First-forbidden transitions in the reactor antineutrino anomaly

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Anomaly Introduction

What's it about in 3 steps:

Where is the anomaly?

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

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Prediction error (mean, σ) or sterile neutrino's, something else

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When new physics lurks, look out for quirks!

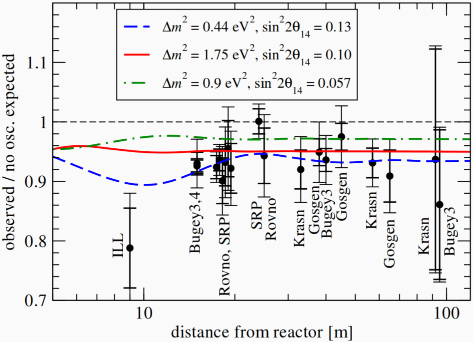
Deficiency and particle physics proposal

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

$$P_{SBL}(\bar{\nu}_\alpha \to \bar{\nu}_\alpha) \simeq 1 - \sin^2 2\theta_{\alpha 4} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Very exciting,

but. . . it is real?



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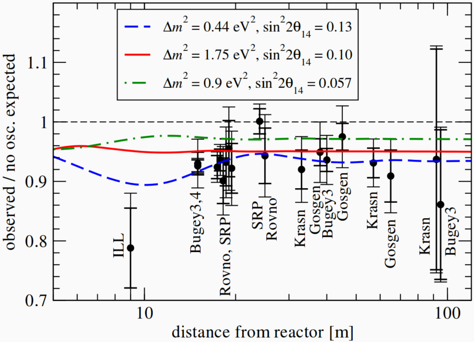
Understanding of

all corrections & nuclear

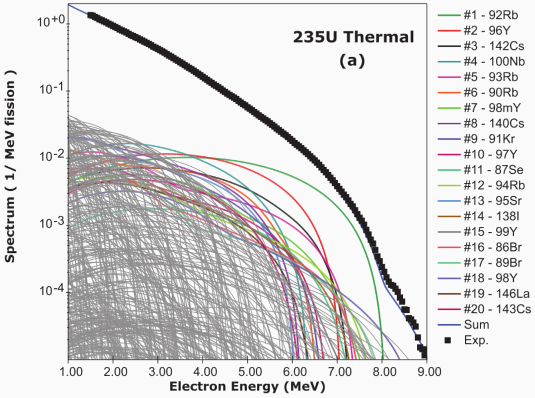
structure is **crucial**!



An *et al.* (Daya Bay Collab.), PRL 118 (2017) 251801 & J. Kopp et al., JHEP 05 (2013) 050

Antineutrino origin

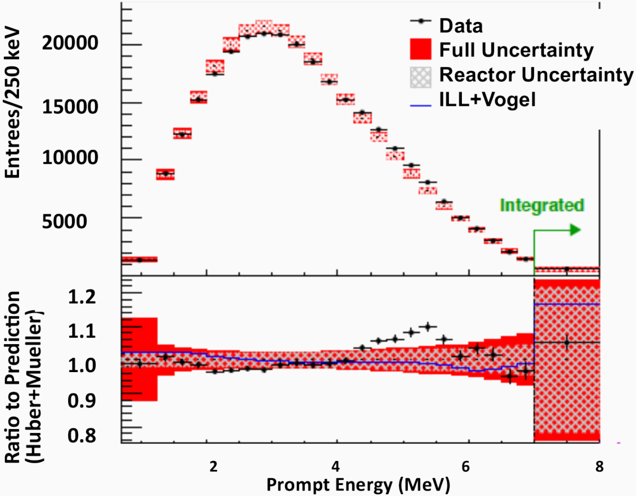
Fission fragments from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu have many β^- branches, but can only measure cumulative spectrum.



