Review of the reactor antineutrinos flux and shape measurements

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GDR neutrino
November 21, 2017

Summary

1. Reactor $\bar{\nu}_e$

. Production / detection

. Prediction of reactor flux

2. Reactor experiments

. Rate measurements

. Shape measurements

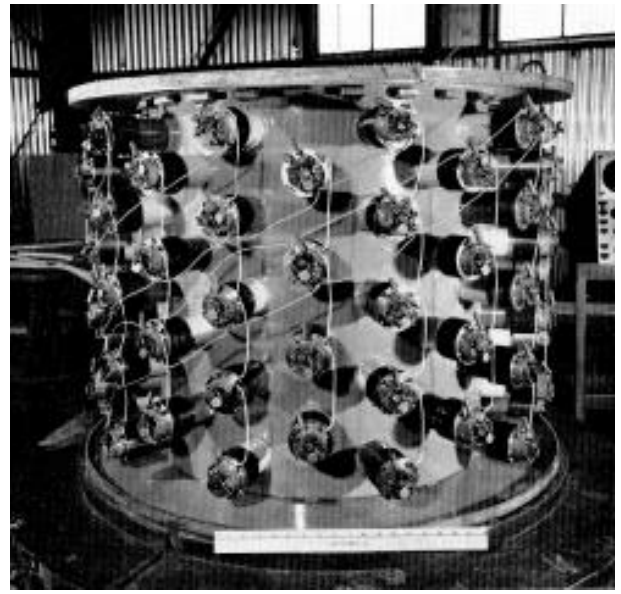
3. Reactor spectrum microstructure and mass hierarchy

.

1. Reactor $\overline{\nu}_e$

Reactor antineutrino

First reactor measurement by Cowan & Reines @Savannah River in 1956



$$\langle \sigma_f \rangle^{SR} = (6.7 \pm 1.5).10^{-43}\ cm^{-2}.fission$$ (22.3%@ 1σ)

Reactor experiments

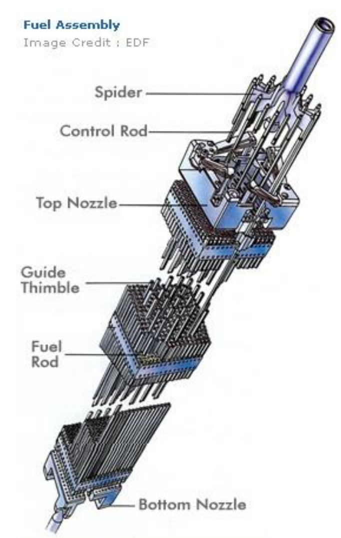
- cheap source / no matter effect (short baseline)
- Intense & pure flux: **$\sim$1.10[20] $\bar{\nu}_e$/s for a 1 GWth reactor ($\sim$3000 MWe)**

Commercial nuclear reactor

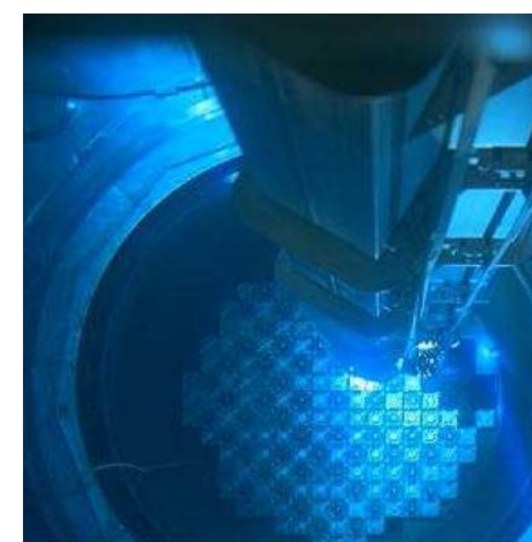
- >99% of thermal power induced by fission of 4 nuclei: **^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu**
- fission products are neutron-rich nuclei:

$$\beta^{-}\ decay:\ {}^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + e^{-} + \boxed{\bar{\nu}_e}$$

$\sim$6 $\bar{\nu}_e$ per fission



Fuel assembly

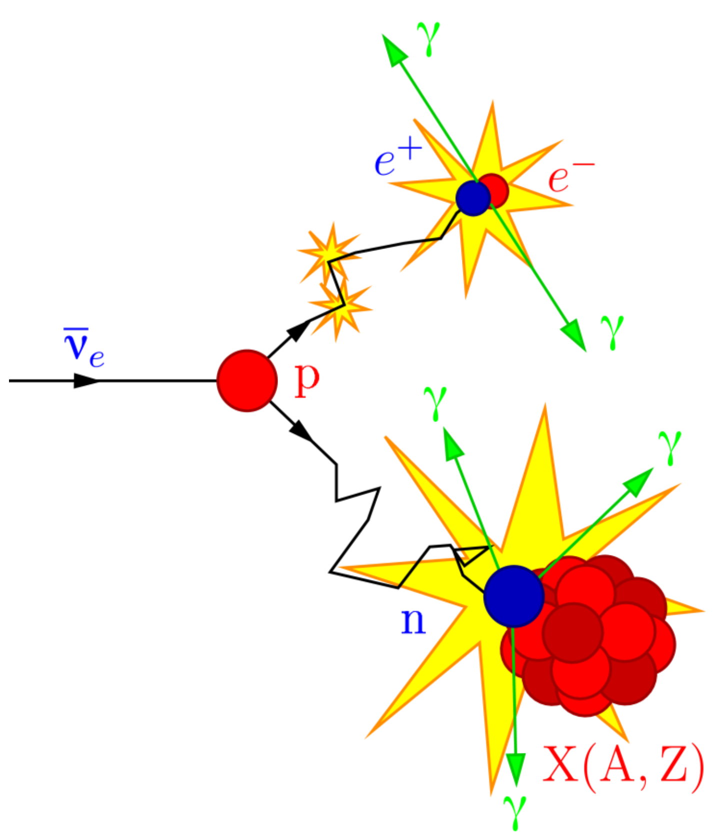


N4-PWR core

Research reactor

- >90% of thermal power induced by fission of **^{235}U**

$\bar{\nu}_e$ detection

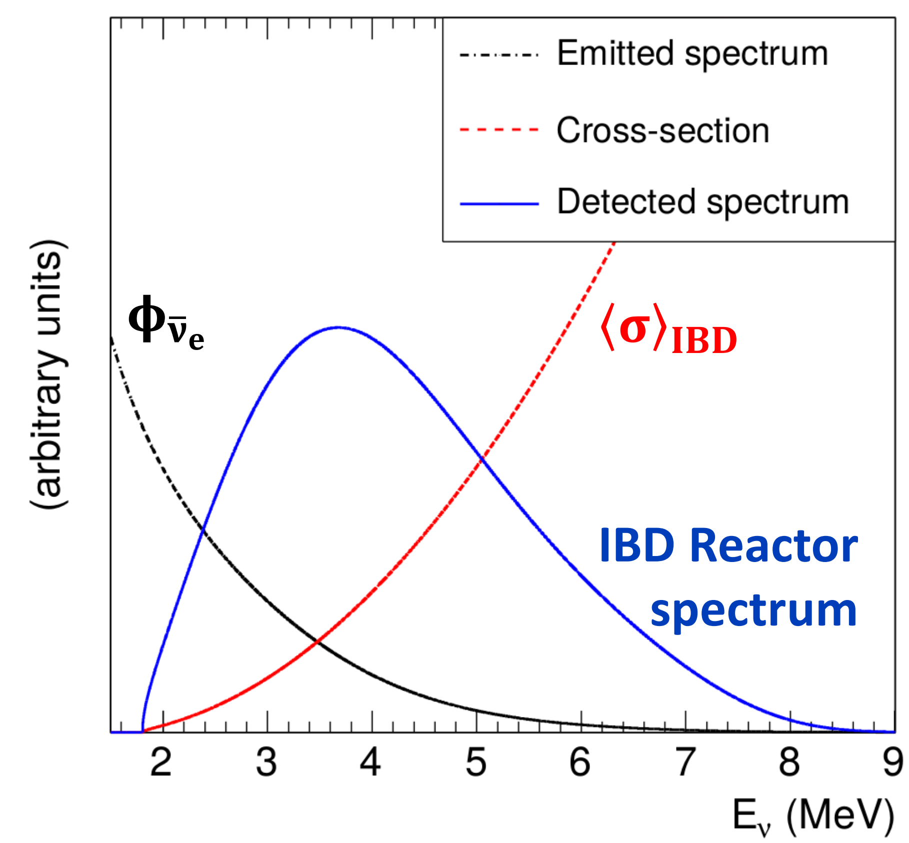


Inverse beta decay reaction (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Energie threshold: 1.8 MeV
$\langle\sigma\rangle \sim 10^{-43}\,\mathrm{cm}^2$

[Phys. Rev. C 83, 054615]



$\bar{\nu}_e$ signature: spatial and temporal correlation between a prompt and a delayed signal

- Prompt signal: ionisation induced by positron + annihilation γ's

$$\Rightarrow \mathrm{E_{vis}} = \mathrm{E}_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$$

- Delayed signal: γ's from neutron capture on nuclei with high crossection

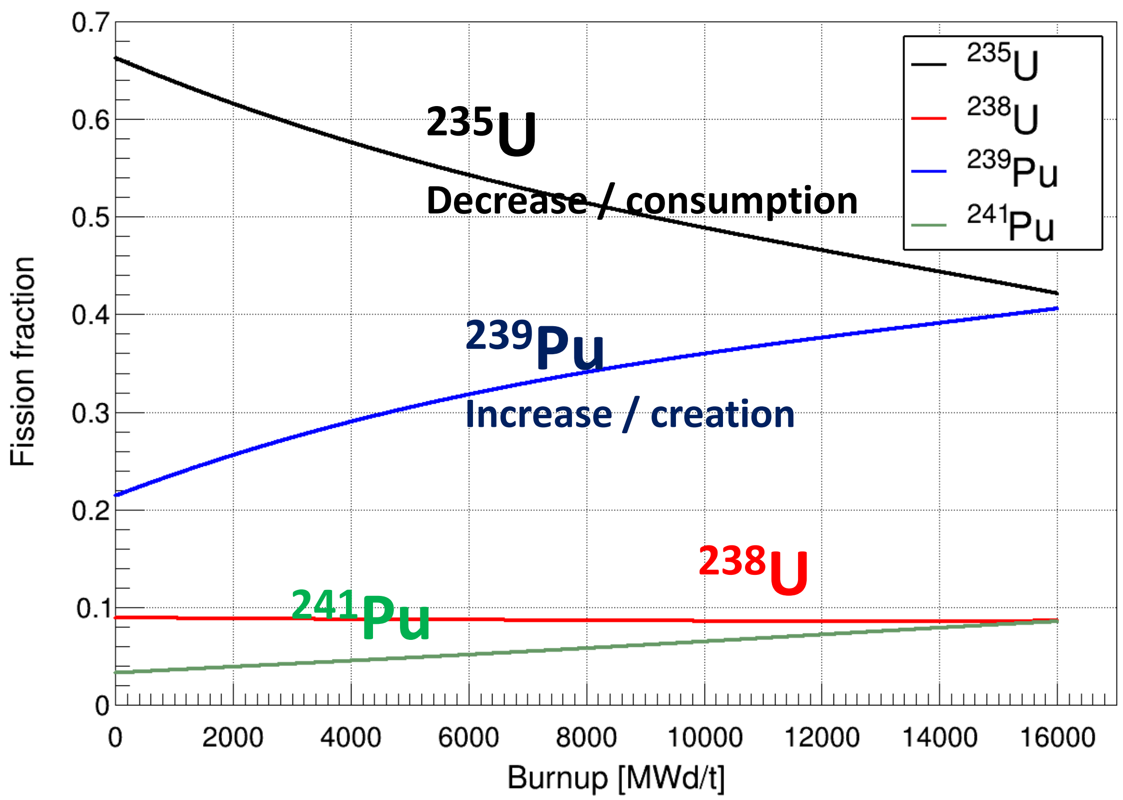
liquid scintillator doped or not with gadolinium
- Gd: 8 MeV / $\tau \sim$ 30µs
- H: 2.2 MeV / $\tau \sim$ 200µs

Expected detector neutrino rate:

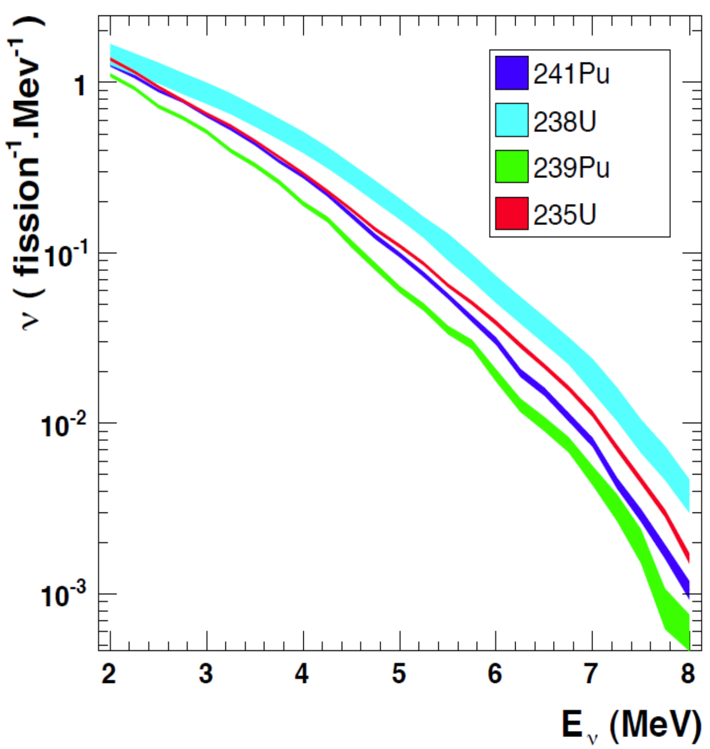
- $N_{\nu}^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle(t)} \times \langle \sigma_f \rangle(t)$
- $\langle \sigma_f \rangle = \int_0^x dE\, \alpha_k S_k(E)\, \sigma_{IBD}(E)$

Antineutrino spectra

- $k = {}^{235}U, {}^{239}Pu, {}^{238}U, {}^{241}Pu$
- Fission fraction: $\alpha_k = FR_k / \sum_k FR_k$
- Mean energy released per fission: $\langle E_f \rangle = \sum_k \alpha_k E_{f,k}$
- Thermal power: $P_{th,r}$
- Distance, proton number and efficiency: L_r, N_p, ϵ



Typical fission rates evolution over a full PWR cycle



Reference anti-neutrinos spectra

⇒ Rate and shape modification of the $IBD_{\bar{\nu}_e}$ spectrum expected with fuel burnup

normalization error (using reference $\bar{\nu}_e$)
$d\phi_{\bar{\nu}_e}/\phi_{\bar{\nu}_e} \sim 2.4\%$

Antineutrino spectra calculation

Spectra from summation / ab-initio method

Relies on nuclear database to build up the total β^-spectrum of a fissionable isotope k.

