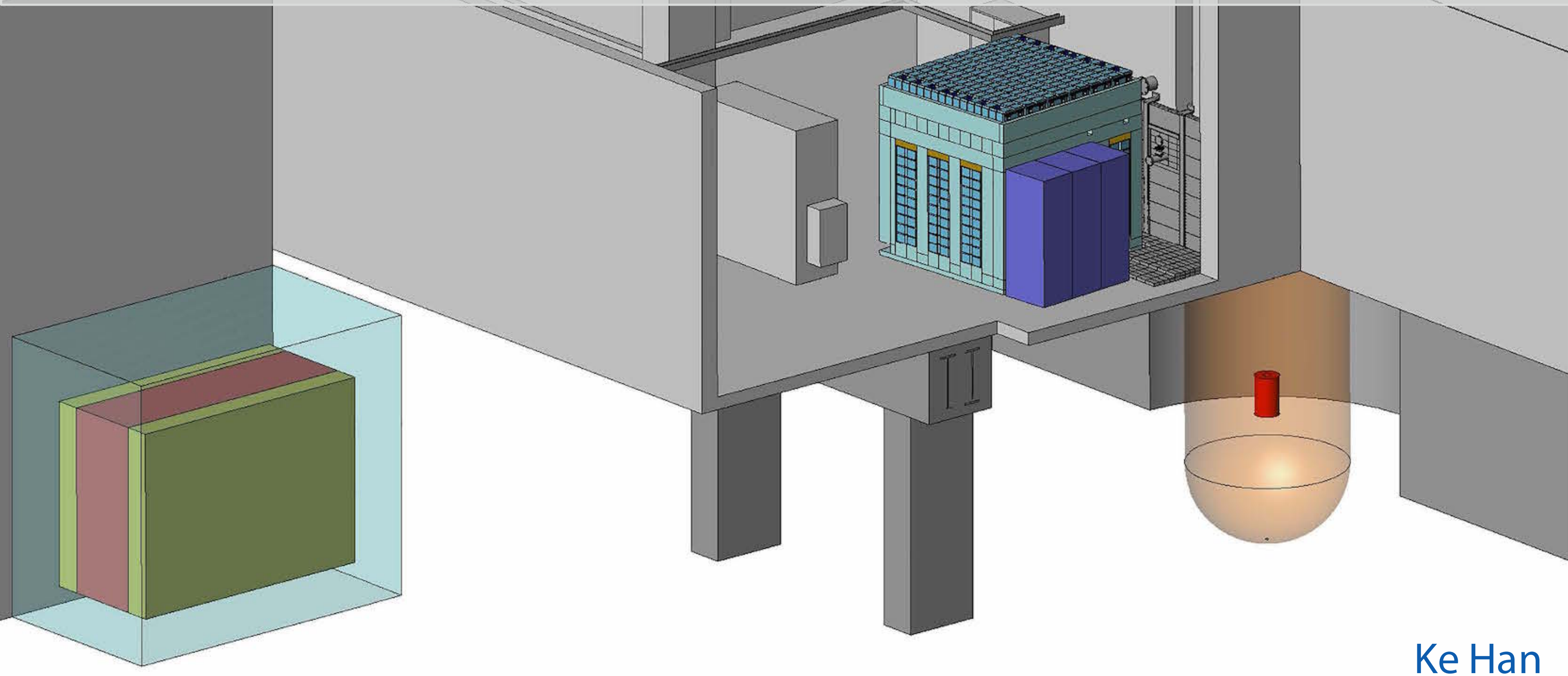
PROSPECT:

Precision Reactor Oscillation and Spectrum Experiment



Ke Han

Yale University

December 16, 2015

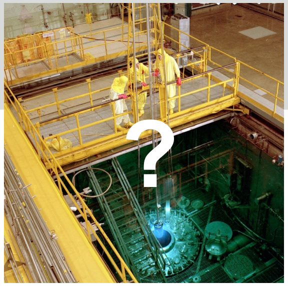
On Behalf of the PROSPECT Collaboration

PROSPECT Yale

Outline

- New physics with reactor neutrinos
  - Sterile neutrino
  - Spectrum measurement
- PROSPECT physics: detector design and sensitivity
- PROSPECT R&D program
- Ongoing work
- Summary

Reactor Neutrino – A tool for discovery



2012 - Measurement of θ_{13} with Reactor Neutrinos

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

Reactor antineutrino

Source

Pure $\bar{\nu}_e$ from β-decays
of n-rich fission products

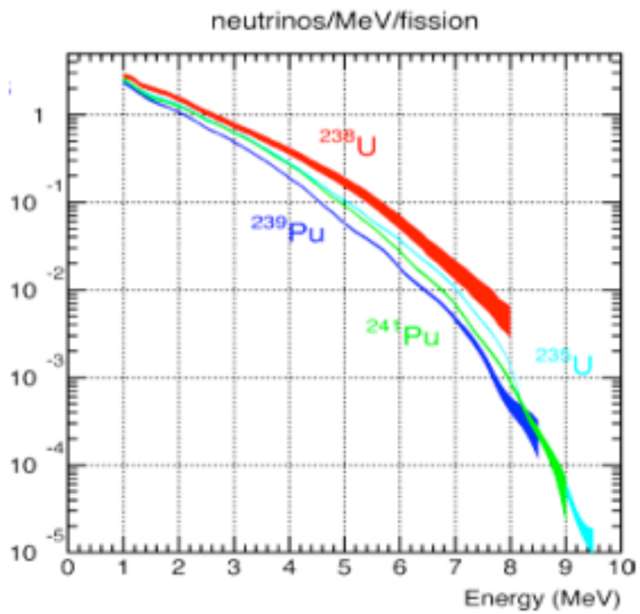
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

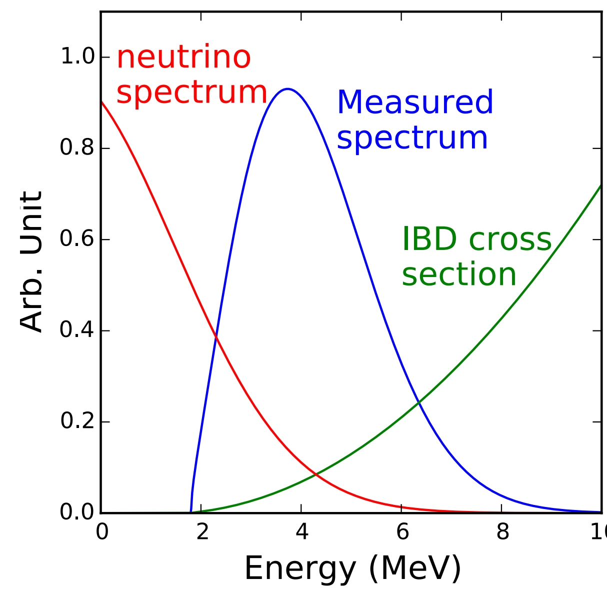
Detection

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

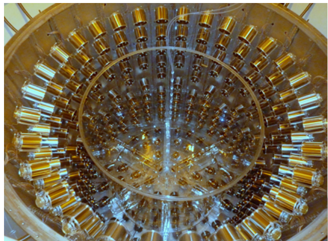
Threshold: neutrinos with E < 1.8 MeV are not detected

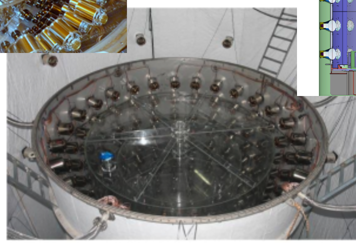
Disappearance experiments

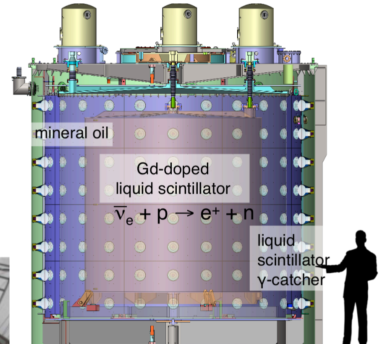


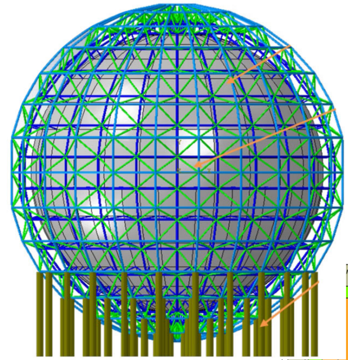


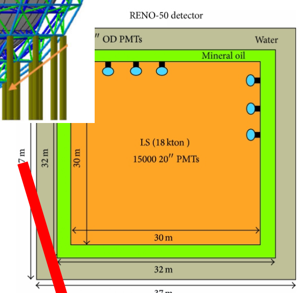
Rich reactor Neutrino program at different baselines

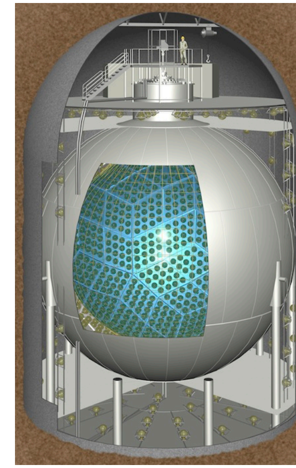


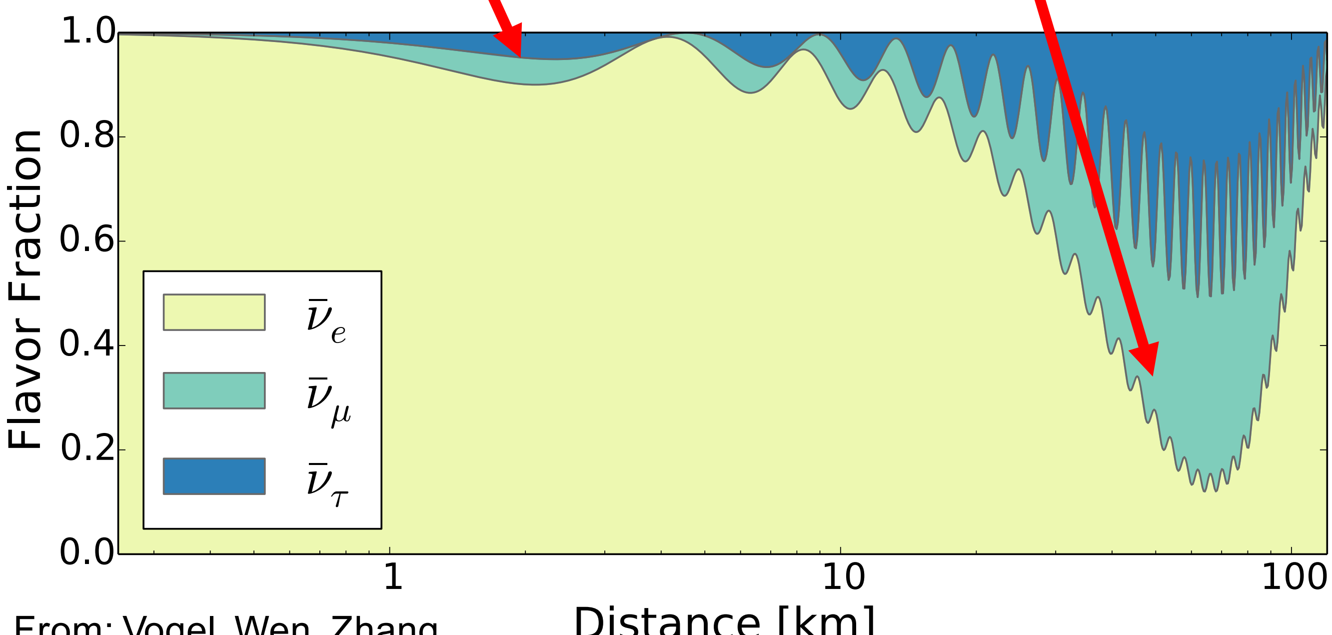






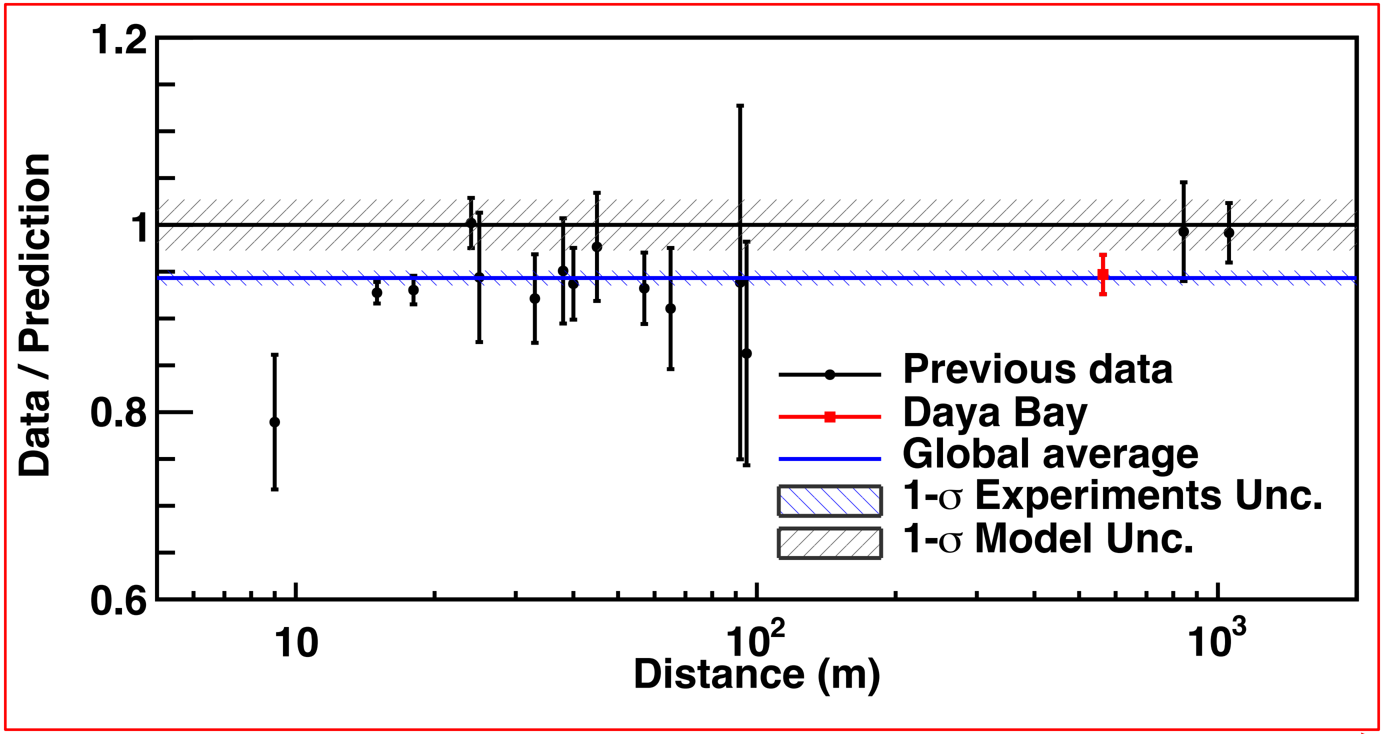


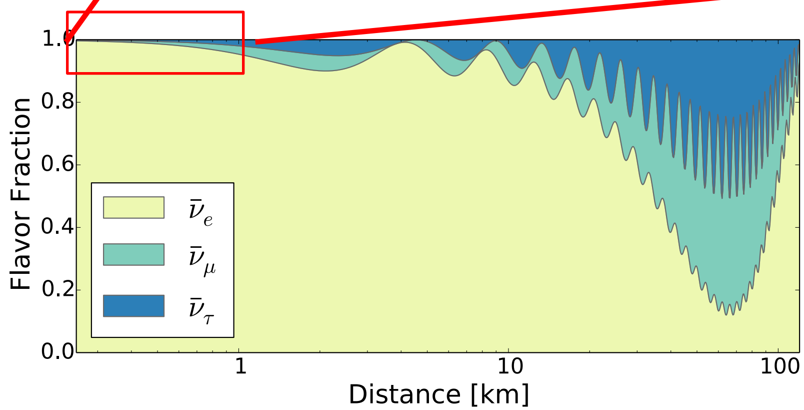




From: Vogel, Wen, Zhang

Reactor antineutrino anomaly: deficit in the observed reactor flux





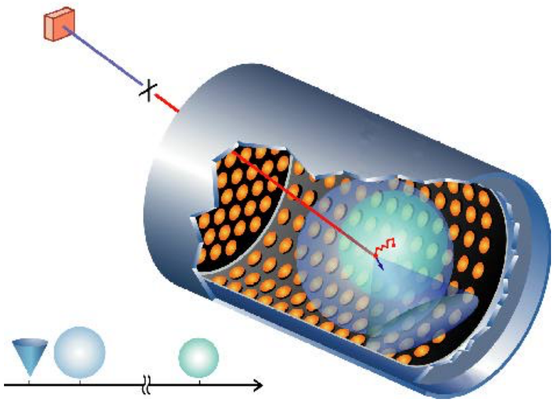
If the deficit is due to anti-ν_e disappearance:
New oscillation signal requires $\Delta m^2 \sim O(1\text{eV}^2)$ and $\sin^2 2\theta \sim 0.1$

