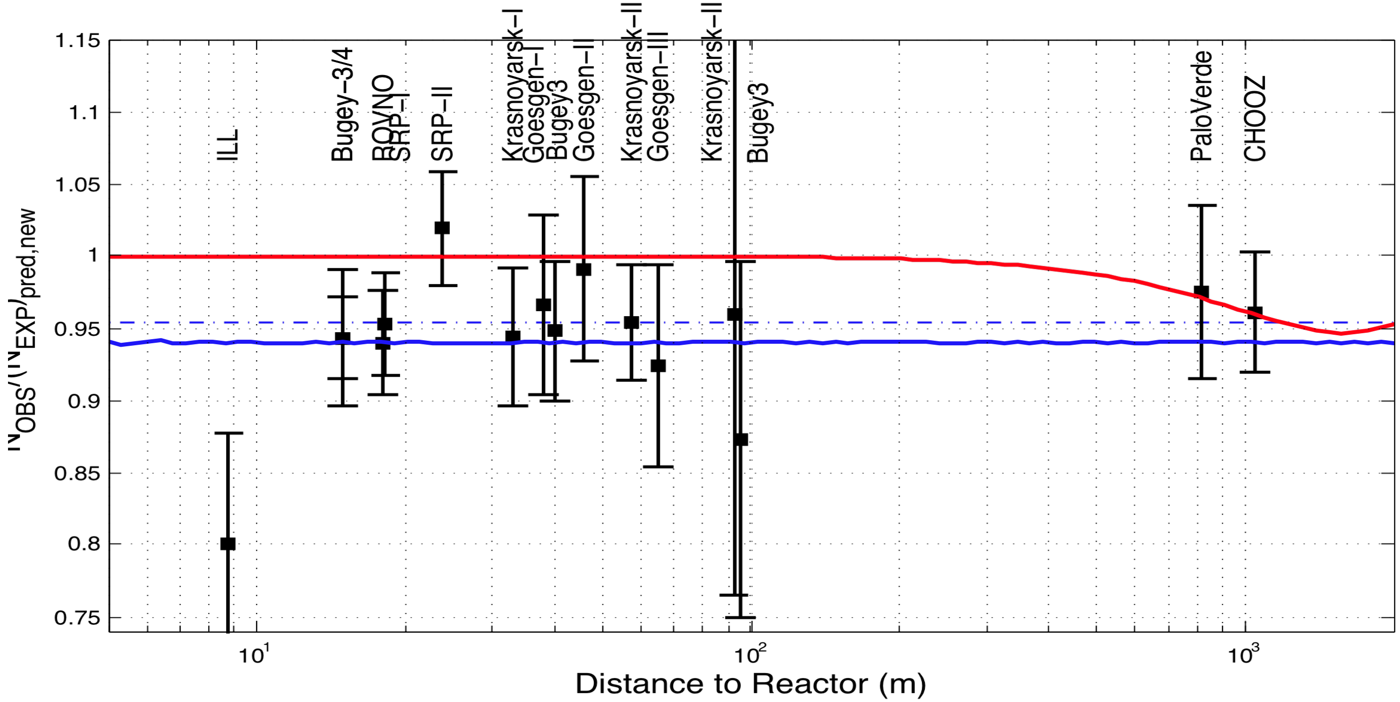
energie atomique • energies alternatives

The Reactor Antineutrino Anomaly



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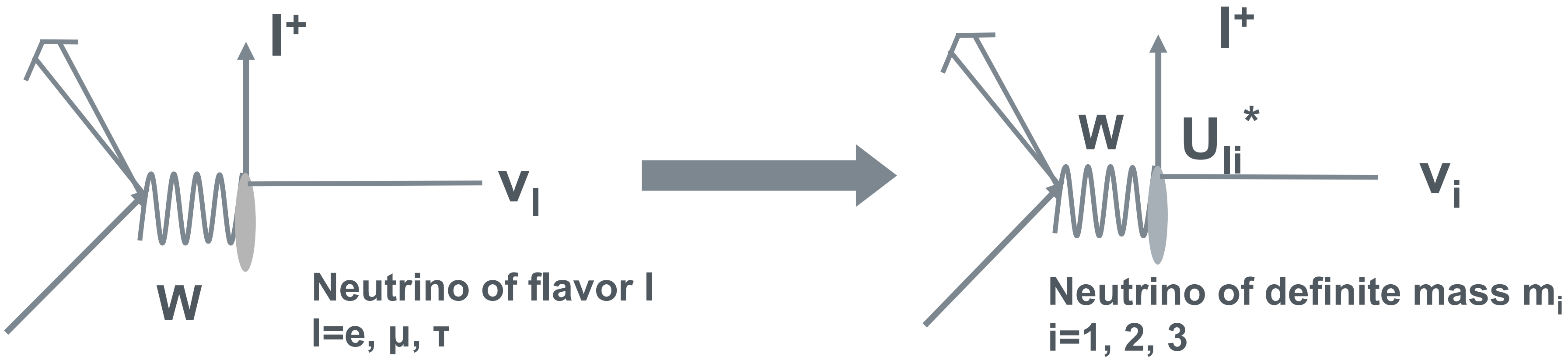
CEA / Irfu

Reactor anti-neutrino spectra

& cross-sections

Neutrino Mass and Mixing

- Neutrino: spin ½, neutral, left handed chirality (~helicity), $\sigma \sim 10^{-43}$ cm^2 (reactor)
- For 10 yrs we know neutrinos have tiny masses and mix: $0.04\ \mathrm{eV} < m_\nu < \sim 1\ \mathrm{eV}$
- Two views on W decay:



Neutrino of flavor l
l=e, μ, τ

Neutrino of definite mass m_i
i=1, 2, 3

- PMNS mixing matrix U relates mass & flavor bases: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$
- First compelling evidence of physics Beyond the Standard Model

Three Active Neutrino Oscillation formalism

$$P(\bar{\nu}_x \rightarrow \bar{\nu}_x) = 1 - \sin^2(2\theta_i)\sin\left(1.27\,\frac{\Delta m_i^2\ (\mathrm{eV}^2)\,L\ (\mathrm{m})}{E\ (\mathrm{MeV})}\right)$$

Atmospheric Cross-Mixing Solar Majorana ~~CP~~ phases

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} : "atm." mixing angle θ_{13} θ_{12} : "solar" mixing angle

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

δ Dirac CP violating phase

2 Majorana phases
(L violating processes)

- 3 masses m_1, m_2, m_3 : $\Delta m^2_{\mathrm{sol}} = m_2^2 - m_1^2\ \&\ \Delta m^2_{\mathrm{atm}} = \left|m_3^2 - m_1^2\right|$
- 3-flavour effects are suppressed because : $\Delta m^2_{\mathrm{sol}} << \Delta m^2_{\mathrm{atm}}\ (1/30)\ \&\ \theta_{13} << 1$

Reactor anti-neutrinos: introduction

- **Electron antineutrinos emitted through Decays of Fission Products**
  - Fissions of: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - $^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \xrightarrow{23\ \mathrm{min}} ^{239}_{93}\mathrm{Np} \xrightarrow{2.3\ \mathrm{d}} ^{239}_{94}\mathrm{Pu}$

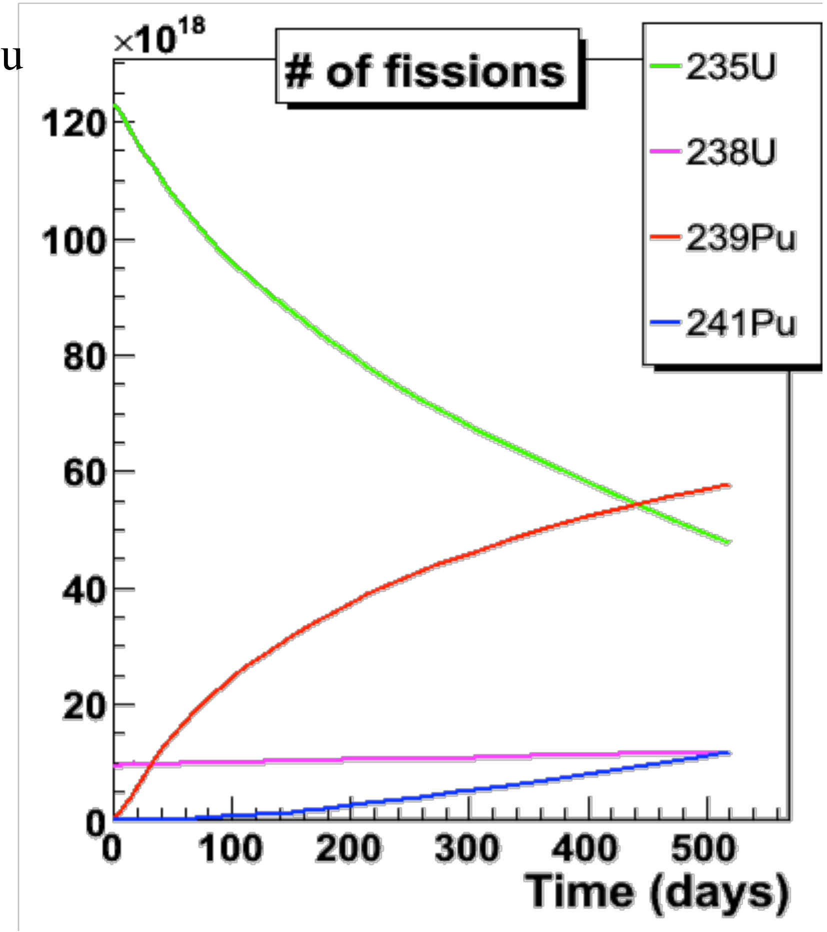
- **Nuclear reactors**

$$1\,\mathrm{GW_{th}} \Leftrightarrow 2.10^{20}\ \nu/\mathrm{s}$$

- **Neutrino Luminosity**

$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$

N_ν : neutrino flux
P_{th}: thermal Power (GW)
γ: reactor constant
k : fuel evolution correction up to 10%



t_0: ~3.5% ^{235}U, 96.5% ^{238}U

Reactor-ν spectra (S_{tot})

spectrum for isotope *k* (^{235,238}U & ^{239,241}Pu)

$$S_{tot}(E_\nu) = \sum_k f_k S_k(E_\nu)$$

fission product *fp* activity

spectrum of fission product *fp*

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

branching ratio of fission product *fp*, branch *b*

spectrum of fission product *fp*, branch *b*

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

$$S^b_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

$$\times \underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\Big(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\Big)}_{\text{Correction}}$$

$$\delta^b_{fp}(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

Reactor-ν flux prediction

- **Stage 1: time evolution of nuclear fuel (k=^{235,238}U & ^{239,241}Pu)**

  → initial fuel composition
  → nuclear core evolution code (core geometry)
  → Thermal power $P_{th}(t)$

- **Stage 2: electron spectra**

  → 750 nuclei, 10^4 β-branches of each nucleus involved
  → theory of β-decay + forbidden decay models
  → accurate measurements at ILL by Schreckenbach et al in the early 1980s for ^{235}U & ^{239,241}Pu with 1.8% normalization error
  → ab-initio calculations for ^{238}U (10% uncertainty)

- **Stage 3: anti-ν_e spectra**

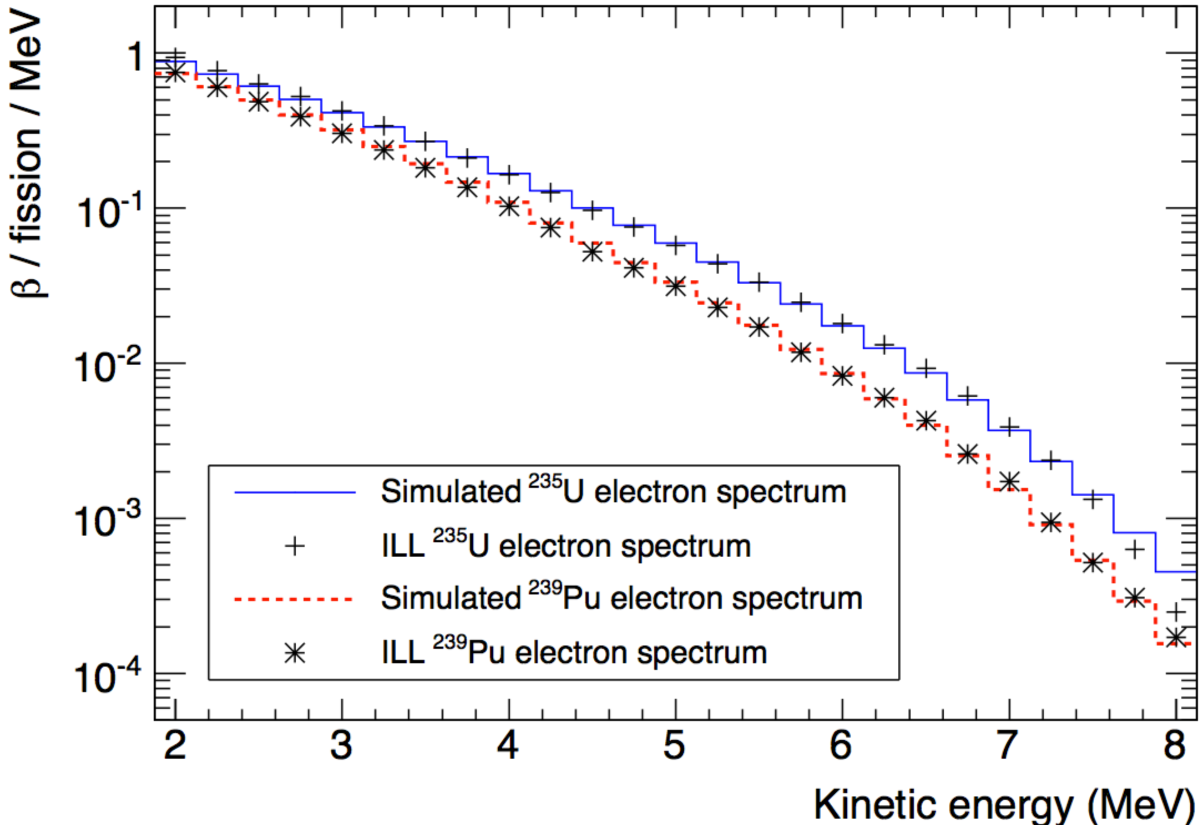
  → need to convert electron to antineutrino spectra
  →“Old approach” by Schreckenbach et al.
  → **New approach developed at Saclay leading to a +3% normalization shift (Th. Mueller et al., Arxiv:1101.2663)**

