Very-Short-Baseline Reactor Experiments

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Nathaniel Bowden

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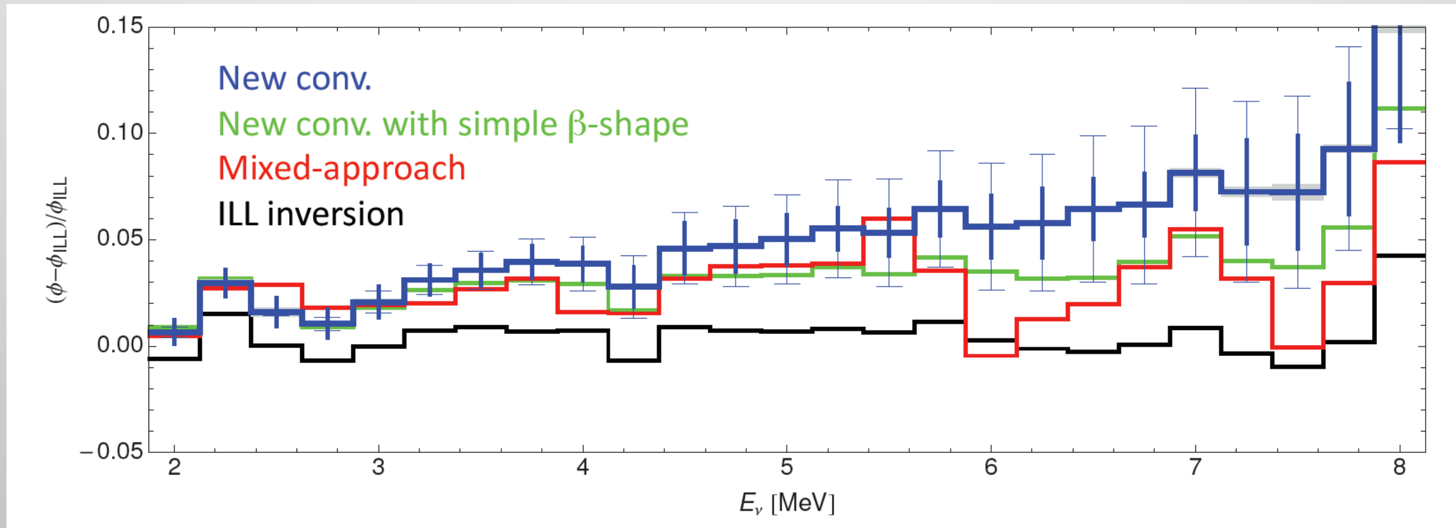
Recent Re-evaluations of the Reactor Antineutrino Flux

- Two largely independent and complementary predictions agree:
  ~4% increase in flux above inverse beta threshold



Mueller, et al: arXiv:1101.2663
Huber: arXiv:1106.0687

- But, there are still considerable uncertainties related to some corrections:
  - high-precision spectral measurements of well understood cores could help
- Reanalysis of past reactor experiments by Mention, et. al., yields the "Reactor Antineutrino Anomaly"

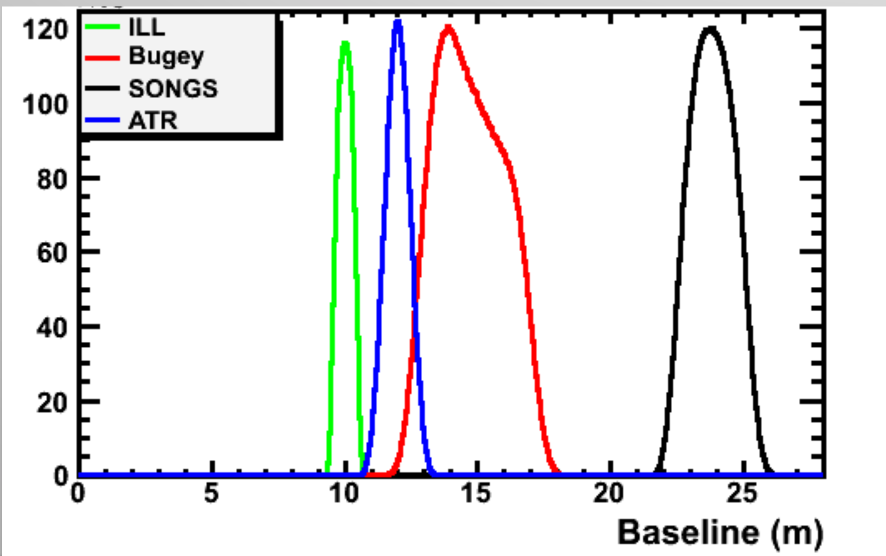
$$N_{obs}/N_{pred} = 0.979 +/- 0.029 => 0.927 +/- 0.023$$

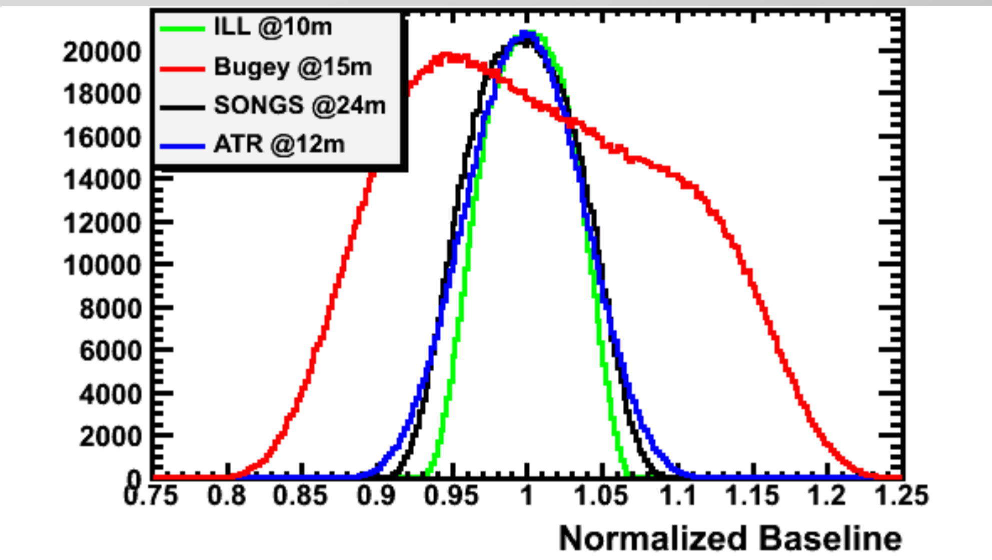
The recent results have sparked a new flurry of interest and activity

- Many "hints" take the form of a deficit or excess relative to an (uncertain) expectation
- Strong desire in community for definitive experiments based on measurement of oscillation patterns in *E* and/or *L*
- Can new short baseline reactor experiments help?

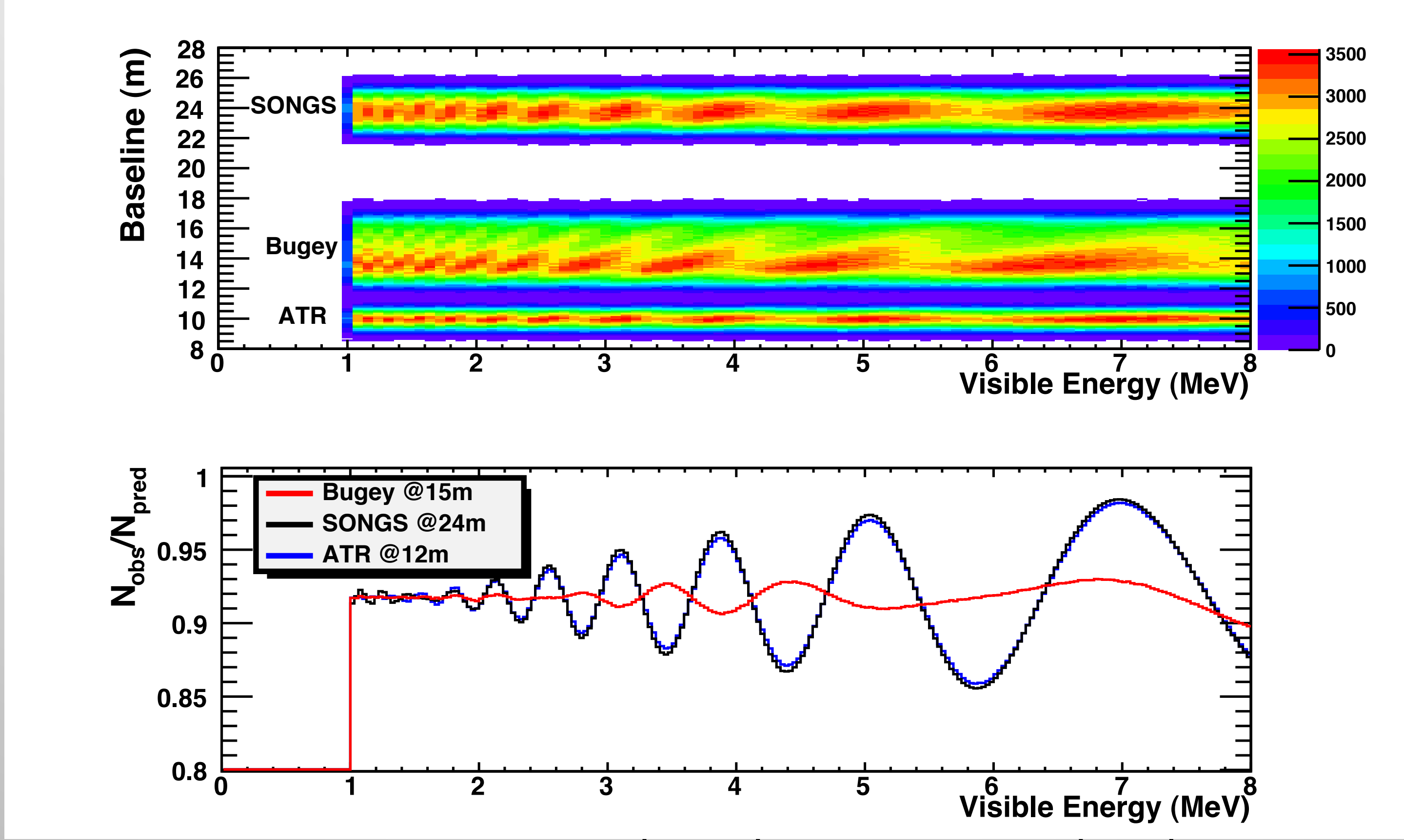
At short baselines a reactor is not a point source

Reactor	Baseline	Core Size (m)	Detector	ΔL/L (FWHM)	Power	Flux ν/m²/s
ILL	10m	Ø0.4 x 0.2 (HEU)	Ø1mx1m	~8%	58 MW_{th}	~1x10^{16}
ATR	12m	~Ø1 x 1 (HEU)	Ø1mx2m	~11%	150 MW_{th}	~2x10^{16}
Bugey3	15m	Ø2.5 x 2.5	1mx1m	~30%	2800 MW_{th}	~2x10^{17}
SONGS	24m	Ø3 x 2	Ø1mx2m	~10%	3400 MW_{th}	~1x10^{17}





Effect of Baseline Distribution



- No previous experiment appears to have been optimized in this respect
- Experiments at appropriate small and large reactors would be complementary:
  - Provide cross check at different baselines and to probe different Δm^2 regions
  - measure flux/spectra from different core compositions

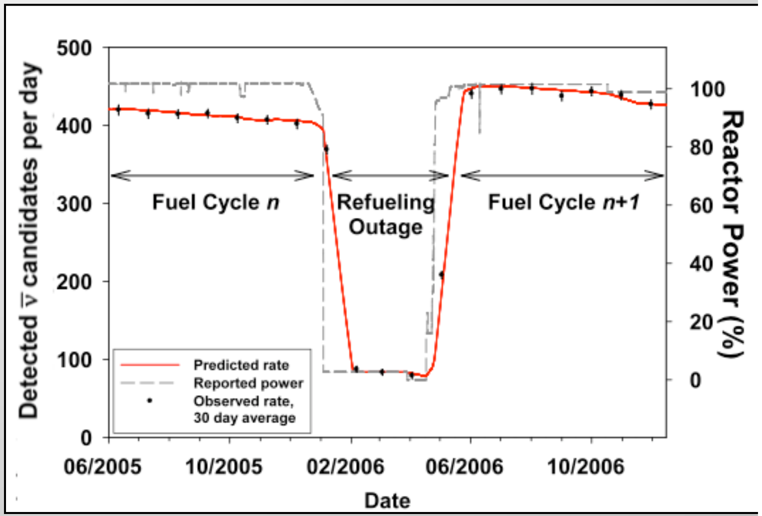
SCRAAM: The Southern California Reactor Antineutrino Anomaly Monitor

- Our proposal is to perform a relatively rapid and inexpensive experimental measurement
  - —Address "Reactor Anomaly" at it's source
  - —Direct sterile oscillation sensitivity via spectral distortion at multiple baselines
  - —High statistics flux and spectrum measurement from a single Pressurized Water Reactor and an HEU Research reactor

- This requires access to locations with high antineutrino flux and appropriate core-detector geometry

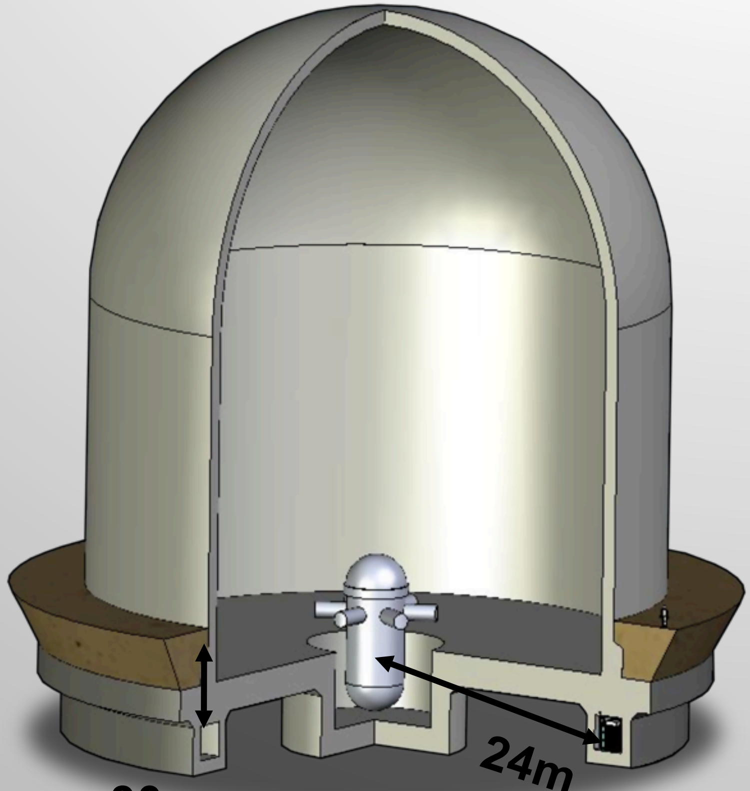
The San Onofre Nuclear Generating Station
Our (nonproliferation) laboratory for over a decade

