First-forbidden transitions in the reactor antineutrino anomaly

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ECT*, April 10th 2019

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Where is the anomaly?

Antineutrino's from β^- decay of reactor fission fragments

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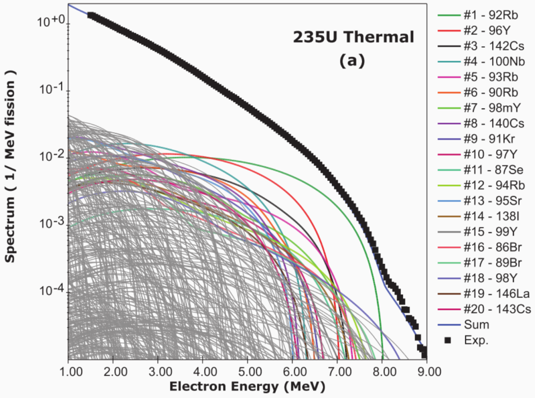
When new physics lurks, look out for quirks!

Antineutrino origin

Fission fragments from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu have many β^- branches, but can only measure cumulative spectrum.

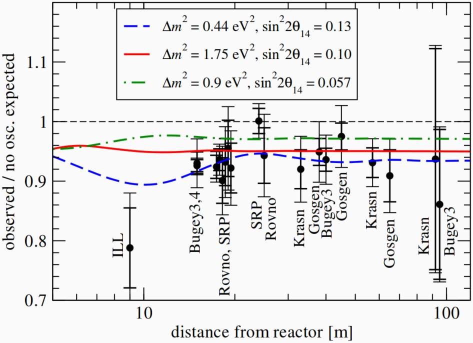


Conversion of all β branches is **tremendous** challenge

A. A. Sonzogni *et al.*, PRC **91** (2015) 011301(R)

Deficiency and particle physics proposal

Current deficiency in neutrino count rate at 94% (2-3σ)



Very exciting, but. . . it is real?

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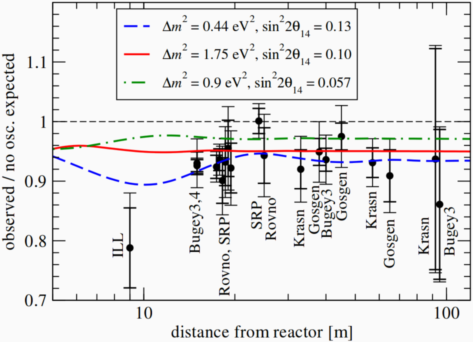
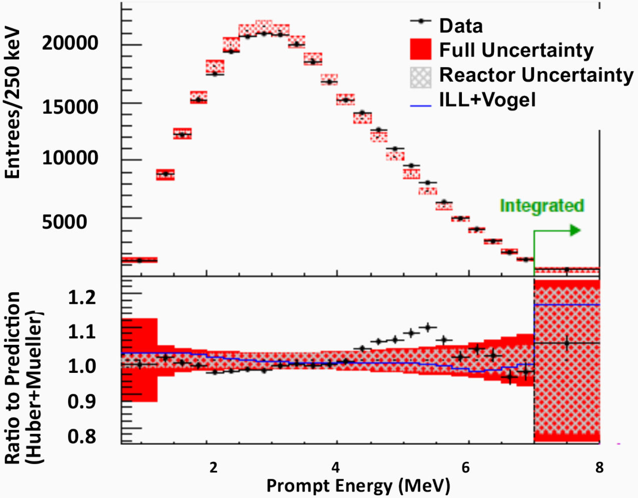


Very exciting, but. . . it is real?

Understanding of all corrections & nuclear structure is **crucial**!

An *et al.* (Daya Bay Collab.), PRL 118 (2017) 251801 & J. Kopp et al., JHEP 05

Reactor bump



Something not understood, most likely **nuclear physics** problem

Hayes & Vogel, ARNPS **66** (2016) 219

Experimental status

Very short baseline experiments

Since 2011, $\sim$ 10 experiments started setting up

Several experiments came online late 2017/2018! Published data from

- DANNS (Russia) 1804.04046
- STEREO (France) 1806.02096
- PROSPECT (USA) 1806.02784
- NEOS (Korea) 1610.05134

Very exciting & more coming soon!