- $S_{\beta,k}(E) = \sum_p A_p \times S_{\beta,p}(E)$

  - p: fission product of the isotope k
  - A_p: activity of fission product p
  - $S_{\beta,p}$: total beta spectrum of the fission product p

- $S_{\beta,p}(E) = \sum_{b=1}^{N_b} Br_p^b \times S_{\beta,p}^b(Z_f, A_f, E_{0,p}^b, E)$

  - b: β branch between the fondamental & the exited state of the daughter
  - Br_p^b and $E_{0,p}^b$: branching ratio / end point of the branch b of nuclei p

- $S_{\beta,p}^b\left(Z_f, A_f, E_{0,p}^b, E\right) = K_p^b \times F(Z_f, A_f, E) \times pE\left(E - E_{0,p}^b\right)^2 \times C_p^b \times (1 - \delta\left(Z_f, A_f, E\right))$

Normalization factor — Fermi fonction — Space phase — Forme factor — Corrective term (finite size, radiative correction, screening)

- Energy conservation: $E_{\bar{\nu}_e} = E_{0,p}^b - E$

Pros	Cons
• $\bar{\nu}_e$ spectrum predictable for all fissionable isotopes ↳ futur reactor • Full $\bar{\nu}_e$ energy range • Suitable for perturbative study (ex: off-equilibrium)	• Important amount of nuclear data: fission yield, branching ratio, associated End point • Very sensitive to missing data and bias one!

⇒ ≈10% uncertainty usually considered for $\bar{\nu}_e$ predicted by summation method

Antineutrino spectra calculation

Spectra from conversion method

Relie on the experimental measurement of the total β fission spectrum and its conversion into a neutrino one.

↳ β spectrum approximate as a superimposition of a set of virtual decay branches i of amplitude a_i and maximal energie E_0^i:

- $S_{\beta,k}(E) = \sum_i a_i \times S_{\beta,k}^i(\bar{Z}(E_0^i), E_0^i, E)$
- $S_{\bar{\nu}_e,k}(E_{\bar{\nu}_e}) = \sum_i a_i \times S_{\beta,k}^i(\bar{Z}(E_0^i), E_0^i, E_0^i - E_{\bar{\nu}_e})$

$S_{\beta,k}^i$: energy spectrum of virtual branch i
$\bar{Z}(E_0^i)$: mean charge of decaying nuclei with maximal energy E_0^i

⇒ Mesure spectrum fitted with parameterized function of a set of $\{a_i , E_0^i\}$ constituting the virtual branches

↳ $\boldsymbol{\beta}$ spectrum reproduce at ~1% level with best fit model

Integral $\boldsymbol{\beta}$ spectrum measurement

^{235}U, ^{239}Pu, ^{241}Pu: « Schreckenbach et al. »: ILL measurement (Grenoble) in the 80'

↳ thermal neutrons flux
↳ irradition from 12 to 48 h.

Normalisation error: $\boldsymbol{\sim 1.8\%\ (1\sigma)}$

^{238}U: « N. Haag et al. » FRM-II measurement (Garching) measurement in 2013.

↳ fast neutron flux
↳ irradition from 11 to 42h.
↳ spectrum normalized to previous ILL measurement

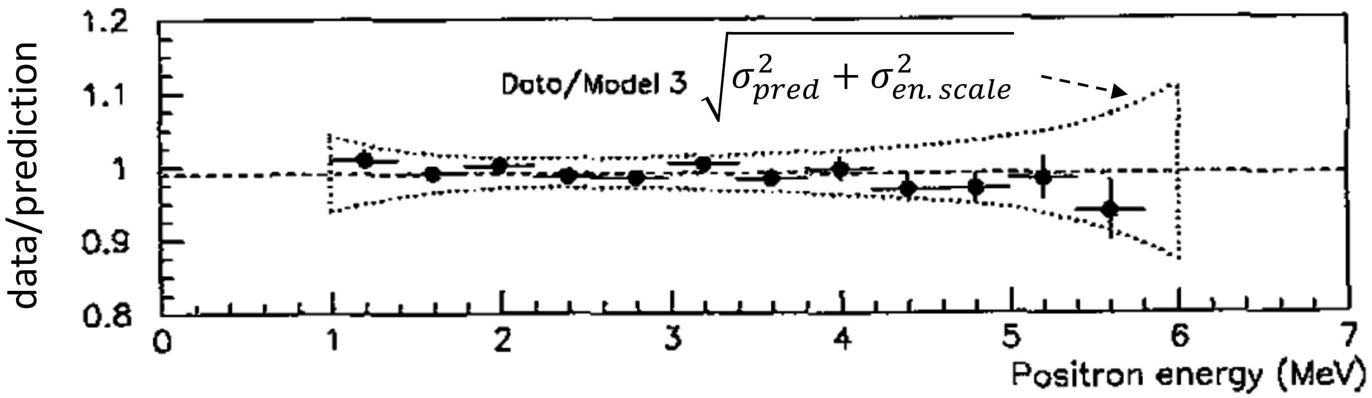
Normalisation error: $\boldsymbol{\sim 2.1\%\ (1\sigma)}$

Reference spectra up to 2011:

- ^{235}U, ^{239}Pu, ^{241}Pu: convertion (Schrekenbach – ILL)
- $^{238}U \Rightarrow$ summation calculation (Vogel)

⇒ **Good agreement between Bugey-3 and prediction**

[Phys.Let. B 374 (1996) 243-248]



2 major review of $\overline{\nu}_e$ calculation in 2011

- [T. Mueller et al., Phys.Rev. C84 (2011) 024617]
  [P. Huber, Phys.Rev. C84 (2011) 024617]

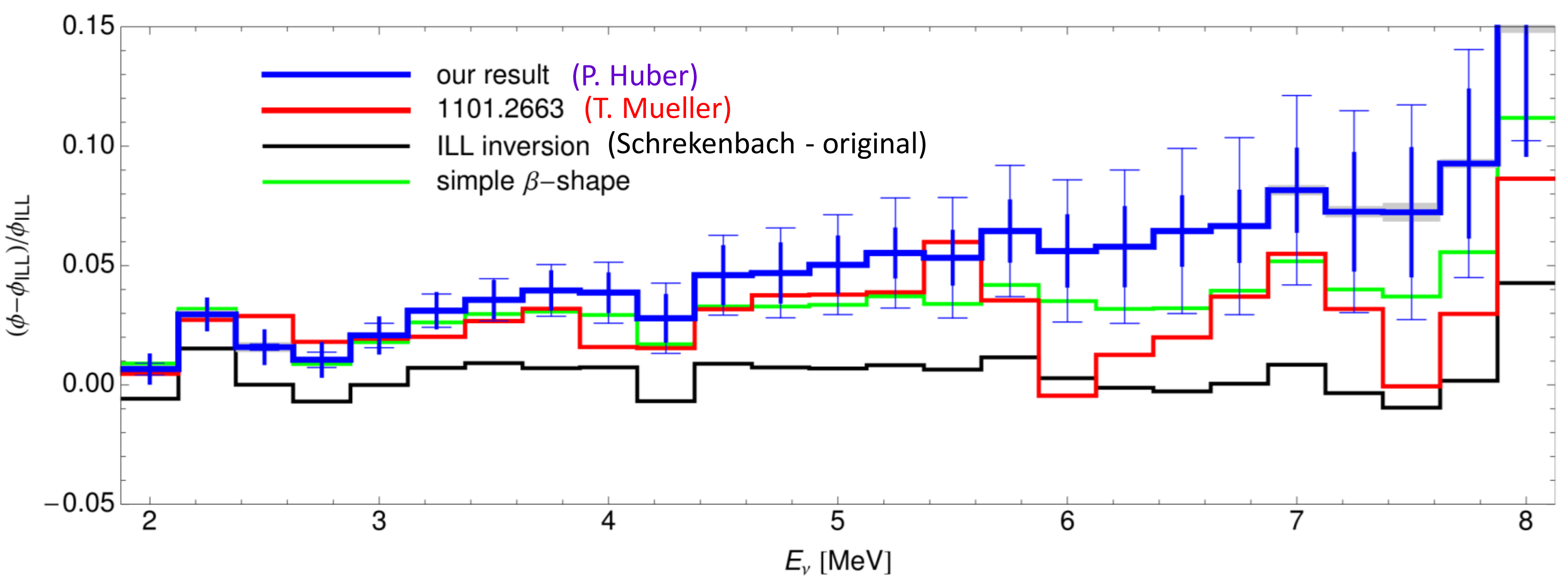
⇒ Review of ILL original convertion calculation for ^{235}U, ^{239}Pu, ^{241}Pu with different approaches

+ ab-initio ^{238}U calculation / off-equilibrium calculation for T. Mueller et al. paper

⇒ **Both agree on new global normalization +3% shift**

⇒ **Also global agreement on new error calculation**

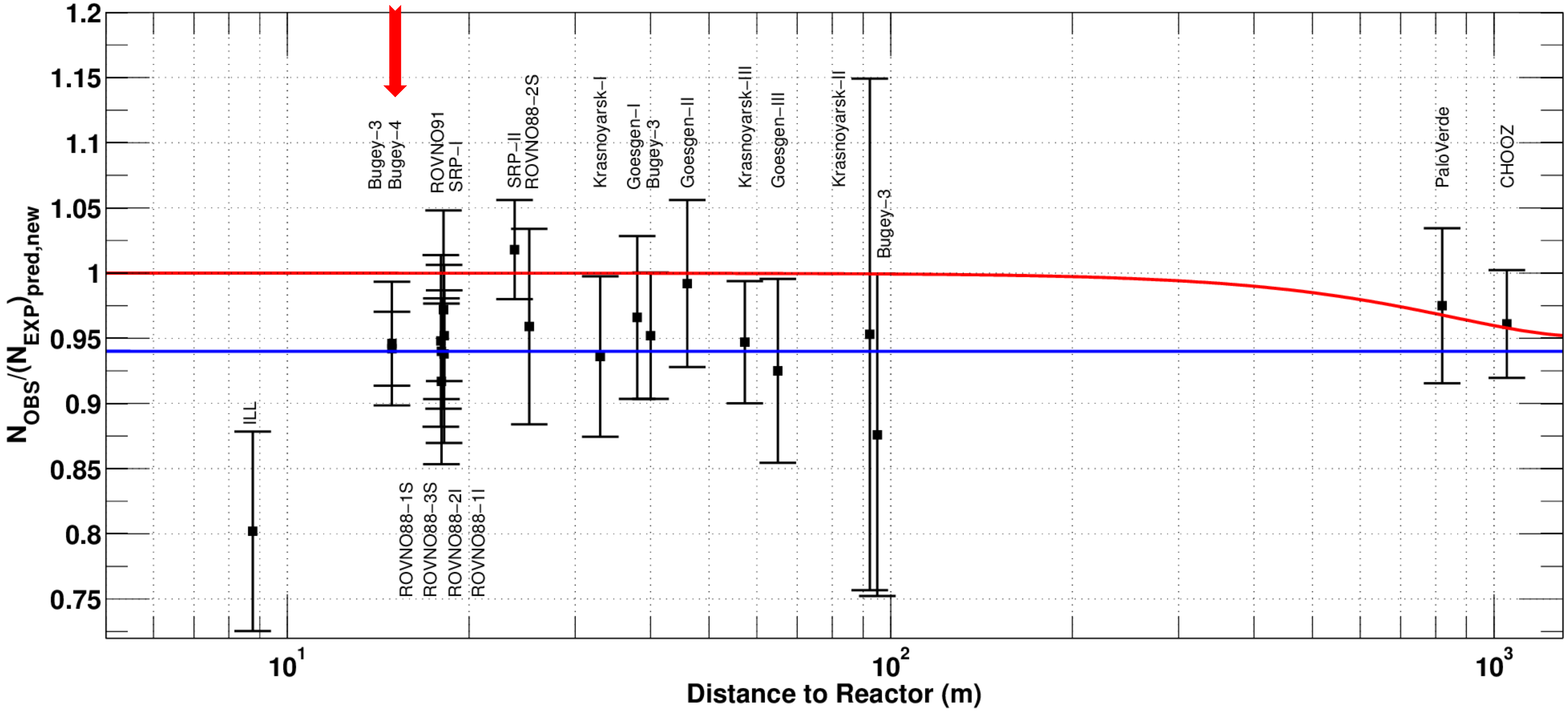
Normalisation error (conversion): $\sim 2/3\%$



Reactor anomaly

Bugey-4 : L ~ 15 m

World reference: $\sigma = 1.4\%$



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

« old evaluation (Schrekenback/Vogel) " of $\bar{\nu}_e$ spectra : N_{obs}/N_{pred} = 0.976 ± 0.024 (1σ)

« new evaluation (Mueller et al.)" of $\bar{\nu}_e$ spectra : N_{obs}/N_{pred} = 0.943 ± 0.023 (1σ)

~6% difference between data and expectation

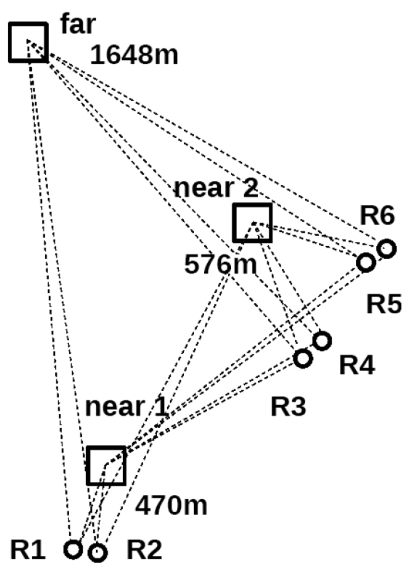
Main Hypothesis: - Underestimation of $\bar{\nu}_e$ spectra uncertainties

- Existence of sterile neutrino with $\Delta m^2 \sim 1\,\text{eV}^2$ et $\theta_{new} \sim 10°$

