Issues with Reactor Antineutrinos: Theory and Experiment

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UK HEP Forum

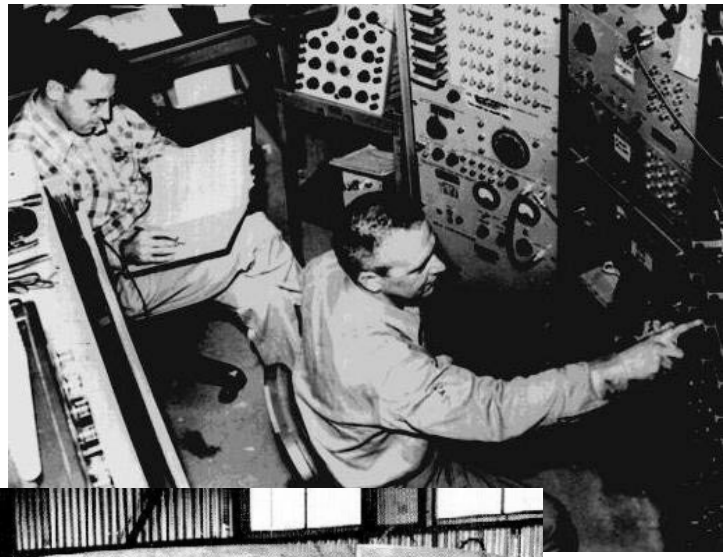
Abingdon, UK

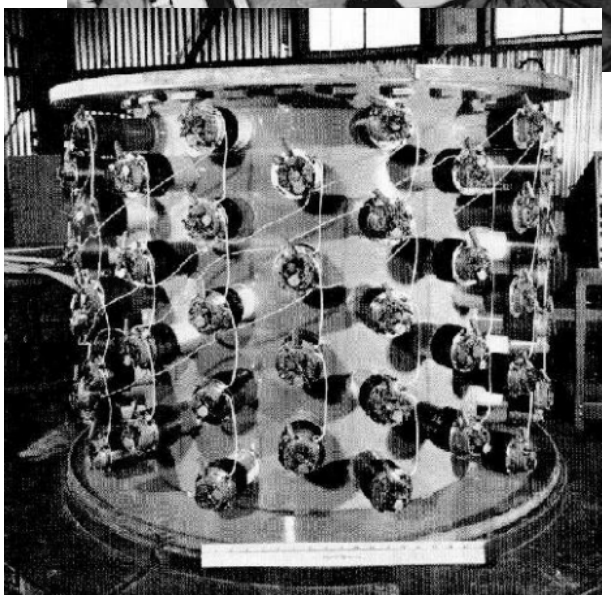
Nov. 6, 2015

The Bright Side

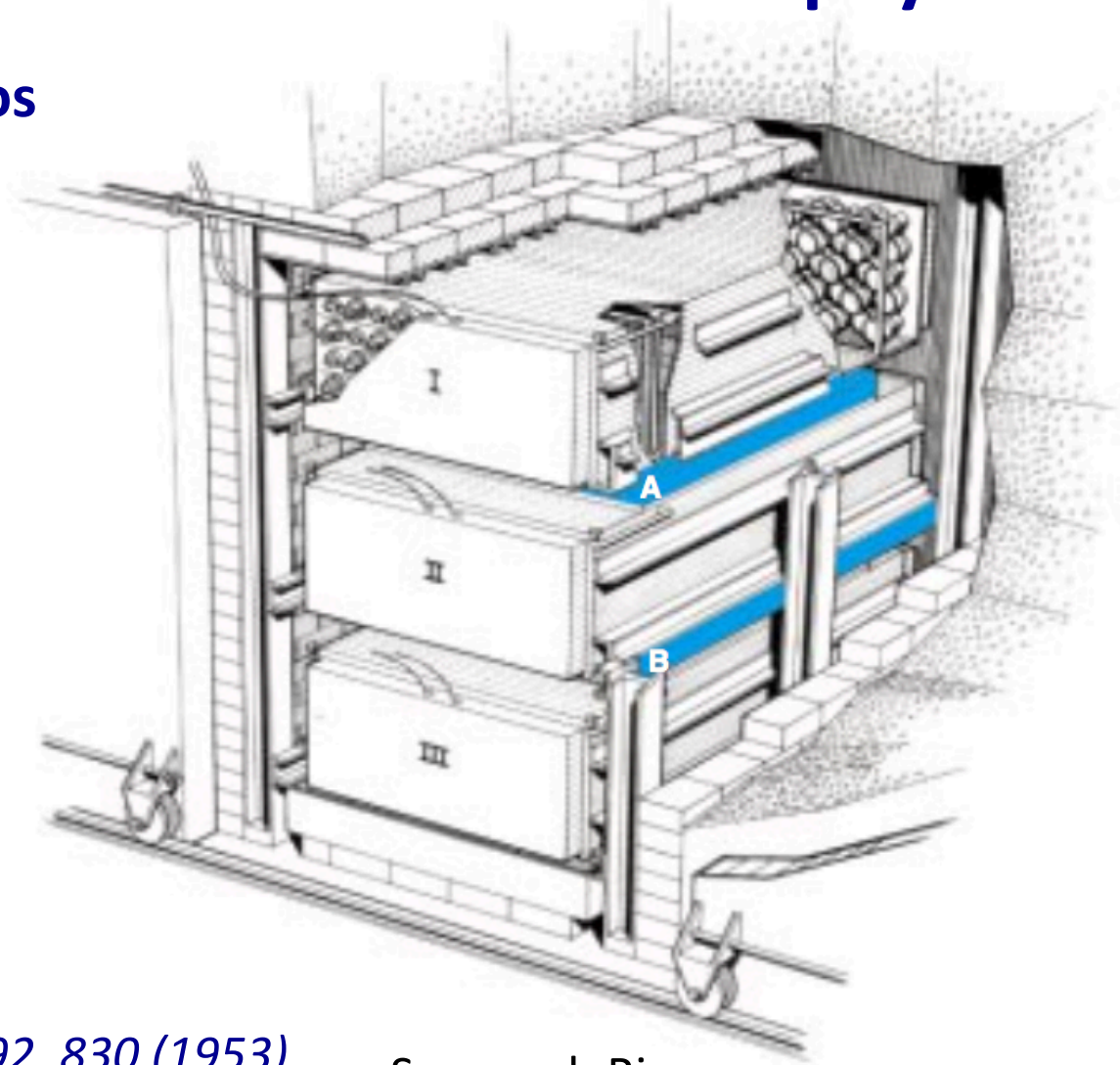
Reactors have been a powerful tool in neutrino physics:

1950s: First detection of neutrinos





Hanford
Phys. Rev. 92, 830 (1953)

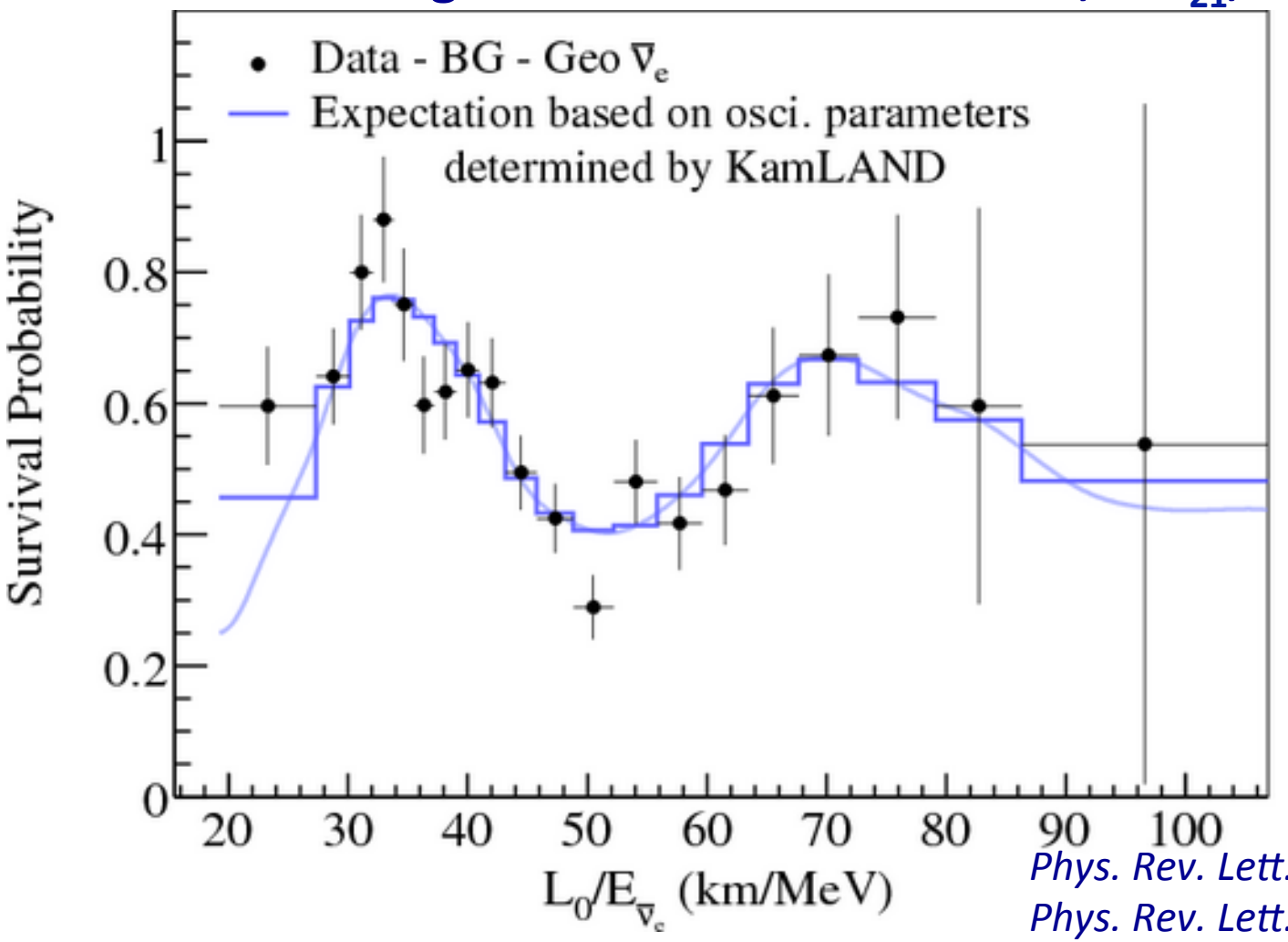


Savannah River
Science 124, 103 (1956)

The Bright Side

Reactors have been a powerful tool in neutrino physics:

2000s: Distinct signal of neutrino oscillation, Δm^2_{21}, θ_{12}



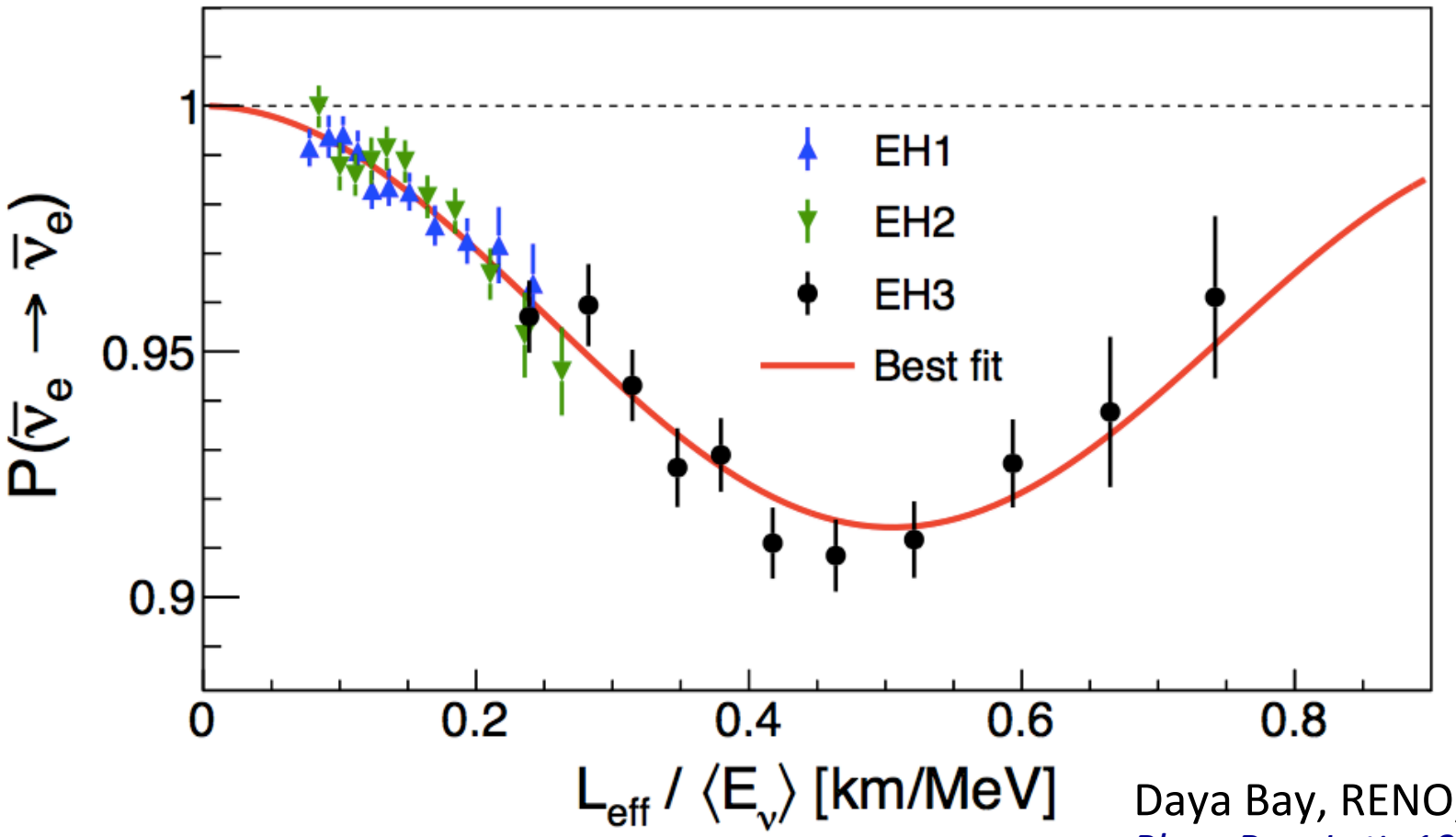
KamLAND

Phys. Rev. Lett. 90, 021802 (2003)
Phys. Rev. Lett. 94, 081801 (2005)
Phys. Rev. Lett. 100, 221803 (2008)

The Bright Side

Reactors have been a powerful tool in neutrino physics:

2012: Precision oscillation at ~0.5 km/MeV, Δm^2_{31}, θ_{13}

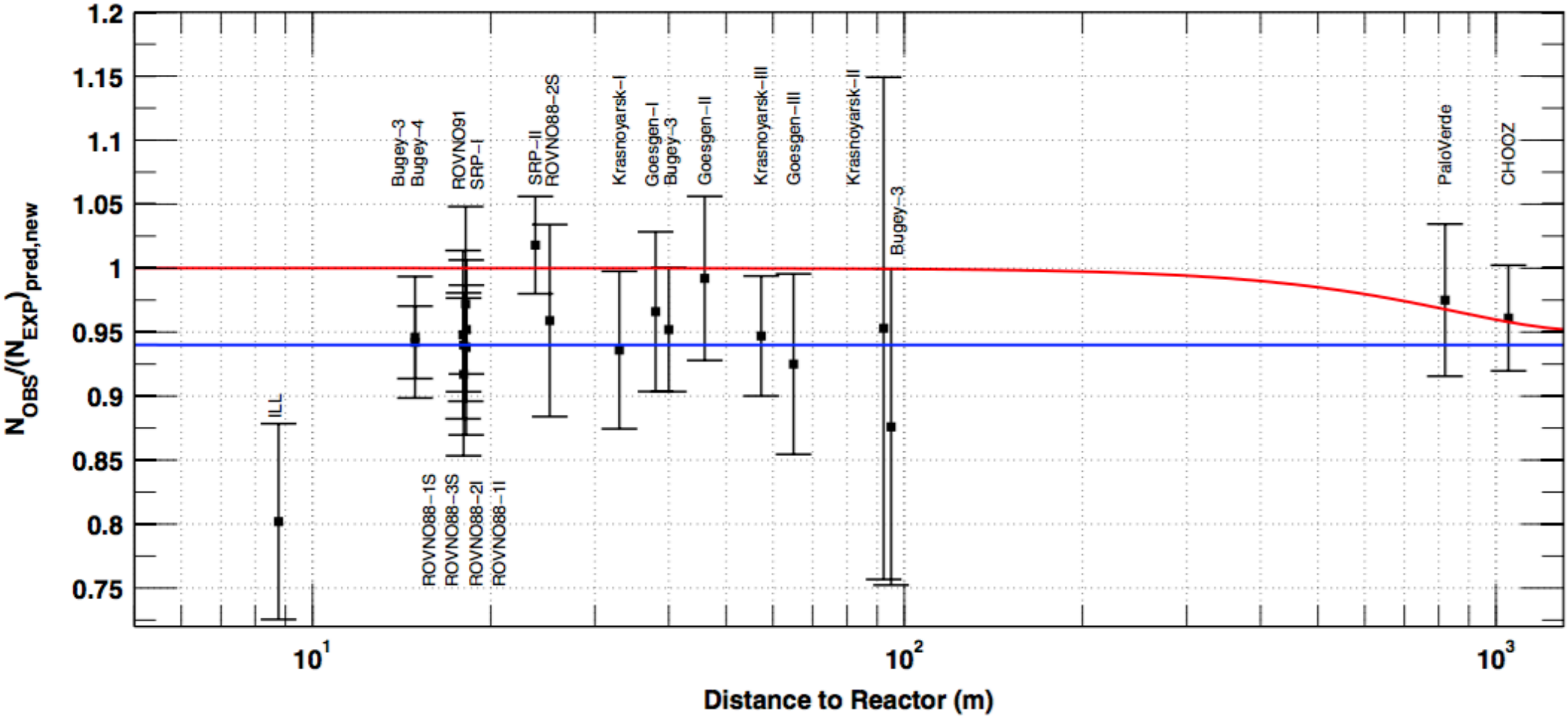


Daya Bay, RENO, DBC
Phys. Rev. Lett. 108, 171803 (2012)
Phys. Rev. Lett. 112, 061801 (2014)
Phys. Rev. Lett. 115, 111802 (2015)

The Dark Side

Discrepancies between $\bar{\nu}_e$ flux measurements and models

2011: Improved models predict flux 6% higher than measurements.