Direct Observation of reactor fuel burnup via antineutrino counting



- We have cultivated an exceptionally strong and trusting relationship with SONGS:
  - Multitude of access requests readily granted, unescorted site access, deployment assistance, fueling data, introductions to other operators, ...
- We possess unparalleled operational experience in this industrial environment:
  - Five detector deployments since 2003

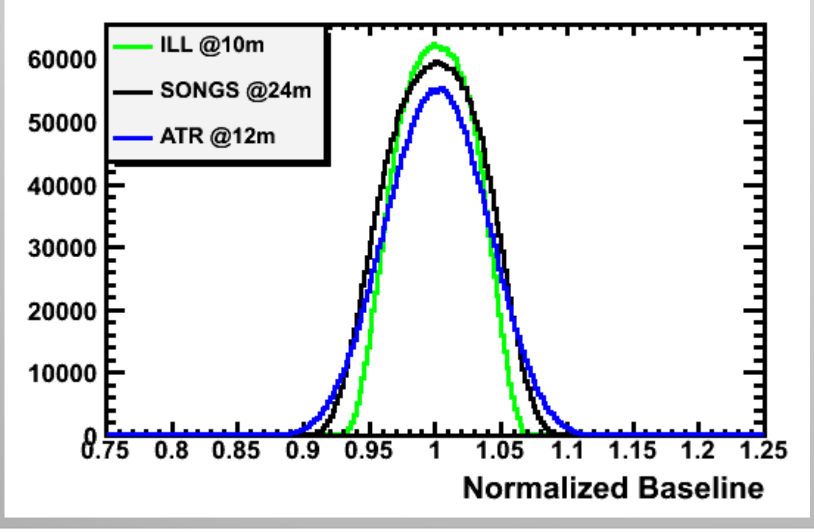
Tendon Galleries are Ideal Deployment Locations

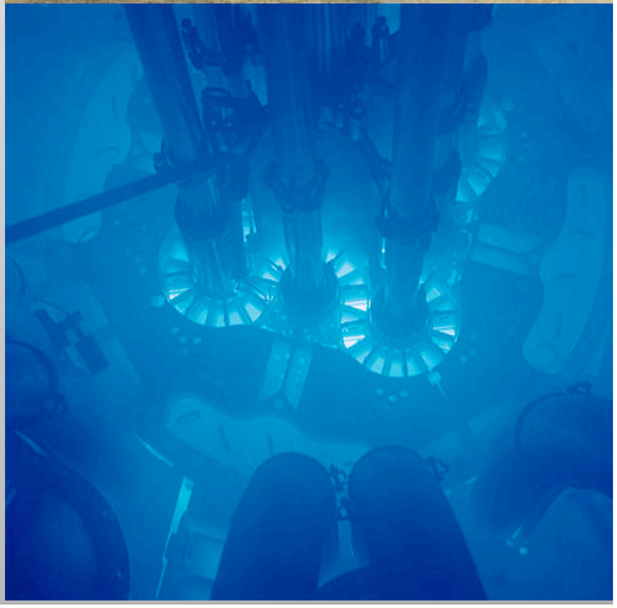


- High Flux: ~10^{17} $\nu/m^2/s$
- 130-180m to other reactor
- Gallery is annular – unfortunately no possibility to vary baseline

Alternate Baseline possibility: The Advanced Test Reactor at INEL

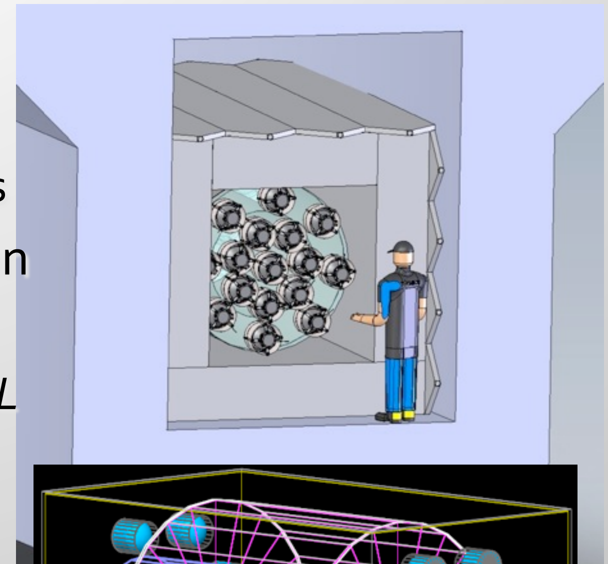
- Highest power research reactor: ~150MW_{th} with unique "serpentine" 1.2m HEU core,
- Excellent background measurement characteristic:
  60 day on, 30 day off cycle
- Potential below grade deployment locations near core
- At 12m baseline, spread similar to that at SONGS

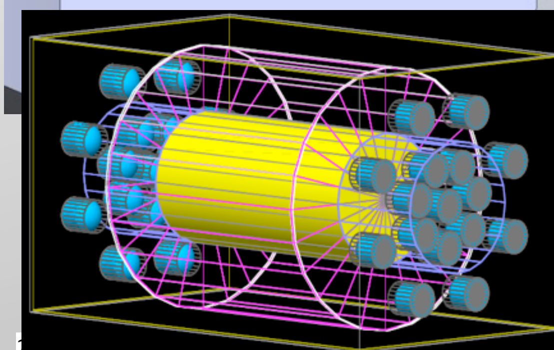


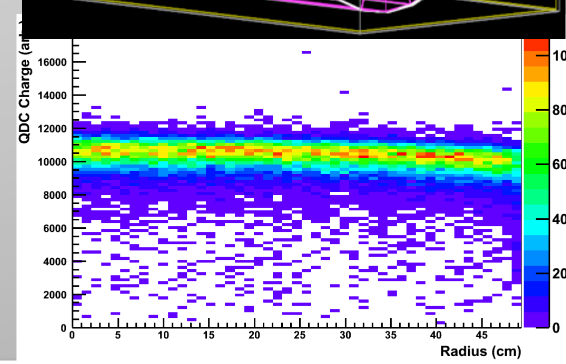


SCRAAM Detector Concept

- Based on validated mechanical design for non-proliferation detectors
  - Understand reactor safety and regulatory requirements
- Relatively narrow geometry needed for SONGS Tendon Gallery: Ø1m x 2m
  - Radial orientation should allow for simultaneous *E* and *L* measurement at ATR
- 1.5 ton L.S. target provides ~9000 IBD/day @ SONGS
  - Conservative 40% efficiency: ~4000/day detected
- Emphasize good light collection and position uniformity: expect <10% energy resolution at 1MeV
- Aim for ~4-5% absolute normalization
  - e.g. include partial "gamma catcher" to increase precision and efficiency
- Component costs: ~$800k





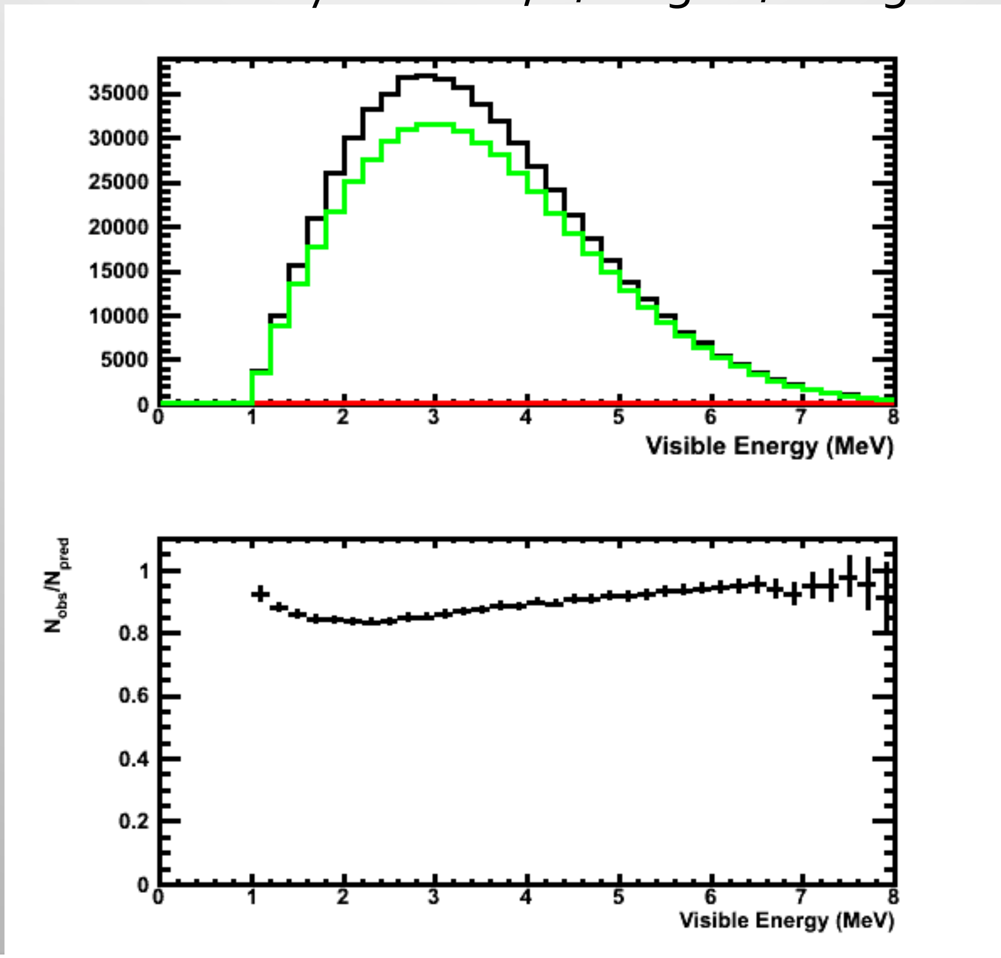


Example Oscillation Patterns:

For SONGS core, spectral sensitivity remains at 24m

150 days, $\sin^2(2\theta) = 0.165$, $\Delta m^2 = 0.15\ eV^2$

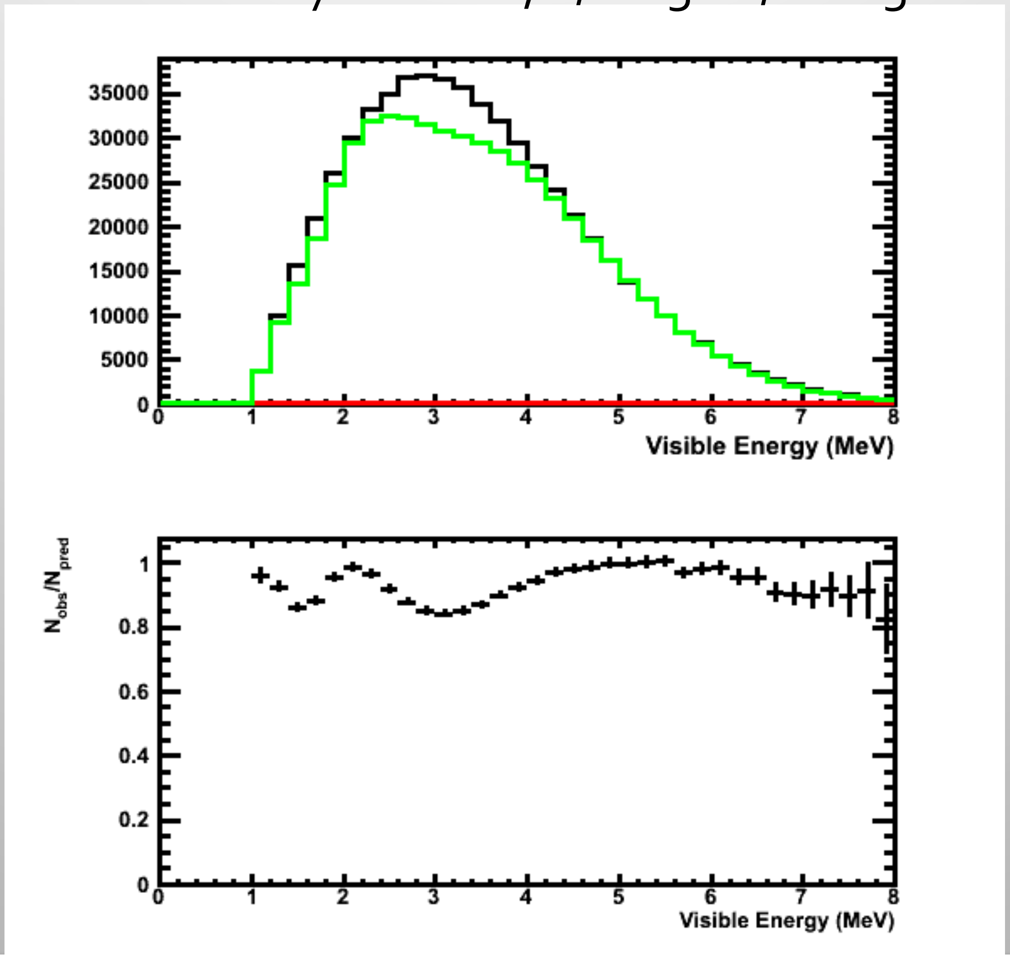
1.5% bin-to-bin systematic, 8/1 Signal/Background



Example Oscillation Patterns:
For SONGS core, spectral sensitivity remains at 24m

150 days, $\sin^2(2\theta) = 0.165$, $\Delta m^2 = 0.60$ eV^2

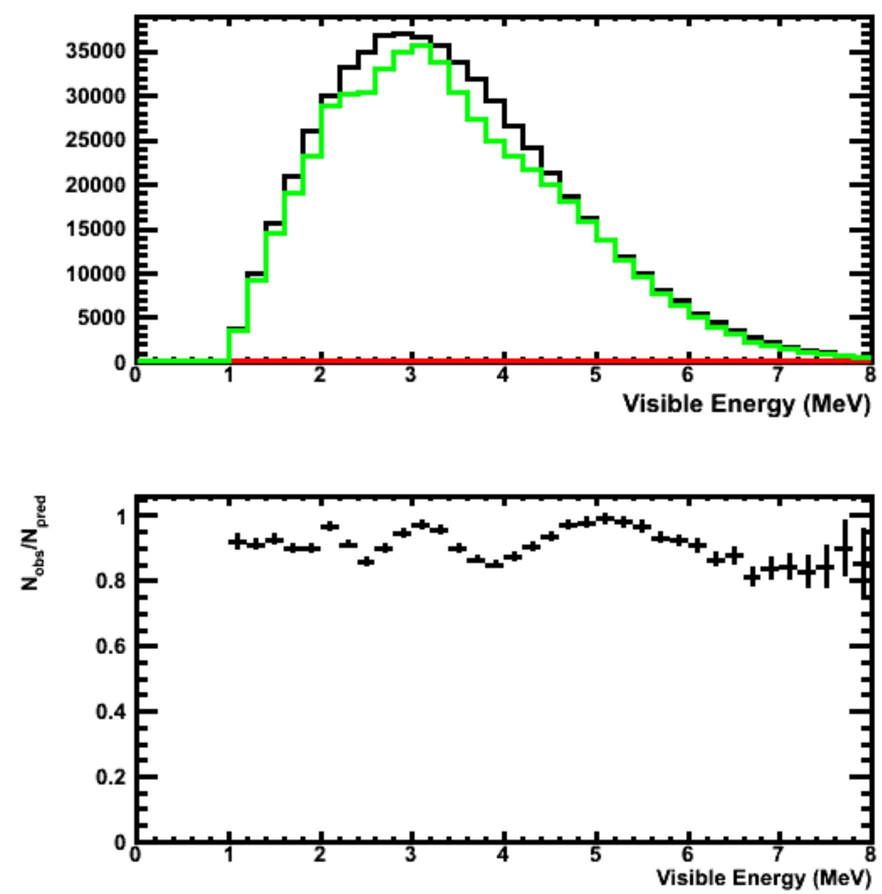
1.5% bin-to-bin systematic, 8/1 Signal/Background



