The Decays of Three Top Contributors to the Reactor $\bar{\nu}_e$ High-Energy Spectrum (^{92}Rb, ^{96gs}Y, and ^{142}Cs) Studied with the Modular Total Absorption Spectrometer (MTAS)

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Neutrino Workshop, NS 2016

Motivation - Reactor Decay Heat

Nuclear Fuel Cycle*

To improve our knowledge on the energy release (γ, β, $\bar{\nu}$, n) from fission products abundant during nuclear fuel cycle – operation safety (loss-of-cooling accident) and operation efficiency, reactor material science, nuclear waste transportation and storage.

Nuclear Structure

To determine true β-decay intensities which helps to identify their origin, and contributes to the verification and improvements of β-strength predictions (including β half-life extrapolations for r-process analysis).

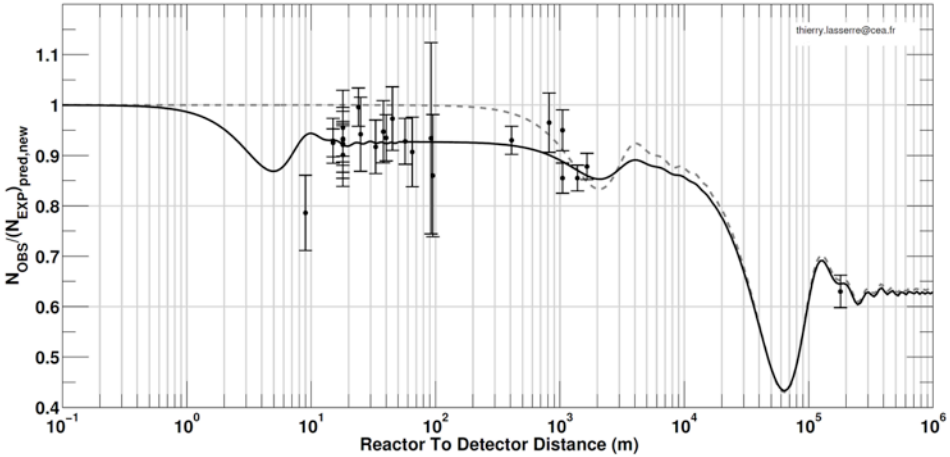
*T. Yoshida and A. L. Nichols, Assessment of Fission Product Decay Data for Decay Heat Calculations: A report by the Working Party on International Evaluation Co-operation of the Nuclear Energy Agency Nuclear Science Committee (Nuclear Energy Agency, Organization for Economic Co-operation and Development, Paris, France, 2007), ISBN 9789264990340.

Motivation - Antineutrino Reactor Precision Measurements

Antineutrino Reactor Anomaly

~6% overall deficiency of antineutrinos

Ratio of measured to expected ~0.946(22)

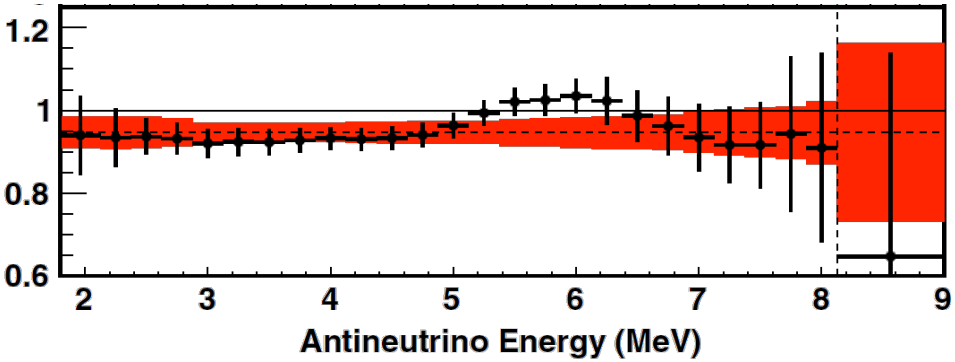


Dashed is expected normalized antineutrino flux.
Solid is sterile antineutrino adjusted normalized flux.

Reactor Anomaly: Mention *et al.*, PRD **83**, 2011

Gando, A. et al. arXiv:1309.6805 [hep-ex]
(KamLand white paper to look for sterile neutrinos)

Antineutrino Reactor Shoulder



Daya Bay: An *et al.*, PRL **116**, 061801 (2016)

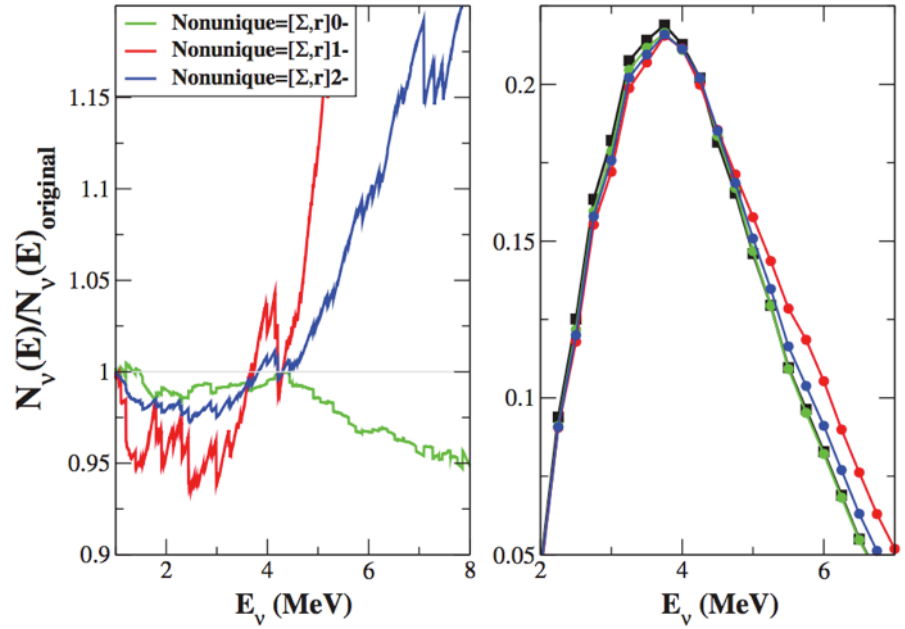
Similar shoulder seen with RENO and Double Chooz

$\bar{\nu}_e$ from Nuclear Reactors

Motivation - What is "Expected" Conversion vs Summation Method

Conversion method is an integral β measurement by fuel type.

β energies are measured by fuel type (^{235}U, ~~^{238}U~~, ^{239}Pu, ^{241}Pu) and then converted to an antineutrino spectrum.
But the β spectrum depends on the individual decay "forbiddenness", *i.e.* allowed, first forbidden, unique first forbidden, second forbidden etc. and converting this to an antineutrino spectrum is not straight forward.
Measuring all of the bs aggregately does not allow precise prediction of antineutrino energies, an average Z is used to calculate an average Fermi function.

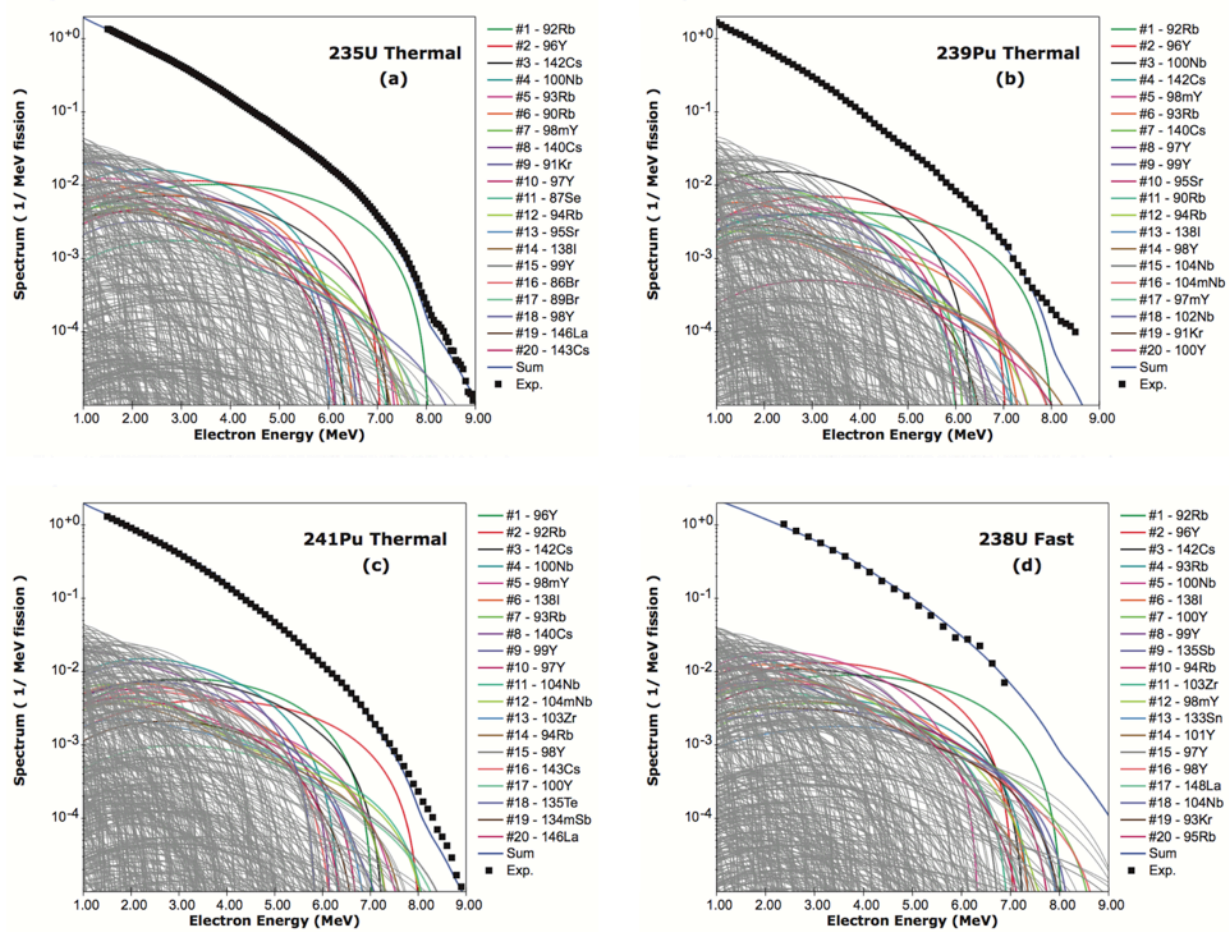


Limitations based on the shape factor for each type of decay and by the weak magnetism corrections are shown in
Hayes, *et al.*, PRL **112**, 202501 (2014)

Motivation - What is "Expected" Conversion vs Summation Method

Summation method converts each β decay produced during fission. There are a lot of β decays, over 800 for each fission product!

But there are a few dominant decays for the anomaly and the shoulder, the top 20 for each fuel type is shown at left.



