The Reactor Antineutrino Anomaly

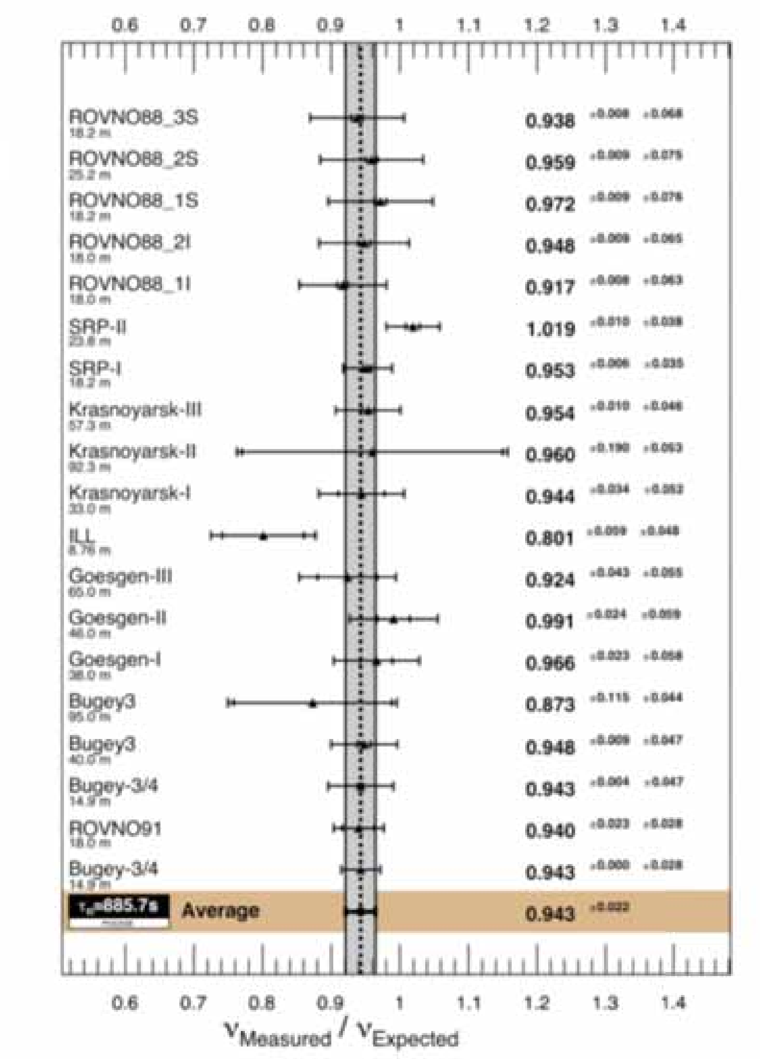
G. Mention, M. Fechner, T. Lasserre,
M. Cribier, Th. Mueller, D. Lhuillier, A. Letourneau,

CEA / Irfu

arXiv:1101.2755 [hep-ex], submitted to PRD

linked to our new "improved prediction of reactor antineutrino spectra", done with Subatech group:
M. Fallot, S. Cormon, L. Giot,
J. Martino, A. Porta, F. Yerma
arXiv:1101.2663 [hep-ex] , submitted to PRC

Rencontres de Moriond EW 2011, La Thuile.

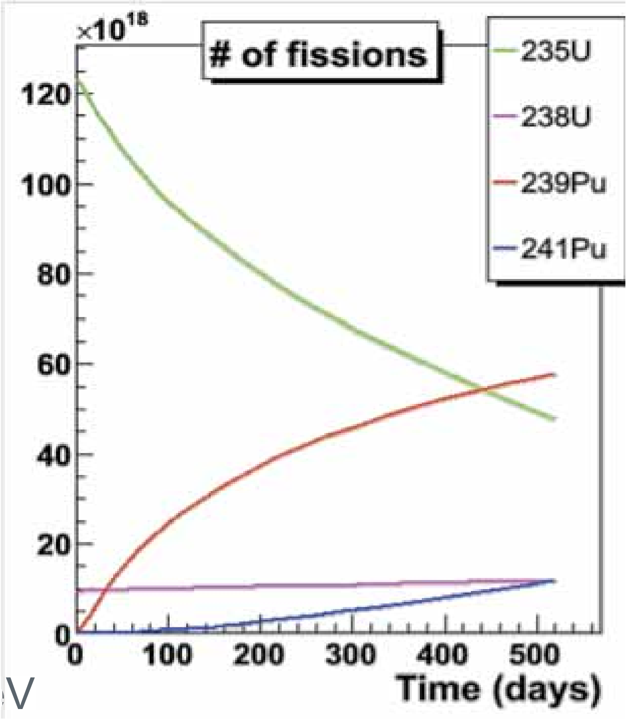


Outline

- A very short introduction to reactor neutrino physics.
- What has changed recently
- Reinvestigating reactor neutrino experiments: the reactor anti-neutrino anomaly
- And in neutrino sector: the Gallium anomaly
- Larger consequences and sterile neutrino hypothesis
- Conclusion & beyond: need of future experimental confirmation of this anomaly

SHORT INTRODUCTION TO REACTOR NEUTRINOS

Reactor anti-neutrinos



- Electron antineutrinos emitted through Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Nuclear reactors $1\ \mathrm{GW_{th}} \Leftrightarrow 2\ 10^{20}\ \bar{\nu}/\mathrm{s}$
- Neutrino Luminosity $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$

  γ: reactor constant
  k : fuel evolution correction up to 10%

- Neutrino detection
  - Inverse Beta-Decay reaction (xsec: $\sigma_{\text{V-A}}$)

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

reaction threshold 1.8 MeV. E_ν from 0 to 10 MeV

  - Reactor experiments measure anti-ν_e interaction rate

$$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\mathrm{th}}}{\langle E_f\rangle}N_p\varepsilon\sigma_f \longrightarrow \sigma_f^{\mathrm{meas.}} = \frac{4\pi R^2 n_\nu^{\mathrm{meas.}}}{N_p\varepsilon}\frac{\langle E_f\rangle}{P_{\mathrm{th}}}$$

  - Often published comparison of σ_f to theory through averaging $\sigma_{\text{V-A}}$ over reactor neutrino spectrum

$\uparrow$

Average cross section per fission

$\downarrow$

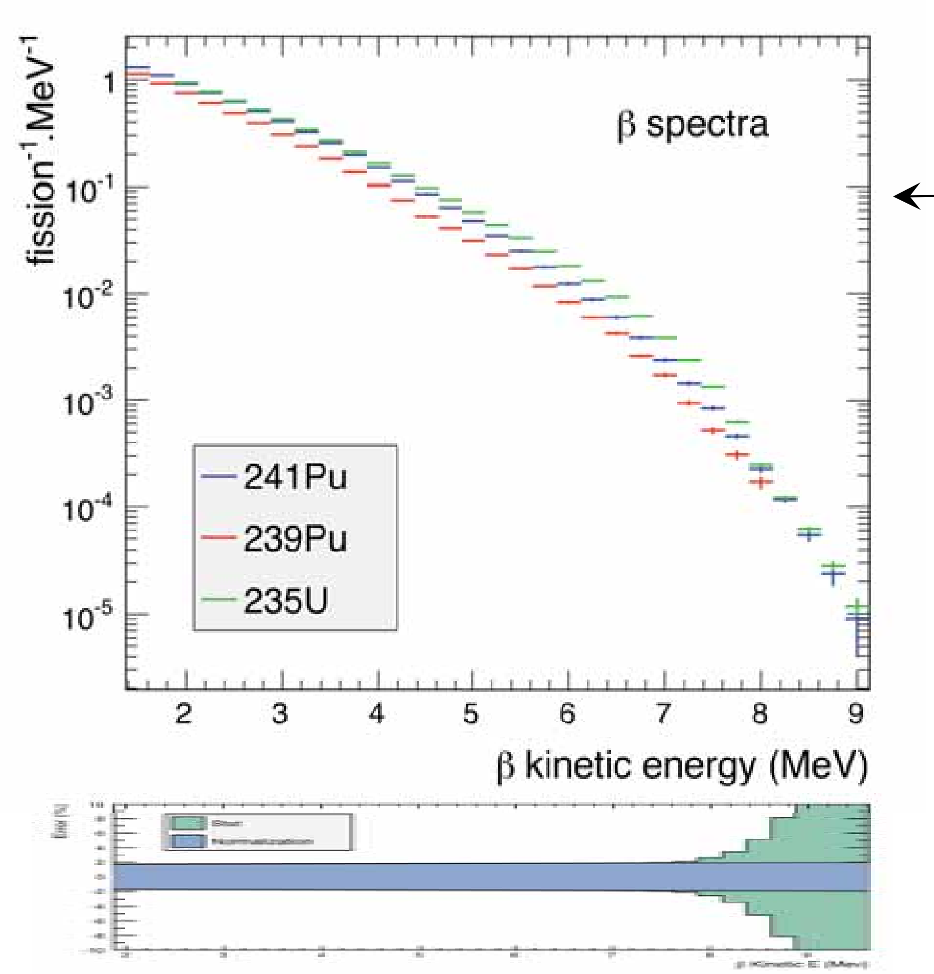
$$n_\nu^{\mathrm{th}} = \int_0^\infty \phi(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu \qquad \sigma_f^{\mathrm{pred.}} = \int_0^\infty \phi_f^{\mathrm{pred.}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu$$

ν flux prediction: Anchor point of ILL electron data

Most precise source of information for anti-ν_e flux prediction:

accurate measurements of β-spectra of ^{235}U, ^{239}Pu, ^{241}Pu fission products @ ILL high resolution magnetic spectrometer in the 80's

$$\sum_{A,Z} \{ {}^{A}_{Z}X \longrightarrow {}^{\;\;A}_{Z+1}Y + e^- + \bar{\nu}_e \}$$



Total electron spectra from the β-decays of ^{235}U, ^{239}Pu and ^{241}Pu fission products.

Normalization of data known at ~**2%** level.

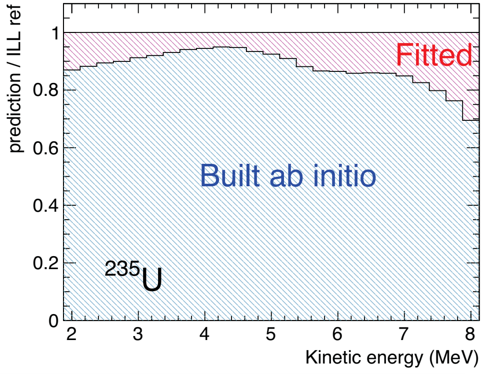
WHAT HAS CHANGED RECENTLY:

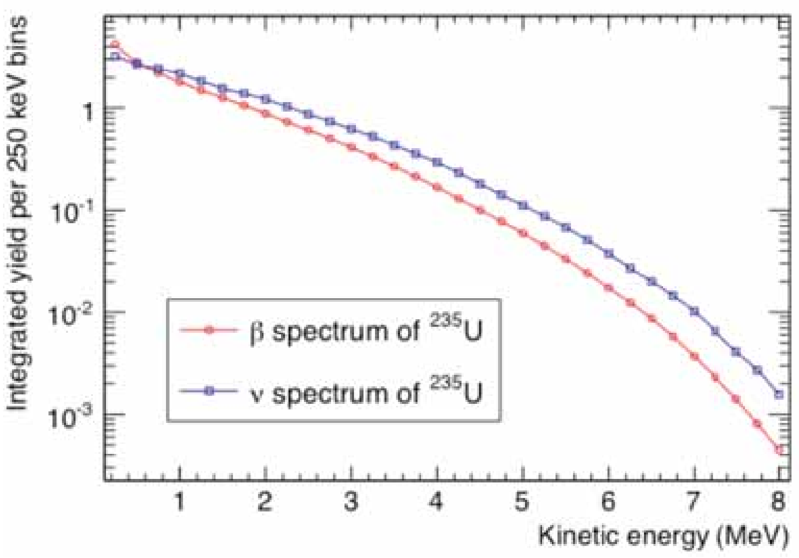
The conversion procedure of ILL β-spectra

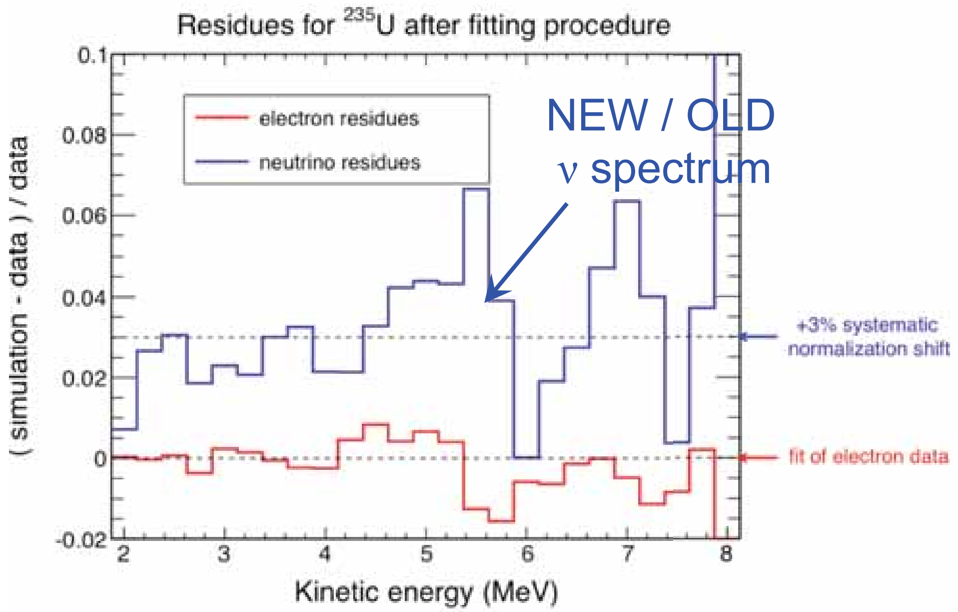
New Saclay-Subatech reactor ν-spectra from ILL β-spectra

arXiv:1101.2663 [hep-ex] , submitted to PRC

- Starting point: same β-spectra from measurement at the ILL reactor in the 80's
- Conversion from electron to anti-ν_e spectra:
    - **OLD**: **30 effective branches** method
    - **NEW**: conversion method taking into account the **whole information of nuclei** measured and stored in **nuclear databases** (~90% info from data bases, ~10% fitted with **5 effective branches**)
- Full Error Propagation and Correlations included