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

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

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

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Very short (<10m) baseline experiments: measure oscillation directly

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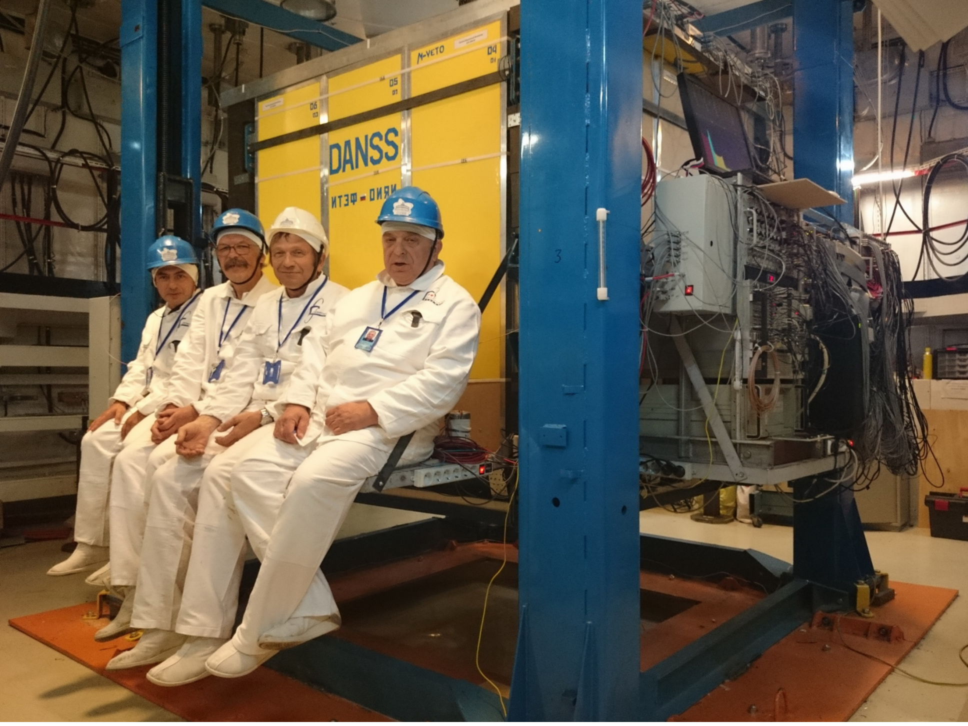
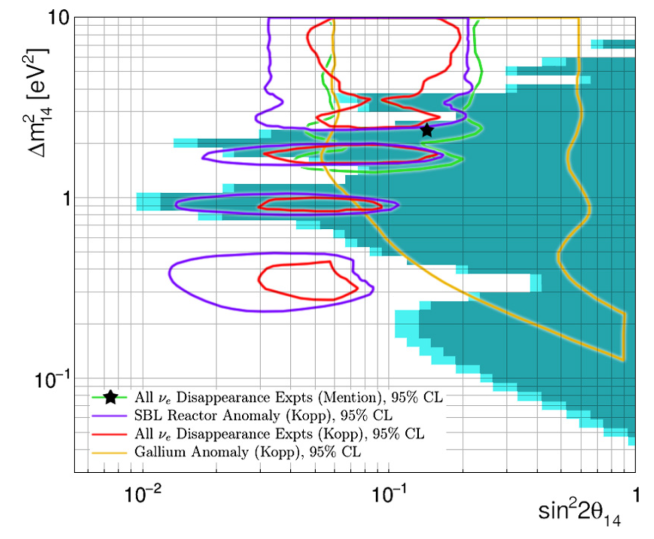
Several experiments came online late 2017/2018! Published data from

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

Very exciting & more coming soon!

