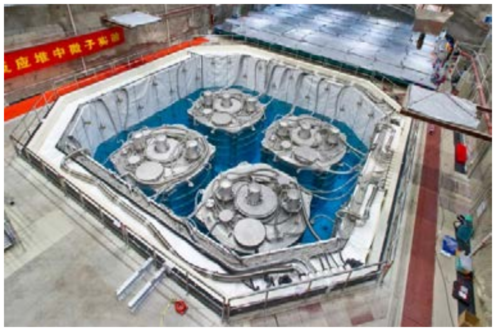
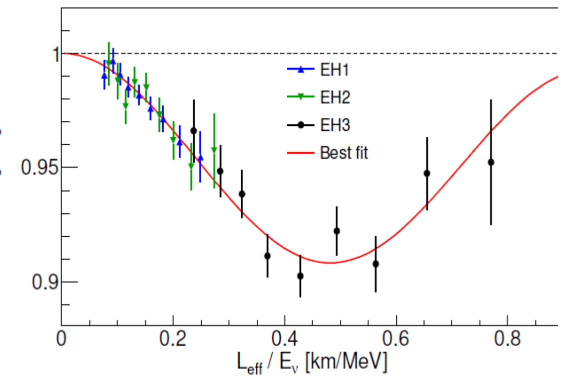
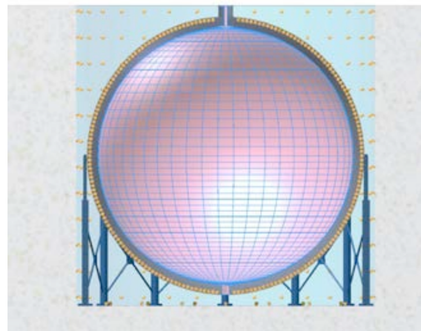
Future Reactor-Based Neutrino Experiments

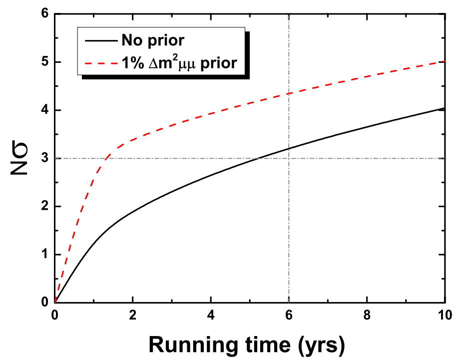
Daya Bay



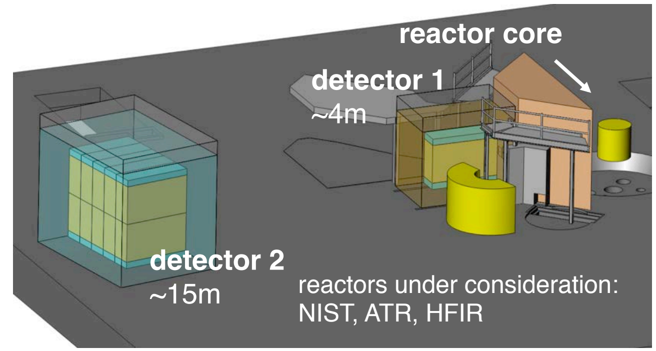


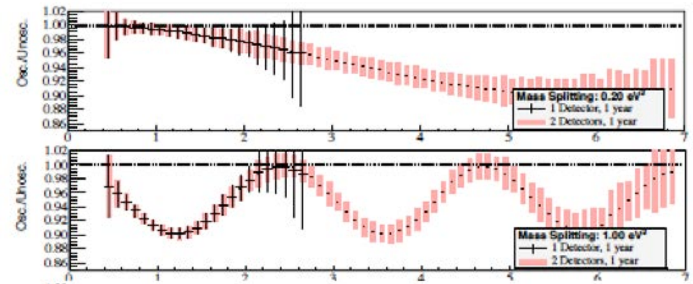
JUNO, RENO-50





PROSPECT

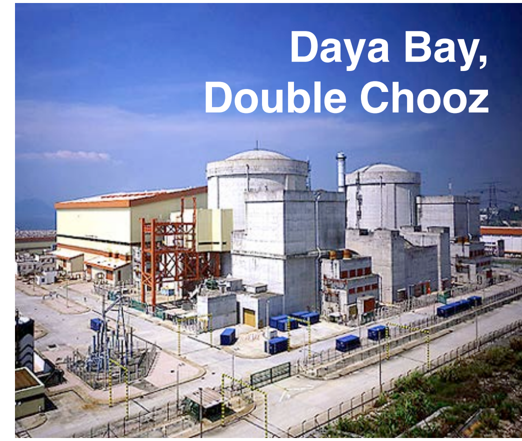




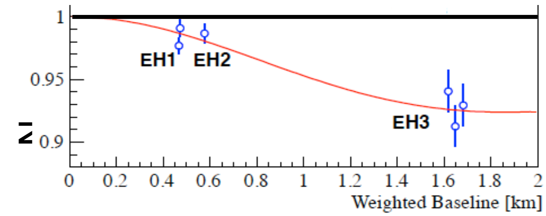
Karsten Heeger
Yale University

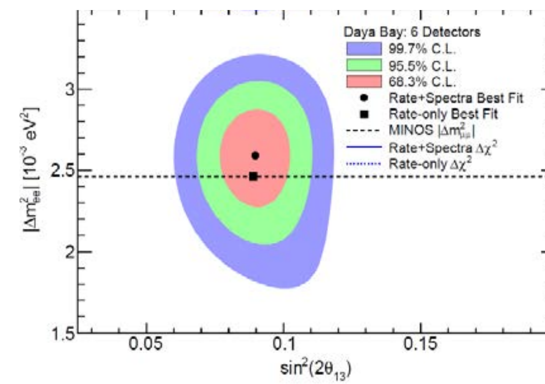
P5 Meeting, FNAL, November 3, 2013

US' Critical Role in Discoveries with Reactor Neutrinos

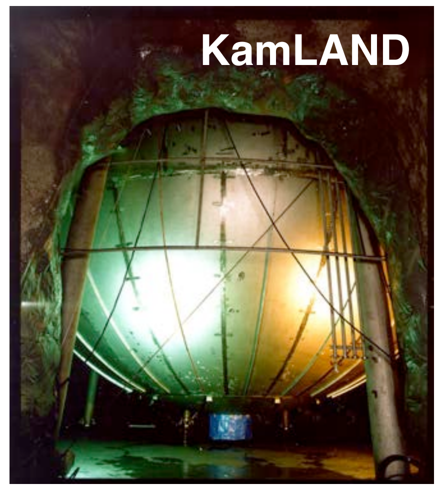


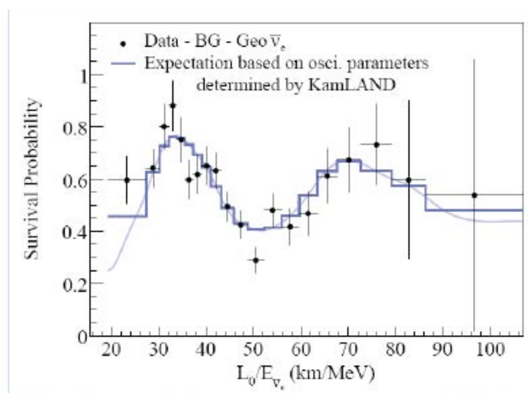
2012 - Measurement of θ_{13} with Reactor Neutrinos





2003 - First observation of reactor antineutrino disappearance



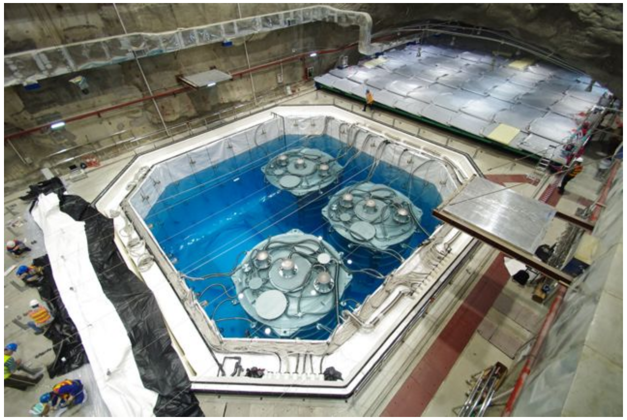


1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos

success built on strong international collaborations

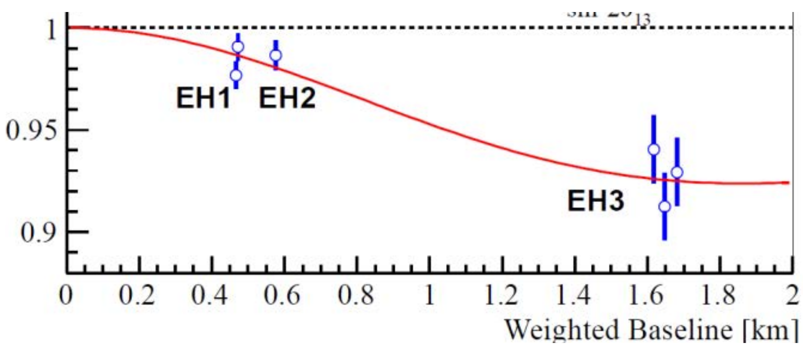
Discovery of θ_{13}



Selected as one of Science's top 10 breakthroughs of 2012.

3 antineutrino detectors in Daya Bay far site (EH3)

*"…result suggests that in the coming decades neutrino physics will be every bit as rich as physicists had hoped…**neutrino physics could be the future of particle physics** — as the fact that neutrinos have mass is not even part of the standard model. If so, **the Daya Bay result may mark the moment when the field took off**."*



$\sin^2 2\theta_{13} = 0.090 \pm 0.009$

installation of Daya Bay experiment now complete

Reactor Experiments - Current Results

From Discovery to Precision Measurements

2012 Daya Bay 5.2σ measurement of non-zero θ_{13}

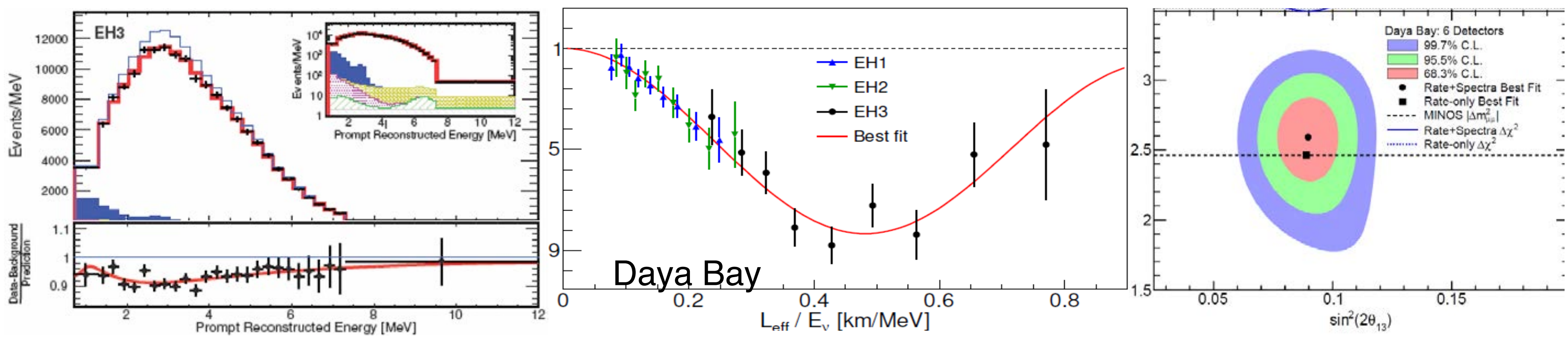
PRL 108:171803 (2012)

