Very Short Baseline Reactor Neutrinos: Motivations and Overview

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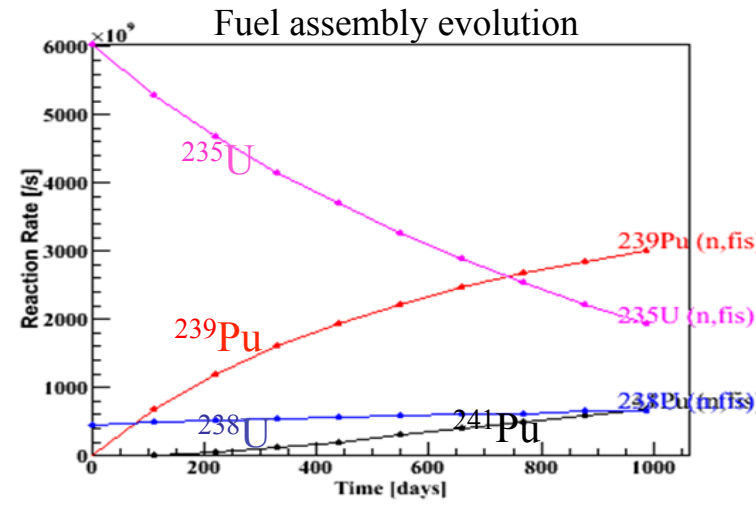
Outline

- Introduction & Motivations
- New Calculations for Reactor Antineutrino Spectra
- Reactor Antineutrino Anomaly (RAA)
- Shape Anomaly
- Fuel dependence
- Very Short Baseline Reactor Antineutrino Experiments
- Flux Models
- Conclusions & Outlooks

Reactors and Beta Decay

- In Pressurized Water Reactors, thermal power mainly induced by 4 isotopes (Low Enriched Uranium):
  - ^{235}U and ^{238}U in fresh fuel
  - Other fissile nuclei (^{239}Pu & ^{241}Pu) created after reactor start by capture and decay processes
  - Burn-up effect => unit GWd/t
- In some research reactors: Highly Enriched Fuel (~93% ^{235}U)



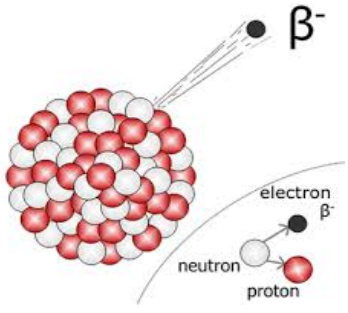
- Fission process gives thermal energy:

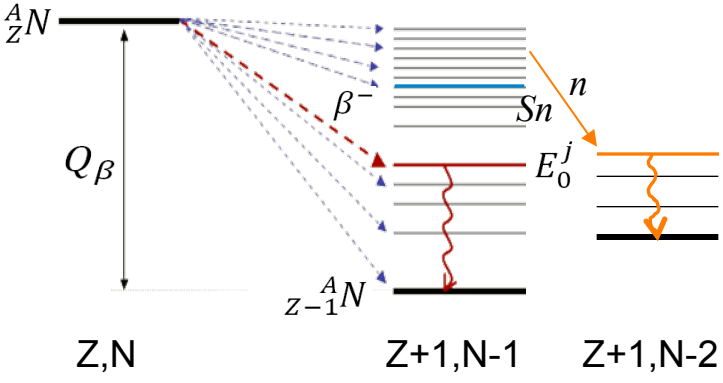
$$n + {}^{235}U \rightarrow {}^{236}U^{*} \rightarrow \mathrm{FP1} + \mathrm{FP2} + \mathrm{neutrons}\,(200MeV)$$

- The fission products (FP) after the fissions are neutron-rich nuclei undergoing β and β-n decays:

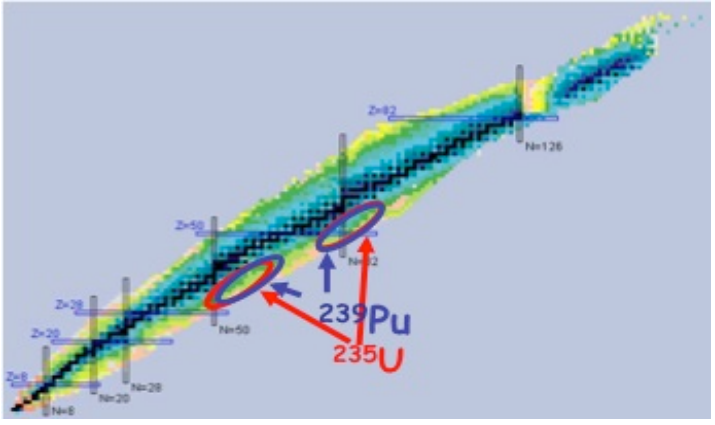
$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_e$$

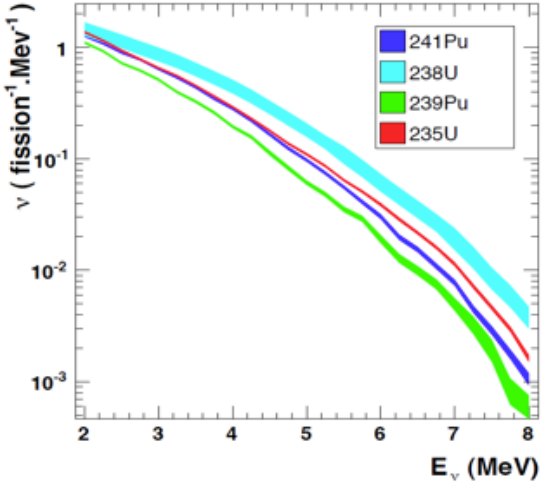
$$\hookrightarrow {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s$$





Antineutrinos for Peace





About 6 antineutrinos emitted per fission
→ About 10^{21} antineutrinos/s emitted by a 1 GW_e reactor

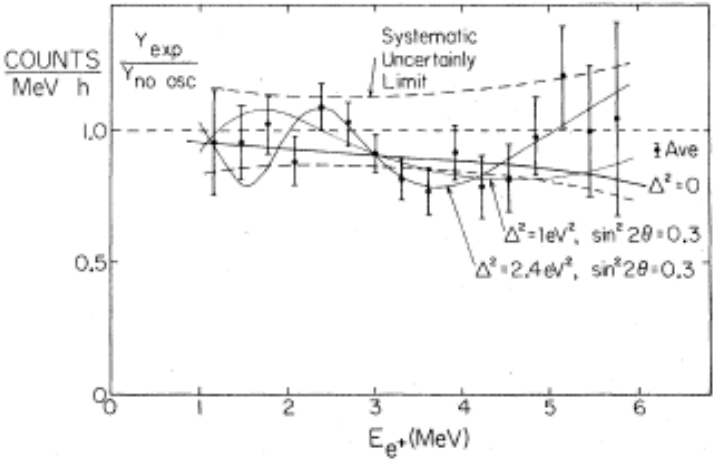
- Use the discrepancy between antineutrino flux and energies from U and Pu isotopes to infer reactor fuel isotopic composition and power
  - ❑ Reactor monitoring, non-proliferation and interest for the IAEA IAEA Report SG-EQGNRL-RP-0002 (2012)
  - ❑ Idea born in the 70s (Mikaelian et al.), demonstrated in the 80s/90s but developed lately

The Summation Method, relying on nuclear data, is the only predictive one for innovative reactors & fuels:

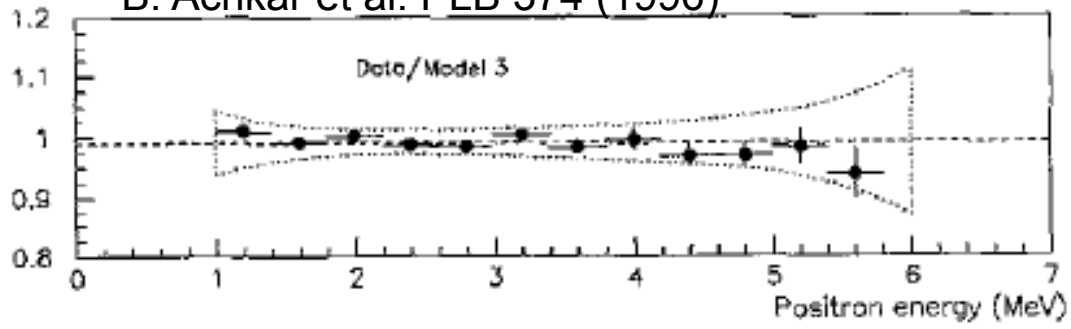
⇒ The **IAEA Nuclear Data Section includes the measurements for reactor antineutrino spectra in their** Priority lists (CRP meetings, TAGS consultant meetings… see P. Dimitriou et al. INDC(NDS)-0676 (2016) **and in 2019 Technical Meeting on Antineutrino Spectra and their Applications, INDC(NDS)-0786 (2019)**)

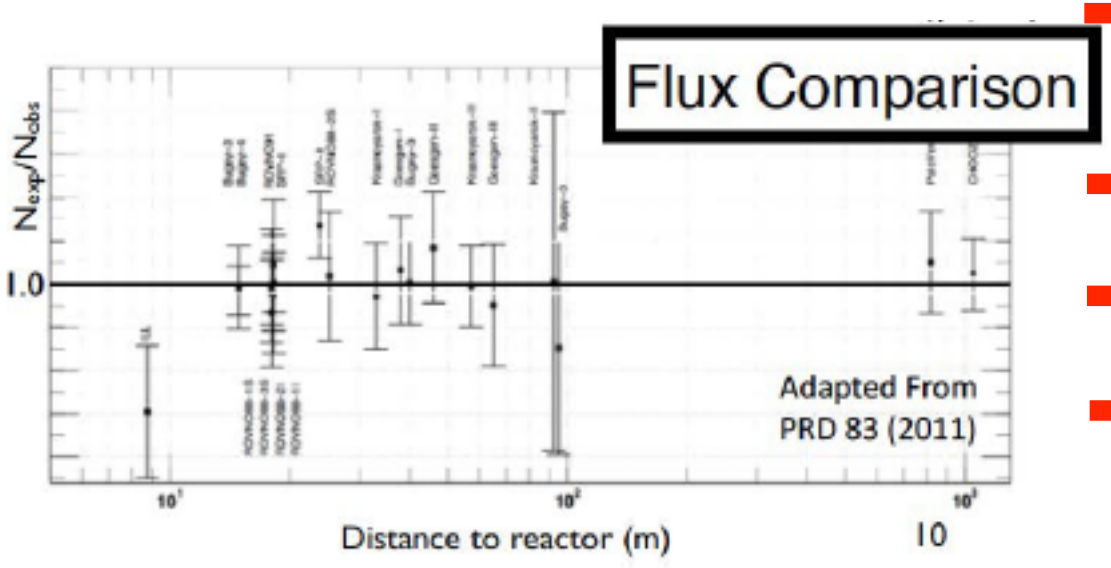
Situation in 1980's-1990's

H. Kwon et al. PRD 24 (1981)



B. Achkar et al. PLB 374 (1996)





Up to 2011:

- Measurement of integral beta spectra of reference measured by Schreckenbach e al. in the 1980's at the ILL reactor**
- Ratio of experiments over ILL converted spectra (Schreckenbach et al.) around 1
- Reactor Antineutrino Spectra well understood
- ILL converted spectra become the reference

**A. A. Hahn et al., PLB 218, 365 (1989) and refs therein.

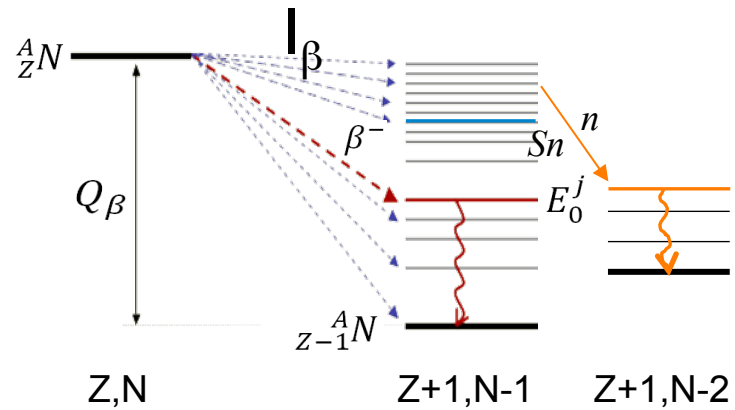
G. Mention et al., PRD83, 073006 (2011)

Get Access to the Antineutrino Spectra

- Over the last 40 years, many computations and improvements of the spectra

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_{e} $$

$$ \hookrightarrow {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$



- Two methods were re-visited in 2011:
  - The **conversion of integral beta spectra of reference measured by Schreckenbach et al. in the 1980's at the ILL reactor** (thermal fission of ^{235}U, ^{239}Pu and ^{241}Pu integral beta spectra), 2 approaches in good agreement:
    - ✓ **Use of nuclear data for realistic beta branches, Z distribution of the branches, 5 fictive beta branches…**
    - ✓ **30 fictive beta branches and nuclear data for realistic Z distribution of the branches**
    - ✓ **Correction for weak magnetism and coulomb effect in both approaches**

    H-M model

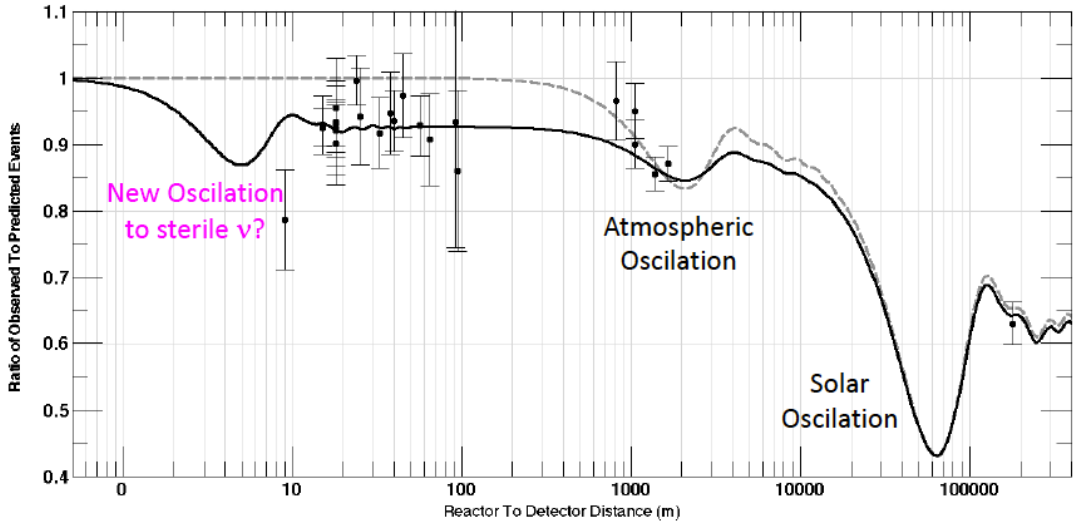
  - The **summation method, summing all the contributions of the fission products** in a reactor core: **only nuclear data : Fission Yields + Beta Decay properties** (several predictions from B.R. Davis et al. Phys. Rev. C 19 2259 (1979), to Tengblad et al. Nucl. Phys. A 503 (1989)136)

    New SM model(s)

Sterile Neutrino hints ?

