Short-baseline Experiments with Reactors

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University of Chicago

- Motivation for future short-baseline reactor experiments
- Experimental requirements
- Potential sites for US experiment; other efforts
- Comments

Snowmass Whitepapers

- S. Hans et al., "Search for Oscillations of Reactor Antineutrinos at Very Short Baselines"
- S. Hans et al., "U.S. Reactors for Antineutrino Experiments"
- S. Hans et al., "Advanced Reactor Antineutrino Detector Development”

I have relied heavily on Heeger, Littlejohn, Mumm, and Tobin, arXiv:1212.2182 and recent talk by Heeger at Aspen 2013.

Motivation for new, short-baseline (L≲10m) reactor experiment

- Variety of anomalies that could indicate additional sterile neutrino states with mass splittings of order 1 eV^2: "reactor anomaly",LSND/MiniBooNE, SAGE/GALLEX calibrations + WMAP,SPT, Planck? (see talk by W. Louis)
- Nuclear safeguards community (see talk by N. Bowden)

Reactor Neutrino Flux and the Reactor Antineutrino Anomoly

Th. A. Mueller et al.``Improved Predictions of Reactor Antineutrino Spectra,'' accepted for publication in Phys. Rev. C, 83 (2011) 054615; arXiv:1101.2663.

G. Mention et al., ``The Reactor Antineutrino Anomoly,'' Phys. Rev. D, 83 (2011) 073006; arXiv:1101.2755.

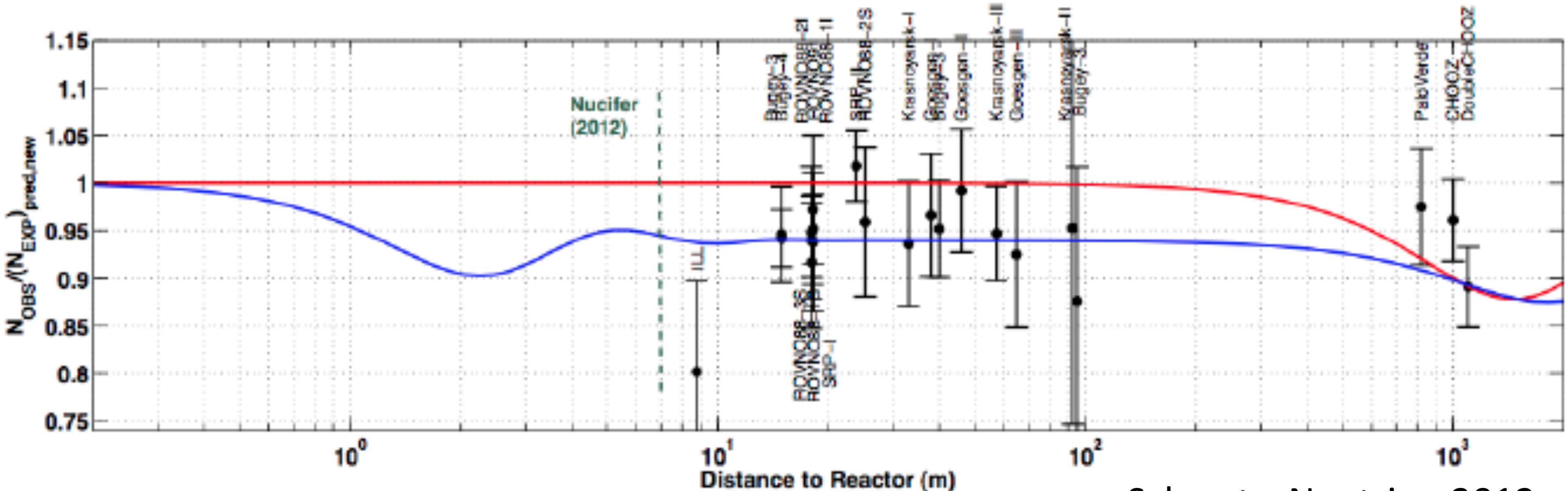
P. Huber, ``On the determination of anti-neutrino spectra from nuclear reactors; arXiv:1106.06874.

As part of preparation for Double Chooz analysis with a single far detector, Mueller et al. applied an improved procedure to go from measured ^{235}U, ^{239}Pu, and ^{241}Pu β^- spectra (at ILL) to neutrino spectra.

The result is a +3% increase in neutrino flux, on average.

Huber, using a different method to go from β^- to ν spectra, finds a similar shift.

G. Mention et al. (arXiv:1101.2755)



Schwetz, Neutrino 2012

For L<100m, accounting for correlations, Mention et al. found $N_{OBS}/N_{EXP} = 0.937\pm0.027$.

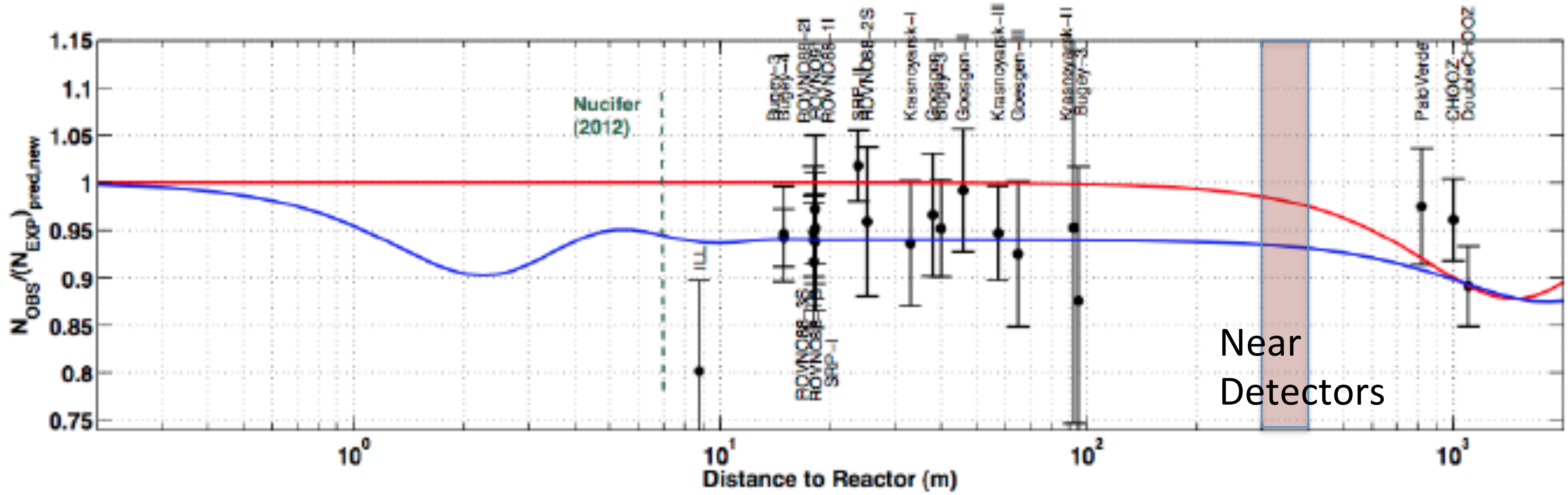
Zhang, Qian, and Vogel (arXiv:1303.0900) include Palo Verde, Chooz, and Double Chooz using measured $\sin^2 2\theta_{13}$ and find $N_{OBS}/N_{EXP} = 0.959\pm0.028$.

Explanations?

- Statistics
- Mistake in flux calculation; perhaps uncertainty in flux calculation is larger than estimated
- Bias in normalization of ILL experiment (uncertainty quoted as 2%)
- Common systematic bias in reactor experiments
- New physics at short baselines. Results are compatible with 4^{th}, non-standard neutrino state with $\Delta m^2 >\sim 1\ eV^2$ and $\sin^2 2\theta \sim 0.1$

→ The last possibility motivates a precise short baseline experiment

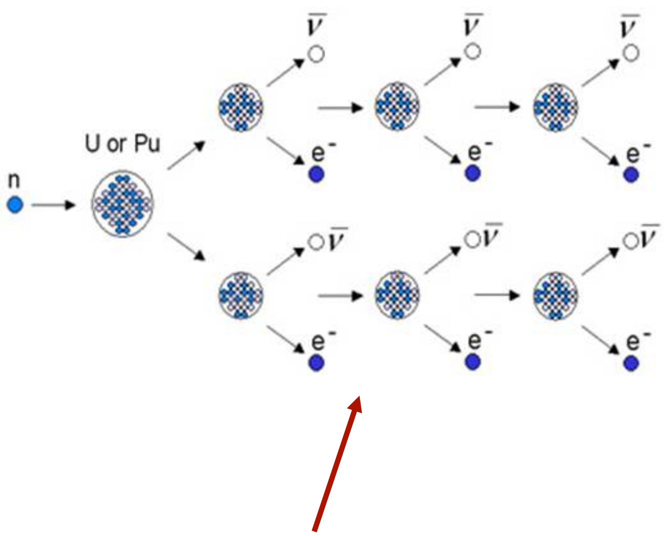
What about near detectors from θ_{13} experiments?



- Absolute near detector rate measurements from Daya Bay, RENO, and Double Chooz will check flux level observed at Bugey, etc. Significance of reactor anomaly will still be limited by uncertainty in flux prediction.
- Near detectors do have some sensitivity to lower Δm^2 oscillations through spectral distortions. Investigated in recent paper by Bergevin, Grant, and Svoboda (arXiv:1303.0310).