Example Oscillation Patterns:
For SONGS core, spectral sensitivity remains at 24m

150 days, $\sin^2(2\theta) = 0.165$, $\Delta m^2 = 1.2\ eV^2$

1.5% bin-to-bin systematic, 8/1 Signal/Background

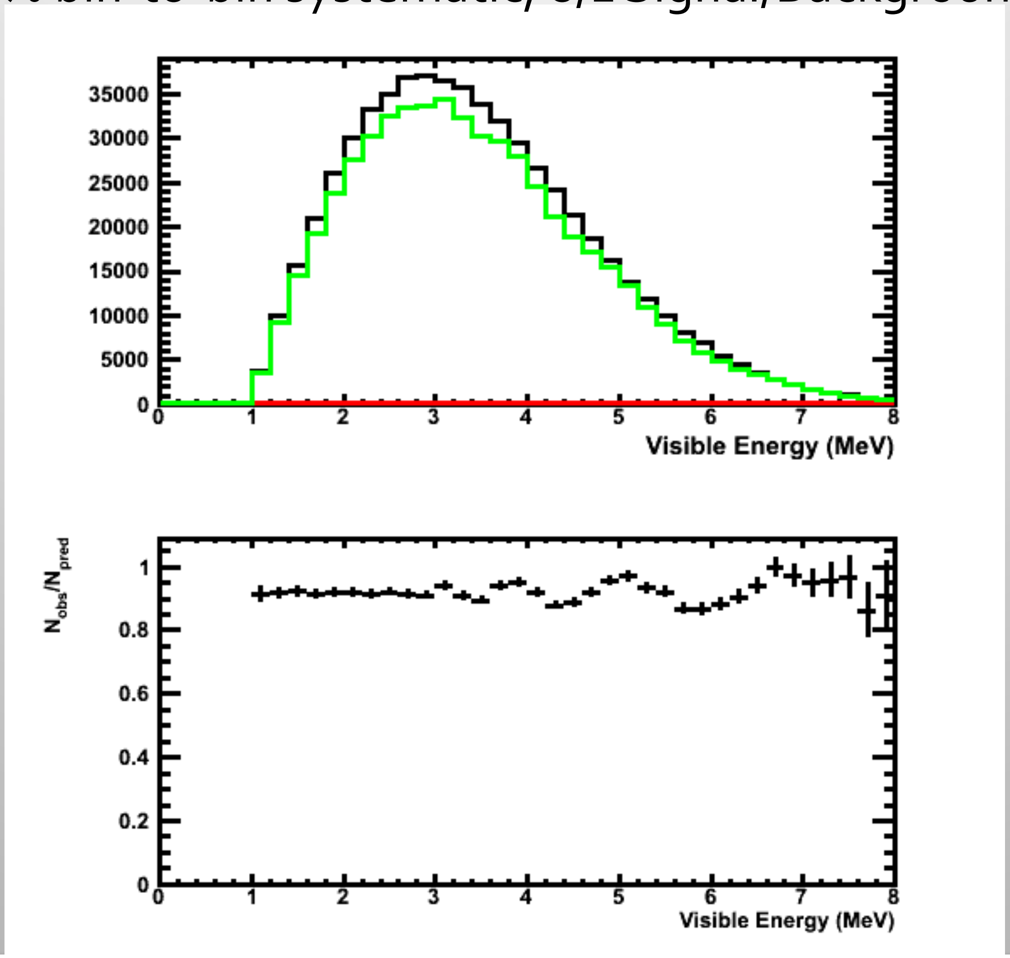


Example Oscillation Patterns:

For SONGS core, spectral sensitivity remains at 24m

150 days, $\sin^2(2\theta)$ =0.165, Δm^2 =2.4 eV^2

1.5% bin-to-bin systematic, 8/1 Signal/Background

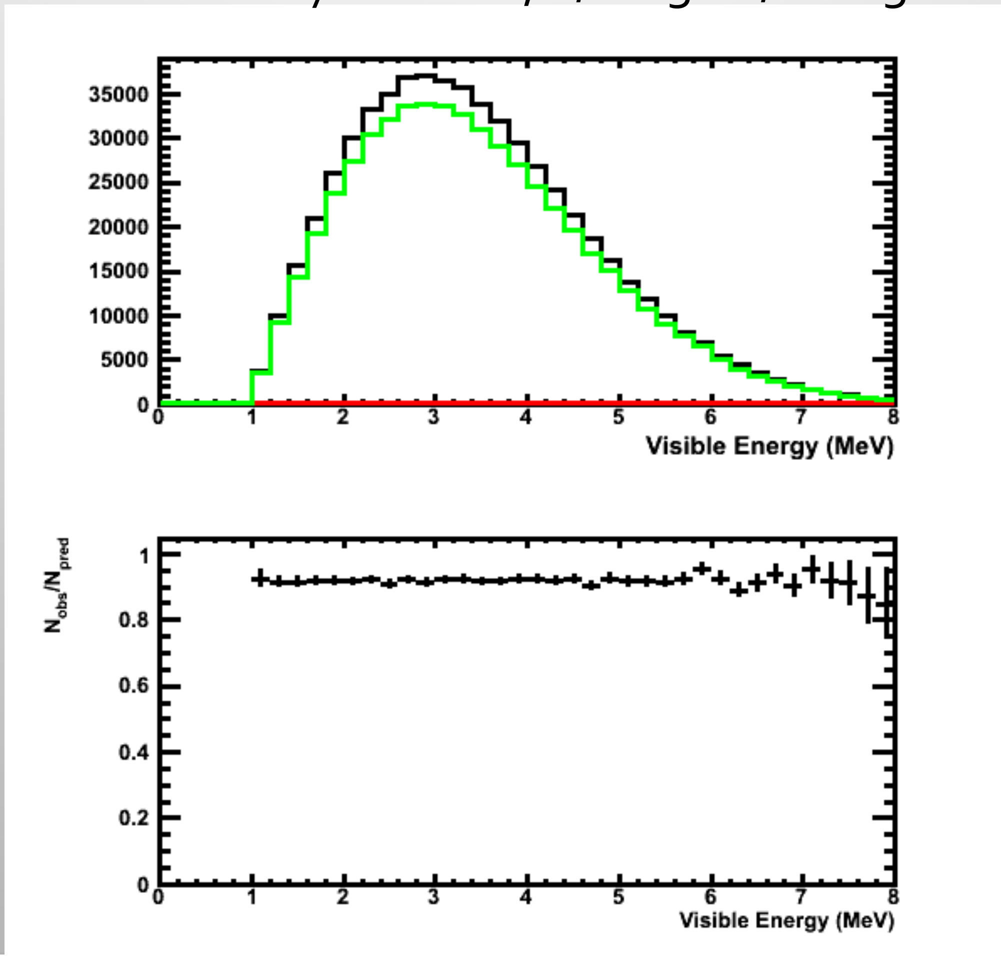


Example Oscillation Patterns:

For SONGS core, spectral sensitivity remains at 24m

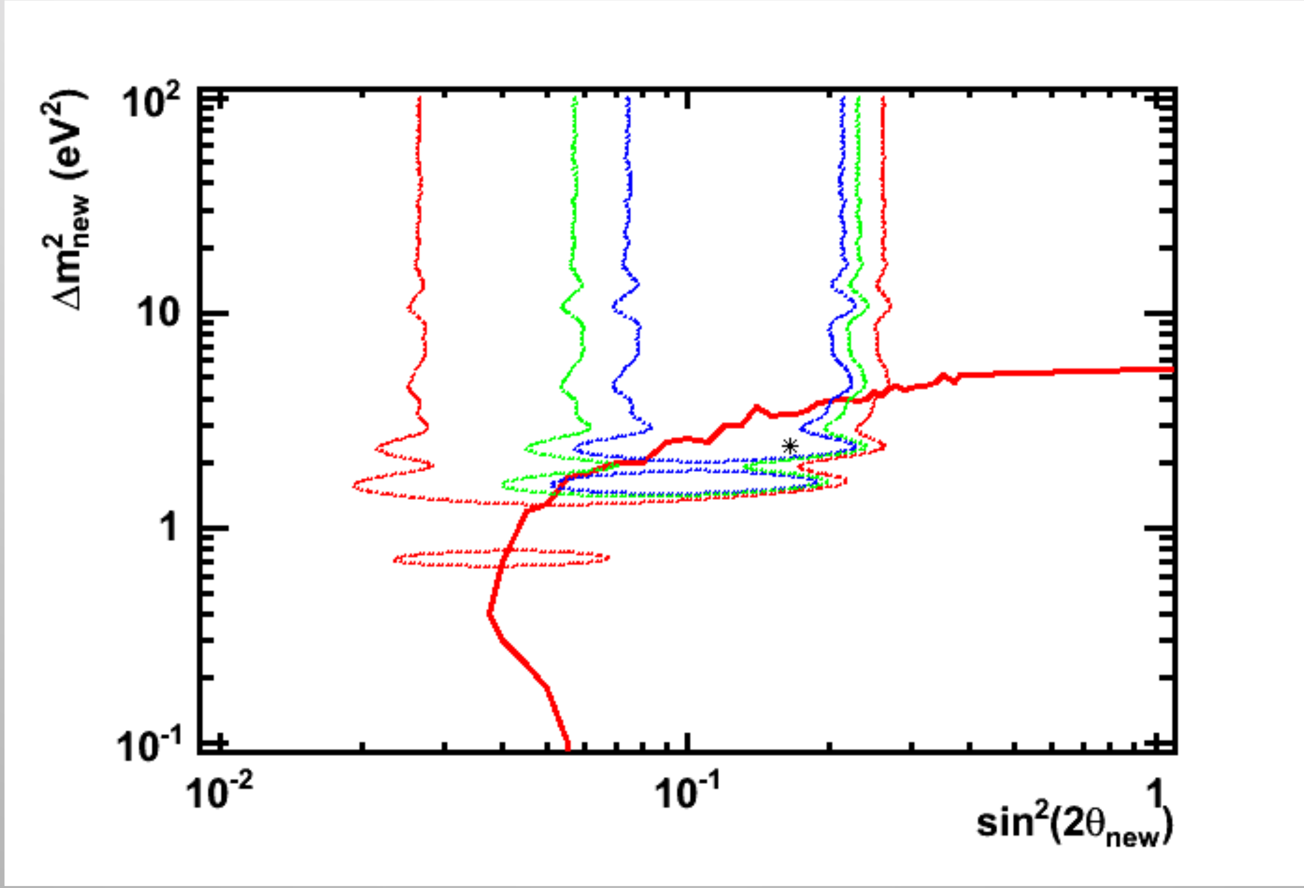
150 days, $\sin^2(2\theta) = 0.165$, $\Delta m^2 = 4.8 eV^2$