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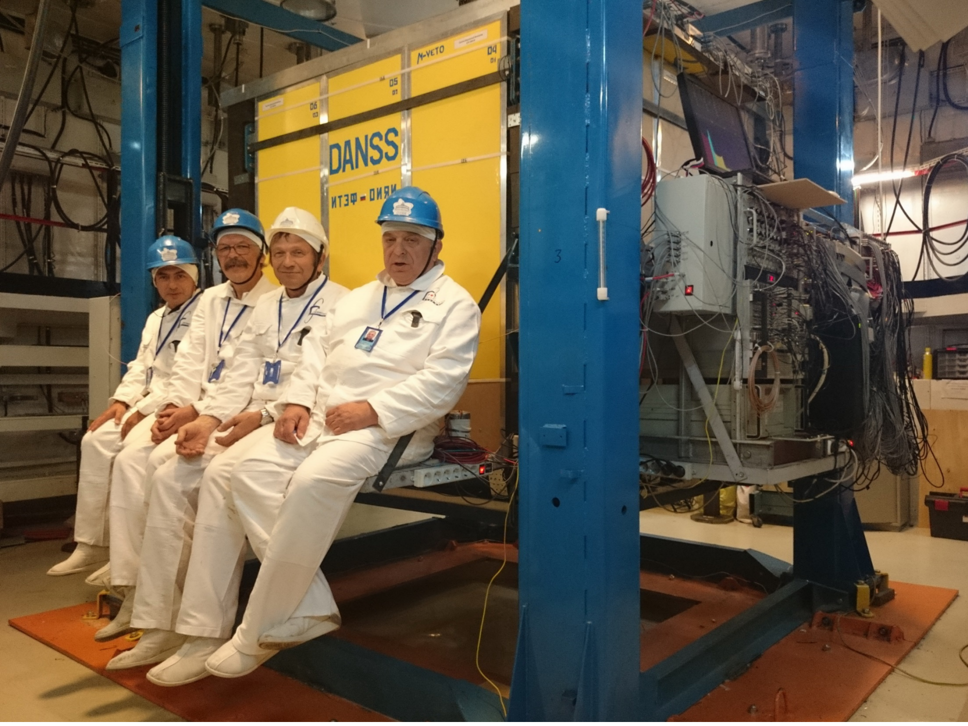
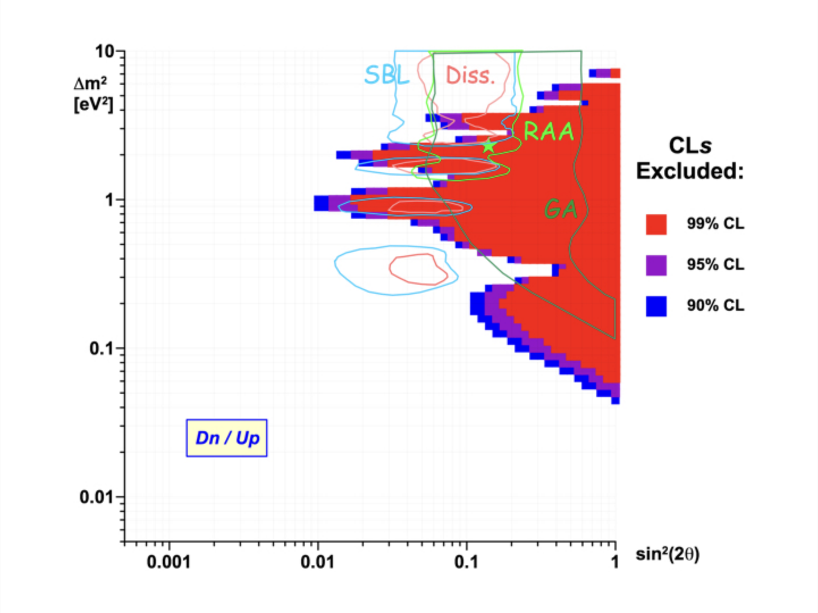
Very exciting & more coming soon!