Reactor Neutrino Experiments

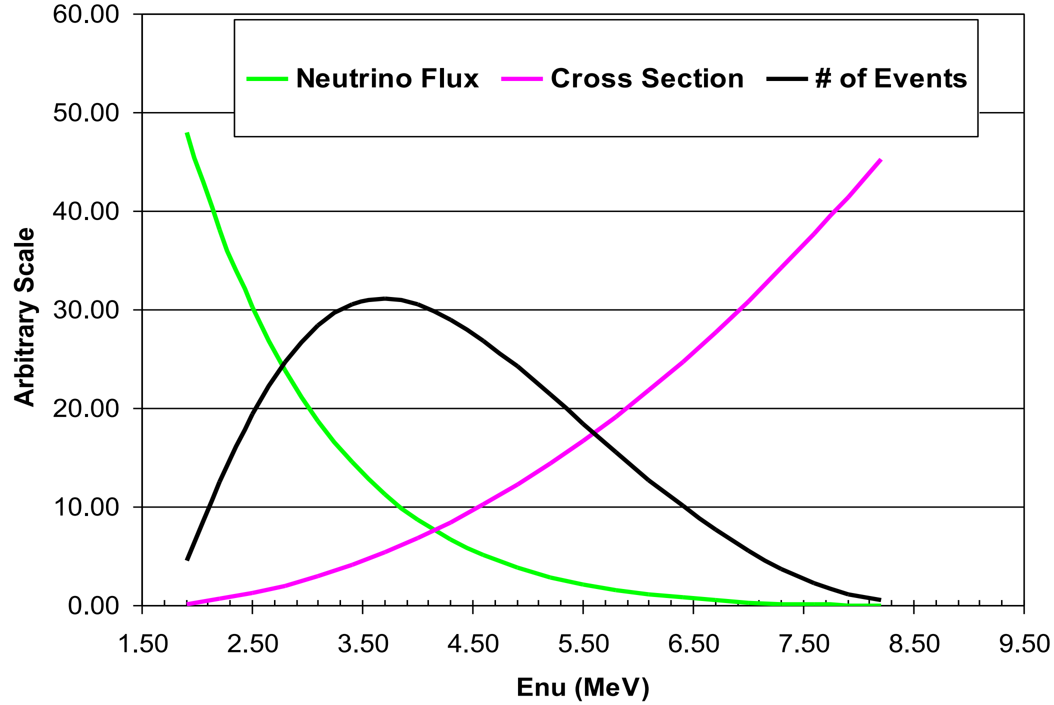
Reactor $\bar{\nu}_e$ production



β⁻ decay of neutron rich fission fragments of U and Pu

Detection through inverse β Decay:

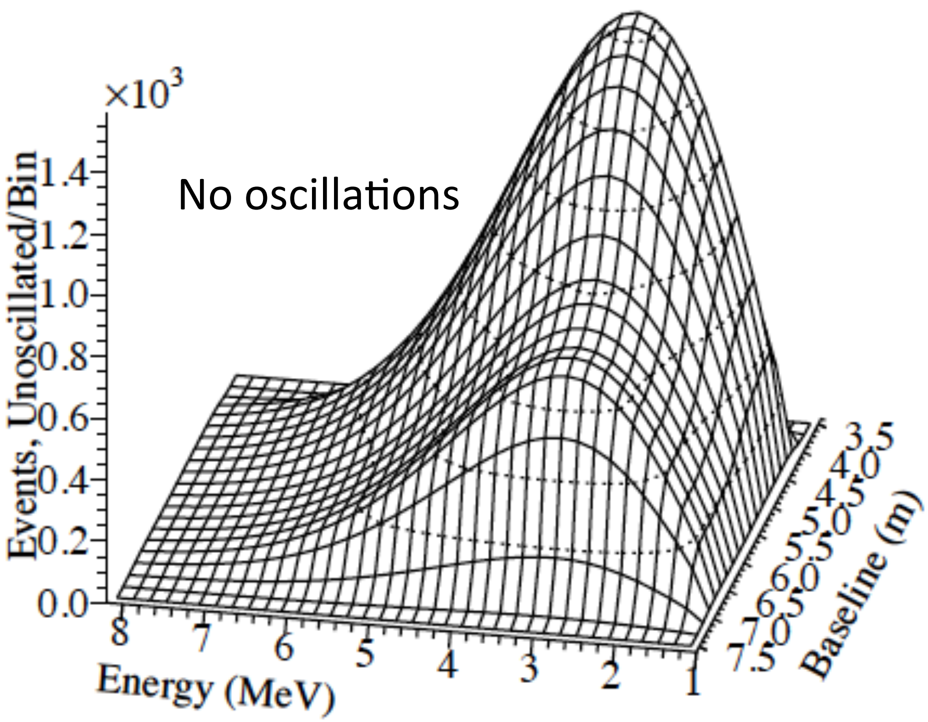
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

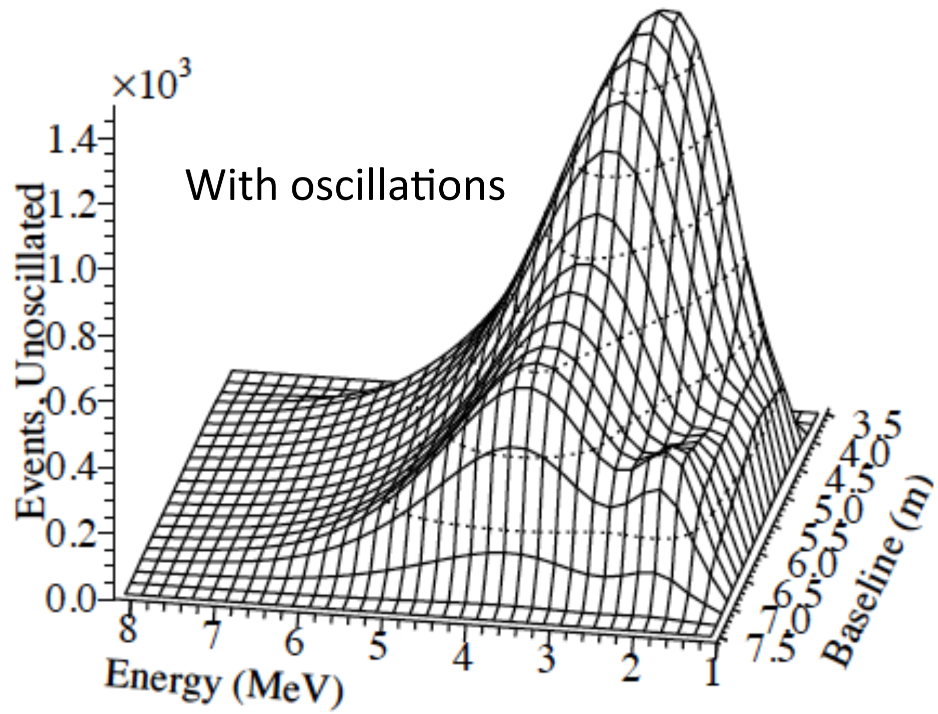


$E_{prompt} = E_\nu - 0.8$ MeV

Oscillation Signal: Energy and baseline dependent effect

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$





$$E.g.,\ \Delta m^2 = 1.8 eV^2, \sin^2 2\theta = 0.5$$

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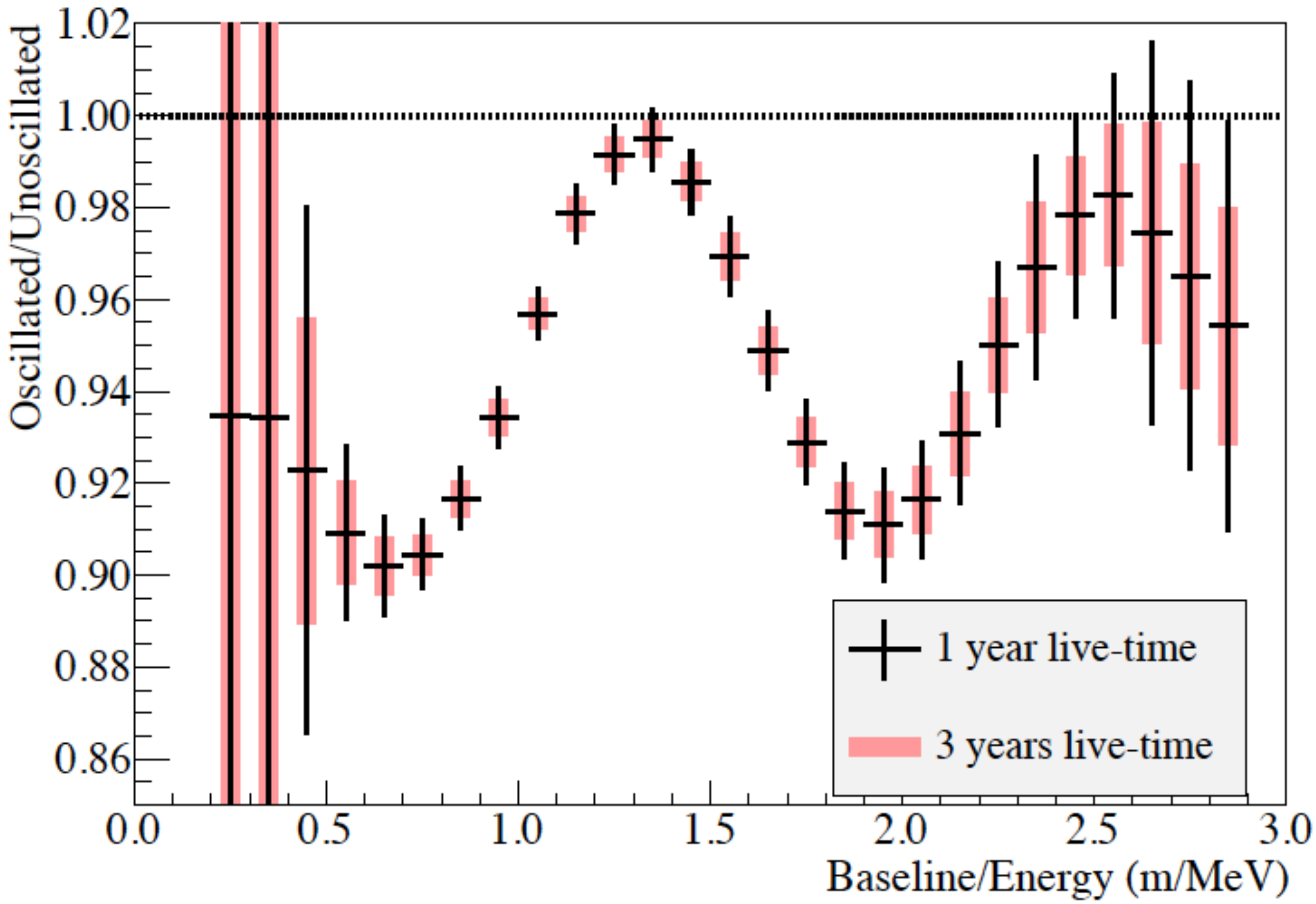