- **Reactor Anomaly:**
  - converted ν spectra = ˜+3% normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)
  - Neutron life-time
  - Off-equilibrium effects

2 flavour simple scheme :
$P_{Osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2_{[eV2]} L_{[m]}/E_{[MeV]})$



G. Mention et al. Phys. Rev. D83, 073006 (2011)

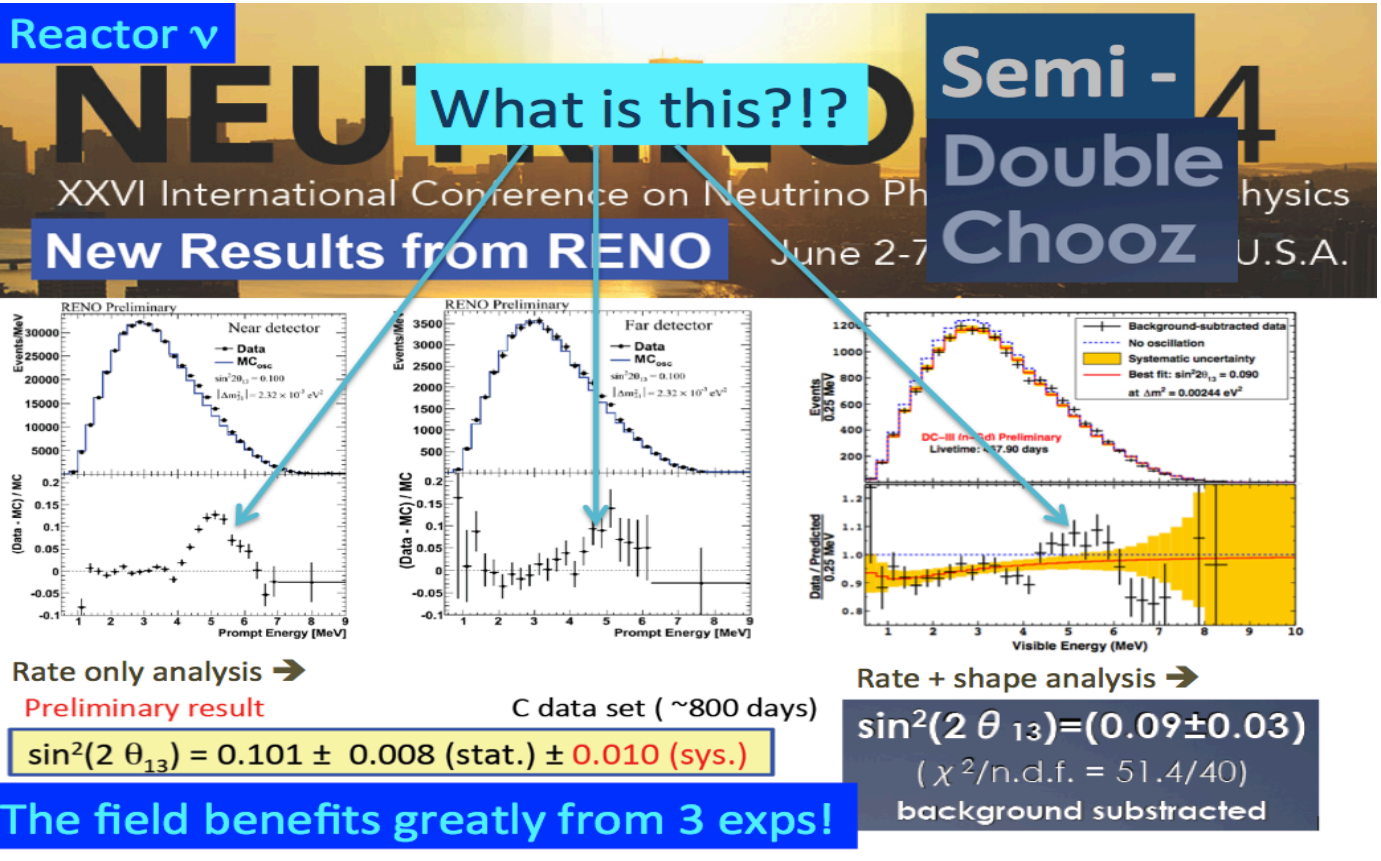
⇒ Looking for sterile neutrinos ($\Delta m^2 \approx 1$ eV^2): numerous projects, model-independent search: SoLid (UK-Fr-Bel-US), STEREO (France), Neutrino-4 (Russia), DANSS(Russia), PROSPECT(USA), NEOS (Korea) + Mega-Curie sources in large ν detector… (white paper: K. N. Abazajian et al.http://arxiv.org/abs/1204.5379.)

⇒ Artifact of flux prediction ?

The « Shape Anomaly »

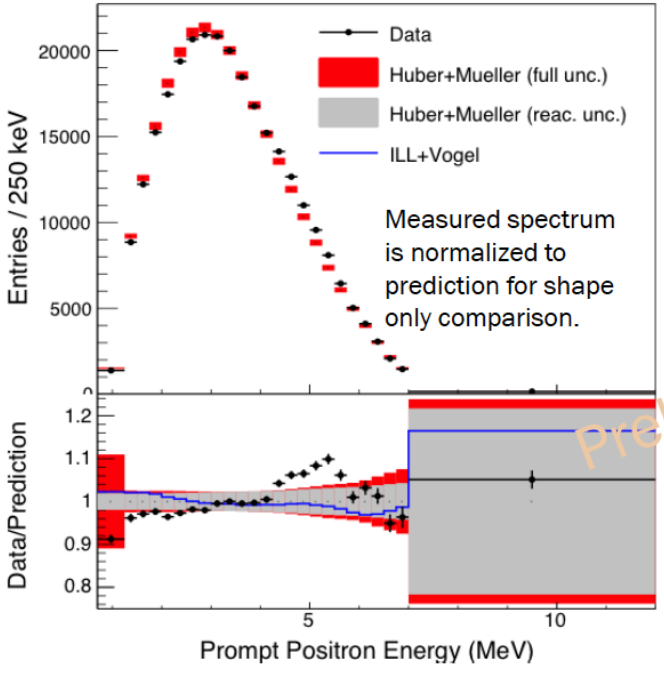
- **Observation of Shape Distorsions w.r.t converted spectra by the 3 large reactor neutrino experiments: Double Chooz, Daya Bay, and Reno:**

First communication by Double Chooz & Reno @Neutrino 2014



Followed by Daya Bay @ICHEP2014

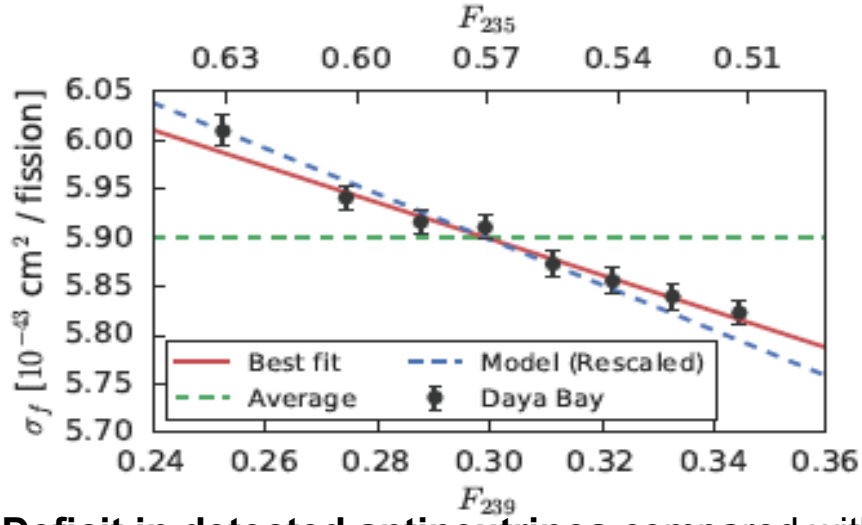
- Absolute shape comparison of data and prediction: χ^2/ndf = 41.8/21



Also observed by the NEOS experiment Phys. Rev. Lett. 118, 121802 (2017)

Context by end of 2017… confirmed in 2019

- **2017: Daya Bay PRL points-out a pb in the converted antineutrino spectra from ^{235}U measured beta spectrum @ILL**



An et al. Phys. Rev. Lett. 118 (2017) + APS Viewpoint

Recent papers from DB (PRL 123 (2019) 111801) and RENO (PRL 122 (2019) 232501) reinforce the conclusions

⇒ **Deficit in detected antineutrinos** compared with predictions **depends on the relative fractions of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu** in the reactor.

⇒ **^{235}U fissions produced 7.8% fewer antineutrinos than predicted**

⇒ In contrast, the discrepancy = **almost zero for ^{239}Pu fissions**

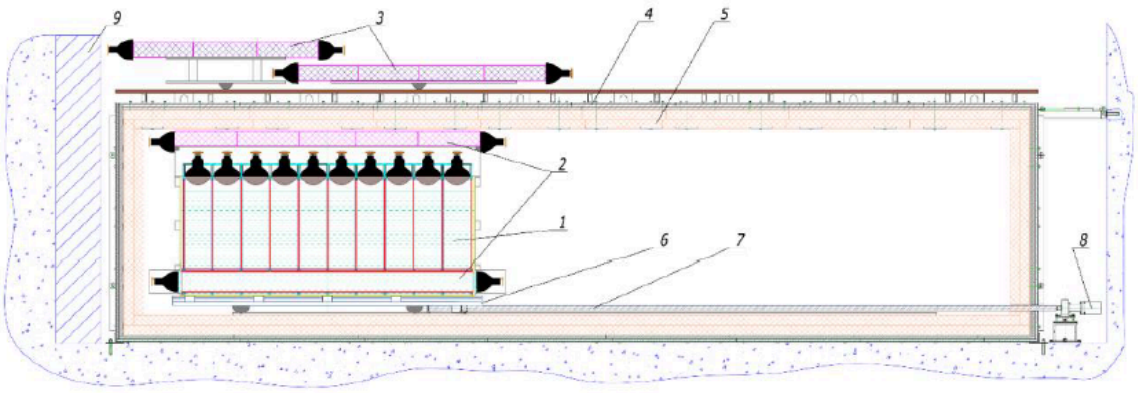
➡ Putting integral beta measurement of ^{235}U of Scheckenbach *et al.* and sterile neutrinos into question

➡ Additional motivation for short baseline neutrino experiments: measurement of ^{235}U antineutrino energy spectrum (opportunity with Highly Enriched Fuel reactors)