Many results @ Neutrino 2018 $\rightarrow$ unceremoniously stole slides from V. Egorov, J. Lamblin, T. Langford & Y. Oh
Very grateful!



M-VETO
DANSS
ИТЭФ ОИЯИ

DANNS (V. Egerov @ Neutrino 2018)



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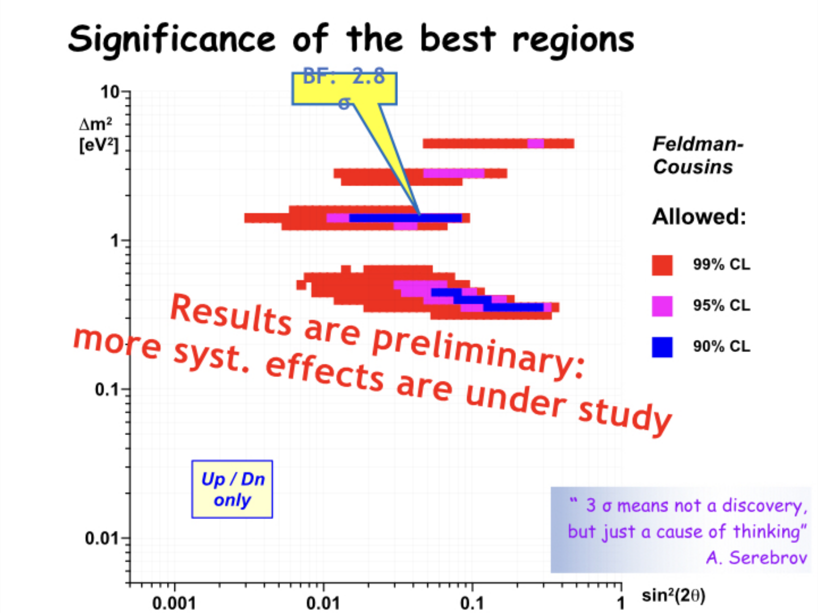
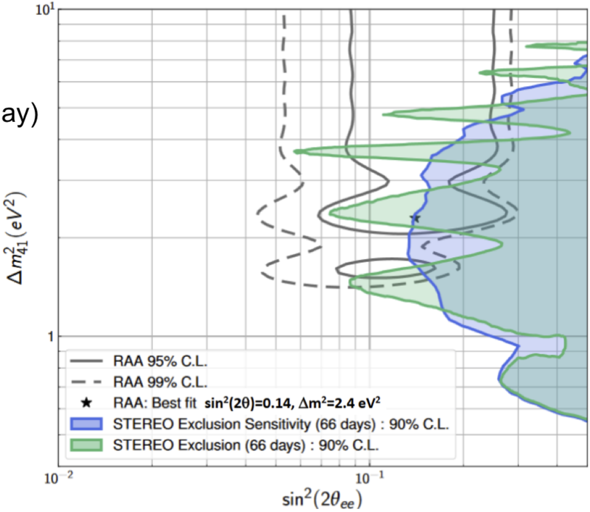


Exclusion contour

- 66 days ON (396 ± 4 $\overline{\nu}_e$ / day)
- Raster scan approach
- Generate pseudo-experiments to estimate the $\Delta\chi^2$ pdf
- arXiv:1806.02096

