THE REACTOR ANTINEUTRINO SPECTRUM

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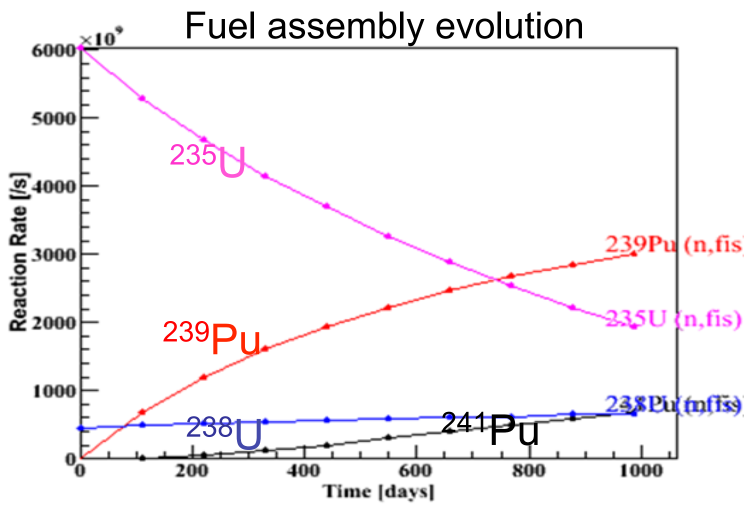
**Solvay Workshop 2017,
Bruxelles**

Reactors and Beta Decay

- In Pressurized Water Reactors, thermal power mainly induced by 4 isotopes:
  - ^{235}U and ^{238}U in fresh fuel
  - Other fissile nuclei (^{239}Pu & ^{241}Pu) created after reactor start by fission/capture process
  - Burn-up effect => unit GWd/t



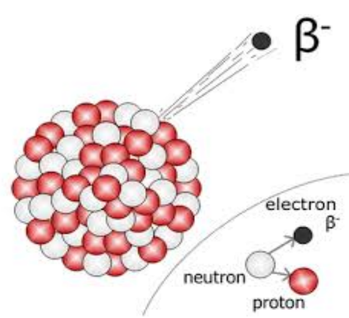
- Fission process gives thermal energy:

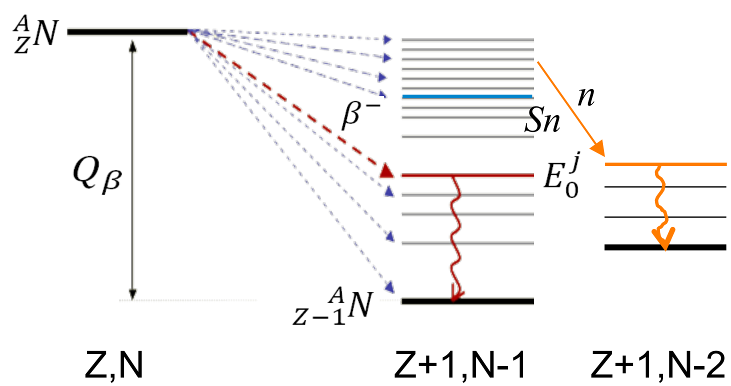
Impossible d'afficher l'image. Votre ordinateur manque peut-être de mémoire pour ouvrir l'image ou l'image est endommagée. Redémarrez l'ordinateur, puis ouvrez à nouveau le fichier. Si le x rouge est toujours affiché, vous devrez peut-être supprimer l'image avant de la réinsérer.

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

Impossible d'afficher l'image. Votre ordinateur manque peut-être de mémoire pour ouvrir l'image ou l'image est endommagée. Redémarrez l'ordinateur, puis ouvrez à nouveau le fichier. Si le x rouge est toujours affiché, vous devrez peut-être supprimer l'image avant de la réinsérer.

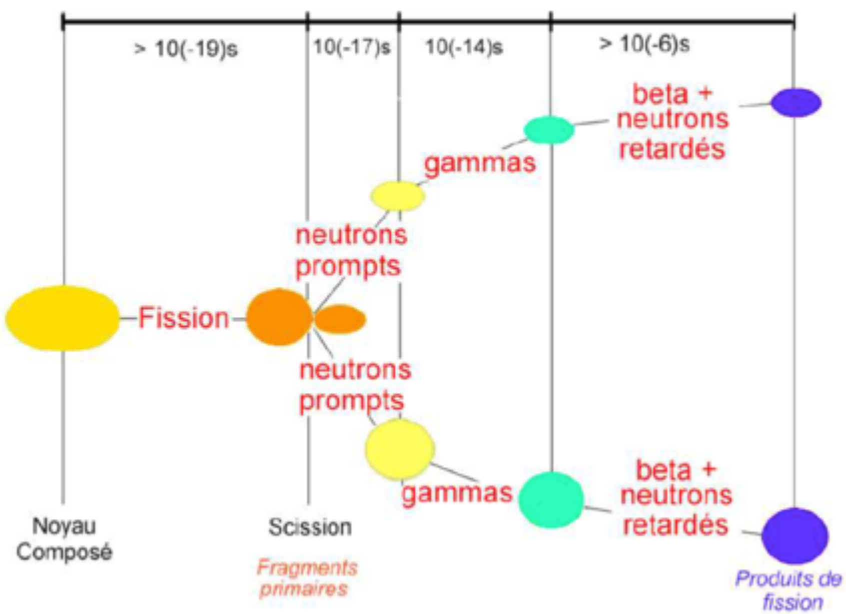
$$ {}_{Z+1}^{A}Y^{*} \rightarrow {}_{Z+1}^{A}Y + \gamma s $$





Beta Decay for Present and Future Reactors

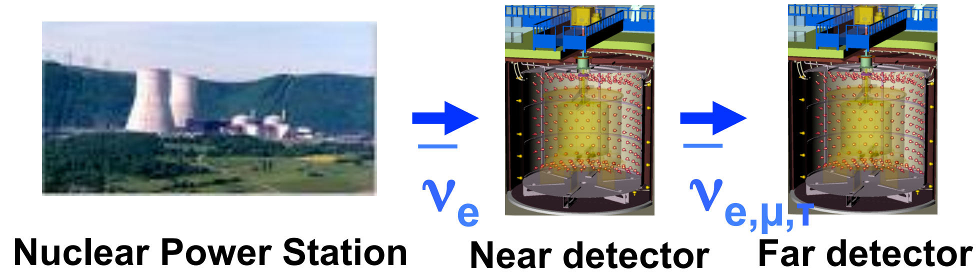
- The exploitation of the products of the beta decay is threefold:
  - ❑ The released γ and β contribute to the "**decay heat**" → critical for reactor safety and economy
  - ❑ The **antineutrinos** escape and can be detected → reactor monitoring, potential non-proliferation tool and essential for fundamental physics
  - ❑ β-n emitters: **delayed neutron fractions** → important for the operation and control of the chain reaction of reactors

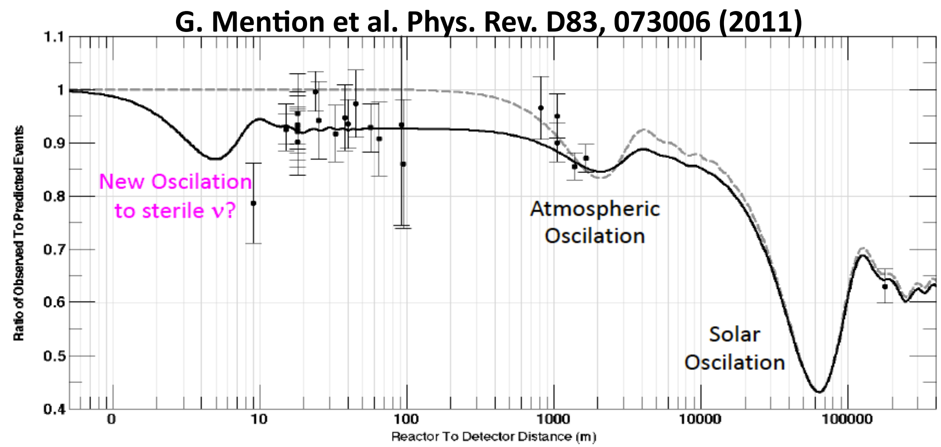


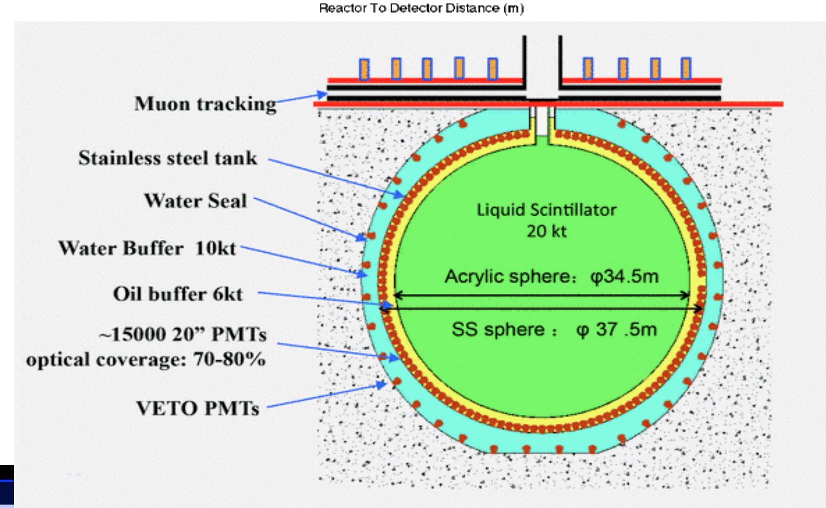
Reactor Antineutrinos are used for

⇒ **Neutrino Fundamental Physics**

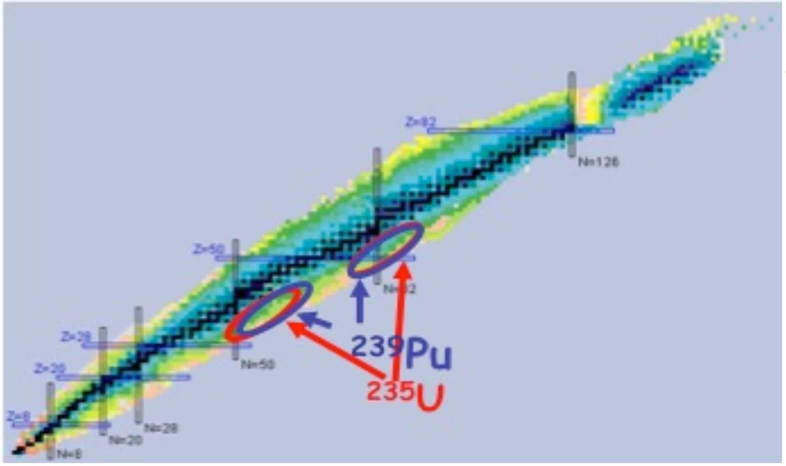
- **Measurement of the θ_{13} oscillation param by Double Chooz, Daya Bay, Reno**
- **Sterile neutrino measurement to explain the "reactor anomaly"**
- **Next generation reactor neutrino experiments like JUNO or background for other multipurpose experiment**