➡ Need for alternative models to converted spectra

Short Baseline Reactor Antineutrino Experiments

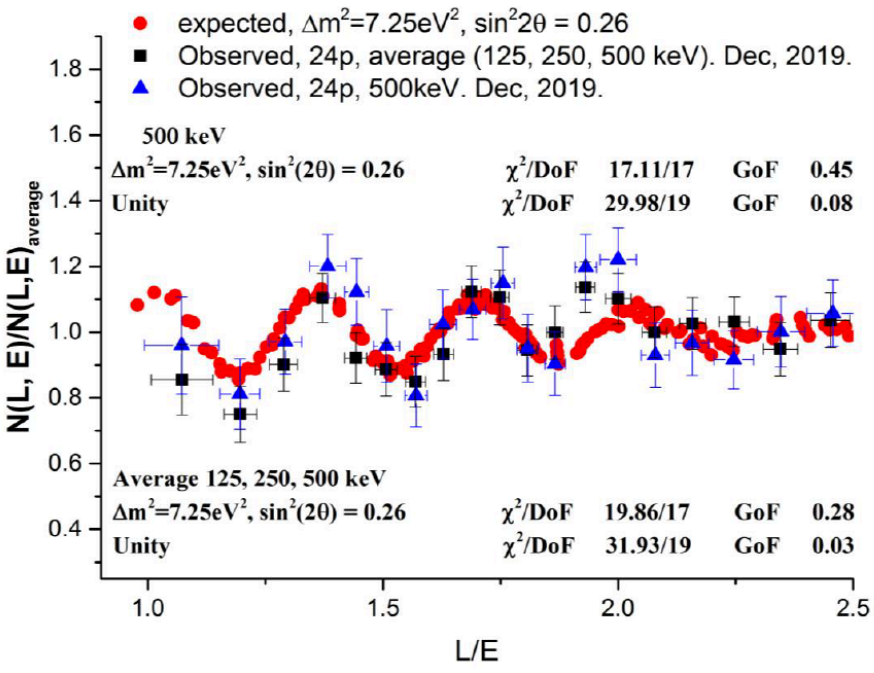
NEUTRINO-4



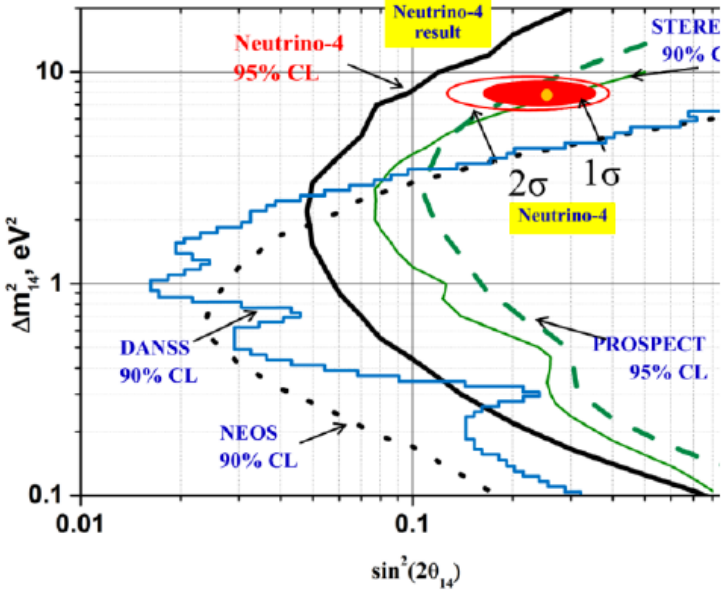
Jetp Lett. 109 (2019) 213.
A.P. Serebrov et al. Arxiv: 2005.05301

2 phases, 720 days ON 417 OFF

@6-12m from compact SM-3 reactor 90MW
Gd-doped segmented LS detector, 1.4 m^3



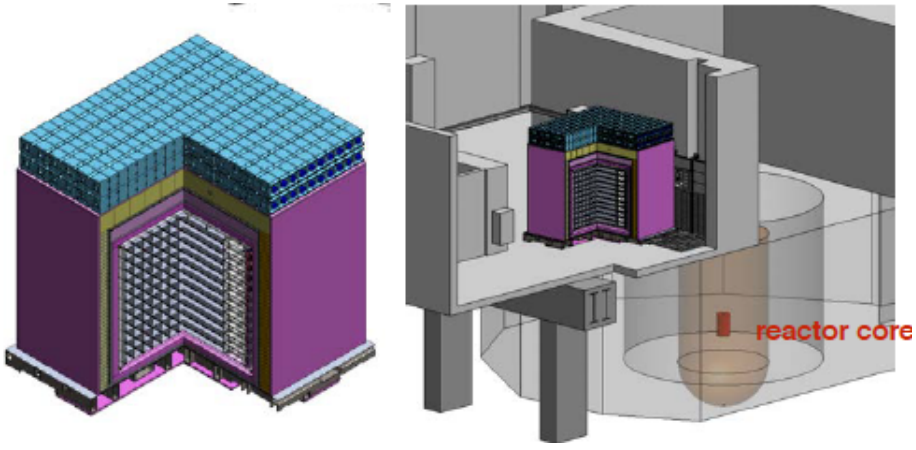
Observed an oscillation effect at CL 2.8σ in vicinity of Δm^2_{14} ≈7.25±1.0 eV^2 and $\sin^2 2\theta_{14}$≈0.26±0.09(2.8)σ.



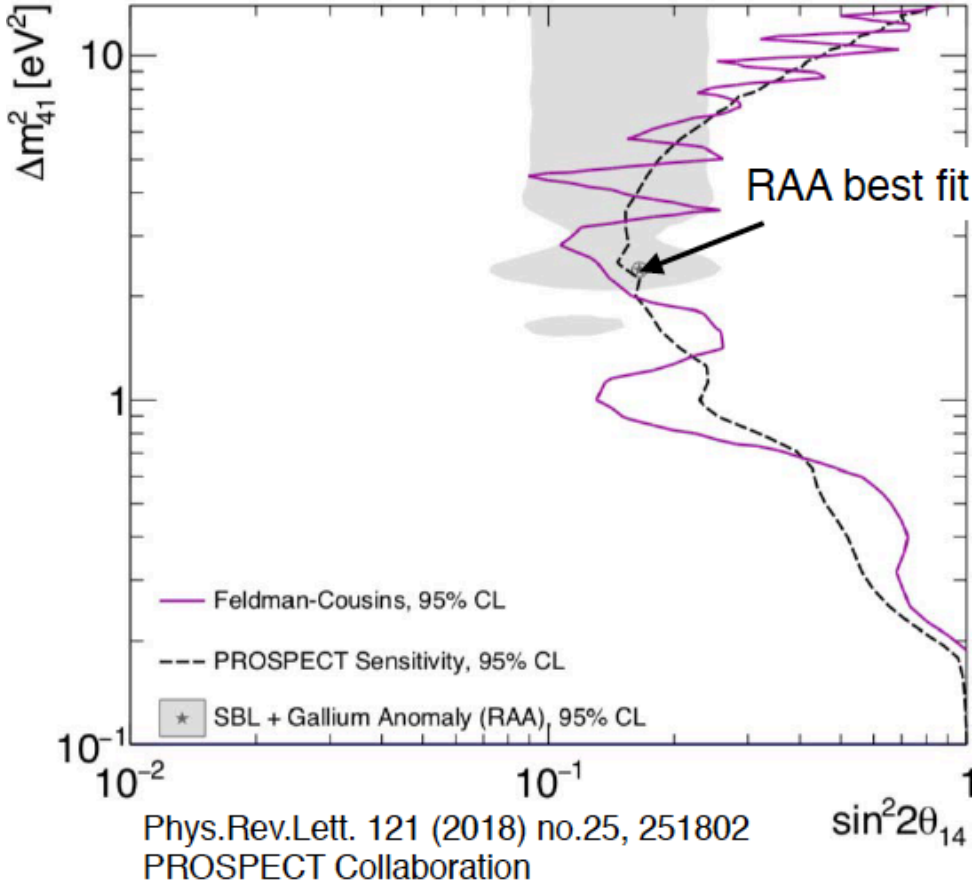
Oscillation excluded by global fits M. Dentler et al. JHEP10 (2018)

See talk in this session

PROSPECT



^{6}Li Liquid Scint. Detector @ 7.9m from HFIR, ORNL, 85MW, Highly-Enriched Uranium (HEU, 93%)
>99% of ν flux from ^{235}U



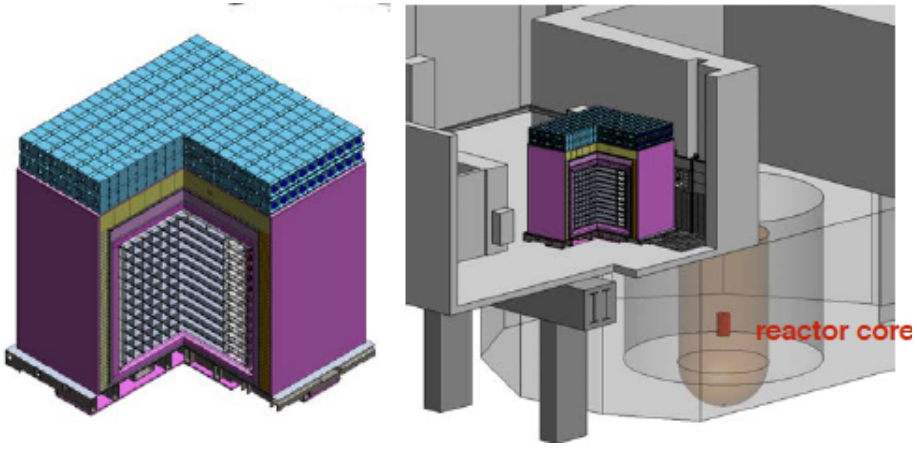
Phys.Rev.Lett. 121 (2018) no.25, 251802
PROSPECT Collaboration

95% exclusion curve based on 33 days Reactor On operation

- **Disfavors RAA best-fit point at >95% CL (2.2σ)**

See talk in this session

PROSPECT



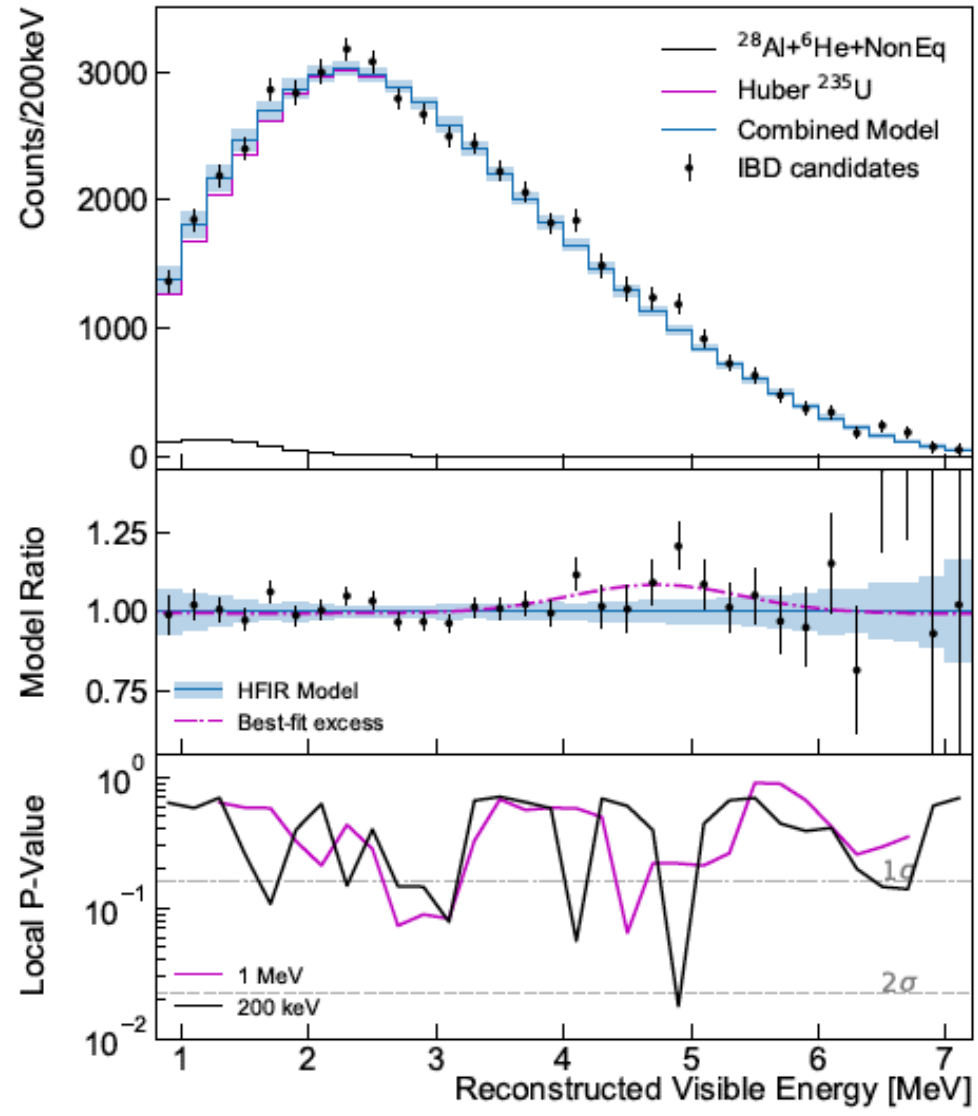
^{6}Li Liquid Scint. Detector @ 7.9m from HFIR, ORNL, 85MW, Highly-Enriched Uranium (HEU, 93%)
>99% of ν flux from ^{235}U

First spectral measurement not conclusive in **Ashenfelter et al. Phys. Rev. Lett. 122, 251801 (2019)**

In arXiv:2006.11210v1:

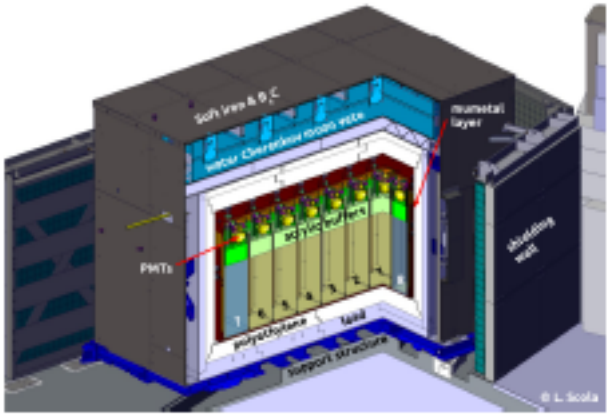
The **newly « reported ^{235}U ν_e energy spectrum measurement shows excellent agreement with Huber's model, with a χ^2/DOF of 31/31 »**

