Status of US Very Short Baseline Reactor Efforts

Bryce Littlejohn
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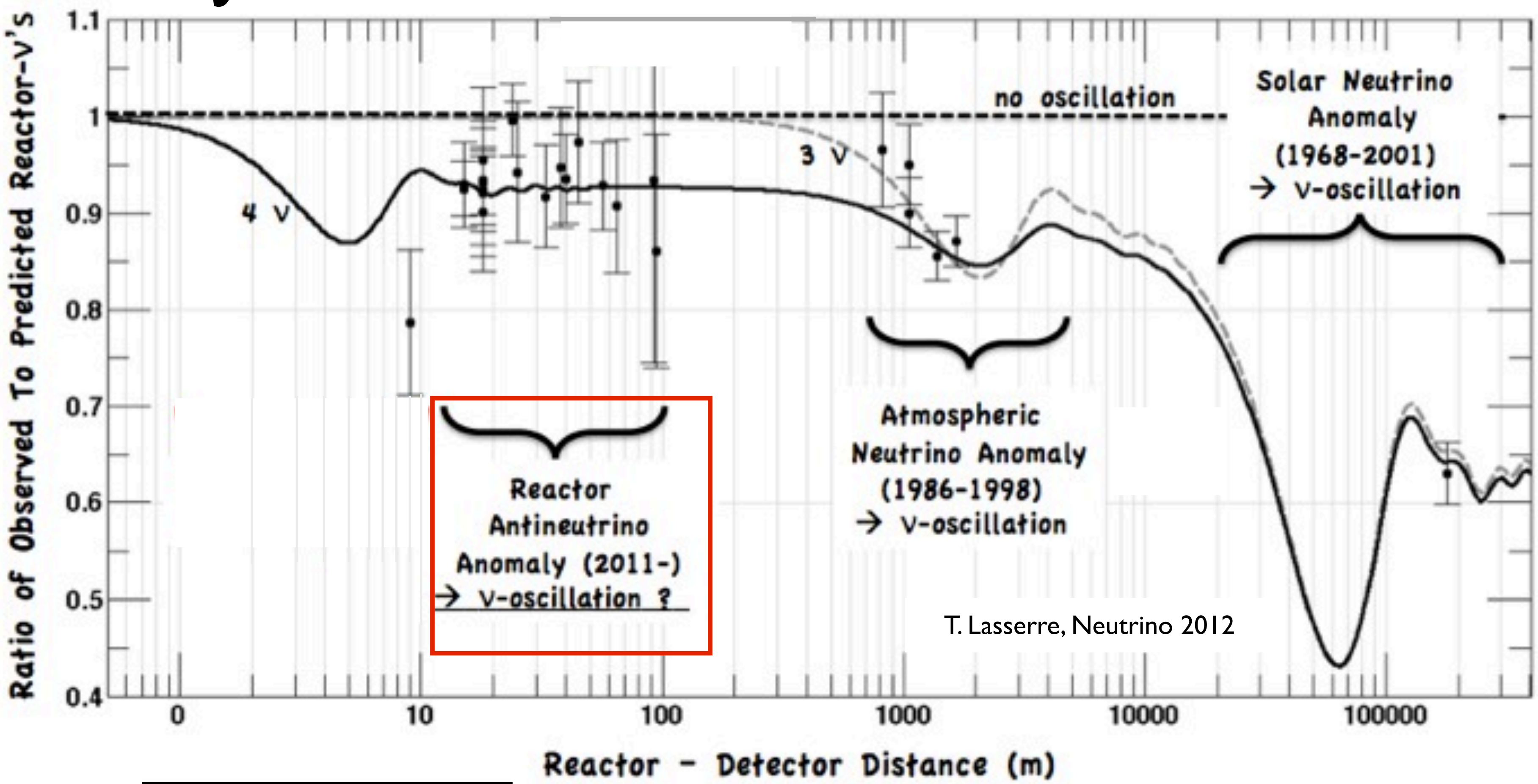
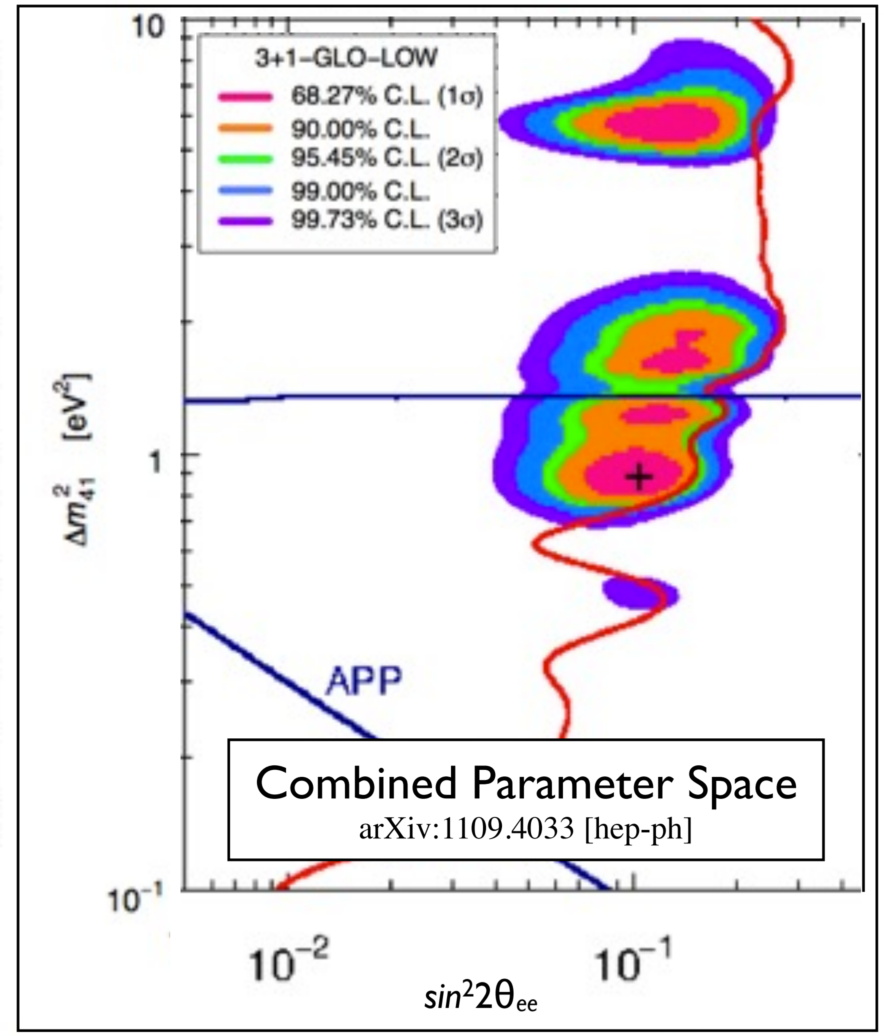
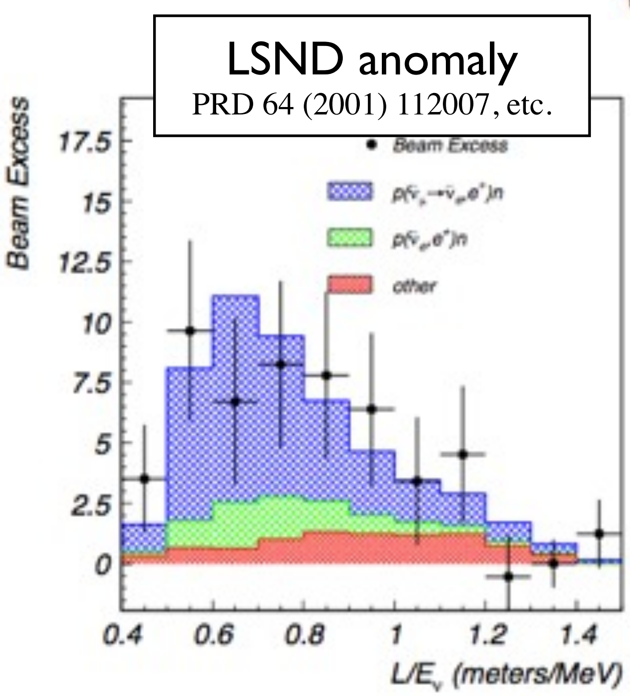
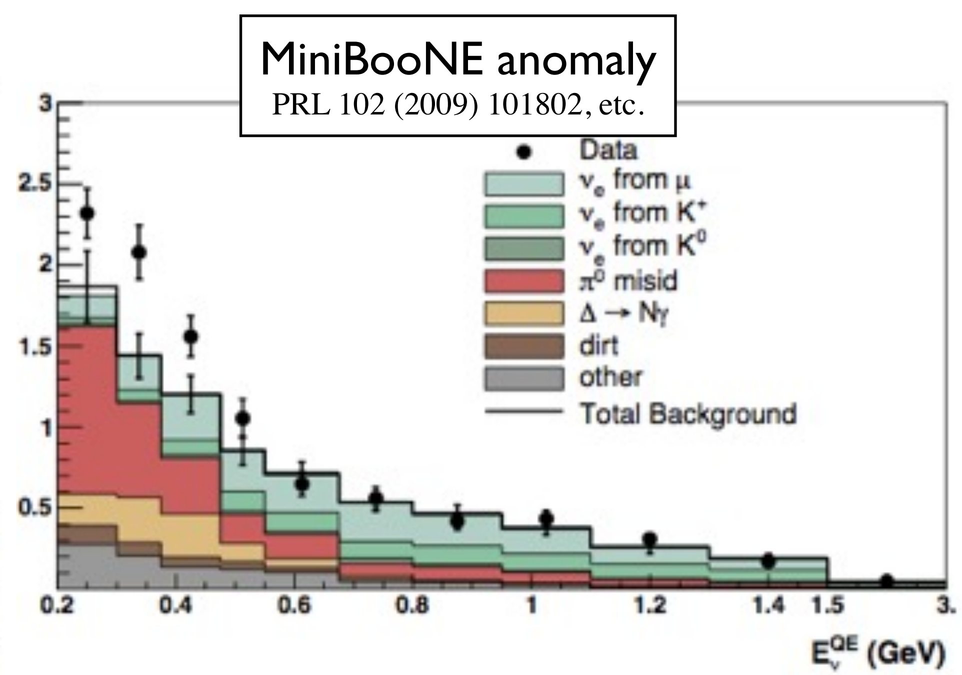
New Physics: Sterile Neutrinos

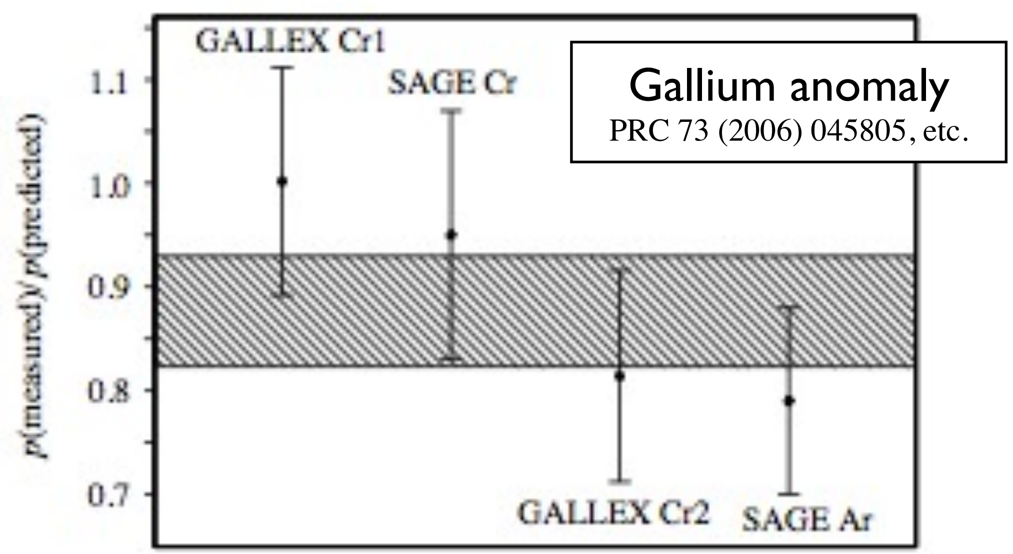
- Many anomalies in ν physics can be collectively explained by existence of eV-scale sterile ν:











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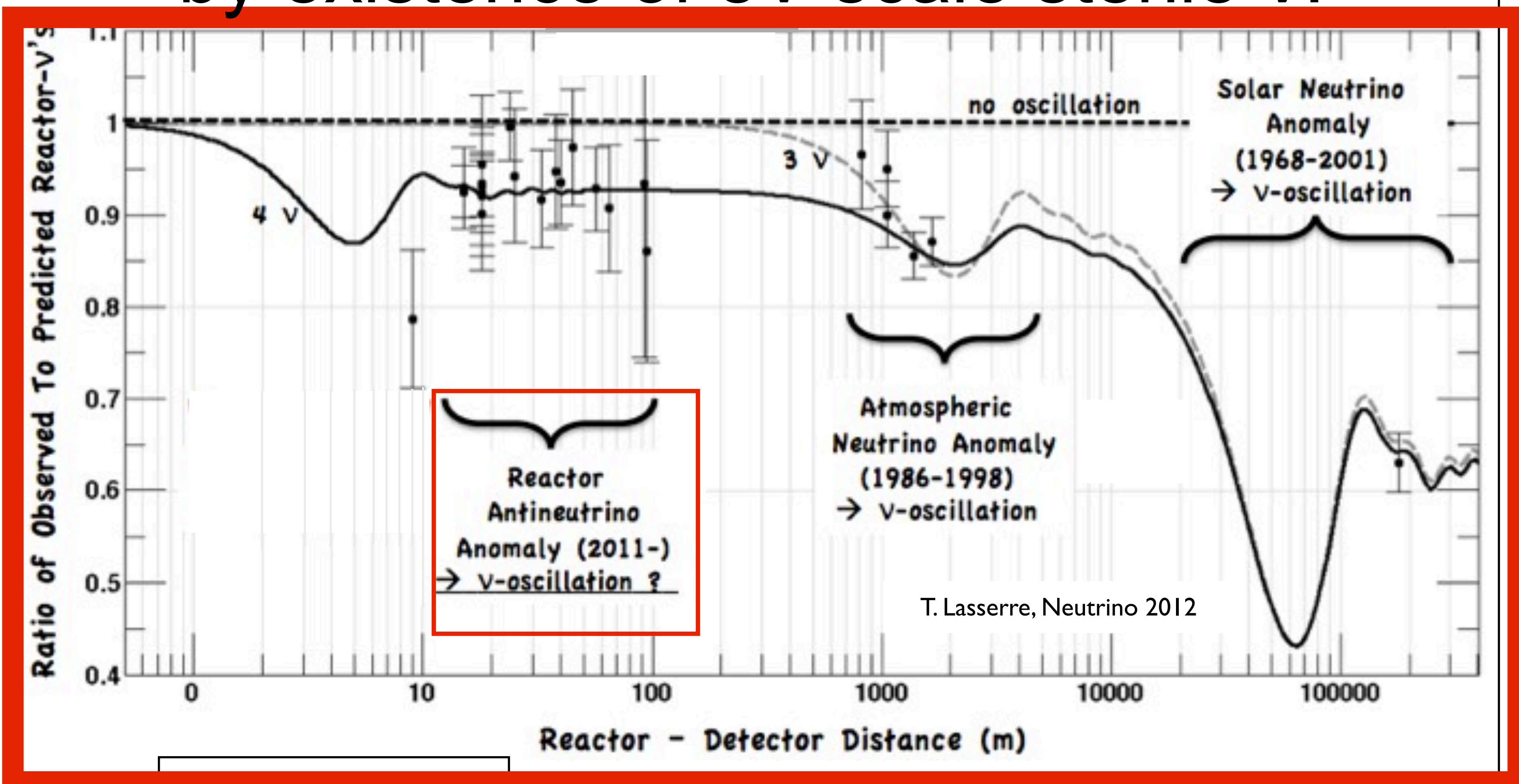
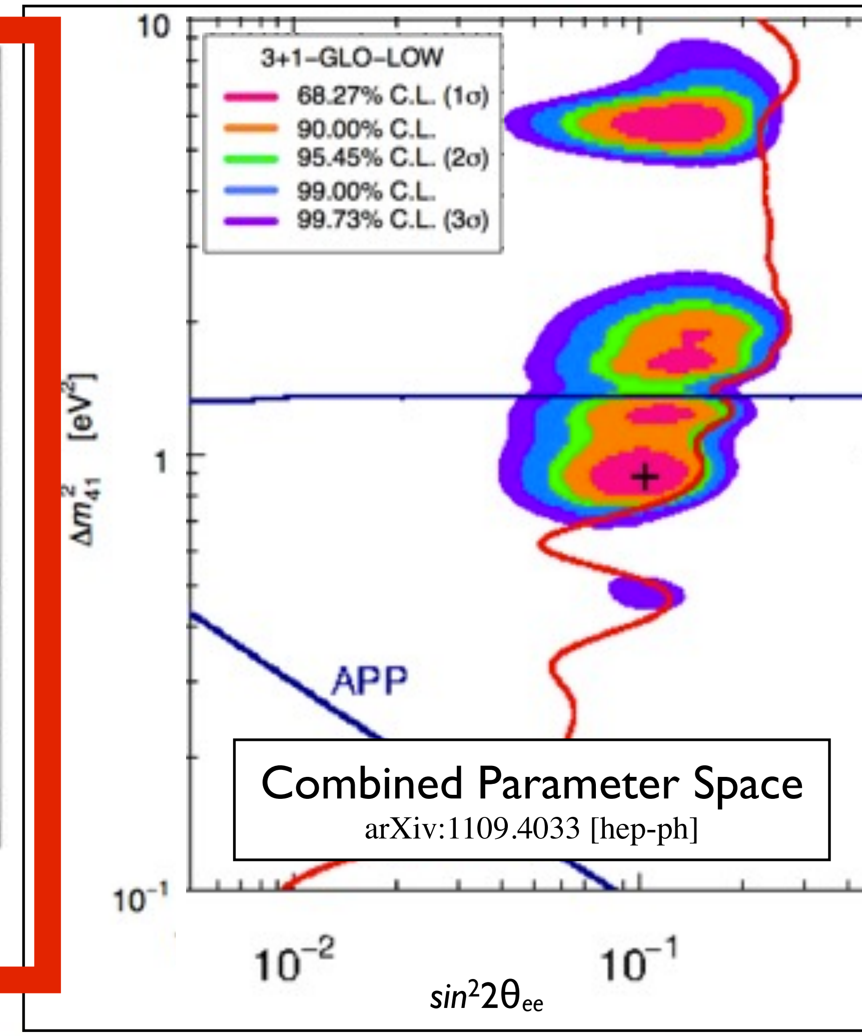
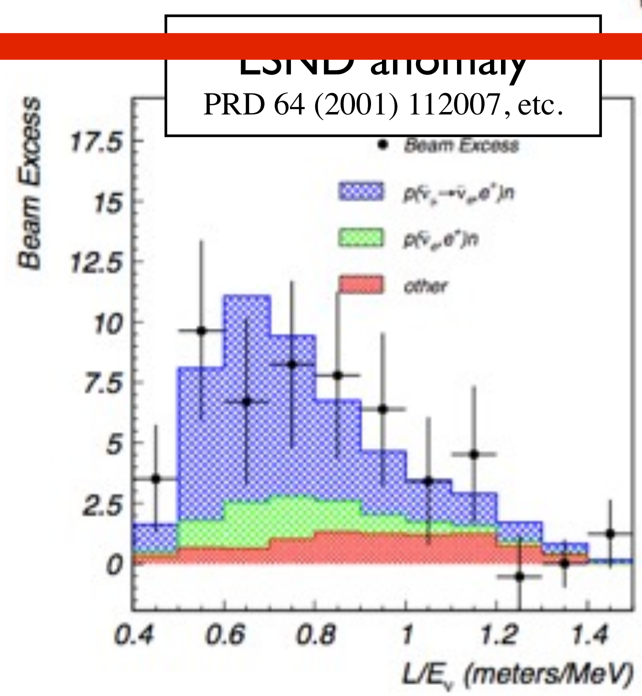
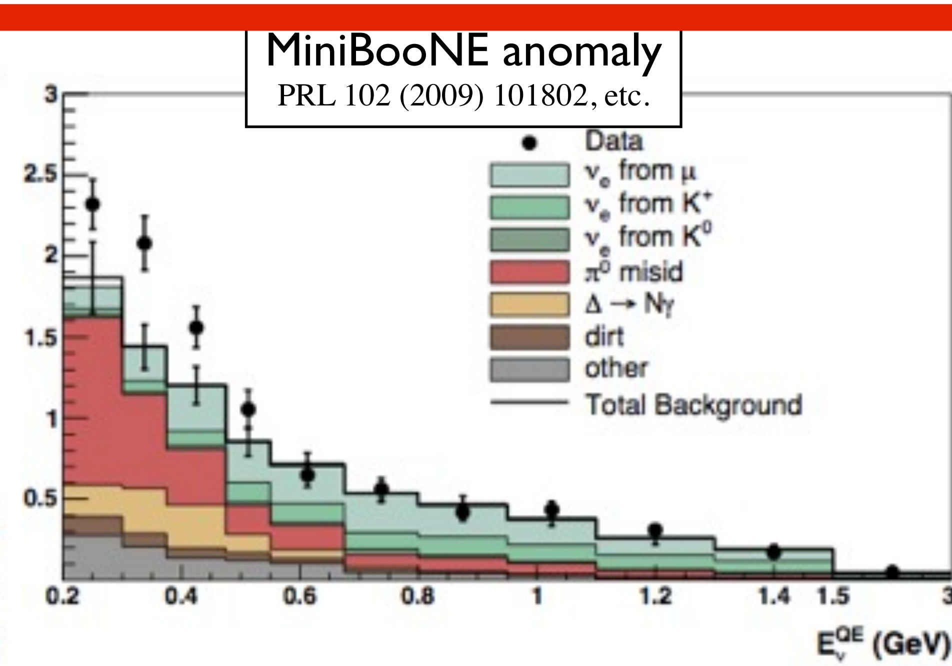
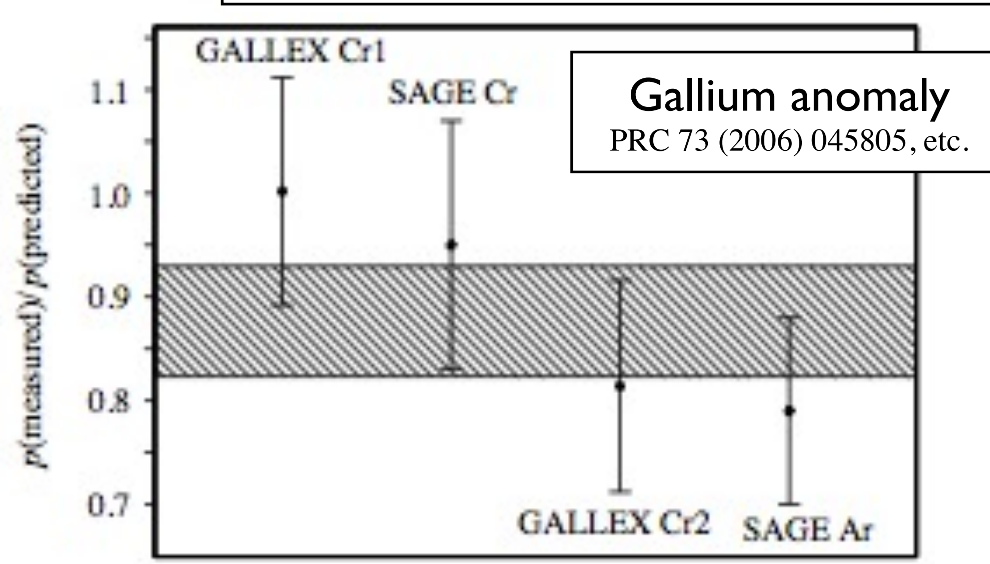