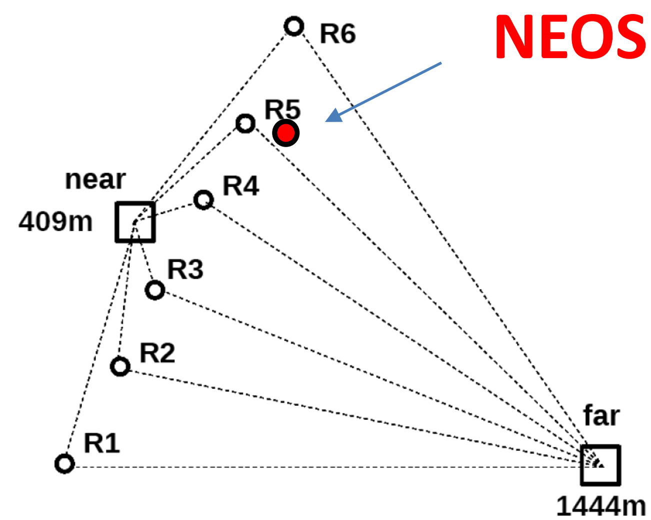
2. Reactor flux and shape measurements

Reactor experiments

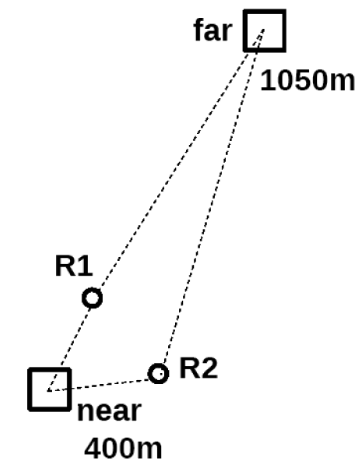
Daya Bay (China)	**RENO** (South Korea)	**Double Chooz** (France)



4 far detectors (1 site)
4 near detectors (2 sites)



1 far detector
1 near detector



1 far detector
1 near detector

	N_{det}	$M_{\nu\text{-target}}$ [ton]	Blindage near/far [mwe]	Reactors [GW_{th}]	Total power [GW_{th}]
Daya-Bay	8	~20	250-265/860	6×2.9	17.4
Double Chooz	2	~8	120/300	2×4.25	8.5
RENO	2	~16	120/450	6×2.8	16.8

+ NEOS experiment: ~1t IBD detector 24@m of 2.8GW

DB, DC and RENO designed for θ_{13} measurement (suppressed correlated uncertainty in near/far comparison)
↳ But…. all achieve : - high statistic with near detector(s)
- small detection systematics
- precise background measurement

⇒ suitable for precise measurement of reactor $\bar{\nu}_e$ rate and shape

Detector design

Multi-layers structure

- Center: Gd doped liquid scintillator
- Intermediate: liquid scintillator (not NEOS)
- Outer: Mineral oil /PMT support

Calibration

- **Light injection system**

  multi-wavelength LED

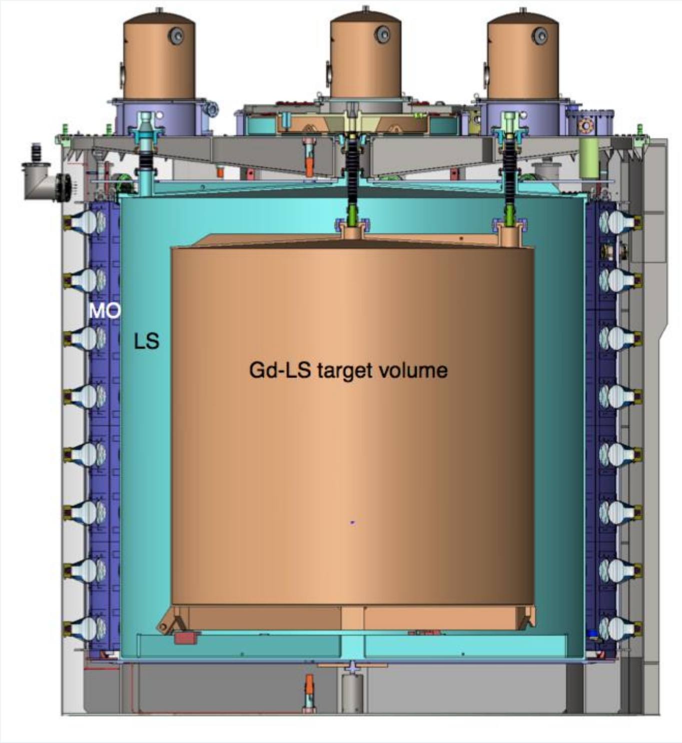
- **Radioactive sources**
  - γ-sources: ^{68}Ge, ^{37}Cs, ^{60}Co
  - n-source: ^{252}Cf

- **Natural sources**

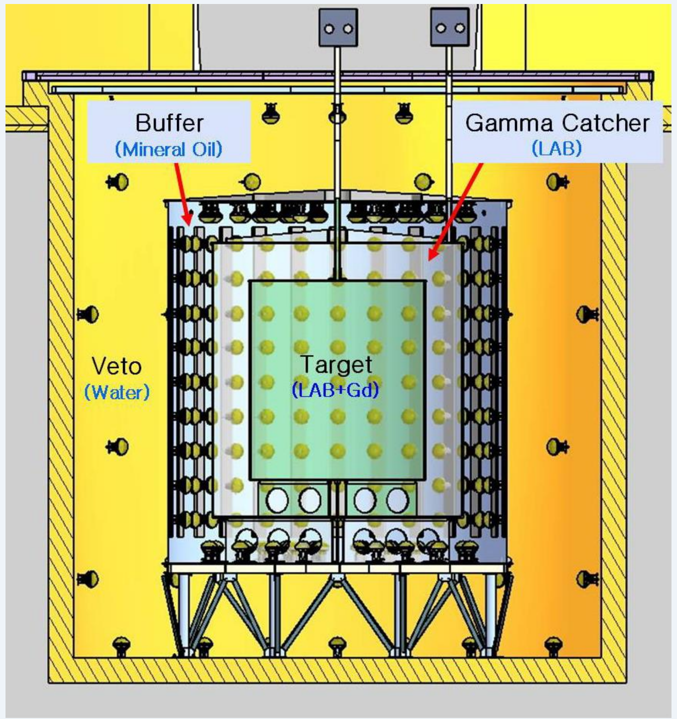
  spallation neutrons capture on Gd, H, C

⇒ 2 main non linearity corrected from calibration:
- light non linearity (liquid)
- charge non linearity (electronic)

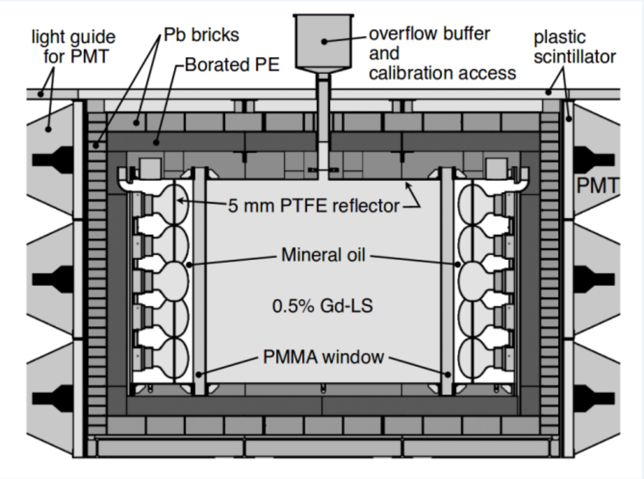
Daya Bay



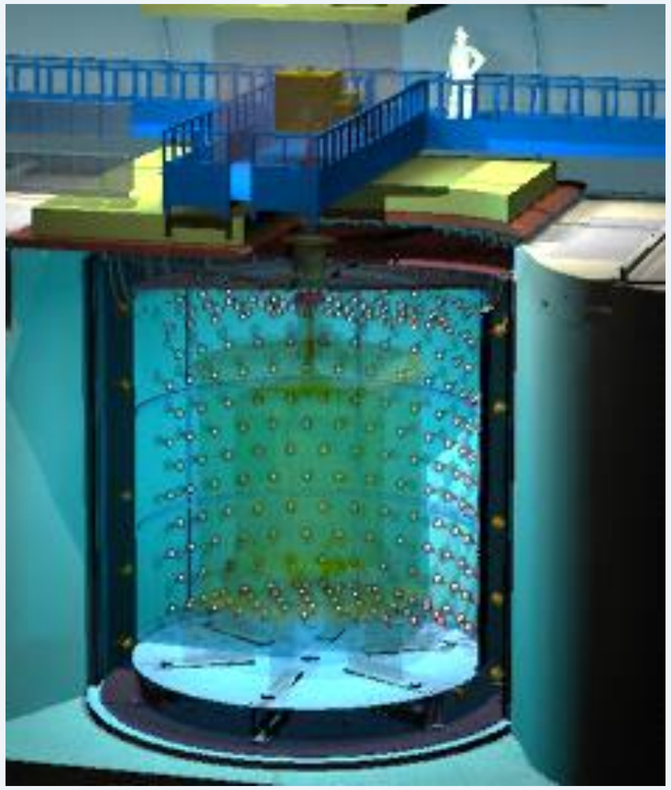
RENO



NEOS



Double Chooz



Mean reactor IBD cross section per fission measurements

Daya Bay:

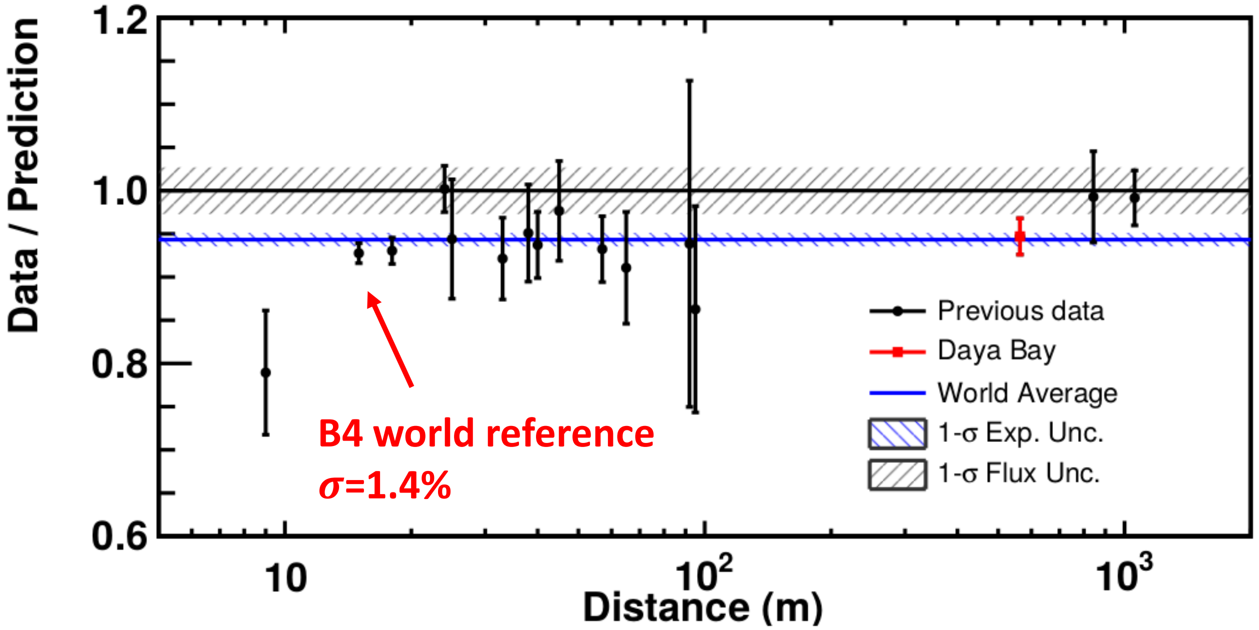
- DB alone (@~580m):

$$\begin{cases} R_{data/pred} = 0.946 \pm 0.020 \text{ (Huber+ Mueller)} \\ R_{data/pred} = 0.992 \pm 0.021 \text{ (ILL+Vogel)} \end{cases}$$

- Global average:

$$\begin{cases} R_{data/pred}\ (w/o\ DB) = 0.942\ \pm\ 0.009\ (\text{exp.}) \\ R_{data/pred}(w/\ DB) = 0.943\ \pm\ 0.008\ (\text{exp.})\ \pm\ 0.023\ (model) \end{cases}$$

[Chinese Physics C, 2017, 41(1): 13002-013002]



⇒ Mean cross section per fission: $\langle\sigma_f\rangle^{DB} = (5.91 \pm 0.12).10^{-43}\ cm^{-2}.fission$ (2.1% @1σ)

RENO:

- Absolute rate measurement: not reported yet
- $R_{data/pred} = 0.946 \pm 0.21$ **(Huber+ Mueller)** @411 m
  (Preliminary - conference report @Neutrino2016)

NEOS:

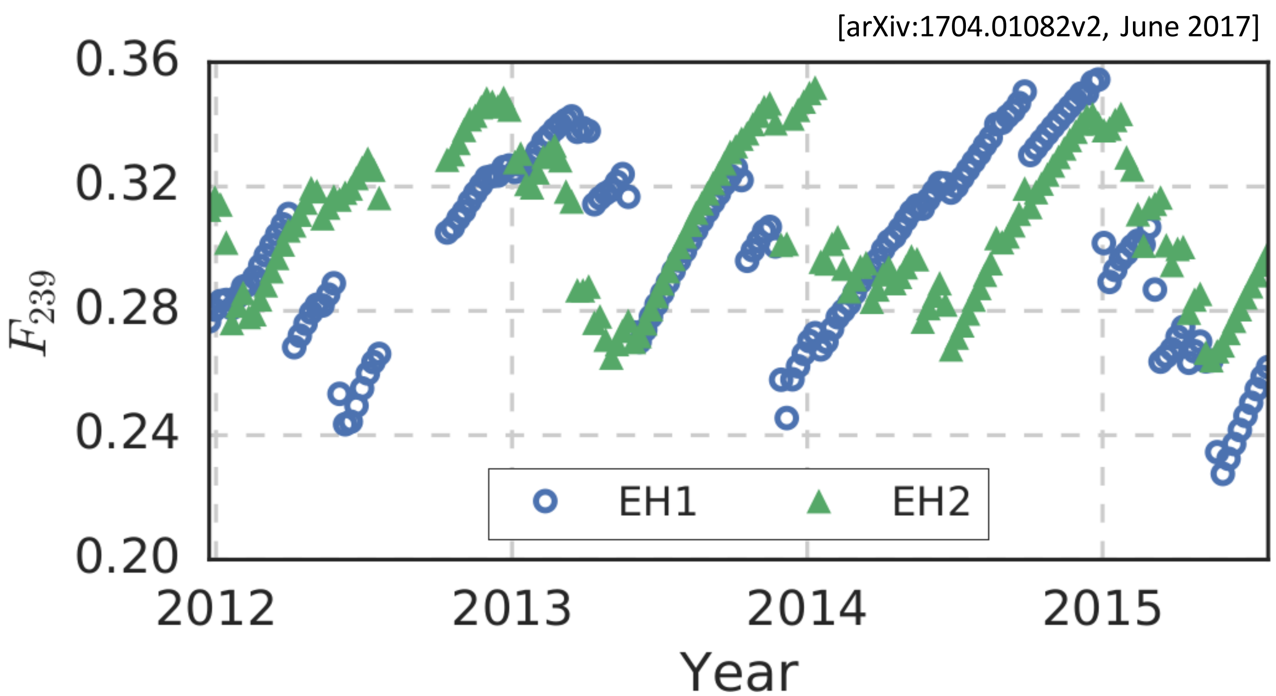
- Absolute rate measurement: not reported yet
- Ratio data/prediction: not reported yet