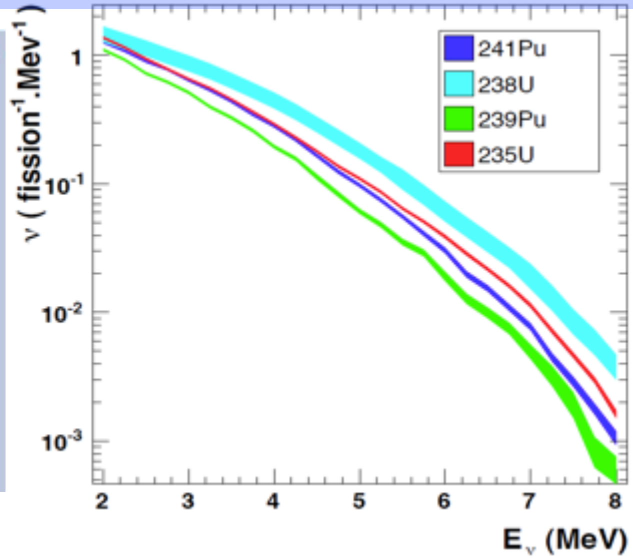






Reactor Antineutrinos





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 & power:

⇒ **reactor monitoring, non-proliferation (see IAEA Report SG-EQGNRL-RP-0002 (2012).)**

Idea born in the 70s, demonstrated in the 80s/90s but developed lately.

- **The International Atomic Energy Agency (IAEA): UN agency => peaceful use of atoms.**
  - ❑ **Safeguards Department is interested in: Inter alia remote and unattended tools, bulk accountancy; Safeguards by design**
  - ❑ **has shown interest in the detection of antineutrinos**

- **The IAEA Nuclear Data Section (NDS) includes the measurements for reactor antineutrino spectra in their Priority lists (CRP meetings, TAGS consultant meetings…)**

Reactor Antineutrino Spectral Knowledge

- **First Double Chooz, Daya-Bay and Reno theta13 results published in Phys. Rev. Lett. in 2012**

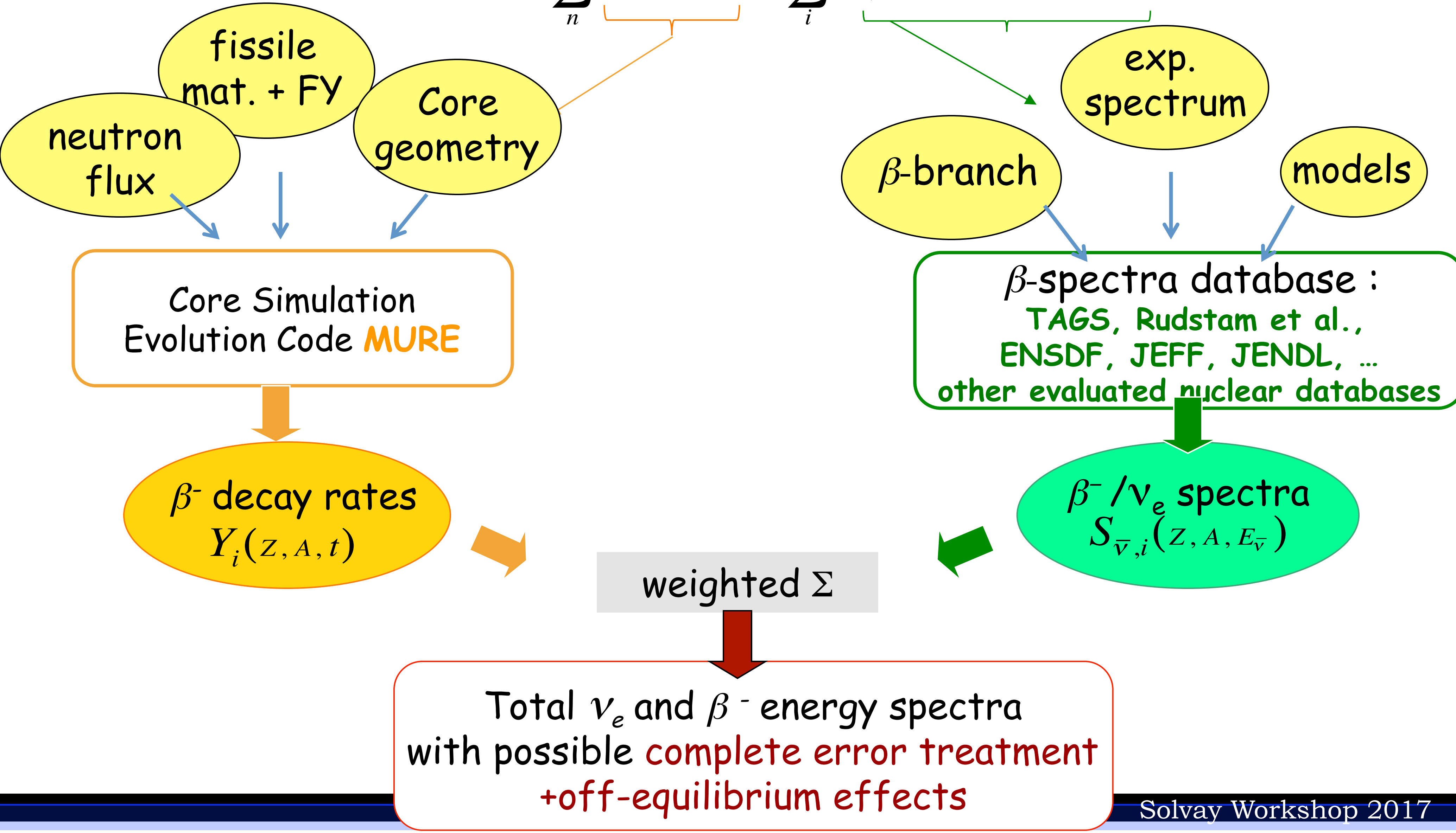
Y. Abe et al Phys. Rev. Lett. 108, 131801, (2012)
F. P. An et al., Phys. Rev. Lett. 108, 171803 (2012).
J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012)

- **The Double Chooz experiment has devoted efforts to new computations of reactor antineutrino spectra (mandatory for the 1st phase !!!)**

- **Two methods were re-visited:**
  - ✓ 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): **use of nuclear data for realistic beta branches, Z distribution of the branches…**
  - ✓ 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)

Summation Method

$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$



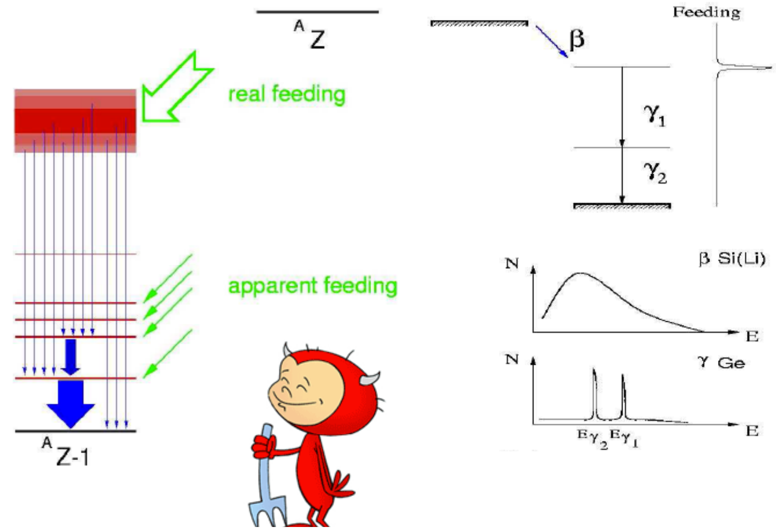
γ Measurement Caveat

- Before the 90s, conventional detection techniques: high resolution γ-ray spectroscopy
  - ❑ Excellent resolution but efficiency which strongly decreases at high energy
  - ❑ Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daugther nuclei (especially with decay schemes with large Q-values)
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra
- Phenomenon commonly called « pandemonium effect** » by J. C Hardy in 1977

** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

➡ **Strong potential bias in nuclear data bases and all their applications**

Picture from A. Algora



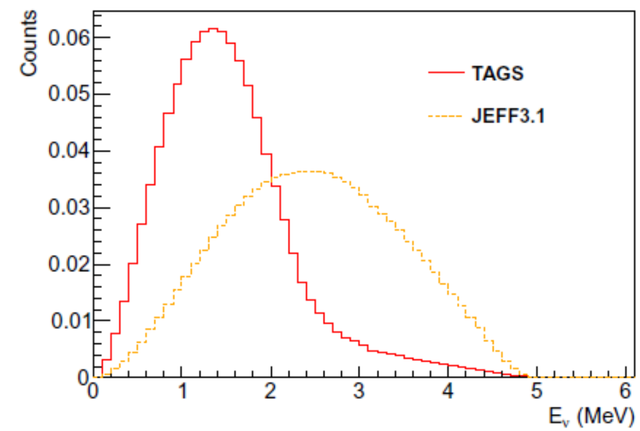


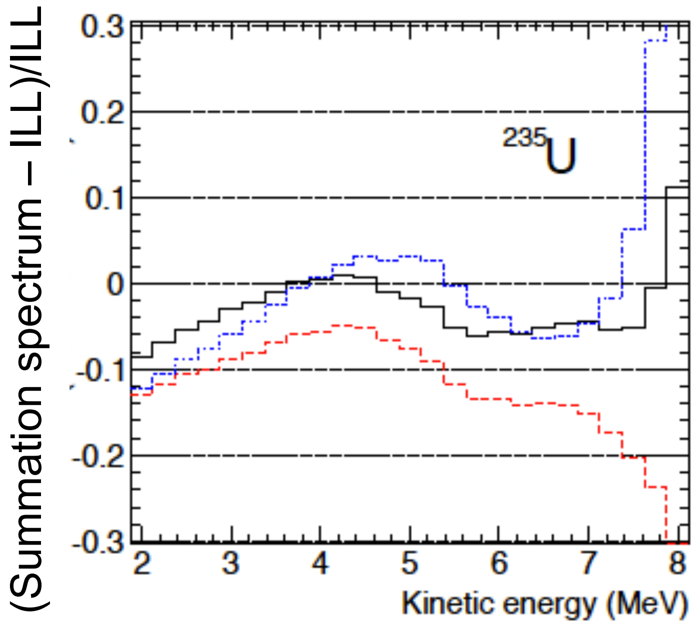
FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

What can nuclear data bring to antineutrino spectra ?

Summation Calculations:

using P. Huber's prescriptions for spectral shape calculations, a careful selection of decay data, and fission yields from JEFF3.1:

$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$



⇒ **Test of various nuclear databases: Pandemonium effect:** **Overestimate of the ILL spectra @ high energy + shape distorsion**

⇒ **Requires new measurements** **of FP beta decay properties**

***MCNP Utility for Reactor Evolution:** http://www.nea.fr/tools/abstract/detail/nea-1845. **Th. Mueller et al.** Phys. Rev. C 83, 054615 (2011)., **C. Jones et al.** Phys. Rev. D 86 (2012) 012001, arxiv.org/abs/1109.5379

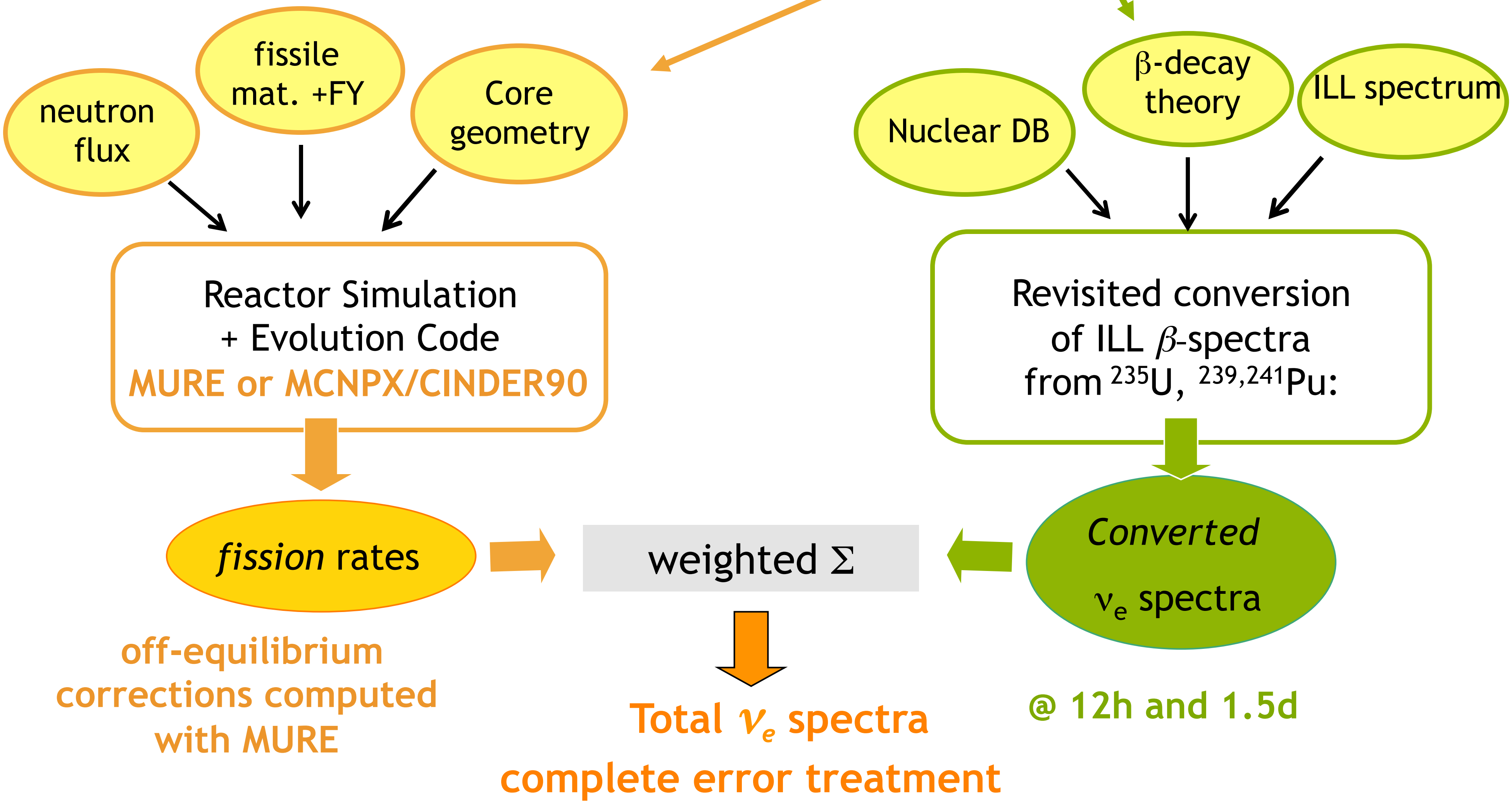
The reactor antineutrino estimates suffer from the Pandemonium Effect: similar to Reactor Decay Heat (Yoshida et al. NEA/WPEC-25 (2007), Vol. 25**)**

⇒ **Importance of the selection of data sets for Summation calculations: i.e. appropriate choice of decay data & fission yields**

⇒ **Improve systematic errors: list of nuclei to measure with TAS experiments**

Conversion Method

$$N_\nu^{emit}(E) = \int_0^{T_{run}} P_{th}(t) \times \sum_{\substack{i\ fuel \\ assemblies}} \frac{\alpha_i(t)}{\sum_k f_i^k(t) E_k} \sum_{\substack{k\ fissile \\ isotopes}} N_\nu^k(E) f_i^k(t) \quad dt$$

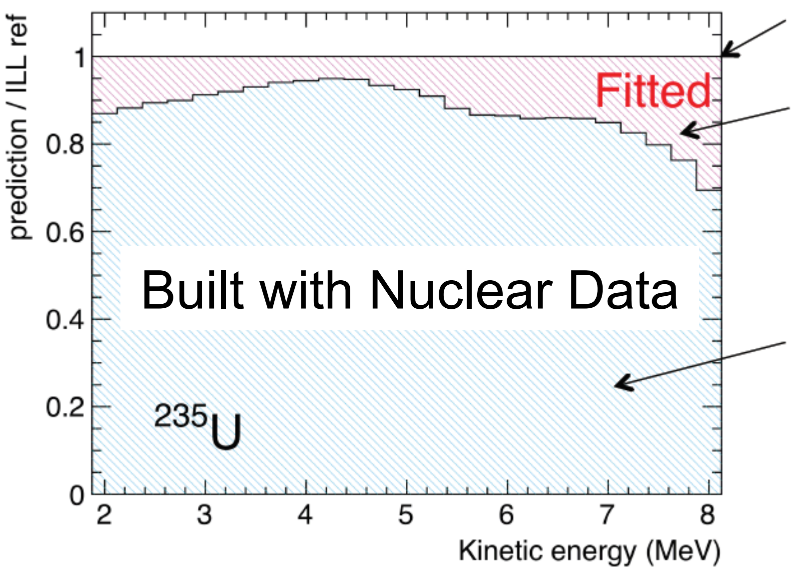


Reactor Antineutrinos: Converted Spectra

- **Calculation of Reactor Antineutrino Spectra from the conversion of the beta spectra measured by Schreckenbach et al. at the ILL reactor in the 80's**
- **Principle: Fit the beta spectrum shape with beta decay branches (nuclear data + fictive branches or only fictive branches), taking into account proper Z distribution of the fission products, proper corrections to Fermi theory and a large enough number of beta branches**

Example: Th.A. Mueller et al, Phys.Rev. C83(2011) 054615:

Ratio of Prediction / Reference ILL data



ILL electron data anchor point

- Fit of residual: five effective branches are fitted to the remaining 10%

  $\Rightarrow$ Suppresses error of full Summation Approach, if assumption that ILL data = only reference

- "true" distribution of all known β- branches describes >90% of ILL e data

  $\Rightarrow$ reduces sensitivity to virtual branches approximations

Ingredients to Build Beta and Antineutrino Spectra

- $N_\beta (W) = K\, pW(W-W_0)^2 F(Z,W)L_0(Z,W)C(Z,W)S(Z,W)G_\beta (Z,W)(1+\delta_{WM}W)$