Reactor-ν flux prediction

- Accurate reproduction of the ILL electron data (within 1%, ILL stat error)
- The emitted antineutrino spectrum is then given by:

$$S_{tot}(E_\nu) = \sum_k f_k S_k(E_\nu)$$

- f_k : contribution of ^{235,238}U & ^{239,241}Pu to the total number of fissions
- S_k : neutrino spectrum of ^{235,238}U & ^{239,241}Pu

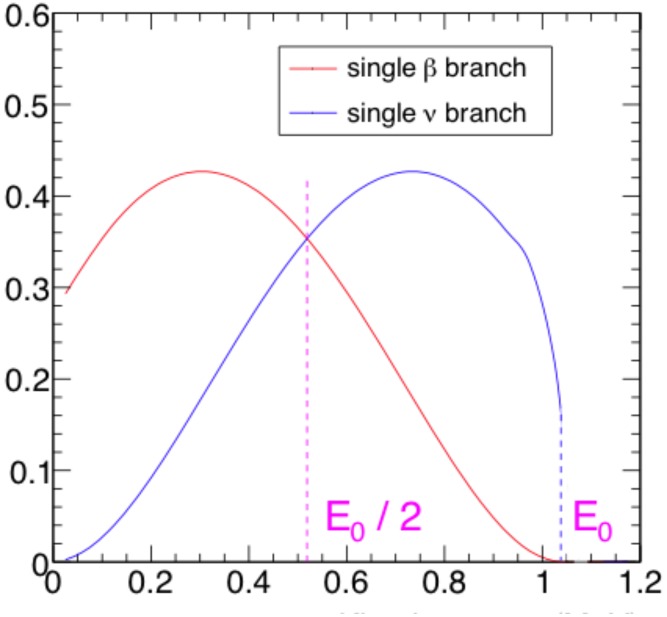


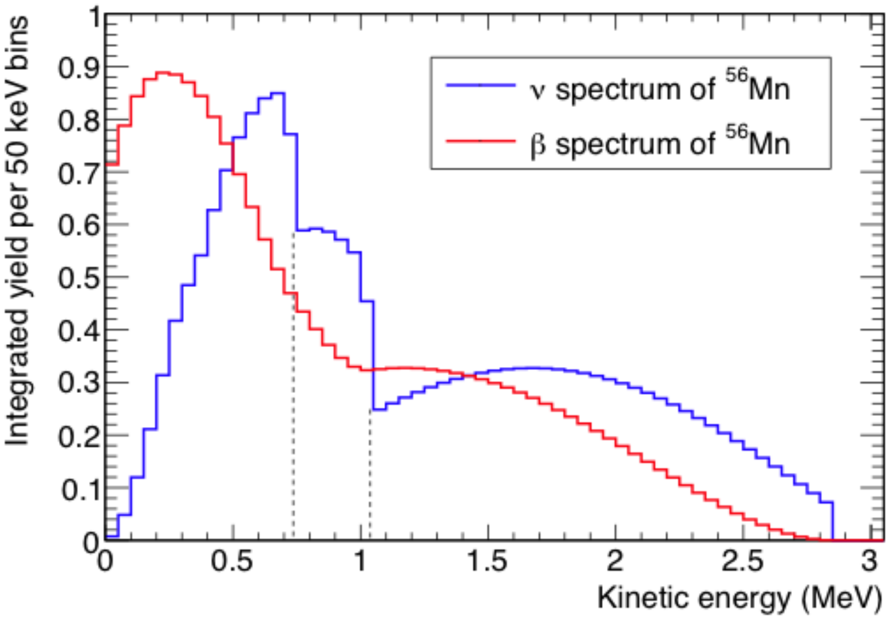
From e^- to anti-ν_e spectra

- **A single beta decay branch:** $${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \overline{\nu}_e$$

- Depends on: branching ration (BR), end point, Z, R, spin-parity
- Energy conservation: $E_e + E_\nu = Q$

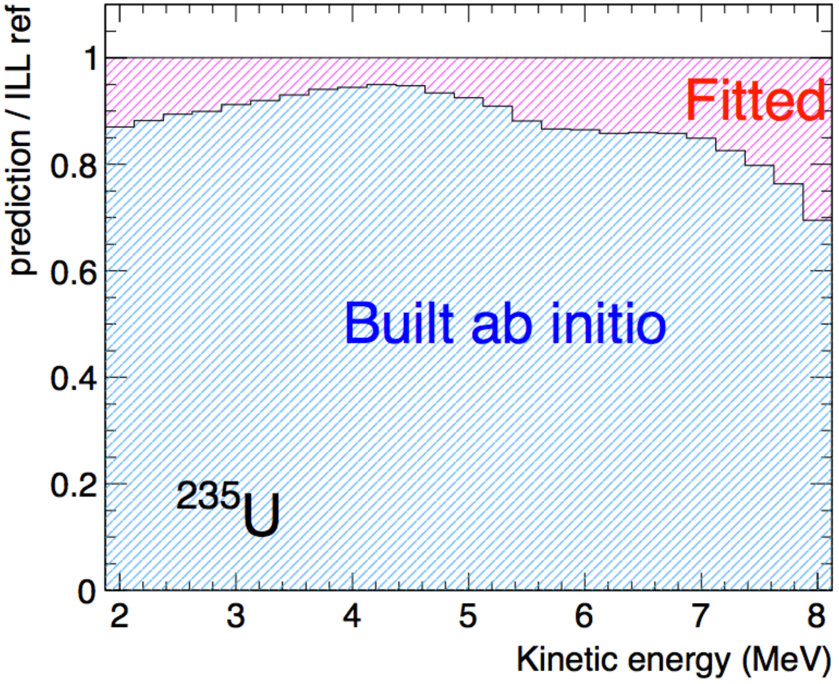
- e^- spectra from fission products have been measured (but ^{238}U)
- Antineutrino spectra are computed from electron spectra…

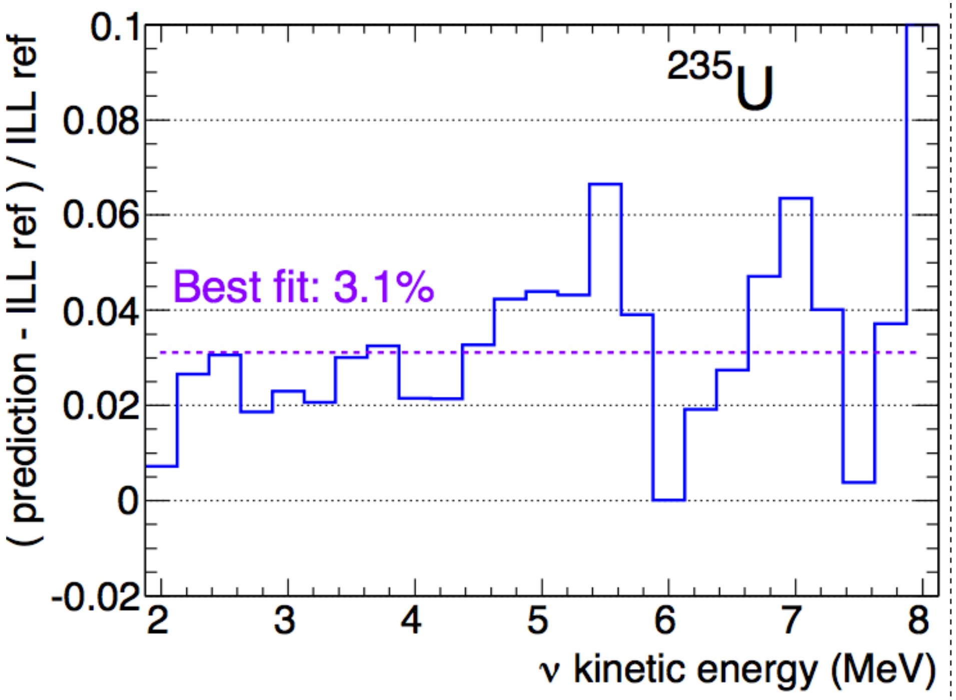




New reactor ν-spectra (Saclay)

- Electron to antineutrino spectra:
  - OLD: 30 ‘effective’ branches method
  - **NEW: conversion method accounting accurately for 95% of the whole information, 10^4 β-branches from nuclear databases (Th. Mueller’s PhD).**
- Full error propagation and correlations included



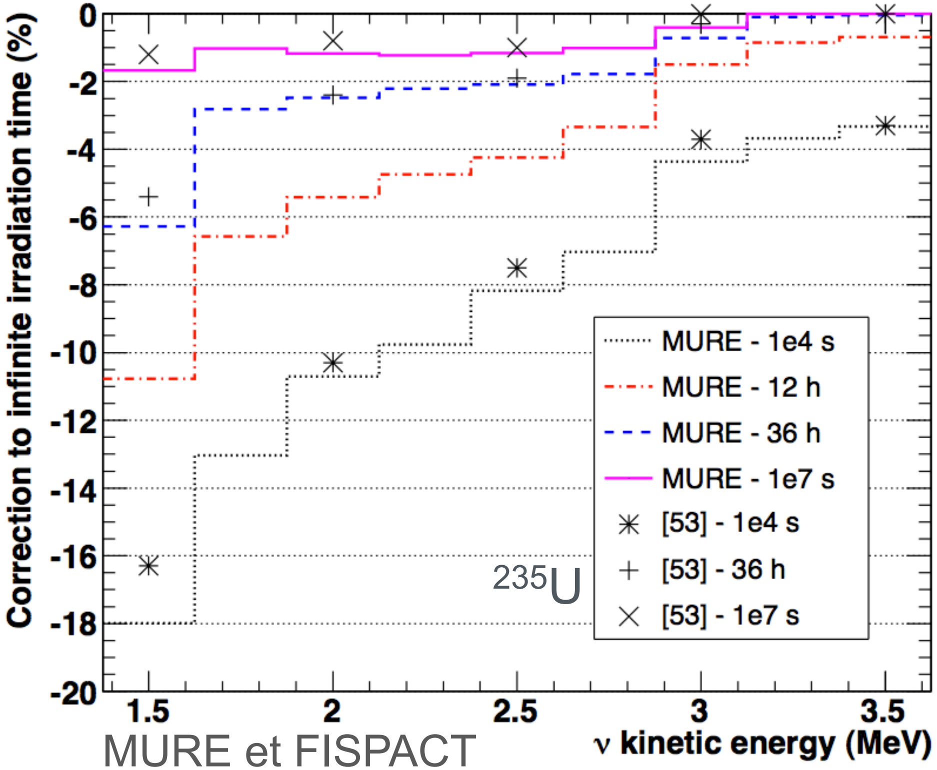


- +3% systematic bias (averaged) with respect to previous results

E<4MeV : Accurate C & WM corrections, E>4 MeV: real branches accounted for

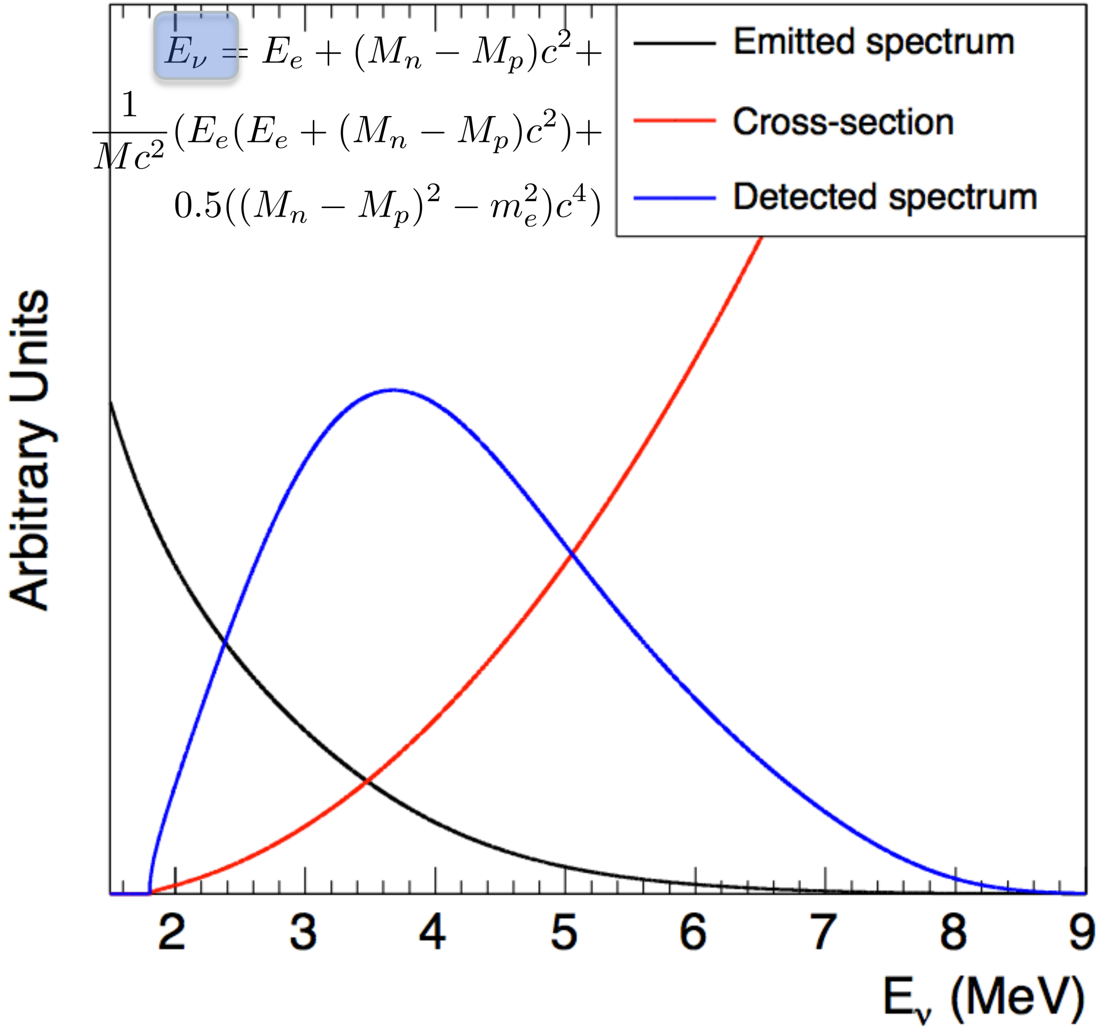
Off-Equilibrium Effects (Subatech)