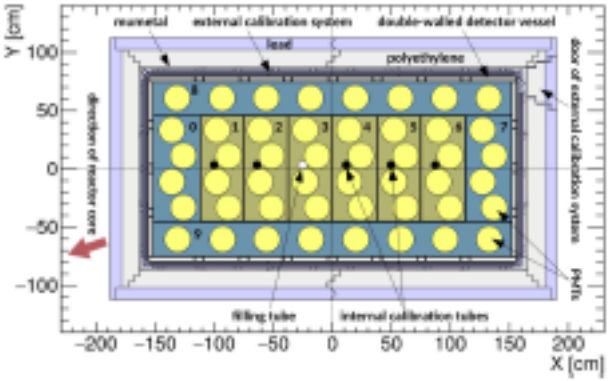
« PROSPECT **disfavors at 2.4σ CL the hypothesis that ^{235}U ν_e are solely responsible for spectrum discrepancies btw model and data at commercial reactor cores. »**



See talk in this session

STEREO

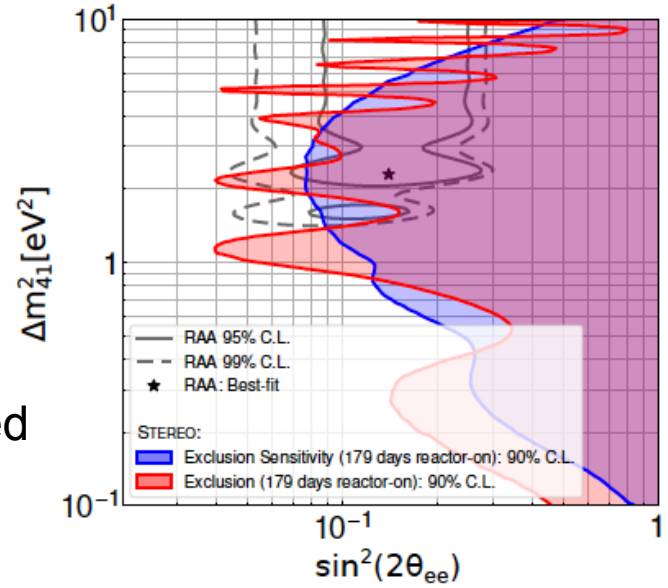




@9.4-11.2m from HFR ILL (France)
6 identical cells filled with Gd-loaded LS

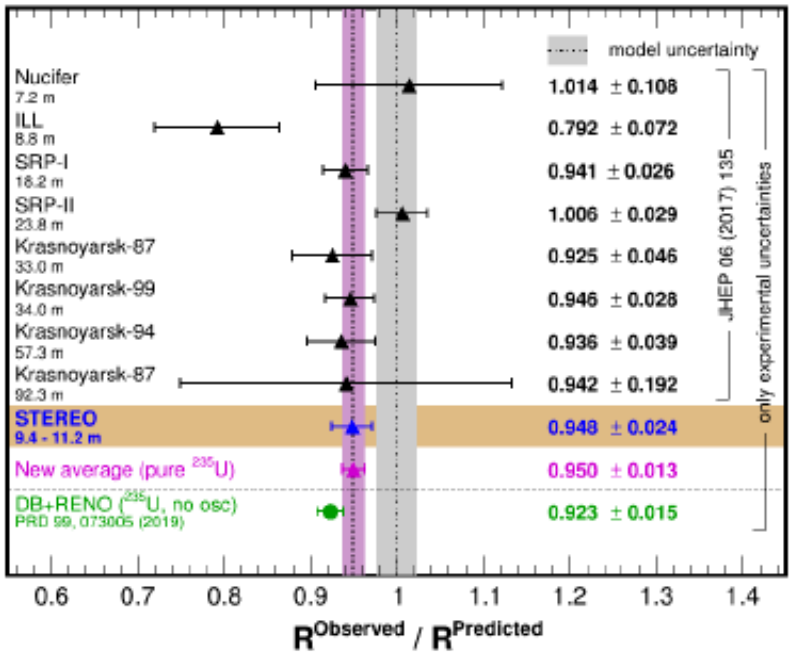
H. Almazan et al. arXiv: 1912.06582

best-fit point of the RAA is rejected at more than 99:9% C.L.



H. Almazan et al. arXiv:2004.04075v1

Precision measurement of antineutrino yield
119 days ON, 211 days OFF
Best-fit value of the RAA (2011) rejected at 99% C.L.
No signs of cell-to-cell systematics



See talk in this session

DANSS

2500 polystyrene-based extruded scintillator strips + Gd-containing surface coating, 1m^3 @10.7, 11.7 and 12.7 m from reactor core of 3.1 GW Kalinin Nuclear Power Plant (LEU) in Russia

I. Alekseev et al. JINST 11 (2016) P11011
I. Alekseev et al. Physics Letters B 787 (2018) 56

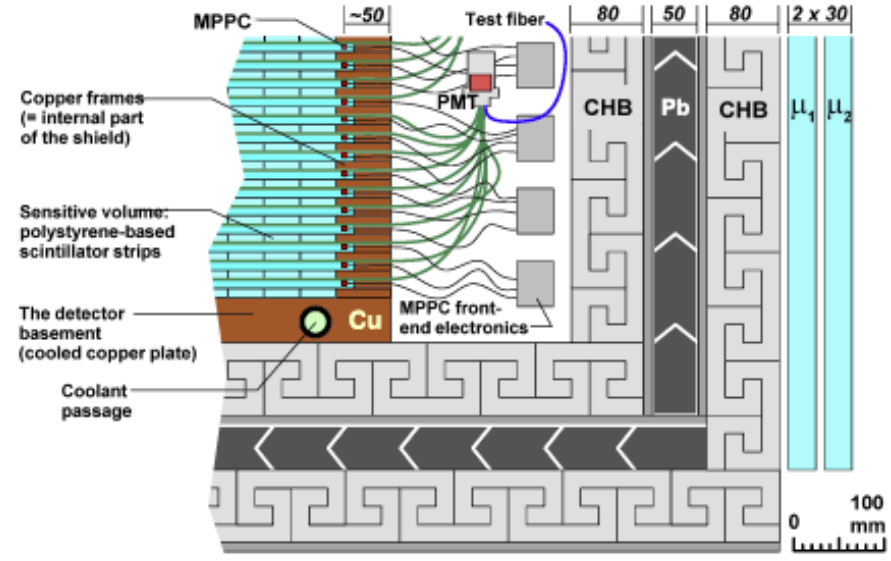
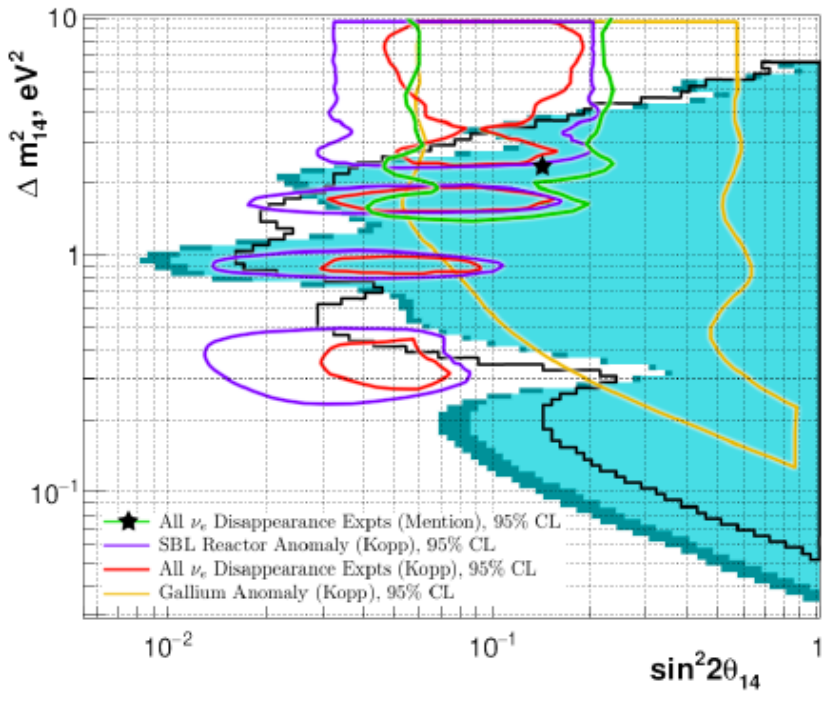


Fig. 1. Simplified cross section of a corner of the DANSS detector.



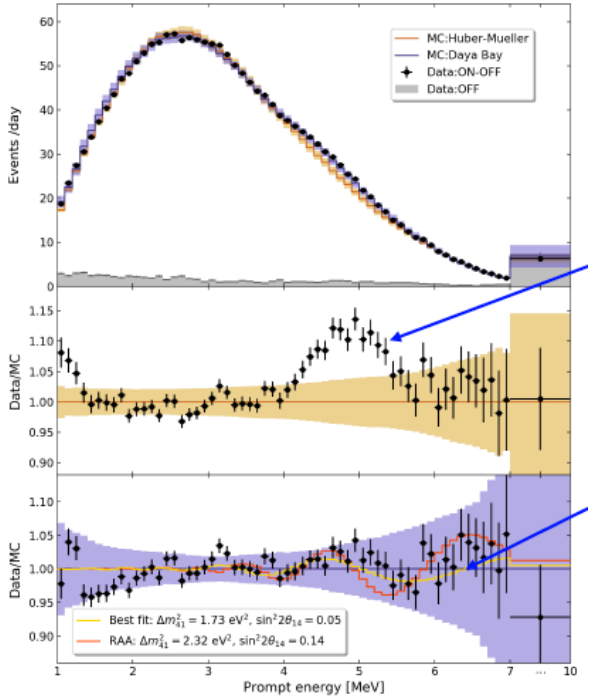
Preliminary results in
M. Danilov et al. arXiv:1911.10140v1
Sensitivity of the experiment improved by a factor 1.4

Obtained excluded area in the Δm^2_{14}; $\sin^2 2\theta_{14}$ plane + initial expectations based on GA and RAA. Results exclude a large part of the sterile neutrino parameter space.

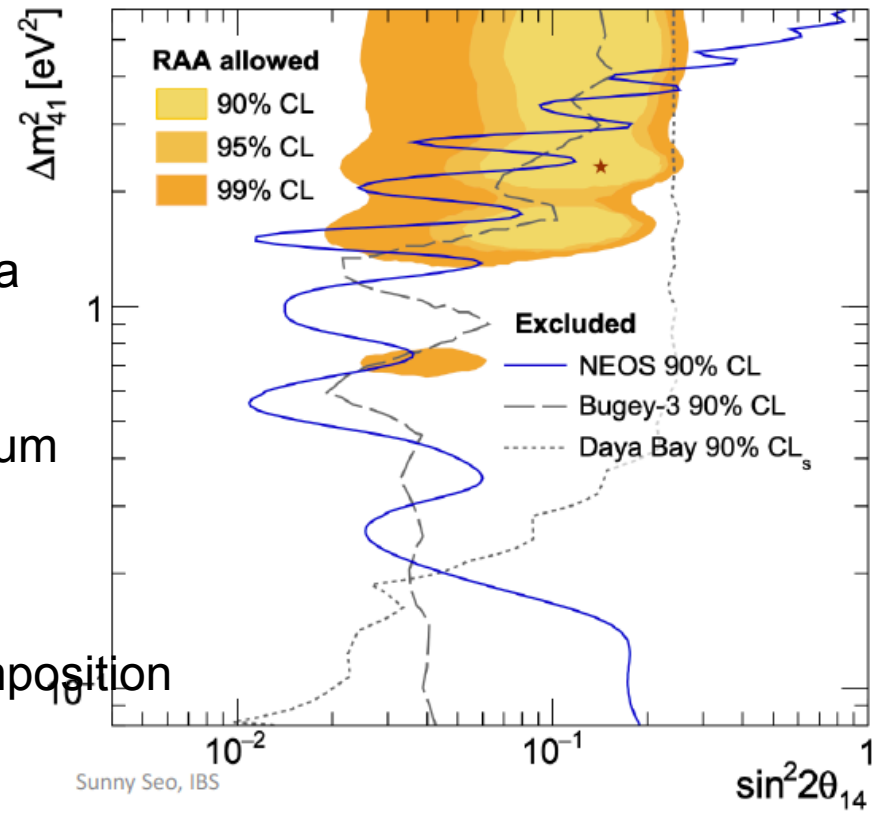
See talk in this session

NEOS

PRL 118, 121802 (2017)



@23.7m of the Hanbit-5 LEU reactor in Yeonggwang, Korea
1000l of Gd-loaded LS
Phase 2 on-going (see talk in this session)



Results from Phase I: 180 (46) days reactor-on(off)data

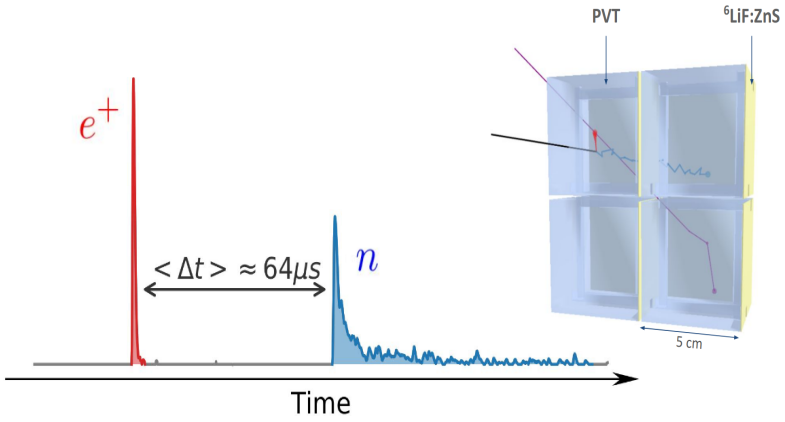
- "5 MeV excess" observation
- No strong evidence of active-to-sterile neutrino oscillation, from comparison with Daya Bay spectrum
- RAA best fit is excluded at 4.3 σ.
- Limited by systematic uncertainty.