A. A. Sonzogni, T. D. Johnson, and E. A. McCutchan, PRC **91**, 011301(R) (2015)

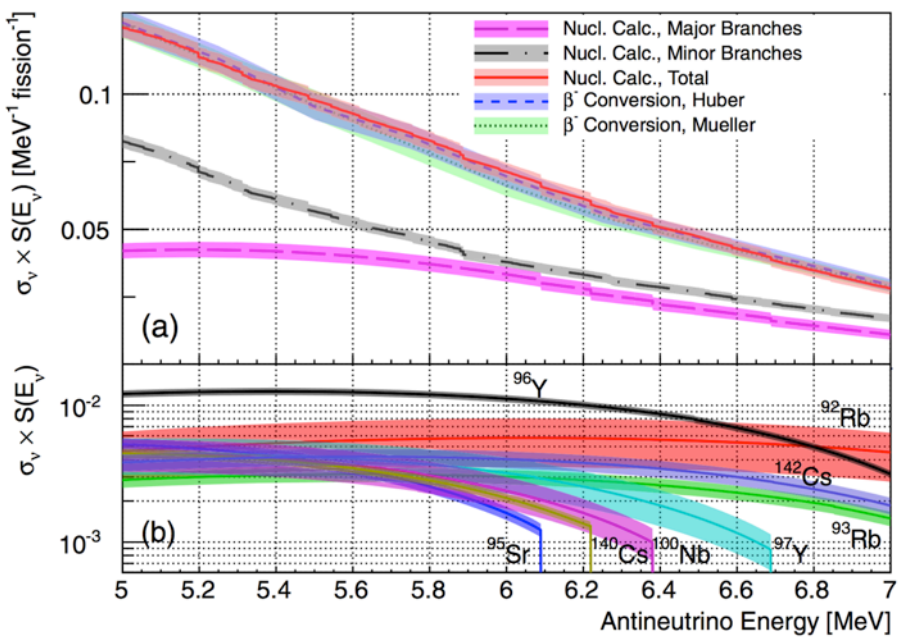
Limitations based on accuracy of the nuclear data.

Motivation - Top Contributors to the Shoulder

TABLE I. Most prominent beta decay branches with $E_{\bar{\nu}} = 5$–7 MeV. The table presents the decay parent, end-point energy, half-life, and decay ft value. The decay type describes the parent and daughter states. The moderate ft values and lack of significant change of J^{π} suggest that all but possibly ^{140}Cs decay with allowed spectral shapes. The rate each branch contributes to the total between 5–7 MeV is N, accounting for the inverse beta decay cross section. The 1σ uncertainty due to the fission yield and branching fraction is σ_N.

Isotope	Q(MeV)	$t(s)$	Log(ft)	Decay type	N (%)	σ_N (%)
^{96}Y	7.103	5.34	5.59	$0^- \rightarrow 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \rightarrow 0^+$	~~7.4~~ ~14	~~2.9~~ ~1
^{142}Cs	7.308	1.68	5.59	$0^- \rightarrow 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \rightarrow 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	6.14	$5/2^- \rightarrow 5/2^+$	3.7	0.5
^{100}Nb	6.381	1.5	5.1	$1^+ \rightarrow 0^-$	3.0	0.8
^{140}Cs	6.220	63.7	7.05	$1^- \rightarrow 0^+$	2.7	0.2
^{95}Sr	6.090	23.9	6.16	$1/2^+ \rightarrow 1/2^-$	2.6	0.3

D.A. Dwyer and T.J. Langford, PRL **114**, 012502 (2015)

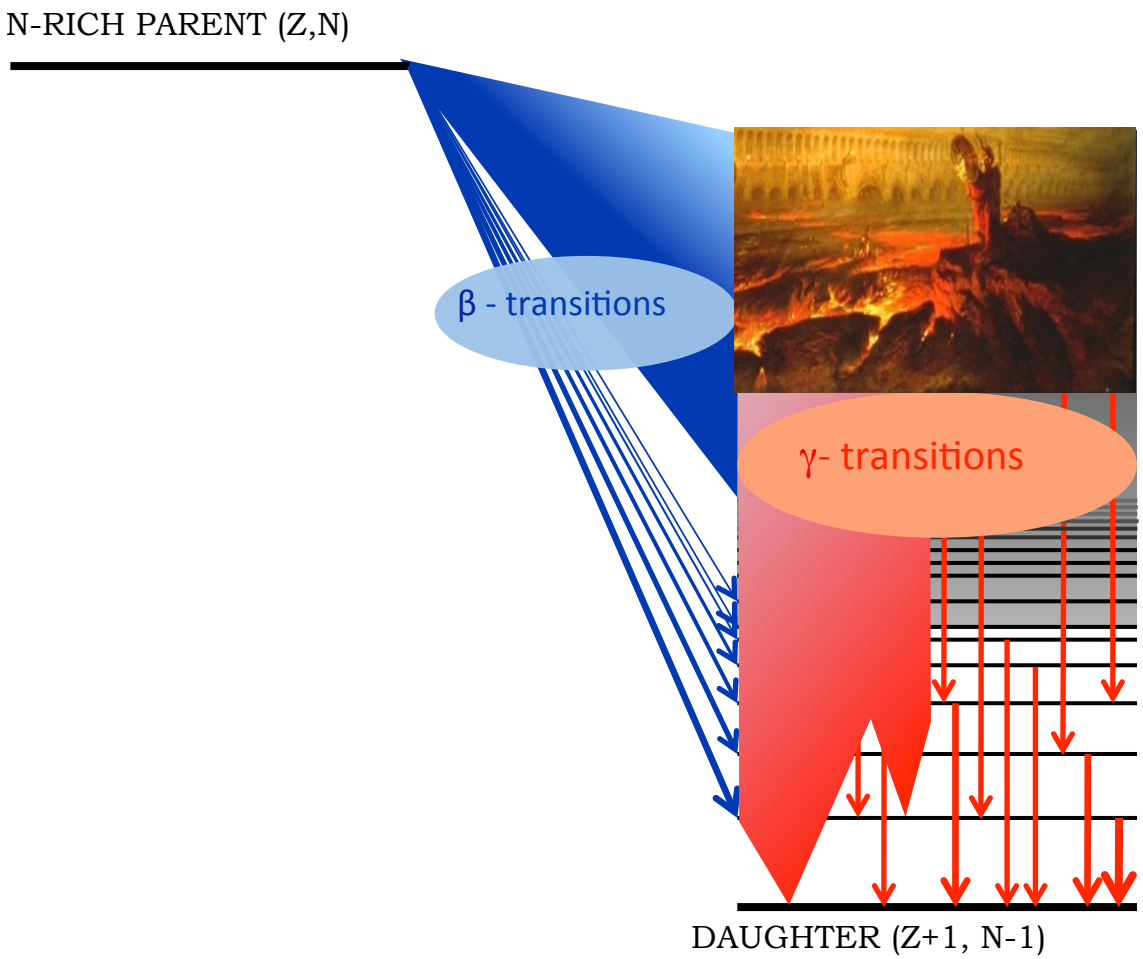


Used older ENSDF ^{92}Rb ground state feeding (50±18%, which was increased to 95.2±.7%).

^{92}Rb now most dominant contributor to "shoulder".

Is there some reason to suspect the accuracy of other nuclear data?

Motivation - Pandemonium Effect



Pandemonium Effect

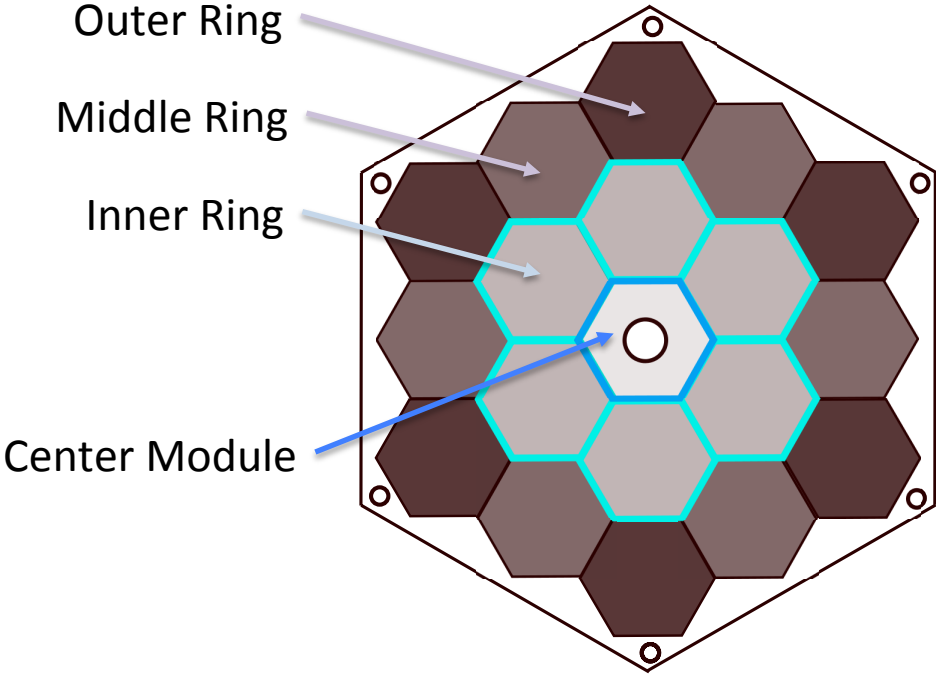
For high-precision, low efficiency detectors, the combination of low efficiency with a high density of states fed by β decay means many multi-γ decays will be misinterpreted as direct β feeding to lower energy levels.

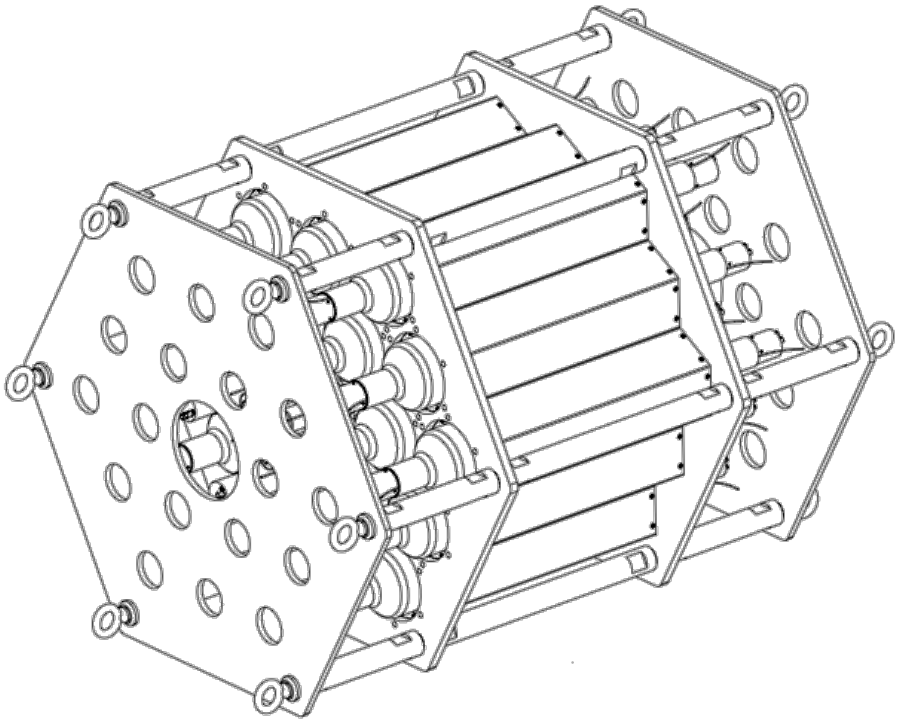
Hardy et al, PL B 71,1977

Greenwood *et al.*,1997, Algora *et al.*, 2010, Zakari-Issoufou *et al.*, 2015

Can the Pandemonium Effect be overcome?

The Modular Total Absorption Spectrometer - MTAS



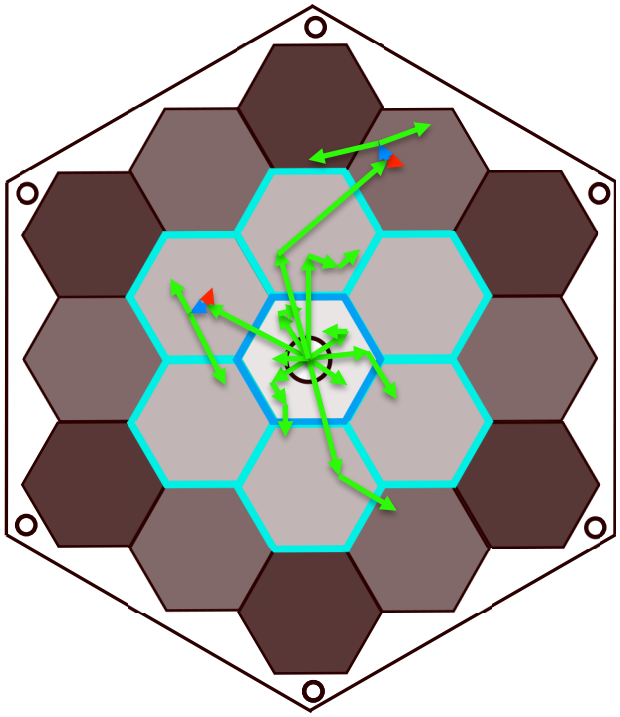


MTAS: 18 - 8”x7”x21” hexagon NaI(Tl) modules
Organized in 3 Rings of 6 modules each (Inner, Middle, and Outer)
1 - Center module, same dimensions but with a 2.5” diameter hole
over a ton of NaI(Tl)!

