(k)eV sterile neutrinos: from the reactor anomaly-that-was to the BeEST

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Subatech, May 23 2022

North Carolina State University & TUNL, USA

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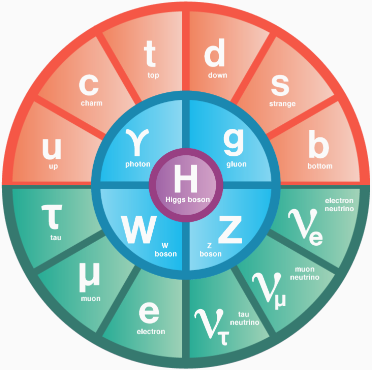
Dark matter introduction

Introduction: Standard Model

Three out of four
fundamental forces (no gravity):

Standard Model



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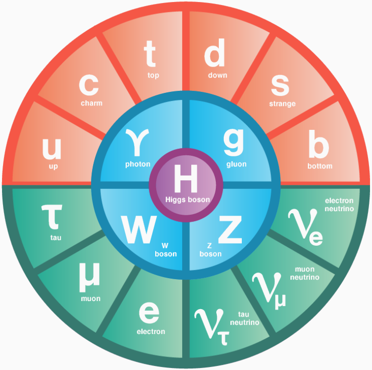

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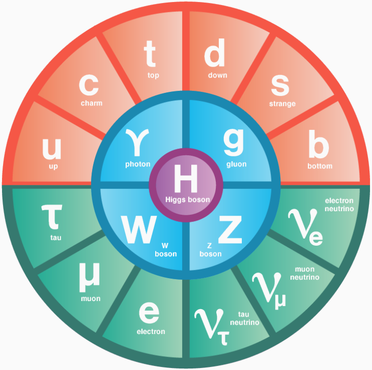

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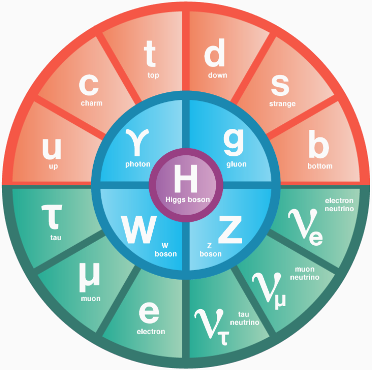

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Open questions: dark matter, gravity, neutrino masses, . . .

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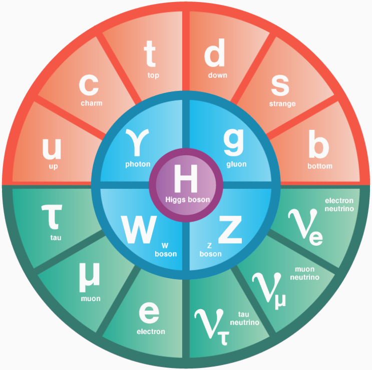

Why dark matter: intuitive

For stars in circular orbits in galaxy, virial theorem says

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

so should be $\propto r^{-1/2}$ towards edge

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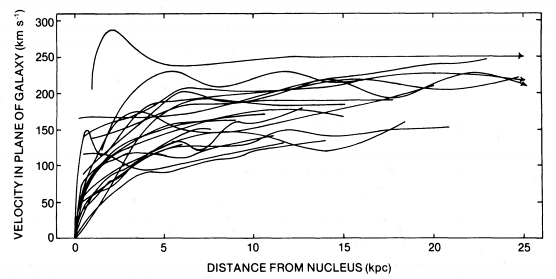
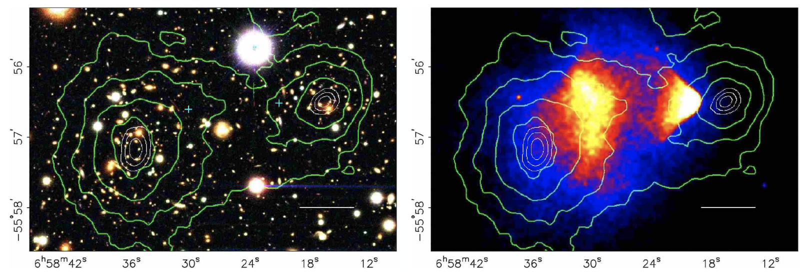


Why dark matter: intuitive

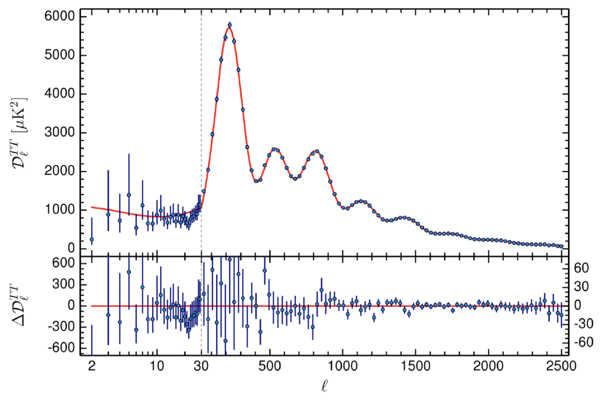
Discrepancy between weak gravitational lensing & X-ray



Most of gravitational mass $\neq$ visible mass!

Cosmic microwave background

Power spectrum of CMB



Best fit gives $\Omega_{DM}/\Omega_b \approx 5$ using ΛCDM

Why & what is dark matter

General assumed DM properties:

- Neutral
- Long-lived
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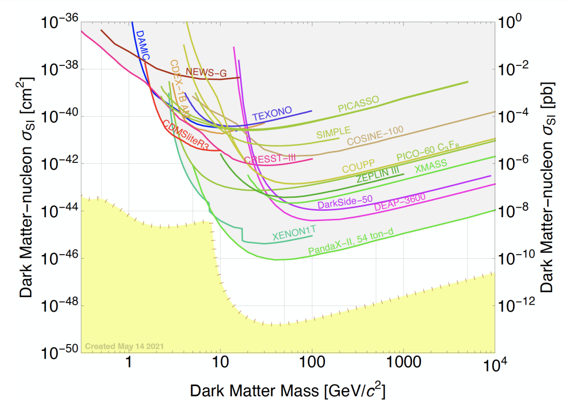
Cosmic microwave background & more explained by ΛCDM (Cold Dark Matter)

