

First-forbidden transitions in the reactor antineutrino anomaly

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Where is the anomaly?

Antineutrino's from decay of reactor fission fragments

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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% (2-3)

$$P_{SBL}(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) \approx 1 - \sin^2 2\theta_{41} \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

Very exciting,
but... it is real?

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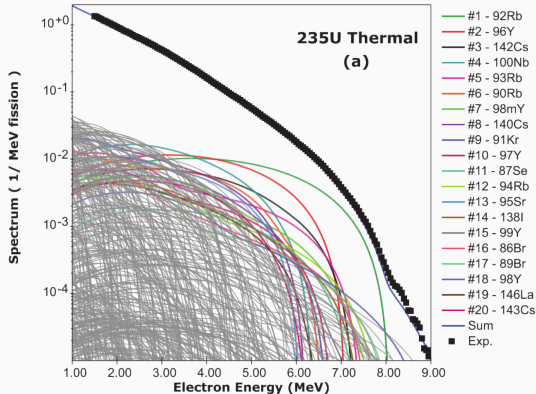
but... it is real?

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

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

Antineutrino origin

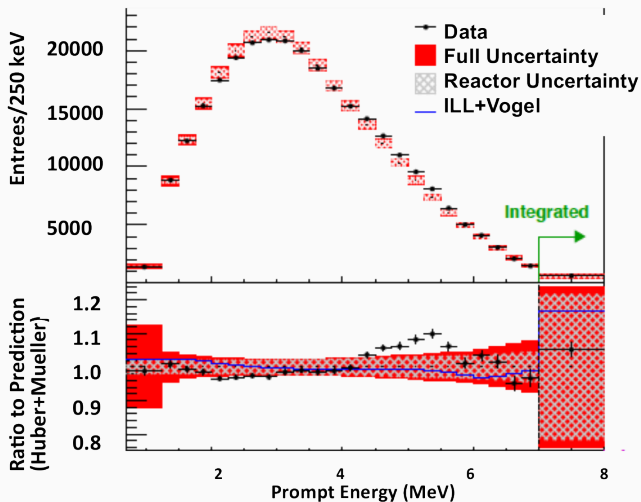
Fission fragments from ^{235}U , ^{238}U , ^{239}Pu and ^{241}Pu have many branches, but can only measure **cumulative** spectrum.



Conversion of all branches is **tremendous** challenge

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

Reactor bump



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

Experimental status

Very short baseline experiments

Since 2011, 10 experiments started setting up

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Very short ($<10\text{m}$) baseline experiments: measure oscillation directly