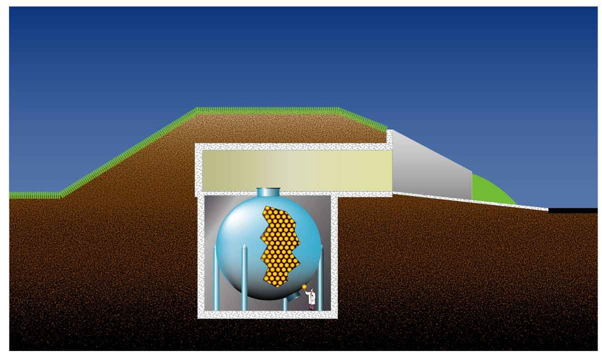
Other hints for sterile neutrinos

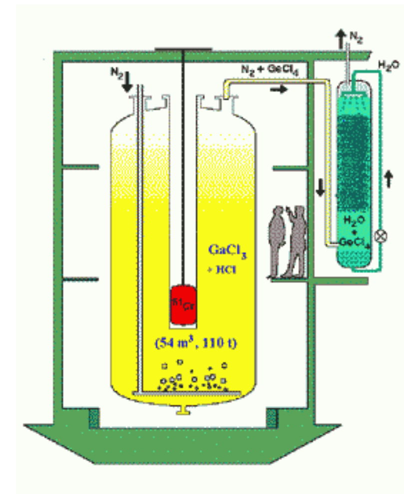
LSND
decay at rest

MiniBooNE
short baseline accelerator

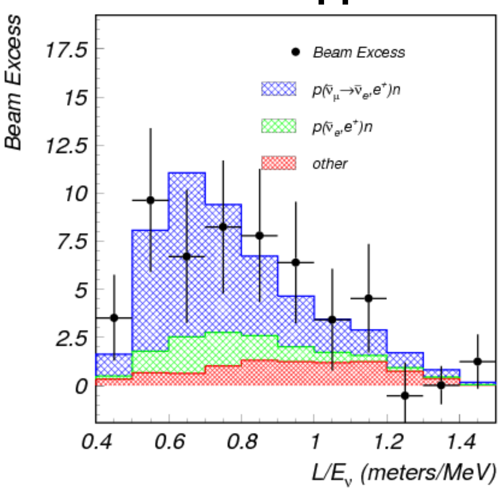
GALLEX/SAGE
Ga source calibration



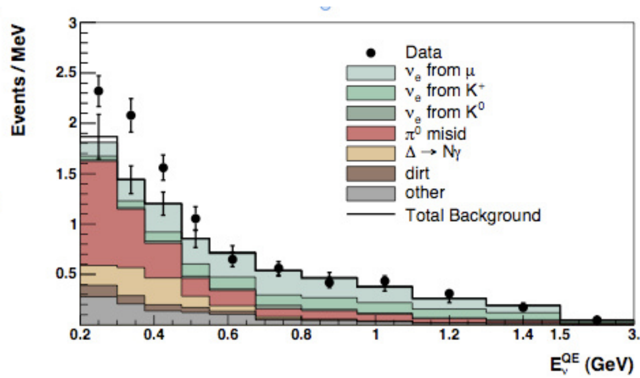




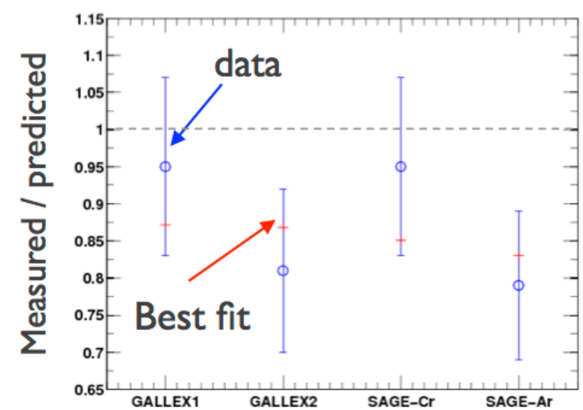
anti-ν_e appearance



low energy (anti-)ν_e appearance

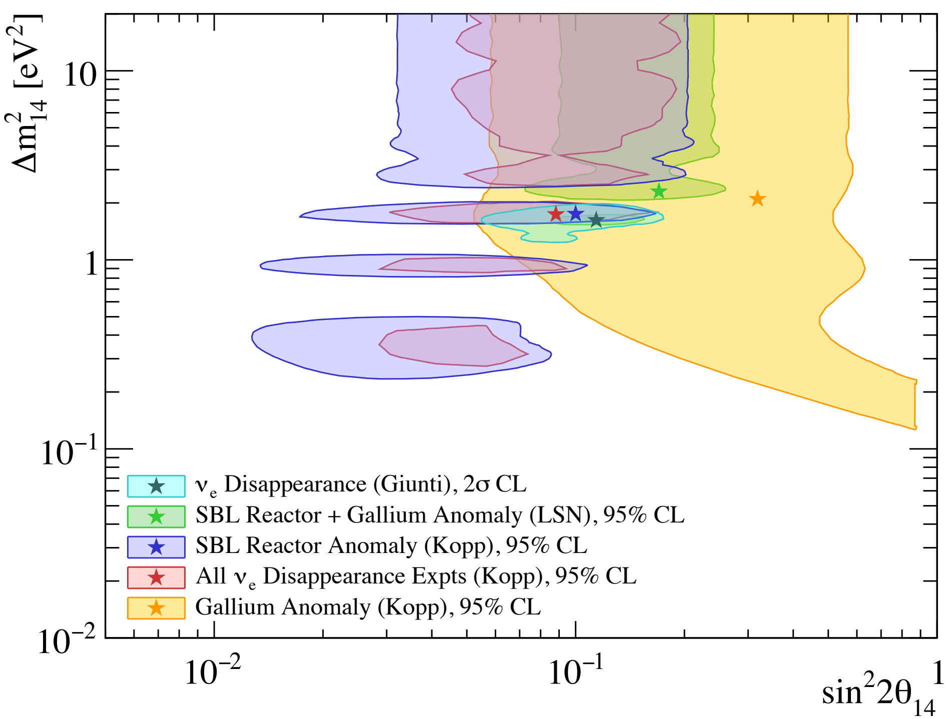


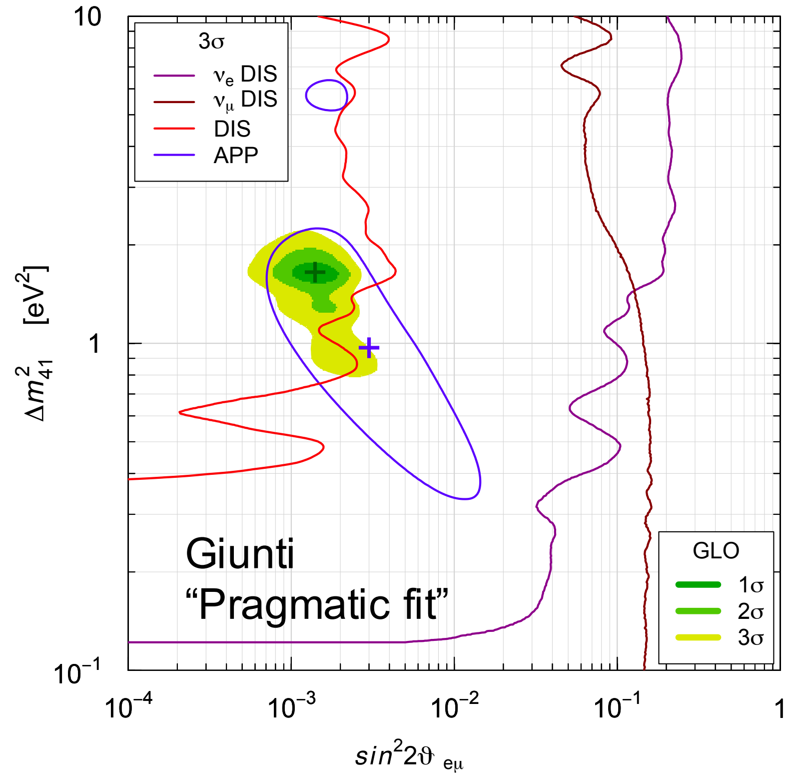
ν_e disappearance



Global fit

- Various fits on ν_e data indicate $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$
- Global fits with ν_u data shows tension in 3+1 or 3+2 models.
- "Pragmatic fit" works better if ignore MiniBoone low energy excess.





Giunti: PRD88 073008 (2013); arXiv:1507.08204

LSN: ArXiv: 1204.5379 (2012)

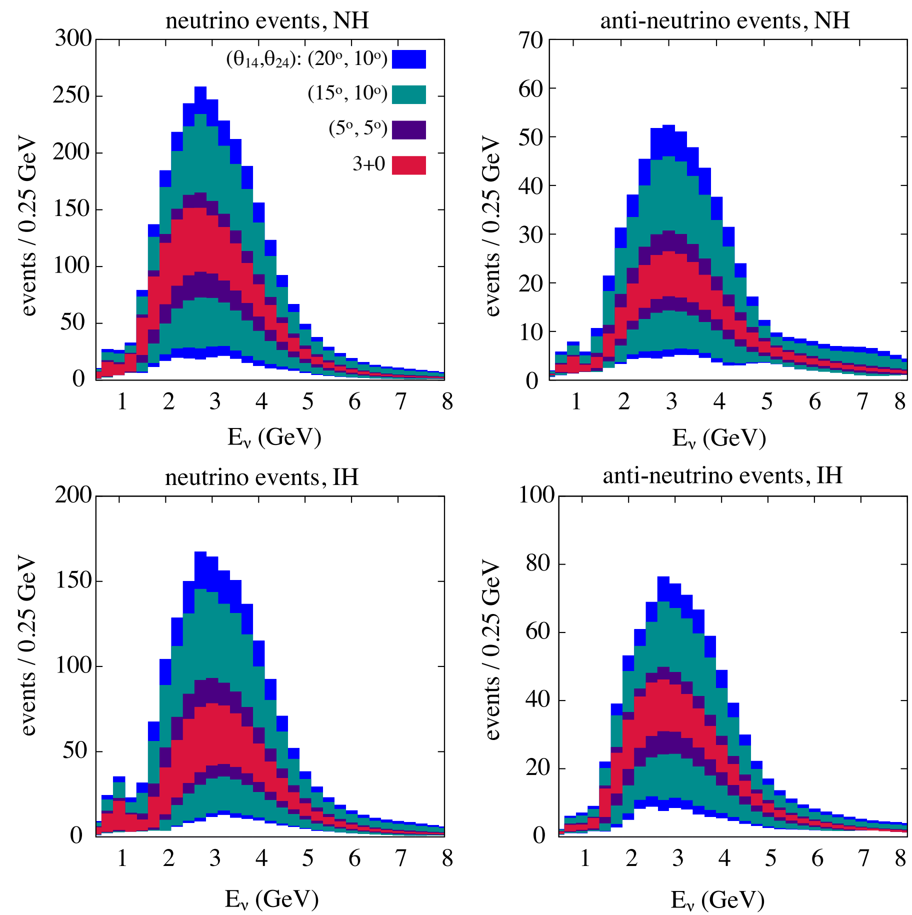
Kopp: JHEP 1305 050 (2013)

Implications for the Future Neutrino Program

eV-scale sterile neutrino would change:

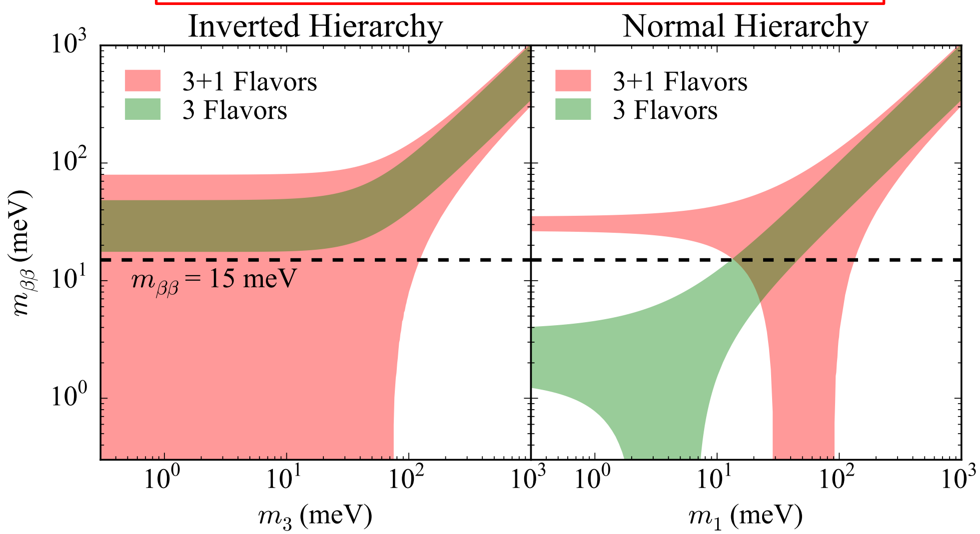
- Expected neutrino spectrum and thus sensitivity to CP violation for long base neutrino program.
- Effective Majorana mass measured by neutrinoless double-beta decay.