Daya Bay 7.7σ Improved measurement

CP**C37**:011001 (2013)

consistent results from Double Chooz and RENO

2013

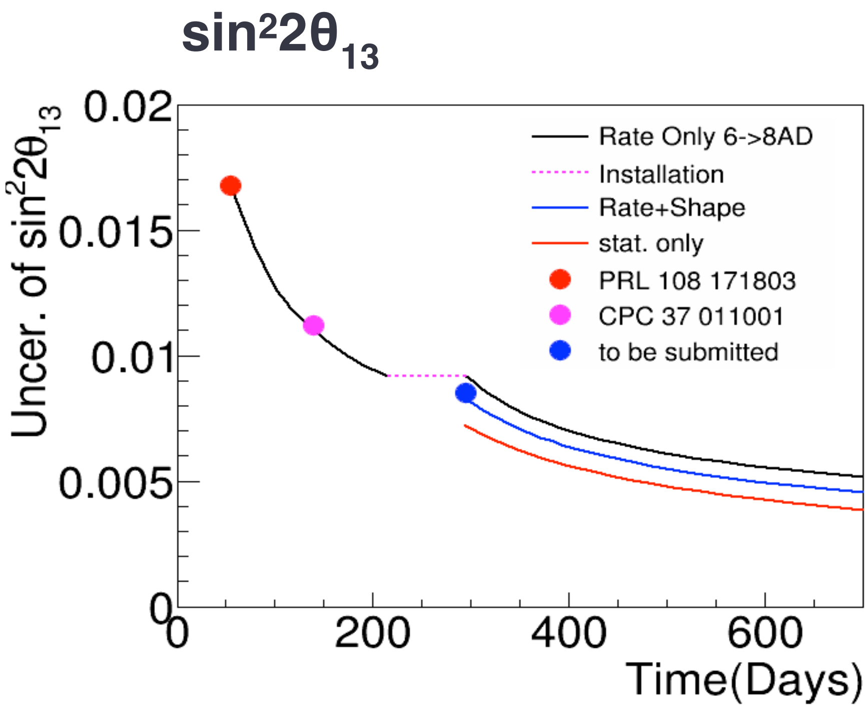


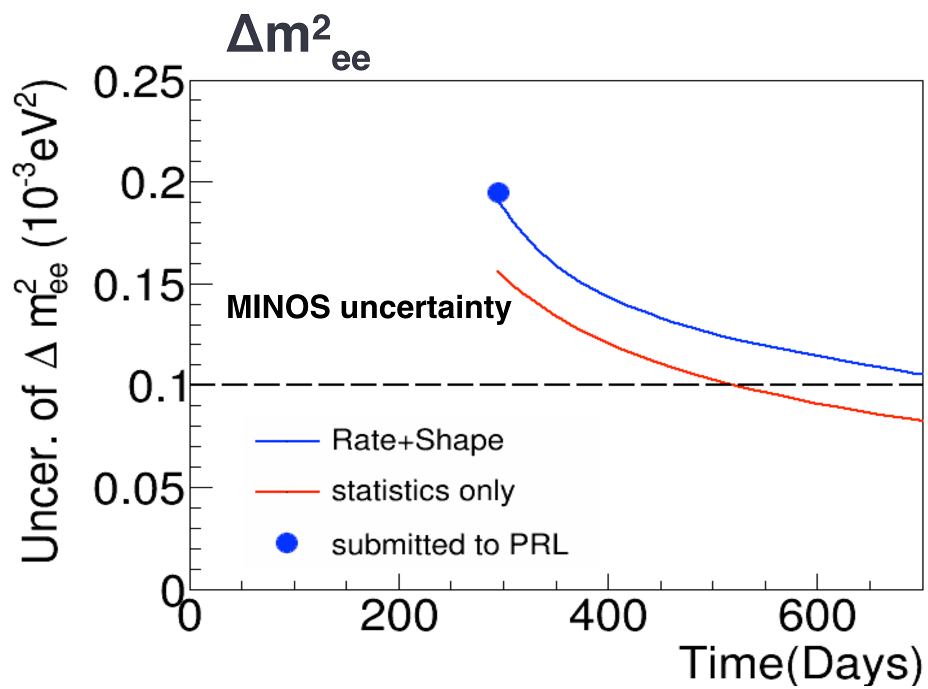
Most precise $\sin^2 2\theta_{13}$ measurement (10%)

First Δm^2_{ee} measurement (`atmospheric' Δm^2 from ν_e agrees with ν_μ from MINOS, consistent with 3-ν model)

Daya Bay - Sensitivity Projections

Towards Precision Measurements



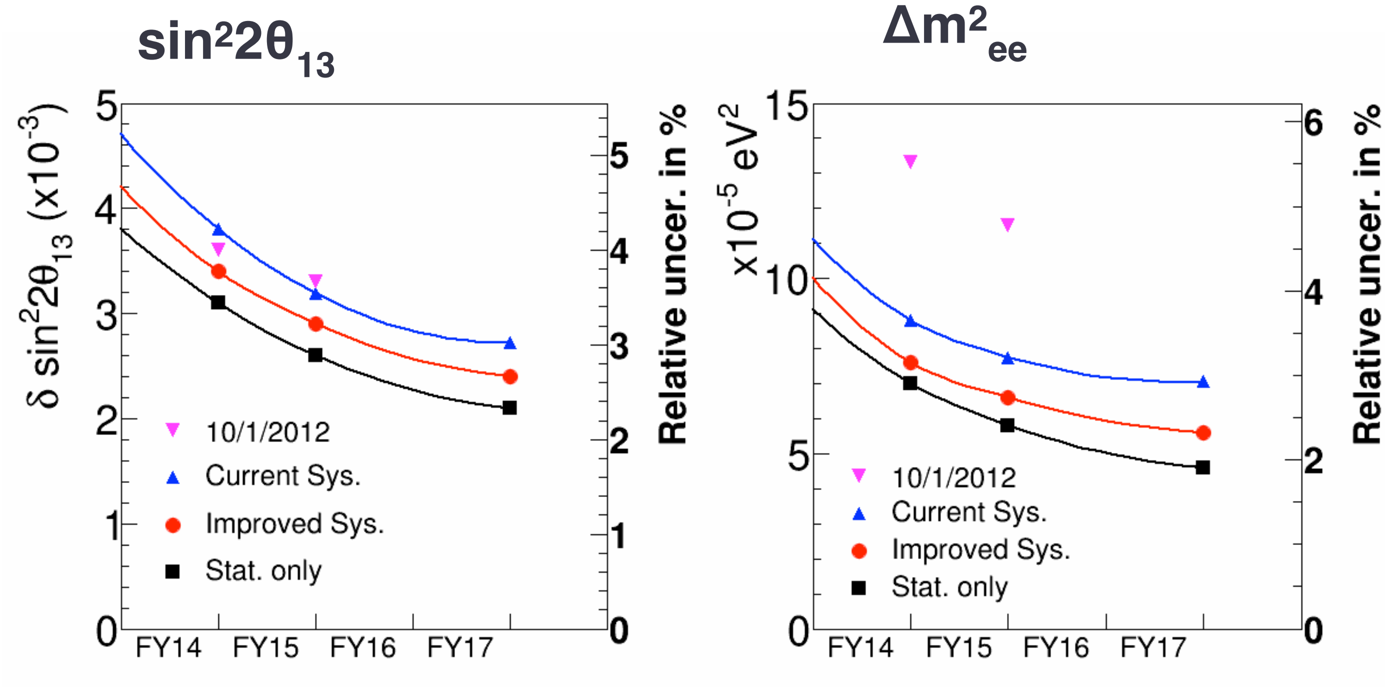


Daya Bay remains statistically limited through FY15

Daya Bay can also improve systematics.

Daya Bay - Sensitivity Projections

Precision Measurements



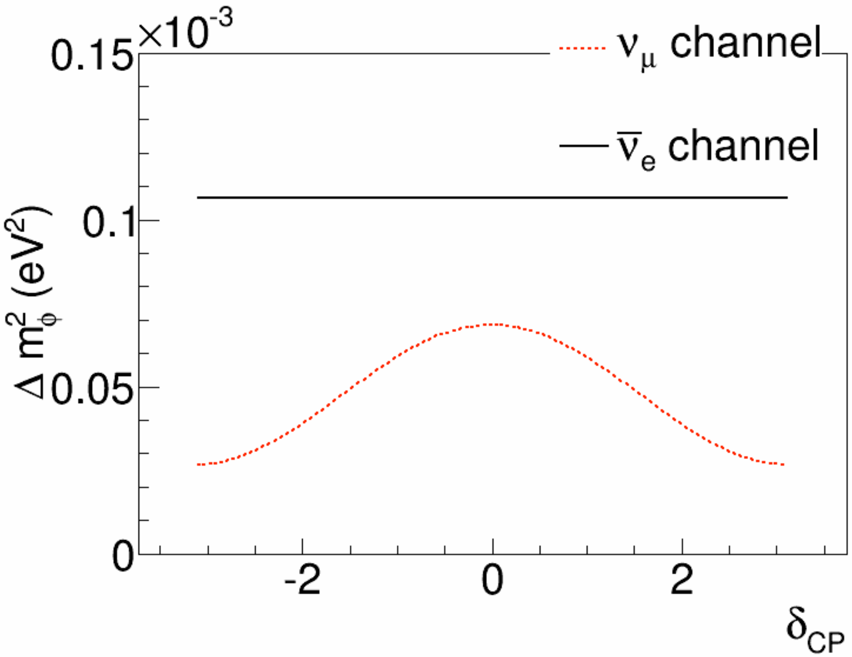
Combination of n-Gd and n-H with anticipated systematics improvements
($\sin^2 2\theta_{13}$ =0.09, Δm^2_{ee} =2.41e-3 eV^2)

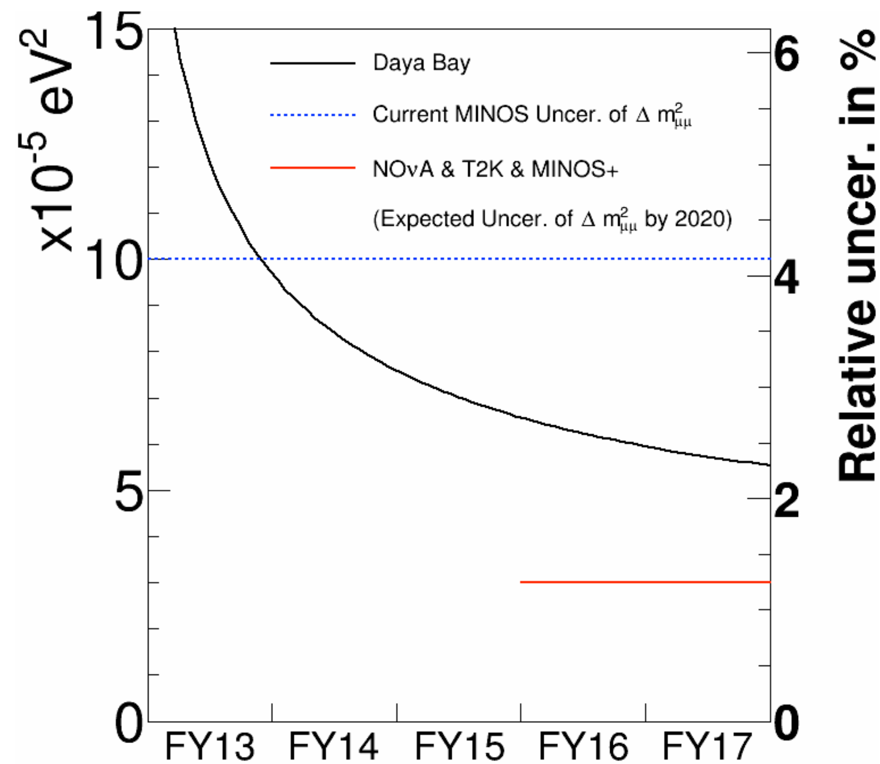
Reactor experiments will provide most precise measurement of $\sin^2 2\theta_{13}$ for the foreseeable future.

Continued data taking provides physics opportunities for young scientists and has long-term impact on future neutrino physics program in the US.

Enhanced Mass Hierarchy Sensitivity

Daya Bay & NOvA/T2K/MINOS+





$$|\Delta m^2_{ee,\mu\mu}| \approx |\Delta m^2_{32}| \pm \frac{\Delta m^2_{\phi\ ee,\mu\mu}}{2}$$

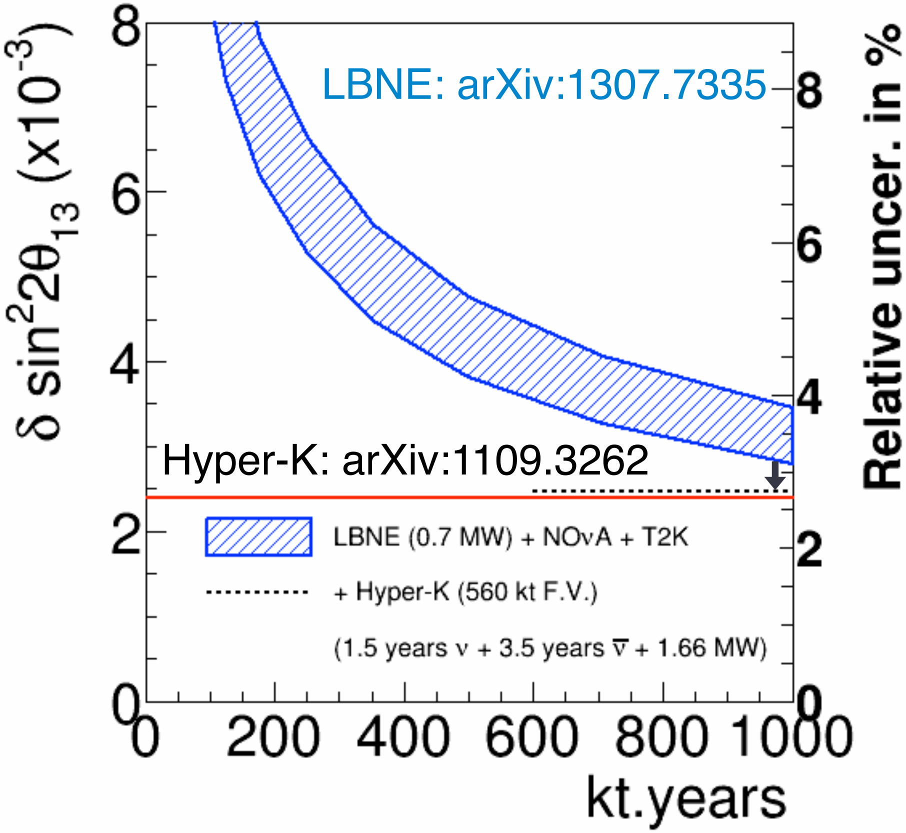
Normal Hierarchy: $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$