Dark matter candidates: WIMPs

Standard possibility is Weakly Interacting Massive Particle (WIMP), but



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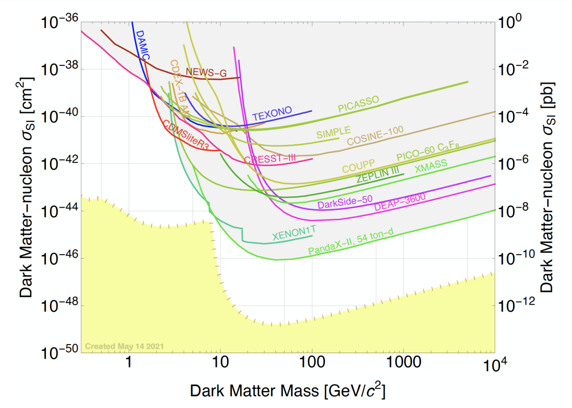
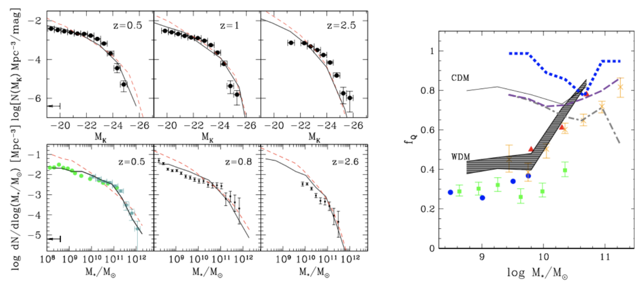


Attention turned to others: axion(-like) particles, dark photons, MACHO's, . . .

ΛCDM problems

Using purely cold DM also gives tension



Additional issues

- Missing dwarf galaxies
- Too-big-to-fail
- ...

Sterile neutrino DM

Sterile neutrinos are an interesting DM candidate

- Standard Model singlet, only couples through oscillation

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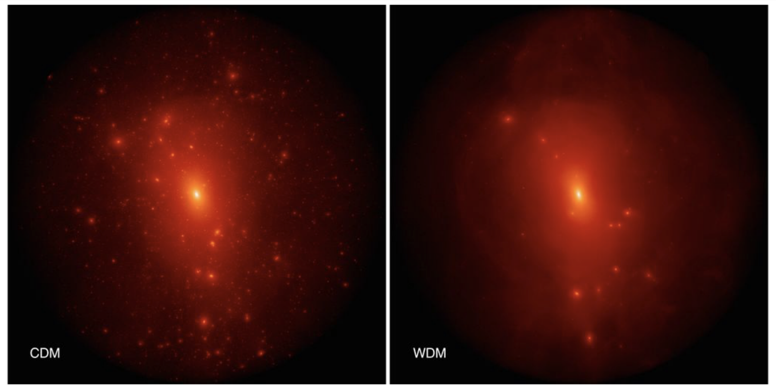
In order to explain *all* DM, mass must be at least $\mathcal{O}(\text{keV})$

$\rightarrow$ warm/hot DM

Sterile neutrino WDM

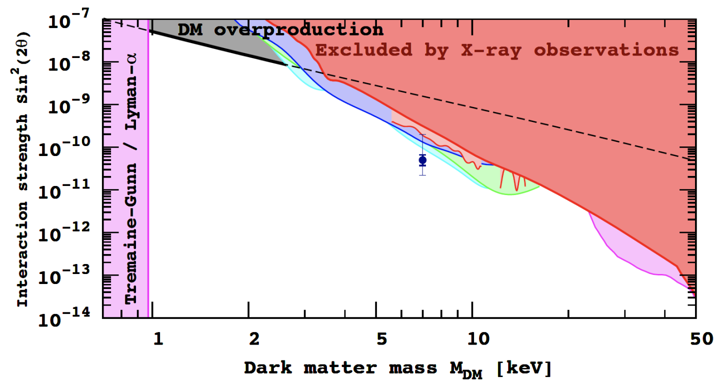
Warm DM washes out short-scale structure → should be easy to see?



Galaxy formation washes out signal

Possible observation?

Sterile neutrino can decay $N \to \nu\gamma$



Still controversial!

Who ordered eV steriles? The reactor anomaly

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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2011: Measured $\# \bar{\nu}_e <$ predicted from β decay

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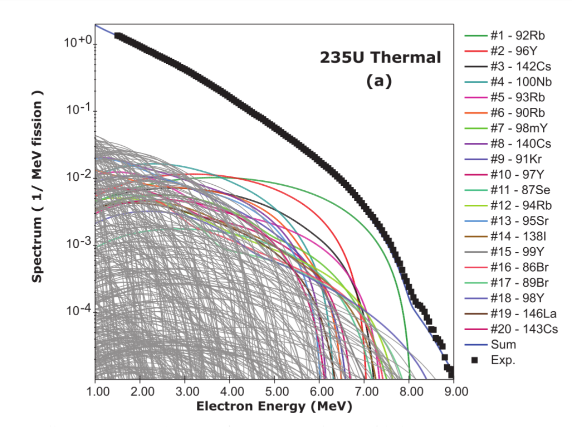
When new physics lurks, look out for quirks!