DUNE



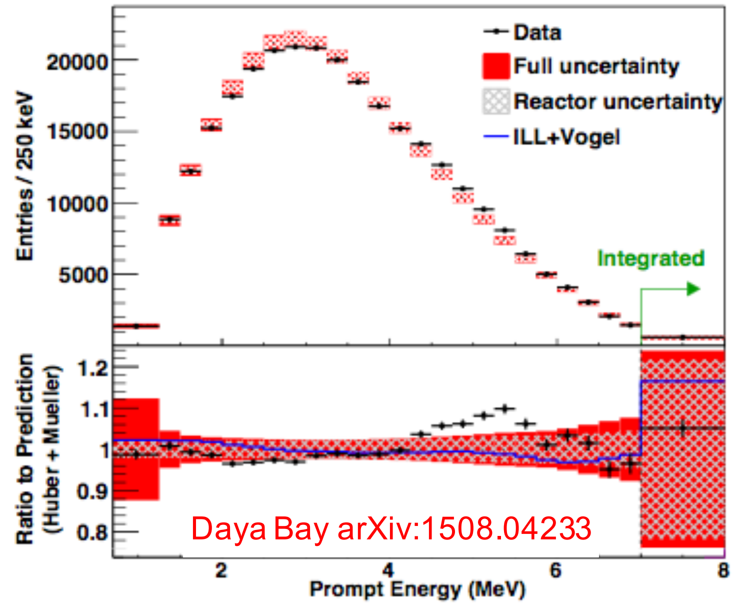
Gandhi, Kayser, Masud, Prakash
arXiv:1508.06275

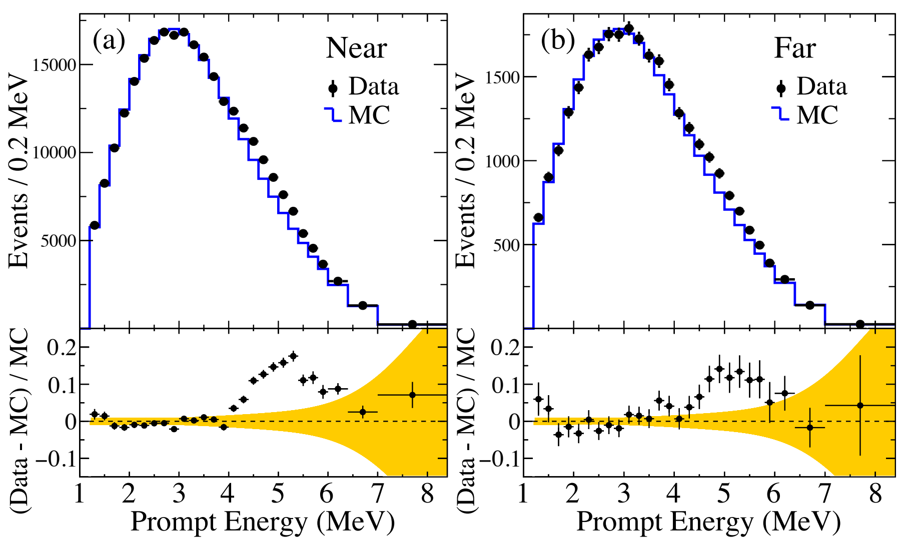
Neutrinoless Double beta-decay



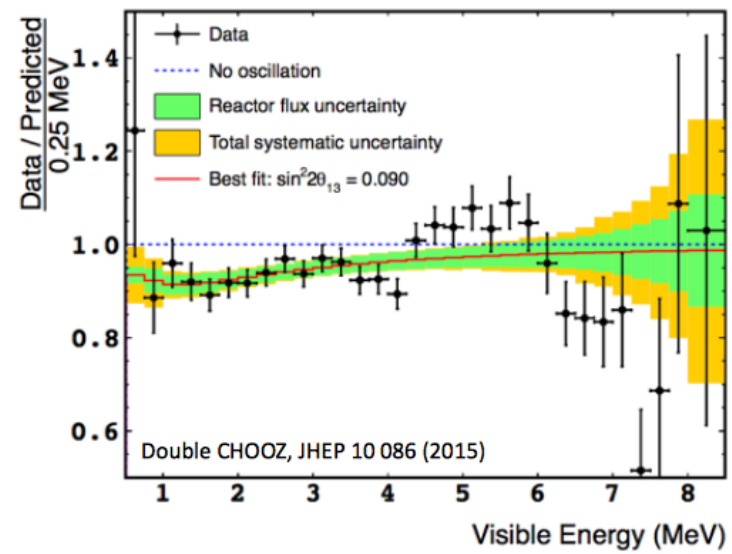
More from reactor neutrinos: spectrum anomaly

- The spectral bump
  - ~10% excess in the 4-6 MeV region when compared to model calculations
- Observed in all three θ_{13} experiments
  - RENO shows the largest bump.





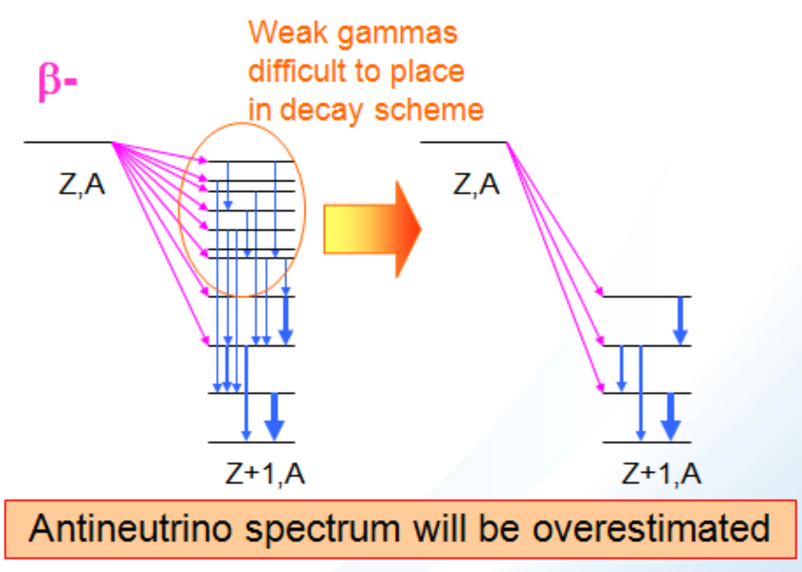
RENO: arXiv: 1511.05849

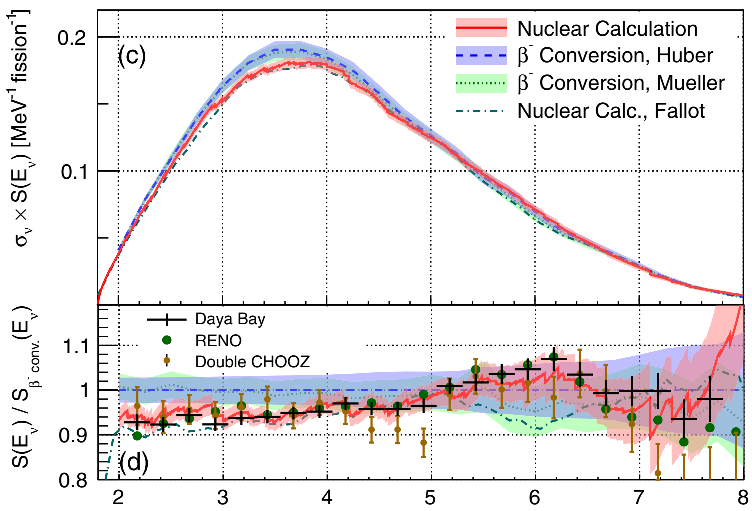


Difficulties in spectrum modeling

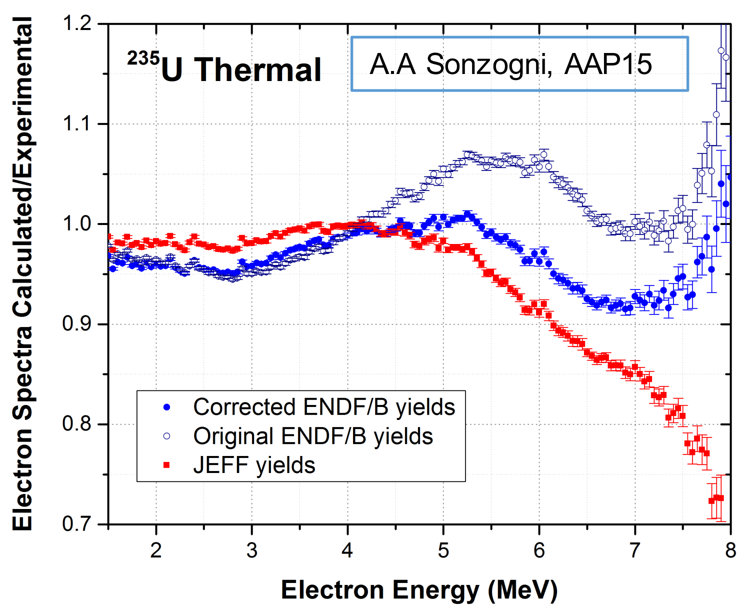
Reactor neutrino spectrum is an admixture of thousands beta branches from fission products of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu

- Conversion method: Cumulative neutrino spectrum from measured beta spectrum
- Summation method: Combine fission yields with decay data in databases
  - Discrepancy between databases
  - Decay schemes



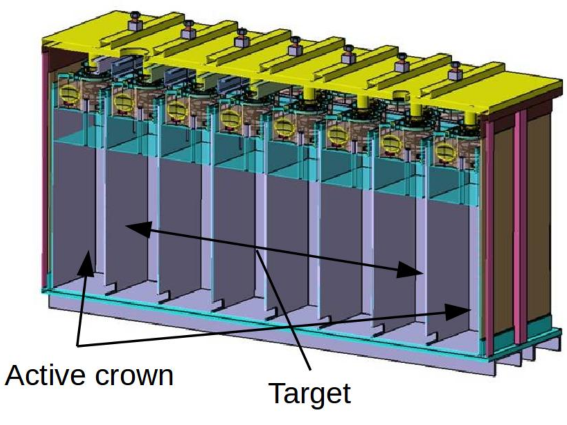


Dwyer, Langford, PRL ***114*** *012502 (2015)*

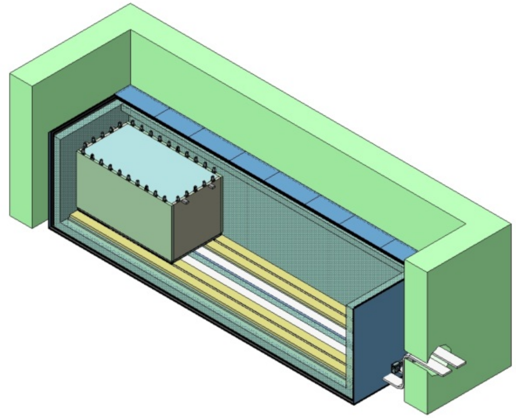


Very short baseline reactor neutrino programs world-wide

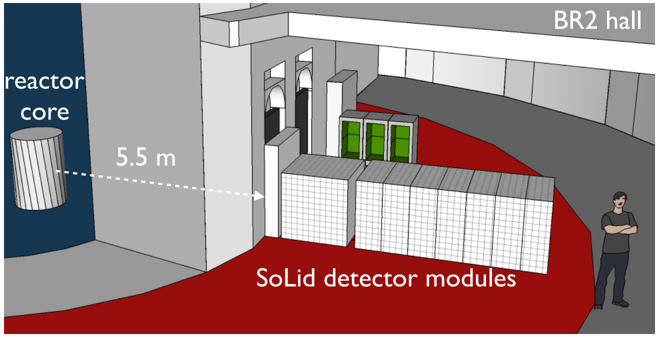
STEREO: Gd-LS detector at 10m from ILL , France



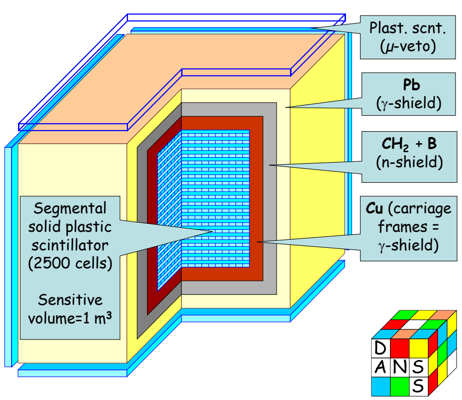
Neutrino-4: Gd-LS detector at 6-12m from SM-3, Russia



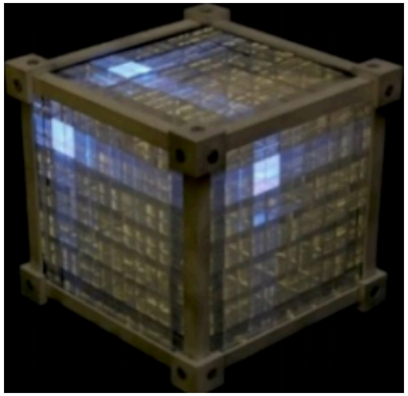
SoLid/CHANDLER: segmented composite scintillator cubes at 5.5 m from BR2, Belgium



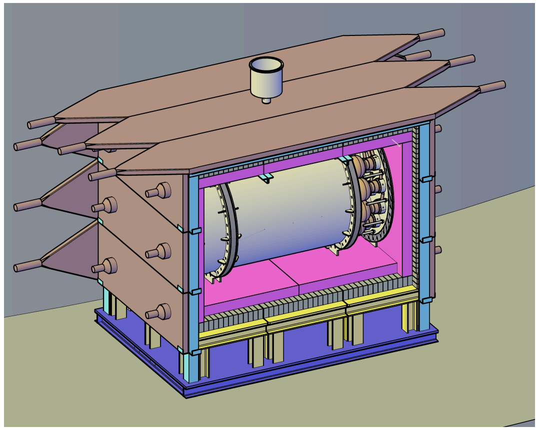
DANSS: Segmented plastic scintillator at ~10m from KNPP, Russia



NuLAT: Boron-loaded plastic scintillator cubes



NEOS: Gd-LS detector at ~30m from Hanbit, Korea

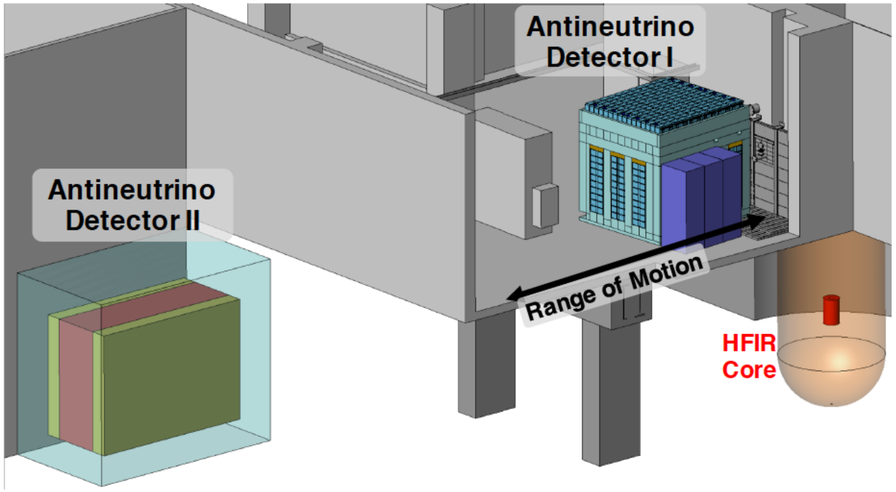


PROSPECT Experiment

Physics Objectives

1. Search for short-baseline oscillation at distances <10m
2. Precision measurement of ^{235}U reactor $\bar{\nu}_e$ spectrum

One Experiment, 2 Detectors



whitepaper, arXiv:1309.7647
PROSPECT collaboration

physics program, arXiv:1512.02202
PROSPECT collaboration

Phase I
one movable detector AD-I,
~7-12 m baseline

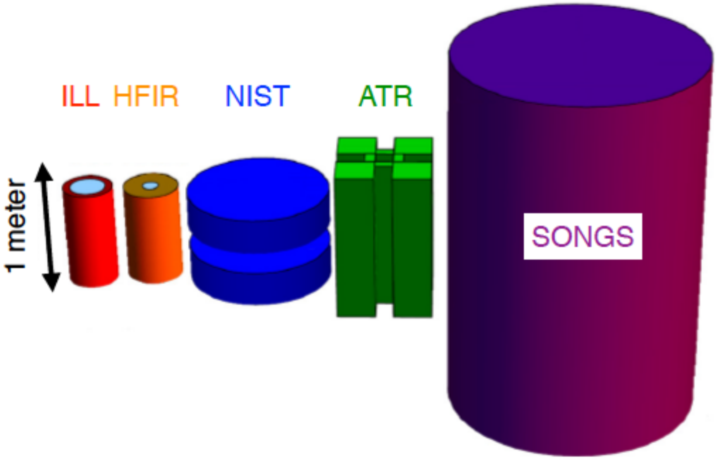
Phase II
two detectors,
movable AD-I, ~7-12m baseline
stationary AD-II, ~15-19m baseline

- movable detector enables systematic control, background checks, and increased physics reach