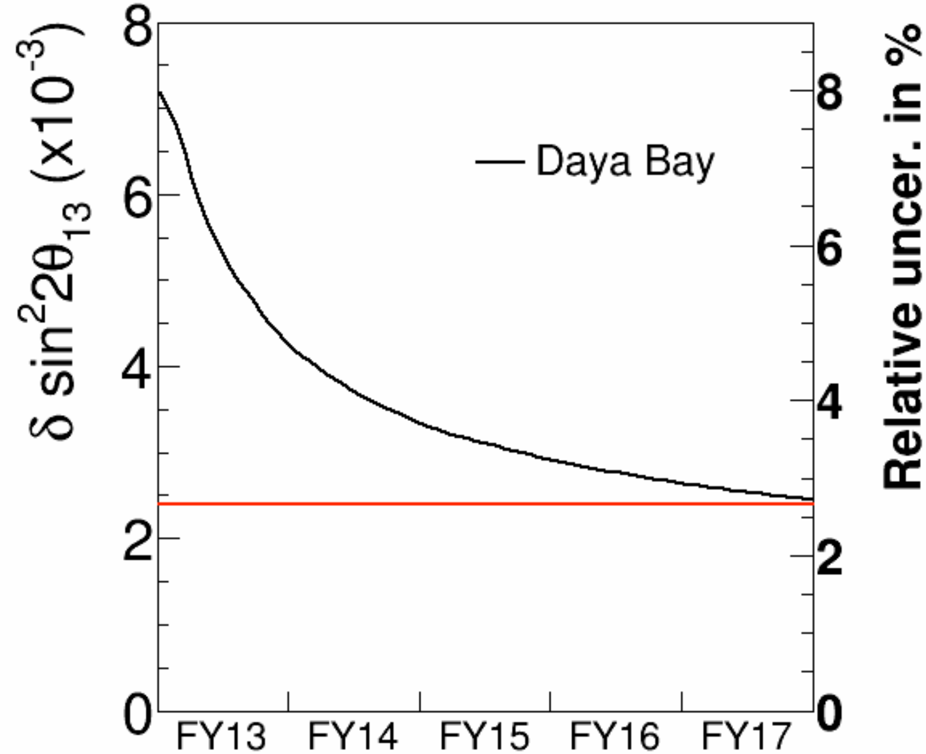
Inverted Hierarchy: $|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$

- Nunokawa, Parke, Zukanovich-Funchal PR**D72**:013009 (2005)
- Qian et al. PR**D87**:033005 (2013)

Unitarity Test Through Overconstraint of $\sin^2 2\theta_{13}$

Daya Bay & LBNE/Hyper-K





Combined ν_e and ν_μ measurements will test PMNS 3-ν model

Precision Measurements with Current Experiments

- **Best measurement of $\sin^2 2\theta_{13}$,**
  - Input to future long-baseline measurements.

- **Precision measurement of spectral distortion and absolute flux.**

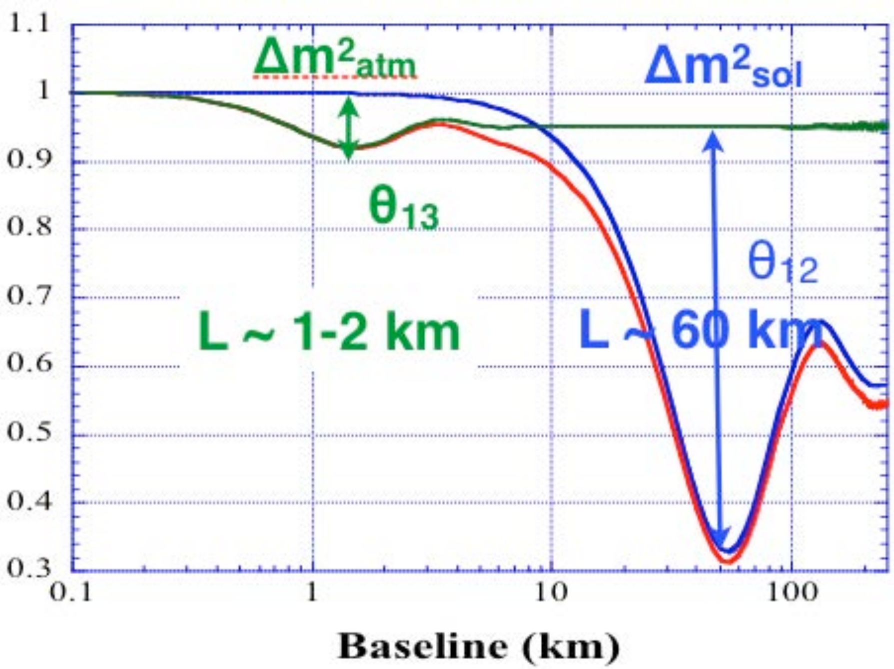
- **Constraints on 0.03–0.55eV sterile neutrino (3+1)**

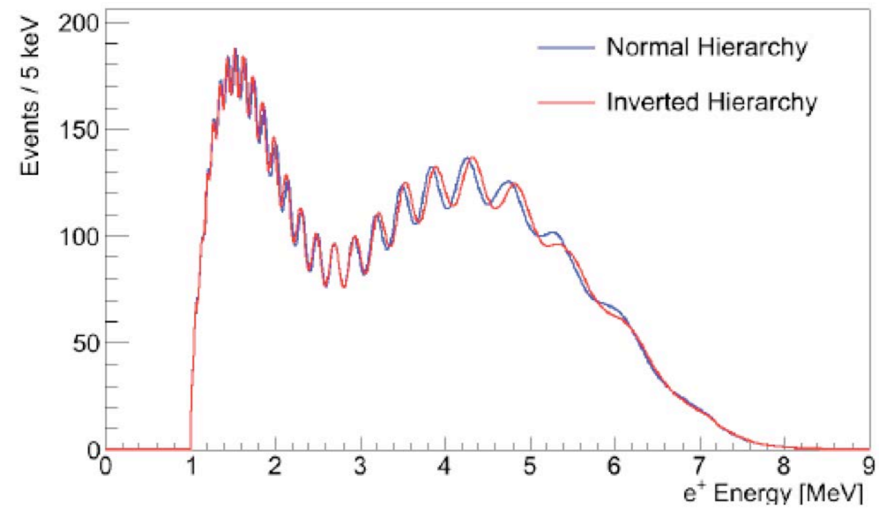
- **Precision Δm^2_{ee} measurement**
  - Enhance MH sensitivity in the NOvA era

- **Precision measurement of $\sin^2 2\theta_{13}$**
  - δ_{CP} , θ_{23}-octant LBNE10 sensitivity improvement
  - PMNS matrix unitarity test with LBNE

Mass Hierarchy and Reactor Neutrinos

Precision Measurement at ~ 58km





arXiv:1307.5487

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

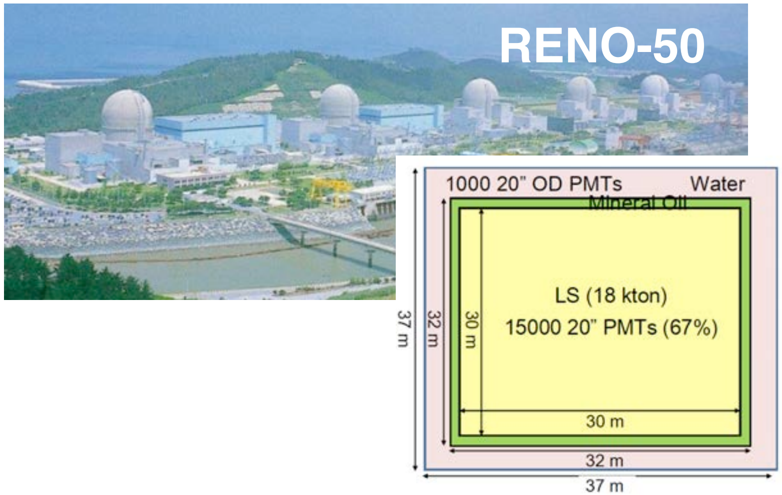
Δm^2_{21} is only 3% of $|\Delta m^2_{32}|$

mass hierarchy is contained in the spectrum

independent of the unknown CP phase

Mass Hierarchy and Reactor Neutrinos

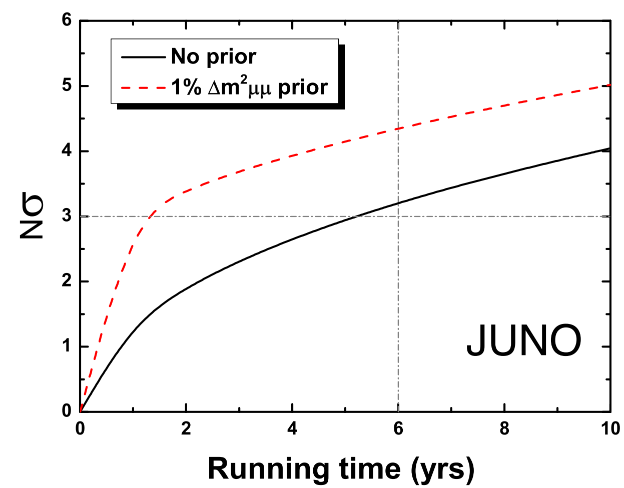
Proposed Projects: JUNO and RENO-50



Precision 3-ν Oscillation Physics

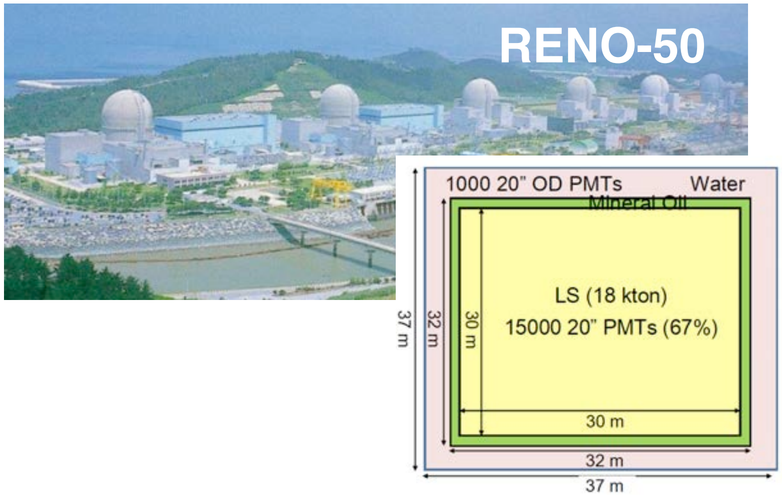
	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	10% (~4% in 3 yrs)	15%

Mass Hierarchy Sensitivity



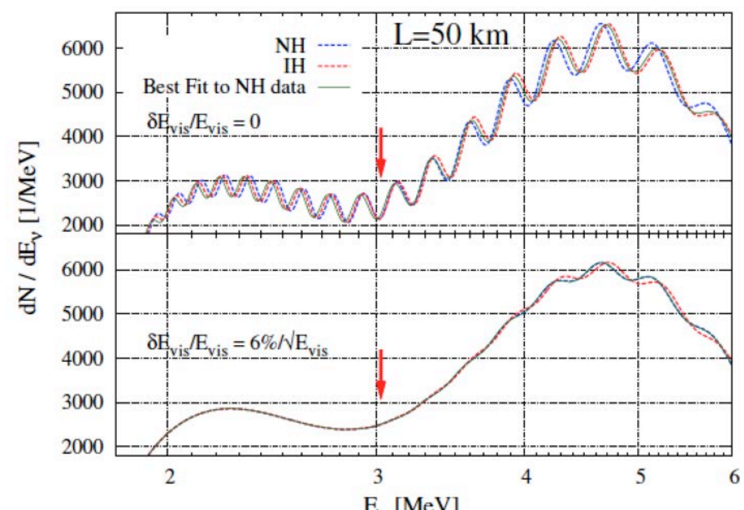
Mass Hierarchy and Reactor Neutrinos

Proposed Projects: JUNO and RENO-50



Technical challenges
- suitable underground site with reactors
- detector size ~20 kton
- energy resolution 3%/√E
- sub-percent energy scale calibrations

Costs
- O(~100M) based on estimates of host countries



S.F. Ge et al, arXiv:1210.8141

Mass Hierarchy and Reactor Neutrinos

arXiv:1307.7419
Snowmass whitepaper

US Interest Group

26 scientists
12 universities
2 national labs

Neutrino mass hierarchy determination and other physics potential of medium-baseline reactor neutrino oscillation experiments *

A.B. Balantekin[13], H. Band[14,13], R. Betts[7], J.J. Cherwinka[13], J.A. Detwiler[11], S. Dye[5], K.M. Heeger[14,13], R. Johnson[3], S.H. Kettell[1], K. Lau[6], J.G. Learned[4], C.J. Lin[2], J.J. Ling[1], B. Littlejohn[3], D.W. Liu[6], K.B. Luk[2], J. Maricic[4], K. McDonald[9], R.D. McKeown[12], J. Napolitano[10], J.C. Peng[8], X. Qian[1], N. Tolich[11], W. Wang[12], C. White[7], M. Yeh[1], C. Zhang[1], and T. Zhao[11]

[1] *Brookhaven National Laboratory, Upton, NY, USA*
[2] *University of California and Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[3] *University of Cincinnati, Cincinnati, OH, USA*
[4] *University of Hawaii, Honolulu, HA, USA*
[5] *Hawaii Pacific University, Kaneohe, HA, USA*
[6] *University of Houston, Houston, TX, USA*
[7] *Illinois Institute of Technology, Chicago, IL, USA*
[8] *University of Illinois at Urbana-Champaign, Urbana, IL, USA*
[9] *Princeton University, Princeton, NJ, USA*
[10] *Rensselaer Polytechnic Institute, Troy, NY, USA*
[11] *University of Washington, Seattle, WA, USA*
[12] *College of William and Mary, Williamsburg, VA, USA*
[13] *University of Wisconsin, Madison, WI, USA*
[14] *Yale University, New Haven, CT, USA*

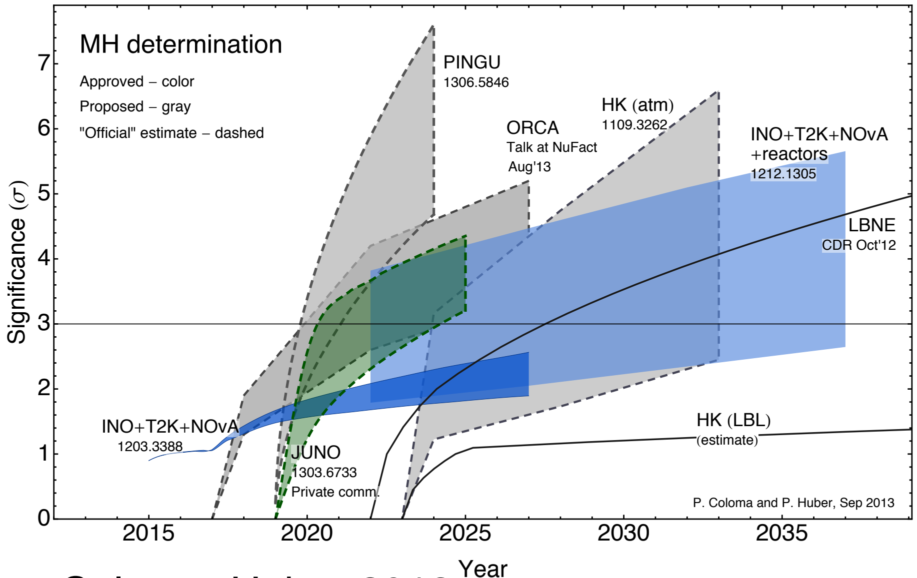
US expertise in critical areas
- liquid scintillator
- detector calibration
- front-end and trigger electronics

Generic R&D can benefit a variety of neutrino projects.