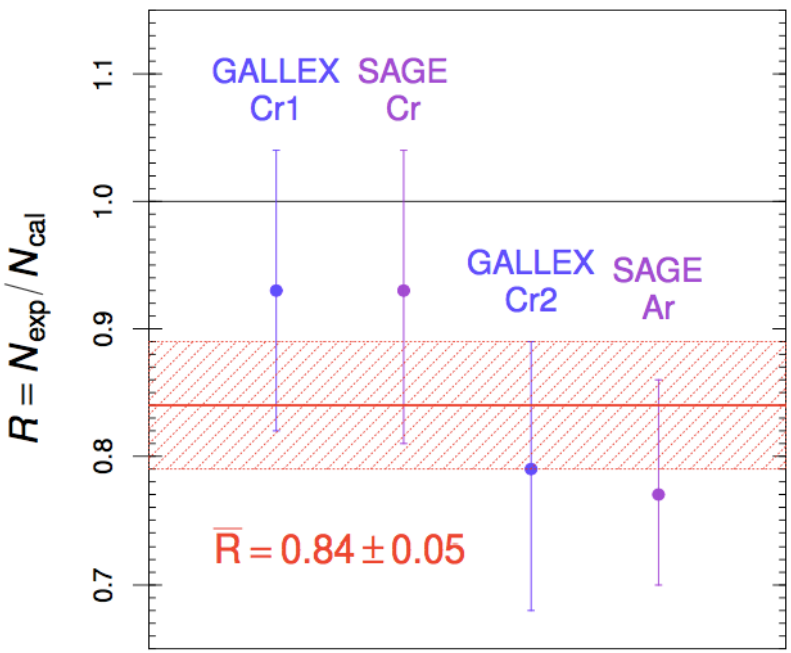


Phys. Rev. D83, 073006 (2011)

The Dark Side

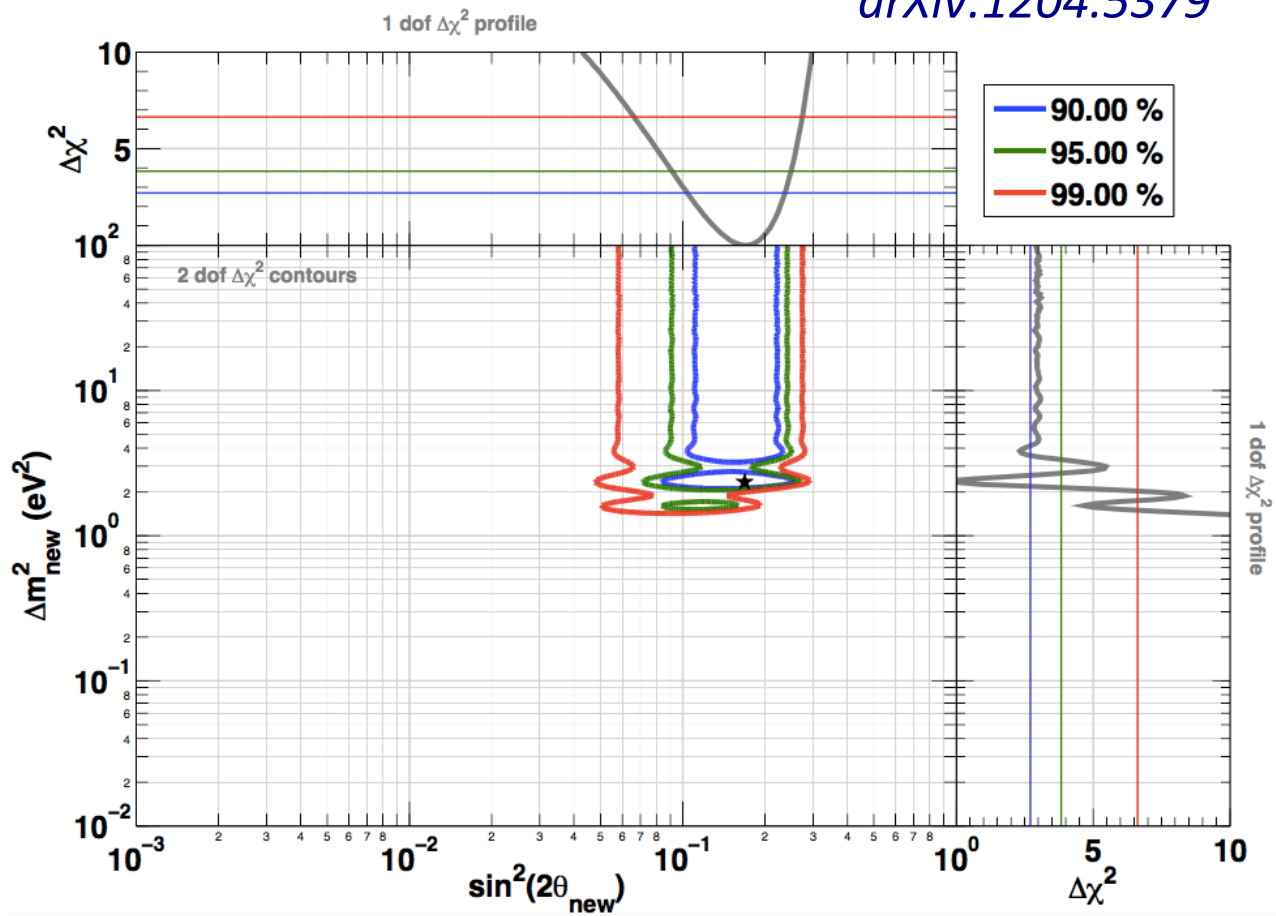
Evidence of oscillation to sterile neutrino states?

1990s: Similar hints in measurements of intense neutrino sources.



Phys. Rev. C83, 065504 (2011)

arXiv:1204.5379

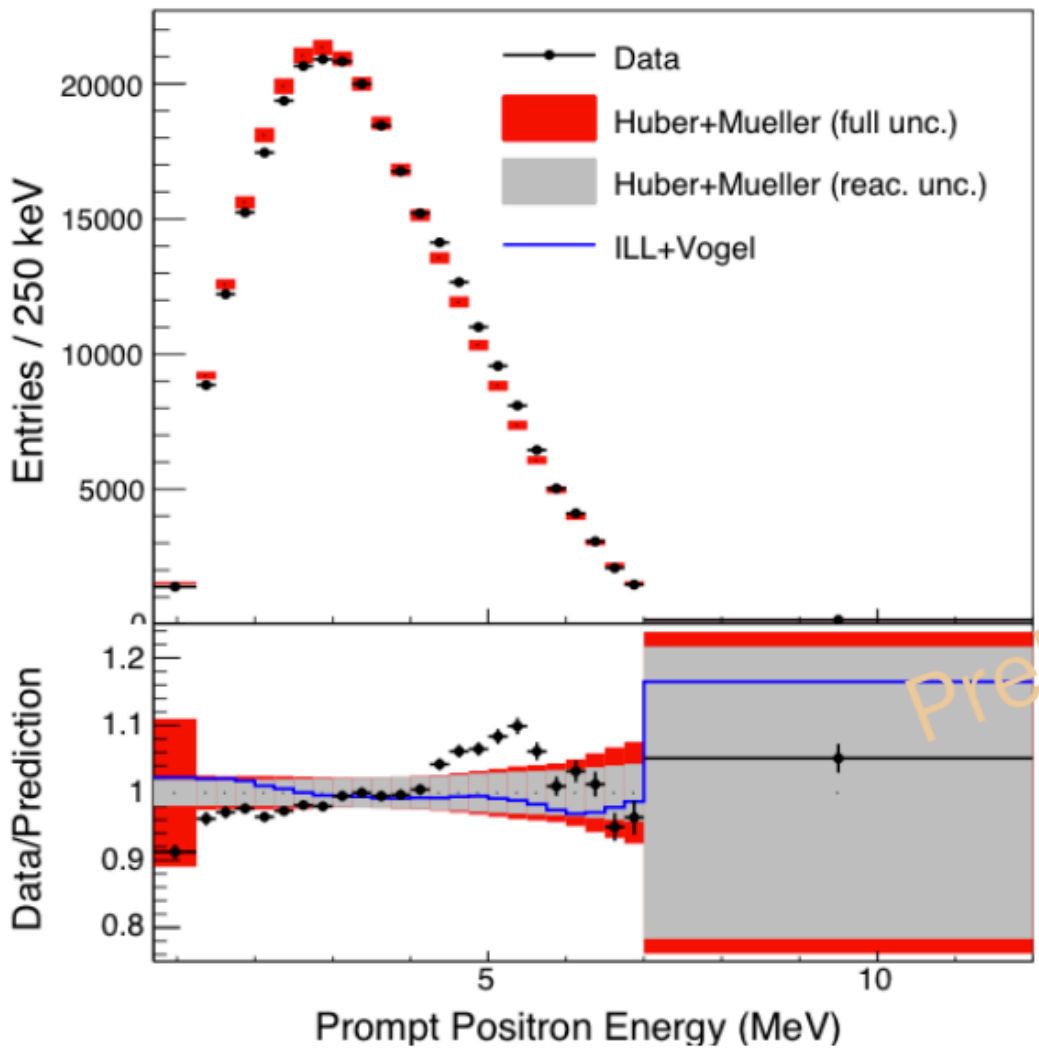


Reactors + source deviations suggest possible ~eV sterile neutrino.

The Dark Side

Discrepancies between $\bar{\nu}_e$ flux measurements and models

2014: Observed energy spectra disagree with existing models.



RENO: *Neutrino 2014*
Double Chooz: *Neutrino 2014*
Daya Bay: *ICHEP 2014*

Looking ahead

Part 1:

- Examine models of antineutrino emission from nuclear reactors

Part 2:

- Discuss discrepancies between models and measurements

Part 3:

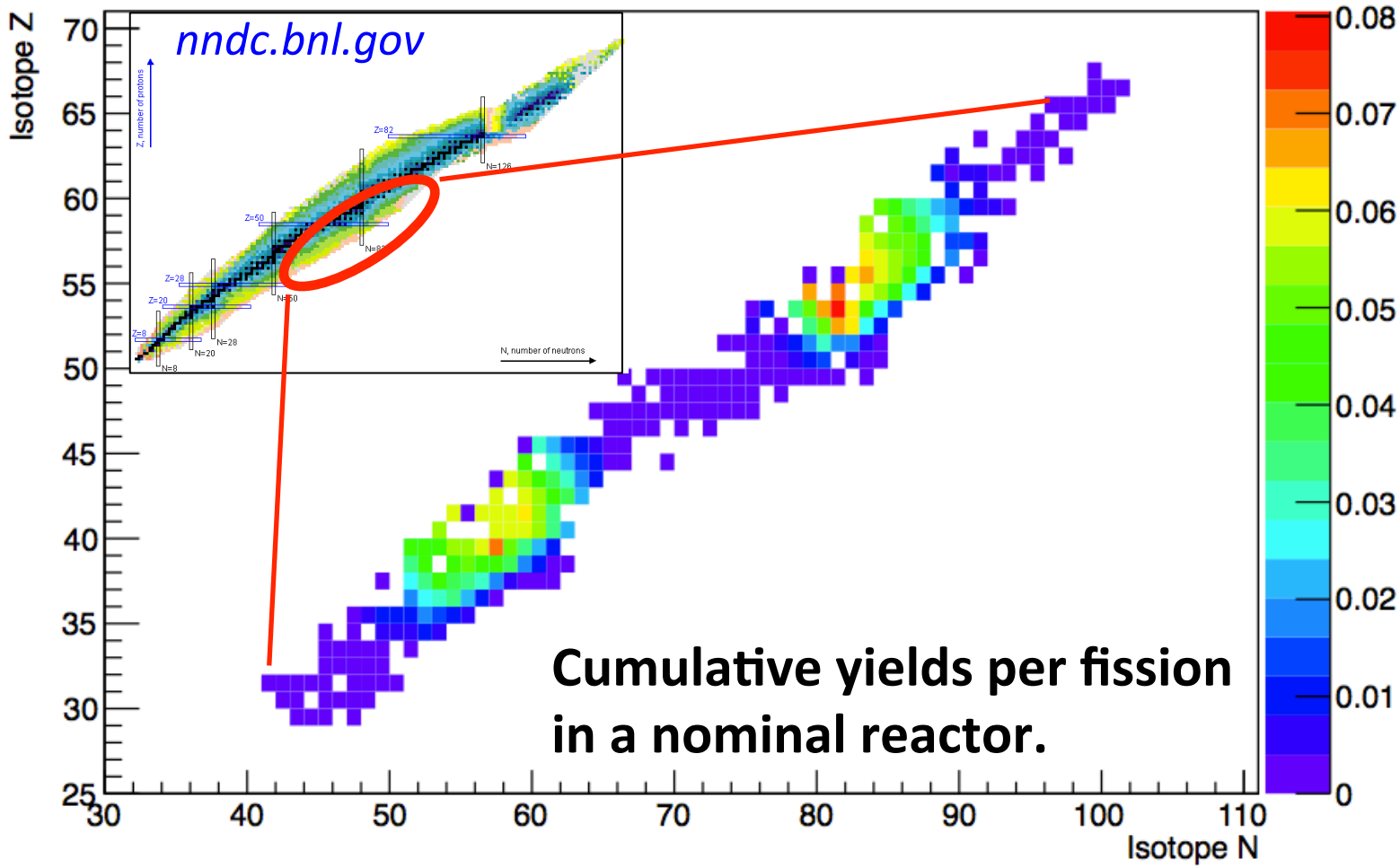
- Present an overview of the future experimental program

Part 1:
Models of Reactor Antineutrino Emission

Reactor Antineutrinos

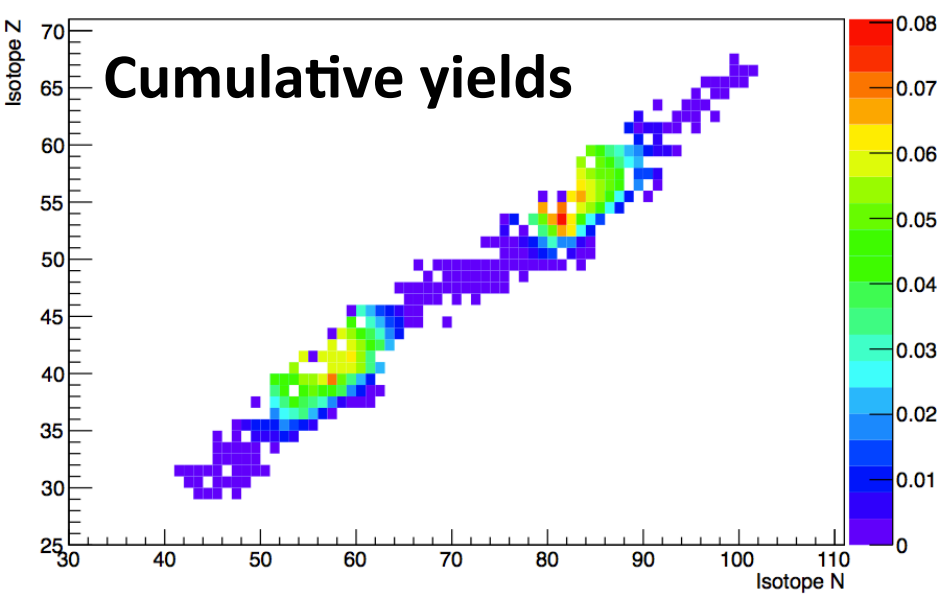
Antineutrino Production:

- Fission of heavy nuclei produce unstable neutron-rich daughters
- Two daughter fragments average ~6 beta decays until stable



Reactor Antineutrinos

Fission yields of daughter isotopes:



Daughter decay rate

$$R_i \simeq \sum_p R_p^f Y_{pi}^c$$

Parent fission rate

Cumulative yield

Instantaneous Yield:

Probability of daughter isotope *i* direct production from fission of parent isotope *p*.

Cumulative Yield Y_{pi}^{c}:

Probability of daughter isotope *i* indirect production, either from initial fission, or via decay.

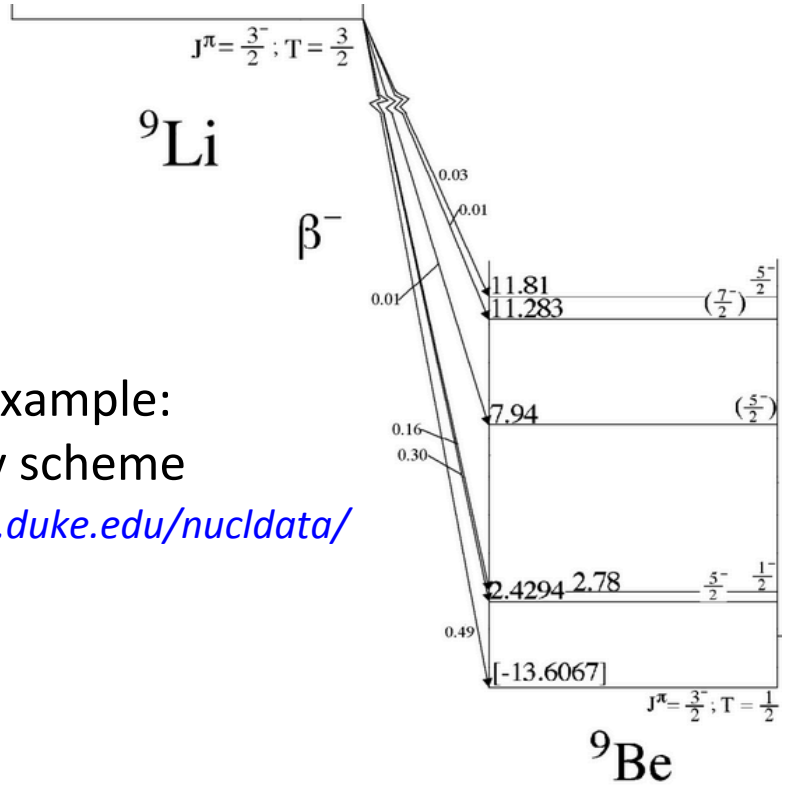
At Equilibrium:

Decay rate equals production rate.