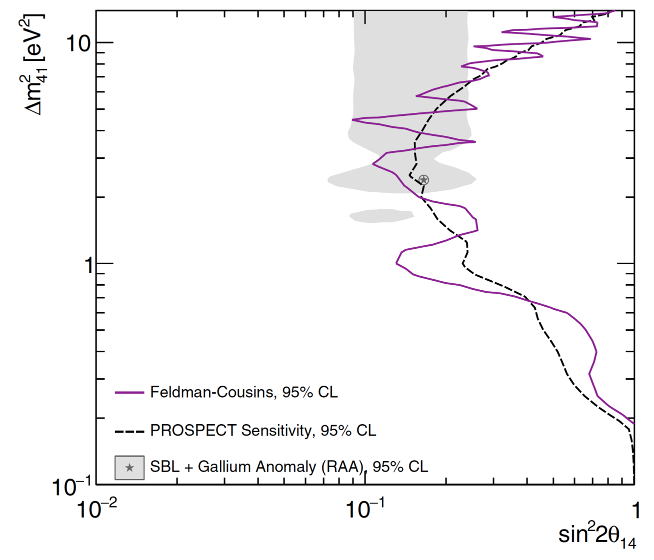

M-VETO
04
05
06
DANSS
ИТЭФ ОИЯИ

VSBL Results: DANSS



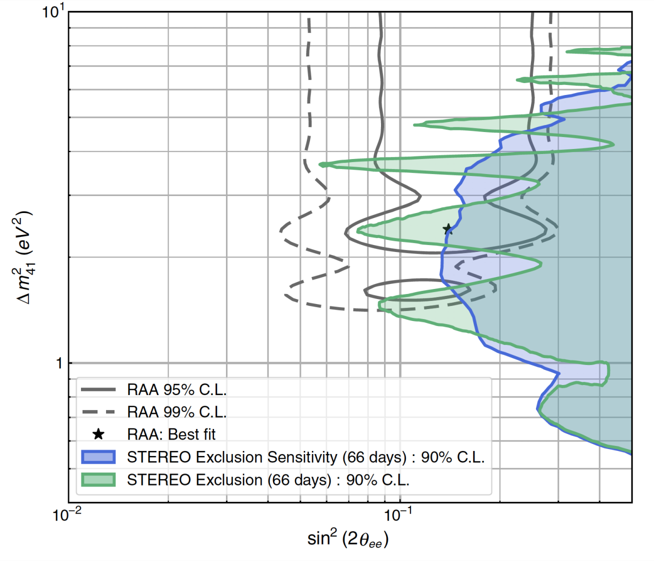
Alekseev *et al.* (DANSS) PLB 787 (2018) 56

VSBL Results: PROSPECT



Ashenfelter *et al.* (PROSPECT) PRL 121 (2018) 251802

VSBL Results: STEREO



Almazán *et al.* (STEREO) PRL 121 (2018) 161801

Current status

Faced with some interesting developments:

1. 2011: Emergence of flux anomaly, sterile neutrinos?

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Things point to deficiencies in databases & theoretical modeling

Theory status

Theory: β participant sketch

Experiment sees nothing, what happens to theory?

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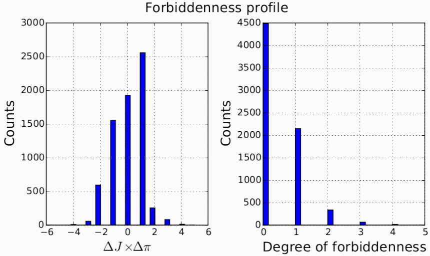
Nuclear β decay is complicated



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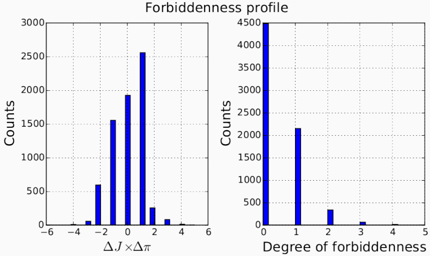

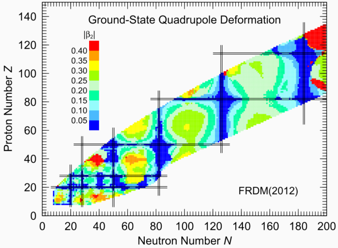

Both greatly influence the spectrum shape!

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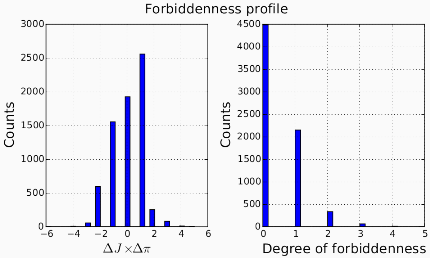

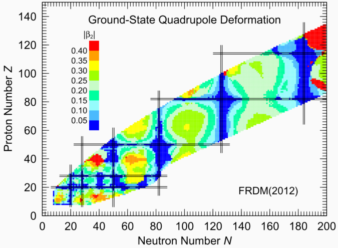

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Additional lower order effects: Atomic, electrostatic, kinematic. . .