- ILL electron reference spectra : 12 hours to 1.8 days irradiation time
- Neutrino reactor experiments irradiation time : >1 year
- **BUT** 10% of fission products have a β-decay life-time long enough to keep accumulating after several days → need a correction through simulation
- This correction was not included prior to the CHOOZ experiment (1999)



MURE et FISPACT
(Subatech Nantes)

Inverse beta decay reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$



$$E_\nu = E_e + (M_n - M_p)c^2 + \frac{1}{Mc^2}(E_e(E_e + (M_n - M_p)c^2) + 0.5((M_n - M_p)^2 - m_e^2)c^4)$$

$$\sigma_f^{pred} = \int_0^\infty S_{tot}(E_\nu)\sigma_{\mathrm{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{pred}$$

New Predicted Cross Section per Fission

- Predicted Cross Section Normalized Per fission
  - → S_{tot} : Reactor Antineutrino Spectrum (Schrekenbach or Saclay)
  - → $\sigma_{V\text{-}A}$: Weak interaction IBD cross section (PRD 29, 1918,1984)

$$\sigma_f^{pred} = \int_0^\infty S_{tot}(E_\nu)\sigma_{\mathrm{V-A}}(E_\nu)dE_\nu$$

$$\sigma_{\mathrm{V-A}}(E_e) = \frac{2\pi^2\hbar^3}{m_e^5 c^7 f \tau_n} p_e E_e (1 + \delta_{rec} + \delta_{wm} + \delta_{rad})$$

→ τ_n : neutron mean lifetime (PDG, a few% variation in 30y)
→ f : phase space factor (NIM A 404 (1998) 305-310)
→ δ_{rec} : proton recoil correction (few 0.1%)
→ δ_{wm} : weak magnetism correction (few 0.1%)
→ δ_{rad} : radiative correction (few 0.1%)

} PRD 29, 1918 (1984)

The Bugey-4 Benchmark

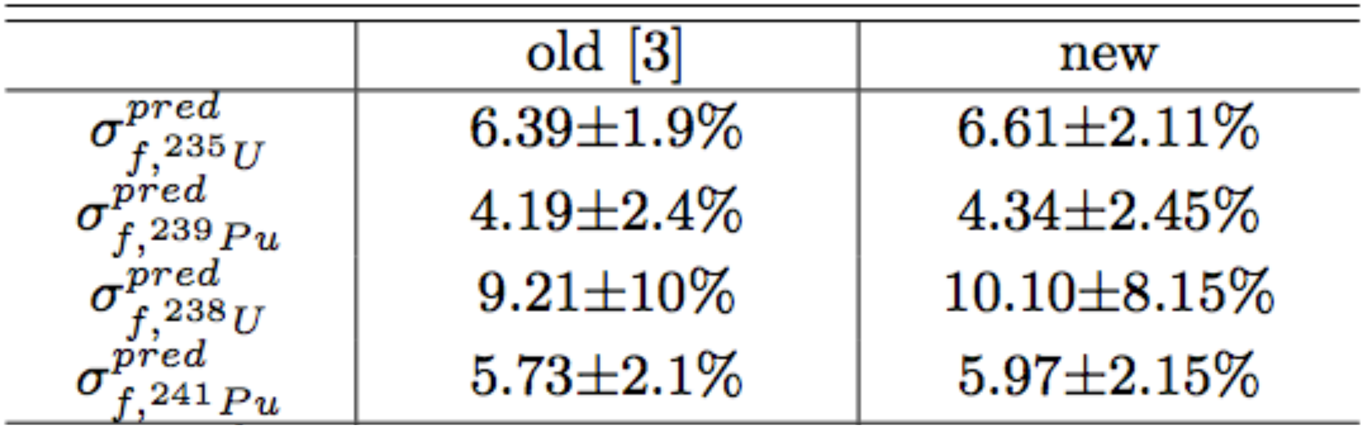
- How do we benchmark our calculations ?
- Compare with reference publication of BUGEY-4 (Phys Lett B 338(1994)383) for isotopes measured by Schreckenbach et al. in the 80's
- Using their inputs:
  - τ_n = 887.4 s
  - "old" spectra using 30 effective branch conversion
  - no off-equilibrium corrections

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±1.8%	4.19±2.3%	5.73±1.9%
Difference	$<10^{-3}$	0.2%	-0.5%

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

- ν-flux: ^{235}U : +2.5%, ^{239}Pu +3.1%, ^{241}Pu +3.7%, ^{238}U +9.8% (σ_f^{pred} ↗)
- Off-equilibrium effects (σ_f^{pred} ↗)
- Neutron lifetime decrease by a few % (σ_f^{pred} ↗)
- 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} →)

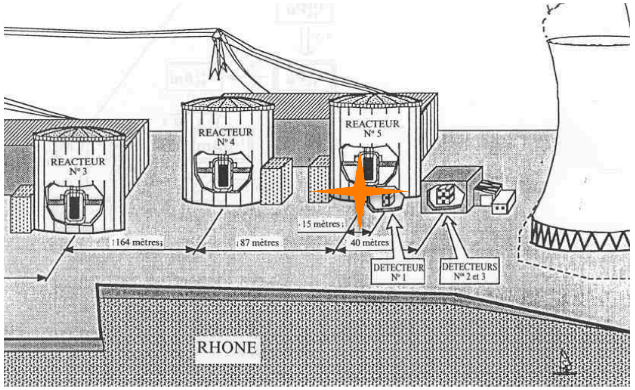


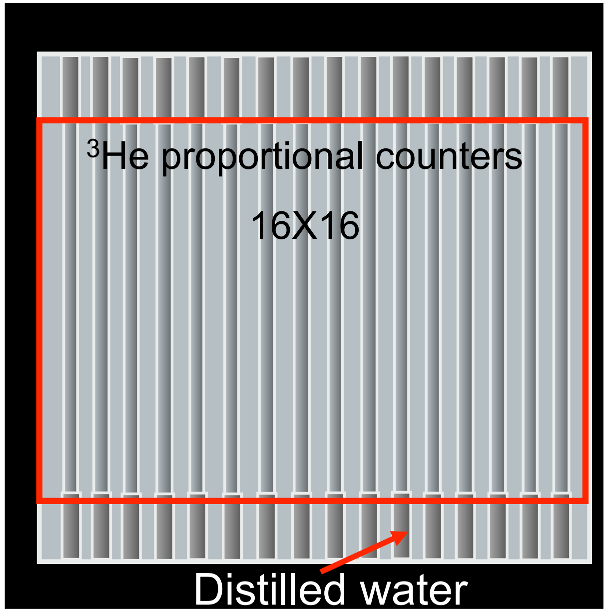
	old [3]	new
$\sigma_{f,^{235}U}^{pred}$	6.39±1.9%	6.61±2.11%
$\sigma_{f,^{239}Pu}^{pred}$	4.19±2.4%	4.34±2.45%
$\sigma_{f,^{238}U}^{pred}$	9.21±10%	10.10±8.15%
$\sigma_{f,^{241}Pu}^{pred}$	5.73±2.1%	5.97±2.15%

Short baseline experiments & near nuclear reactors

The Bugey-4 Benchmark

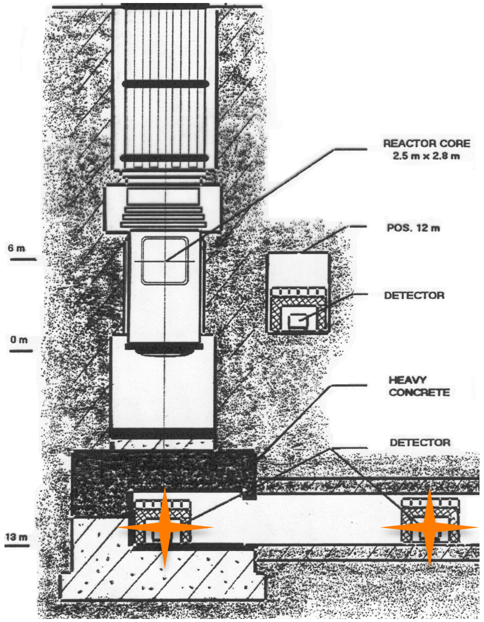
- Bugey PWR EdF plant, early 1990s
- Integral detector : water target containing ^{3}He counters, only neutrons are detected
- Fuel composition: 53.8% ^{235}U, 32.8% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- Neutron lifetime used in original paper: 887.4s
- **Published ratio of $\sigma_f^{measured}$ to σ_f^{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 $\sigma_f^{pred,new}$**
- **May impact the Chooz limit**

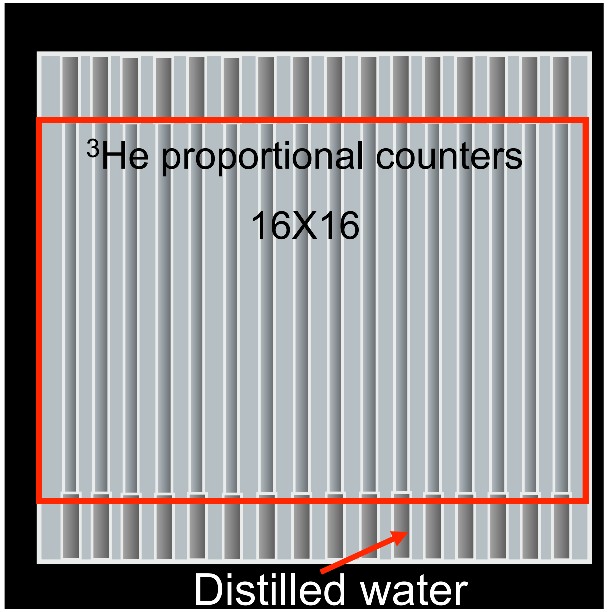




The ROVNO experiment (JETP Lett., 54, 1991, 253)

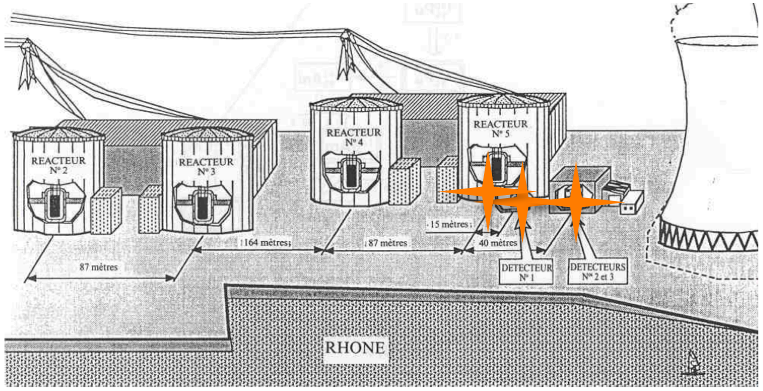
- Rovno VVER nuclear plant, 1983-1991
- Integral detector : water target containing ^{3}He counters, only neutrons are detected
- Fuel composition: 61.4% ^{235}U, 27.4% ^{239}Pu, 7.4% ^{238}U, 3.8% ^{241}Pu
- Neutron lifetime used in original paper: 888.6 s
- **Published ratio:**
  0.985±0.038
- **Revised ratio with new spectra:**
  0.940±0.037
- Uncertainties:
  - Stat: <1%
  - Syst : 3.8%
- Correlated with: Bugey-4 (same detector)

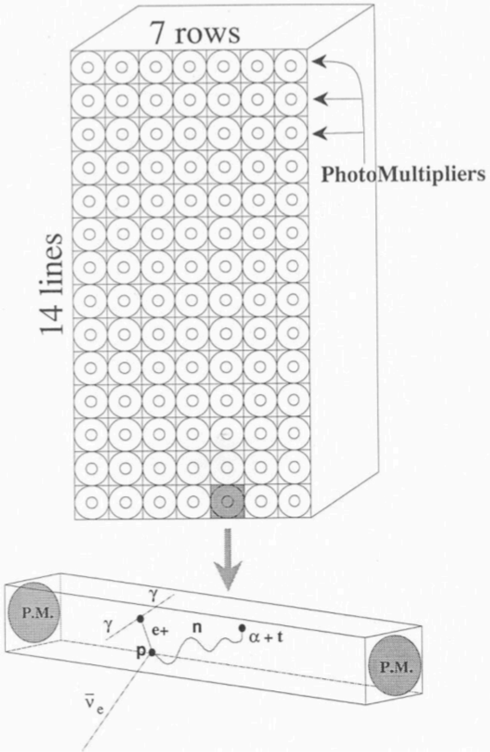




The Bugey-3 experiment (Nucl Phys B434, 504, 1995)

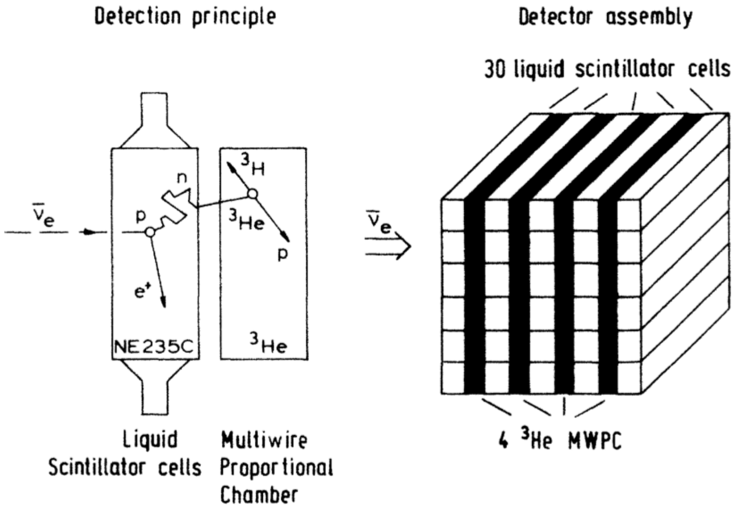
- Bugey PWR reactor, EdF
- 3 identical liquid scintillator segmented detectors doped with ^{6}Li for n capture
- Fuel composition typical of PWR – 53.8% ^{235}U, 32.8% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- Neutron lifetime in original paper: 889 s
- **Published ratios at 14m, 42m and 95m: 0.988±0.050, 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