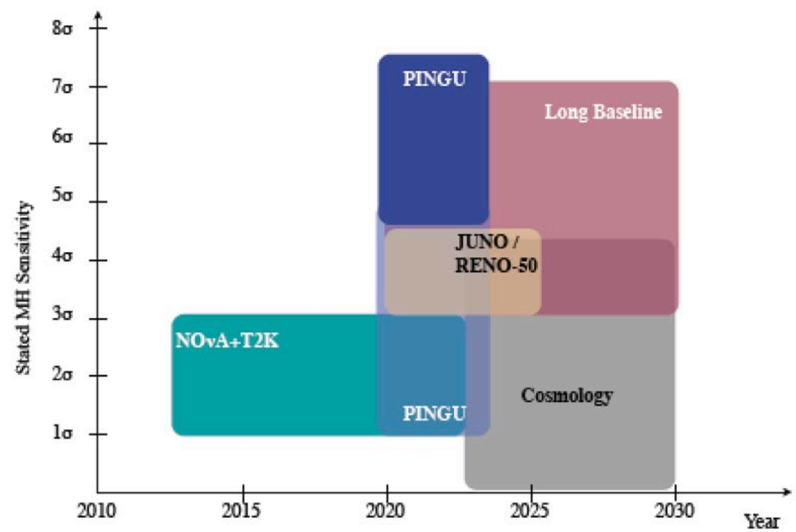
Mass Hierarchy and Reactor Neutrinos

Projections of Sensitivity and Schedule

Based on claimed sensitivities



Coloma, Huber 2013

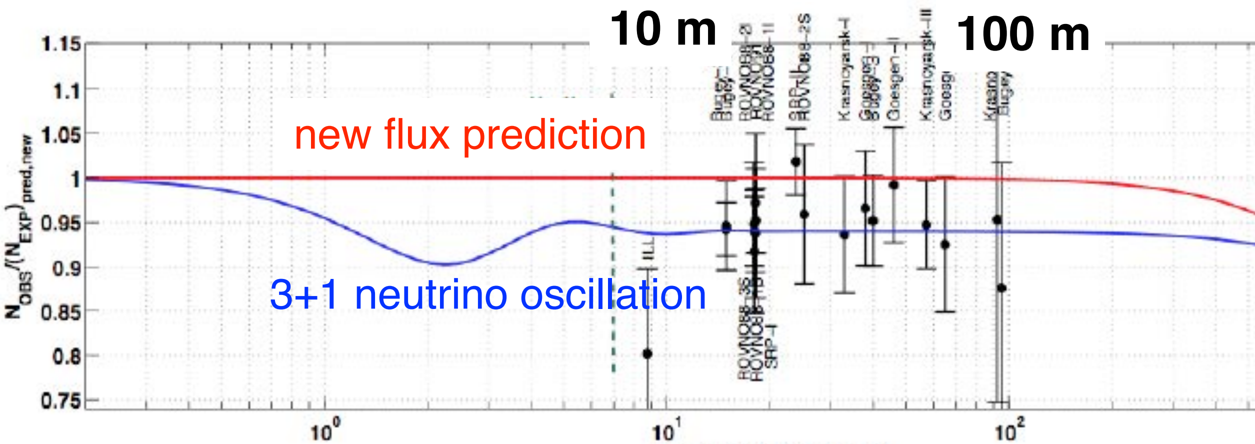


Cahn et al, arXiv: 1307:5487

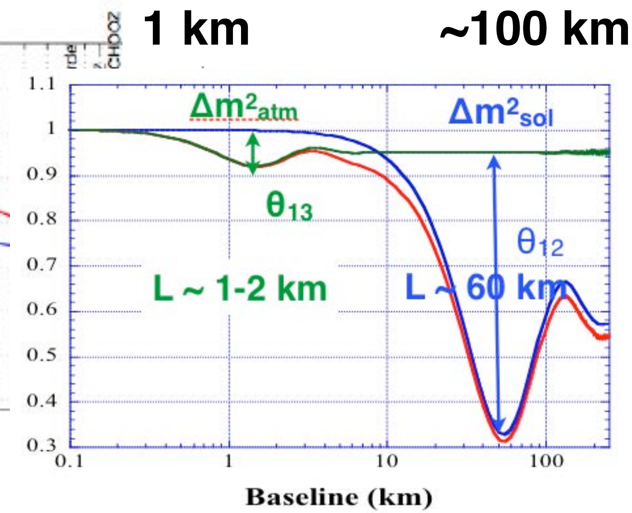
Complementarity of techniques can improve sensitivity of a combined measurement

Short-Baseline Reactor Experiments

Baselines



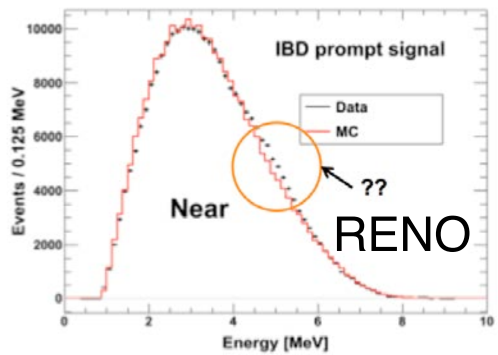
adapted from Schwetz, Neutrino2012



Reactor Anomaly

apparent deficit in observed reactor flux

Reactor Spectra



One of several anomalies

LSND ($\overline{\nu}_e$ appearance)
MiniBoone (ν_e appearance)
Ga anomaly
N_{eff} in cosmology
Reactor anomaly ($\overline{\nu}_e$ disappearance)

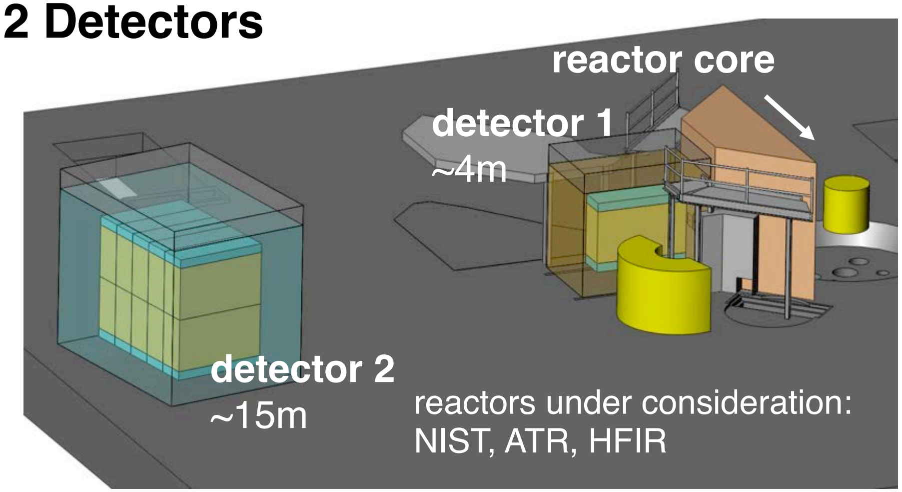
Do we understand reactor flux predictions and spectrum?

Short-Baseline Reactor Experiment

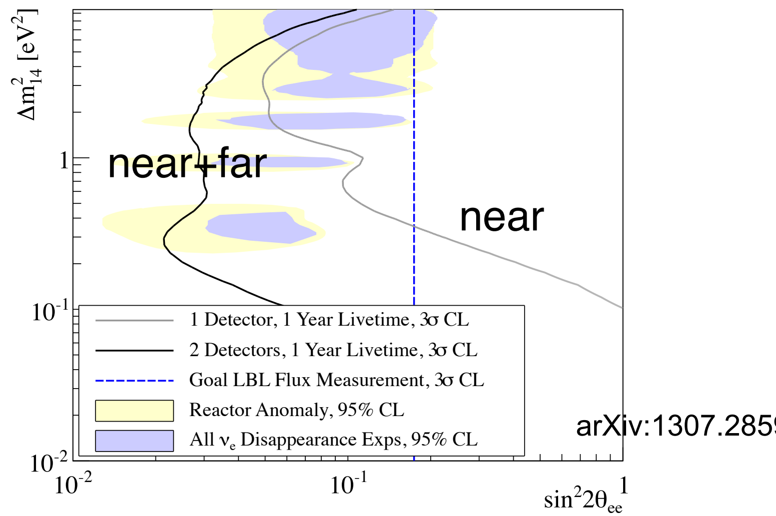
PROSPECT - A US-Based Short Baseline Experiment

A Precision Reactor Neutrino Oscillation and Spectrum Experiment

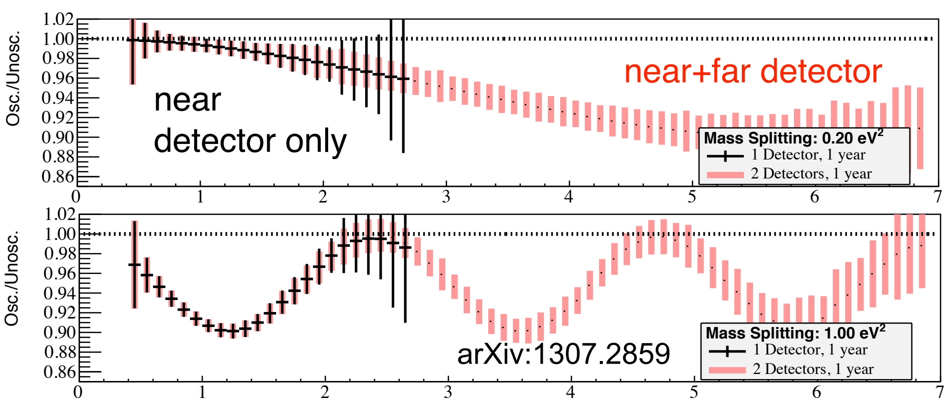
2 Detectors



Scientific Reach



Map out L/E Oscillations



Phased Approach

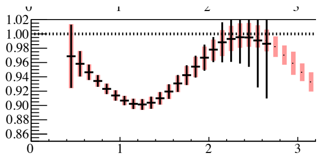
phase 1- near detector

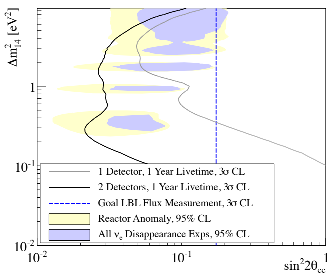
phase 2 - near + far detectors

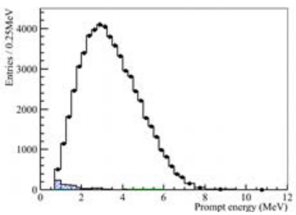
3σ in 1 year

5σ in 3 years

Short-Baseline Reactor Experiment - Objectives





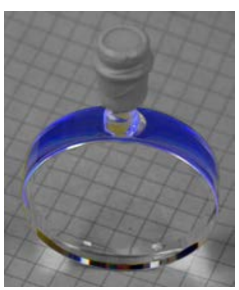


Primary Physics Objectives

Definitive short-baseline oscillation search with high sensitivity

Test of the oscillation region suggested by reactor anomaly and $\overline{\nu}_e$ disappearance channel (3 years of run time can exclude virtually all the implied oscillation region at 5σ)

Precision measurement of reactor $\overline{\nu}_e$ spectrum for physics and safeguards