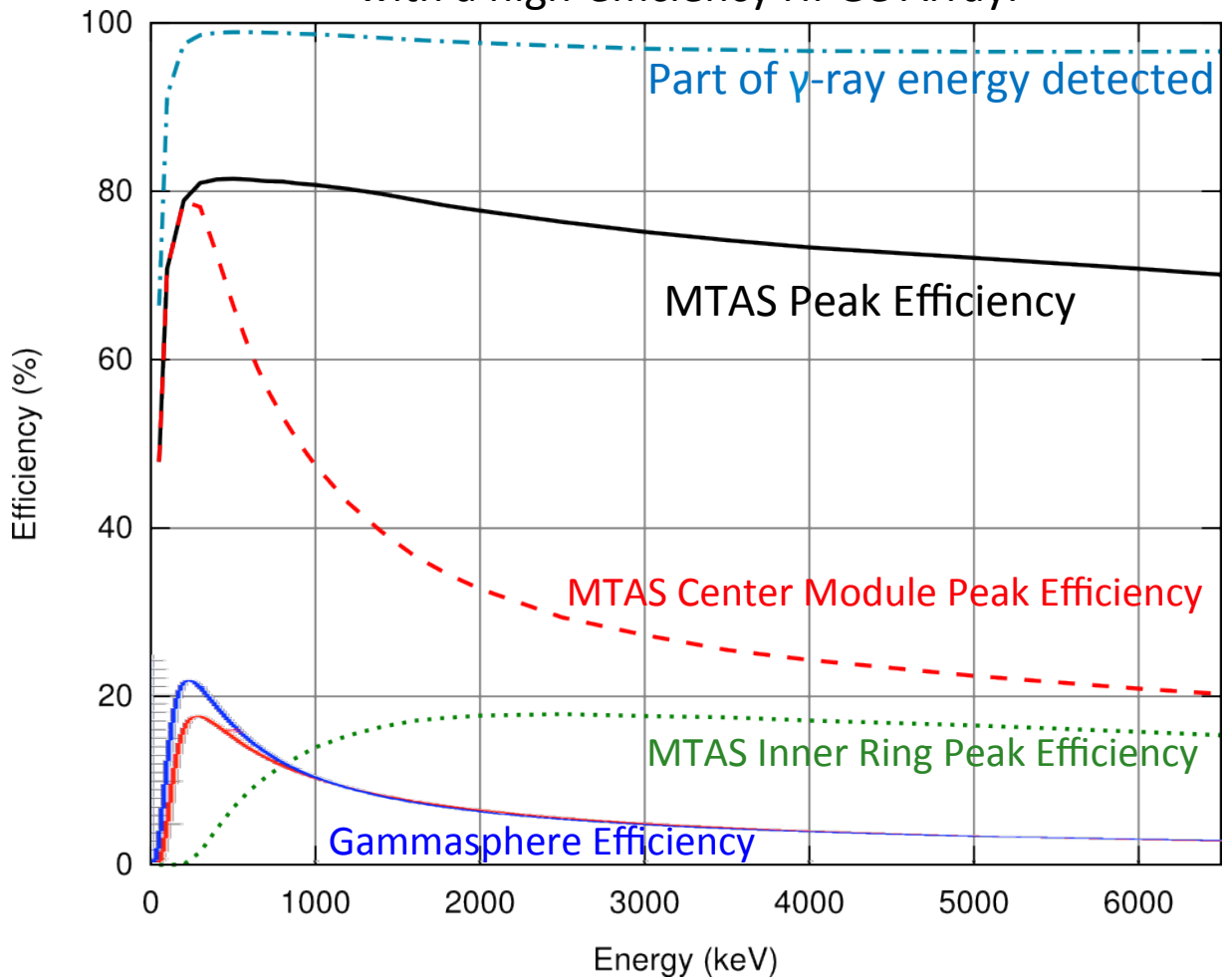
Other total absorption spectrometers include the TAS at ISOLDE, Lucrecia, TAS at GSI (now at UML), SuN (MSU), DTAS (Valencia, Jyvaskyla).

What MTAS Detects - γ-Rays

γs in MTAS

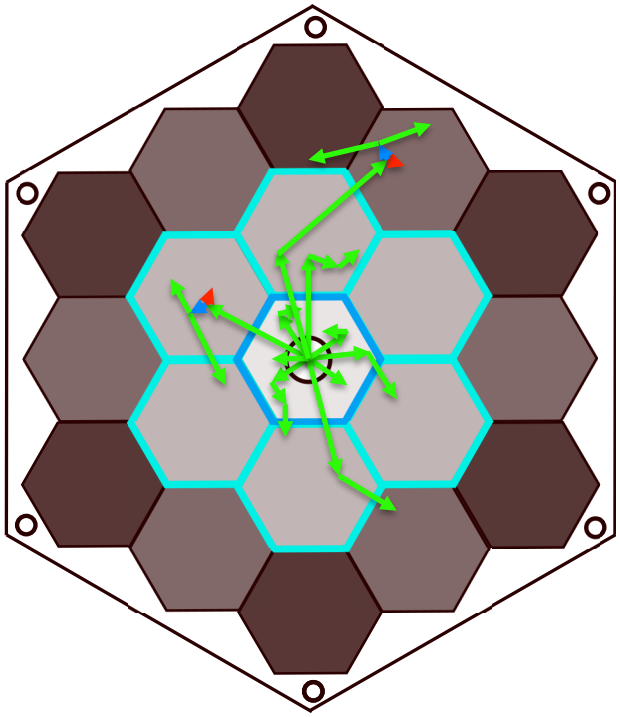


Efficiency of various MTAS regions and comparison with a high-efficiency HPGe Array.



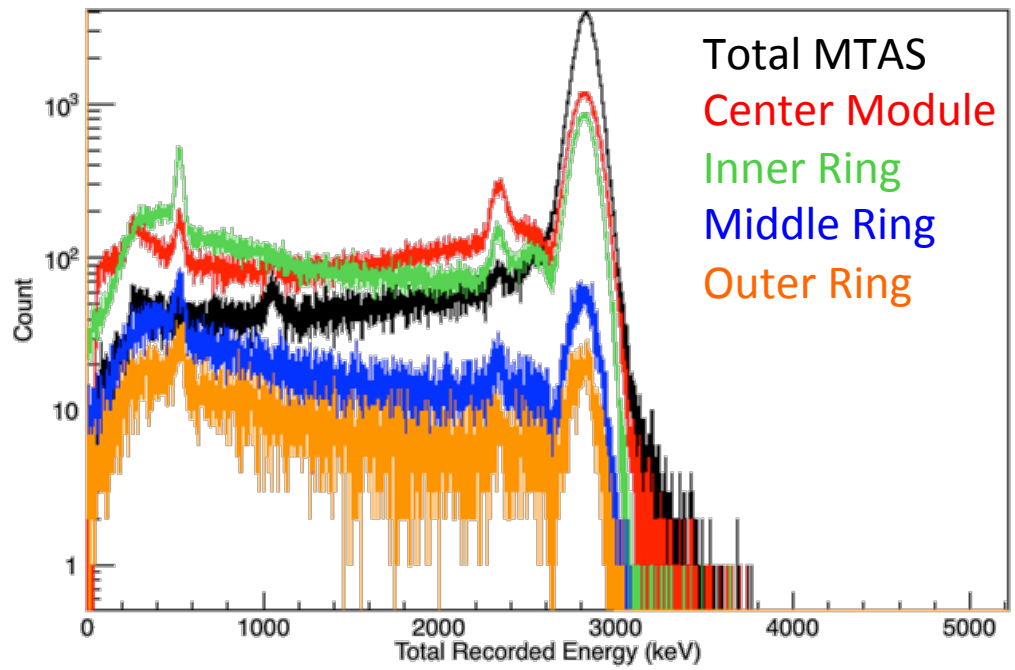
What MTAS Detects - γ-Rays

γs in MTAS



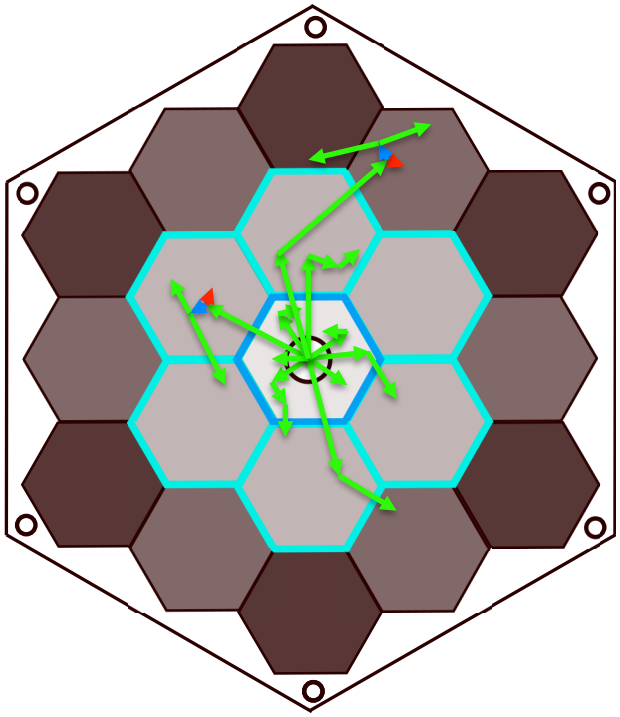
Includes nonlinear light production.

