The Reactor Antineutrino Anomaly

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Introduction

- New spectra calculations presented by David Lhuillier in previous talk
- Increase of cross-section per fission
- Changes in other cross-section parameters ($\tau_n$)
- → Check past measurements, and re-compute $R=\text{measured/expected}$
- Re-investigate shape constraints for the ILL experiment
- What does it mean for neutrino oscillations?

Outline:
- The reactor anti-$\nu$ anomaly: rates in every experiment
- The ILL shape measurement
- Putting it all together
- This talk contains updated material
Computing the expected rate/spectrum


- Correct neutrino energy for proton recoil
- Recoil, WM and radiative corrections
- We used those of Vogel (1984), different from thos of Fayans but found to be numerically similar by Fayans himself
The Bugey-4 Benchmark

- Use Bugey-4's **calculations** to check ours
- Using their inputs:
  - $\tau_n = 887.4$ s
  - “old” spectra using 30 effective branch conversion
  - no off-equilibrium corrections

<table>
<thead>
<tr>
<th></th>
<th>$^{235}$U</th>
<th>$^{239}$Pu</th>
<th>$^{241}$Pu</th>
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<tbody>
<tr>
<td><strong>BUGEY-4</strong></td>
<td>6.39±1.9%</td>
<td>4.18±2.4%</td>
<td>5.76±2.1%</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td>6.39±1.8%</td>
<td>4.19±2.3%</td>
<td>5.73±1.9%</td>
</tr>
<tr>
<td><strong>Difference</strong></td>
<td>&lt;10^{-3}</td>
<td>0.2%</td>
<td>-0.5%</td>
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</table>

Final agreement to better than 0.1% on best known $^{235}$U, using Bugey-4 inputs. Validates our calculation code.
The New Cross Section Per Fission

- $\nu$-flux: $^{235}\text{U}$: +2.5\%, $^{239}\text{Pu}$ +3.1\%, $^{241}\text{Pu}$ +3.7\%, $^{238}\text{U}$ +9.8\% ($\sigma_{f}^{\text{pred}} \uparrow$)
- Off-equilibrium corrections now included ($\sigma_{f}^{\text{pred}} \uparrow$)
- Neutron lifetime decrease by a few \% ($\sigma_{f}^{\text{pred}} \uparrow$)
- Slight evolution of the phase space factor ($\sigma_{f}^{\text{pred}} \Rightarrow$)
- Slight evolution of the energy per fission per isotope ($\sigma_{f}^{\text{pred}} \Rightarrow$)
- Burnup dependence: $\sigma_{f}^{\text{pred}} = \sum_{k} f_{k} \sigma_{f,k}^{\text{pred}}$ ($\sigma_{f}^{\text{pred}} \Rightarrow$)

<table>
<thead>
<tr>
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<th>old [3]</th>
<th>new</th>
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<tr>
<td>$\sigma_{f,235\text{U}}^{\text{pred}}$</td>
<td>6.39±1.9%</td>
<td>6.61±2.11%</td>
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<tr>
<td>$\sigma_{f,239\text{Pu}}^{\text{pred}}$</td>
<td>4.19±2.4%</td>
<td>4.34±2.45%</td>
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<tr>
<td>$\sigma_{f,238\text{U}}^{\text{pred}}$</td>
<td>9.21±10%</td>
<td>10.10±8.15%</td>
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<tr>
<td>$\sigma_{f,241\text{Pu}}^{\text{pred}}$</td>
<td>5.73±2.1%</td>
<td>5.97±2.15%</td>
</tr>
</tbody>
</table>
Short baseline experiments near nuclear reactors
The 5 ROVNO88 measurements (Sov Phys JETP67, 1988)

- Rovno VVER nuclear plant, 1983-1986
- Integral detector with PE target containing $^3$He counters, only neutrons are detected
- Liquid Scintillator detector
- Measurements at 18m and 25 m
- Typical fuel composition: 60.7% $^{235}$U, 27.7% $^{239}$Pu, 7.4% $^{238}$U, 4.2% $^{241}$Pu, depends on position
- Neutron lifetime used in original paper: 898.8 s
- Published ratios:
  - 0.969, 1.001, 1.026, 1.013, 0.990
- Revised ratio with new spectra:
  - 0.917, 0.948, 0.972, 0.959, 0.938
- Uncertainties:
  - Stat: <0.9%
  - Syst : 7-8%
- Correlated with: Bugey-4, Rovno91 (integral measurement only), and with each other
The ROVNO experiment (JETP Lett., 54, 1991, 253)