Where $W=E/m_ec^2$, K = normalization constant,

$pW(W-W_0)^2$ = phase space, to be modified if forbidden transitions

$F(Z,W)$ = „traditional" Fermi function

$L_0(Z,W)$ and $C(Z,W)$ = finite dimension terms (electromagnetic and weak interactions)

$S(Z,W)$ = screening effect (of the Coulomb field of the daughter nucleus by the atomic electrons)

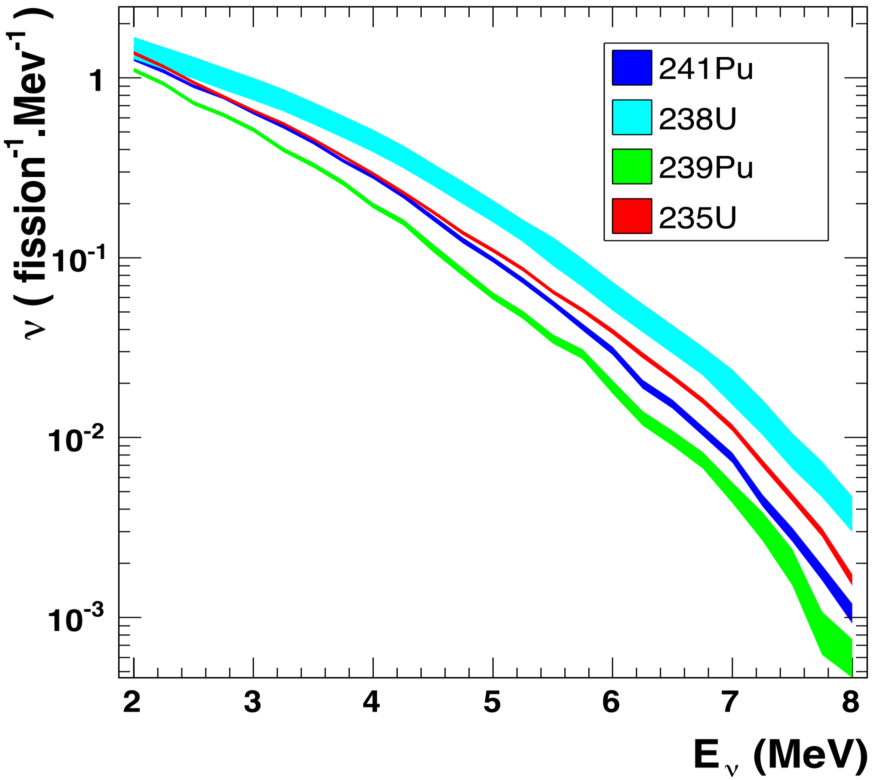
$G_\beta (Z,W)$ = radiative corrections involving real and virtual photons

δ_{WM} = weak magnetism term

The first results were published in Th.A. Mueller et al, Phys.Rev. C83(2011) 054615

Followed by P. Huber, Phys.Rev. C84 (2011) 024617

Newly Converted Spectra



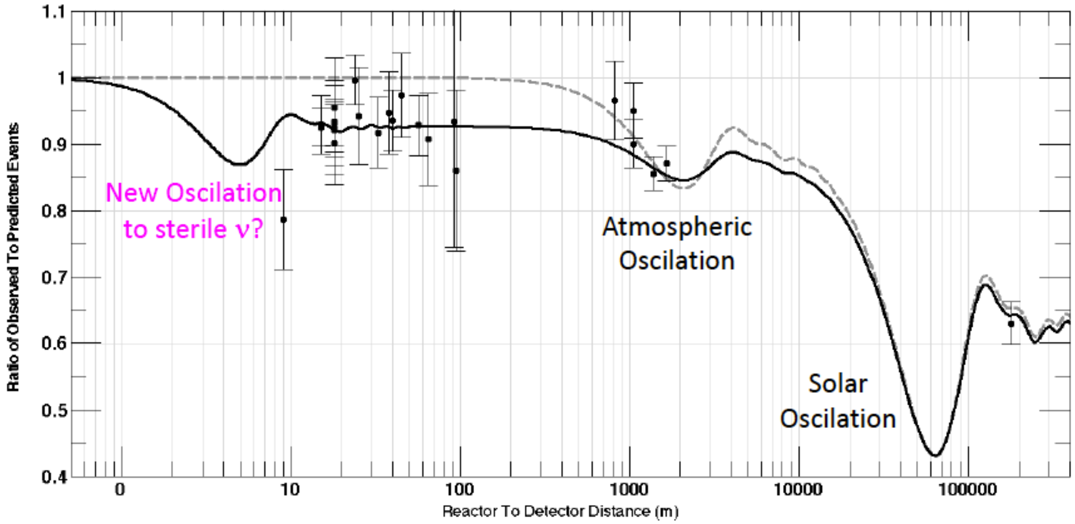
- Recent re-evaluations by
  - ✓ Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
  - ✓ P. Huber, Phys.Rev. C84 (2011) 024617
- Off-equilibrium corrections included (computed with summation method MURE)
- Summation calculations: provided the used databases for the conversion + a new ^{238}U prediction

Recent works defining new reference on the neutrino flux prediction for neutrino physics

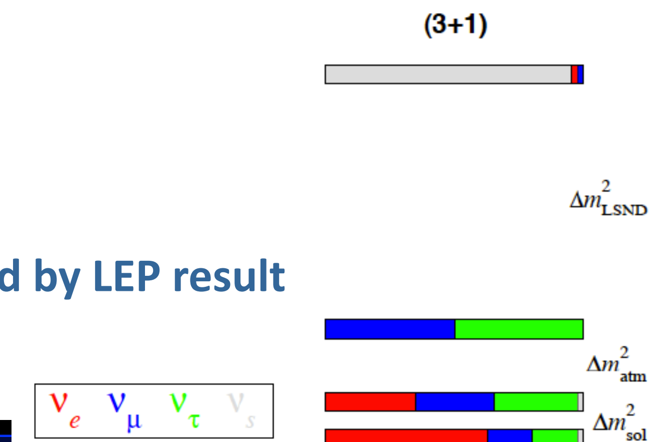
Sterile Neutrino hints ?

- **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)



⇒ Light sterile neutrino state ?

could explain L=10-100m anomalies, $\Delta m^2 \approx 1$ eV²
Candidate(s) can't interact via weak interaction : constrained by LEP result on 3 families => so can only exist in sterile form

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

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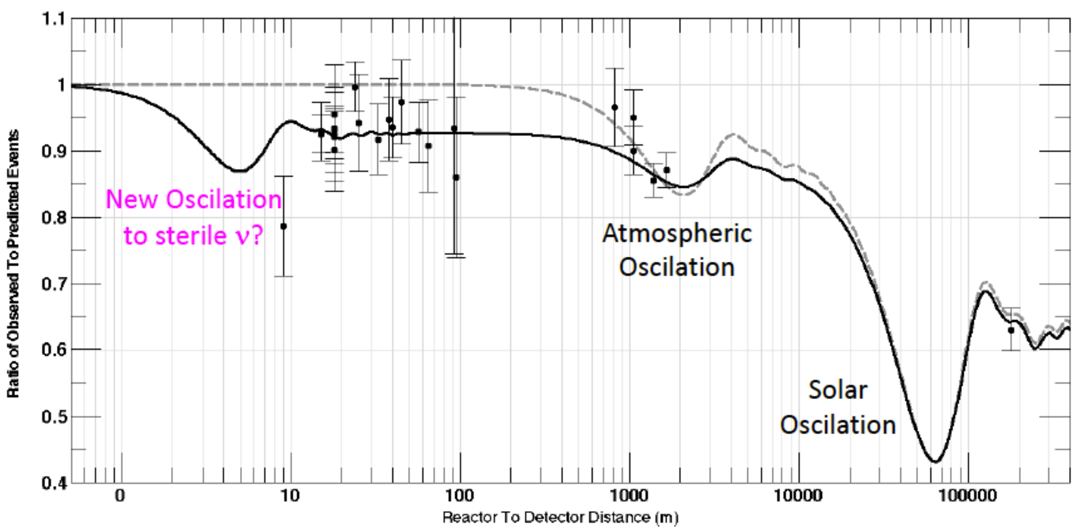


G. Mention et al. Phys. Rev. D83, 073006 (2011)

⇒ **Now looking for sterile neutrinos as a potential explanation to the reactor anomaly: numerous projects: SoLid (UK-Fr-Bel-US), STEREO (France), Neutrino-4 (Russia), DANSS(Russia), PROSPECT(USA), + Mega-Curie sources in large ν detector… (white paper: K. N. Abazajian et al., http://arxiv.org/abs/1204.5379.)**

Are Converted Spectra Reliable ? 1

- By now the reactor antineutrino prediction with the smallest systematic errors
- But potential additional sources of systematic errors:
  - ❑ *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…

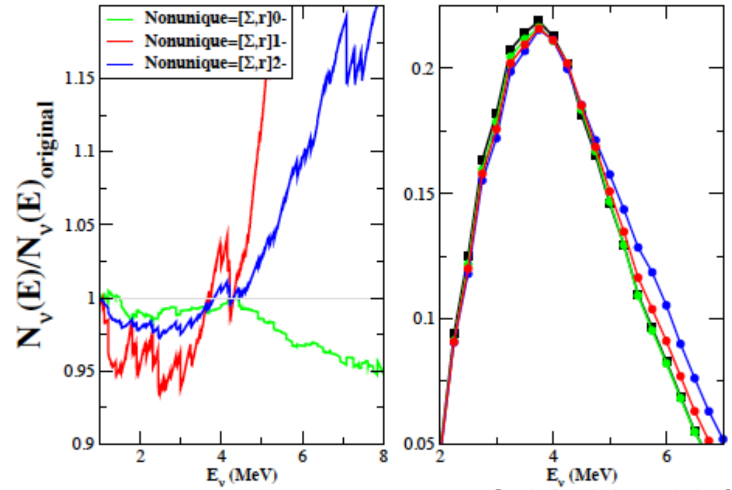
D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015): The finite size effects and the weak magnetism corrections obtained in Huber's paper for the allowed (GT) decays are estimated to give a reduction in the number of low energy antineutrinos of 2 – 3%.