ENDF/B.VII.1 database provides cumulative yields for >1300 fission daughter isotopes.

Beta Decay

Calculation of beta decay energy spectrum:



Simple Example:
^{9}Li decay scheme
www.tunl.duke.edu/nucldata/

Decay Branches:

Isotope decays to one of multiple states, probability f_{ij}

Branch Spectra:

Spectra calculated including:
Coulomb, radiative, finite size, weak magnetism corrections.

ENSDF:
Evaluated Nuclear Structure Data File

A. Hayes:
Provided tabulated ENSDF decay data for fission daughters

Total Reactor Spectrum:

Branching fraction

$$S(E_{\overline{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\overline{\nu}})$$

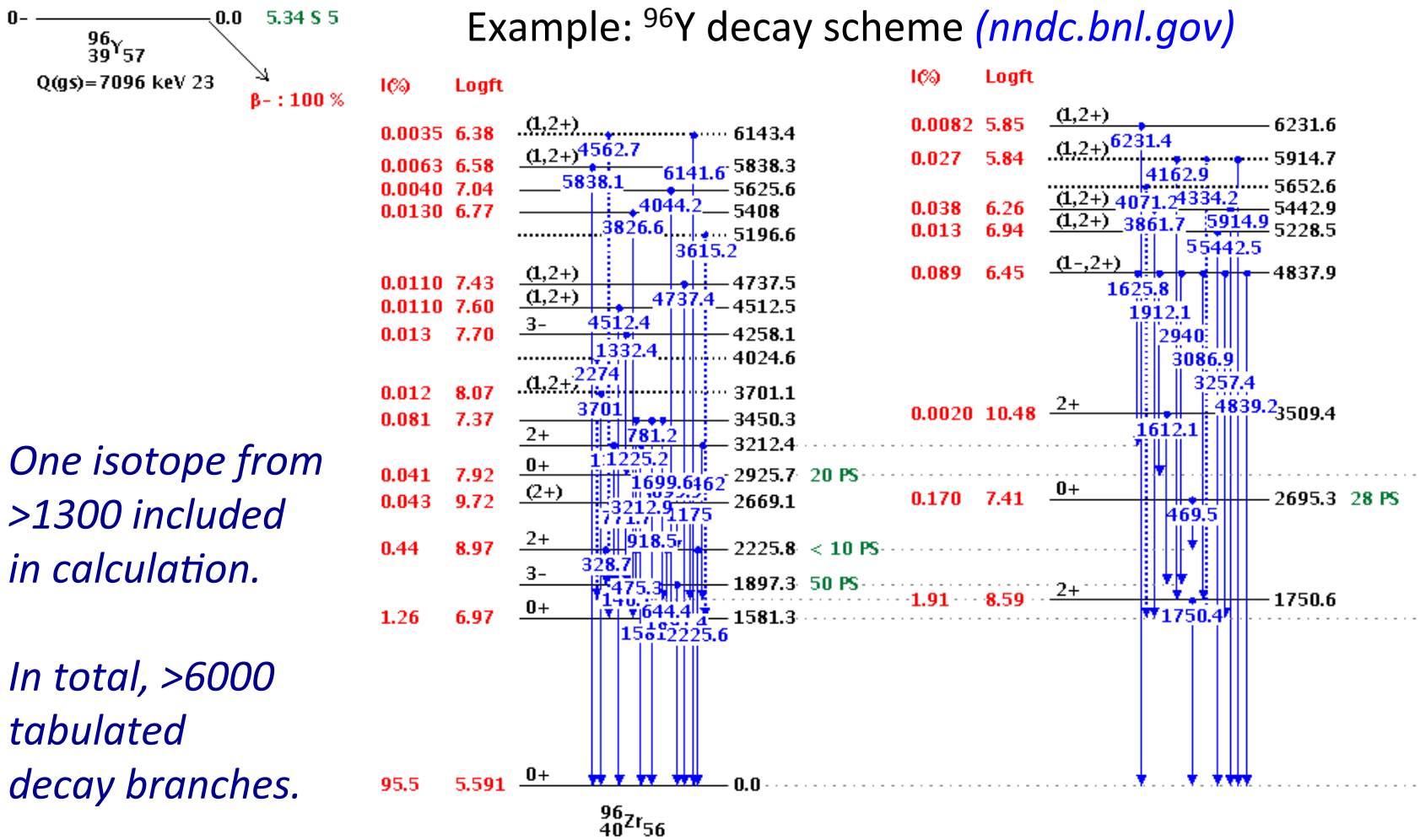
Daughter decay rate

Branch spectrum

Nuclear Structure

Complex decays of neutron rich fission daughters.

Example: ^{96}Y decay scheme *(nndc.bnl.gov)*



One isotope from >1300 included in calculation.

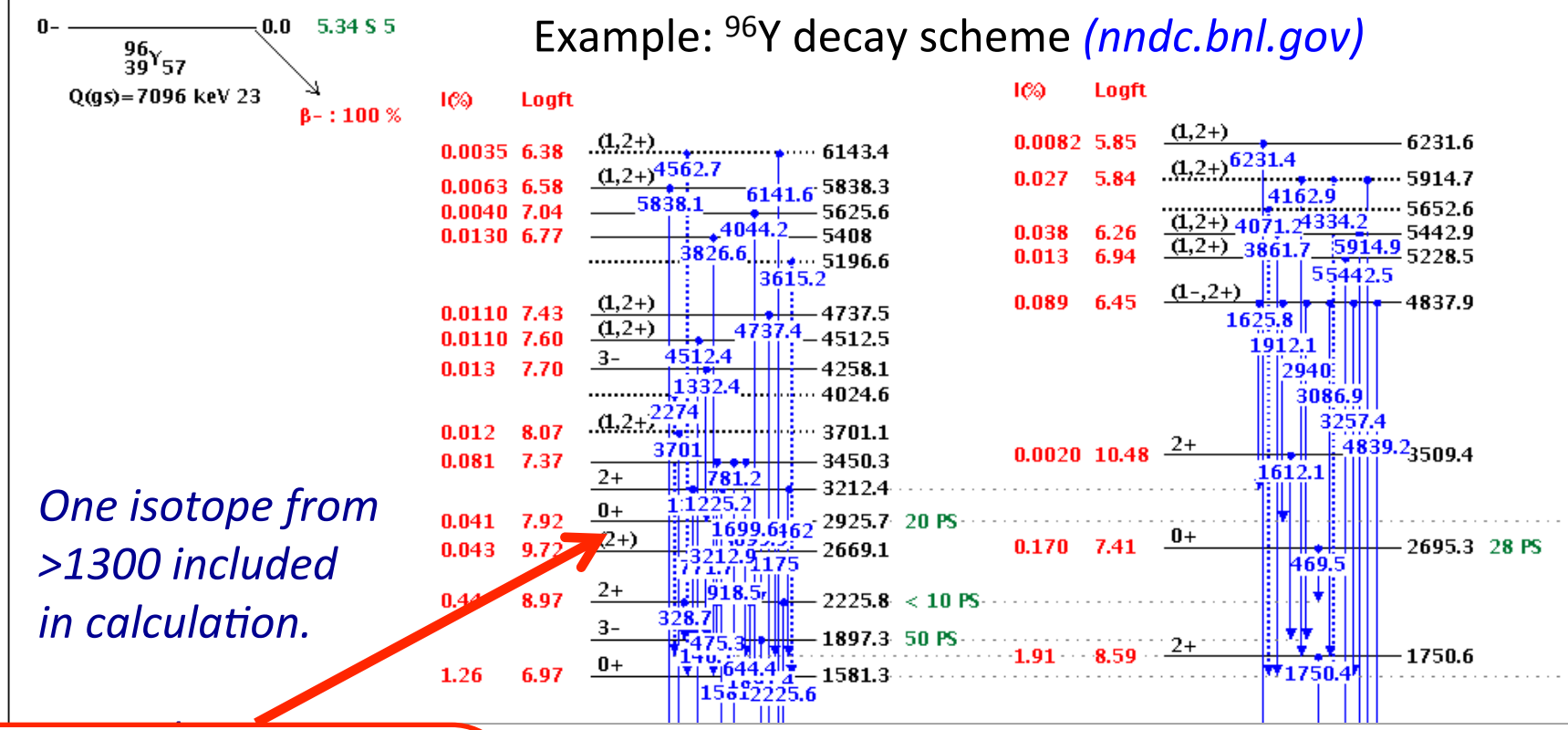
In total, >6000 tabulated decay branches.

Fission yield and decay branch uncertainties can be considerable.

Nuclear Structure

Complex decays of neutron rich fission daughters.

Example: ^{96}Y decay scheme *(nndc.bnl.gov)*



One isotope from >1300 included in calculation.

Here Be Dragons…

Significant uncertainty when directly calculating energy spectrum.

Missing Details:

Are tabulated fission and decay data comprehensive?

- Fission: What about possible very short-lived unstable daughters?
- Decay: 6% of yield has no corresponding ENDF decay information

eg. Phys. Rev. C24, 1543 (1981)

Biased Data:

Are there systematic biases in the yield or beta decay data?

- Uncertainty from assumption of reactor equilibrium, parent fission rates.
- Pandemonium Effect: Tabulated branches biased toward high-endpoints.

eg. Phys. Rev. Lett. 109, 202504 (2012)

Beta Decay Shape Corrections:

How do forbidden decay corrections impact spectrum?

- Mismatch of decay initial-final spin and parity can distort spectrum

eg. Phys. Rev. Lett. 112, 202501 (2014)

β^- Conversion

Alternative: Use cumulative β^- spectrum to predict $\bar{\nu}_e$ spectrum

Method:

Expose fission parents to thermal neutrons

Measure total outgoing β- energy spectra

Predict corresponding $\bar{\nu}_e$ spectra

Phys. Lett. B160, 325 (1985), Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989), Phys. Rev. Lett. 112, 122501 (2014)
Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)

Results:

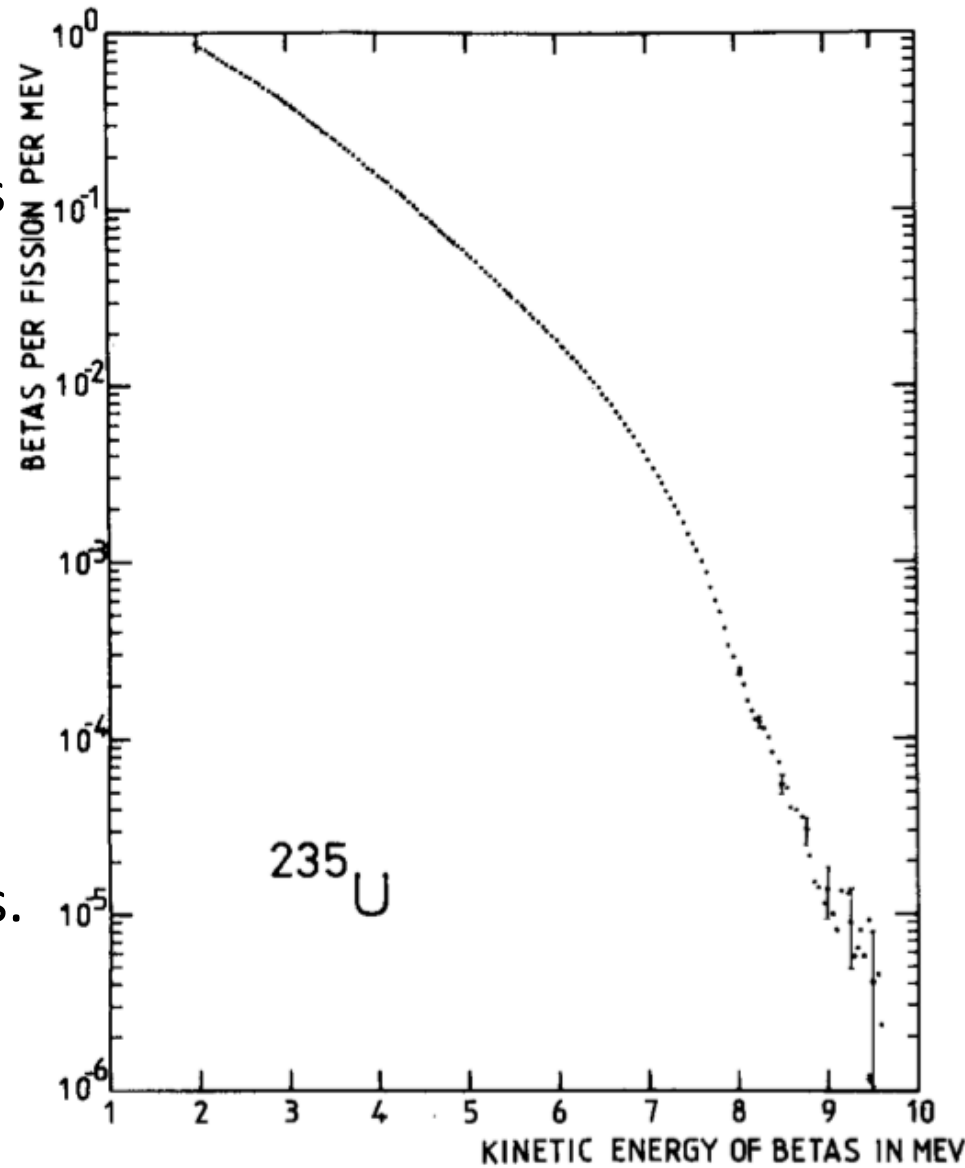
More precise than *summation* predictions

Standard approach for ~30 years

Predicts 6% higher flux than reactor msmts.

Reactor Anomaly, Sterile Neutrinos?

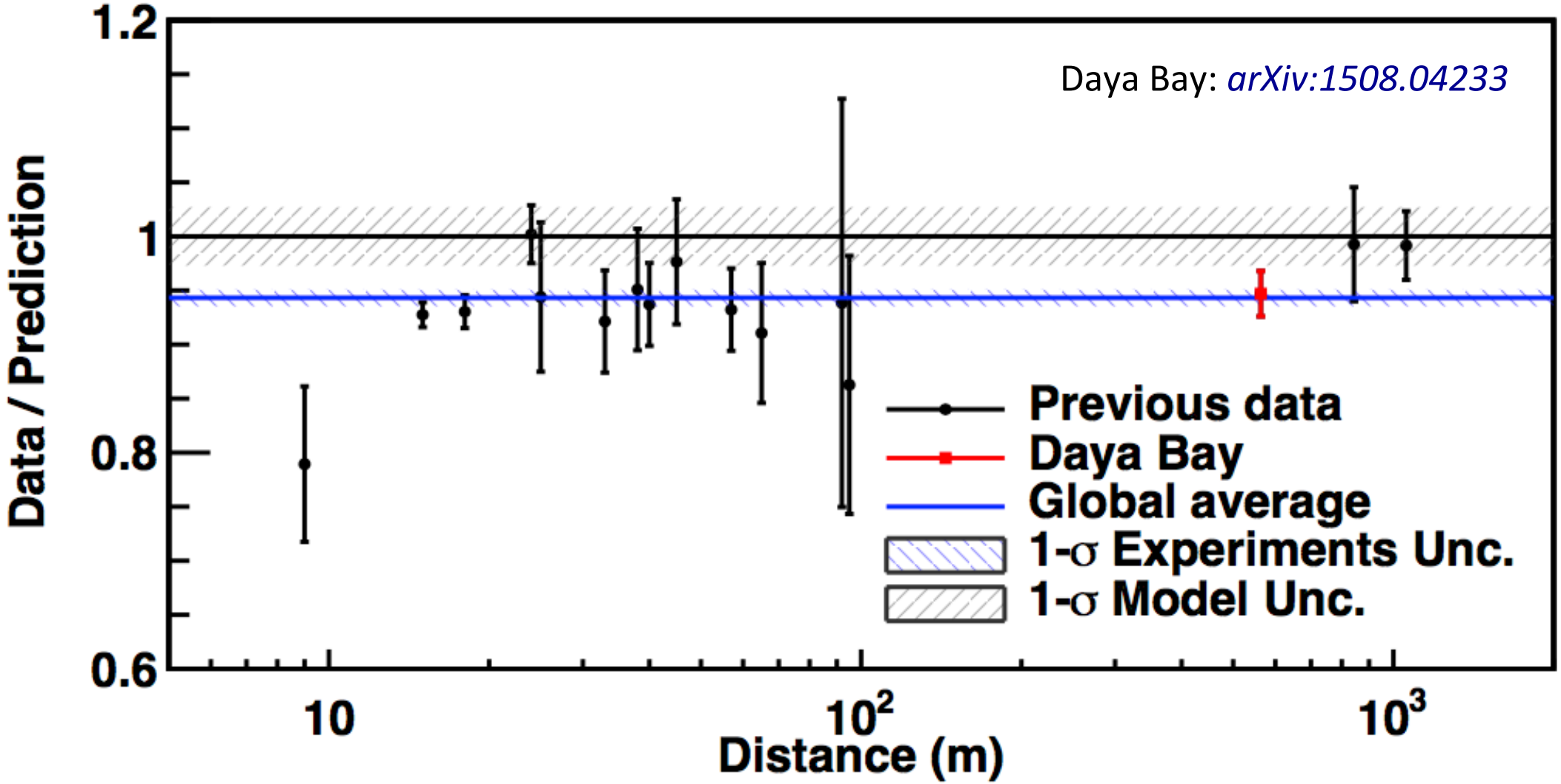
Phys. Rev. D83, 073006 (2011)



Part 2:
Comparisons with measurements

The Reactor Flux Anomaly

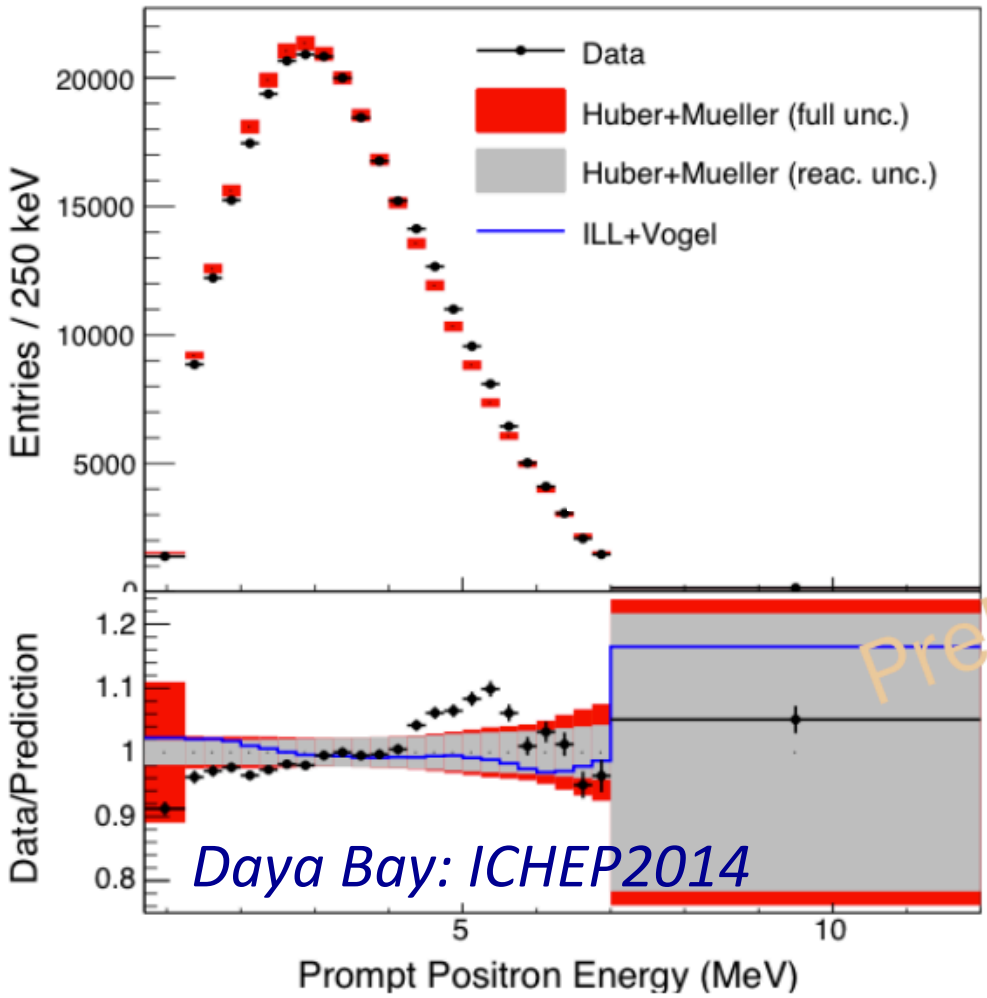
Latest measurements confirms 6% discrepancy with β^- conversion.