- Rovno VVER nuclear plant, late 80s
- **Upgraded** integral detector: water target containing $^3$He counters, only neutrons are detected
  - Fuel composition: 61.4% $^{235}$U, 27.4% $^{239}$Pu, 7.4% $^{238}$U, 3.8% $^{241}$Pu
  - Neutron lifetime used in original paper: 888.6 s
  - Published ratio: $0.985\pm0.038$
  - Revised ratio with new spectra: $0.940\pm0.037$
  - Uncertainties:
    - Stat: <1%
    - Syst: 3.8%
  - Correlated with: Bugey-4 (same detector)
Bugey-4: most precise measurement

- Bugey PWR EdF plant, early 1990s
- Integral detector: water target containing $^3$He counters, only neutrons are detected
  - Fuel composition: 53.8% $^{235}$U, 32.8% $^{239}$Pu, 7.8% $^{238}$U, 5.6% $^{241}$Pu
- Neutron lifetime used in original paper: 887.4s
- Published ratio of $\sigma_f^{\text{measured}}$ to $\sigma_f^{\text{pred}}$: 0.987±0.030
- Revised ratio with new spectra & updates 0.943±0.029
- Uncertainties:
  - Stat: negligible
  - Syst: 3% (Most Sensitive Exp.)
- Correlated with: ROVNO (same detector)
- Visible tension between this precise measurement and $\sigma_f^{\text{pred,new}}$
- May impact the Chooz limit

Distilled water

$^3$He proportional counters 16X16
The Bugey-3 experiment (Nucl Phys B434, 504, 1995)

- Bugey PWR reactor, EdF
- 3 identical liquid scintillator segmented detectors doped with $^6$Li for n capture
- Fuel composition typical of PWR – 53.8% $^{235}$U, 32.8% $^{239}$Pu, 7.8% $^{238}$U, 5.6% $^{241}$Pu
- Neutron lifetime in original paper: 889 s
- Published ratios at 14m, 42m and 95m: 0.988±0.050, 0.994±0.051, 0.915±0.13
- Revised ratios with new spectra: 0.940±0.047, 0.943±0.048, 0.873±0.12
- Uncertainties:
  - Stat: 0.4%, 1.0%, 13.2%
  - Syst : 5.0%
- Correlated with: none, but the three measurements are correlated together
The Gösgen experiment (Phys Rev D34, 2621, 1986)

Gösgen PWR, Switzerland, 1981-1984

- Liquid scintillator segmented detector + $^3$He counters for neutron capture
  - Detector placed at 37.9m, 45.9m, 64.7m
  - 3 fuel compositions published. Typical:
    - 61.9% $^{235}$U, 27.2% $^{239}$Pu, 6.7% $^{238}$U, 4.2% $^{241}$Pu
  - Neutron lifetime used in original paper: 897 s
  - Published ratios: 1.018±0.066, 1.045±0.068, 0.975±0.074
  - Revised ratios with new spectra:
    - 0.966±0.062, 0.991±0.064, 0.924±0.070
  - Uncertainties:
    - Stat: 2.4%, 2.4%, 4.7%
    - Syst: 6.0%
  - Correlated with ILL + 3 measurements are correlated together
The ILL experiment (Phys Rev D24, 1981, 1097)

- ILL RR in Grenoble, 1979-1980
- Liquid scintillator segmented detector + $^3$He counters for neutron capture
  - Detector placed at 8.76(15) m
  - Fuel composition: almost pure $^{235}$U
  - Data reanalyzed in 1995 by sub-group of collaboration to correct 10% error in reactor power
- Neutron lifetime: 889 s in 95
- Published ratio: $0.832 \pm 0.079$ (1995)
- Revised ratio with new spectra: $0.801 \pm 0.076$
- Uncertainties:
  - Stat: 3.5%
  - Syst: 8.9%
- Correlated with Gosgen
Krasnoyarsk reactor in Russia

- Integral detector filled with PE+ $^3$He counters for neutron capture
- Detector placed at 33m, 92m from 2 reactors (1987) and 57.3m from 2 reactors (1994)
- Fuel composition: mainly $^{235}$U
- Neutron lifetime in original paper: 899 s
- Published ratios: $1.013 \pm 0.066, 1.031 \pm 0.068, 0.989 \pm 0.074$
- Revised ratios with new spectra: $0.944 \pm 0.062, 0.954 \pm 0.064, 0.954 \pm 0.070$
- Uncertainties:
  - Stat: 3.6%, 1% at 57m, 19.9% at 92.3m
  - Syst: 4.8% to 5.5% (corr)
- Correlated together (same detector, WINS)
The (last) Savannah River experiments