Antineutrino origin

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



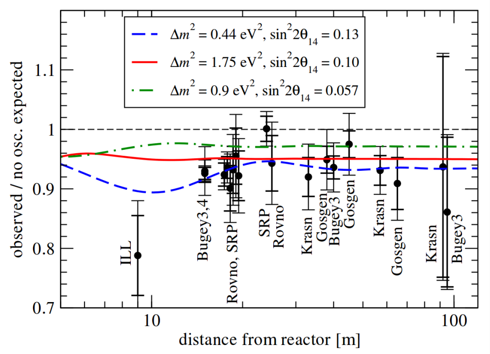
Conversion of all β branches is **tremendous** theory challenge

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

Deficiency and particle physics proposal

2011: Deficiency in neutrino count rate at 94% (2-3σ)

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



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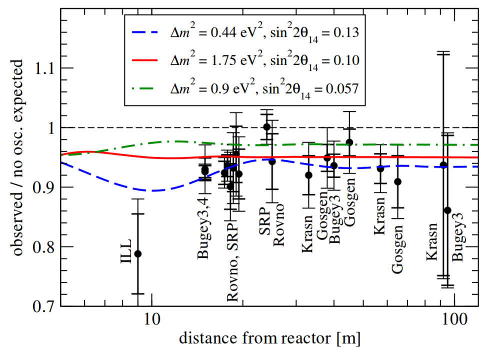
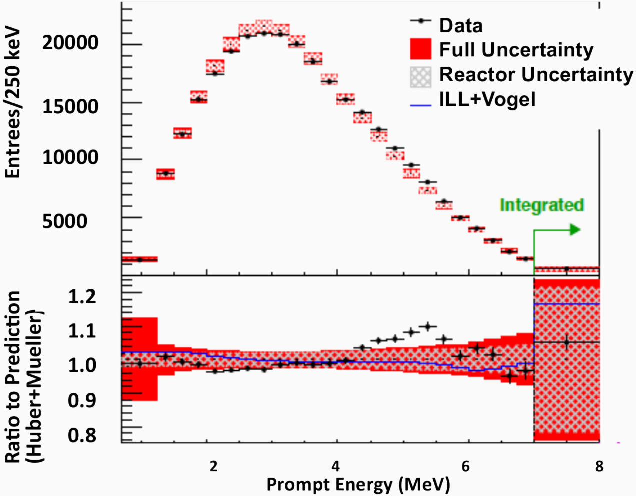
Understanding of all corrections & nuclear structure is **crucial**!



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

Reactor bump



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

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

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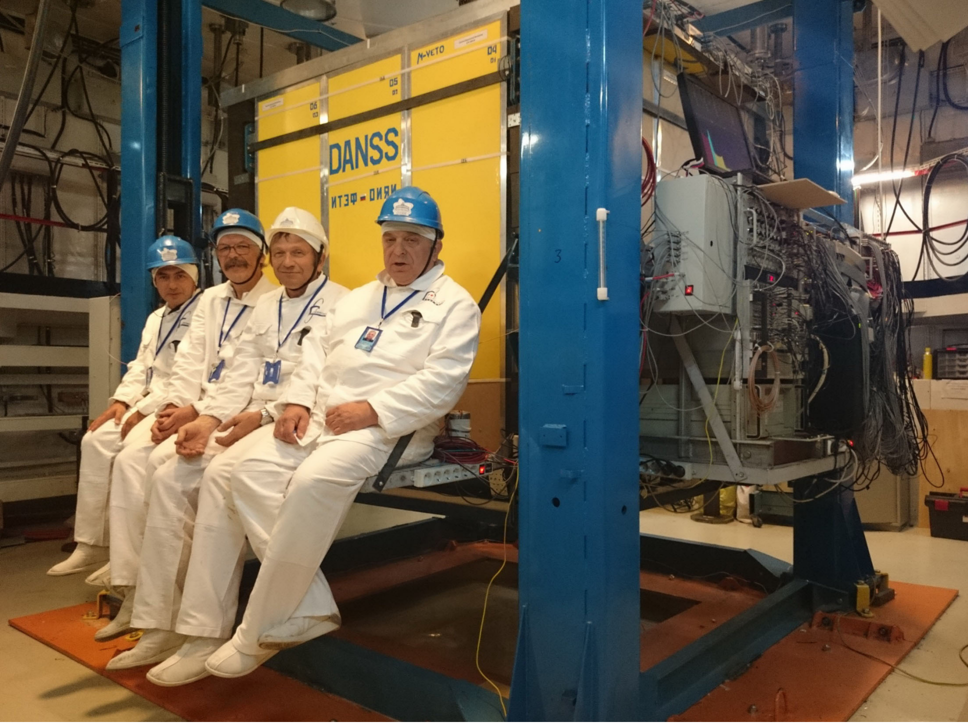
Very short ($<$10m) baseline experiments: measure oscillation directly

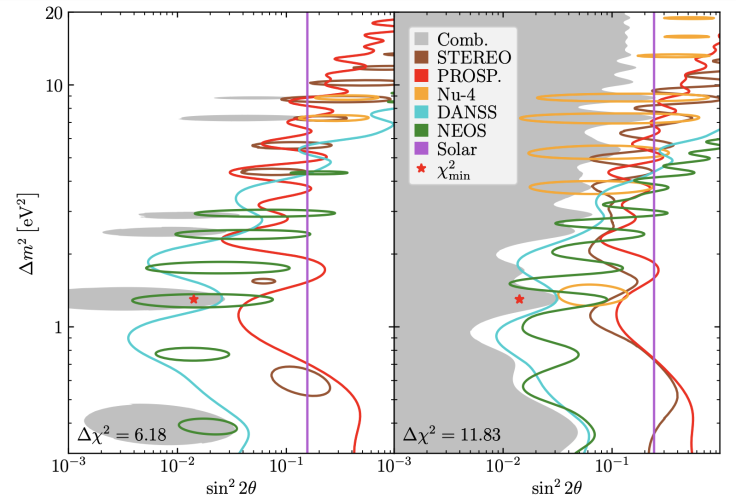
Several experiments came online late 2017/2018! Published data from

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

and more, most have final results!