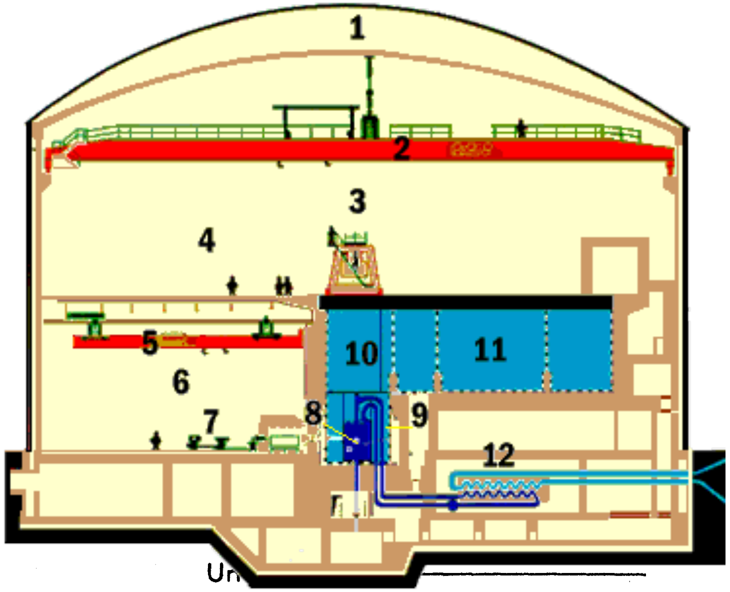
The Gösgen experiment (Phys Rev D34, 2621, 1986)

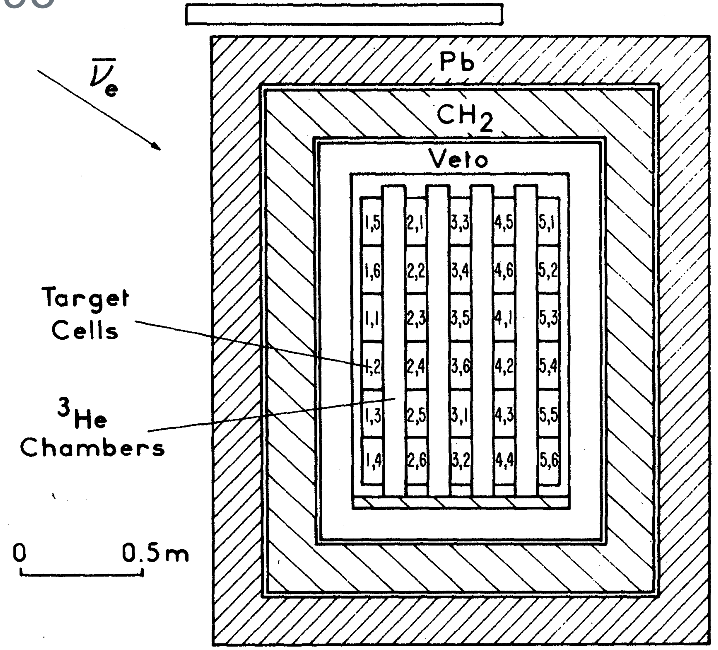
- Gösgen PWR, Switzerland, 1981-1984
- liquid scintillator segmented detector
  + ^{3}He counters for neutron capture
- Detector placed at 37.9m, 45.9m, 64.7m
- 3 fuel compositions published. Typical:
  61.9% ^{235}U, 27.2% ^{239}Pu, 6.7% ^{238}U, 4.2% ^{241}Pu
- Neutron lifetime used in original paper: 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



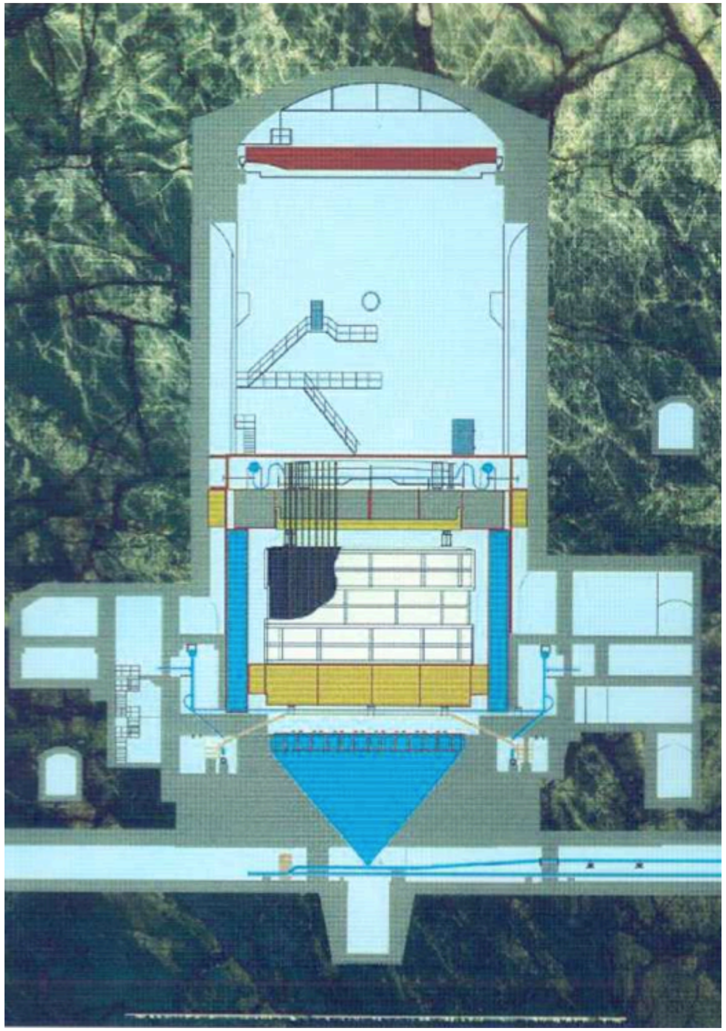
The ILL experiment (Phys Rev D24, 1981, 1097)

- 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 in ^{235}U
- Data reanalyzed in 1995 by sub-group of collaboration to correct 10% error in reactor power
- Neutron lifetime: 926 s in 81 & 889 s in 95
- **Published ratio:** **0.832±0.079 (1995)**
- **Revised ratio with new spectra:** **0.801±0.076**
- Uncertainties:
  - Stat: 3.5%
  - Syst : 8.9%
- Correlated with Gosgen





The Krasnoyarsk measurements

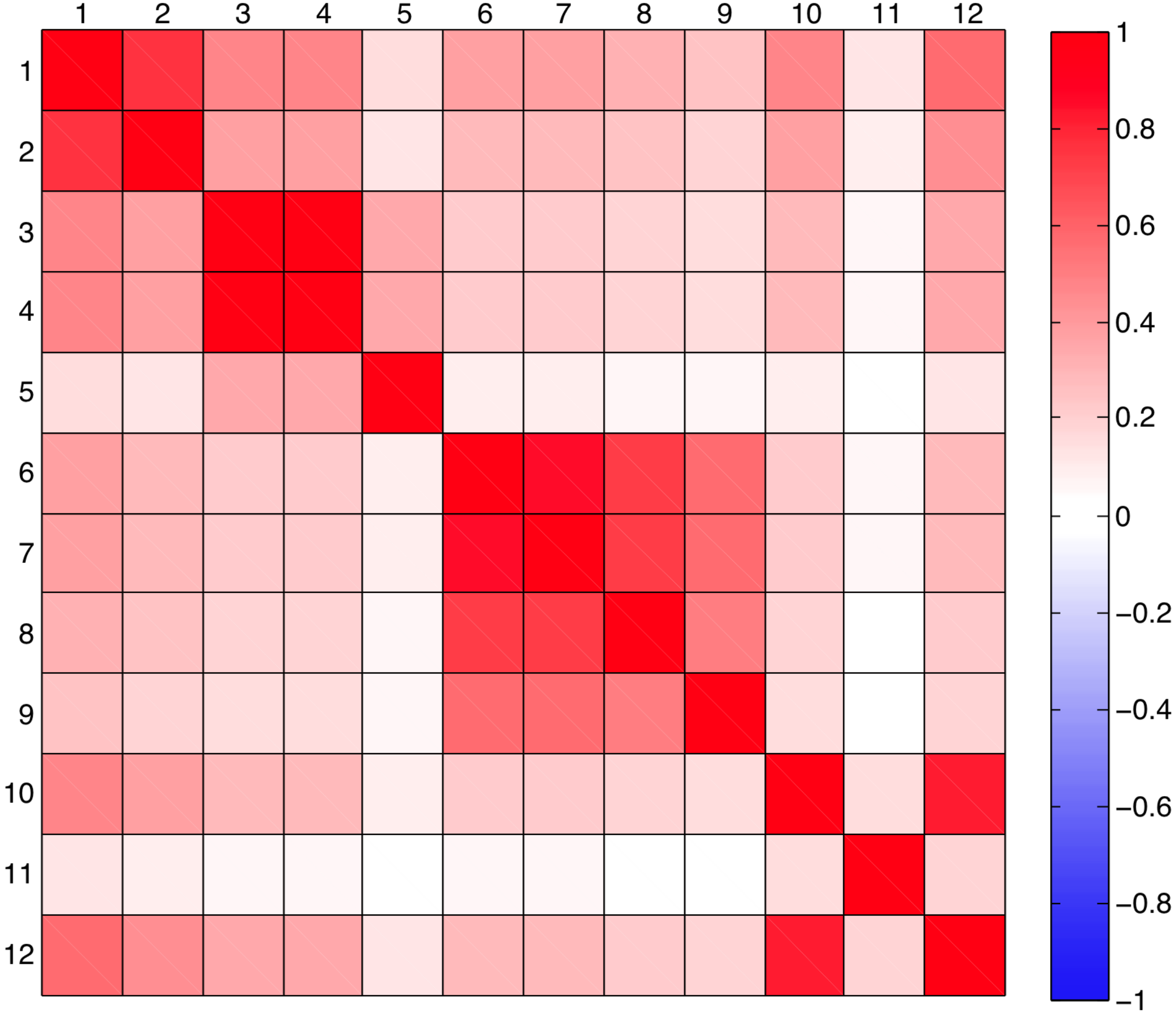


- Krasnoyarsk reactor in Russia
- Integral detector filled with PE+ ^{3}He counters for neutron capture
- Detector placed at 33m, 92m from 2 reactors (1987) and 57.3m from 2 reactors (1994)
- Fuel composition: mainly ^{235}U
- Neutron lifetime in original paper: 899 s
- **Published ratios: 1.013±0.066, 1.031±0.068, 0.989±0.074**
- **Revised ratios with new spectra: 0.944±0.062,0.954±0.064, 0.954±0.070**
- Uncertainties:
  - Stat: <2%, 19.9% at 92.3m
  - Syst : 4.15%
- Correlated together (same detector, WINS)

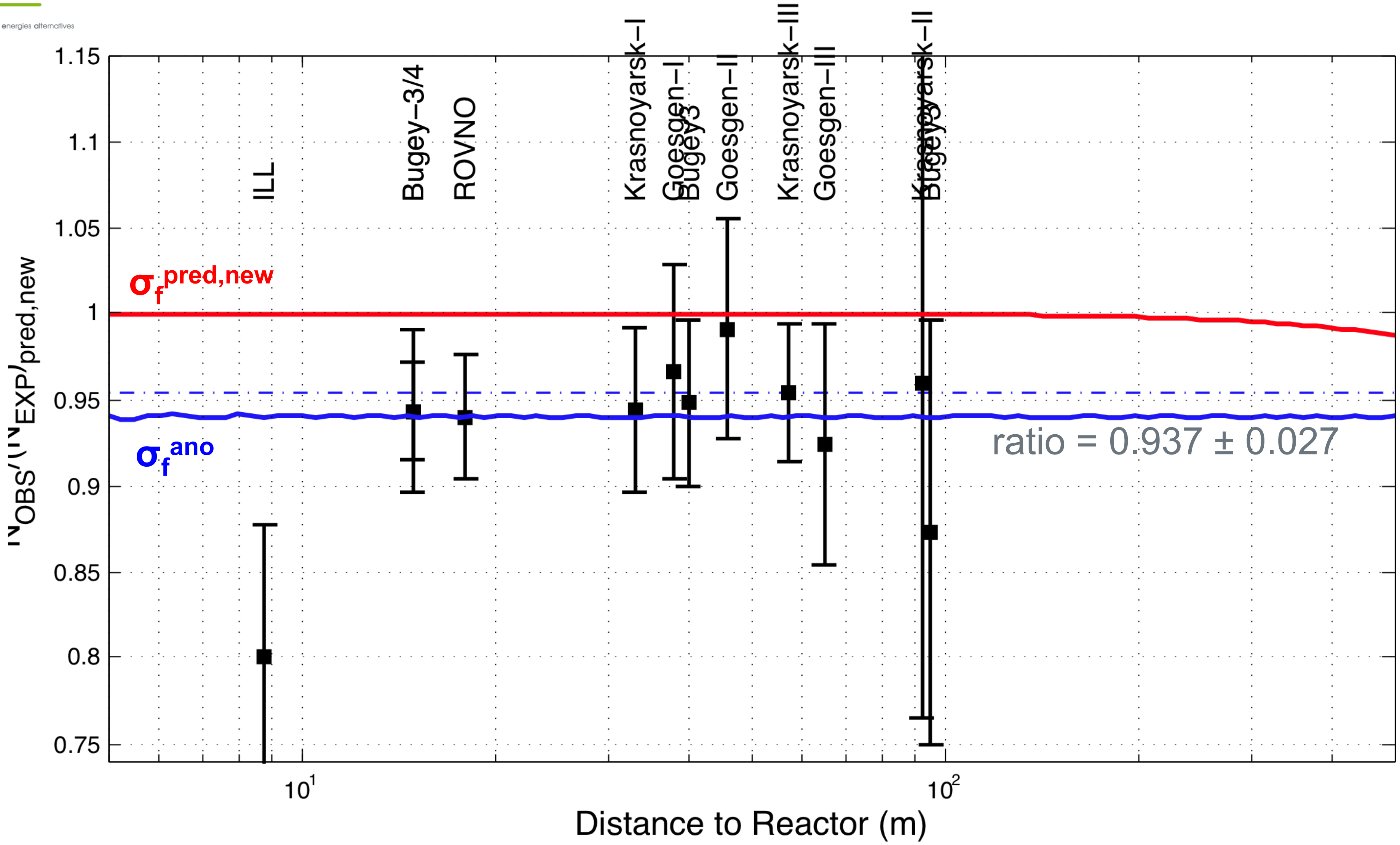
Experimental correlation matrix

An extra 2.7% systematic error on the reactor antineutrino spectra is fully correlated between all measurements