MTAS response to a simulated 2850 keV γ-ray + allowed β spectrum for ^{137}Xe



What MTAS Detects - γ Rays

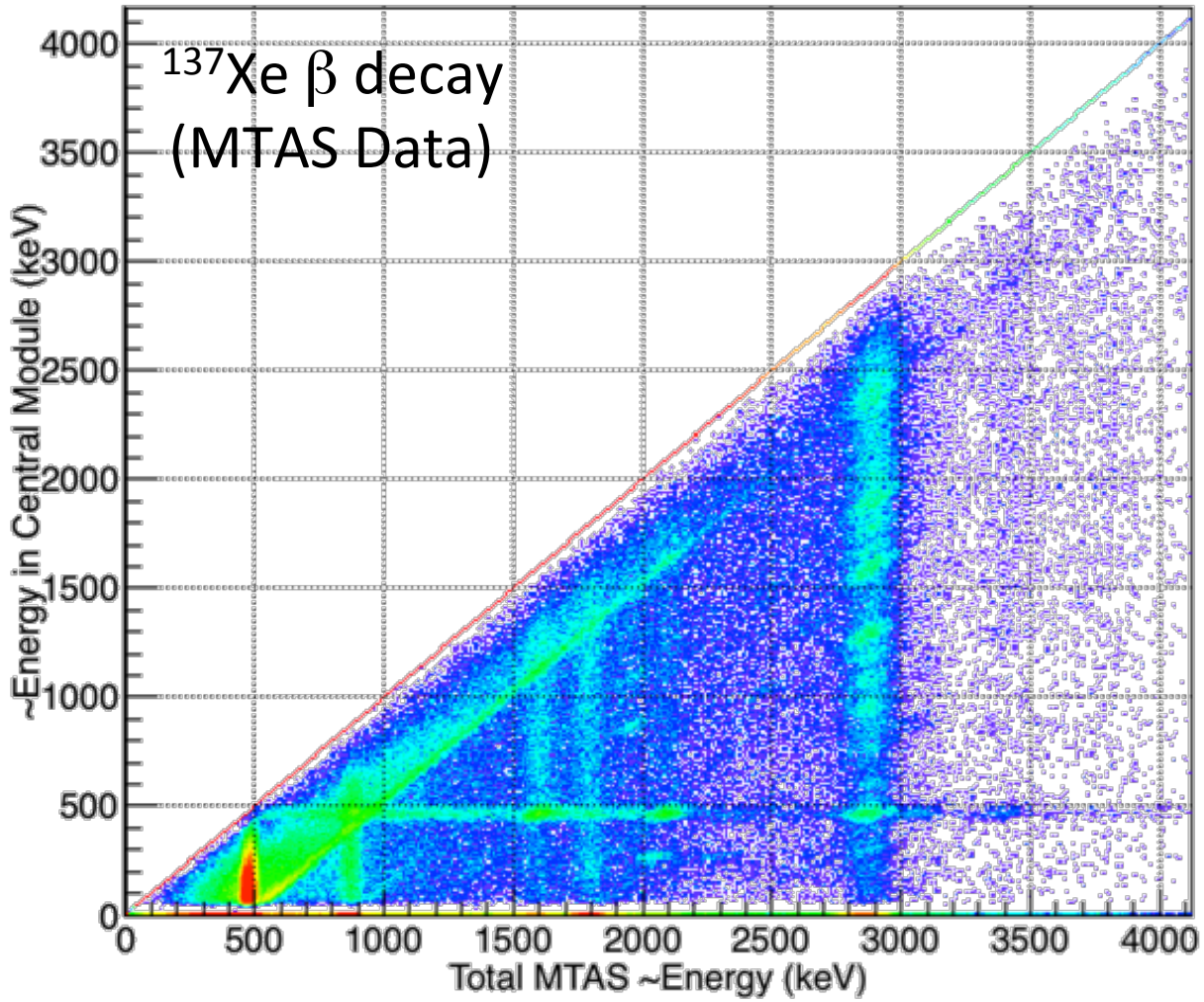
γs in MTAS



Segmentation is powerful.

Can see dominant decay paths from various energy levels.

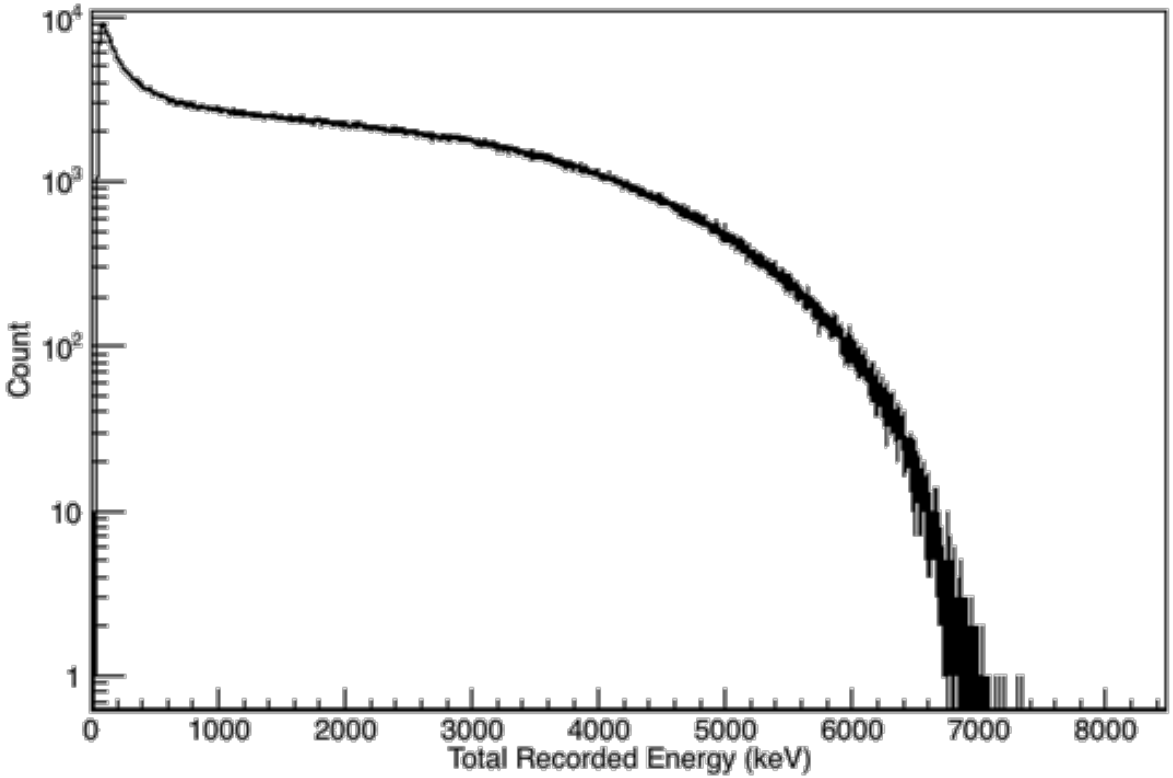
MTAS Center vs Total Energy



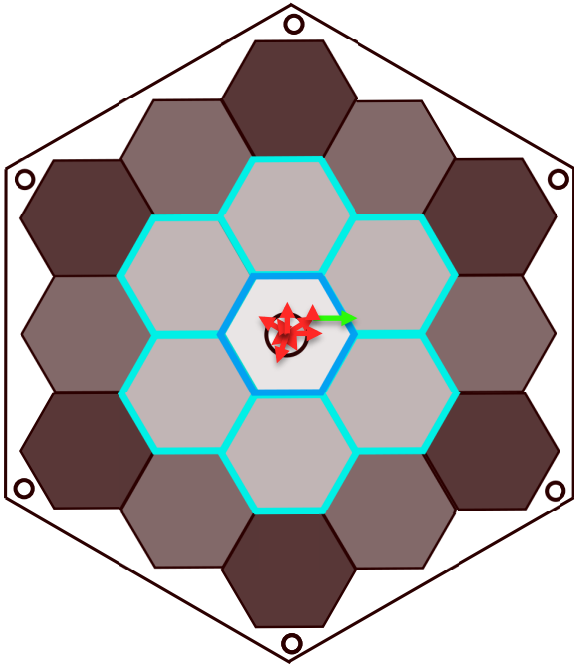
B.C. Rasco, *et. al.*, JPS Conf. Proc. 6, 107 (2015)

What MTAS Detects - βs

Simulated Total MTAS response to βs from ^{92}Rb ground state to ^{92}Sr ground state decay (Q_β = 8095 keV)



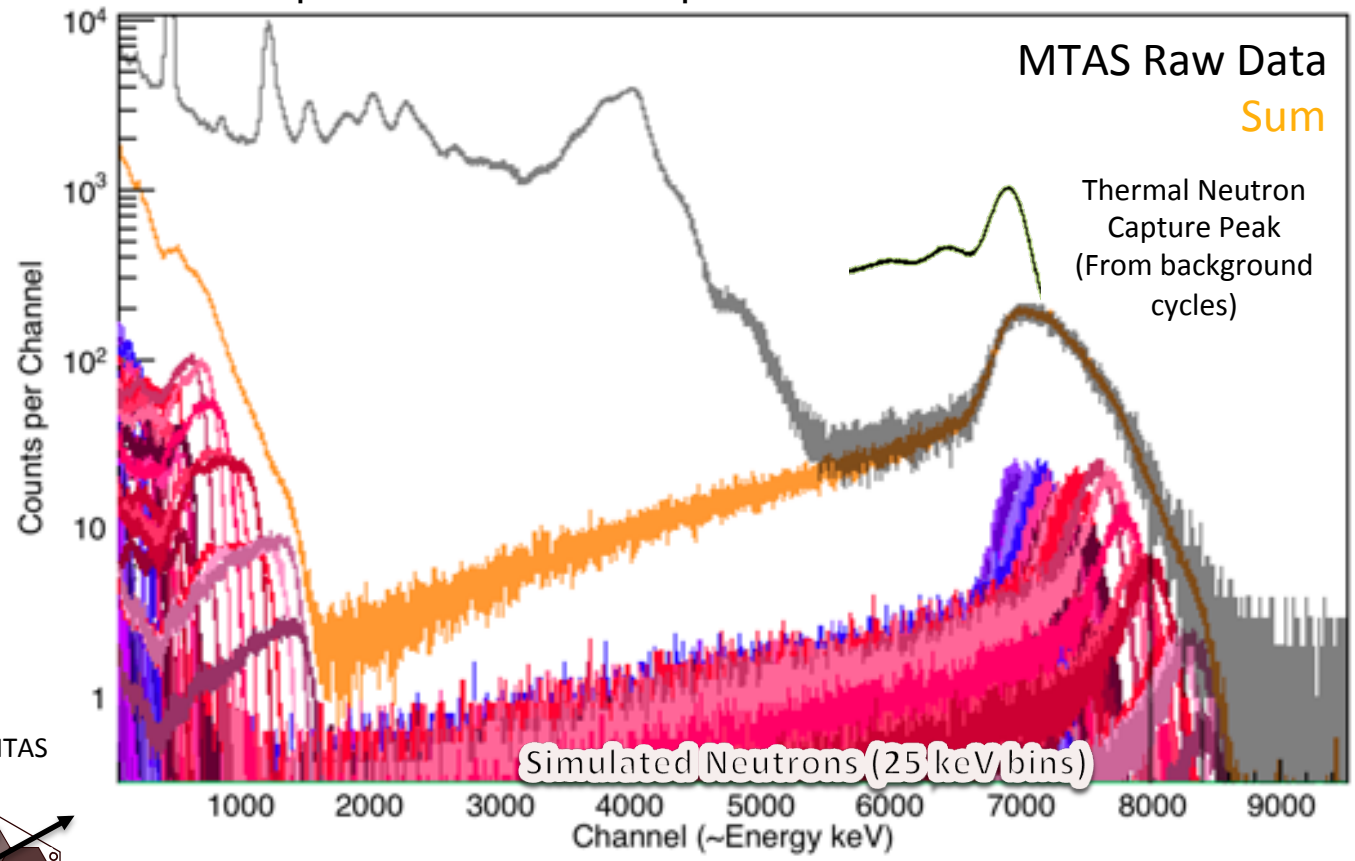
βs in MTAS



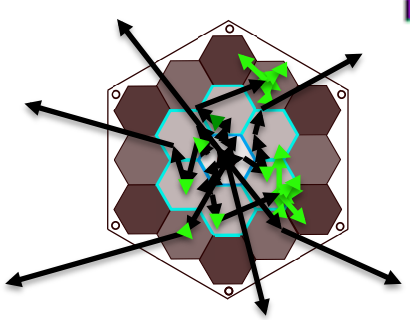
For ^{92}Rb decay to the ^{92}Sr ground state
~55% of the decay βs trigger the silicon detectors
and leave energy in MTAS