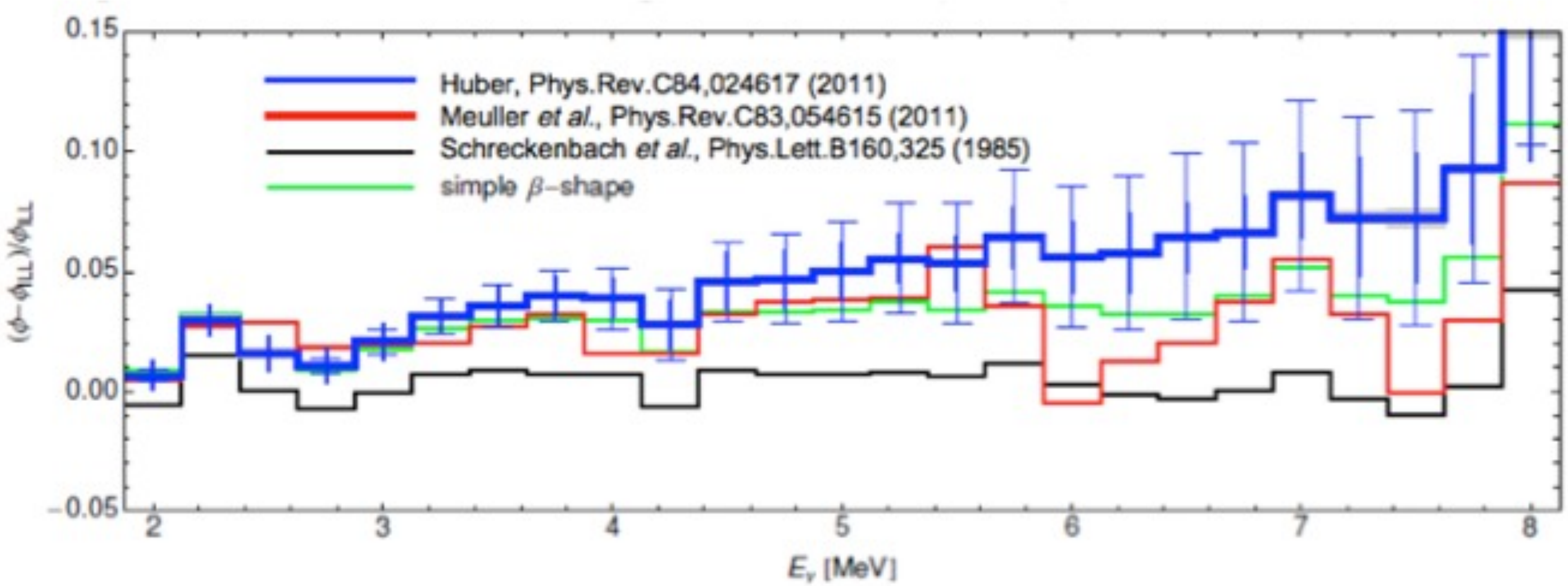






The Reactor Antineutrino Anomaly

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

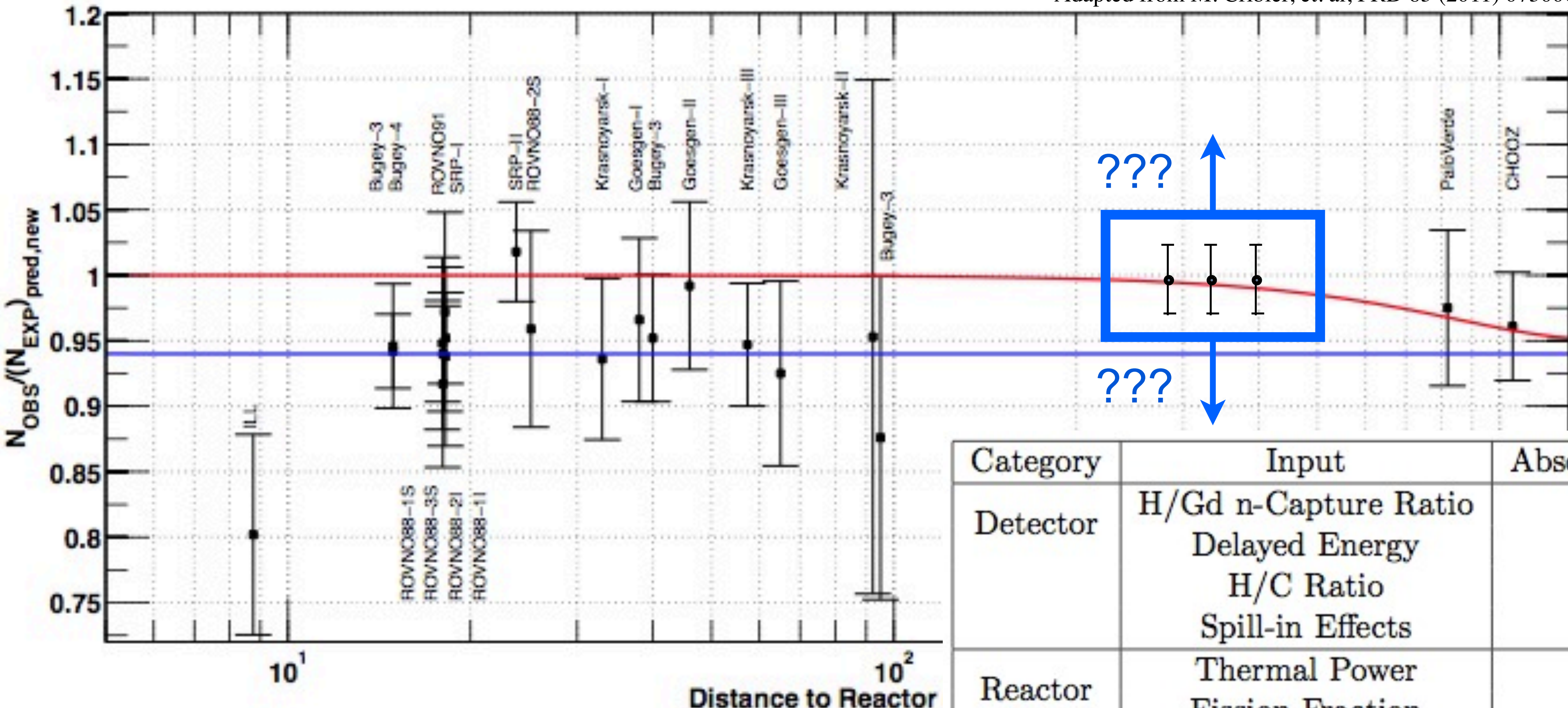


- Other smaller corrections increase prediction:
  - New neutron lifetime measurement (+1%)
  - Proper treatment of non-equilibrium reactor isotopes (+1%)
- Near-agreement between measurements, prediction becomes 5.7% measurement deficit!
- How to double-check this deficit's cause?

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	0.5	0.2
	Delayed Energy	0.6	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	1.9	0.96
		Flux Prediction	2.5 - 3.5

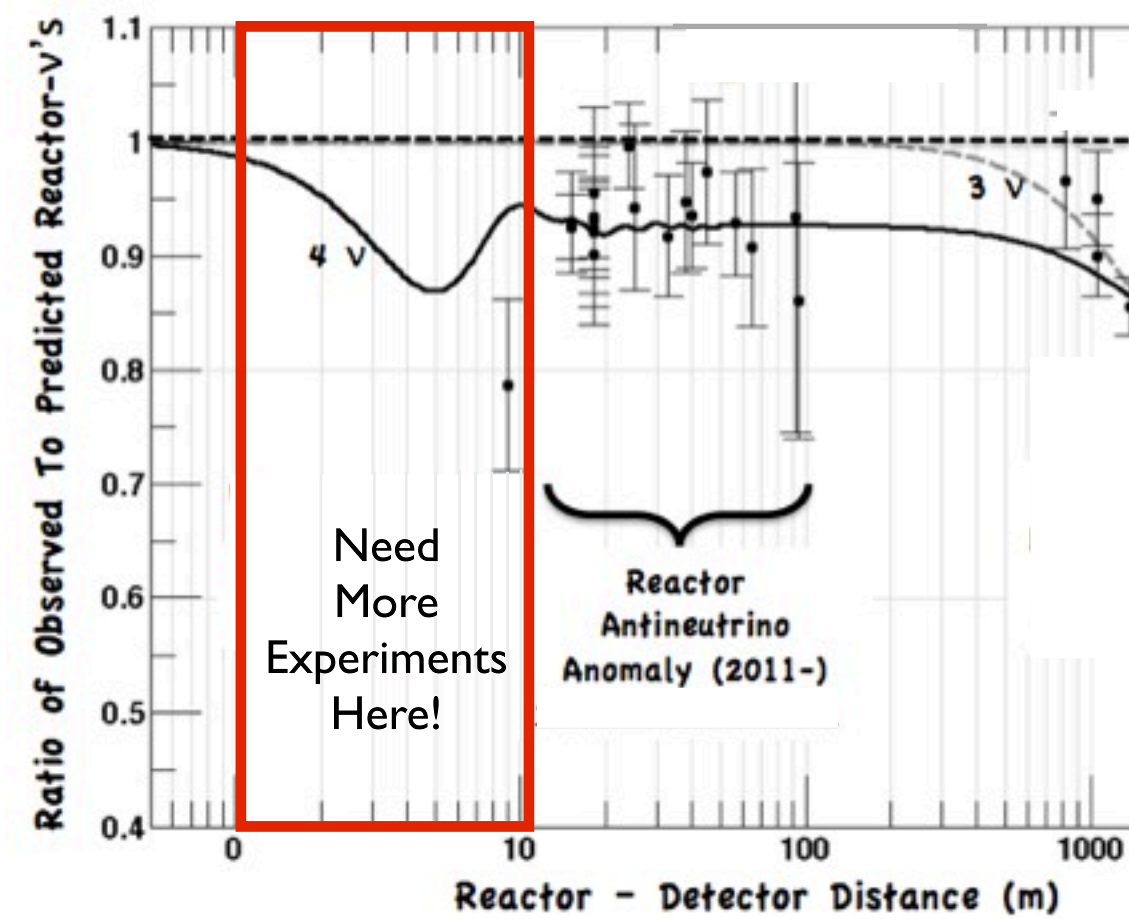
Adapted from PhD Thesis, B. Littlejohn

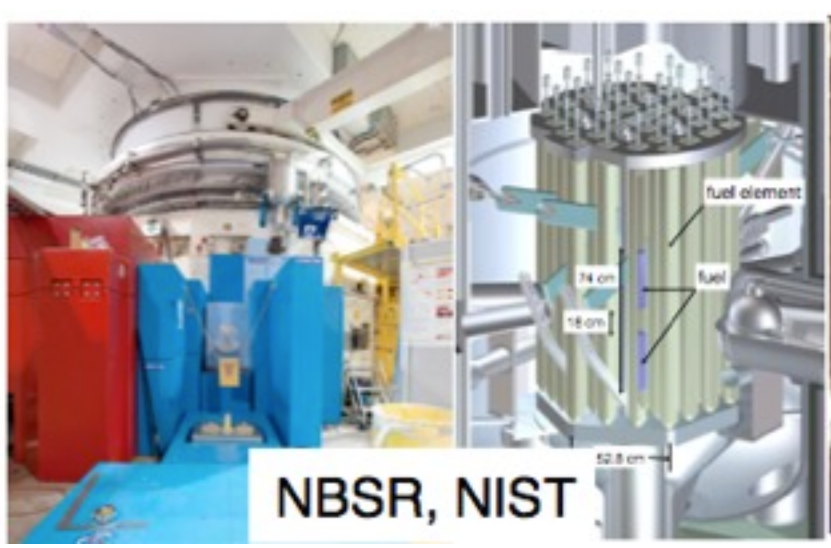
- Better statistics and systematics than previous SBL exps.
  - O(1%) level uncertainty, along with from 2.7% reactor flux prediction uncertainty

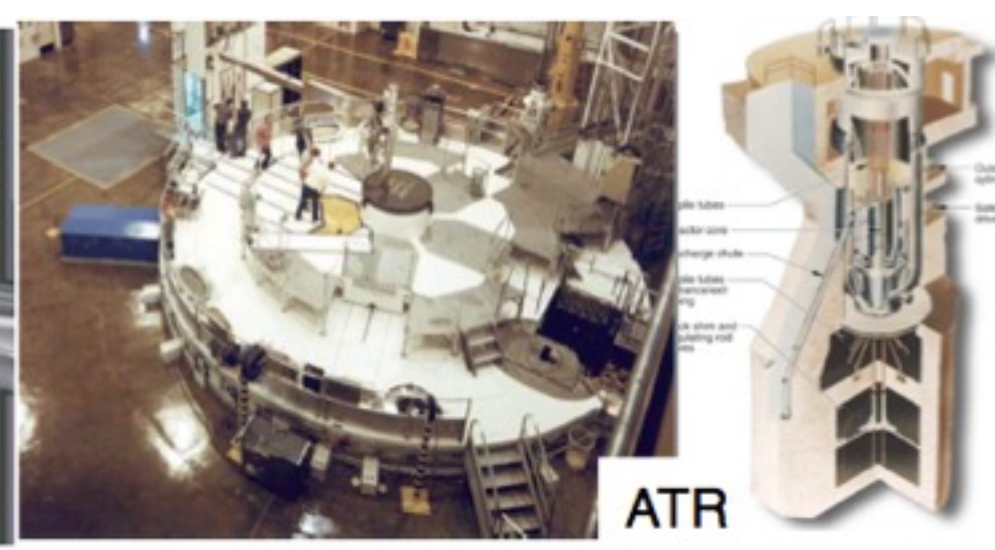
Opportunities at Research Reactors

- Need a definitive MeV-scale very short-baseline (VSBL) test
  - Absolute reactor flux checks are good, but not good enough
- US research reactors provide a venue for oscillation searches at shortest-ever reactor baselines