M-VETO
04
05
06
DANSS
ИТЭФ ОИЯИ
3

Current reactor status



2111.12530

Overview of reactor $\bar{\nu}_e$ decade

Faced with some interesting developments:

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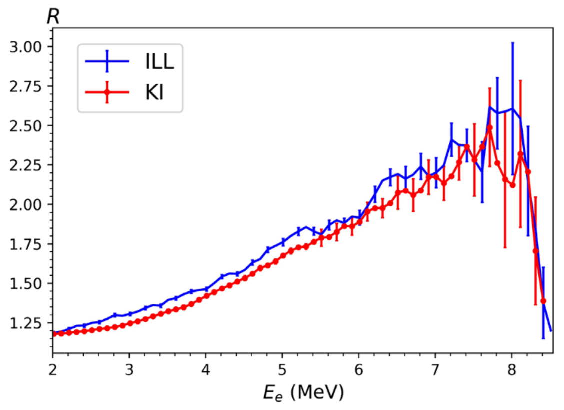
4. Also 2017: fuel dependencies in spectra
5. 2021: New e^- spectral measurements!
6. Also 2021: BEST confirms Gallium anomaly

New e^- spectral measurements

Daya Bay & others point towards normalization issues with ^{235}U

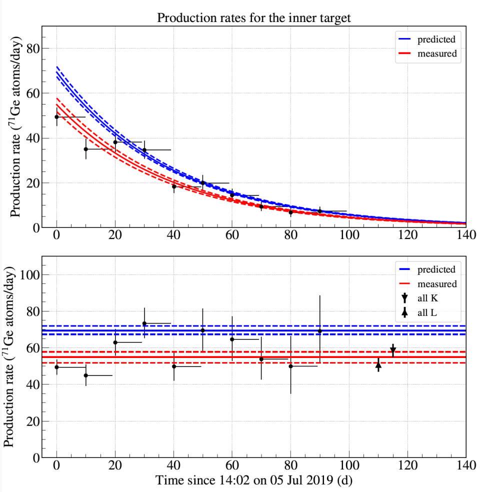


Kurchatov Institute measured $^{e}S_5/^{e}S_9$ and found 5%! ~~Anomaly~~?

PRD 104 (2021) L071301

BEST

^{51}Cr deficiency in measured ν_e



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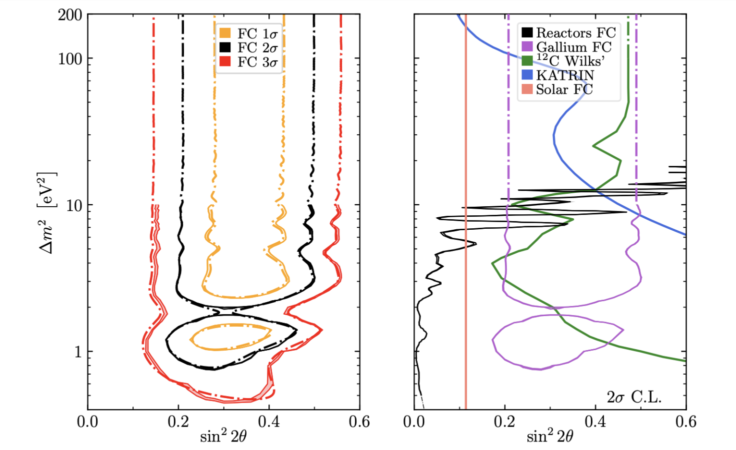
Global fits



Clear tension between strong BEST result & solar, $\Delta m^2 \gtrsim 10$ eV^2?

2111.12530

Theory: β participant sketch

Experimental sterile signature unclear, what happens to theory?

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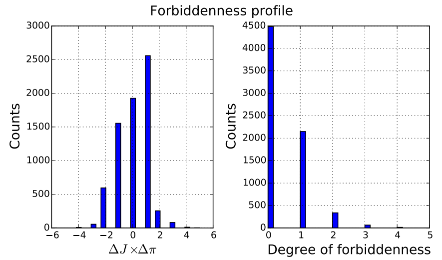

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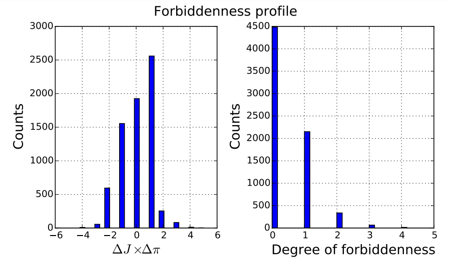

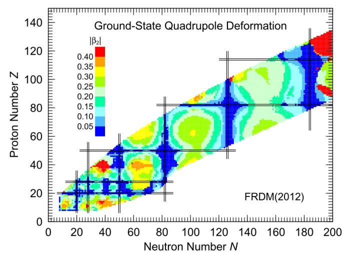

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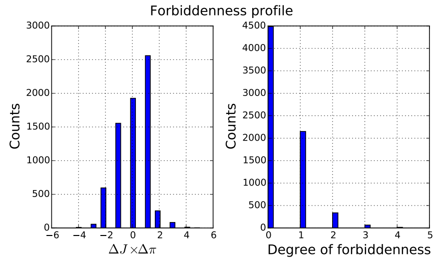

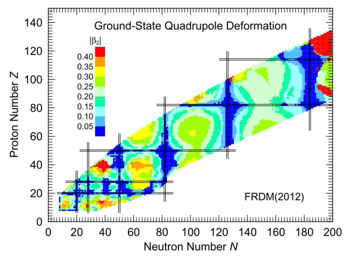

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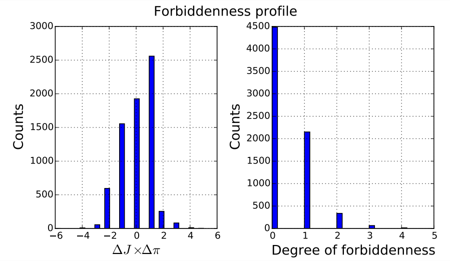

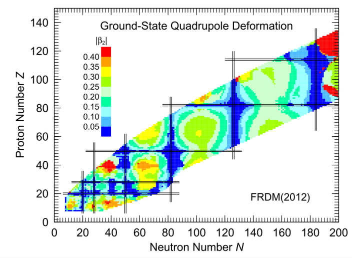

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Do our best and try to convert $\sim$ 8000 β branches per actinide

How to calculate the β spectrum shape

Active participation of QED, QCD & WI → Complicated system

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Quark → Nucleon → Nucleus → Atom → Molecule

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$$\begin{aligned} N(W)dW = \frac{G_V^2 V_{ud}^2}{2\pi^3} & F_0(Z,W)\, L_0(Z,W)\, U(Z,W)\, R_N(W,W_0,M) \\ & \times\ Q(Z,W,M)\, R(W,W_0)\, S(Z,W)\, X(Z,W)\, r(Z,W) \\ & \times\ C(Z,W)\, D_C(Z,W,\beta_2)\, D_{\mathrm{FS}}(Z,W,\beta_2) \\ & \times\ pW(W_0-W)^2\, dW \end{aligned}$$

