PROSPECT: A Precision Reactor Oscillation and Spectrum Experiment

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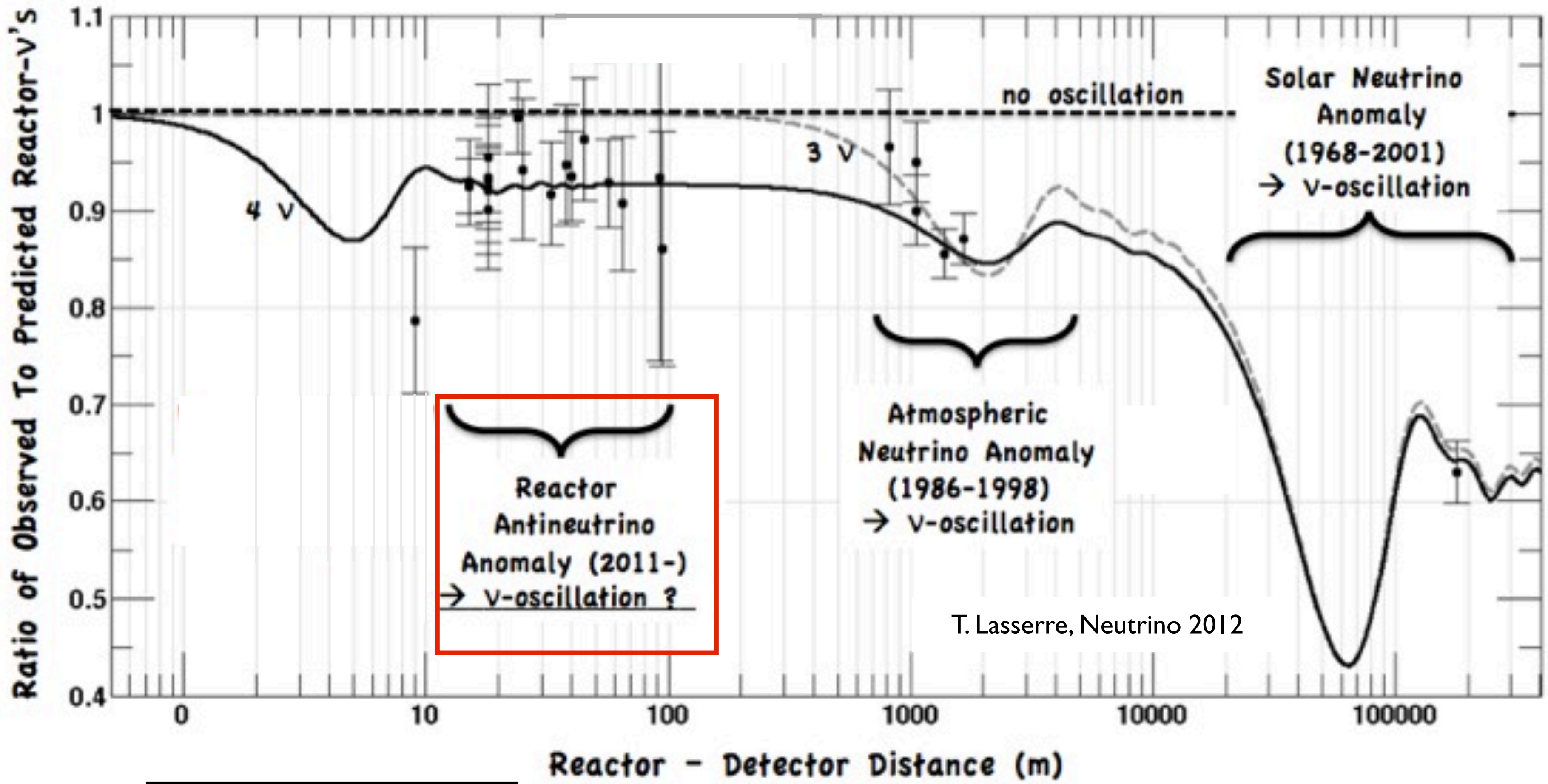
University of Cincinnati

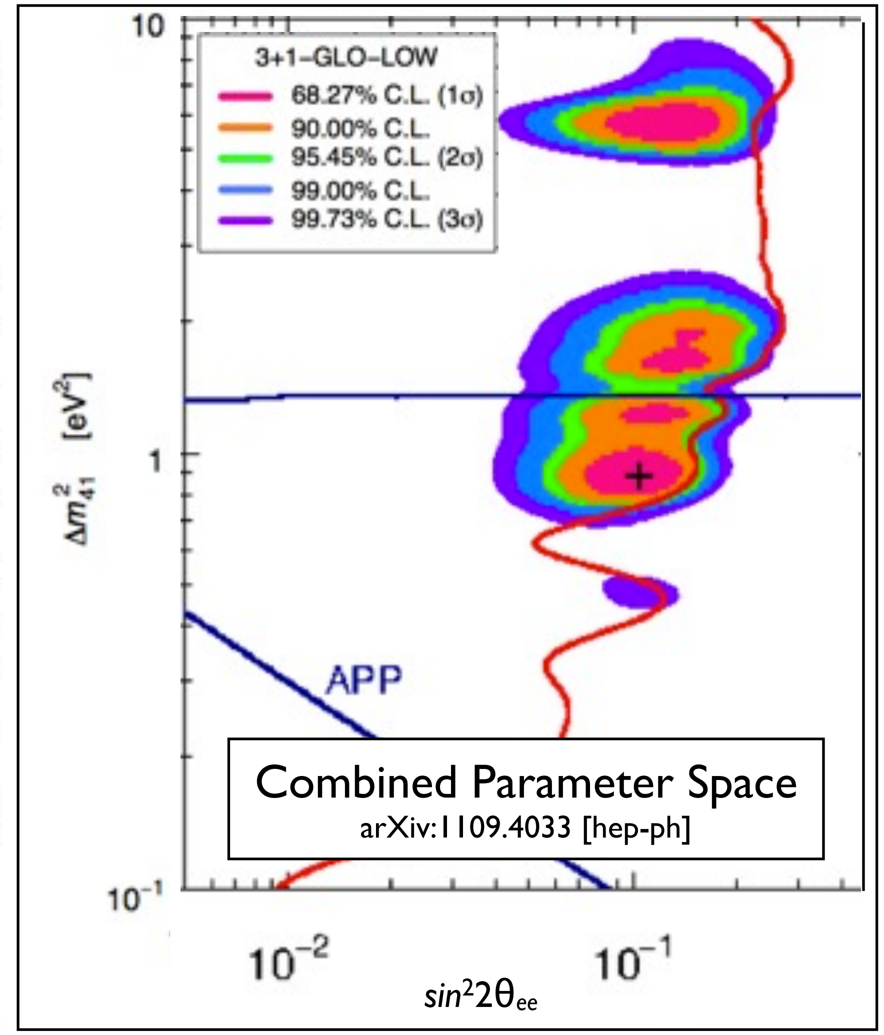
On Behalf of the PROSPECT Collaboration

New Physics: Sterile Neutrinos

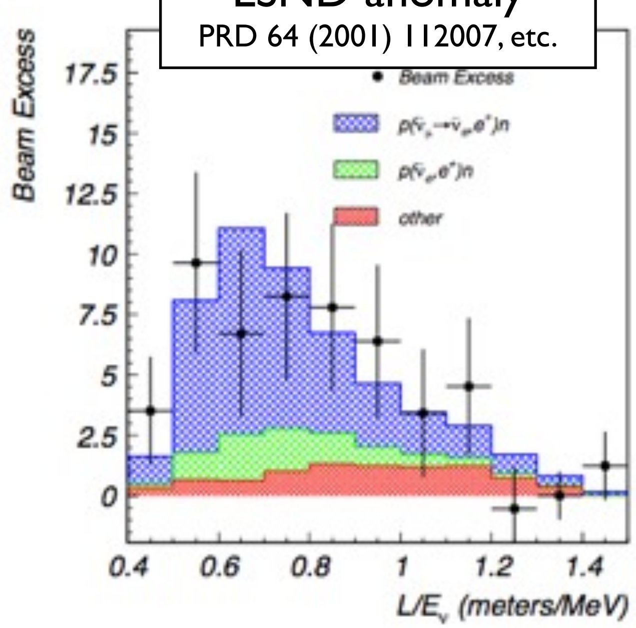
- Many anomalies in ν physics can be collectively explained by existence of eV-scale sterile ν:



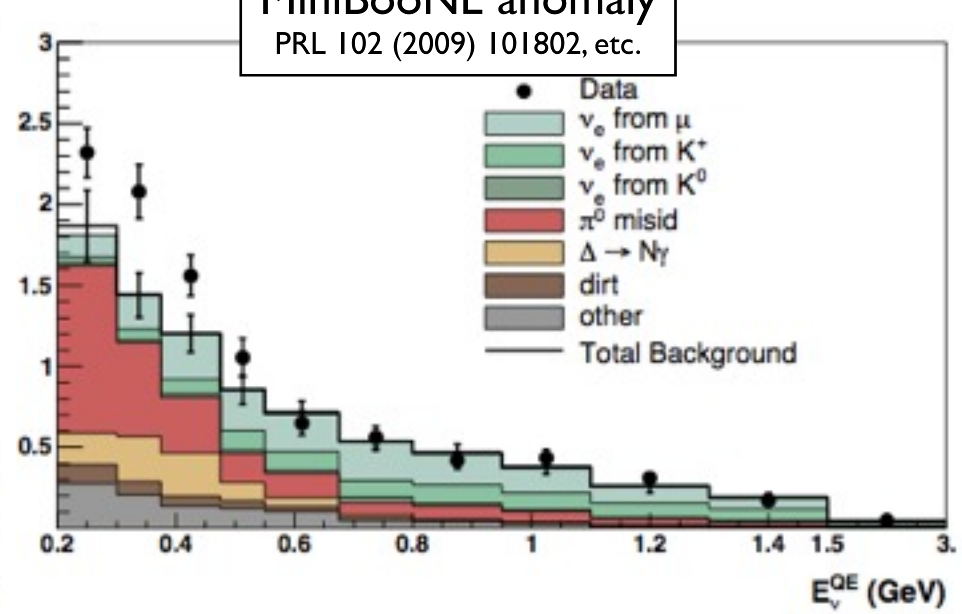
T. Lasserre, Neutrino 2012



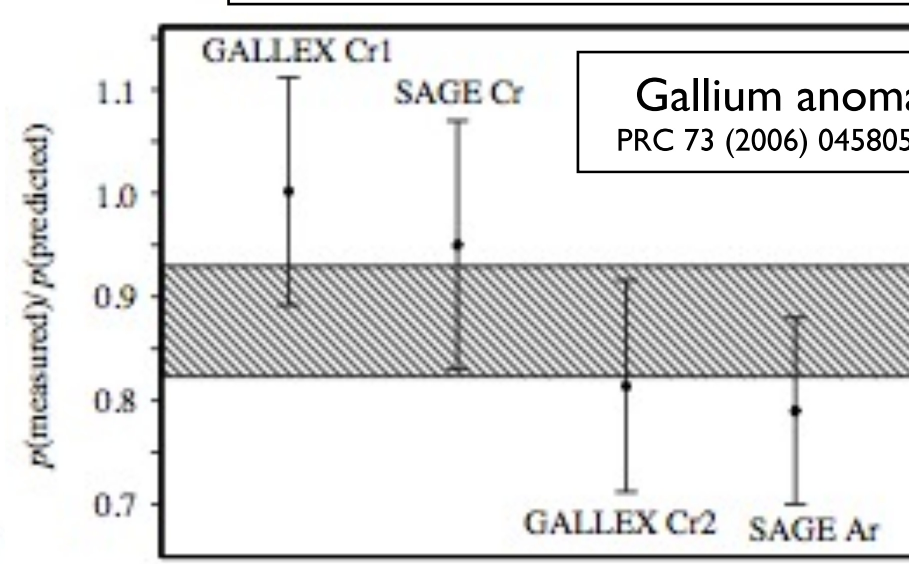
Combined Parameter Space
arXiv:1109.4033 [hep-ph]



LSND anomaly
PRD 64 (2001) 112007, etc.



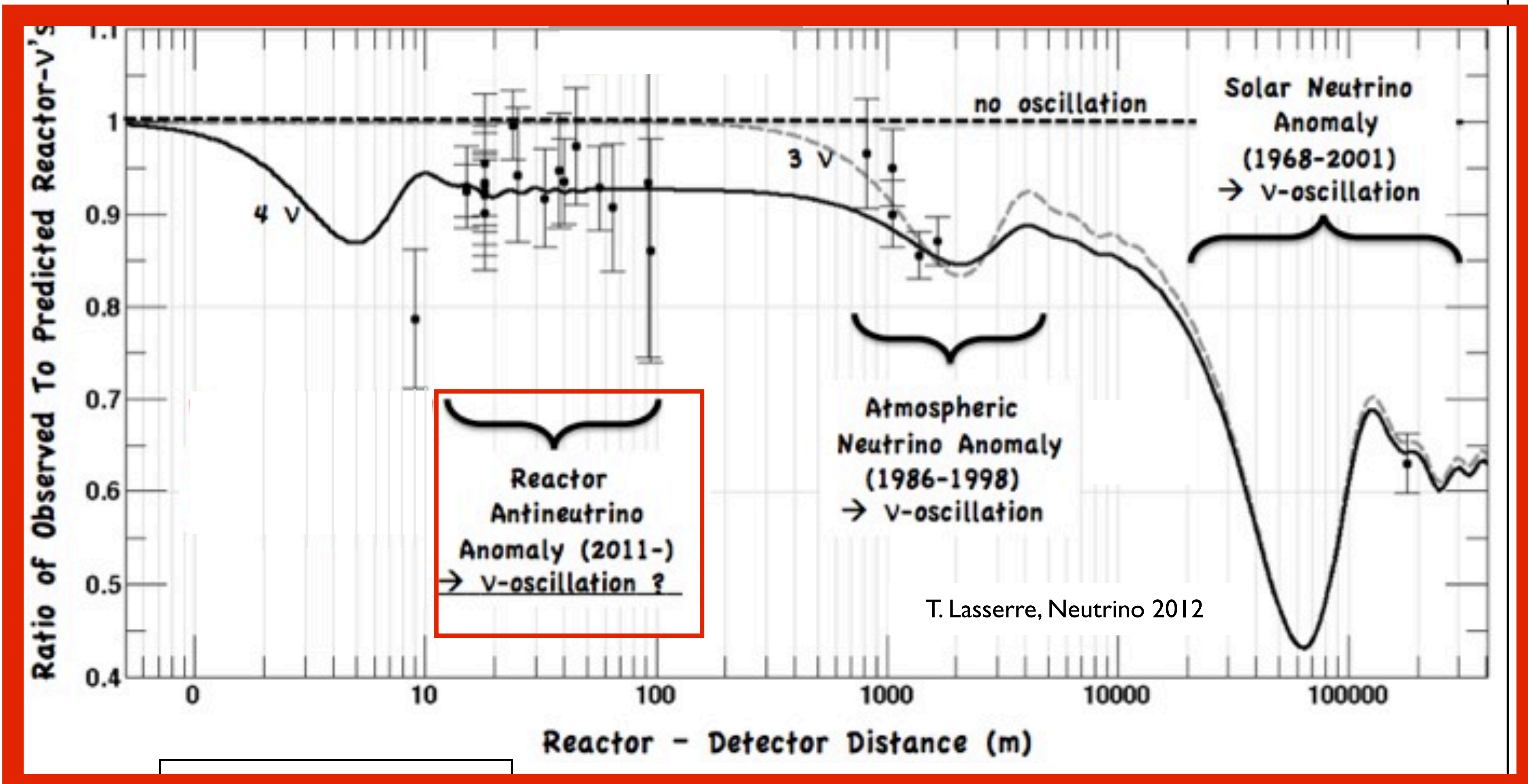
MiniBooNE anomaly
PRL 102 (2009) 101802, etc.