Reactor	Power (MW_{th})	Baselines (m)	Reactor On (Days)	Reactor Off (Days)
NIST	20	4-20	42	10
HFIR	85	6-8	24	18
ATR	250 (licensed) 110 (operational)	7-8 (restricted) 12-20 (full access)	48-56	14-21



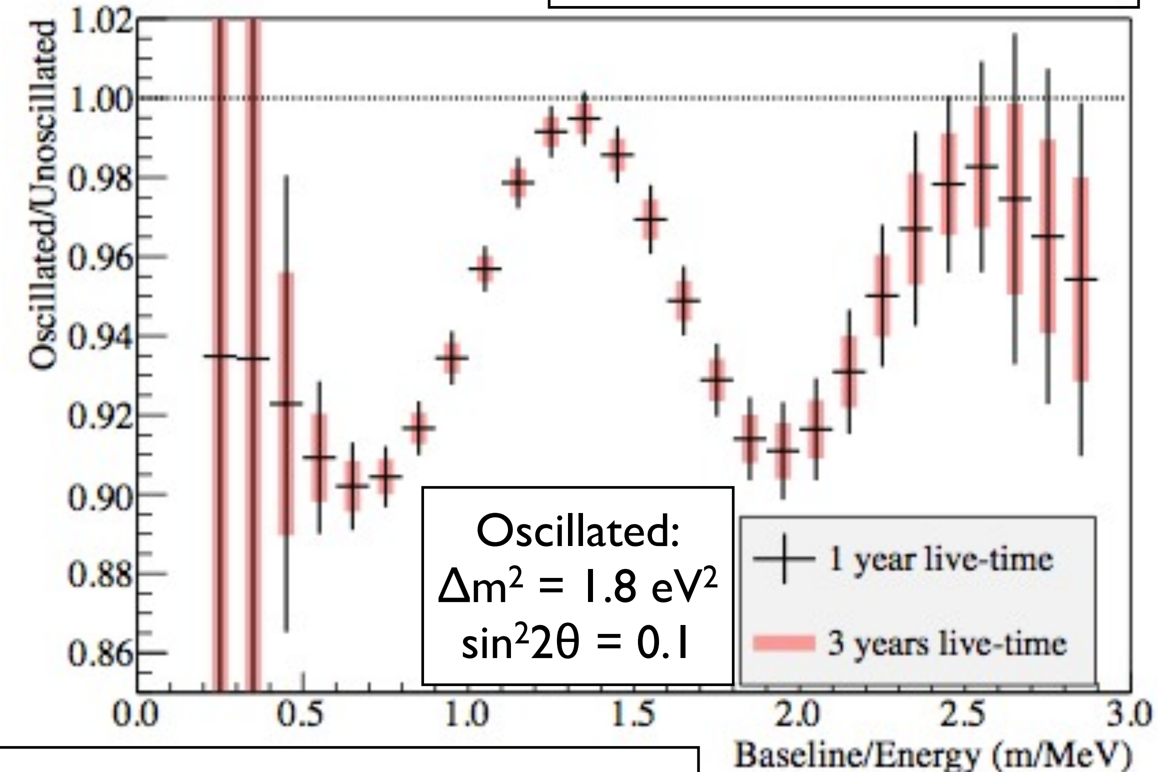




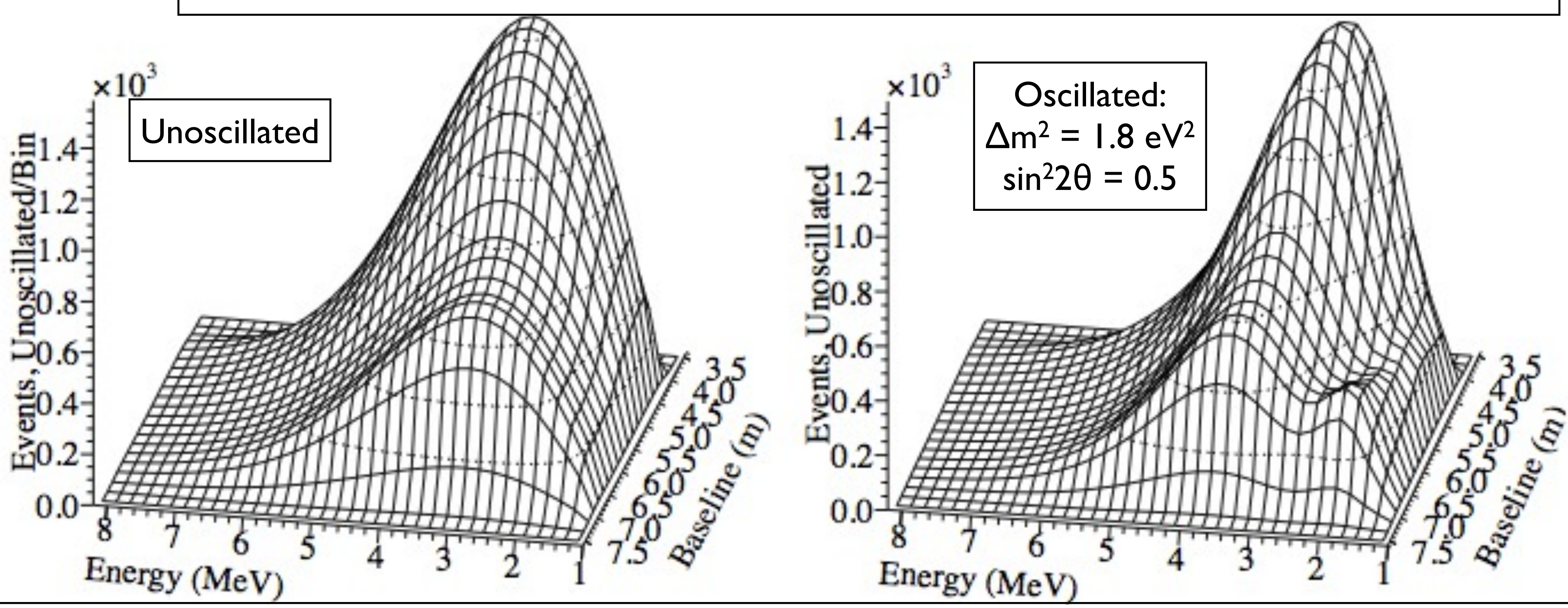
Very-Short-Baseline Reactor Signal

- 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

Important Variables

- Many important aspects in observing these oscillations:
  - Position and energy resolution
  - Detector position and length
  - Core size
  - Backgrounds
  - Statistics

Heeger, Mumm, Tobin, BRL
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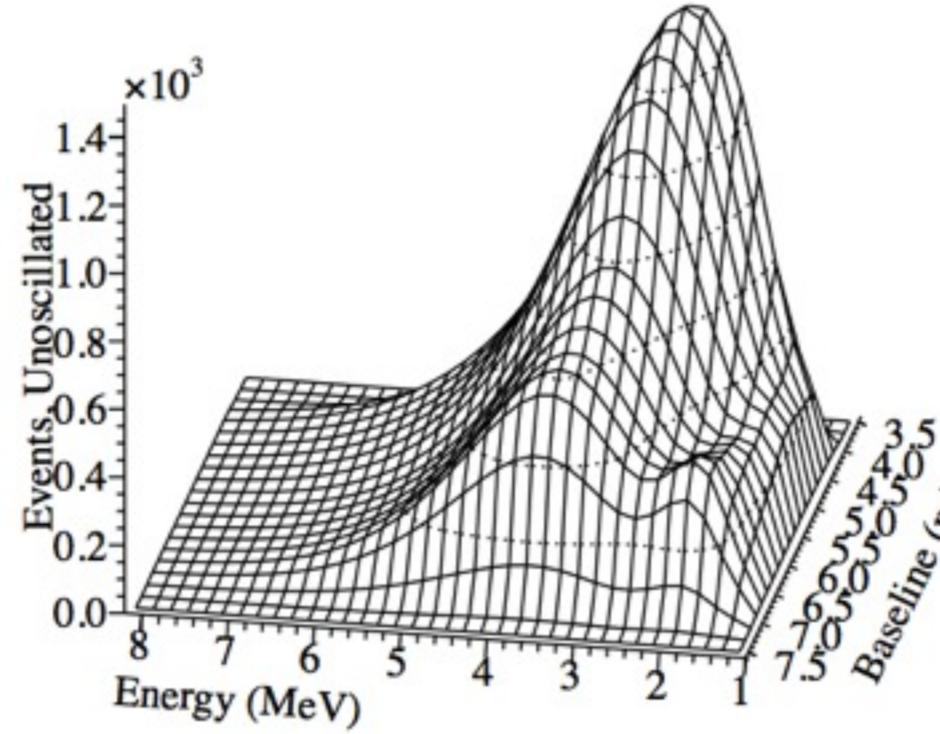
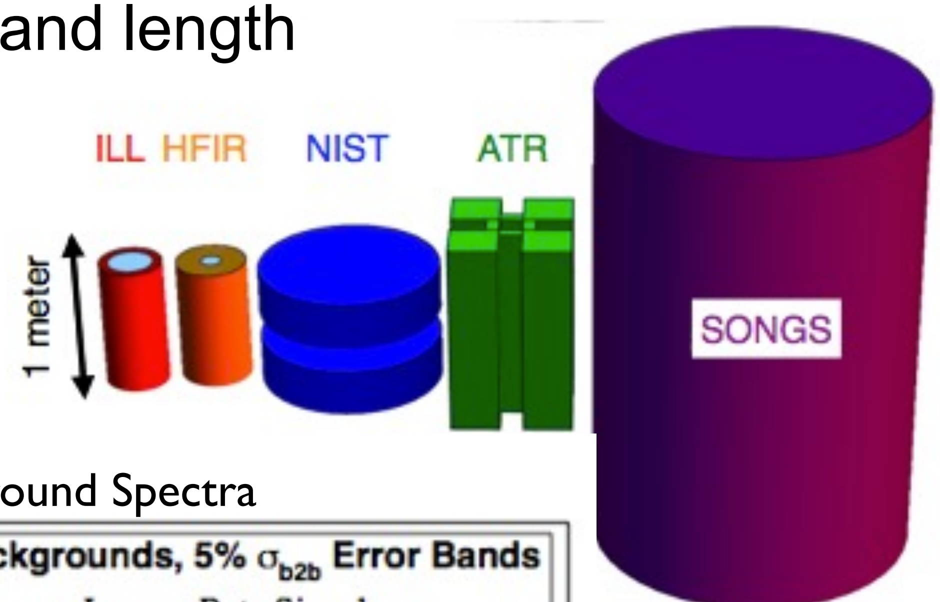
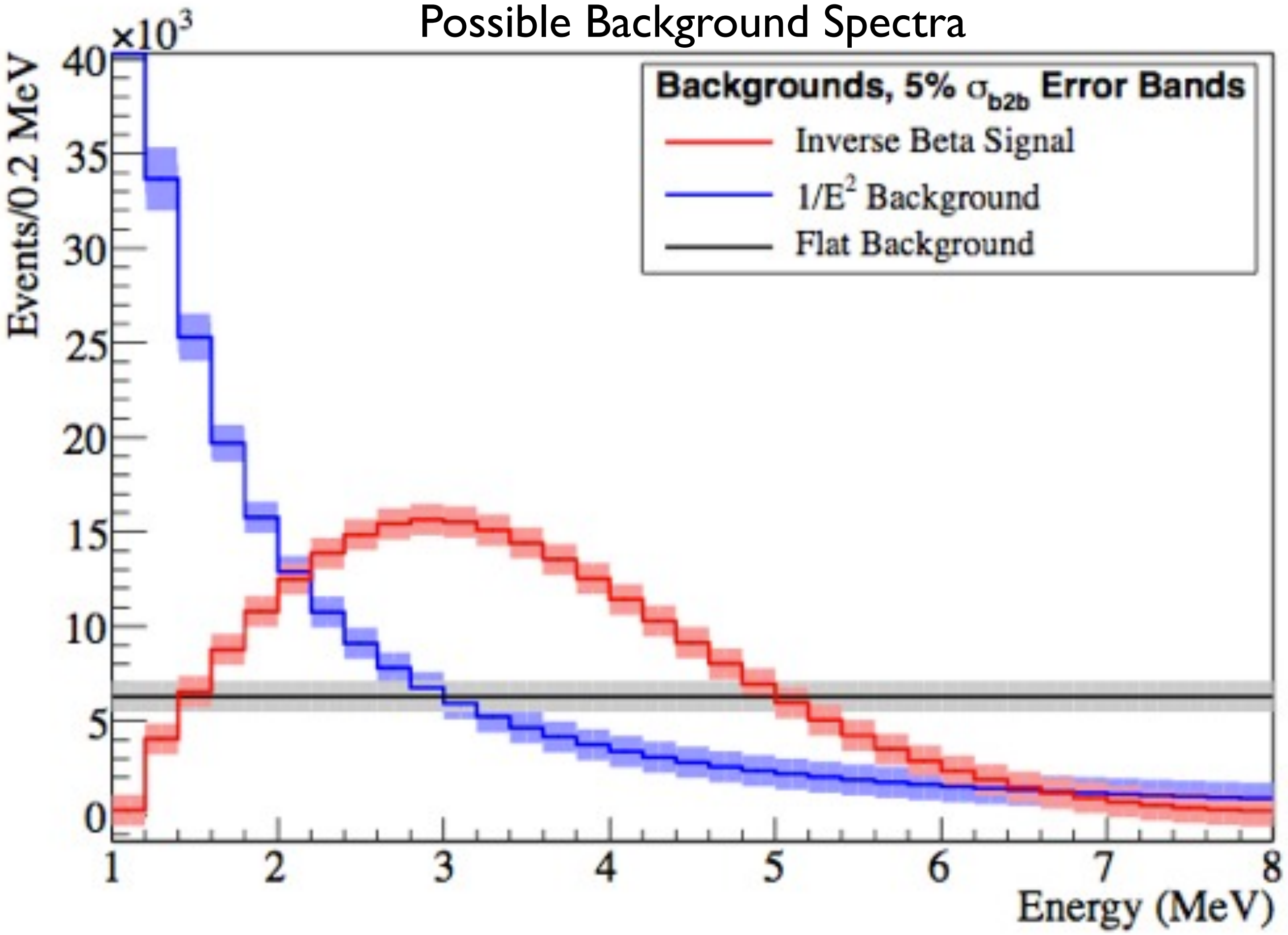
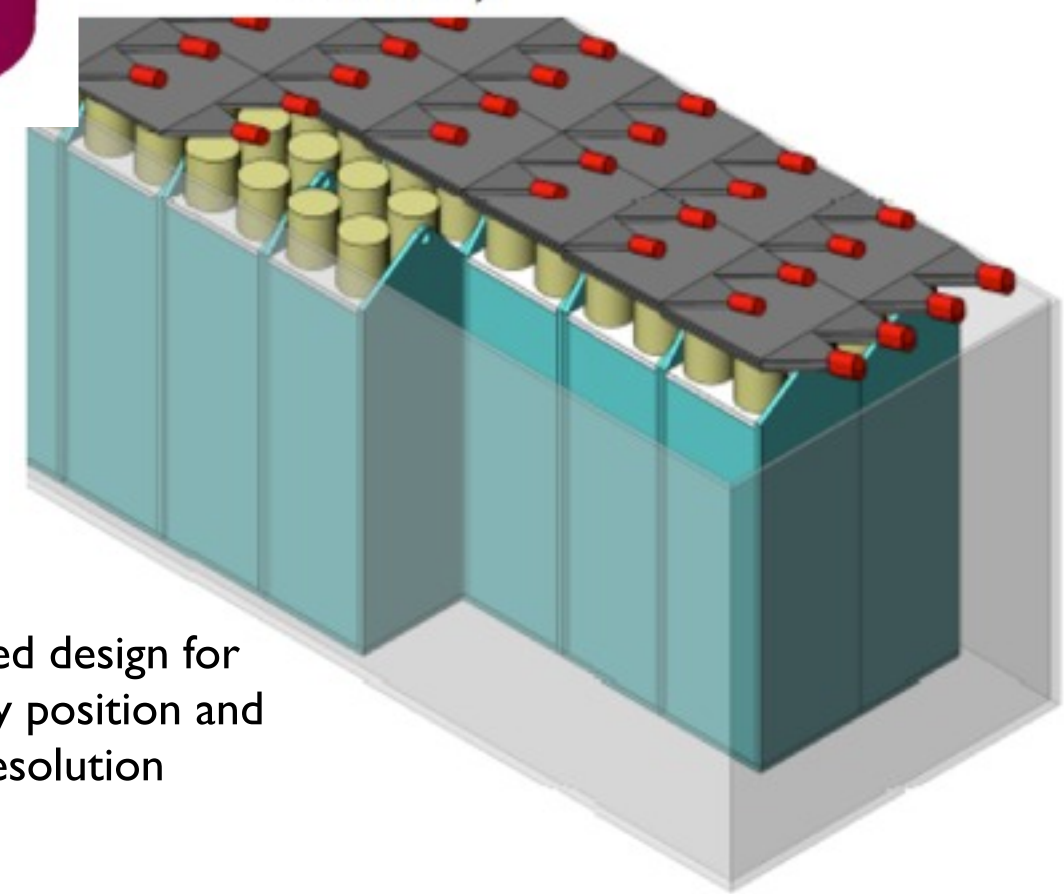