LH *et al.*, Rev. Mod. Phys. 90 (2018) 015008; 1709.07530

β spectrum shape

Central element in analysis is knowledge of β spectrum shape

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

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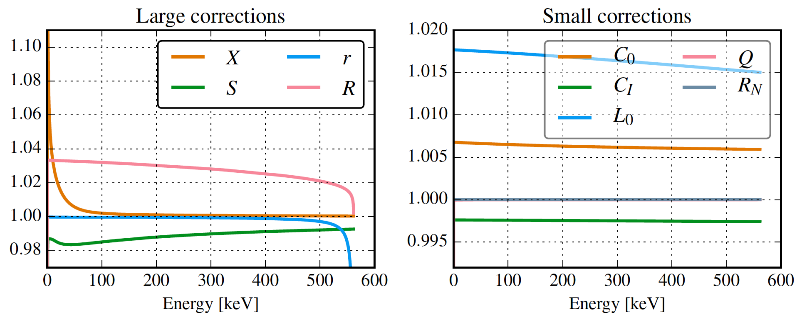

LH, Severijns, Comp. Phys. Comm. 240 (2019) 152; github.com/leenderthayen/BSG

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but maybe not the best?

Forbidden shape factors

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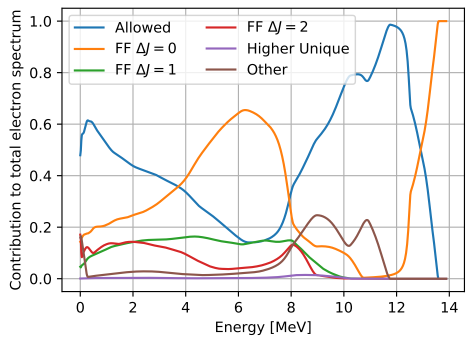

Experimental ROI (2-8 MeV) is dominated by forbidden decays

LH *et al.*, PRC 99 (2019) 031301(R), LH *et al.*, PRC 100(2019) 054323

Shape factor

Back to the chalk board!

General shape factor

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

λ_k, μ_k Coulomb functions of $\mathcal{O}(1+(\alpha Z)^2)$

Behrens, Bühring, Electron radial wave functions, 1982

First-forbidden transitions

Depending on spin-parity change, C can be relatively simple

$$C_{0^-} \propto 1 + \mathcal{O}(10^{-2})$$

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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

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

Higher in E you go, fewer branches contribute

First-forbidden transitions

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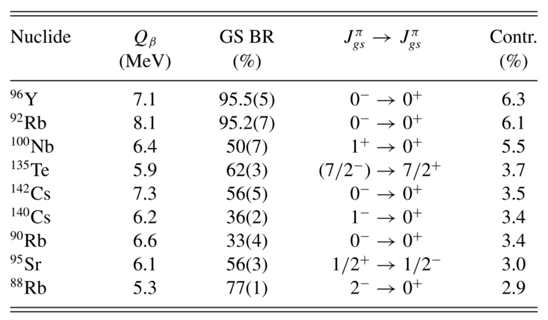
Higher in E you go, fewer branches contribute

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



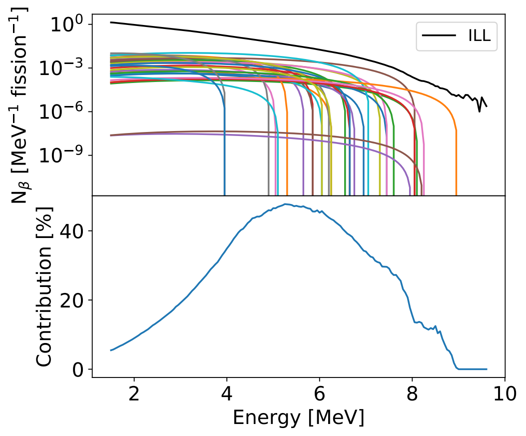
Nuclide	Q_β (MeV)	GS BR (%)	$J^\pi_{gs} \rightarrow J^\pi_{gs}$	Contr. (%)
^{96}Y	7.1	95.5(5)	$0^- \rightarrow 0^+$	6.3
^{92}Rb	8.1	95.2(7)	$0^- \rightarrow 0^+$	6.1
^{100}Nb	6.4	50(7)	$1^+ \rightarrow 0^+$	5.5
^{135}Te	5.9	62(3)	$(7/2^-) \rightarrow 7/2^+$	3.7
^{142}Cs	7.3	56(5)	$0^- \rightarrow 0^+$	3.5
^{140}Cs	6.2	36(2)	$1^- \rightarrow 0^+$	3.4
^{90}Rb	6.6	33(4)	$0^- \rightarrow 0^+$	3.4
^{95}Sr	6.1	56(3)	$1/2^+ \rightarrow 1/2^-$	3.0
^{88}Rb	5.3	77(1)	$2^- \rightarrow 0^+$	2.9

Breakdown ^{235}U @ 5 MeV

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

Forbidden shape factors

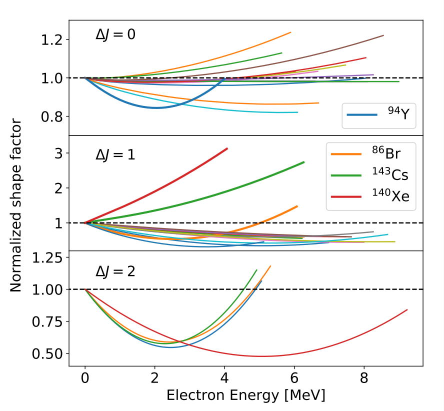
Picked 36 dominant forbidden transitions



explains $> 40\%$ of flux in ROI (4-7 MeV)

Forbidden shape factors

Picked 36 dominant forbidden transitions, calculated shape factor in nuclear shell model



