Sterile Neutrinos: Experimental Searches

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Symmetry Tests in Atoms and Nuclei

KITP - UCSB

Sep. 19, 2016

Why Sterile Neutrinos?

Experimental Motivation:

Reactor antineutrinos:

Models of rate and spectra disagree with measurements

Intense radioactive sources:

ν_e rate slightly less than expected in radiochemical detectors

Accelerator Neutrinos:

Discrepancies in the appearance of ν_e in ν_μ beams

Theoretical Motivation:

Majorana neutrino mass:

Implies additional heavy neutrino states

Beyond the Standard Model:

Many extensions imply sterile neutrino states

Cosmology:

Potential candidates for dark matter

Overview

Today: Focus on three aspects

1) The trouble with absolute measurements.

- Expected vs. observed reactor ν_e rate and spectra disagree

2) The strength of relative measurements.

- Stringent limits from recent measurements

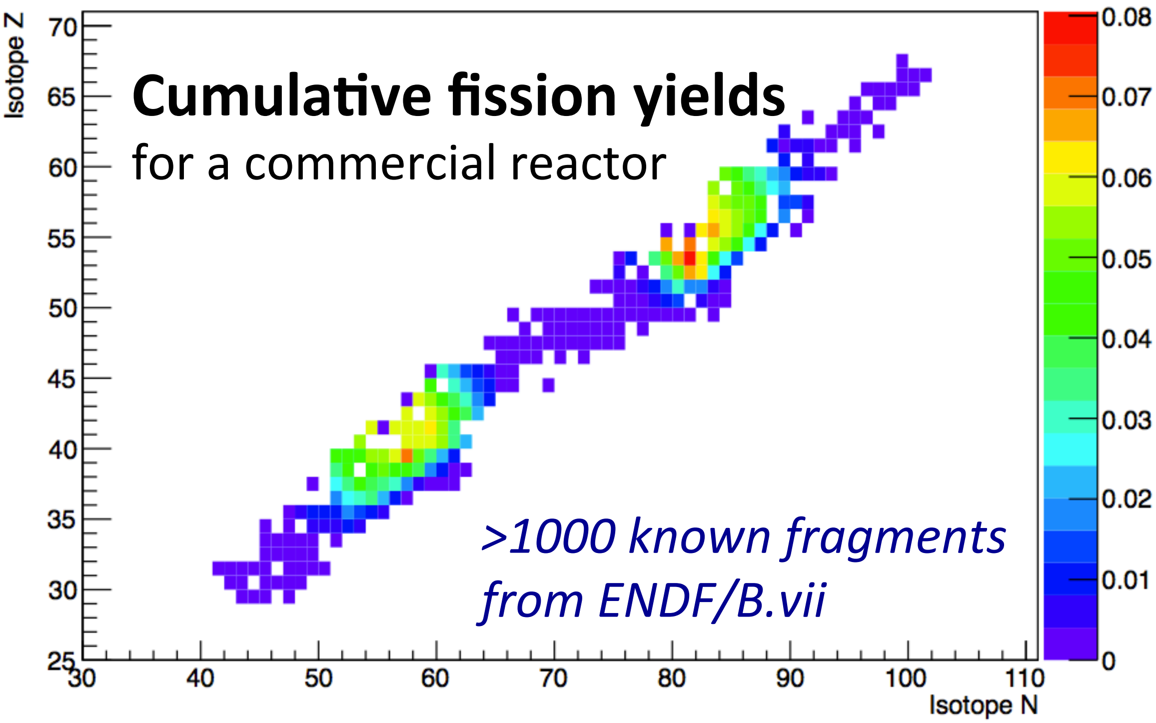
3) Looking forward

- Upcoming searches for sterile neutrinos

Part 1:
The Trouble with
Absolute Measurements

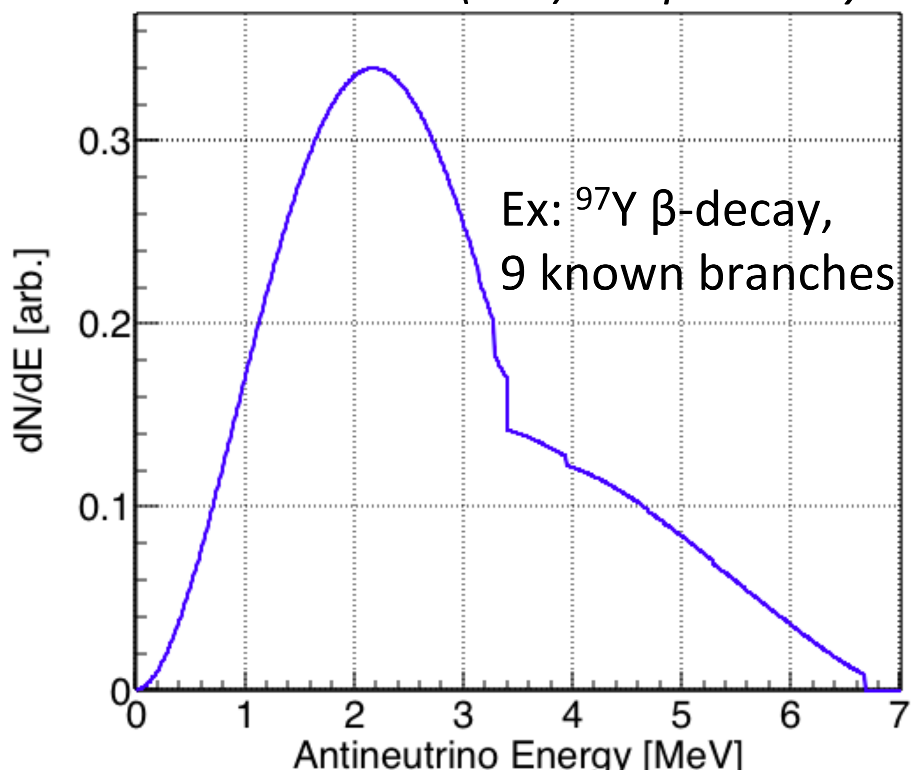
Reactor Antineutrinos

Fission of actinides (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) produce neutron-rich daughter fragments.



β-decays of daughters emit electrons and antineutrinos.

O(10k) unique decays



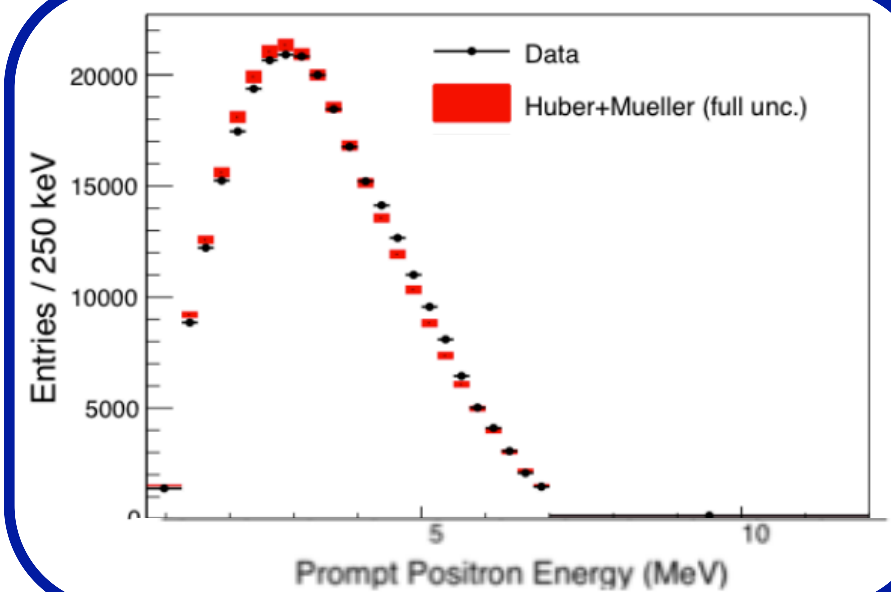
Total Reactor $\bar{\nu}_e$ Spectrum:

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

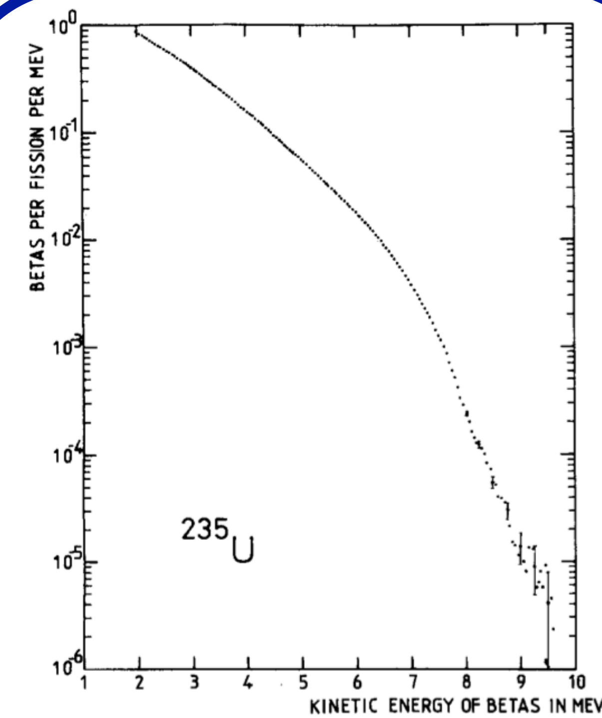
Daughter decay rate (R_i), *Branching fraction* (f_{ij}), *Branch spectrum* (S_{ij})

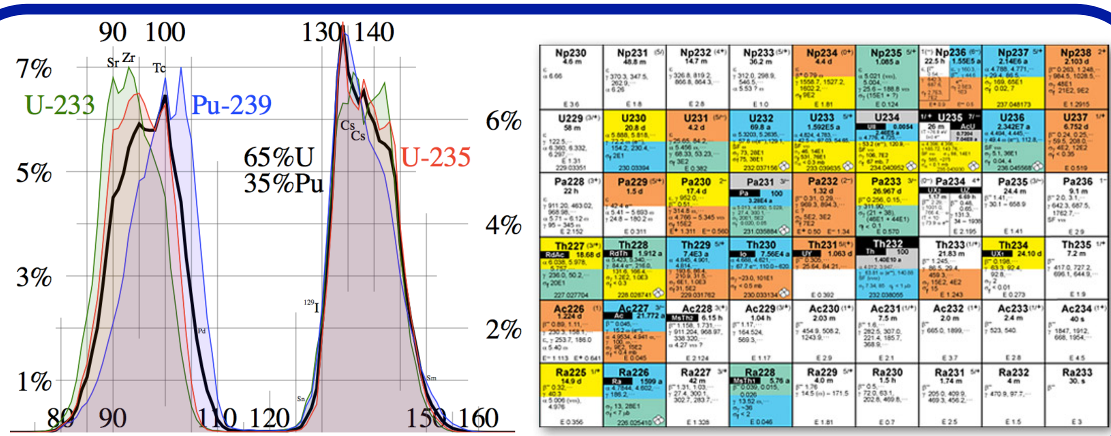
The 'Cast' of Measurements

Reactor $\overline{\nu}_e$ Measurements



Fission e⁻ Measurements





Fission and Nuclear Decay Measurements

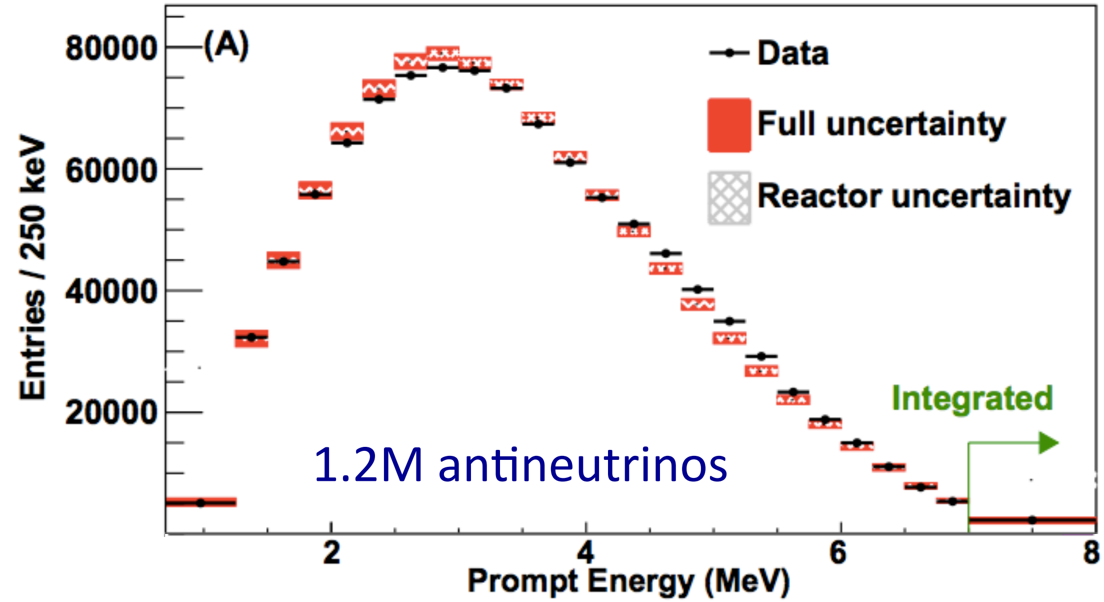
Fission Antineutrino Emission

Recent experiments:

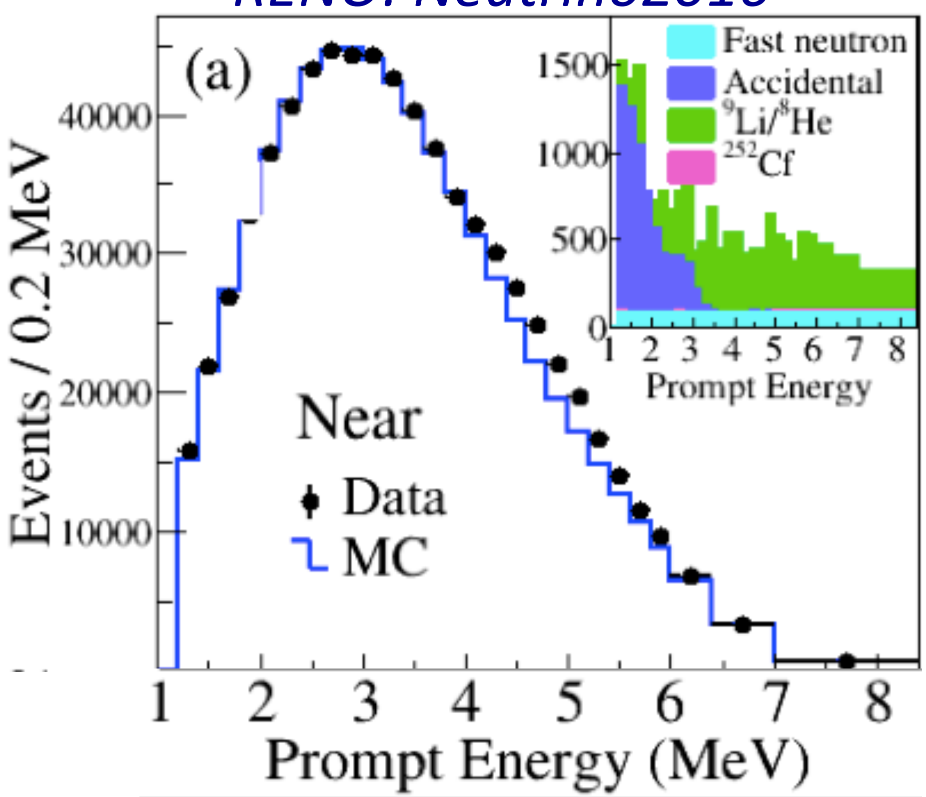
High statistics: 10^6 antineutrinos

Low background: ~1%-level

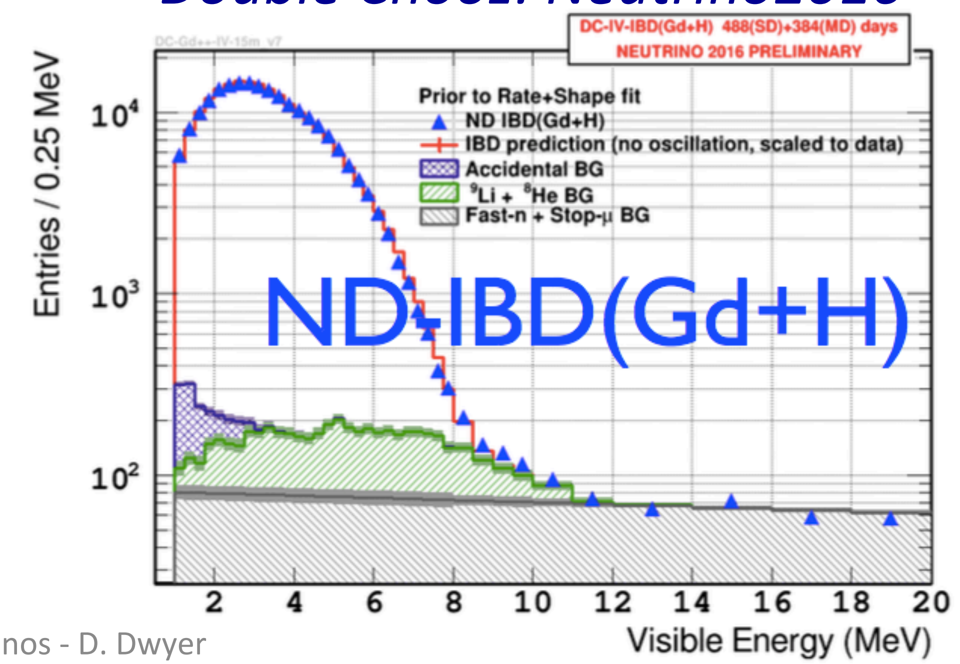
Daya Bay: arXiv:1607.05378



RENO: Neutrino2016



Double Chooz: Neutrino2016

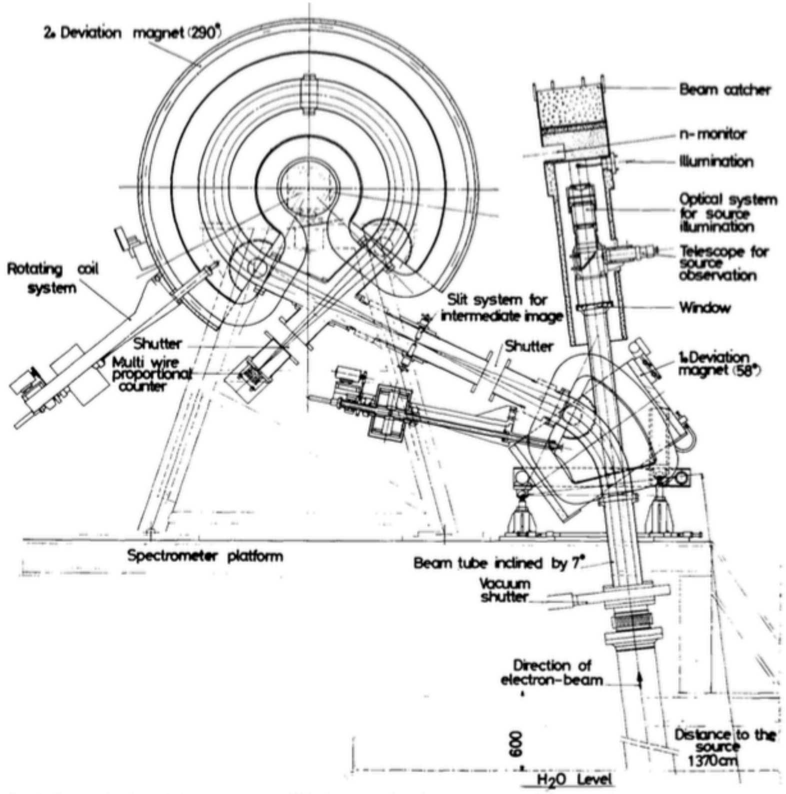


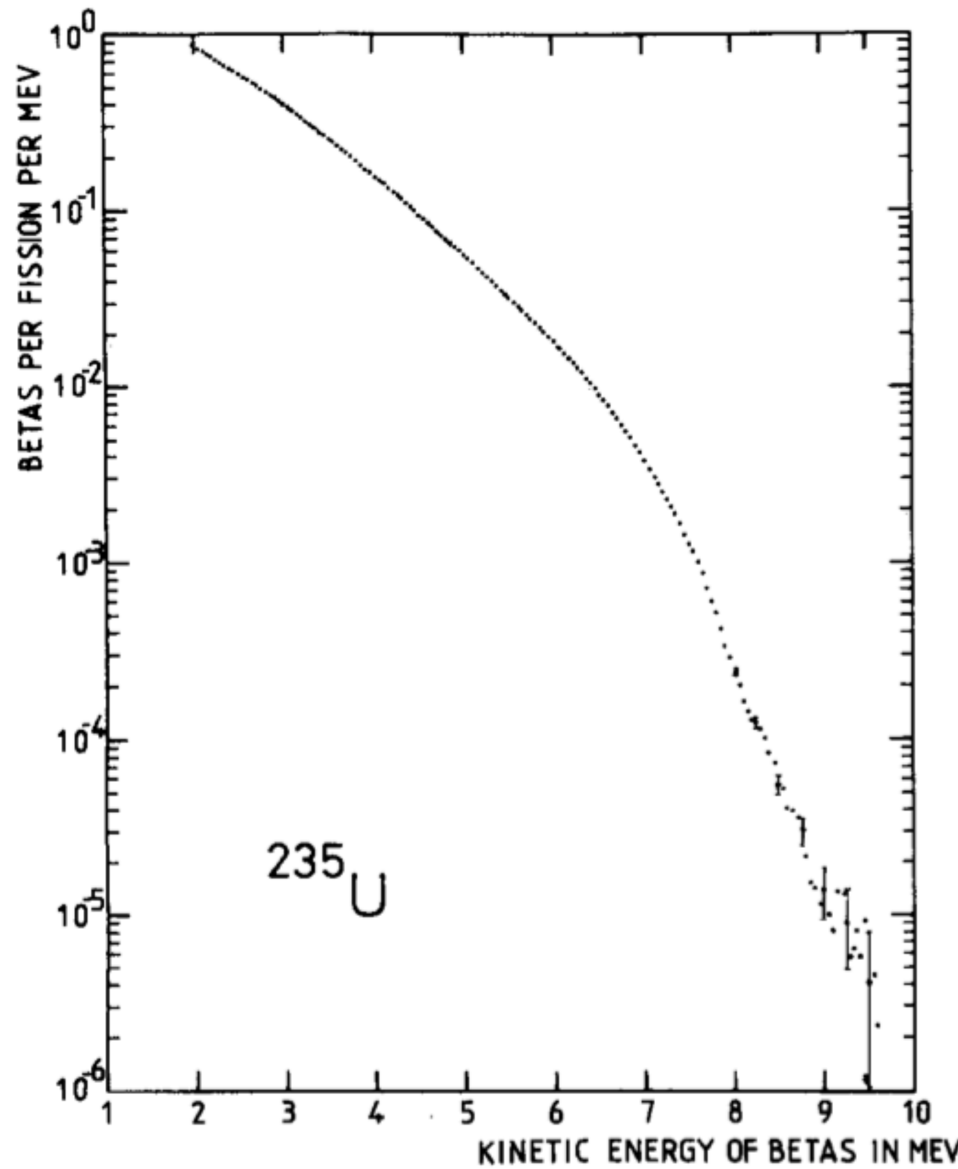
Fission Electron Emission

Measurements at ILL:

Expose fission parents to thermal neutrons
Measure total outgoing β- energy spectra
Uncertainties at the ~2%-level

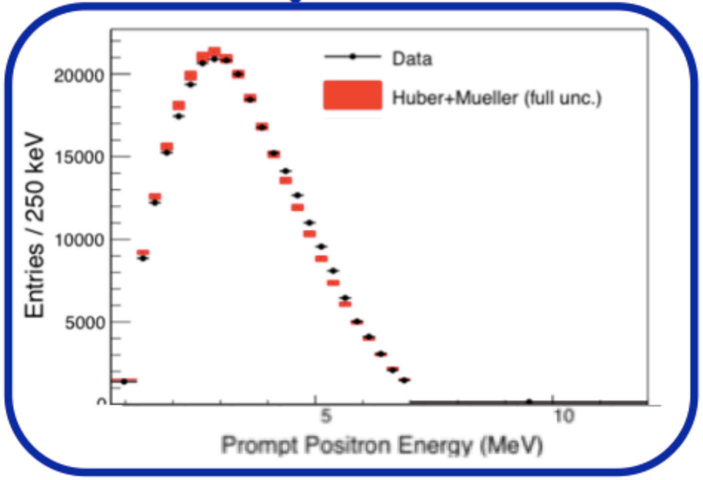
Phys. Lett. B160, 325 (1985), Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989), Phys. Rev. Lett. 112, 122501 (2014)
Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)





β⁻ Conversion

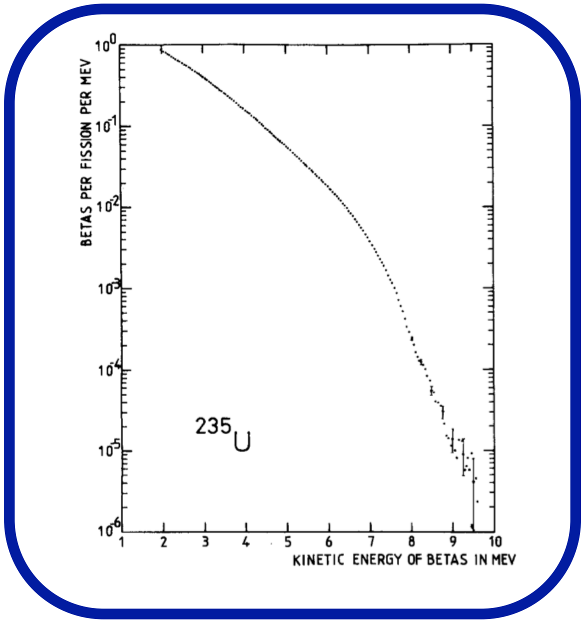
Reactor $\overline{\nu}_e$ Measurements



Vogel, Huber

Phys. Rev. C76, 025504 (2007)
Phys. Rev. C84, 024617 (2011)

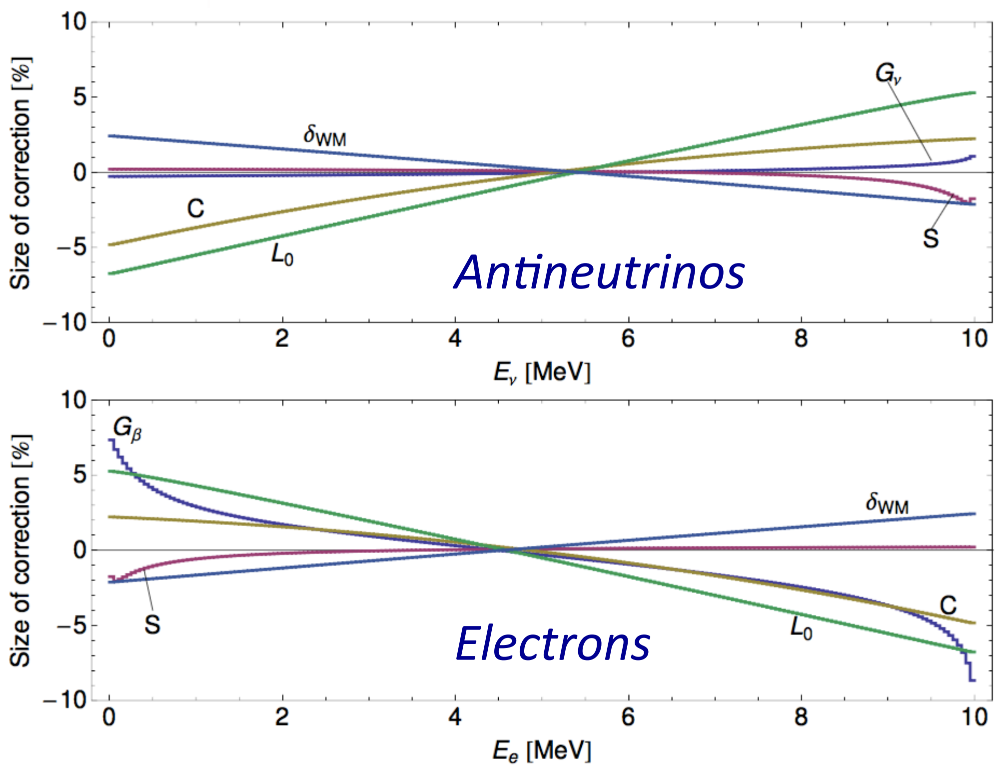
Fission e⁻ Measurements



Nuclear corrections:

Differ for e⁻ and $\overline{\nu}_e$.