DC:

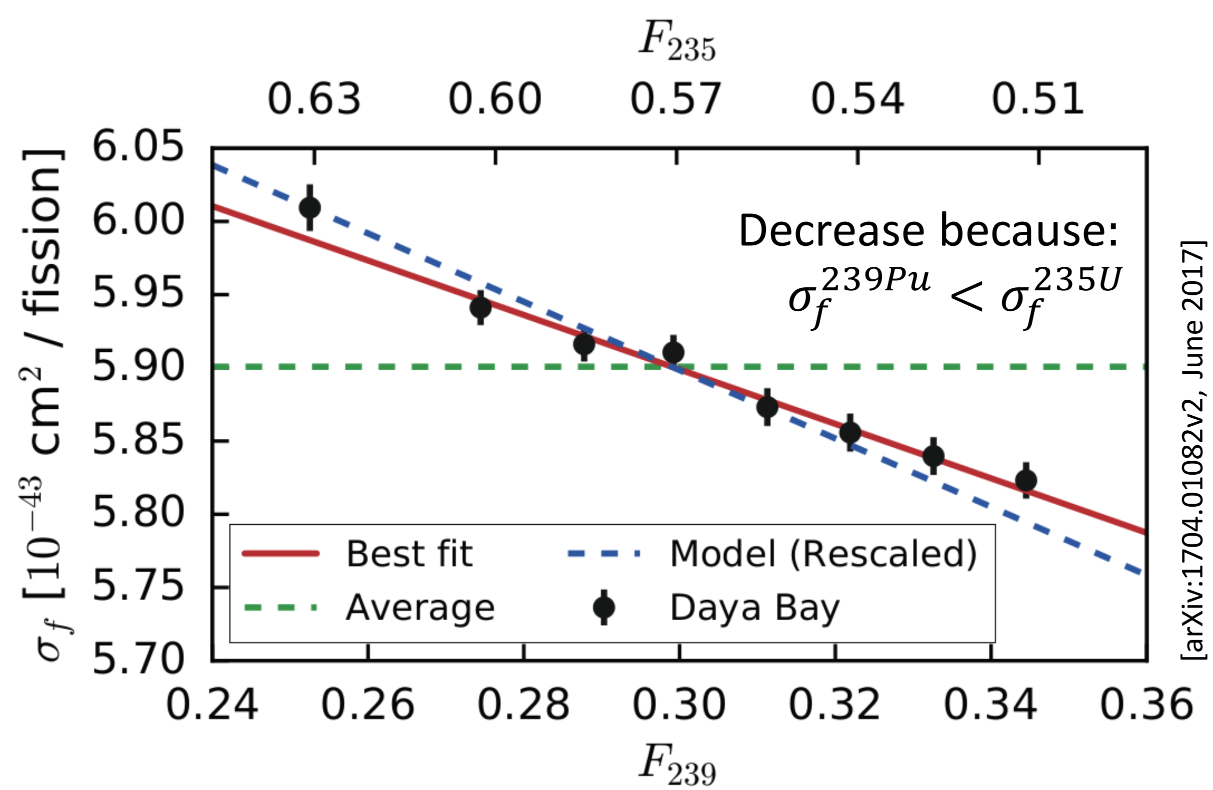
- **Mean cross section per fission: $\langle\sigma_f\rangle^{DC} = (5.64 \pm 0.06).10^{-43}\ cm^{-2}.fission$ (1.1% @1σ)**
  (Preliminary - seminar report @Cern 2016)
- Ratio data/prediction: not reported yet

Reactor $\bar{\nu}_e$ rate measurements

Mean reactor IBD cross section per fission measurements & fuel evolution in Daya Bay (2.2 M events)



(top) Effective fission fraction of ^{239}Pu in DB near sites EH1 and EH2

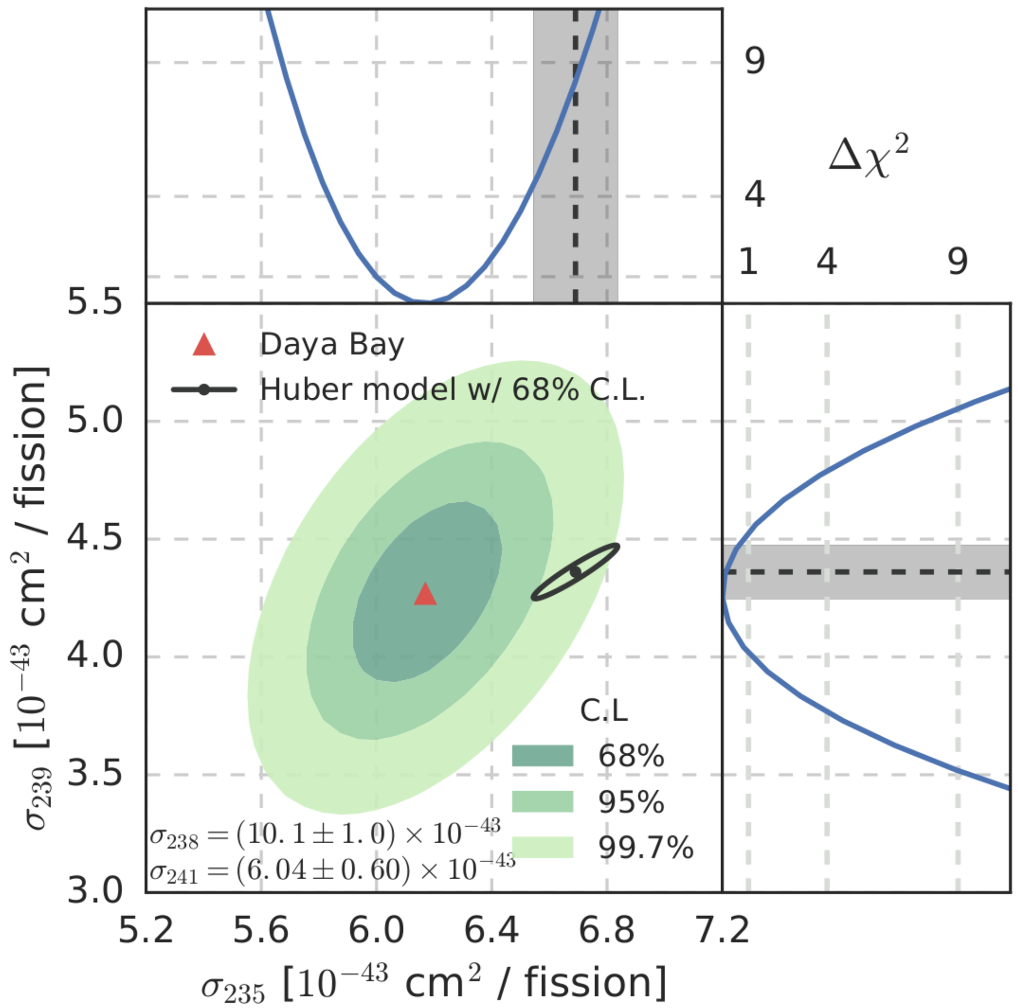


Mean cross-section per fission respect to the ^{239}Pu fission fraction

DB measured fuel evolution !

- $\frac{d\langle\sigma_f\rangle^{DB}}{dF_{239}} = (-1.86 \pm 0.18).\mathrm{cm}^{-2}.\mathbf{fission\ with}\ \chi^2/NDF = 3.5/6$
- **Predicted $\frac{d\langle\sigma_f\rangle}{dF_{239}}$ (H+M) differ from measurement by 3.1σ $\Rightarrow$ new tension model/data**

New Daya Bay results and the reactor anomaly



[arXiv:1704.01082v2, June 2017]

@580m:

- $\langle\sigma_f\rangle^{DB}_{235U} = (6.17 \pm 0.17).10^{-43}\ cm^{-2}.fission$
  ⇒7.8% lower than H+M model
- $\langle\sigma_f\rangle^{DB}_{239Pu} = (4.27 \pm 0.26).10^{-43}\ cm^{-2}.fission$
  ⇒consistent with H+M model

⇒ Indication of a preference for an incorrect prediction of the ^{235}U flux as the primary source of the reactor anomaly

[A. Hayes & al. arxiv:1707.07728, Jul 2017]: DB reanalysis using spectra from summation method
[The present analysis suggests that there is currently insufficient evidence to draw any conclusions on this issue. As we have shown, an analysis based on the summation method explains all of the features seen in the evolution data…]

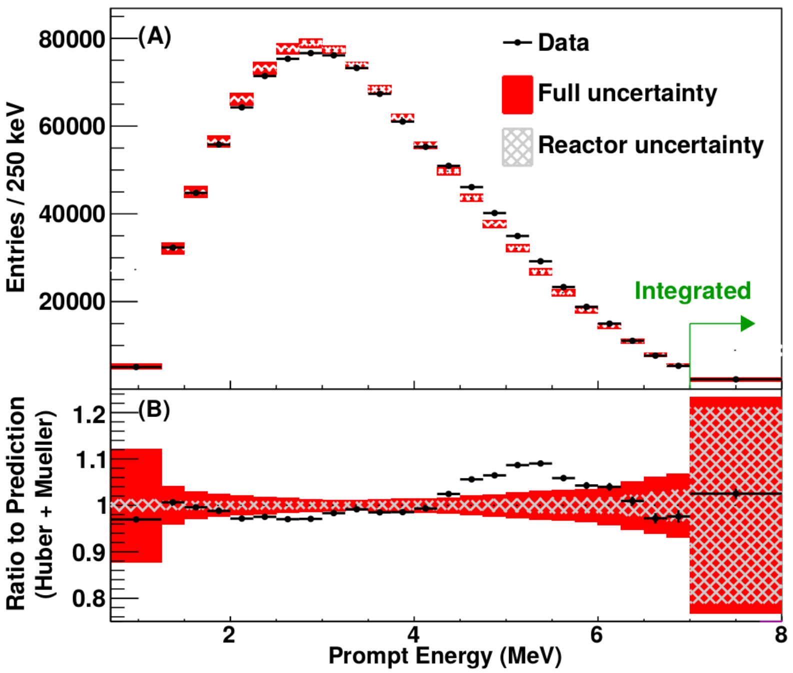
[C. Guinti & al. arxiv:1708.01133v1 aug 2017]: DB reanalysis using sterile hypothesis and combination with previous experiment

⇒ No disagreement with DB conclusion but other scenario are flavor when analysis only past experiment combining past and new DB results ⇒ **BUT all low significance!**

Reactor $\bar{\nu}_e$ shape measurement

Daya Bay

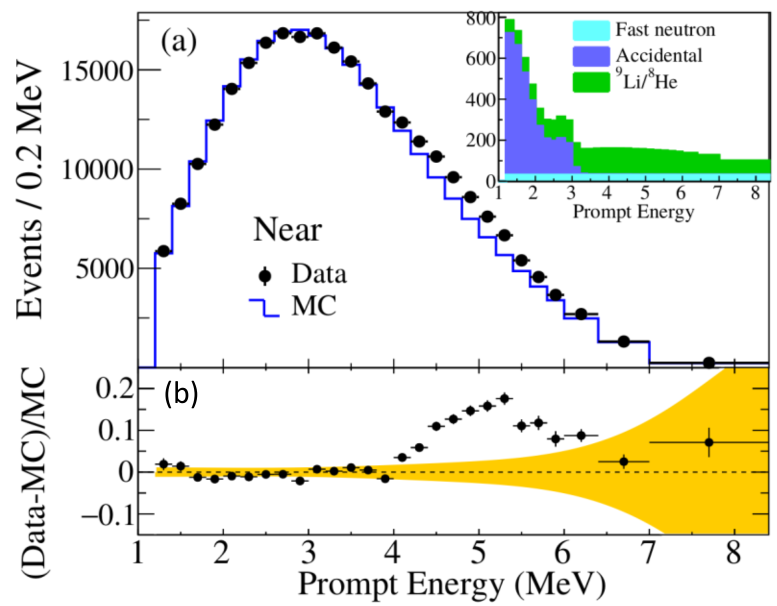
[arXiv:1610.04802v1 / 1230 days]



(b) Ratio of the near's data to the oscillated flux prediction (HM)

RENO

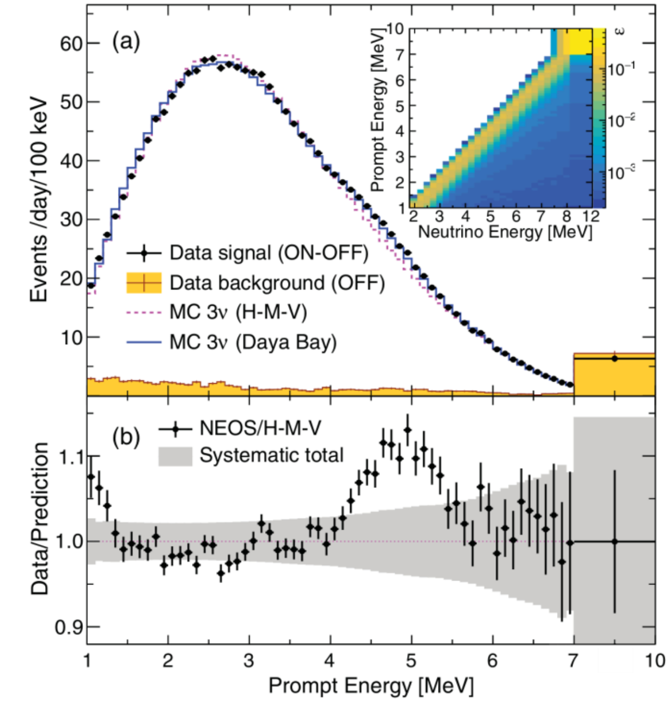
[Phys. Rev. Lett. 116, 211801 / 500 days]



(b) Relative discrepency between the near data to the oscillated flux prediction (HM)