- Result: **+3% bias** (averaged) with respect to previous results
- Similar results for all measured isotopes (^{235}U, ^{239}Pu, ^{241}Pu)

Off-equilibrium corrections to ILL β-spectra measurements

arXiv:1101.2663 [hep-ex] , submitted to PRC

MURE evolution code: core composition and off equilibrium effects

(Subatech Nantes)

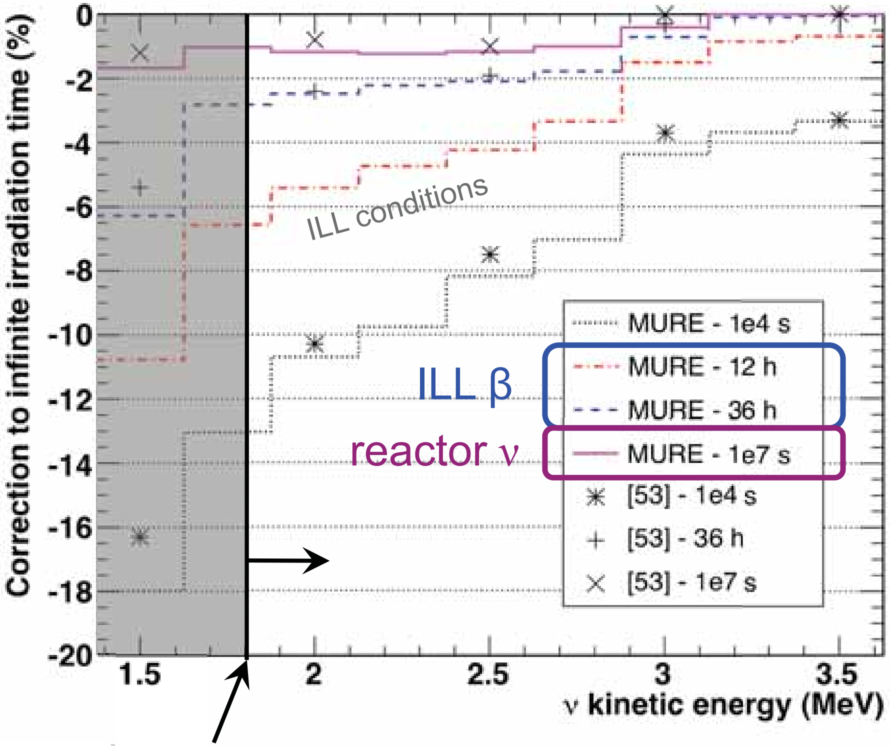
$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

- Full simulation of reactor core
  → absolute prediction of isotopes inventory.

- Relative off-equilibrium effect: close to beta-inverse threshold**, a significant fraction of the ν spectrum takes weeks to reach equilibrium**

→ Sizeable correction in the ν oscillation range that depends on the exact chronology of ILL data taking.

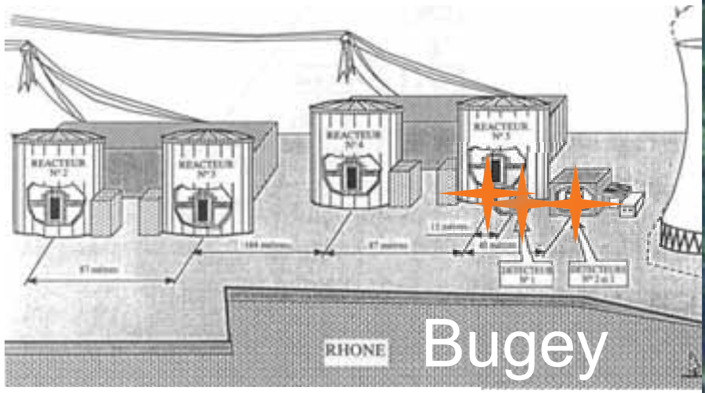
Relative change of ν spectrum
w.r.t. infinite irradiation time

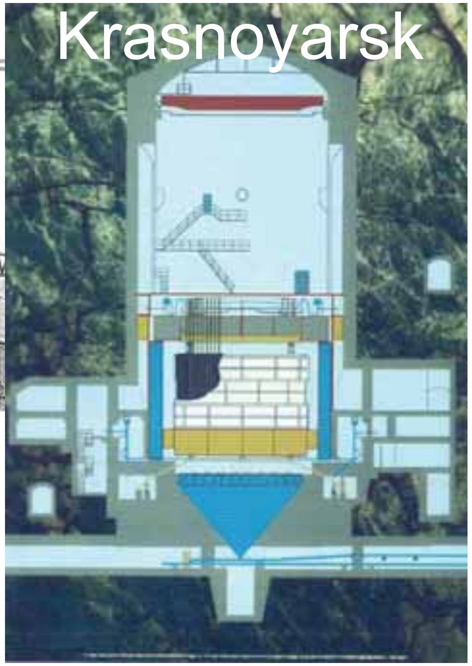


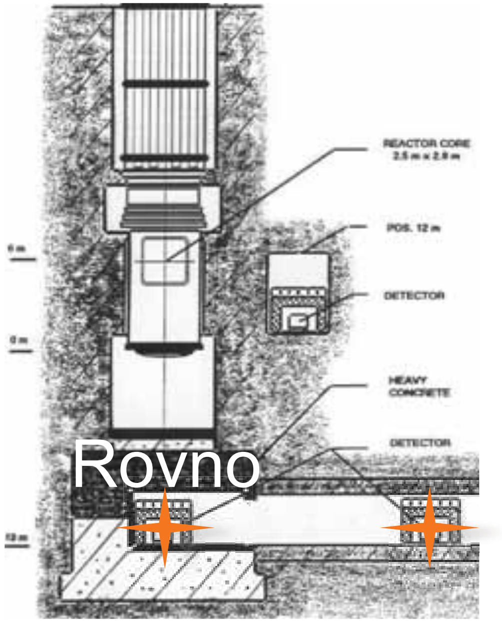
$\bar{\nu}_e + p \longrightarrow e^+ + n$ reaction threshold

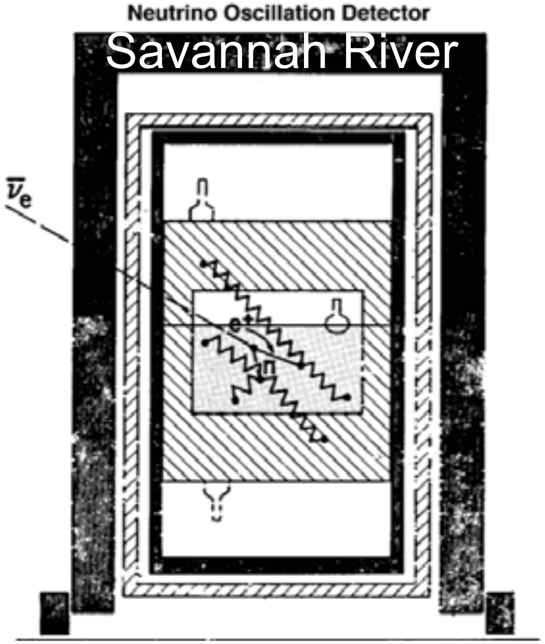
CONSEQUENCES ON REACTOR MEASUREMENTS

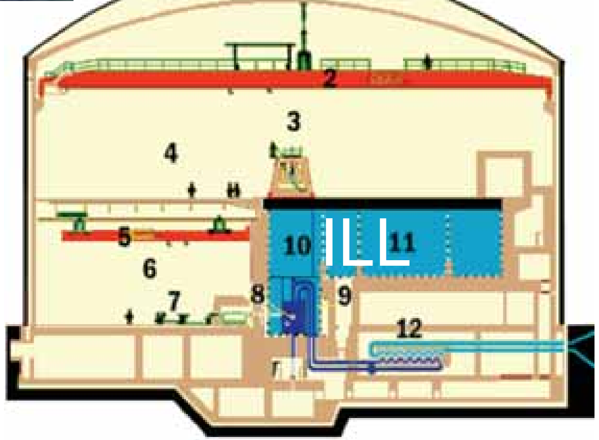
19 Experimental results at distances below 100 m











Measured neutrino rates and cross sections per fission σ_f

The Bugey-4 Benchmark

- Bugey-4 is the most precise experiment
- Use Bugey-4's **calculations** to check ours
- Compare with reference publication of BUGEY-4 (*Phys. Lett. B 338 (1994), 383*) for isotopes measured by Schreckenbach et al. (ILL β-spectra)
- Using their inputs:
  - τ_n = 887.4 s
  - **OLD** spectra using 30 effective branch conversion
  - no off-equilibrium corrections (ILL @<36h irradiation time, Bugey measurement ~ 1 y <= require off-equil corrections in principle)

corss section per fission

$$\sigma_{f,k}^{\mathrm{pred.}} = \int_0^\infty \phi_{f,k}^{\mathrm{pred.}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu \qquad k = {}^{235}\mathrm{U},\ {}^{239}\mathrm{Pu},\ {}^{241}\mathrm{Pu}$$

OLD prediction comparisons:

our code vs. published info.

10^{-43} cm^2/fission	**^{235}U**	**^{239}Pu**	**^{241}Pu**
BUGEY-4	6.39±1.9%	4.18±2.4%	5.76±2.1%
This work	6.39±1.9%	4.19±2.4%	5.73±2.1%
Difference	< 10^{-3}	0.2%	-0.5%

Final agreement of our code to **better** than **0.1%** on best known **^{235}U,** using Bugey-4 inputs. **Validates our calculation code**.

The New Cross Section Per Fission

- **ν-flux**: ^{235}U : +2.5%, ^{239}Pu +3.1%, ^{241}Pu +3.7%, ^{238}U +9.8% (σ_f^{pred} ➚)
- **Off-equilibrium corrections** now included (σ_f^{pred} ➚)
- **Neutron lifetime** decrease by a few % (σ_f^{pred} ➚) ($\sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n$)
- Slight evolution of the phase space factor (σ_f^{pred} ➔)
- Slight evolution of the energy per fission per isotope (σ_f^{pred} ➔)
- Burnup dependence: $\sigma_f^{pred} = \sum_k f_k \sigma_{f,k}^{pred}$ (σ_f^{pred} ➔)

10^{-43} cm^2/fission	old [3]	new	relative effect
$\sigma_{f,^{235}U}^{pred}$	6.39±1.9%	6.61±2.11%	**+3.4%**
$\sigma_{f,^{239}Pu}^{pred}$	4.19±2.4%	4.34±2.45%	**+3.6%**
$\sigma_{f,^{238}U}^{pred}$	9.21±10%	10.10±8.15%	**+9.6%**
$\sigma_{f,^{241}Pu}^{pred}$	5.73±2.1%	5.97±2.15%	**+4.2%**

The reactor anti-neutrino anomaly

Comparison of cross sections per fission

$$\sigma_f^{\text{meas.}} = \frac{4\pi R^2 n_\nu^{\text{meas.}}}{N_p \varepsilon} \frac{\langle E_f \rangle}{P_{\text{th}}}$$

$$\sigma_f^{\text{pred.}} = \int_0^\infty \phi_f^{\text{pred.}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu$$

$$\boxed{\text{Ratio} = \frac{\sigma_f^{\text{meas.}}}{\sigma_f^{\text{pred.}}}}$$