Possible Background Spectra



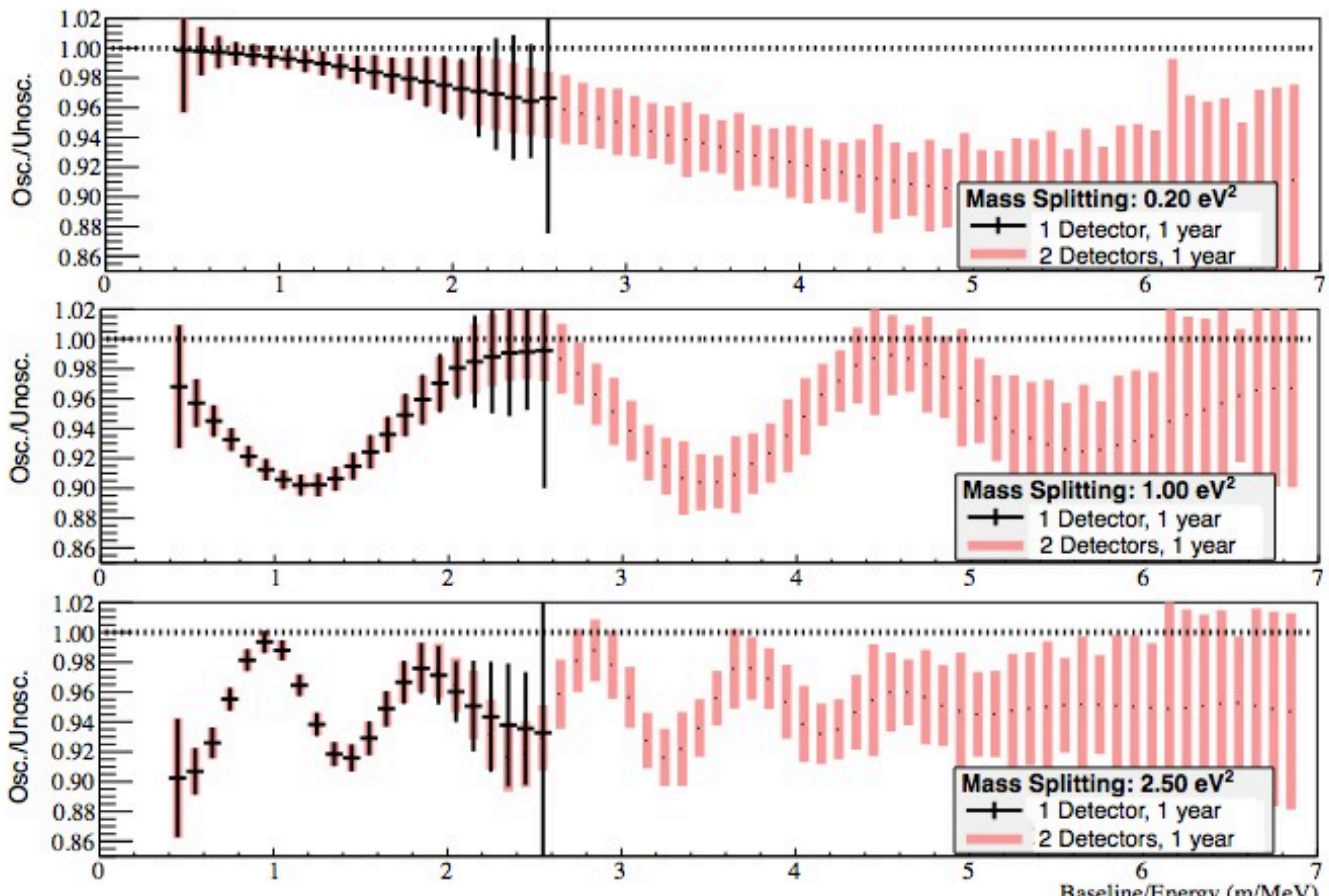


Segmented design for necessary position and energy resolution

Important Variables: Two Detectors

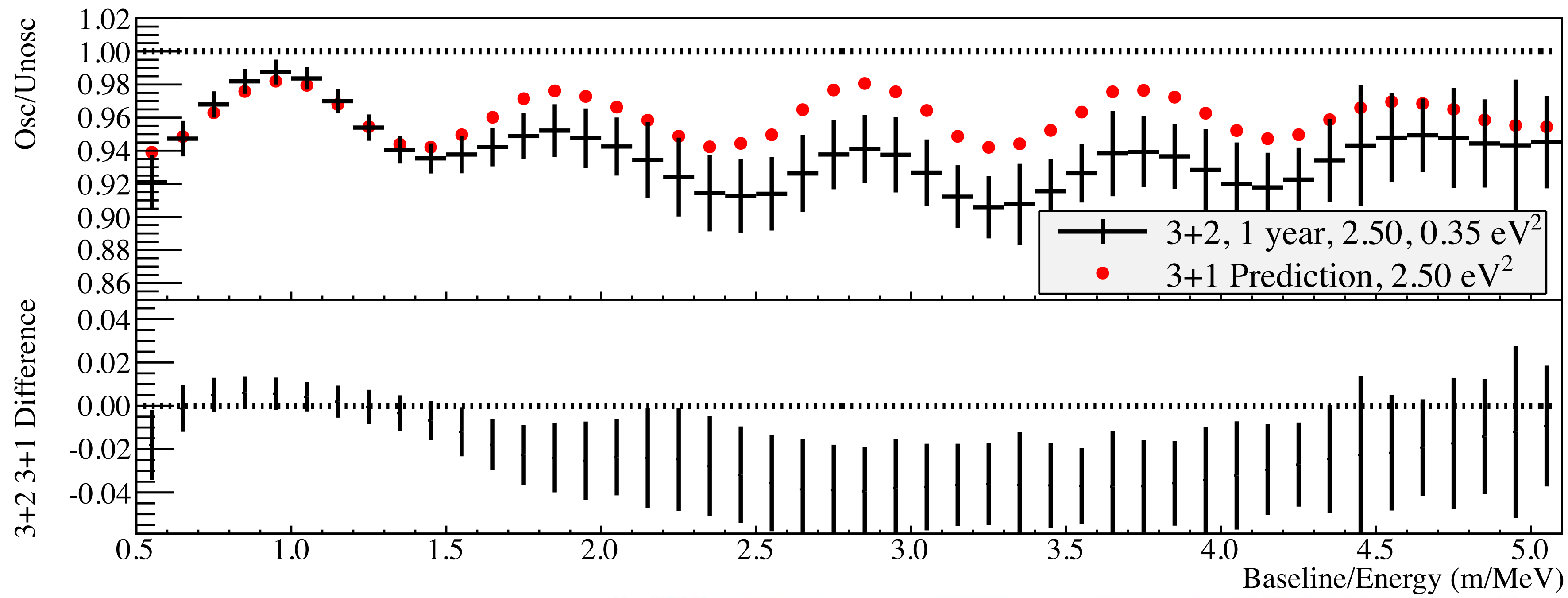
Heeger, Mumm, BRL
In Preparation

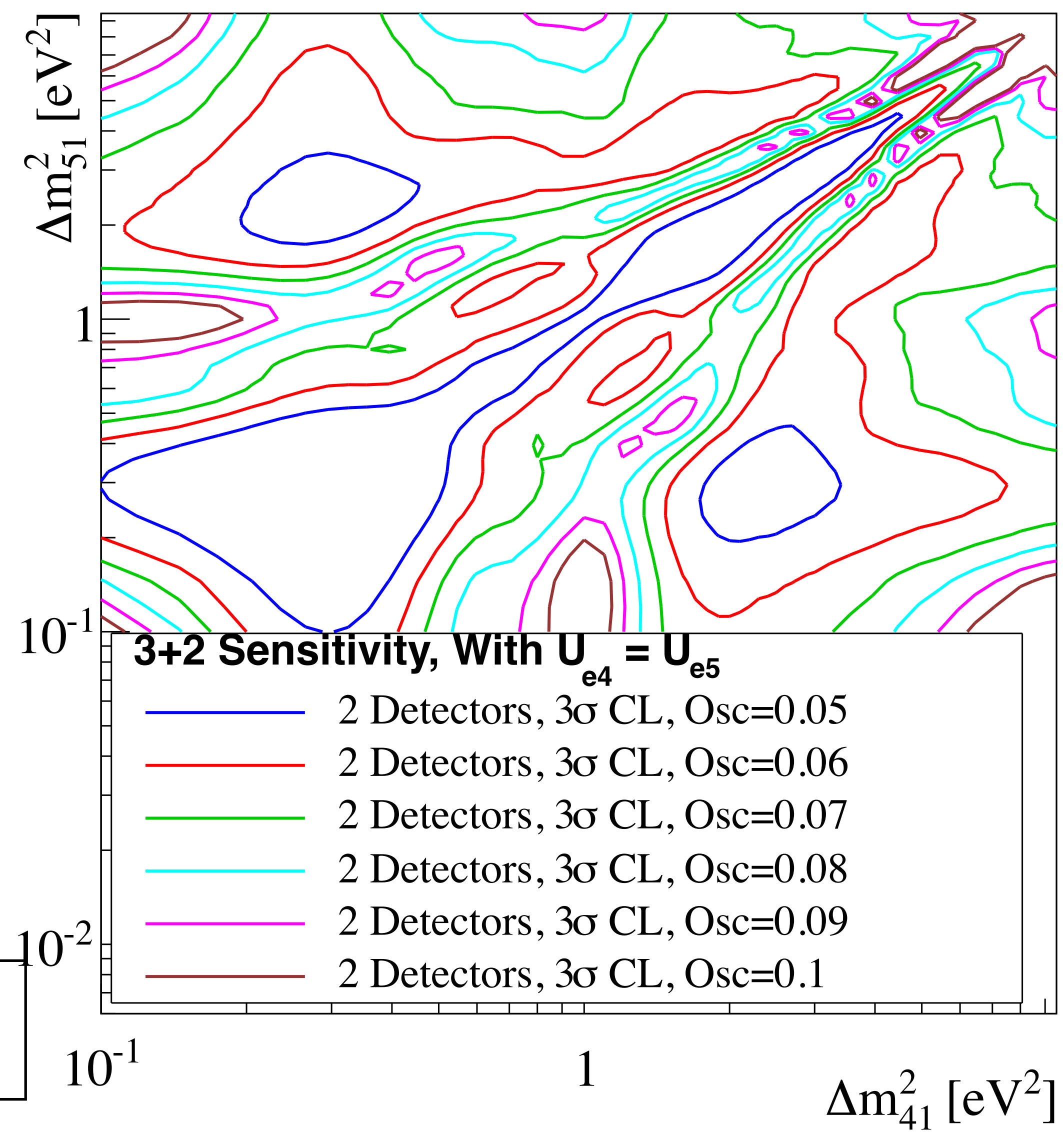
- Significant benefits using multiple detector deployments and increased L/E coverage
  - Example: 3m long detectors at 4 and 15 m closest distances

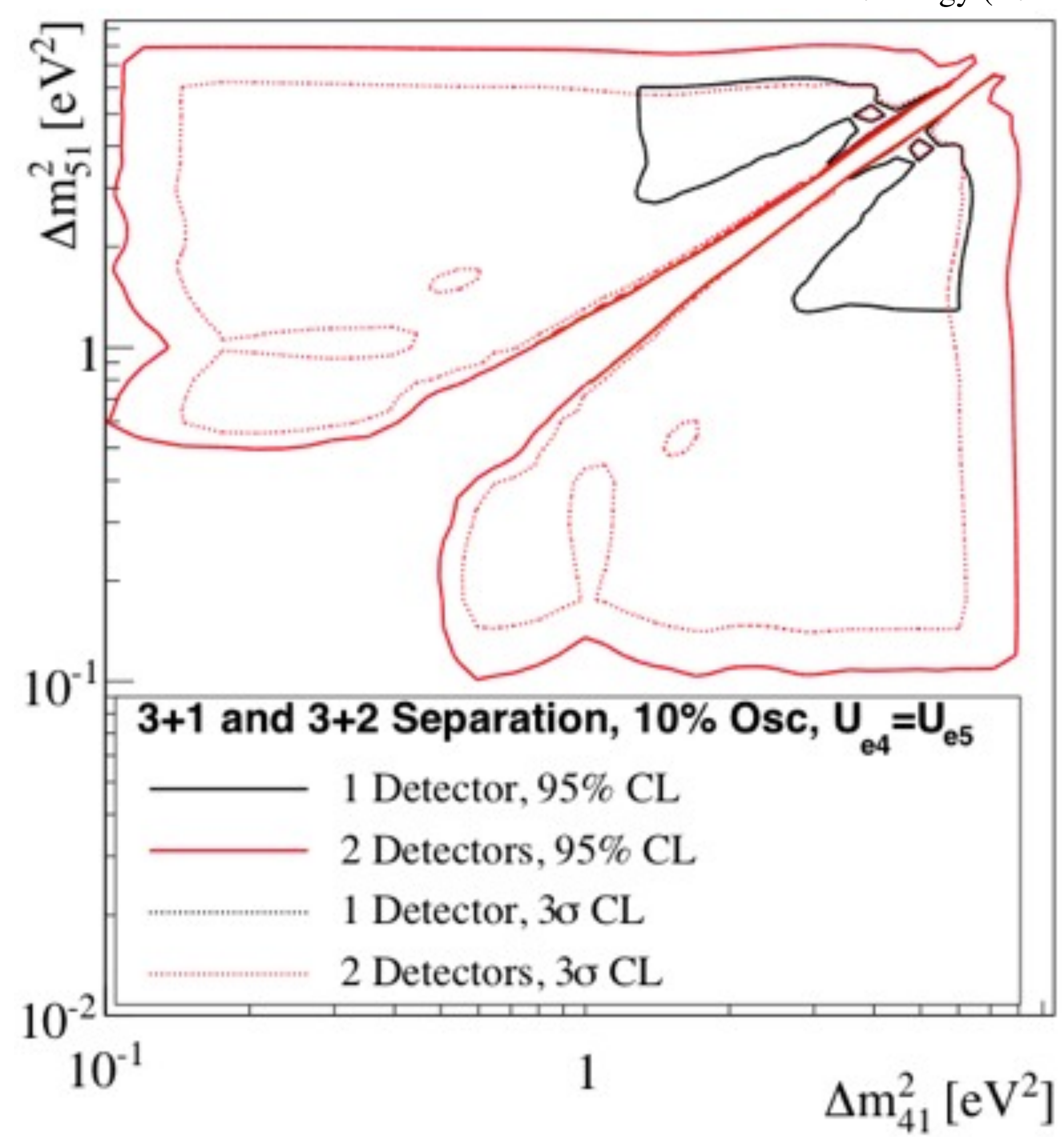


How Many Sterile Neutrinos?