NEOS

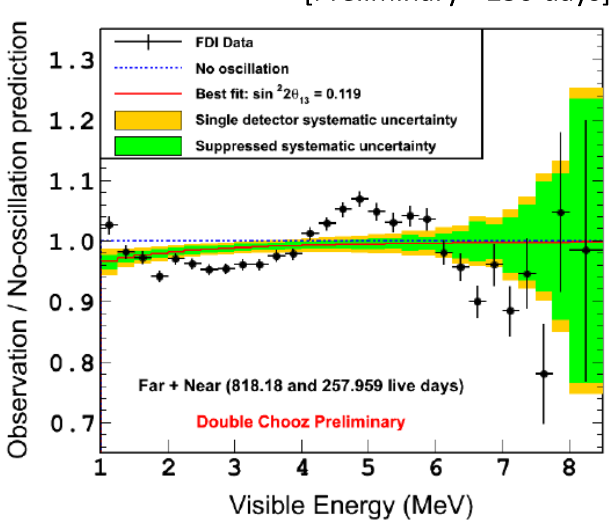
[Phys. Rev. Lett. 118, 121802 (2017) / 180 days]



(b) Ratio of the near data to the flux prediction (Huber + Haag)

Double Chooz

[Preliminary - 250 days]

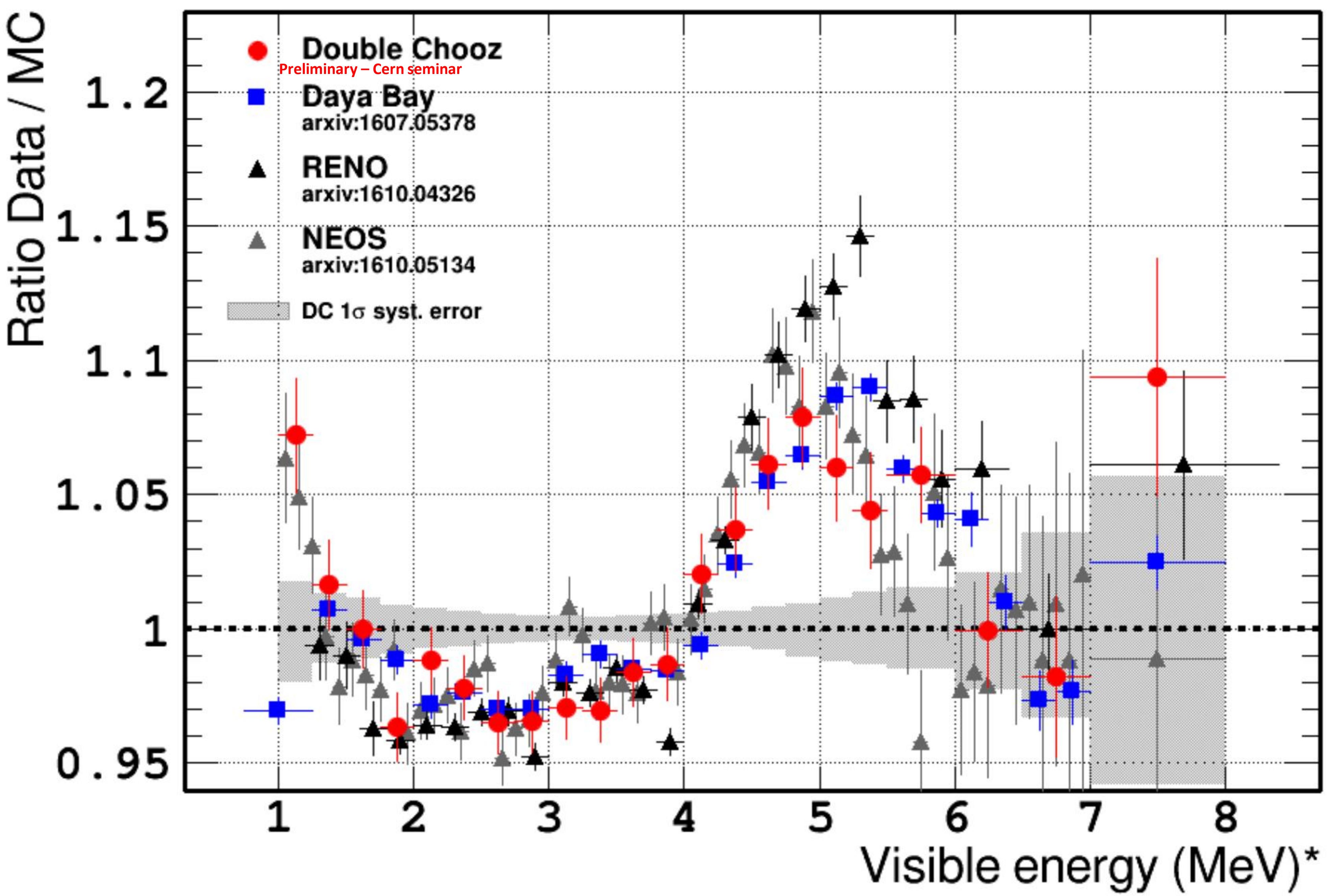


(b) Ratio of the near data to the unoscillated flux prediction (Huber + Haag)

⇒ **DC/DB/RENO: compatibility between near and far data are within the θ_{13} induced oscillation**

⇒ **All experiments exhibit a distortion when compared to the MC flux prediction**

data vs spectra from summation method



* can slightly differ from one experiment to another due to detector effects

DC: 210 000 events
DB: 1.2 million events
Reno: 280 000 events
NEOS: not provided

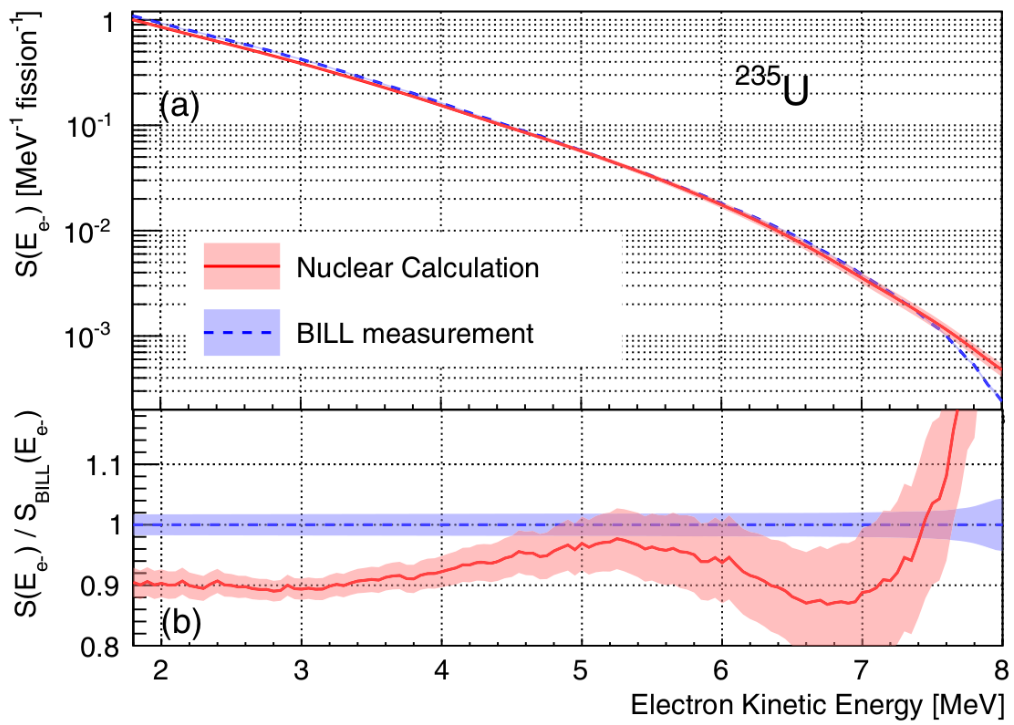
- Normalized ratio: only shape distortion
- Reference $\bar{\nu}_e$ spectra: - ^{235}U, ^{239,241}Pu: P. Huber
  - ^{238}U: Mueller et al. (Day Bay/RENO/NEOS), Haag (DC)

  ↳ Maximal effect: $\leq$ 2% in the range [1, 7] MeV

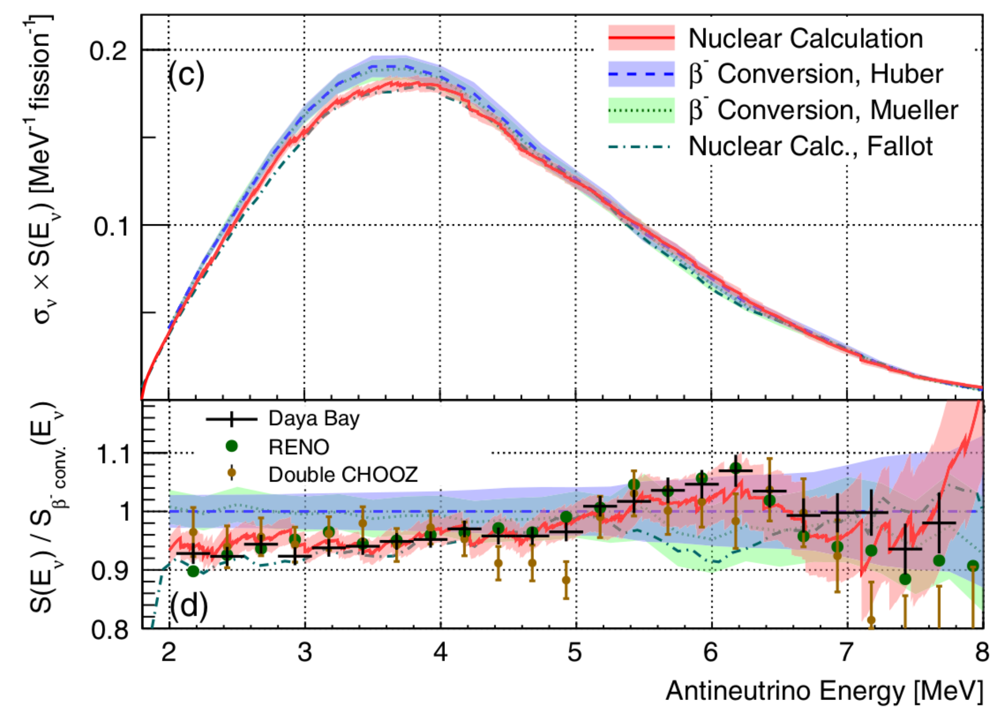
The shape distortion

(1) data vs spectra from ab-initio method

[D.A. Dwyer, T.J. Langford, PhysRevLett.114.012502 (jan 2015)]

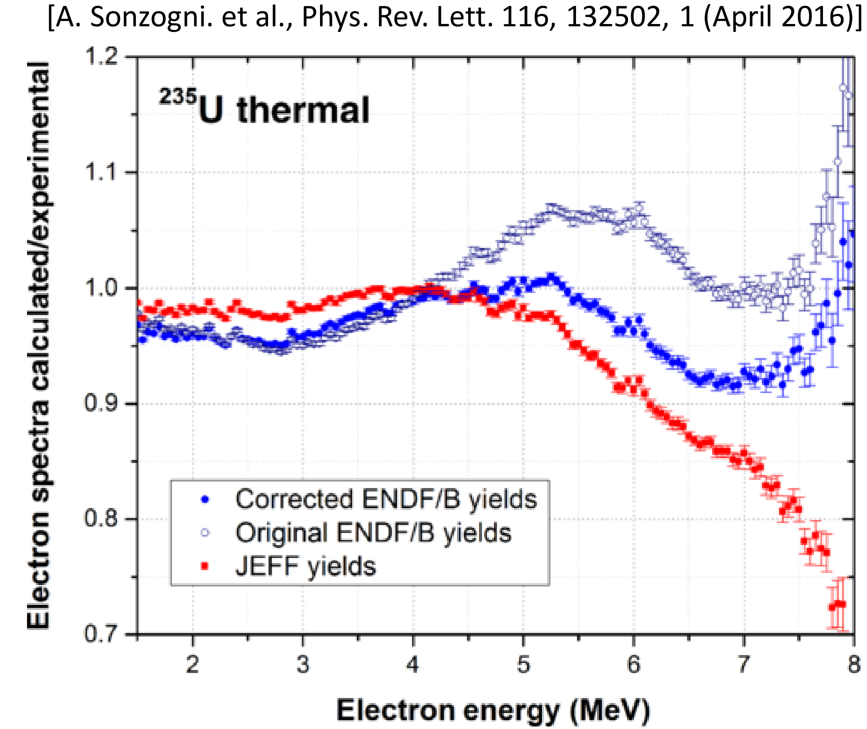


[D.A. Dwyer, T.J. Langford PhysRevLett.114.012502 (jan 2015)]



- Spectra from ab-initio method differ significantly when generated using fission yieds of JEFF-3.1.1 or ENDF/B-VII.1 (see also Hayes et al. PRD92, 033015 (2015))
- ENDF/B-VII.1 $\Rightarrow$ shoulder in the 4-6 MeV region

[A. Sonzogni. et al., Phys. Rev. Lett. 116, 132502, 1 (April 2016)]



2016….

- **Erroneous yields of ^{86}Ge** and all of its daughters for ^{235}U fission yield discover in ENDF/B-VII.1: strong effect in 5-7 MeV region

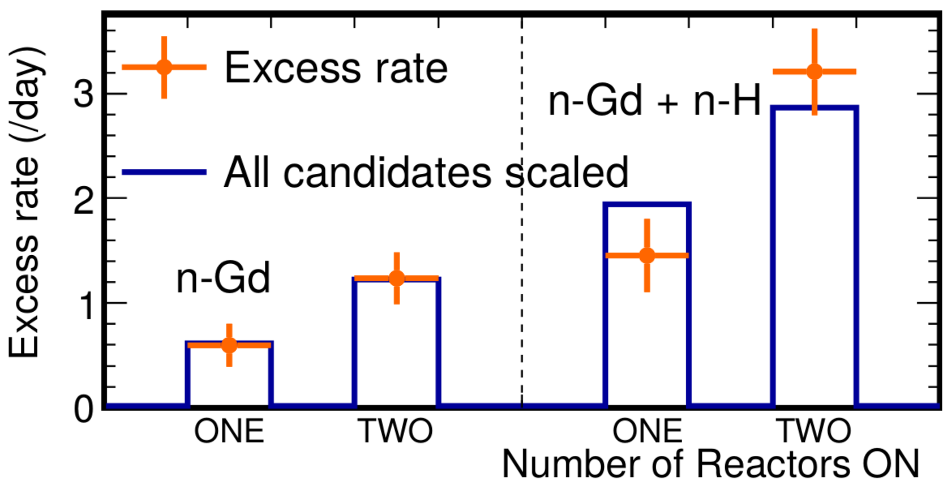
After this (and other) corrections: closer agreement between β and $\bar{\nu}_e$ spectrum generated with ENDF/B-VII.1 orJEFF-3.1.1
↳ 6% agreement over whole spectrum

The shape distortion

(2) Unknown background / $\bar{\nu}_e$ source?