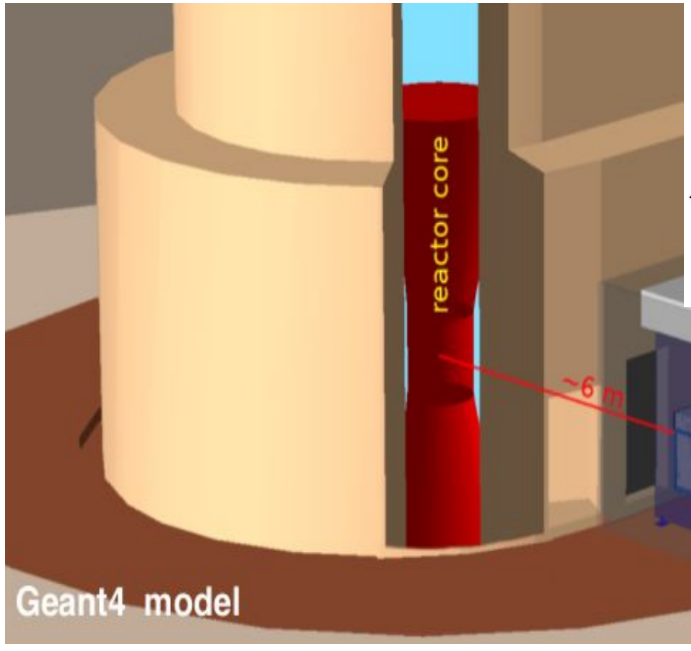
Expected from Phase II:
Time evolution of reactor ν flux/shape; spectral decomposition
Rate+Shape analysis

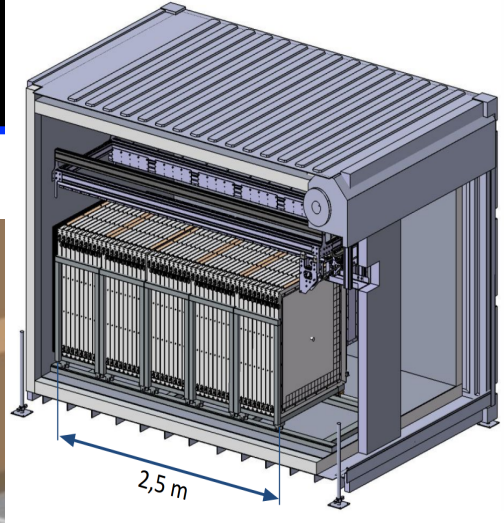
See talk in this session

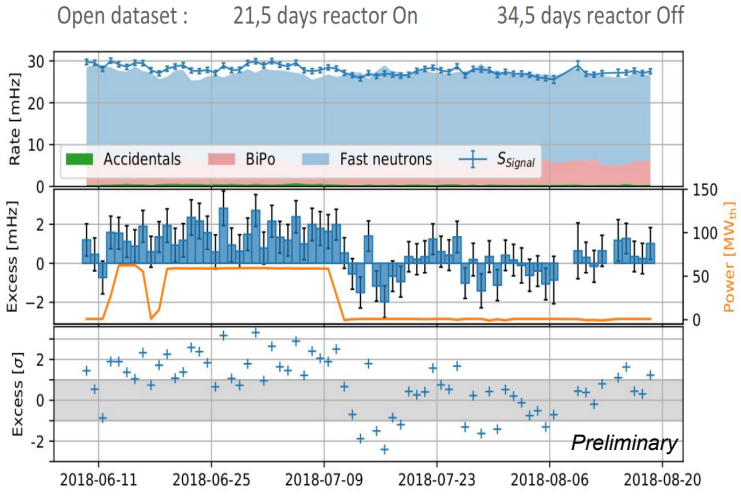
SoLid@BR2

- BR2: Research Reactor HEU $P_{th} \approx 60$ MW, Belgium
- SoLid Detector, 1.6t @6-9m
  - Very highly segmented detector
  - PVT covered with Li:ZnS(Ag) foils

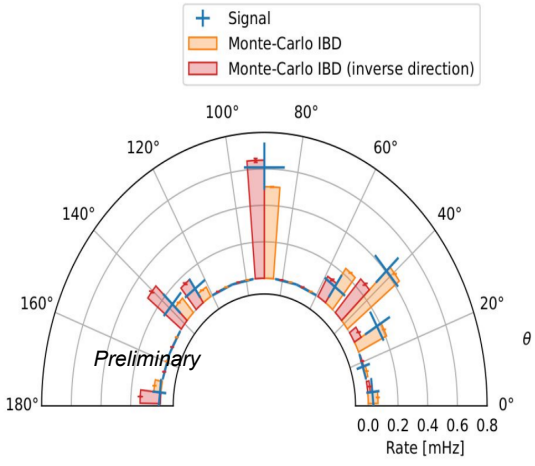








≈140 events/day excess, 5.4σ significance over the whole period



SoLid technology sensitive to $\bar{\nu}_e$ directionality

- Evidence of neutrino signal, upcoming oscillation analysis.
- Sensitivity to directionality from very high segmentation.
- Upgrade of MPPC, planned this summer.

Slide from G. Lehaut (LPC Caen

Reactor Antineutrino Flux Models

Converted Spectra: Underestimated Uncertainties

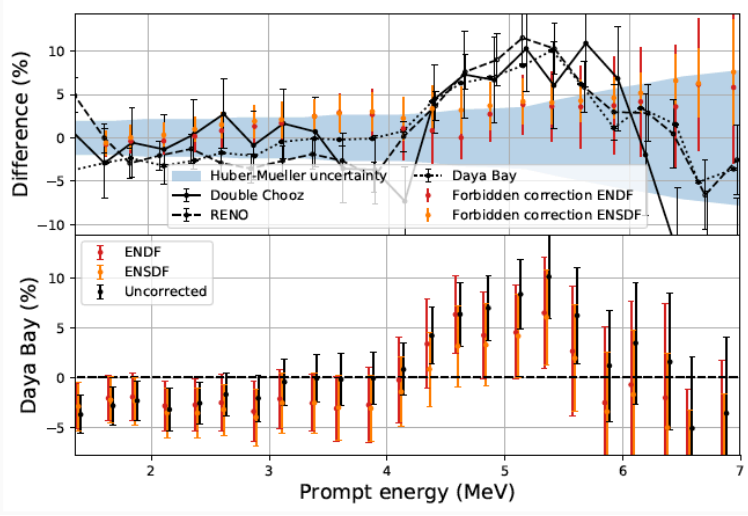
- ***ILL data = unique and precise reference*** => **Need for a second measurement with similar accuracy to exclude potential systematics on the ILL data normalization and shape !!!**
- ***Large uncertainty for Weak Magnetism term: the*** **most uncertain one among the corrections to the Fermi theory !**

  P. Huber PRC84,024617(2011): could change the normalization of the spectra if very different value…

  D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015): The finite size effects and the weak magnetism corrections obtained in Huber's paper for the allowed (GT) decays are estimated to give a reduction in the number of low energy antineutrinos of 2 – 3%.
- ***Impact of the conversion method itself*** **? Quoting A.C. Hayes: depending on the adopted average effective Z distributions used in the fit of the ILL spectra, converted spectra could vary easily by 5%**
- ***Treatment of forbidden decays => could change normalization & shape of spectra:***

A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014),
D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015),
X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314,
L. Hayen et al. Phys. Rev. C 031301(R)(2019)
L. Hayen et al., PRC.100.054323

➡ **Measurements of the shape factors for the most important forbidden decays are needed to disentangle models, and understand the shape anomaly**



The Summation Method & γ Measurement Caveat

- SM independent from the integral measurement of Schreckenbach et al. @ ILL. Spectra can be computed with the SM, for one isotope k:

$$S_k(Z,A,E) = \sum_{fp=1}^{N_{fp}} A_{fp} \times \sum_{b=1}^{N_b} I_{\beta_{fp}}{}^{b} \times S_{fp}{}^{b}\left(Z_{fp}, A_{fp}, E_{0\,fp}{}^{b}, E\right))$$

Caveat: totally rely on modern nuclear DB and their biases!

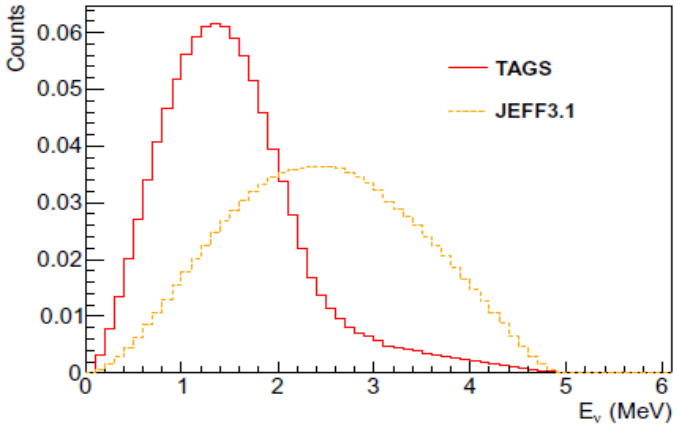


FIG. 1. Illustration of the pandemonium effect on the ^{105}M nucleus anti-ν energy spectrum presents in the JEFF3.1 da base and corrected in the TAS data.

- **Incomplete or biased nuclear decay schemes**: overestimate of the high-energy part of the FP β spectra
- Phenomenon commonly called « **pandemonium effect**** » ** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)
- Solution is **TAGS measurements** (Total Absorption γ-ray Spectroscopy)

M. Fallot et al. PRL 109 (2012) 202504

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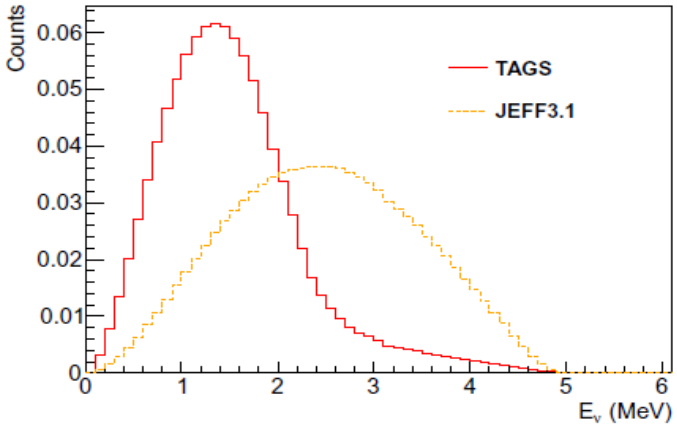

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- Solution is **TAGS measurements** (Total Absorption γ-ray Spectroscopy)
- **Reduced list of contributors and priority lists for new measurements established independently by 2 SM models, in agreement**

A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016), A. A. Sonzogni et al. PRL 119, 112501 (2017), PRC 98 041323(2018) (2018)

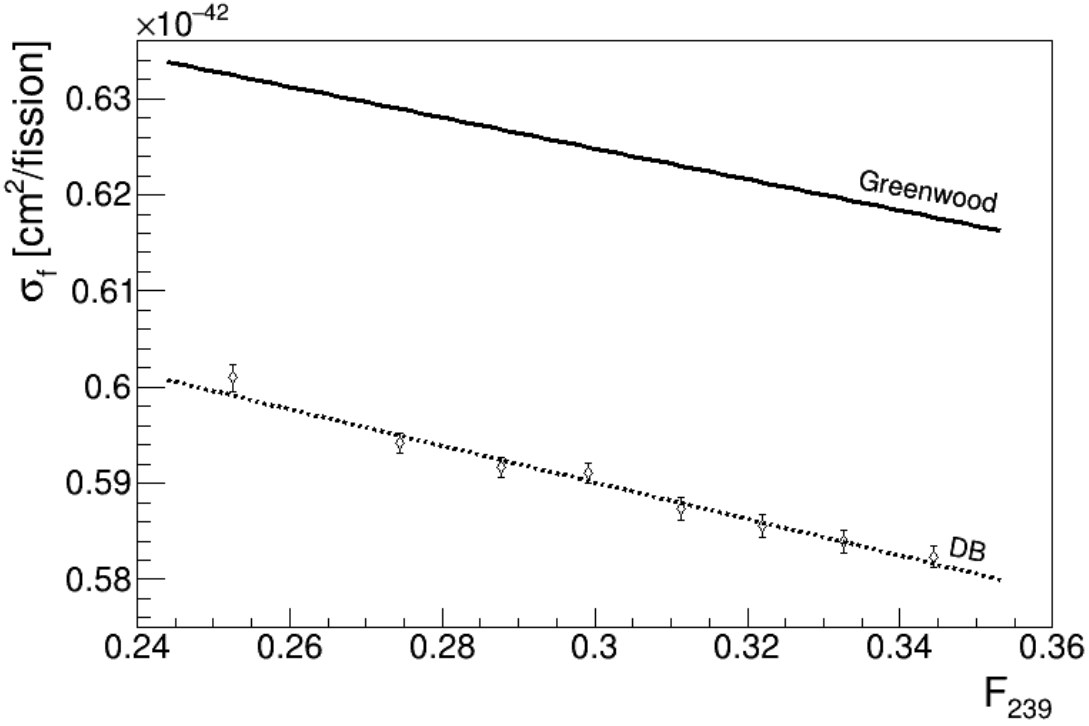
M. Fallot et al. PRL 109 (2012) 202504
A.-A. Zakari-Issoufou et al. PRL 115, (2015) 102503
P. Dimitriou et al. INDC(NDS)-0676 (2016)

➡ **Expected distortion of the antineutrino energy spectra computation with SM**
➡ **Assumed level of uncertainty in Mueller et al. 2011: 10-15%**

Our IBD Yield Calculation Including TAGS vs DB

- The IBD yields dependency with F239 including TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation

M. Fallot et al. PRL 109,202504 (2012), **SM-2012**
A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015), **SM-2015**
E. Valencia et al., PRC 95, 024320 (2017) + S. Rice et al. PRC 96 (2017) 014320 **SM-2017**
V. Guadilla et al. PRL122, (2019) 042502 **SM-2018**



- Impact of the inclusion of the TAGS data (Pandemonium free):

⇒ **Systematic reduction of the detected flux**

⇒ **Systematic reduction of the discrepancy with Daya Bay results**

⇒ Implies an increasingly smaller discrepancy with the inclusion of future TAGS data, **leaving less and less room for a reactor anomaly**.