- Sensitive to 3+2 oscillations
- Can distinguish 3+1 from 3+2

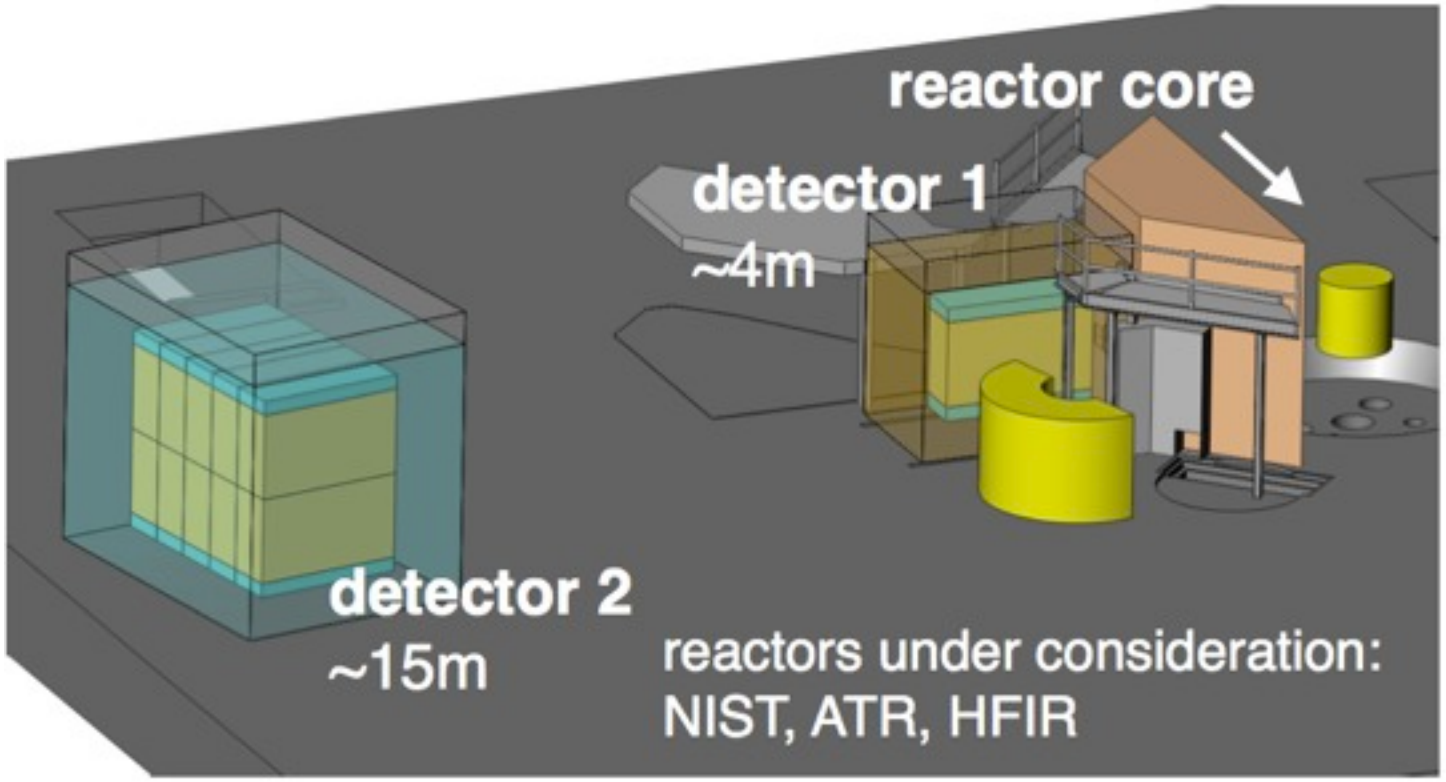






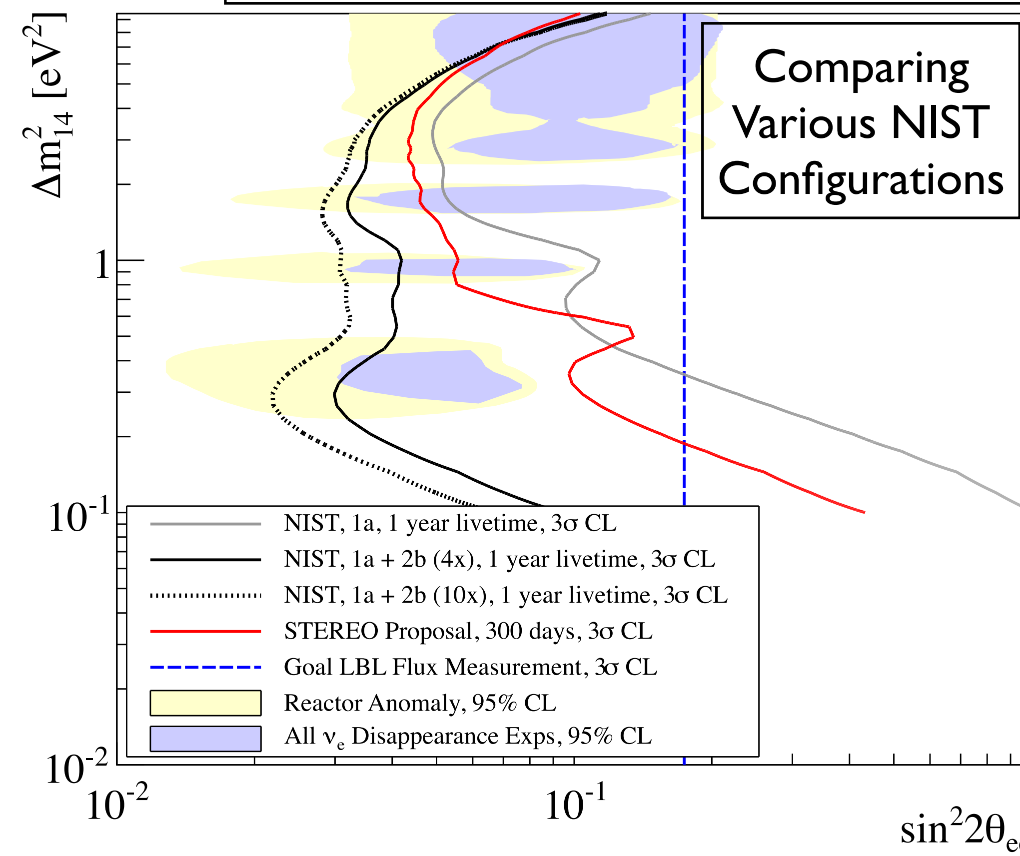
BRL, Heeger, Mumm, In Preparation

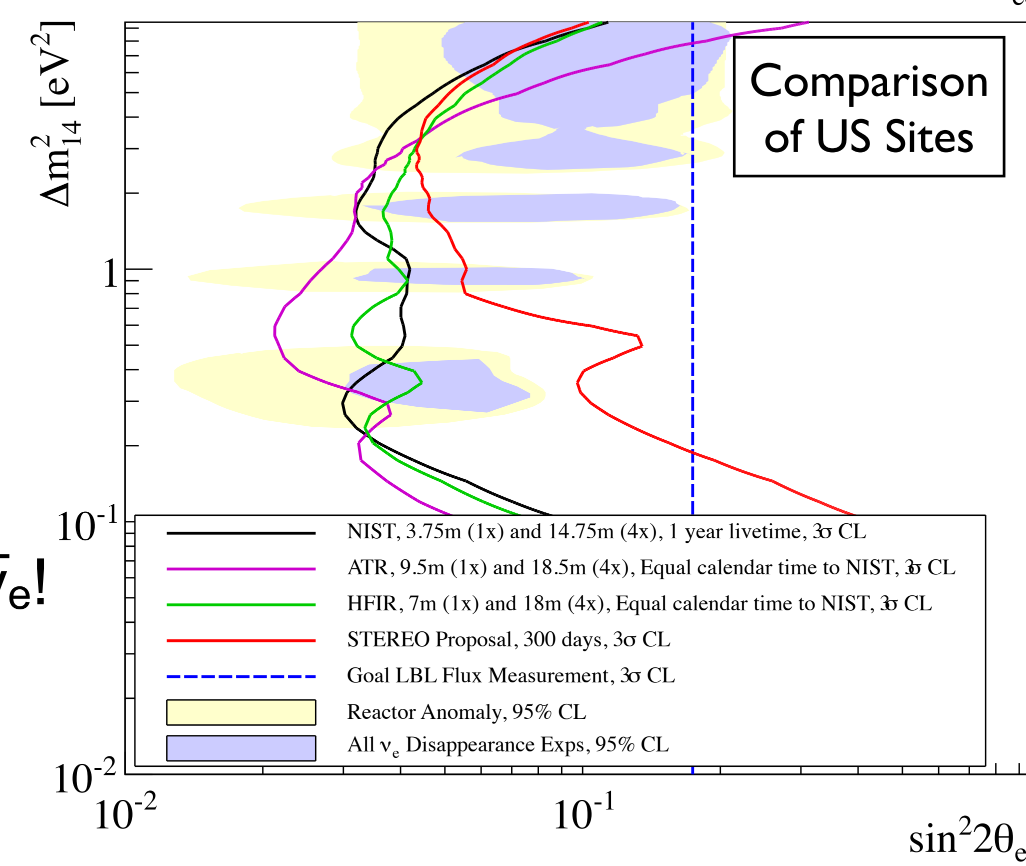
A Two-Detector Oscillation Experiment



- Capable of ruling out most suggested parameter space
  - Feasible at three US sites
- Can be built in phased approach
  - On a shorter timescale, given relatively simple detector design
  - Relatively cost effective: small detectors, free $\overline{\nu}_e$!
- Competitive in the international context

Heeger, Mumm, Bowden, Cherwinka, BRL





Proposed Deployment: NIST

- Engineering and space considerations allow a moveable ton-scale detector deployment at ~4 meters
  - Additional larger detector at further distances

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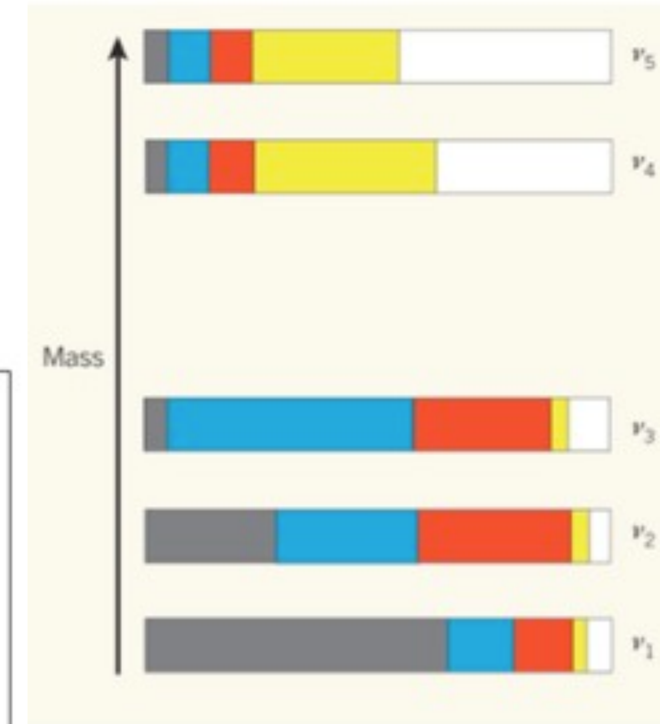
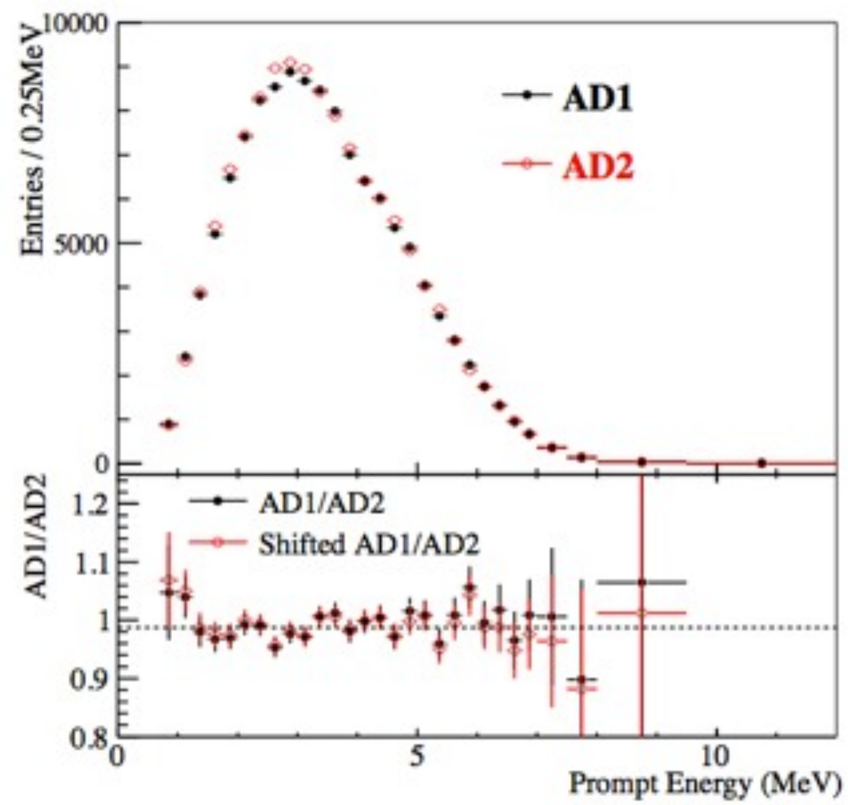
Heeger, Mumm, Cherwinka

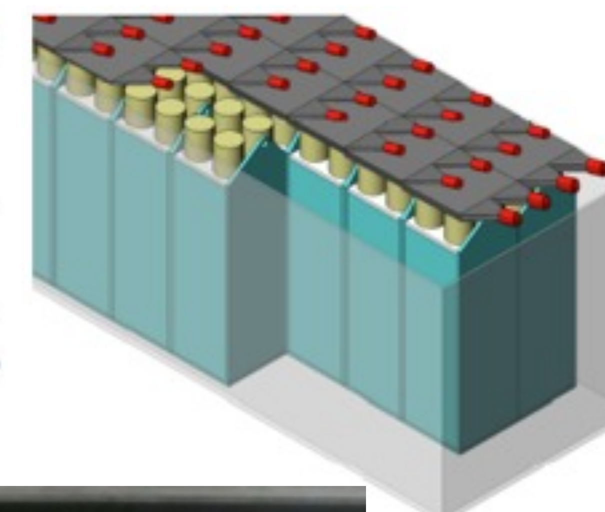
Scientific Opportunities

- Searches for new physics
  - Searching for <u>sterile neutrino oscillations</u> at short baselines

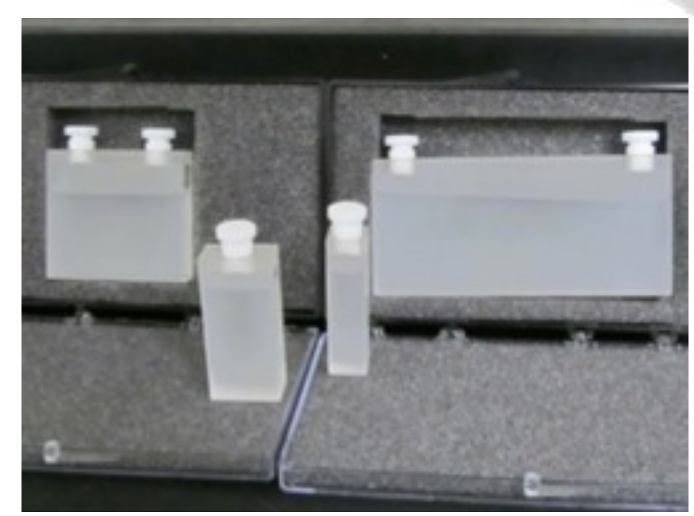


- Reactor physics
  - <u>Precise spectral measurement</u> of neutrinos from highly enriched uranium core (U-235 neutrinos)
  - Investigate research reactor enrichment conversion (low to hi)



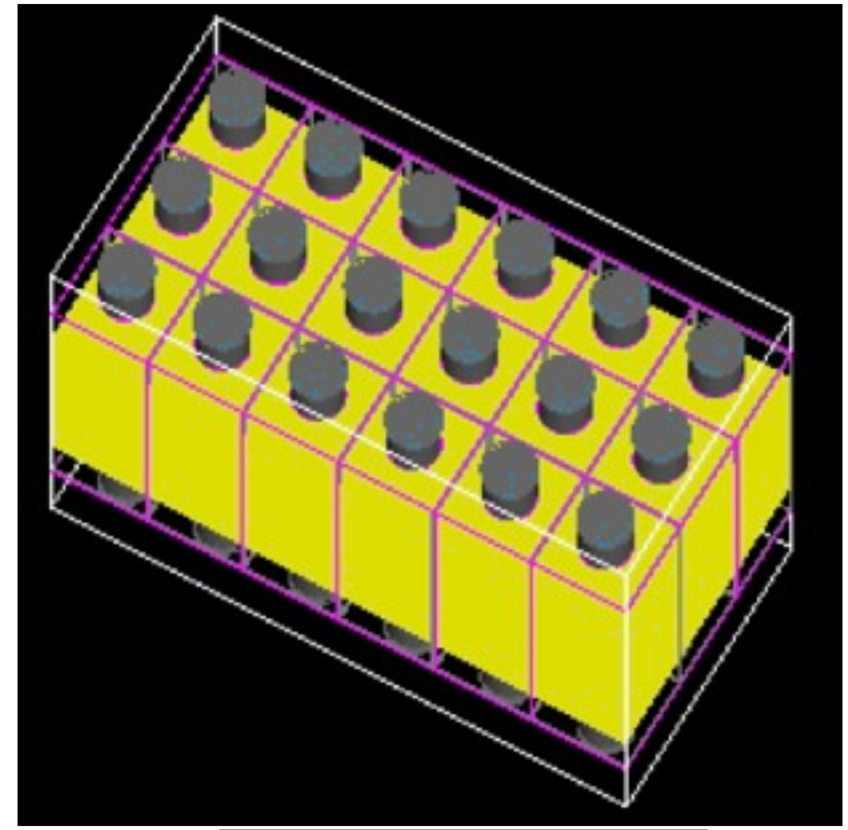


- Detector Development
  - Demonstration of <u>on-surface antineutrino detection</u>
  - Synergies with applied antineutrino physics and non-proliferation communities
  - <u>Development of scintillators</u> for neutron detection: pulse-shape discriminating Li-LS, Gd-LS

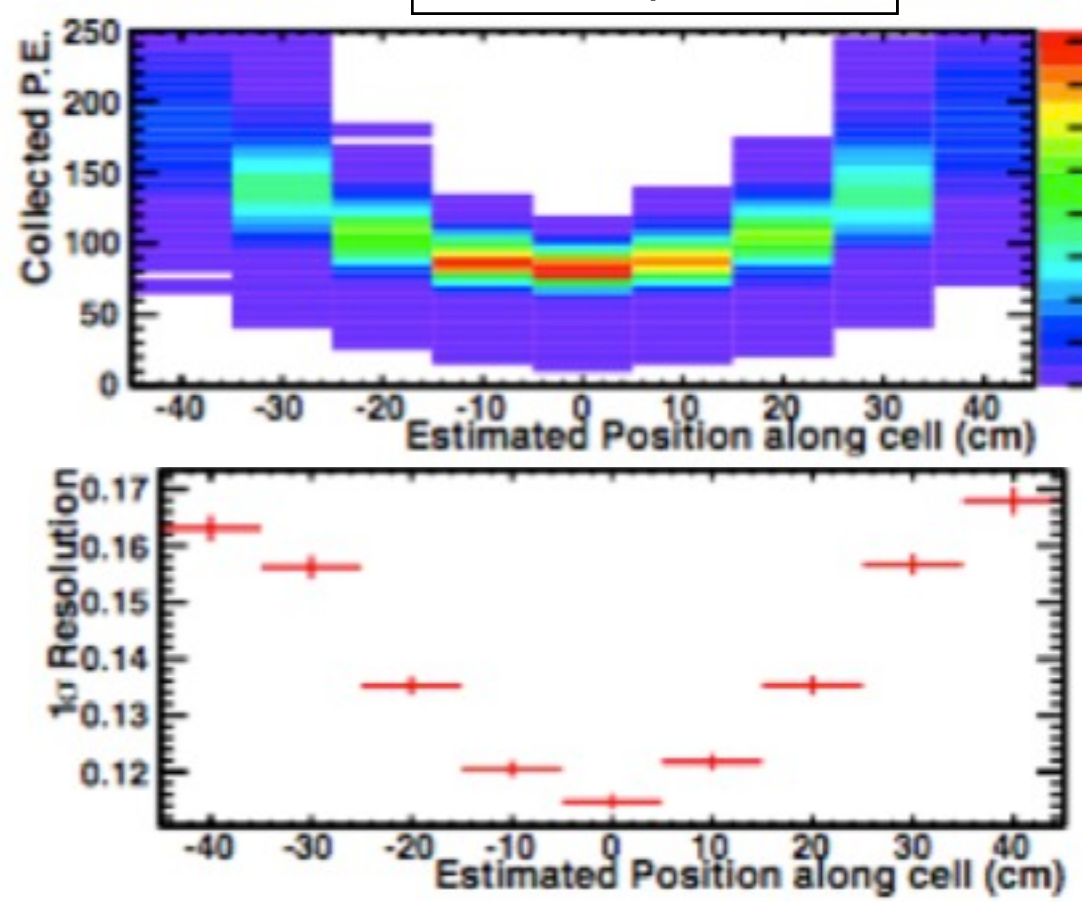


R&D Status: Detector Simulation

- Geant4-based detector simulation: Segmented LiLS or GdLS detector
- Beginning to investigate detector response:
    - Light yield and its uniformity
    - Prompt, delayed efficiencies
    - Energy, position resolution
    - Topology, PSD cuts
- Beginning to study detector requirements, optimizations
    - Detector size, cell size
    - Cell separator thickness (dead volume)
    - PMT and LS properties
    - Calibration program



Provided by T. Classen



R&D Status: Background Measurements

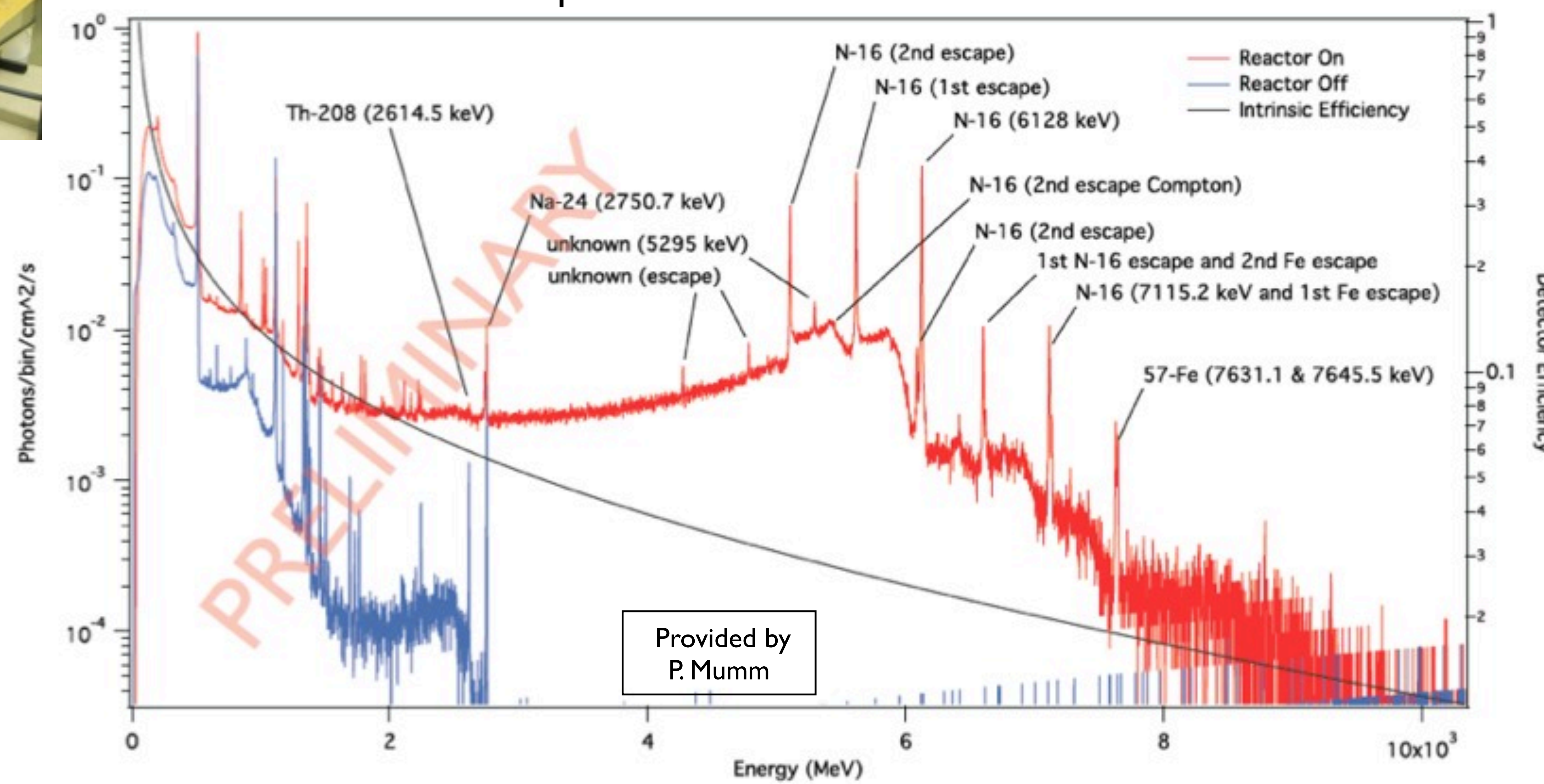
- Performing gamma, muon, and neutron measurements
  - Have specialized detectors for each particle type
  - Full survey of detector area in May 2013 for all three particle types