OLD or NEW

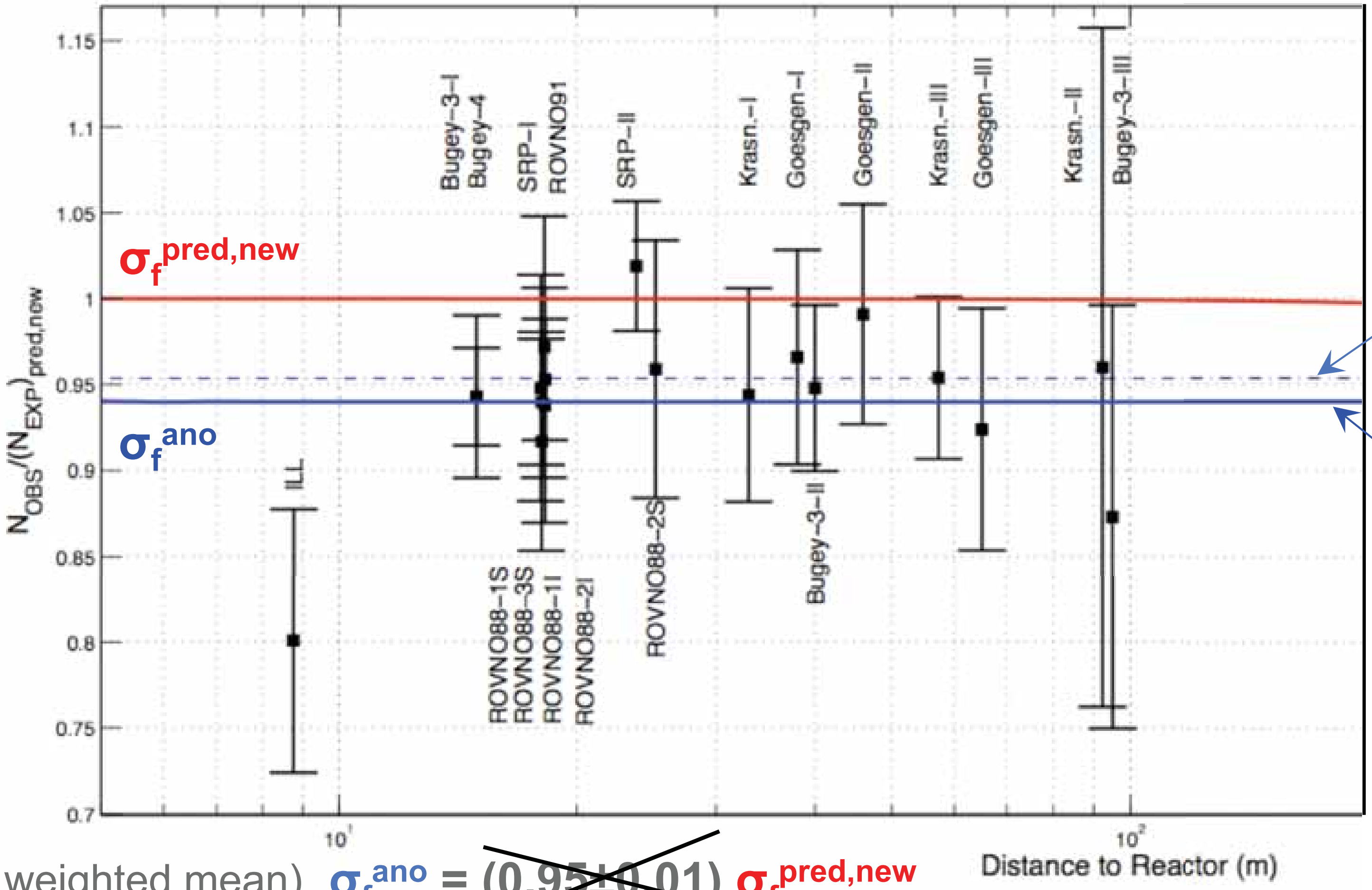
OLD or NEW

- Corrected OLD ratio include
  - Off-equilibrium corrections
  - PDG 2010 neutron lifetime (note that $\sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n$)

    [PDG 2010: τ_n = 885.7 s]
- NEW ratio = new ν-flux

Experiment	Distance in meters	τ_n (in s) in publication	Corrected OLD ratio	NEW ratio
Bugey-4	15	887.4	0.985	0.943
Rovno 91	18	888.6	0.985	0.940
Bugey-3	15	889	0.988	0.943
Bugey-3	40	889	0.994	0.948
Bugey-3	95	889	0.915	0.873
Goesgen-I	38	897	1.018	0.966
Goesgen-II	46	897	1.045	0.991
Goesgen-III	65	897	0.975	0.924
ILL	9	889	0.832	0.801
Krasnoyarsk-I	33	899	0.978	0.944
Krasnoyarsk-II	92	899	0.995	0.960
Krasnoyarsk-III	57	899	0.989	0.954
SRP-I	18	887	0.987	0.953
SRP-II	24	887	1.055	1.019
Rovno 88-I1	18	898.8	0.969	0.917
Rovno 88-I2	18	898.8	1.001	0.948
Rovno 88-S1	18	898.8	1.026	0.972
Rovno 88-S2	25	898.8	1.013	0.959
Rovno 88-S3	18	898.8	0.990	0.938

Visual illustration of the anomaly



"naive mean"

correlated

(naive weighted mean) $\sigma_f^{ano} = \cancel{(0.95\pm0.01)}\ \sigma_f^{pred,new}$

(correlated weighted mean) $\sigma_f^{ano} = (0.943\pm0.023)\ \sigma_f^{pred,new}$

mean value
of measured quantities

from new flux
conversion from ILL β-spectra

Error budget & Correlations

- Our guiding principles: Be conservative & stable numerically

- We correlated experiments in the following way:
  - 2% systematic on flux fully correlated over all measurements of β-spectra of ILL

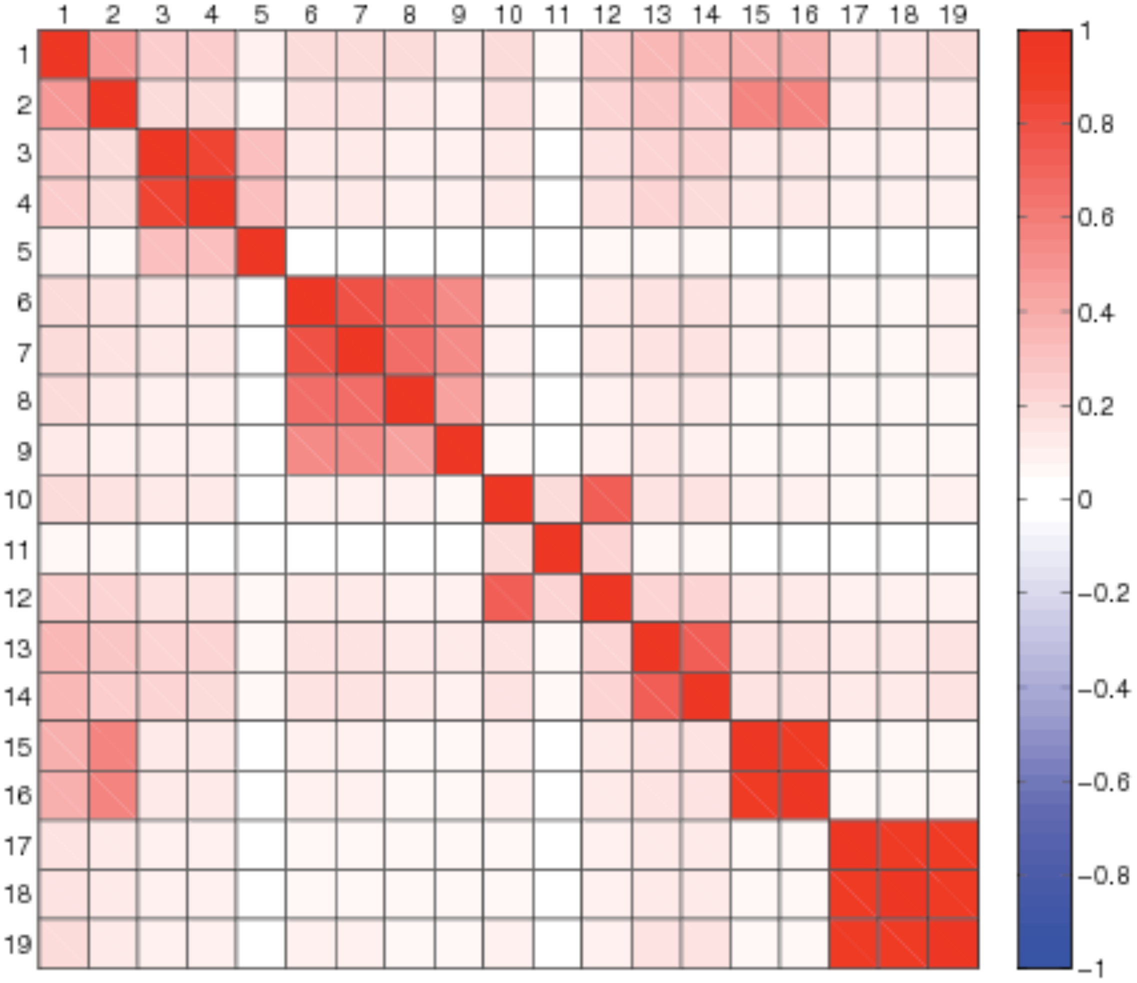
- Non-flux systematic error correlations across measurements:
  - Same experiment with same technology: 100% correlated
  - ILL shares 6% correlated error with Gösgen although detector slightly different. Rest of ILL error is uncorrelated.
  - Rovno 88 integral measurements 100% corr. with Rovno 91 despite detector upgrade, but not with Rovno 88 LS data
  - Rovno 88 integral meas. 50% correlated with Bugey-4

Experiments correlation matrix on ratios = meas./pred.

(in %)

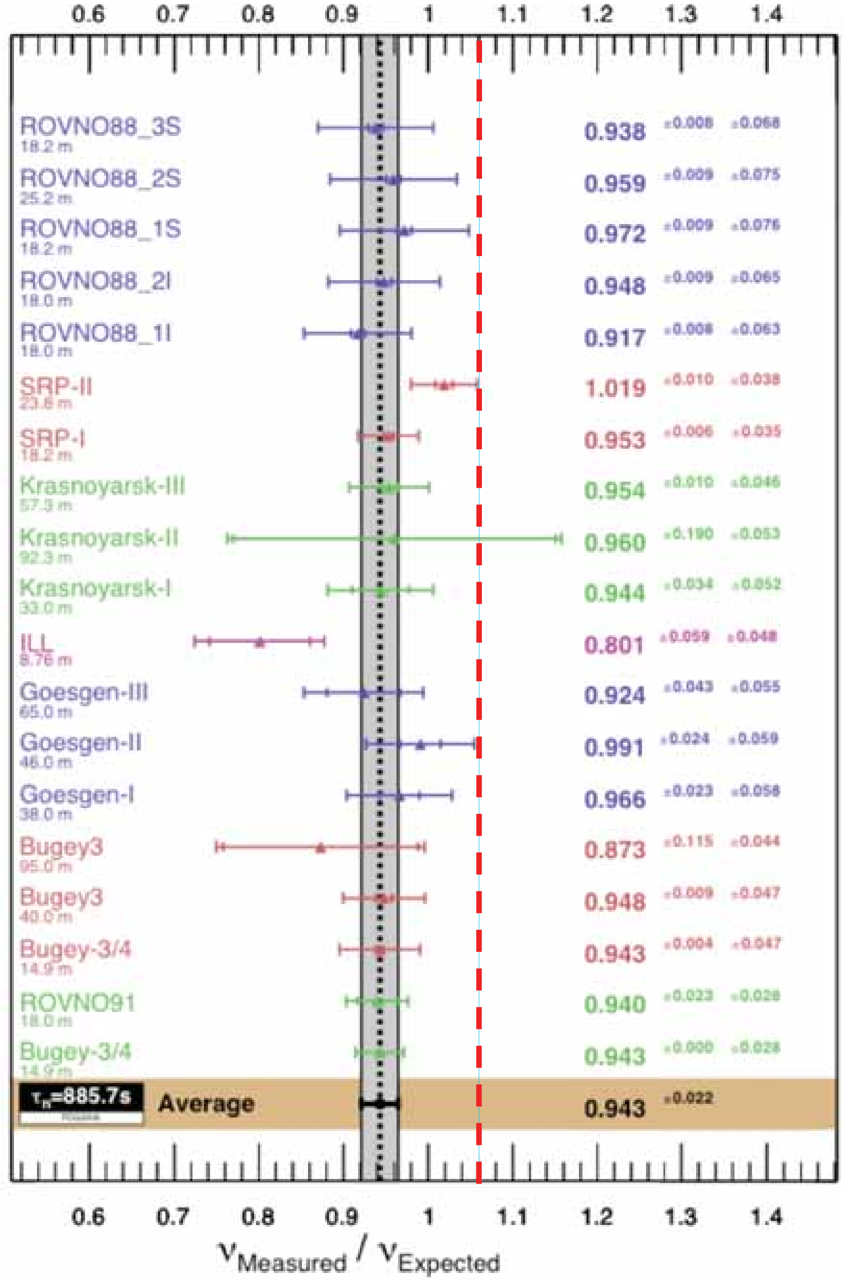
$\vec{R}$	$\Sigma_{tot.}$	$\Sigma_{cor.}$
Bugey-4 15m	3.0	3.0
Rovno91 18m	3.9	3.0
Bugey-3 15m	5.0	5.0
Bugey-3 40m	5.1	5.0
Bugey-3 92m	14.1	5.0
Goesgen 38m	6.5	6.0
Goesgen 45m	7.6	6.0
Goesgen 65m	9.5	6.0
ILL 9m	5.1	4.1
Krasno 33m	5.1	4.1
Krasno 92m	20.3	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7	3.7
SRP II 25m	3.8	3.7
Rovno88 1I 18m	6.9	6.9
Rovno88 2I 18 m	6.9	6.9
Rovno88 1S 18m	7.8	7.2
Rovno88 2S 25m	7.8	7.2
Rovno88 3S 18m	7.2	7.2

C (correlation matrix on Ratios)



- Main pink color comes from the 2% systematic on ILL β-spectra normalization uncertainty
- The experiment block correlations come from identical detector, technology or neutrino source

The reactor anti-neutrino anomaly



$$\chi^2 = \left(r - \overrightarrow{\mathrm{R}}\right)^T W^{-1} \left(r - \overrightarrow{\mathrm{R}}\right)$$

Weights: $W = \Sigma^2_{\text{unc.}} + \Sigma_{cor.} C \, \Sigma_{cor.}$

with $\Sigma^2_{\text{unc.}} = \Sigma^2_{\text{tot.}} - \Sigma^2_{\text{cor.}}$

The synthesis of published experiments at reactor-detector distances ≤ 100 m leads to a ratio R of observed event rate to predicted rate of

μ = 0.976 ± 0.024 (**OLD flux**)

With our **NEW flux** evaluation, this ratio shifts to

μ = **0.943 ± 0.023**,

leading to a deviation from unity at 98.6% C.L.