- Savannah River, USA, late 80s - early 90s
  - Liquid scintillator doped with 0.5% Gd
  - Detector placed at 18.2 m and 23.8 m
  - Fuel composition: difference with pure $^{235}$U below 1.5%
  - Neutron lifetime used in original paper: 887 s
  - Published ratios: $0.987 \pm 0.037, 1.055 \pm 0.040$
  - Revised ratios with new spectra: $0.953 \pm 0.036, 1.019 \pm 0.039$
  - Uncertainties:
    - Stat: 0.6% and 1.0%
    - Syst: 3.7%
  - Correlated together

(Revised) Savannah River, USA, late 80s - early 90s
- Liquid scintillator doped with 0.5% Gd
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- Fuel composition: difference with pure $^{235}$U below 1.5%
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- Uncertainties:
  - Stat: 0.6% and 1.0%
  - Syst: 3.7%
- Correlated together

(PRD53, 6054, 1996)
Correlations

- Correlations are difficult to take into account and will impact the result

- Our guiding principles:
  - Be conservative
  - Be stable numerically: if small changes in correlations cause large changes in result, something is off...

- We correlated experiments in the following way:
  - 2% systematic on flux 100% correlated over all measurements
    Different from 2.7% published on arxiv:
    2% is the part corresponding to the normalization error on the ILL e- data
  - 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.
    - Rovno88 integral measurements 100% corr. with Rovno 91 despite detector upgrade, but not with Rovno88 LS data
    - Rovno88 integral meas. 50% correlated with Bugey-4
Experimental correlation matrix

- Bugey-4 15m
- Rovno91 18m
- Bugey-3 15m
- Bugey-3 40m
- Bugey-3 92m
- Goesgen 38m
- Goesgen 45m
- Goesgen 65m
- ILL 9m
- Krasno 33m
- Krasno 92m
- Krasno 57m
- SRP I 18m
- SRP II 25m
- Rovno88 1I 18m
- Rovno88 2I 18m
- Rovno88 1S 18m
- Rovno88 2S 25m
- Rovno88 3S 18m
The reactor neutrino anomaly
The reactor anti-neutrino anomaly

\[ \sigma_{\text{f, pred,new}} \]

\[ \sigma_{\text{f, ano}} \]
We use least-squares estimators and $\chi^2$ distributions to get confidence bounds.

Our data points are ratios of gaussians:

- Numerator: measurement, gaussian with stat & syst error
- Denominator: theoretical calculation, assumed to have Gaussian fluctuation of 2%
- Are the ratios normally distributed?

Toy MC w/ correlated denominator with 2% fluctuation $\rightarrow 10^6$ events

- Numerators correlated using previous matrix
- Estimate weighted average $R$ of 19 random points with correlations.

$P$-value for ($R \geq 1$) : 1.3% ($2.22\sigma$) compared to naive Gaussian $2.29\sigma$.

Our contours are reweighted by $(2.22/2.29)^2$ to take this slight non-normality into account $\chi^2_{\text{min}}$ of data to straight line in the 18% quantile

$\rightarrow$ Data not incompatible with fluctuations
The reactor rate anomaly

- Each short baseline experiment < 100m from a reactor observed a deficit of anti-$\nu_e$ compared to the new expectation
- The effect is statistically significant at more than 2 $\sigma$
- Effect partly due to re-evaluation of cross-section parameters, especially updated neutron lifetime
- Three possibilities:
  - Our calculations are wrong. We don’t think so… we encourage nuclear physics groups to cross-check independently
  - Bias in all short-baseline experiments near reactors: unlikely! Different fuel compositions & detection techniques advocate against trivial bias
  - New physics at very short baselines, explaining a deficit of anti-$\nu_e$:

  Oscillation towards a 4$^{th}$, sterile $\nu$?
  a 4$^{th}$ oscillation mode with $\theta_{\text{new}}$ and $\Delta m^2_{\text{new}}$
The reactor rate anomaly

- Combine all rate measurements, no spectral-shape information
- Fit to anti-$\nu_e$ disappearance hypothesis

Absence of oscillations disfavored at 98.64% C.L.
Next step: include shape analyses of experiments with best shape information
Spectral shape analysis of Bugey-3

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

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

- 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 8m 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

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 $a$:

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

- 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
- **Needed error**: 11%, uncorrelated, in each bin.
- **We can reproduce the results quite well**
- **Question for ILL experts in the room**: How large is the shape systematic?