- Bugey-4
- Rovno 18m
- Bugey-3 15m
- Bugey-3 40m
- Bugey-3 92m
- Goesgen 38m
- Goesgen 45m
- Goesgen 65m
- ILL 9m
- Krasno 33m
- Krasno 92m
- Krasno 57m



The reactor anti-neutrino anomaly



The reactor rate anomaly

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

- **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-ν_e :

    Oscillation towards a 4th neutrino fits the data
    → a large $\Delta m^2_{new} >> 0.1\ eV^2$ → a fourth neutrino state?
    → a 4th oscillation mode with θ_{new} and Δm^2_{new}

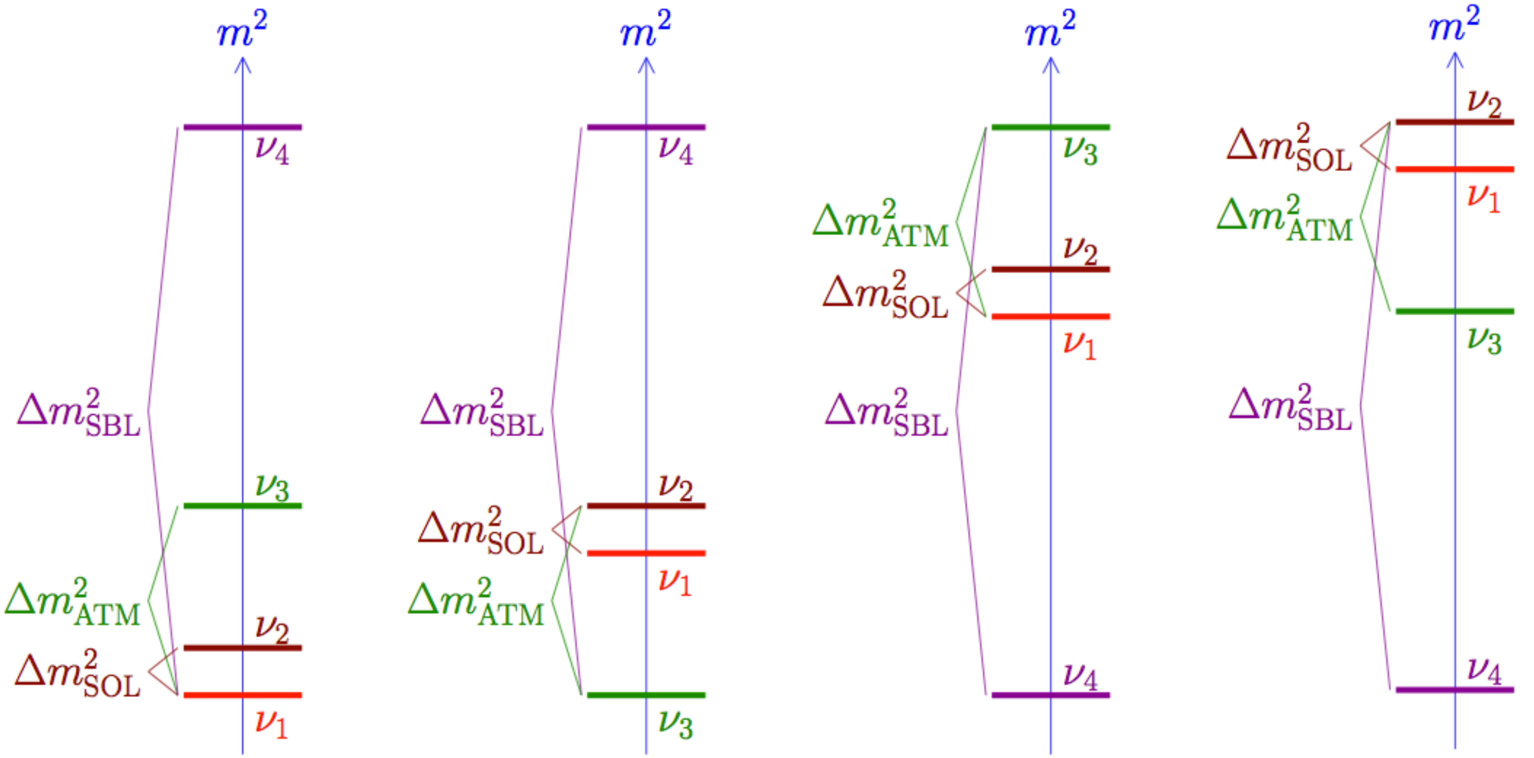
Sterile Neutrinos

- Sterile = No Standard Weak Interactions
- Active-ν can oscillate into Sterile Neutrinos

$\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \quad \nu_5 \quad \cdots$

$\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_{s_1} \quad \nu_{s_2} \quad \cdots$

ACTIVE STERILE

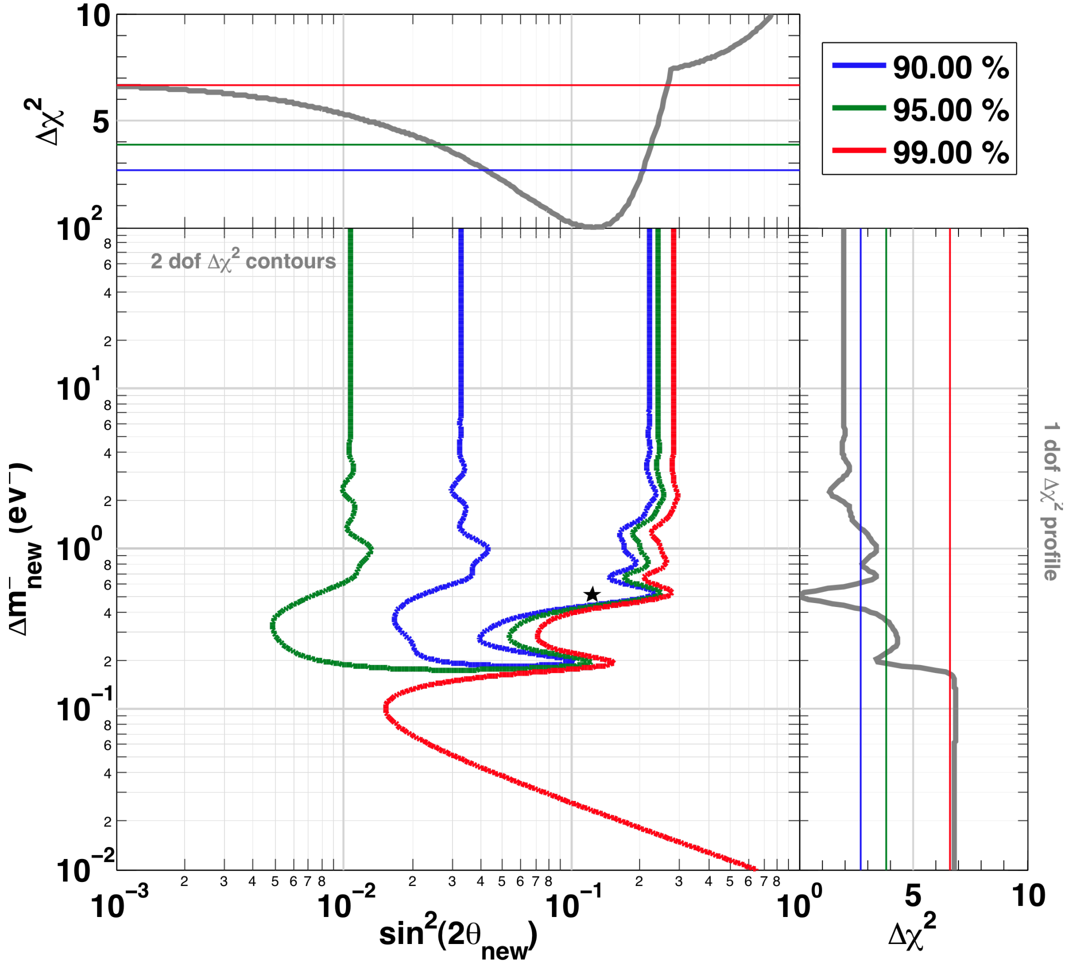


"normal" "3ν-inverted" "4ν-inverted" "fully-inverted"

3+1 schemes from C. Giunti

The reactor rate anomaly

- Combine all rate measurements, no spectral-shape information
- Fit to anti-ν_e disappearance hypothesis



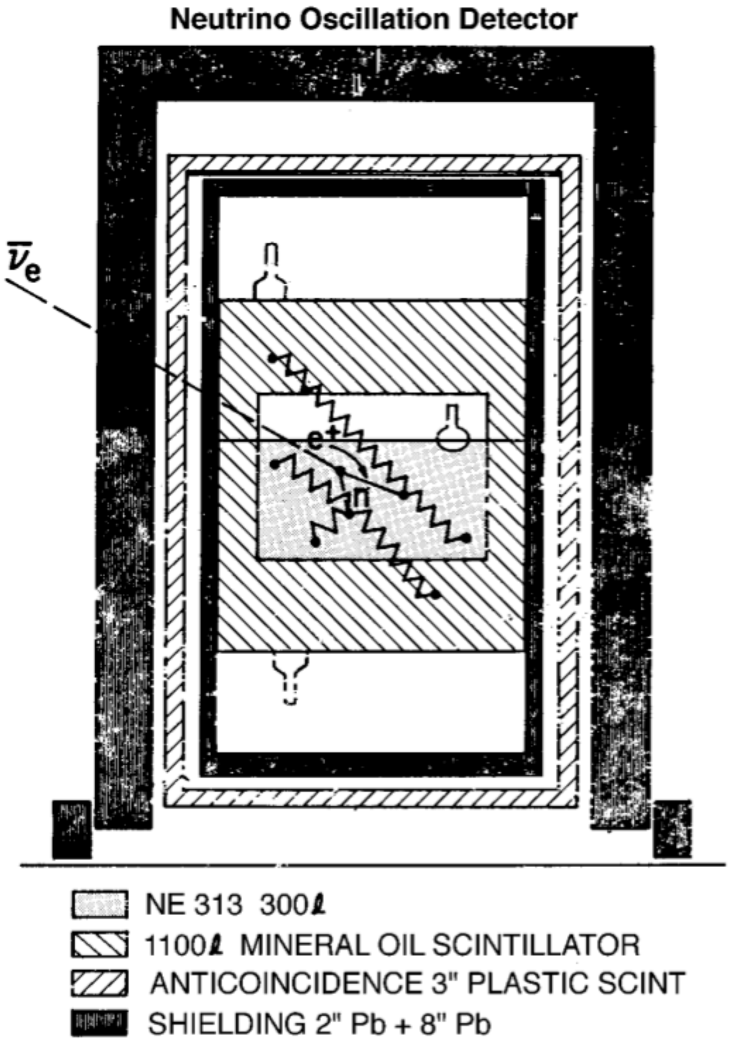
- Absence of oscillations disfavored at 96.2% C.L.
- Next step: include shape analyses of experiments with best shape information

NEW

The Savannah River (last) experiments

- Savannah River, USA, late 80s - early 90s
- liquid scintillator doped with 0.5% Gd
- Detector placed at 18.2m 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±0.037,1.055±0.040**
- **Revised ratios with new spectra: 0.987±0.036,1.019±0.039**
- Uncertainties:
  - Stat: 0.6% and 1.0%
  - Syst : 3.7%
- Correlated together

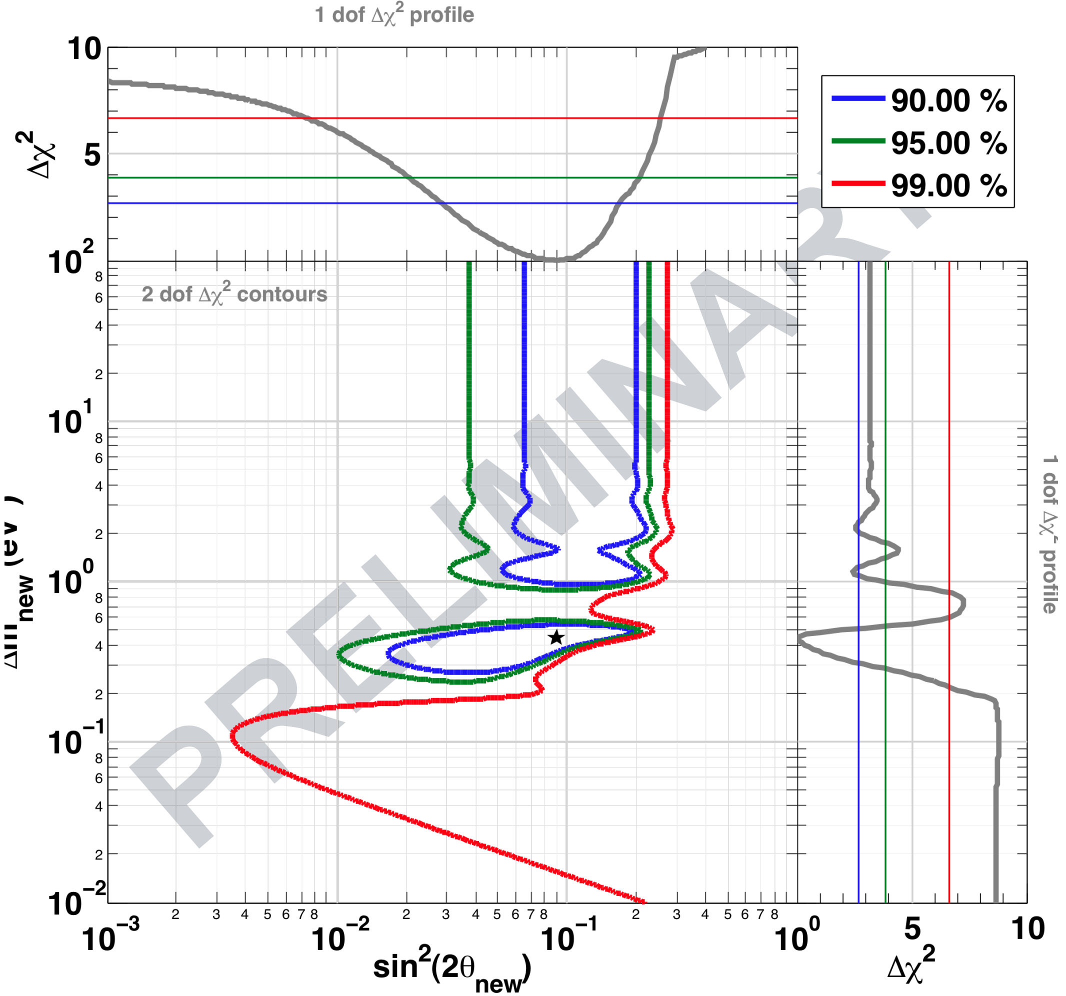
(PRD53, 6054, 1996)