- phased approach mitigates risks

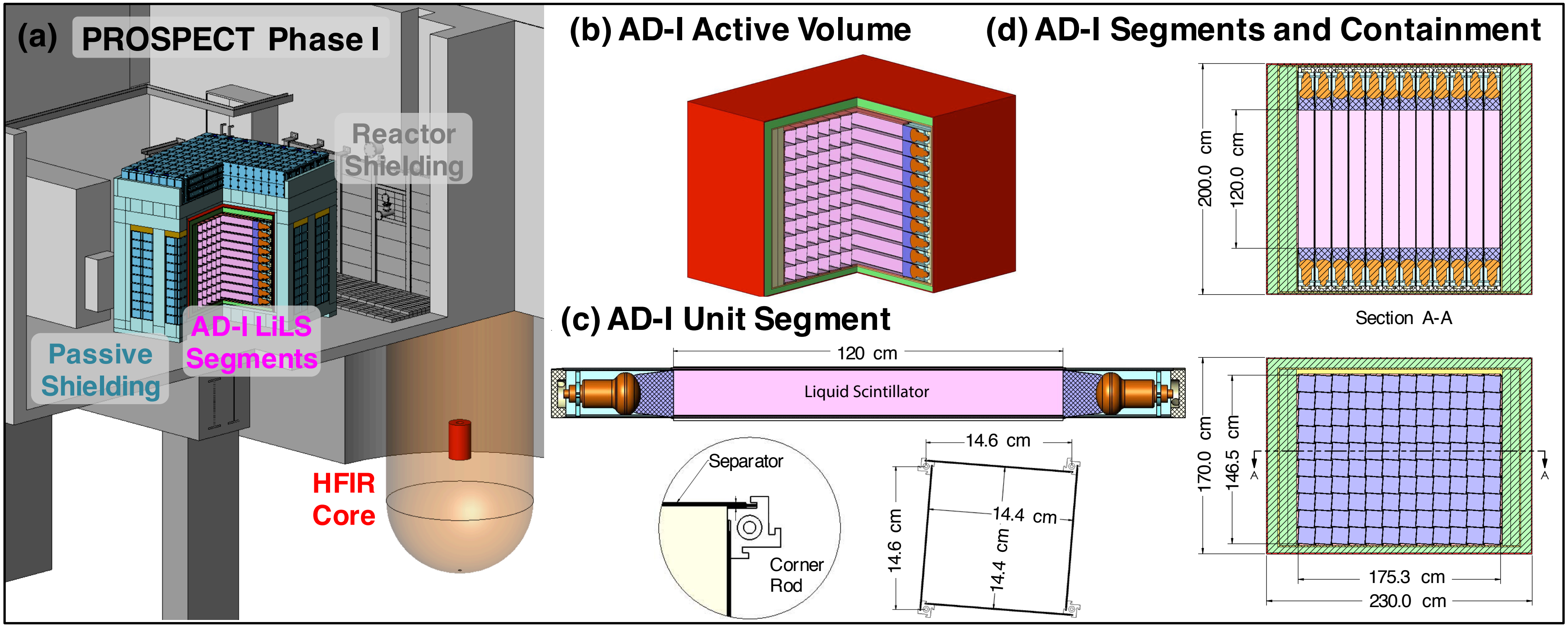
High Flux Isotope Reactor (HFIR) at ORNL

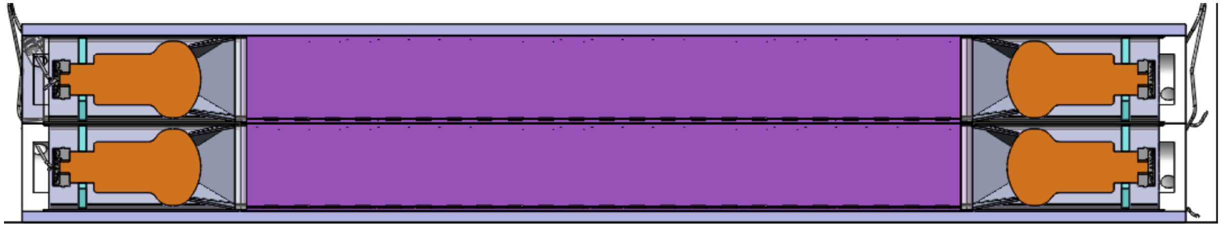
- HEU reactor provides static spectrum of mainly ^{235}U.
- Compact core avoids oscillation washout
- Frequent outages for background measurement
- Multiple accessible baselines
- Detailed core models

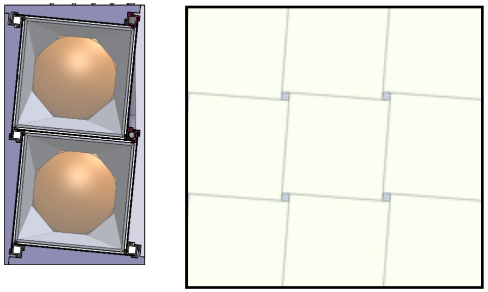


Site	Power	Duty Cycle	Near Baseline	Average Near Flux	Far Baseline	Average Far Flux
NIST	20 MW_{th}	68%	5.3m	1	17.0m	1
HFIR	85 MW_{th}	41%	7.9m	1.1	17.9m	2.3
ATR	110 MW_{th}	68%	10.1m	1.5	18.8m	4.5

PROSPECT Phase I detector



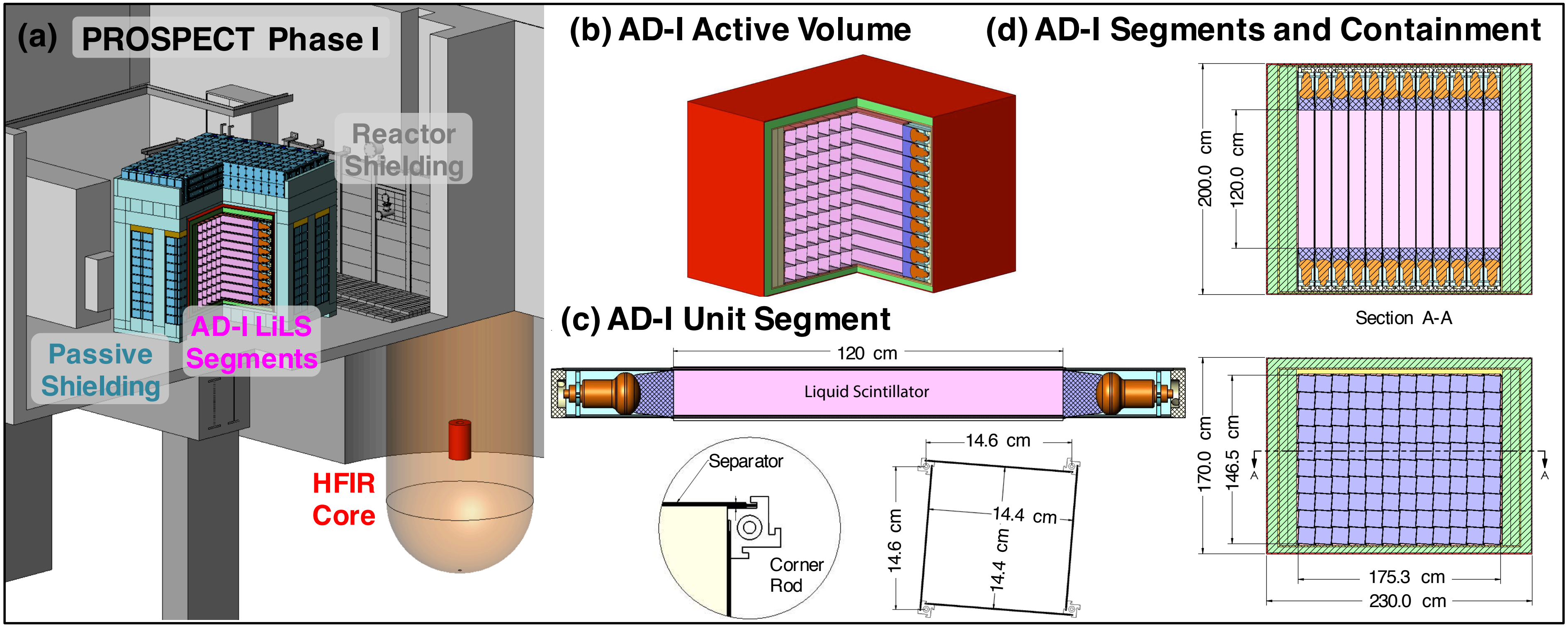




Antineutrino Detector Segments

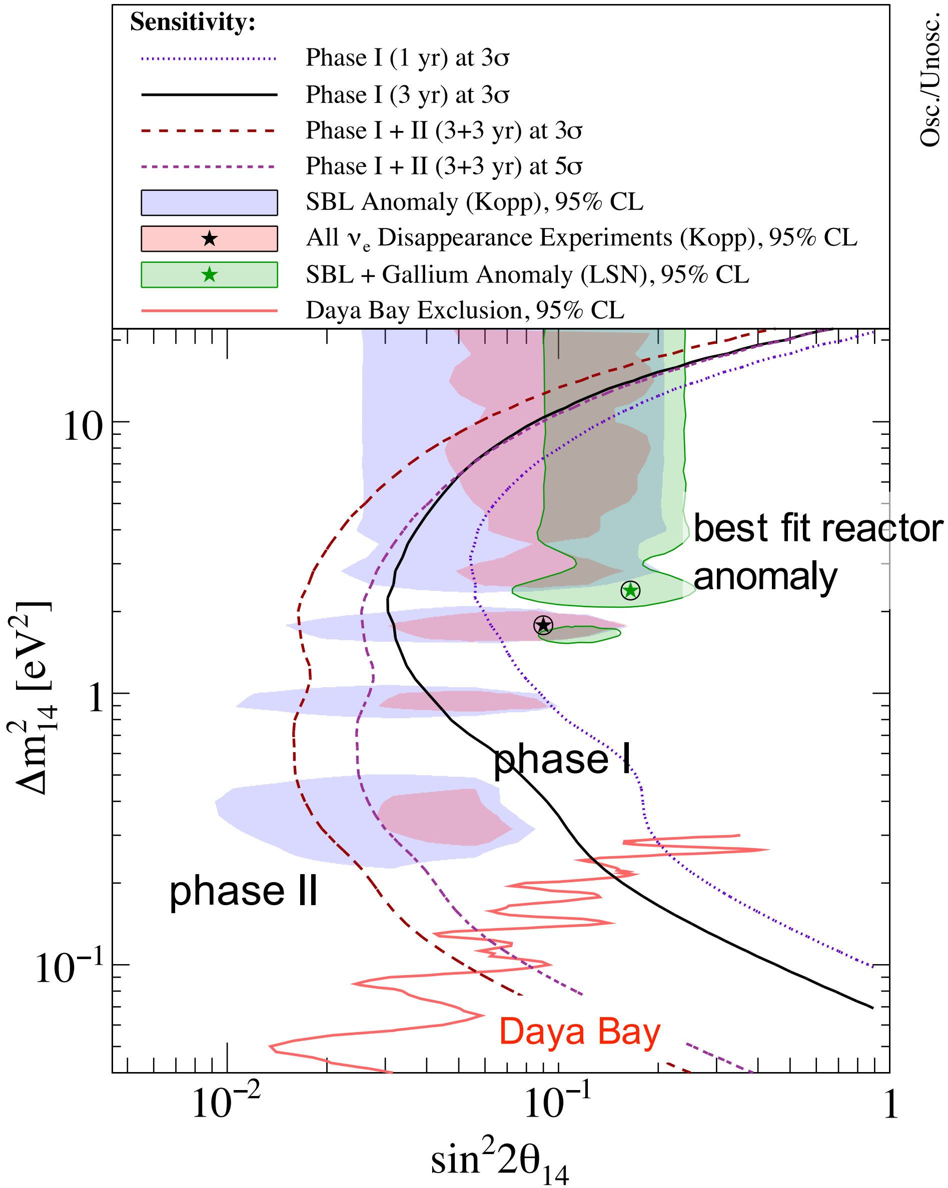
PMT + Light Guide + Optical Separator + ^{6}LiLS

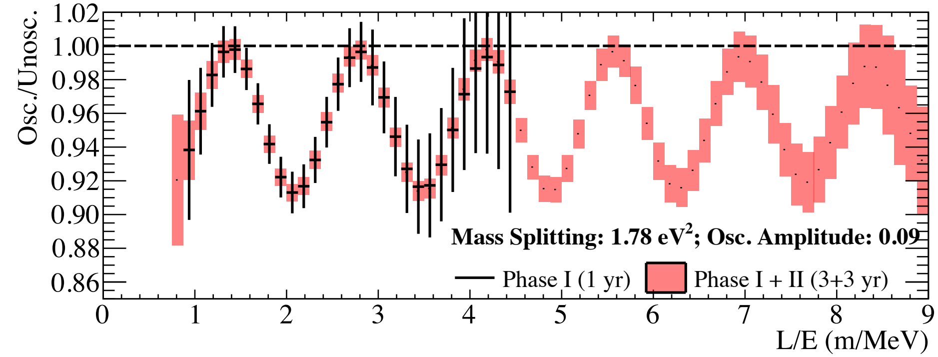
PROSPECT Phase I detector



- 3000L of ^{6}Li liquid scintillator
- 120 scintillator loaded segments, ~15x15x120cm
- Double ended PMT readout, light guides, 4.5%/√E resolutions
- Thin optical separators, minimal dead material
- Containment vessel, filled in place

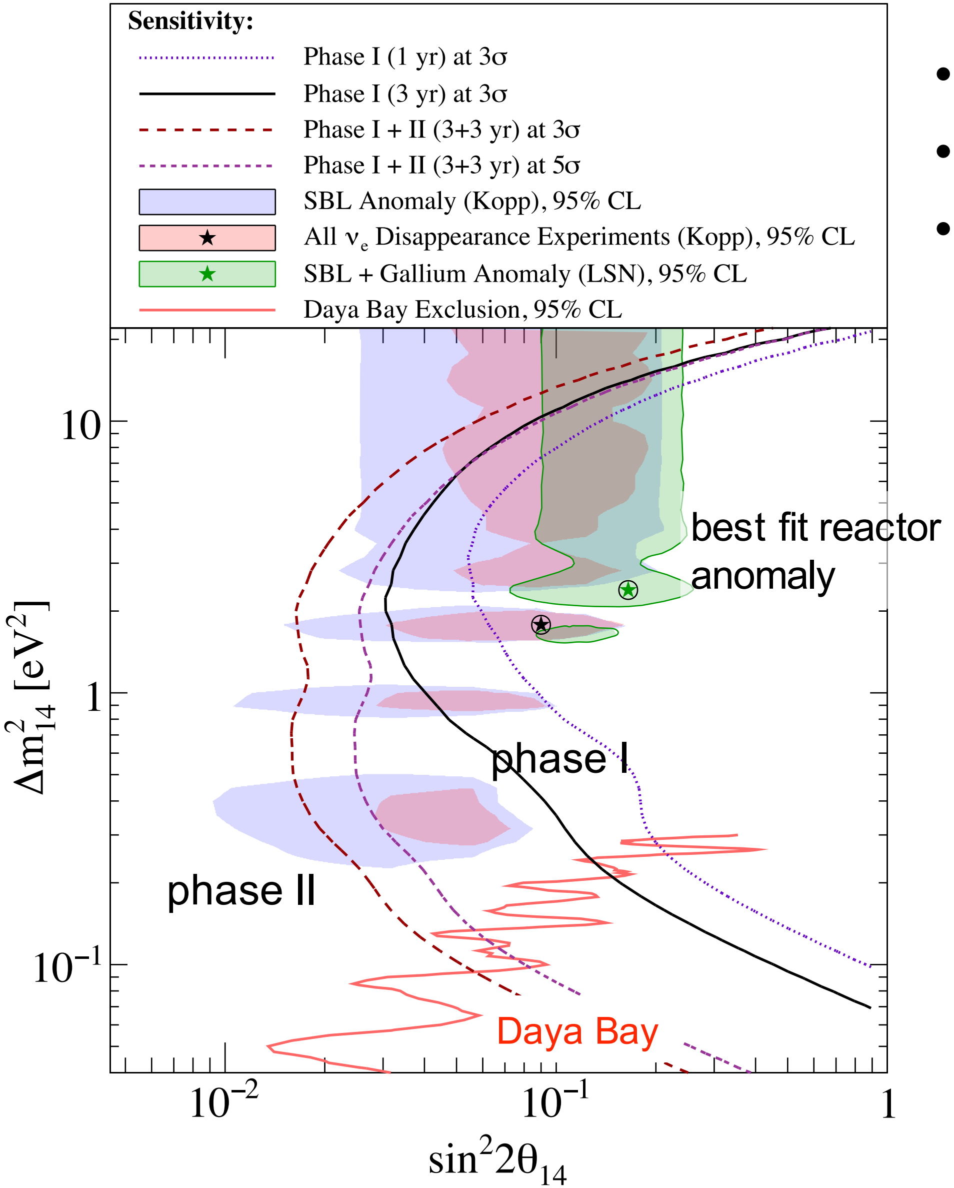
Sensitivity reach





Antineutrino Detector 1 (AD-I)	
Cross-section	1.2×1.45 m^2
Proton density	5.5×10^{28} p/m^3
Total Target Mass	2940 kg
Fiducialized Target Mass	1480 kg
Baseline range	4.4 m
Efficiency in Fiducial Volume	42%
Position resolution	15 cm
Energy resolution	$4.5\%/\sqrt{E}$
S:B Ratio	3.1, 2.6, 1.8
Closest distance	6.9 m, 8.1 m, 9.4 m
Antineutrino Detector 2 (AD-II)	
Total Target Mass	∼10 ton
Fiducialized Target Mass	∼70%
Baseline range	∼4 m
Efficiency in Fiducial Volume	42%
Position resolution	15 cm
Energy resolution	$4.5\%/\sqrt{E}$
S:B ratio	3.0
Closest distance	15 m
Operational Exposure	
Phase I	1, 3 years
Phase II	3 years