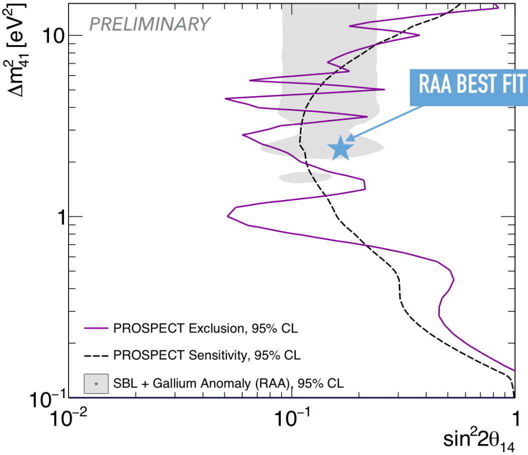


→ **Best fit value of the RAA rejected at 97.5% C.L.**


Assembly in 30s (video)
ASSEMBLY OF FIRST ROW
NOVEMBER 1, 2017
YALE WRIGHT LAB

OSCILLATION SEARCH RESULTS

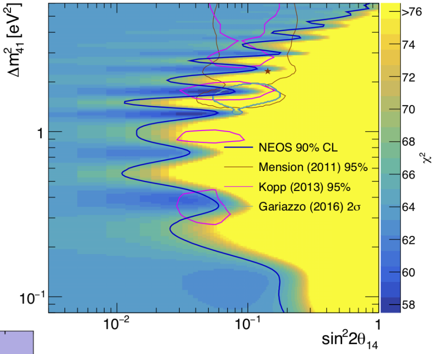
- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/baseline correlations
- Critical χ^2 map generated from toy MC using full covariance matrix
- 95% exclusion curve based on 33 days Reactor On operation
- *Direct test of the Reactor Antineutrino Anomaly*

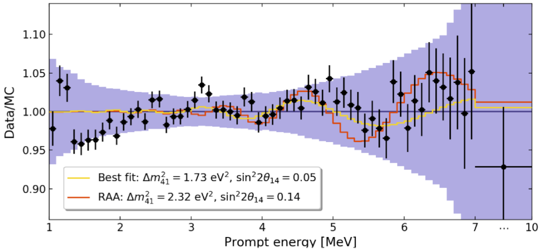


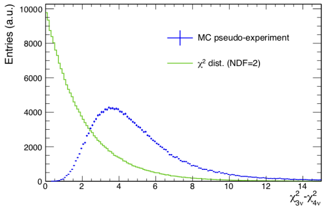
Disfavors RAA best-fit point at >95% (2.3σ)

Active-to-sterile oscillation

- Normalized with the Daya Bay shape
- Best fits at:
  (1.73 eV², 0.05), (1.30 eV², 0.04)
  with $\chi^2(3\nu)$-$\chi^2(4\nu)$ = 6.5,
  p-value = 0.22
- Fine structures in reactor ν spectrum or oscillation?







VSBL Summary

Great progress from all experiments

Several experiments are taking data

Best Reactor anomaly fit $(\Delta m^2_{41}, \sin^2\theta_{4e})$ excluded with $\geq 3\sigma$ by several experiments

Theory status

Theory: β participant sketch

Experiment sees nothing, what happens to theory?

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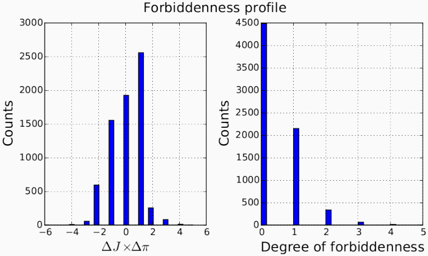
Nuclear β decay is complicated



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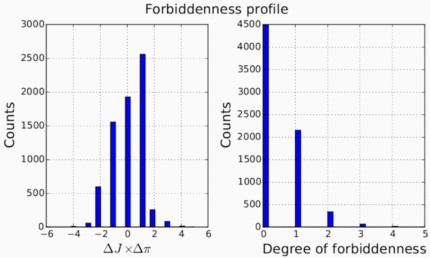

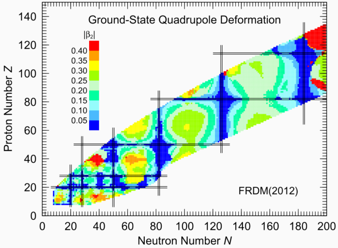

Both greatly influence the spectrum shape!

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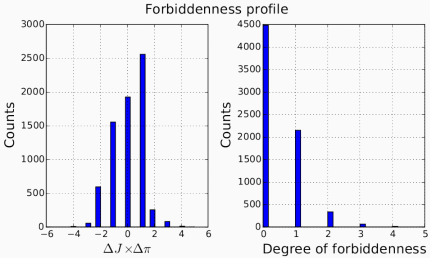

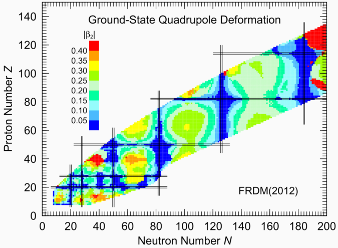

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Additional lower order effects: Atomic, electrostatic, kinematic...