NEW

The reactor rate anomaly including SRP

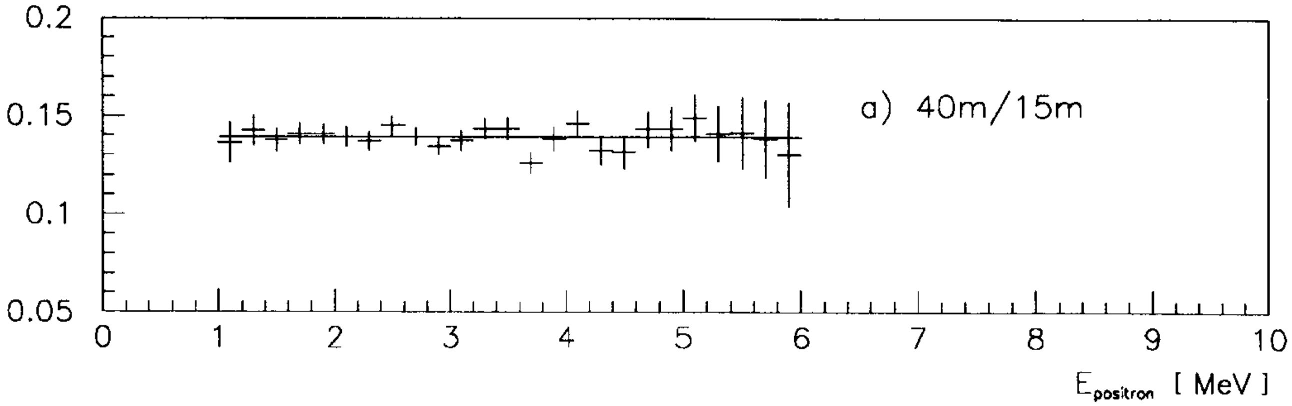
- Combine all rate measurements, no spectral-shape information
- Fit to anti-ν_e disappearance hypothesis



- Absence of oscillations disfavored at 98.7% C.L.
- Next step: include shape analyses of experiments with best shape information

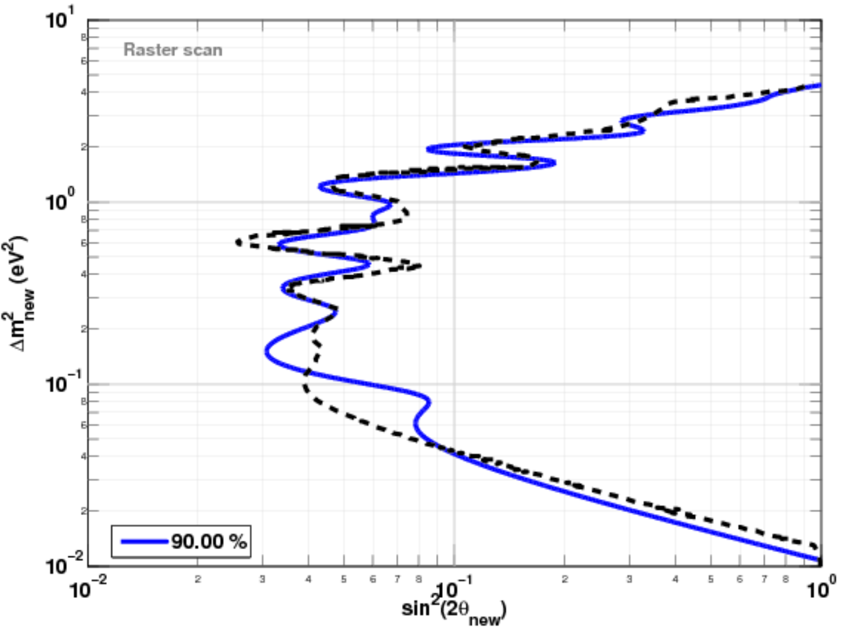
Spectral shape analysis of Bugey-3

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



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

  - 2% relative systematic error

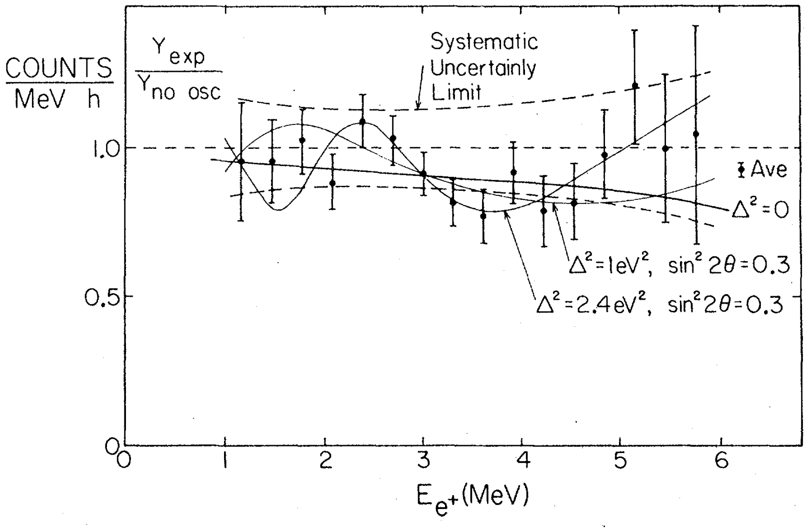


- Our reproduction of the collaboration's raster-scan analysis
- Use of a global-scan in combined analysis

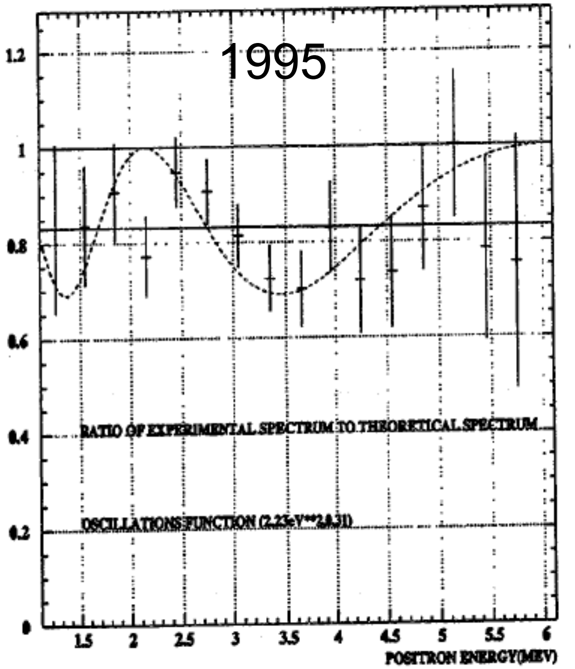
The 1981 ILL measurement

- 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

1981



1995



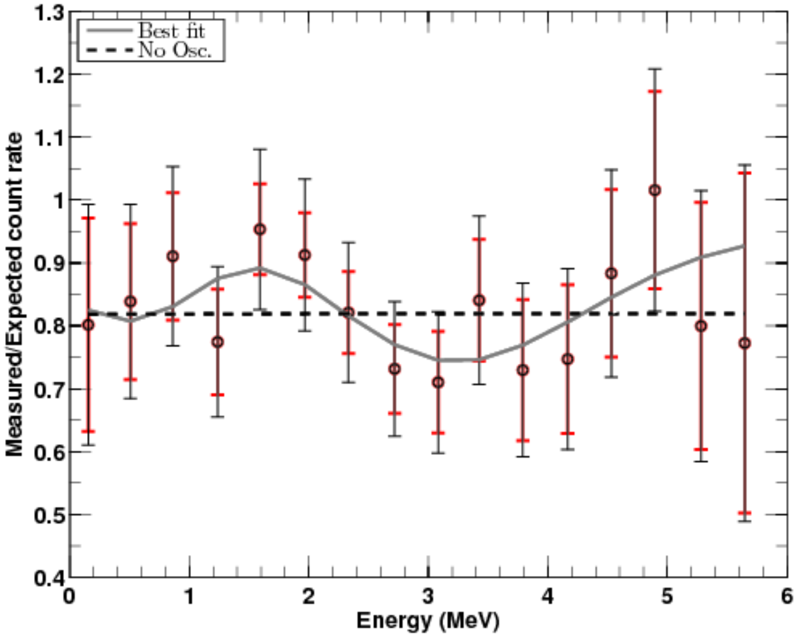
Large errors, but looks like an oscillation pattern by eye ?

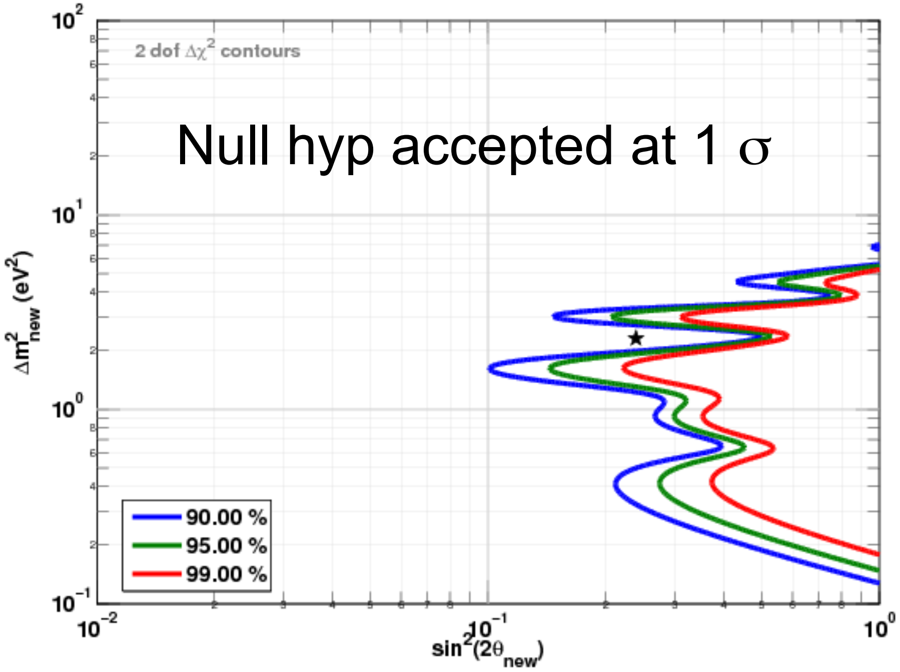
Our analysis of ILL shape distortion

Estimator sensitive to shape only by minimization over parameter a:

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

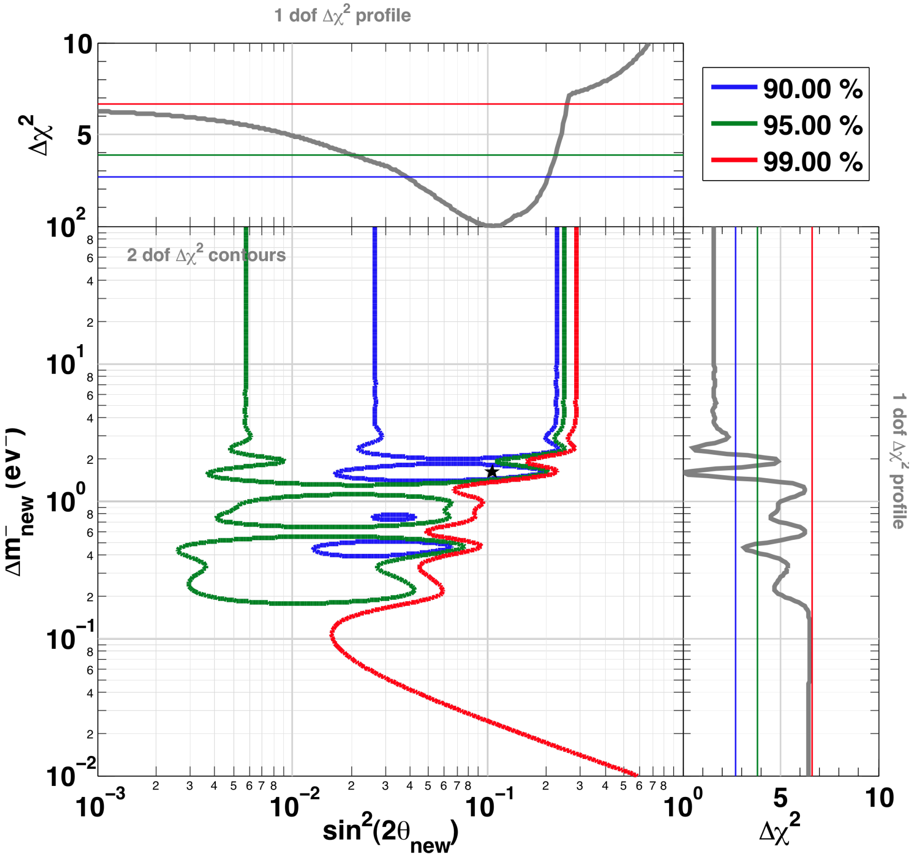
Systematic error of 11% added in every bin to reproduce the collaboration's 1981 & 1995 results