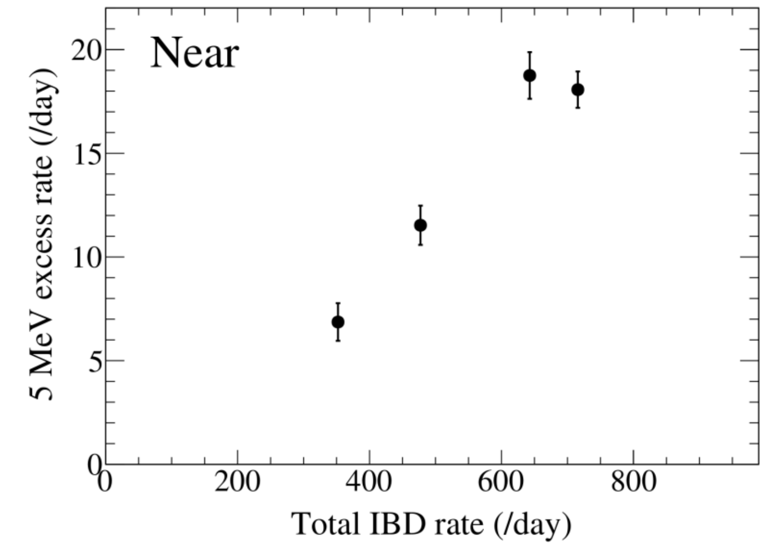
Double Chooz @Far detector

[Phys. Rev. Lett. 116, 211801]



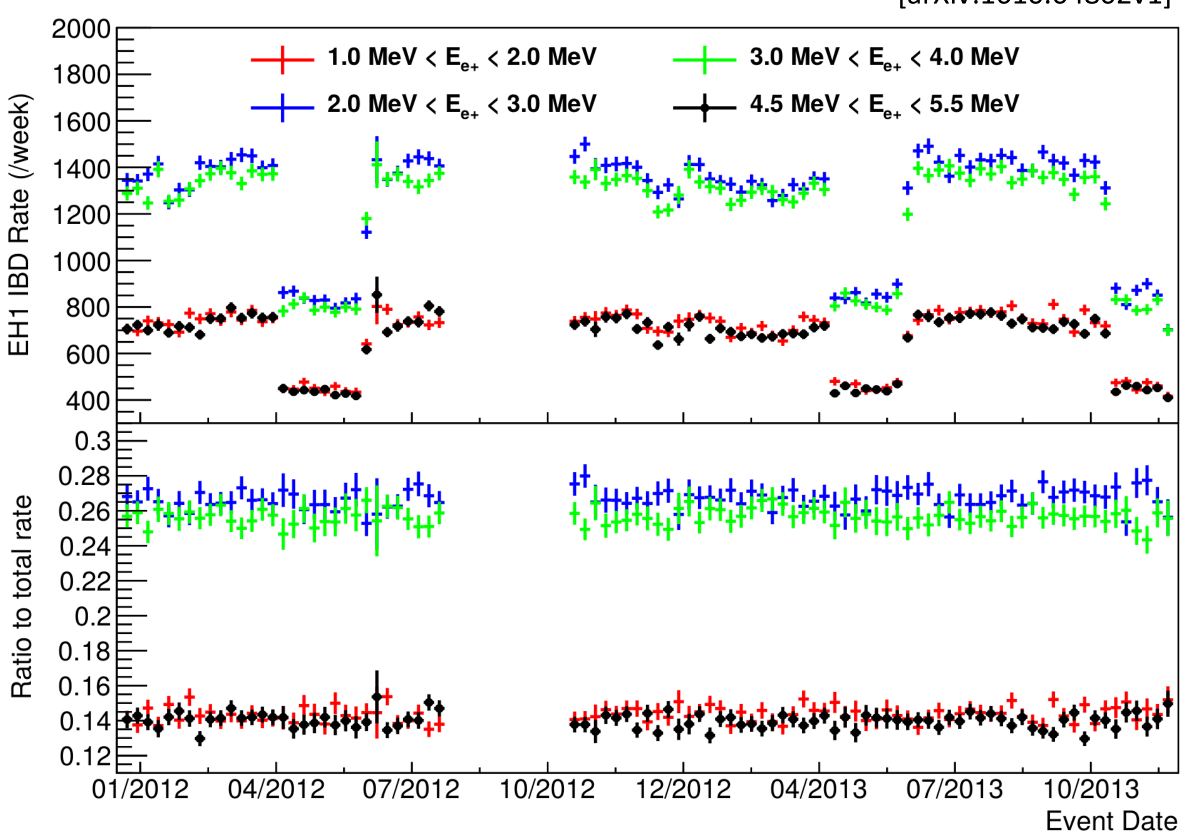
RENO @Near detector

[Phys. Rev. Lett. 116, 211801]



Daya Bay @Near detectors

[arXiv:1610.04802v1]



Excess @5 MeV correlated with the expected number of events for all the three reactor experiments

⇒ **Excess is not an unknown background**

Antineutrinos produce by non-fission sources of antineutrinos in the reactor?

...excluded from MC study with MCNP

[A.Hayes2015 et al.]

The shape distortion

(3) Is there any isotope favored for the bump?

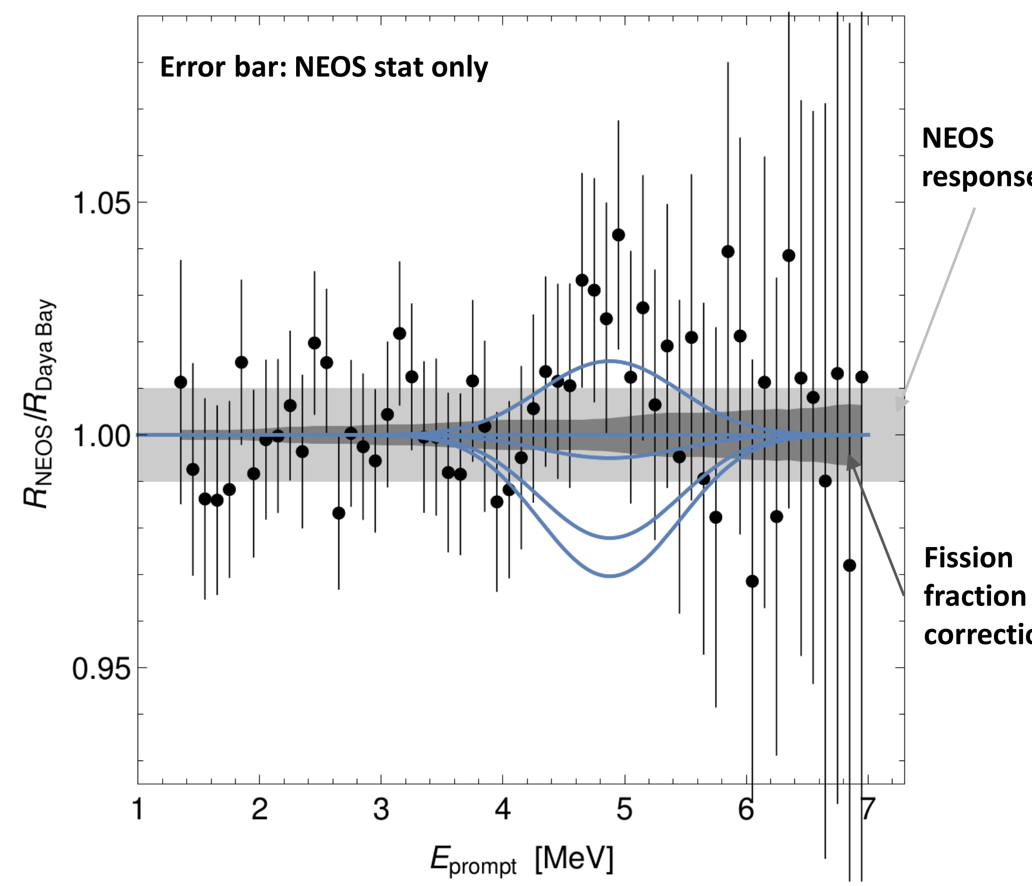
[P. Huber, 10.1103/PhysRevLett.118.042502 (jan 2017)]

P. Huber: Combined analysis of NEOS and Daya Bay data

Fit of the bump for five hypothesis (absolute flux left free):

- only in ^{235}U, only in ^{238}U, only in ^{239}Pu, only in ^{241}Pu, equal in the fourth

⇒ *Take advantage of double ratio analysis to cancel most of flux prediction uncertainties*



Points: Double ratio of NEOS and Daya Bay data to the H+M prediction (Correction for fission fraction are included)
Lines: fit results

Isotope	^{235}U	^{238}U	^{239}Pu	^{241}Pu	equal
$R_{\mathrm{NEOS}}/R_{\mathrm{DayaBay}}$	1.021	0.993	0.971	0.960	1.000
χ^2	46.9	51.6	60.3	66.0	49.9
σ	0.34	1.93	3.27	3.92	1.55

TABLE I. χ^2-values for the the bump being caused by a single isotope or in equal parts by all isotopes. The fit has 57-1 degrees of freedom and the χ^2-minimum is 46.7 and occurs at a value of the double ratio of 1.022.

Results

- **^{239}Pu & ^{241}Pu isotopes disfavored as sole source of the bump @ 3–4 standard deviations.**
- **Fit slightly prefers ^{235}U as the sole source for the bump**

⇒ With 4 more statistic @NEOS: ability to distinguish @3σ the sole ^{235}U hypothesis from the case of equal contributions

The shape distortion

(4) Approximation in the summation method calculation

A. Hayes talk @ν-Phys2016: Examined different ways of estimating the $\bar{Z}(E_0^i)$ of the fission product in the summation calculation

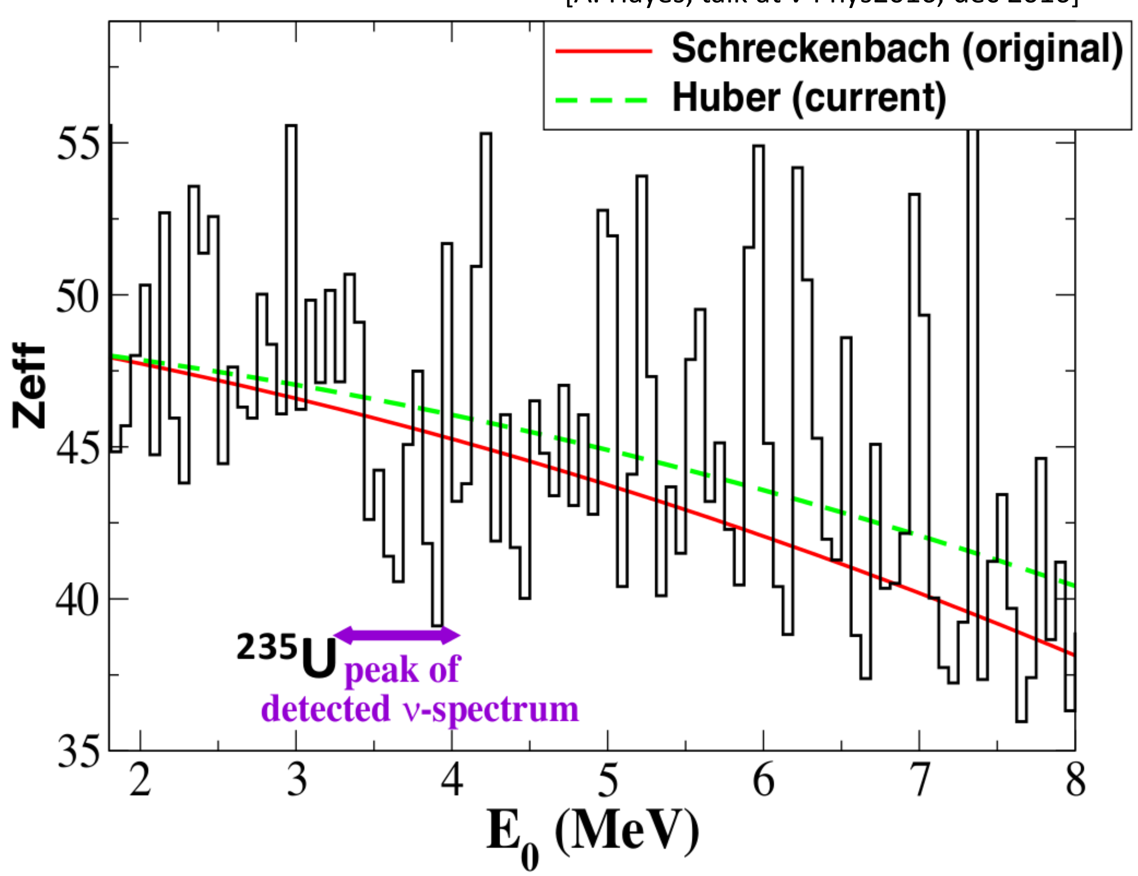
$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z_{eff}(E_0))(1+\ \delta)$$

- Huber's parameterization of Z_{eff} accounts for ~50% of the current « anomaly »