Sensitivity reach



- 4σ test of best fit after 1 year
- >3σ test of favored region after 3 yr
- 5σ test of allowed region after 3+3 yr

Antineutrino Detector 1 (AD-I)	
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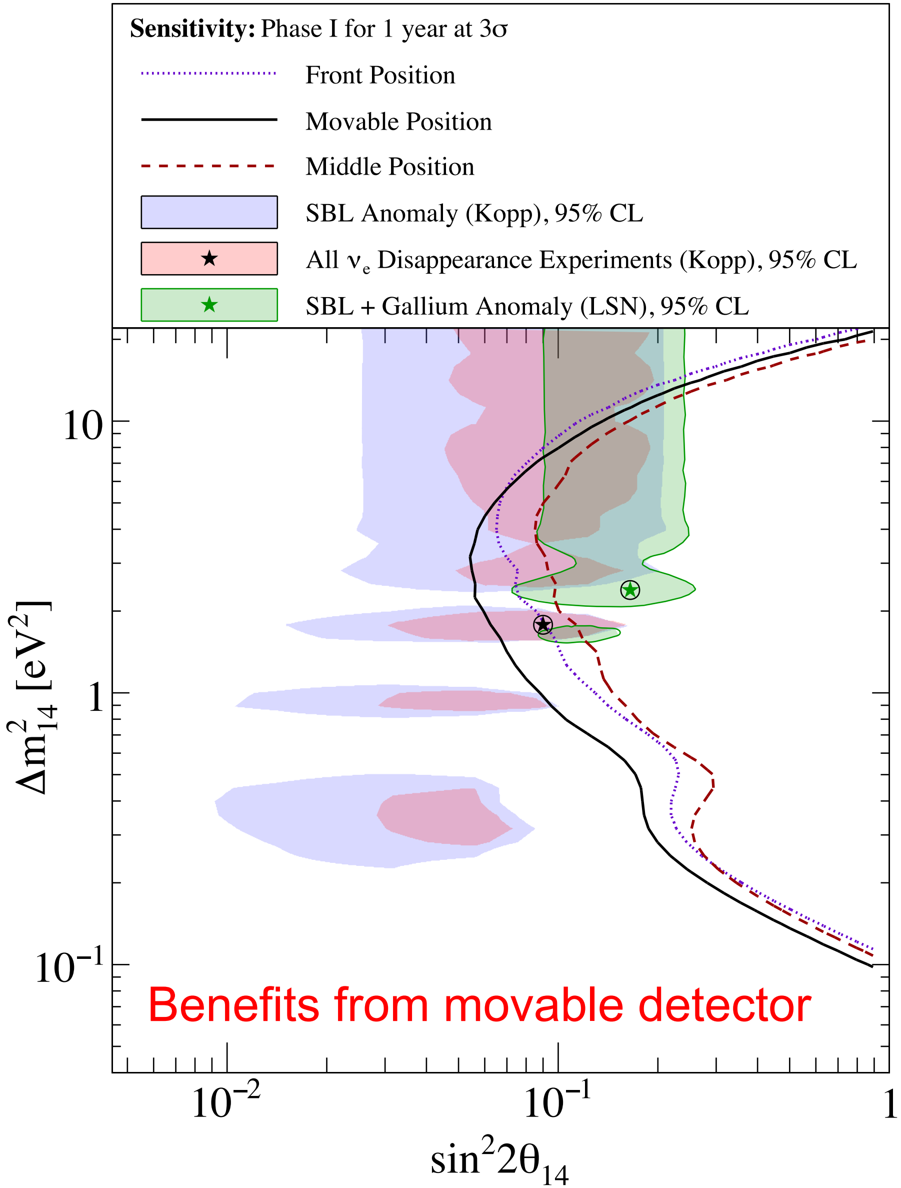
Position resolution	15 cm
Energy resolution	$4.5\%/\sqrt{E}$
S:B Ratio	3.1, 2.6, 1.8
Closest distance	6.9 m, 8.1 m, 9.4 m
Antineutrino Detector 2 (AD-II)	
Total Target Mass	~10 ton
Fiducialized Target Mass	~70%
Baseline range	~4 m
Efficiency in Fiducial Volume	42%
Position resolution	15 cm
Energy resolution	$4.5\%/\sqrt{E}$
S:B ratio	3.0
Closest distance	15 m
Operational Exposure	
Phase I	1, 3 years
Phase II	3 years

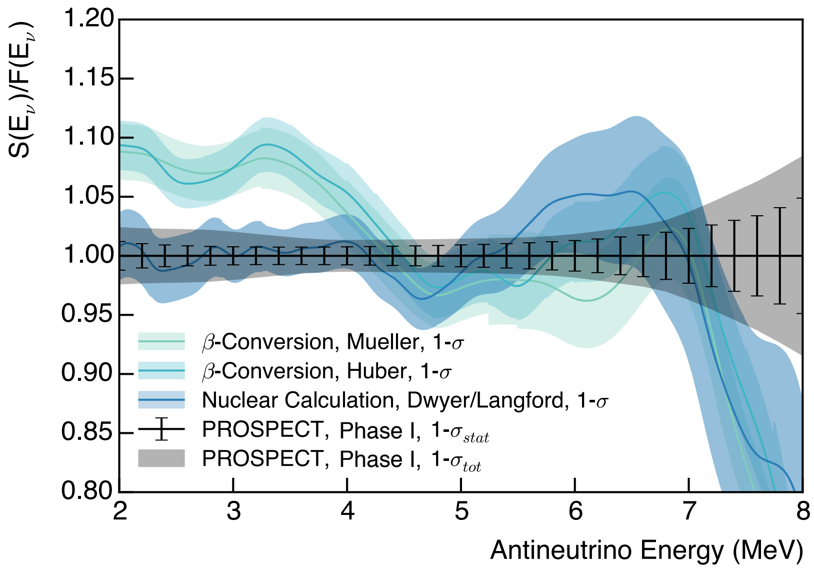
Sensitivity vs. detector parameters



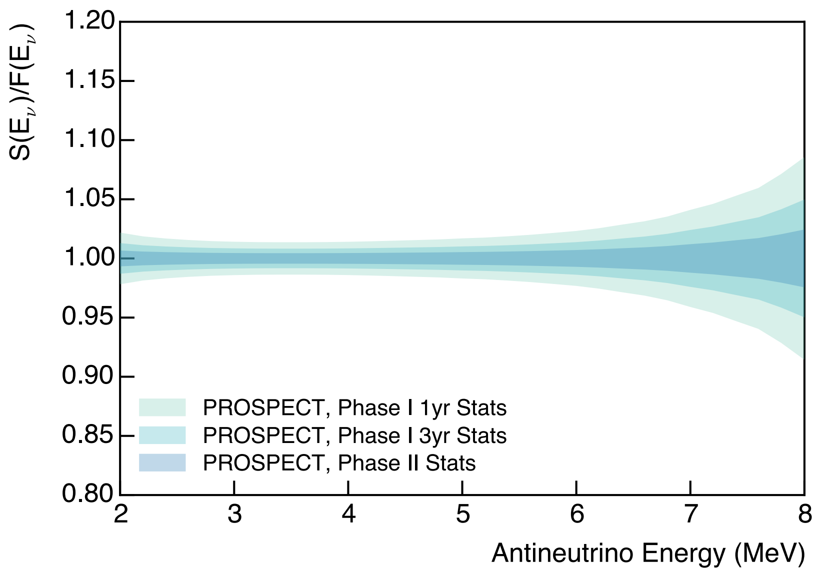
- Baseline coverage
- Detector mass
- Detection efficiency
- Background suppression

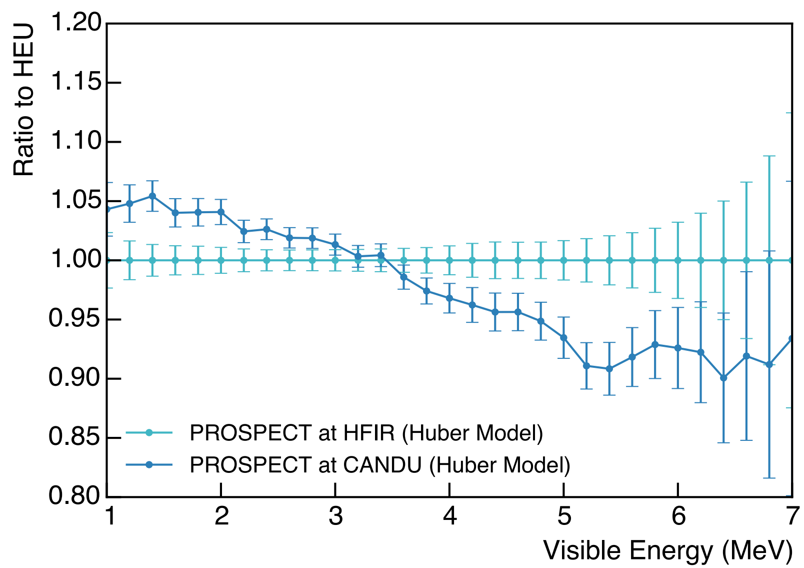
	Decreased	Nominal	Increased
Position	*Front only* 2.79	*Movable* 4.60	*Middle only* 2.37
Position Resolution	*10cm* 4.69	*14.6cm* 4.60	*20cm* 4.46
Efficiency	*32%* 3.84	*42%* 4.60	*52%* 5.26
Energy Resolution	*3%* 4.61	*4.5%* 4.60	*20%* 4.20
Background Suppression	$\times$*0.33* 3.92	– 4.60	$\times$*3* 5.00
Bin-to-Bin Uncertainty	*0.5%* 4.69	*1.0%* 4.60	*2.0%* 4.30
Relative Segment Normalization	*0.5%* 4.60	*1.0%* 4.60	*2.0%* 4.59
Detector Size	*10×8* 3.23	*12×10* 4.60	*14×12* 6.02

Testing models of the ^{235}U neutrino spectrum



- Directly test/constrain reactor antineutrino spectrum predictions
- Compare different reactor cores
- A better understanding of the reactor neutrino spectrum will aid precision medium-baseline reactor experiments





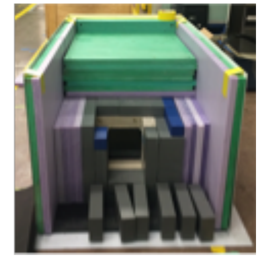
PROSPECT Detector and Shielding at HFIR Development

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

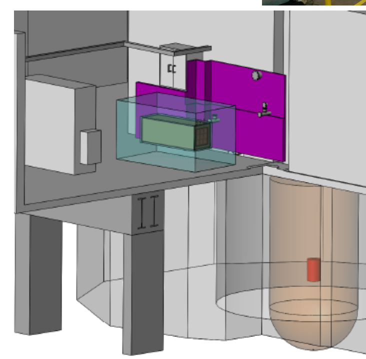
12.5 length
1.7 liters
^{6}LiLS



multi-layer shielding

PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

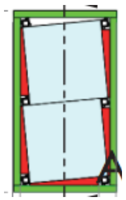
1m length
23 liters
LS, ^{6}LiLS



local reactor shielding

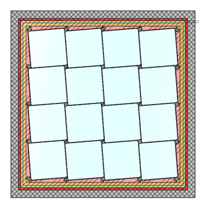
PROSPECT-50
Baseline design prototype
Winter 2015

1x2 segments
1.2m length
50 liters
^{6}LiLS



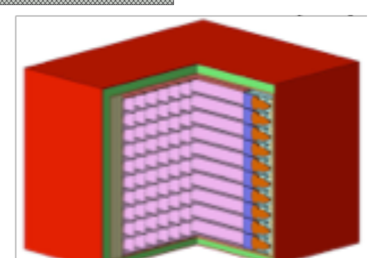
PROSPECT-400*
Fiducialization and background studies
Mid 2016

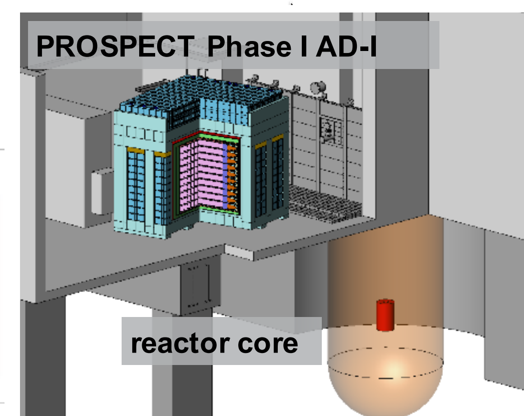
4x4 segments
1.2m length
400 liters
^{6}LiLS



PROSPECT AD-I
Physics measurement
Late 2016

10x12 segments
1.2m length
~3 tons
^{6}LiLS

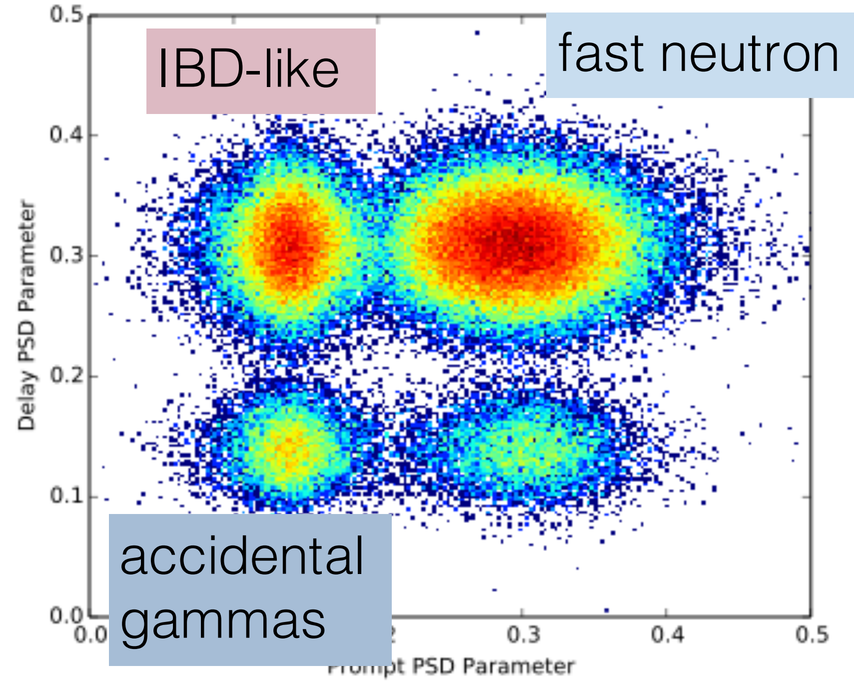


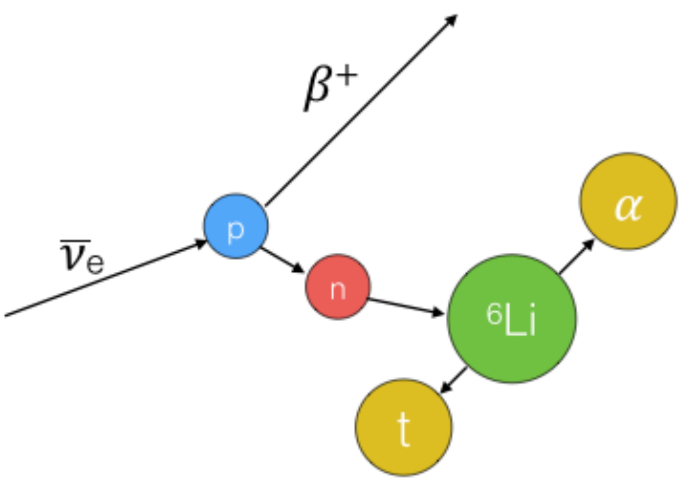


**Technically ready to proceed directly to near detector with available funding*

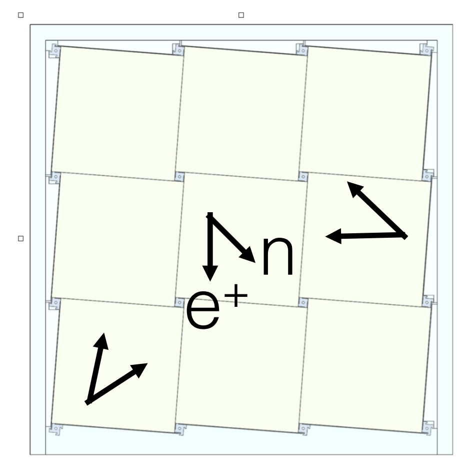
Li loaded liquid scintillator (LiLS) with pulse shape discrimination (PSD)