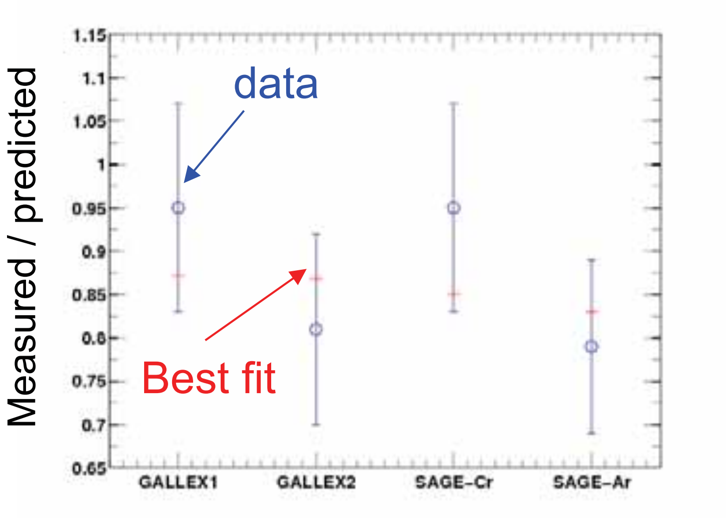
χ^2_{min} = 19.6/18

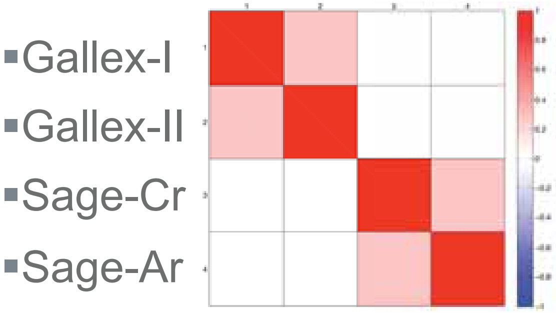
THE GALLIUM ANOMALY

BASED ON GIUNTI & LAVEDER, PRD82 053005 (2010)

The Gallium anomaly

- 4 calibration runs with intense (~ MCi) ν_e (not anti-ν_e!) sources.
- Neutrinos detected through radiochemical counting of Ge nuclei: $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$
  - 2 runs at GALLEX with a ^{51}Cr source (720 keV ν_e emitter)
  - 1 run at SAGE with a ^{51}Cr source
  - 1 run at SAGE with a ^{37}Ar source (810 keV ν_e emitter)
  - **All observed a deficit of neutrino interactions compared to the expected activity.**
- Our analysis:
  - Monte-Carlo simulation of GALLEX and SA + correlated the 2 GALLEX runs together and the 2 SAGE runs together (a bit more conservative than Giunti & Laveder PRD82 053005, 2010 to combine GALLEX & SAGE)





R = meas./pred. rates = 0.86 ± 0.06 (1σ)

THE STERILE NEUTRINO HYPOTHESIS

Sterile neutrino hypothesis

What are sterile neutrinos: neutrino states which do not couple neither to Z^0 nor $W^\pm$ (LEP Z^0 width measurement implies only 3 active neutrinos).

It's a 4th neutrino state.

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_{\text{new}} & \sin\theta_{\text{new}} \\ -\sin\theta_{\text{new}} & \cos\theta_{\text{new}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{\text{new}} \end{pmatrix}$$

$$P_{\nu_e\to\nu_e}(L,E) = |\langle\nu_e(L)|\,\nu_e(L=0)\rangle|^2 = 1 - \sin^2(2\theta_{\text{new}})\sin^2\left(\frac{\Delta m^2_{\text{new}}L}{E}\right)$$

$$\Delta m^2_{\text{new}} = m^2_{\text{new}} - m^2_1$$

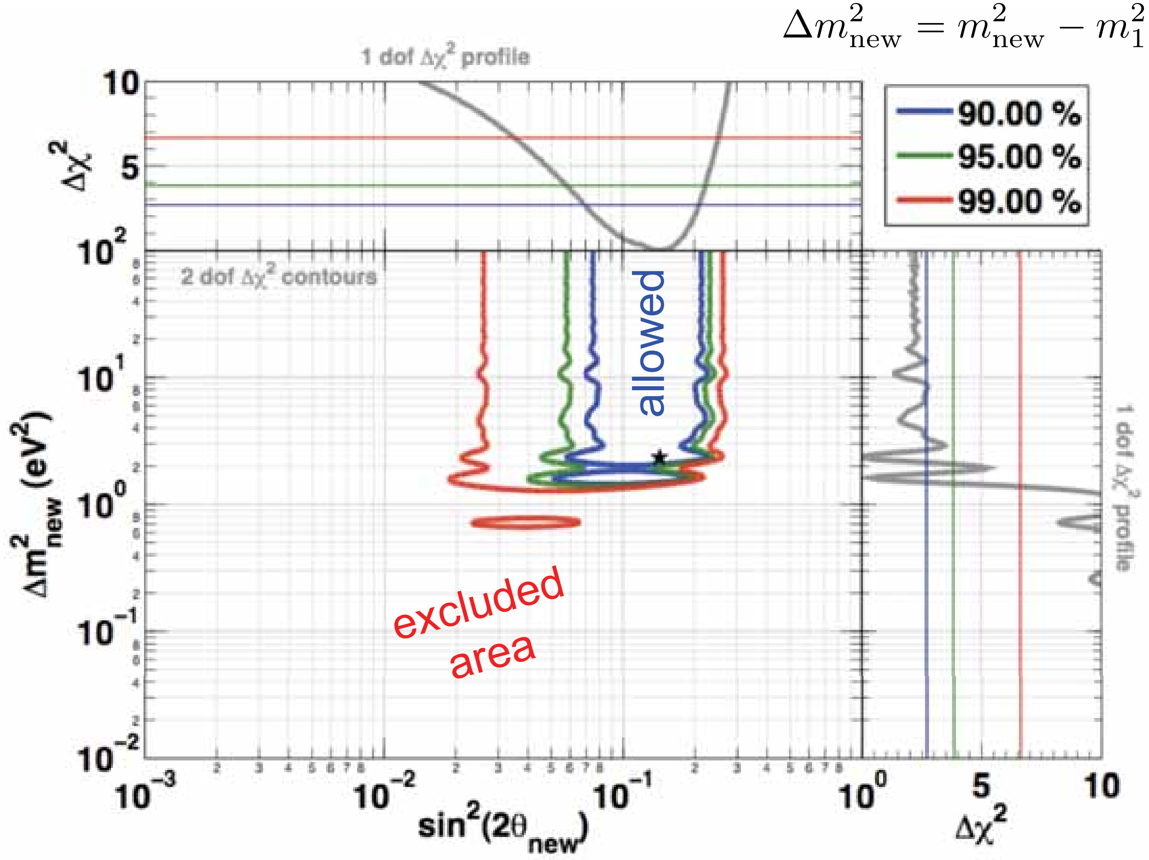
Combination of

- Reactor rates experiments
- Gallium rates experiments

- Moreover: added spectral (Energy dependant info from Reactor experiments Bugey-3 and ILL)

Compared with

- prediction with sterile oscillation hypothesis



Best fit:

$\sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.07$ (1σ)
$\Delta m^2_{\text{new}} > 1.5$ eV^2 @ 99% C.L.

Conclusion on the reactor rate anomaly

- Each short baseline experiment < 100 m from a reactor observed a deficit of anti-ν_e compared to the new expectation

- Rate+shape short-baseline data compatible with anomaly seen at Gallium experiments with MCi sources

- Possibilities of deficit explanations:
  - Our calculations are wrong.
    We don't think so… we encourage nuclear physics groups to cross-check independently
  - Bias in the normalization of the ILL measurement (given with a ~2% uncertainty).
  - Bias in all short-baseline experiments near reactors: unlikely!
    Different fuel compositions & detection techniques advocate against trivial bias
  - Need also a bias in Gallium experiments since comparable deficits have been observed

  - Hint of new physics at short baselines, explaining a deficit of anti-ν_e:
    - Overall, no-oscillation hypothesis disfavored at 99.8% CL
    - Data compatible with Δm^2 >~ 1 eV^2 and $\sin^2(2\theta)$~0.1

Need experimental confirmation / infirmation

- Clear experimental confirmation / infirmation is needed:
  - Nucifer: small detector, 7 m from the small Osiris research reactor @ CEA Saclay

  - Insert a MCi source into large detector with energy & spatial resolution, e.g. SNO+, Borexino, KamLAND

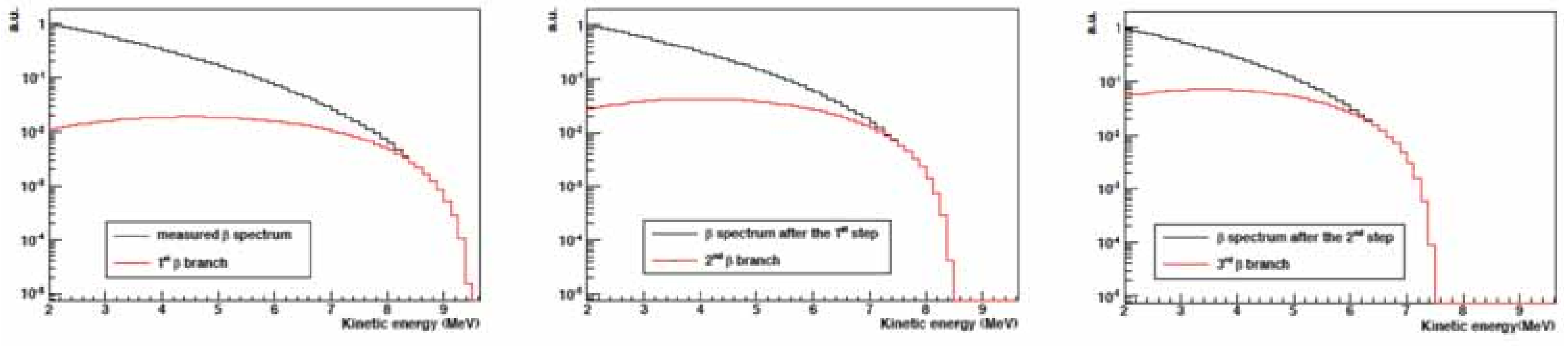
Many workshops on this active topic!

- Workshop on Sterile Neutrinos and on the Reactor (anti)-Neutrino Anomaly, Munich, February 8th
- Workshop: Beyond 3 neutrinos, LNGS, May 3-4, 2011
- Workshop on Short Baseline neutrino experiments, Fermilab, May 12-14, 2011
- Workshop, Virginia Tech., September, 2011.

BACKUP SLIDES

ILL data: OLD conversion to ν spectra

Lost info of single β-branches → fit e^- (50 keV bins) spectrum with a sum of 30 effective branches



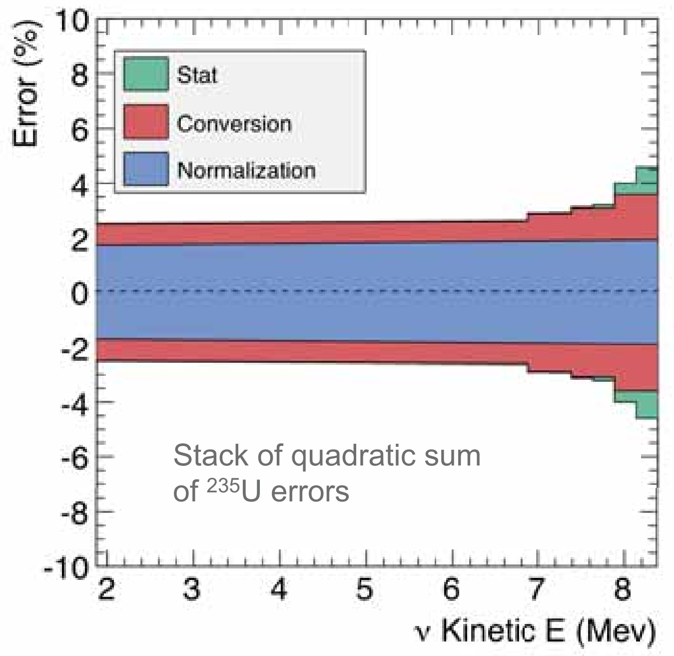
- All theory included in these effective branches but:
  - What Z? : Mean fit on nuclear data *Z=f(E0)*

$$Z(E_0) \approx 49.5 - 0.7 E_0 - 0.09 E_0^2, \quad Z \geq 34$$

  - What A_{CW}? : effective correction

$$\Delta N_\nu^{C,W}(E_\nu) \approx 0.65 \times (E_\nu - 4 MeV) \quad \%$$

- Conversion error from envelop of all numerical studies

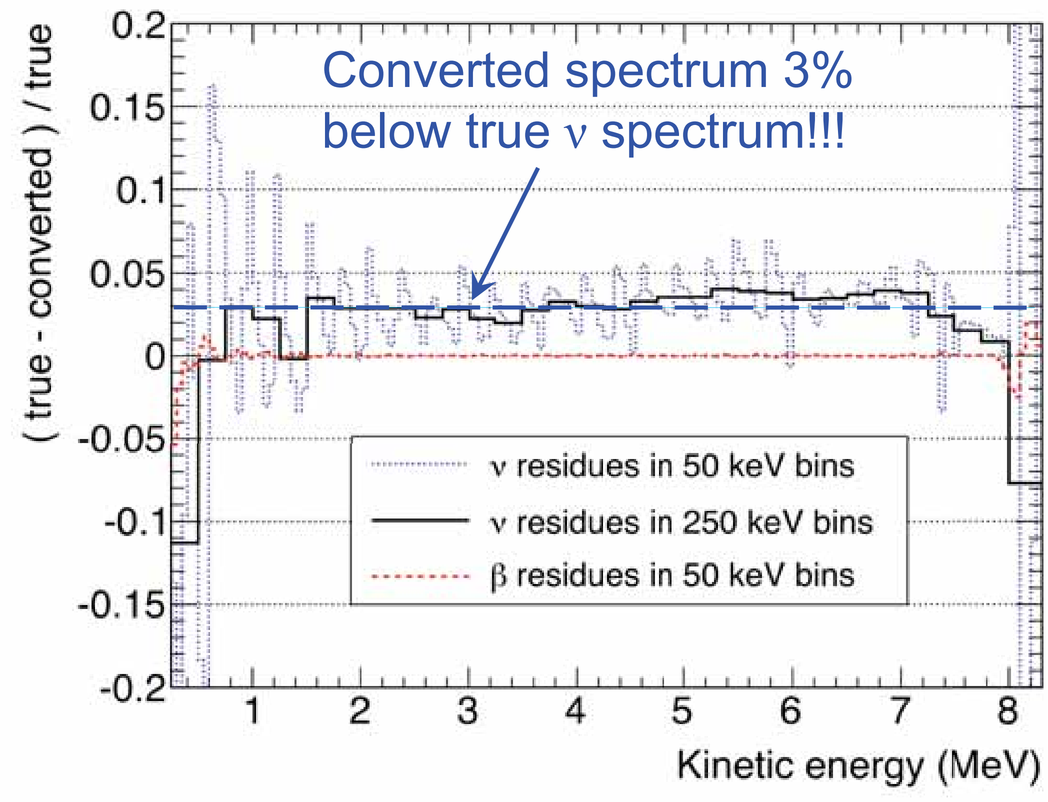


Stack of quadratic sum of ^{235}U errors

Consistency check

Stringent test

1. Define “true” e^- and ν spectra **from reduced set** of **well-known branches** from ENSDF nuclei data base.
2. Apply exact same **OLD** conversion procedure to true e^- spectrum.
3. Compare the converted ν spectrum to the true one.
4. This technique gives a 3% bias compared to the true ν spectrum