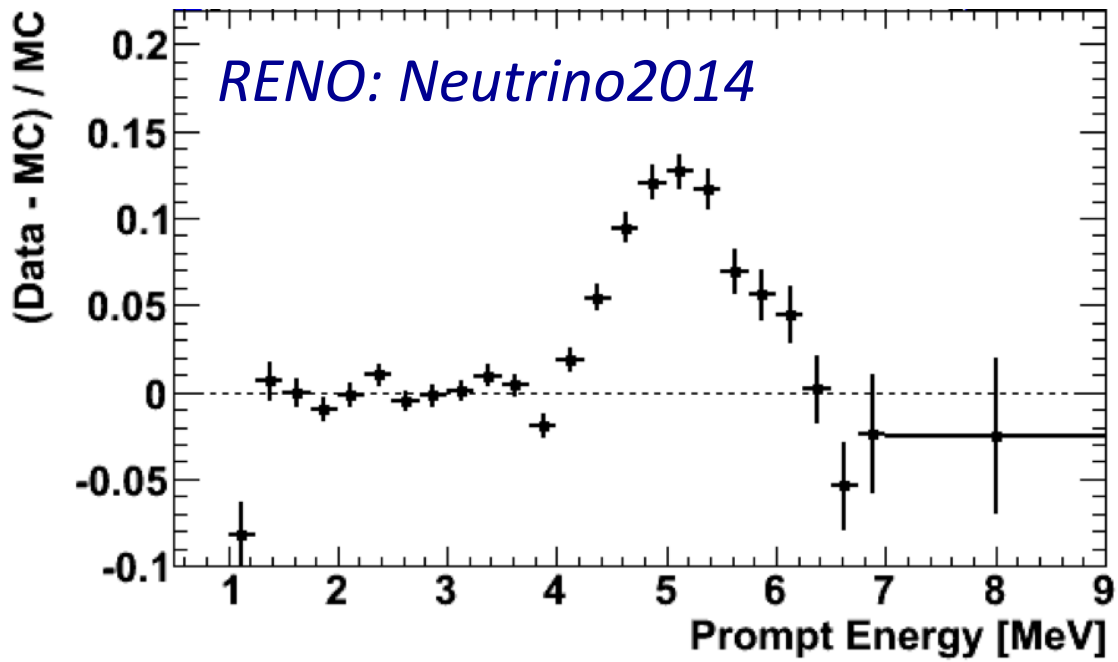


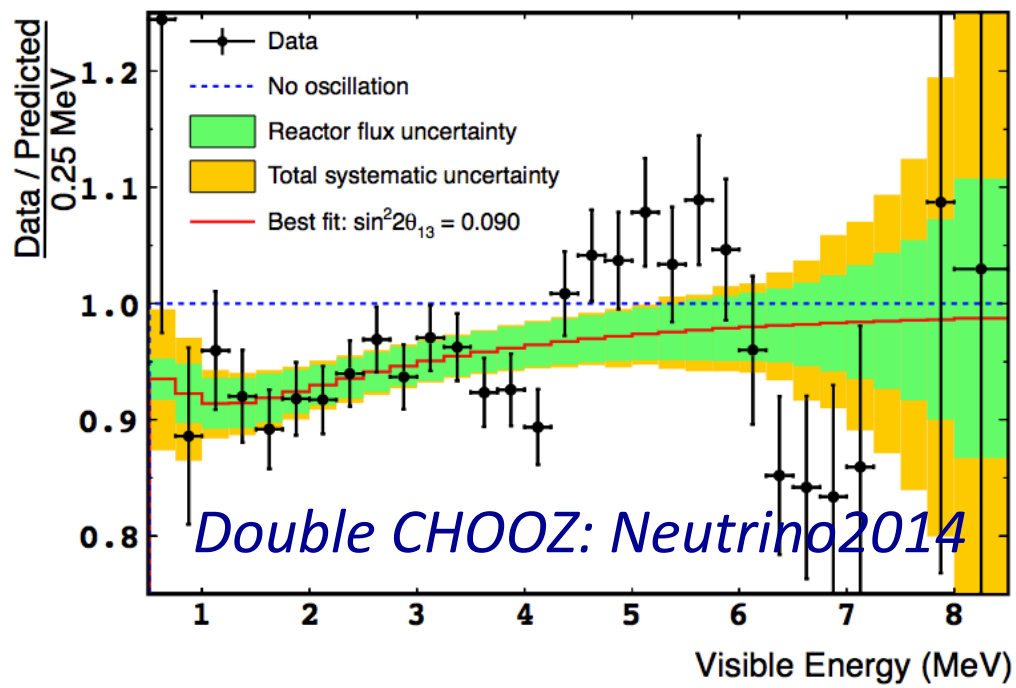
Summation models: total flux uncertainty too large (5%-10%) to confirm or refute.

$\bar{\nu}_e$ Spectrum Disagreement

Recent $\bar{\nu}_e$ measurements also disagree with β^- conversion models.

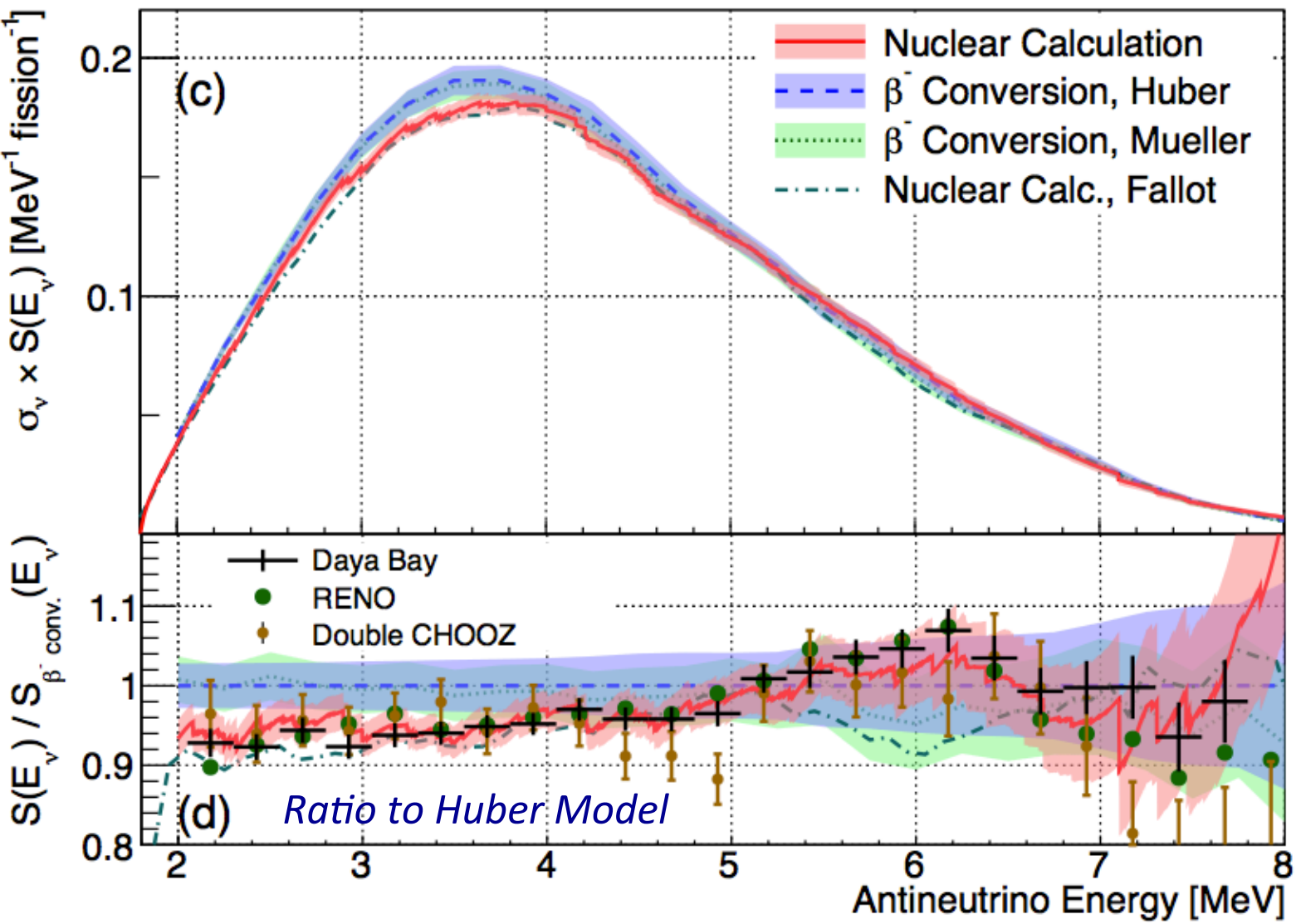






Reactor $\overline{\nu}_e$ Spectrum

Summation calculation unexpectedly agrees with recent msmts.



D.Dwyer, T.Langford
PRL 114, 012502 (2015)

Note:
Preliminary data compared using approx.
$E_\nu \approx E_{e+} + 0.8$ MeV

Data normalization adjusted to accurately compare shape.

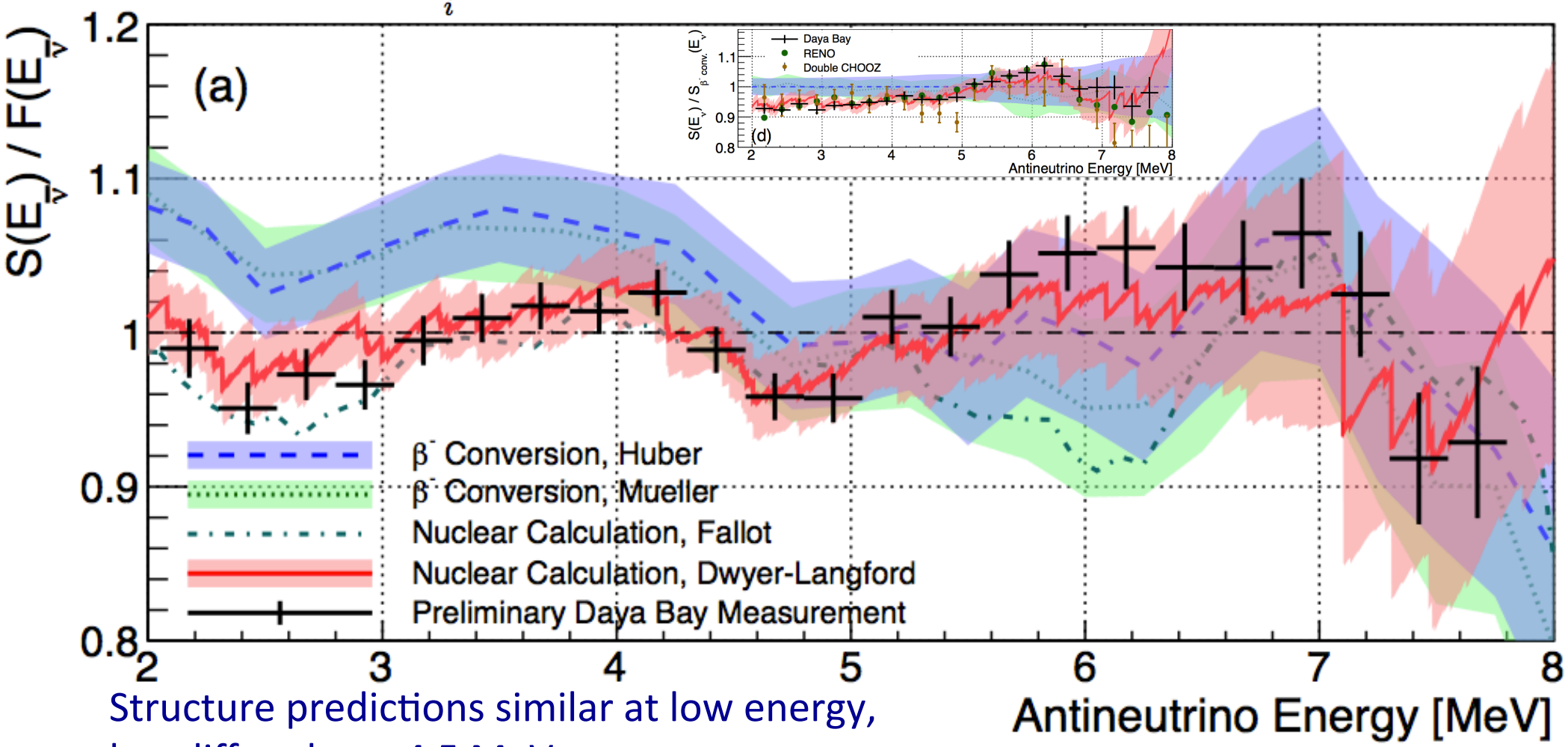
How do large calc. uncertainties not cause more tension with measurements?

Detailed $\bar{\nu}_e$ Spectrum Shape

Structure clearer when compared with smooth approximation *F(E)*

$$F(E_{\bar{\nu}}) = \exp\left(\sum_i \alpha_i E_{\bar{\nu}}^{i-1}\right)$$

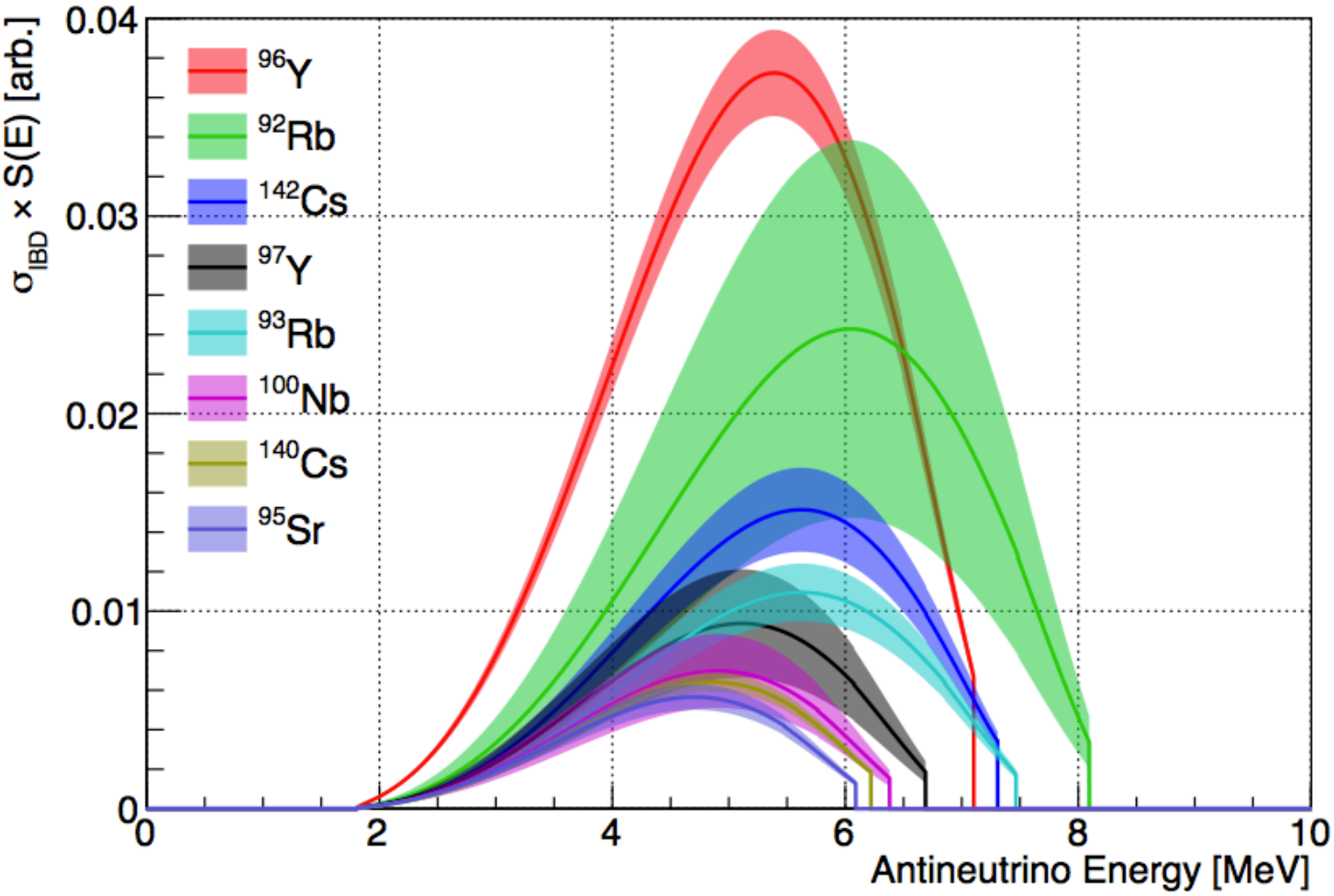
α = {0.4739, 0.3877, −0.3619, 0.04972, −0.002991}



Structure predictions similar at low energy, but differ above 4.5 MeV

Dominant Branches

Eight prominent branches cause 5-7 MeV excess in the calculation.