$$E.g.,\ \Delta m^2 = 1.8 eV^2, \sin^2 2\theta = 0.1$$

Important parameters for reactor experiment to study high Δm^2 oscillations

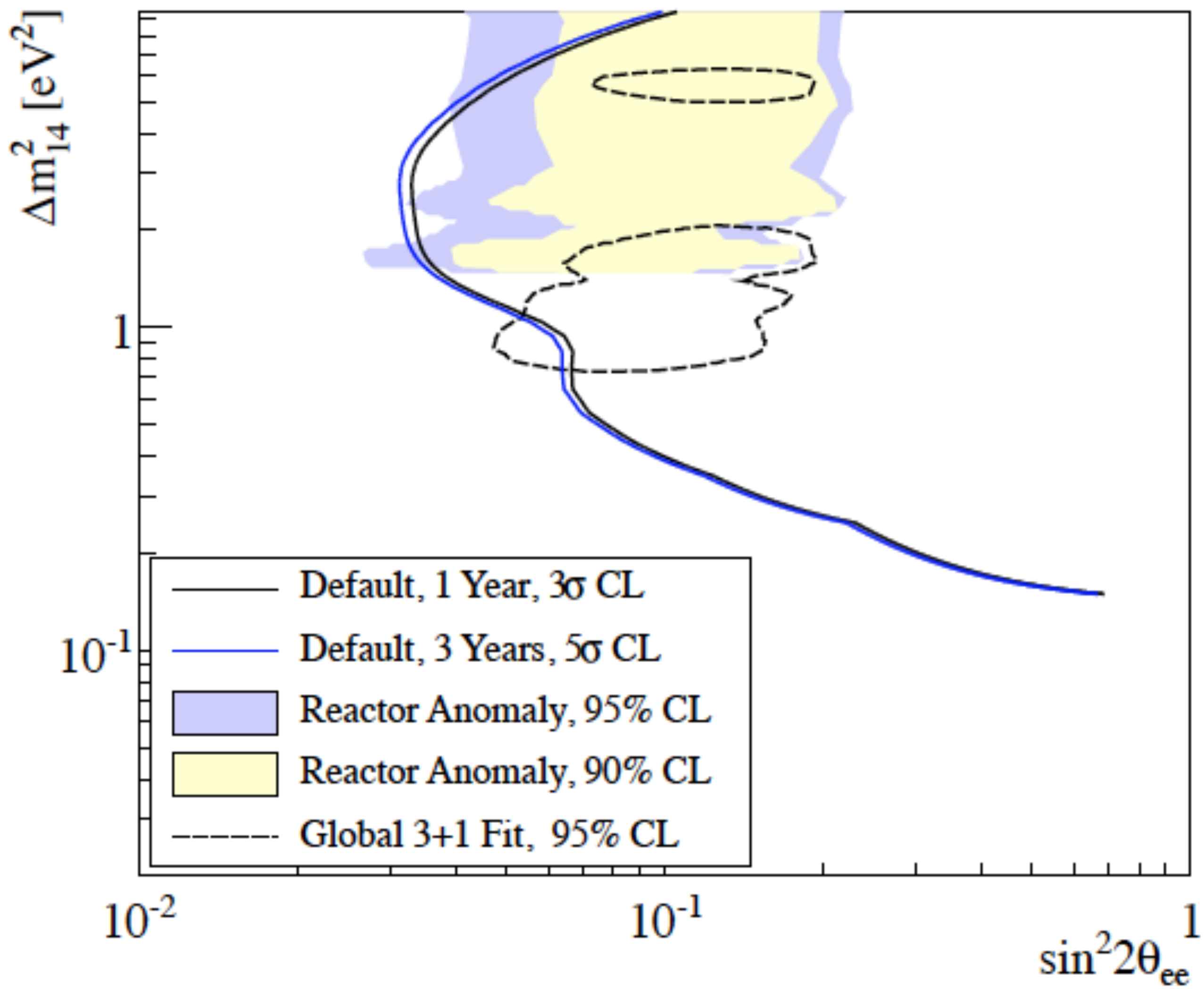
- Reactor core size
- Baseline
- Reactor fuel
- Reactor power, duty cycle
- Detector mass, E resolution, position resolution
- Background ←

Nominal Experimental Parameters

Parameter		Value	Comment	Reference
Reactor	Power	20 MW	NIST-like	[31]
	Shape	cylindrical	NIST-like	[31]
	Size	0.5 m radius, half-height	NIST-like	[31]
	Fuel	HEU	Research reactor fuel type	[31–33]
Detector	Dimensions	$1\times1\times3$ m	3 meters of available baseline	-
	Efficiency	30%	In range of SBL exps. (10-50%)	[25, 28, 29]
	Proton density	$6.39\times10^{28}\,\frac{p}{m^3}$	From Daya Bay GdLS	[34]
	Position resolution	15 cm	Daya Bay-like	[27]
	Energy resolution	$10\%/\sqrt{E}$	Daya Bay-like	[35]
Other	Run Time	1 year live-time	-	-
	Closest distance	4 m	NIST-like	-
	S:B ratio	1:1	In range of SBL exps. (1-25)	[22, 25, 28]
	Background shape	$1/E^2$	Similar to SBL experiments	[22, 25, 27]

From Heeger et al., arXiv:1212.2182

Estimated Sensitivity for Nominal Experiment

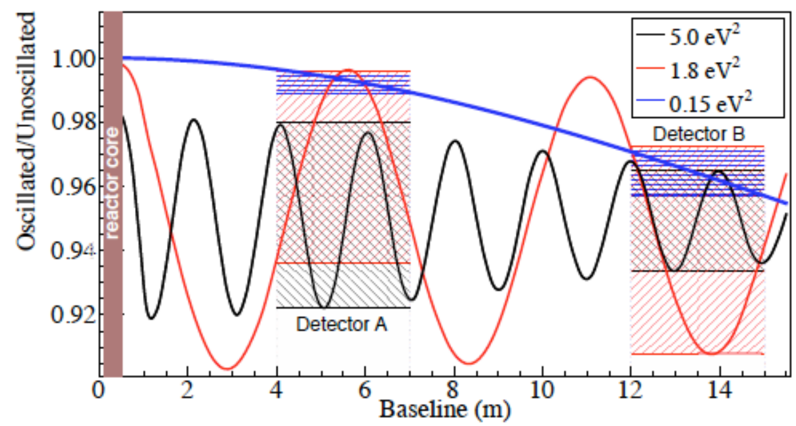


Sensitivity based only on spectral distortion

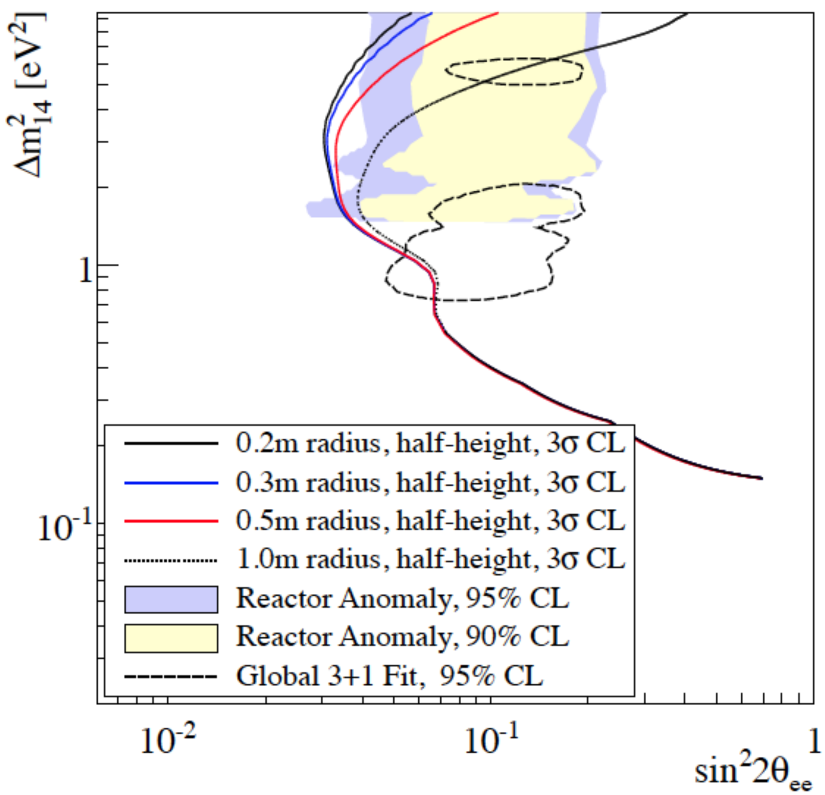
Reactor curves from Mention et al.; global fit from Giunti and Laveder, hep-ph/1109.4033.