L.H. *et al.*, Rev. Mod. Phys. 90 (2018) 015008

State of the art

Approaches split up in 2:

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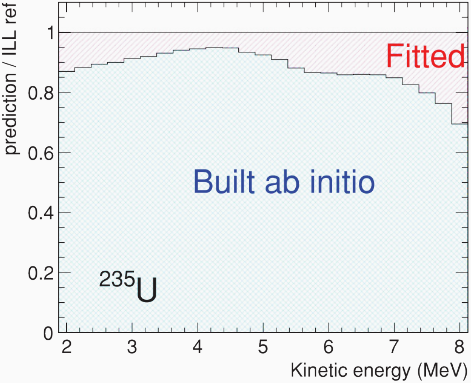
Approaches split up in 2:

1. **Conversion** method: virtual β branch fits
2. **Summation** method: Build from databases & extrapolate a la #1



Much of *ab initio* is based on same spectral assumptions

Huber, PRC **84** (2011) 024617; Mueller *et al.*, PRC **83** (2011) 054615

Analysis problems

Current methods have many issues:

- Estimated average b/Ac from spherical mirrors, but highly transition and deformation dependent
- Incorrectly estimates $(\alpha Z)^{n>1}$ effects, $\mathrm{RNA}(\langle Z\rangle^{n>1}) \neq \langle \mathrm{RNA}(Z^{N>1})\rangle$!
- Fixed endpoints on grid
- ^{239}Pu/^{235}U is wrong
- All transitions assumed allowed
- Quenching of g_A is absent
- ...

Using Machine Learning to try to mitigate these effects

An *et al.* (Daya Bay Collab.), PRL 118 (2017) 251801 & Hayes *et al.*, arXiv:1707.07728

Forbidden decays

Forbidden shape factors

Roughly $\sim 30\%$ of 8000 transitions are forbidden, usually assumed of negligible importance

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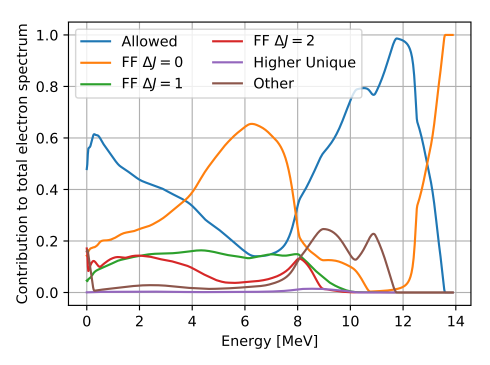

Experimental region of interest (2-8 MeV) is dominated by forbidden decays

Shape factor

General shape factor

$$C(Z,W) = \sum_{k_e,k_\nu,K} \lambda_{k_e} \left\{ M_K^2(k_e,k_\nu) + m_K^2(k_e,k_\nu) - \frac{2\mu_{k_e}\gamma_{k_e}}{k_e W} M_K(k_e,k_\nu) m_K(k_e,k_\nu) \right\},$$

where

$$\lambda_{k_e} = \frac{\alpha_{-k_e}^2 + \alpha_{+k_e}^2}{\alpha_{-1}^2 + \alpha_{+1}^2},$$

$$\mu_{k_e} = \frac{\alpha_{-k_e}^2 - \alpha_{+k_e}^2}{\alpha_{-k_e}^2 + \alpha_{+k_e}^2} \frac{k_e W}{\gamma_{k_e}},$$

are Coulomb functions of $\mathcal{O}(1)$

Behrens, Bühring, Electron radial wave functions, 1982

First-forbidden transitions

Depending on spin-parity change, C can be simple

$$C_{0^-} \propto 1 + \frac{2R}{3W} b + \mathcal{O}(\alpha Z R, W_0 R^2)$$

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$$C_{1^-} \propto 1 + aW + \mu_1 \gamma_1 \frac{b}{W} + cW^2$$

or rather simple, again

$$C_U \propto \sum_{k=1}^{L} \lambda_k \frac{p^{2(k-1)} q^{2(L-k)}}{(2k-1)![2(L-k)+1]!}$$