Secondary Physics and Applied Goals

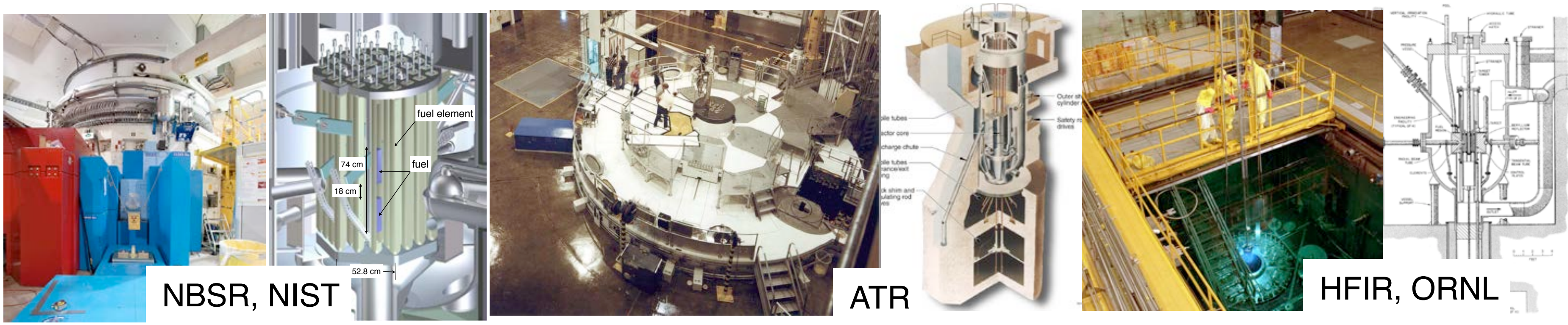
^{6}Li doped scintillator development

Segmented antineutrino detectors for near-surface operation; develop antineutrino-based reactor monitoring technology for safeguards

Possible first measurement of antineutrinos from spent fuel

US Research Reactors

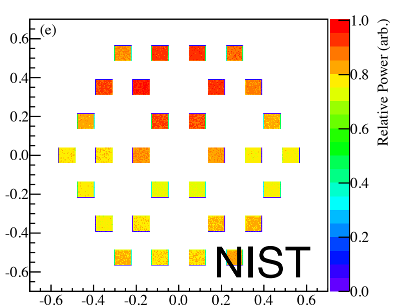
US Operates High-Powered Research Reactors

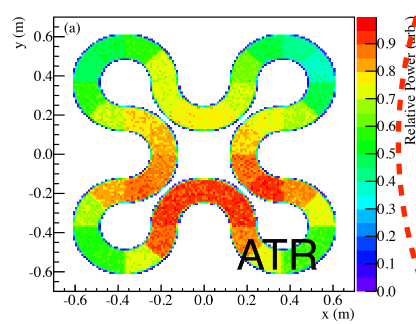


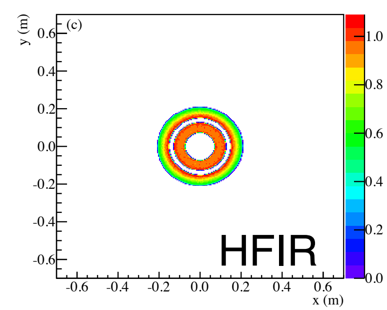
Site	Power (MW_{th})	Duty Cycle	Near Detector		Far Detector	
			Baseline (m)	Avg. Flux	Baseline (m)	Avg. Flux
NIST	20	68%	3.9	1.0	15.5	1.0
HFIR	85	41%	6.7	0.96	18	1.93
ATR	120	68%	9.5	1.31	18.5	4.30

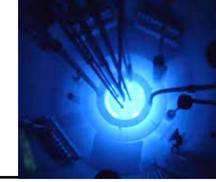
commercial core

Reactor Cores



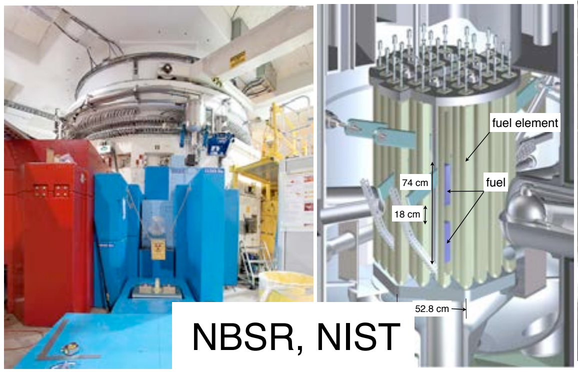




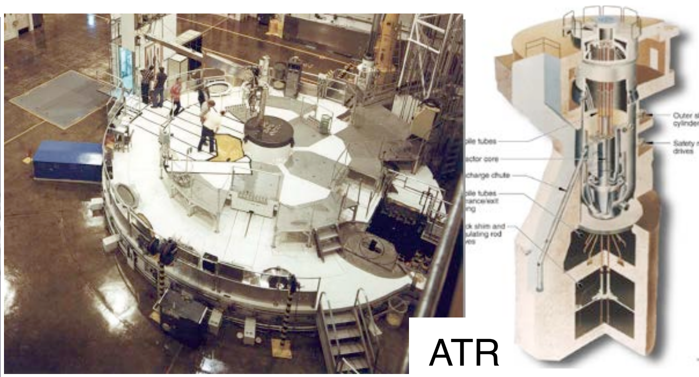


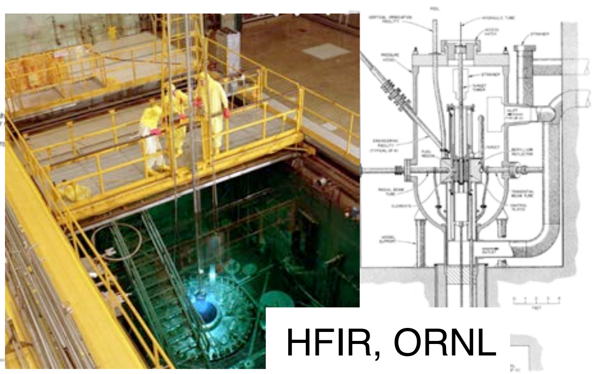
US Research Reactors

US Operates High-Powered Research Reactors

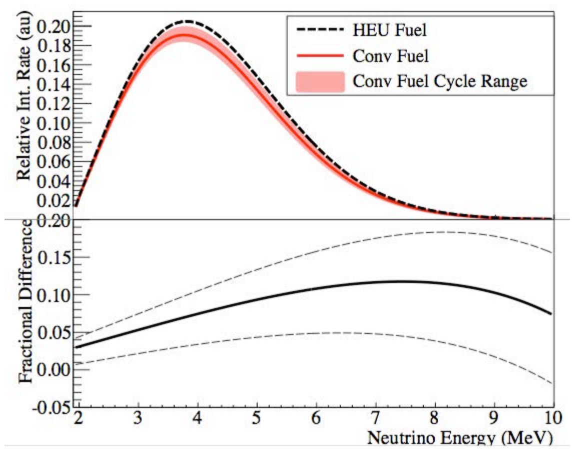


NBSR, NIST


ATR

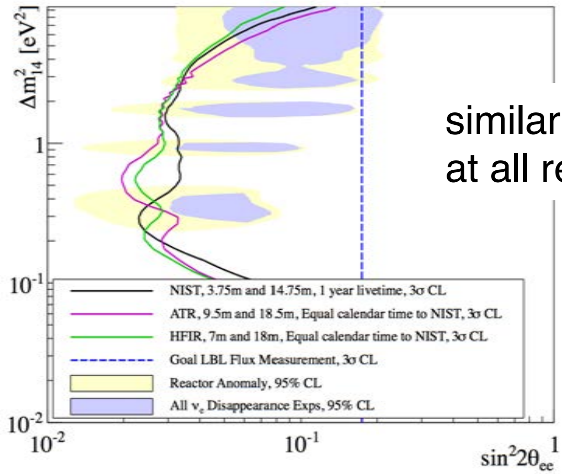

HFIR, ORNL

HEU Reactor Fuel



HEU, no time variation
Reactor off periods for background studies
Ability to reconfigure/run for extended periods

Sensitivity

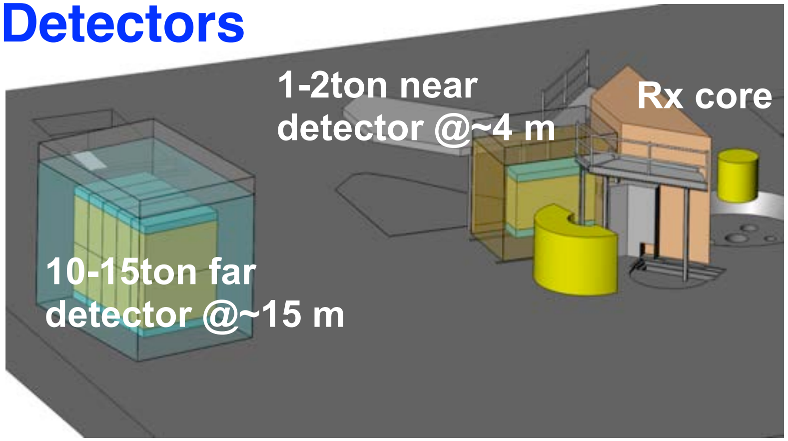


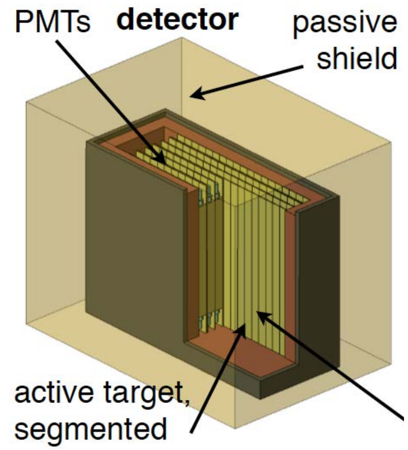
similar scientific reach at all reactor sites

Opportunities for R&D, backup options for detector deployment

Experimental Approach

Detectors





Multiple detectors

Segmented detectors for position resolution and background rejection

Doped scintillator target

Challenges

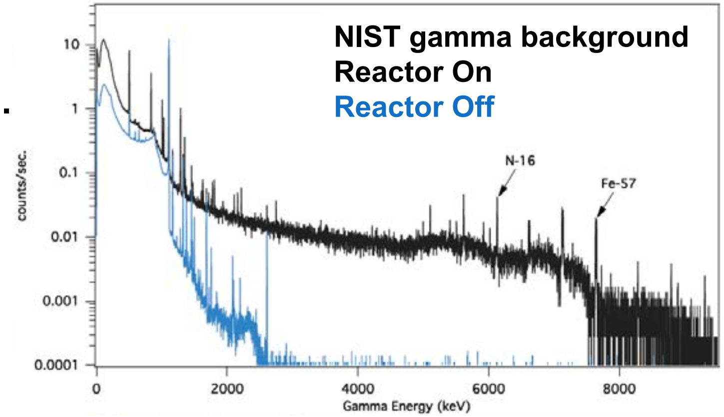
Reactor correlated background and limited overburden.
Event-by-event discrimination of backgrounds
Relative normalization and calibration of detector elements.

Unique Features of PROSPECT Short-Baseline Experiment

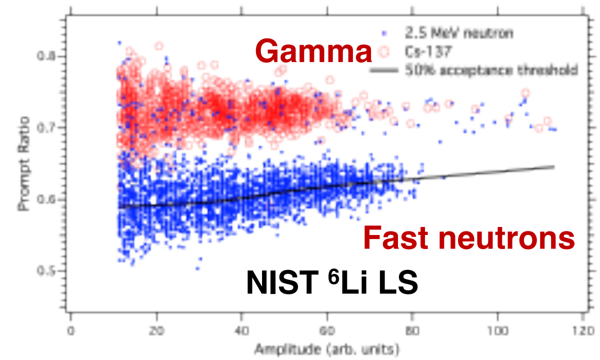
Sensitive to oscillations within single detector and between near and far detector (relative measurement, not absolute measurement)
^{6}Li-loaded scintillator detector
Near+far detectors, phased approach from R&D to full experiment
3 available sites in US (different characteristics, backup plan)
5σ measurement possible

Ongoing R&D

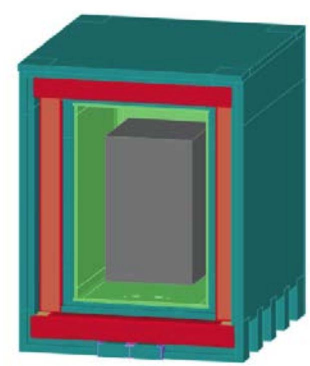
Background Measurements
- Measurements being performed/planned at all sites.
- Assess and compare Reactor On/Off background.



Scintillator Development
- Investigating high flash point solvent systems with ^{6}Li doping and PSD
- Retaining GdLS as proven backup option



Detector Concept/Prototyping
- Studying response and particle ID capabilities of segments
- Developing prototype detector segments for simulation validation, scintillator characterization and PSD studies
- Plan to deploy in miniTimeCube shield at NIST



miniTimeCube shield at NIST

Shielding
- Optimizing configuration, comparison of data and MC.

Status & Schedule

Status

PROSPECT collaboration studying feasibility, developing conceptual design, performing R&D. Need R&D support for engineering to develop firm cost and schedule.

Technically Driven Schedule

2013-14: Feasibility R&D with detector test modules close to reactor core

2014-15: Demonstration with near detector (~1-2 ton), measurement of spectrum

2016: Test of favored parameter region at 3σ.

2016-18: Full experiment with near+far detectors, 5σ test of anomaly

Opportunities

- Measurement of the reactor spectrum at very short baselines. Timely test of anomaly and reactor predictions at high significance.

- Complementary to accelerator-based experiments, strong overlap with safeguards efforts.

- Opportunity for small experiment at modest cost (<$4M for near detector). Ideal for training of young scientists.

PROSPECT Collaboration

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Department of Physics, Yale University, New Haven, CT 06520

arXiv:1307.7647
Snowmass whitepaper

PROSPECT collaboration

35 scientists
10 universities
5 national labs

Summary

Reactor neutrinos are a tool for discovery. Reactors are flavor pure sources of $\overline{\nu}_e$

US has had a major role in recent discoveries with reactor experiments.
Size and timescale of projects ideal for training next-generation neutrino scientists.

Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$, and **reactor antineutrino flux and spectra**. Precision measurements will be input to the long-term neutrino program.

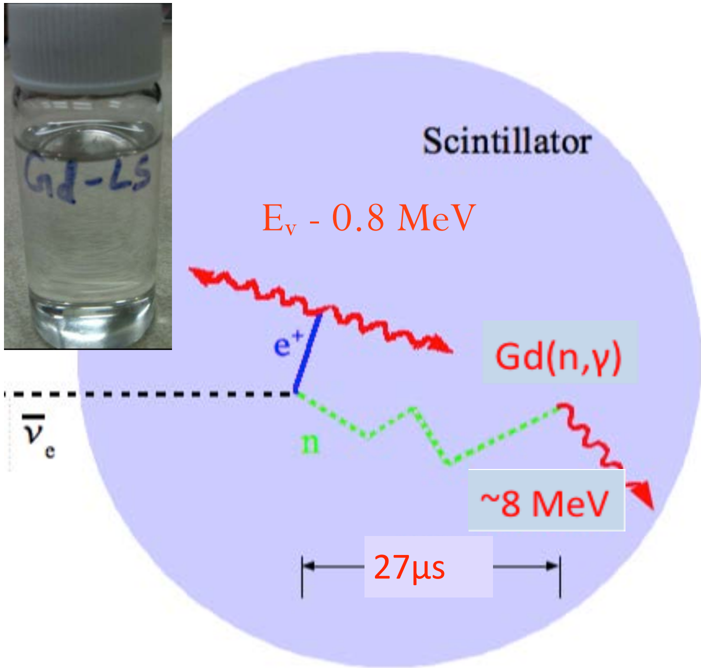
Medium-baseline experiments **(L~60km)** are technically demanding but may offer <1% **precision oscillation physics and a window to the mass hierarchy.**

Short-baseline **(L~10m)** measurements offer opportunities for precision studies of the **reactor spectrum** and a definitive search for **short-baseline oscillation** at modest cost.

Request support of P5 to continue US role in successful history of reactor neutrino physics.

End

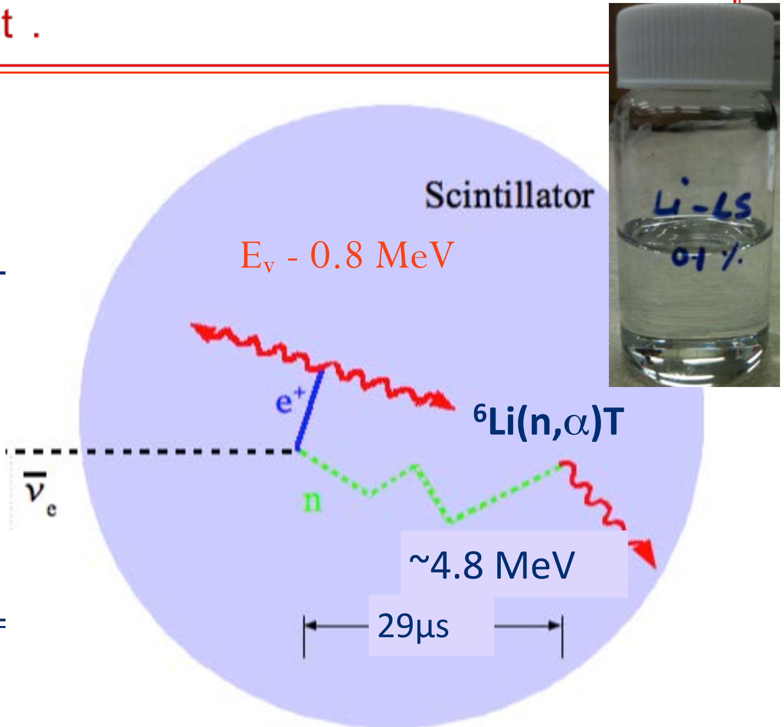
Reactor IBD Event: $\bar{\nu}_e + p \rightarrow e^+ + n$



$\mathbf{n_{th} + {}^{A}Gd \rightarrow {}^{A+1}Gd + \gamma's\ (\sigma{\sim}55{,}000\ barn):}$

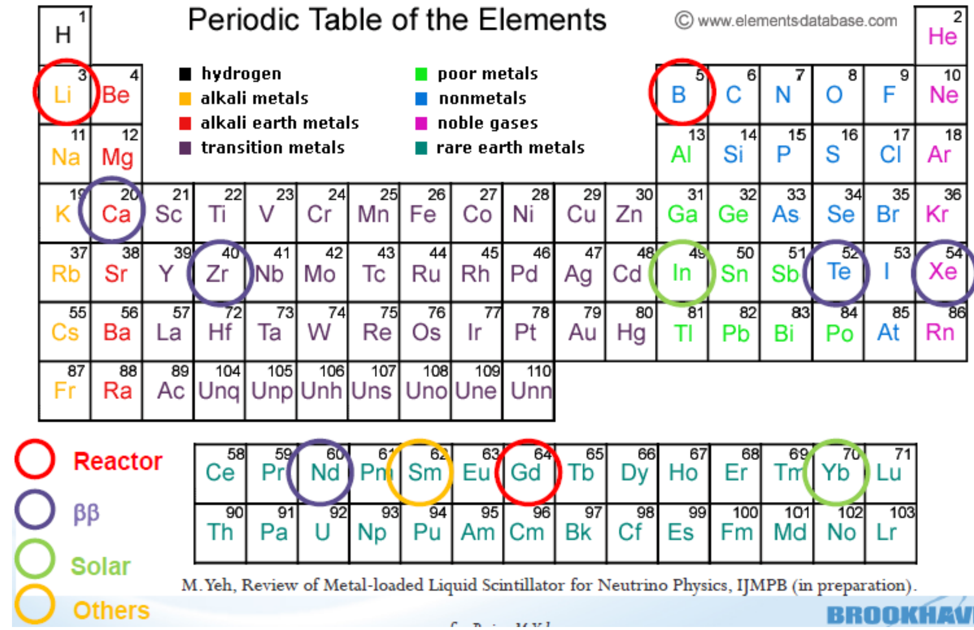
- S% of ~10,000 optical photons /MeV and $\lambda_{1/e}$ at ~20m.
- Stability of 3 years demonstrated by Daya Bay experiment .

- $\mathbf{n_{th} + {}^{6}Li \rightarrow \alpha + {}^{3}H\ (\sigma{\sim}940\ barn):}$
  - S% of ~5,000 optical photons /MeV and $\lambda_{1/e}$ at 2.6m (i.e. Bugey-3).
  - Stability degraded in few months of deployment (**needs R&D's**).



Scintillator Choice for PROSPECT

- **^{6}Lithium-loaded scintillator:**
  - Conventional loading vs. water-based loading
  - Stability over experimental lifetime
  - High light-yield
  - Long optical transmission
  - Background rejection (PSD)
- **Gadolinium-loaded scintillator:**
  - Background rejection check
  - Production plan (back-up)



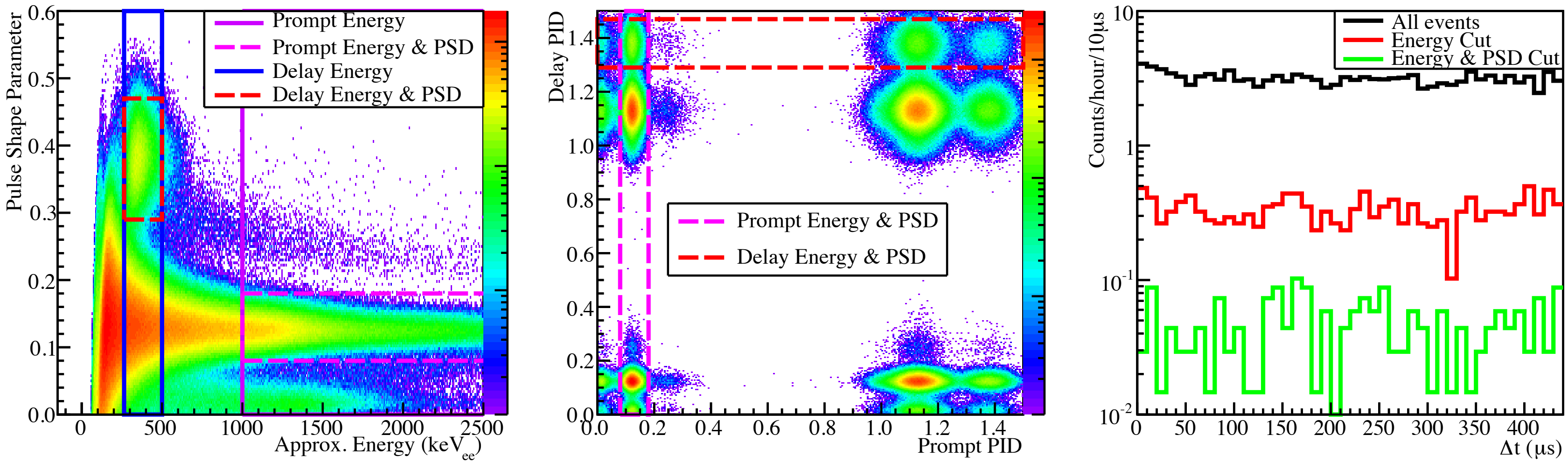
- Expertise, equipment, and facility from BNL, NIST, and LLNL in liquid & plastics scintillator applications
  - capable of engineering a suitable scintillator in a timely and cost-effective way.

Liquid Scintillator Development

Identifying high-flashpoint scintillators that support 6Li doping (while maintaining proven Gd-doped scintillator as an option)

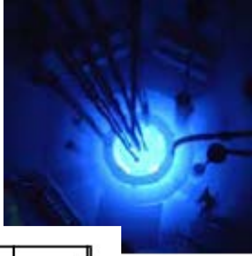
Studying material compatibility and scintillator stability

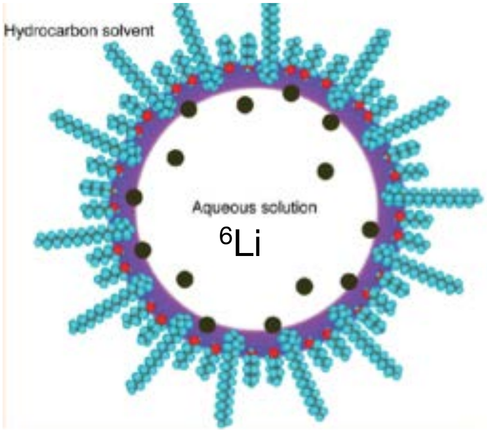
Currently optimizing detector geometry for Pulse Shape Discrimination capability



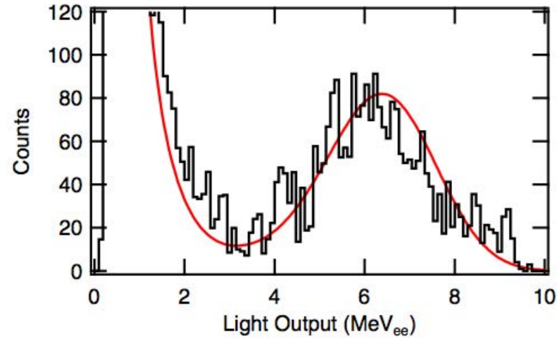
Data from a 7.5 cm right cylindrical of unshielded ^{6}Li-doped *plastic* scintillator exposed to ambient background.

Micro-emulsion Scintillator (^{6}Li doped)

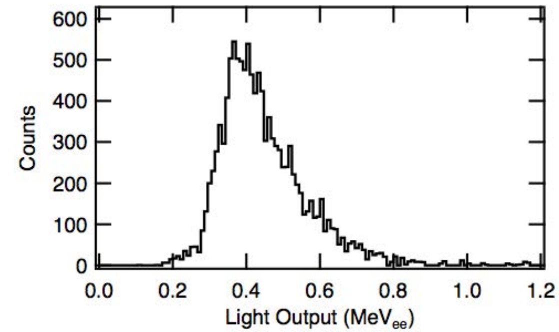




Scattering events (14 MeV n)



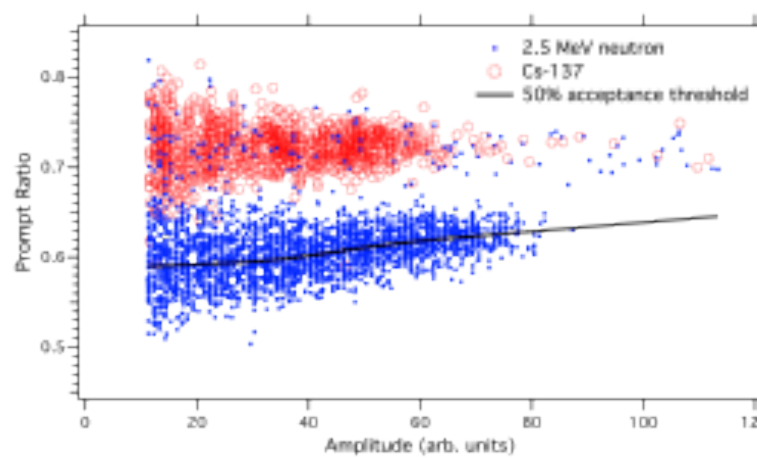
Neutron Capture



- Developing scintillator with Li-loading using micro-emulsions
  - 0.4 % ^{6}Li demonstrated
  - Simple chemistry
  - High flash point
  - PSD potential
- Further development and characterization in progress
  - Measure attenuation length
  - Long term stability
  - Refine PSD measurements

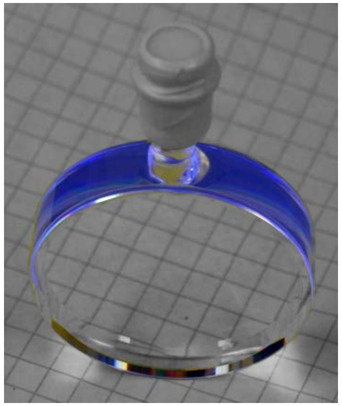
- NIST has the capability of carrying out a TOF PSD measurement.