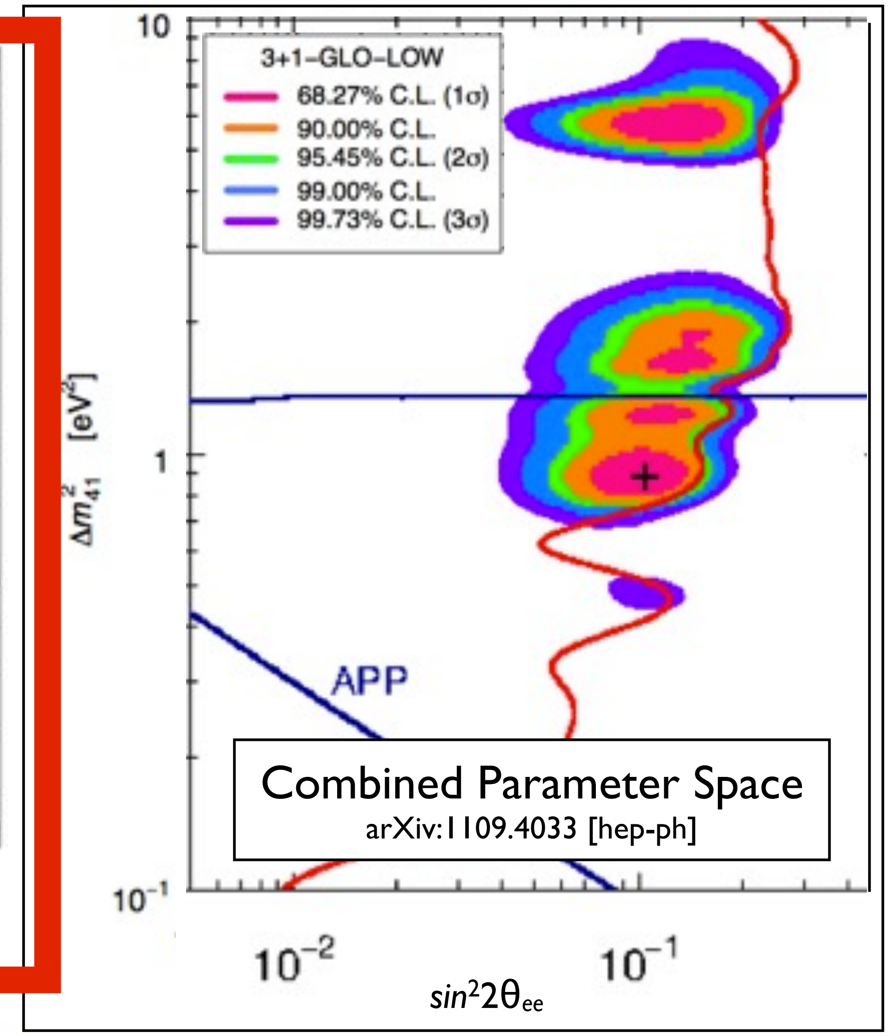


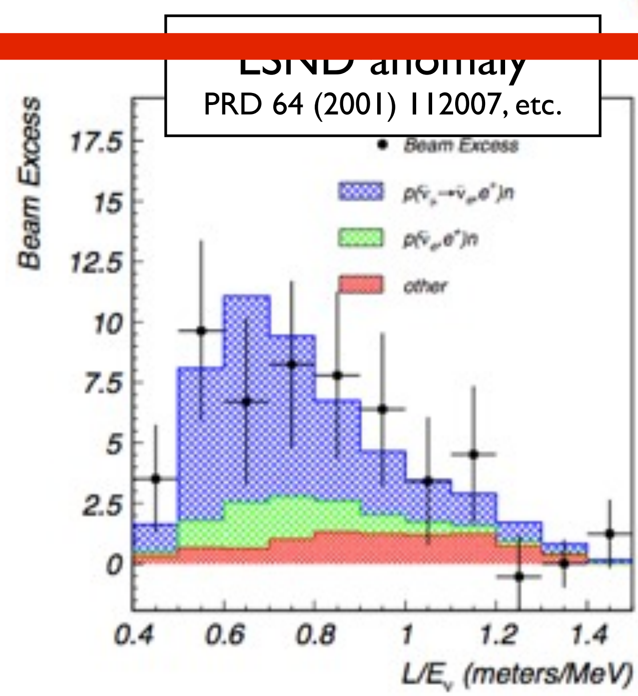
Gallium anomaly
PRC 73 (2006) 045805, etc.

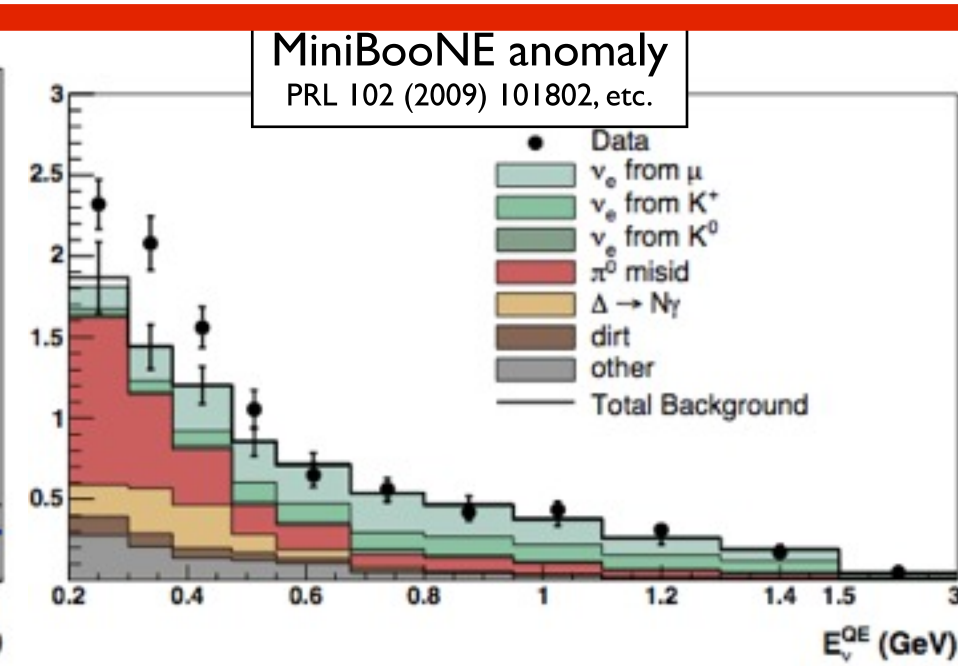
New Physics: Sterile Neutrinos

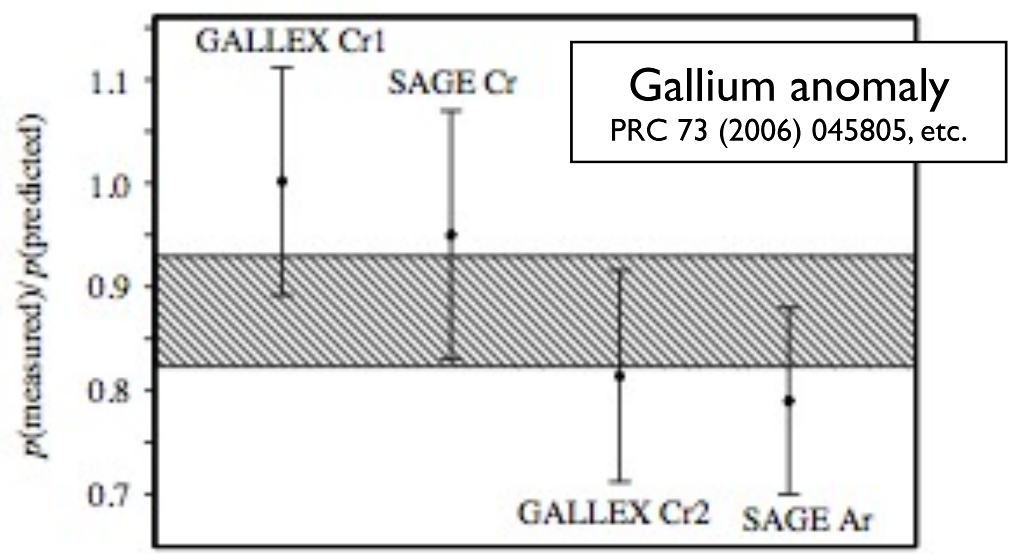
- Many anomalies in ν physics can be collectively explained by existence of eV-scale sterile ν:





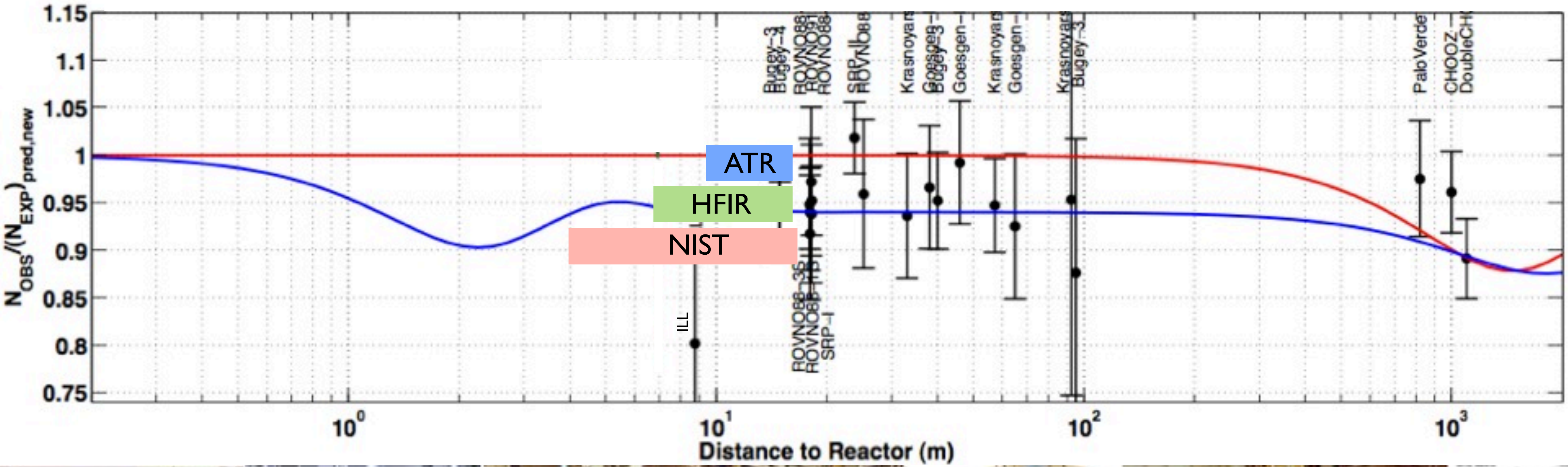


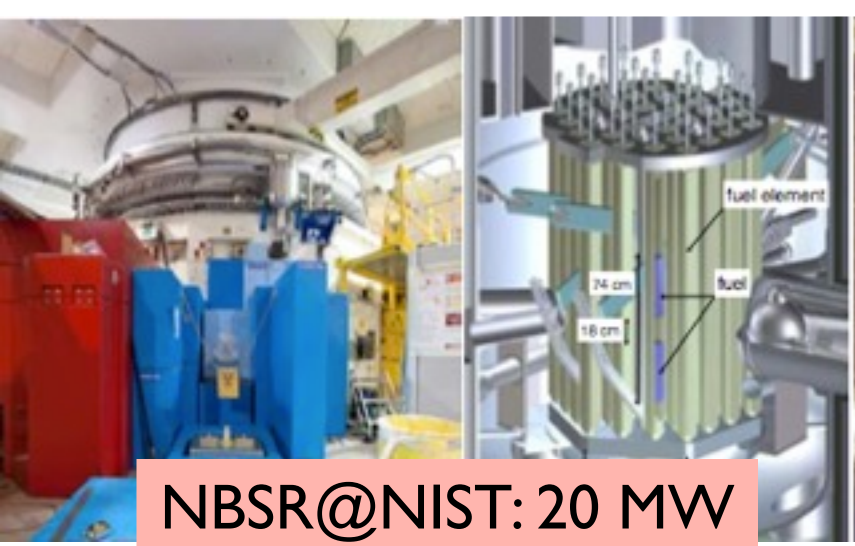




Opportunities at Research Reactors

- Need an MeV-scale short-baseline (SBL) probe of L/E behavior
  - Absolute reactor flux checks are nice, but not good enough
- US research reactors provide a venue for oscillation searches at shortest-ever reactor baselines