First-forbidden transitions

There are several complicating factors, however

- Expressions of previous slide are correct for *pure* transitions, generally higher-order matrix elements contribute

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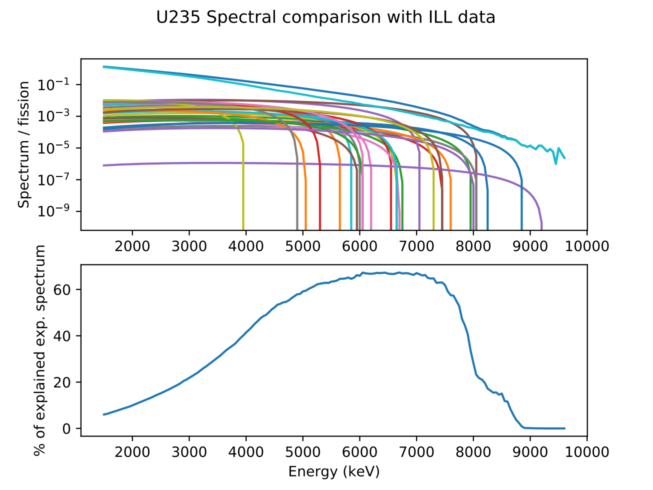
Challenging, but attempt to establish uncertainty

First-forbidden transitions

Also get lucky: higher energy needs less # branches to represent large part of flux

Forbidden shape factors

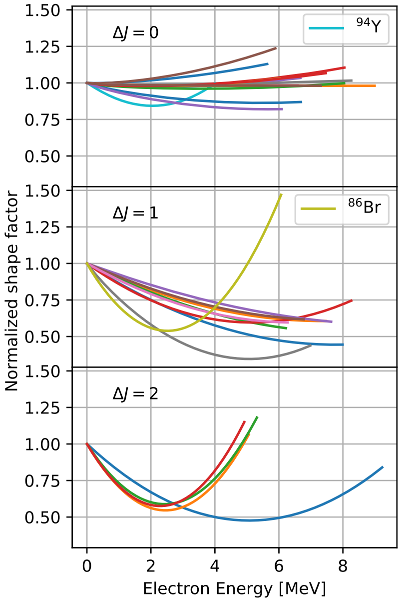
Picked 29 dominant forbidden transitions



$> 50\%$ in region of interest (4-7 MeV)

Forbidden shape factors

Picked 29 dominant forbidden transitions, calculated shape factor in nuclear shell model



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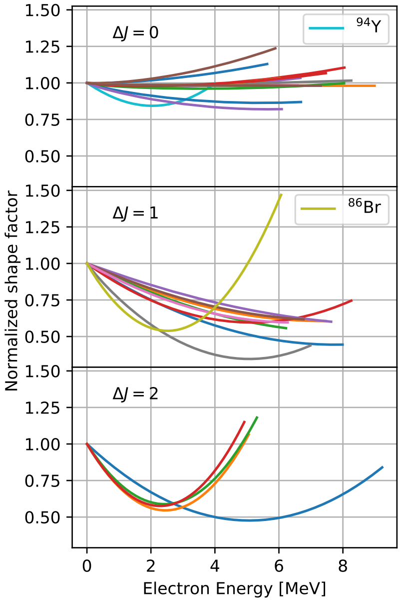
$$\frac{dN}{dE} \propto pE(E_0 - E)^2 F(Z, E)$$

$$\boldsymbol{C(Z, E)}$$

Allowed: $C = 1$

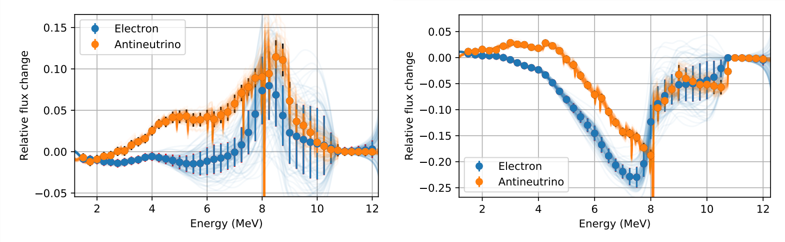
As expected, large spectral changes



Forbidden spectral changes

Uniform behaviour for each ΔJ allows for parametrisation
$\rightarrow$ Use Monte Carlo for correction of **all** forbidden decays