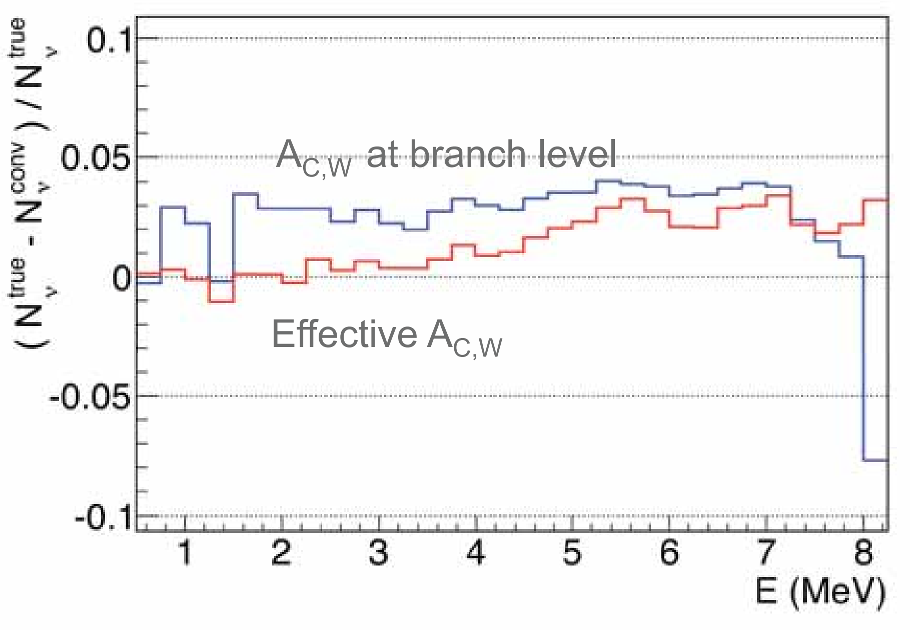
Converted spectrum 3% below true ν spectrum!!!

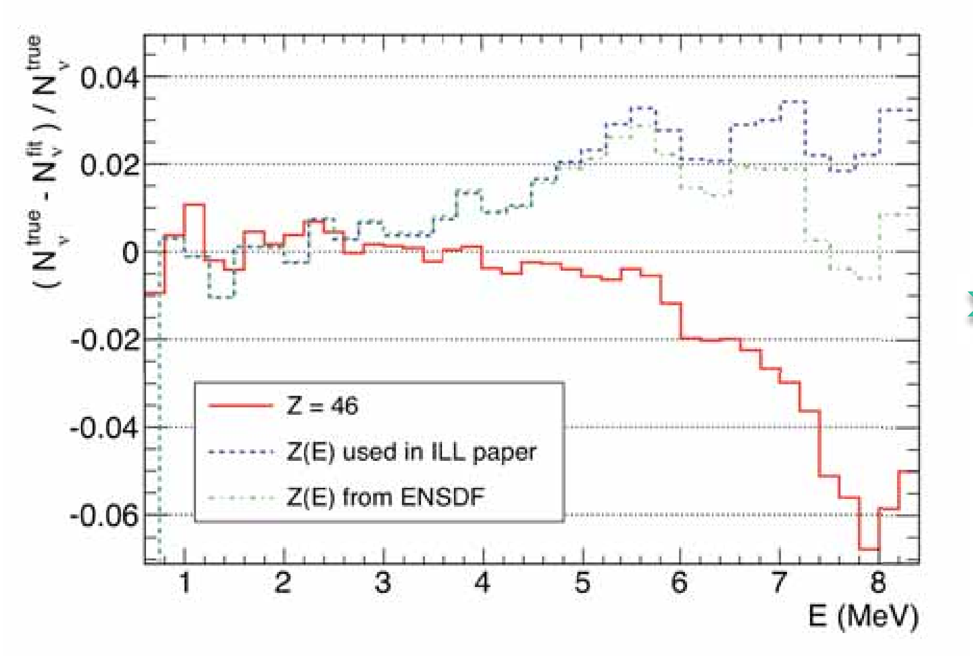
=> The **OLD** effective conversion method biases the predicted ν spectrum at the level of -3% in normalization.

Origin of the 3% shift

- **E <4 MeV**: deviation from effective linear $A_{C,W}$ correction of ILL data

$$\Delta N_{\nu}^{C,W}(E_{\nu}) \approx 0.65 \times (E_{\nu} - 4\,MeV) \quad \%$$



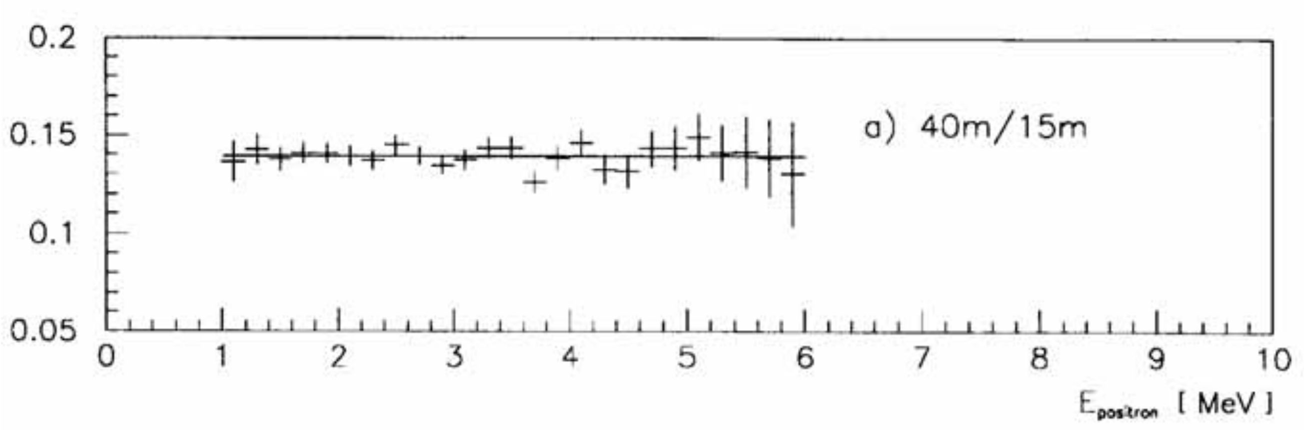


- **E >4 MeV**: mean fit of $Z(E_0)$ doesn't take into account the very large dispersion of Z around the mean curve

$$Z(E_0) \approx 49.5 - 0.7 E_0 - 0.09 E_0^2, \quad Z \geq 34$$

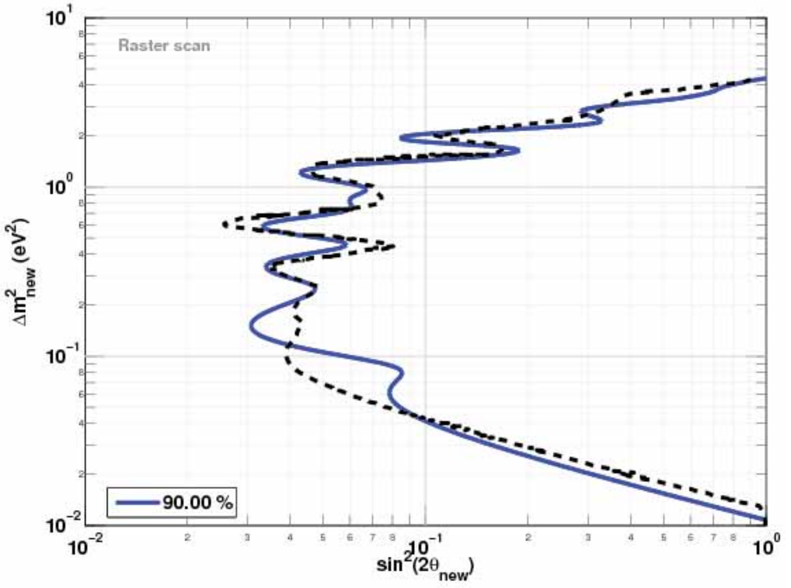
Spectral shape analysis of Bugey-3

- Bugey-3 spectral measurements at 15 m, 40 m, 90 m
  - Best constraint from high statistics R=15 m / 40 m ratio



$$\chi^2 = \sum_{i=1}^{N=25} \left(\frac{(1+a)R^i_{th} - R^i_{obs}}{\sigma_i} \right)^2 + \left(\frac{a}{\sigma_a} \right)^2$$

- 2% relative systematic error
- Reproduction of the collaboration’s raster-scan analysis
- Use of a global-scan in combined analysis

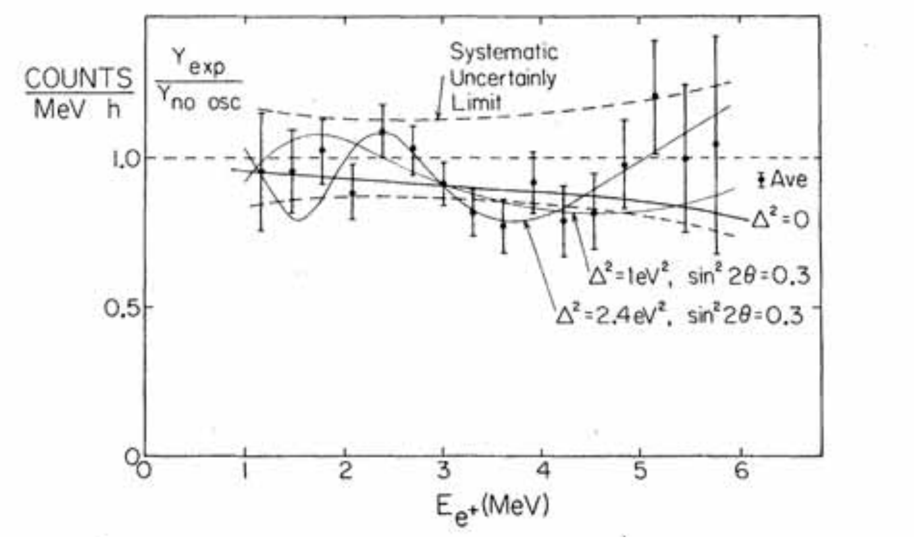


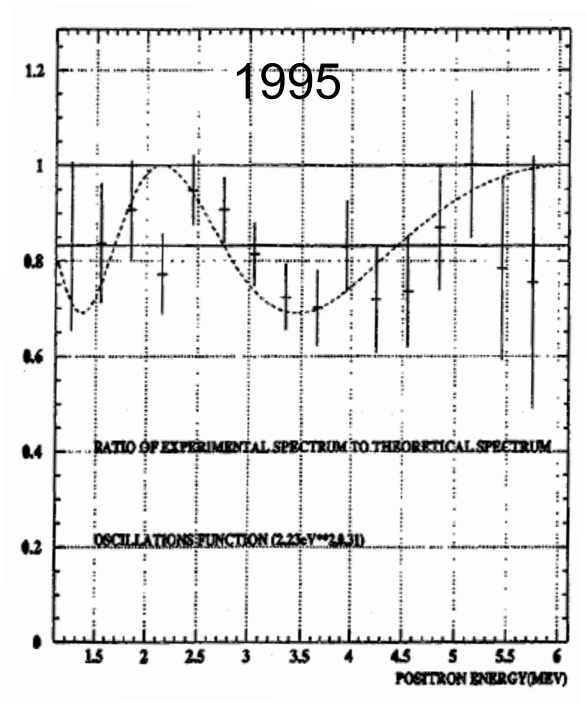
The 1981 ILL measurement

- Reactor at ILL with almost pure ^{235}U, with small core
- Detector 8 m from core
- Reanalysis in 1995 by part of the collaboration to account for overestimation of flux at ILL reactor

  Affects the rate but not the shape analysis

1981





Large errors, but looks like an oscillation pattern by eye ?