1.5% bin-to-bin systematic, 8/1 Signal/Background



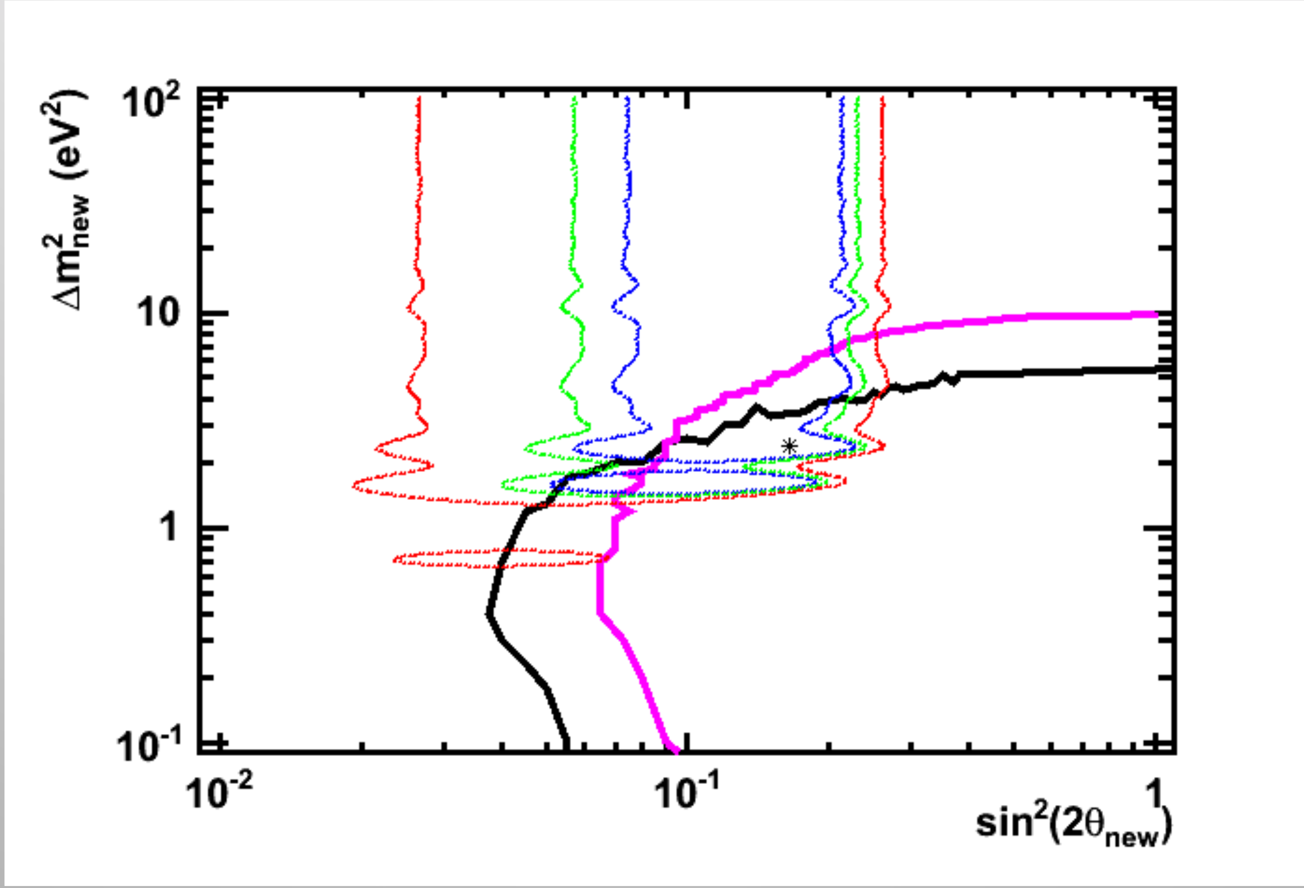
Exclusion Estimates

- 99% C.L.; 150 days@ SONGS
- 1.5% Energy scale error, 8/1 Signal/Background



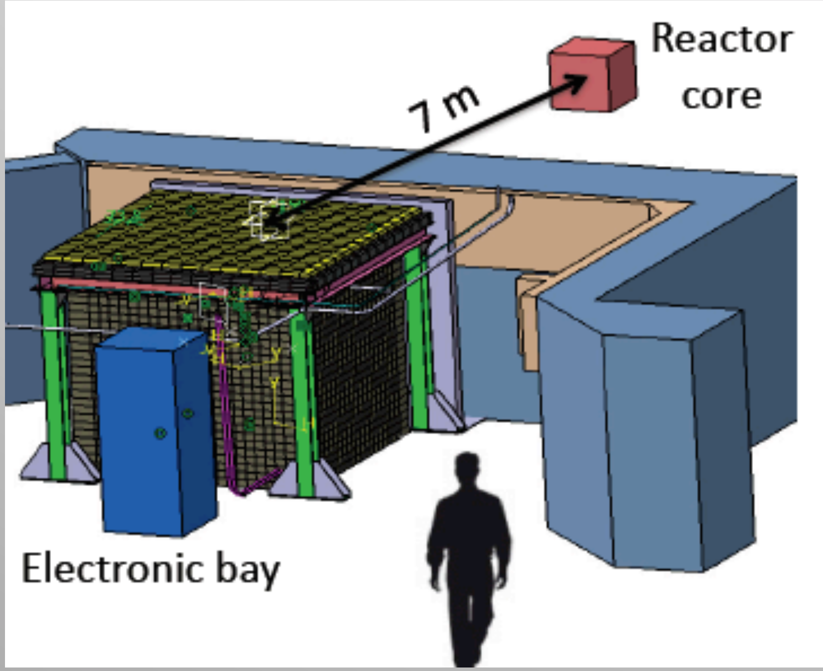
Exclusion Estimates

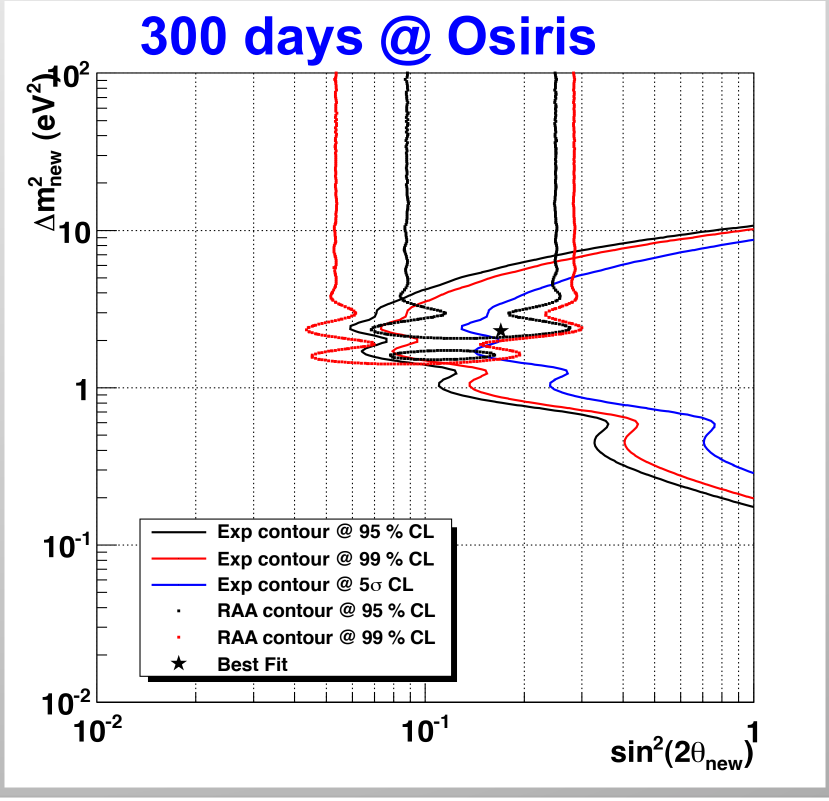
- 99% C.L.; 150 days@ SONGS; 300 days @ ATR
- 1.5% Energy scale error, 8/1 Signal/Background



Other efforts: Nucifer Nonproliferation detector (France)

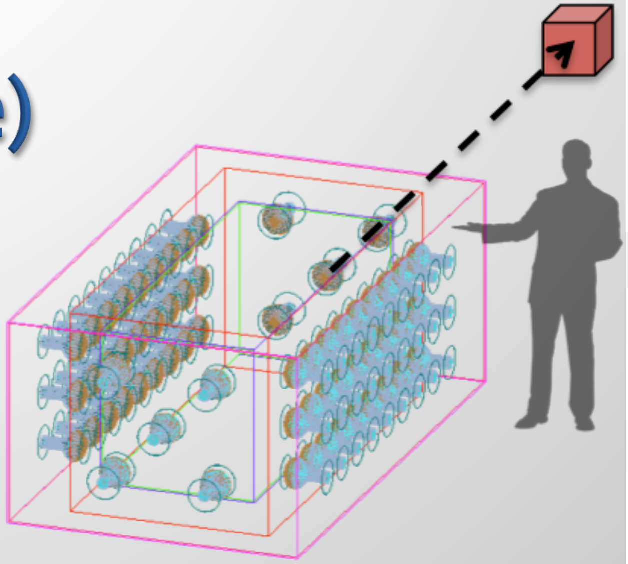
- 7m from 70MW research reactor core; 650 ν/day
- Substantial shielding required due to reactor correlated background

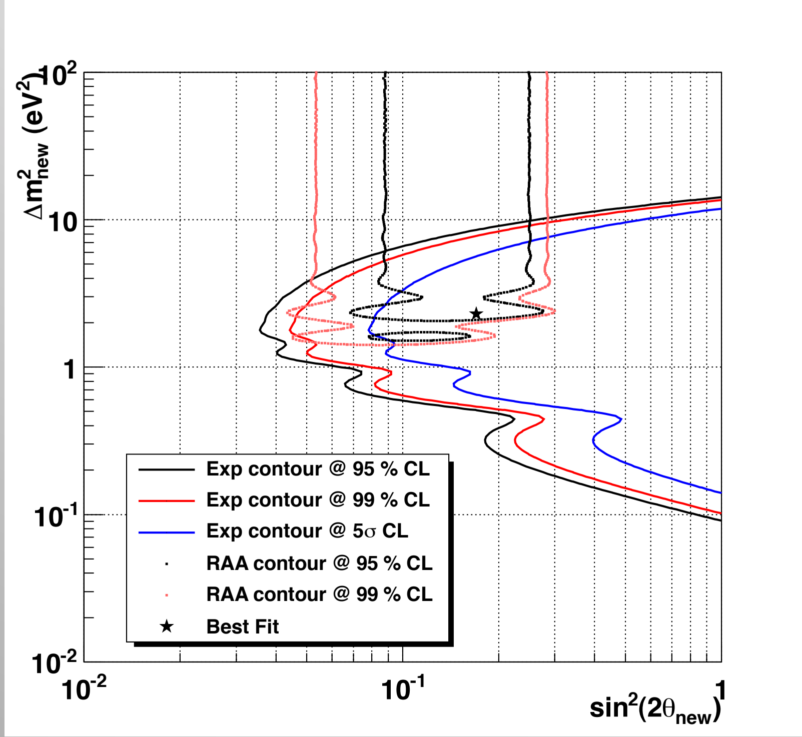




Other efforts: Stereo (France)

- Proposed for ILL research reactor
- Goal is to measure unique signature of an oscillation pattern using the full L/E dependence, providing overage of the reactor anomaly contour at high significance level.

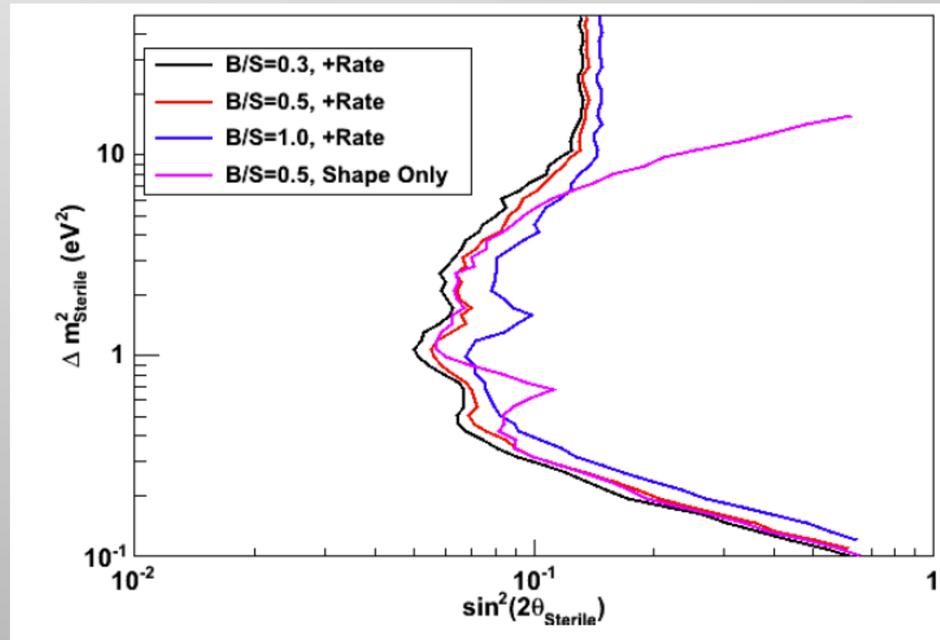




- 8 ILL cycles (1.5 year running)
- L_o = 10 m
- S/B = 1.5
- Threshold E_{vis}>2 MeV
- Neutron cut = 6 MeV
- 5 baseline bins of 40 cm
- $\sigma_{baseline/evt} \approx$ 25 cm
- Complete det response
- 700 ν/d

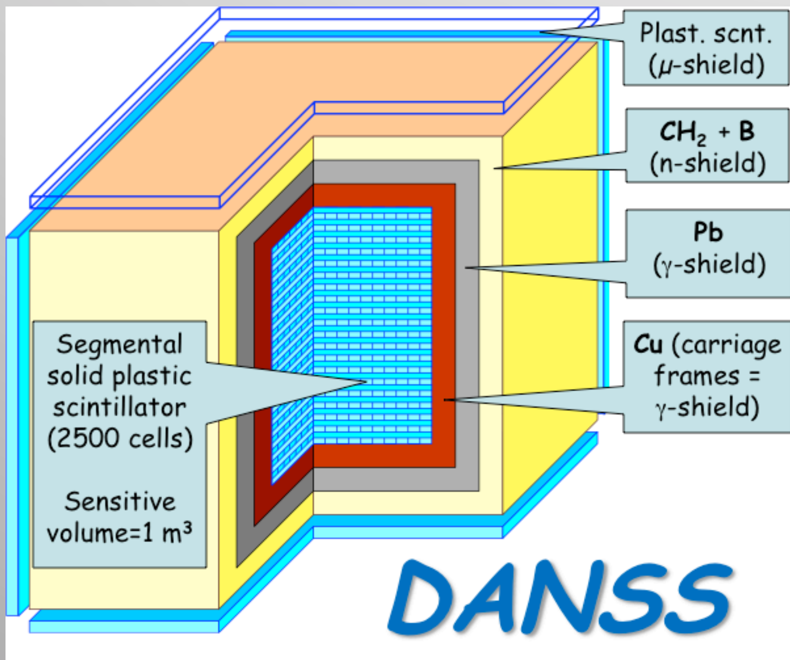
Other efforts: Hanaro (South Korea)

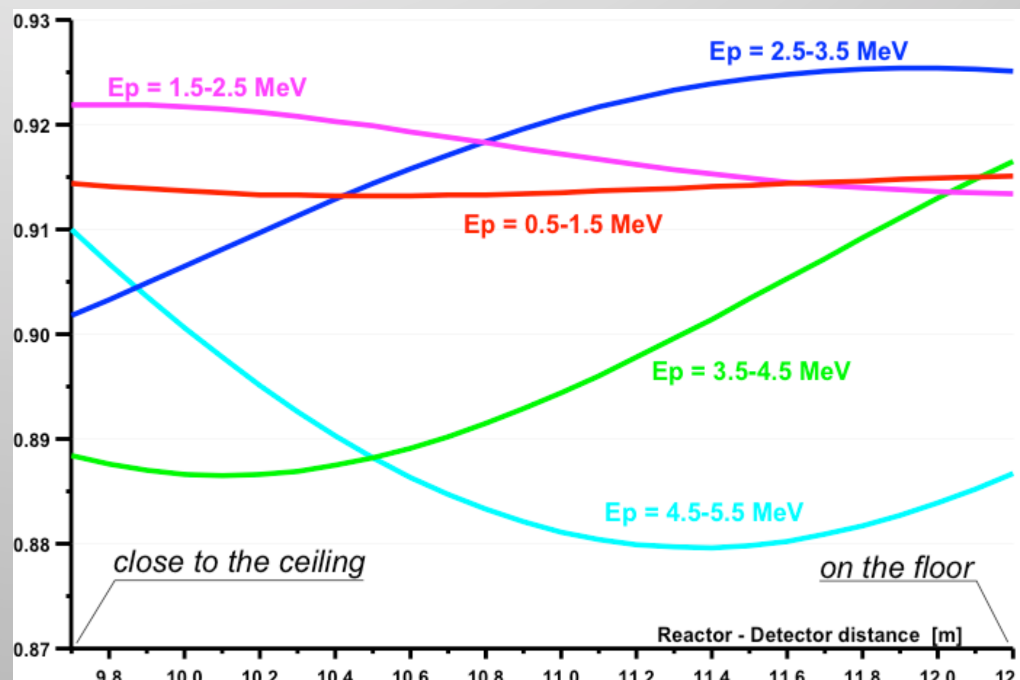
- 5-7m from 30MW research reactor core; ~600 ν/day for proposed 0.5ton ^{6}Li doped L.S. detector
- On-site measurement have found large reactor correlated gamma and neutron backgrounds; little overburden



Other efforts:
DANSS Nonproliferation detector (Russia)

- Highly segmented P.S. detector close to 3GW reactor core; 10^4 ν/day
  - Energy resolution 30% (1σ) at 4MeV
  - Possibility to move detector vertically between 9.7-12.2 meter baseline
- Group is also investigating compact core research reactor site