NBSR@NIST: 20 MW

Gaithersburg, MD

ATR@INL: 110 MW

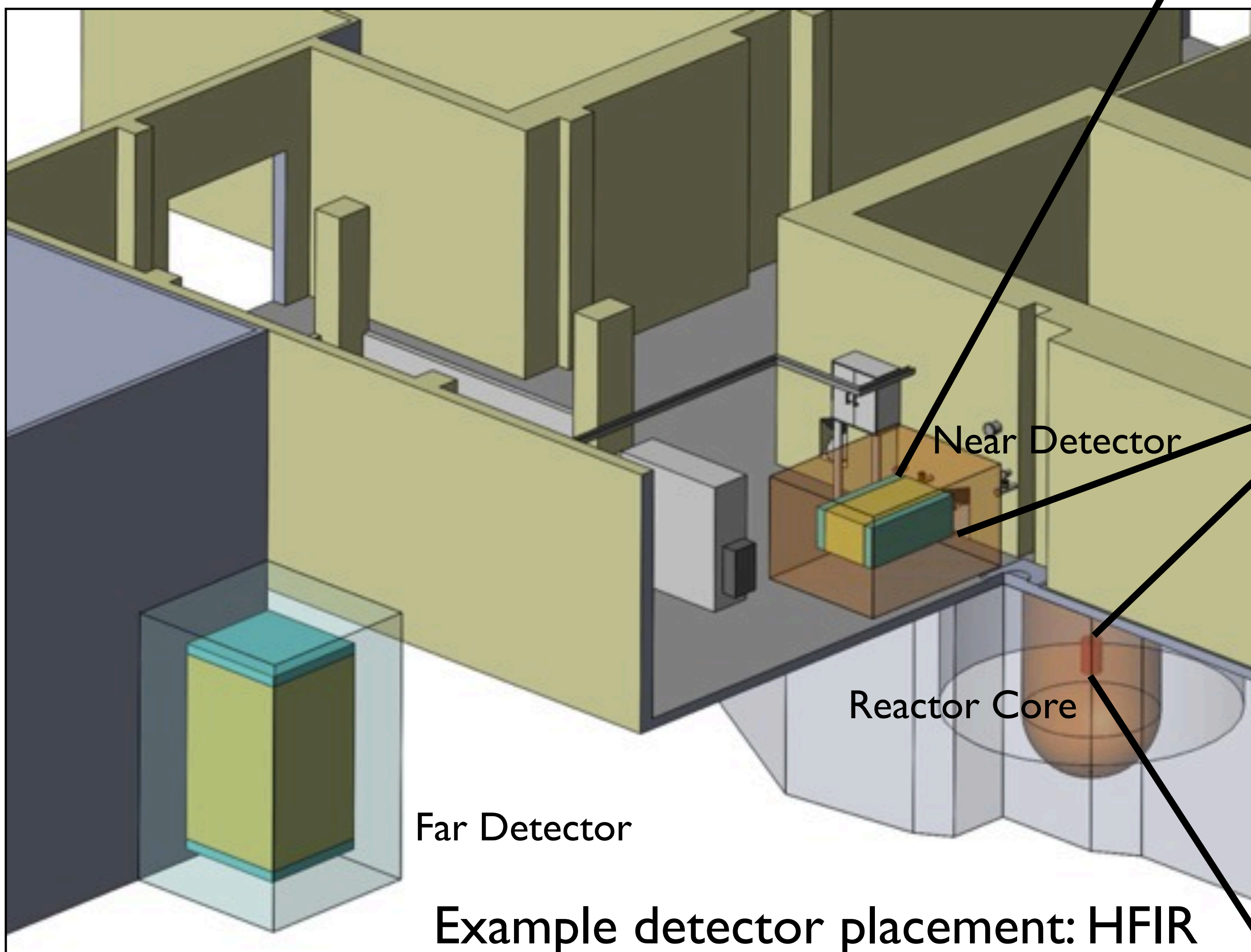
Idaho Falls, ID

HFIR@ORNL: 85 MW

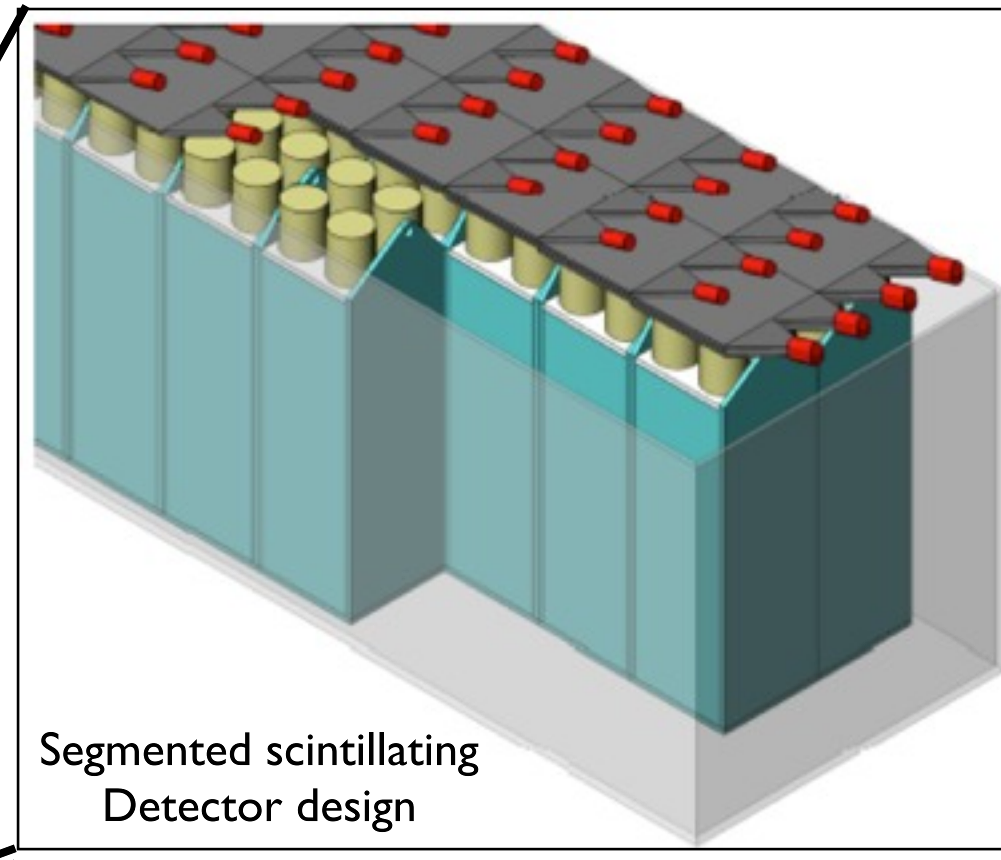
Oak Ridge, TN

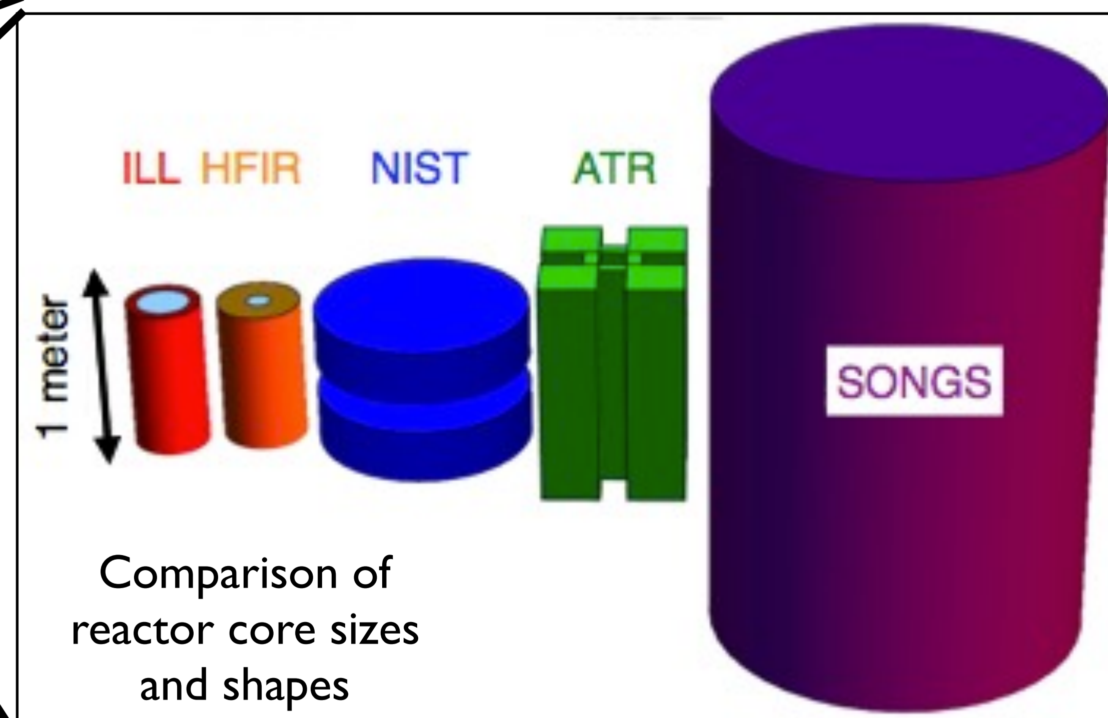
PROSPECT Experiment Design

- Segmented scintillator detectors sited at short baselines from a compact, highly-enriched reactor core
  - Ton-scale segmented near detector target
  - Ten ton-scale segmented far detector target
  - Movable near detector



Example detector placement: HFIR


Segmented scintillating Detector design

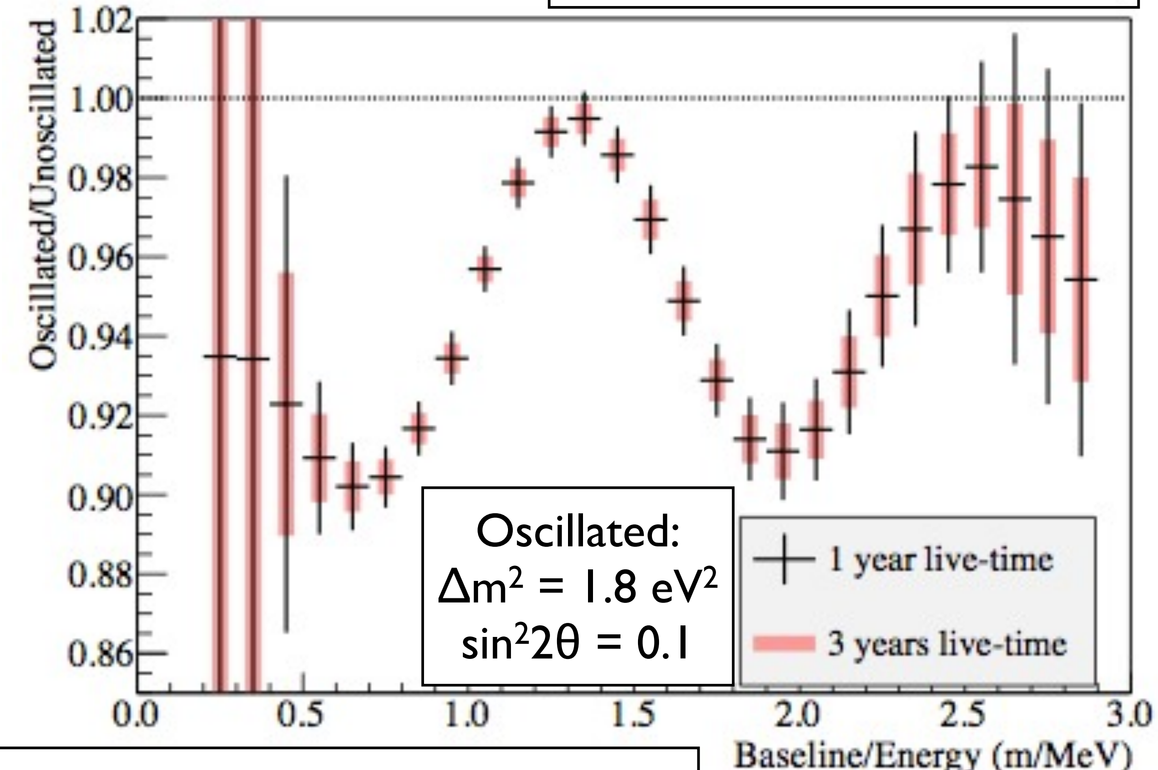


Comparison of reactor core sizes and shapes

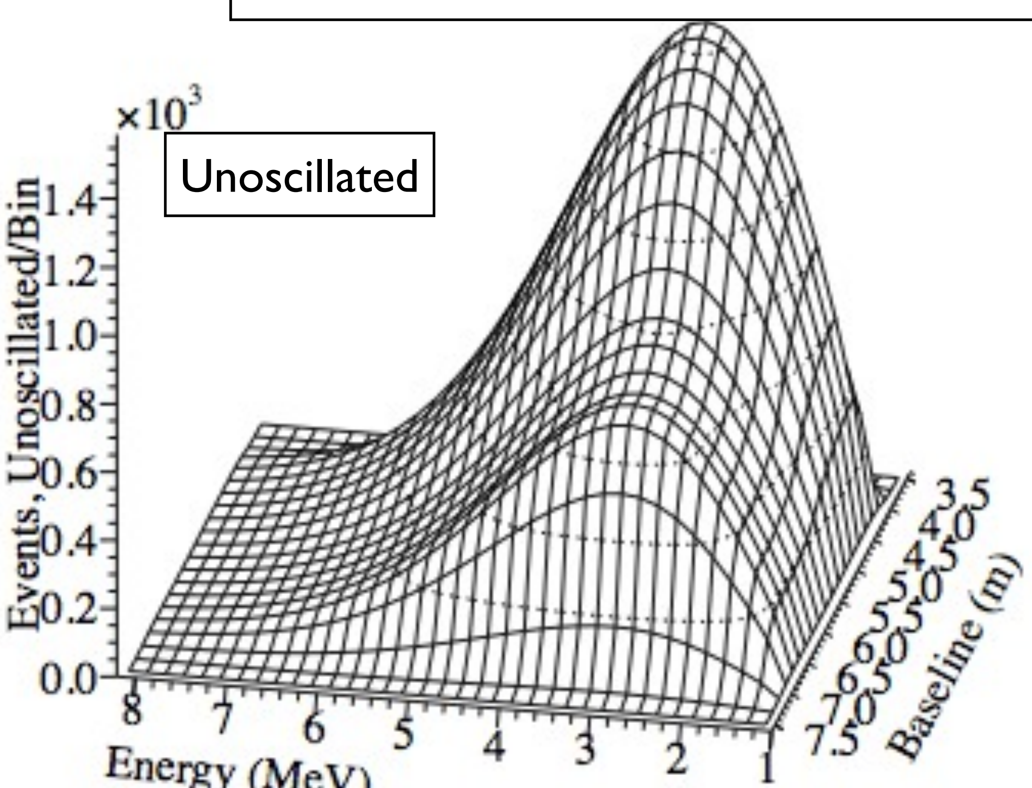
Very-Short-Baseline Reactor Signal

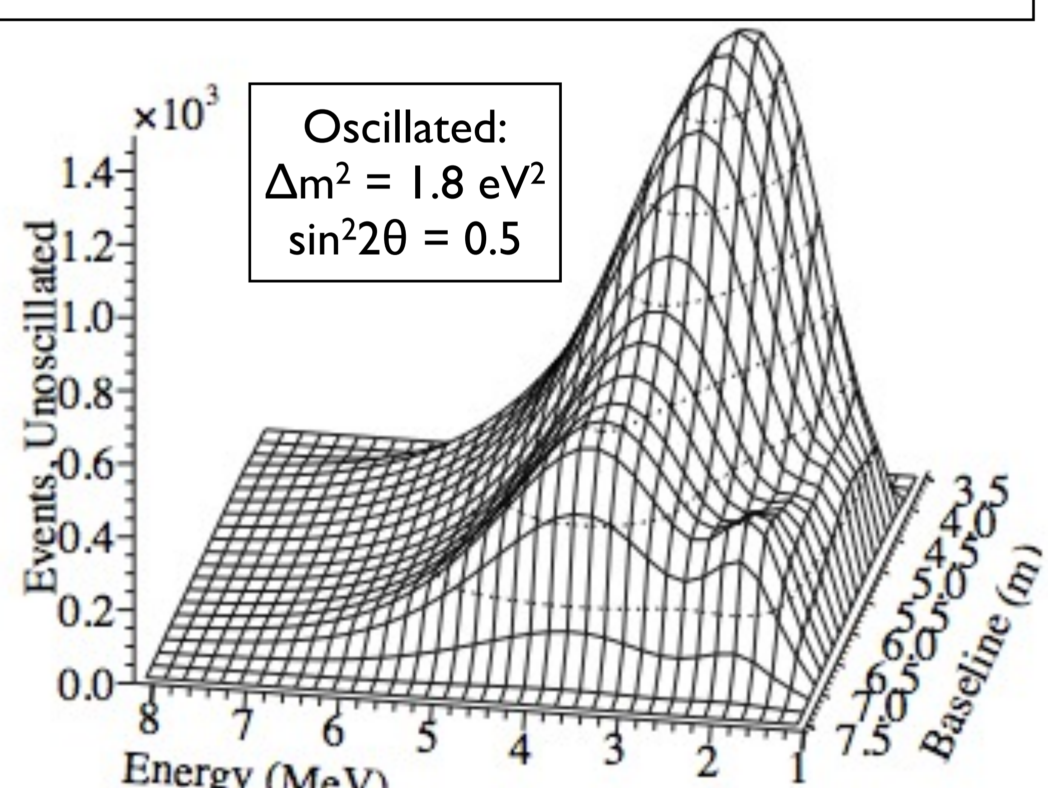
- Detect reactor neutrinos via inverse beta decay interaction in liquid scintillator detector
- Look for spectral distortions in position, energy
- Characteristic L/E oscillation pattern