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

Analysis procedure

Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

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Approaches split up in 2:

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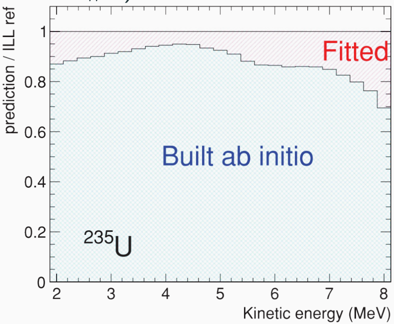
Approaches split up in 2:

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



Much of *summation* is based on same spectral assumptions Huber, PRC **84** (2011) 024617; Mueller *et al.*, PRC **83** (2011) 054615

Thoughts on state of the art

2 elements which require pause

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1. Central problem when comparing to ILL data

Everything below 1.8 MeV in electron spectrum is unconstrained, but ends up all over the antineutrino spectrum

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Everything that changes the shape below 1.8 MeV changes the anomaly → essential to get this right

Thoughts on state of the art

2 elements which require pause

2. Depending on method, questionable approximations
   - Incorrectly estimates $(\alpha Z)^{n>1}$ effects, $\mathrm{RAA}(\langle Z\rangle^{n>1}) \neq \langle \mathrm{RAA}(Z^{N>1})\rangle$!
   - Estimated average b/Ac from spherical mirrors, but highly transition and deformation dependent
   - All transitions assumed allowed/unique
   - No Coulomb corrections to unique shape factors
   - ...

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 for anomaly

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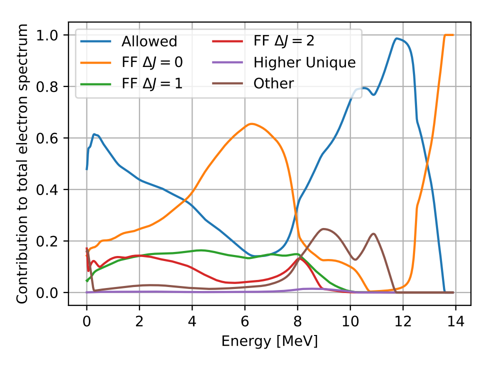

Experimental region of interest (2-8 MeV) is dominated by forbidden decays LH, J. Kostensalo, N. Severijns, J. Suhonen, PRC 99 (2019) 031301(R)

β spectrum shape

Central element in analysis is knowledge of β spectrum shape

$$\frac{dN}{dW} \propto pW(W_0 - W)^2 F(Z, W) C(Z, W) \ldots$$

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Approximations in state-of-the-art for non-unique forbidden transitions

- Treat as allowed
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Approximations in state-of-the-art for non-unique forbidden transitions

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are . . . not great

Shape factor

General shape factor

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

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 ($R \sim 0.01$)

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

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

or rather simple, again

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

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There are several complicating factors, however

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Challenging, but attempt to establish uncertainty

First-forbidden transitions

Cause for despair, but there's a helping hand:

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Higher in E you go, fewer branches contribute

First-forbidden transitions

Cause for despair, but there's a helping hand:

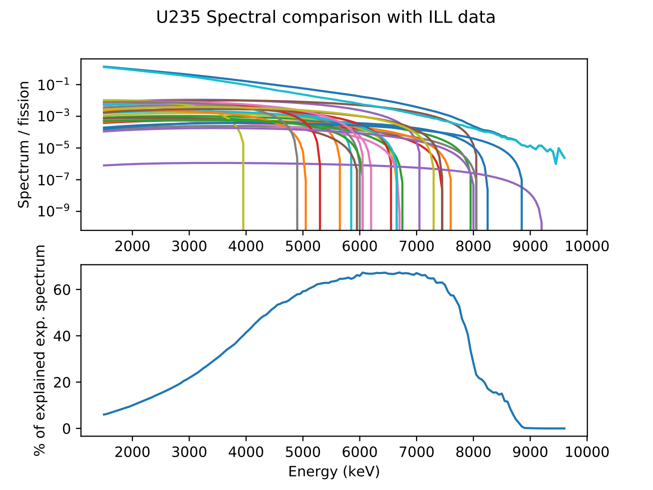
Higher in E you go, fewer branches contribute