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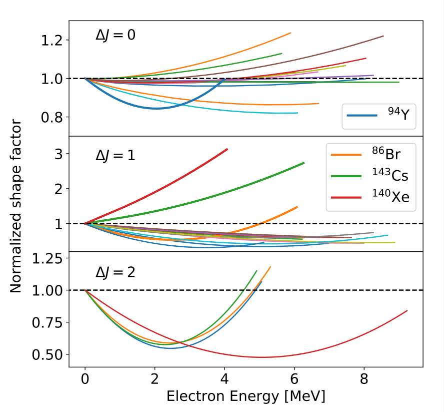
$$\frac{dN}{dE} \propto pE(E_0 - E)^2 F(Z, E)$$

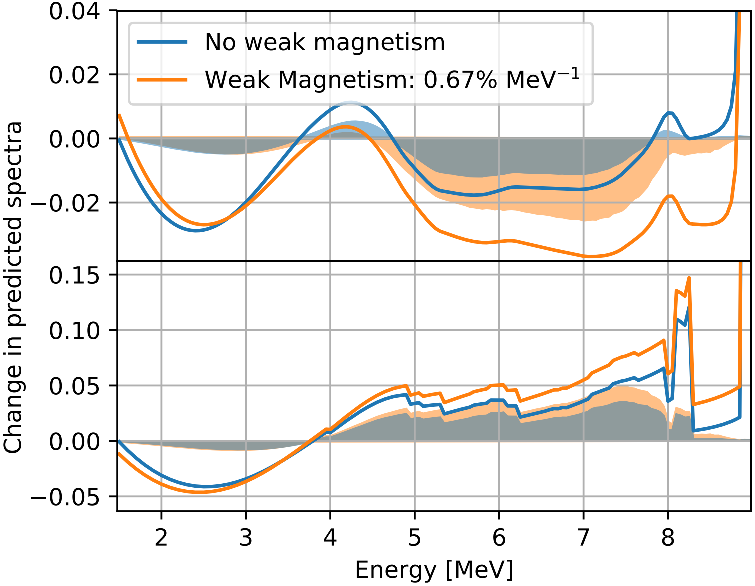
$$\boldsymbol{C(Z, E)}$$

Allowed: $C \approx 1$

As expected,
large spectral changes



Spectral changes



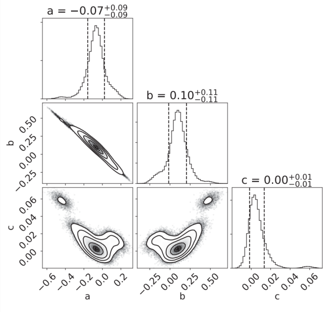
Parametrization

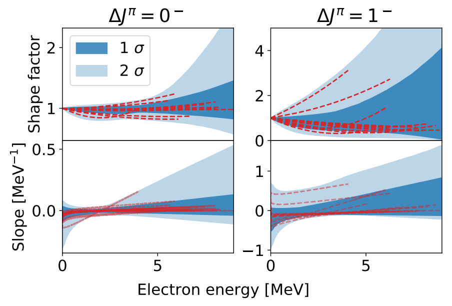
Calculated 36 → what about the others?

Parametrization

Calculated 36 → what about the others?

Construct conservative shape factor distributions for each ΔJ



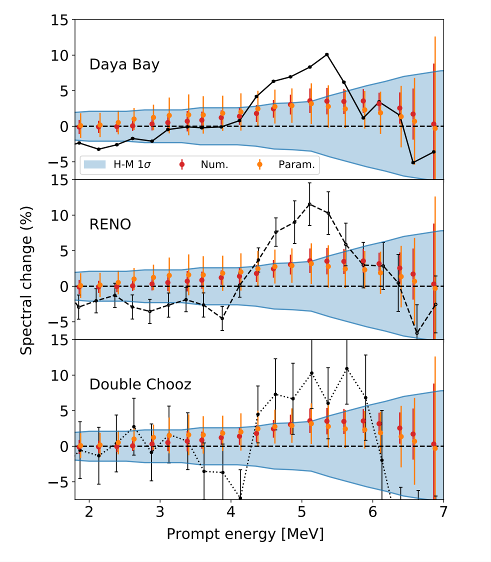


Monte Carlo sampling for remaining 2500 branches

→ Uncertainty due to forbidden branches (first time)

Forbidden transitions & the bump

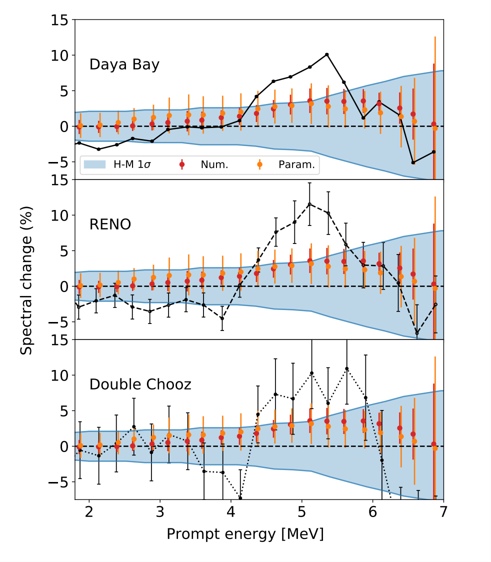
Use spectrum changes forcing agreement with experimental e^- spectrum



Forbidden transitions & the bump

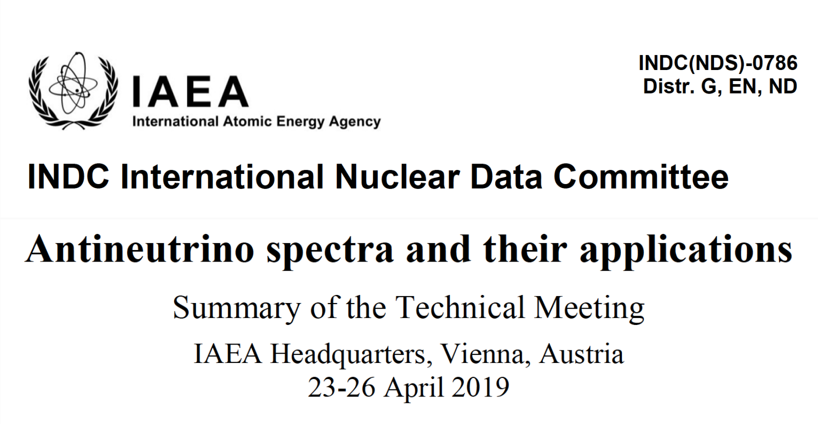
Use spectrum changes forcing agreement with experimental e^- spectrum