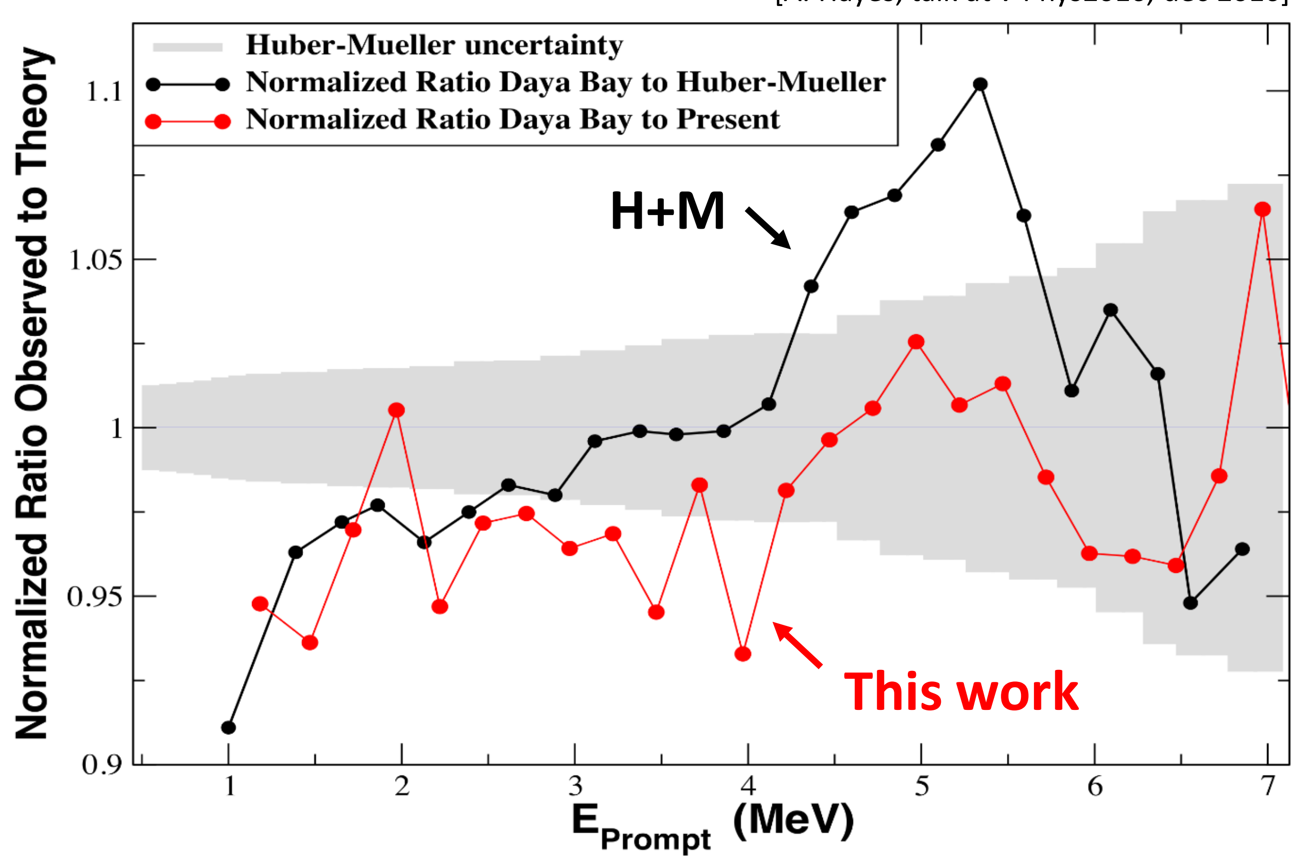
⇒ Instead of using a quadratic fitted function over the energy range, best Z_{eff} determined in each energy range

↳ Bump can be lower with a « better » description of the Z-effective

[A. Hayes, talk at ν-Phys2016, dec 2016]



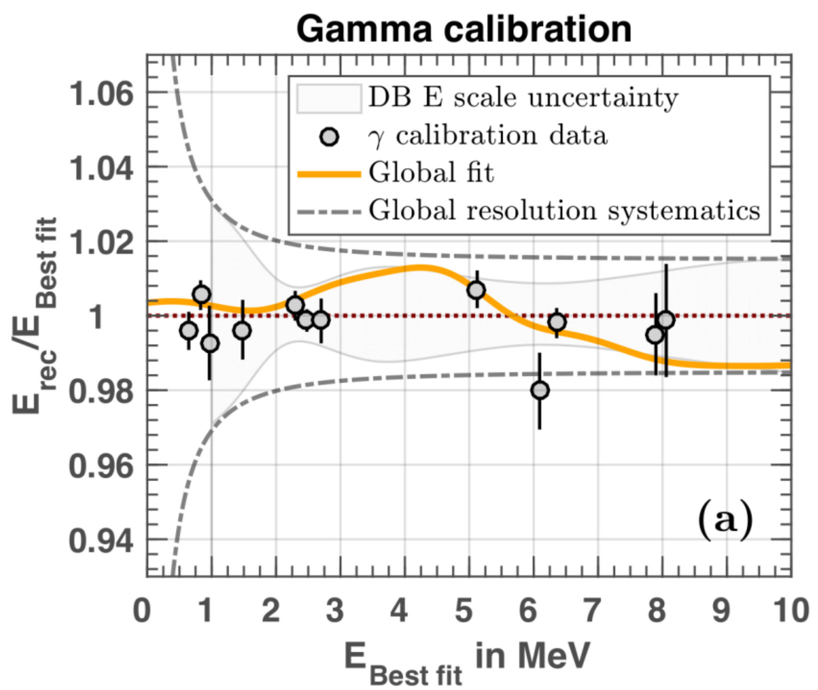
[A. Hayes, talk at ν-Phys2016, dec 2016]



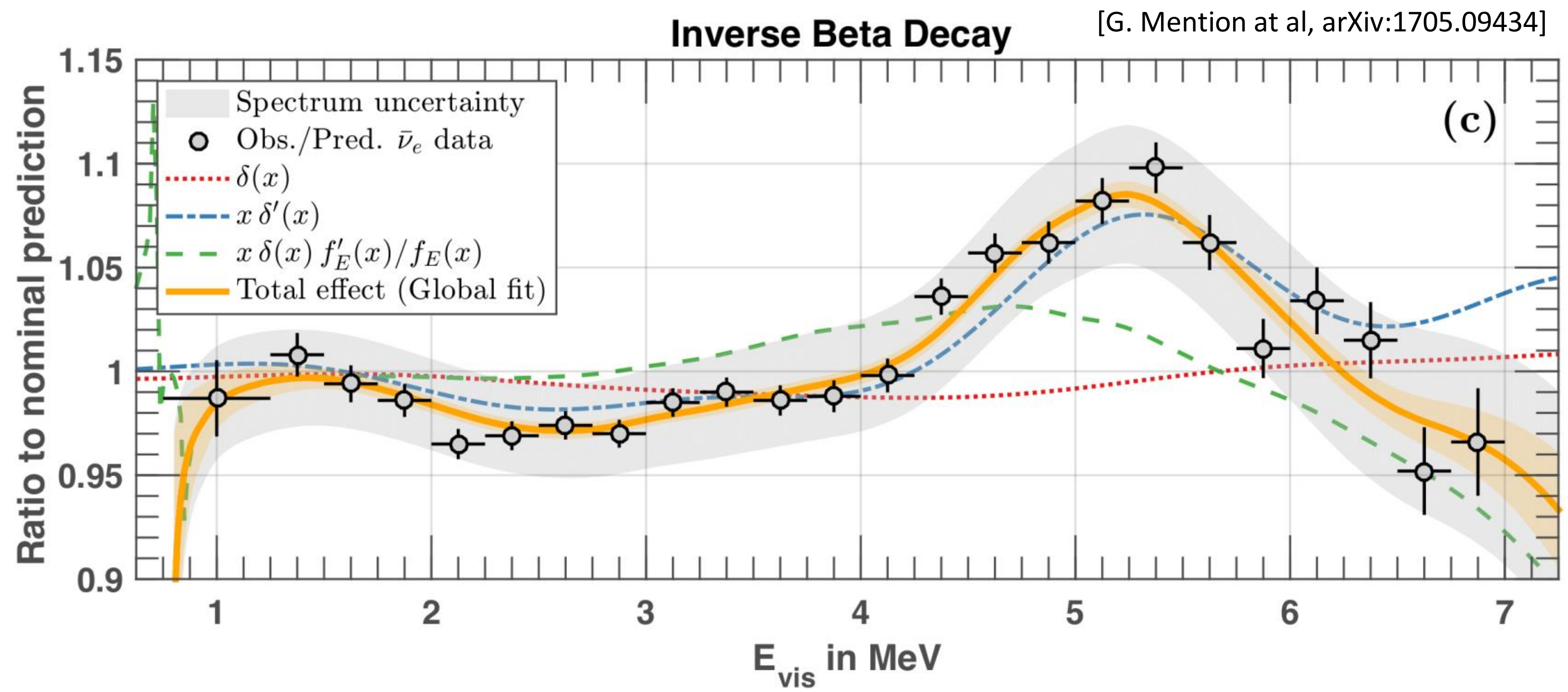
(5) Energy scale bias?

[G. Mention at al, arXiv:1705.09434, may 2017]:

- Fit of a potentially neglected residual energy scale component on the calibration data coming from an electronic charge collection non linearity
- DayaBay data: Calibration results / Unfolded spectrum



Ratio between reconstructed energies and Daya Bay nominal best fit



Ratio of Daya Bay $IBD_{\bar{\nu}_e}$ spectrum to the prediction.

- Daya Bay observed spectrum distortion versus the flux prediction can be recover with a ~1% bias on the energy scale around 4 MeV
- Energy scale nonlinearies: migration effect only ⇒ No modification of the total rate expected (i.e. no effect on the reactor anomaly)
- Hypothesis can be check with new calibration point(s) in this region

3. Reactor spectrum microstructure

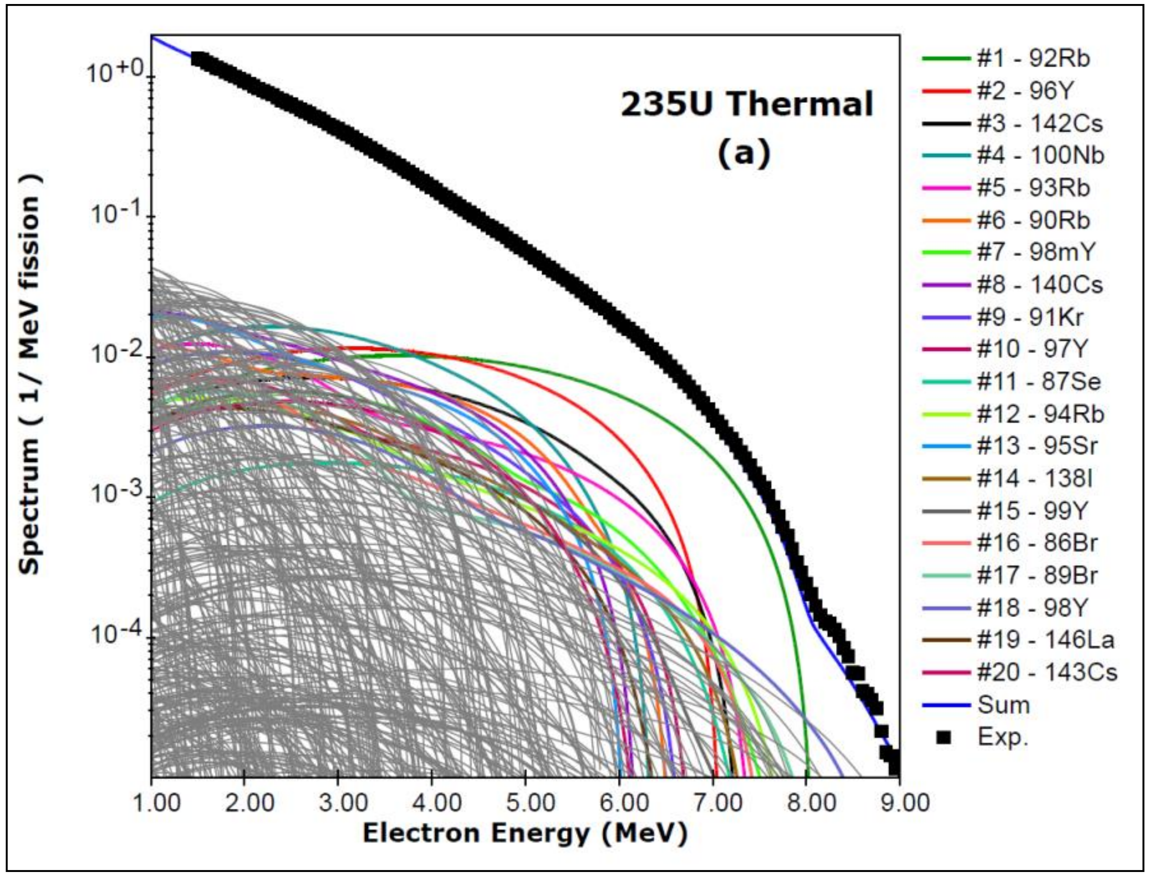
Micro-structure of the IBD $\bar{\nu}_e$ spectrum

$\boldsymbol{\beta^-}$ **spectrum**: Sum of thousand of unique beta branches

- Calculation from summation method predict substructure in the electron/antineutrino spectrum from coulomb effect

  ↳ Difficult to predict with spectrum predicted by conversion method (reference spectrum)

[A. Sonzogni - IAEA Consultant meeting 2014 #3 - 2015]



^{235}U electron spectrum

[A. Sanzoni et al., arxiv:1710.00092v2, oct 2017]

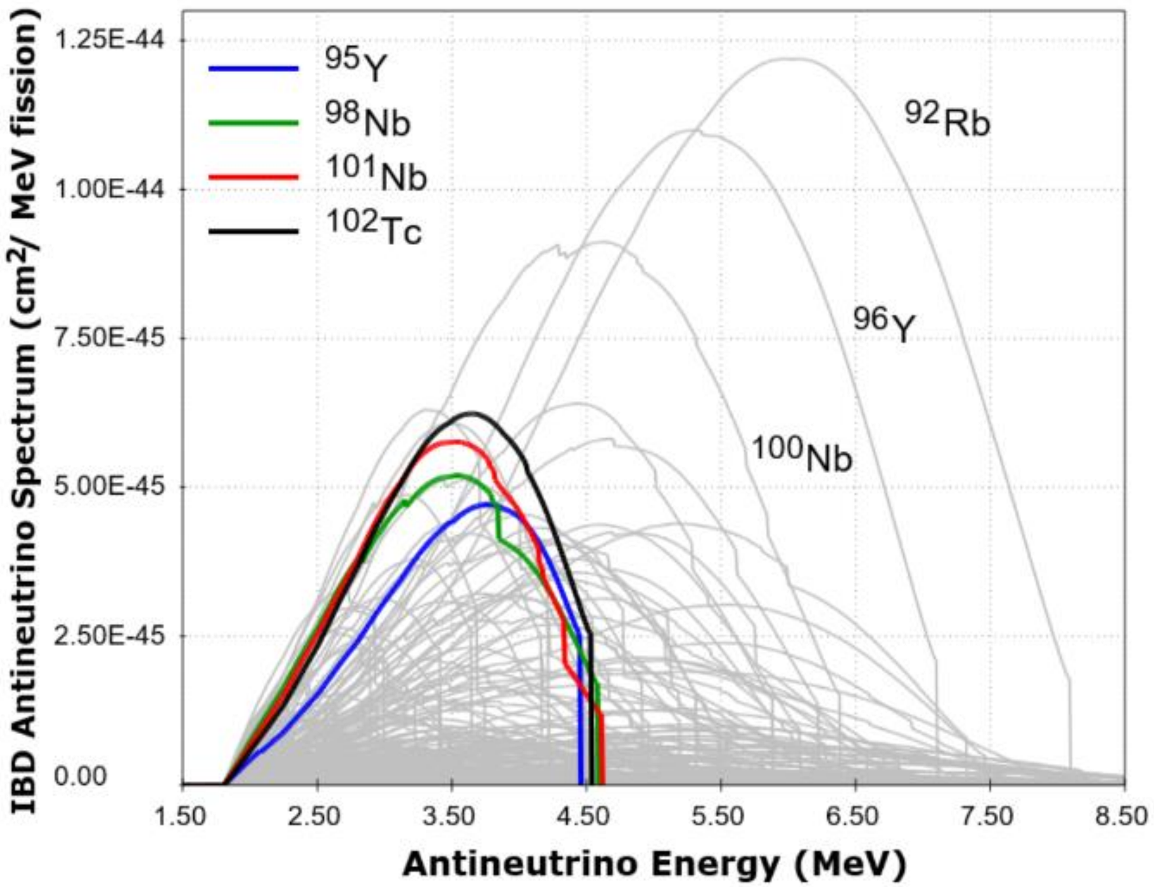


Illustration of $IBD\ \bar{\nu}_e\ spectrum\ for\ few\ fission\ product$

Discontinuity introduce by the sum of each unique decay branch

↳ contribution of a strongly populated fission product
↳ sharp cutoffs in the individual antineutrino spectra