- Inverse beta decay (IBD) prompt signal followed by delayed neutron capture.
- Localized signal events in LiLS detector segments
- PSD strongly suppresses cosmogenic correlated and reactor-induced uncorrelated backgrounds





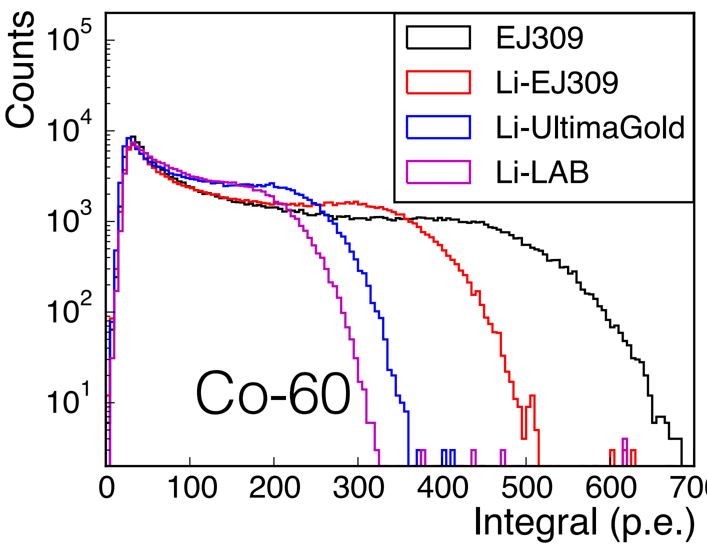
prompt signal: 1-10 MeV positron from inverse beta decay
delay signal: quenched 0.6 MeV signal from neutron capture on ^{6}Li; 40μs delayed

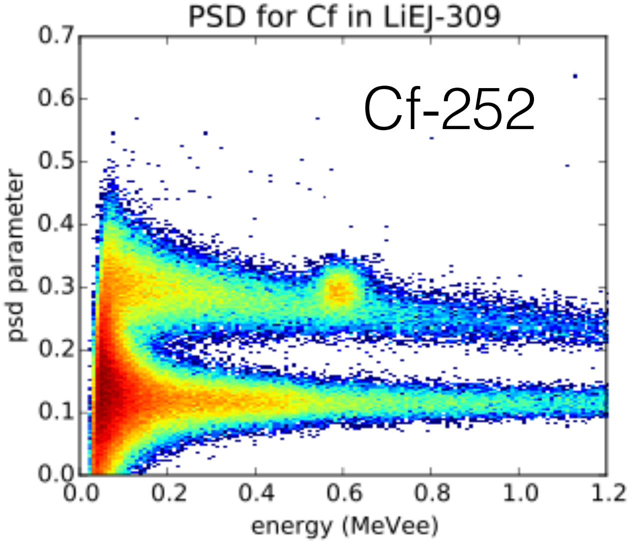


Li-EJ309 with excellent light yield and PSD

- EJ-309 light yield (LY) = 11500 ph/MeV
- Li loaded EJ-309 LY = 8200 ph/MeV (measured)
- Prominent neutron capture peak in LiLS
- PSD FOM at (n, Li) is 1.79

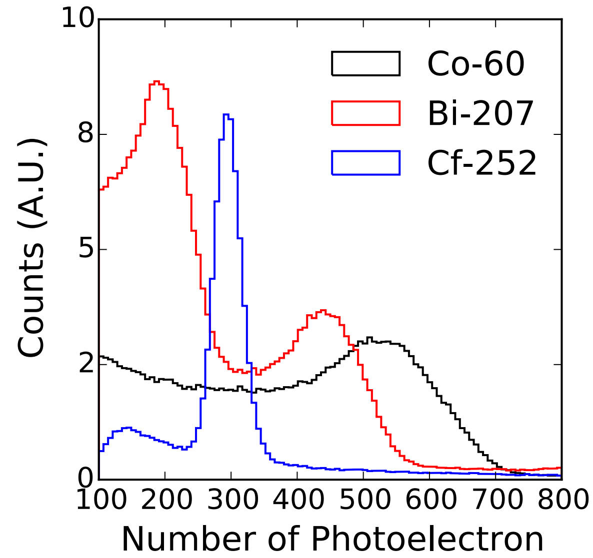
- EJ-309 is non-toxic, non-flammable
- Extensive studies with LAB, Ultima Gold

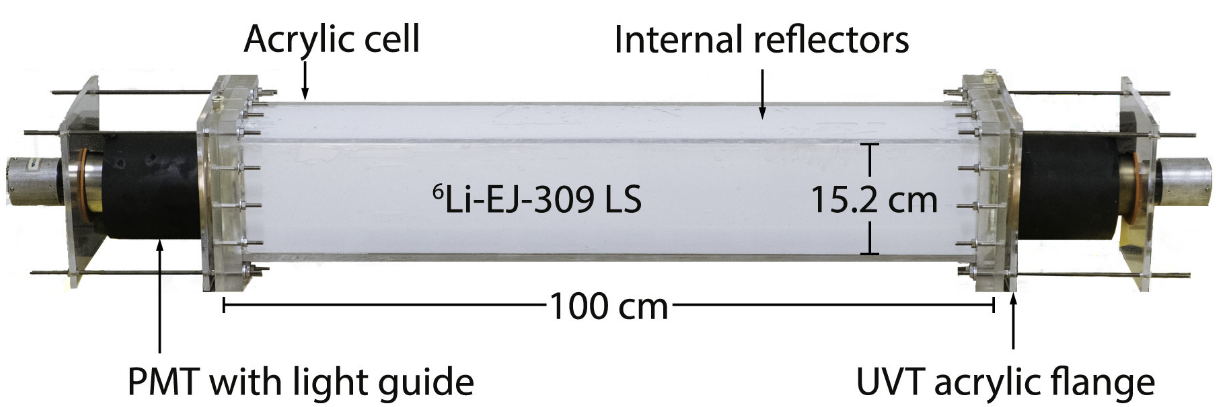


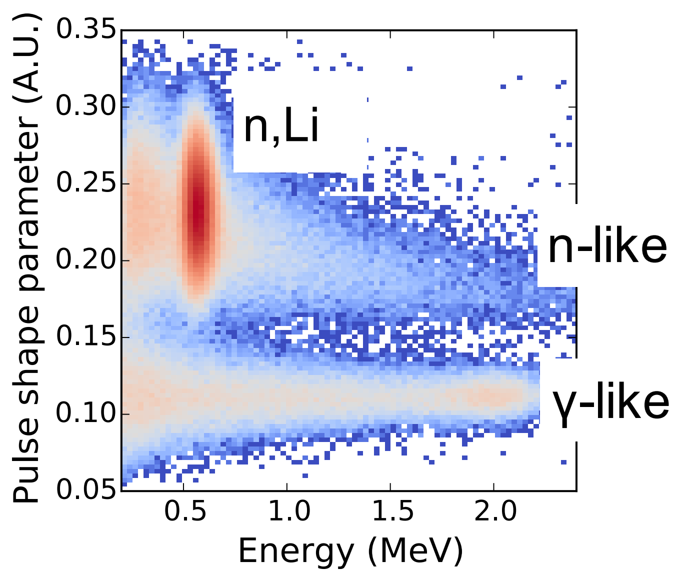


Light collection and PSD validated in full size segments

- PROSPECT-20 detector with unloaded EJ309 and LiLS
- Light collection 522±16 PE/MeV
  - Reach PROSPECT goal → 4.5%/√E
- PSD FOM = 1.4
  - Reject 99.9% of the background while keep 99.9% of the signal
- Unloaded LS studies described in JINST 10 P11004, arXiv:1508.06575
  - Optimized detector configuration
  - Reflector choice