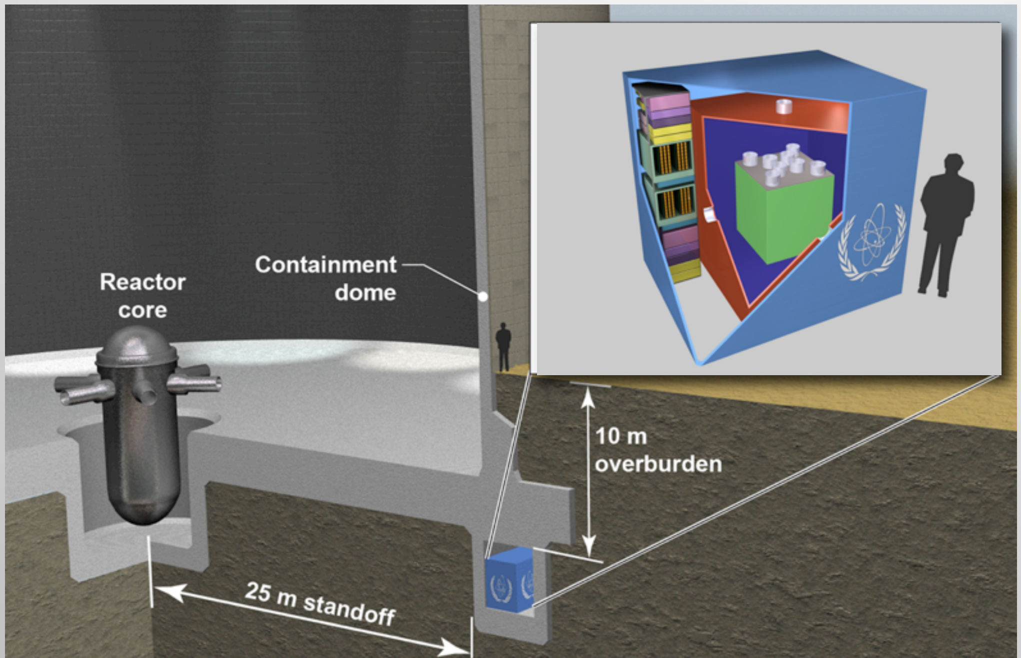




Conclusions

- Short baseline reactor efforts have continued, attempting to develop a new safeguards technique
  - The reactor access, reactor simulation, and detector design expertise from the applied community can be exploited to probe the "RAA"
- Short baseline measurements at appropriate small research and large power reactors would be complementary:
  - Provide multiple baseline cross-check, probe different Δm^2 regions, and measure spectra from different core compositions
  - SONGS appears optimal for a power reactor deployment
  - ATR appears very promising as a research reactor deployment site
- SCRAAM would rapidly exclude a large fraction of the ~ $1 eV^2$ "RAA" allowed phase space, and have good discovery potential in the "best-fit" region

There is increasing interest in (Short Baseline) Antineutrino Monitoring of Reactors



AAP 2011

IAEA International Atomic Energy Agency
Atoms for Peace

AGENDA

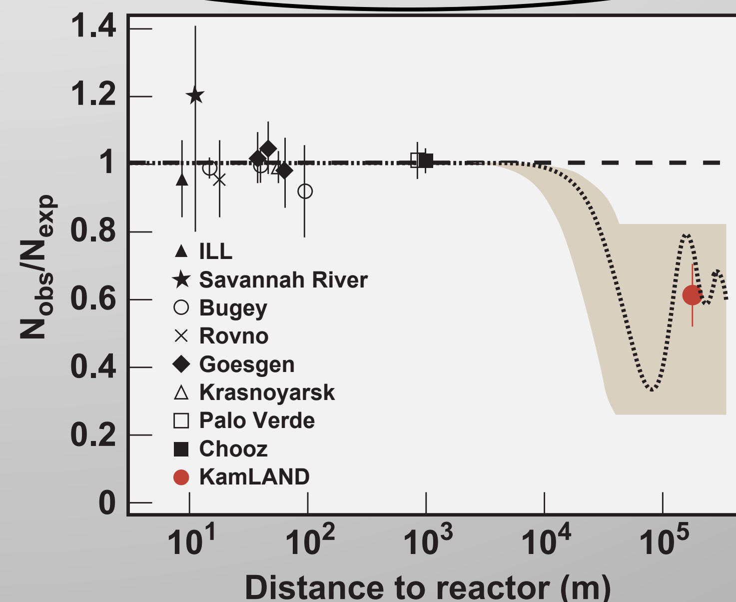
Ad Hoc Working Group on Safeguards Applications of Antineutrino Detectors, 14 September 2011, Vienna, Austria

Basic science laid the foundation for this monitoring technique

- Reines and Cowan, 1956:
  - First to detect antineutrinos using a reactor source and a liquid scintillator detector

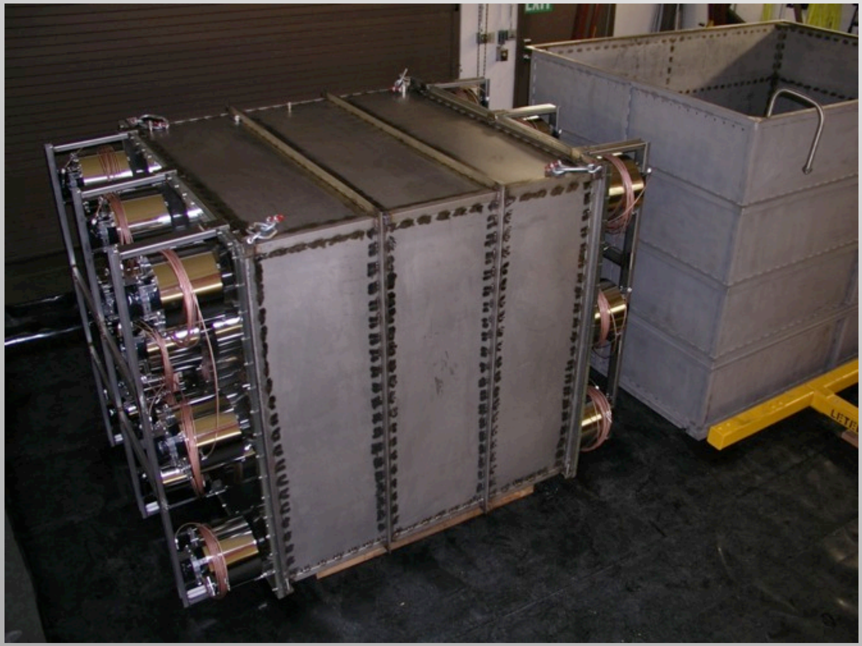
- Three decades of neutrino oscillation studies have provided:
  - ~~A mature technology base~~
  - A quantitative understanding of reactors as an antineutrino source

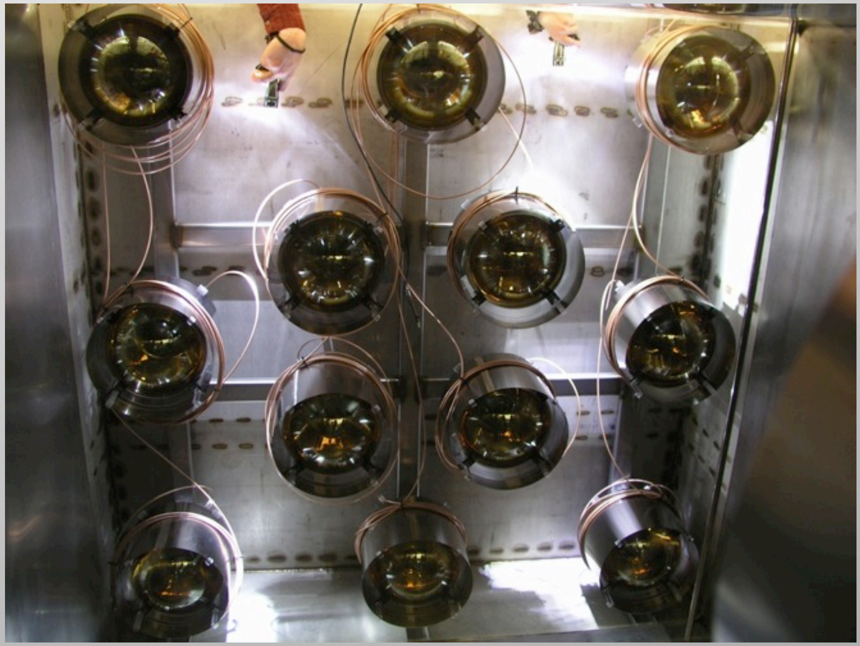
?



We have completed considerable R&D on detectors of this scale

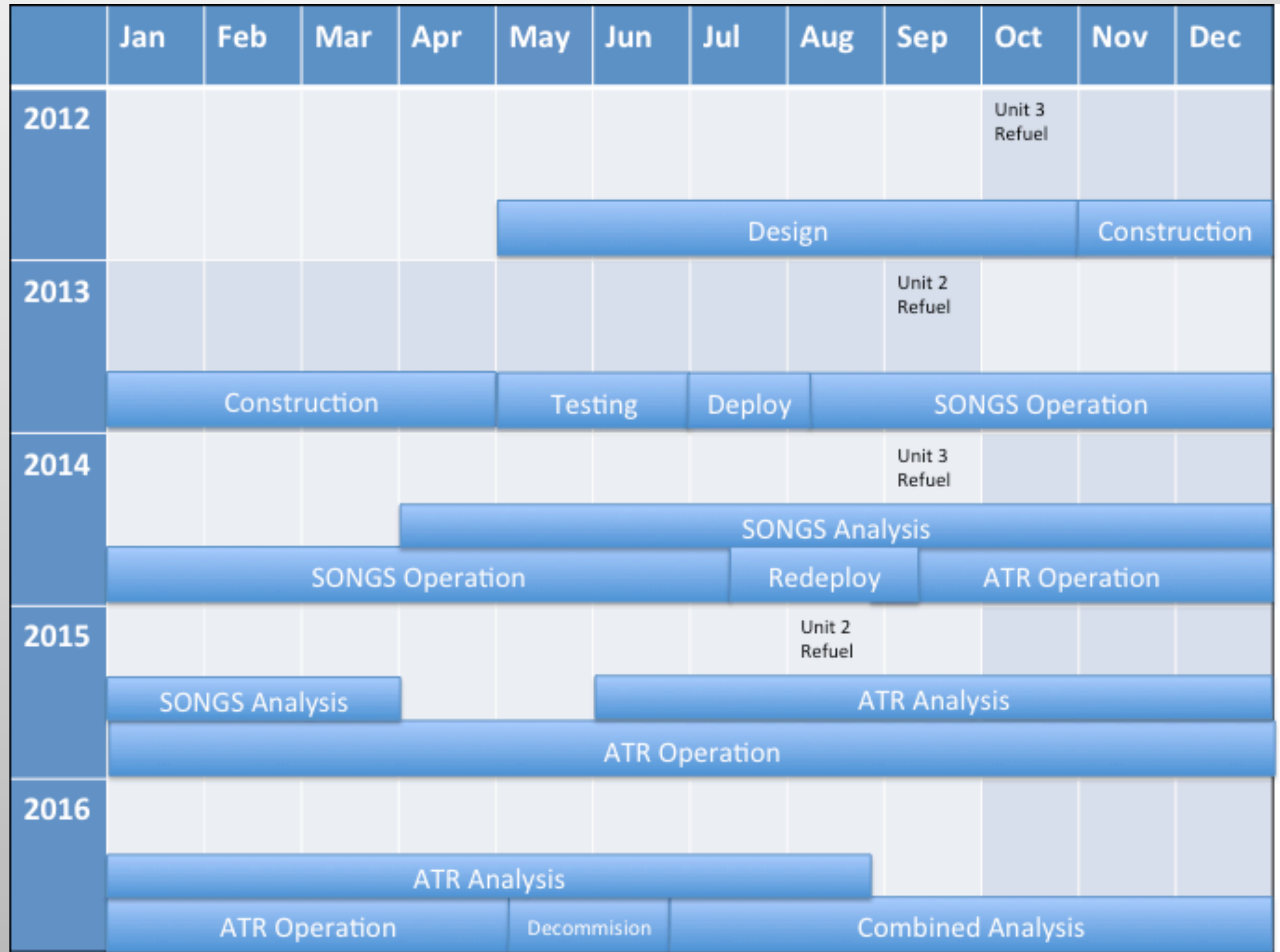
- Most recent: 3.6 ton liquid scintillator detector (BC-525, 0.1% Gd)
  - For deployment at a CANDU6 reactor in 2012
    - Fresh ^{235}U core! Collaborating with UCD for absolute flux measurement
  - Understand safety and regulatory requirements for reactor site
  - Validated mechanical design for double ended PMT readout





Nominal Schedule

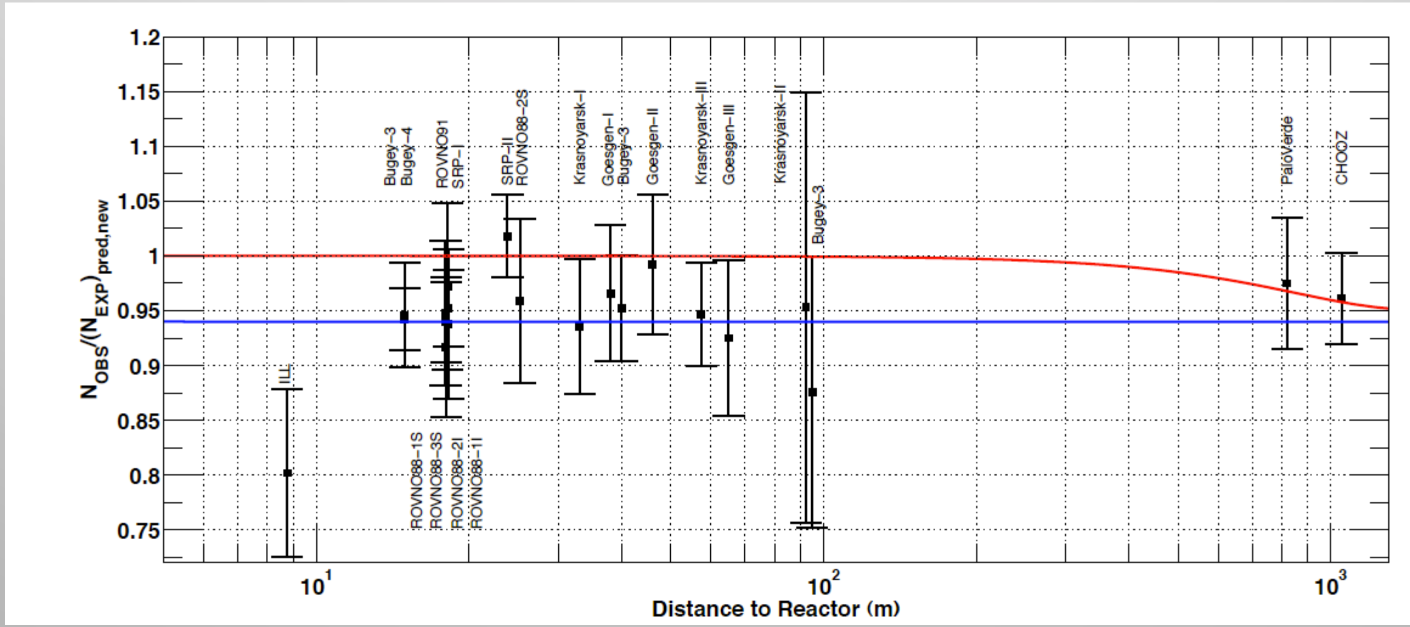
- SONGS outages are key; ~50 day background measurement:
  - Unit 2 Sept. '13
  - Unit 3 Sept, '14
- Given our recent experience, 15-18 months from design to deployment seems feasible
- Could have first results within ~9 months of data taking



The Reactor Antineutrino Anomaly

- Mention, et al, re-analyzed many previous short baseline reactor experiments, in light of their new antineutrino flux prediction
- The result: new global "Reactor Antineutrino Anomaly"