Heeger, Mumm, Tobin, BRL
PRD D**87** (2013)



One 3x1x1 m³ detector, 1m³ 20 MW HEU core, 4m closest distance





30% Efficiency

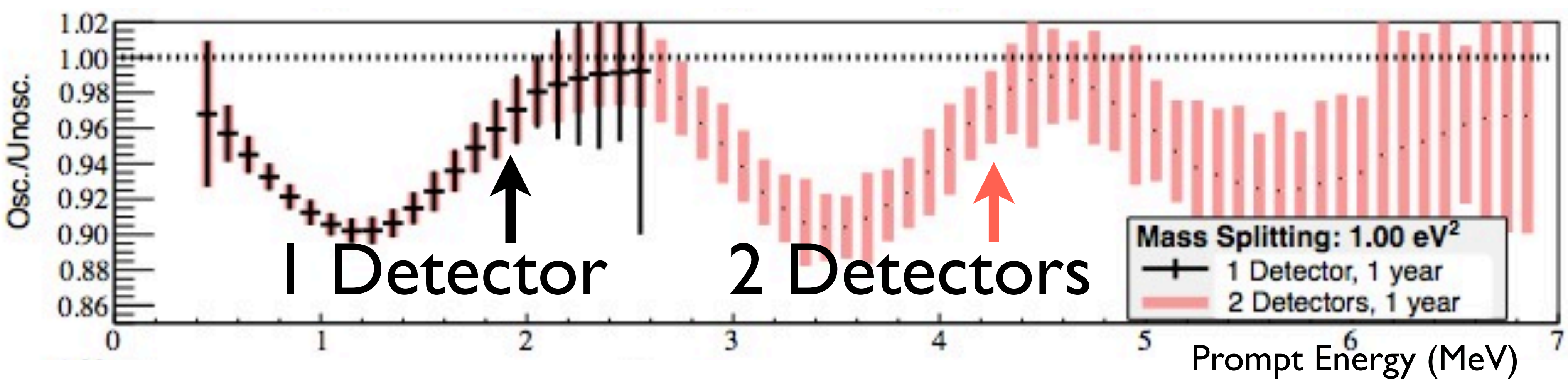
15cm position resolution

10%/Sqrt(E) Energy Resolution

Multiple Segmented Detectors

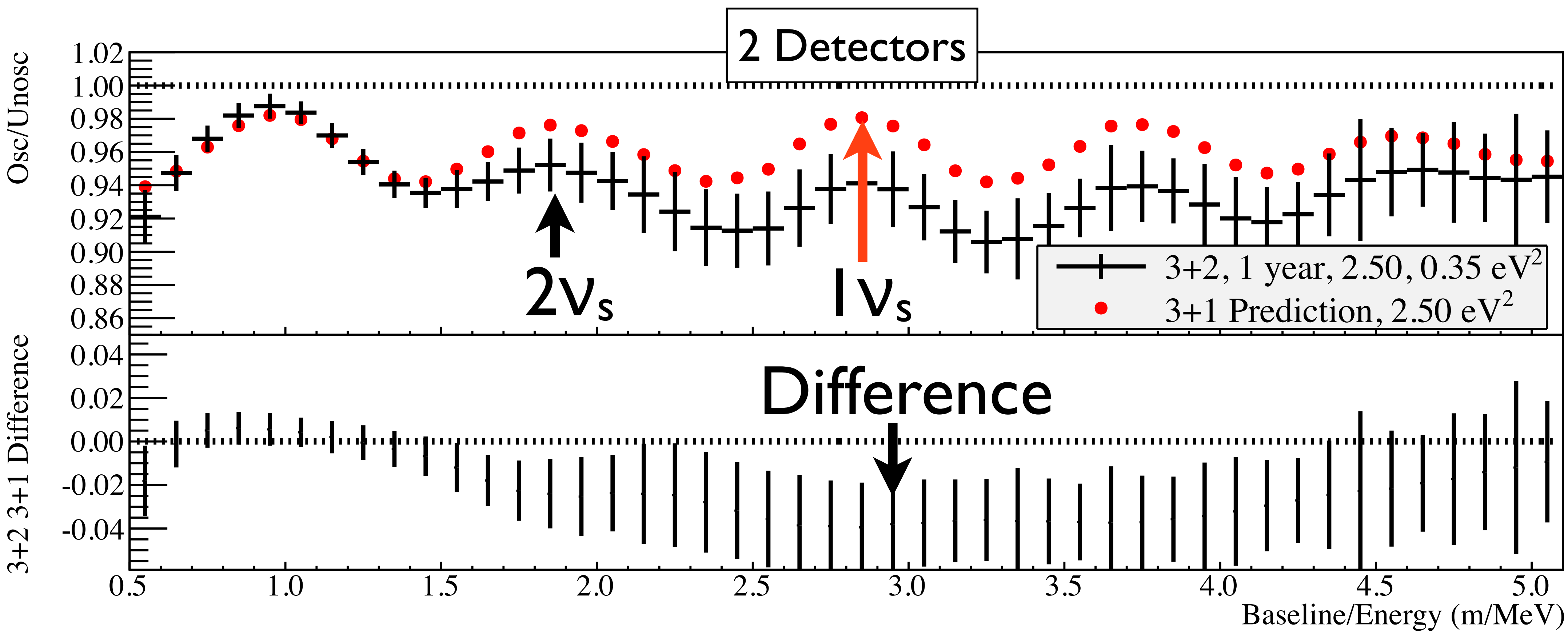
- Multiple detectors give better L/E coverage
  - Example: 2m long detectors at 4 and 15 m closest distances to a 20 MW reactor

Heeger, Mumm, BRL
arXiv:1307.2859 (2013)



Error bars: Statistical unc.

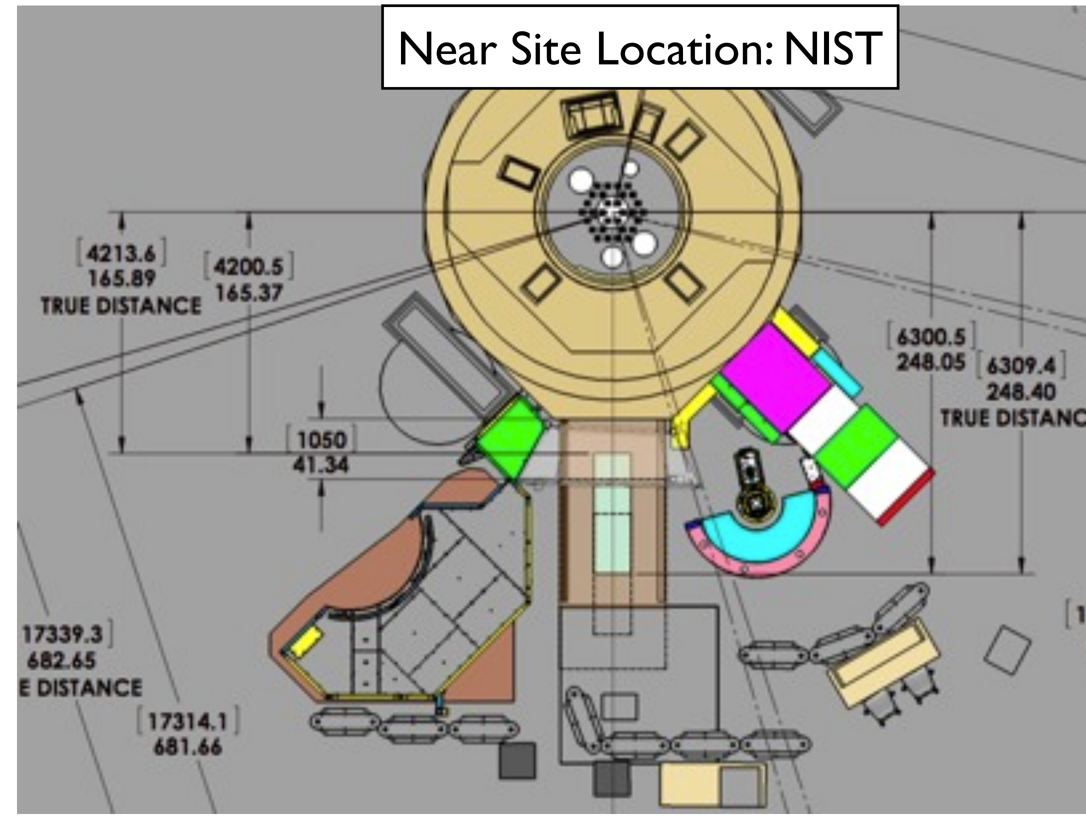
- Ability to distinguish existence of multiple sterile ν!

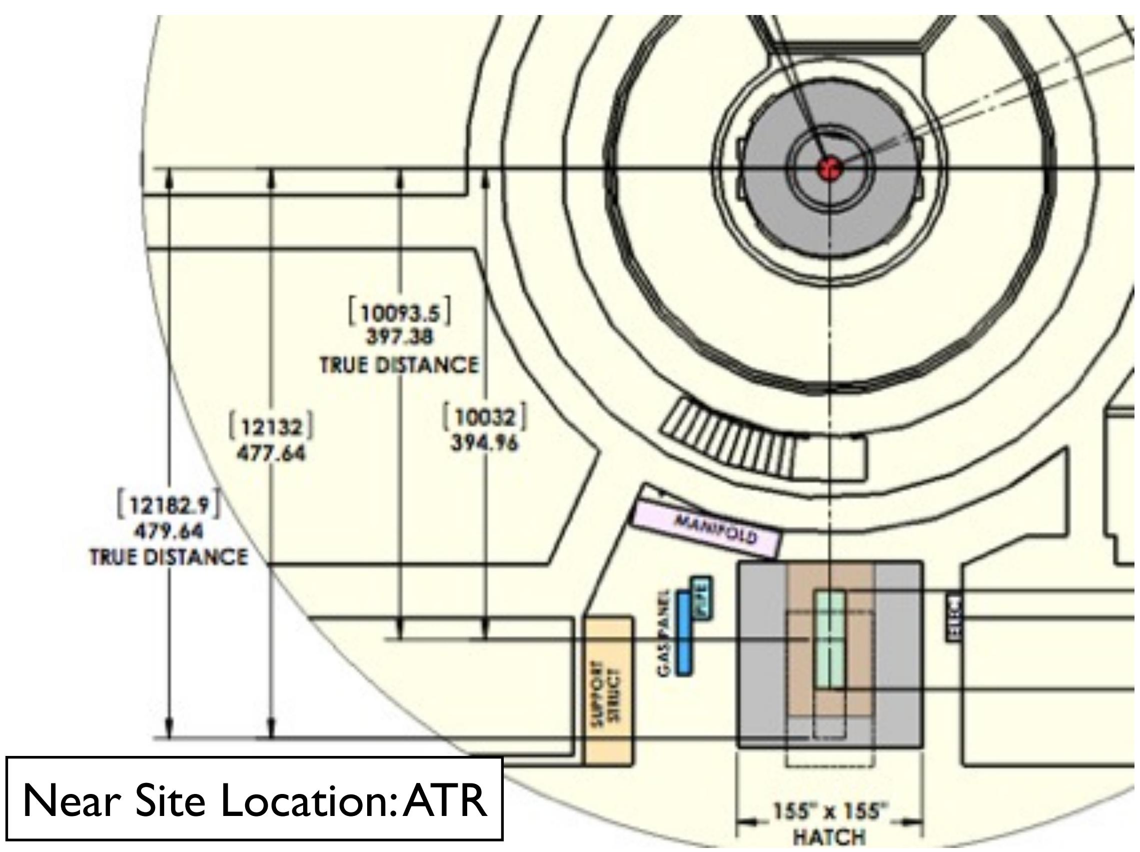


Error bars: Statistical unc.