- Coulomb
- Finite nuclear size
- Weak magnetism
- Screening
- Radiative

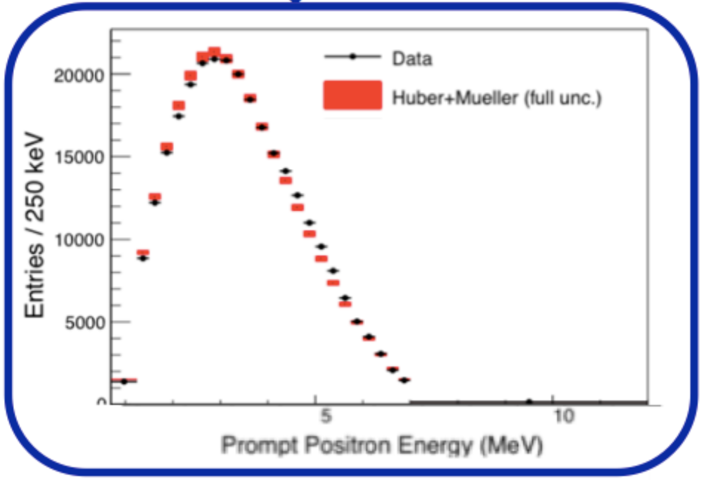


Example:

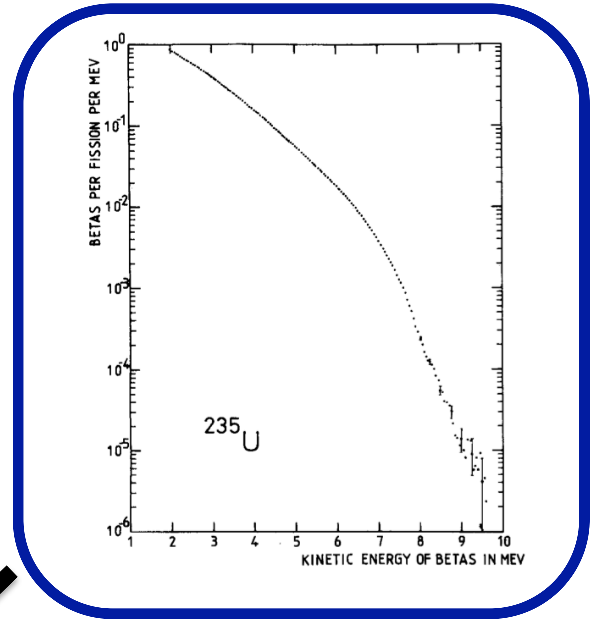
$^{117}_{46}$X with E_0=10 MeV

β^- Conversion

Reactor $\overline{\nu}_e$ Measurements



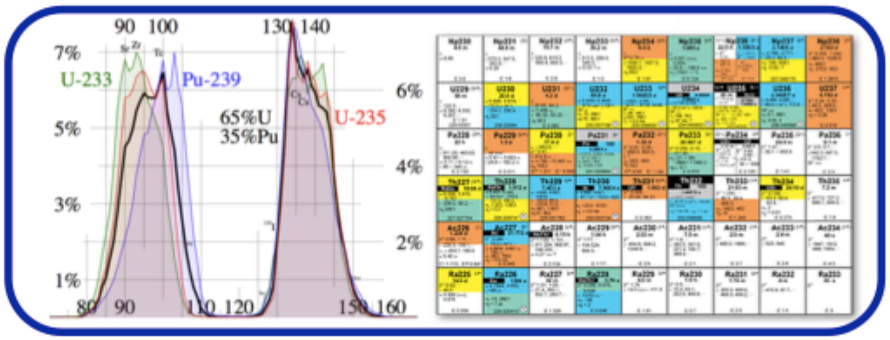
Fission e^- Measurements



Vogel, Huber

Mueller *et al.*

Phys. Rev. C83, 054615 (2011)

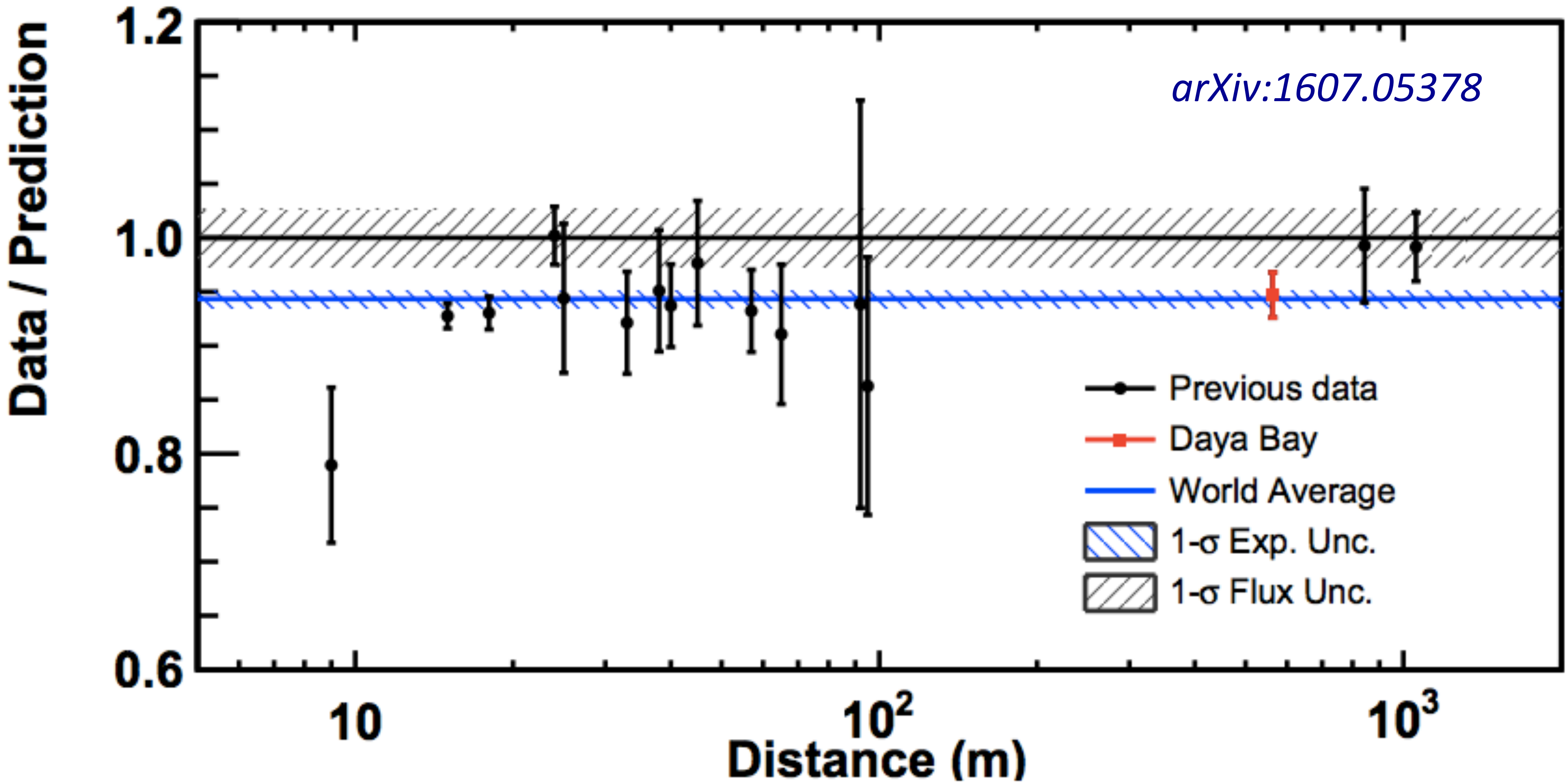


Models predict $\overline{\nu}_e$ rate and spectrum with ~3% precision.

Fission and Nuclear Decay Measurements

Rate Discrepancy

Measurement of total antineutrino flux disagrees with models

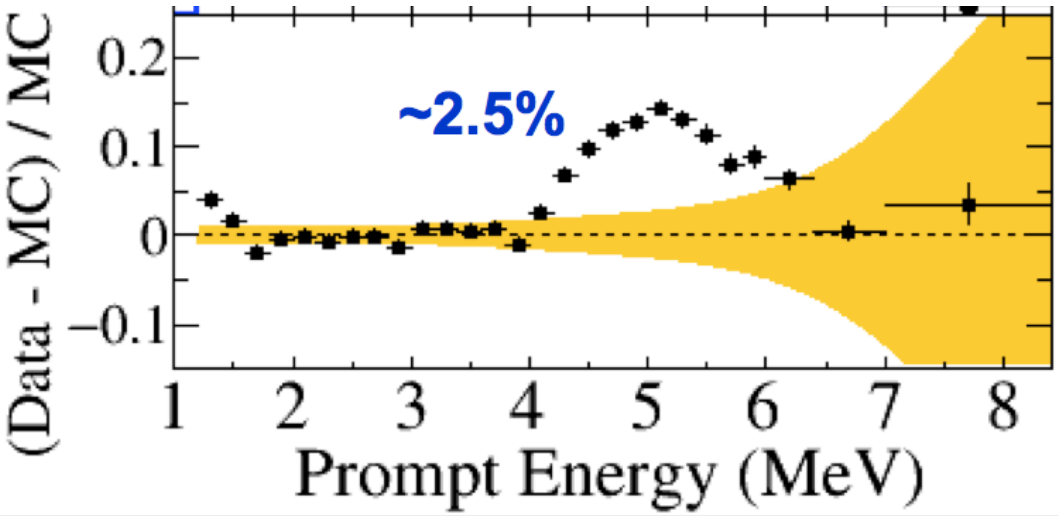


a.k.a. The Reactor Anomaly: Phys. Rev. D83, 073006 (2011)

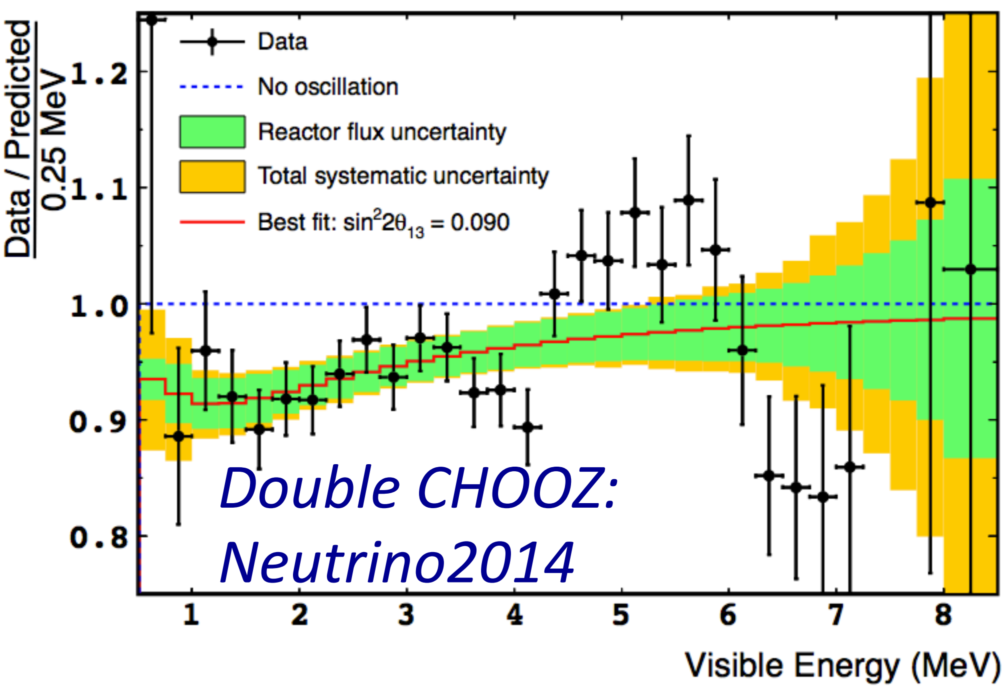
Considered possible evidence of non-interacting (*sterile*) neutrino states.

Spectrum Discrepancy

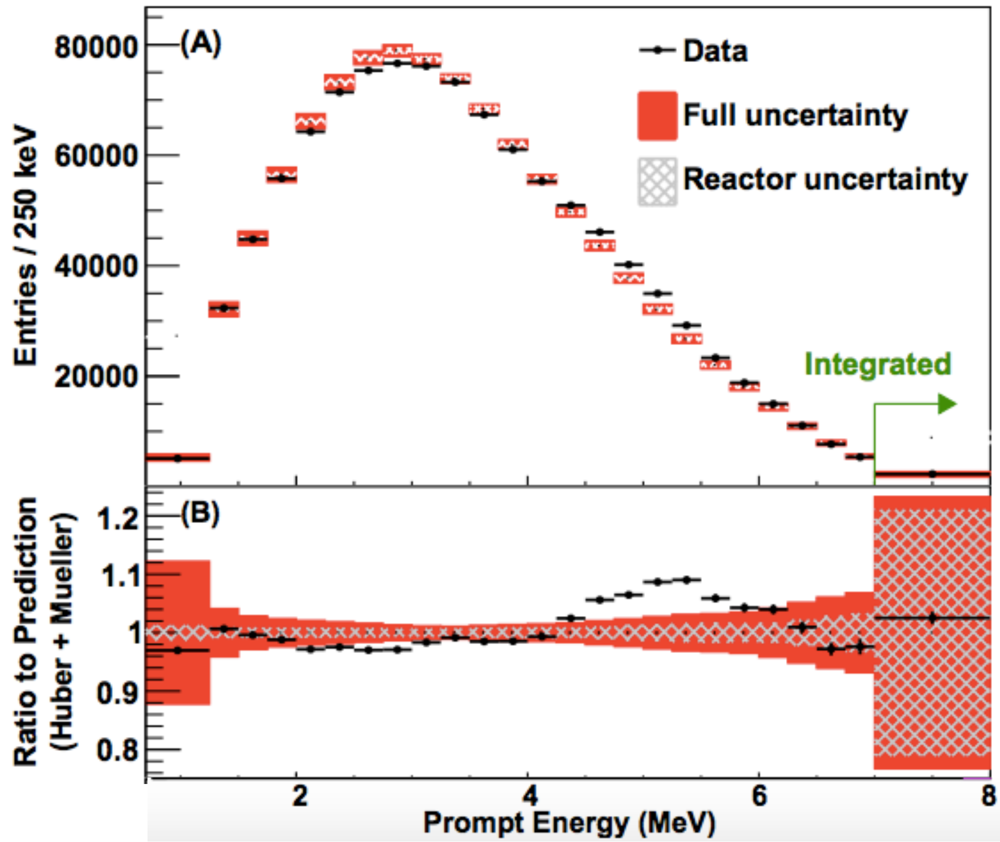
RENO: Neutrino2016



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



Daya Bay: arXiv:1607.05378



Possible origins?

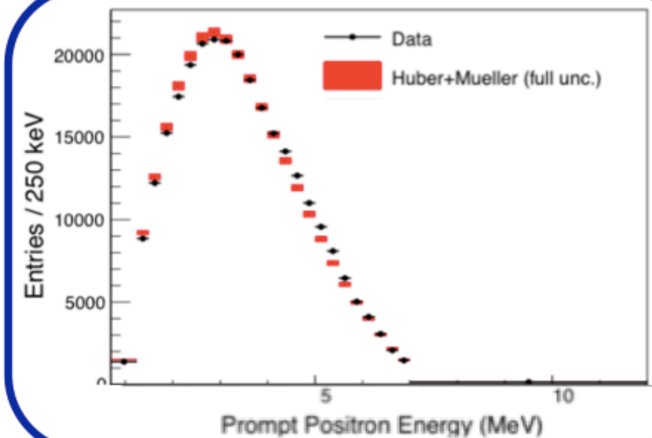
What might cause the difference between the e^- and $\bar{\nu}_e$ spectra?

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

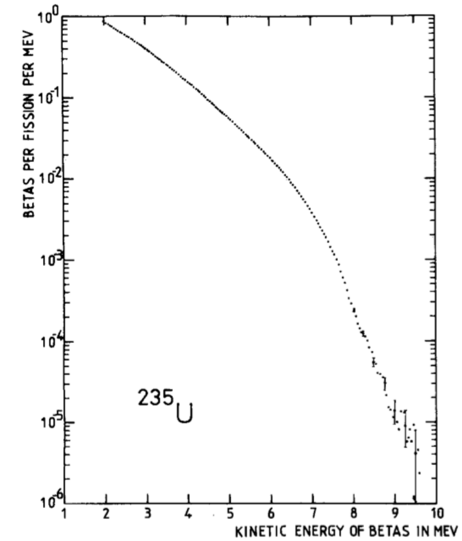
- ✗ 1) Non-fission sources of antineutrinos
- ✗ 2) The forbidden nature of some beta decay transitions
- ✗ 3) ^{238}U fission as a source of the shoulder
- ✓ 4) The relatively harder PWR neutron spectrum
- ✓ 5) A possible error in the in the ILL beta-decay measurements

Summation Calculation

Reactor $\bar{\nu}_e$ Measurements



Fission e^- Measurements



Vogel,
Fallot,
Sonzogni,
Hayes,
Dwyer+Langford

Fission and Nuclear Decay Measurements

Here Be Dragons…

Existing nuclear databases have significant uncertainties

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?