  - ❑ *Impact of the conversion method* **?**
  - ❑ *Treatment of forbidden decays => could change normalization & shape of spectra…*

Are Converted Spectra Reliable ? 2

❑ …Treatment of forbidden decays => could change normalization & shape of spectra:

A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014)



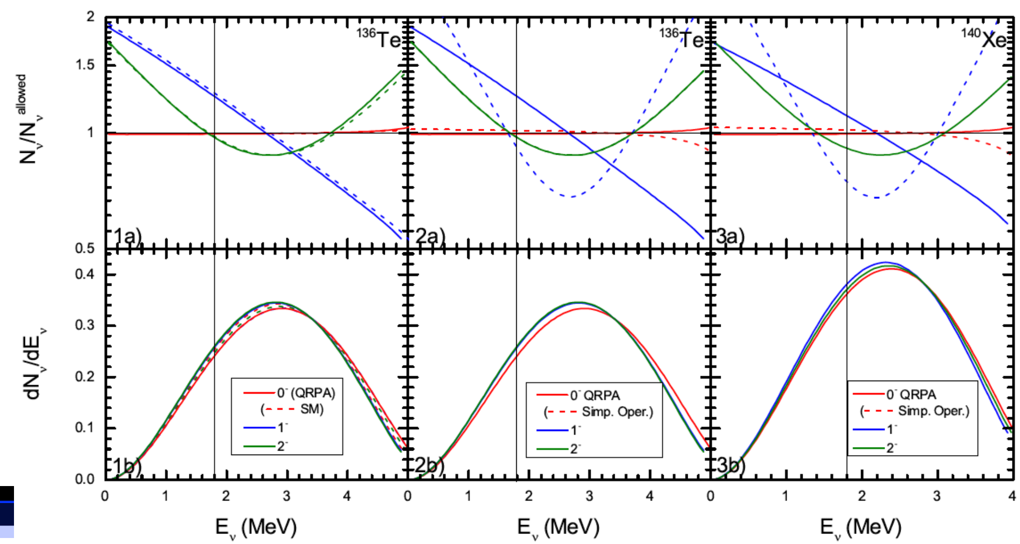
⇒ Large log(ft) contribute importantly to the spectra (˜30%) but we don't know how many of them are forbidden non-unique transitions, nor the spin/parity of the transitions

⇒ Need inputs from Nuclear Physics

See also D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015)
Using microscopic models : Shell Model and QRPA

⇒ The forbidden transitions further increase the uncertainty in the expected spectrum

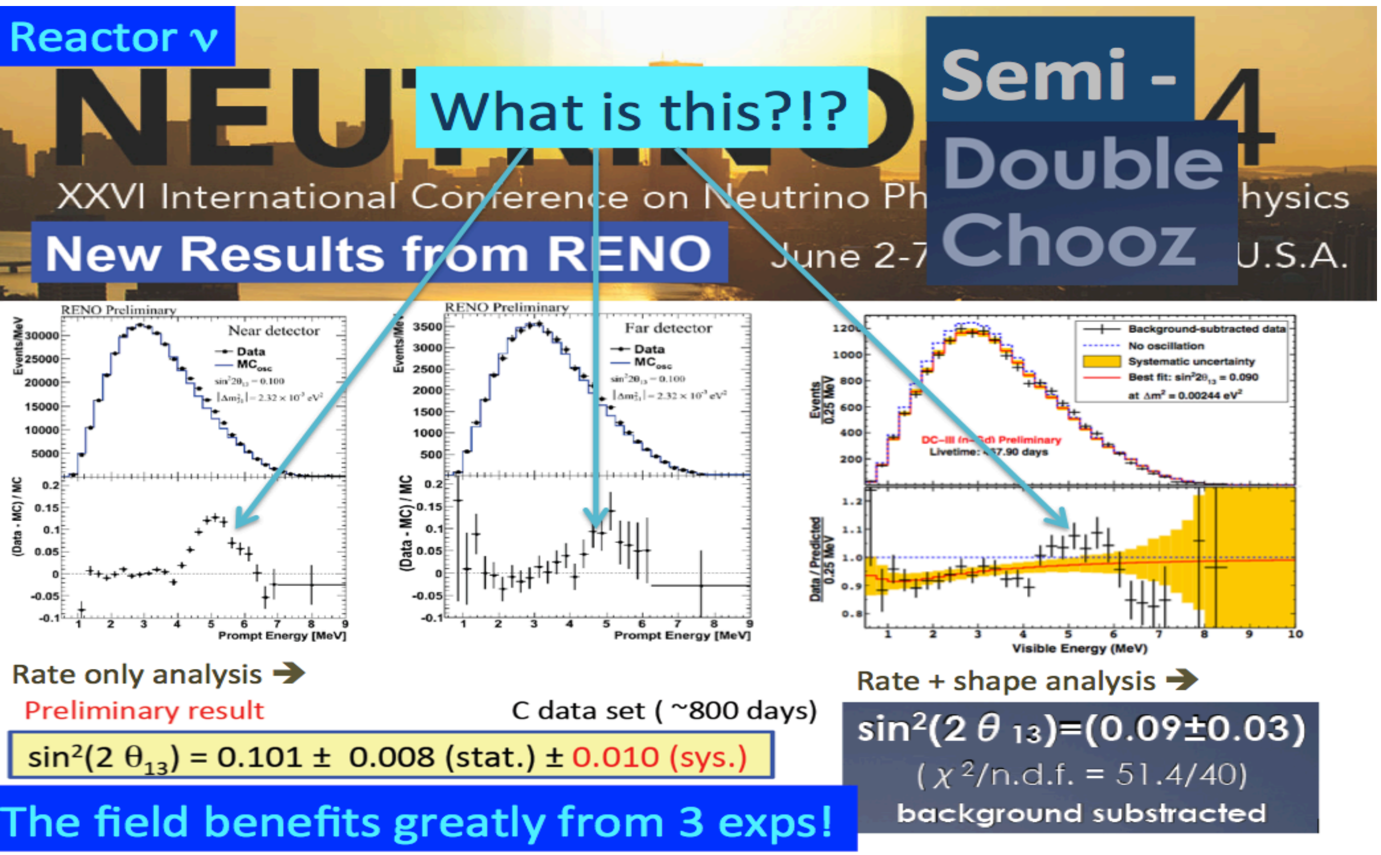
⇒ Two equal fits to Schreckenbach's β-spectrum, lead to nu-spectra that differ by 4%



Are Converted Spectra Reliable ? 3

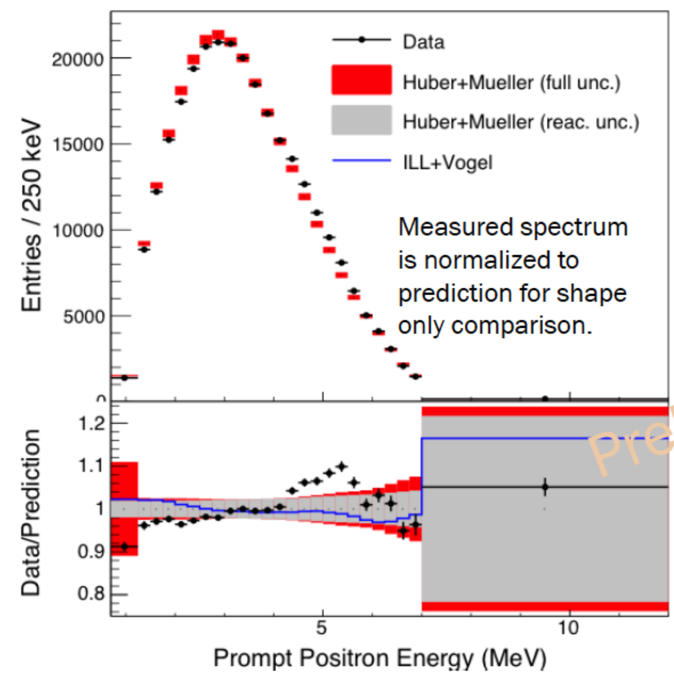
- **Observation of Shape Distorsions w.r.t converted spectra by the 3 large reactor neutrino experiments: Double Chooz, Daya Bay, and Reno:**

First communication by Double Chooz & Reno @Neutrino 2014



Followed by Daya Bay @ICHEP2014

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



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

The only alternative to converted spectra in absence of new integral measurements relies on the nuclear data with the summation method…

A Reduced List of Important Contributors

Summation calculations (in agreement!) give the following priority list of nuclei, with a large contribution to the PWR antineutrino spectrum in the high energy bins:

TABLE I. Main contributors to a standard PWR antineutrino energy spectrum computed with the MURE code coupled with the list of nuclear data given in Ref. [12], assuming that they have been emitted by ^{235}U (52%), ^{239}Pu (33%), ^{241}Pu (6%), and ^{238}U (8.7%) for a 450 day irradiation time and using the summation method described in Ref. [12].