Experiment Locations, Facilities

- Identified, characterized detector sites at each location
  - Space constraints
  - Floor-loading
  - Backgrounds (next talk)
  - On-site resources, support, access
- Site decision is imminent
  - Facilities interested in hosting experiment
  - Scientific collaborators from each site





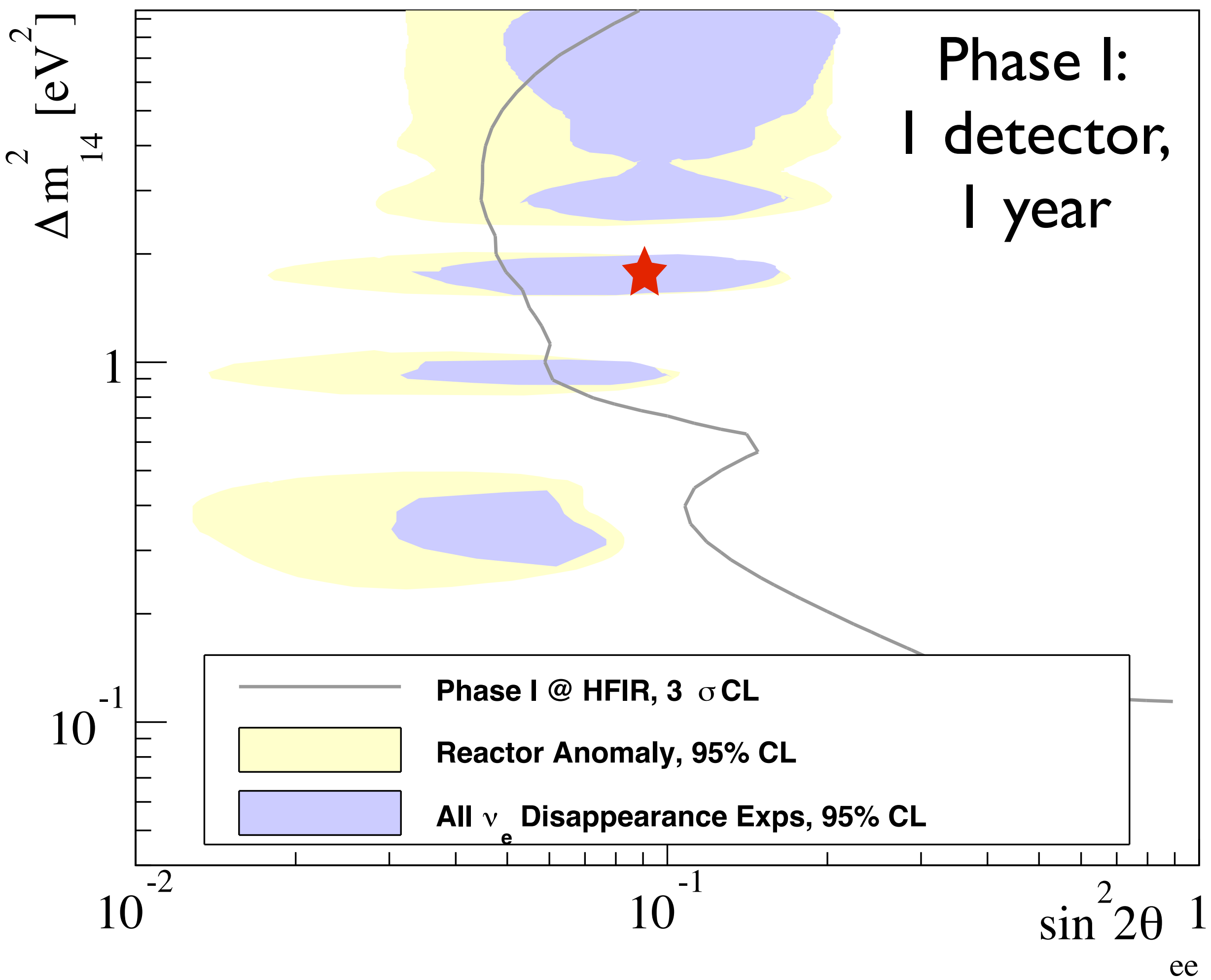
Sensitivity Estimates

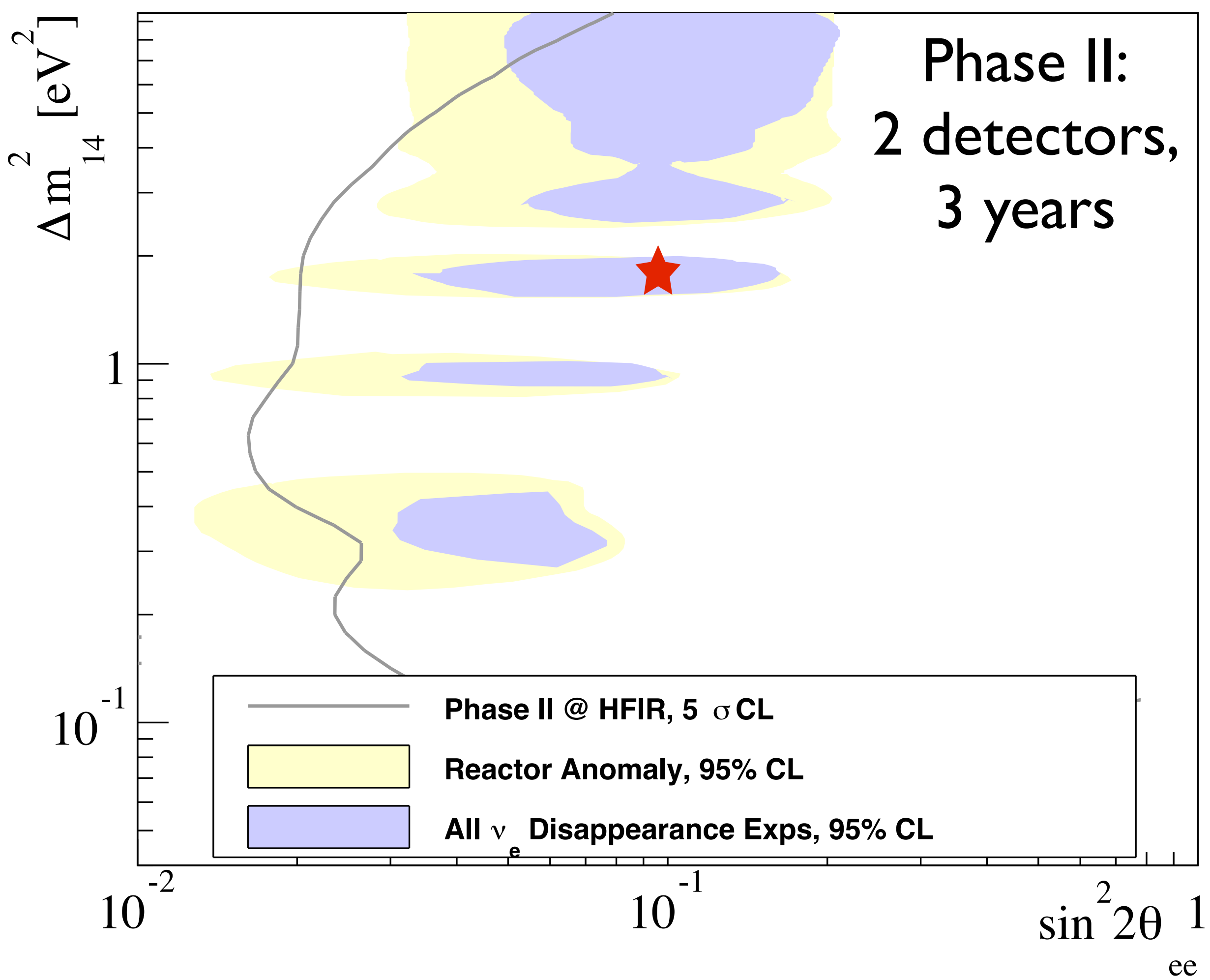
- Can use experiment inputs to estimate event rates/spectra, sensitivity to sterile neutrino oscillation
- Phase I: probe favored oscillation parameters on short timescale
  - Larger near detector, currently being investigated for some sites, will enhance Phase I sensitivity
- Phase II: address majority of suggested parameter space at 5σ

Estimated Signal Statistics

Site	Phase I, 1 year, 1det	Phase II, 3 year, 2det
HFIR	190k	2.1M

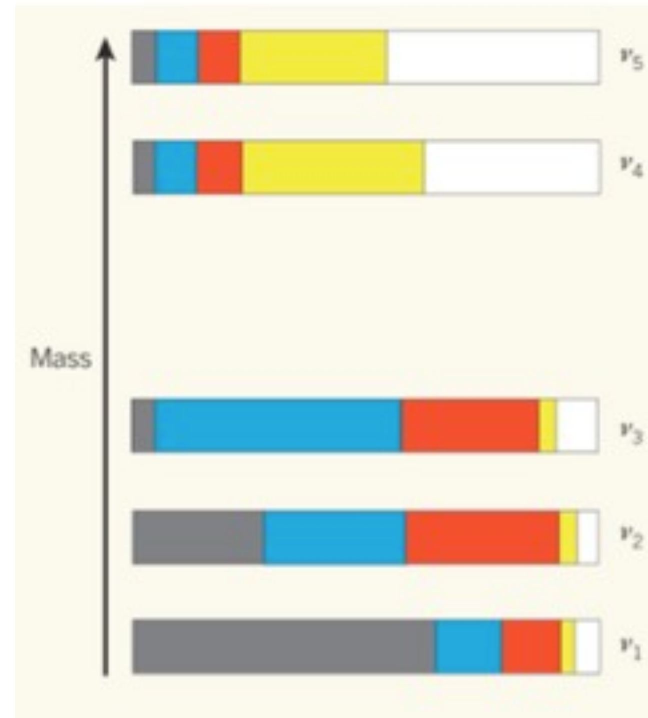
Assumes 30% detection efficiency

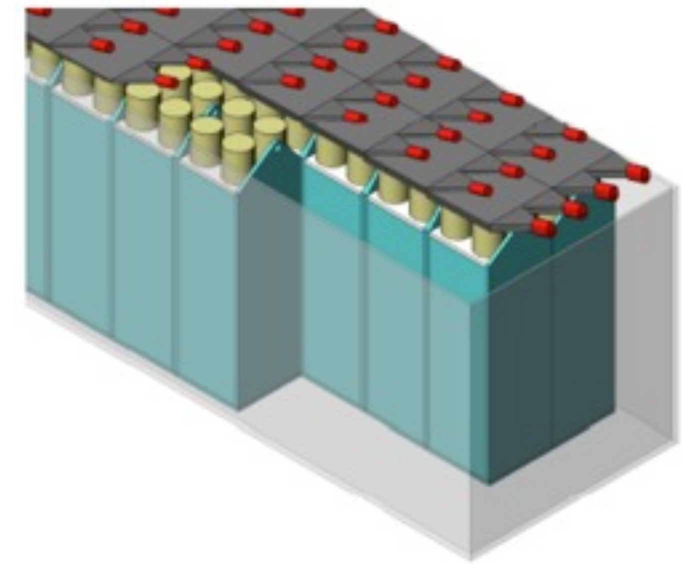




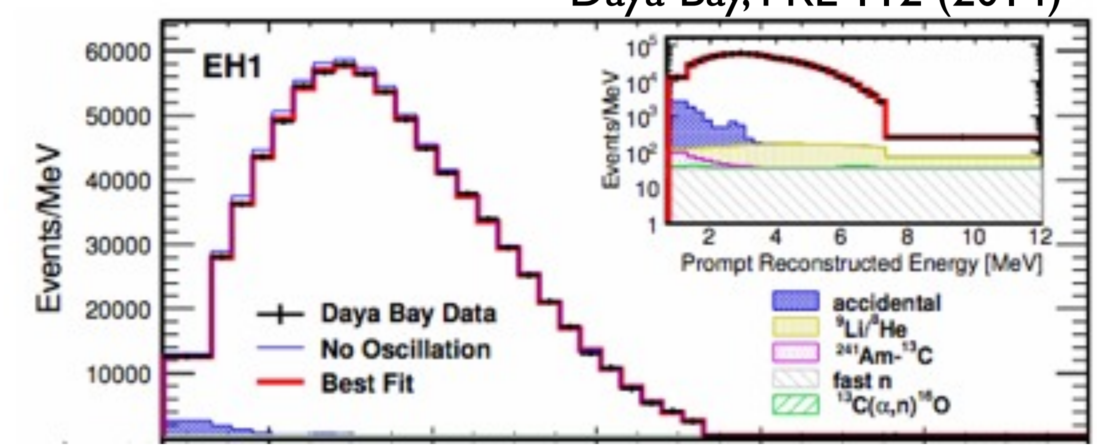
Scientific Opportunities

- Searches for new physics
  - Searching for sterile neutrino oscillations at short baselines
- Reactor physics
  - Precise spectral measurement of neutrinos from highly enriched uranium core (U-235 neutrinos)
- Detector Development
  - Development of scintillators for neutron detection: pulse-shape discriminating Li-LS, Gd-LS
  - Demonstration of on-surface antineutrino detection
  - Synergies with applied antineutrino physics and non-proliferation communities





Daya Bay, PRL 112 (2014)



Summary

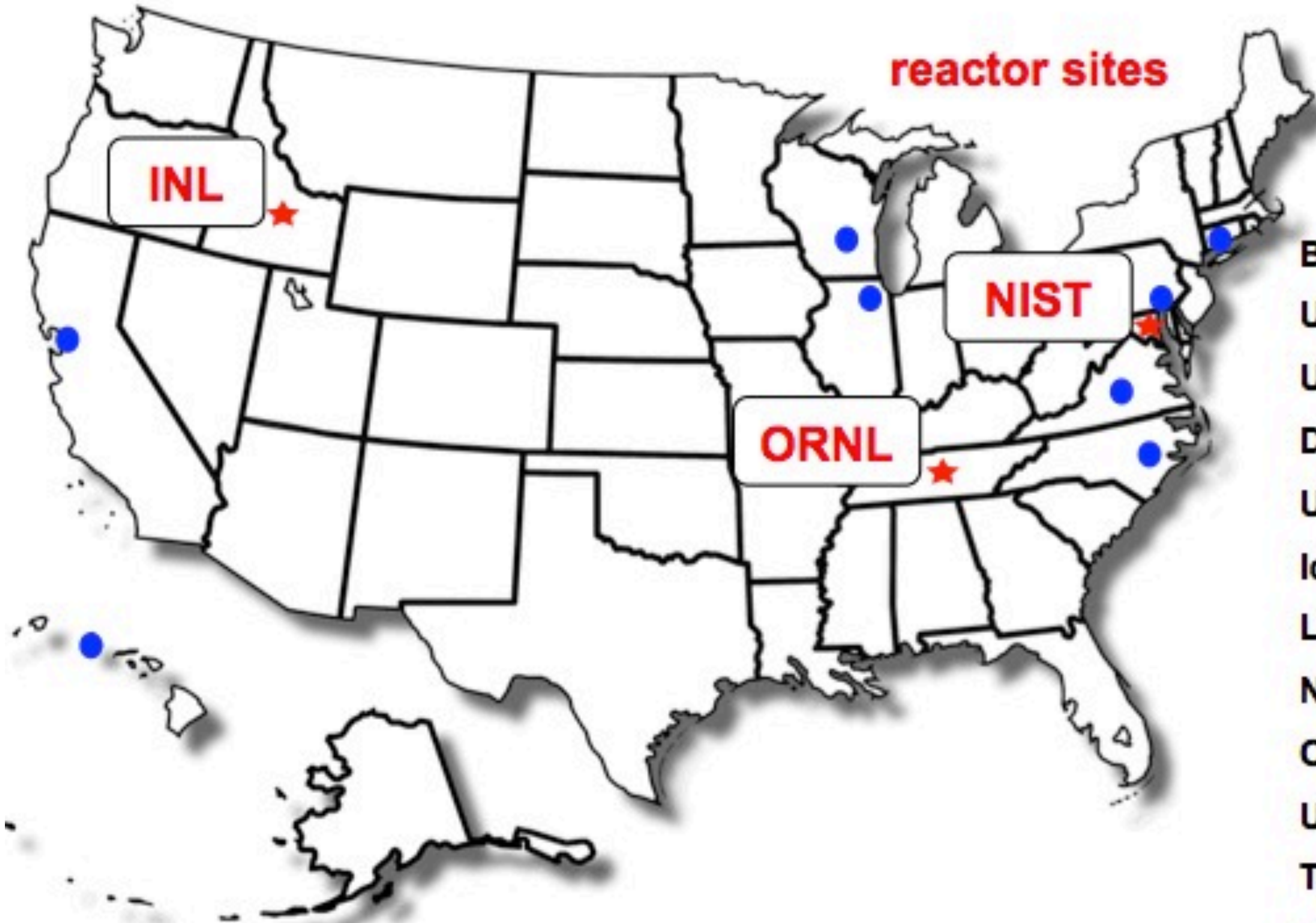
- US research reactors provide an opportunity for a high-precision, short-baseline reactor experiment

- PROSPECT will address the reactor anomaly and hints of oscillations to sterile neutrinos
  - Phase I probes favored oscillation parameters on a short timescale with a single detector
  - Phase II can address preferred region of reactor anomaly to 5σ

- PROSPECT offers opportunities for novel detector development and applications in reactor monitoring

Thanks!