Muon Detector

Gamma Spectrometer

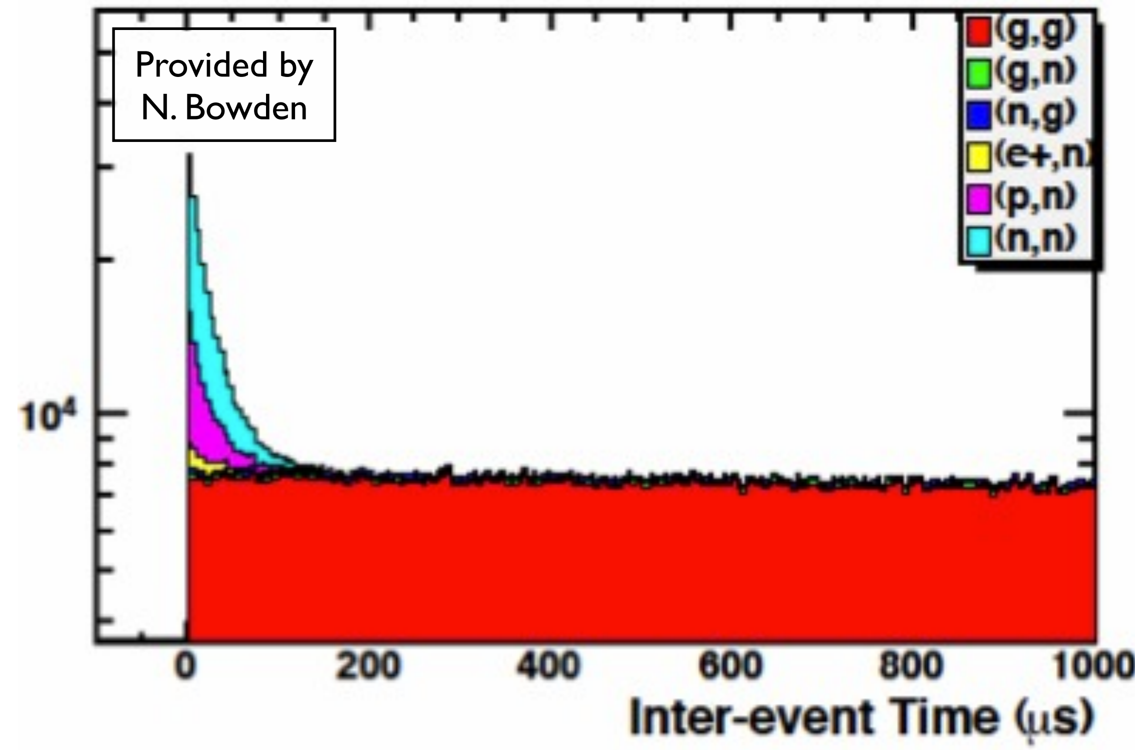
Neutron Detector: FANS-I

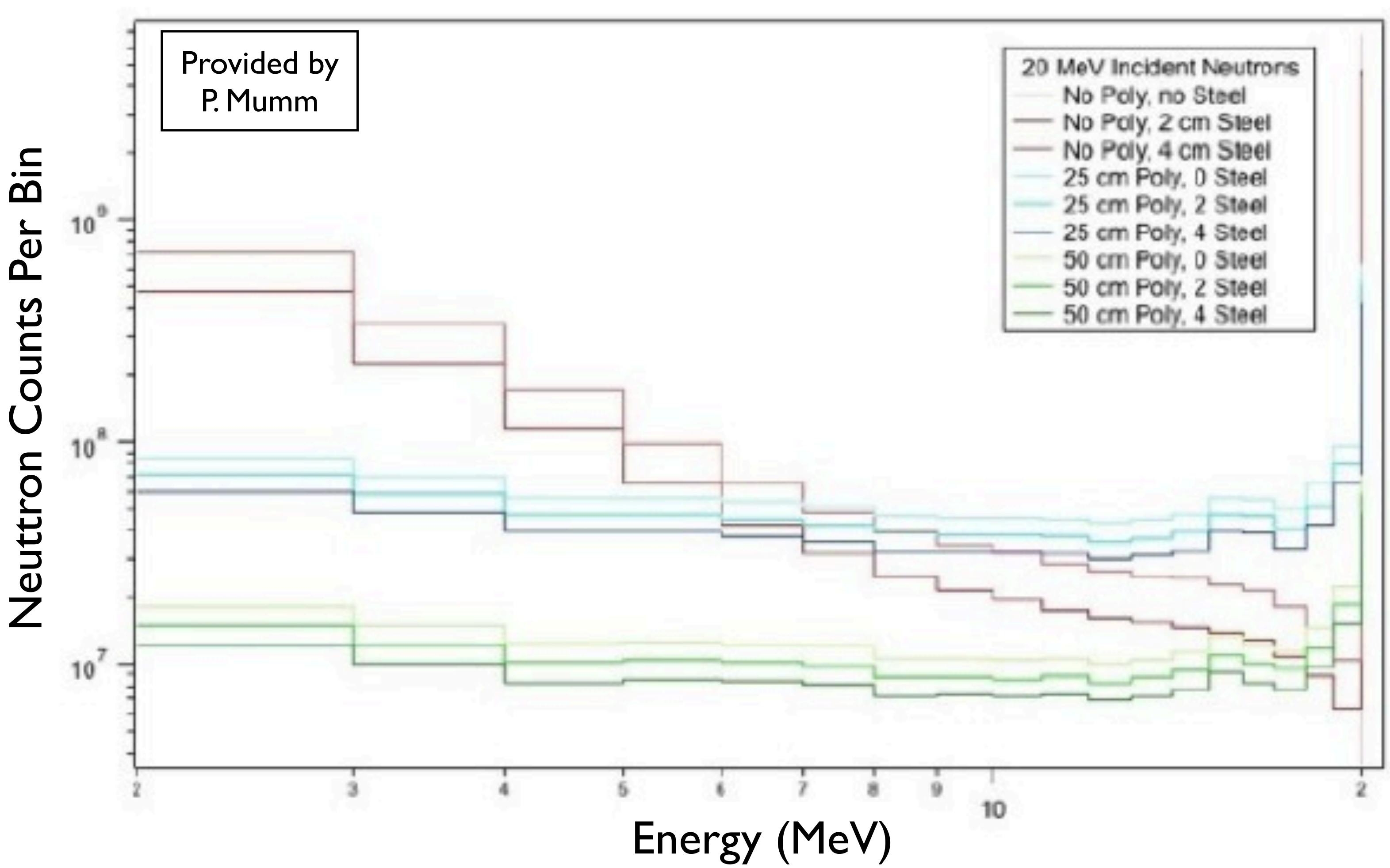
Gamma spectra: reactor-on and reactor-off

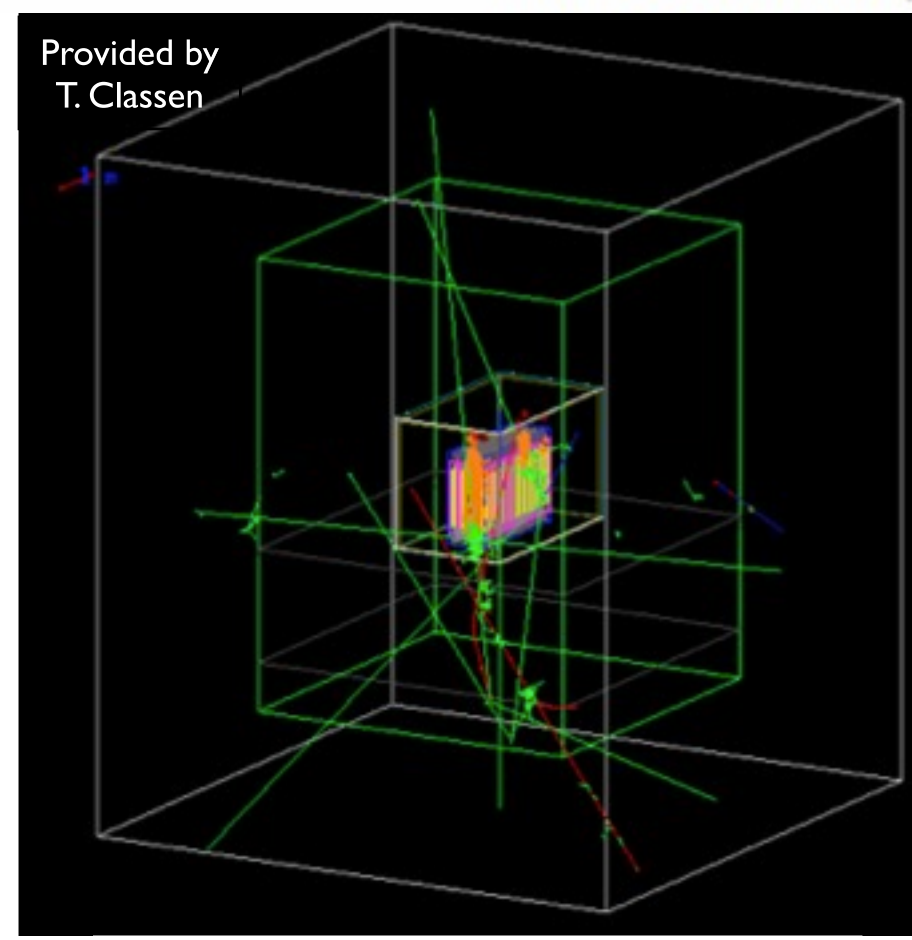


R&D Status: Background Simulations

- Neutron shielding studies: MCNP
  - Tie in with Geant4 simulation eventually
- Cosmics studies: CRY + Geant4
- Time correlated background simulations from previous US non-proliferation efforts







Cosmic Muon Traversing Detector

Current US Interest Group

Current Collaborators

26 individuals; 12 institutions

S. Hans, M. Yeh
Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973

J.G. Learned, J. Maricic
University of Hawaii, Honolulu, Hawaii 96822

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Center for Neutrino Physics, Virginia Tech, Blacksburg, VA 24061

A.B. Balantekin, H.R. Band, J.C. Cherwinka, K.M. Heeger, W. Pettus, D. Webber
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ATR National Scientific User Facility, Idaho National Laboratory, Idaho Falls, ID 83401

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National Institute of Standards and Technology, Gaithersburg, MD 20899

R. Henning
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599 and Triangle Universities Nuclear Laboratory, Durham NC 27710

C. Bryan, D. Dean, Y. Efremenko, D. Radford,
Oak Ridge National Laboratory, Oak Ridge, TN 37831

Summary

- US research reactors provide an opportunity for a high-precision, short-baseline reactor experiment
- This experiment can definitively address the reactor anomaly and the light sterile neutrino hypothesis
- This experiment additionally offers a broad range of other new physics opportunities and applications
- US interest group is developing a conceptual design and has begun detector and background R&D efforts

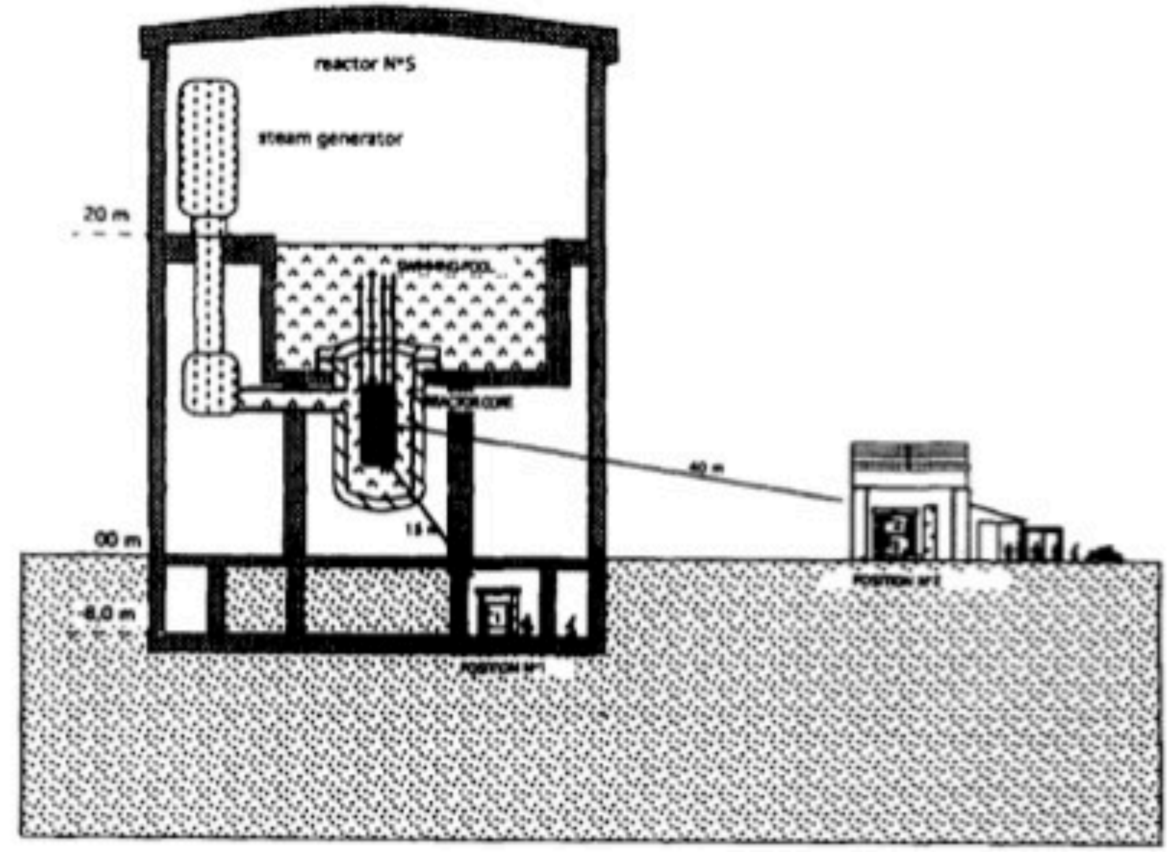
Backup

Experimental Parameters

Parameter		Value	Comment
Reactor	Power	20 MW	NIST-like
	Shape	cylindrical	NIST-like
	Size	0.5 m radius, half-height	NIST-like
	Fuel	HEU	Research reactor fuel type
Detector	Dimensions	$1 \times 1 \times 3$ m	3 meters of 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	15 cm	Daya Bay-like
	Energy resolution	$10\%/\sqrt{E}$	Daya Bay-like
Background	S:B ratio	1	In range of SBL exps. (1-25) In range of VSBL R&D (1)
	Background shape	$1/E^2$ + Flat	Low-Energy Accidentals ($1/E^2$) Neutron Bkg (Flat Approximation)
Other	Run Time	1 year live-time	-
	Closest distance	4 m	NIST-like