PSD demonstrated



LLNL ^{6}Li-doped Organic Scintillator R&D

Developed compound for homogeneous introduction of polar ^{6}Li into non-polar aromatics

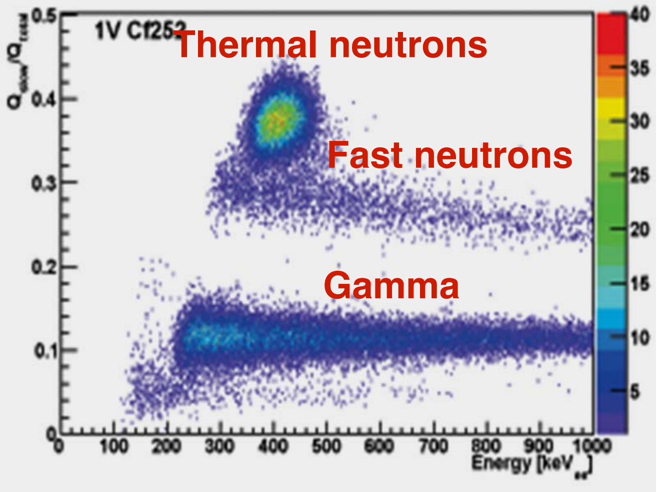


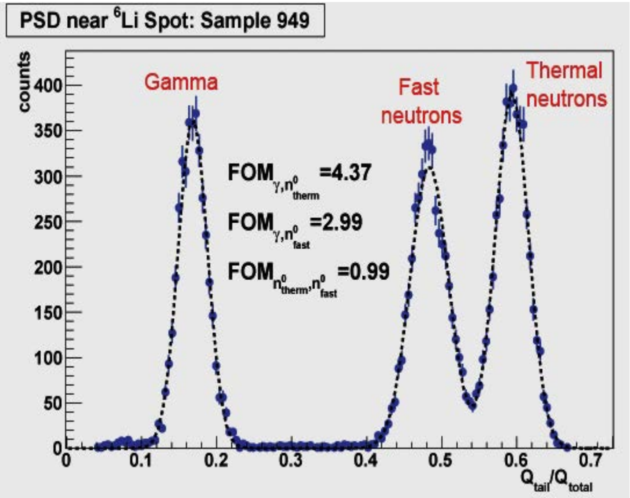
3” Li-loaded plastic

Li-loaded liquid

Status:

- ^{6}Li loaded plastic entering commercialization
- Excellent PSD demonstrated in low-flash point ^{6}Li loaded liquid
- Further R&D required for high-flash point liquids

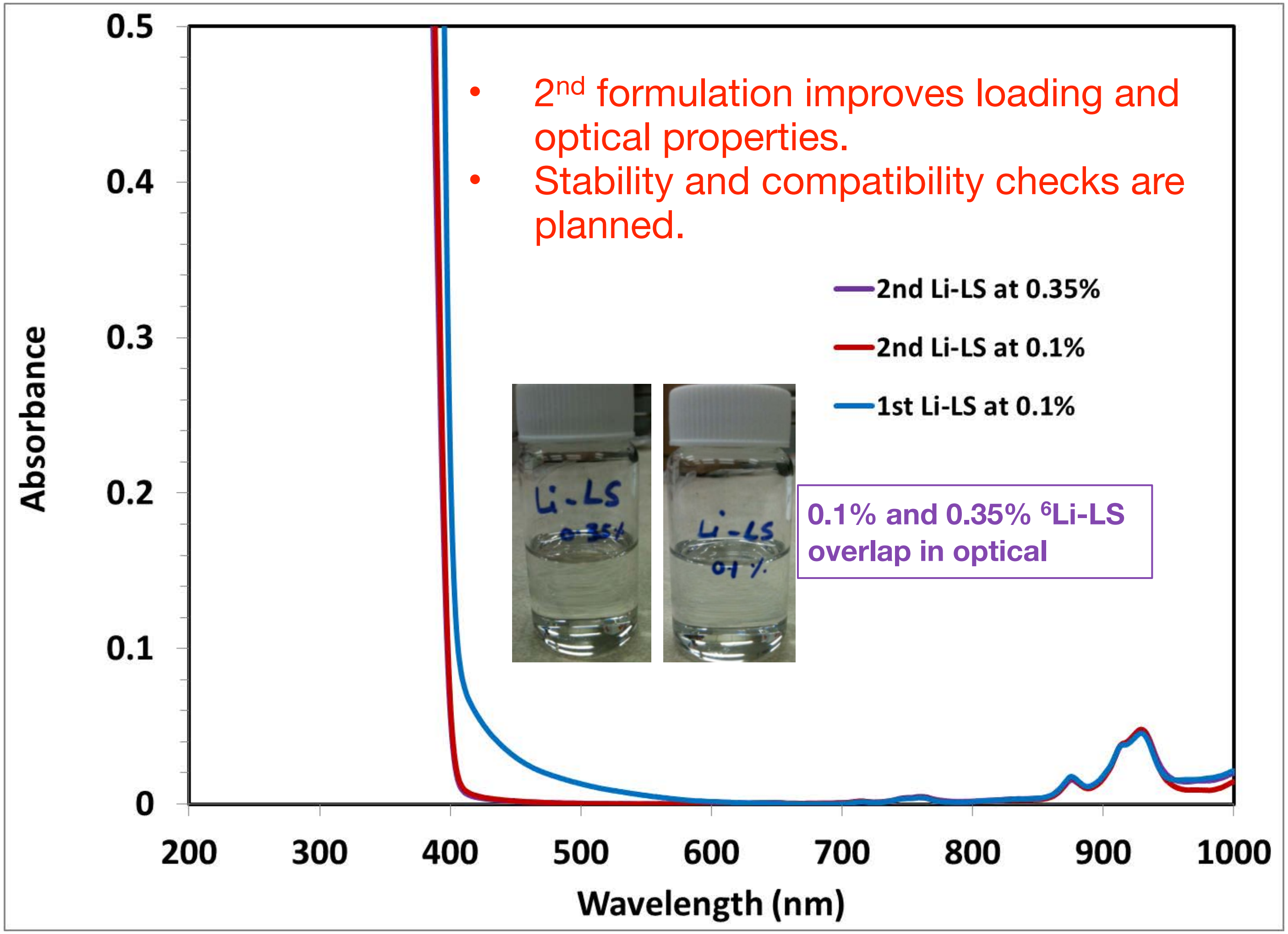




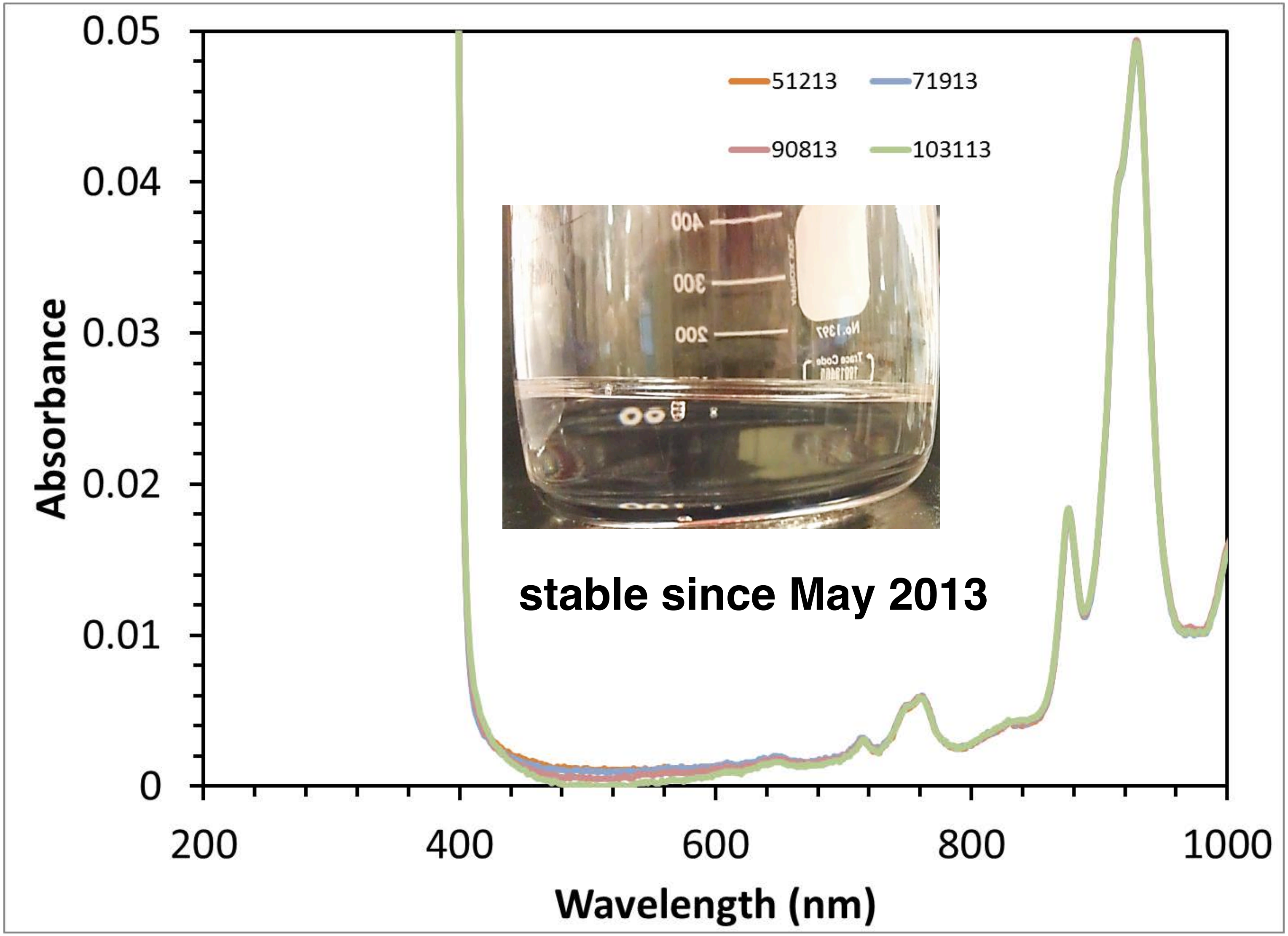
Excellent “triple” PSD demonstrated for crystals, liquids, and plastic

Improved optical and loading for Li-LS

(2^{nd} formulation)



0.1% Li-LS (2nd formula)



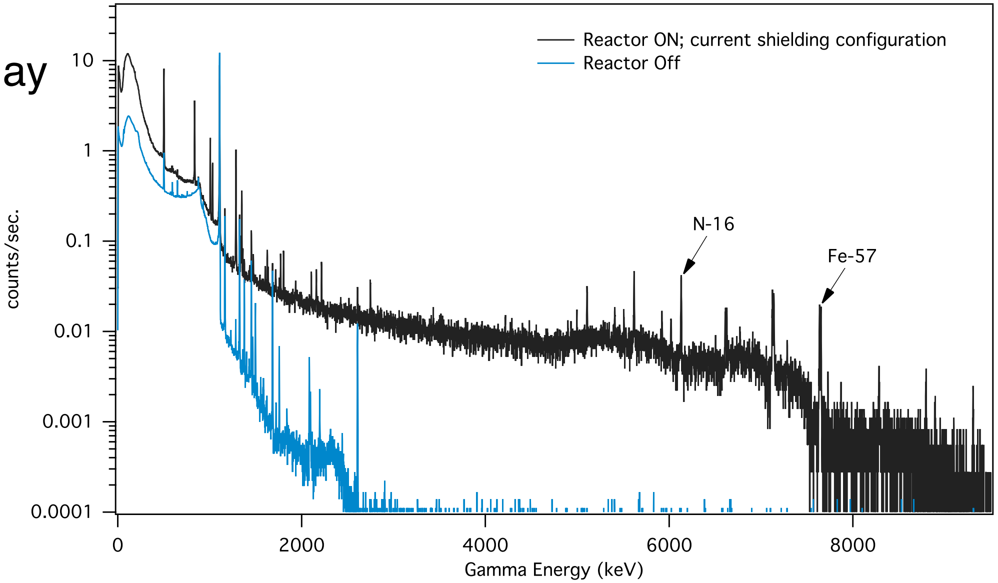
LS Summary

- R&D:
  - Produce 10 liters (each) of 0.1% ^{6}Li- and 0.1% Gd- LS for prototyping testing in Jan. 2014
    - side-by-side comparison
    - formulations of 0.1% ^{6}Li-LS (1st) and 0.1% Gd-LS to readiness of detector measurement.
- In parallel
    - Continue the scintillator development (2nd formulation of 0.1% Li-LS shows improved performance than 1st formulation).
    - Optimize the 0.1% ^{6}Li-LS and 0.1% Gd-LS performance (including enhanced background rejection, if needed) within safety requirements; followed by compatibility and stability tests.
- Finalize the scintillator optimization (in plan, produce larger scale in hundreds of liters of the refined, selected scintillator for 2nd detector deployment).
- A 10-ton scintillator production plan for the proposed PROSPECT experiment.