M. Estienne et al. **PRL 123, (2019) 022502** http://arxiv.org/abs/1904.09358

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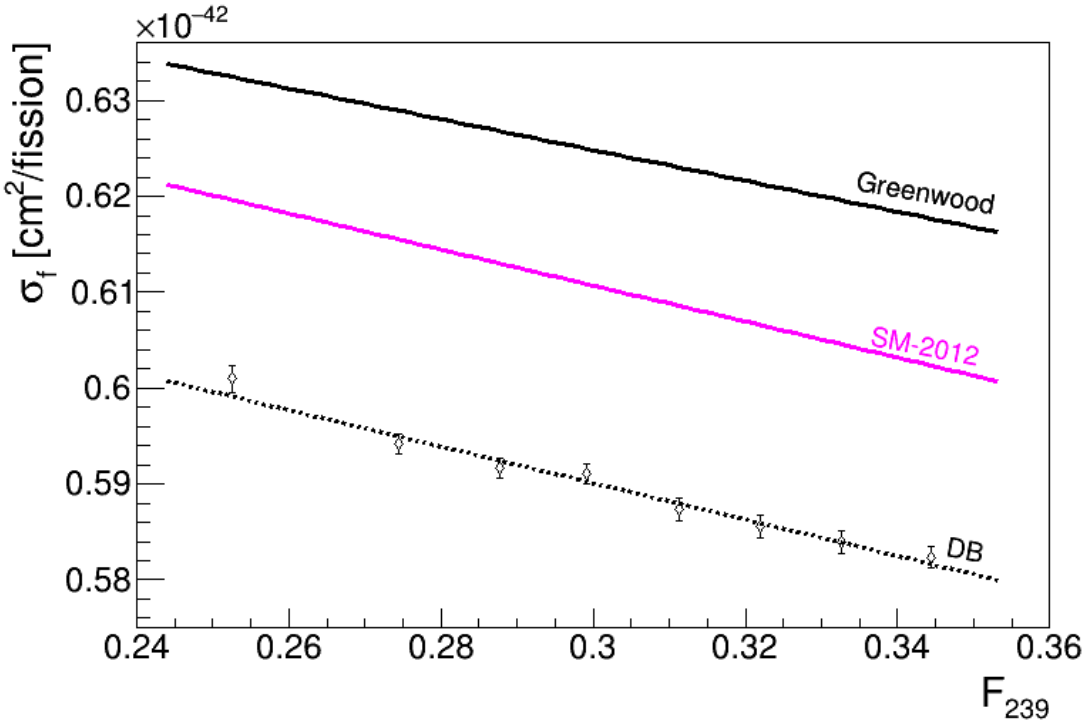

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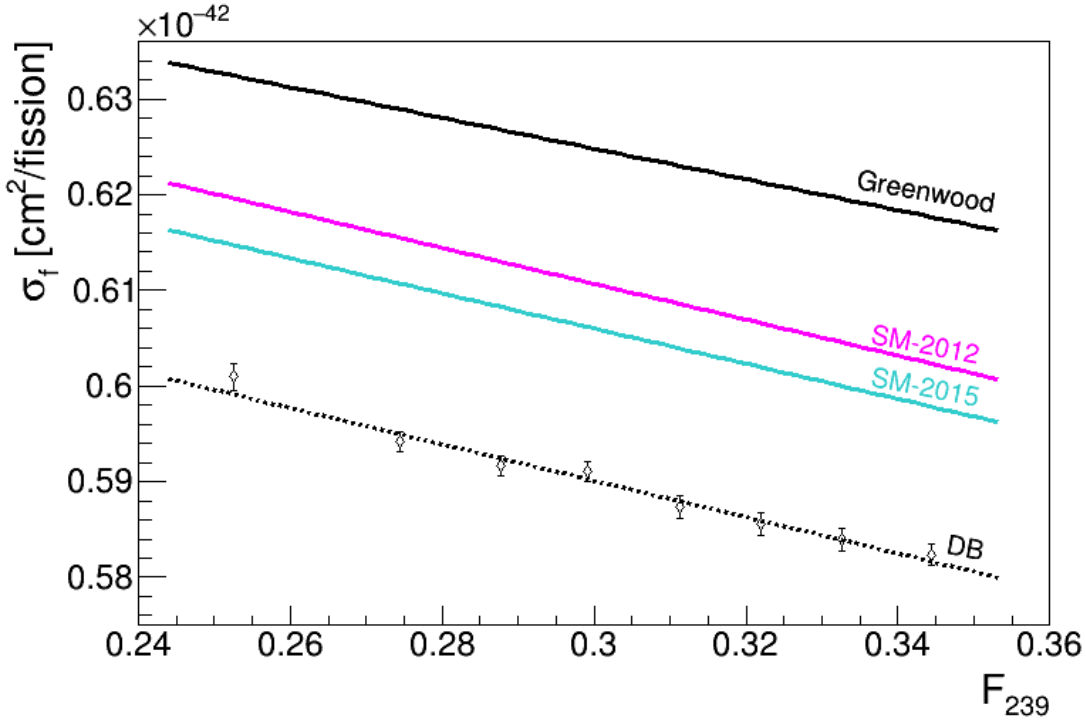

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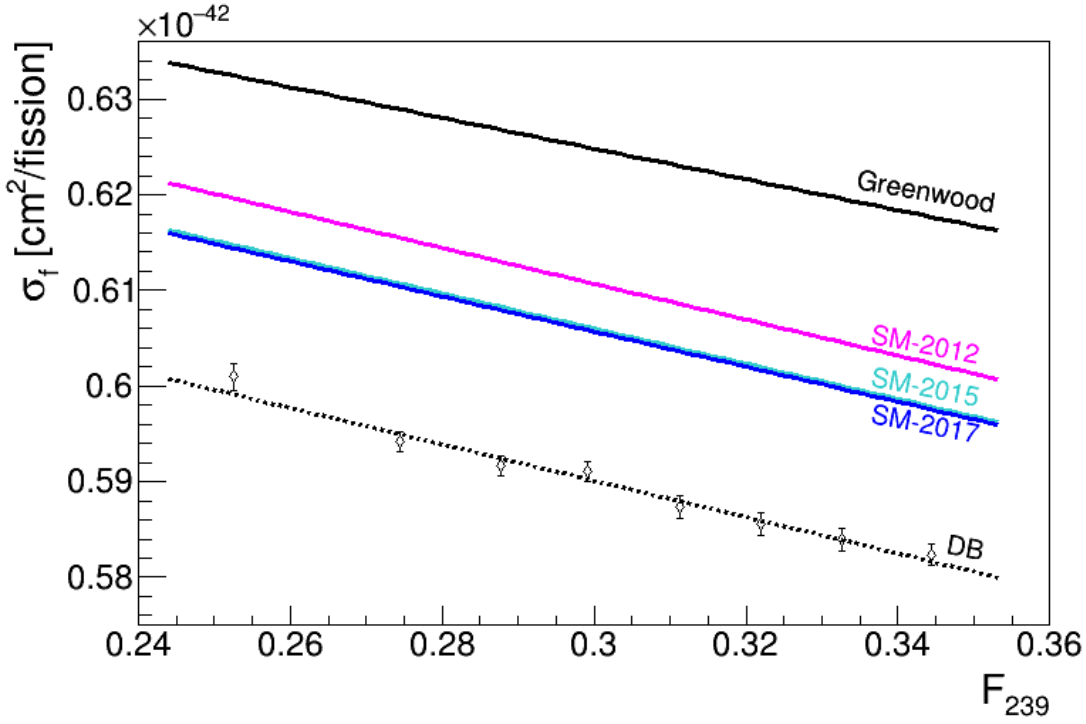

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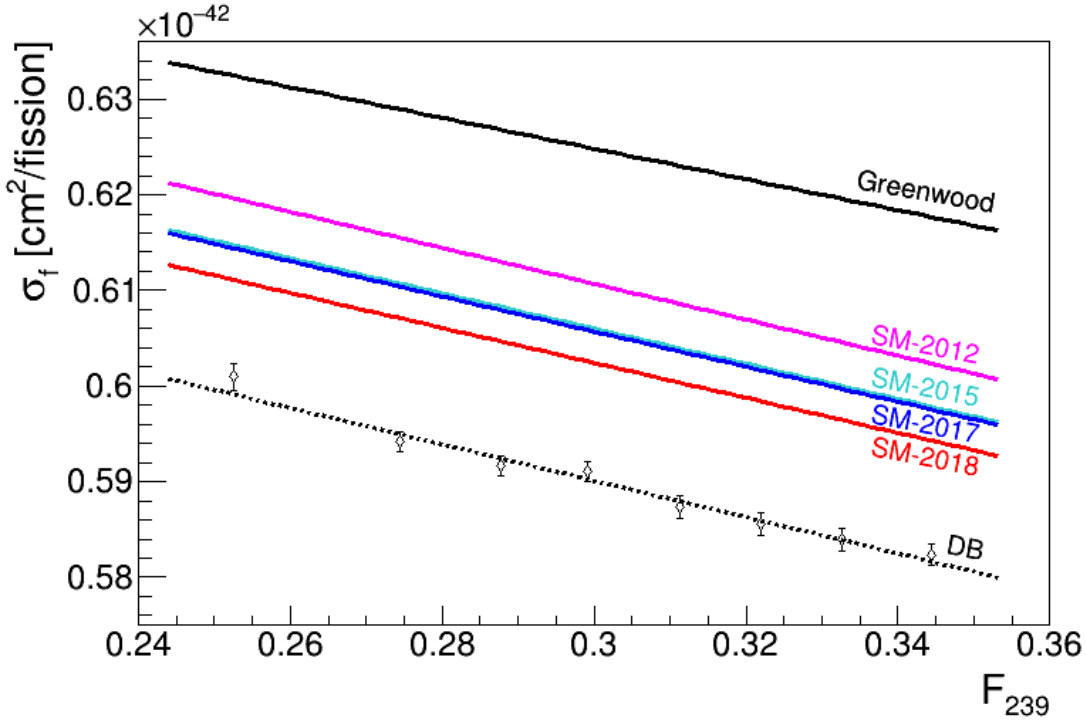

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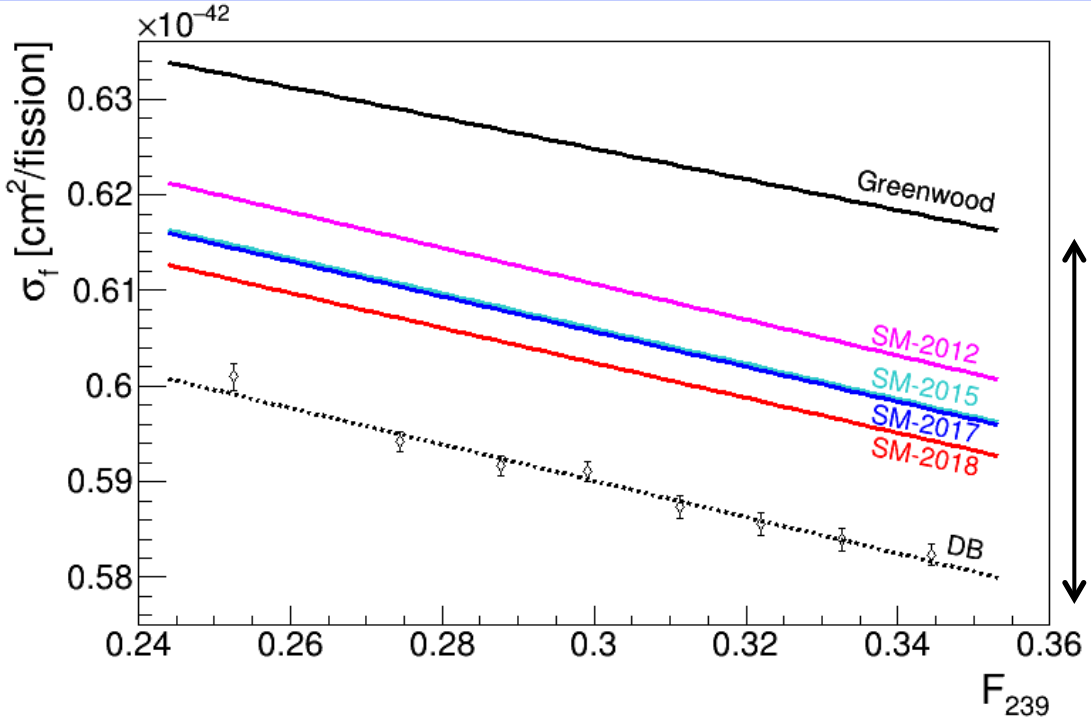


M. Estienne et al. PRL 123, (2019) 022502
http://arxiv.org/abs/1904.09358

6% (Greenwood TAGS, ~Huber-Mueller)

3% (+TAGS 2012, ~< Hayes et al. 3.5%)

2.4% (+TAGS 2015 & 2017)

1.9% (+ TAGS 2018)