	4–5 MeV	5–6 MeV	6–7 MeV	7–8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	...
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	...	...
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	...	...
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	...
^{95}Sr	2.65%	2.96%	...	...
^{94}Rb	1.32%	2.06%	2.84%	3.96%

The number of contributors in these bins is small enough to give the hope to produce summation calculations with reduced systematic errors due to decay data at a relatively short time scale

A.-A. Zakari-Issoufou et al. Phys. Rev. Lett. 115, 102503

TAGS Solution to Pandemonium Effect

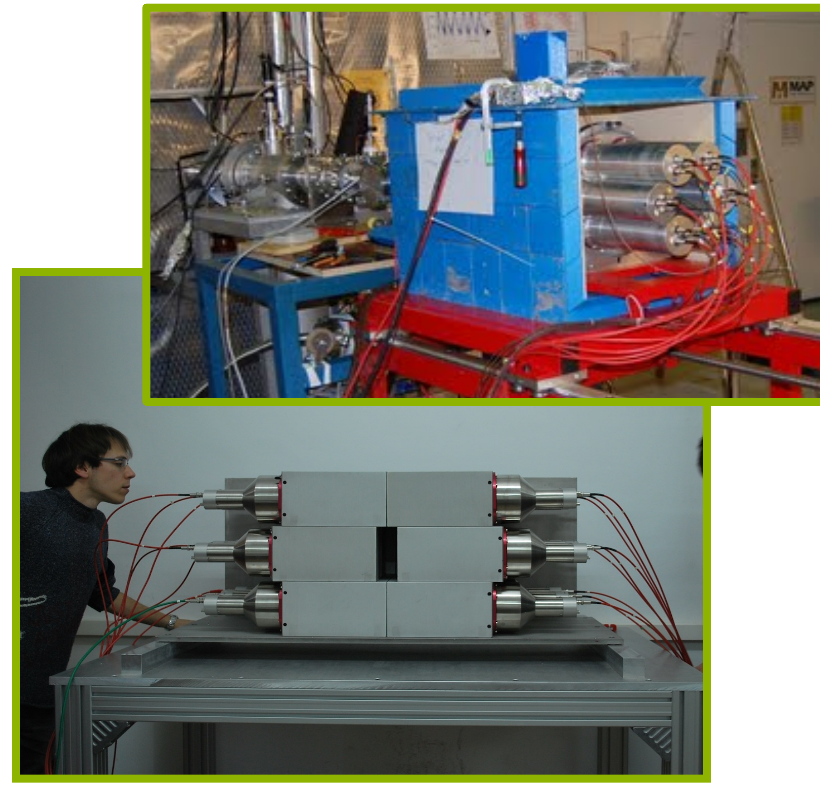
- **Decay Total Absorption Spectrometer (DTAS – IFIC): used in Jyväskylä in Feb. 2014 for the reactor antineutrino proposal:** 18 modules 15x15x25 cm3 NaI(Tl) + 5" PMT
  - **12 nuclei for antineutrinos measured & 11 for decay heat**

- **BAF_2 TAGS (Surrey-Valencia): used for the 2009 measurement at IGISOL-JYFLTRAP**: ^{86}Br, ^{87}Br, ^{88}Br, ^{91}Rb, **^{92}Rb, ^{93}Rb,** ^{94}Rb

M. Fallot et al., PRL109,202504 (2012)
A.-A. Zakari-Issoufou et al. PRL 115, 102503 (2015)
J. –L. Tain et al. PRL 115, 062502 (2015)
E. Valencia et al., Phys. Rev. C 95, 024320 (2017)
S. Rice et al. Phys. Rev. C 96 (2017)014320.

Collab. : IFIC, Subatech, Surrey, IPNO, IGISOL, CIEMAT, BNL, Istanbul, …

Pure beams required: Use of the double Penning trap from JYFL

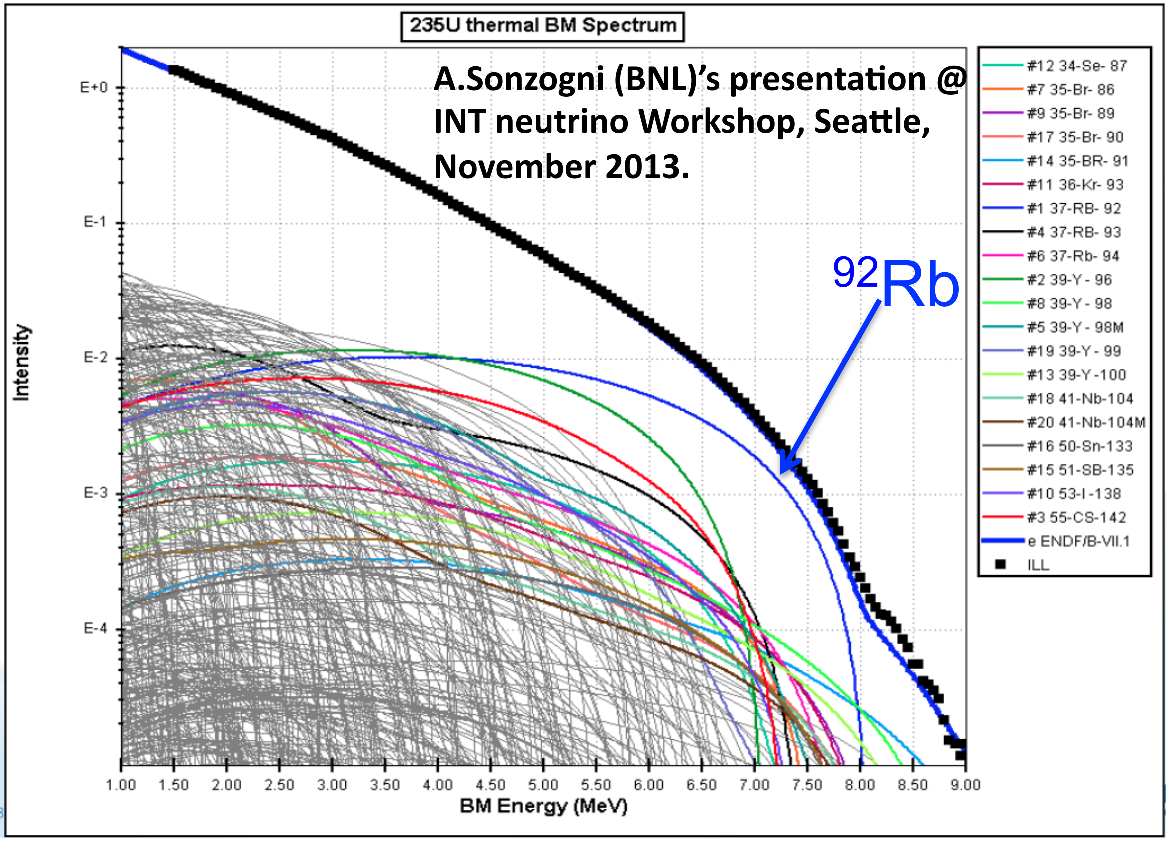


2 TAGS arrays developed by the Valencia team (Spain, B. Rubio, J.L. Tain, A. Algora et al.):

V.Guadilla et al.,, Nucl. Inst. and Meth. B, Online (2015)

A Result: the Case of ^{92}Rb

- ✓ Candidate **Pandemonium nucleus**, GS-GS 1st forbidden transition with high I_b
- ✓ **Big contribution in ^{235}U and ^{239}Pu ν spectra:** respectively expected to be around **32% and 25.7% in [6-7] MeV, 34% and 33% in [7-8] MeV**



Our summation calculations give the following priority list:

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed with MURE using the summation method [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-

^{92}Rb =~16% of the antineutrino energy spectrum emitted by PWRs in the region of energy 5 to 8 MeV !!!

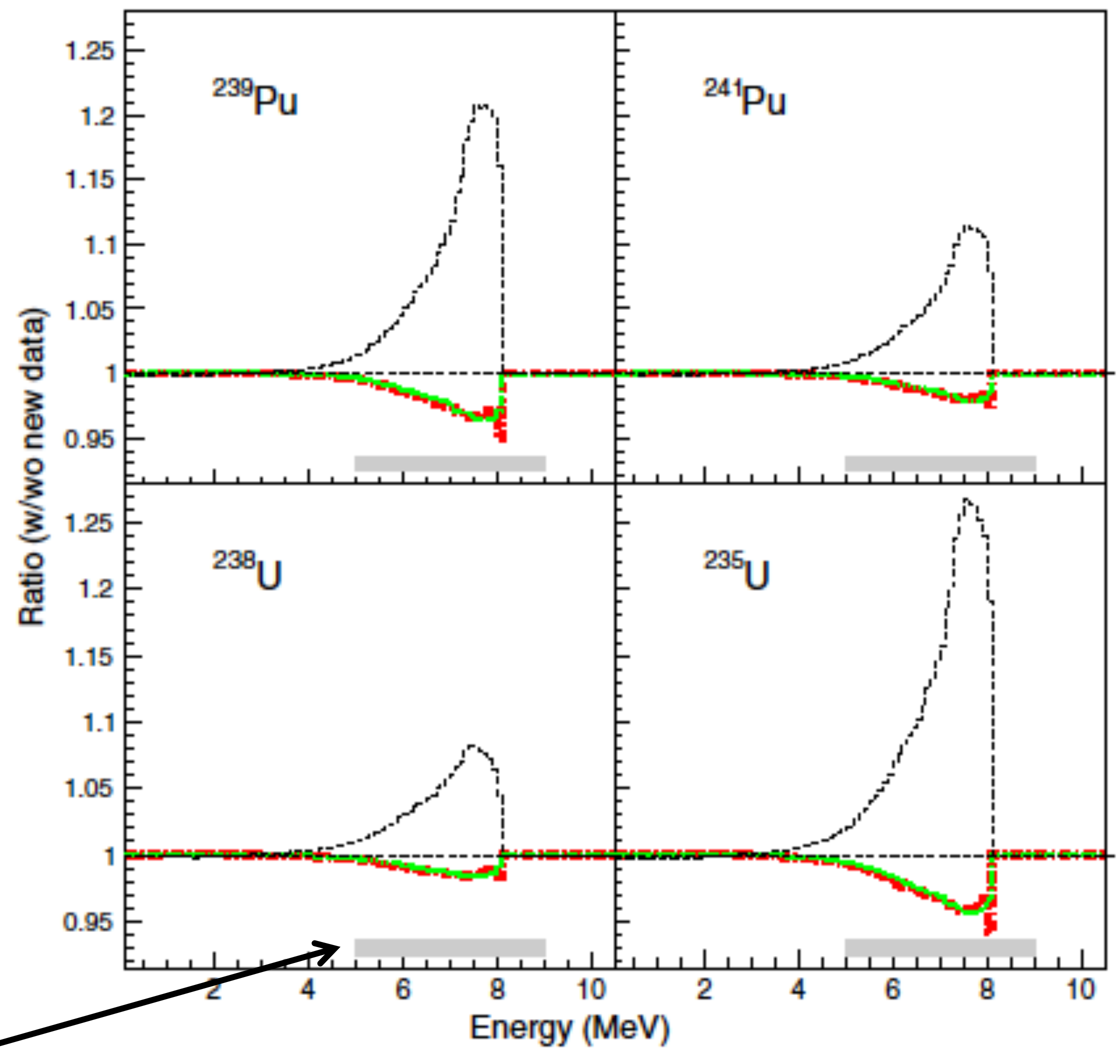
A.-A. Zakari-Issoufou et al. PRL 115, 102503