What MTAS Detects - Neutrons

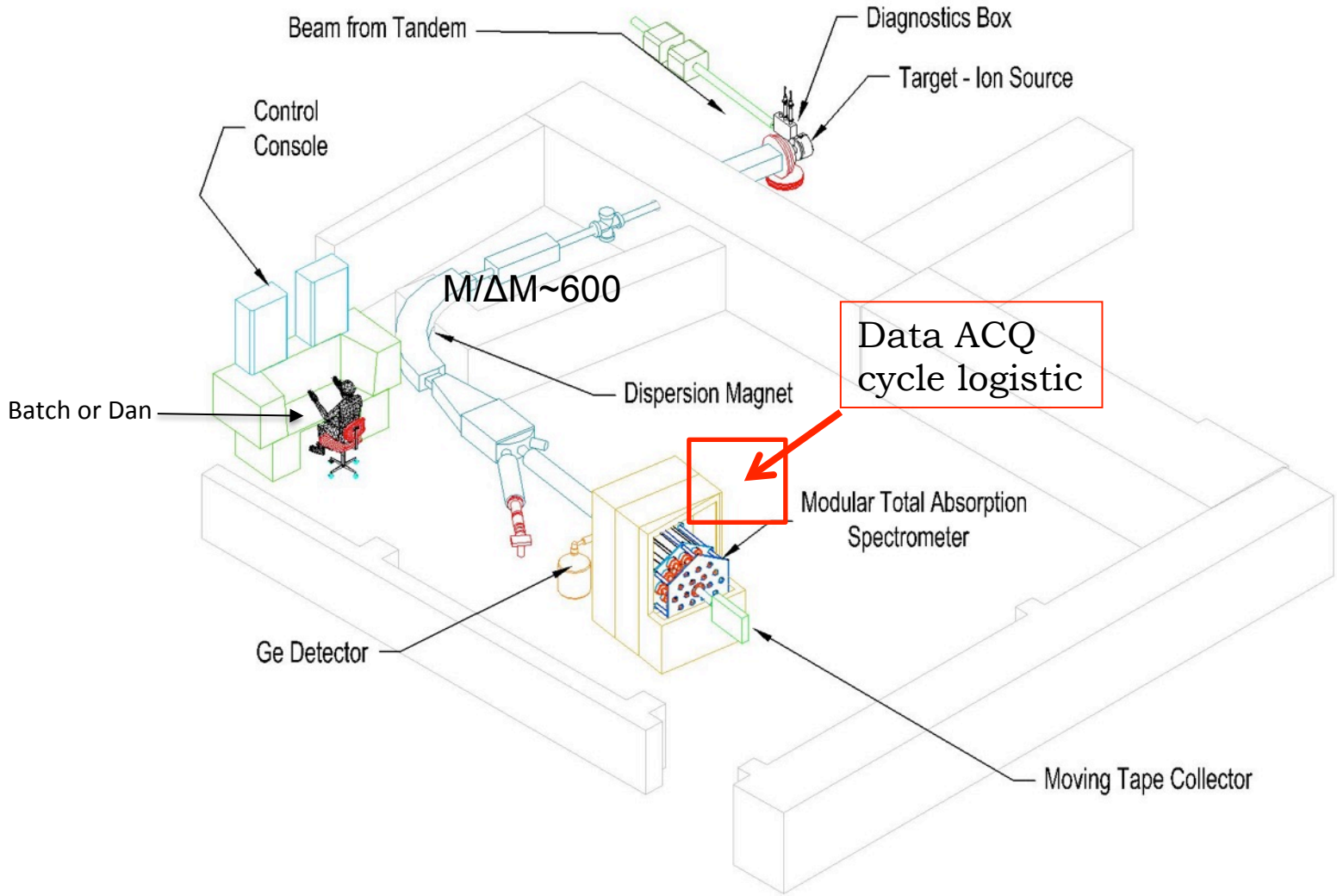
^{137}I Q_{β}= 6027 keV, $Q_{\beta\text{-}n}$= 2002 keV



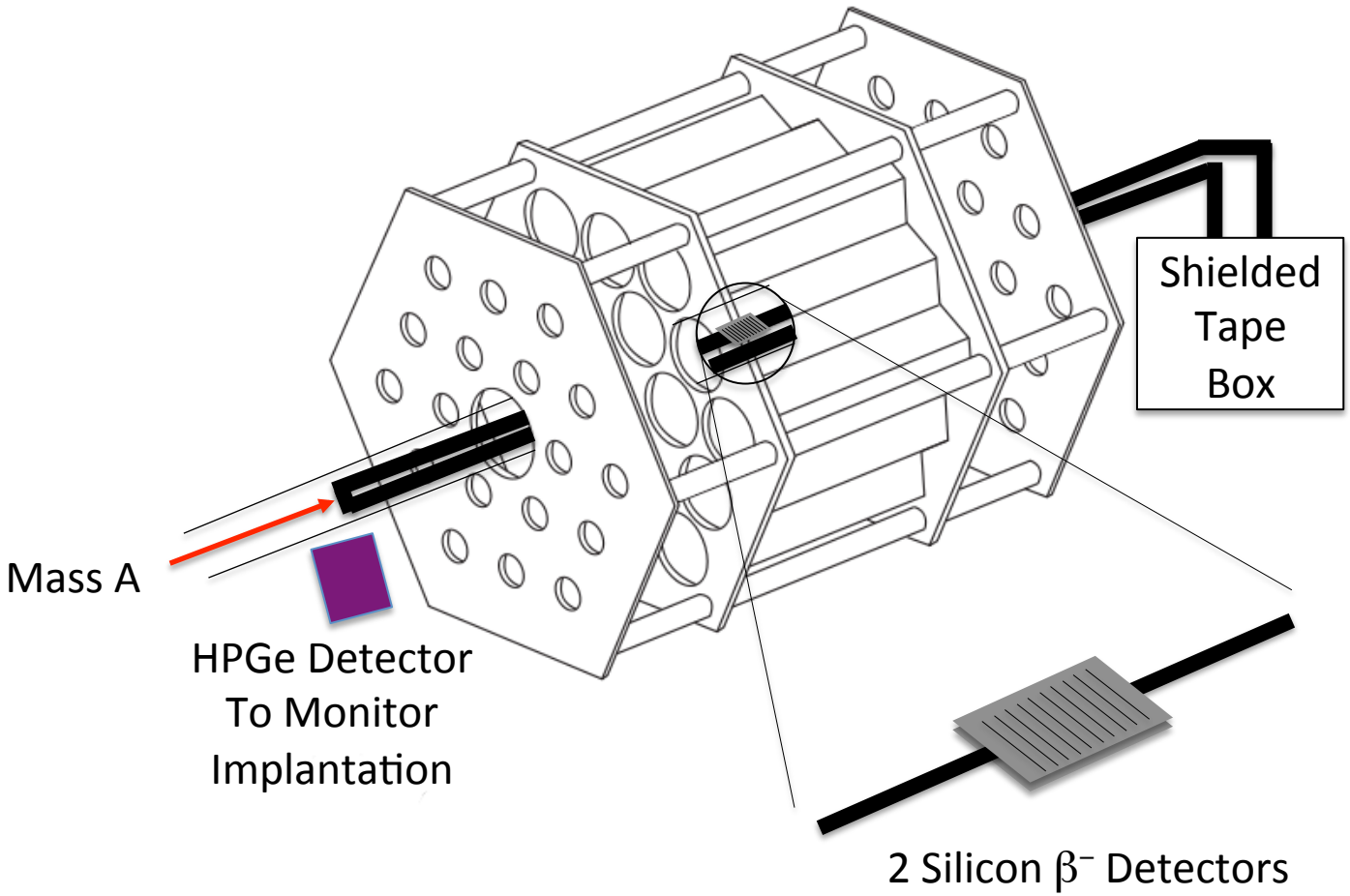
Neutrons in MTAS



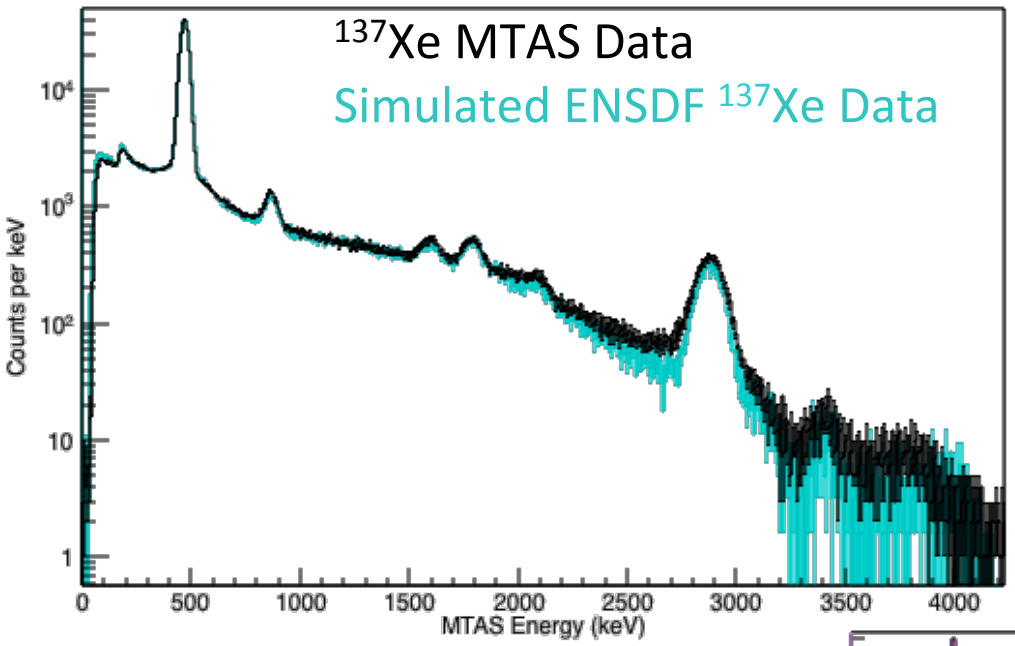
New Experiments with MTAS and Pure Beams at ORNL



MTAS - β Detectors and Tape System



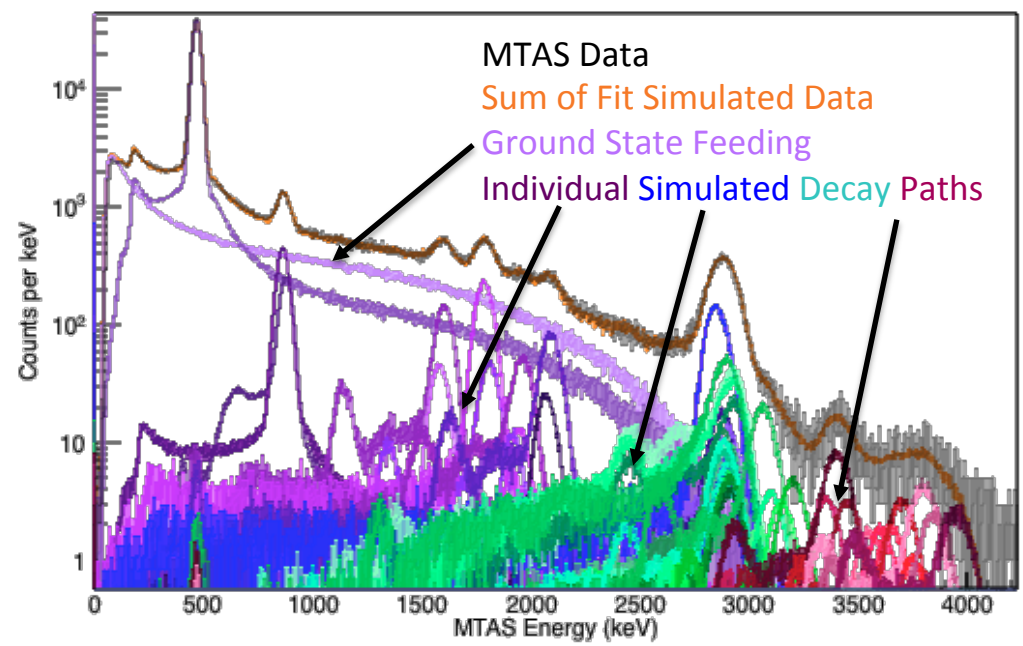
MTAS *Validation* - ^{137}Xe



Q_β= 4162.4 (3) keV $T_{1/2}$= 3.818 (13) m

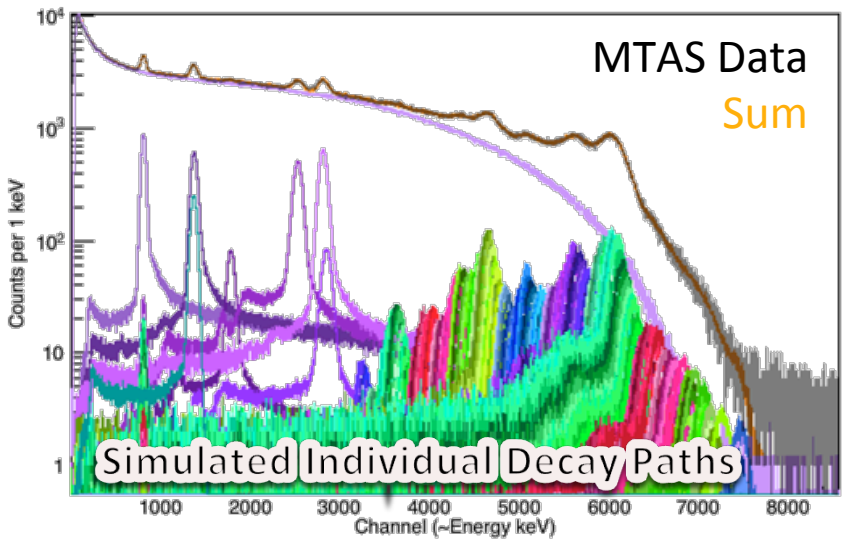
A slight increase in feeding to the higher energy levels

Otherwise our feeding intensities are in agreement with the current ENSDF evaluation.