From 5 MeV onwards: $\gtrsim$ 90% of flux with less than 50 branches

Sonzogni *et al.*, 91 (2015) 011301

Forbidden shape factors

Picked 29 dominant forbidden transitions



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

Forbidden shape factors

Picked
(now $>$)29 dominant
forbidden transitions,
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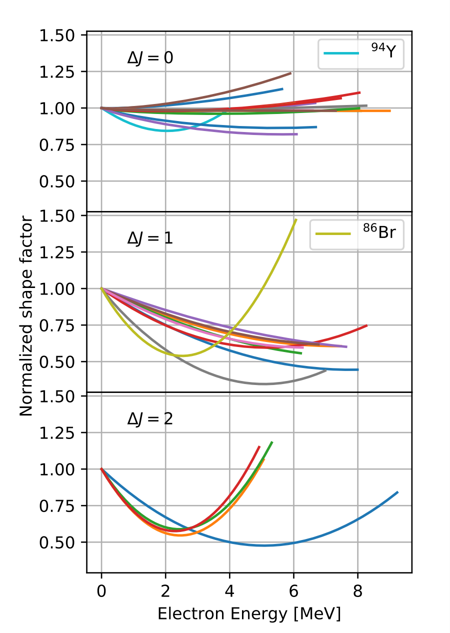

Forbidden shape factors

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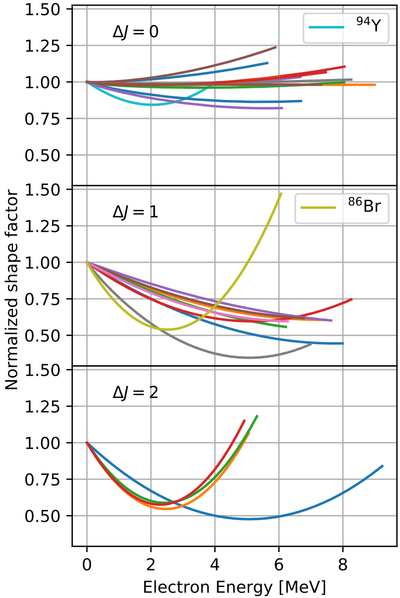
$$\frac{dN}{dE} \propto pE(E_0 - E)^2 F(Z, E)$$

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

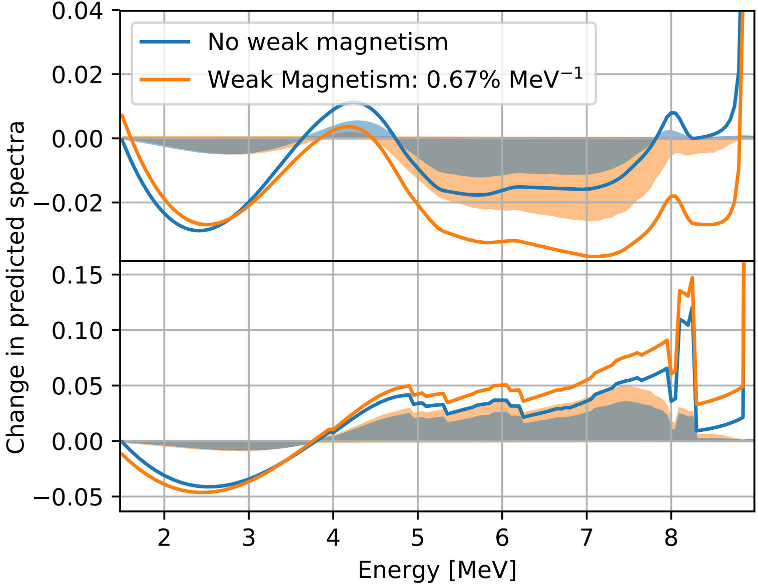
Allowed: $C \approx 1$

As expected, large spectral changes

LH *et al.*, PRC 99 (2019) 013301(R)