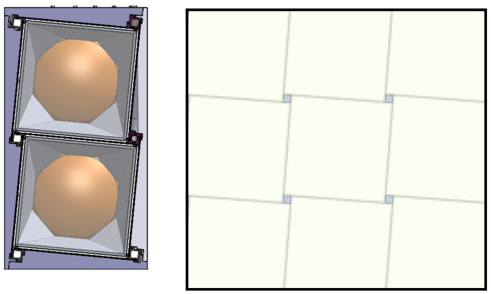




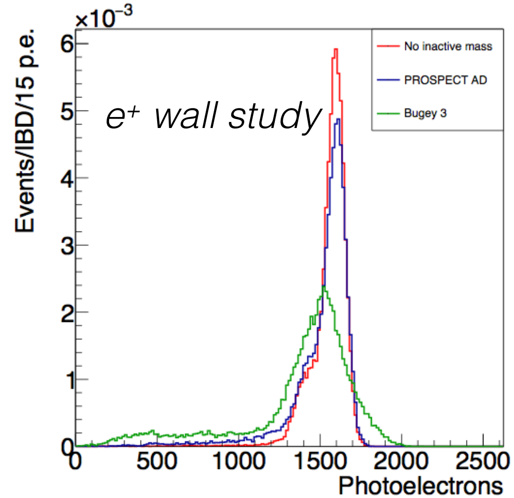


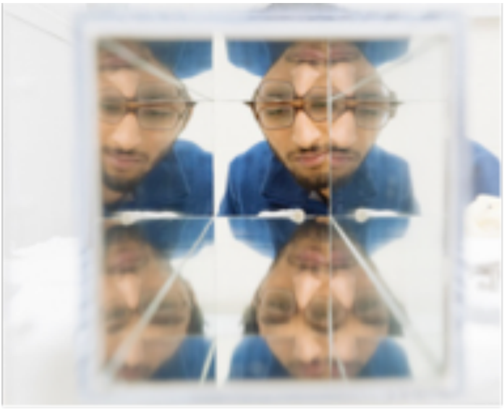
Antineutrino Detector Segmentation

Low-mass, optical separators

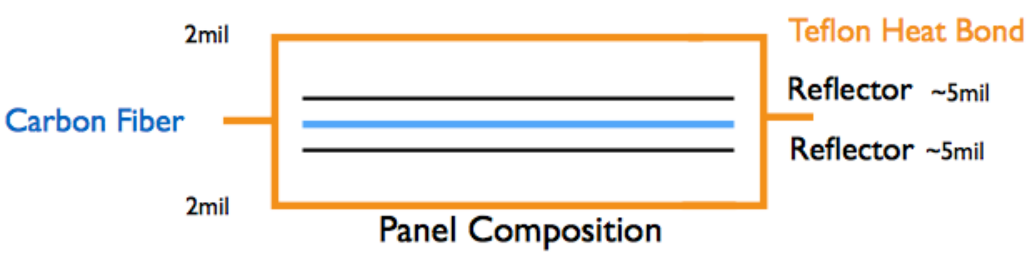


minimum dead material





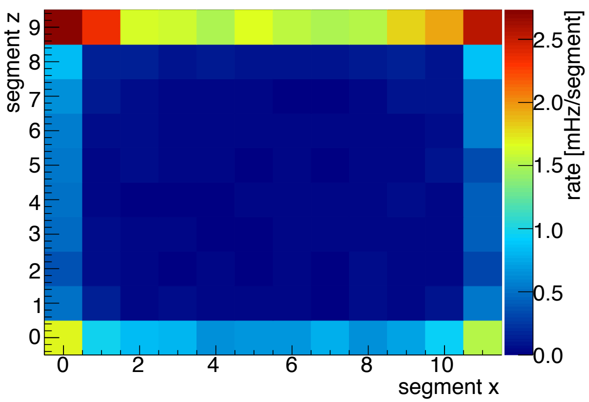
Low-mass reflector prototypes



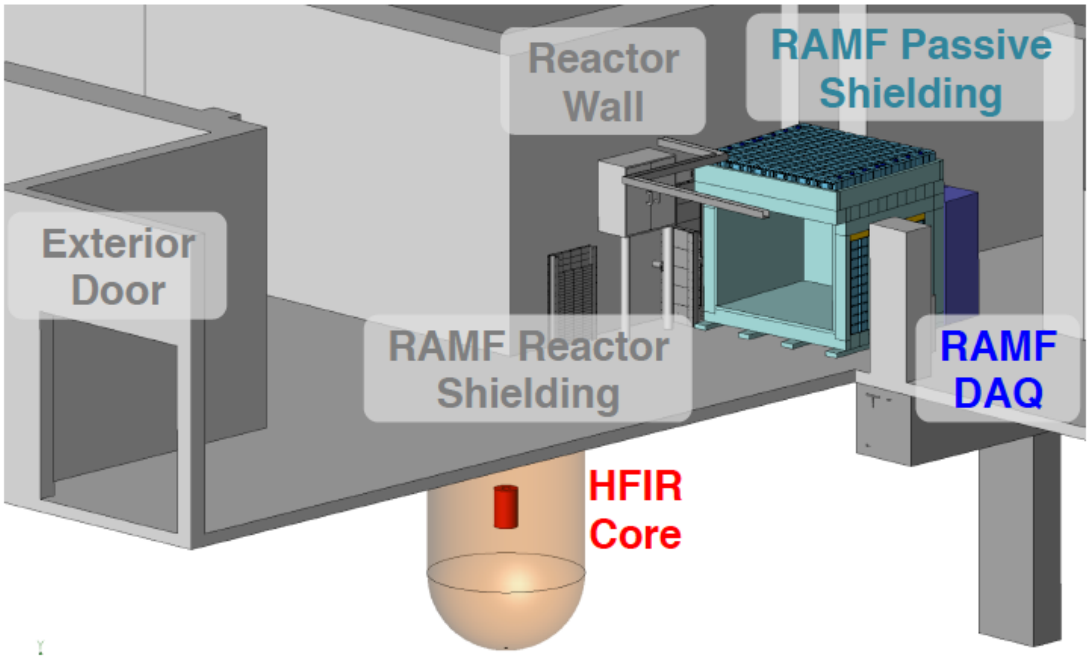
1mm thick

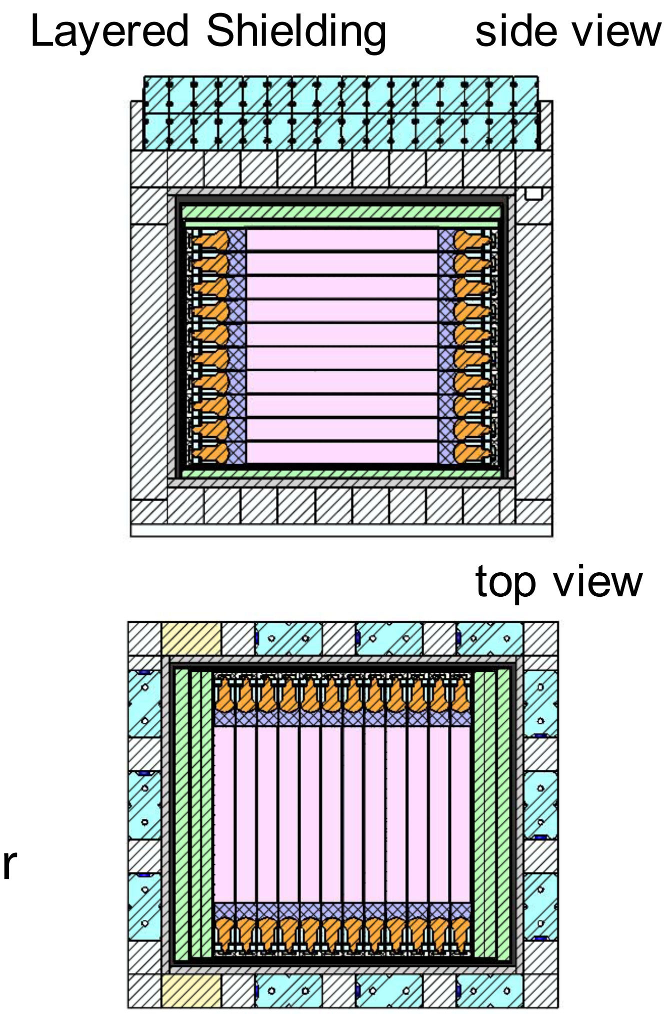
Fiducialization

Phase I AD-1, IBD-like neutron segment



Shielding: Reactor Antineutrino Measurement Facility (RAMF) at HFIR

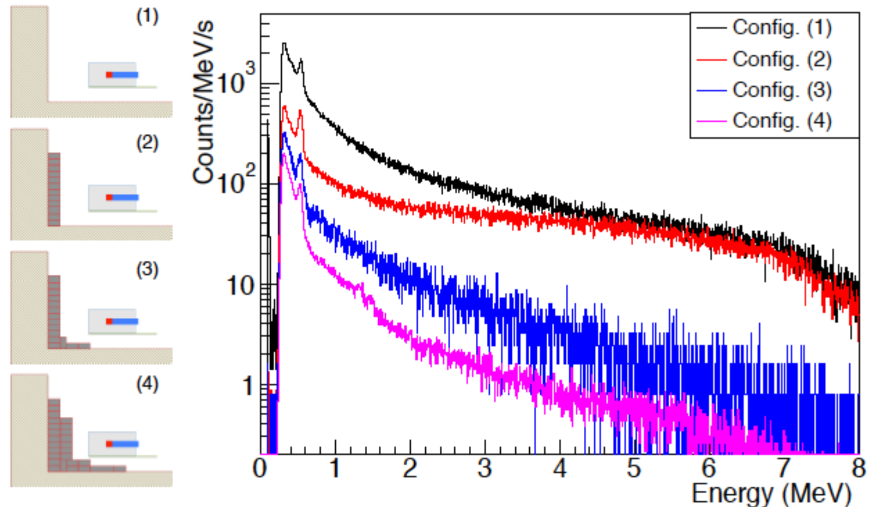


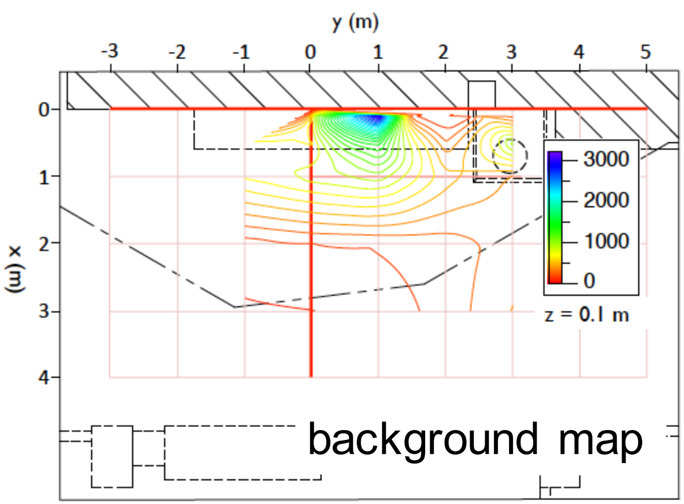


- local shielding next to reactor wall
- multi-layer passive shield around detector (water bricks, HDPE, borated HDPE, lead)
- general purpose digitizing electronics and DAQ

PROSPECT Backgrounds at HFIR

varying reactor shields

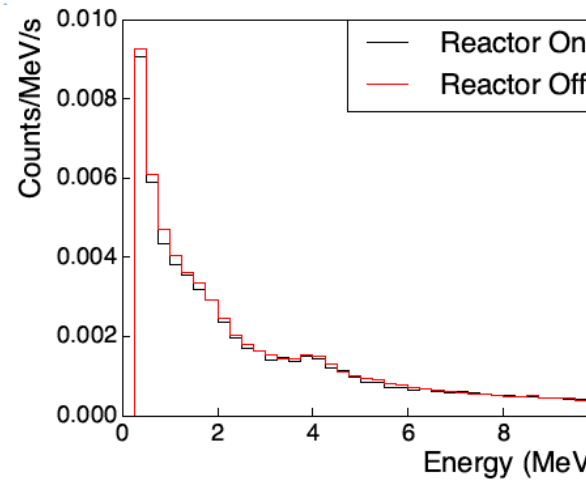




IBD-like events for reactor-on and off

reactor generated backgrounds are minimal

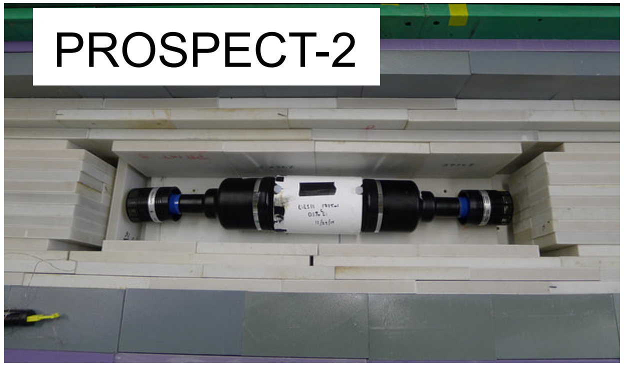
IBD-like backgrounds are cosmogenic

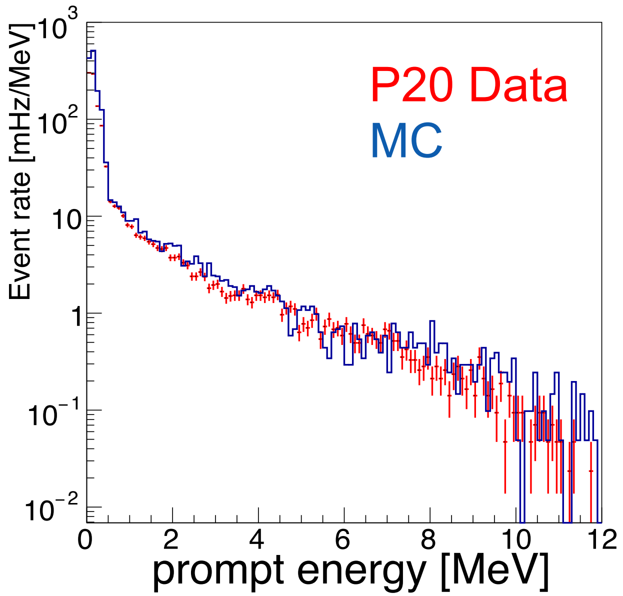


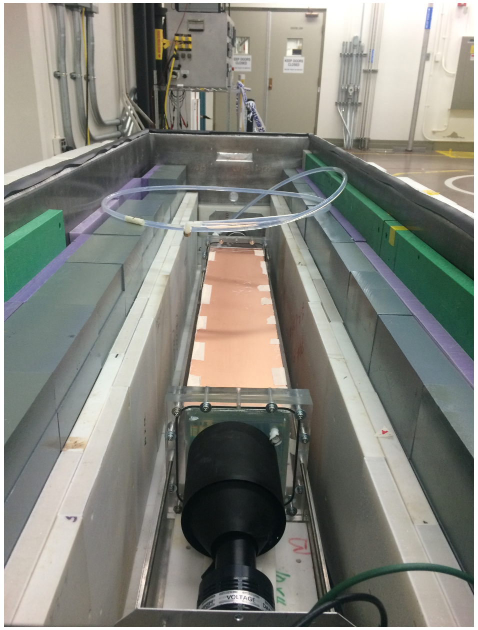
Nucl. Instrum. Meth. A806 (2016) 401–419, arXiv:1506.03547, PROSPECT collaboration

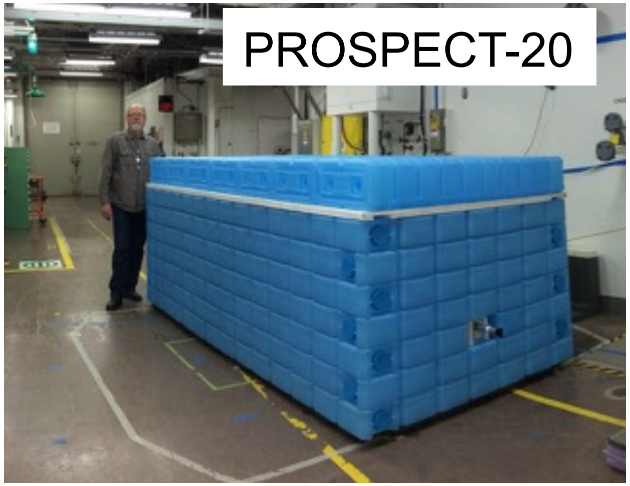
Prototypes onsite

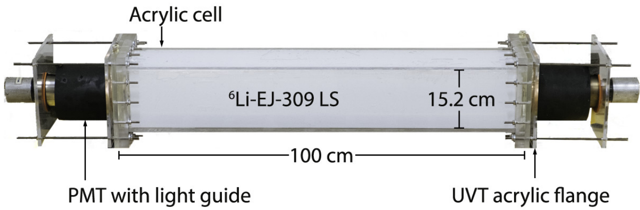
- PROSPECT-20 measured cosmic backgrounds during reactor-off
- Monte Carlo agrees reasonably with data
- Confident in extrapolating MC to Phase I detector
- Will measure these backgrounds during reactor-off time in Phase I









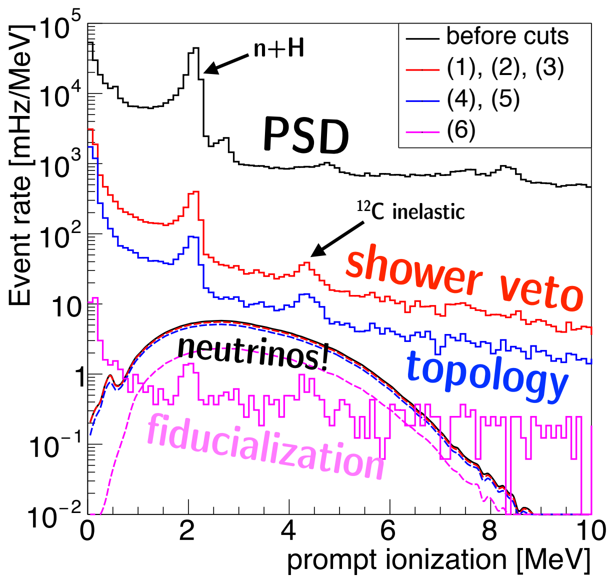


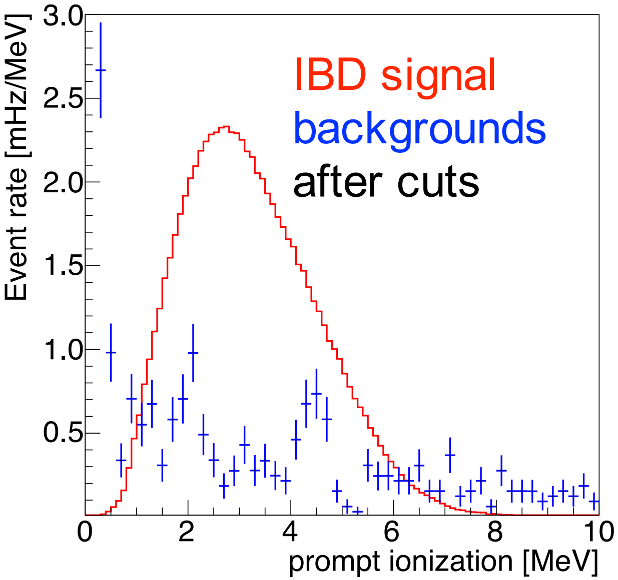
PROSPECT Signal & Background

- Signal (dashed) and background (solid) prompt spectra are shown through selection cuts
- S/B better than 1:1 is predicted.
- Rate and shape of the residual IBD-like background can be measured with high precision during reactor off periods.

Cuts	IBD signal		Cosmic BG	
Exposure	*Daily*	*Phase I*	*Daily*	*Phase I*
PSD	1630	7.3e5	2.1e6	9.5e8
Time (1, 2, 3)	1570	7.1e5	3.4e4	1.5e7
Spatial (4, 5)	1440	6.5e5	9900	4.5e6
Fiducial (6)	660	3.0e5	250	1.1e5

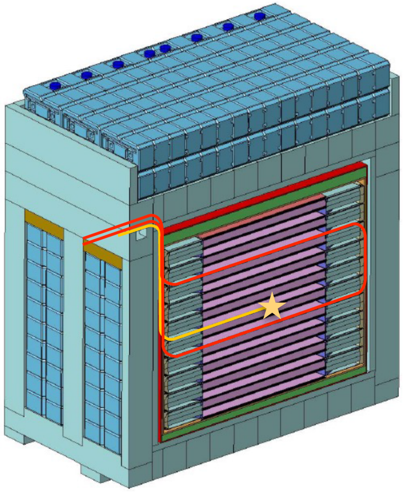
Simulated event rates (0.8 ≤ E ≤ 7.2 MeV) after applying background rejection cuts



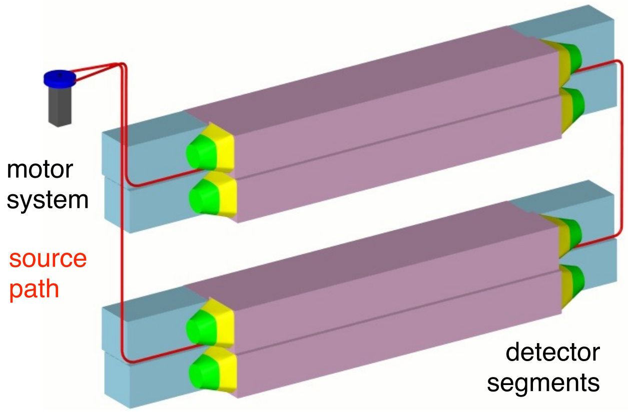


Optical and source calibration

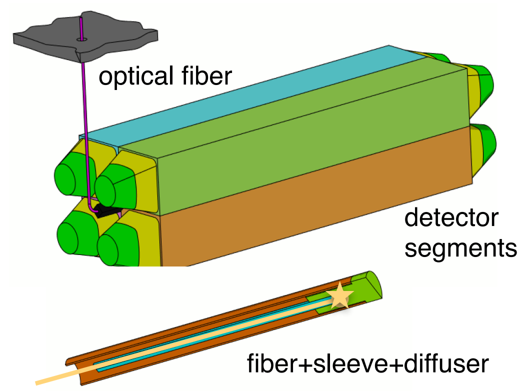
antineutrino detector
with optical and source calibration



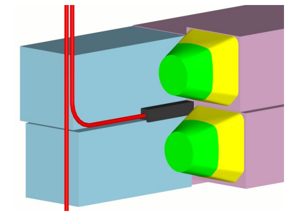
source deployment system
with string and guide tubes



optical calibration system
with string and guide tubes



routing between segments
and PMT modules



pulsed laser sources
- LiLS light transmission
- PMT gain and timing

encapsulated γ sources
- energy scale
- scintillator non-linearity

neutron sources
- PSD calibration
- neutron detection efficiency

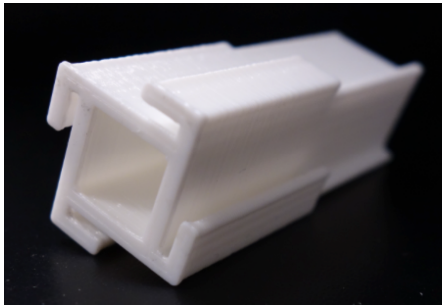
radioactive and cosmogenic backgrounds will be used to monitor and calibrate detector response between source deployments

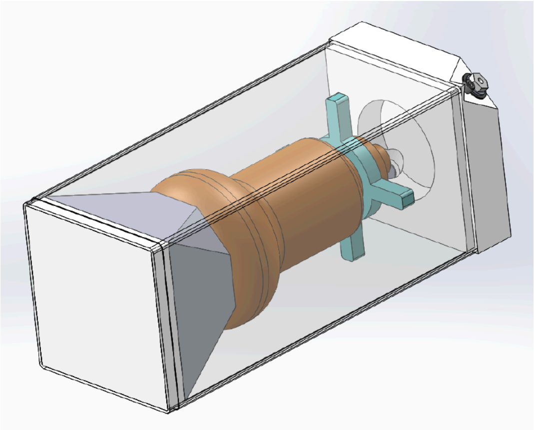
Example: PROSPECT-20
- through going muons
- ^{40}K
- n capture on ^{6}Li