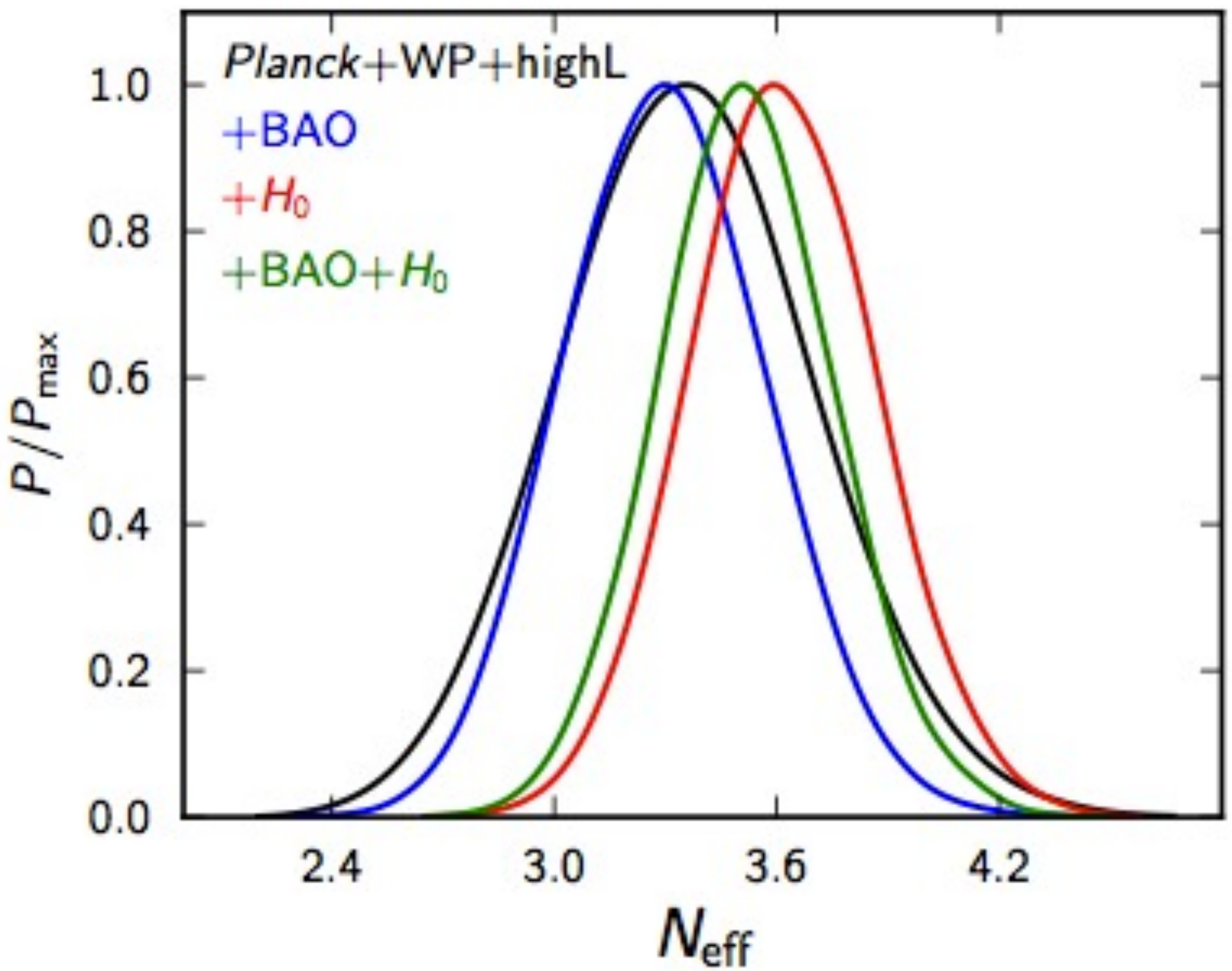
Compare to Bugey III

- 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

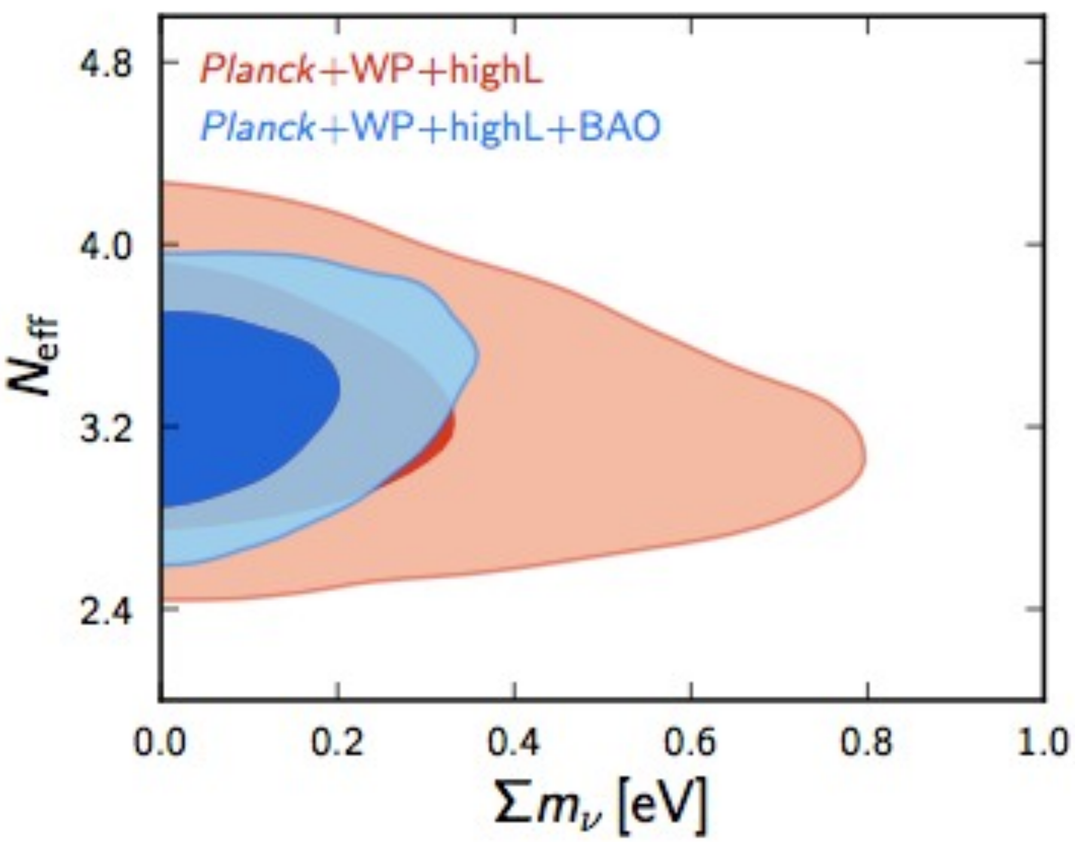


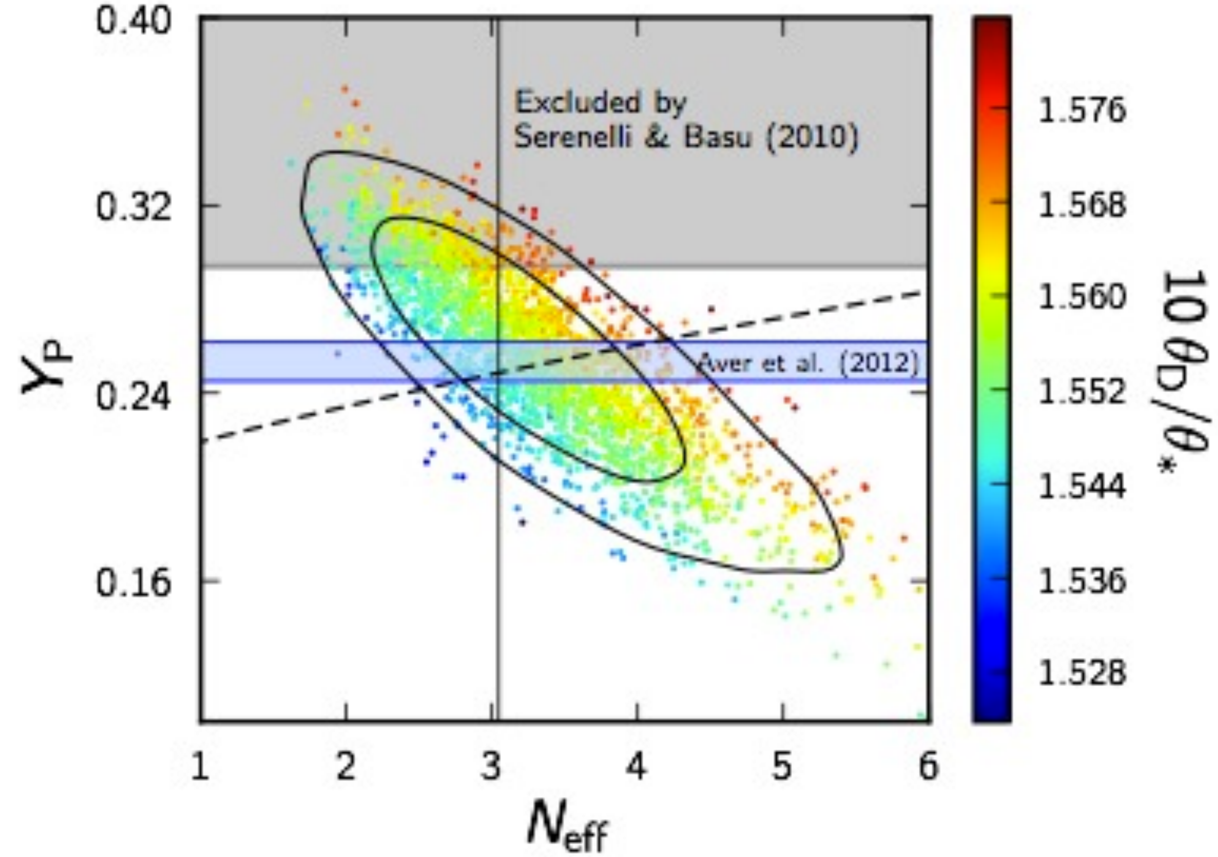
- shorter baseline
  - at US research reactors can get as close as 4m (Bugey > 15 m)
- better scintillator stability
  - some of the Bugey modules/detectors deteriorated
  - demonstrated stability of Gd-LS at Daya Bay for several years. Daya Bay scintillator produced by BNL
- possibly better pulse shape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

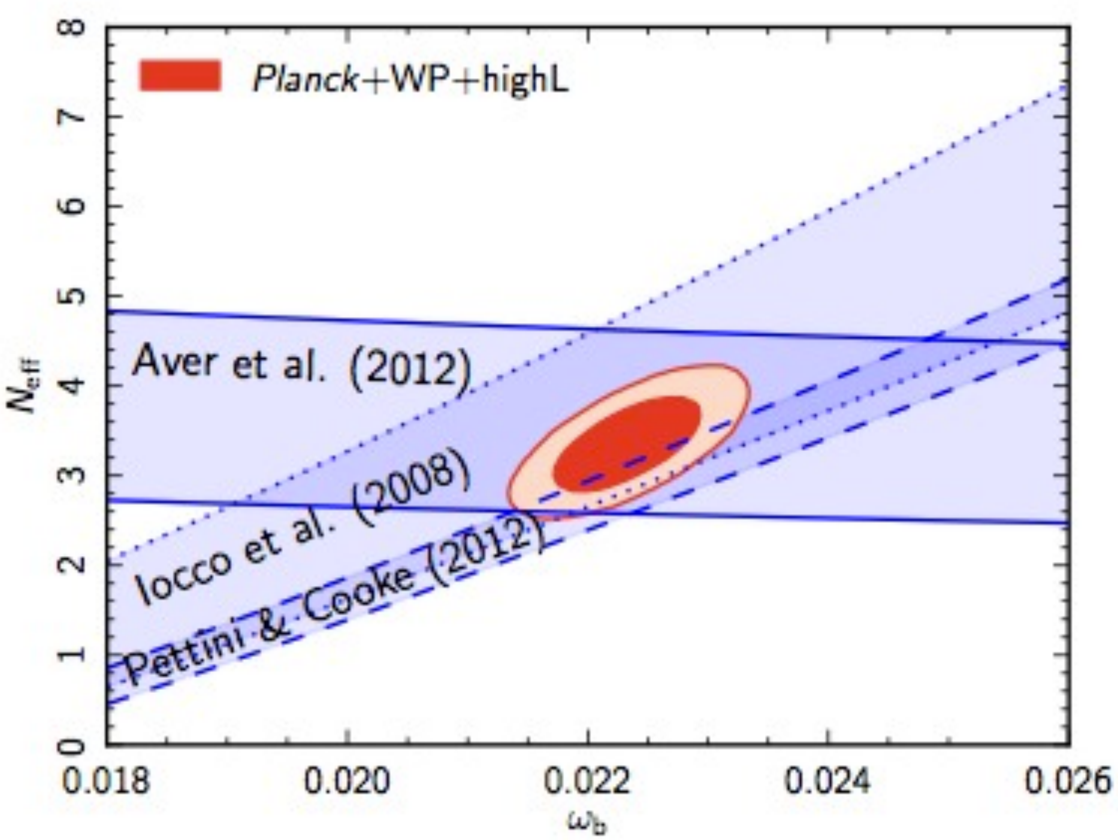
Sterile Neutrinos With Planck?

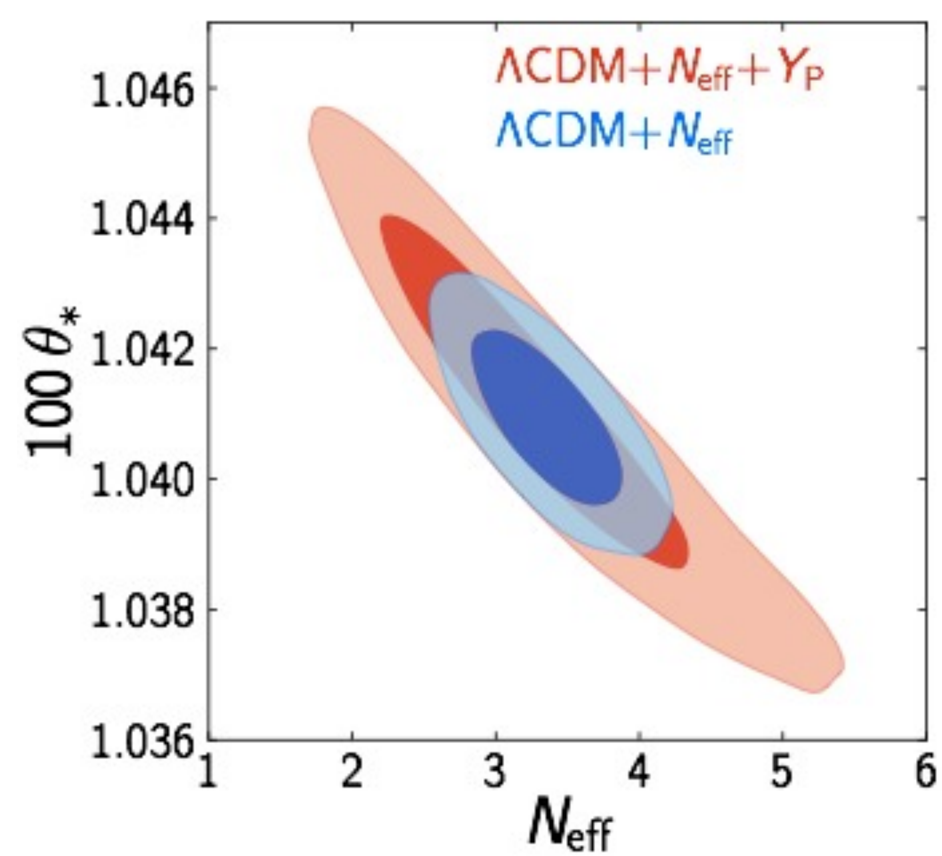


Sterile Neutrinos With Planck?