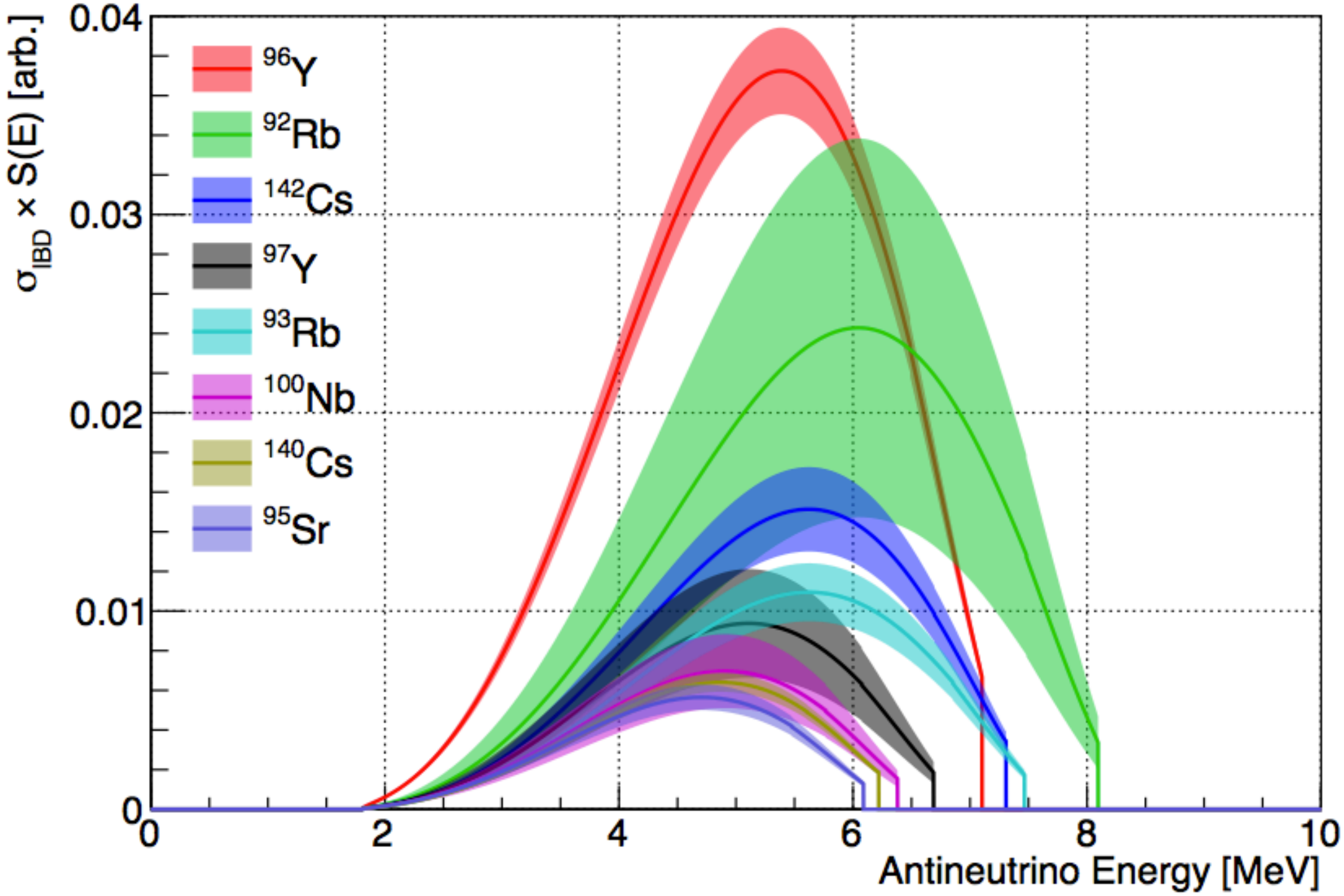
- Mismatch of decay initial-final spin and parity can distort spectrum

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

Dominant Branches

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

Dwyer and Langford, Phys. Rev. Lett. 114, 012502 (2015)



Energy Spectra:
Allowed shape
+ IBD cross-section

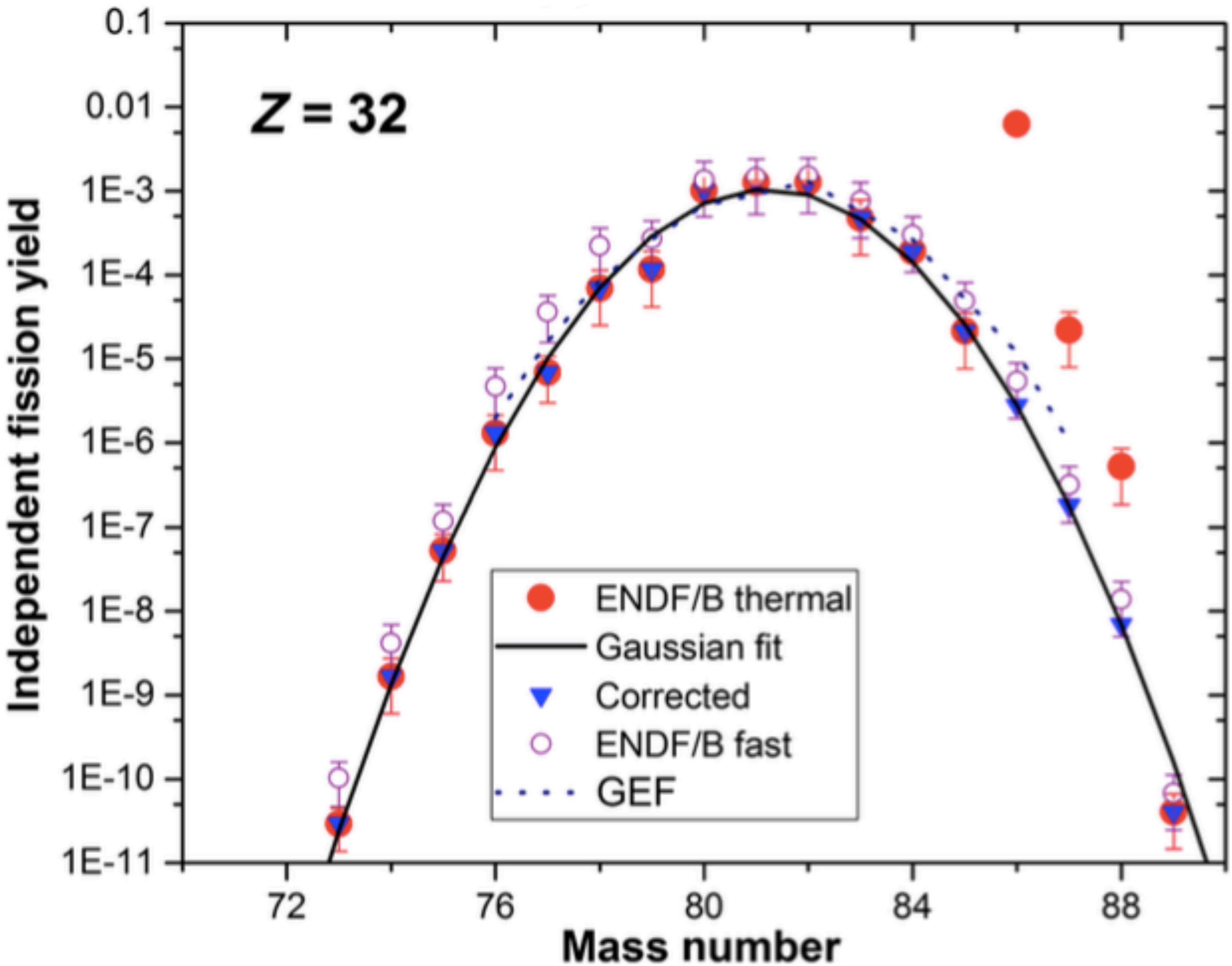
Uncertainties:
Fission Yield
Branch fraction
^{92}Rb most significant

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

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

Nuclear Data Woes

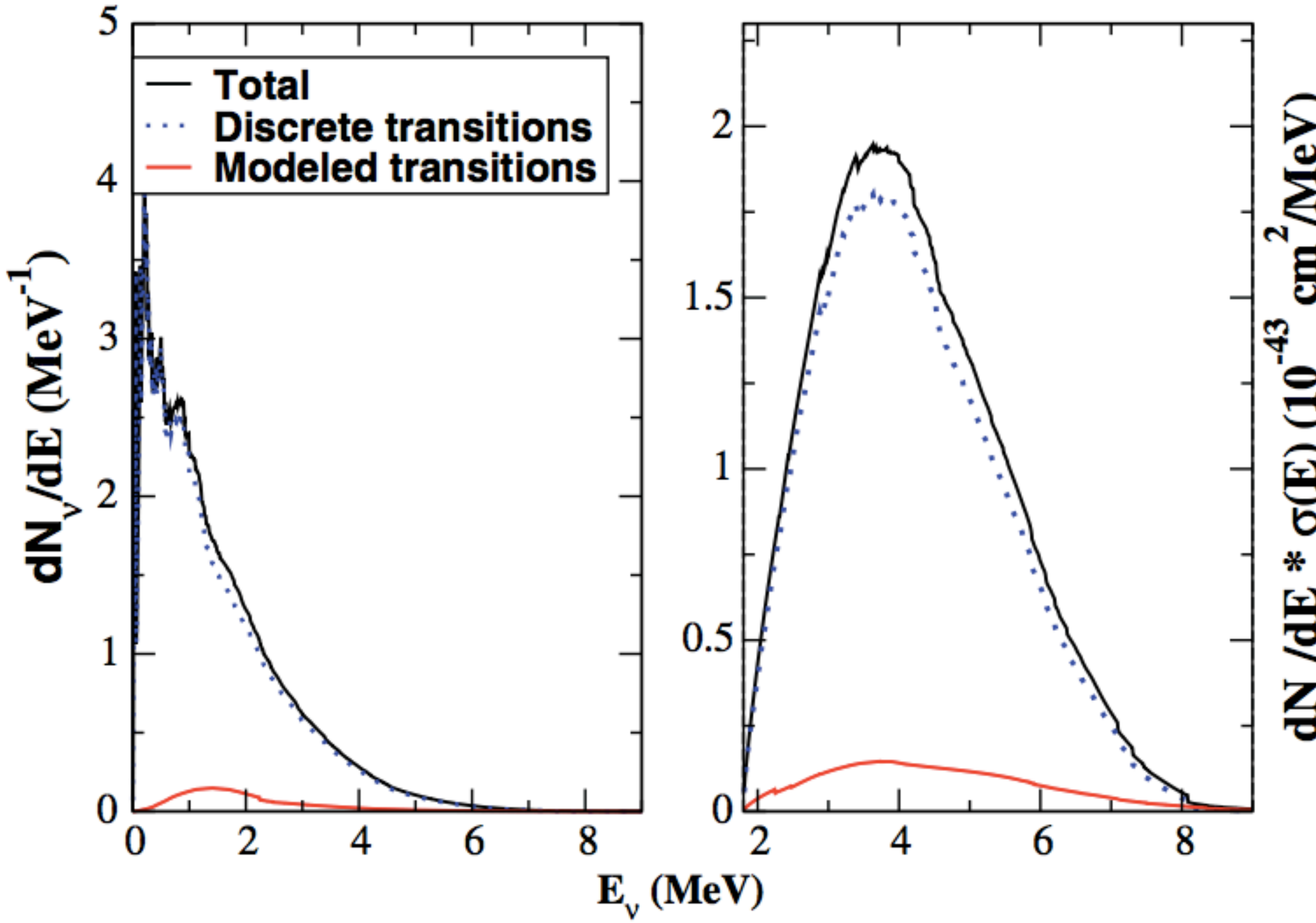
Recent error found in ENDF/B.vii thermal fission yield tables.



Sonzogni et. al., Phys. Rev. Lett. 116, 132502 (2016)

Missing Decays

Fission daughter nuclei with unknown decays must be modeled.

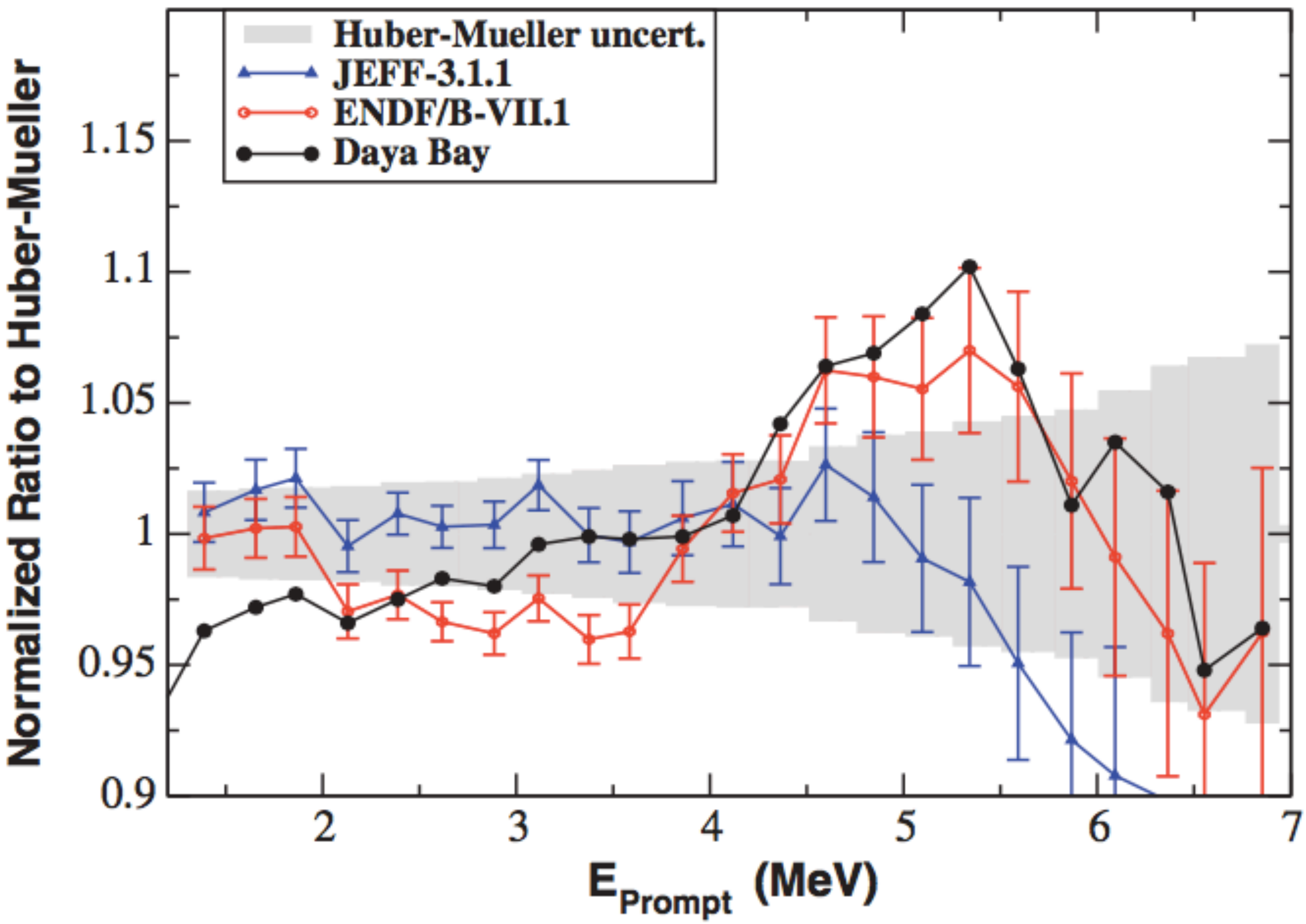


~70% of daughters lack decay data, but only amount to ~5% of reactor yield.

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

Inconsistent Databases

Calculated spectrum depends on which nuclear database is used.



Key difference: ^{96}Y fission yield.