Look at difference in cumulative spectrum shapes

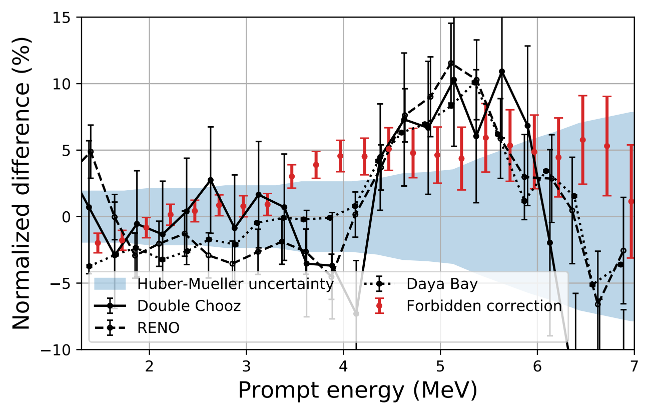


Allowed   Unique

Large spectral changes, downward trend $\sim 5\%$ wrt Unique
Monte Carlo allows for uncertainty estimation

Forbidden transitions & the bump

Use spectrum changes with Schreckenbach correspondence



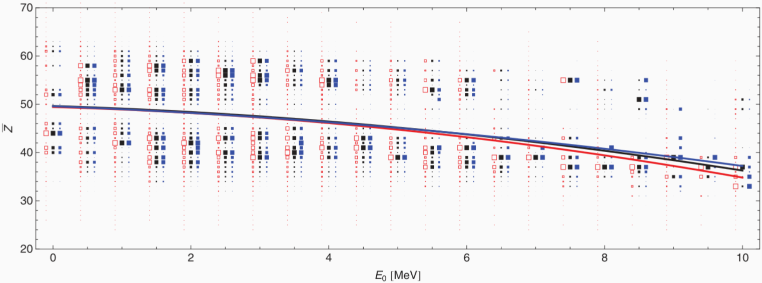
Bump strongly mitigated, still further research

arXiv: 1805.12259, submitted to PRL

Modern conversion analysis

Extrapolation & Virtual branches

How to construct these fictitious β branches?



Parametrised $\bar{Z}(E_0)$ fit with simple polynomial

P. Huber, PRC **84** (2011) 024617

Extrapolation & Virtual branches

Typical procedure

1. Make grid for E_0 in $[2, 12]$ MeV
2. Every gridpoint $E_{0,i}$, choose $Z(E_{0,i})$
3. Assume allowed shape, extrapolate average nuclear matrix elements
4. Fit VB intensities to cumulative exp. spectrum

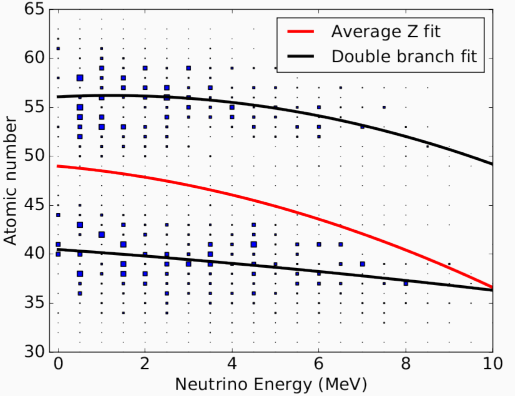
$$S(E_e) = \sum_i c_i S(E_e, \bar{Z}(E_{0,i}), E_{0,i})$$