^{92}Rb

Q_β= 8095 (6) keV $T_{1/2}$= 4.48 (3) s



ENSDF Ground State Feeding: 95.2±.7%
(up from 50±18% in 2007)
and 87.5±2.5%*

*A.-A. Zakari-Issoufou *et al,* PRL **115**, 102503

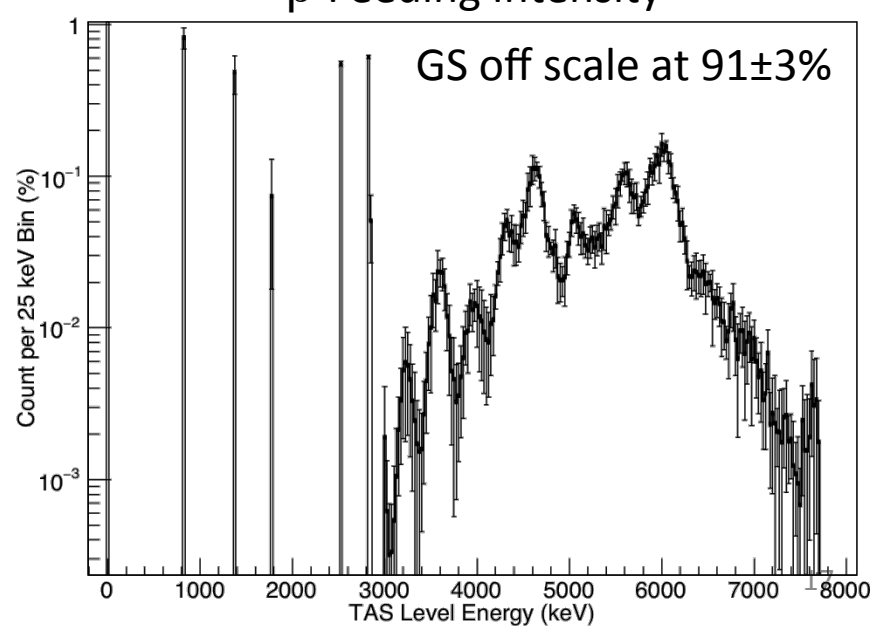
MTAS Ground State Feeding: **91±3%**

Our uncertainty mainly from ground state β simulation.

Ground state feeding insensitive to exact decay pattern from higher states.

When we vary the decay paths only the β-feeding to the non-ground state levels changes noticeably.

β-Feeding Intensity



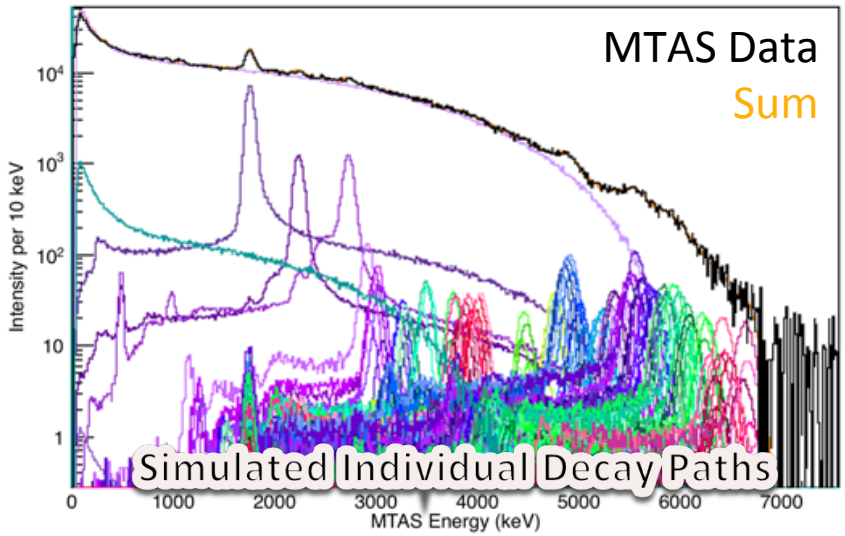
96gsY

Q_β= 7103 (6) keV $T_{1/2}$= 5.34 (5) s

ENSDF Ground State Feeding: 95.5±.5%

MTAS Ground State Feeding: **95.5±2.0%**

Uncertainty mainly from ground state β simulation

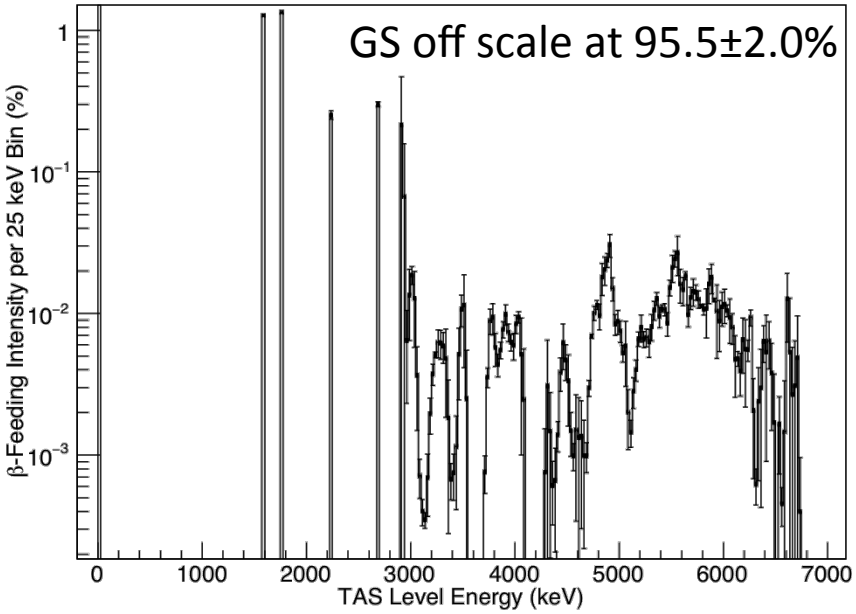


No ^{96m}Y (1140 keV, (8^+), $T_{1/2}$=9.6(2) s) measured.

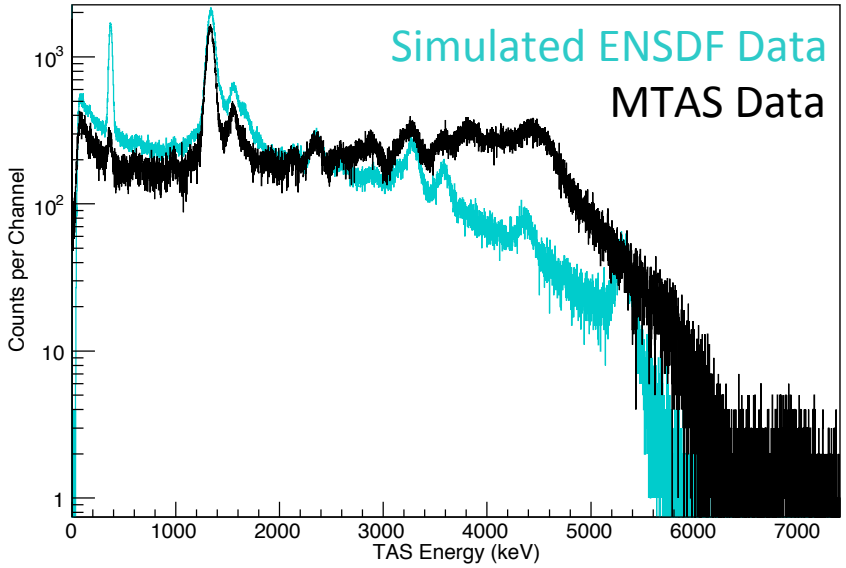
1.5 MeV $0^+ \rightarrow 0^+$ E0 decay, hard to detect with 1 mm silicon beta detectors.

Future experiments will have an array of β detectors to choose from.

β-Feeding Intensity



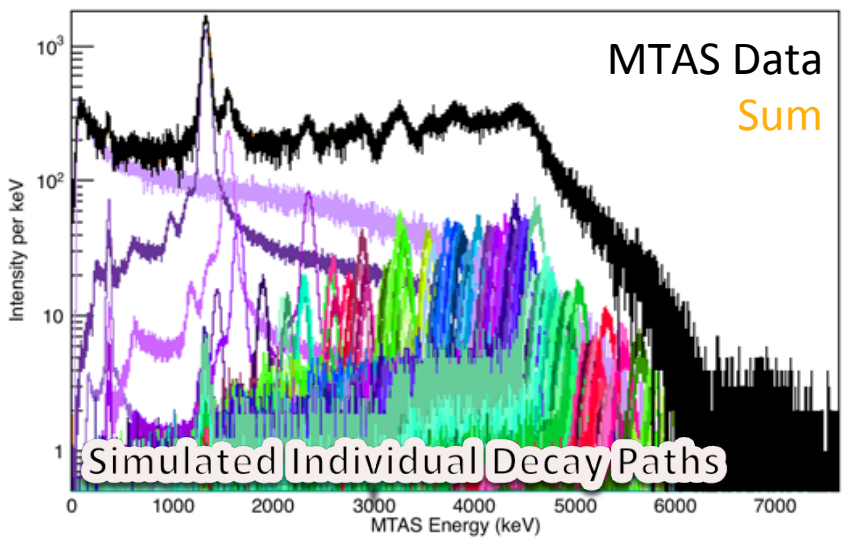
^{142}Cs



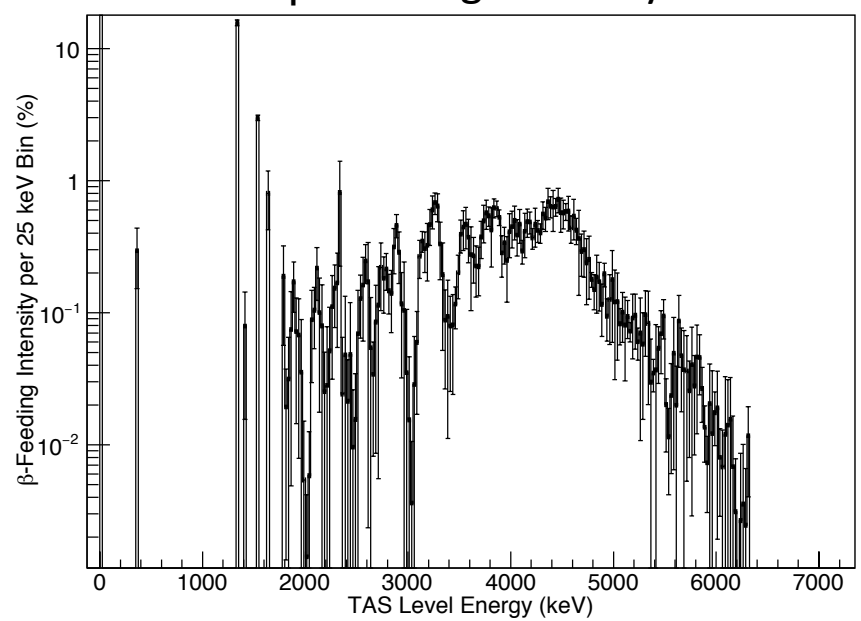
Q_β= 7325 (9) keV $T_{1/2}$= 1.684 (14) s