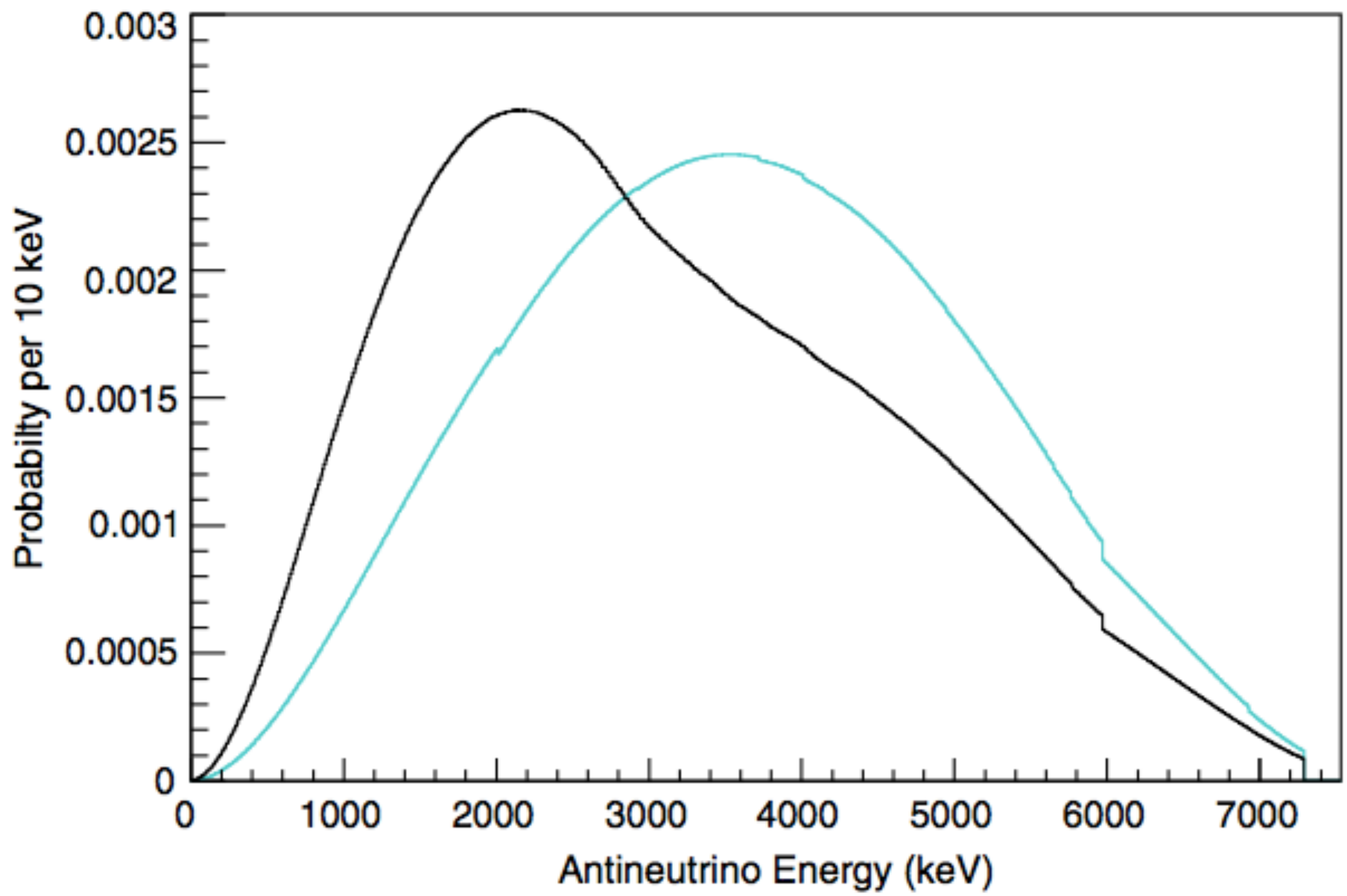
Hayes et. al., Phys. Rev. D92, 033015 (2015)

Total Absorption Spectroscopy

Recent measurements of prominent daughters: ^{96gs}Y, ^{92}Rb, ^{142}Cs

Total Absorp. Spec.
@ ORNL (MTAS)

Rasco et. al., Phys. Rev. Lett. 117, 092501 (2016)

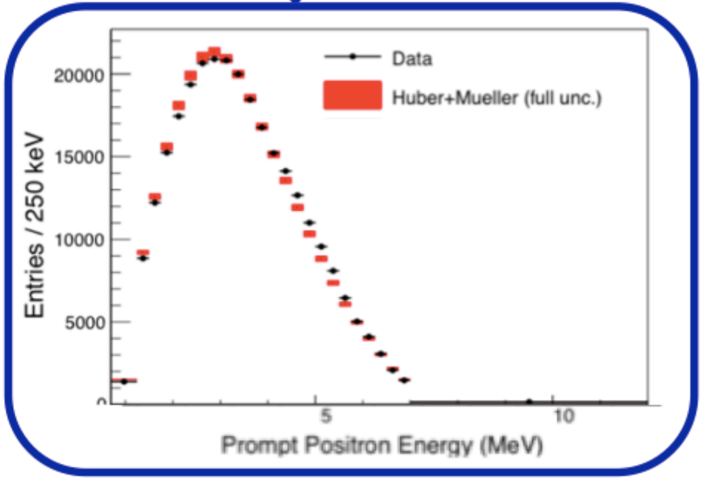


Results in significant changes in β-decay spectra of ^{142}Cs and ^{92}Rb

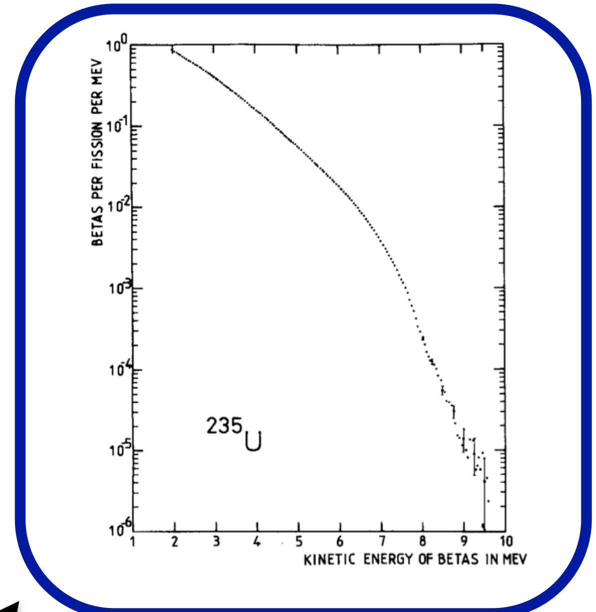
See also IGISOL DTAS: Guadilla et. al., NIM B376, 334 (2016)

Summary

Reactor $\bar{\nu}_e$ Measurements



Fission e⁻ Measurements



~~Rate~~

~~Spectrum~~

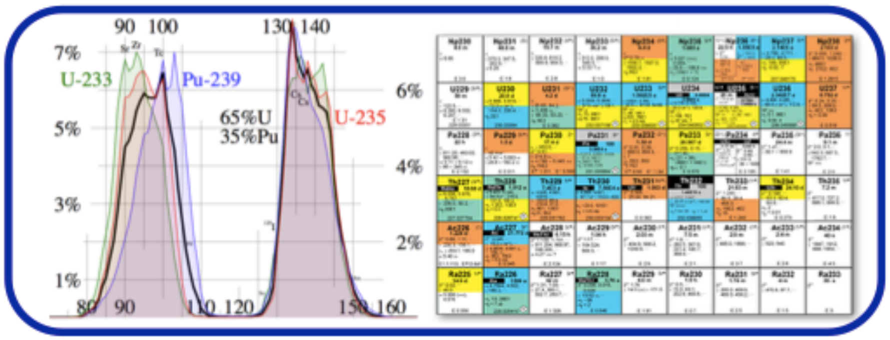
Origin?

Different fission neutron energy?

Problem with e⁻ measurements?

Rate? (Difficult)

Spectrum? (Potential)

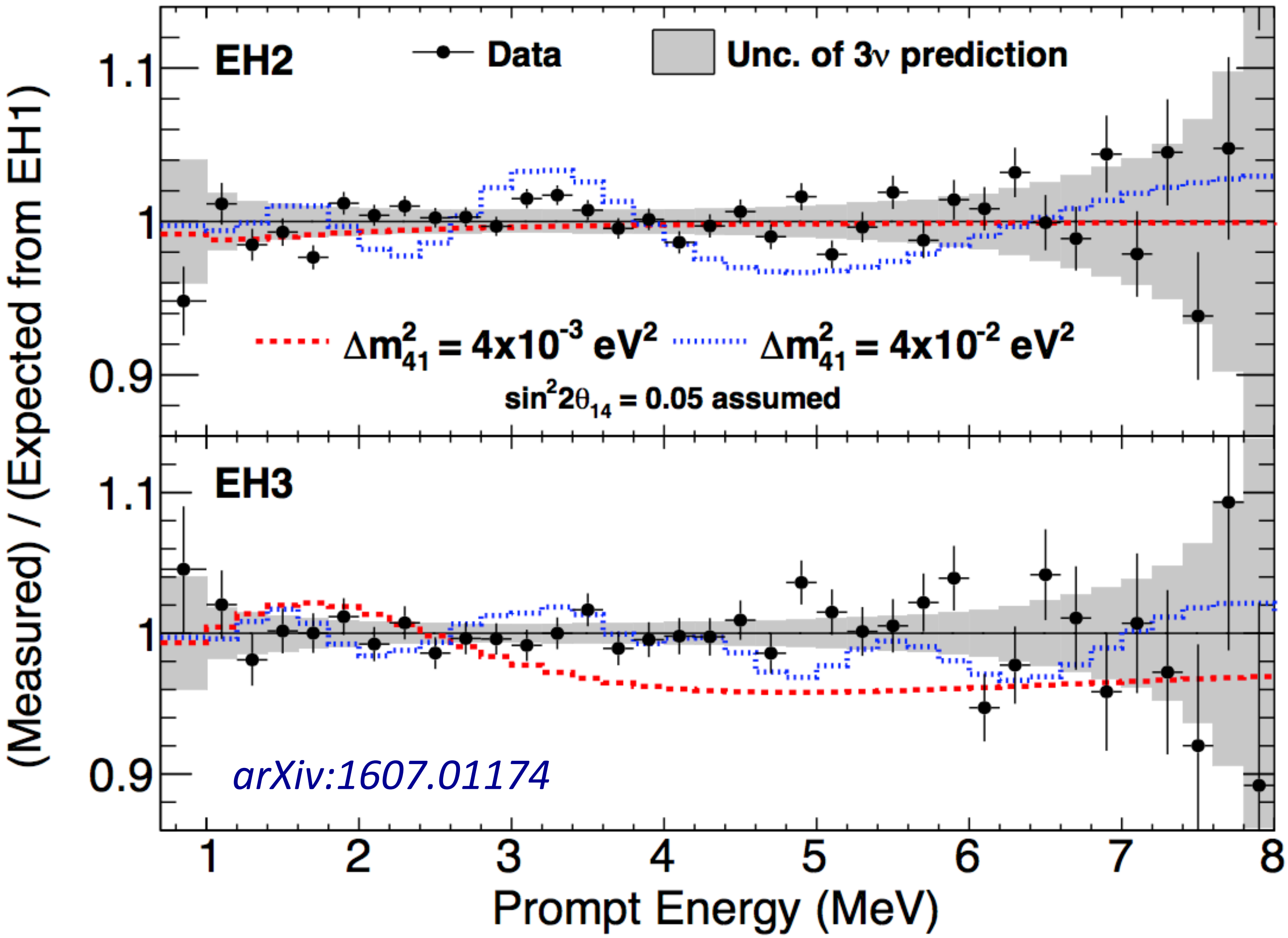


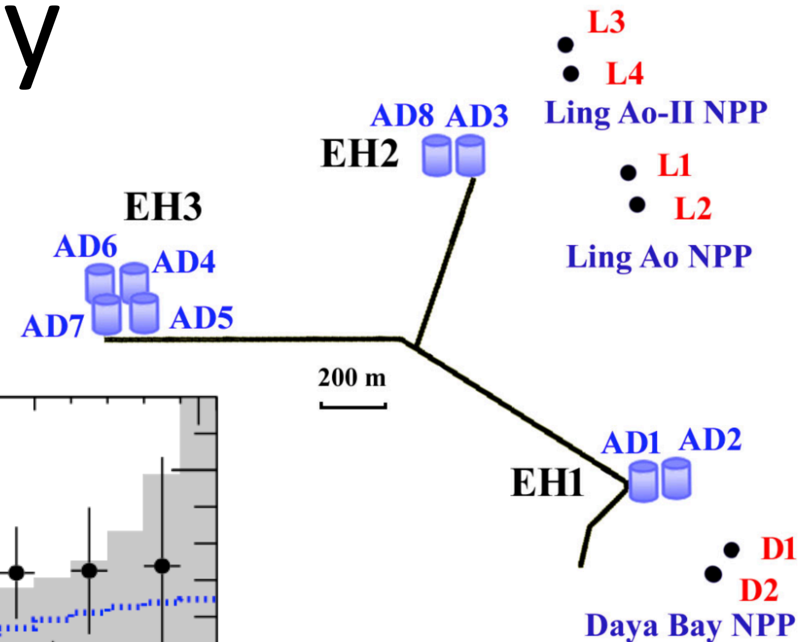
Fission and Nuclear Decay Measurements

Part 2:
The Strength of
Relative Measurements

Daya Bay

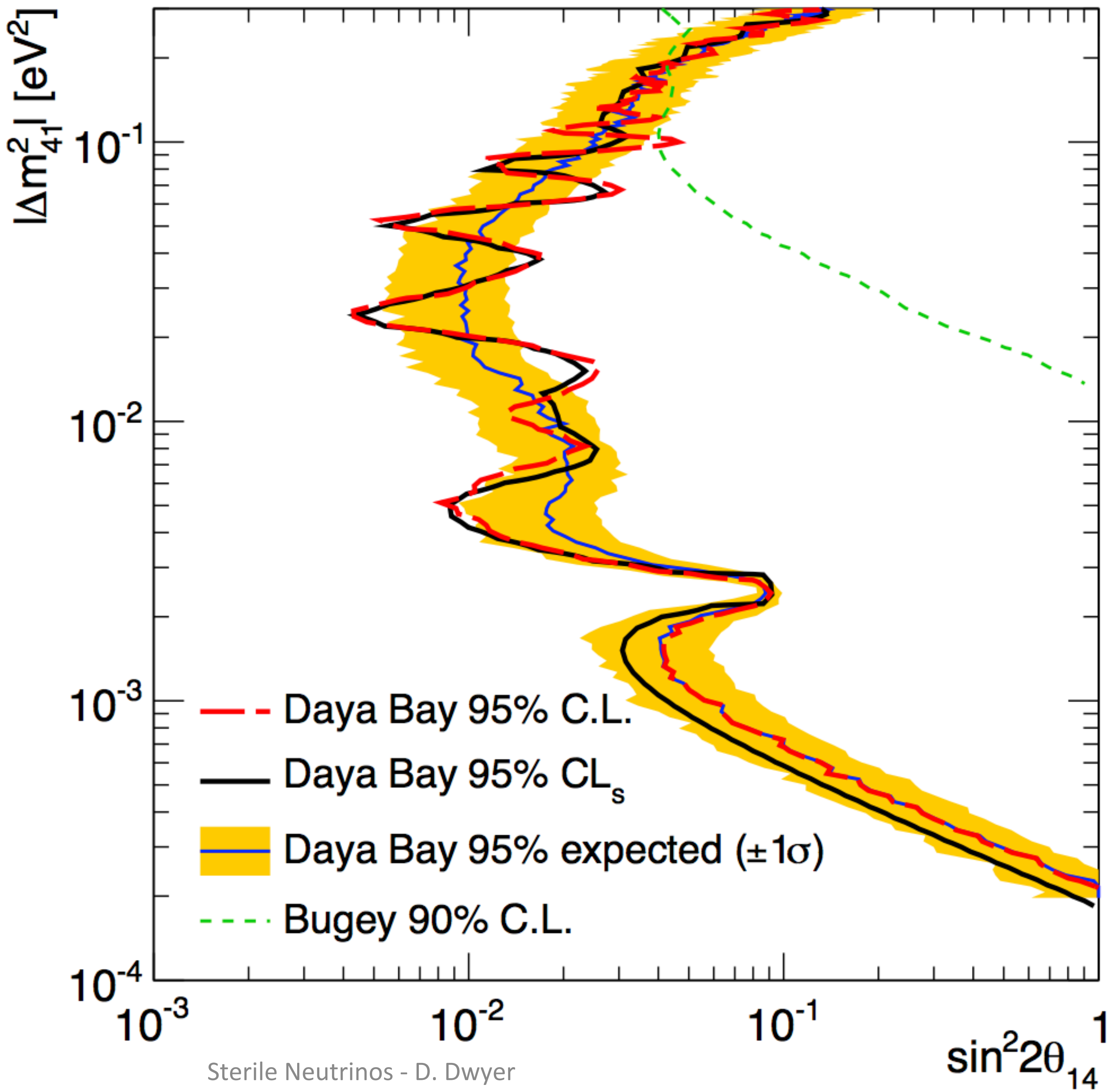
No evidence of spectral distortion from to sterile neutrinos