Energy Spectra:
Allowed shape
+ IBD cross-section

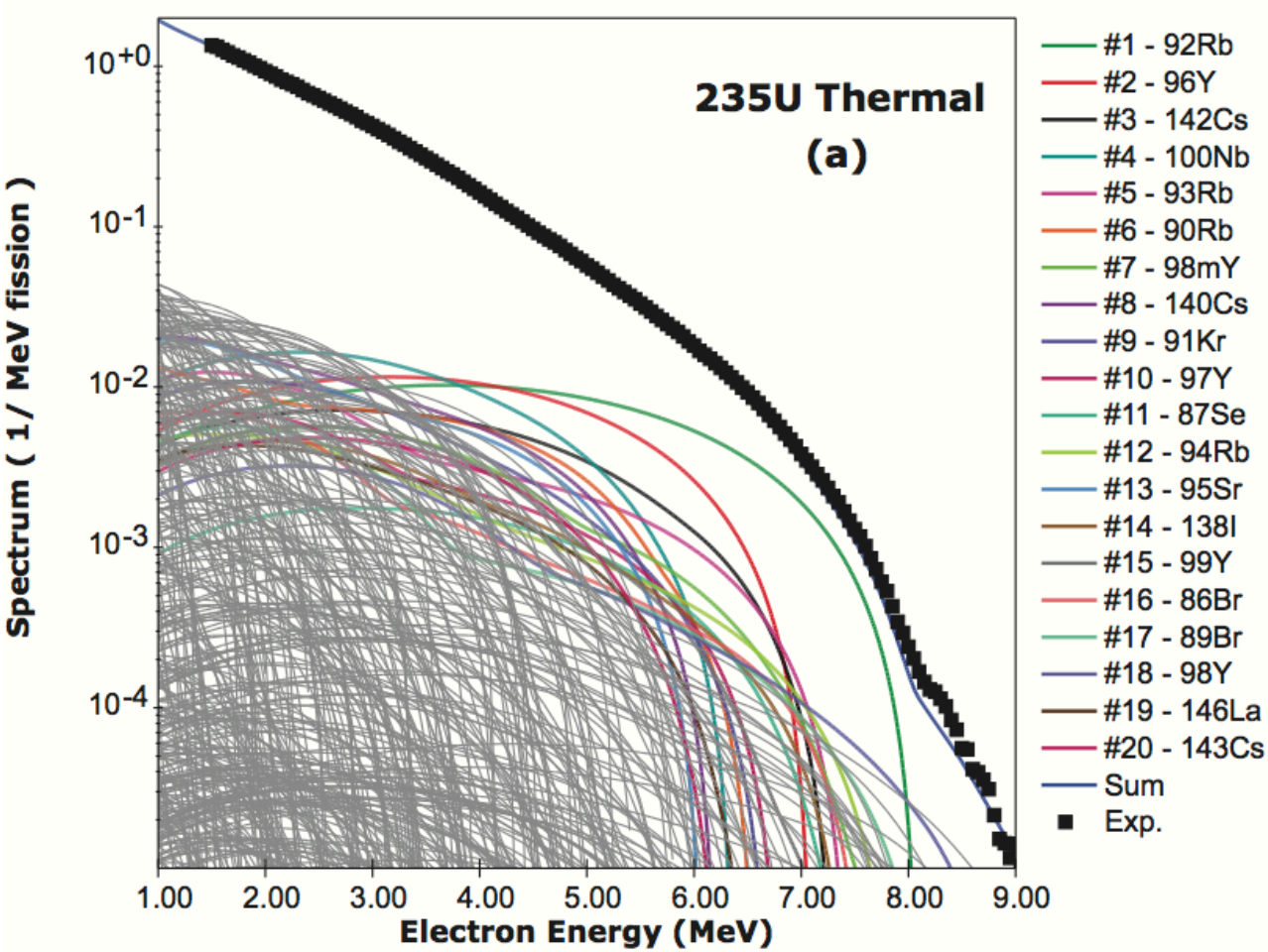
Uncertainties:
Fission Yield
Branch fraction
^{92}Rb most significant

If nuclear data accurate, calculated 5-7 MeV shoulder seems robust.

Are the fission yields and branching fractions accurate for these prominent branches?

Dominant Branches

Recent calculations also identify similar aspects of spectrum

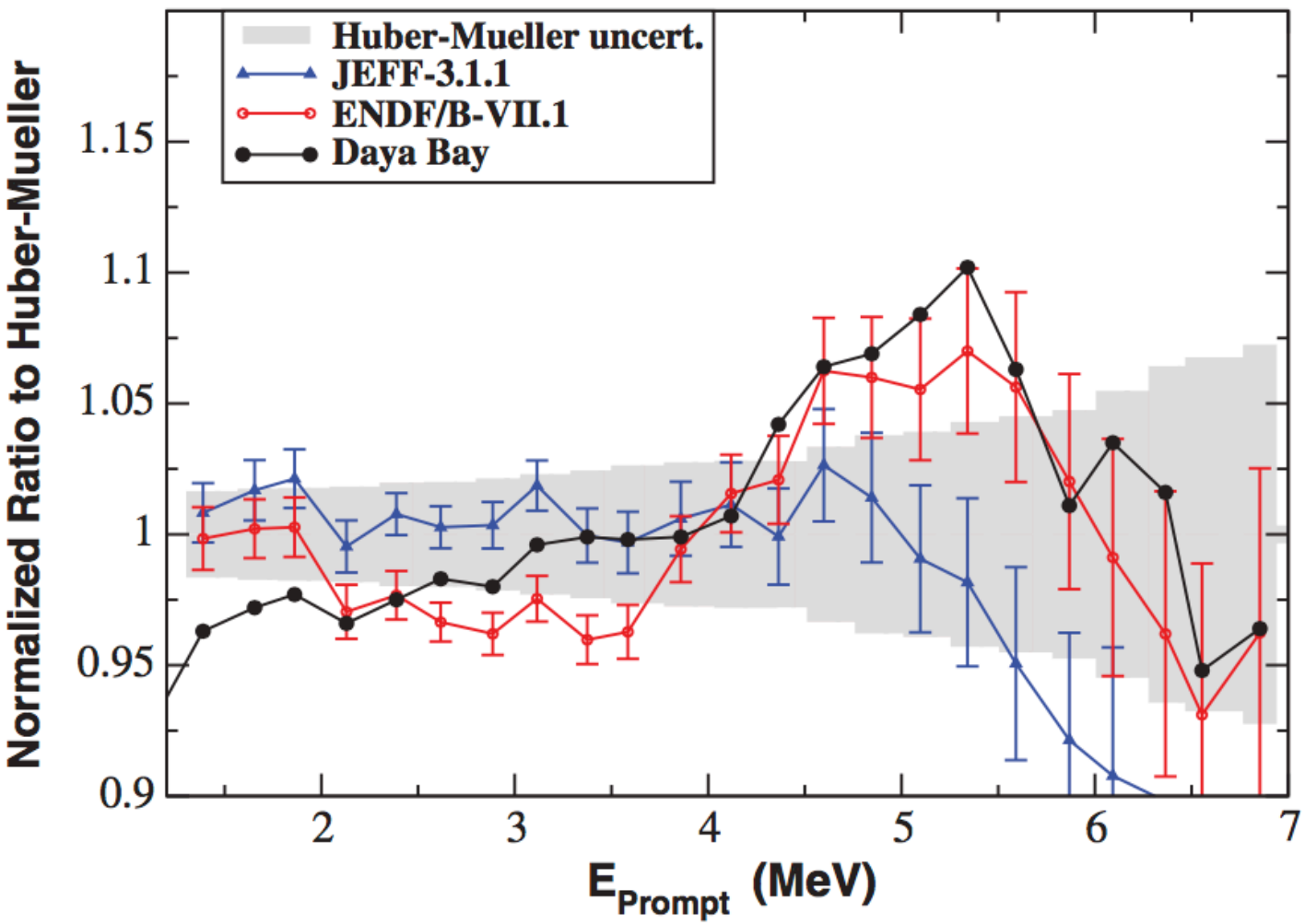


Light, odd-N, odd-Z fission fragments dominate emission

A.A.Sonzogni, T.D.Johnson, and E.A.McCutchan
Phys. Rev. C91, 011301(R) (2015)

Database Discrepancies

Summation spectra dependent on choice of nuclear database.



European (JEFF) database
- Agrees with β^- conversion
- Disagrees with $\bar{\nu}_e$ spectra

US (ENDF) database:
- Disagrees with β^- conversion
- Agrees with $\bar{\nu}_e$ spectra

Possible Origins:
- Differences in neutron spectra in reactors?
- ^{238}U fission?
- Error in original β^- spectra?

A. Hayes et al., Phys. Rev. D92, 033015 (2015)

Part 3:
Future Experimental Prospects

Future Experiments

Two experimental routes to addressing discrepancies.

Direct searches for sterile neutrinos.

Precision tests of reactor $\overline{\nu}_e$ emission.

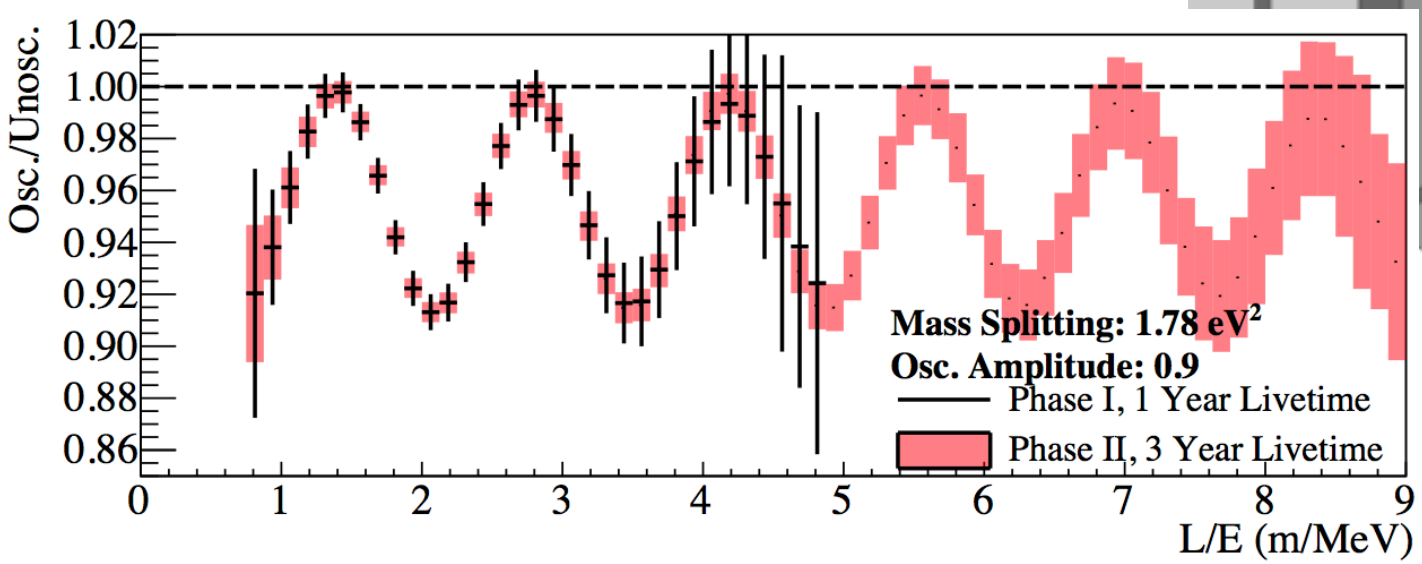
Direct Searches

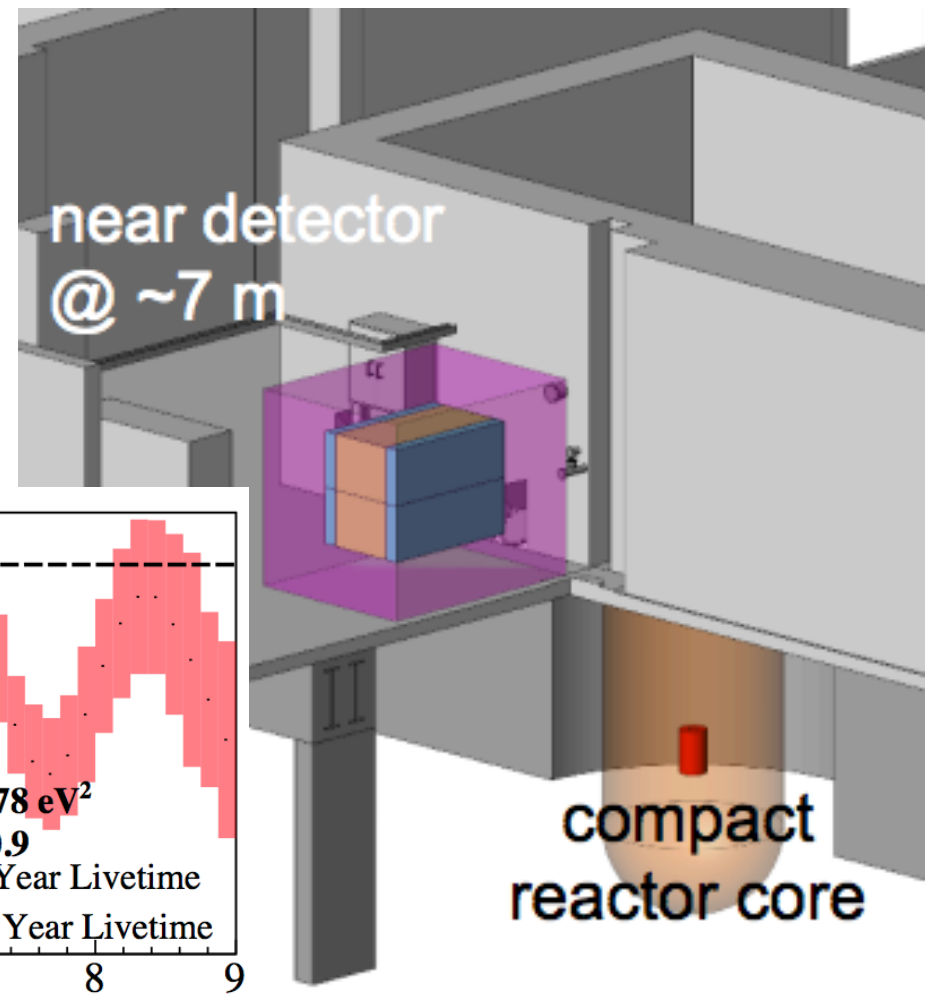
Smoking gun for sterile neutrinos: L/E dependence

Search for distance/energy dependence of oscillation across one detector.

~eV sterile neutrino implies oscillation length of ~1 meter.

Need a detector within a few meters of operating nuclear core.