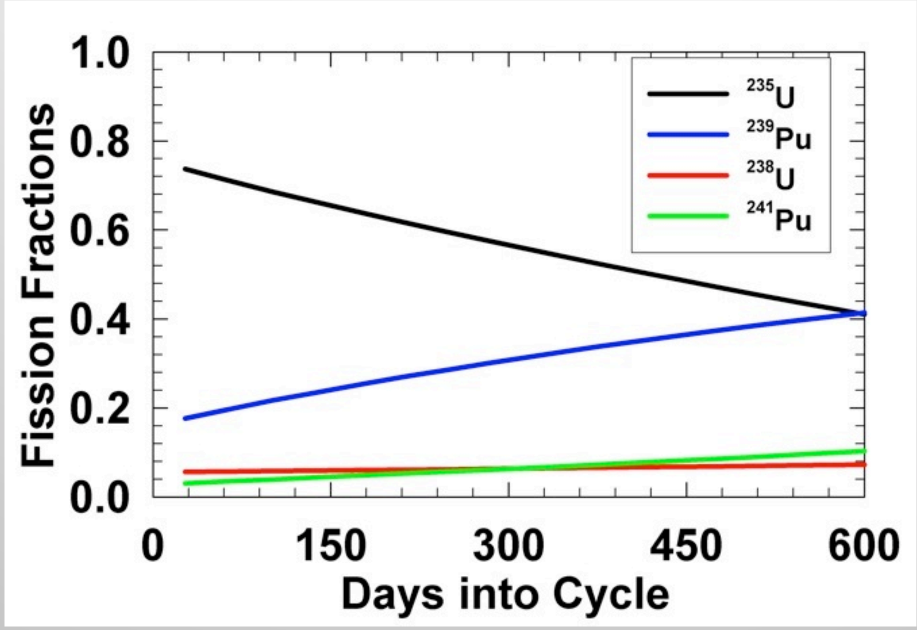
$$N_{obs}/N_{pred} = 0.979 \pm 0.029 \Rightarrow 0.943 \pm 0.023$$



arXiv:1101.2755v4

SONGS Core evolution is well understood

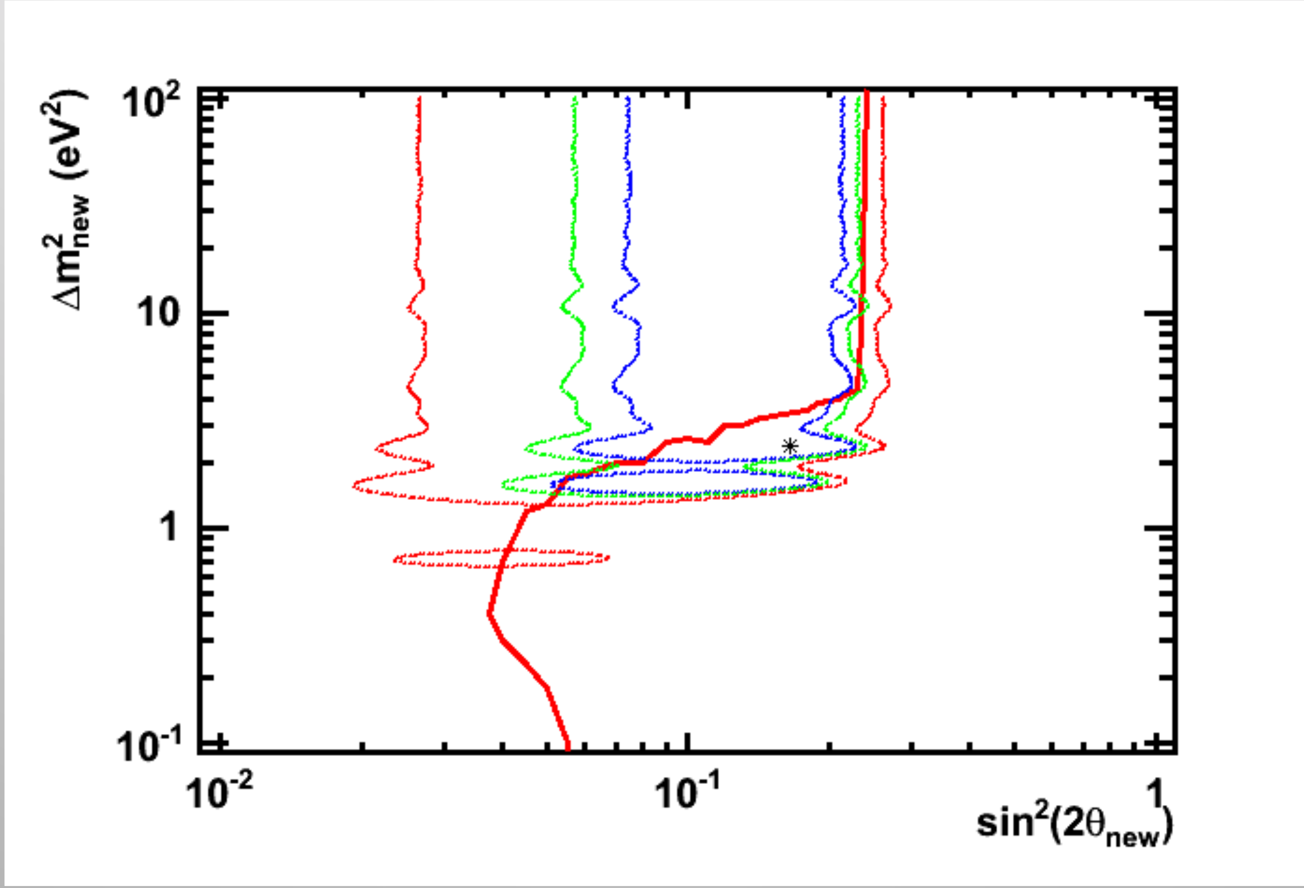
- Again, through our long interaction with SONGS we have access to operator fueling and reactor data



- Unlike the theta13 near detectors, the SCRAAM spectrum measurement would effectively be from a single core
  - In the absence of spectral distortion, this measurement could better constrain prediction uncertainties

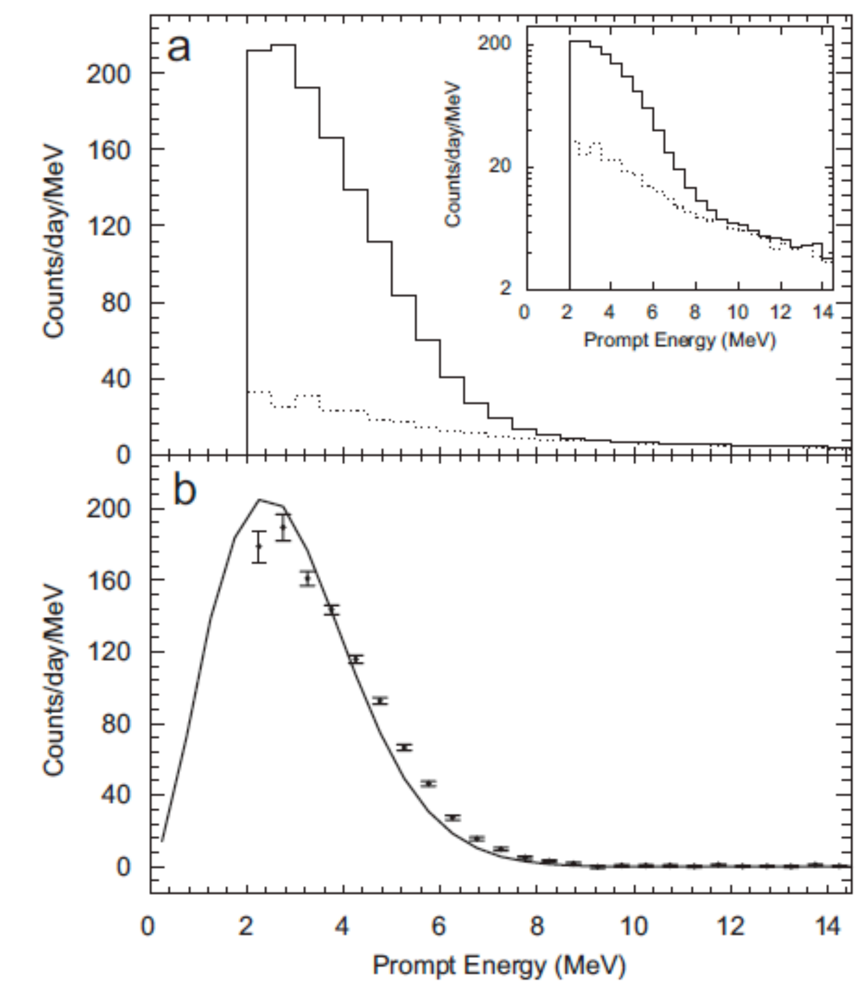
Exclusion Estimates: Shape + Rate

- 150 days, 99% C.L.
- 4% Normalization, 1.5% Energy scale error, 8/1 Signal/Background

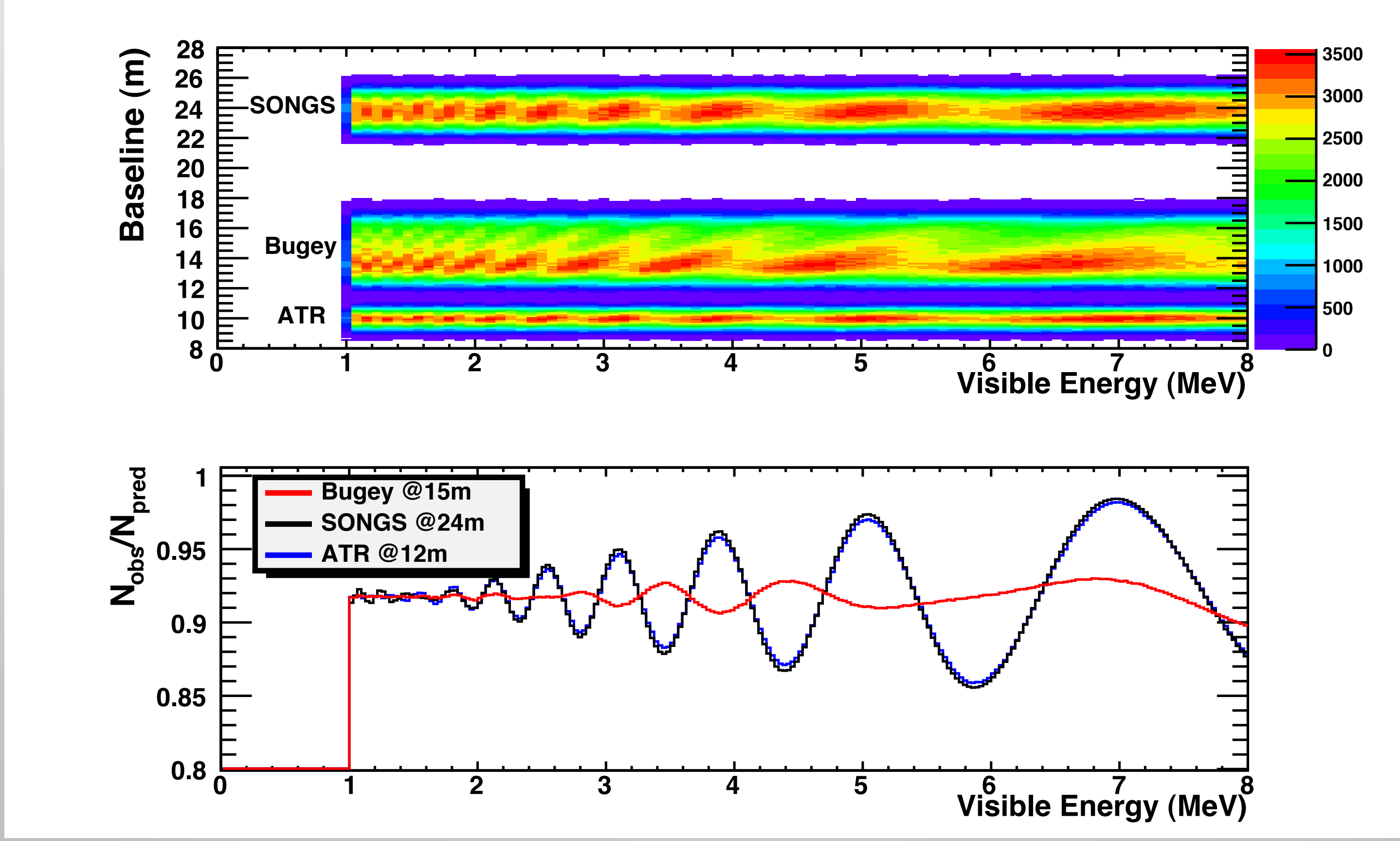


SONGS Backgrounds

- Our SONGS1 detector had S/B of ~4/1
- Background was primarily:
  - Fast neutron recoil followed by capture
  - Multiple neutron capture
- There is reason to believe that we can do considerably better with SCRAAM:
  - SONGS1 had only 95% muon veto and "non-hermetic" shielding
  - Improved neutron capture efficiency and analysis will allow rejection many more multiple neutrons



Effect of Baseline and Baseline Distribution



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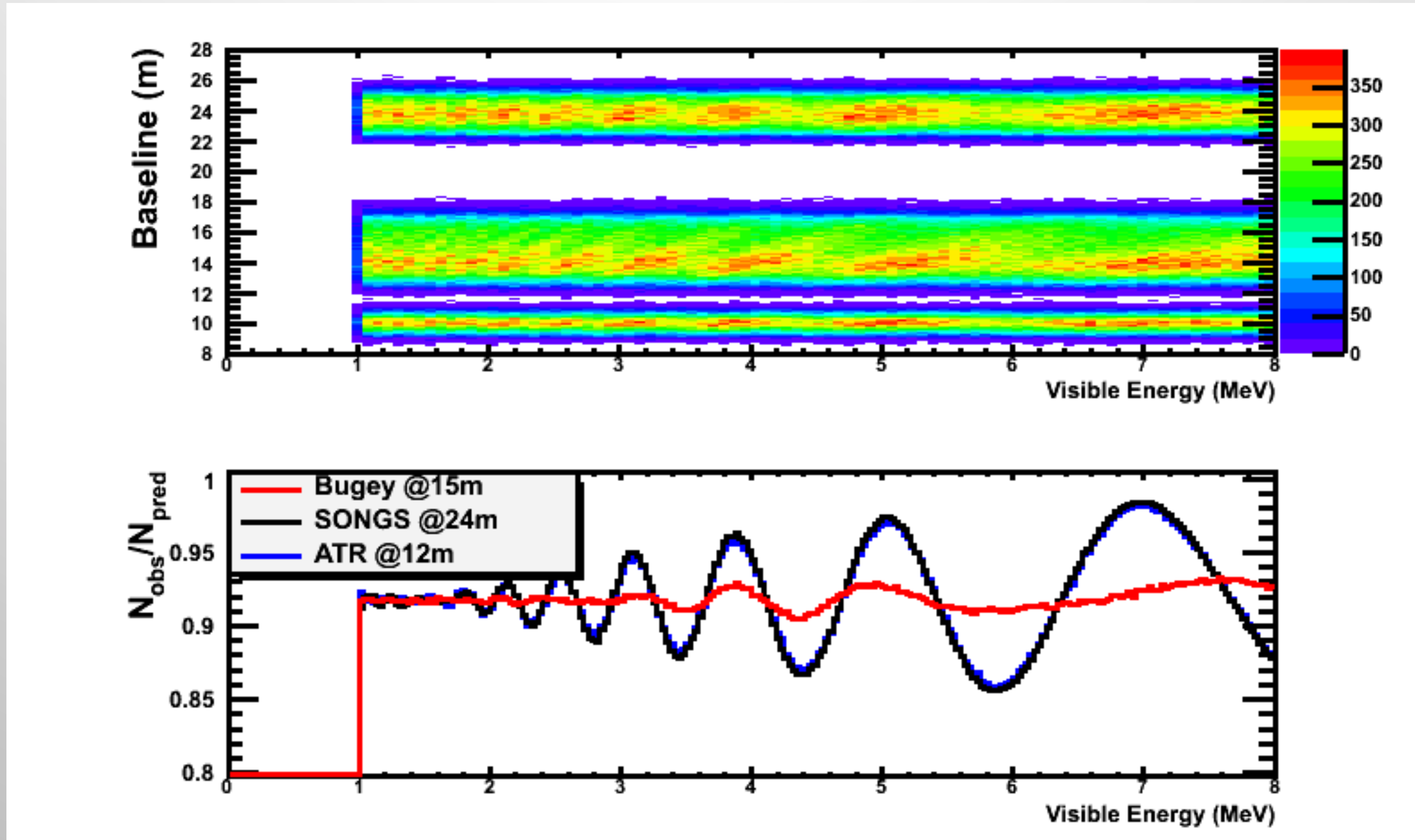