ENSDF Ground State Feeding: 56±5%

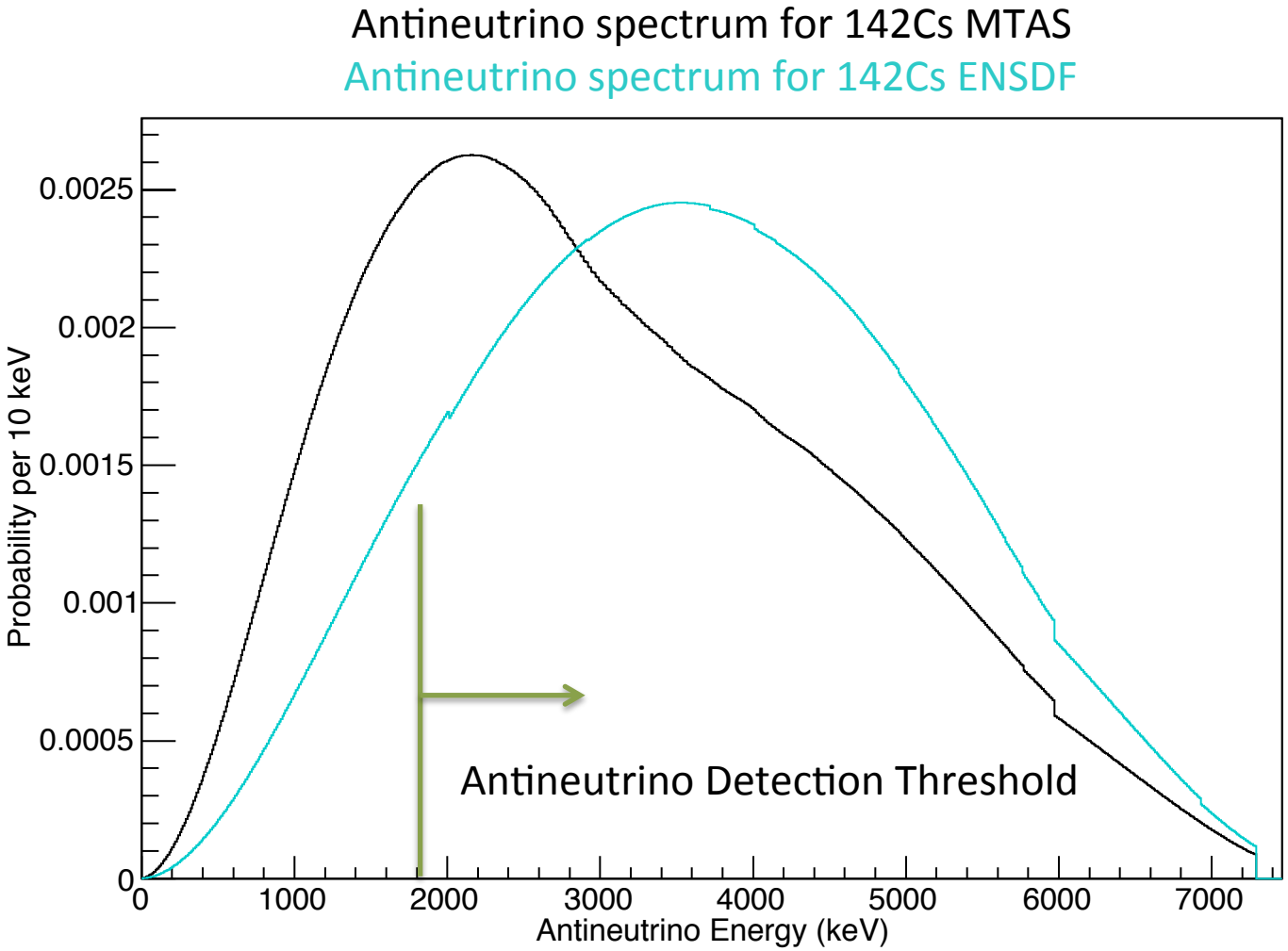
MTAS Ground State feeding: **44±2%**



β-Feeding Intensity



Changes to the ^{142}Cs anti-ν_e Flux

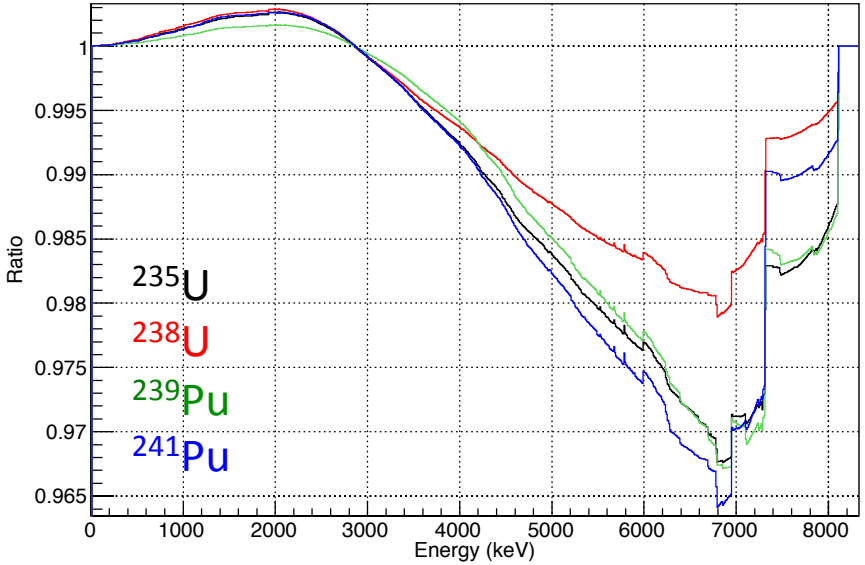


Fraction Change Below 1.8 MeV: 11% to 23(3)%.

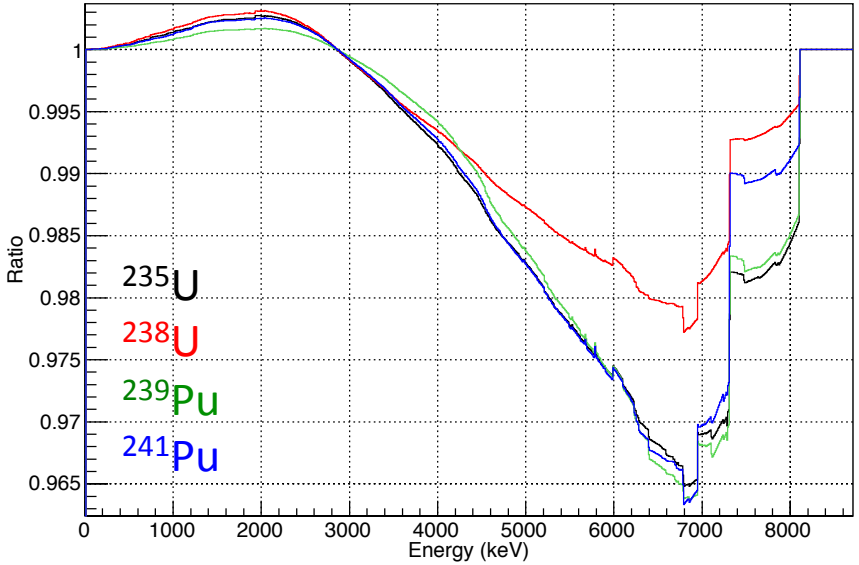
Fraction Change Above 5 MeV: 20% to 14(1)%

Changes to the anti-ν_e Shoulder

Ratio of antineutrino production for new MTAS Data / Previous Data for modified ^{92}Rb, ^{96gs}Y, and ^{142}Cs calculated by fuel type.



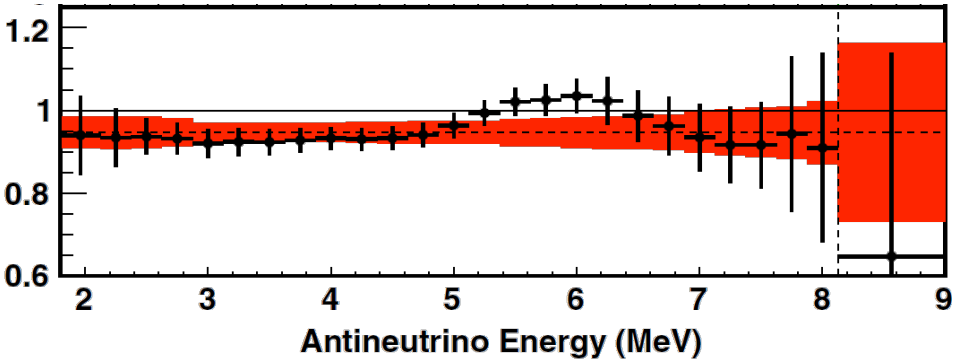
ENDF/B-VII.1 & ENSDF Calculation



JEFF & ENSDF Based Calculation

Unity line in this graph will change shape in a similar manner as above.

For the summation calculation this increases the shoulder ratio by about 0.02 at 6 MeV.



Daya Bay: An *et al.*, PRL **116**, 061801 (2016)

MTAS - lower mass fission peak (39 decays measured)
January 2012, March, October-December 2015, January 2016

Nb 89 2.03 h	Nb 90 14.60 h	Nb 91 680 y	Nb 92 34.7 My	Nb 93 100.	Nb 94 20.3 ky	Nb 95 34.991 d	Nb 96 23.35 h	Nb 97 72.1 m	Nb 98 1 2.86 s	Nb 99 15.0 s	Nb 100 1.5 s	Nb 101 7.1 s	Nb 102 1.3 s
Zr 88 83.4 d	Zr 89 78.41 h	Zr 90 51.45	Zr 91 11.22	Zr 92 17.15	Zr 93 1.53 My	Zr 94 17.38	Zr 95 64.032 d	Zr 96 2.80	Zr 97 16.90 h	Zr 98 30.7 s	Zr 99 2.1 s	Zr 100 7.1 s	Zr 101 2.3 s
Y 87 79.8 h	Y 88 106.65 d	Y 89 100	Y 90 64.00 h	Y 91 58.51 d	Y 92 3.54 h	Y 93 10.18 h	Y 94 18.7 m	Y 95 10.3 m	Y 96 2 ν 5.34 s	Y 97 ν 3.75 s	Y 98 ν 548 ms	Y 99 1.470 s	Y 100 735 ms
Sr 86 9.86	Sr 87 7.00	Sr 88 82.58	Sr 89 50.53 d	Sr 90 28.79 y	Sr 91 9.63 h	Sr 92 2.66 h	Sr 93 7.423 m	Sr 94 75.3 s	Sr 95 ν 23.90 s	Sr 96 1.07 s	Sr 97 2 429 ms	Sr 98 653 ms	Sr 99 269 ms
Rb 85 72.17	Rb 86 18.642 d	Rb 87 27.83	Rb 88 17.78 m	Rb 89 15.15 m	Rb 90 2 ν 2.6 m	Rb 91 58.4 s	Rb 92 2 ν 4.492 s	Rb 93 ν 5.84 s	Rb 94 ν 2.702 s	Rb 95 ν 377.5 ms	Rb 96 203 ms	Rb 97 169.9 ms	Rb 98 114 ms
Kr 84 57.00	Kr 85 10.776 y	Kr 86 17.30	Kr 87 76.3 m	Kr 88 2.84 h	Kr 89 1 3.18 m	Kr 90 1 32.32 s	Kr 91 ν 8.57 s	Kr 92 1.840 s	Kr 93 1.286 s	Kr 94 210 ms	Kr 95 114 ms	Kr 96 80 ms	Kr 97 63 ms
Br 83 2.40 h	Br 84 31.80 m	Br 85 2.90 m	Br 86 1 ν 55.1 s	Br 87 1 55.65 s	Br 88 1 ν 16.36 s	Br 89 ν 4.40 s	Br 90 1.910 s	Br 91 0.64 s	Br 92 343 ms	Br 93 102 ms	Br 94 70 ms	Br 95 50 ms	Br 96 20 ms
Se 82 8.73	Se 83 22.3 m	Se 84 3.1 m	Se 85 33 s	Se 86 14.1 s	Se 87 5.8 s	Se 88 1.53 s	Se 89 410 ms	Se 90 >300 ns	Se 91 270 ms	Se 92 100 ms	Se 93 50 ms	Se 94 20 ms	