Details of our reanalysis of the ILL shape

Estimator sensitive to shape only by minimization over parameter "*a*":

$$\chi^2_{\mathrm{ILL,shape}} = \sum_{i=1}^{N=16} \left(\frac{(1+a)R^i_{th} - R^i_{obs}}{\sigma_i} \right)^2$$

- Difficult to assess the systematic error needed to reproduce the results of 1981 & 1995

- 1981: 2% energy scale error on shape
  11% systematic on normalization → does not affect shape fit

- 1995: 8.87% error on normalization, no shape error is reported
  Contour plot difficult to interpret

- Our first approach: simple fit to shape, with stat error only in each bin

- Unknown systematics: error on distance to the core?

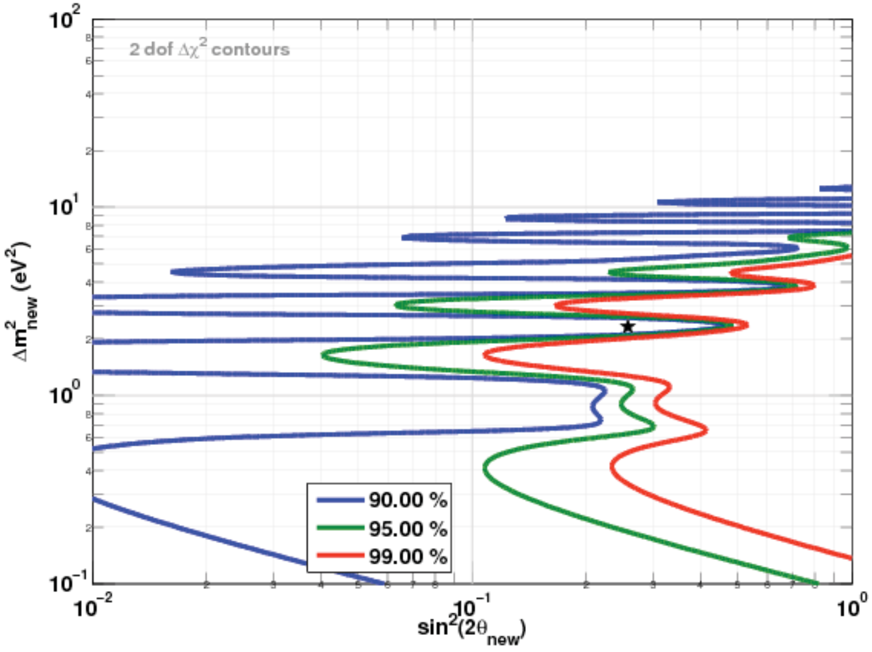
Our ILL reanalysis (cont'd)

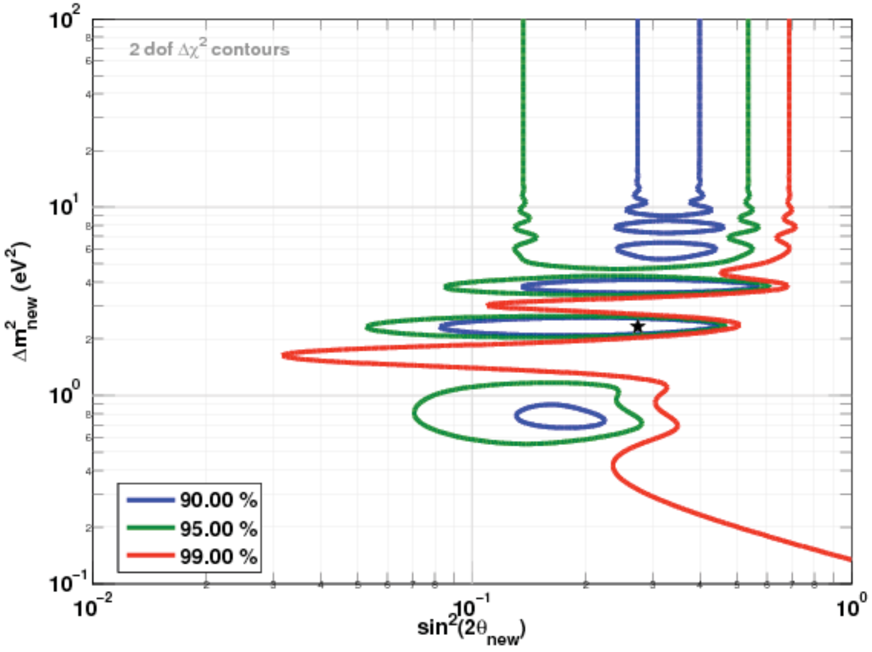
SHAPE ONLY FIT

5% systematics
uncorr. in each bin

RATE + SHAPE FIT

5% systematics on shape
1995 systematics on rate

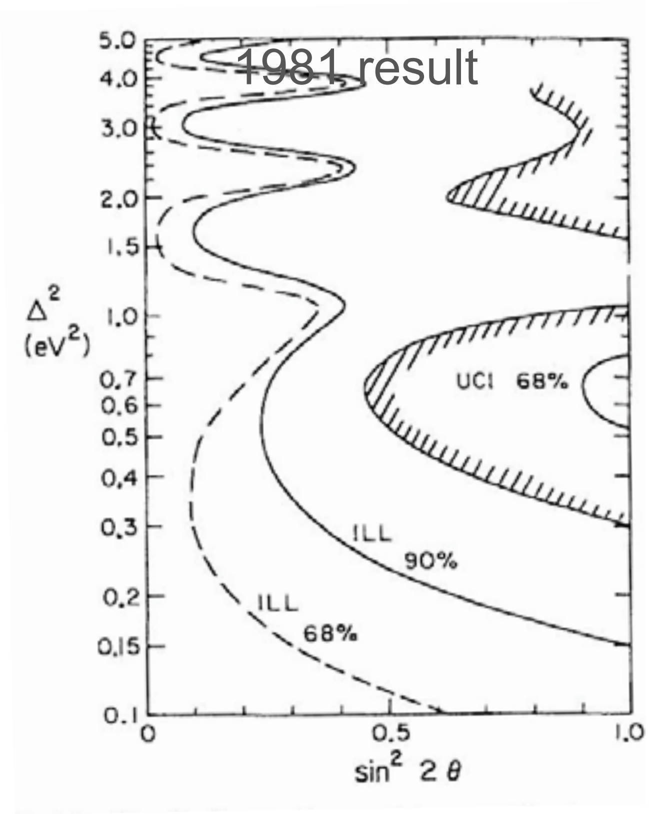


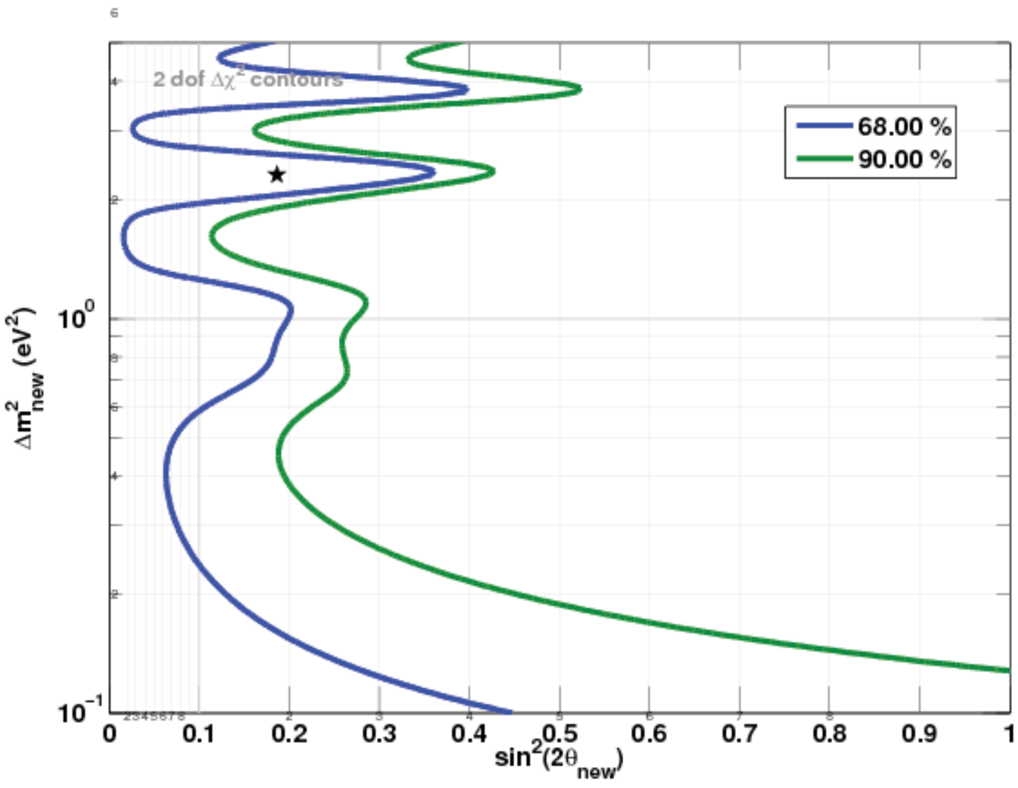


- No evidence for oscillation
- Need systematics larger than 5% on shape to reproduce ILL collaboration's contours

Our ILL analysis

- 1981: Try to reproduce published contour
- 1995: Contour plot hard to follow, reproduce claim that global fit disfavors no-oscillation at 2σ
- How? Add uncorrelated systematic in each bin until it's large enough
- Quick simulation: Required error = 11%, uncorrelated, in each bin (mostly equivalent to the finite size of the reactor core in full simulation).
- We can reproduce the results quite well

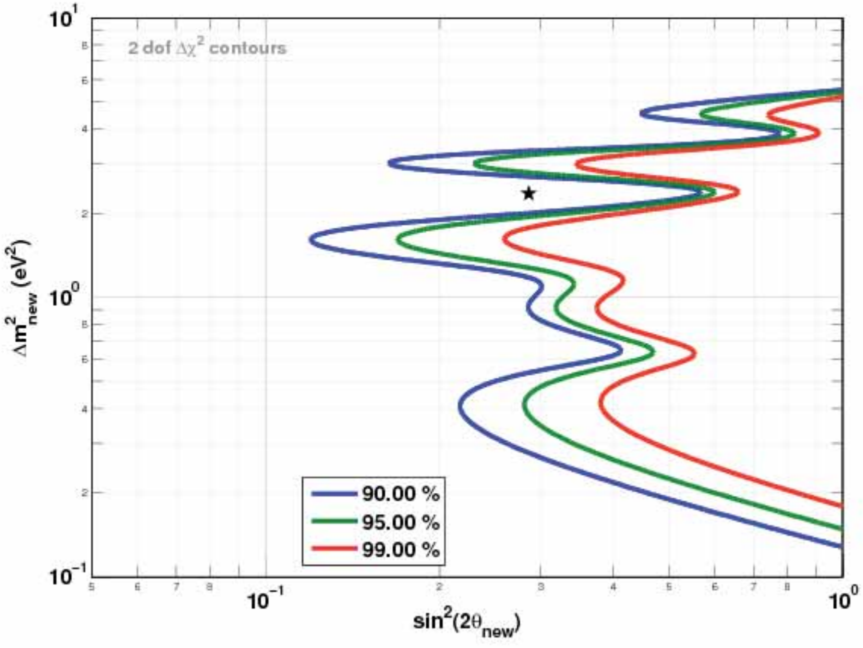

1981 result

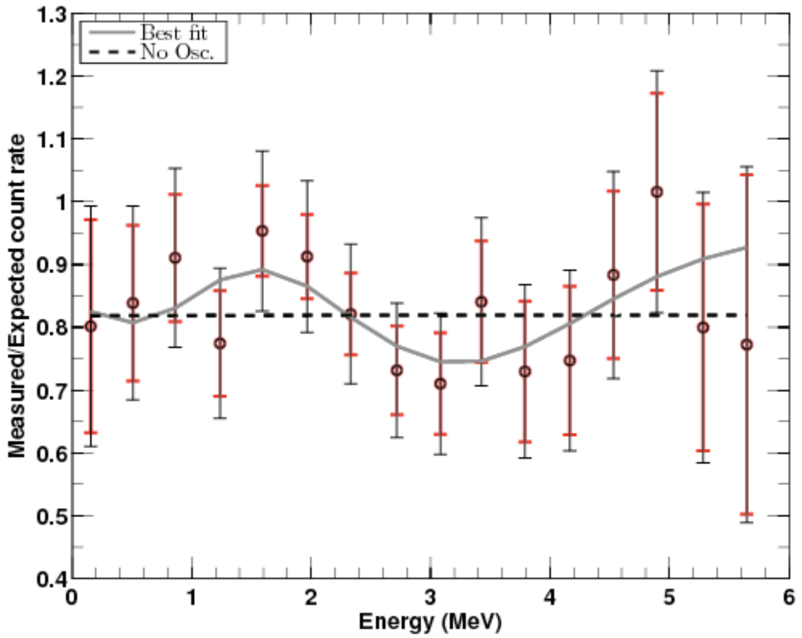


Conclusion on the ILL re-analysis (our published result)

- With the extra systematic, we reproduce the older results
- We needed to add a 11%, uncorrelated systematic in each bin in the shape only fit in our fast simulation.
- Running with the re-evaluated ratios, we obtain the following shape-only contour