- ✓ Priority 2 for **Decay Heat** in U/Pu cycle and Priority 1 in Th/U cycle

Impact of ^{92}Rb on Antineutrino Spectra

Ratio between the antineutrino spectra calculated using the results presented in Z. Issoufou et al. PRL 115, 102503 with respect to the data on ^{92}Rb decay used in:

- M. Fallot et al., Phys. Rev. Lett. 109, 202504 (2012): **thick red dashed-dotted line,**
- A. A. Sonzogni, T. D. Johnson, and E. A. McCutchan, Phys. Rev. C 91, 011301(R) (2015): **green dotted line,**
- D. A. Dwyer and T. J. Langford, Phys. Rev. Lett. 114, 012502 (2015): **black dashed line.**



Gray horizontal bar: indicates the region of the distorsion observed by reactor antineutrino experiments with respect to converted spectra.

TAS data now obtained for…

…8 nuclei out of the top 11

	4–5 MeV	5–6 MeV	6–7 MeV	7–8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	···
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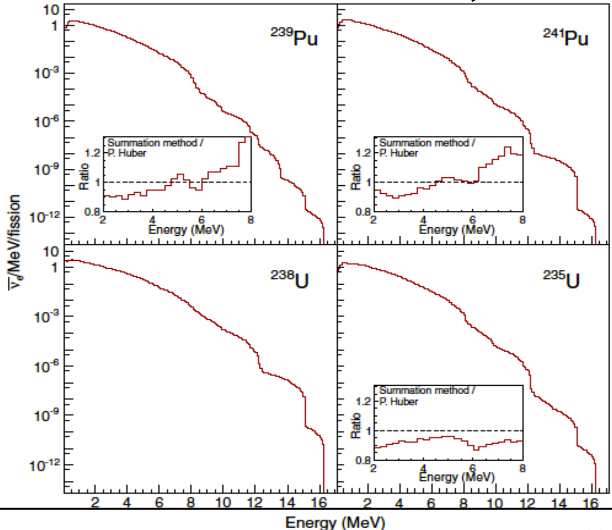
^{135}Te	4.01%	3.58%	···	···
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	···
^{95}Sr	2.65%	2.96%	···	···
^{94}Rb	1.32%	2.06%	2.84%	3.96%

See new results showing the impact of $^{86-88}$Br and ^{91,92,94}Rb and new analysis results about ^{100,100m}Nb, in *A. Algora's talk*

See also B. C. Rasco et al., Phys. Rev. Lett. 117, 092501 (2016),
B.C. Rasco et al. Phys. Rev. C 95, 054328 (2017)
A. Fijalkowska et al. Phys. Rev. Lett. 119, 052503 (2017)

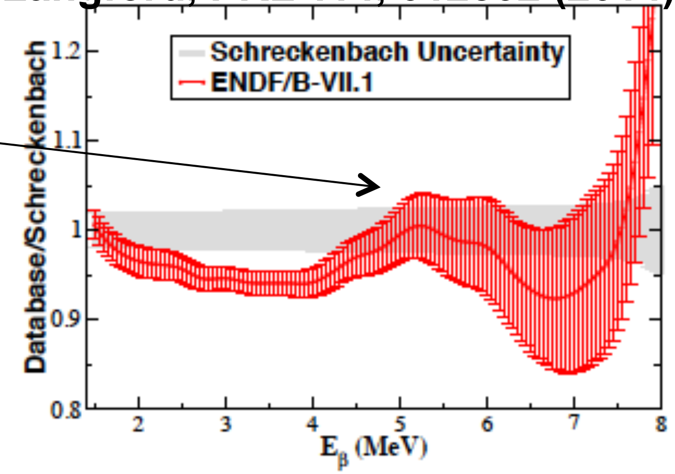
Summation Calculations…

M. Fallot et al. PRL109,202504 (2012)



Emphasis on Pandemonium effect, and careful choice of nuclear data

Dwyer & Langford, PRL 114, 012502 (2014)

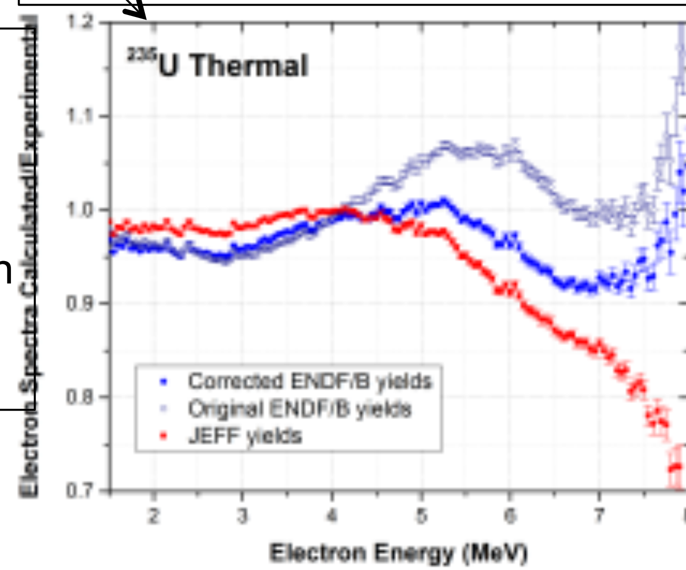


ENDF database predicts an analogous bump in the beta-spectrum relative to Schreckenbach.

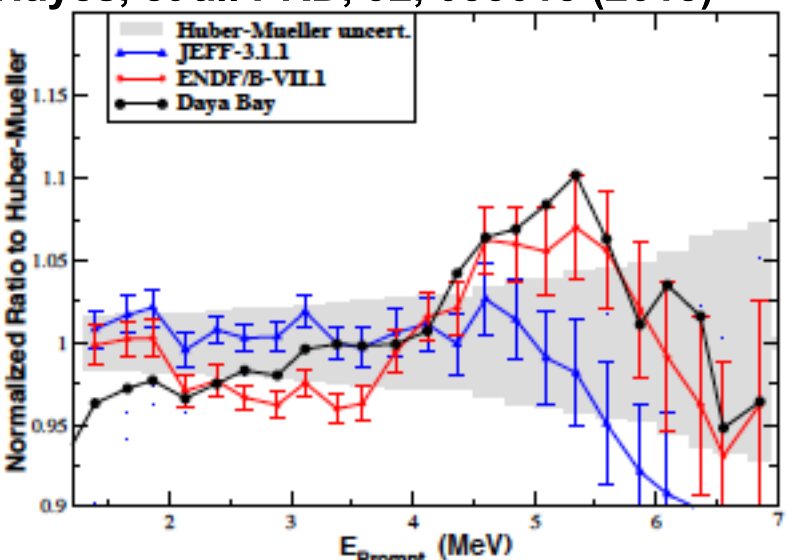
But D&L did not take into account TAGS data nor correct fission yields !!!

Sonzogni, et al. PRL,2016

Careful Study of fission yields data

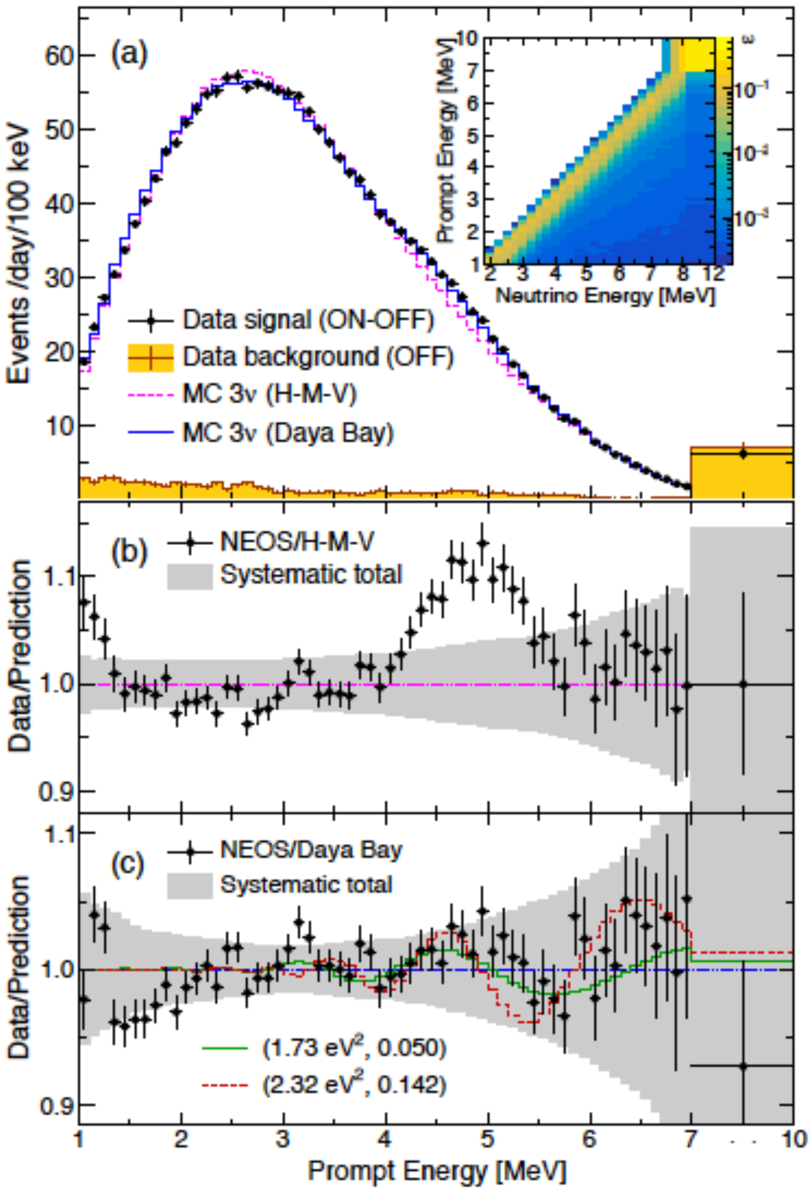


Hayes, et al. PRD, 92, 033015 (2015)