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

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

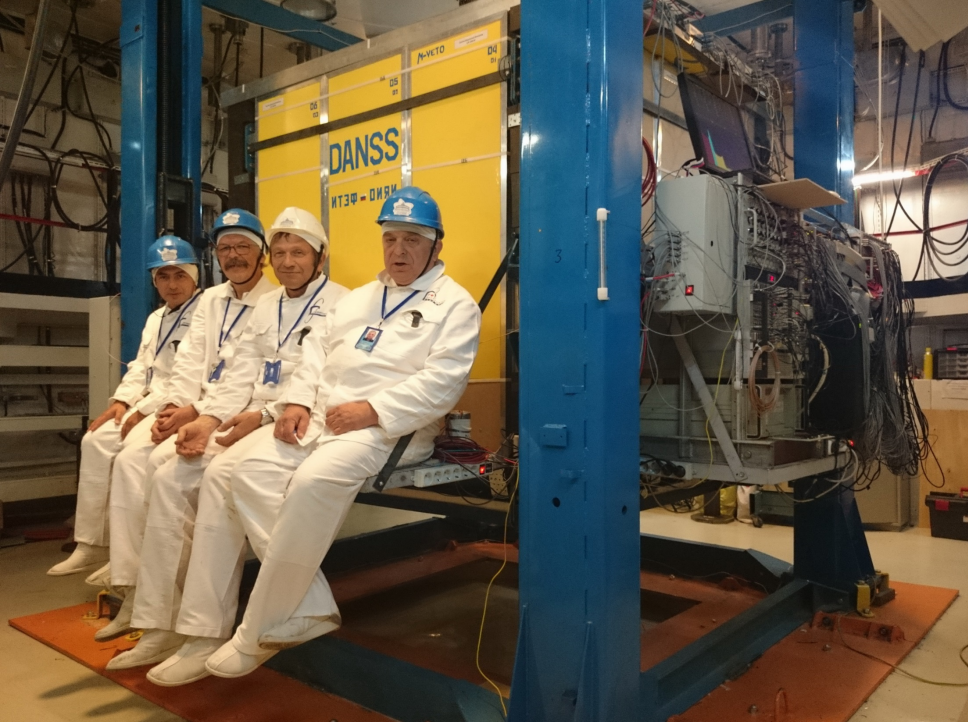
DANSS (Russia) 1804.04046

STEREO (France) 1806.02096

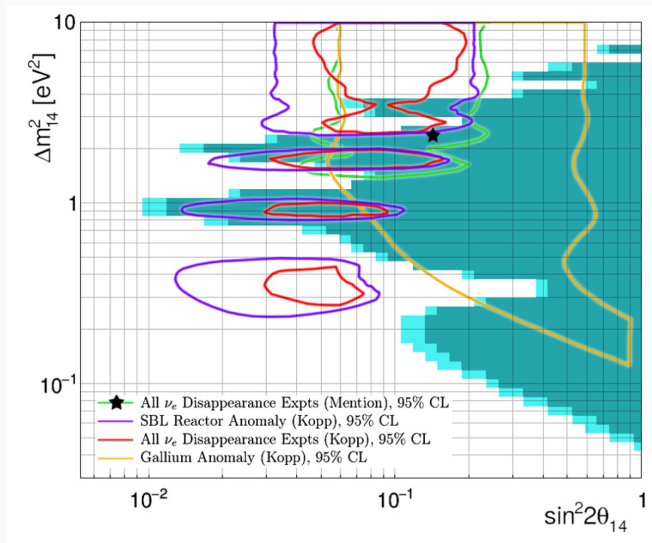
PROSPECT (USA) 1806.02784

NEOS (Korea) 1610.05134

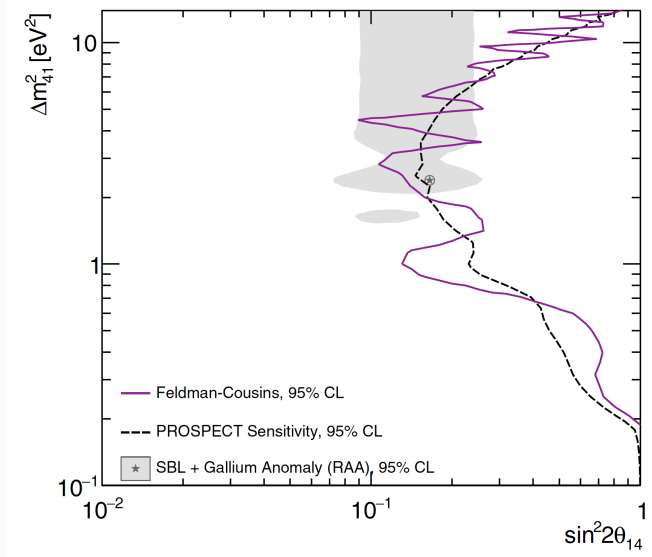
Very exciting & more coming soon!



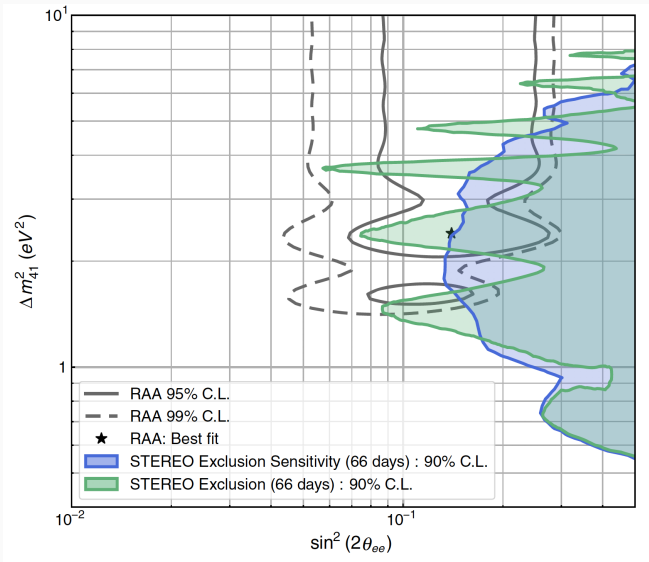
VSBL Results: DANSS



VSBL Results: PROSPECT



VSBL Results: STEREO



Faced with some interesting developments:

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Things point to deficiencies in databases & **theoretical modeling**

Theory status

Theory: participant sketch

Experiment sees nothing, what happens to theory?