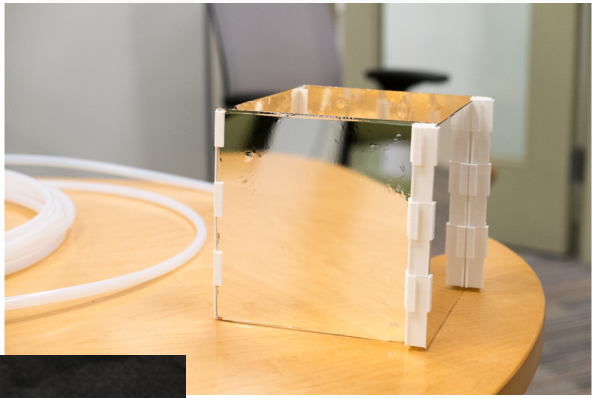
R&D on scintillator spiking with ^{227}Ac
- segment uniformity, relative LiLS mass measurements

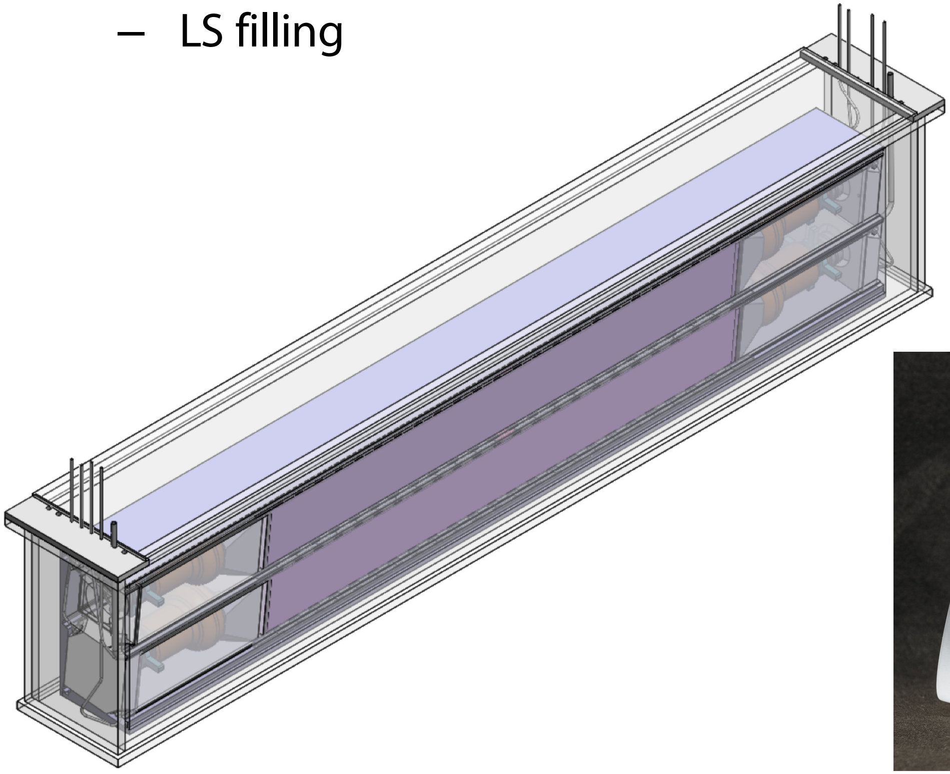
Ongoing: PROSPECT-50

- Mechanical prototype to validate detector components and test operation of subsystems.
  - PMT housing with light guide
  - Reflectors
  - Calibration
  - LS filling



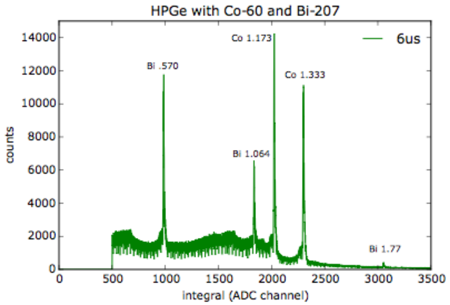


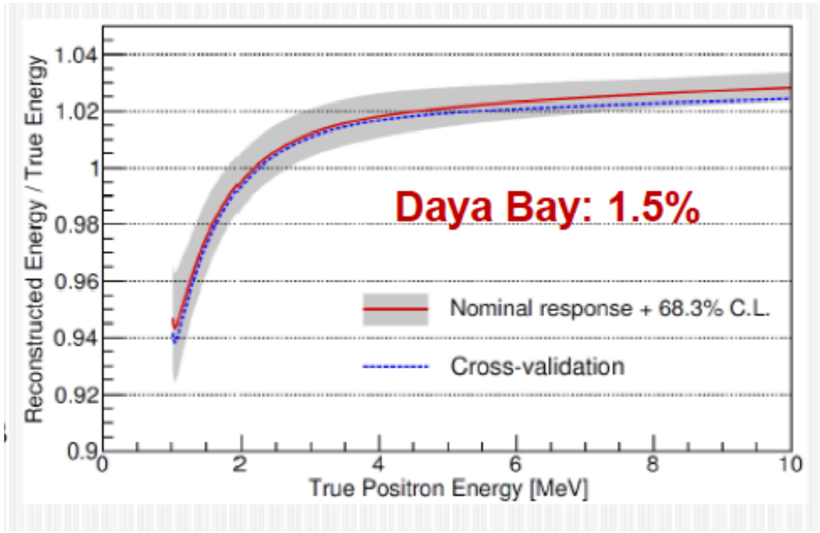




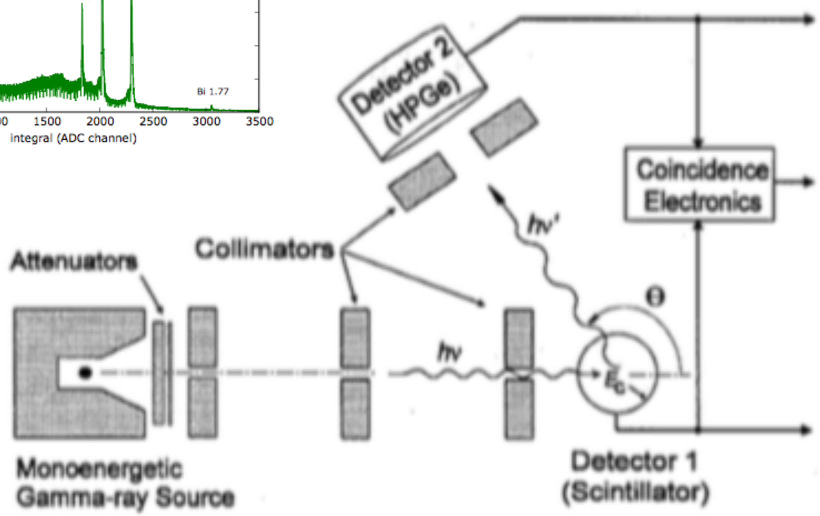
Ongoing: detector nonlinearity with a Compton spectrometer

- Study non-linearities at low energies using mono-energetic electrons with Compton coincidence spectrometer.
  - Liquid scintillator
  - Detector (end-to-end)
- HPGe detector commissioning and simulation underway





From J. Cao, TAUP 2015



PROSPECT Collaboration

Collaboration photo onsite at
High Flux Isotope Reactor, Oak Ridge National Laboratory, Summer 2015

Brookhaven National Laboratory
Drexel University
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
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University

~ 60 collaborators
13 institutions
3 national laboratories

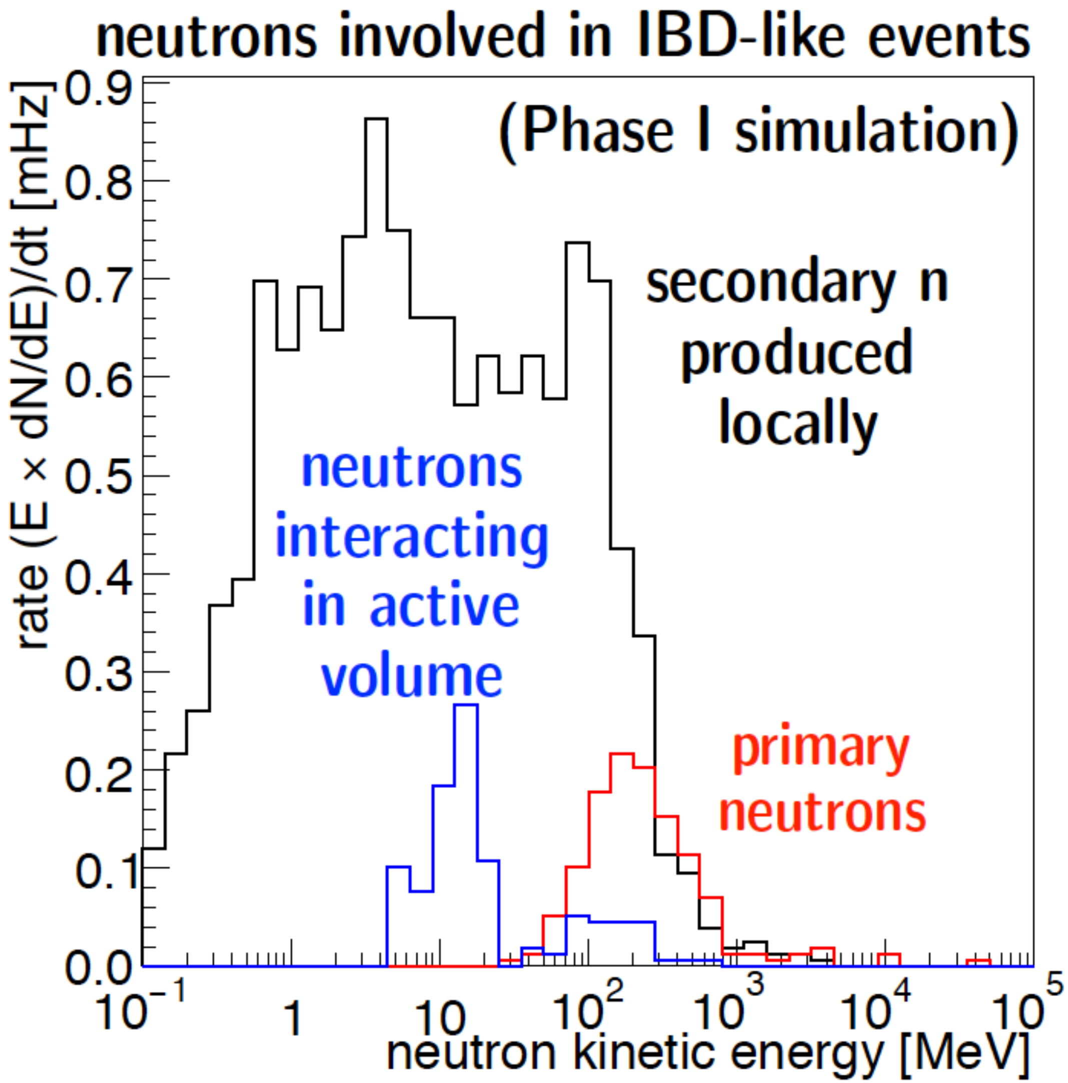
Summary

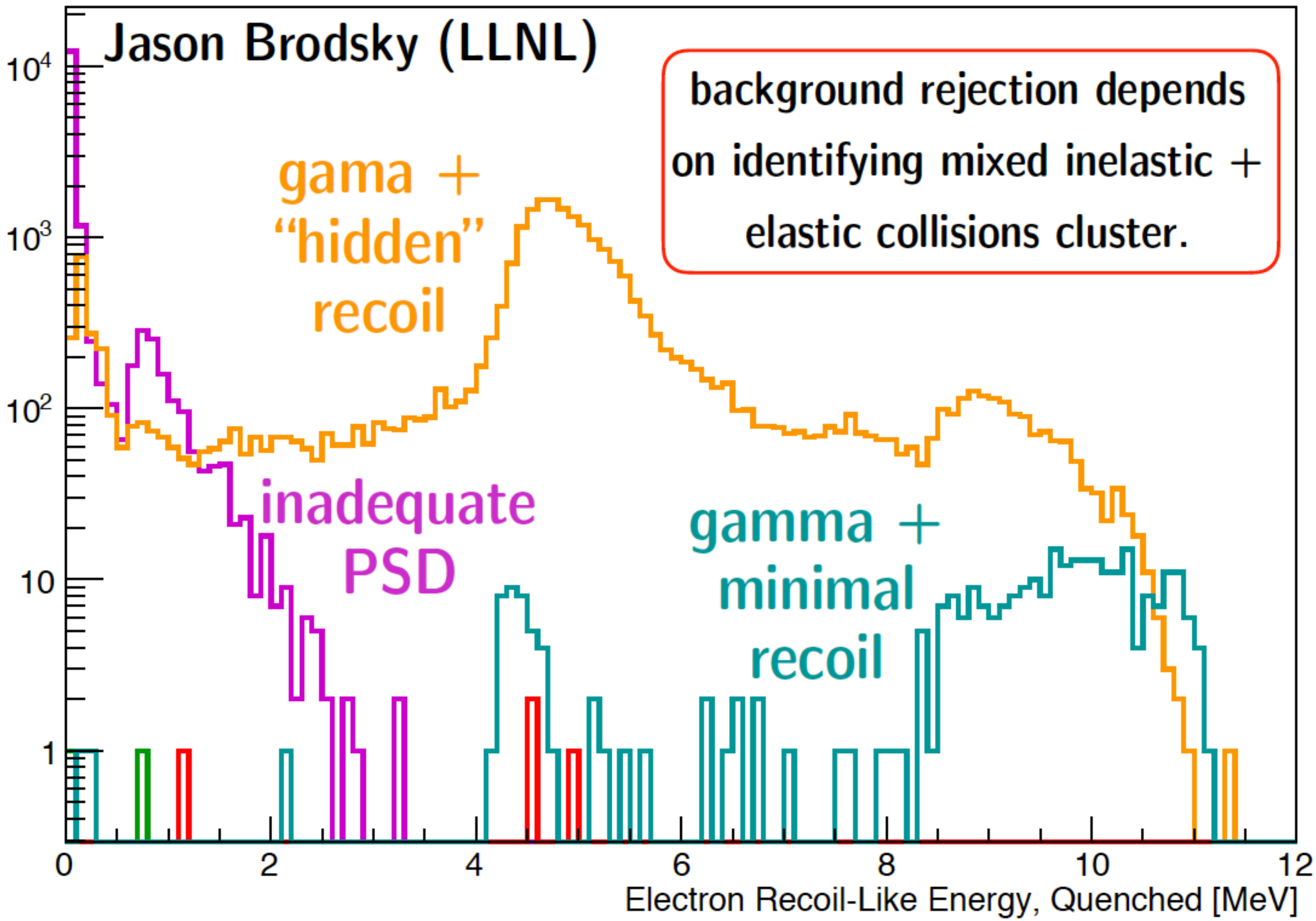
- New data are needed to address the existing reactor anomalies.
- PROSPECT Phase I will
  - Probe favored region of eV-scale sterile neutrinos at >3σ with 3 years of data.
  - Measure ^{235}U ν_e spectrum, address spectral deviation, and provide new constraints on reactor antineutrino models complementary to current and future LEU measurements.
- PROSPECT R&D
  - Have developed LiLS detectors that can mitigate reactor- and cosmic related backgrounds.
  - Multiple detectors have been deployed at HFIR in preparation for full-size detector.
  - Completed R&D for technical verification and to mitigate technical, cost, and schedule risks.
- Ready to proceed with construction of Phase I.
- Data taking in 2017 with first physics results in 2018 possible.

PROSPECT R&D and Technical Activities

Recent PROSPECT papers

- The PROSPECT Physics Program: arXiv:1512.02202
- Light Collection and Pulse-Shape Discrimination in Elongated Scintillator Cells for the PROSPECT Reactor Antineutrino Experiment: . arXiv:1508.06575, JINST 10 P11004
- Background Radiation Measurements at High Power Research Reactors: arXiv:1506.03547, Nucl. Instrum. Meth. A806 (2016) 401
- PROSPECT - A Precision Reactor Oscillation and Spectrum Experiment at Short Baselines: arXiv:1309.7647


neutrons involved in IBD-like events
(Phase I simulation)
secondary n produced locally
neutrons interacting in active volume
primary neutrons
rate (E × dN/dE)/dt [mHz]
neutron kinetic energy [MeV]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
10^{-1}
1
10
10^2
10^3
10^4
10^5



Jason Brodsky (LLNL)
background rejection depends
on identifying mixed inelastic +
elastic collisions cluster.
gama +
"hidden"
recoil
inadequate
PSD
gamma +
minimal
recoil
10^4
10^3
10^2
10
1
0
2
4
6
8
10
12
Electron Recoil-Like Energy, Quenched [MeV]