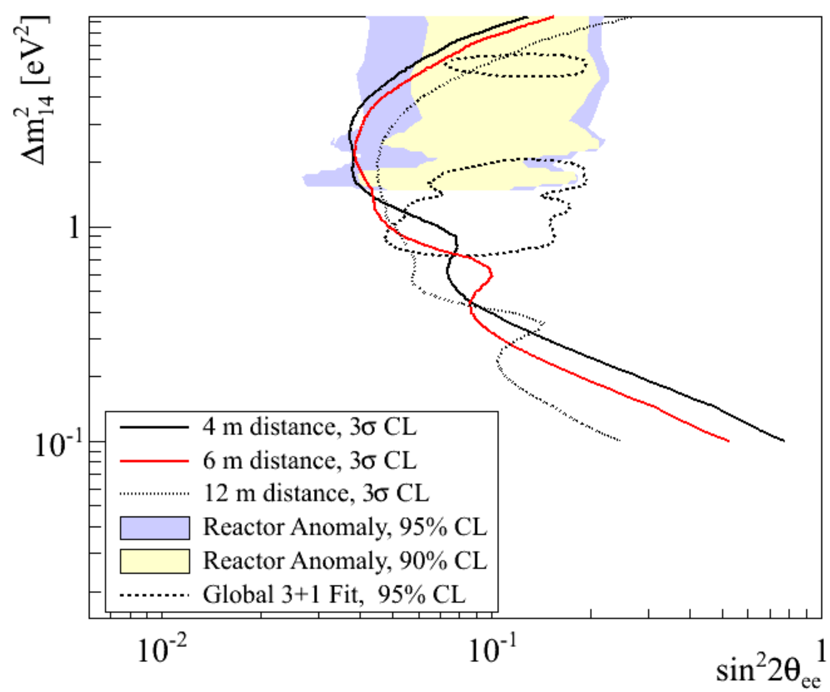
Core Size and Baseline

Effect of Baseline



Effect of Core Size





Commercial vs. Research Reactors

Commercial

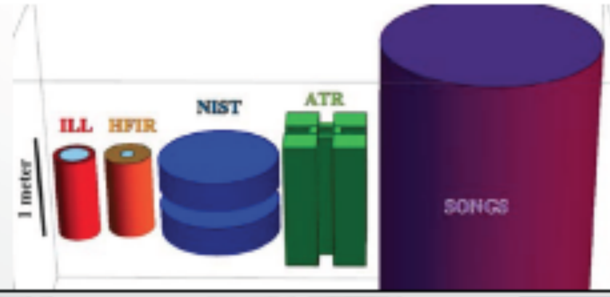
- High power
- No reactor off time
- Extended core (3-4m diameter)
- Limited access near core
- Few percent ^{235}U enrichment (contributions from ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu)

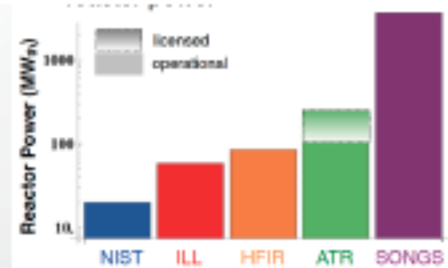
Research

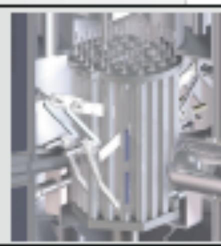
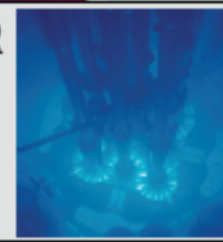
- Lower power
- Reactor off time
- Compact core
- Short detector baselines possible
- Highly enriched fuel (~all $\bar{\nu}_e$ from ^{235}U fission products)

Better for high Δm^2 search

Potential U.S. Reactor sites

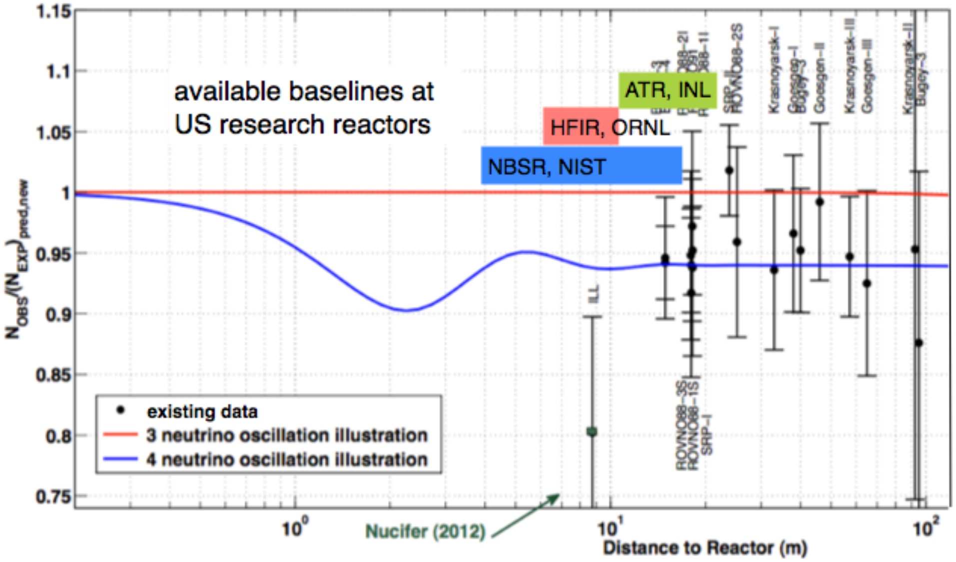




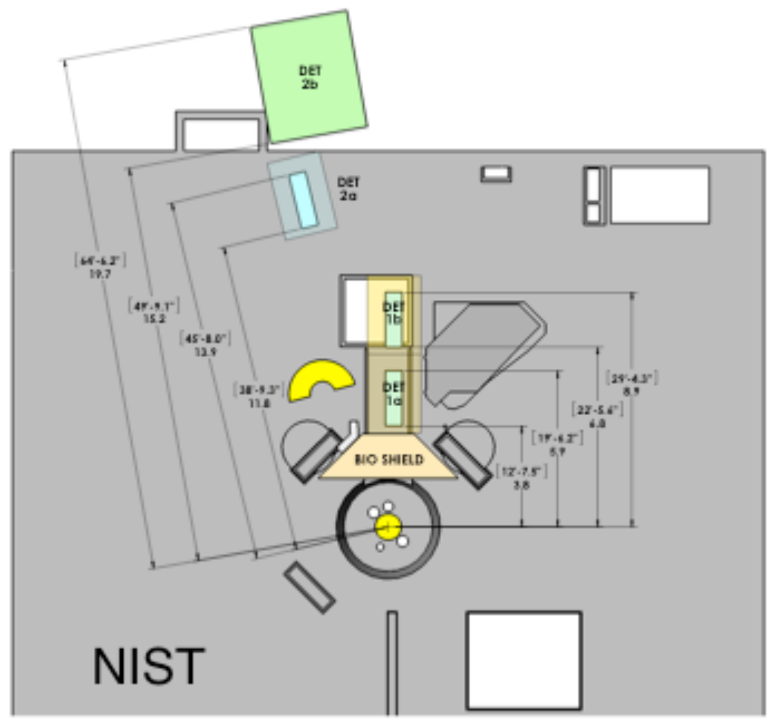
Reactor	NBR NIST 	HFIR ORNL 	ATR INL 	SONGS 
Power (MW_{th})	20	85	150	3400
Core Size	Ø100cm x100cm	Ø60cm x100cm	Ø110cm x110cm	Ø3m x 3.8m
Operating Cycle	~1/3 reactor off	~1/3 reactor off	~1/3 reactor off	Currently offline, limited cycle likely
Potential Deployment Sites	4-13m baseline Above-grade, minimal overburden	6-8m baseline Above-grade, minimal overburden	12-20m baseline Below-grade, minimal overburden	24 baseline, 25 m.w.e overburden
Reactor γ/n Background	Measurements underway	Measurements planned	Measurements planned	Negligible

From N. Bowden

Accessible Baselines at US Research Reactors



Shortest baseline defined from center of core to edge of active detector volume



NIST
4-13m and 15 to ~20m

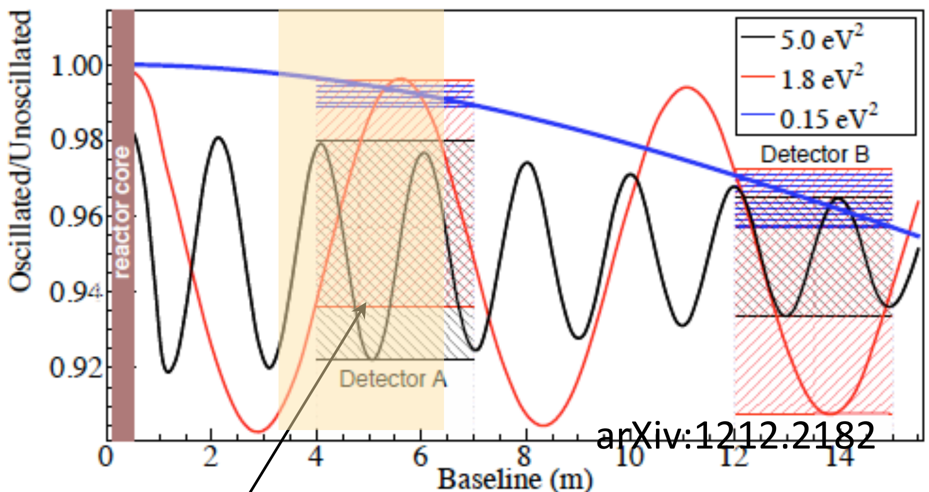
ATR
11-18m and 21-27m

HFIR
6-8m
(possible additional locations)

Single vs. Multiple Detectors

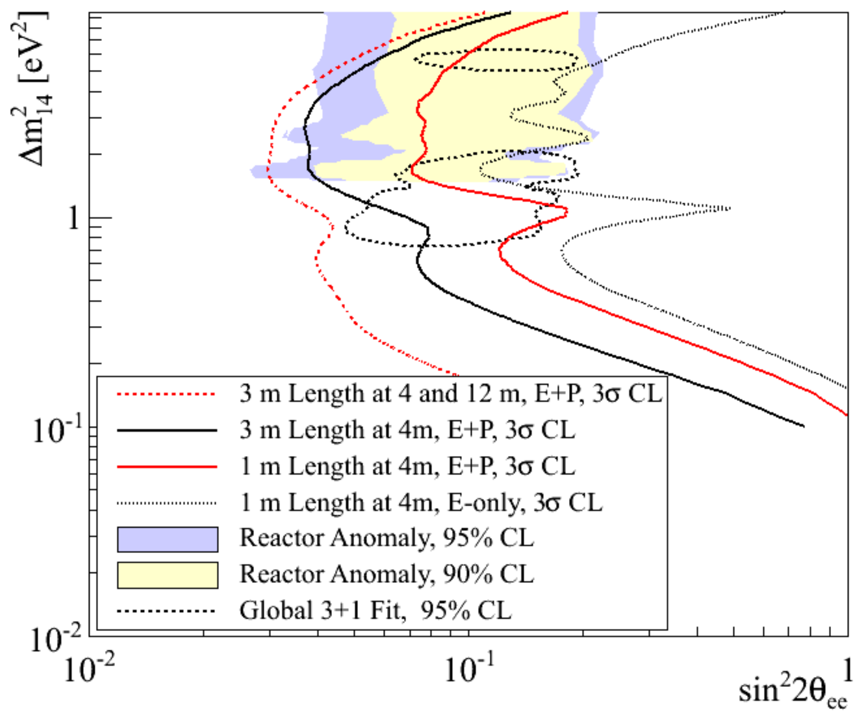
Advantages of multiple detectors:

- Can span larger range of baselines (unless single detector is very long)
- Can be moved and swapped for systematic studies
- Reduced sensitivity to predicted reactor spectrum
- Staging possible

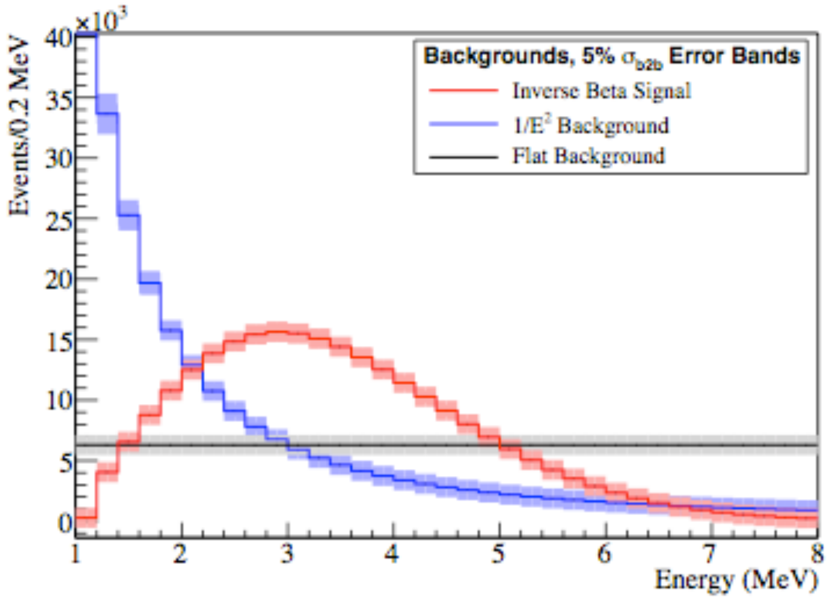


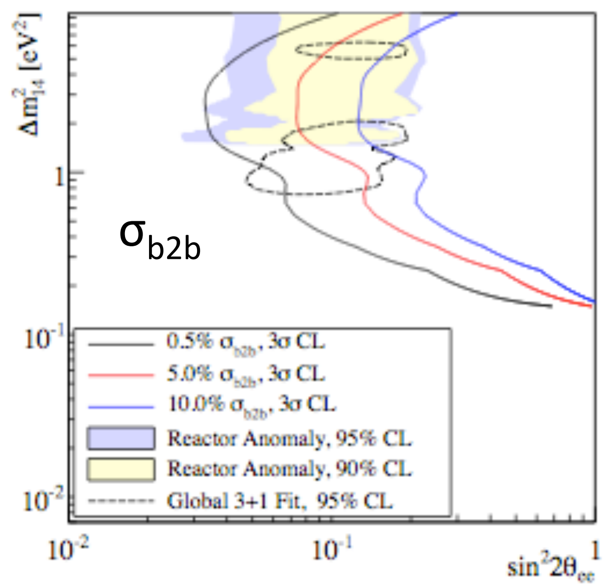
baseline range of 1 detector

Different baseline ranges

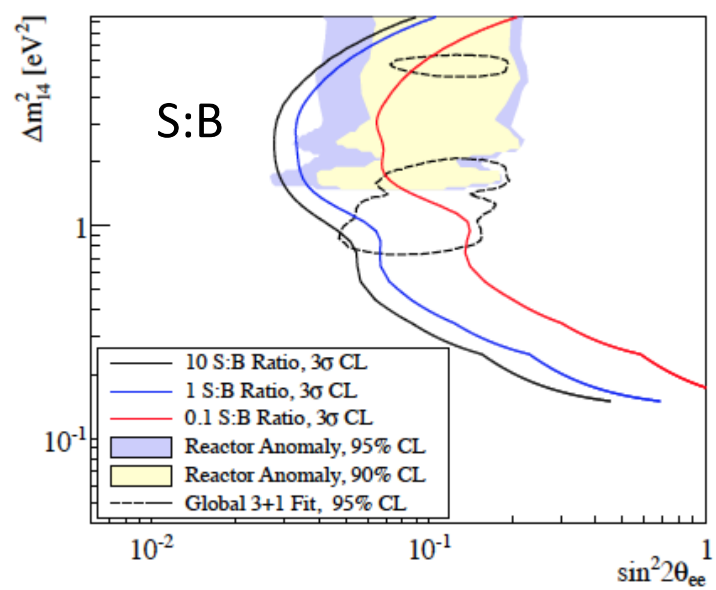


Backgrounds





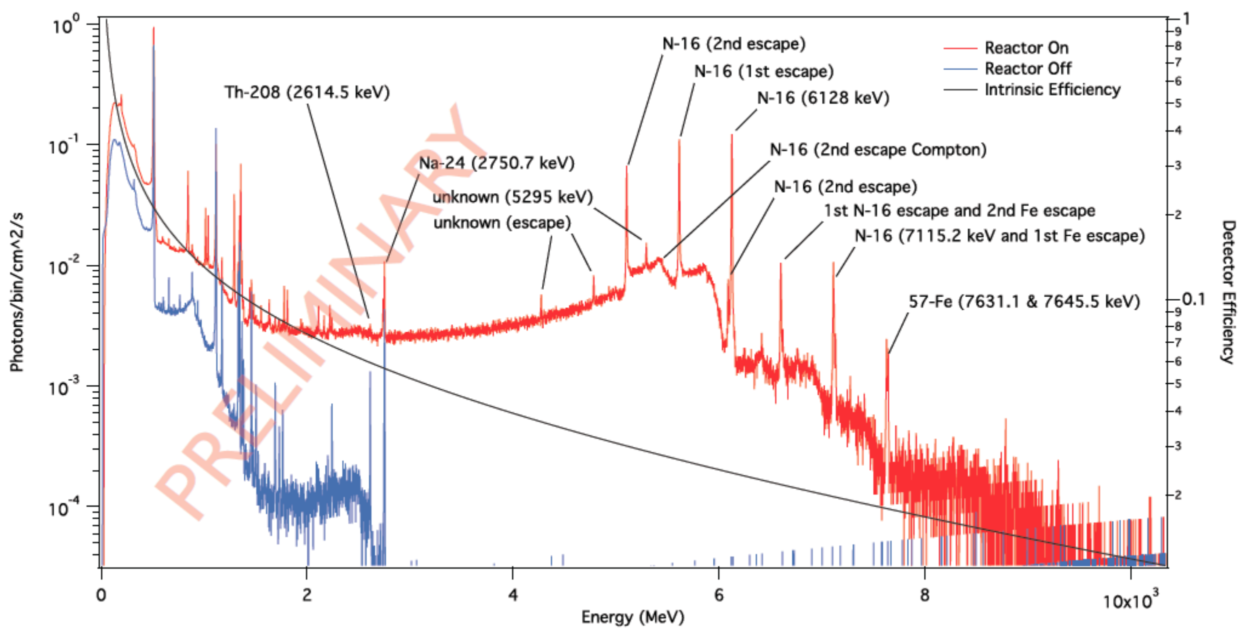
It is critical to control backgrounds and to understand residual background spectrum



- All previous short-baseline reactor experiments with minimal overburden have failed to see neutrino signal (S:B often 1:50-100.) See talk by N. Bowden.
- In addition to high muon-related backgrounds, there are significant backgrounds correlated with reactor operation.

Background measurements (fast n, muon, gamma) at potential sites underway

E.g. gamma backgrounds measured with Ge detector at NIST

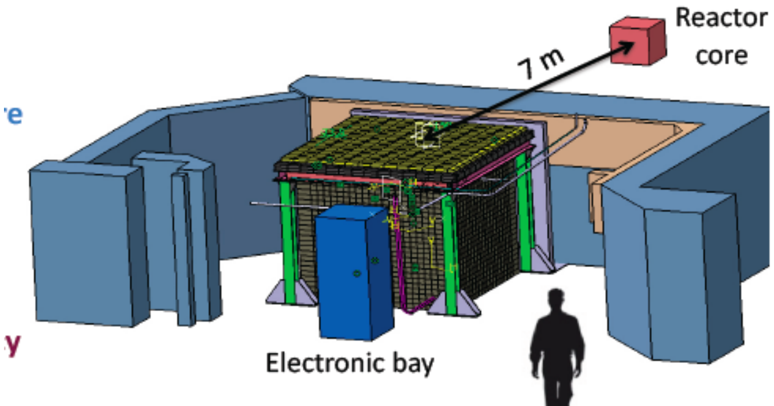


- High background rates will probably require segmented detectors (e.g., Bugey-3, Palo Verde)
- ^{6}Li-doped scintillator with good PSD may be required for operation at reactor with little overburden; ^{6}Li doped materials under development at BNL,LLNL,NIST,SNL.