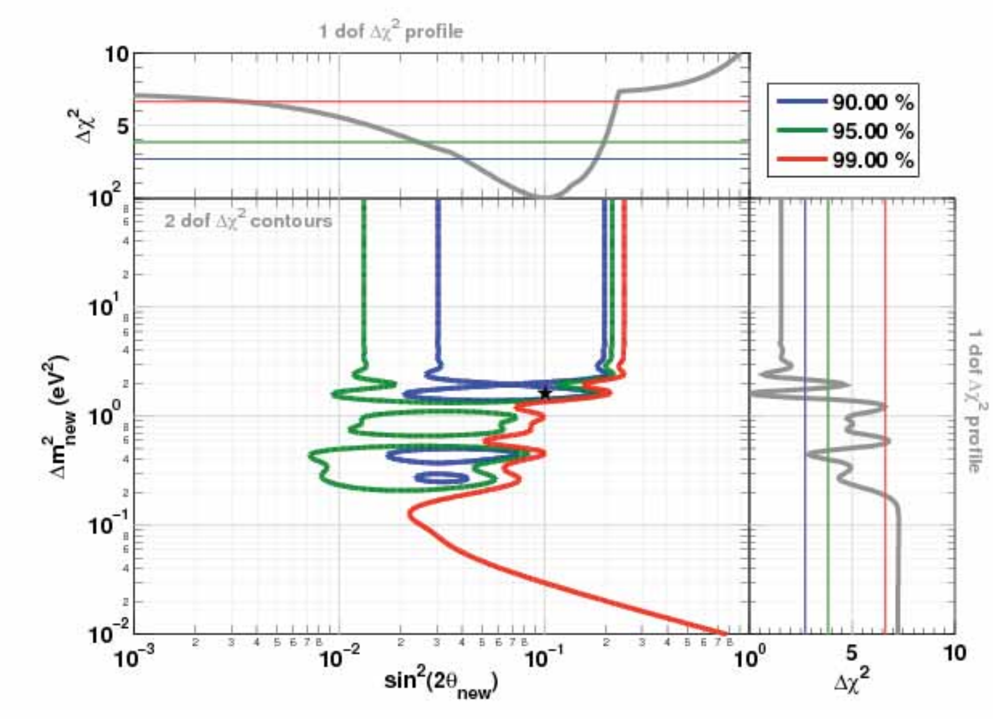
Null hyp accepted at 1 σ



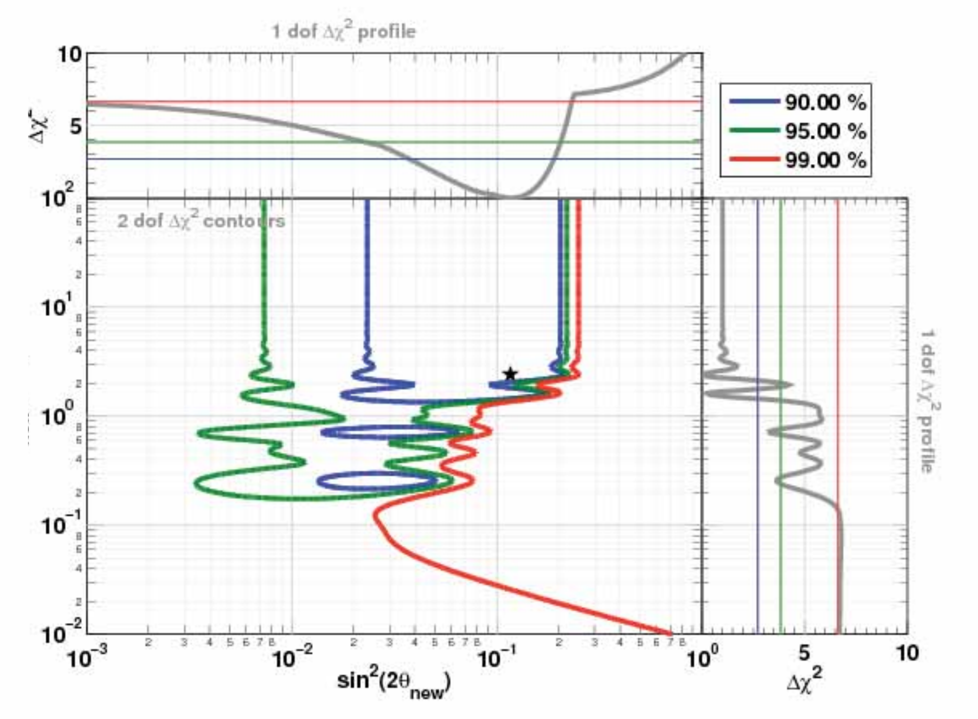


Combined Reactor rate+shape contours

Rate + Bugey-3 only



Rate + Bugey-3+ ILL



No oscillation disfavored at 96.51% CL with full rate+shape combination

Best fit: $\sin^2(2\theta)$~0.12, Δm^2~2.4 eV^2

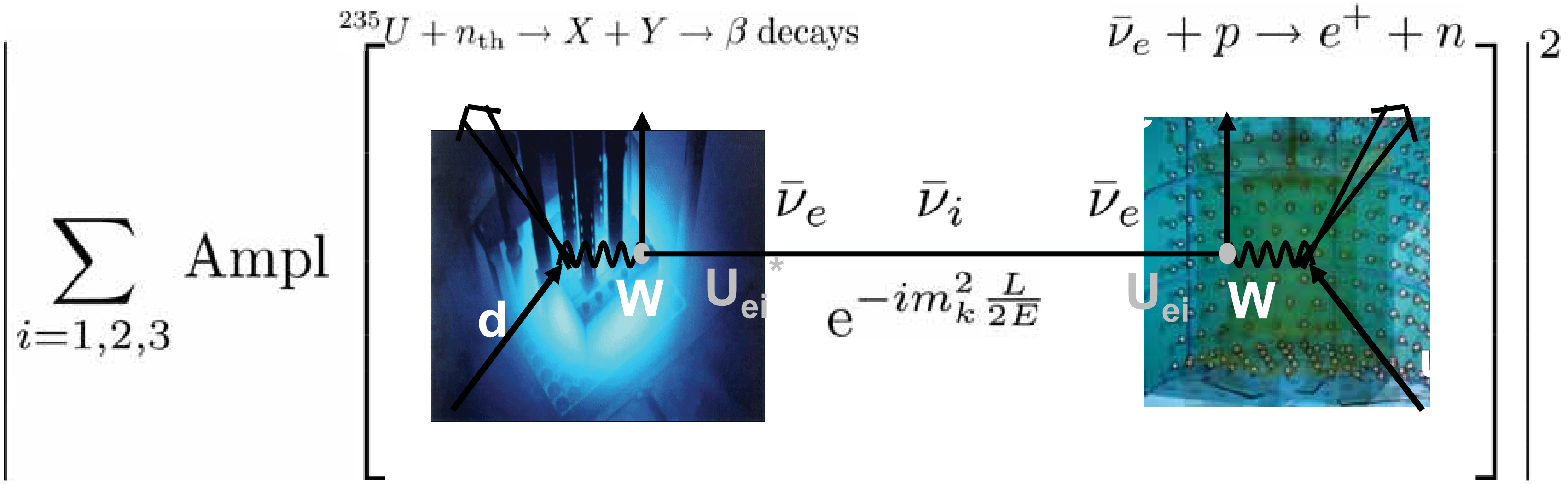
θ_{13} at Reactors

- anti-ν_e disappearance experiments
- $\sin^2(2\theta_{13})$ measurement independent of δ-CP,

  negligible matter effects, independent of sign(Δm^2_{13}) & Δm^2_{12}

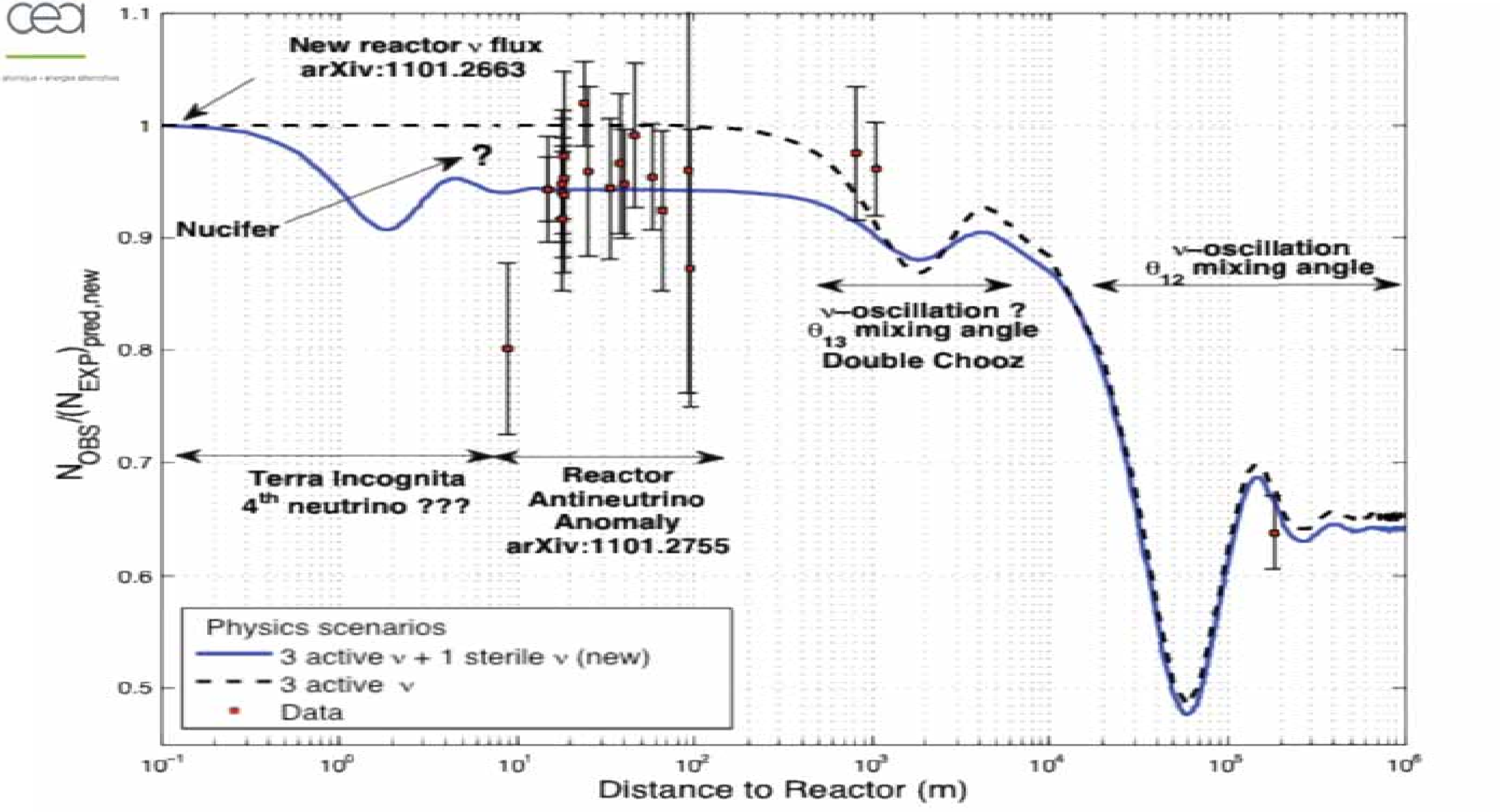
'only' θ_{13}

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) =$$



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \left[\sum_k U^{\star}_{ek} \mathrm{e}^{-im_k^2 \frac{L}{2E}} U_{ek} \right]^2 = 1 - \sin^2(2\theta_{13}) \left[\sin^2 \left(1.27 \frac{\Delta m^2_{\mathrm{atm}}[\mathrm{eV}^2 L[\mathrm{m}]]}{E[\mathrm{MeV}]} \right) \right] + O\left(\frac{\Delta m^2_{\mathrm{sol}}}{\Delta m^2_{\mathrm{atm}}} \right)$$

How to measure θ_{13}?



Long baseline reactor experiments

- Experiments with baselines > 500 m
- How do you normalize the expected flux, knowing the fuel composition?

in this slide assume Bugey-4 fuel comp.

- **If near + far detector, not an issue anymore**

Choices

σ_f^{pred}

Use $\sigma_f^{pred,new}$ =6.102 10^{-43} cm^2/fission ± 2.7%

Use $\sigma_f^{pred,old}$=5.850 10^{-43} cm^2/fission ± 2.7%

σ_f^{exp}

Use σ_f^{exp} Bugey-4=5.750 10^{-43} cm^2/fission ± 1.4%
Chooz’s choice: use lower error (total 2.7% instead of 3.3%)
Bugey-4 is a kind of “near detector” for Chooz

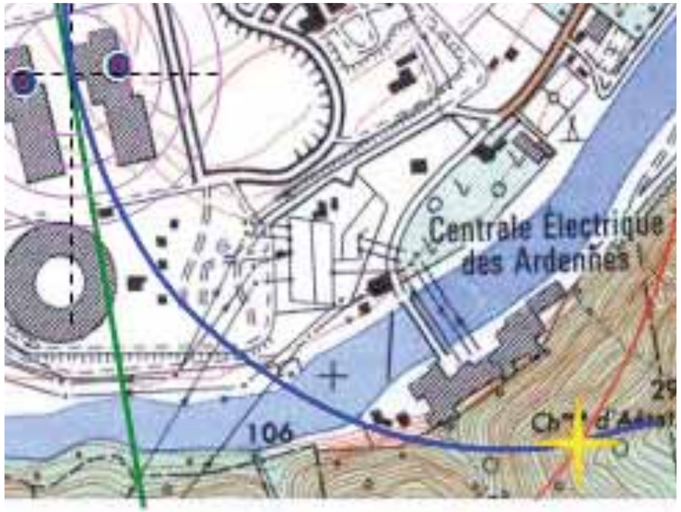
Use $<\sigma_f^{exp}>=\boldsymbol{\sigma_f^{ano}}$=5.39 10^{-43} cm^2/fission ± 1% (?)
Average over short-baseline expts.