Bump mitigated + increased theoretical uncertainties



LH *et al.*, PRC 99 (2019) 031301(R), LH *et al.*, PRC 100(2019) 054323

IAEA: Delegates of major experiments & theorists



INDC(NDS)-0786
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IAEA
International Atomic Energy Agency

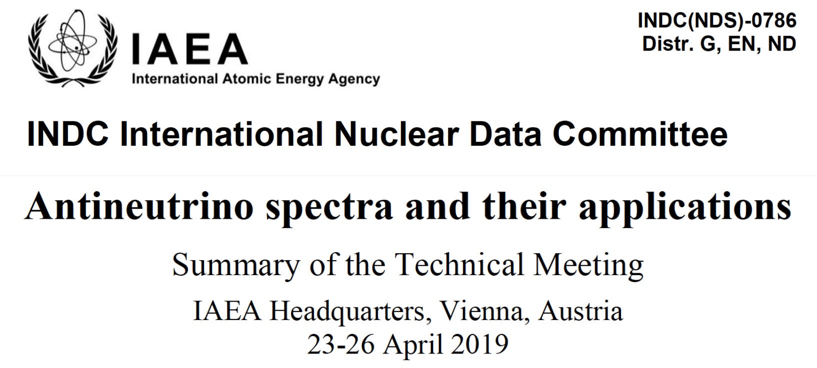
INDC International Nuclear Data Committee

Antineutrino spectra and their applications

Summary of the Technical Meeting

IAEA Headquarters, Vienna, Austria
23-26 April 2019

IAEA: Delegates of major experiments & theorists



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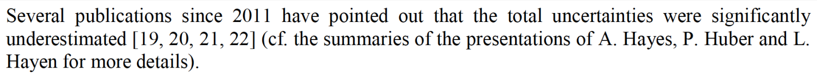
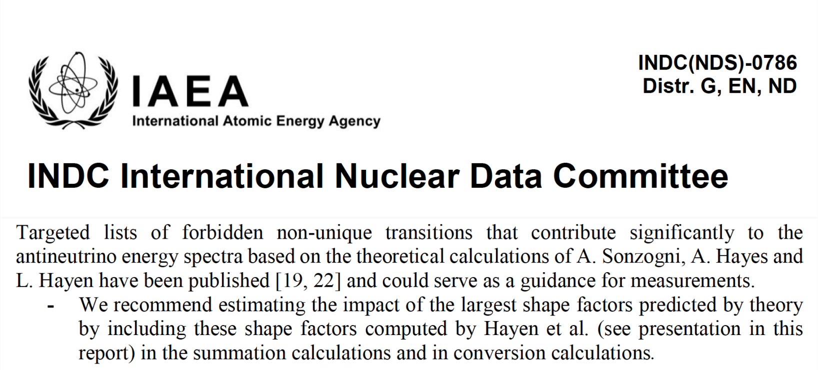


Several publications since 2011 have pointed out that the total uncertainties were significantly underestimated [19, 20, 21, 22] (cf. the summaries of the presentations of A. Hayes, P. Huber and L. Hayen for more details).

→ **Consensus** that uncertainties are *significantly underestimated*

IAEA: Delegates of major experiments & theorists



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Targeted lists of forbidden non-unique transitions that contribute significantly to the antineutrino energy spectra based on the theoretical calculations of A. Sonzogni, A. Hayes and L. Hayen have been published [19, 22] and could serve as a guidance for measurements.

- We recommend estimating the impact of the largest shape factors predicted by theory by including these shape factors computed by Hayen et al. (see presentation in this report) in the summation calculations and in conversion calculations.

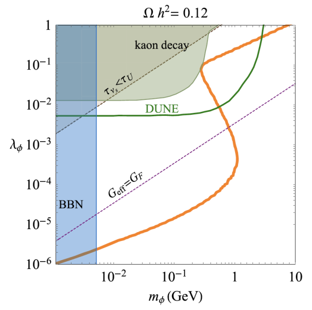
Currently ongoing work at Subatech, campaigns at JYFL, ORNL

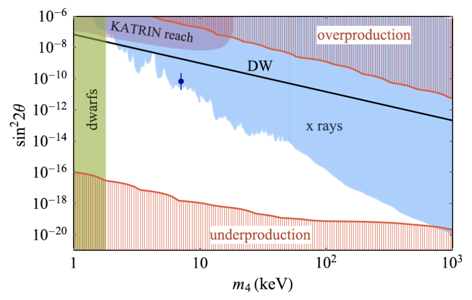
→ access to <1.8 MeV $\bar{\nu}_e$ for coherent scattering!

keV sterile neutrino's with the BeEST

Detecting keV steriles with β recoil spectroscopy

keV-scale sterile neutrino's are well-motivated





But how to measure? PRL 124 (2020) 081802

Detecting keV steriles with β recoil spectroscopy

Measure the recoiling nucleus in electron capture!

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Advantages:

- Two-body process means clean signature (single peak)
- Q value in β decay means sensitivity to keV N

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Measure the recoiling nucleus in electron capture!

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- Q value in β decay means sensitivity to keV N

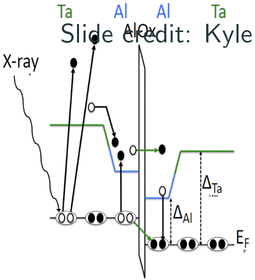
But generally very hard! Final state effects, detector response, ...