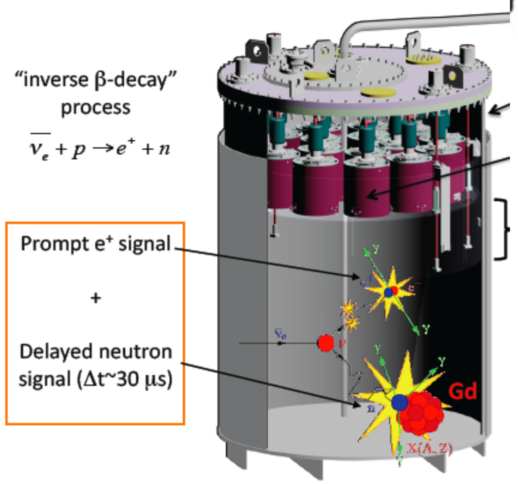
Other short baseline experiments

- Nucifer at OSIRIS
- STEREO at ILL
- NEUTRINO-4 in Gatchina
- Experiment at China Advanced Research Reactor (arXiv:1303.0607)

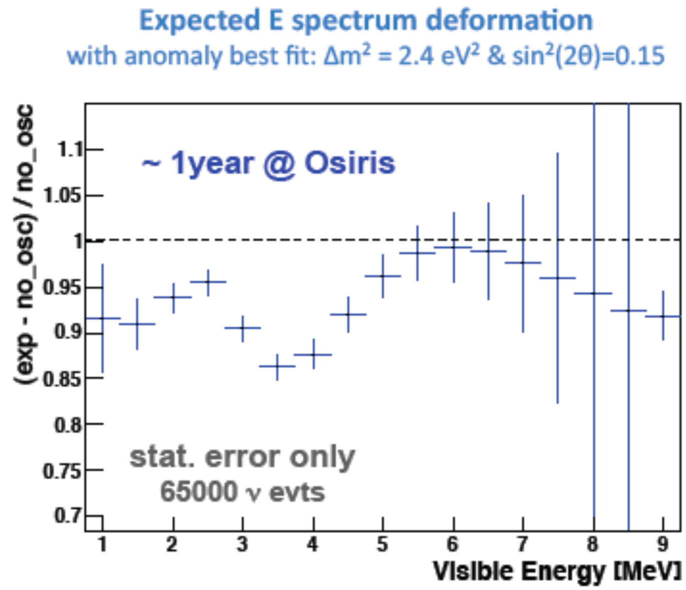
NUCIFER at Osiris

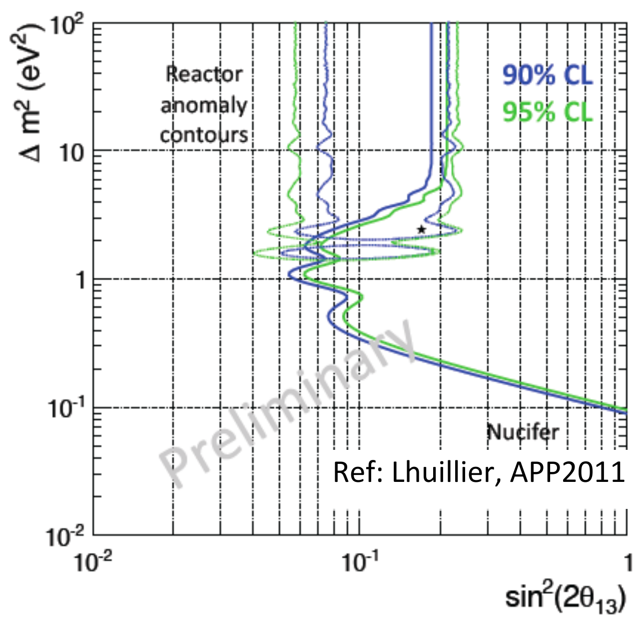


core: σ~0.3m
baseline: 7m



- Norm error = 4%
- 100 days full power @ Osiris
- S/B = 1 (?), assuming same shapes (worst case).
- E resol = 0.15*E



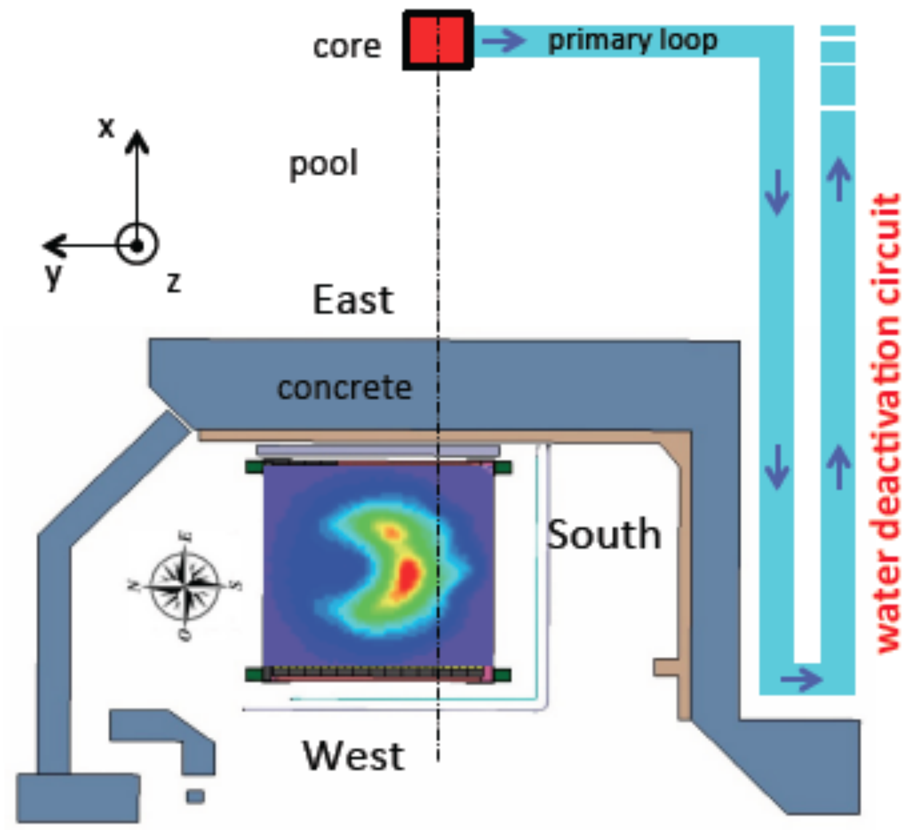


Pre-industrial, unattended reactor neutrino monitor

May be used to test reactor anomaly with compact core.
PSD R&D for background rejection.

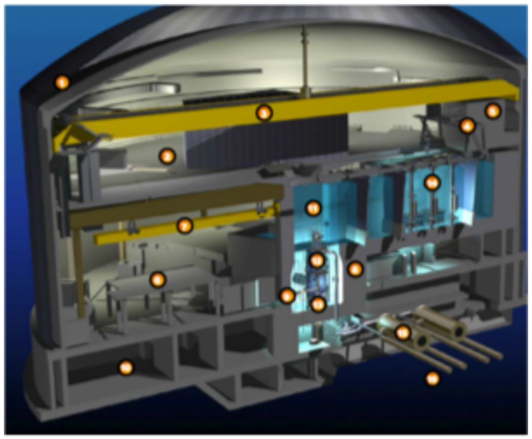
Huge unexpected reactor-on background from water deactivation circuit. Lesson for future experiments:

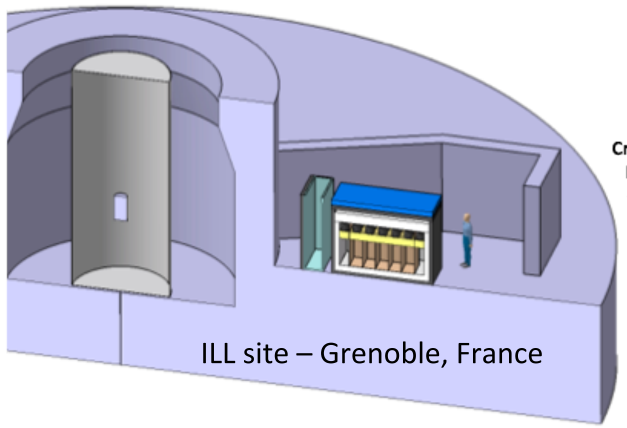
It is critical to measure and understand backgrounds at detector site.