5. Invert spectra using $E_\nu = E_0 - E_e$

Database extrapolation

Database contains much more information to use

Trivial extension to improve $(\alpha Z)^2$ behaviour, fixed weights



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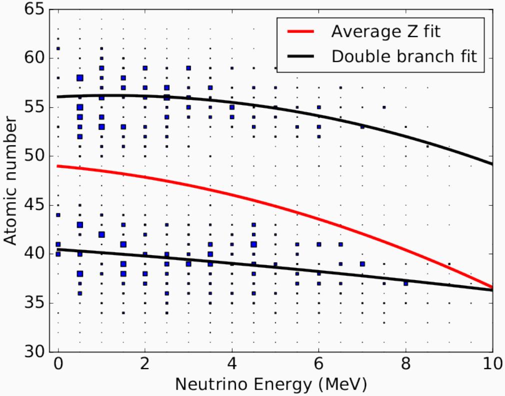
Employ Machine Learning clustering algorithms to find better patterns



Clustering & Machine Learning

Nuclear β decays live in high-dimensional vector spaces

- Z, A
- Log ft values
- Branching Ratio, E_0, daughter excitation
- $\Delta J^{\Delta\pi}$ (forbiddenness, unique)
- Initial and final deformation
- ...

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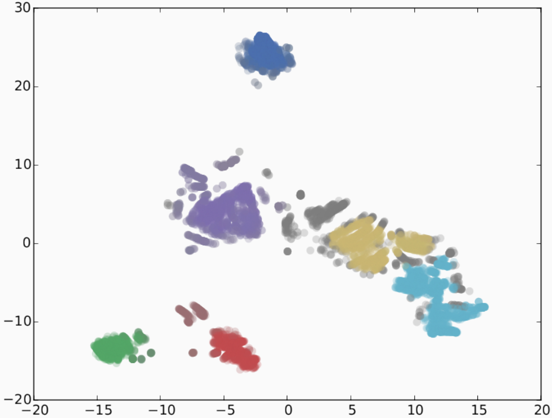
Clusters in high dimensions are smeared in 2D projections

Clustering visualisation

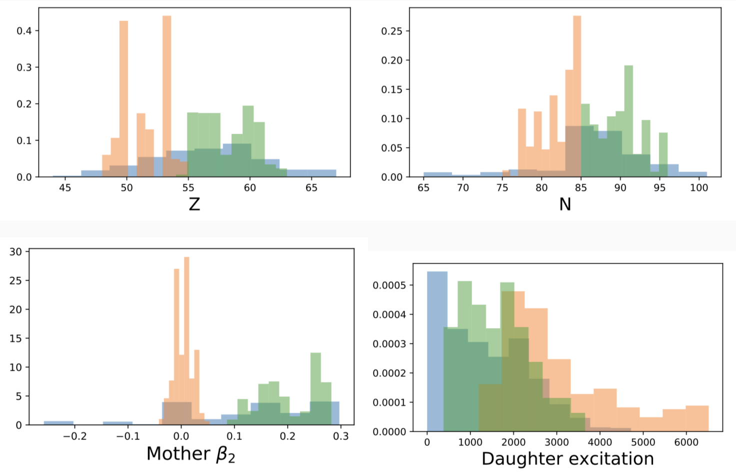
Use dimensional reduction (t-SNE) to visualise results



Clear clusters, intercluster distance irrelevant here

Intercluster comparison

Example comparison for 3 clusters



Large differences visible for simple histograms!

Monte Carlo sampling

How to combine these results?

Instead of a single $Z(E_0)$ fit, use
Multidimensional Cluster Markov Chain Monte Carlo (MC^3)

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Build a **distribution** of anomaly $\rightarrow$ better uncertainty estimate

Virtual β branch creation

Procedure:

For each E_0 bin, for each cluster, build sampling distribution

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fission yield $\times$ BR

Likelihood ($P(d|\theta)$): probability for point to belong to cluster

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Modification of prior allows for compensation/study of pandemonium

MC^3 moving forward

Clusters contain nuclear structure information, can stochastically deduce matrix element corrections

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Done correctly, realistic uncertainty & anomaly including correlations