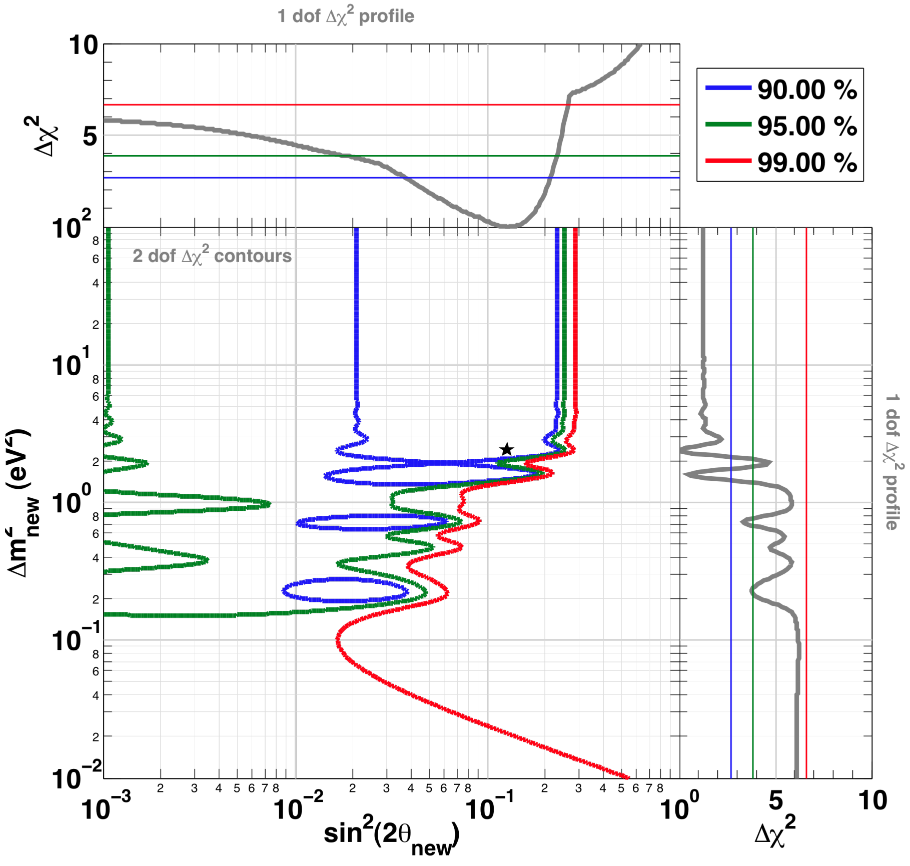

Null hyp accepted at 1 σ

Combined Reactor rate+shape contours

Rate + Bugey-3 only



Rate + Bugey-3+ ILL



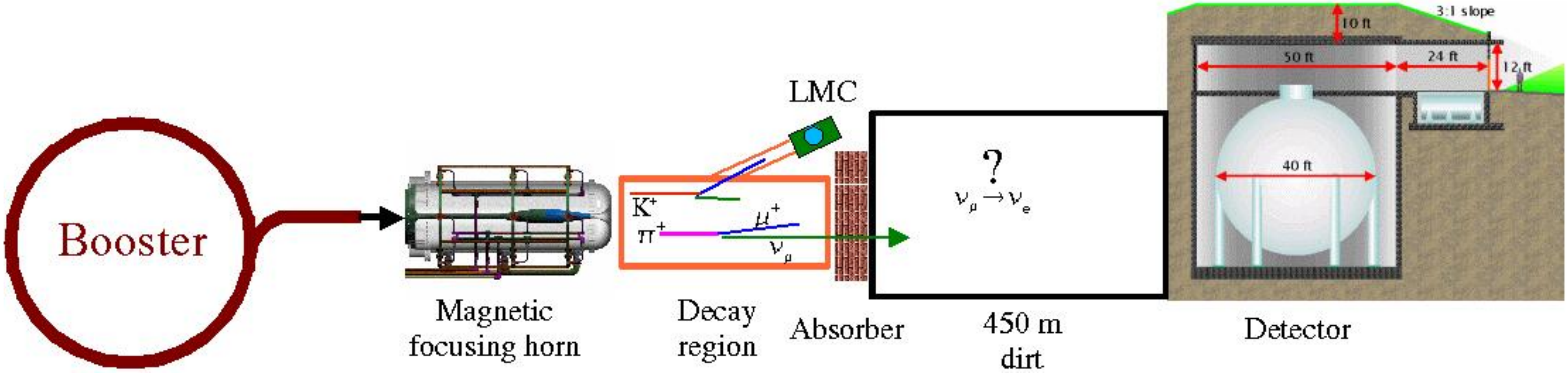
Re-analysis of

Miniboone-ν neutrino data

& Gallium calibration run

Miniboone

- Beam experiment, based at Fermilab, to test the LSND anomaly
- Produce a ν_μ beam, and study it with a mineral oil detector scintillation & Cherenkov light
- Good separation between muons & electrons, ie ν_μ vs ν_e separation
  - E-like sample: mis-identified ν_μ, and beam ν_e
  - Mu-like sample: ν_μ events

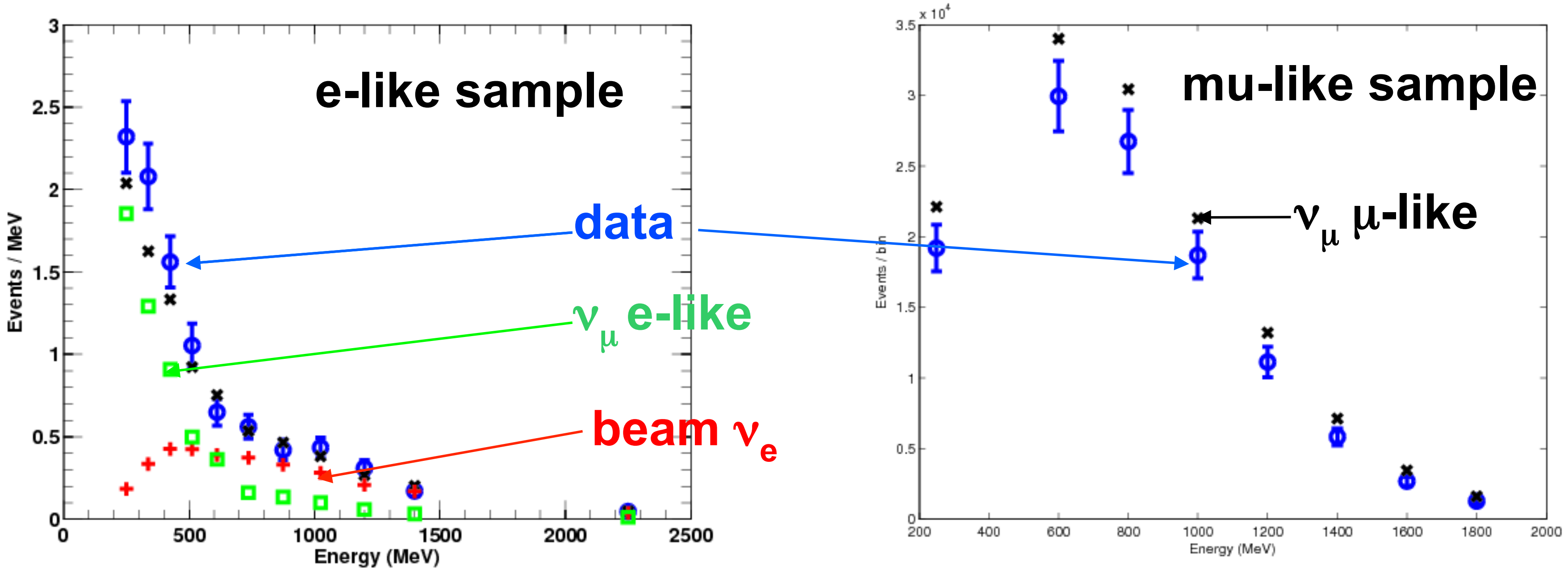


- Neutrino data was taken from 2002 to 2005
- Now taking anti-neutrino data: not addressed in this presentation

The Miniboone neutrino data

Our non-standard analysis:

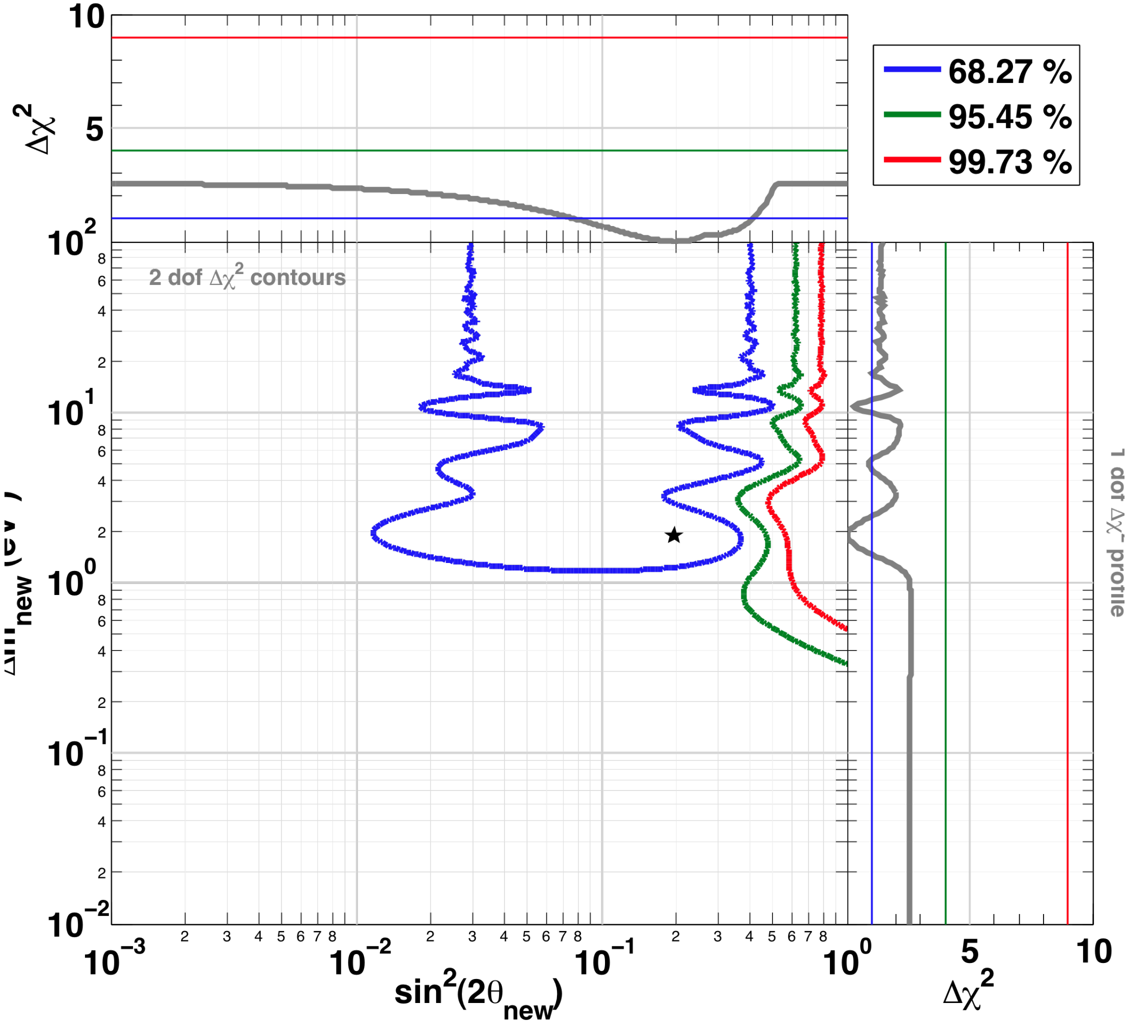
- Follows Giunti & Laveder PRD82 053005 (2010)
- Include ν_e disappearance, but ν_μ do not oscillate
- Beam normalization is a free parameter, constrained by high statistics muon-like sample



Systematics in ν_μ sample are strongly correlated

Our Miniboone-ν interpretation

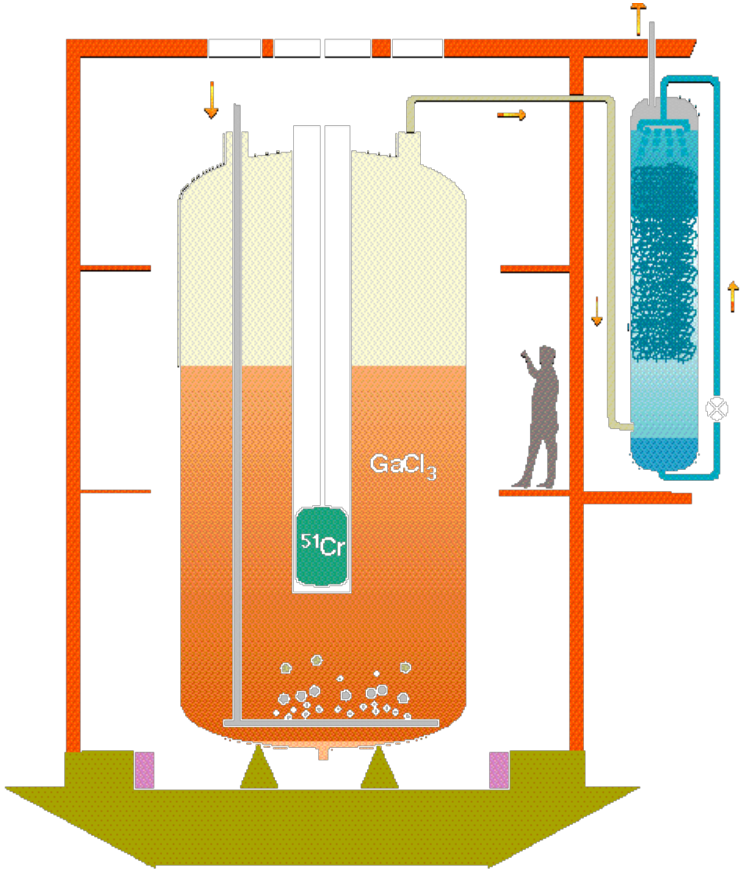
- **Non standard analysis:**
  - Follows Giunti & Laveder PRD82 053005 (2010)
  - Include ν_e disappearance, but ν_μ do not oscillate