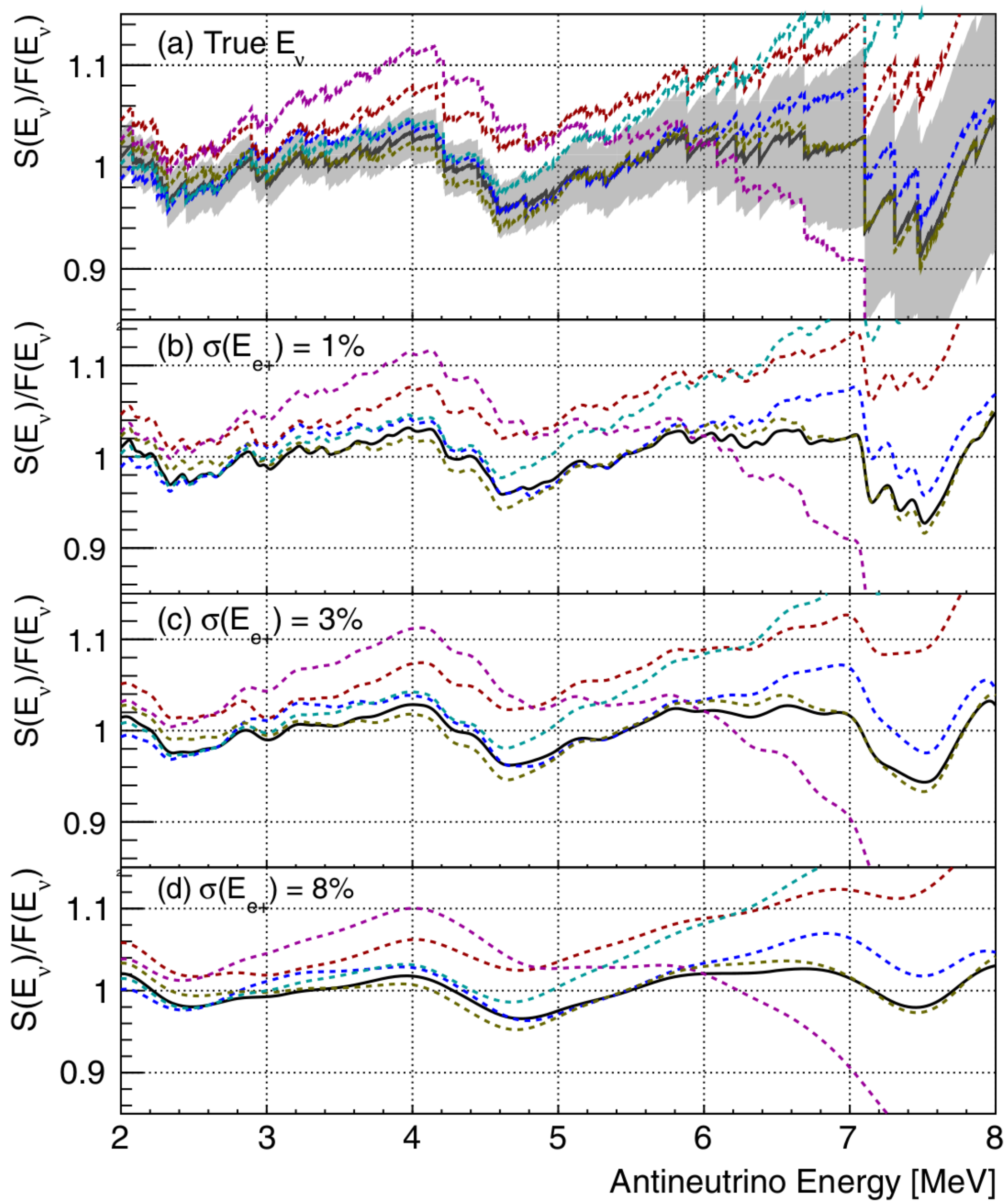
Micro-structure of the IBD $\bar{\nu}_e$ spectrum

$\boldsymbol{\beta^-}$ **spectrum**: Sum of thousand of unique beta branches

- Calculation from summation method predict substructure in the electron/antineutrino spectrum from coulomb effect

  ⇘ Difficult to predict with spectrum predicted by conversion method (reference spectrum)

[D.A. Dwyer, T.J. Langford, 10.1103/PhysRevLett.114.012502 (jan 2015)]



(a) - black: calculated $\bar{\nu}_e$ energy spectrum for a nominal reactor divided by a smooth approximation
- grey band: 1σ systematic due to fission yield
- other color: same than black but for randomized fission yield

(b,c,d) Same spectra acouting for different detector energy resolution: 1%, 3%, 8%

⇒ **Percent sublevel structure expected**

- Current experiments: 6-8% energy resolution

  ⇘ only sensitive to larger scale feature

- **Future experiment: $\lesssim$ 3% energy resolution**

  ⇘ **can detect some of the microstructure**

Micro-structure of the IBD $\bar{\nu}_e$ spectrum

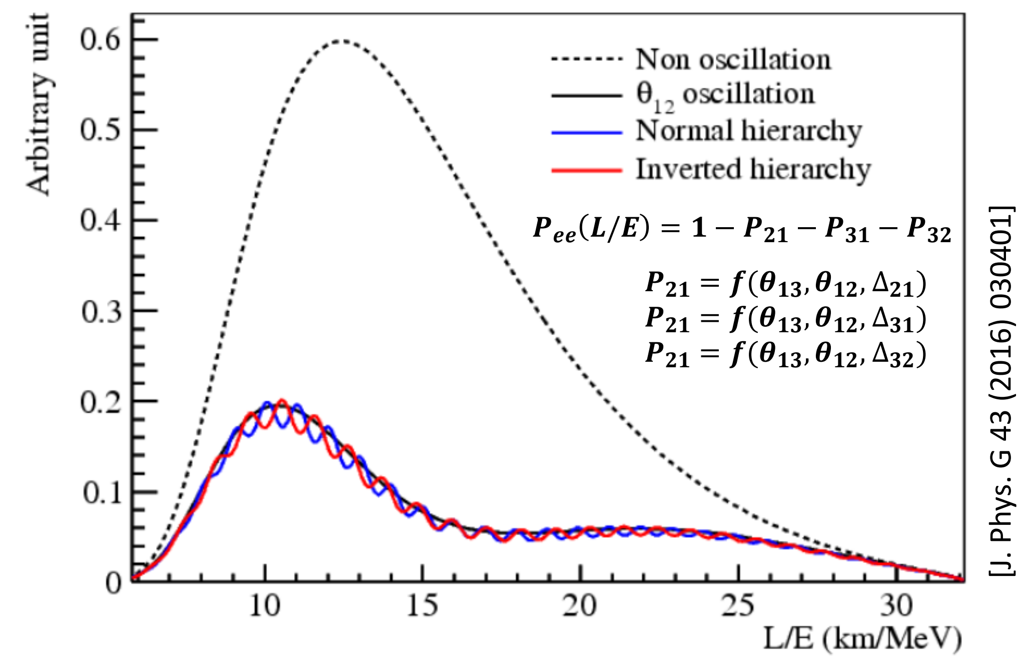
JUNO: mass hierarchy measurement with medium baseline reactor neutrino experiment

- Far detector @53 km from powerfull complex
- Far detector data compared to a flux prediction based on precise spectrum measurement (Daya Bay)

$$S^{JUNO} = S^{DB} + \sum_k (\alpha_k^{JUNO} - \alpha_k^{DB}) S_k^{ref}$$

$\Rightarrow$ **High energy resolution of 3%$\sqrt{E(MeV)}$**

Reactor neutrino spectra @60 km assuming sin2(2θ13) = 0.1



[J. Phys. G 43 (2016) 030401]

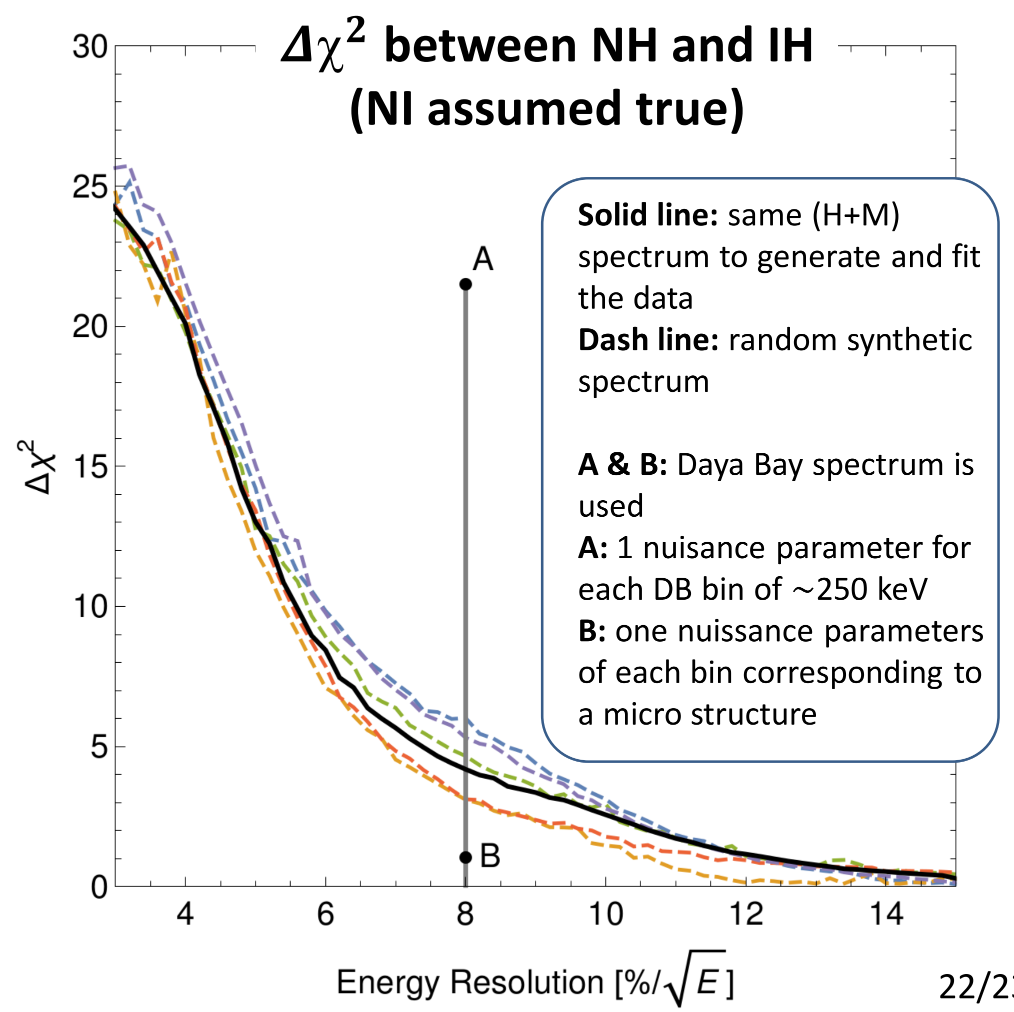
[D. V. Forero et al., arXiv:1710:0787, oct 2017]:
The benefit of a near detector for Juno

Simulation with near and far detector using 100 bins @50keV
- ↳ Far detector with 3% energy resolution
- ↳ Near detector with tunable energy resolution

$\Rightarrow$ Reactor flux have a 50 keV microstructure

$\Rightarrow$ Non linearity in the energy response have a negligible impact

$\Rightarrow$ ***Paper quote: [Reference $\bar{\nu}_e$ measurement with an energy resolution very similar to the far detector is needed to exclude any sensitivity reduction due to the unknown microstructure of the antineutrino flux]***



Conclusion

- Measurement of reactor flux and shape with unprecedented precision:
  ↳ ~ 1-2% for the rate, few percent for the shape

- Still unsolved tension between data and prediction: - Reactor anomaly
  - Shape distortion
  - Rate evolution with reactor burnup

  ↳ several hypothesis… no clear answer yet: a lot of new recent dedicated studies!

- Better understanding and characterization of the tension expected soon with new released from sterile experiment
  ↳ research reactors with highly enriched ^{235}U fuel: PROSPECT, SoLid, STEREO…
  ↳ commercial reactors with mixed fuel compositions: DANSS, NEOS, Neutrino-4…

Backup

Daya Bay systematics breakdown of the Mean cross-section per fission

Table 8. Summary of contributions to the total uncertainty of the reactor antineutrino flux measurement.

	Uncertainty
statistics	0.1%
oscillation	0.1%
reactor	0.9%
detection efficiency	1.93%
Total	2.1%

The best-fit oscillation curve is shown in Fig. 15. Disregarding the normalization, the measurement is consistent within the three-neutrino paradigm. On the other hand, the normalization is inconsistent with the Huber+Mueller model prediction within the model uncertainties. We will further discuss the implication in Sec. **5.3**.

Source	ϵ	$\delta\epsilon/\epsilon$
Target protons	-	0.92%
Flasher cut	99.98%	0.01%
Capture time cut	98.70%	0.12%
Prompt energy cut	99.81%	0.10%
Gd capture fraction	84.17%	0.95%
nGd detection efficiency	92.71%	0.97%
Spill-in correction	104.86%	1.00%
Combined	80.60%	1.93%