Spectral changes



Parametrization

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Uniform behaviour for each ΔJ separately invites a parametrization

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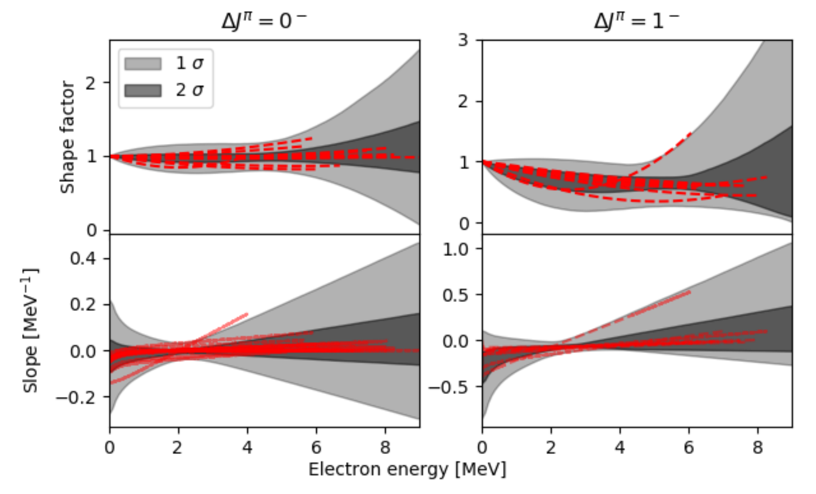
Uniform behaviour for each ΔJ separately invites a parametrization

Fit each calculated shape factor using simple polynomial, obtain distributions of correlated fit parameters for each ΔJ

Parametrization

Construct conservative shape factor distributions for each ΔJ



Directly applicable to conversion method!

Forbidden spectral changes

Perform Monte Carlo sampling over **all** forbidden branches to propagate uncertainty into final calculation

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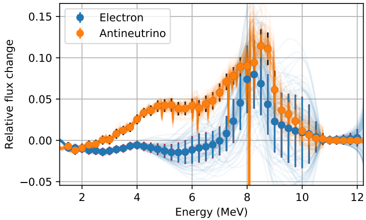
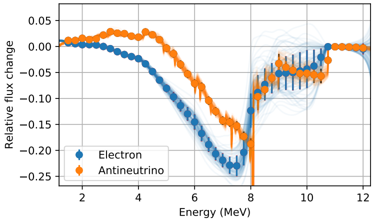
Look at difference in cumulative spectrum shapes





Allowed

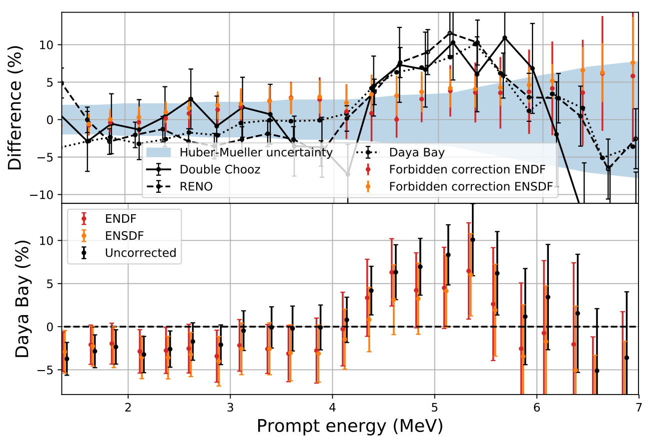
Unique

Large spectral changes for **all** actinides

Monte Carlo allows for uncertainty estimation

Forbidden transitions & the bump

Use spectrum changes with Schreckenbach correspondence



Bump significantly mitigated, still further research

LH, J. Kostensalo, N. Severijns, J. Suhonen, PRC 99 (2019) 031301(R)