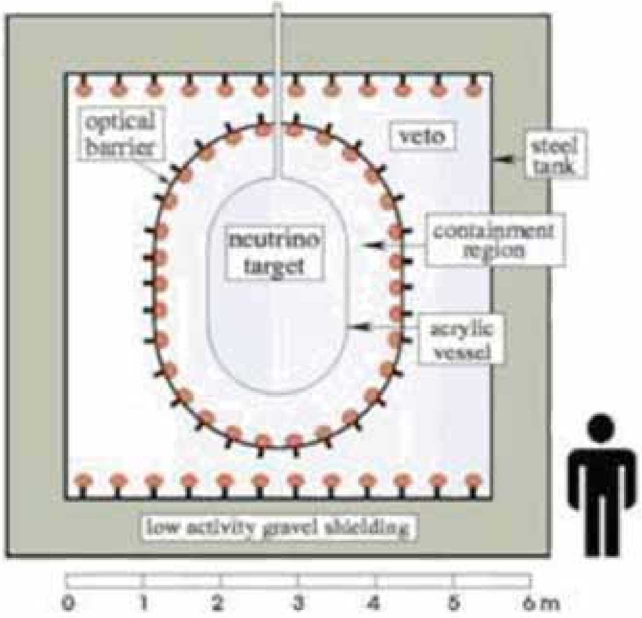
CHOOZ

- Chooz Power Station, late 90s
- liquid scintillator doped with 1g/l Gd

  5 tons, 8.4 GW, 300 mwe
- Detector placed at 1050m for the 2 cores
- Look for an oscillation at atmospheric frequency

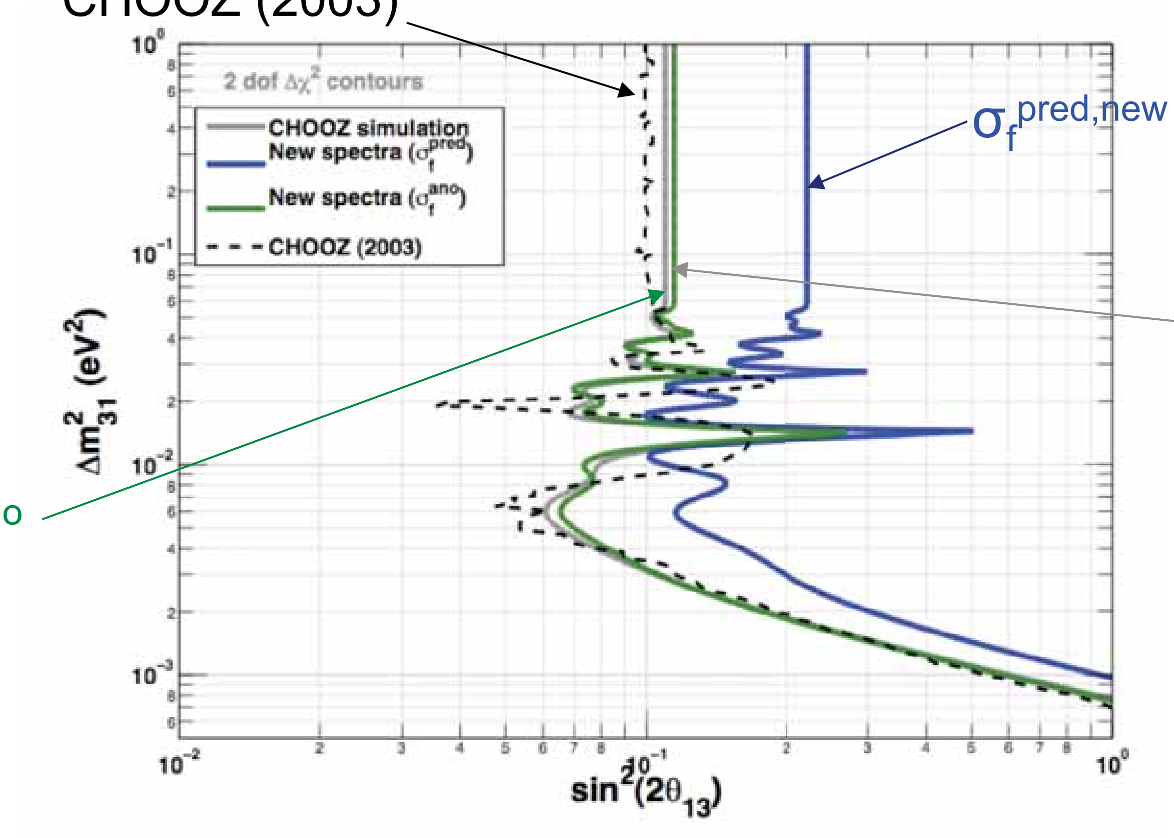
  θ_{13} mixing angle sensitivity, or more…
- Fuel composition typical of starting PWR – 57.1% ^{235}U, 29.5% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- Neutron lifetime used in original paper: 886.7 s
- **Published ratios: 1.01±0.043**
- **Revised ratios with new spectra: 0.954±0.041**
- Uncertainties:
  - Stat: 2.8%
  - Syst : 2.7% (3.3% in our work)





CHOOZ reanalysis

- The choice of σ_f changes the limit on θ_{13}
- Chooz original choice was σ_f^{exp} from Bugey-4 with low error
- If $\sigma_f^{pred,new}$ is used, limit is worse by factor of 2
- If σ_f^{ano} is used with 2.7%, we obtain the original limit
- If $\sigma_f^{ano,}$ which error should be used? → need expert inputs



CHOOZ (2003)

$\sigma_f^{pred,new}$

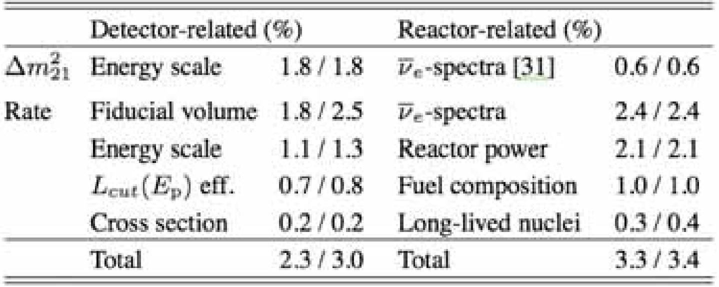
Chooz reproduction

σ_f^{ano}

Reanalysis of KamLAND's 2010 results

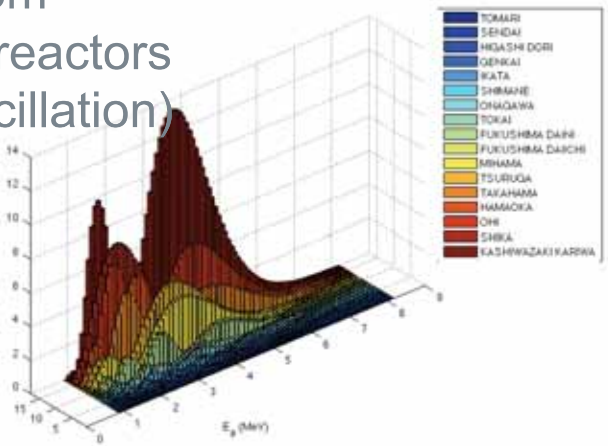
arXiv:1009.4771v2 [hep-ex]

Systematics

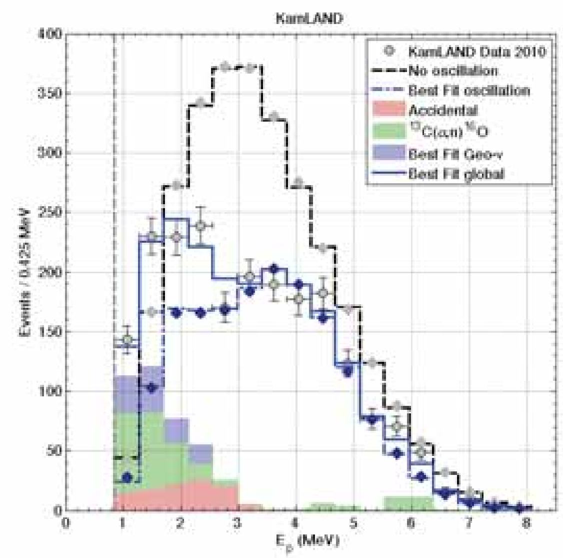


	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [31]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	2.4 / 2.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{\rm cut}(E_{\rm p})$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	3.3 / 3.4

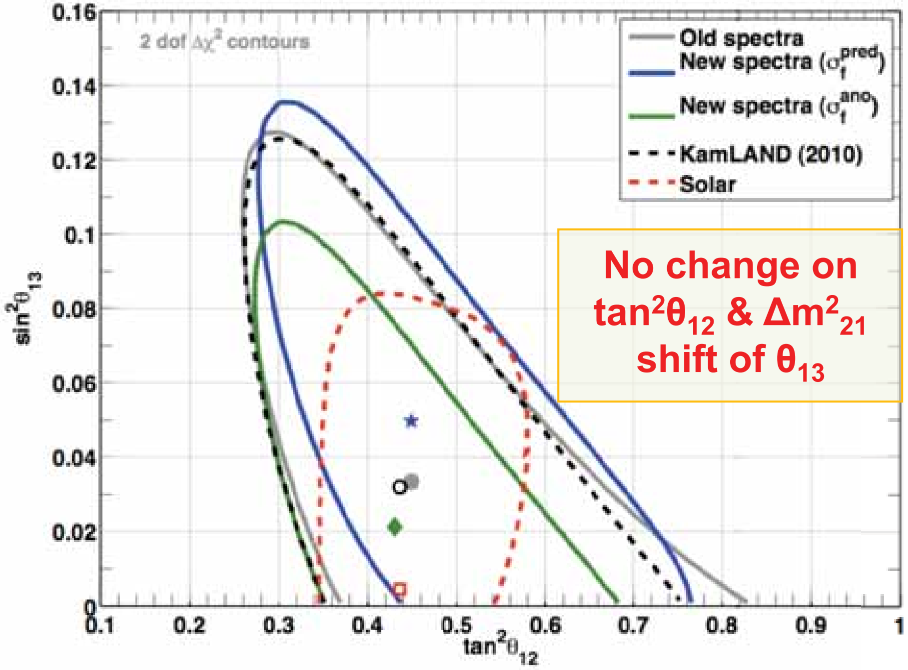
Spectra from Japanese reactors (with ν_e oscillation)



Reproduced KamLAND spectra within 1% in [1-6] MeV range



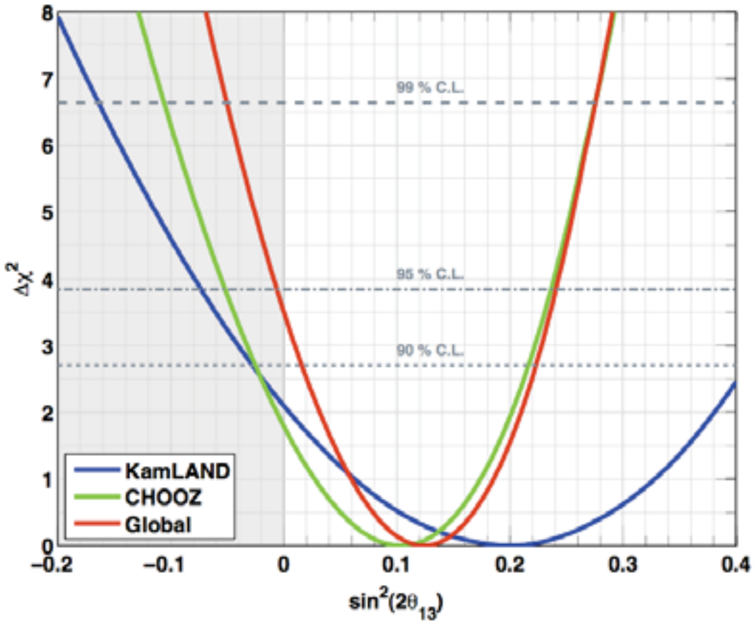
With new spectra predictions



No change on $\tan^2\theta_{12}$ & Δm^2_{21} shift of θ_{13}

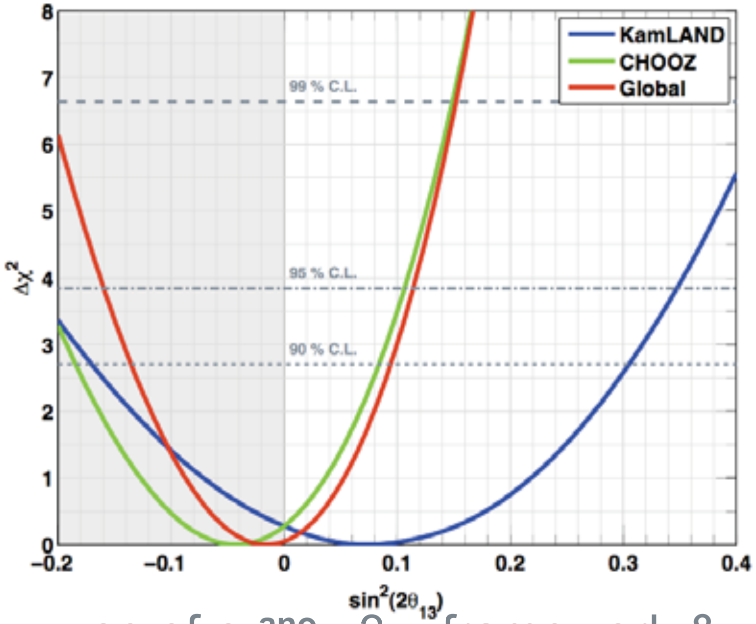
CHOOZ and KamLAND combined limit on θ_{13}

Normalization with $\sigma_f^{pred,new}$



use of $\sigma_f^{pred,new}$, 3-ν framework & 2.7% uncertainty

Normalization using σ_f^{ano}



use of σ_f^{ano} , 3-ν framework & 2.7% uncertainty (arbitrary…)

- **Our interpretation:**
  - No more hint on θ_{13}>0 from reactors
  - Global 90 % CL limit stays identical to published values
  - Multi-detector experiments are not affected