Daya Bay

arXiv:1607.01174

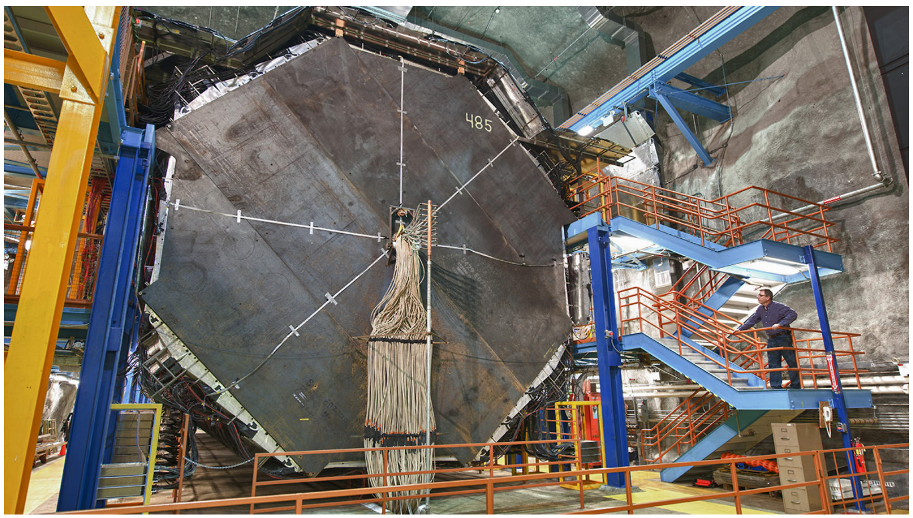


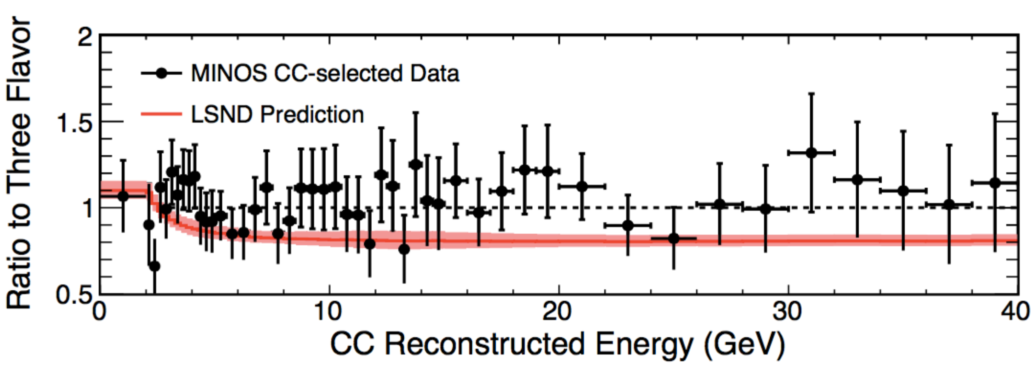
Stringent limits on mixing with a sterile neutrino with Δm^2 from 10^{-3} to 0.3 eV^2

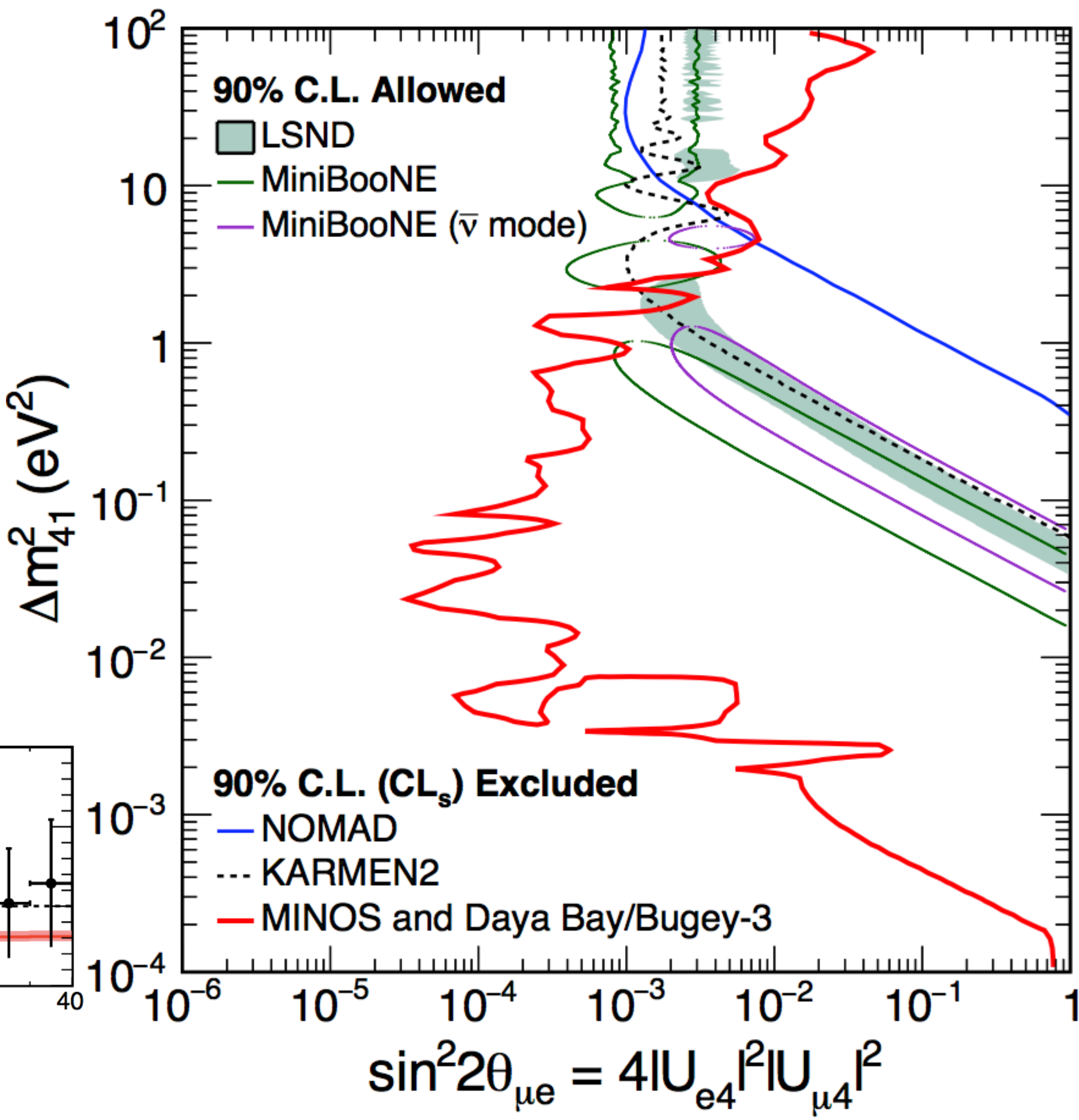
MINOS, Daya Bay, Bugey

arXiv:1607.01177

Ratio of MINOS far to near spectra, combined with reactor U_{e4} limit, exclude much of the LSND allowed region.

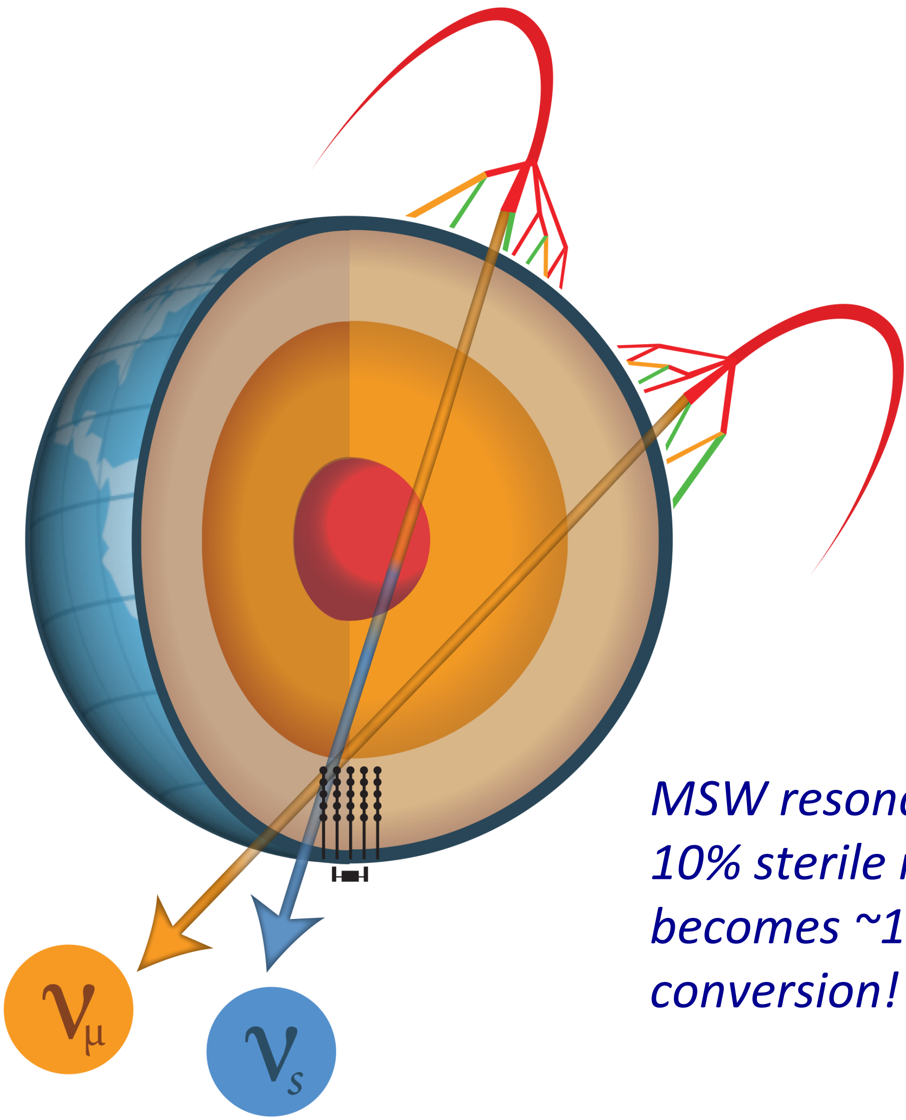






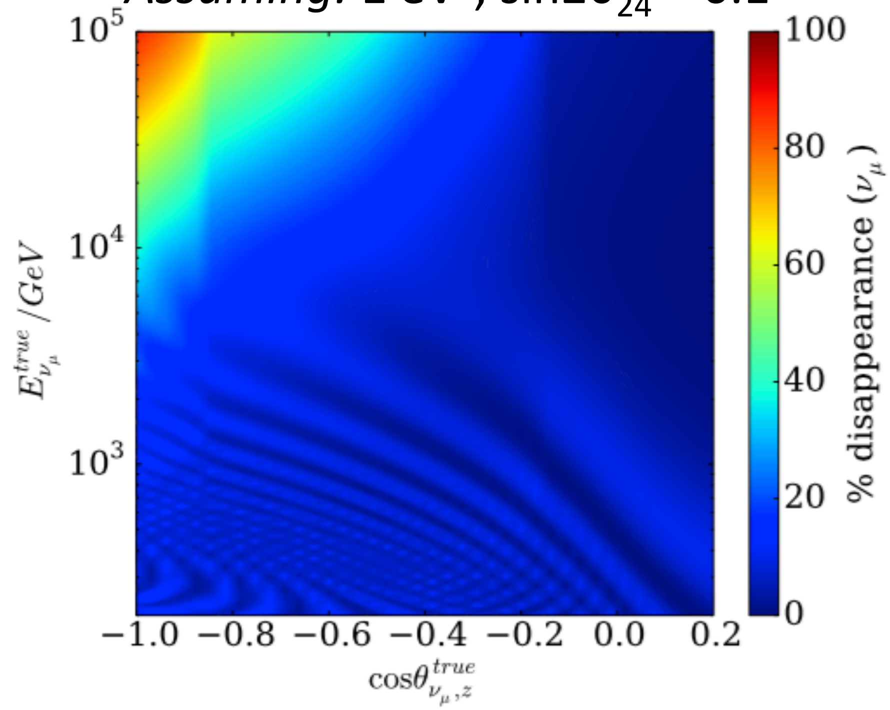
IceCUBE

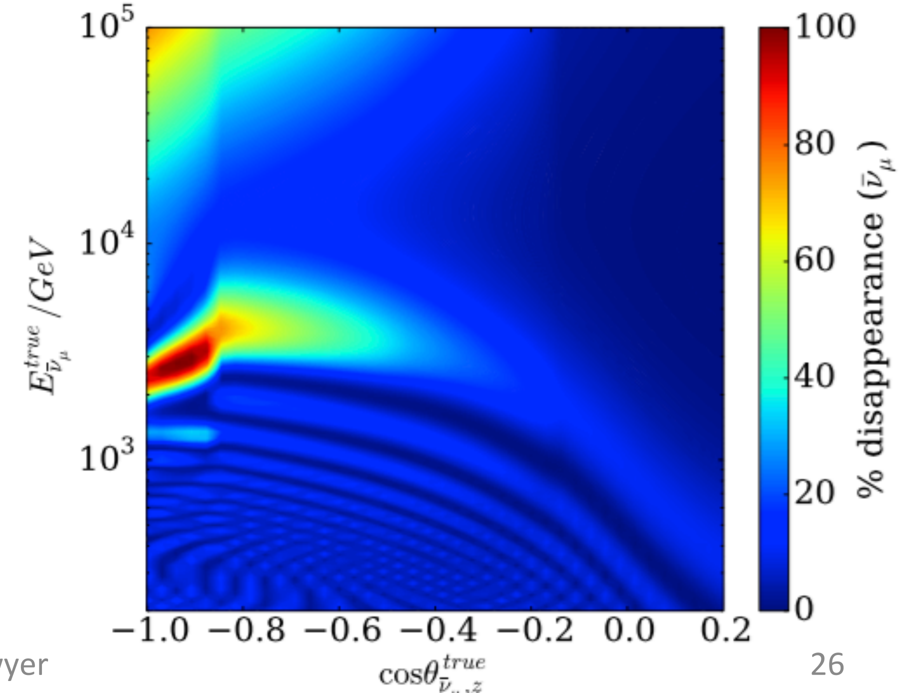
Sterile neutrino would cause MSW resonant conversion of atmospheric neutrinos.



MSW resonance: 10% sterile mixing becomes ~100% conversion!