PROSPECT Collaboration



- Brookhaven National Laboratory
- University of Chicago
- University of Cincinnati
- Drexel University
- University of Hawaii
- Idaho National Laboratory
- Lawrence Livermore National Laboratory
- National Institute of Standards and Technology
- Oak Ridge National Laboratory
- University of North Carolina
- Triangle Universities Nuclear Laboratory
- University of Wisconsin
- Virginia Tech
- College of William and Mary
- Yale University

Snowmass
whitepaper
arXiv:1307.7647

35 scientists
10 universities
5 national labs

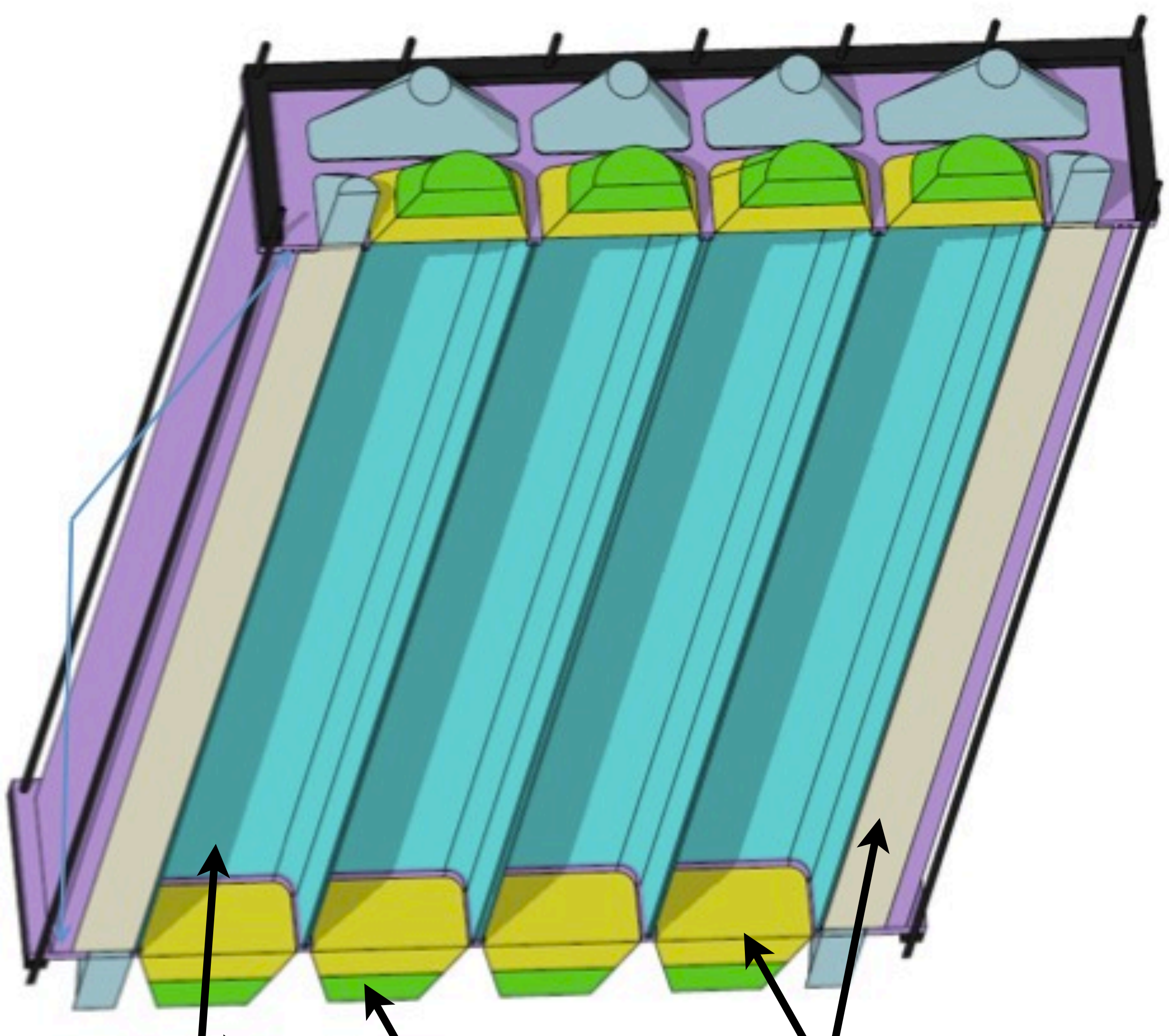
Backup

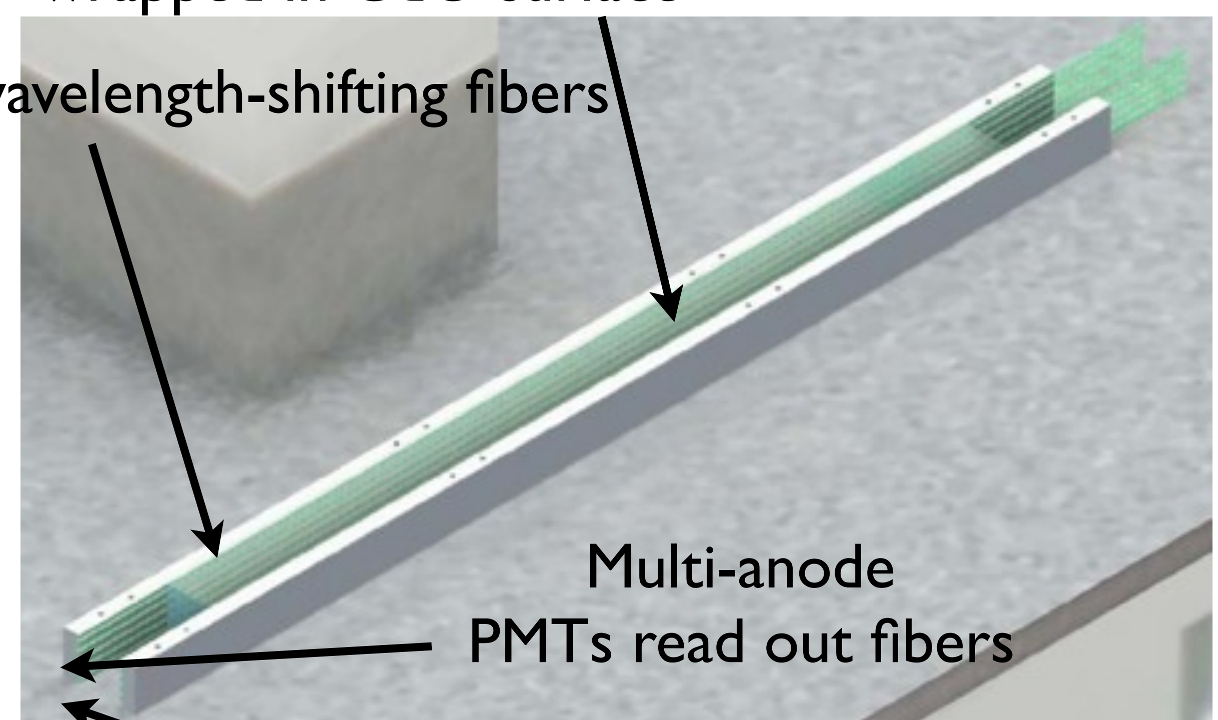
Experimental Parameters

Parameter		Value	Comment
Reactor	Power	85 MW	HFIR-like
	Shape	cylindrical	HFIR-like
	Size	0.3 m radius, half-height	HFIR-like
	Fuel	HEU	Research reactor fuel type
Detector	Dimensions, Near	$1.2 \times 0.65 \times 2.1$ m	2.1 meters available baseline
	Dimensions, Far	$2.4 \times 3.25 \times 2.1$ m	2.1 meters available baseline
	Efficiency	30%	In range of SBL exps. (10-50%)
	Proton density	$6.39 \times 10^{28} \frac{p}{m^3}$	In range of LS Exps
	Position resolution	10 cm	Possible detector segmentation width
	Energy resolution	$10\%/\sqrt{E}$	Daya Bay-like
Background	S:B ratio	1	In range of SBL exps. (1-25) In range of SBL R&D (1)
	Background shape	$1/E^2$ + Flat	Low-Energy Accidentals ($1/E^2$) Neutron Bkg (Flat Approximation)
Other	Run Time (nominal)	1-3 years live-time	-
	Closest Distance, Near	7.1 m	Available at HFIR
	Closest Distance, Far	15.7 m	Available at HFIR
	Prompt Energy Threshold	2.0 MeV	-

Conceptual Detector Designs

- Solid and liquid R&D being pursued by collaborators
- Will make detector technology choice in coming months





Relative Systematics: Analysis Cuts

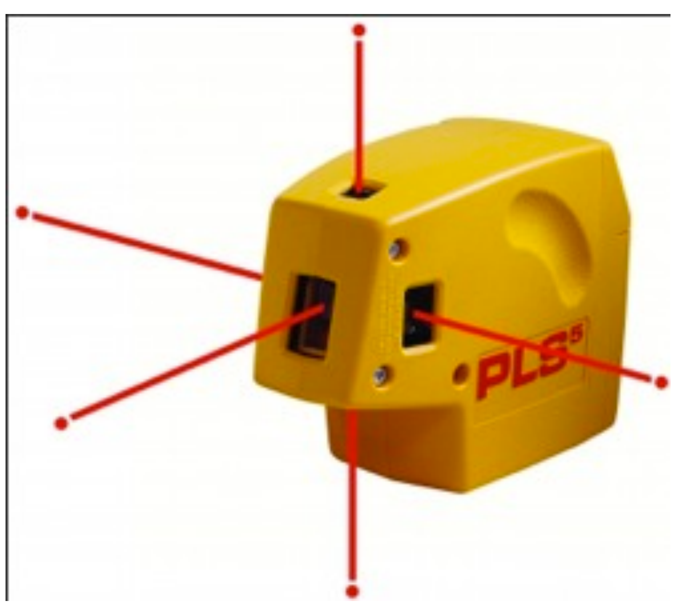
- Apply analysis cuts to identify signal events; each cut will have a related segment-uncorrelated uncertainty:
  - Prompt and Delayed Energy
    - Bugey-III claims a 0.35% relative energy scale uncertainty for its ‘good’ detector segments -- ones that did not have electronics issues. This was achieved solely with an external gamma/neutron calibration source. (NIM A374 (1996))
    - Daya Bay demonstrated <0.35% relative energy scale uncertainty principally based on background comparisons between detectors (PRL 112 (2014))
    - Based on these experiences, it is reasonable for us to aim for this level of energy scale uncertainty with proper background-based or internal/external calibration sources
  - Prompt and Delayed PSD
    - All cells will share a common batch of scintillator, as well as identical geometries and building materials
    - It is hard to imagine significant significant relative differences in PSD for this reason
    - Plan is underway for testing PSD variability with cell properties and geometry with MC and with test cells
    - Of course, on the real detector, relative calibration with neutron and gamma sources will be essential to ensuring small relative systematics.

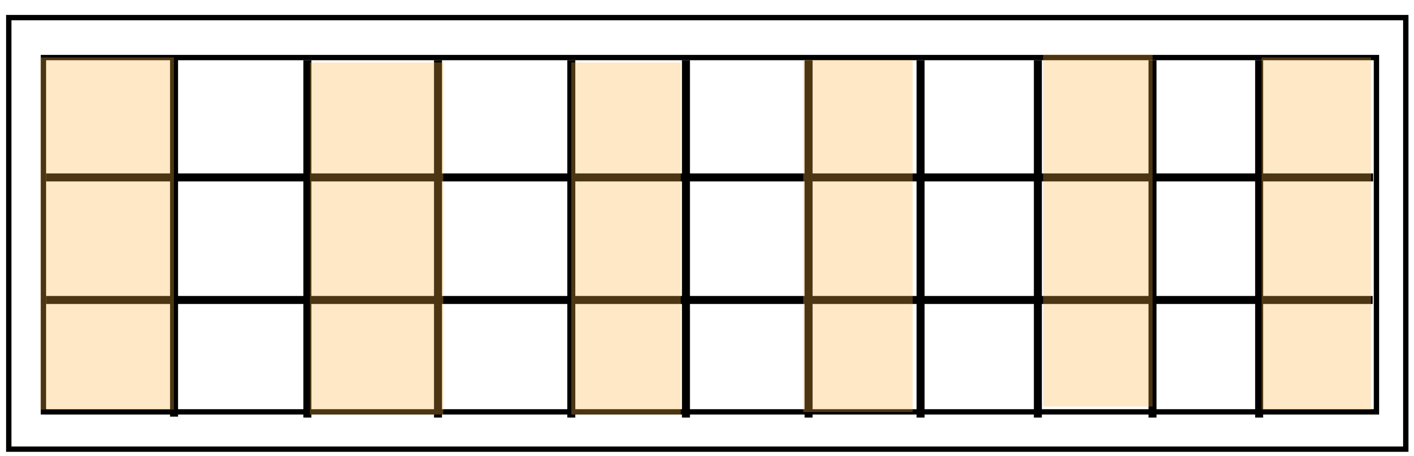
Relative Systematics: Analysis Cuts

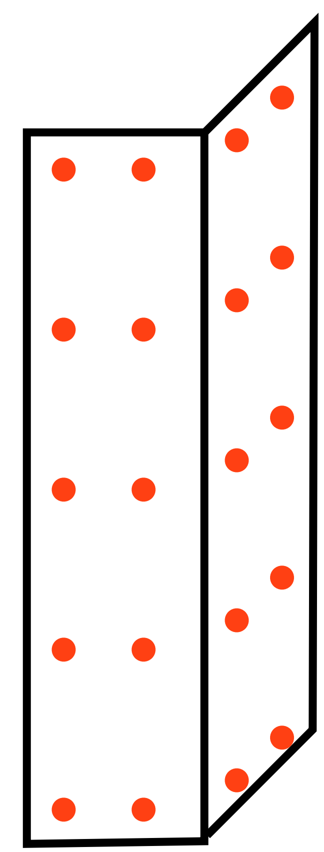
- Apply analysis cuts to identify signal events; each cut will have a related segment-uncorrelated uncertainty:
  - Coincidence Time
    - Will likely use a relatively loose timing cut, giving high efficiency and little relative uncertainty;
    - Since scintillator is shared between segments major differences in neutron capture time seem unlikely.
    - As demonstrated by Daya Bay (Chin. Phys. C37 (2013)) , spallation neutrons can provide an excellent high-statistics cross-check of this relative systematic between segments
  - Topological Cuts
    - Will likely use a very loose topological cut, giving high signal efficiency and little relative uncertainty
    - Plan is underway for studying topological cut efficiencies and relative variations with cell geometry in MC

Relative Systematics: Target Mass

- If oscillation measurement is being made relatively between segments, differences in target mass between segments must be known
- PROSPECT R&D: With mm-scale dimensional precision can be achieved on 10cm scale cell, statistics will likely dominate relative target mass uncertainty
- A variety of metrological tools can achieve this precision
    - Practice and develop metrology techniques on detector prototypes