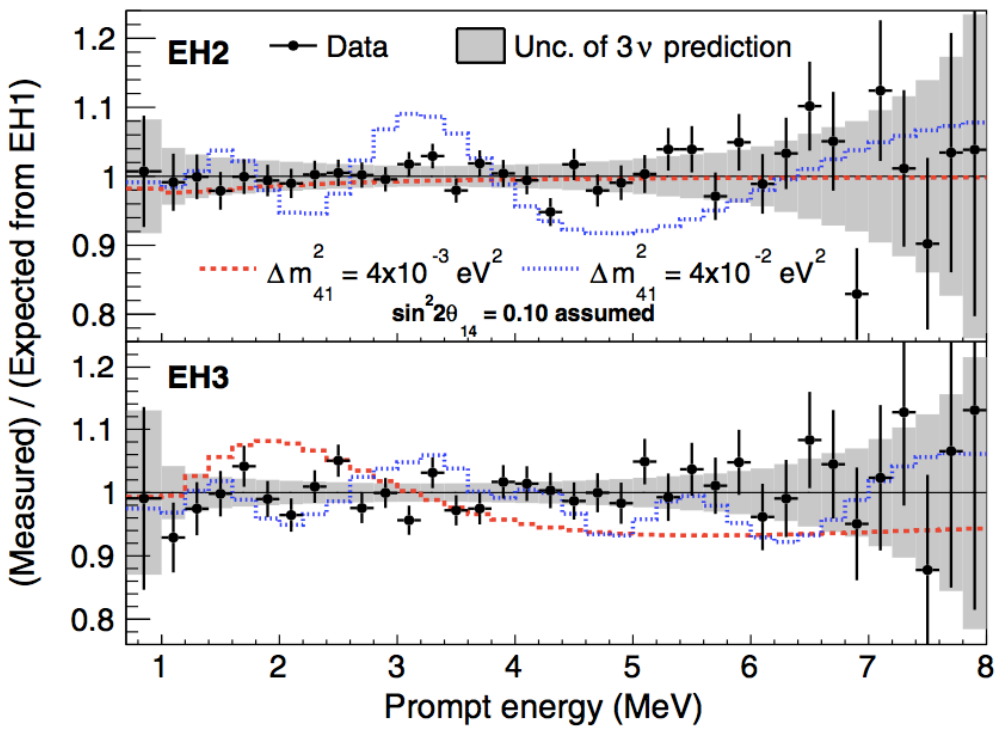
Existing Limits

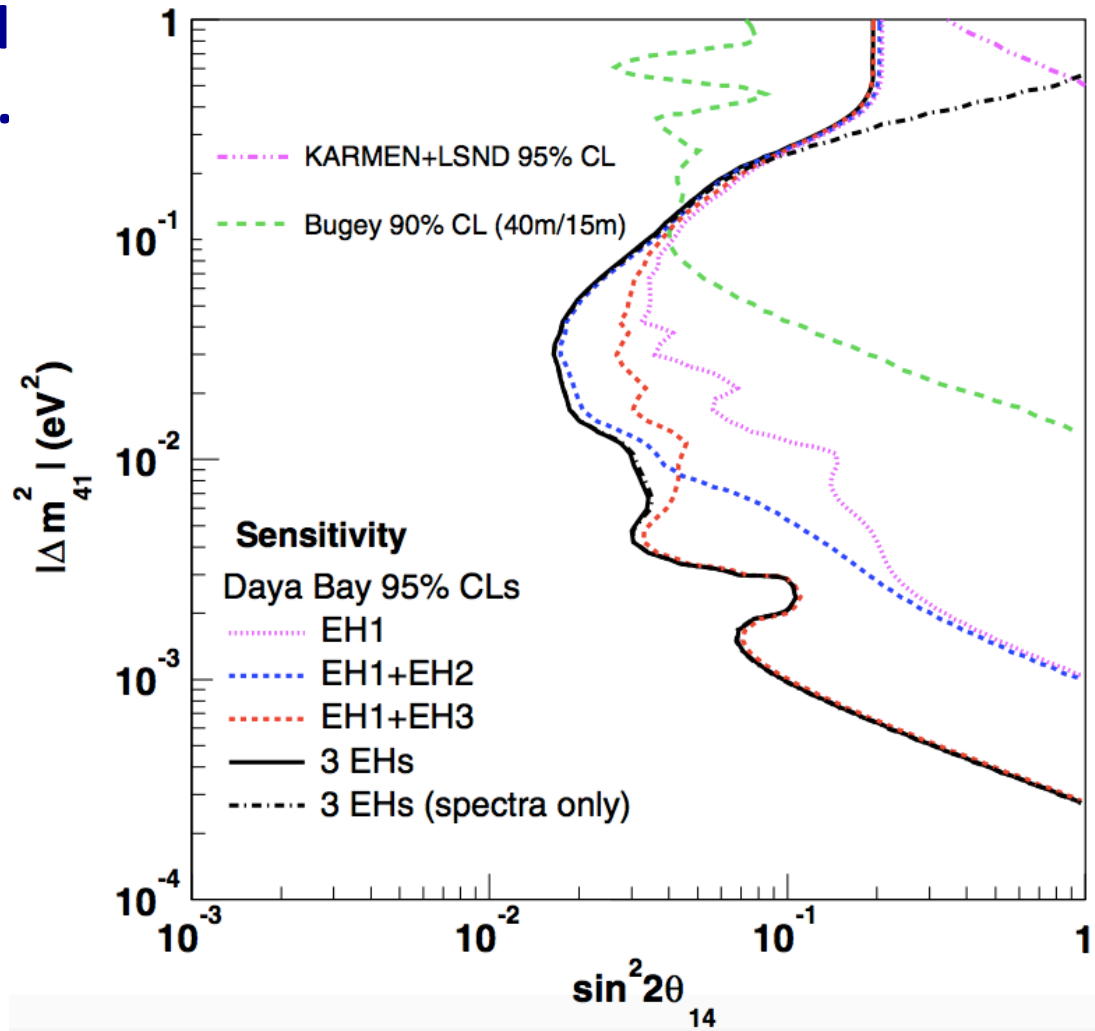
Compare rate and spectra measured with detectors at multiple distances.

Bugey: 15 m, 40 m

Daya Bay: 300 m - 1900 m

Nucl. Phys. B434, 503 (1995)
Phys. Rev. Lett. 113, 141802 (2014)





Need to be closer to reactor core…

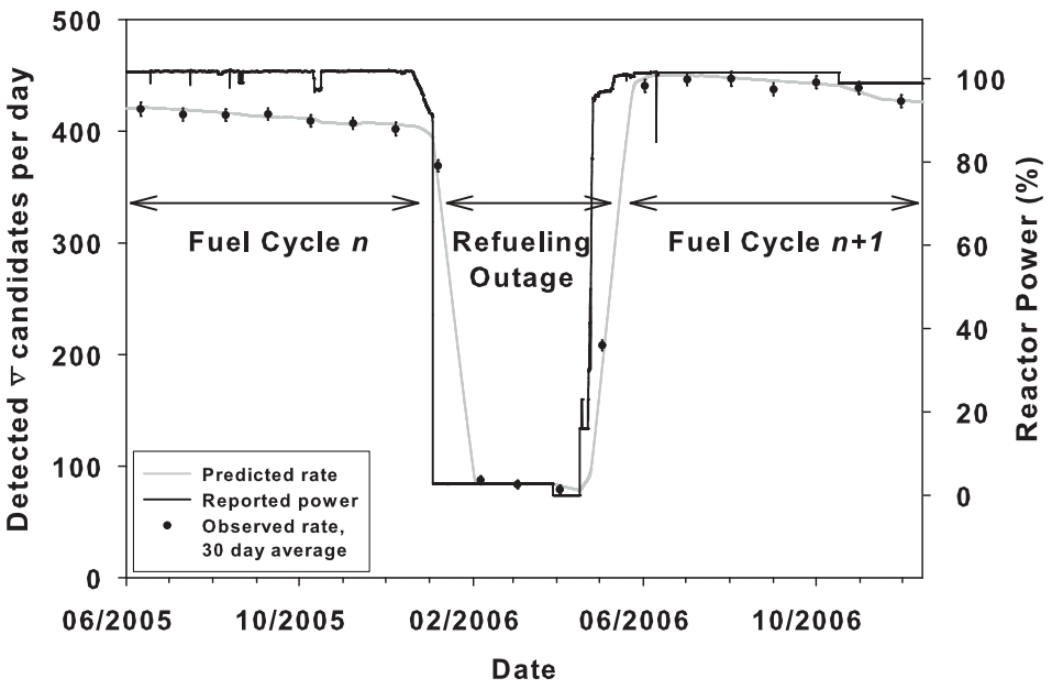
Not so easy…

SONGS1:

Demonstrated detection at ~25m from San Onofre reactor core.

Signal: ~400 interactions / day
Background: ~100 interactions / day

NIM A572, 985 (2007)

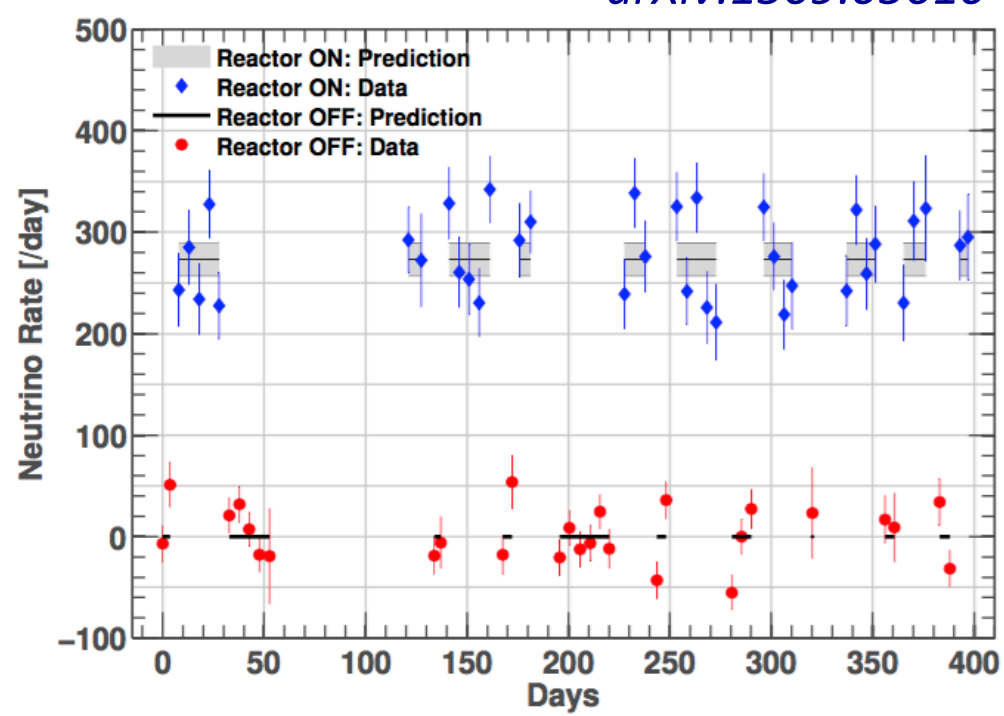


Nucifer:

Demonstrated detection at ~12m from OSIRIS reactor core.

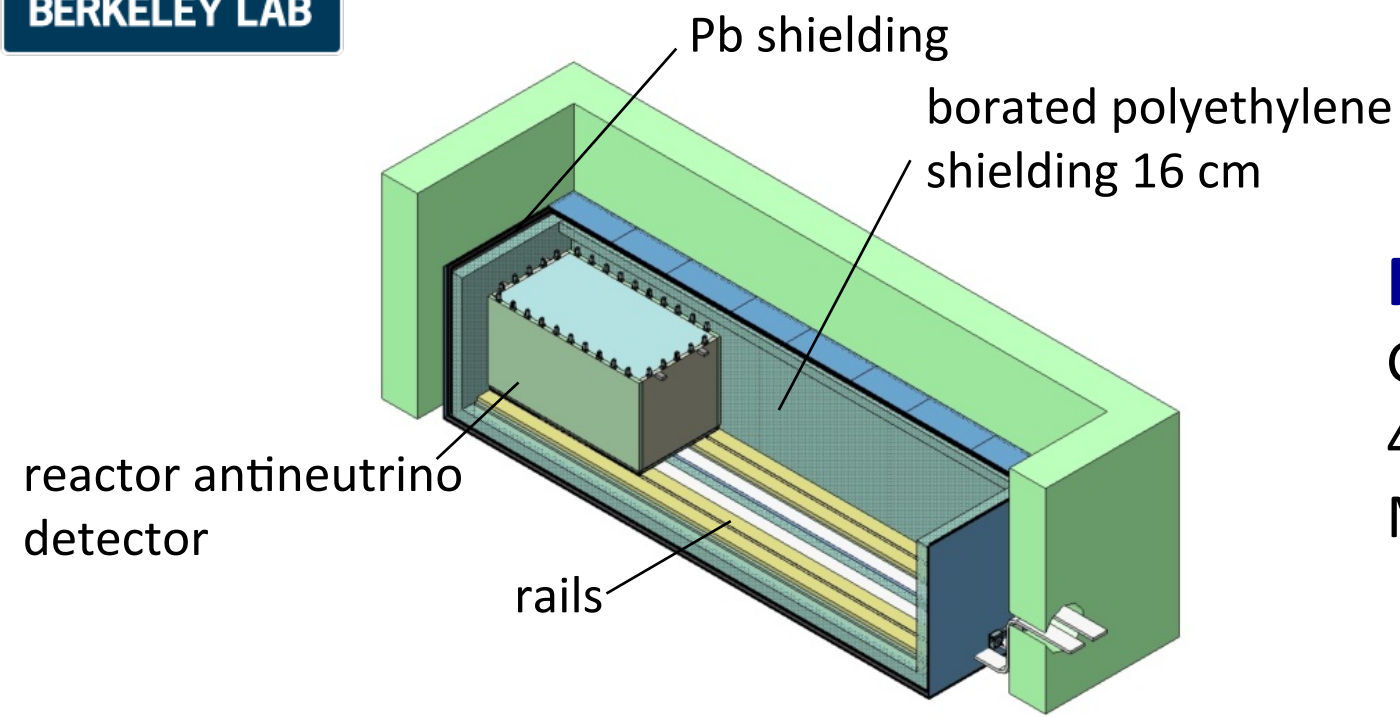
Signal: ~300 interactions / day
Background: ~1000 interactions / day

arXiv:1509.05610



Lesson: Difficult to measure faint neutrinos meters from nuclear core.

Neutrino-4



Prototype:

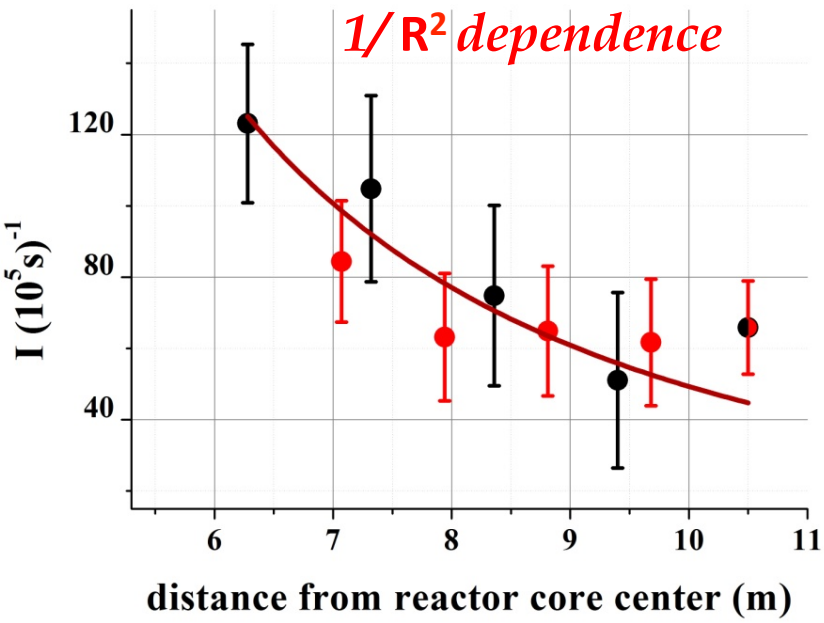
Gd-doped LS (BC-525)

400 l

Movable:

Mounted on rails

6 - 12 m



SM-3 Reactor

100 MW

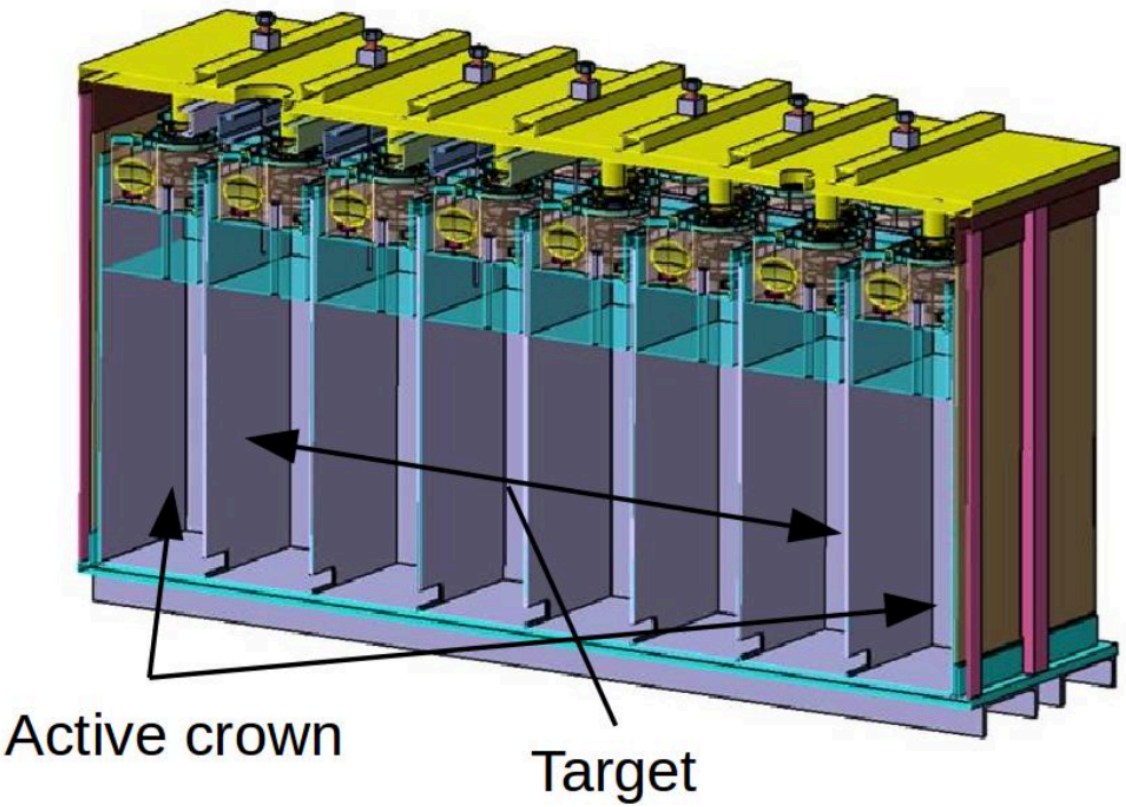
Compact (40 cm)

Dimitrovgrad, Russia

Signal: 130 / 10^5 s

A. Serebrov, AAP-2014

STEREO



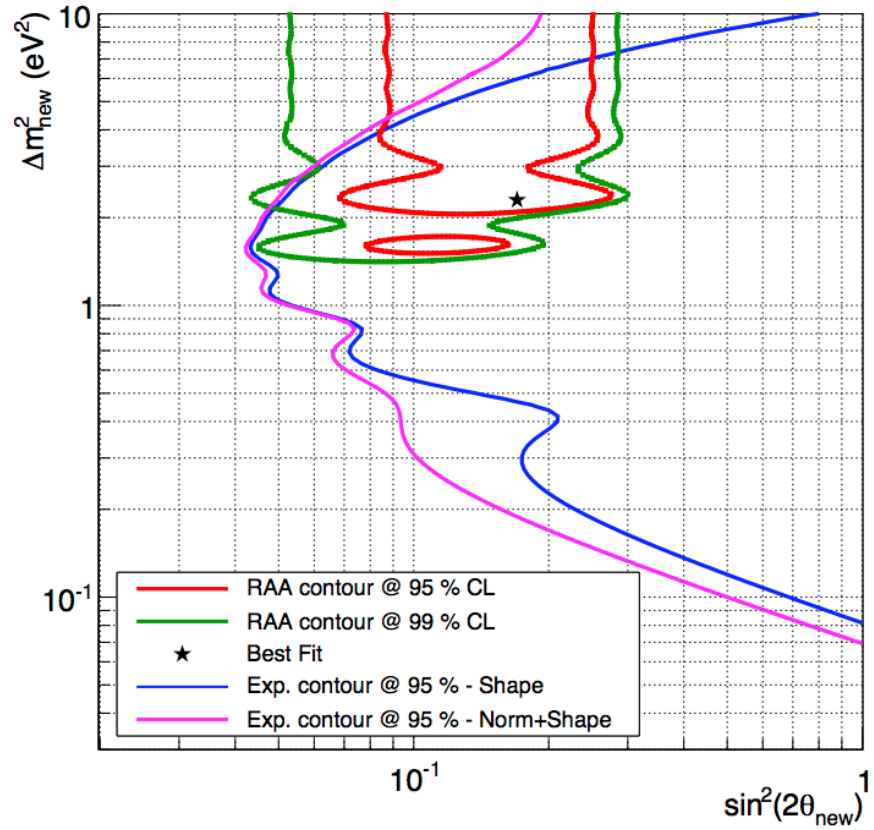
STEREO:

Building on experience from Nucifer

Segmented detector:

-> Direct search for sterile oscillation

ILL reactor in Grenoble



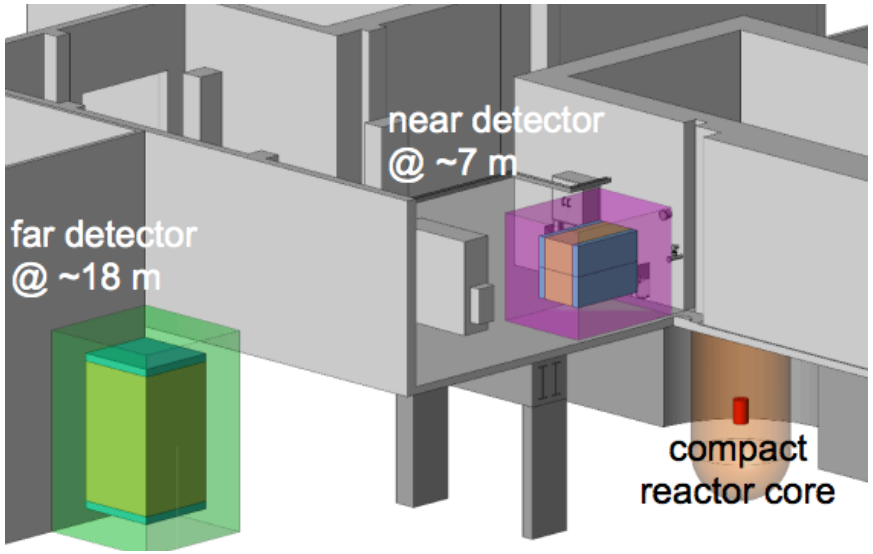
Design Targets:

Normalization: ~4%

Signal / Background: 1.5

Signal rate: ~410 / day

PROSPECT



PROSPECT:

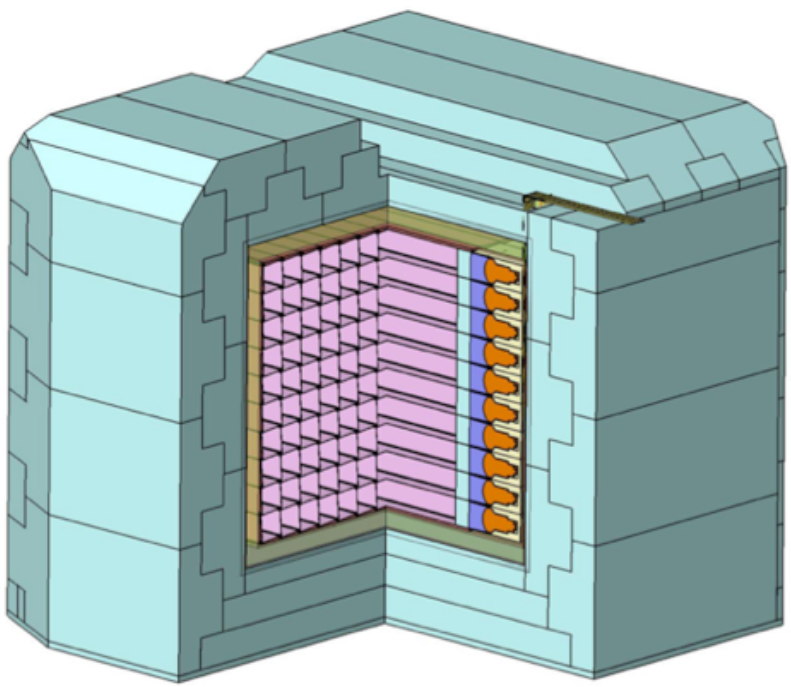
A Precision Oscillation and Spectrum Measurement

Design: (Phase 1)

2-ton highly-segmented liquid scintillator detector
Compact (~40cm), intense HFIR reactor at ORNL
~7 m from core, probes short-distance effects
~10^6 antineutrino interactions per year

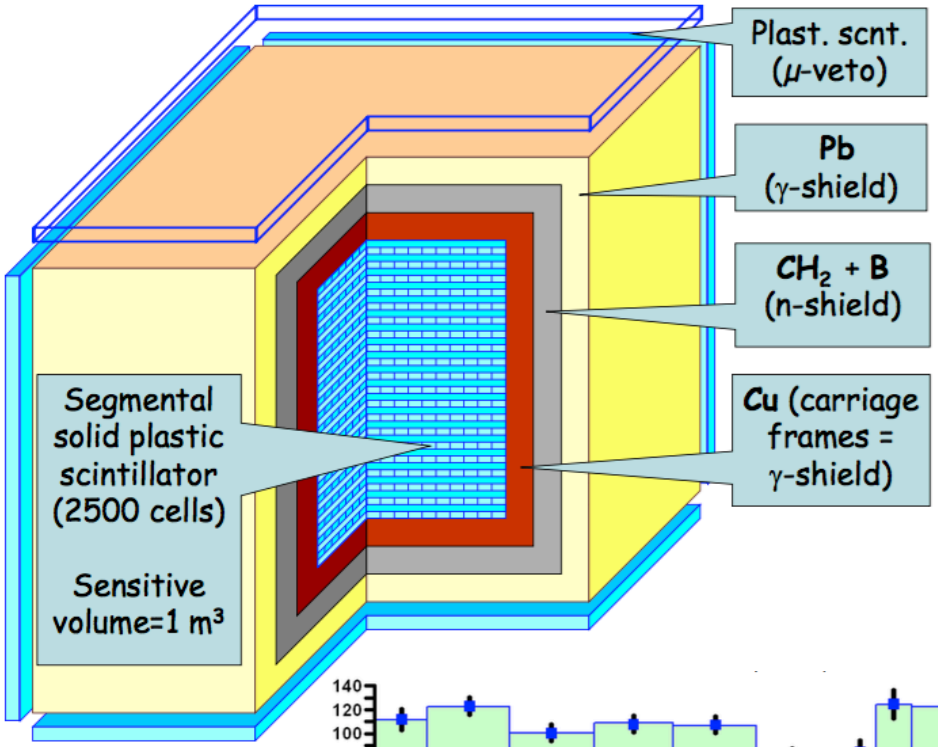
Prototypes:

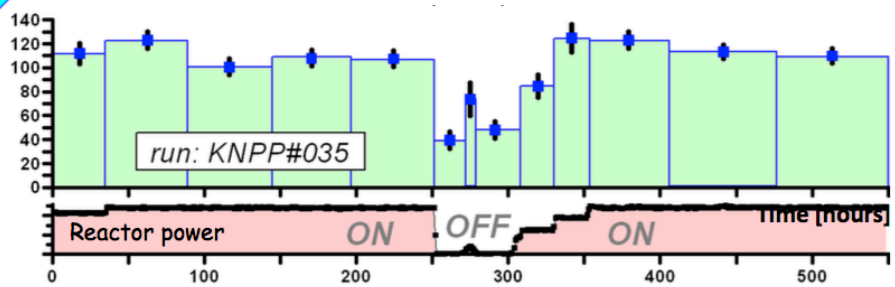
2 l and 20 l detectors deployed at HFIR reactor.
Demonstrated good detector performance and S/B.

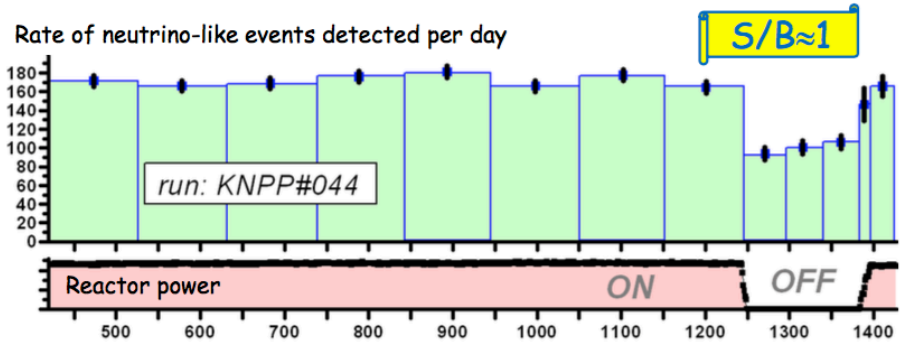


Positive results with prototype installed at HFIR

DANSS







Detector:

1m³ plastic scintillator strips
Wavelength-shifting fibers

Movable:
Vertical lift beneath reactor
9.8 – 12.2 m

Kalinin nuclear power plant
Power: 3000 MWth

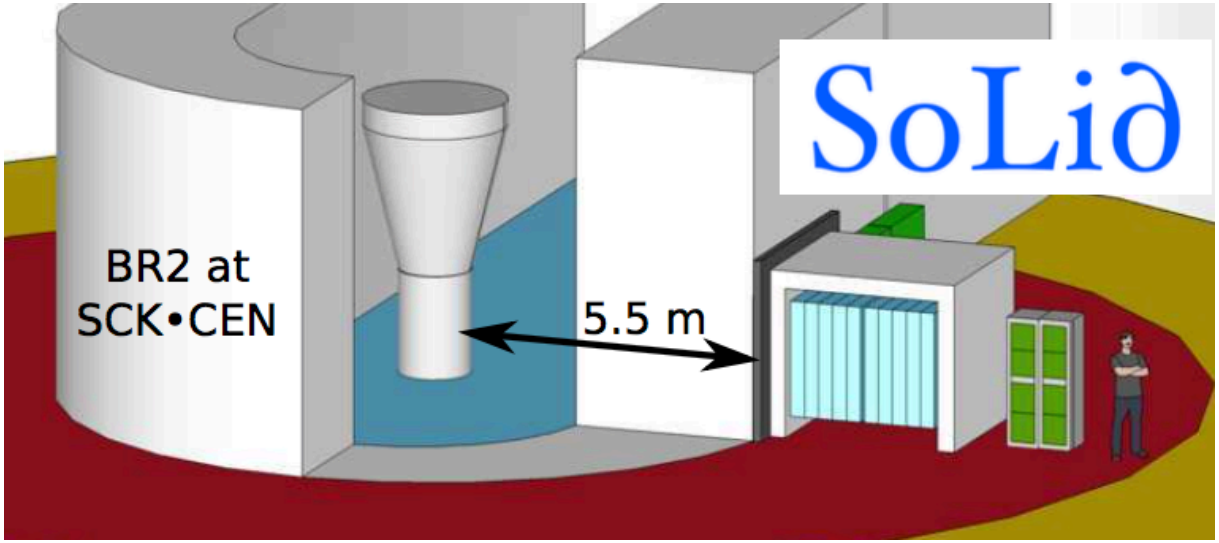
Signal: 10,000 / day

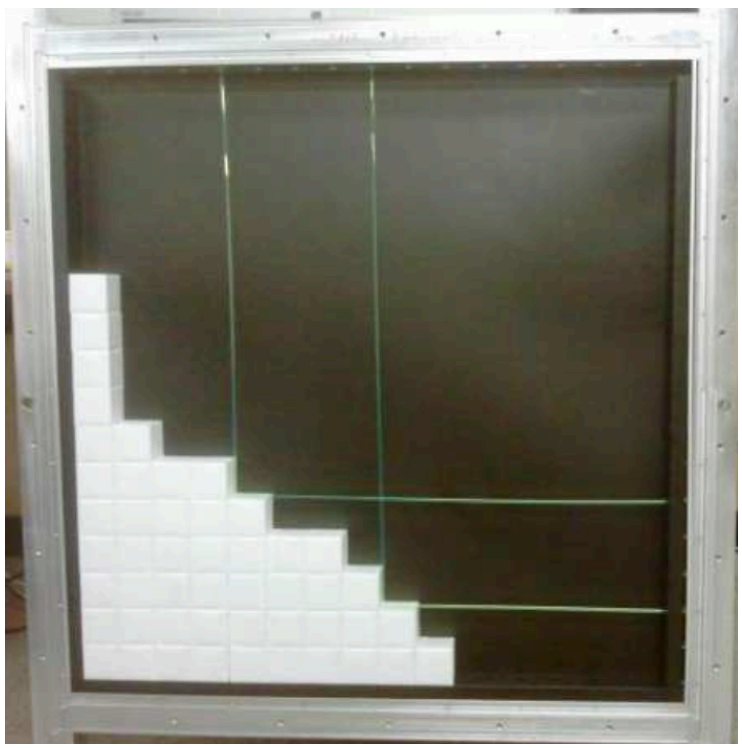
Prototype:

40 kg
Signal:
S/B: 1
Energy res.: 10 p.e. / MeV

V. Egorov, AAP-2014

SoLid





SoLid:

Innovative design

-Plastic scintillator cubes

-Wavelength shifting fibers

-Neutron: ^{6}LiF:ZnS(Ag) layer

Phases:

Prototype: 8 kg

Phase 1: 288 kg

Phase 2: 2.88 ton

BR2 Reactor (Belgium)

Compact HEU reactor

Distance: 5 - 10 m

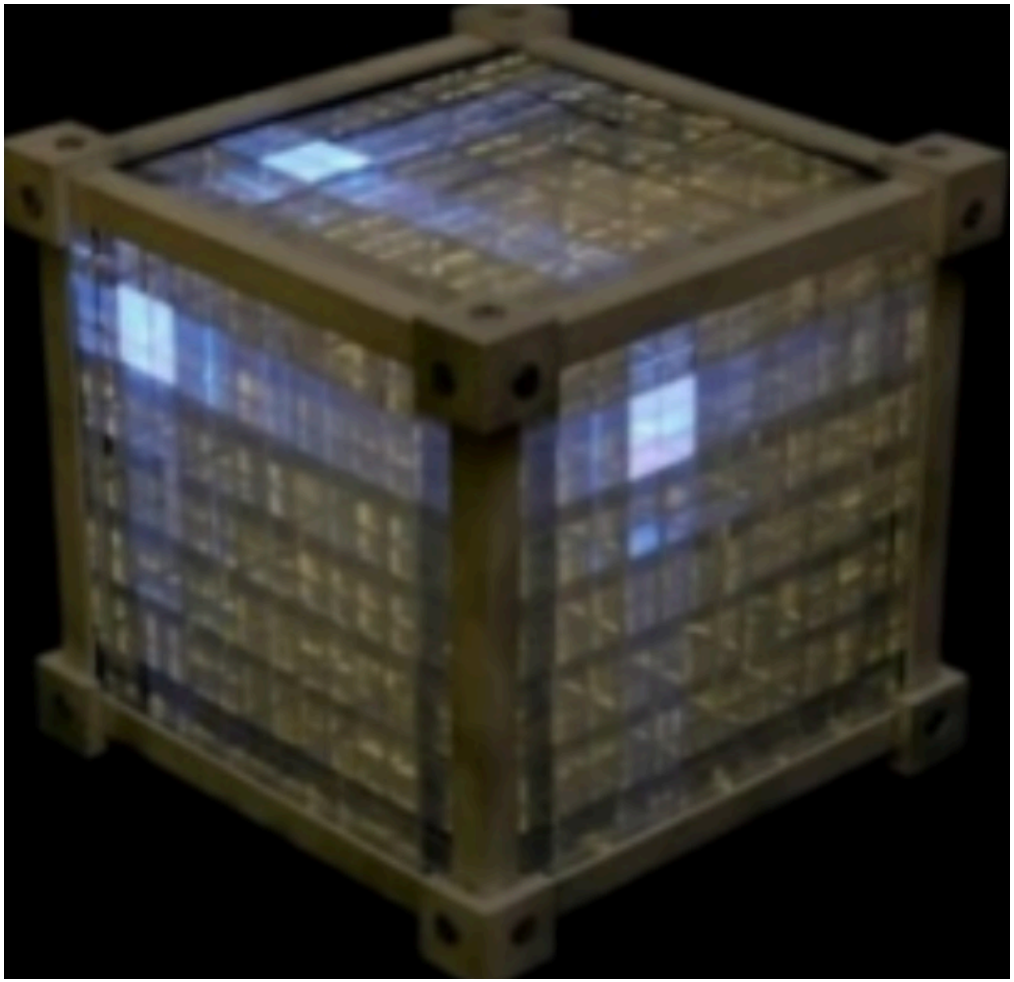
N. Ryder, AAP-2014

NuLat / Chandler

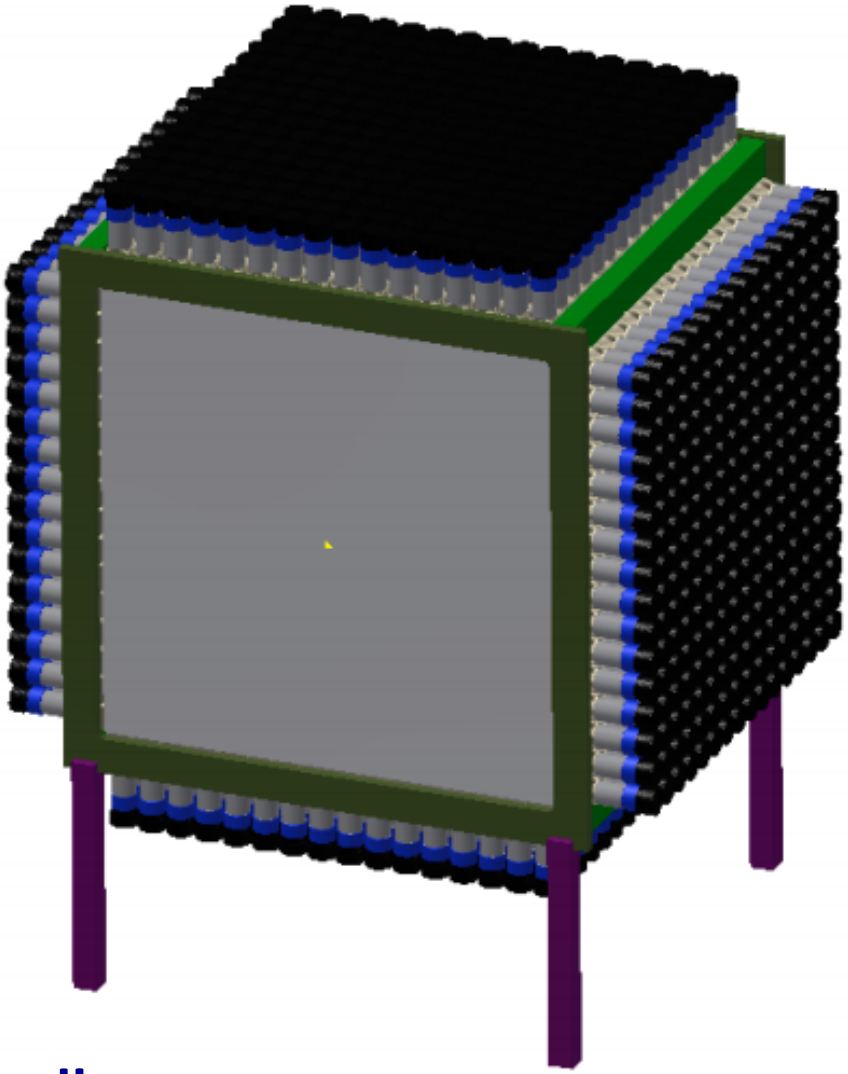
NuLat:

Based on LENS neutrino detector design

Relies on total internal reflection for position



G. Jocher, AAP-2014



Chandler:

Hybrid of NuLat and SoLid designs

Radioactive Source Experiments

Source Experiments:

Use intense radioactive sources as neutrino emitters.