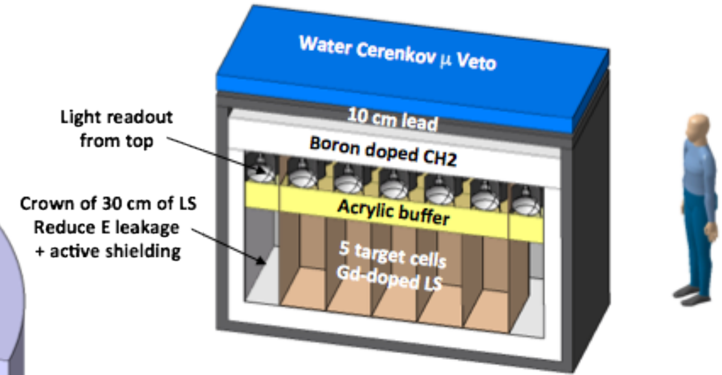


Barycenters of the PMT's charges

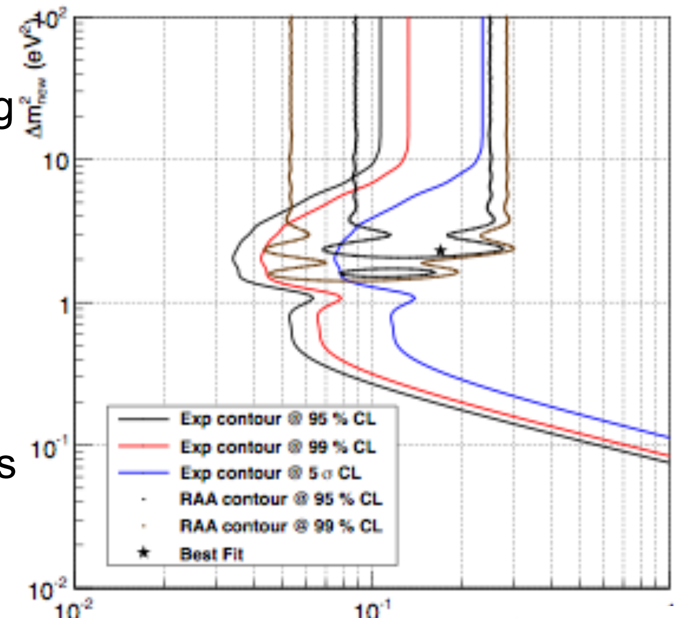
STEREO at ILL







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

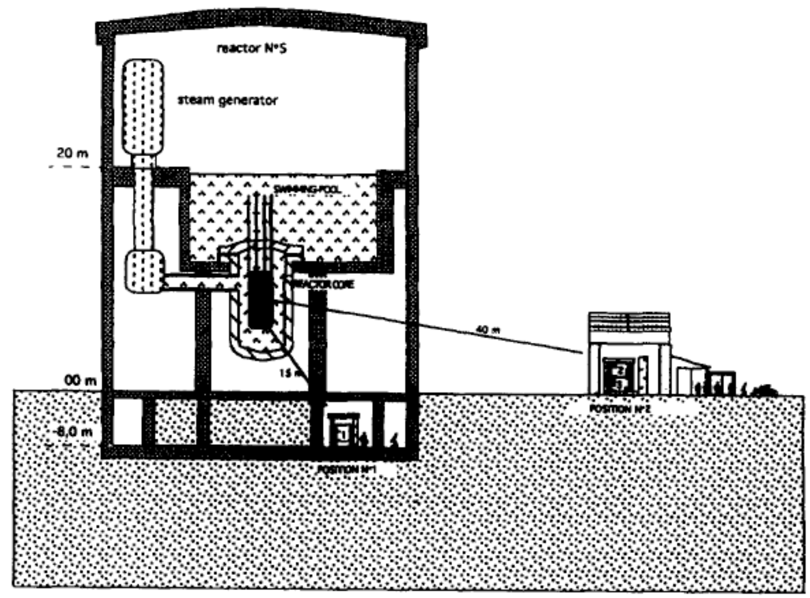
Comments

- Opportunity for reactor experiments to provide significant information on possible sterile neutrino states relatively quickly and cheaply (<$5M)
- Complementary to other approaches (e.g., sources)
- Good US sites for such an experiment: short minimum baseline, relatively high-power, compact cores, and possibility of covering extended baseline with multiple detectors
- **BUT**, successful experiment depends on sufficient reduction of background and understanding of residual background shape. It must be demonstrated that these challenges can be met at particular sites.
- Excellent synergy between sterile neutrino search and goals of nuclear safeguards community -- both R&D to develop detectors and experimental results. (E.g., measurement of ν_e spectrum from pure ^{235}U.)

BACKUP

What are the expected improvements over Bugey-3?

- 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

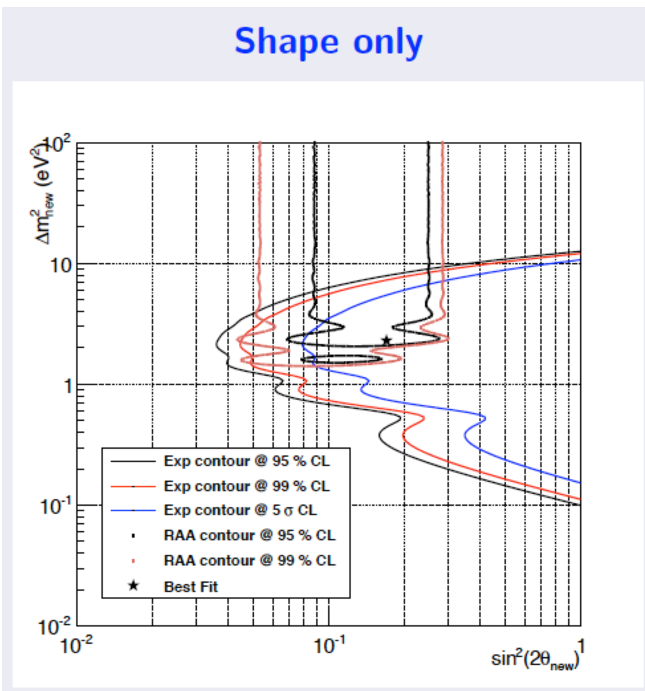


- shorter baseline
  - at US research reactors can get as close as 4m (Bugey > 15 m)
- better scintillator stability
  - some of the Bugey modules/detectors deteriorated
- possibly better pulse shape discrimination (PSD)?

How does US reactor experiment compare to STEREO?

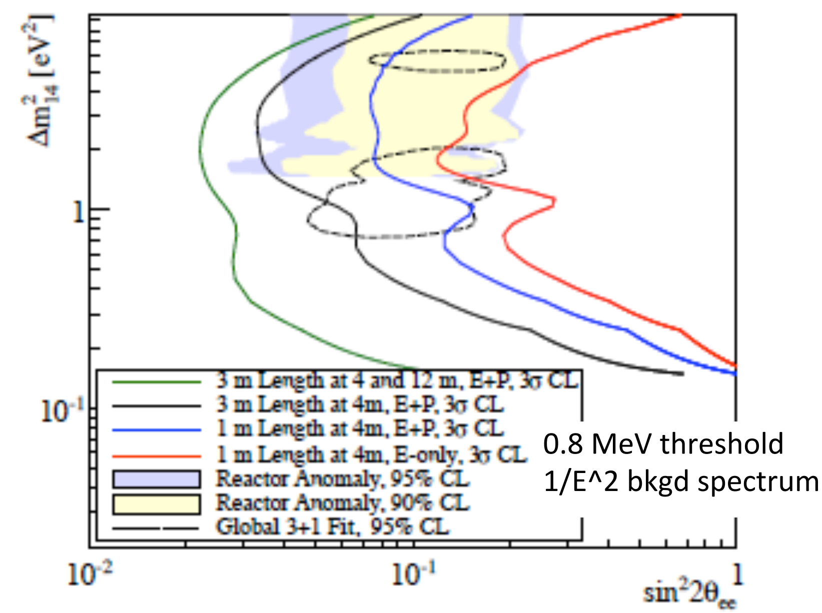
- US sites allows for deployment of multiple detectors
- By using Li, we are likely to have better bkgd rejection
- By being closer (at least in principle) we have relaxed requirements for resolution at high Δm^2
- US concept appears to have better sensitivity

STEREO at ILL



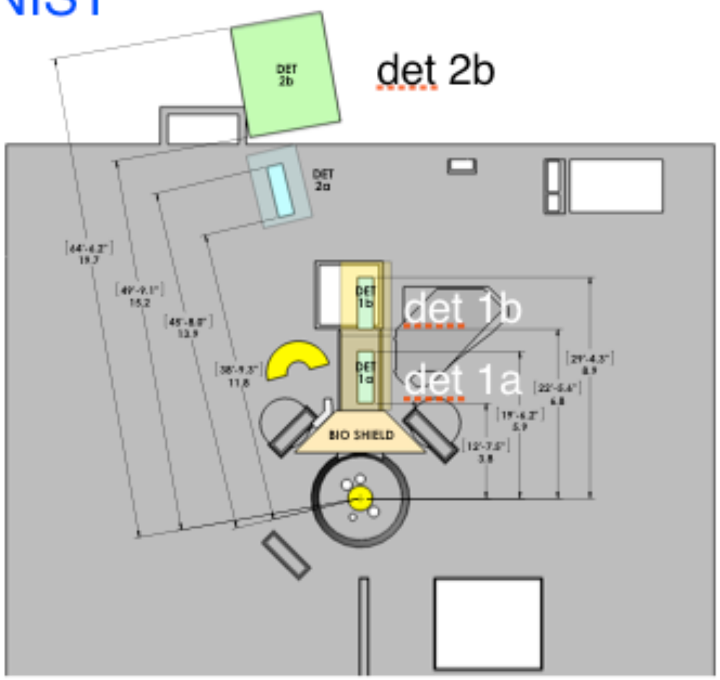
US reactor exp (different configurations)

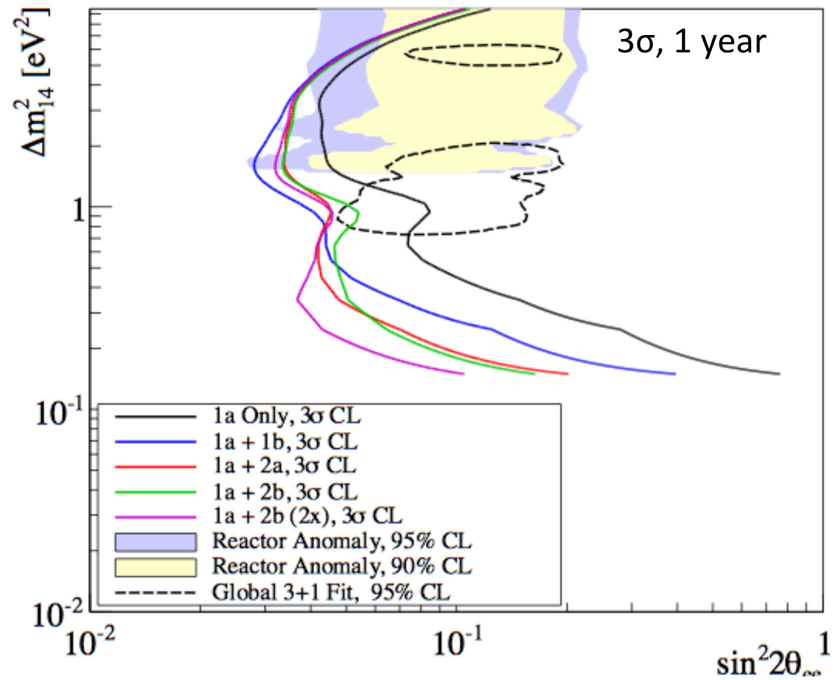
shape only

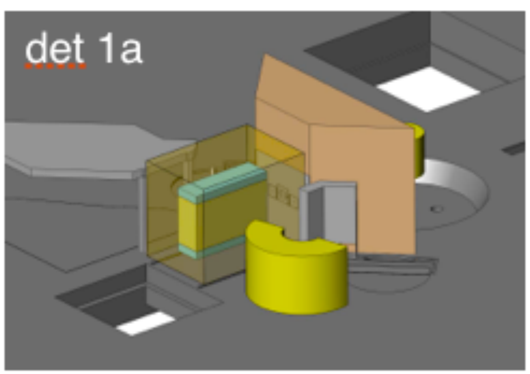


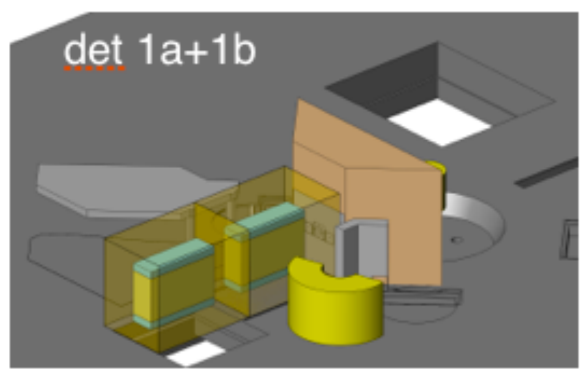
Example of a Phased, Multiple Detector Experiment