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Estimate uncertainty using Monte Carlo methods

Reactor bump is significantly mitigated, increased uncertainty weakens anomaly

Uncertainty estimation

Care only about shape, not absolute magnitude

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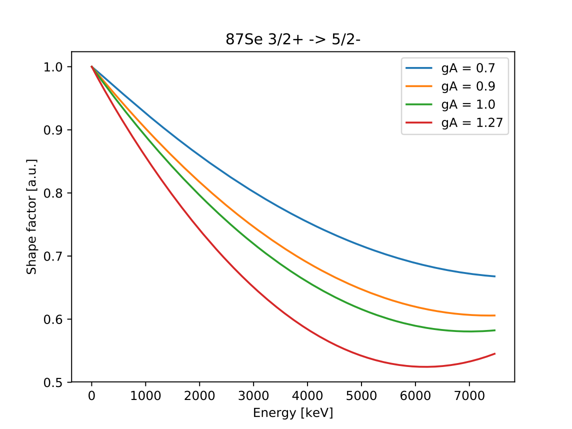
Shape factor can have (significant) dependence on what value for g_A^{eff} is used



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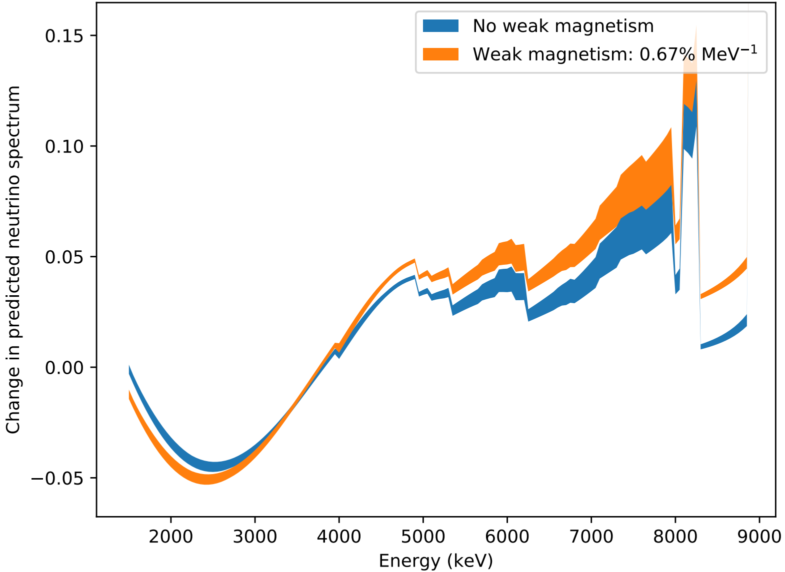

Matrix elements

Up to first order, deal with 6 matrix elements

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ΔJ	Matrix elements	Forbidden
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1	${}^{A}\mathcal{M}_{111}, {}^{A}\mathcal{M}_{121}, {}^{V}\mathcal{M}_{101}, {}^{A}\mathcal{M}_{110}$	$0 \to 0$
2	${}^{A}\mathcal{M}_{211}$	$0 \to 0, \frac{1}{2} \to \frac{1}{2}, 1 \to 0$

Behrens-Bühring notation: ${}^{V/A}\mathcal{M}_{KLs}$

- s: timelike (0, scalar) or spacelike (1, vector)
- L: Angular momentum from multipole decomposition
- K: total J of operator ($|L - s| \leq K \leq L + s$)

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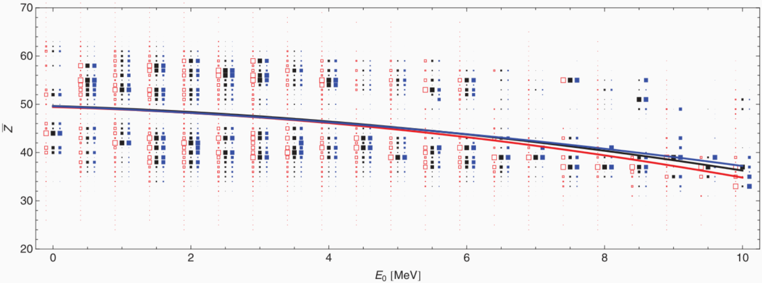
General: 1 dominant matrix element $\to$ easy, $> 1 \to$ harder