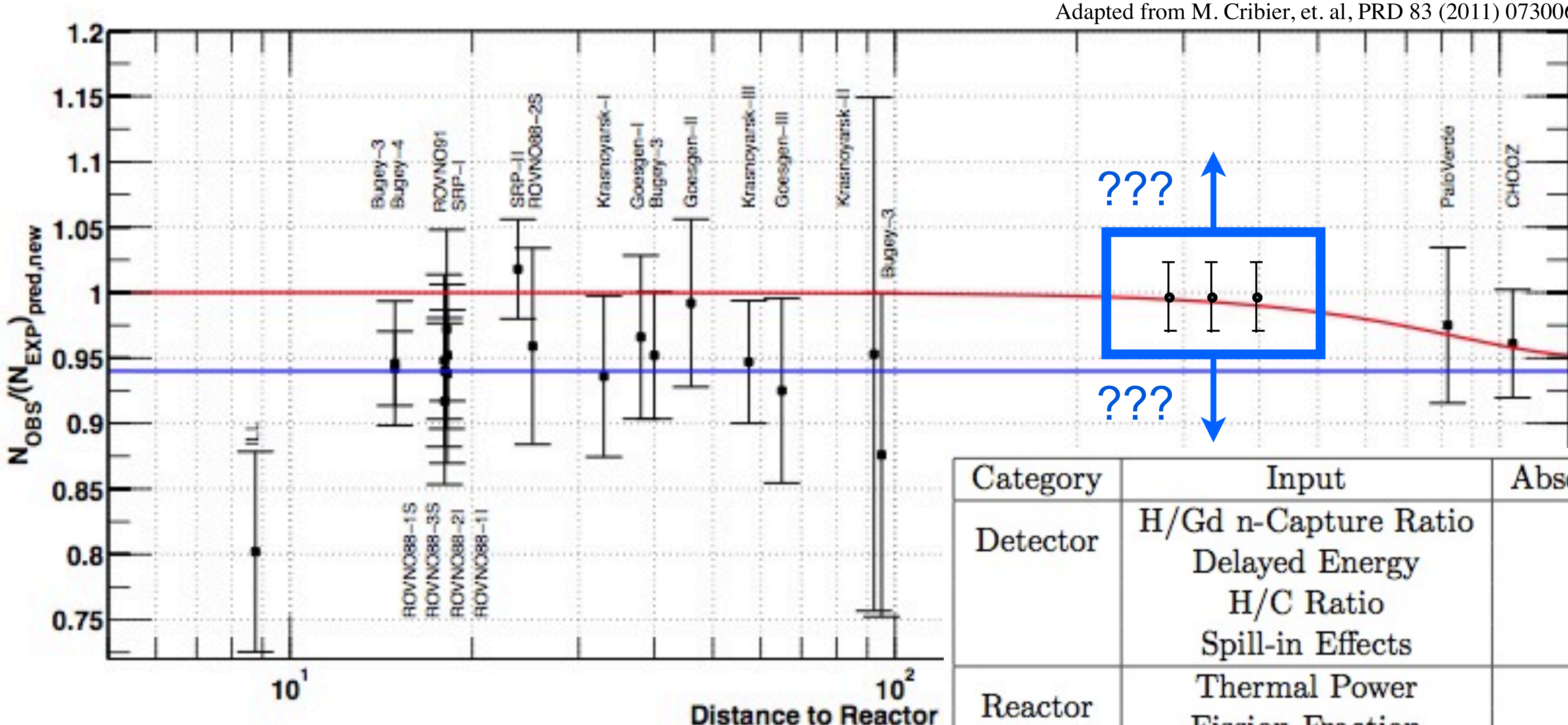




θ_{13} Experiments: Absolute Flux

- Upcoming absolute checks on reactor anomaly from Daya Bay and RENO (sooner), Double Chooz (later)

Adapted from M. Cribier, et. al, PRD 83 (2011) 073006



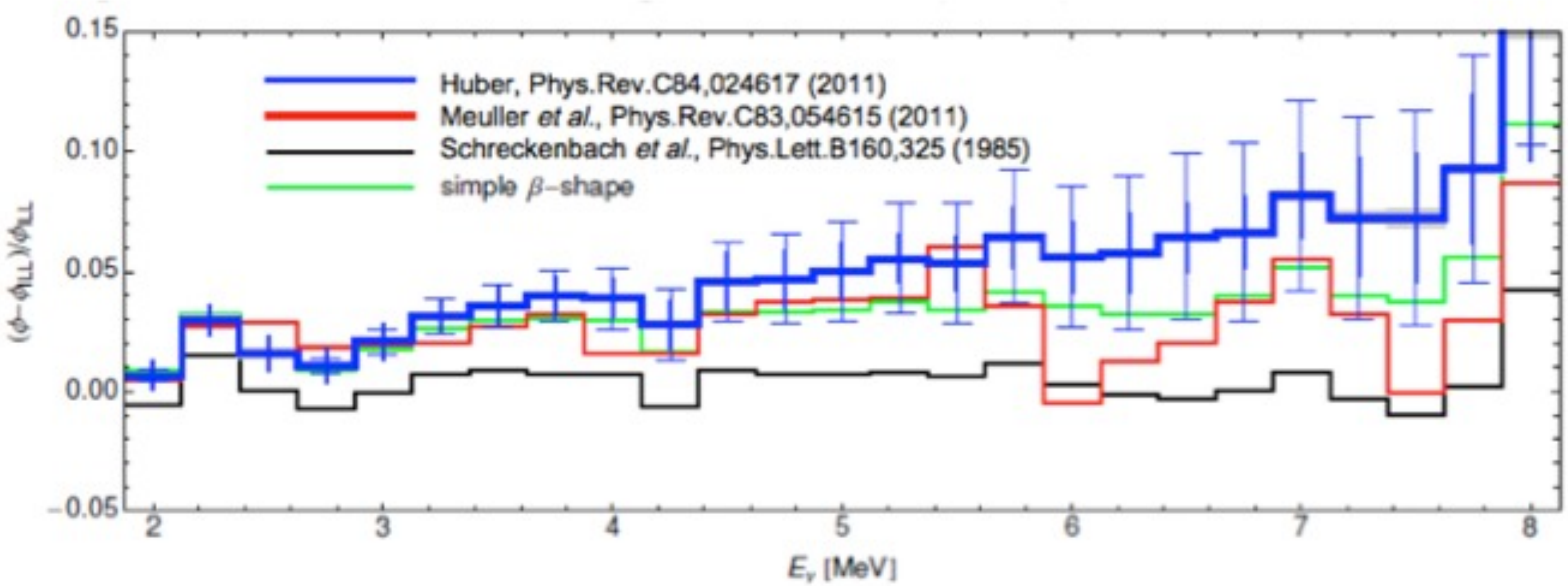
Category	Input	Absolute Unc. (%)	Goal (%)
Detector	H/Gd n-Capture Ratio	0.9	0.2
	Delayed Energy	0.9	0.3
	H/C Ratio	0.47	0.3
	Spill-in Effects	1.5	0.3
Reactor	Thermal Power	0.5	0.5
	Fission Fraction	0.6	0.6
	Total	2.4	0.96
		Flux Prediction	2.5 - 3.5

Adapted from PhD Thesis, B. Littlejohn

- Better statistics and systematics than previous SBL exps.
  - O(1%) level uncertainty, along with from 2.7% reactor flux prediction uncertainty

The Reactor Antineutrino Anomaly

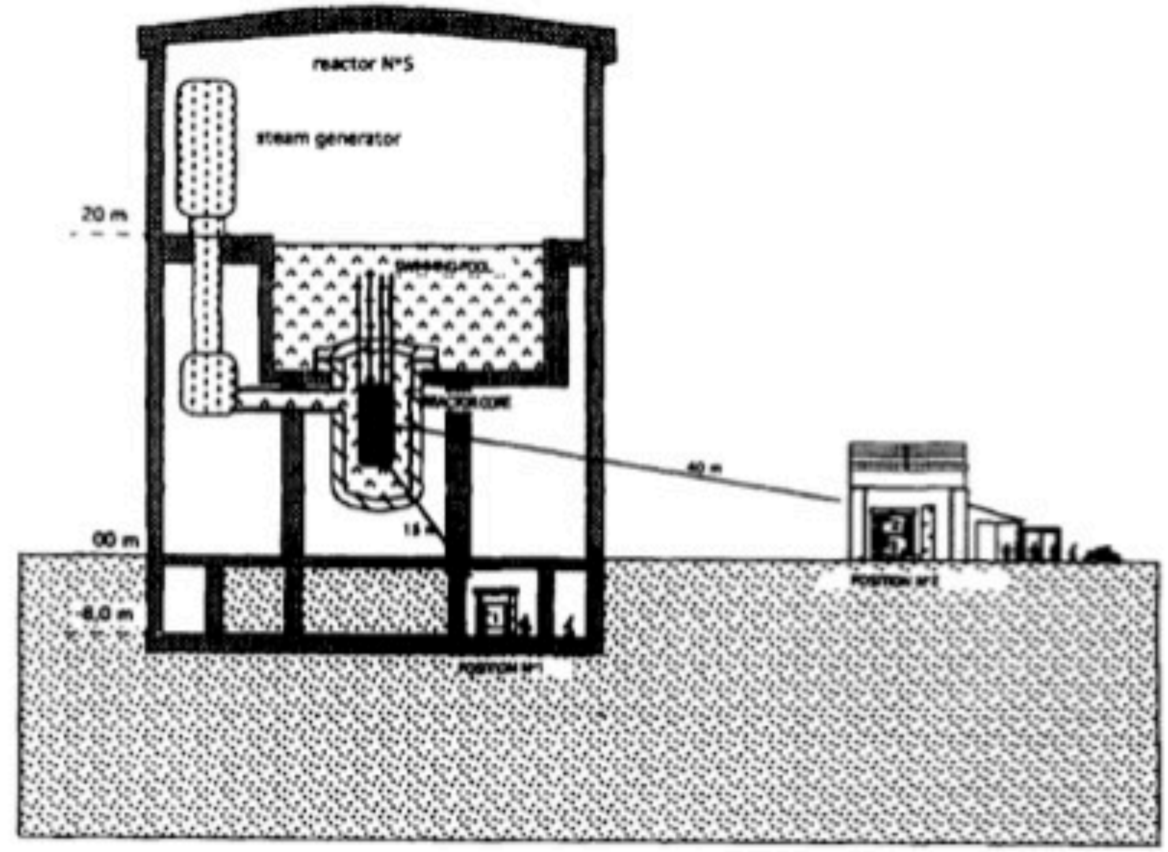
- Main impetus: re-calculation of reactor flux predictions
    - Flux prediction increased by 3.5%, much from new nuclear information



- Other smaller corrections increase prediction:
    - New neutron lifetime measurement (+1%)
    - Proper treatment of non-equilibrium reactor isotopes (+1%)
- Near-agreement between measurements, prediction becomes 5.7% measurement deficit!
- How to double-check this deficit's cause?

Compare to Bugey III

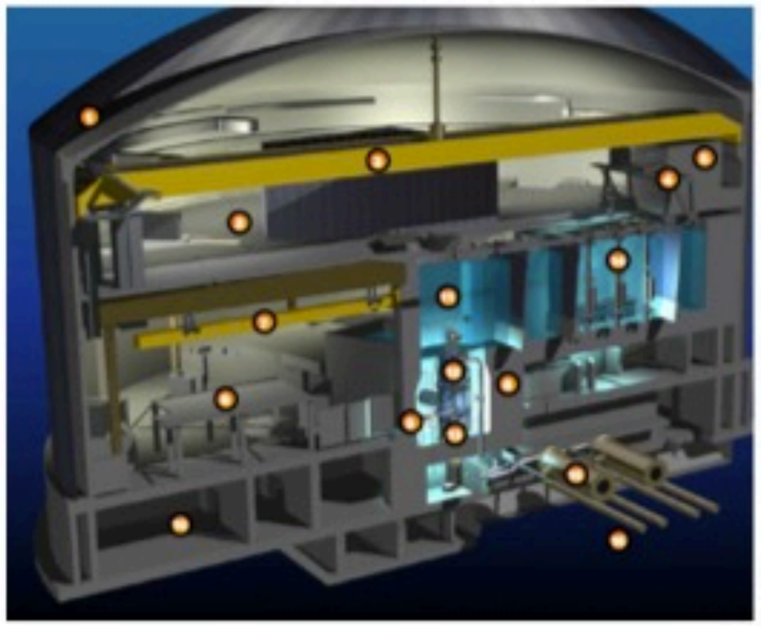
- smaller core size
  - Bugey ran at a PWR, and to make matters worse, the shortest baselines were almost below it, looking along the long axis of that core

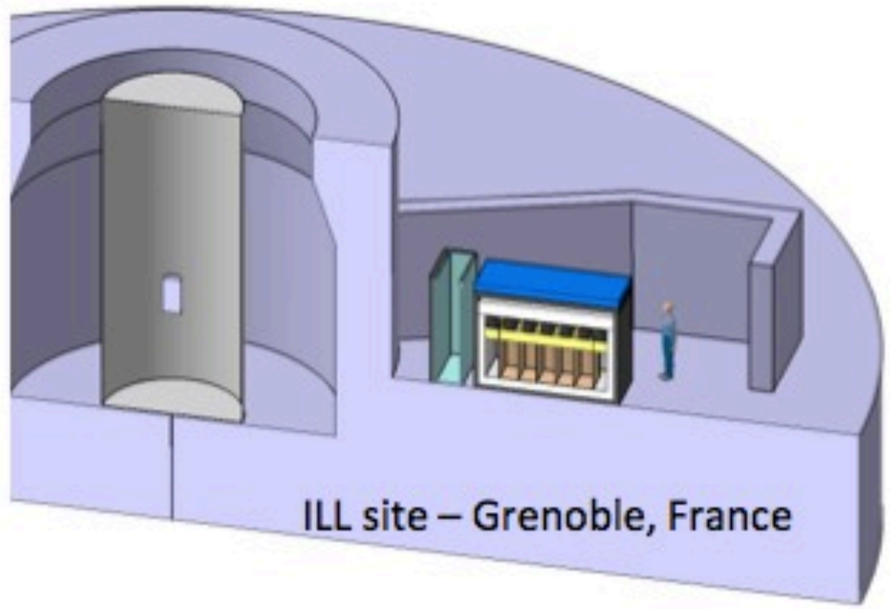


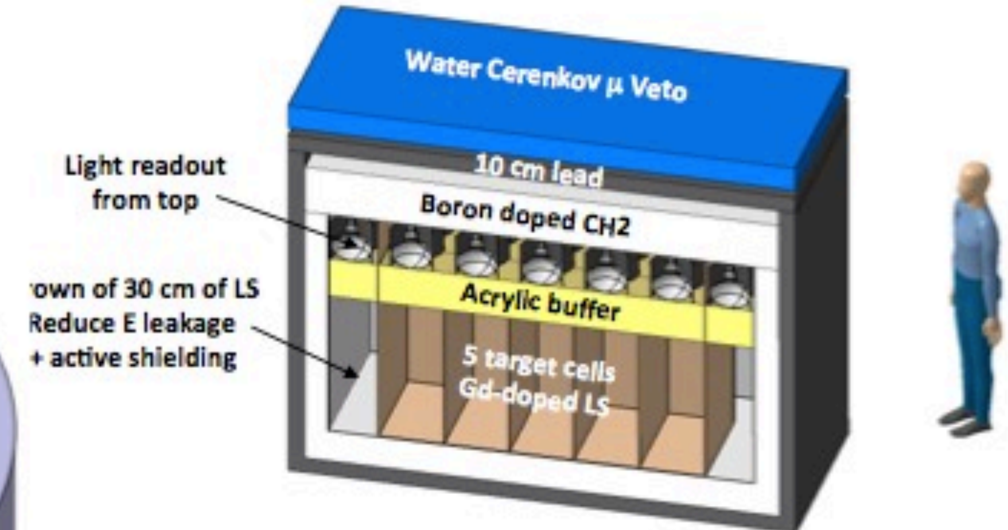
- shorter baseline
  - at US research reactors can get as close as 4m (Bugey > 15 m)
- better scintillator stability
  - some of the Bugey modules/detectors deteriorated
  - demonstrated stability of Gd-LS at Daya Bay for several years. Daya Bay scintillator produced by BNL
- possibly better pulse shape discrimination (PSD)?