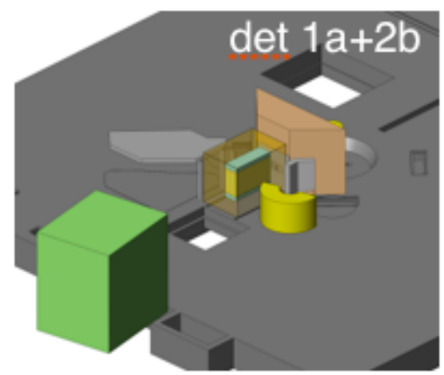
NIST











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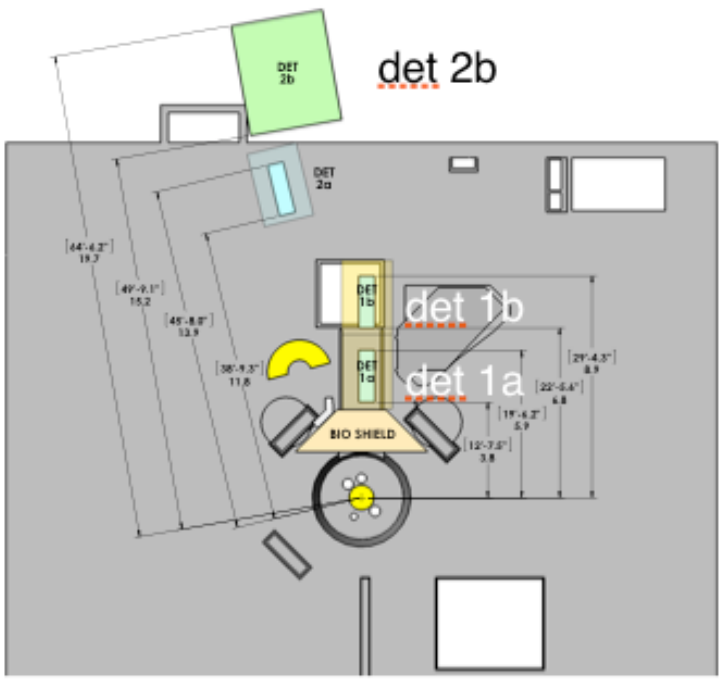
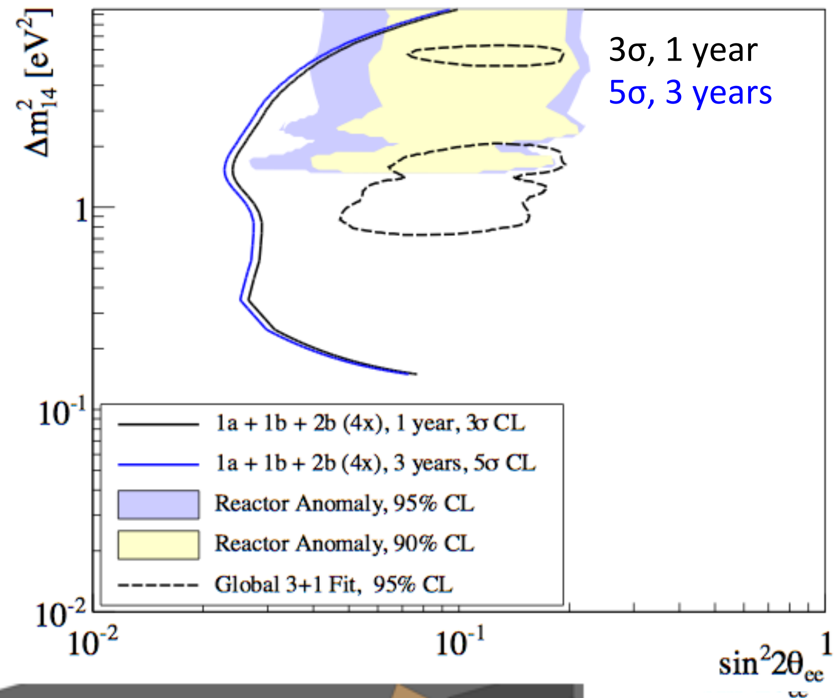
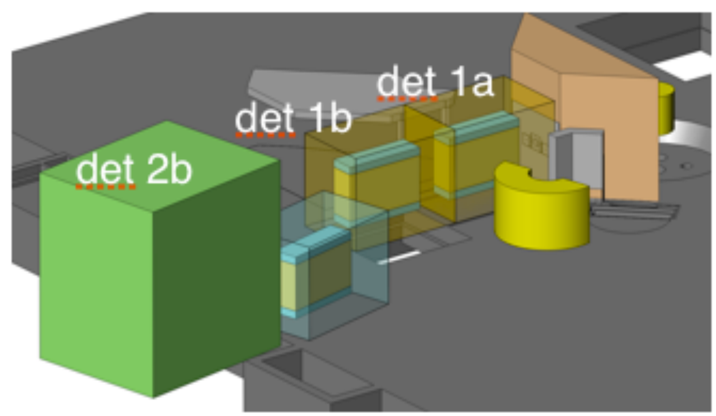




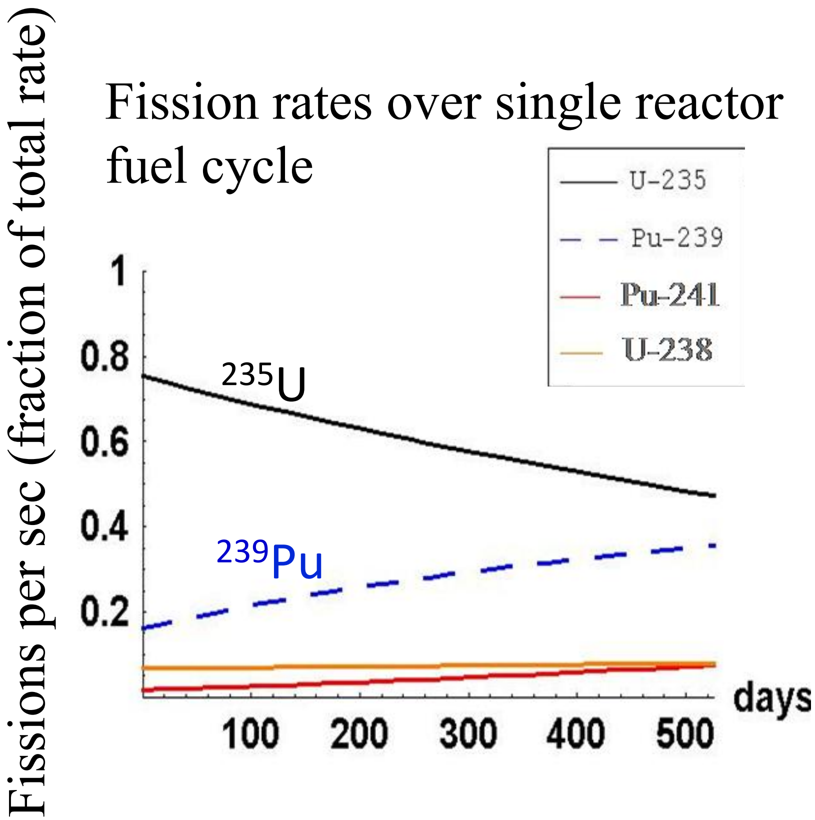


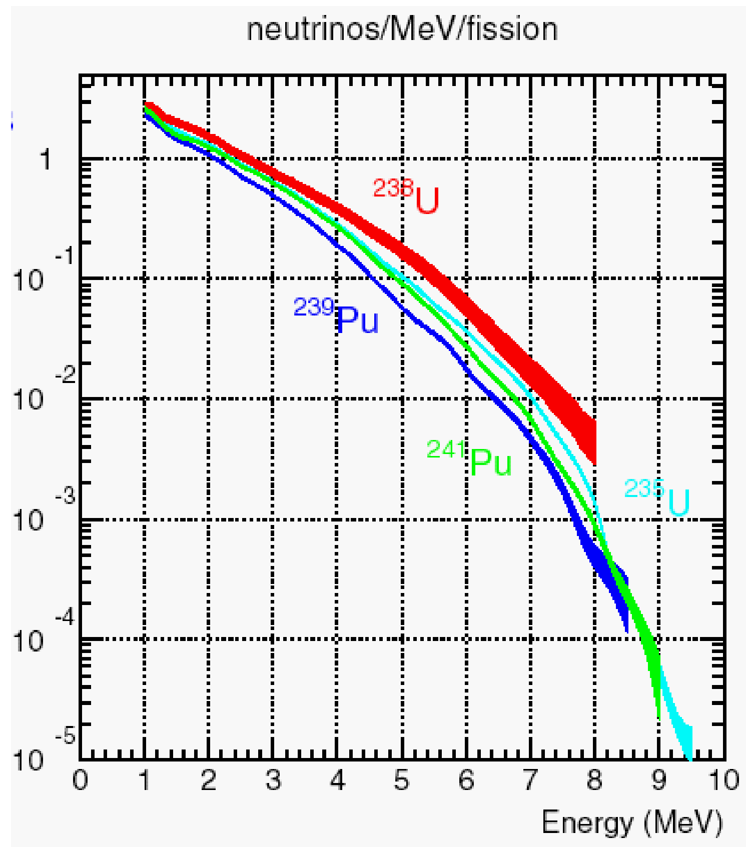
Cherwinka, Mumm, Littlejohn, KMH

To predict rate and spectrum of neutrinos from reactor, one must consider ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu, account for evolution of the reactor core over the fuel cycle, and consider all of the possible β branches.

Direct measurements of electron spectra from thin layers of ^{235}U, ^{239}Pu, and ^{241}Pu in a beam of thermal neutrons are used as constraints.

Fission rates over single reactor fuel cycle





➡ Total ν flux uncertainty estimated to be about 2-3%