However, the European database JEFF does not predict the bump for Daya Bay or RENO. The bump in ENDF is largely a mistake in the database for fission yields…

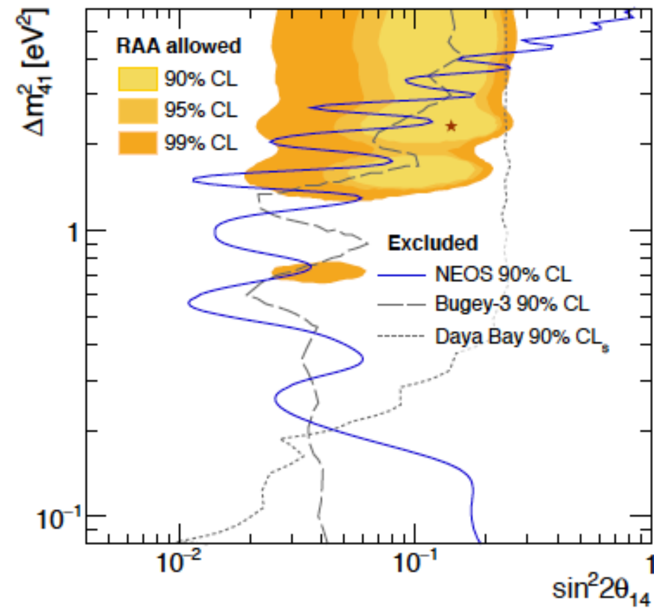
NEOS Results



NEOS: ~24 m away from a Korean power reactor

``bump" clearly observed, *but* no evidence for sterile neutrinos

Green and red lines indicate the best fit for the 3+1 oscillation scheme as indicated.

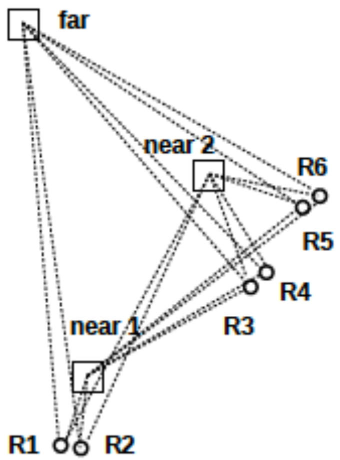


Exclusion plot in the 3+1 sterile neutrino scheme by NEOS.
The best fit point of Mention et al. (*) is disfavored by $\Delta\chi^2 = 5.4$.

Phys. Rev. Lett. 118, 121802 (2017)

Status by end 2017…

In 2017: **Daya Bay's new result about the reactor anomaly: pb is in the ^{235}U spectrum!!!**



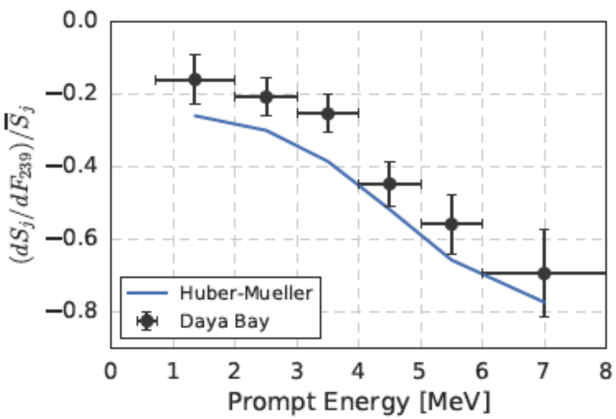
F. P. An et al. (Daya Bay Collaboration), ``Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay," Phys. Rev. Lett. 118 (2017).

⇒ Measured antineutrinos from **six 2.9-thermal-gigawatt reactor cores**, which were located either at Daya Bay or at the Ling Ao power plant in China

⇒ **Deficit in detected antineutrinos** compared to 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**—enough of a discrepancy to explain by itself the entire antineutrino anomaly !!!

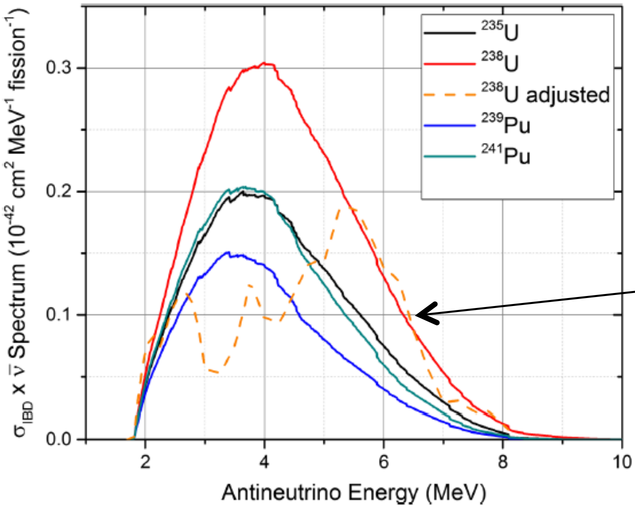
⇒ In contrast, the discrepancy = **almost zero for ^{239}Pu fissions**.



Previous hints were pointing to ^{235}U: ArXiv:1609.03910, 1608.04096, 1512.06656.

BUT https://arxiv.org/abs/1709.04294: **sterile neutrino hypothesis cannot be rejected based on global data**

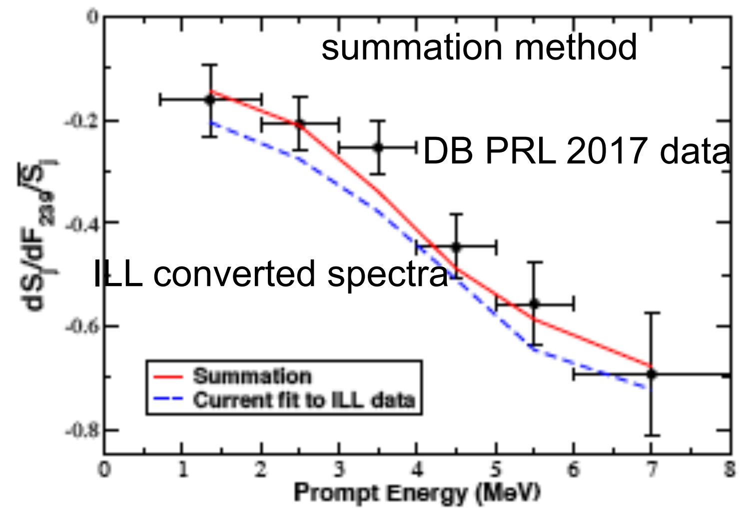
Even more recent studies…



A. A. Sonzogni, E. A. McCutchan, and A. C. Hayes PRL 119, 112501 (2017)

Dashed is the 238U spectrum adjusted to match the DB data: Clearly disfavors the hypothesis of the ^{238}U contribution origin

Hayes et al. arXiv:1707.07728



« an analysis based on the summation method explains all of the features seen in the evolution data, but it predicts an average IBD yield that is 3.5% higher than observed ».

⇒ Underlines the importance of experimental shape factors for both conversion and summation calculations

+ X.B. Wang, J. L. Friar and A. C. Hayes: **Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314:** investigate uncertainties on FS and WM corrections to allowed β-decay

Summary

- **The reactor anomaly:**
  - ❑ Uncertainties on the converted ILL spectra are underestimated (nuclear physics inputs: first forbidden non-unique beta decays)
  - ❑ Suspicions on the 235U ILL or ILL-converted spectrum (DB PRL 2017, Huber PRL 2017, Giunti 2016, …) ?
  - ❑ NEOS first results don't see evidence for sterile neutrinos, wait for other experiments !
  - ❑ Global analysis cannot reject the sterile hypothesis arXiv:1709.04294

- **The „bump“ (i.e. energy distorsion w.r.t. predictions from ILL converted):**
  - ❑ Seen by DC, DB, Reno, NEOS, and previously Chooz
  - ❑ Cannot come from ^{238}U, not from fast fissions, not an oscillation pattern, not first forbidden non-unique transitions
  - ❑ Not seen by summation method with up-to-date ingredients

The Story of the Reactor Antineutrino Spectrum…

...That's how we have ended with a problem common to particle AND nuclear physics...

We don't know yet the end of the story !!!

⇒ Measure antineutrino energy spectrum at research reactors: SoLid, STEREO, DANSS, NEOS...

⇒ Measure the shape of the ~20 most important beta decay electron spectra

⇒ Keep going with Pandemonium free measurements (TAS)