International Context

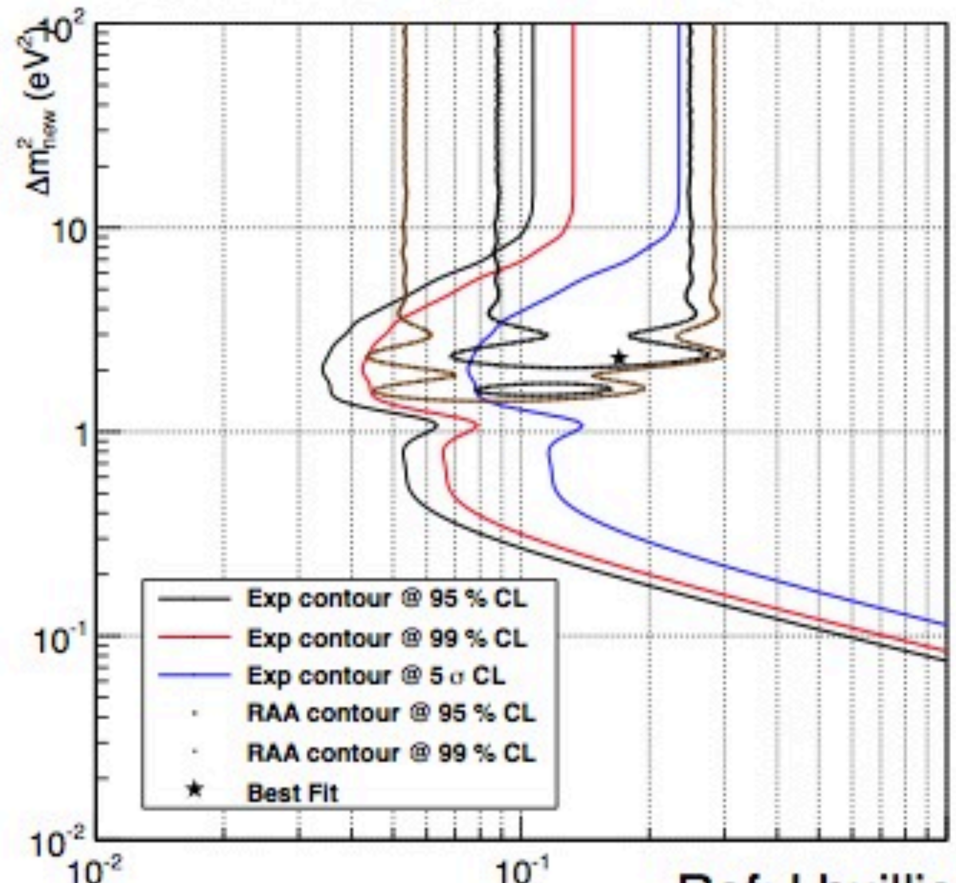
STEREO at ILL







Shape analysis +
3.5 % uncertainty on normalization



Ref: Lhuillier

Reactor Site

50 MW compact core
(φ=40cm, h=80 cm)

Short baseline
[7-9] m

Pure ^{235}U spectrum

Background Rejection

Large passive and active shielding
15 m.w.e. overburden

Pulse Shape Discrimination

Segmented detector

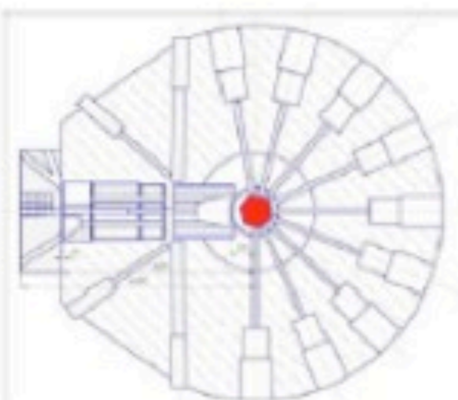
On-site measurements in progress

Aim for first data in 2015
Funding decision in 2013

International Context

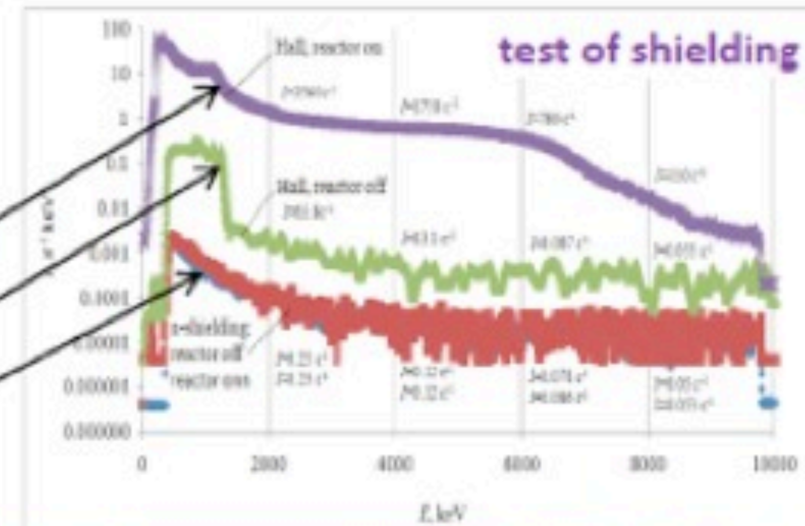
NEUTRINO-4 experiment

Preparation at WWR-M reactor (18 MW) in PNPI (Gatchina)



Reactor power - 18 MW
Size of active core – 0.6 m

reactor on without shielding
reactor off without shielding
reactor on/off with shielding



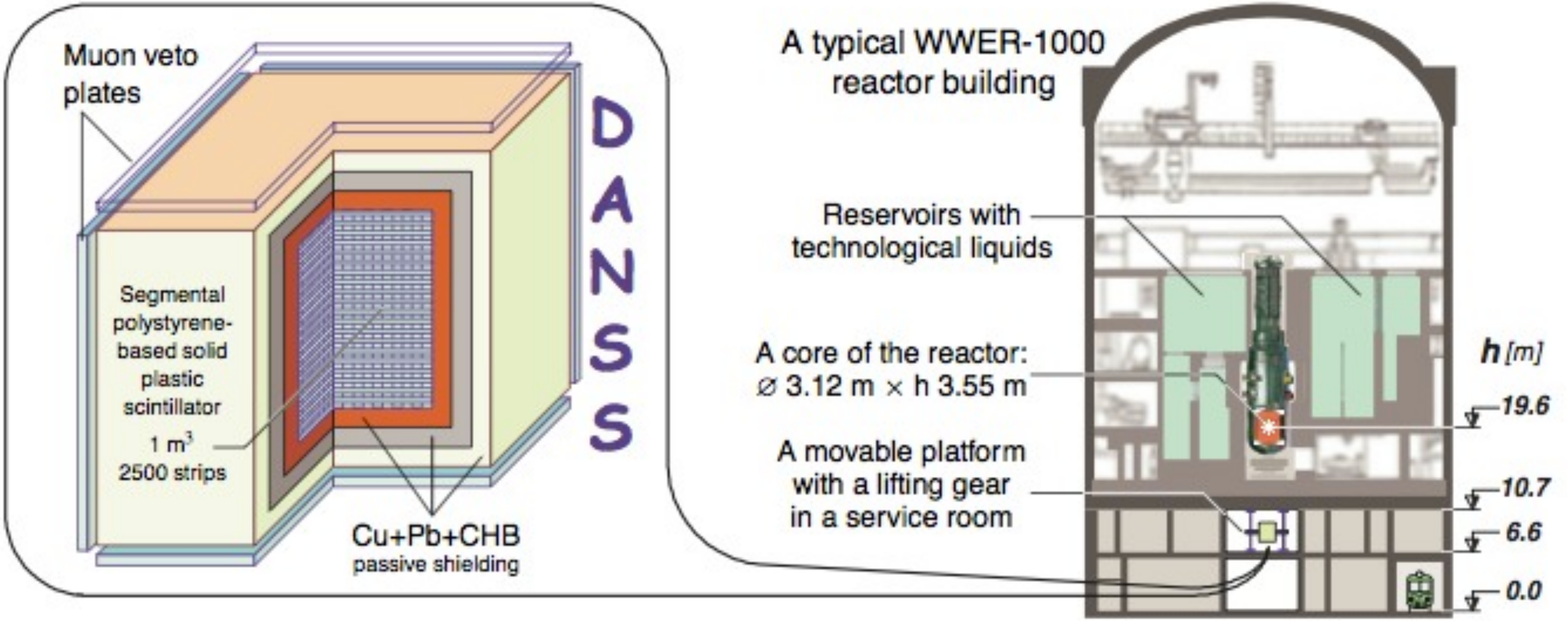
Installation of 2 sections test antineutrino detector with liquid scintillator (total volume 0.4 m³)

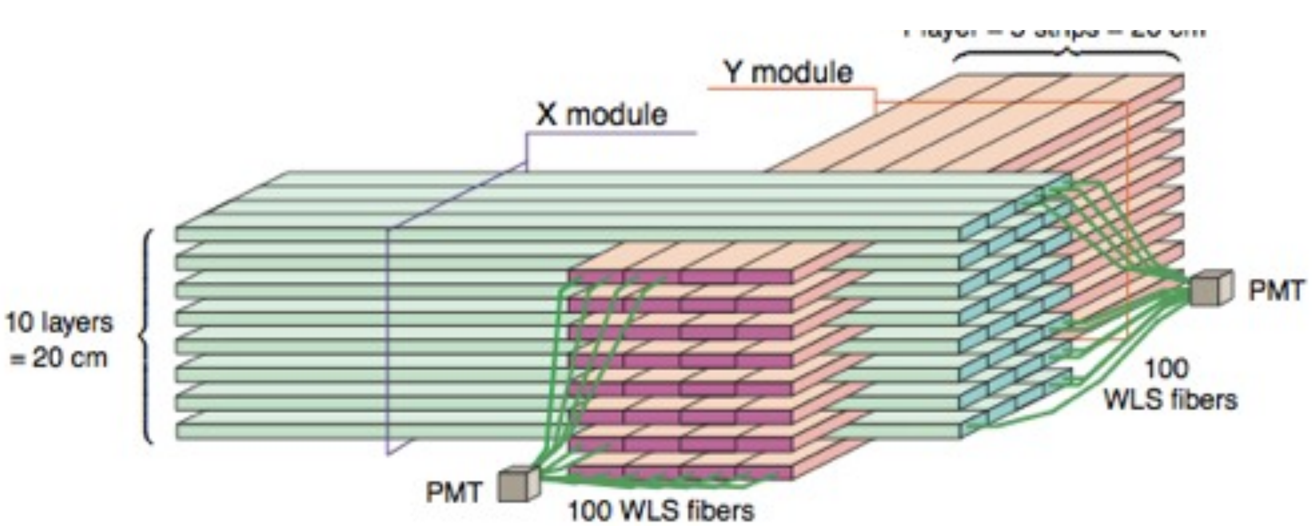
Installation of anticoinsidence shielding from plastic scintillator 0.5x0.5x0.125 m³ with PMT (32 pieces)

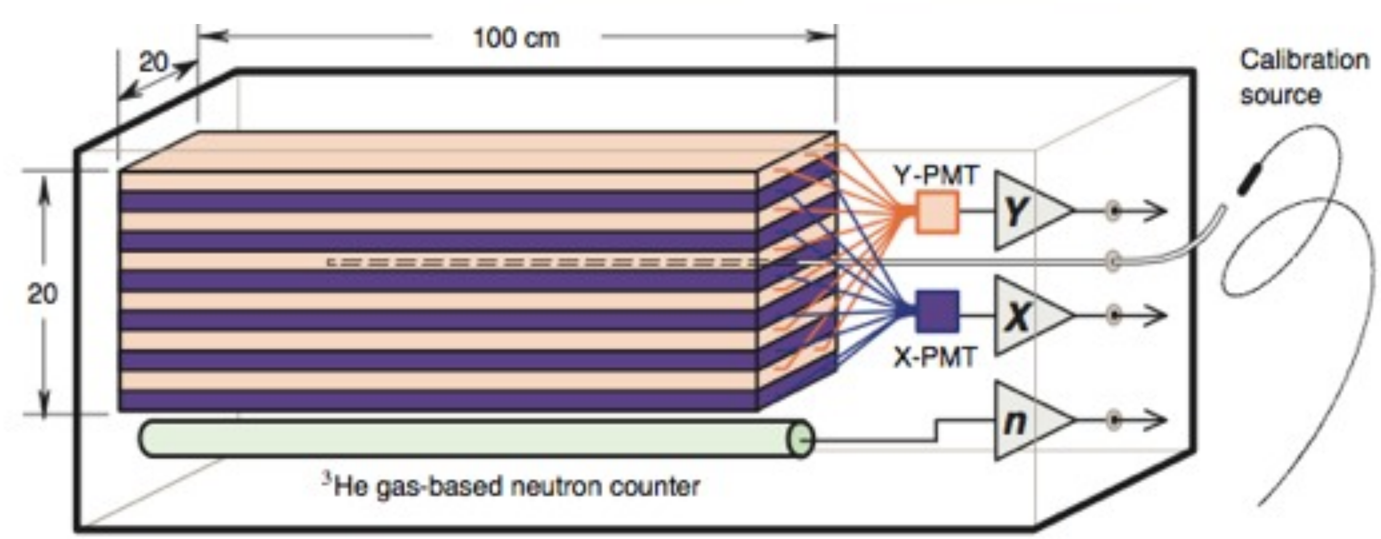
A.Serebrov, PNPI

International Context

DANSS (DANSSino) arXiv:1304.3696







SOX

- Possibility of a Ce-144 source deployed just outside the Borexino detector
- Relies on absolute rate as well as shape information