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**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. Is this plausible for this experiment?
- Running with the re-evaluated ratios, we obtain the following shape-only contour

Null hyp accepted at 1 $\sigma$
No oscillation disfavored at 96.51% CL with full rate+shape combination
Best fit: $\sin^2 2\theta \sim 0.12$, $\Delta m^2 \sim 2.4 \text{ eV}^2$
The Gallium anomaly
The Gallium anomaly

- 4 calibration runs with intense (~ MCi) neutrino (not anti-neutrino!) sources:
  - 2 runs at GALLEX with a $^{51}$Cr source (750 keV $\nu_e$ emitter)
  - 1 run at SAGE with a $^{51}$Cr source
  - 1 run at SAGE with a $^{37}$Ar source (810 keV $\nu_e$ emitter)
- All observed a deficit of neutrino interactions compared to the expected activity. Hint of oscillation?

- Our analysis:
  - Monte-Carlo to compute mean path length of neutrino in Ga tanks, for GALLEX & SAGE
  - Correlate the 2 GALLEX runs together and the 2 SAGE runs together

![Data and Best fit](image)
Correlation study

- The 4 runs are correlated together
  - Gallex runs ~10% stat error, 5.6% and 7.4% systematics
  - SAGE runs: 12% (Cr) and 8% (Ar) stat error, 5.7% and 7% syst

- Again, potential deviation from normality in ratios

- Toy MC: draw uncorrelated numerators (within stat errors) and correlated denominators according to systematics

- Fit 4 ratios by constant $\bar{R}$, including correlations

- $P(\bar{R}>1) = 1.24\% (2.24\sigma)$ instead of 0.80% in Gaussian approx

- Data $\chi^2_{\text{min}}$ in 68% quantile of $\chi^2_{\text{min}}$ distribution for toyMC
The Gallium anomaly

- Effect reported in C. Giunti & M. Laveder in PRD82 053005 (2010)
- Significance reduced by additional correlations in our analysis
- No-oscillation hypothesis disfavored at 97.7% C.L.
Putting it all together: reactor rates + shape + Gallium + MB

The no-oscillation hypothesis is disfavored at 99.86% CL
Long baseline reactor anti-neutrino experiments and $\theta_{13}$
\[ P(\bar{v}_e \rightarrow \bar{v}_e) = \sum_{i=1,2,3} \text{Ampl}_i \]

\[ \sum P(\bar{v}_e \rightarrow \bar{v}_e) = \left[ \sum_i U_{ei}^* -i m_i^2 \frac{L}{2E} U_{ei} \right]^2 = 1 - \sin^2(2\theta_{13}) \left[ \sin \left( 1.27 \frac{\Delta m^2_{\text{atm}}}{E \text{(MeV)}} \right) \right] + O\left( \frac{\Delta m^2_{\text{sol}}}{\Delta m^2_{\text{atm}}} \right) \]
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

Use $\sigma_{f}^{\text{pred,new}} = 6.102 \times 10^{-43} \text{ cm}^2/\text{fission} \pm 2.7\%$

Use $\sigma_{f}^{\text{pred,old}} = 5.850 \times 10^{-43} \text{ cm}^2/\text{fission} \pm 2.7\%$

Choices

Use $\sigma_{f}^{\text{exp, Bugey-4}} = 5.750 \times 10^{-43} \text{ cm}^2/\text{fission} \pm 1.4\%$

Chooz’s choice: use lower error (total 2.7\% instead of 3.3\%)

Bugey-4 is a kind of “near detector” for Chooz

Use $<\sigma_{f}^{\text{exp}}>=\sigma_{f}^{\text{ano}} = 5.39 \times 10^{-43} \text{ cm}^2/\text{fission} \pm 1\%$ (?)

