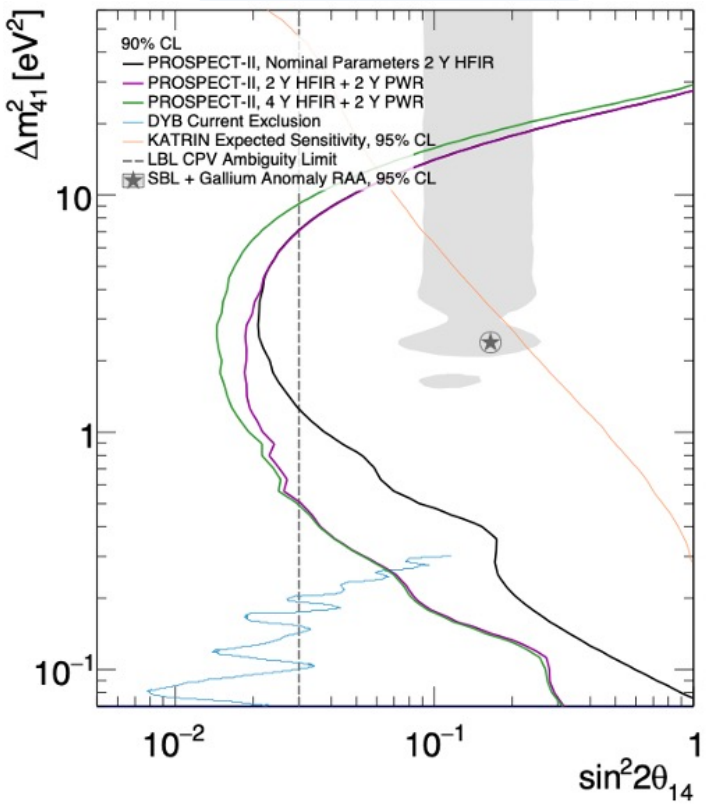
PROSPECT, arXiv:2107.03934



PROSPECT, arXiv:2107.03934



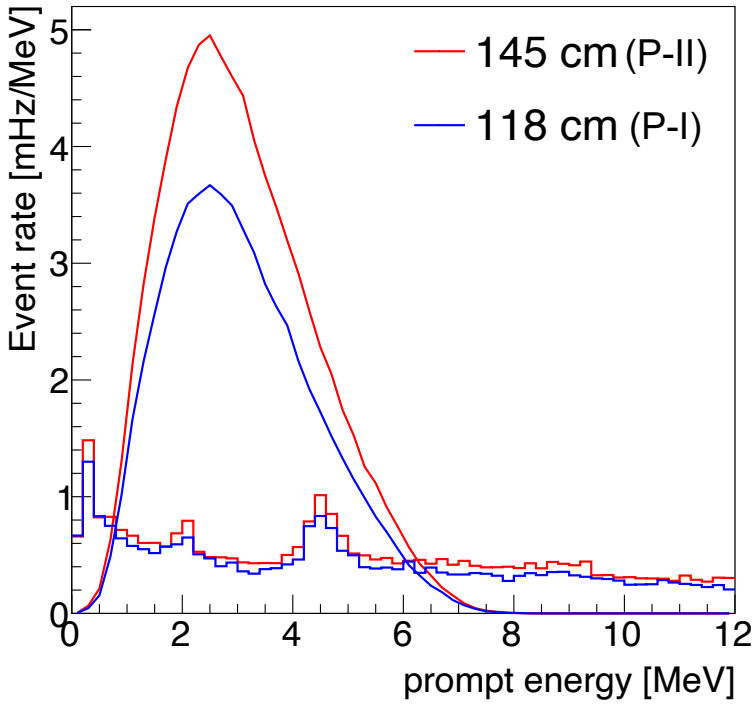
PROSPECT, arXiv:2107.03934



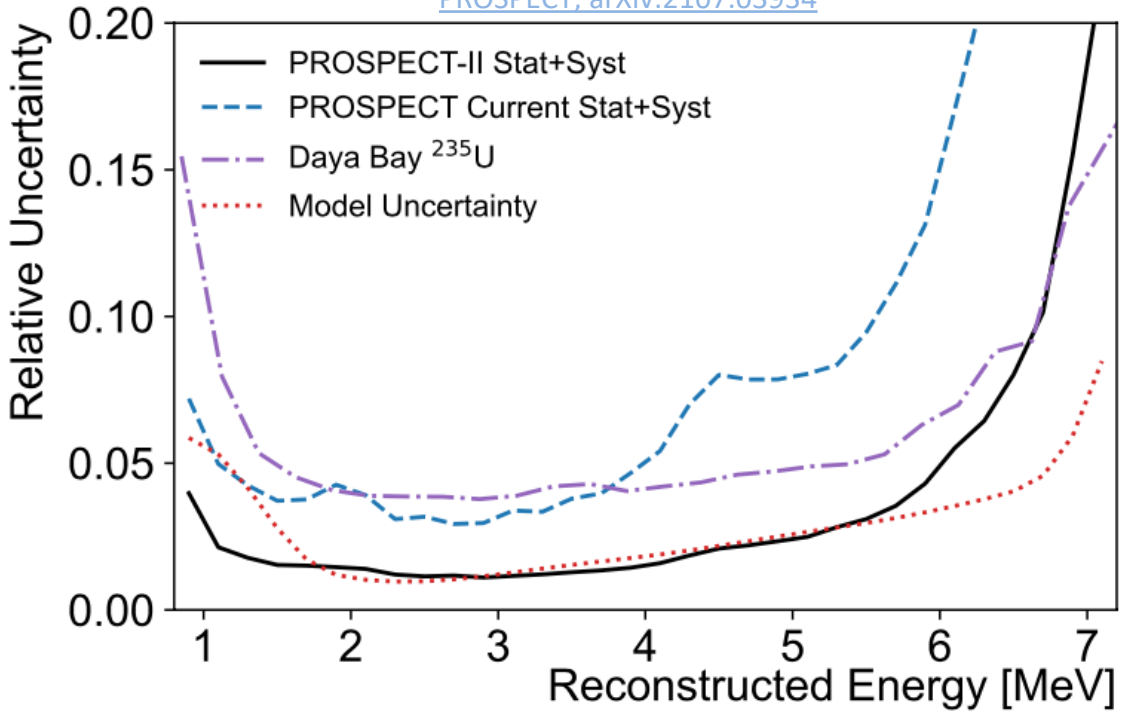
- P-II provides the best coverage of any short-baseline reactor experiment at $\Delta m^2_{41} > 1.5$ eV^2
- Together with future KATRIN data, P-II can help to clear CPV ambiguity and fully cover the GA and RAA regions.