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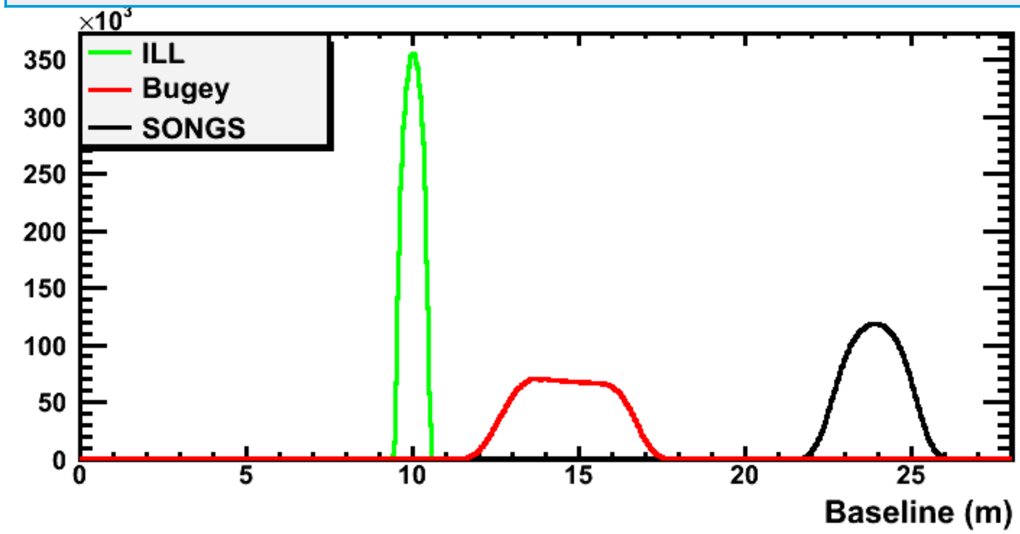
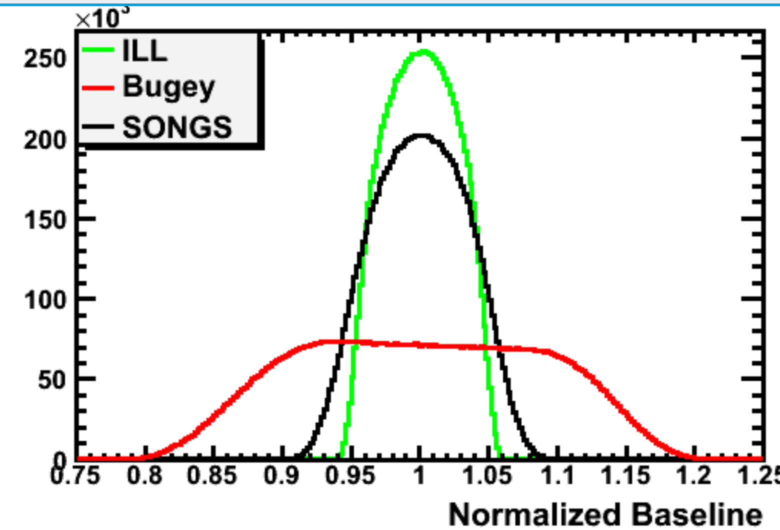
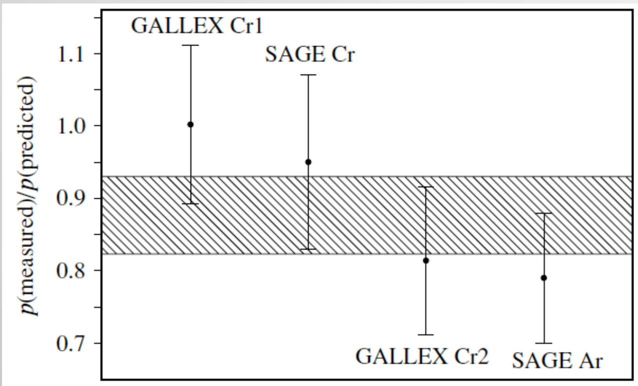
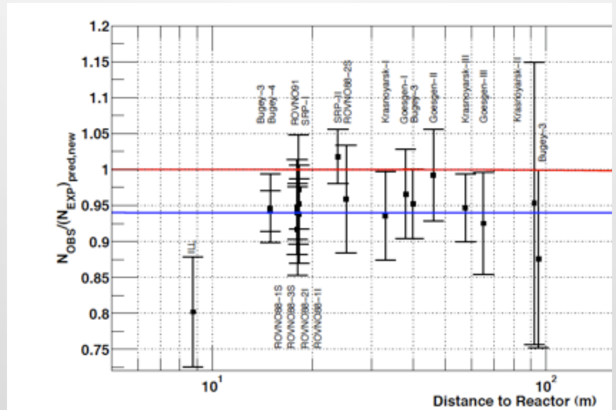




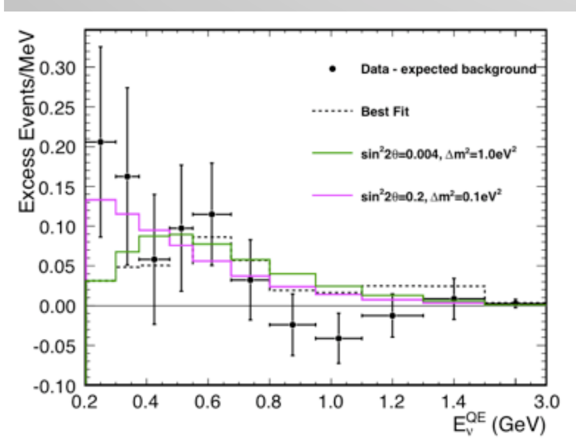
The Reactor Anomaly is consistent with other hints at sterile flavor(s)



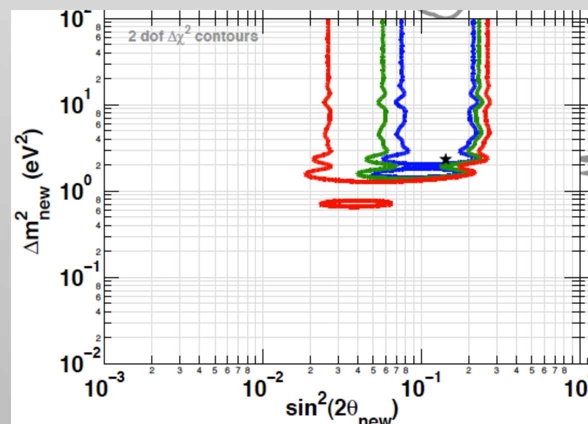
SAGE/GALLEX



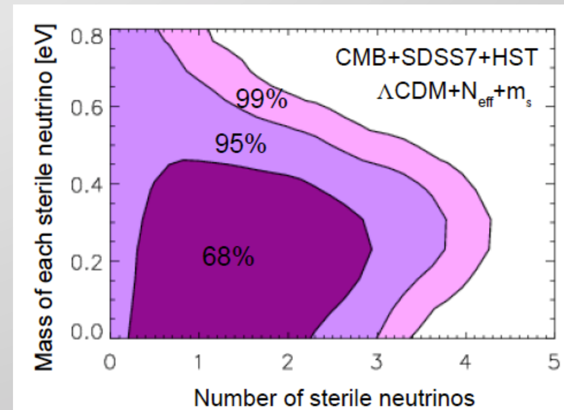
Reactor Anomaly



MiniBOONE



Combined



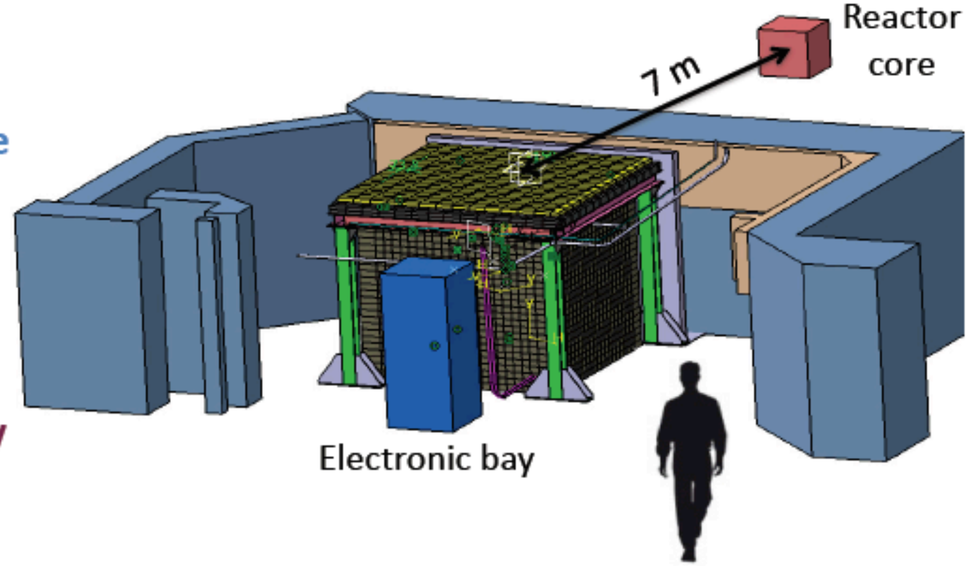
Astrophysical measurements are also consistent with ~eV sterile(s)

A compact core effort: Nucifer
(see also Y.D. Kim poster)

Nucifer @ Osiris

- 70 MW reactor
- Nucifer 7 m from the core
- 15 mwe overburden

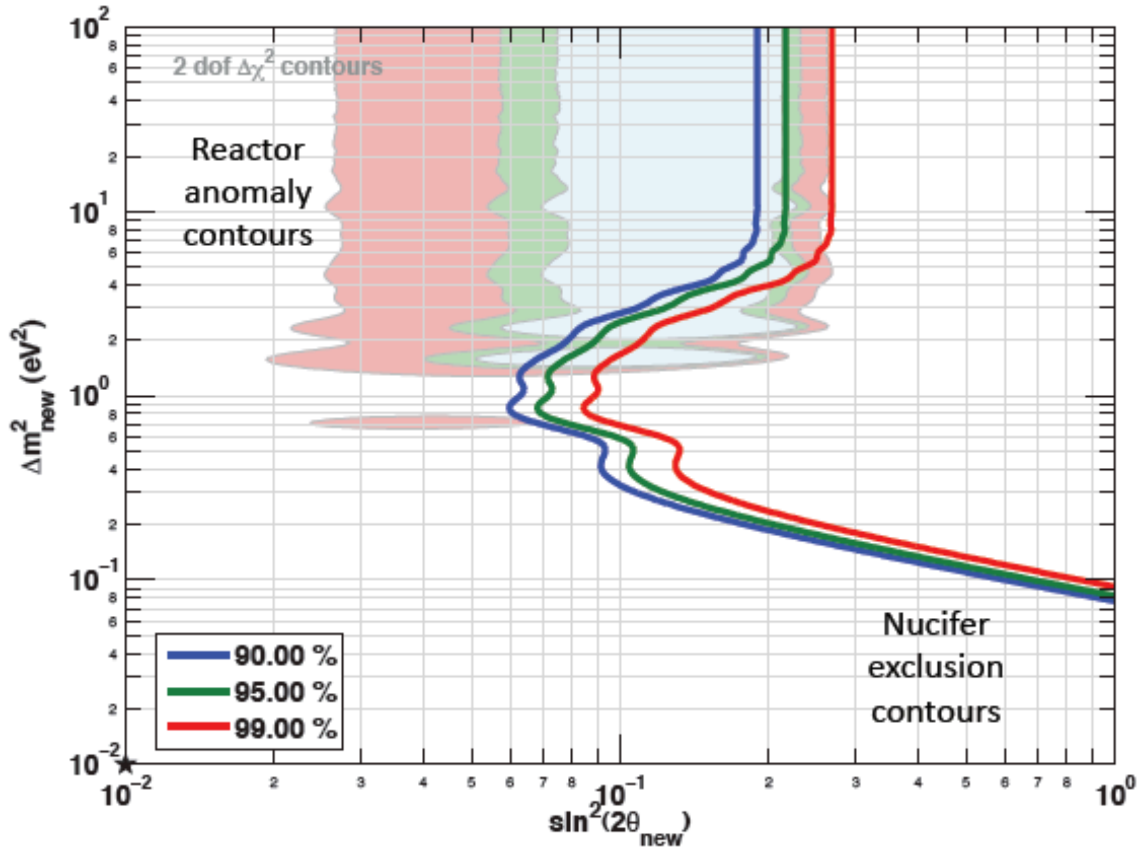
650 ν/day expected
Assuming 50% det efficiency



- **Reactor Background:**
  - Additional 10 cm lead shielding needed due to reactor induced γ rays

- **Based on simulation and on site measurements:**
  - $S/B_{accidentals} = 1$
  - $S/B_{correlated} = 0.25$ before PSD cut, ~2.5 expected after PSD selection. Reactor OFF 33% of the time, will allow final background subtraction.