Meet superconducting tunnel junctions

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, making it among the fastest high-resolution quantum sensors available
  → "High" Rate (10^4 s^{-1} per pixel)

Ideal for RIB experiments at ISAC

Slide credit: Kyle Leach



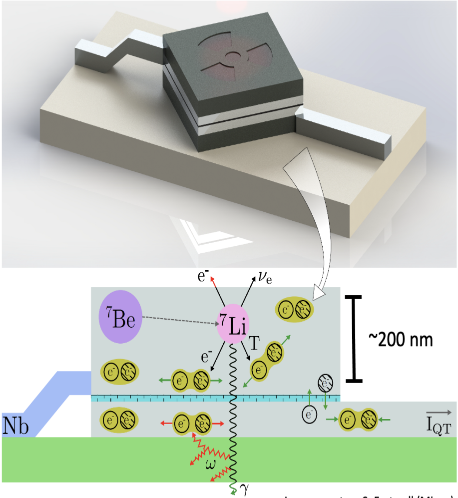
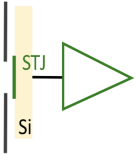


Image courtesy S. Fretwell (Mines)

Superconducting tunnel junctions

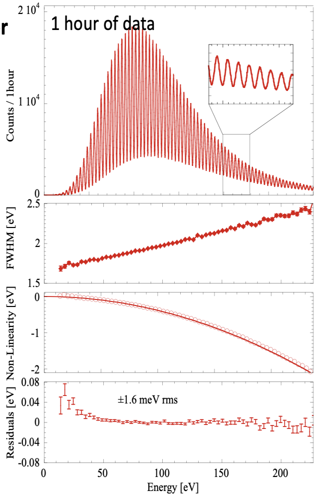


- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage

Slide credit: Kyle Leach

- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity (10^{-4} per eV)

Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK

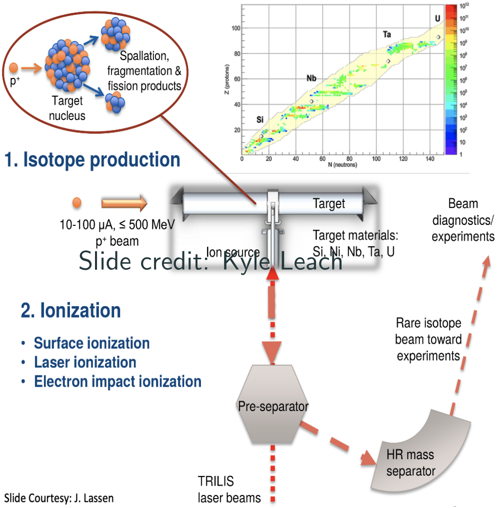


S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

Superconducting tunnel junctions

Slide credit: Kyle Leach

Superconducting tunnel junctions



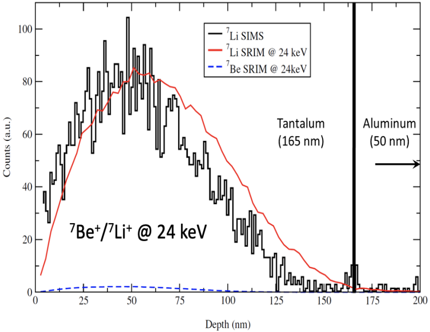
1. Isotope production

2. Ionization

- **Surface ionization**
- **Laser ionization**
- **Electron impact ionization**

Slide credit: Kyle Leach

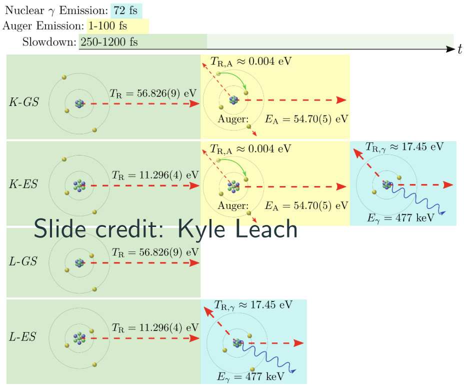
Slide Courtesy: J. Lassen



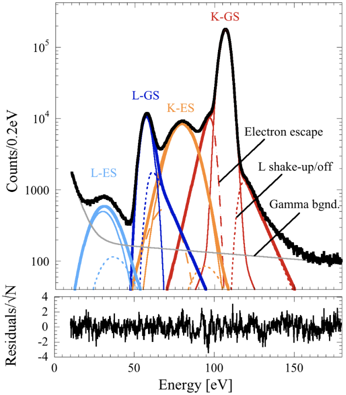
Our current method with ^{7}Be for the BeEST:

- Done at the ISAC Implantation Station
- Inactive (room temperature) sensor array
- Clear and ship sensor to lab (LLNL)
- Receive, handle, and cool to < 100 mK

Superconducting tunnel junctions



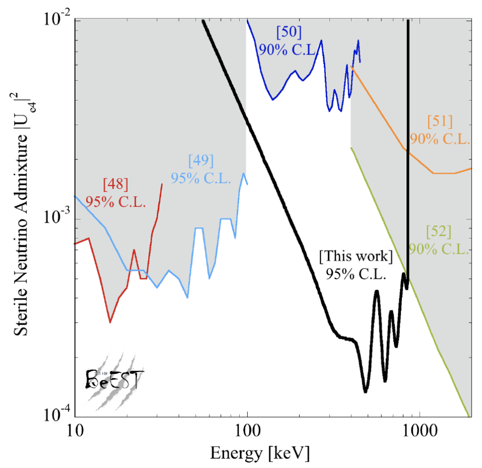
Slide credit: Kyle Leach



S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

First results

In first physics run, already competitive



PRL 126 (2021) 021803

Conclusion

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Sterile neutrinos are interesting & well-motivated dark matter candidates

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eV-scale steriles from reactor anomaly are open question, still!

Forbidden β transition play significant role in reactor $\bar{\nu}_e$ prediction, ongoing work at Subatech!

keV-scale steriles under investigation with new exciting technology, already competitive!

Backup

Analysis procedure

Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

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Approaches split up in 2:

1. **Conversion** method: virtual β branch fits

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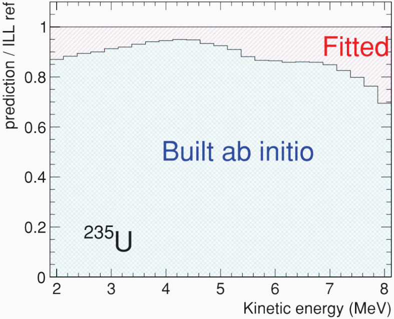
Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

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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Everything below 1.8 MeV in electron spectrum is unconstrained,
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2 elements which require pause

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

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

First-forbidden transitions

There are several complicating factors, however

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

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Challenging, but attempt to establish uncertainty