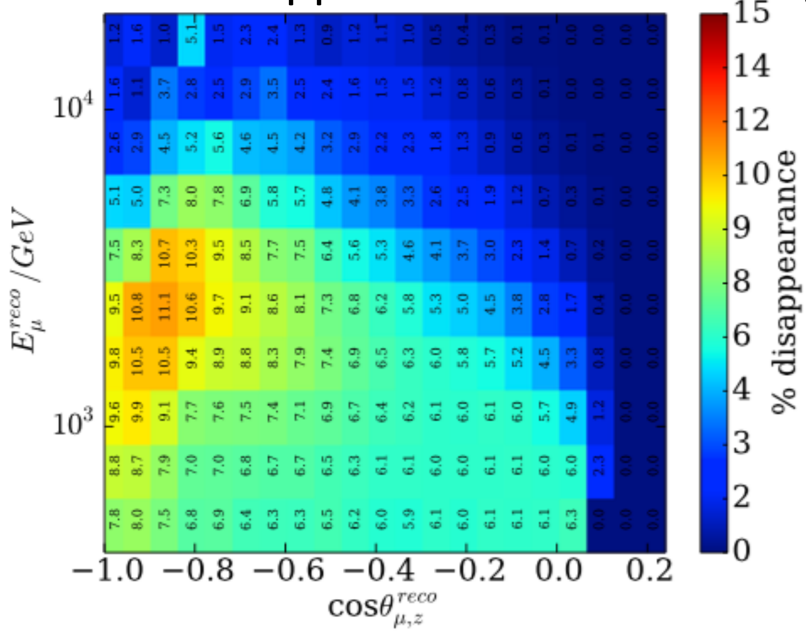
Assuming: 1 eV^2, $\sin 2\theta_{24}$ = 0.1



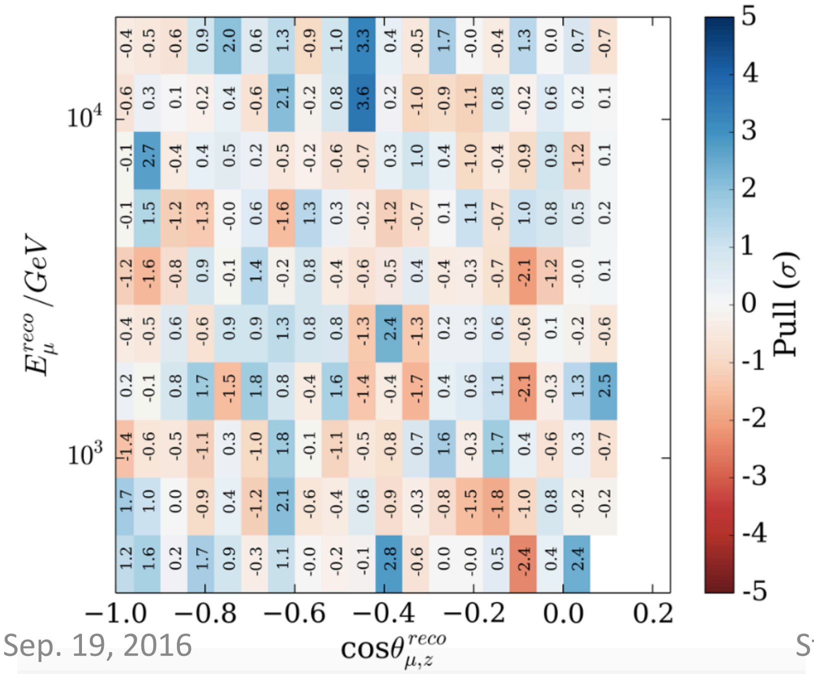


IceCUBE

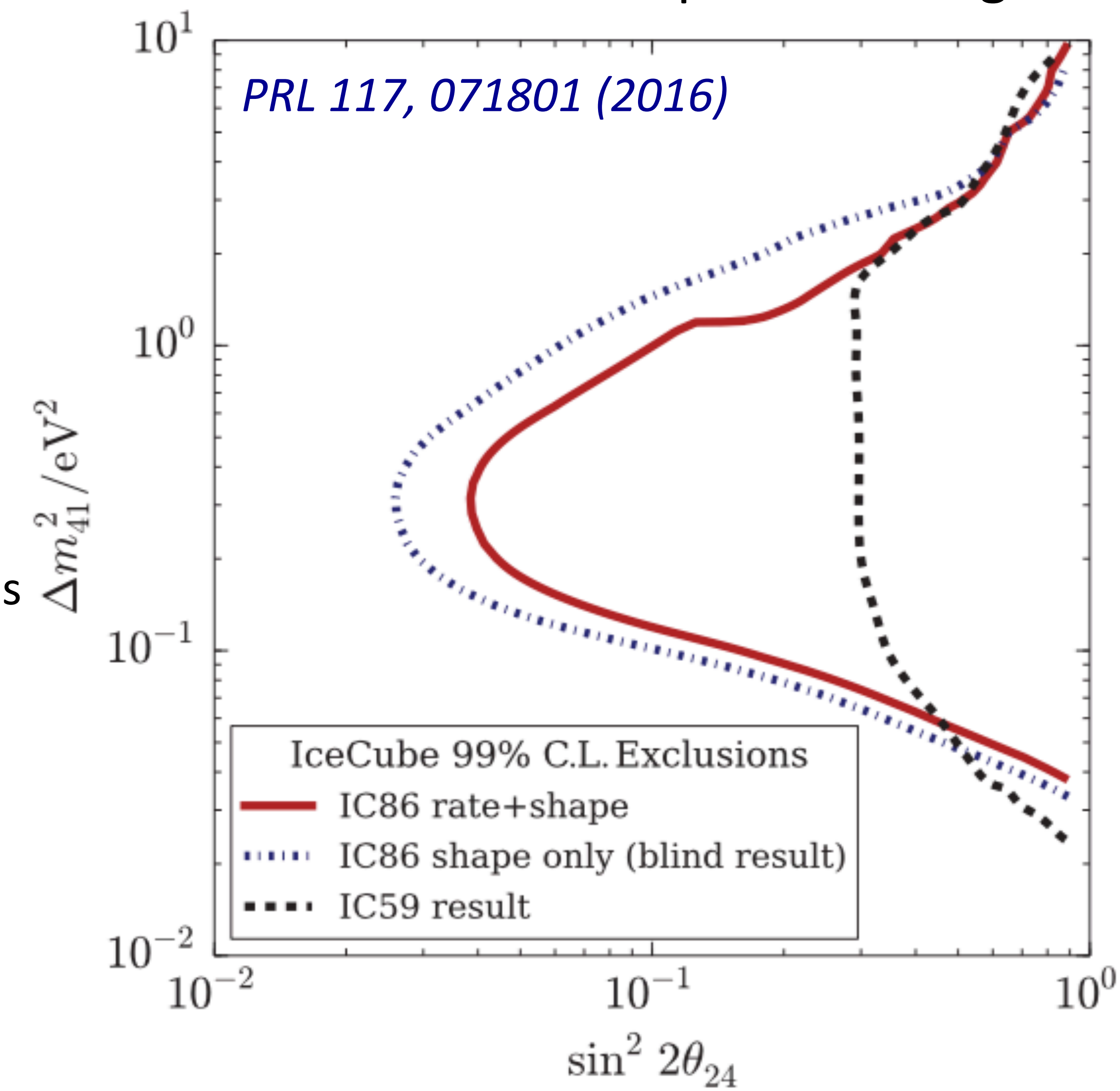
Predicted disappearance in IceCUBE signal



Result consistent with no-sterile hypothesis



Result excludes LSND preferred region.

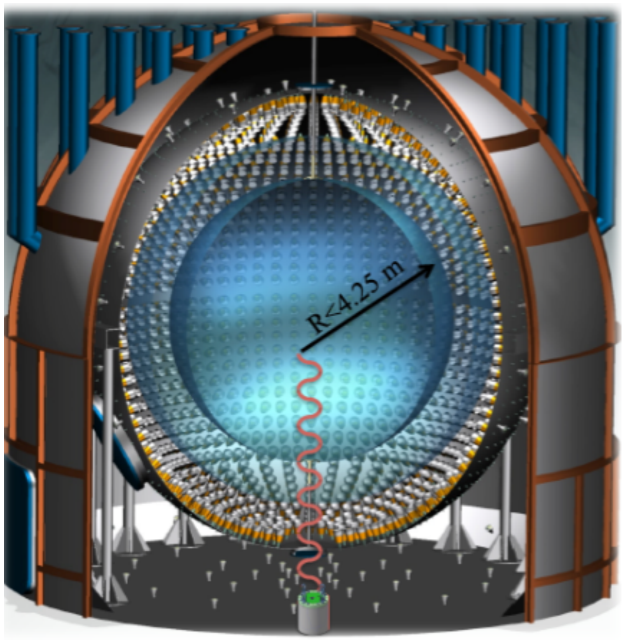


Part 3:
Looking Forward

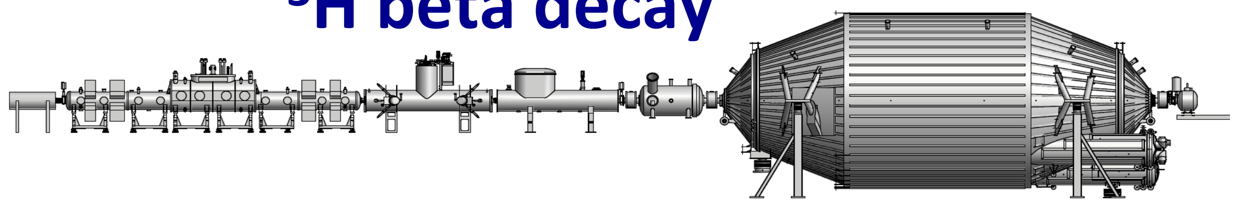
Many experimental routes

See talks by T. Lasserre and G. Fuller

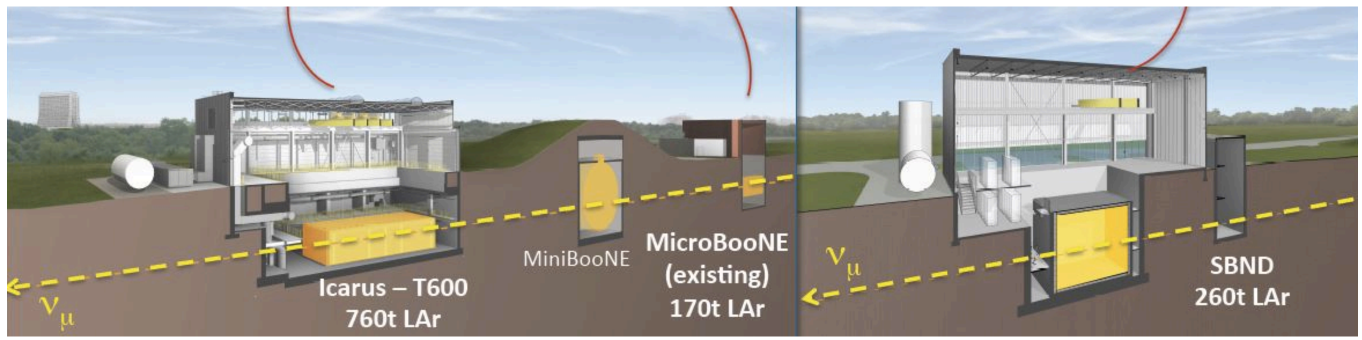
Intense Radioactive Sources



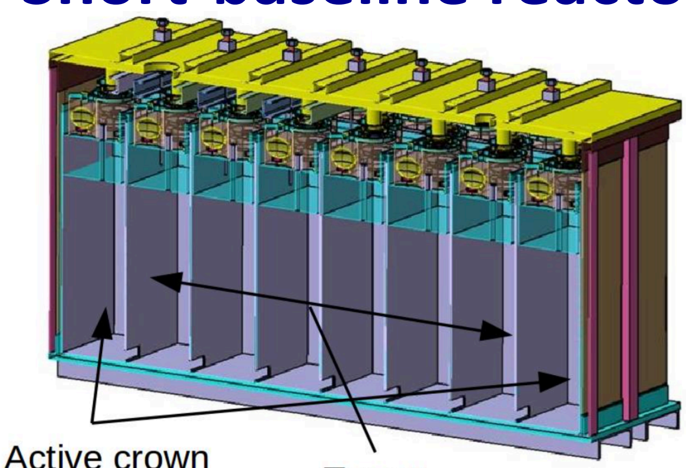
^{3}H beta decay



Accelerator Neutrinos

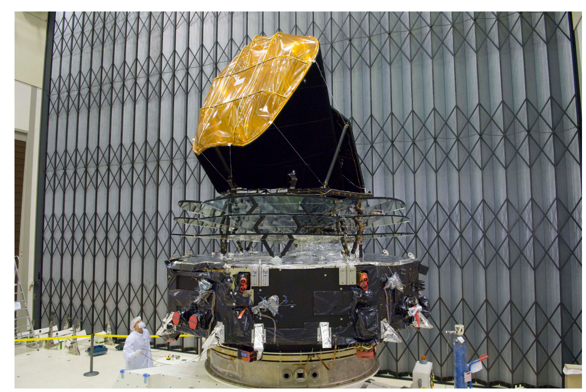


Short-baseline reactor



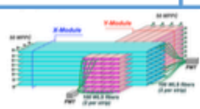
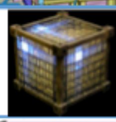
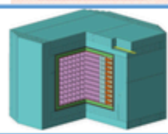
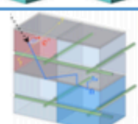
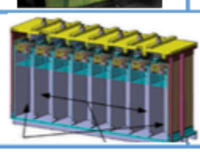
CEνNS

Astrophysics



Future Reactor Experiments

N. Bowden, Neutrino2016

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Not so easy…

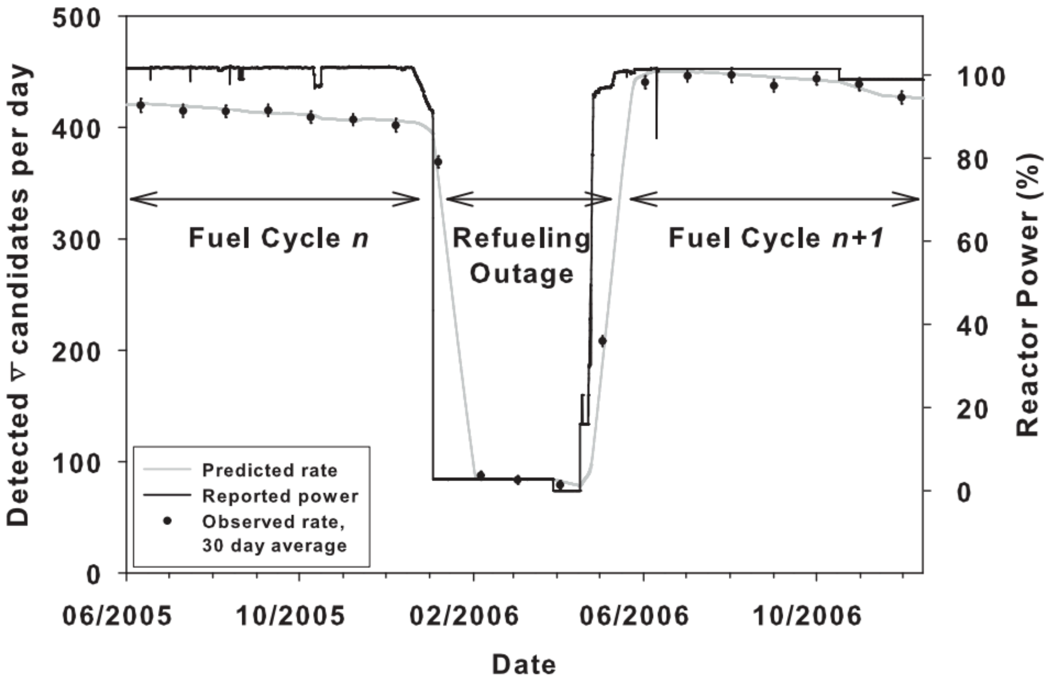
SONGS1:

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

Signal: ~400 interactions / day

Background: ~100 interactions / day

NIM A572, 985 (2007)



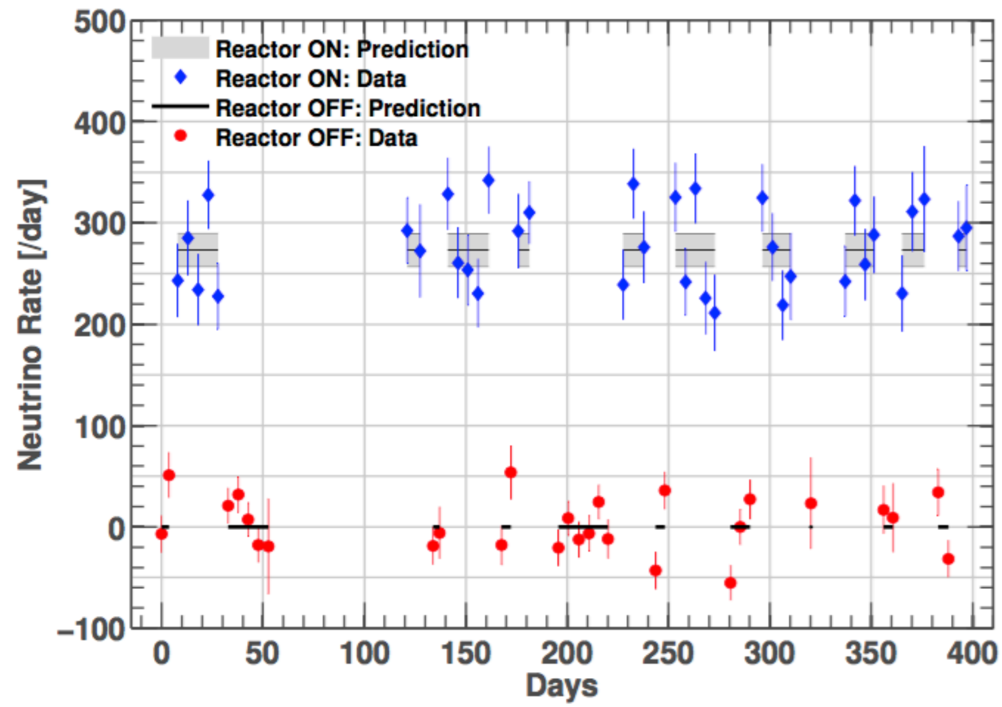
Nucifer:

Demonstrated detection at ~12m from OSIRIS reactor core.

Signal: ~300 interactions / day

Background: ~1000 interactions / day

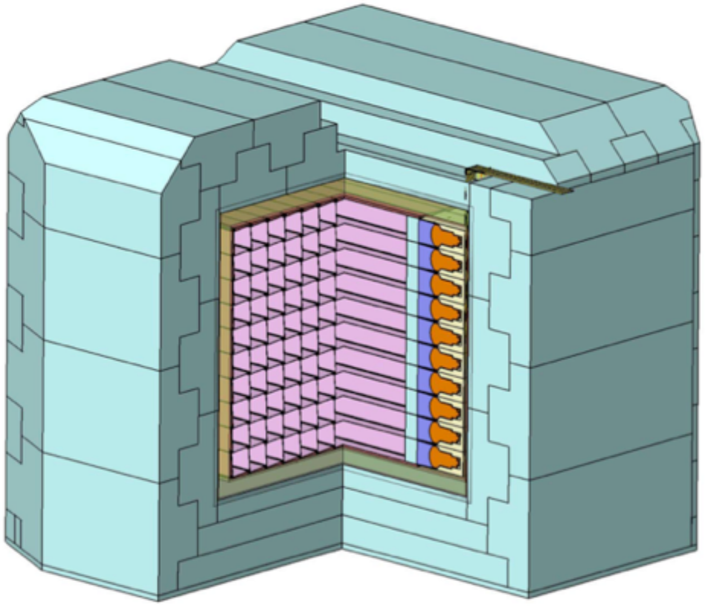
arXiv:1509.05610

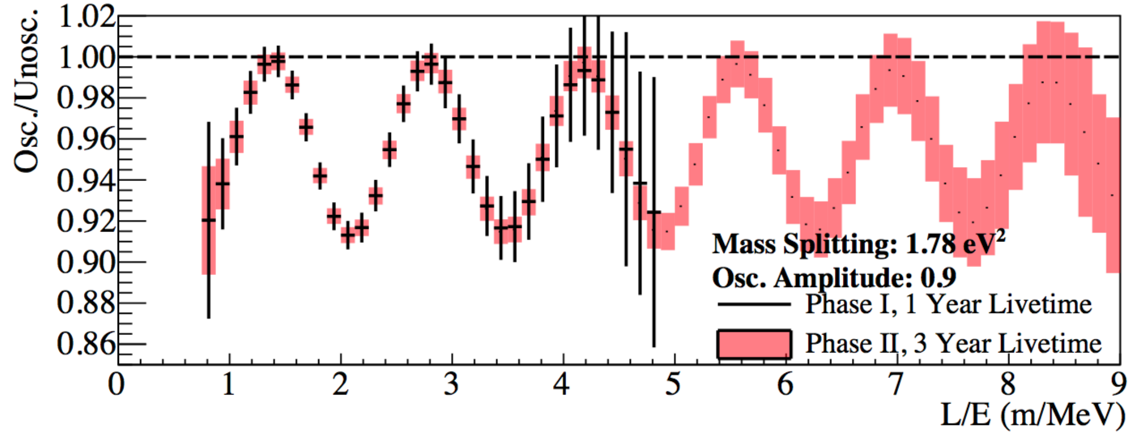


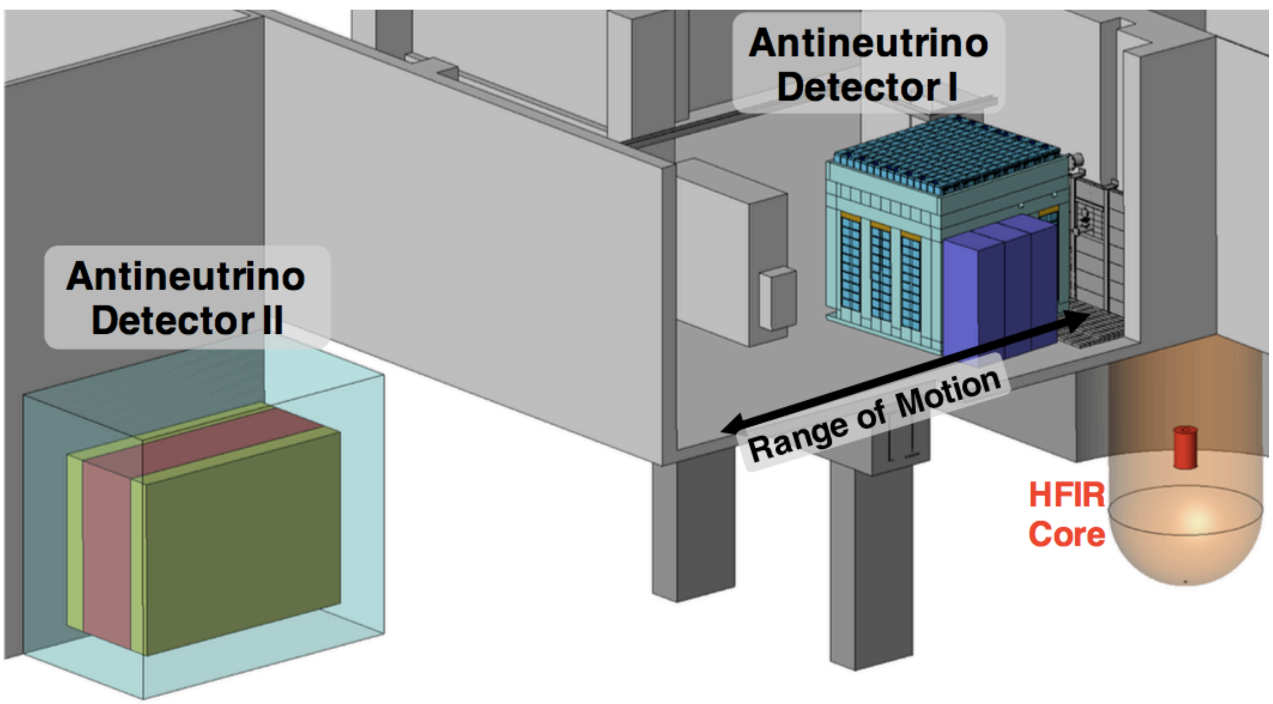
Lesson: Difficult to measure faint neutrinos meters from nuclear core.

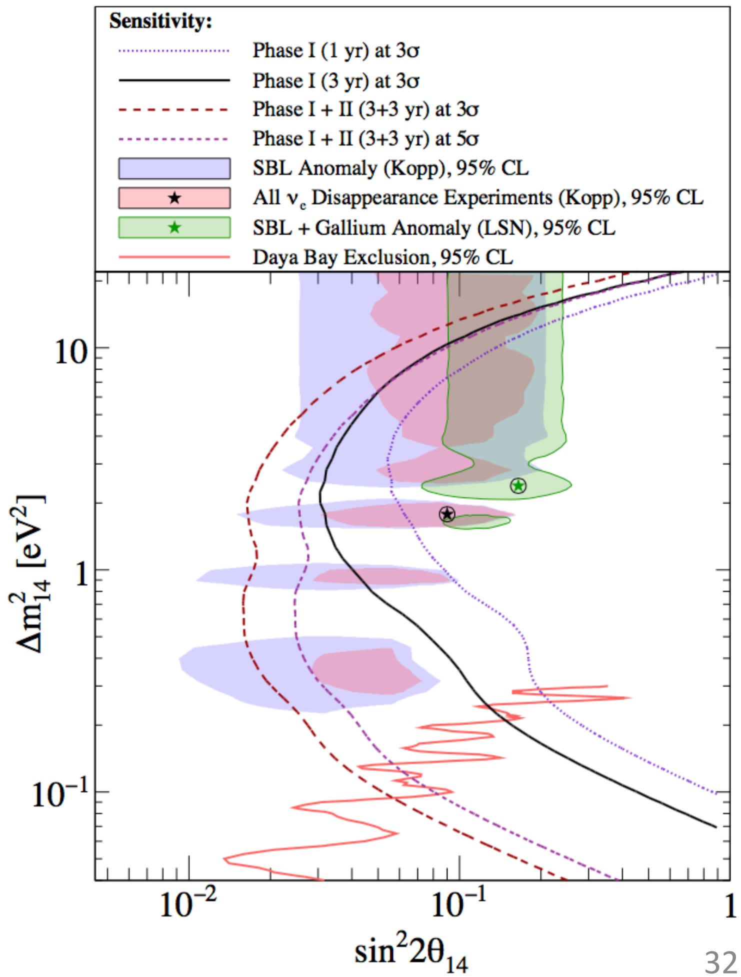
Example: PROSPECT

arXiv:1512.02202



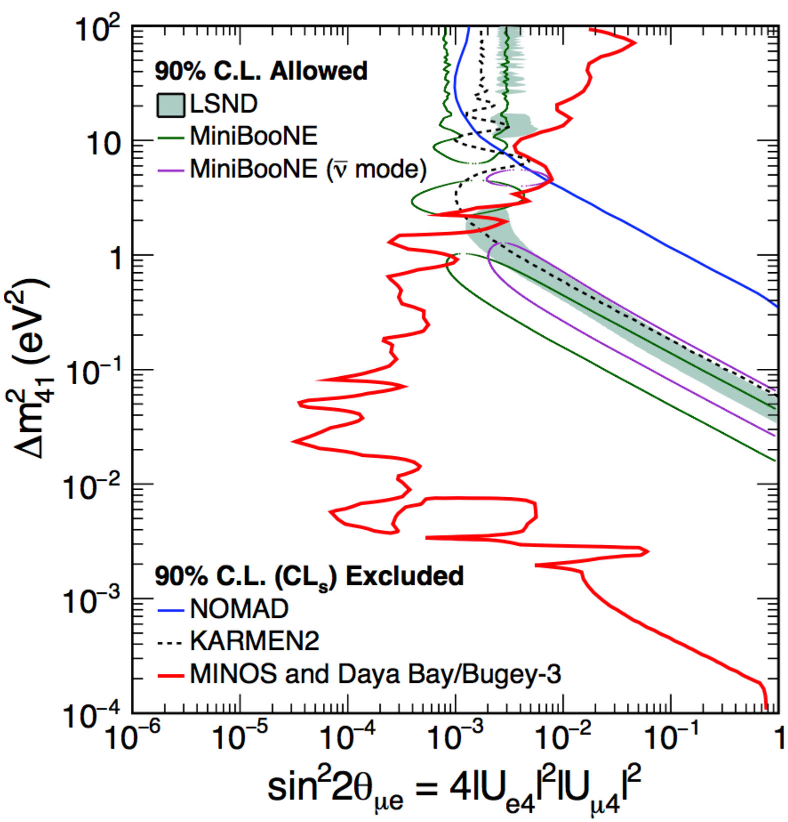






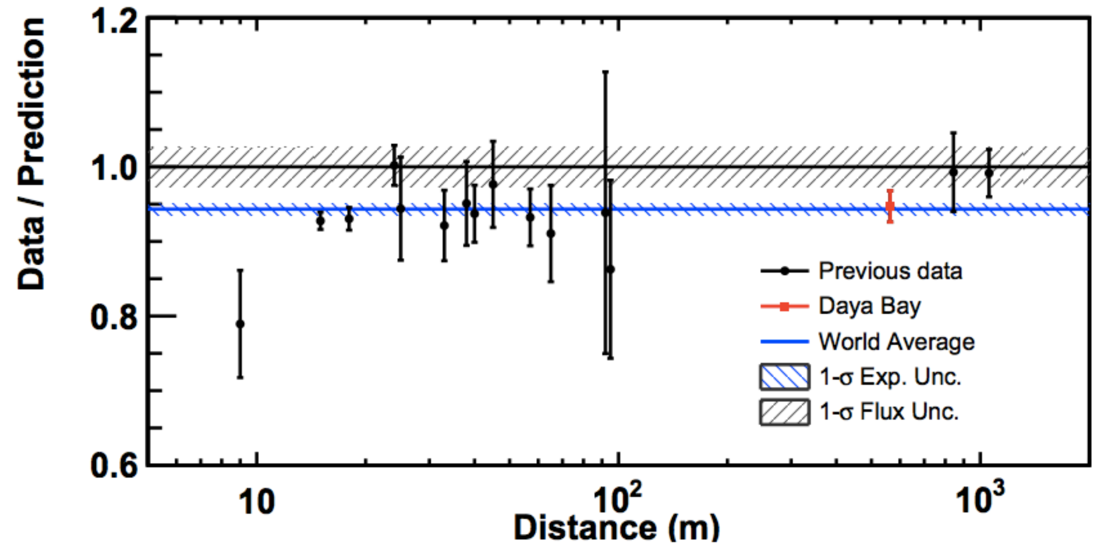
Summary

Sterile neutrinos: Potential new physics beyond the Standard Model



Recent progress via relative measurements

Existing hints: real, or subtle artifacts of absolute measurements?



Broad program will search for sterile neutrinos (at ~eV and beyond)