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

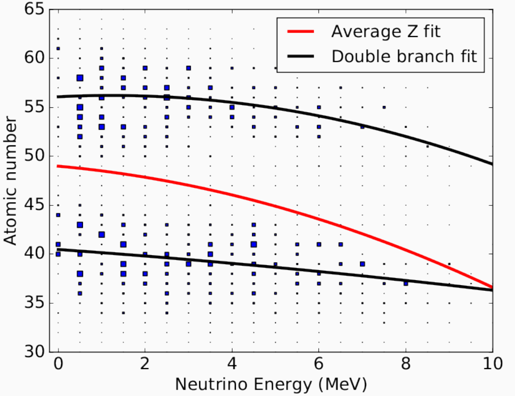
$$S(E_e) = \sum_i c_i S(E_e, \bar{Z}(E_{0,i}), E_{0,i})$$

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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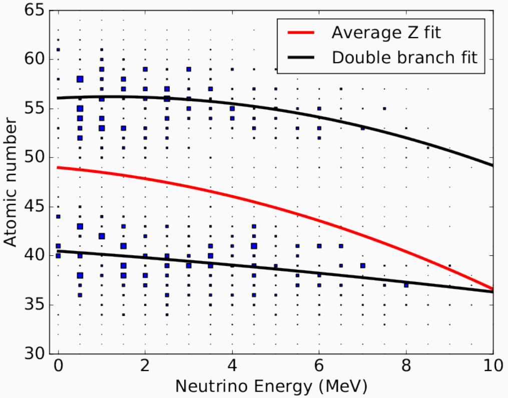
Employ Machine Learning clustering algorithms to find better patterns



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
- $\ldots$

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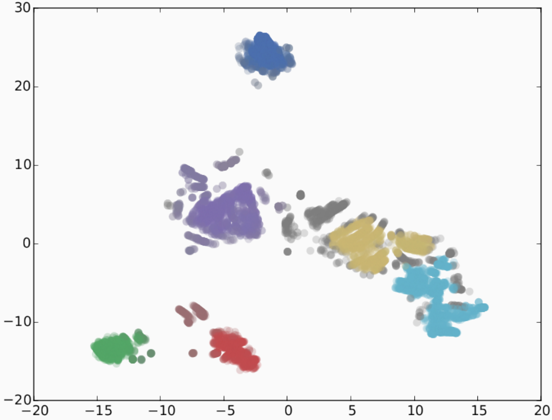
- . . .

Clusters in high dimensions are smeared in 2D projections

Clustering visualisation

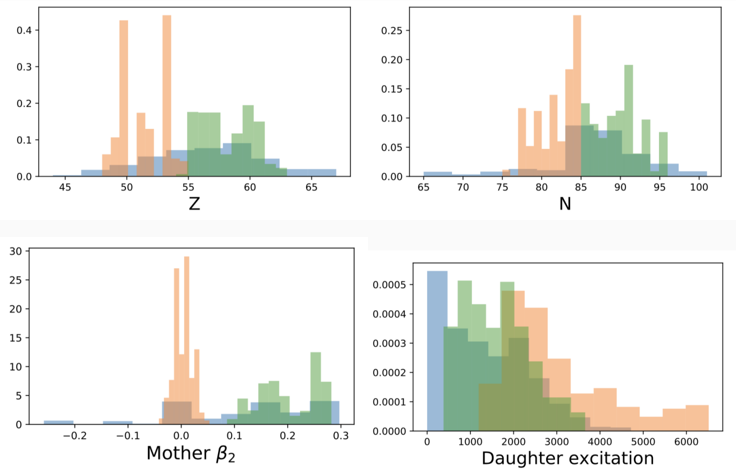
Use dimensional reduction (t-SNE) to visualise results



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

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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

Also relevant for ab initio approach!

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Database driven, but must be careful about introduction of biases

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Done correctly, realistic uncertainty & anomaly including correlations