Testing the 4th ν hypothesis



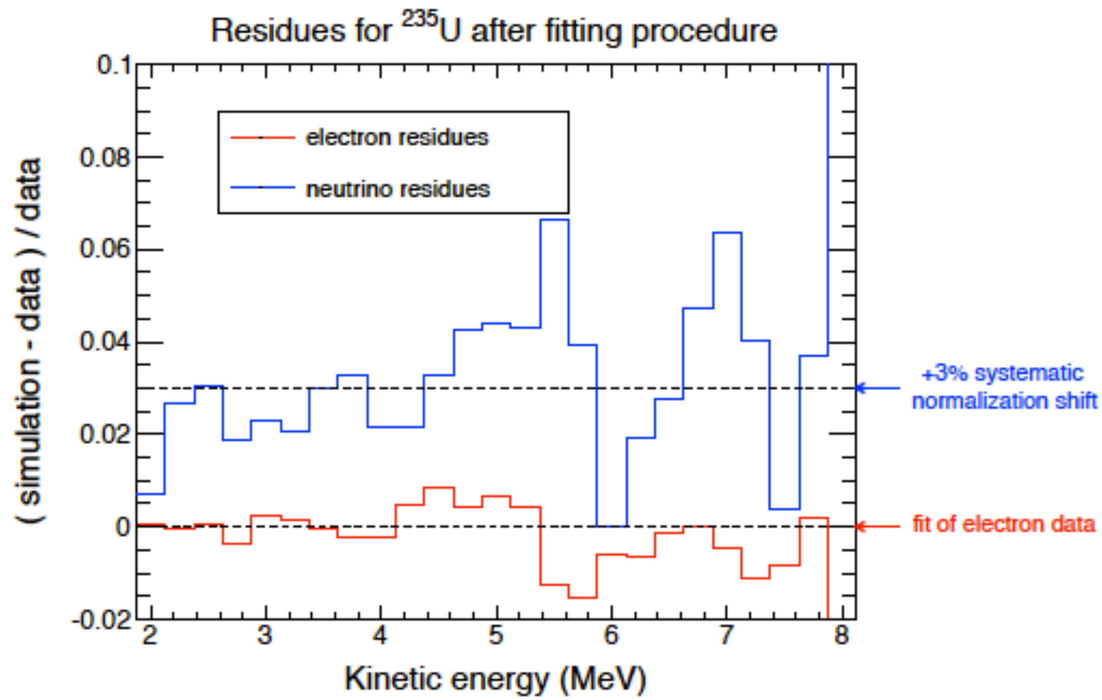
100 days full power @ Osiris:

- 4% norm error
- E resol = 0.15*E
- 2% E scale error
- S/B = 1 (?), assuming same shapes (worst case).

LLNL-PRES-528693

New mixed approach (cont'd)

Residuals to ref. ILL data

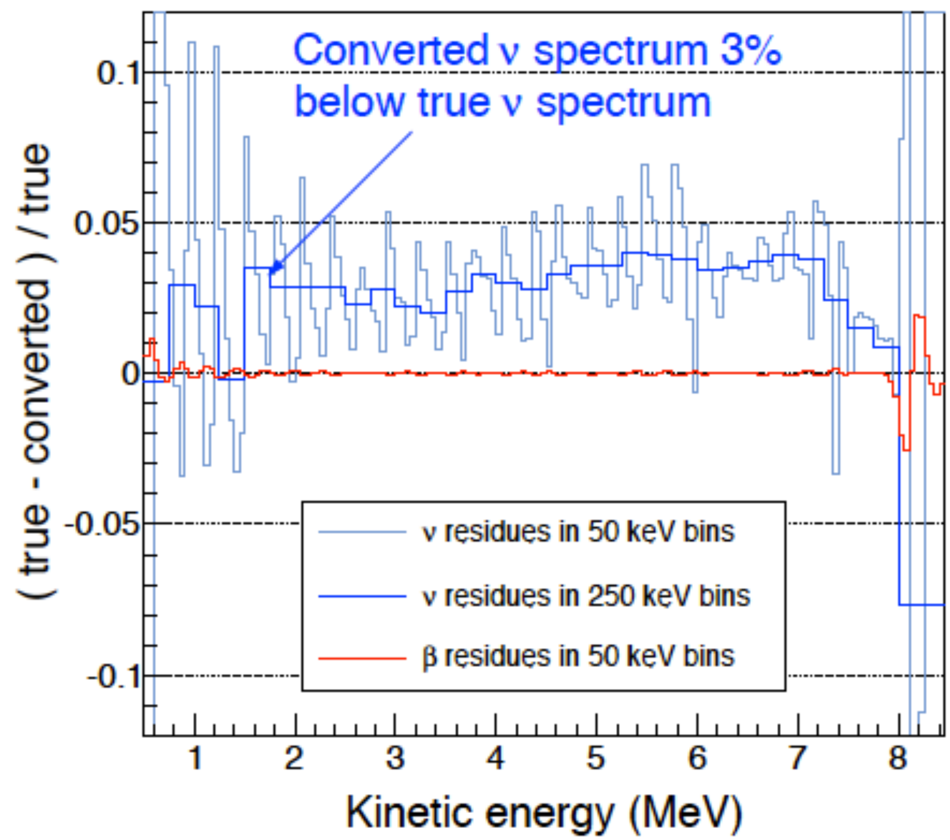


- Corrected Fermi theory applied on all β-branches
- $+3\%$ normalization shift with respect to old ν spectrum
- Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)
- Stringent tests performed, origin of the biais identified

NB: this $+3\%$ shift is above the IBD threshold, the total integral of emitted spectrum remains unchanged (1 β and 1 ν per decay)

Consistency check

1. Define "true" β and ν spectra from reduced set of well-known branches from ENSDF nuclei database. "Perfect knowledge" of both β and ν spectra.
2. Apply exact same OLD conversion procedure to true β spectrum
3. Compare converted ν spectrum to the true one

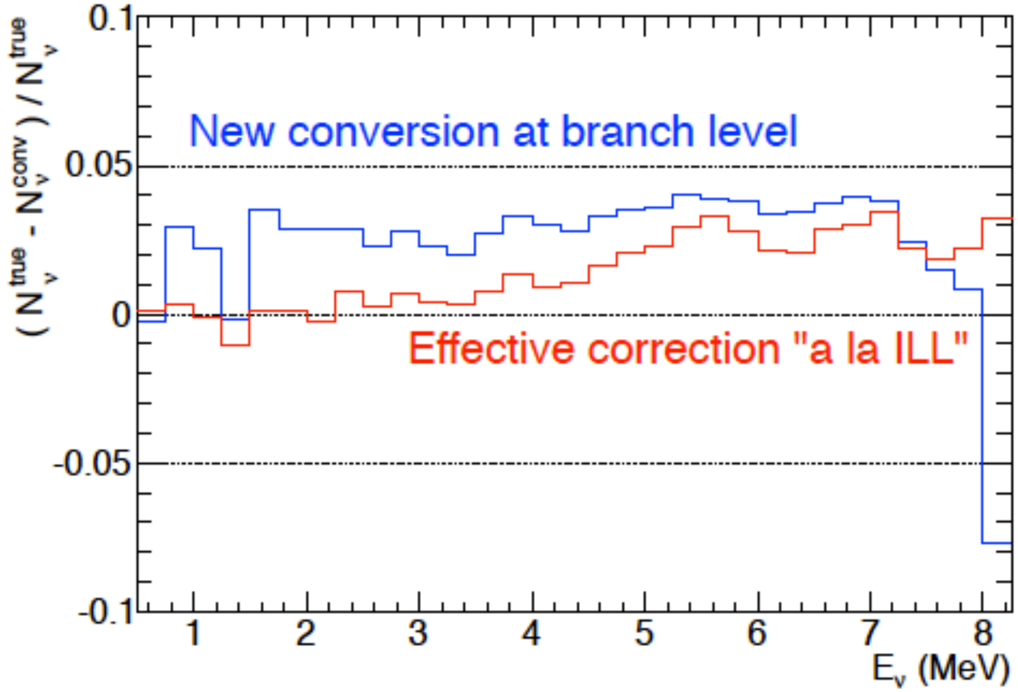


⇒ OLD technique leads to a -3% bias w.r.t the true ν spectrum

Origin of the 3% shift - $E < 4$ MeV

- Effective linear correction $\Delta N_\nu^{L_0,\mathrm{WM}}(E_\nu) = 0.65 \times (E_\nu - 4\ \mathrm{MeV})\%$ of ILL data replaced by correction at β-branch level:

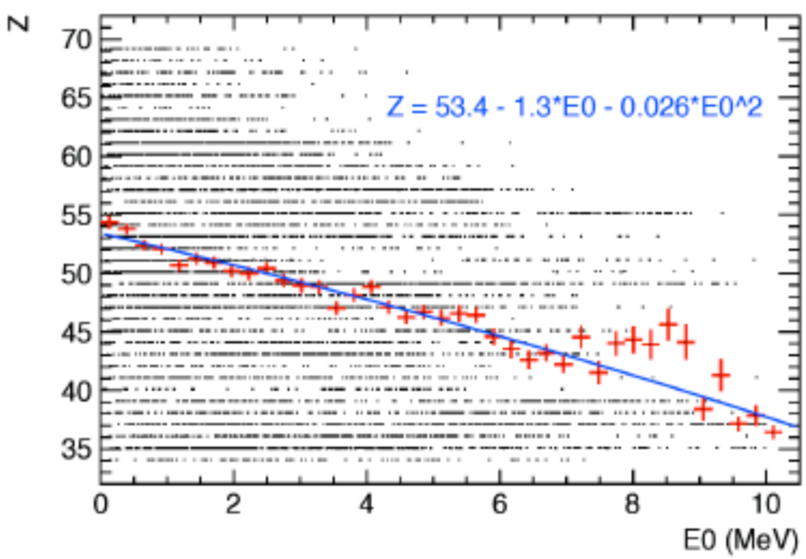
$$L_0 \approx -\frac{10Z\alpha R}{9\hbar c} \times E \text{ and } \delta_{\mathrm{WM}} \approx \frac{4}{3}\frac{\mu_p - \mu_n}{M_N}\left|\frac{G_V}{G_A}\right| \times E$$

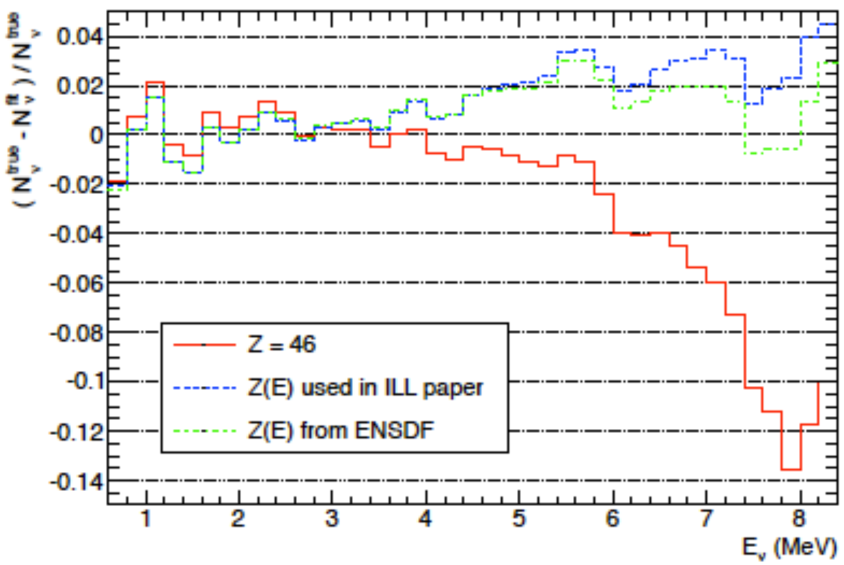


- Correct a bias. Assume 100% syst. error
- Still the correction at branch level neglects all effects of nuclear structure Uncertainty could be larger than 100%?

Origin of the 3% shift - $E > 4$ MeV

- Mean fit of nuclear charge $Z(E_0) = 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$ doesn't reflect accurately enough the Z distribution



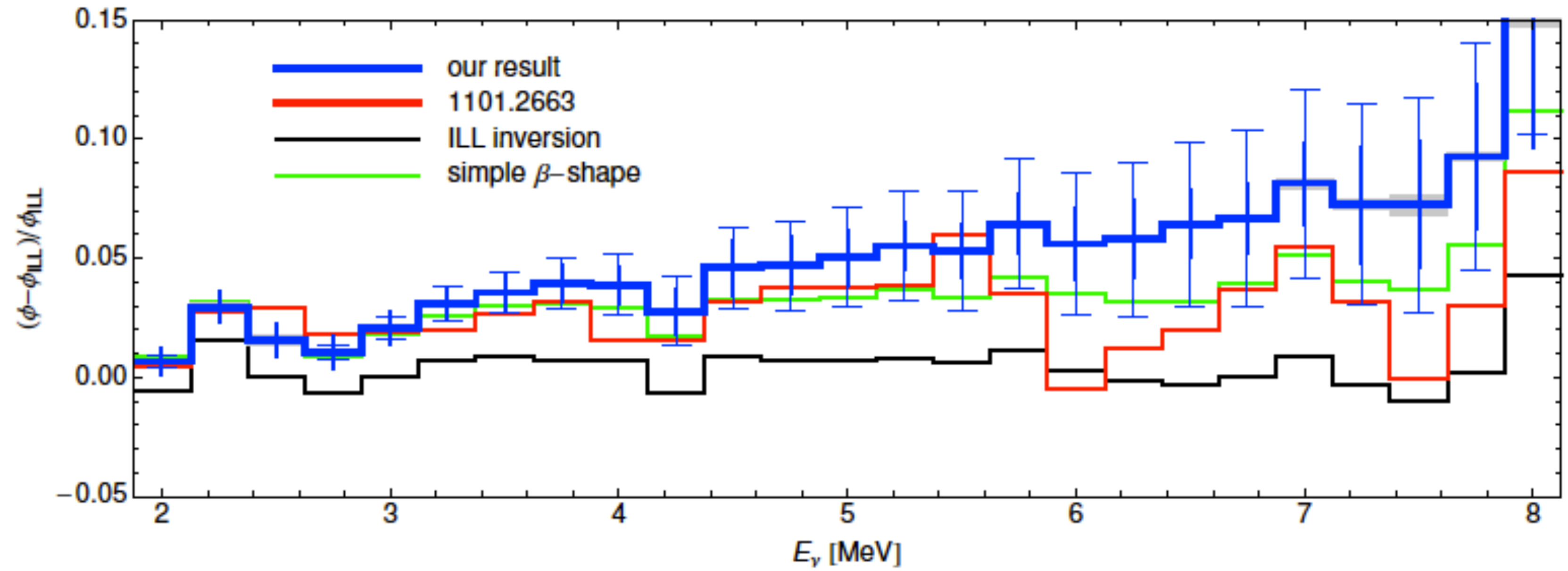


What we learned

- Mixed approach:
  - ILL conversion procedure have 2 independent biases ($\approx 1.5\%$ each in total detected rate):
    - Low energy: correction to Fermi theory should be applied at branch level
    - High energy: mean Z fit is not accurate enough
  - Combination of all "well known" nuclear data can provide a good proxy for neutrino spectra ($\approx 90\%$ of experimental spectrum described)
- Revisit conversion procedure:
  - Apply all above
  - Complementary approach, minimizing the use of nuclear data

$\rightarrow$ P. Huber, Phys. Rev. C84, 024617 (2011)

Well established deviation from ILL spectra



- Confirms global increase of predicted spectrum
- Extra deviation at high energy from more complete correction to Fermi theory (weak interaction in the finite volume of the parent nucleus)
- Fixes remaining oscillations of mixed-approach prediction