- The remaining discrepancy with the Daya Bay flux **reduces to only 1.9%**
- Even with the inclusion of the 2018 TAGS data, the **bump is still there** i.e. for the moment, it still **cannot be explained** by ingredients of the nuclear databases.
- **With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ^{235}U and ^{239}Pu (contrary to H.-M.)** and about 1% for ^{238}U and ^{241}Pu

+US TAGS measurements not yet included (some overlap): B. C. Rasco et al., PRL117, 092501 (2016), B.C. Rasco et al. PRC 95, 054328 (2017), A. Fijalkowska et al. PRL 119, 052503 (2017)

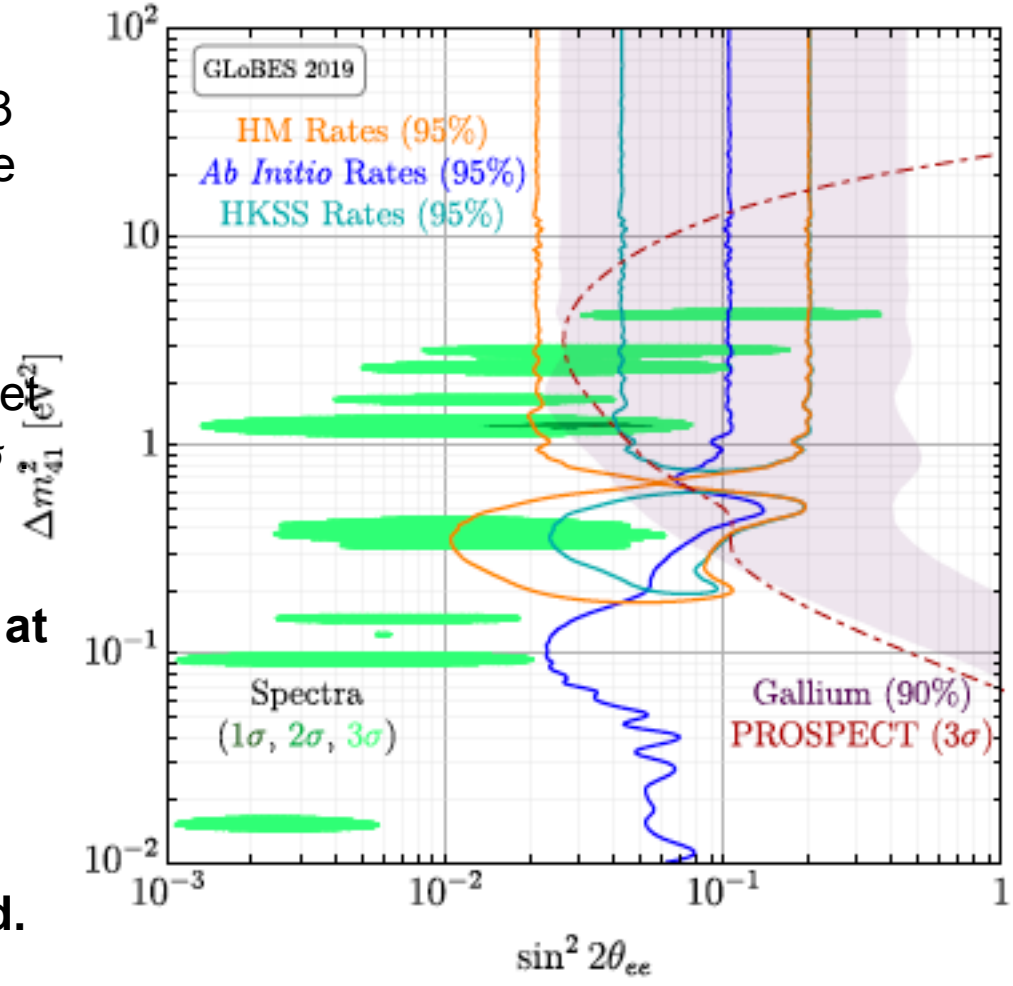
Models in Global Analysis

Reanalyzed the global reactor ν_e data set using 3 reactor antineutrino flux predictions: HM, Estienne et al., Hayen et al.

Estienne et al. 's calculation decreases the significance from 2.3σ to 0.95σ, whereas Hayen et al.'s calculation increases the significance to 2.8σ

Shape anomaly still robust with respect to varying the flux model and is found to persist at the 3.1σ level.

Null results from current reactor experiments would leave a significant fraction of the currently favored parameter space unexplored.



J. M. Berryman and P. Huber Phys. Rev. D 101, 015008 (2020)

Other global analyses in Giunti et al. PRD 99, 073005 (2019), A. Diaz et al. arXiv:1906.00045v3, S. Boeser et al. PPNPP 111 103736 (2019)

Conclusions & Perspectives

- **High stats HEU reactor measurements crucial for understanding**
- **Measurements @ LEU reactors crucial for disentangling ^{235}U and ^{239}Pu contributions**
- **Still new experimental results from very short baseline experiments expected:** more statistics + absolute ^{235}U antineutrino energy spectrum measurement, **variety of detector and reactor designs required for solving the puzzle(s)**
- **RAA best fit disfavoured by experiments, but still significant part of the parameter space uncovered**
- **Shape anomaly** still not understood by any model **=> forbidden decays** ?
  - ❑ Theoretical predictions not in agreement, Need for measurements of shape factors
- **Conversion Method** has **underestimated uncertainties** (method itself, forbidden decays, etc.)
- **Summation Method has been improved**, thanks to the huge experimental effort with TAGS over a decade, « Bringing the Summation Method to another level » (cf. IAEA INDC(NDS)786 2019) and is only @1.9% from the Daya Bay flux
  - ❑ **Still TAGS measurements needed,** especially to improve above 4.5-5 MeV
  - ❑ **Calculation of the uncertainties mandatory**
- Significant improvement in energy resolution proposed by **JUNO-TAO could constitute a benchmark for nuclear data, evidencing the individual components of the fission products (see A. A. Sonzogni, M. Nino, and E. A. McCutchan PRC 98, 014323)**

IAEA Technical Meeting 2019

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Participants

- Leendert Hayen
- Jun Cao
- Liangjian Wen
- Yufeng Li
- Zeyuan Yu
- Fengpeng An
- Liang Zhan
- Cecile Jollet
- Muriel Fallot
- Madalina Wittel
- Karl-Heinz Schmidt
- Tadashi Yoshida
- Soo-Bong Kim
- Sunny Seo
- Marek Karny
- Marzena Wolinska
- Dmitry Svirida
- Alejandro Algora
- Jose Tain
- Antonin Vacheret
- Alejandro Sonzogni
- Toshihiko Kawano
- Filip Kondev
- Krzysztof Rykaczewski
- B.S. Rasco
- Anna Hayes-Sterbenz
- Jonathan Link
- Bryce Littlejohn
- Yuri Efremenko
- Patric Huber
- Karsten Heeger
- Nathaniel Bowden
- Frederik Tovesson
- Patric Huber
- Karsten Heeger
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Technical Meeting on Nuclear Data for Anti-neutrino Spectra and Their Applications

23-26 April 2019, IAEA Headquarters, Vienna, Austria

The Nuclear Data Section of the International Atomic Energy Agency is holding a Technical Meeting on Nuclear data for anti-neutrino spectra and their applications, from 23 to 26 April 2019.

The idea is to bring together experts from the broad spectrum of physics, theory and measurements, related to anti-neutrino studies for basic sciences (mixing angle in neutrino oscillations) and for applications (reactor monitoring with anti-neutrino detection), to review the current status of:

-neutrino anomalies and the sterile neutrino hypothesis
-existing measurements of integral beta spectra
-recent Daya Bay, Double Chooz and Reno results on spectra measurements
-results from short baseline experiments Prospect, SoLid, Neutrino-4/DANSS, NEOS
-conversion method and uncertainties, corrections
-summation method and impact of nuclear data (beta decay data; fission yield data; uncertainties and correlations)
-nuclear data libraries (ENDF/B; JEFF; JENDL)

The goal is to (a) assess the sensitivity of the observations to uncertainties affecting large and short-baseline anti-neutrino measurements, (b) address the limitations and uncertainties of the theoretical methods (conversion vs summation), (c) estimate their dependence on the available data (beta spectra, decay data, fission yields), and finally (d) make recommendations for the existing measurements, theories and evaluations and e) new proposals for the future where needed.

The meeting will start on Tuesday 23 April in the afternoon, and finish on Friday 26th April again in the afternoon.

The meeting will include presentations from experts covering the above listed topics and discussions that will lead to a list of recommendations for the relevant scientific community. A summary report of the meeting will be published as an INDC(NDS) report.

A list of abstracts is given below. Presentations will be uploaded as they become available.

Preliminary Agenda

Abstracts

#	Author	Title	Link
1	P. Huber	Antineutrino spectrum prediction and nuclear data	DOC

TAGS COLLABORATION

IFIC Valencia: A. Algora, B. Rubio, J.A. Ros, V. Guadilla, J.L. Tain, E. Valencia, A.M. Piza, S. Orrigo, M.D. Jordan, J. Agramunt

SUBATECH Nantes: J.A. Briz, M. Fallot, A. Porta, A.-A. Zakari-Issoufou, M. Estienne, T. Shiba, A.S. Cucoanes

U. Surrey: W. Gelletly

IGISOL Jyvaskyla: H. Penttilä, Äystö, T. Eronen, A. Kankainen, V. Eloma, J. Hakala, A. Jokinen, I. Moore, J. Rissanen, C. Weber

CIEMAT Madrid: T. Martinez, L.M. Fraile, V. Vedia, E. Nacher

IPN Orsay: M. Lebois, J. Wilson

BNL New-York: A. Sonzogni

Istanbul Univ.: E. Ganioglu

Special thanks to the young researchers working in the project:
L. Le Meur, J.A. Briz, V. Guadilla, E. Valencia, S. Rice, A. -A. Zakari-Issoufou
Discussions with and slides from: A. Algora, J. L. Tain, B. Rubio, S. Cormon, A. Cucoanes, M. Estienne, M. Fallot, L. Giot, A. Porta, T. Shiba, …are acknowledged

THANK YOU

Fine Structure in the Antineutrino Spectra

Using Summation Method:
« With better resolution and small bin intervals, the contributions from individual nuclides, not captured in the conversion, begin to appear.
Must rely on nuclear databases to understand them »
A. Sonzogni et al. @ AAP2018 proposed that the ν oscillation feature seen in the ratio NEOS/ Daya Bay is due to ^{99}Nb, ^{143}La, ^{92}Y, ^{99}Zr.

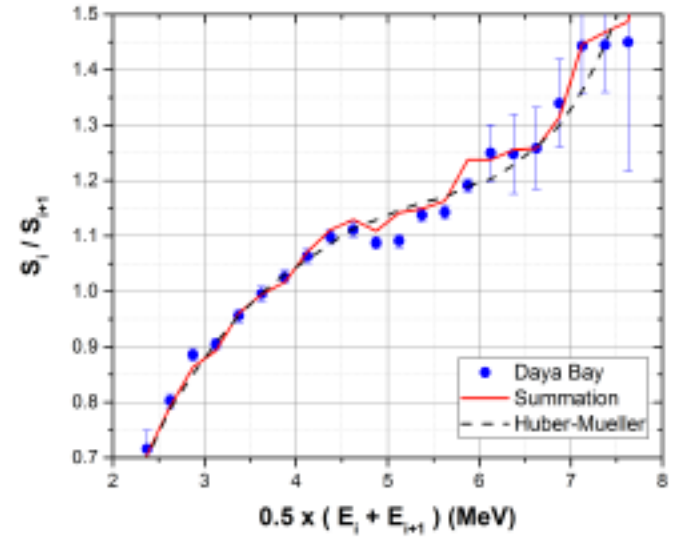


FIG. 4. Ratio of two consecutive IBD spectrum points from the Daya Bay experiment (symbols), Huber-Mueller model (dashed black line) and summation method (full red line). For clarity's sake, the calculated points are connected with a straight line, instead of a step function as in Fig. 3.

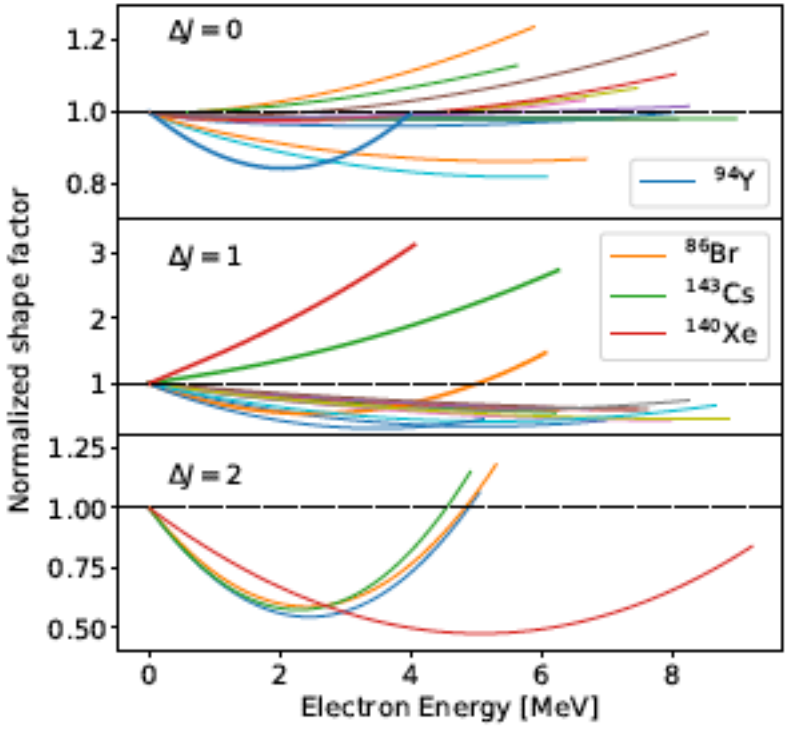
A. A. Sonzogni, M. Nino, and E. A. McCutchan PRC 98, 014323

➡ If correct, these features should be seen by other experiments.