PROSPECT-II projected spectrum and flux sensitivity

PROSPECT, arXiv:2107.03934



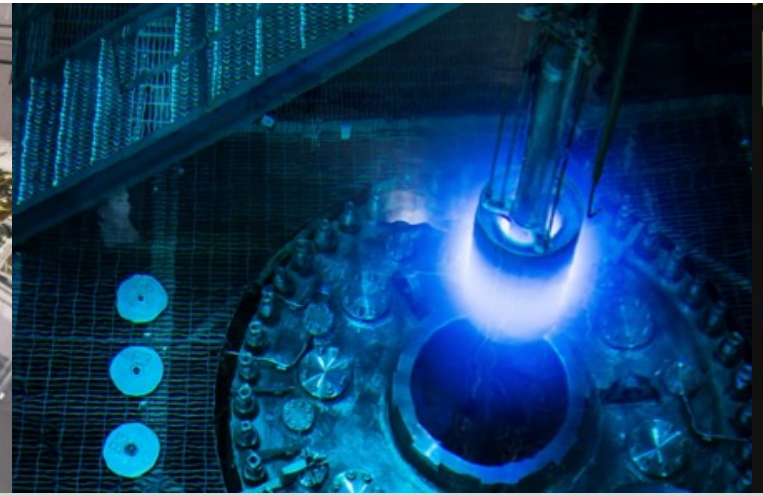
PROSPECT, arXiv:2107.03934

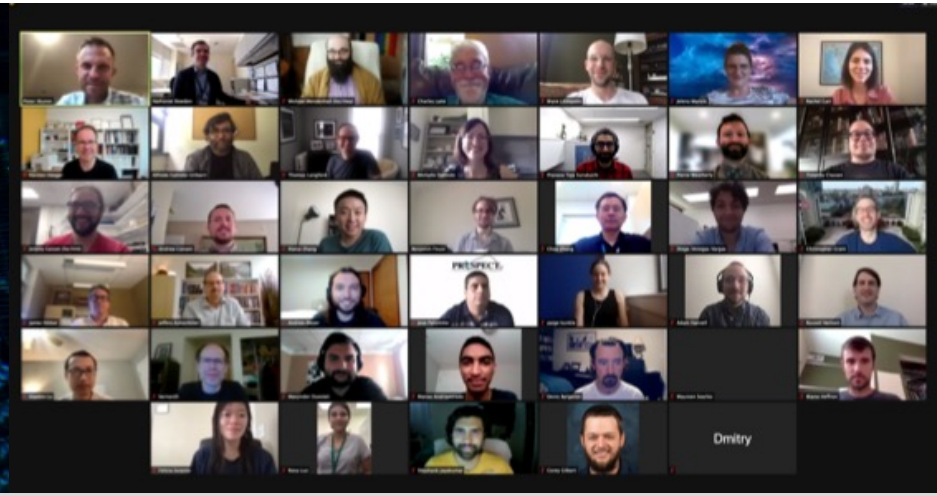


- Precision on ^{235}U spectrum shape measurement will exceed that achievable in LEU-based evolution measurement, and uncertainties will be below the claimed model uncertainties
- PROSPECT will address the hypothesis for the origin of this feature (n=0, no bump from ^{235}U; n=1.78, bump entirely from ^{235}U) at high confidence levels.

Conclusions

- PROSPECT-II design retains most of the elements of PROSPECT-I. Major changes include:
  - Moving PMT out of the scintillator volume (cross-talk has minimal impact on our background rejection)
  - The use of an external calibration system, which has comparable performance with PROSPECT-I's internal calibration system
- The detector is relocatable, allowing for HEU and LEU measurements with the same detector → minimizing detection system-related uncertainties.
- PROSPECT-II anticipates taking data in 2023 at HFIR for two years, and with a two-year run at HFIR, PROSPECT-II can offer:
  - Coverage of 1-20 eV^2 region beyond the reach of other reactor experiments
  - Help to clear CPV ambiguity, and address GA, and RAA remaining regions when combined with future KATRIN
  - New HEU measurement with uncertainties below the claimed model uncertainties





Acknowledgement

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Parameters for sensitivity projections

Parameter		P1	P2 at HFIR	P2 at LEU
Reactor	Power (MW_{th})	85		3000
	Cylinder Size ($d \times h$, m^2)	0.4×0.5		3×3
	Fuel	HEU		LEU
	Cycle Length	24 d		1.5 y
Detector	Segmentation	11×14	11×14	
	Segment Area (cm^2)	14.5×14.5	14.5×14.5	
	Segment Length (m)	1.17	1.45	
	Target Mass (ton)	~4.0	4.8	
	Light collection (PE/MeV)	~380	500	
	Detection Efficiency	~40%	40%	
Exposure	Average Baseline (m)	7.9	7.9	25
	Reactor-On Days (d)	105	336	548
	Reactor-Off Days (d)	78	360	61
	Signal:Background	1.4	4.3	19.3
	IBD Statistics (N_{IBD})	50560	3.74×10^5	2.72×10^6
	Effective Statistics (N_{eff})	15195	2.08×10^5	1.79×10^6

PROSPECT, arXiv:2107.03934

P-1: Parameters realized in PROSPECT-I, as analyzed in PROSPECT, PRD 103, 032001 (2021)

P2 at HFIR: Parameters anticipated for the PROSPECT-II run at the High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory

P2 at LEU: Parameters estimated for a PROSPECT- II deployment at a commercial pressured water reactor (PWR) using low-enriched uranium (LEU) fuel

backup