Background Surveys at US Reactors

Expected neutrino signal (near) ~1000/day

Near reactor w/ little to no overburden

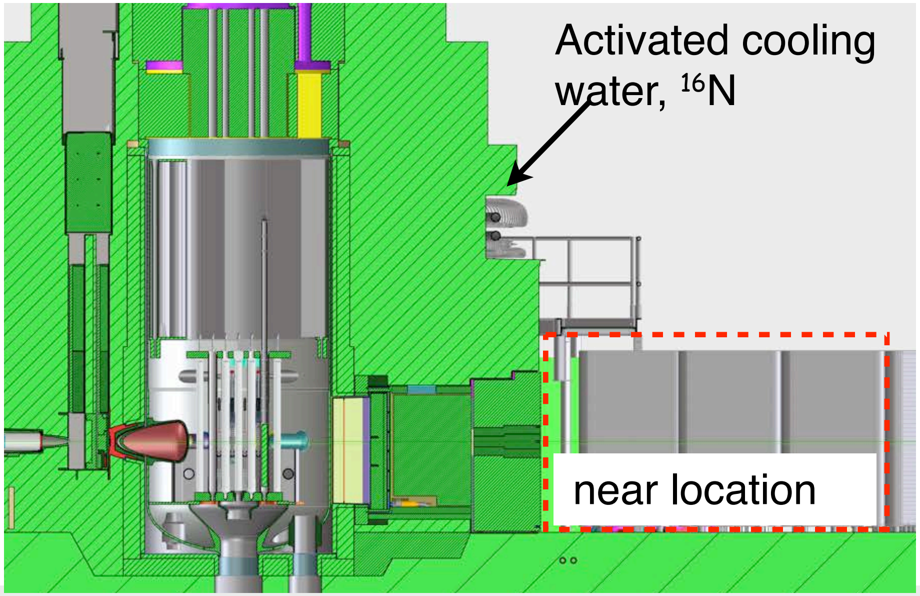


Accidental Coincidences

1. Gammas (primarily neutron capture)
2. Fast neutrons (reactor and cosmogenic)

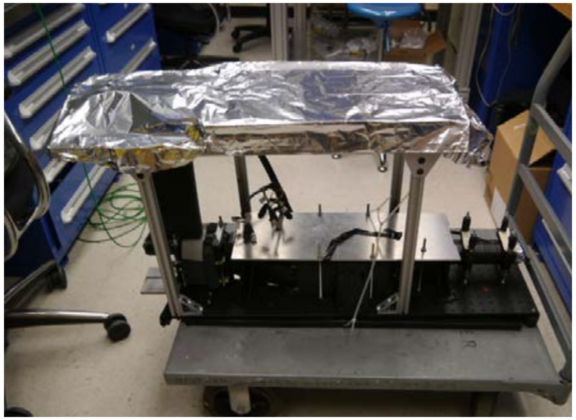
Correlated events

1. Fast neutrons (reactor and cosmogenic)
2. Cosmics (muons + secondaries)
3. Radioisotopes (e.g. ^{8}He, ^{9}Li)

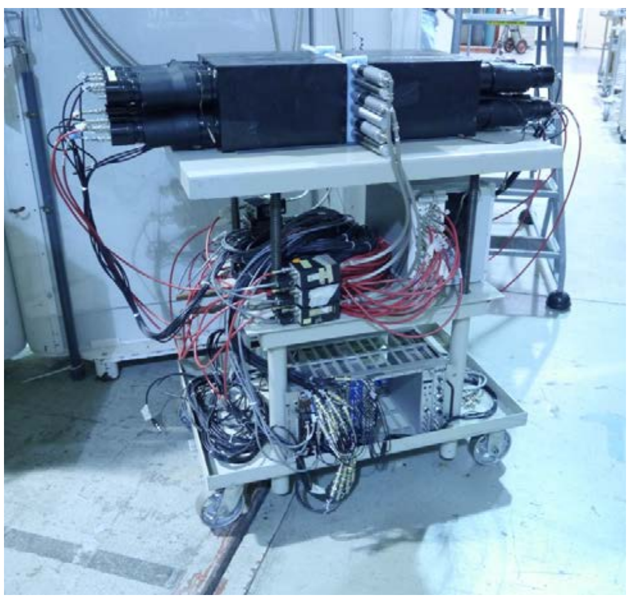


Detailed background surveys in progress

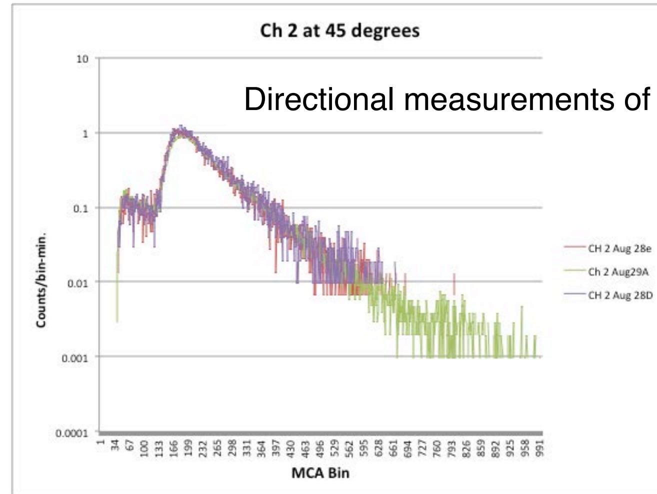
Background Surveys at US Reactors



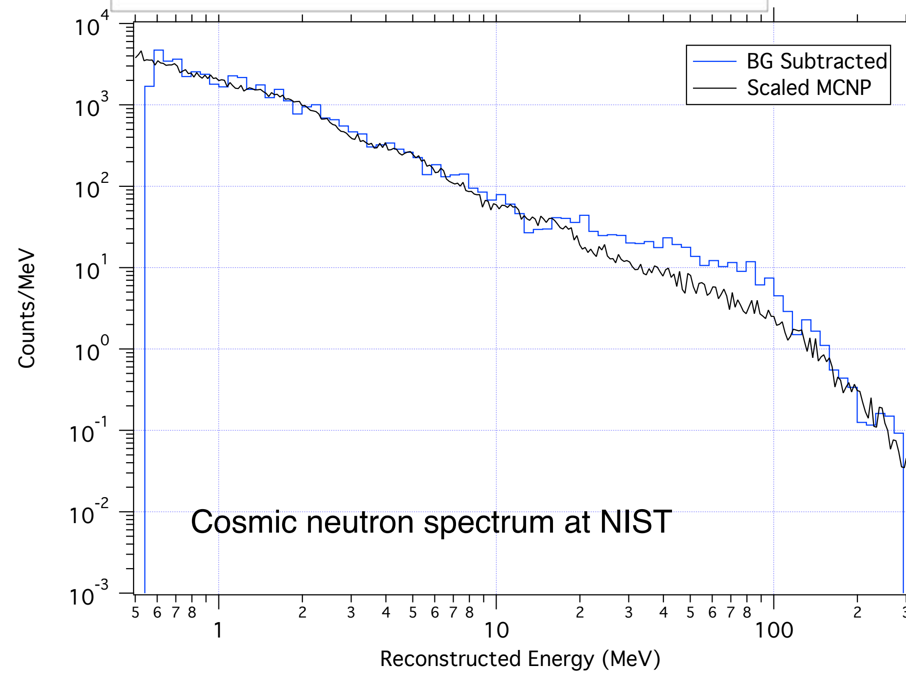
Muon telescope



FaNS-1 neutron spectrometer



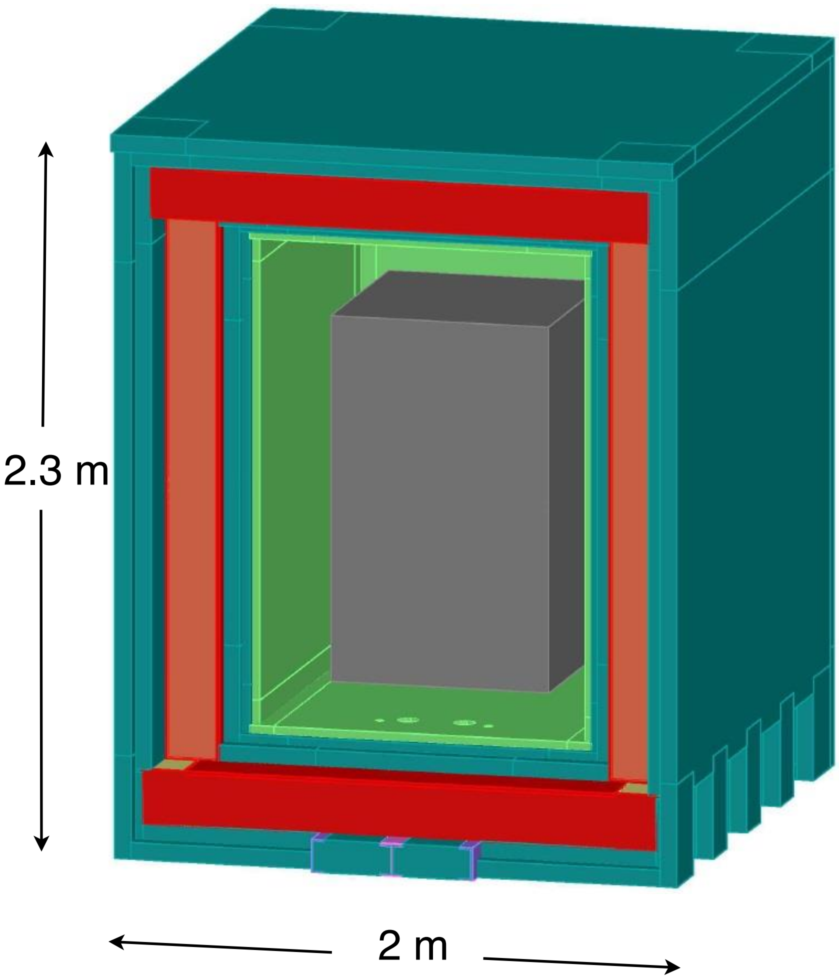
Directional measurements of overburden



Cosmic neutron spectrum at NIST

Prototyping, Shielding and MC Validation

miniTimeCube Shield
(Design substantially complete)



Several prototype segments will be fully characterized an then run *in situ* at NIST reactor.

Combined with a shield being built for the miniTimeCube experiment, these will be used to:

❶ Validate Shielding Monte Carlo

❷ Scintillator Testing

❸ in situ background measurements

US Research Reactors

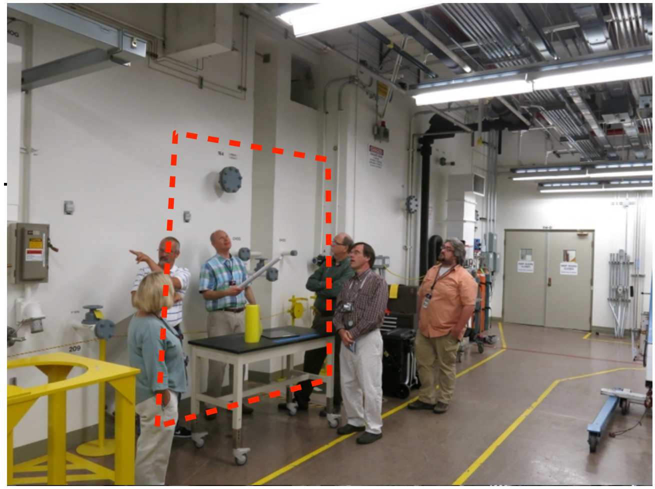
Reactor Parameters and Baselines

Site	Power (MW_{th})	Duty Cycle	Near Detector		Far Detector	
			Baseline (m)	Avg. Flux	Baseline (m)	Avg. Flux
NIST	20	68%	3.9	1.0	15.5	1.0
HFIR	85	41%	6.7	0.96	18	1.93
ATR	120	68%	9.5	1.31	18.5	4.30

Proposed Near Detector Sites

NBSR, NIST

ATR, INL



HFIR, ORNL

US Research Reactors

Reactor Parameters and Baselines

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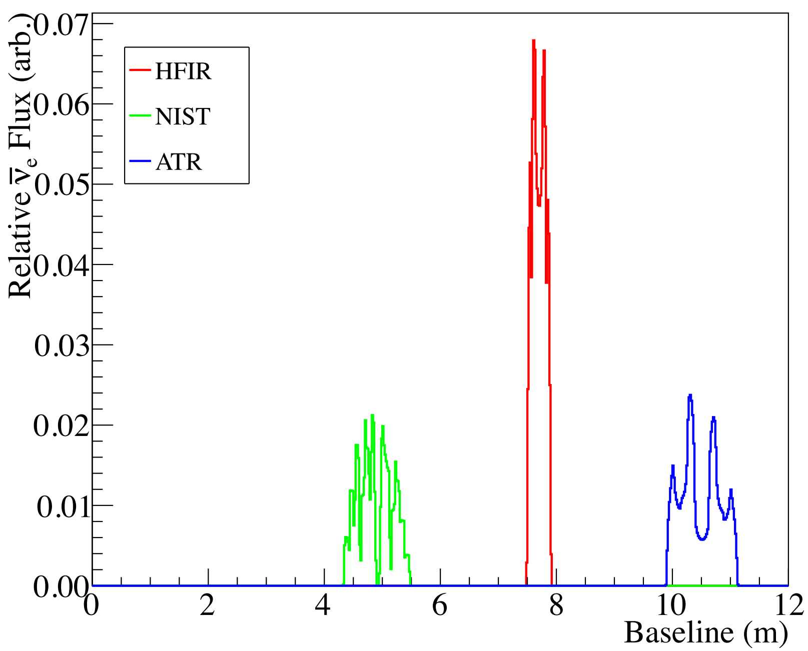
Normalized Flux at Near Detectors



Sensitivity