➡ The JUNO-TAO experiment, with a very good energy resolution, may allow to perform such identification of individual fission product contributions

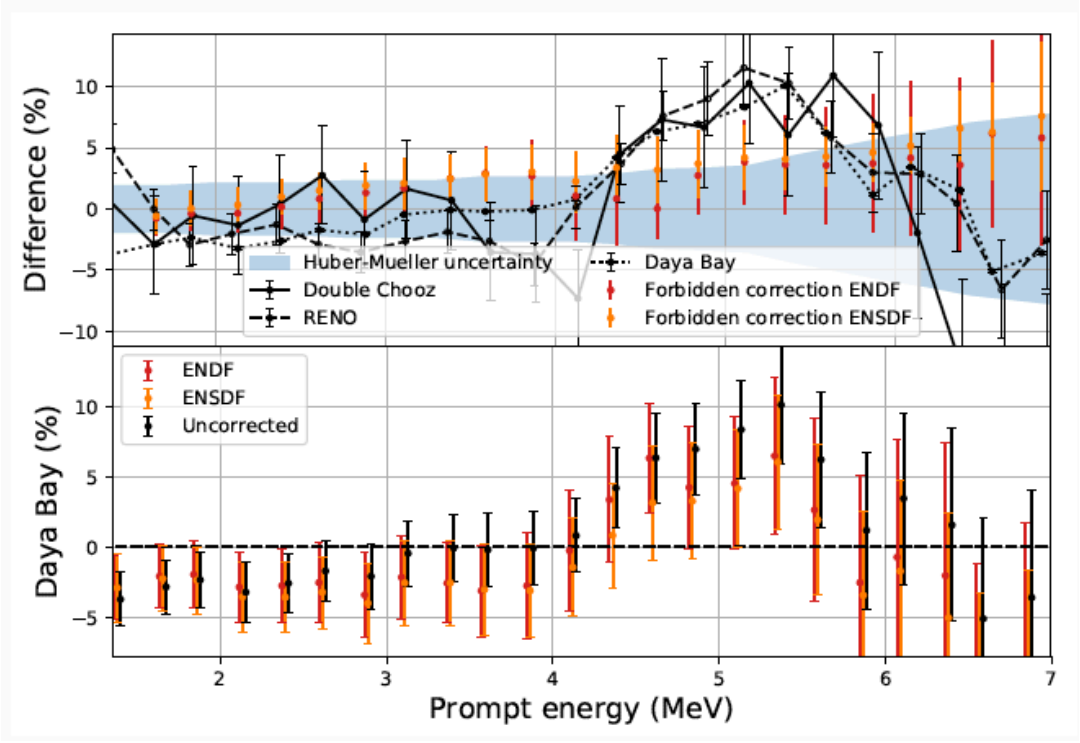
Explanation for the shape anomaly ?

Calculation of the shape factors for forbidden decays: discrepancies among models, largest shape factors from L. Hayen et al.



L. Hayen et al., PRC.100.054323

Bump signicantly mitigated, still further research

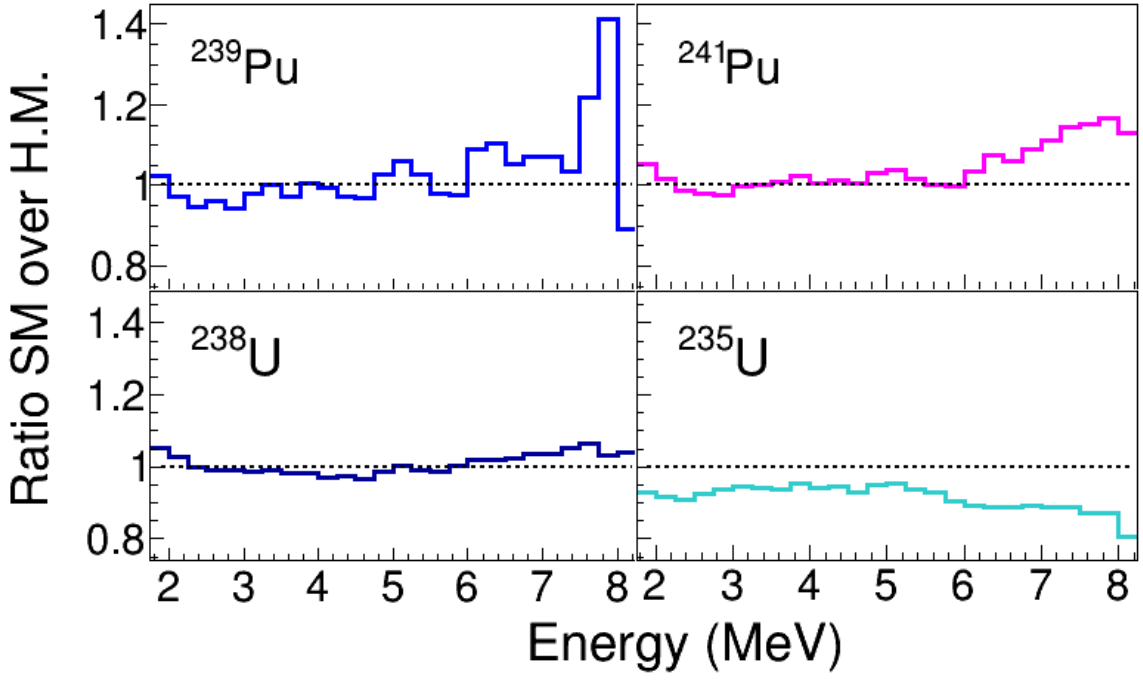


L. Hayen et al., PRC 99 (2019) 031301(R)

➡ **Measurements of the shape factors for the most important forbidden decays are needed to disentangle models, and understand the shape anomaly**

Comparison with H-M individual spectra

M. Estienne et al. http://arxiv.org/abs/1904.09358 accepted in Phys. Rev. Lett.



- The ratios with converted spectra have become flatter up to ~6 MeV compared with SM-2012
- The normalisation of ^{235}U still disagrees (same as in 2012), confirming Daya Bay's result
- ^{238}U: ratio w.r.t. Mueller et al 's version of the SM: spectrum remains stable with the update of databases and inclusion of new TAGS results up to ~6 MeV

⇒ Overall the SM model shows a fairly good shape agreement with Huber's spectra up to 6 MeV (in the error bars of the converted spectra in this energy range, except for ^{239}Pu)

⇒ The energy range matters indeed, because the antineutrino data are also more uncertain above 6 MeV

« Robustness » of the prediction

Table extracted from Mueller et al. Phys. Rev. C 83, 054615 (2011)

Kinetic E (MeV)	Nuclear databases	Forbid. treatment	$A_{C,W}$ corrections	Missing info.
2.00	1.2	0.2	0.1	10
2.25	1.3	0.2	0.2	10
2.50	1.3	0.1	0.3	10
2.75	1.3	0.1	0.3	10
3.00	1.4	0.4	0.4	10
3.25	1.6	0.7	0.5	10
3.50	1.7	0.1	0.5	10
3.75	1.9	1.3	0.6	10
4.00	2.2	1.6	0.6	10
4.25	2.5	1.6	0.7	10
4.50	2.8	1.4	0.8	10
4.75	3.2	1.0	0.8	10
5.00	3.8	0.5	0.9	10
5.25	4.4	0.2	0.9	10
5.50	5.2	0.2	0.9	15
5.75	6.1	0.2	0.9	15
6.00	7.1	0.2	1.0	15
6.25	8.0	0.3	1.0	15
6.50	9.0	0.4	1.1	15
6.75	10.1	0.4	1.1	15
7.00	10.9	0.5	1.1	20
7.25	11.0	0.7	1.1	20
7.50	10.7	0.8	1.1	> 20
7.75	11.1	0.8	1.2	> 20
8.00	13.3	1.2	1.3	> 20

TABLE II. Sources of errors in the ^{235}U electron spectrum as predicted by the *ab initio* approach. All errors are given in percent at 1σ (68% CL).

- **The agreement of the SM-2018 spectra with the shape of the H-M spectra is better than 5-10% !**
- **it is rather ±2-3% on the energy range dominating the flux**
- Robustness of the SM w.r.t the choice of decay data data tested:

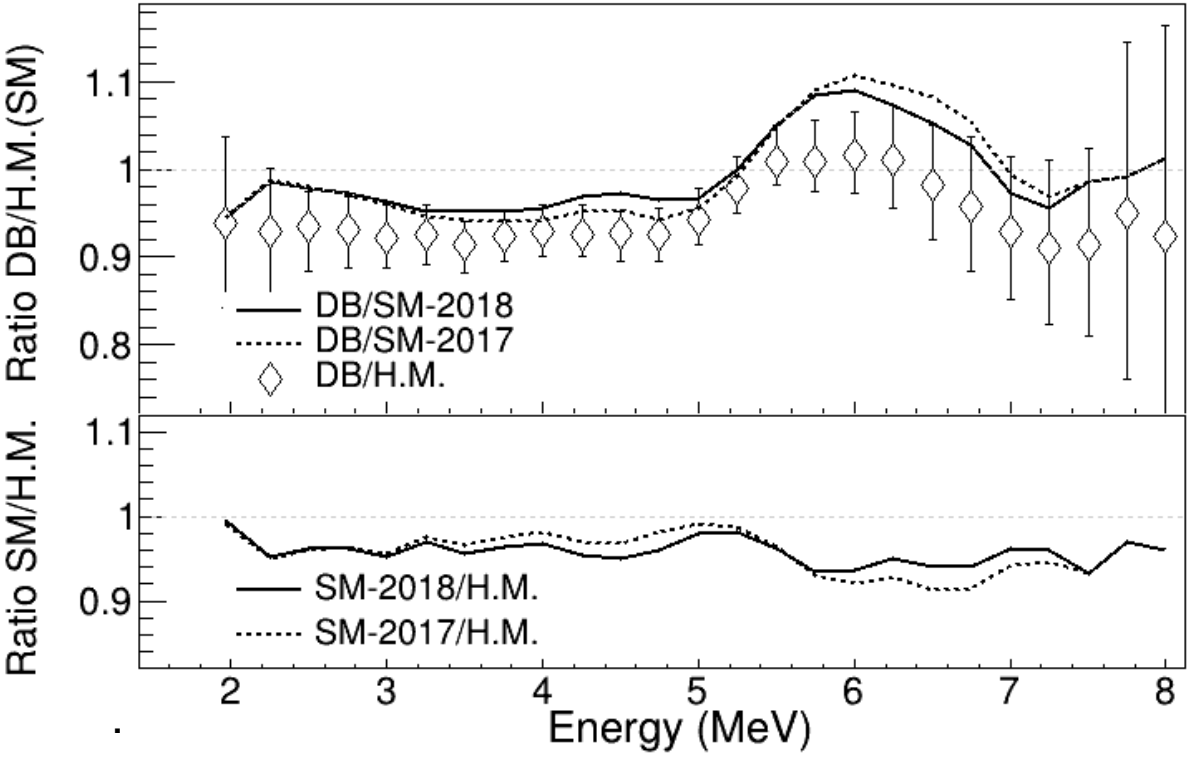
⇒ **remains robust in the 2 to 5 MeV range at the 2% level, i.e. a much better situation than the "10%" of missing information published in 2011 in Mueller et al.**

⇒ **The level of agreement is confirmed by the 1.9% discrepancy with the DB flux**

⇒ will allow computing associated decay data uncertainties (only possible if Pandemonium effect is not too strong!)

Comparison with Daya Bay results and H-M Predictions

M. Estienne et al. PRL 123, (2019) 022502 http://arxiv.org/abs/1904.09358



- Comparison of the full detected antineutrino energy spectrum obtained with the summation model, **without any renormalization**, with the measurements from Daya Bay.
- The **2018 data improve the agreement with Daya Bay** (ratio DB/SM closer to 1)

- Even with the inclusion of the 2018 TAGS data, the **bump is still there** i.e. for the moment, it still **cannot be explained** by ingredients of the nuclear databases.

- **With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ^{235}U and ^{239}Pu (contrary to H.-M.)** and about 1% for ^{238}U and ^{241}Pu

IBD Average Yields

	DB	SM 2018	SM 2017	SM 2012	SM from [42]	H-M
σ_f (10-43cm^2)	5.9±0.13	6.01	6.05	6.10	6.11	6.22±0.14
$\frac{d\sigma_f}{dF_{239}}$(10-43cm^2)	-1.86±0.18	-1.82	-1.83	-1.87	-2.05	-2.46±0.06
σ_5 (10-43cm^2)	6.17± 0.17	6.28	6.31	6.38	6.49	6.69±0.15
σ_9 (10-43cm^2)	4.27± 0.26	4.42	4.44	4.47	4.49	4.36±0.11
σ_8 (10-43cm^2)	10.1±1.0	10.14	10.20	10.27	10.2	10.1±1.0
σ_4 (10-43cm^2)	6.04±0.6	6.23	6.27	6.29	6.4	6.04±0.6
σ_5/σ_9	1.445±0.097	1.421	1.421	1.427	1.445	1.53± 0.05

- The agreement of the individual contributions of ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U with the detected antineutrino flux and of the slope of the IBD yield with the burnup with that measured by the DB experiment is improved by our new model.

- **With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ^{235}U and ^{239}Pu (contrary to H.-M.)** and about 1% for ^{238}U and ^{241}Pu

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