Priority "1" (**6** nuclei) and "2" (**4**) for decay heat simulation established by a Nuclear Energy Agency in 2007. **The same activities have priority for "anomaly" analysis**. Most important nuclei (**13**) for reactor high-energy $\bar{\nu}$ according to Sonzogni *et al.*, PRC 2015 and Dwyer-Langford PRL 2015

OAK RIDGE National Laboratory

MTAS - higher mass fission peak ***(38 decays measured)***

January 2012, March, October-December 2015, January 2016

Ce 139 137.641 d	Ce 140 88.450	Ce 141 32.508 d	Ce 142 11.114	Ce 143 33.039 h	Ce 144 284.8 d	Ce 145 2.98 m	Ce 146 13.52 m	Ce 147 56.4 s	Ce 148 56 s	Ce 149 5.3 s
La 138 0.090	La 139 99.910	La 140 1.6781 d	La 141 3.92 h	La 142 92.6 m	La 143 2 14.3 m	La 144 40.9 s	La 145 2 24.8 s	La 146 ν 6.27 s	La 147 4.015 s	La 148 1.26 s
Ba 137 11.232	Ba 138 71.698	Ba 139 83.06 m	Ba 140 12.752 d	Ba 141 18.27 m	Ba 142 10.7 m	Ba 143 14.5 s	Ba 144 11.5 s	Ba 145 2 4.31 s	Ba 146 ν 2.22 s	Ba 147 893 ms
Cs 136 13.16 d	Cs 137 30.1671 y	Cs 138 32.2 m	Cs 139 9.27 m	Cs 140 ν 63.7 s	Cs 141 24.94 s	Cs 142 3 ν 1.689 s	Cs 143 ν 1.791 s	Cs 144 994 ms	Cs 145 582 ms	Cs 146 323 ms
Xe 135 9.10 h	Xe 136 8.87	Xe 137 1 3.83 m	Xe 138 ν 14.08 m	Xe 139 1 39.68 s	Xe 140 1 13.60 s	Xe 141 1.73 s	Xe 142 1.22 s	Xe 143 511 ms	Xe 144 388 ms	Xe 145 188 ms
I 134 52.0 m	I 135 6.61 h	I 136 1 45s 84 s 1	I 137 1 24.2 s	I 138 ν 6.4 s	I 139 2.29 s	I 140 860 ms	I 141 430 ms	I 142 ~200 ms	I 143 100 ms	I 144 50 ms
Te 133 12.5 m	Te 134 41.8 m	Te 135 2 ν 18.6 s	Te 136 17.5 s	Te 137 2.49 s	Te 138 1.4 s	Te 139 >300 ns	Te 140 300 ms	Te 141 100 ms	Te 142 50 ms	
Sb 132 1 2.79 m	Sb 133 2.5 m	Sb 134 780 ms	Sb 135 1.68 s	Sb 136 923 ms	Sb 137 450 ms	Sb 138 500 ms	Sb 139 300 ms			
Sn 131 56.0 s	Sn 132 39.7 s	Sn 133 1.45 s	Sn 134 1.12 s	Sn 135 530 ms	Sn 136 250 ms	Sn 137 190 ms				

Priority 1, 2, 3 : **12** decays
reactor high-energy $\bar{\nu}$

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What is next?

A LOT of analysis of the measured decays.

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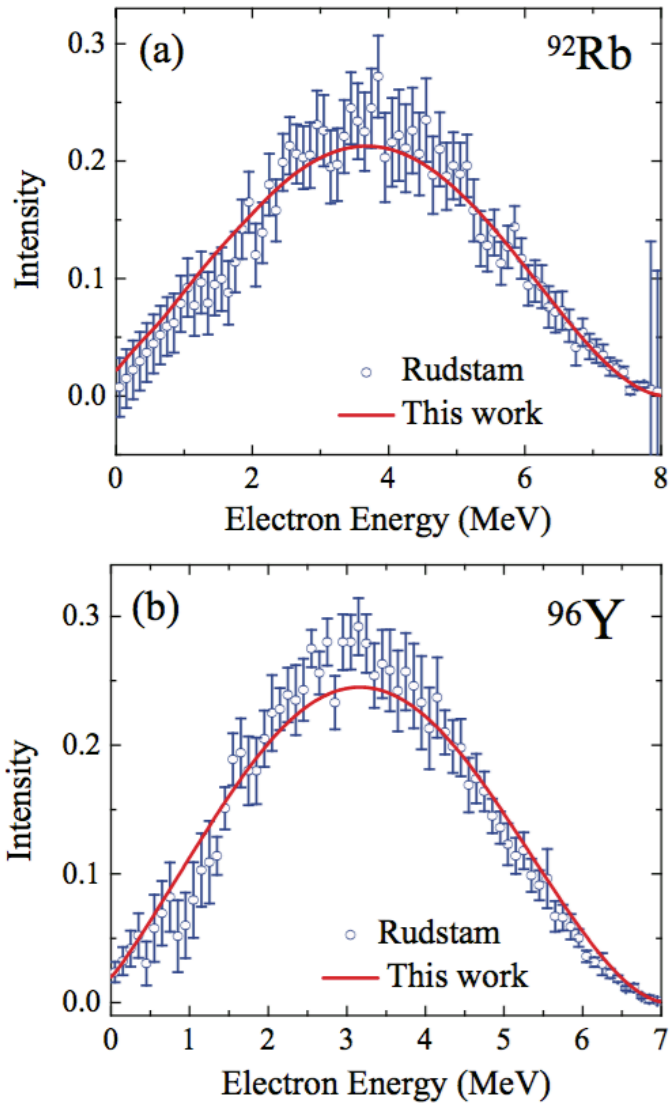
Thank You

Backup Slides

$0^+ \rightarrow 0^+$ Allowed Shape?



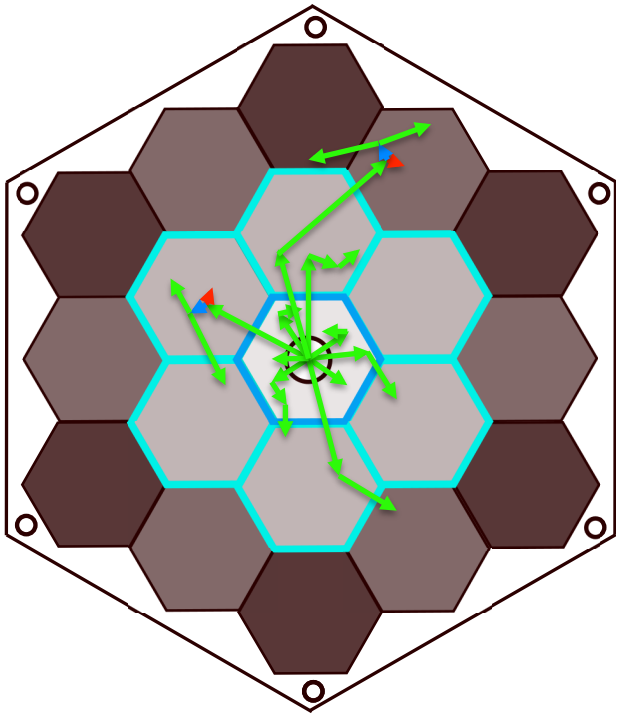
A. A. Sonzogni, T. D. Johnson, and E. A. McCutchan, PRC **91**, 011301(R) (2015)

A more general discussion is given in

D.L. Fang and B.A. Brown, Phys. Rev. C 91, 025503 (2015)

What MTAS Detects - γ-Rays

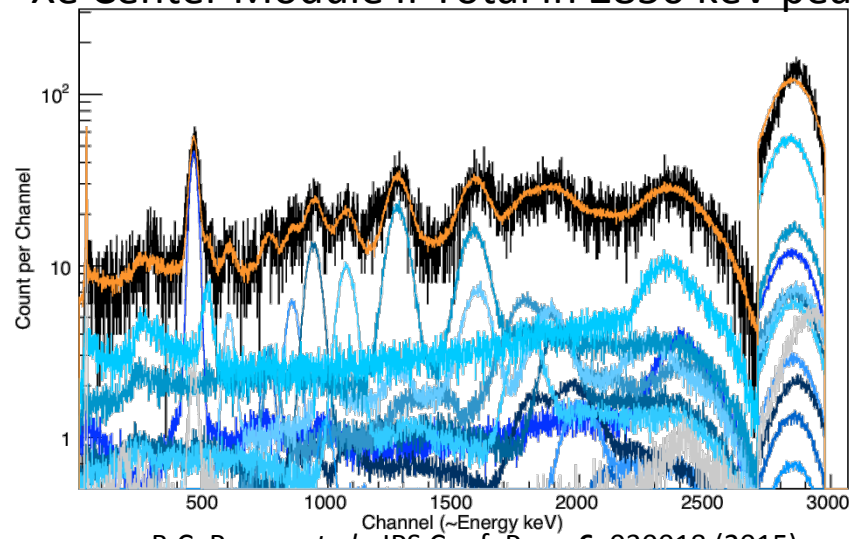
γs in MTAS



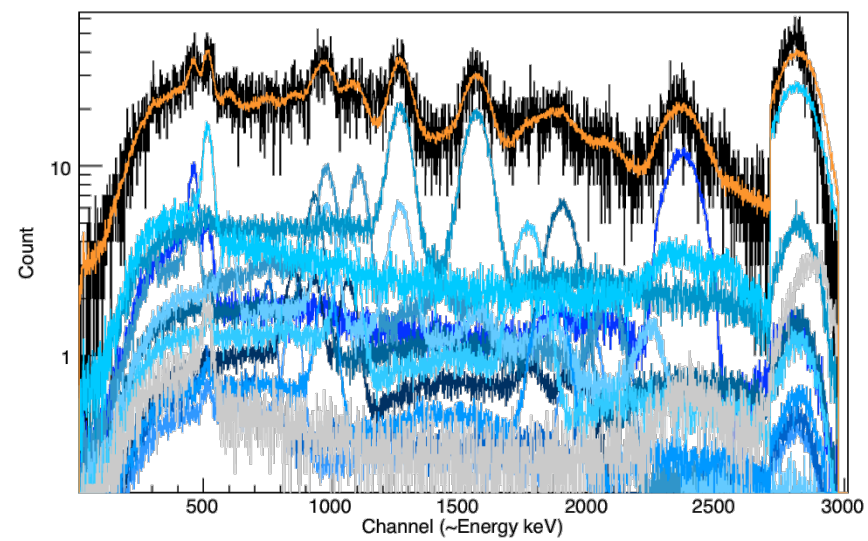
Segmentation is powerful.

Can get relative decay path probabilities.

^{137}Xe Center Module if Total in 2850 keV peak



B.C. Rasco, *et al.*, JPS Conf. Proc. **6**, 030018 (2015)



^{137}Xe Inner Ring if Total in 2850 keV peak