Average over short-baseline expts.
- 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
- $\theta_{13}$ 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)
The choice of $\sigma_f$ changes the limit on $\theta_{13}$

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

**Diagram:**

- $\sigma_f^{\text{ano}}$ 2.7% error
- $\sigma_f^{\text{ano}}$ 1% error

**CHOOZ (2003)**
KamLAND experiment

- Reactor anti-neutrino experiment with average baseline around 180 km.
- 80% of total flux comes from reactors 140 to 210 km away.
  - ~ 1 kt liquid scintillator detector

~ 4% syst. uncert. on normalization
~ 1-2% syst. on energy scale.

arXiv:1009.4771v2 [hep-ex]
Reanalysis of KamLAND’s 2010 results

arXiv:1009.4771v2 [hep-ex]

Systematics

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<thead>
<tr>
<th>Detector-related (%)</th>
<th>Reactor-related (%)</th>
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<tbody>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$\bar{\nu}_e$-spectra [31]</td>
</tr>
<tr>
<td>Energy scale</td>
<td>1.8 / 1.8</td>
</tr>
<tr>
<td>Rate</td>
<td>$\bar{\nu}_e$-spectra</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>1.8 / 2.5</td>
</tr>
<tr>
<td>Energy scale</td>
<td>1.1 / 1.3</td>
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<tr>
<td>$L_{\text{cut}}(E_p)$ eff.</td>
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<tr>
<td>Cross section</td>
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<tr>
<td>Total</td>
<td>2.3 / 3.0</td>
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<tr>
<td></td>
<td>Total</td>
</tr>
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<td></td>
<td>3.3 / 3.4</td>
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Reproduced KamLAND spectra within 1% in [1-6] MeV range

Spectra from Japanese reactors (with $\nu_e$ oscillation)

With new spectra predictions

No change on $\tan^2\theta_{12}$ & $\Delta m^2_{21}$ shift of $\theta_{13}$
Normalization with $\sigma^{\text{pred,new}}_f$

- Use of $\sigma^{\text{pred,new}}_f$, 3-v framework & 2.7% uncertainty

**Our interpretation:**
- No more hint on $\theta_{13}>0$ from reactors
- Global 90 % CL limit stays identical to published values
- Multi-detector experiments are not affected
The choice of normalization is crucial for reactor experiments looking for $\theta_{13}$.

- A deficit observed at long baseline can either be caused by $\theta_{13}$ or by new physics closer to the core (oscillation towards a 4th neutrino, $\theta_{\text{new}}$).

- If the sterile hypothesis from this work is proven, then using $\sigma_f^{\text{pred,new}}$ with 2.7% error is justified, together with a 3+N neutrino framework.

- Using $\sigma_f^{\text{ano}}$, effects at short distances are absorbed:
  - 3 neutrino framework
  - Error budget: weighted standard deviation of experimental errors ~1-2%?
Conclusion

- New calculation of anti-$\nu_e$ spectra produced at a nuclear reactor
  Overall interaction rate is increased by +3.5% compared to previous calculations
- Re-analysis of (almost) all past short baseline experiments:
  - Average measured/expected ratio = 0.943±0.023
  - Reactor anti-neutrino anomaly
  - Is it new physics? A sterile neutrino?
- Rate+shape short-baseline data compatible with anomaly seen at Gallium experiments with MCi sources, and Miniboone $\nu$ data
  - Overall, no-oscillation hypothesis disfavored at 99.84% CL
  - Data compatible with $\Delta m^2 \gtrsim 1$ eV$^2$ and $\sin^2 2\theta \sim 0.1$
  - Compatible with LSND & Miniboone data?
- Middle/Long-baseline reactor experiments: deficit from anomaly could be mis-interpreted as a hint for non-zero $\theta_{13}$
  - Revised constraint: $\sin^2 2\theta_{13} < 0.095$ at 90%CL $\rightarrow$ No “hint”
  - Relax tension between Chooz+KamLAND and solar data
Conclusion and Outlook

- Assuming a 4th, sterile neutrino with mass ~ 1 eV exists, could it be detectable?
  - Direct $\beta$ spectrum measurements: within sensitivity of KATRIN
  - If Majorana, the contribution of such a state would be of interest to future $\beta\beta0\nu$ experiments

- Slightly favored by some cosmological models:
  - WMAP+BAO fit $4.34\pm0.87$ neutrino-like radiations
  - But compatibility of 1 eV neutrino should be studied carefully (to much hot dark matter?)

- Clear experimental confirmation / infirmation is needed:
  - Nucifer: small detector, 7 m from the small Osiris core
  - Insert a MCi source into large detector with energy & spatial resolution, eg SNO+, Borexino, KamLAND