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Nuclear decay is complicated

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Both greatly influence the spectrum shape!

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

Analysis procedure

Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

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Approaches split up in 2:

1. Conversion method: virtual branch ts

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Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

Approaches split up in 2:

1. Conversion method: virtual branch ts
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

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,
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Everything below 1.8 MeV in electron spectrum is unconstrained,
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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 $\langle Z \rangle^{n>1}$ effects, $RAA(hZ^{n>1}) \notin hRAA(Z^{N>1})!$

Estimated average $\langle \sigma \rangle = A_c$ 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 & Hayee et al.,
arXiv:1707.07728

Forbidden decays

Forbidden shape factors

Roughly 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 SH, J. Kostensalo, N. Severijns, J. Suhonen, PRC 99 (2019)

031301(R)

Central element in analysis is knowledge of spectrum shape

$$\frac{dN}{dW} / pW(W_0 - W)^2 F(Z; W) C(Z; W) :::$$

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

Treat as allowed

Treat as unique forbidden

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$$\frac{dN}{dW} / \rho W (W_0 - W)^2 F(Z; W) C(Z; W) :::$$

(Almost) everything but shape factor C , is under control

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

Treat as allowed

Treat as unique forbidden

are ... not great

Shape factor

General shape factor

$$C(Z; W) = \sum_{k_e; k; K} M_K^2(k_e; k) + m_K^2(k_e; k) - \frac{2 k_e k_e}{k_e W} M_K(k_e; k) m_K(k_e; k);$$

where

$$k_e = \frac{k_e^2 + k_e^2}{k_e^2 + k_e^2};$$
$$k_e = \frac{k_e^2 + k_e^2}{k_e^2 + k_e^2} \frac{k_e W}{k_e};$$

are Coulomb functions of $O(1)$

Behrens, Bhring, Electron radial wave functions, 1982

First-forbidden transitions

Depending on spin-parity change ϵ , can be simple \mathbb{R} (0:01)

$$C_0 \sim 1 + \frac{2R}{3W} b + O(\frac{ZR}{W_0 R^2})$$

First-forbidden transitions

Depending on spin-parity change ϵ , can be simple \mathbb{R} (0:01)

$$C_0 / 1 + \frac{2R}{3W} b + O(ZR; W_0 R^2)$$

very difficult

$$C_1 / 1 + aW + \frac{b}{W} + cW^2$$

First-forbidden transitions

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$$C_0 \sim 1 + \frac{2R}{3W} b + O\left(\frac{ZR}{W_0 R^2}\right)$$

very difficult

$$C_1 \sim 1 + aW + \frac{b}{W} + cW^2$$

or rather simple, again

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

First-forbidden transitions

There are several **complicating factors**, however

Coulomb corrections at all levels: Fermi function, higher order corrections, modified radial behaviour

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Very sensitive to nuclear structure, strong suppression makes cancellations extra dangerous

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Challenging, but attempt to **establish uncertainty**

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

First-forbidden transitions

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Higher in E you go, fewer branches contribute

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Higher in E you go, fewer branches contribute

From 5 MeV onwards & 90% of ν ux 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

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calculated shape factor

in nuclear shell model

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$$\frac{dN}{dE} / \rho E(E_0 - E)^2 F(Z; E) \\ C(Z; E)$$

Allowed: $C = 1$

As expected,

large spectral changes

Spectral changes

Can we use knowledge of these transitions to say something about the other 3000?

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Uniform behaviour for each J separately invites a parametrization

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Uniform behaviour for each J separately invites a parametrization

Fit each calculated shape factor using simple polynomial, obtain distributions of correlated t parameters for each J

Construct conservative shape factor distributions for each

Directly applicable to conversion method!