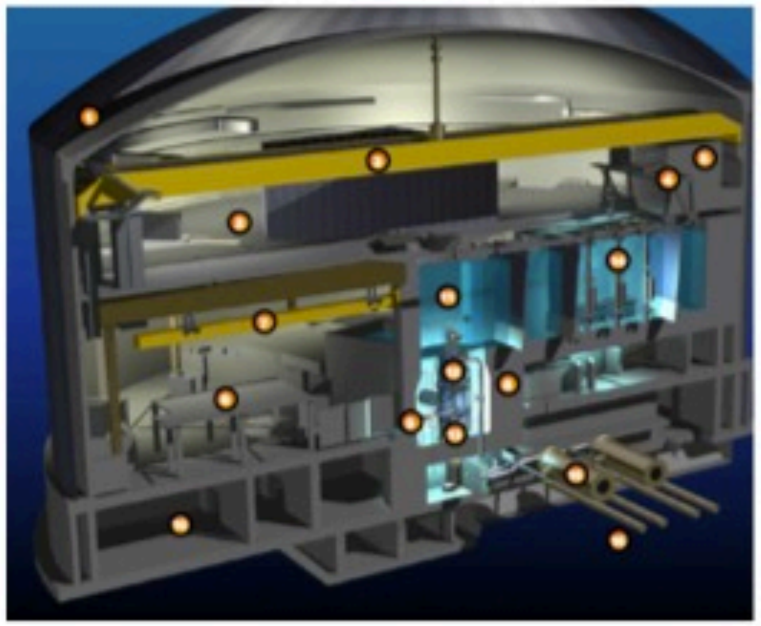


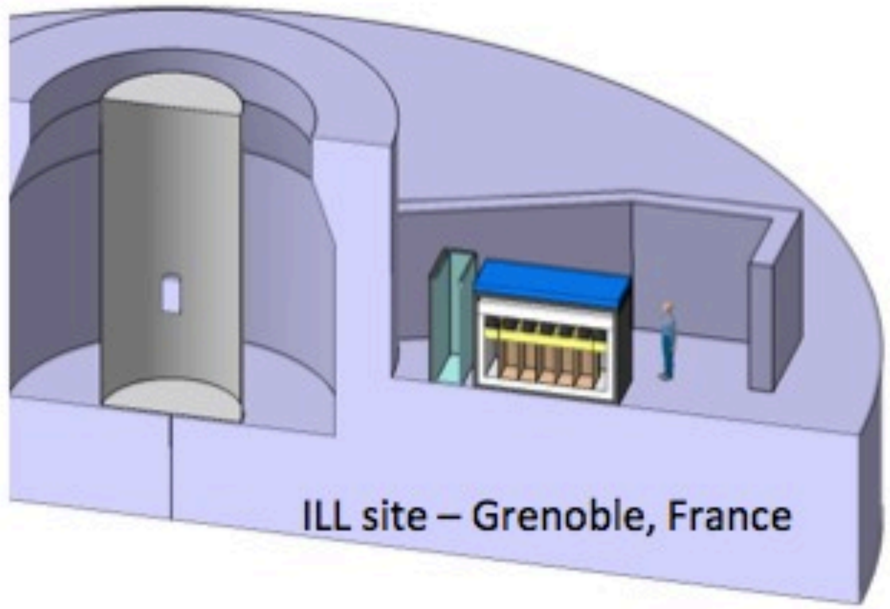


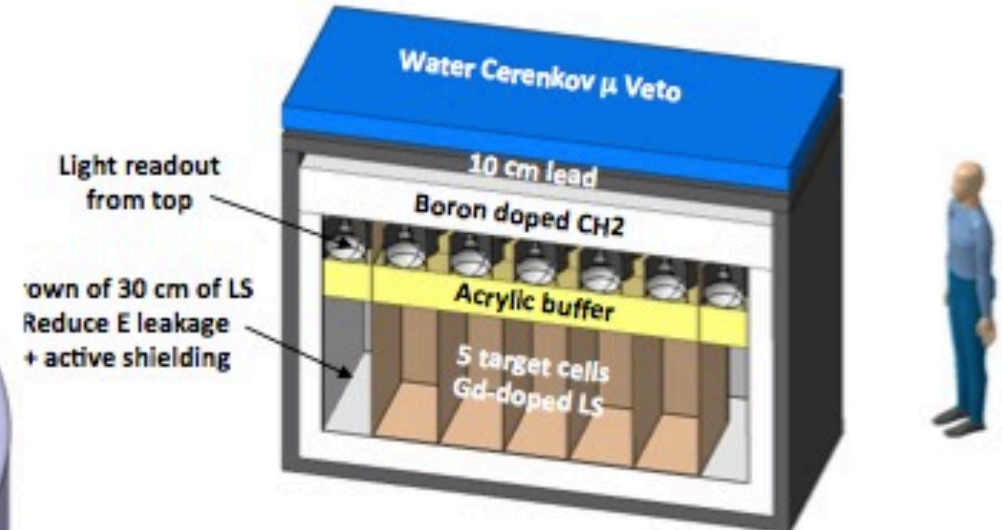


International Context

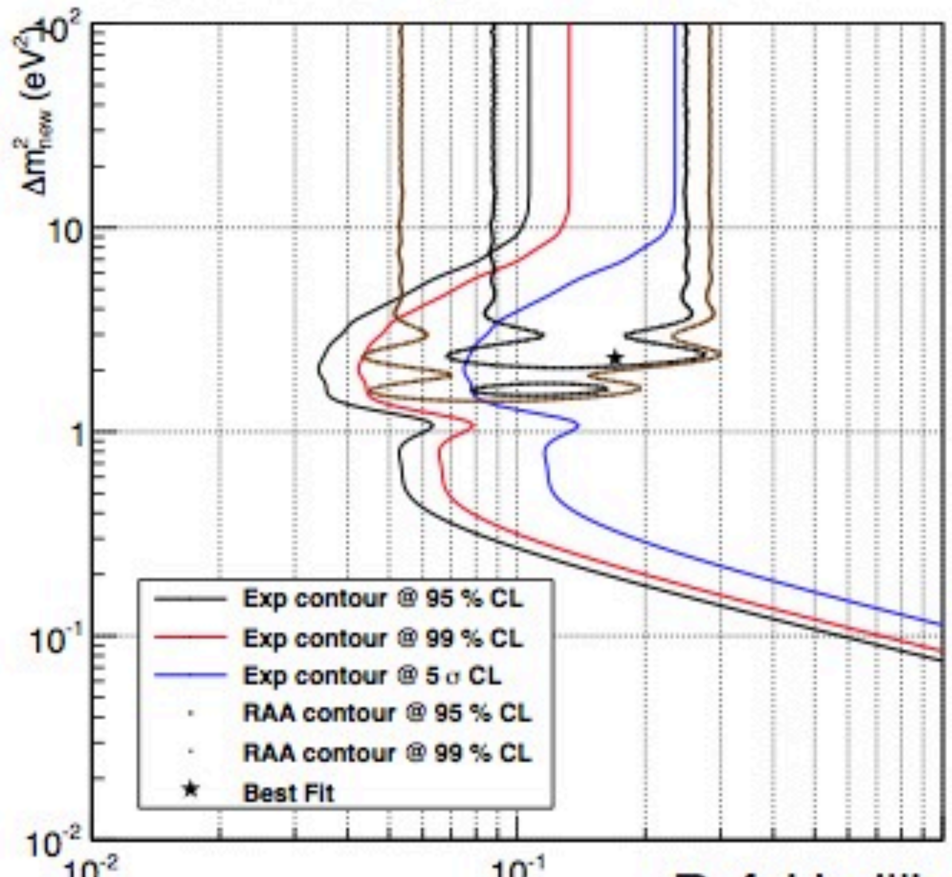
STEREO at ILL







Shape analysis +
3.5 % uncertainty on normalization



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

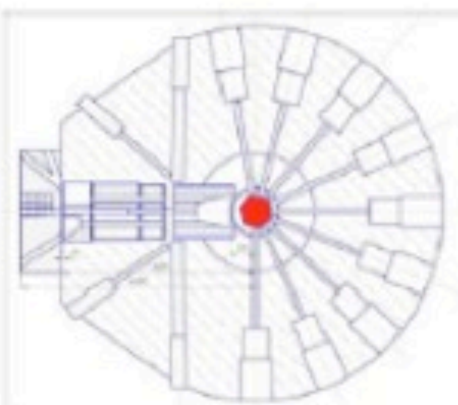
On-site measurements in progress

Aim for first data in 2015
Funding decision in 2013

Ref: Lhuillier

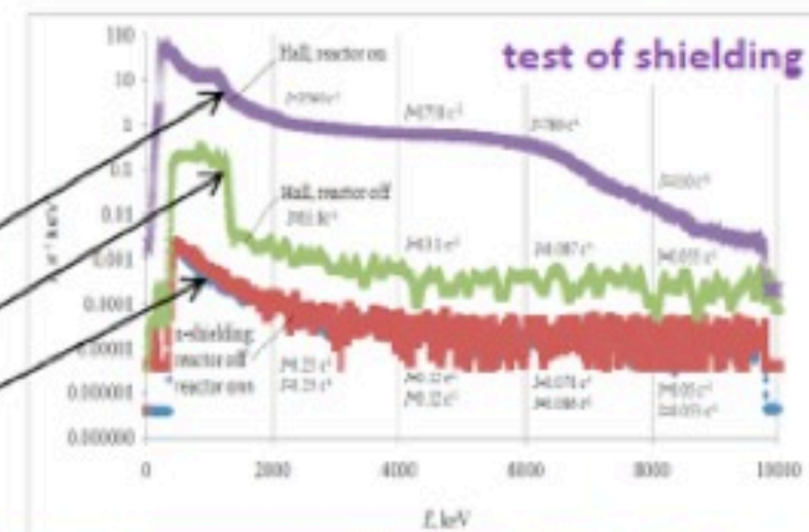
International Context

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



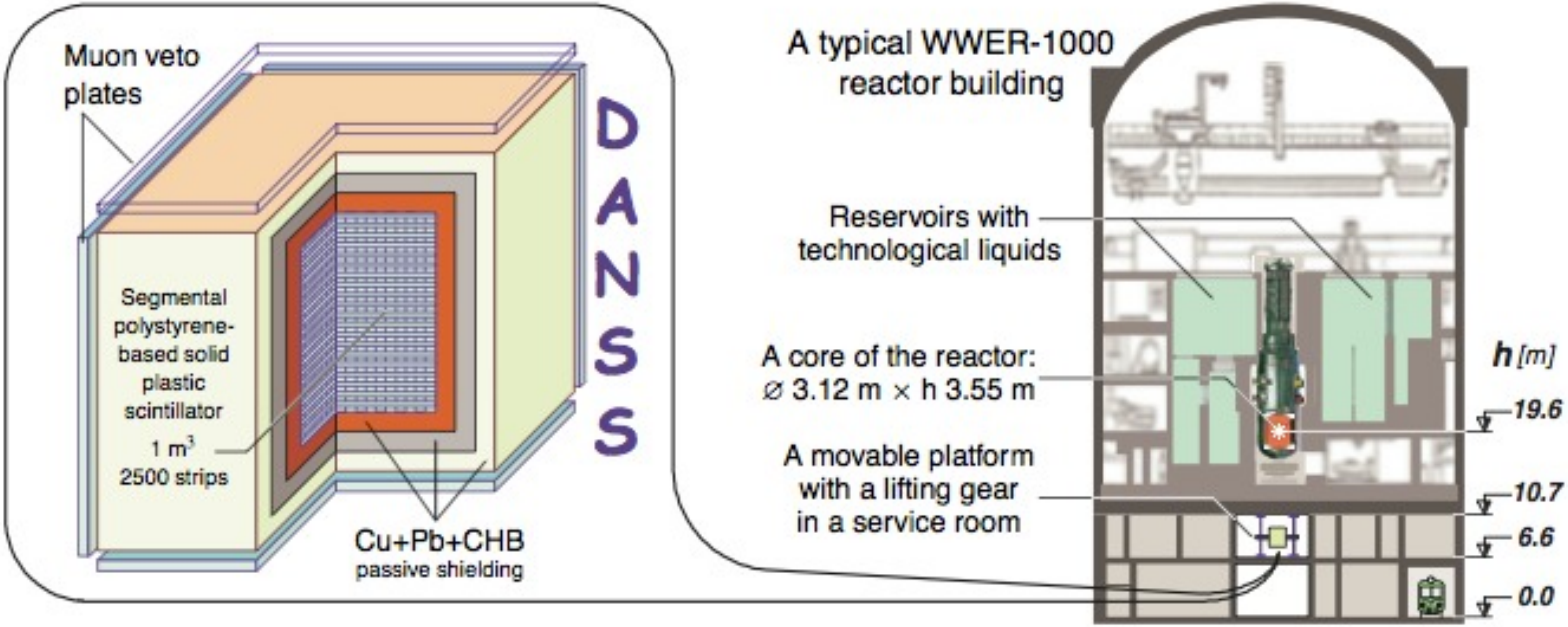
Installation of 2 sections test antineutrino detector with liquid scintillator (total volume 0.4 m^3)

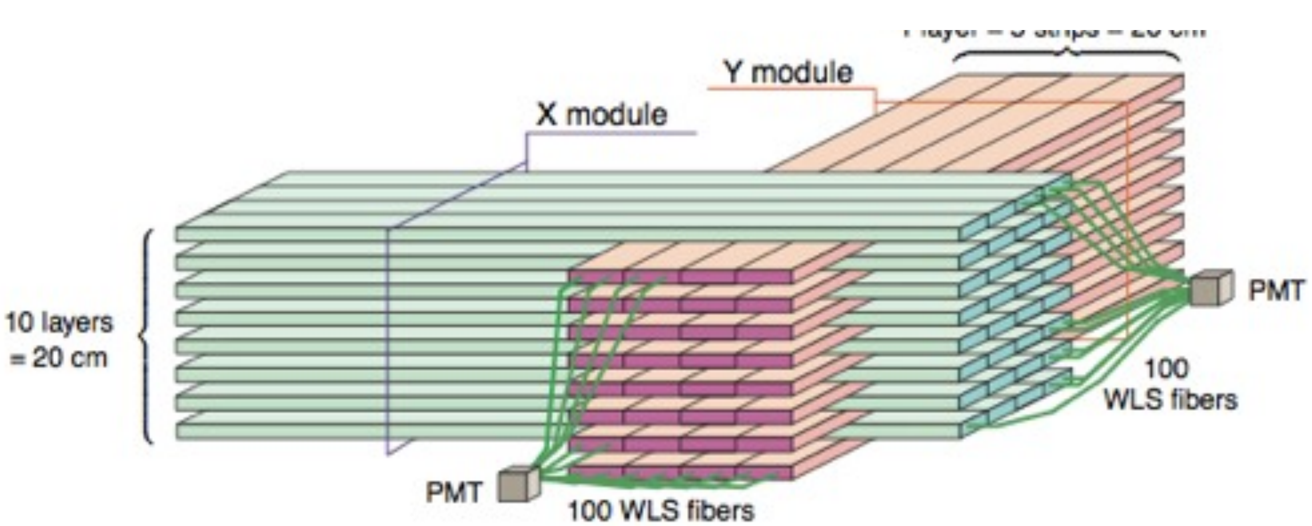
Installation of anticoinsidence shielding from plastic scintillator 0.5x0.5x0.125 m^3 with PMT (32 pieces)

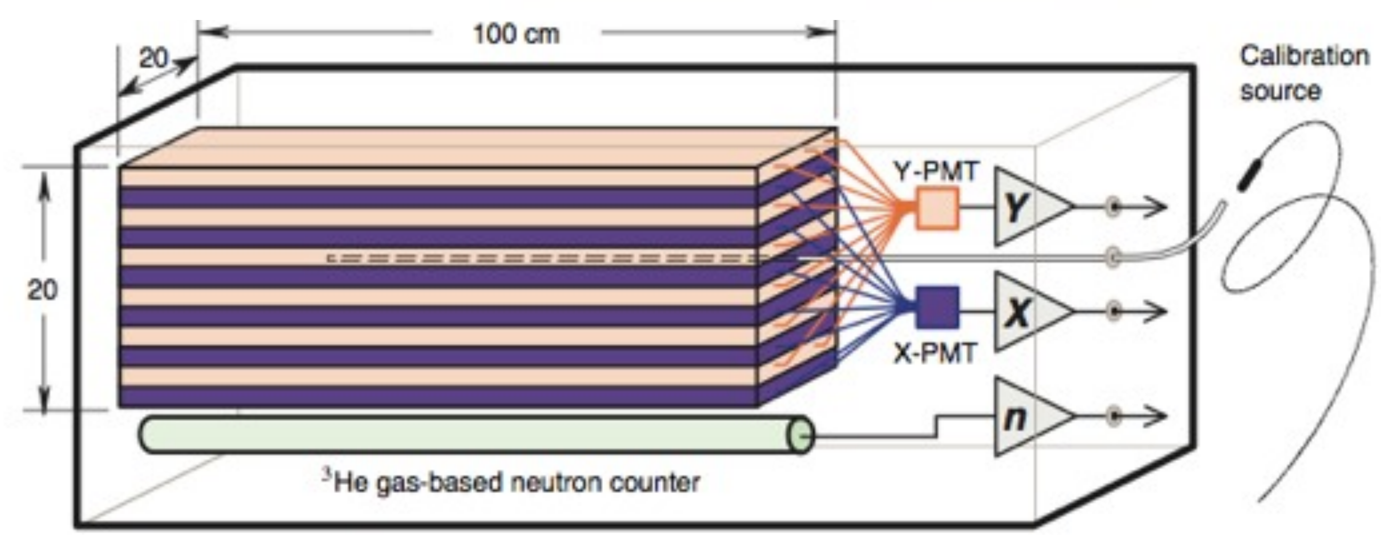
A.Serebrov, PNPI

International Context

DANSS (DANSSino) arXiv:1304.3696







More 3+2: Interference

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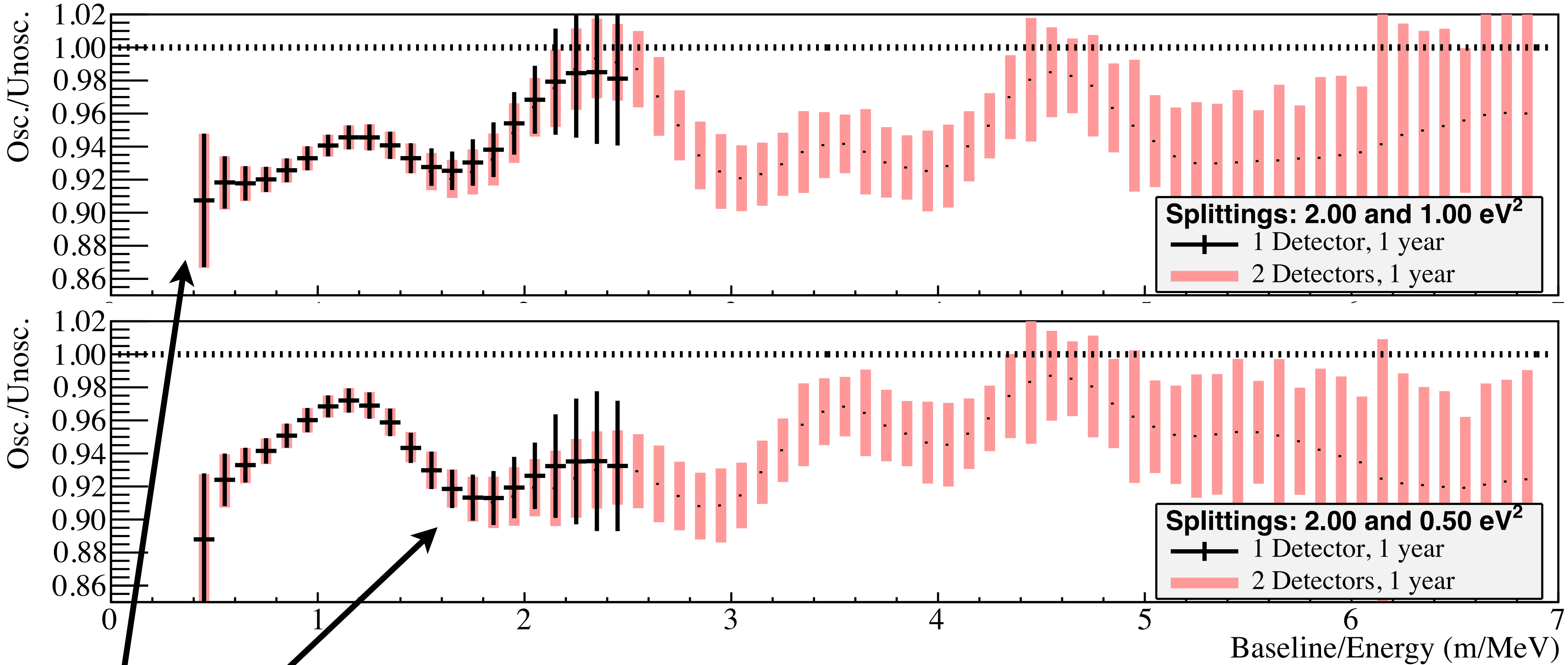

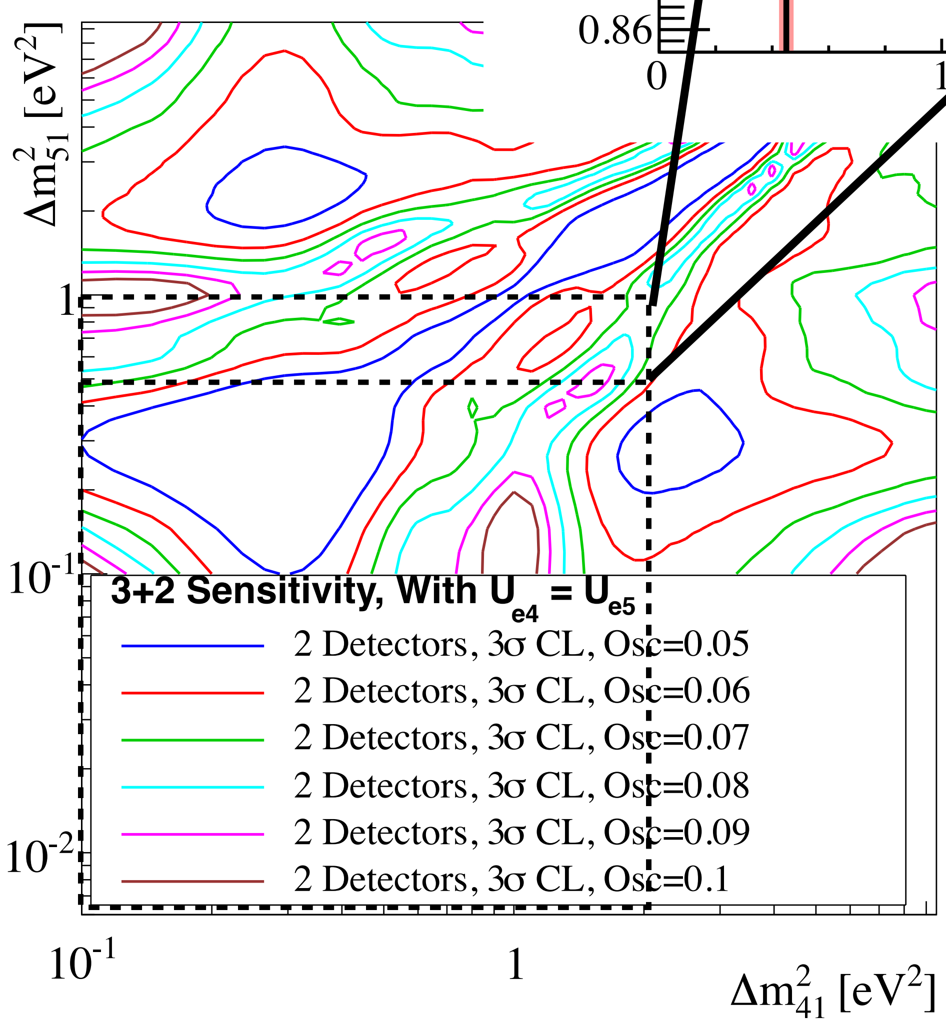

- Destructive interference reduces sensitivity for particular sterile mass-squared splitting combinations
- Especially when first oscillation period's amplitude is suppressed

More 3+2: Unequal Mixing

- Also have investigated unequal mixing to different sterile states

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