^{144}Ce: antineutrinos

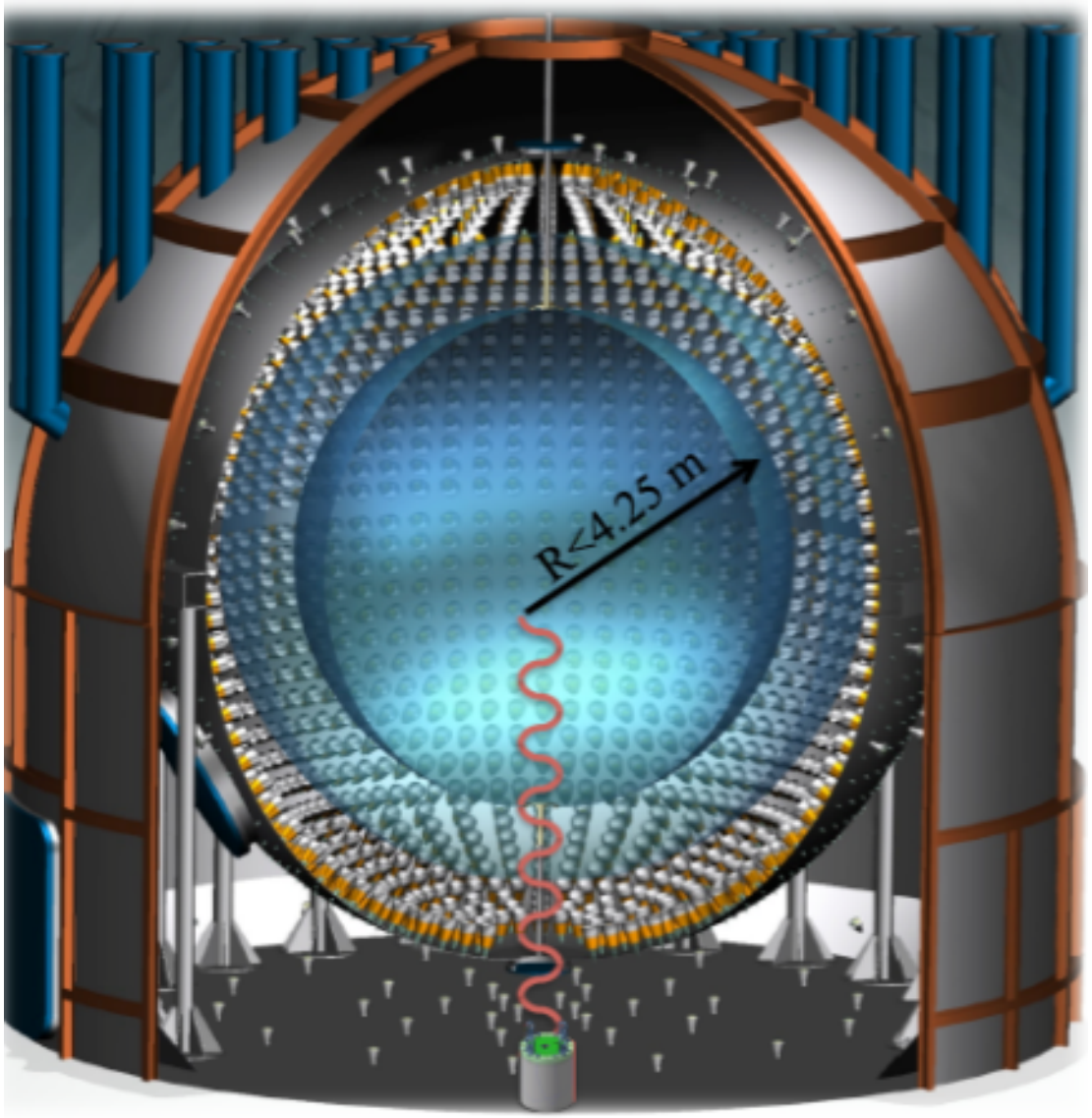
^{51}Cr: neutrinos

SOX:

Use Borexino detector @ Gran Sasso

Look for sterile oscillation pattern across detector volume.

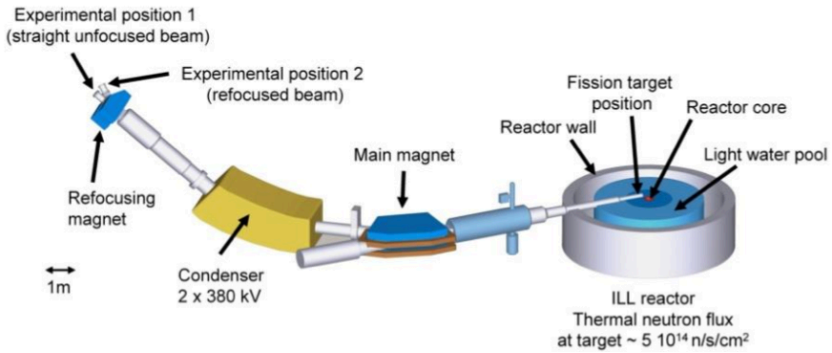
~4 PBq ^{144}Ce source currently being manufactured in Russia.
Aiming for measurement in ~2016.



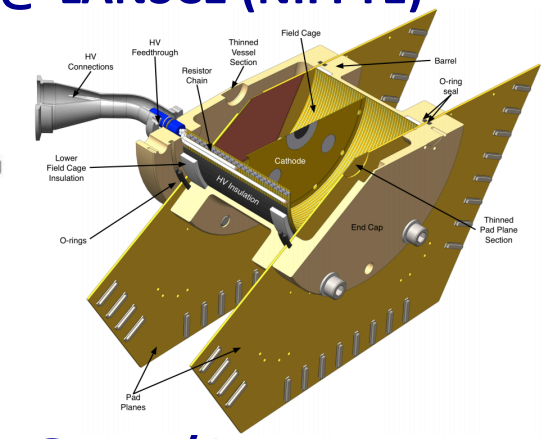
Phys. Rev. D91, 072005 (2015)

Improving Nuclear Data

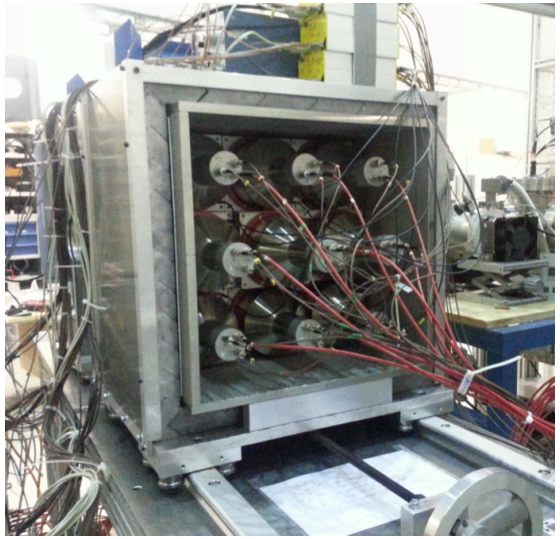
Fission Yields @ ILL (Lohengrin)



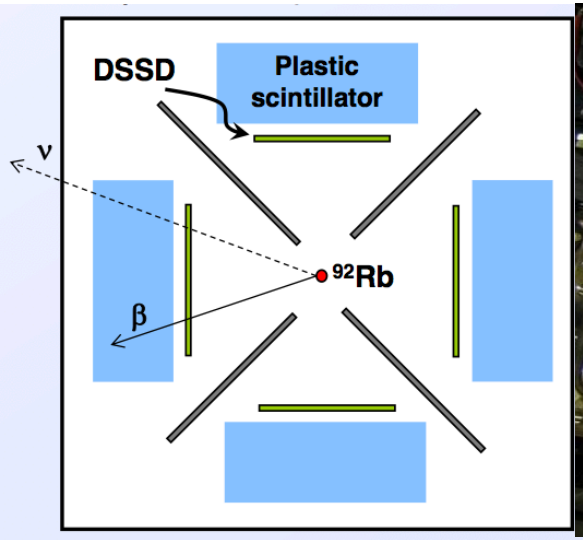
Fission Yields @ LANSCE (NIFFTE)

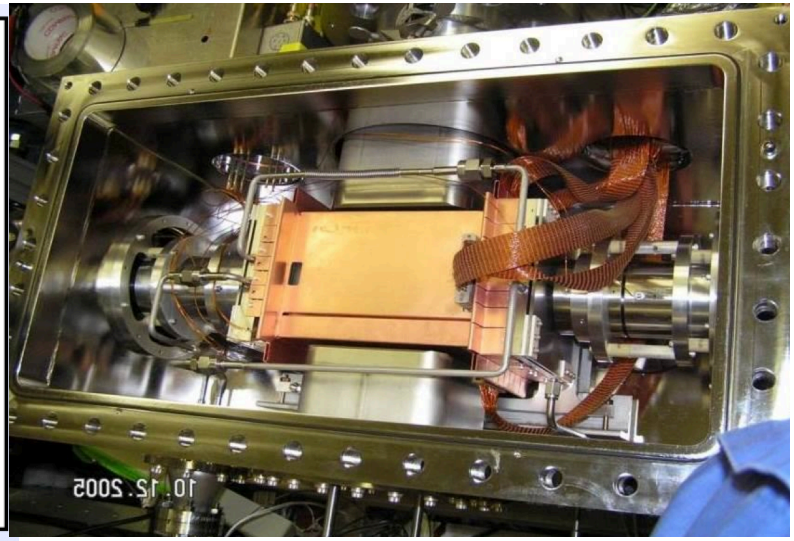


Total Absorp. Spec. @ IGISOL (DTAS)



Precision β⁻ Spec. with Trapped Ions @ ANL/CARIBU





Total Absorp. Spec. @ ORNL (MTAS)

Some examples of planned measurements of these decays:

N.D. Scielzo, private comm. [G.Li et al., PRL 110, 092502 (2013)]

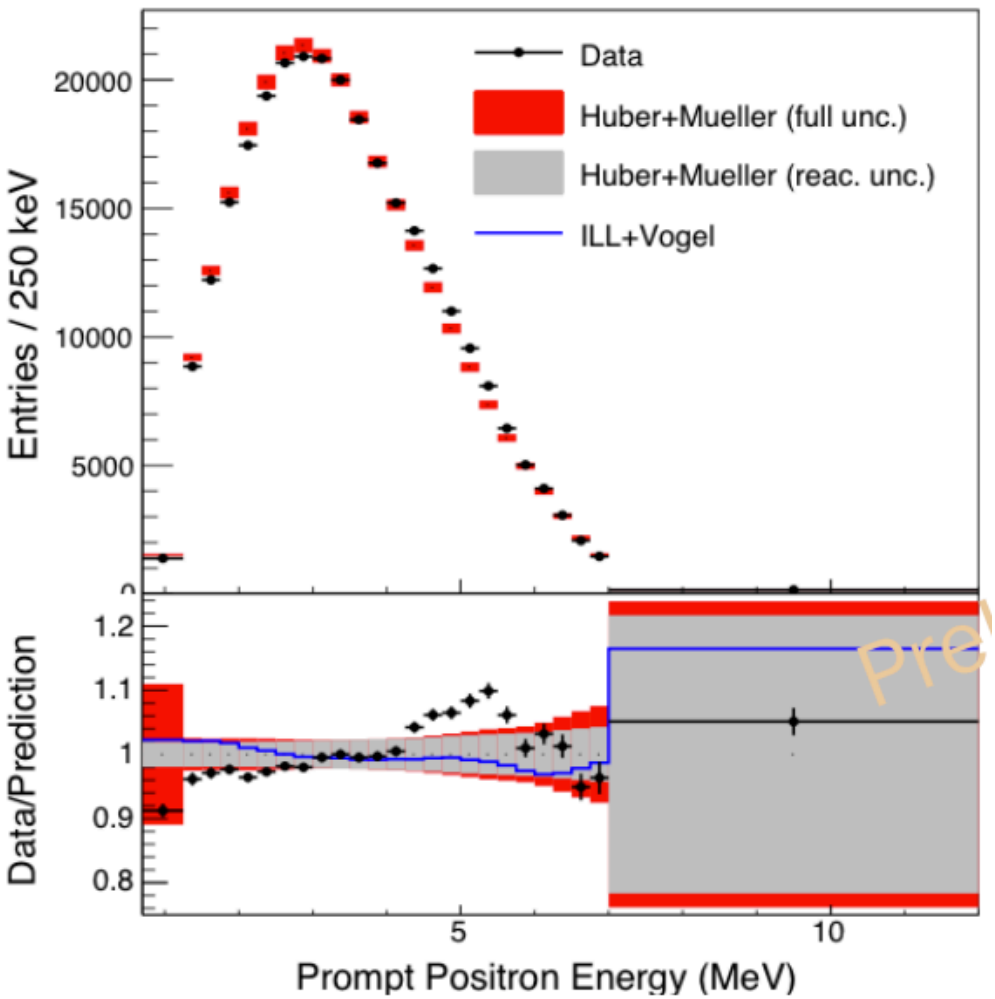
A.-A. Zakari-Issoufou et al., EPJ Web of Conferences 66, 10019 (2014)

M. Heffner et al. (NIFFTE Collaboration), arXiv:1403.6771

Precision Reactor Spectra

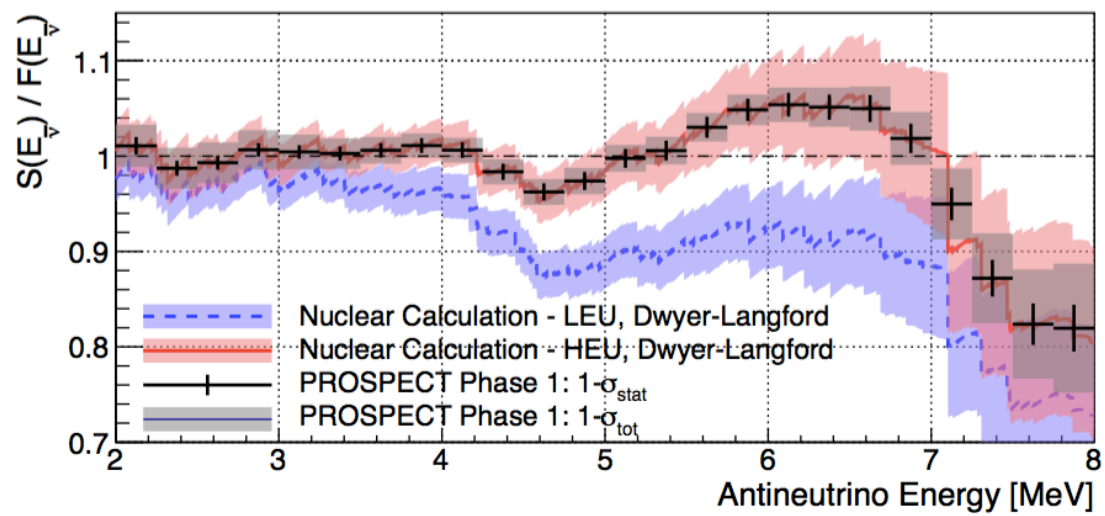
Low-enriched uranium reactors:

Expect continued improvements from Daya Bay, RENO, Double Chooz (~10^7 $\bar{\nu}_e$)



High-enriched uranium reactors:

If backgrounds and systematics controlled, PROSPECT, SoLid, etc. may provide precision spectra.



Comparison of measured LEU vs. HEU spectra can potentially clarify issues with reactor models.

Conclusions

Particle physics successes using reactor antineutrinos:

- First ν detection, distinct evidence for ν oscillation, Δm^2_{21}, θ_{12}, Δm^2_{31}, θ_{13}

But discrepancies between measurements and models:

<u>β^- conversion models:</u>

- Provide the most precise estimates of flux and spectra (~3%)
- Predicts ~6% higher flux than measurements (*i.e. the rate anomaly*)
- Energy spectrum inconsistent with measurements (*i.e. the 'bump'*)

<u>Nuclear summation models:</u>

- Rely on fission yields and decay data of >1000 isotopes
- Suffer from significant unquantified uncertainties (~10%?)
- Spectrum shows surprising agreement with recent $\bar{\nu}_e$ measurements

Future measurements:

- Direct searches for oscillation to sterile neutrinos
- Improved measurements and models of reactor $\bar{\nu}_e$ emission

Upcoming measurements have significant potential to resolve these questions.