Forbidden spectral changes

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

Forbidden spectral changes

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

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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First forbidden transitions were shown to be **dominant** in region of interest

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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^e is used

Matrix elements

Up to 1st order, deal with 6 matrix elements

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J	Matrix elements	Forbidden
0	${}^A M_{000}$	-
1	${}^A M_{111}; {}^A M_{121}; {}^V M_{101}; {}^A M_{110}$	0! 0
2	${}^A M_{211}$	0! 0; $\frac{1}{2}!$ $\frac{1}{2}; 1!$ 0

Behrens-Bühring notation: ${}^V = {}^A M_{KLs}$

s: timelike (0, scalar) or spacelike (1, vector)

L: Angular momentum from multipole decomposition

K: total J of operator ($J_L = s_j$ K = L + s)

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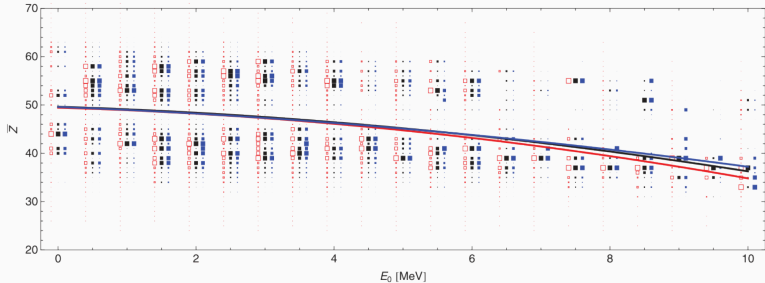
K: total J of operator ($|L - s| \leq K \leq L + s$)

General: 1 dominant matrix element easy, > 1! harder

Modern conversion analysis

Extrapolation & Virtual branches

How to construct these fictitious 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

$$S(E_e) = \prod_i c_i S(E_e; \bar{Z}(E_{0;i}); E_{0;i})$$

5. Invert spectra using $E = E_0 \quad E_e$

Database extrapolation

Database contains much more information to use

Trivial extension

to improve

(Z)² behaviour,

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Employ

Machine Learning

clustering

algorithms to find

better patterns

Nuclear decays live in high-dimensional vector spaces

Z, A

Log ft values

Branching Ratio, E_0 , daughter excitation

ΔJ^Δ (forbiddenness, unique)

Initial and final deformation

...

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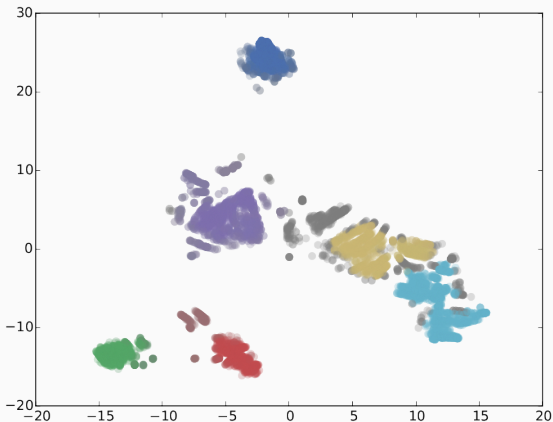
Initial and final deformation

...

Clusters in high dimensions are smeared in 2D projections

Clustering visualisation

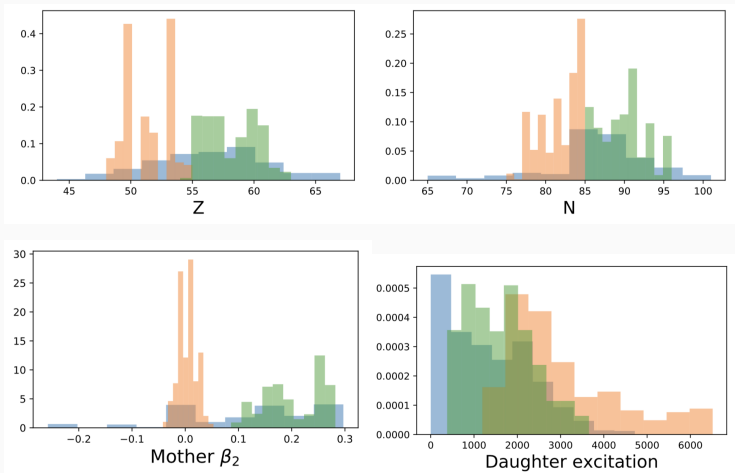
Use dimensional reduction (t-SNE) to visualise results



Clear clusters, intercluster distance irrelevant here

Intercluster comparison

Example comparison for 3 clusters



Large differences visible for simple histograms!

How to combine these results?

Instead of a single $Z(E_0)$ fit, use

Multidimensional Cluster Markov Chain Monte Carlo (MC³)

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Build a **distribution** of anomaly ! better uncertainty estimate

Virtual branch creation

Procedure:

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

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Bayes' theorem:

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Modification of prior allows for compensation/study of pandemonium

MC³ moving forward

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

Also relevant for *ab initio* approach!

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Done correctly, *realistic uncertainty & anomaly* including correlations