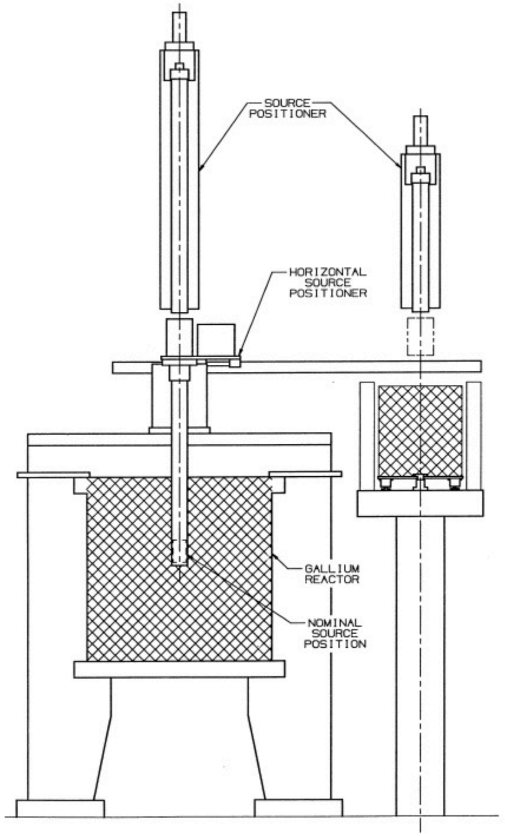
- Beam normalization is a free parameter, constrained by high statistics muon-like sample
- Marginal significance
- Compatible with reactor result
- Best fit compatible wsith reactor anomaly (72% CL)

Radioachemical experiments Gallex (left) & Sage (right)

- GALLEX ($GaCl_3$) and SAGE (liquid Ga) were radiochemical experiments, counting the conversion rate of Ga to ^{71}Ge by (solar) neutrino capture



30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl

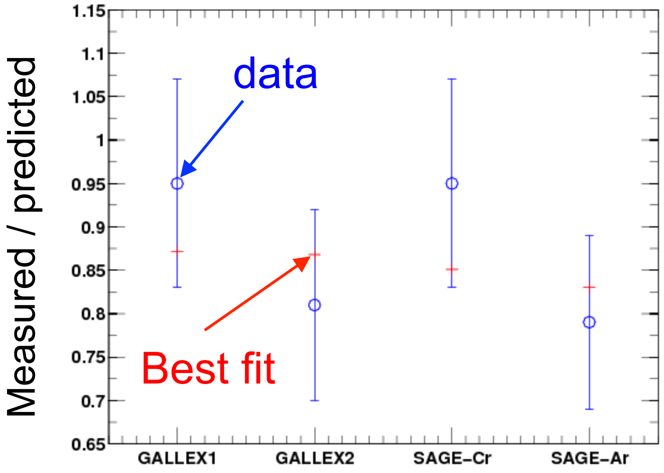


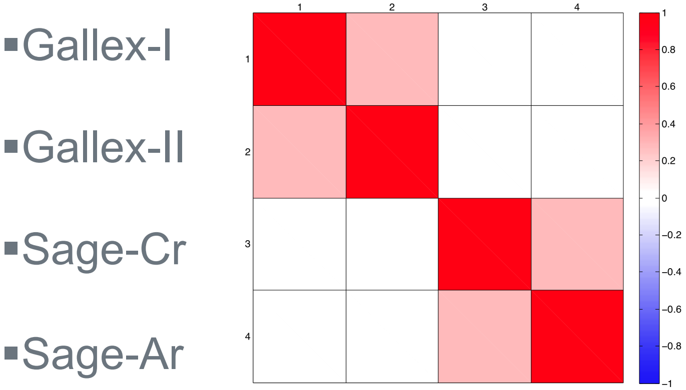
30 to 57 tons of gallium
(metal) in 10 tanks

Our Gallium calibration run re-analysis

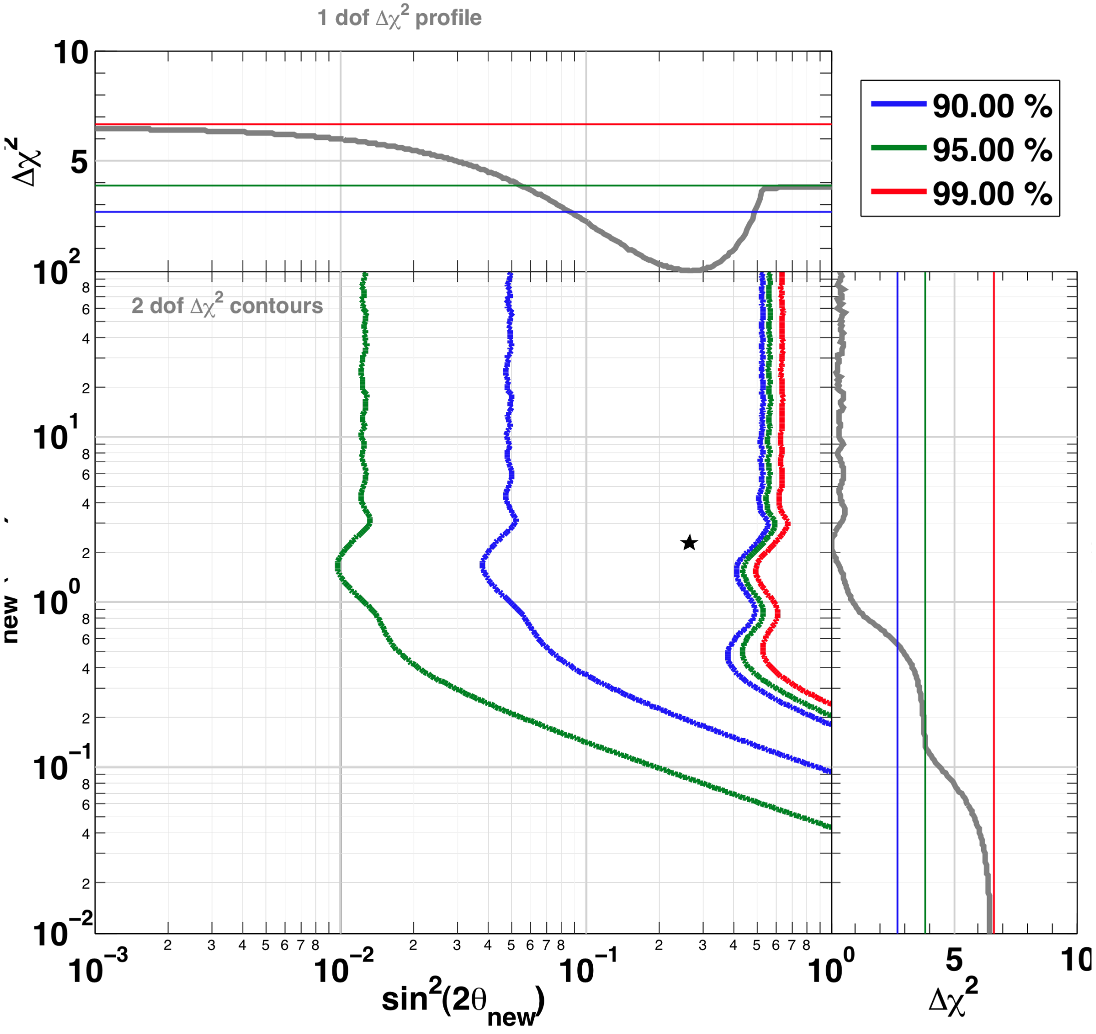
- 4 calibration runs with intense (~ MCi) neutrino (not anti-neutrino!) sources:
  - 2 runs at GALLEX with a ^{51}Cr source (750 keV ν_e emitter)
  - 1 run at SAGE with a ^{51}Cr source
  - 1 run at SAGE with a ^{37}Ar source (810 keV ν_e emitter)
  - **All observed a deficit of neutrino interactions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

- Our analysis based on PRD82 053005 (2010):
  - 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



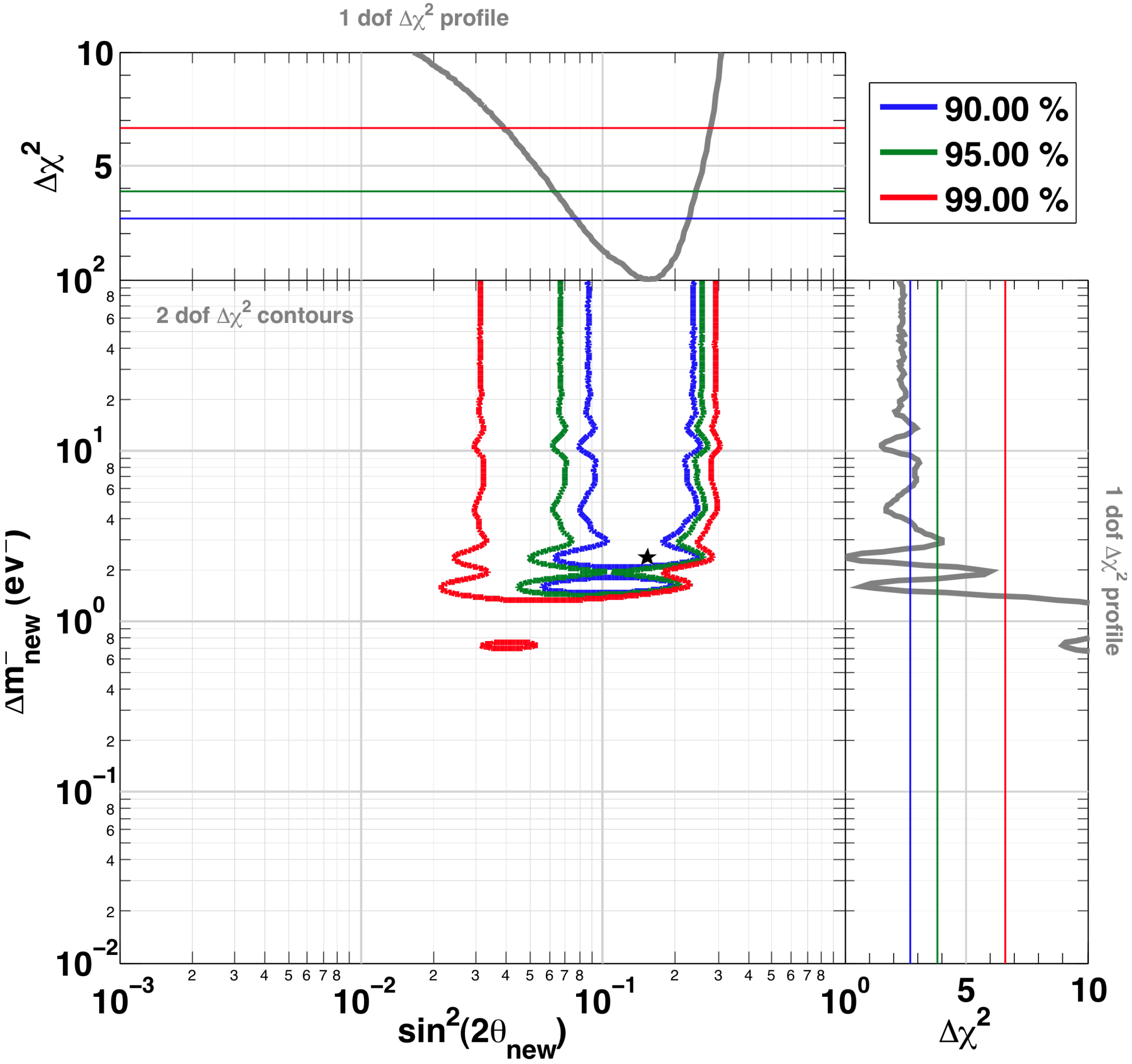


The Gallium anomaly



- 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

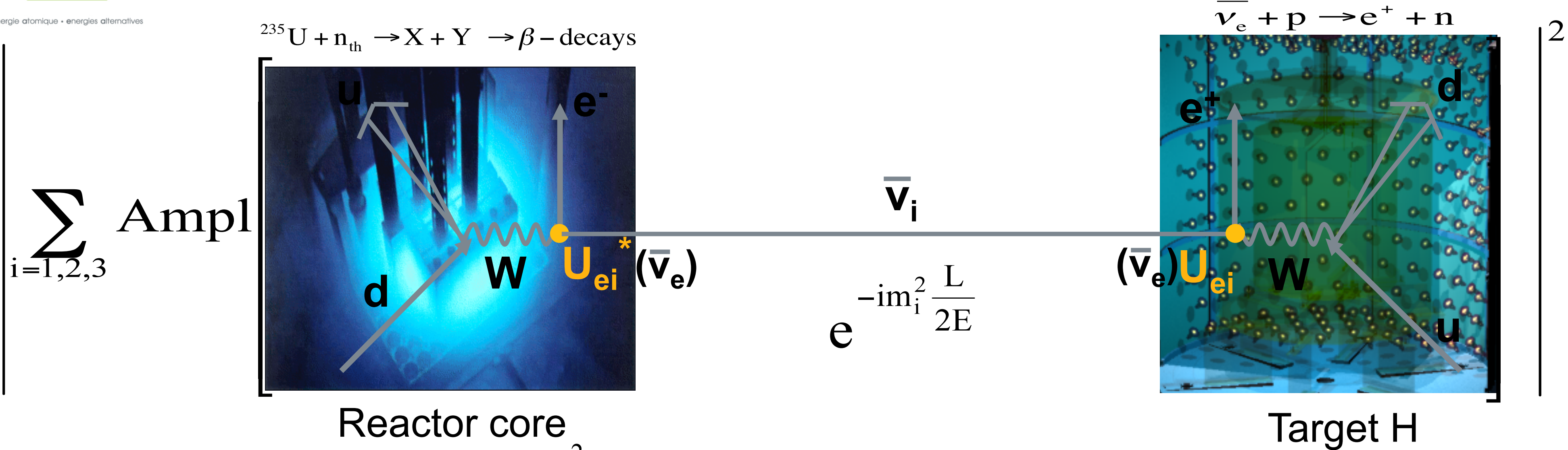


The no-oscillation hypothesis is disfavored at 99.84%

Long baseline reactor anti-ν experiments and θ_{13}

θ_{13} at Reactors

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



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

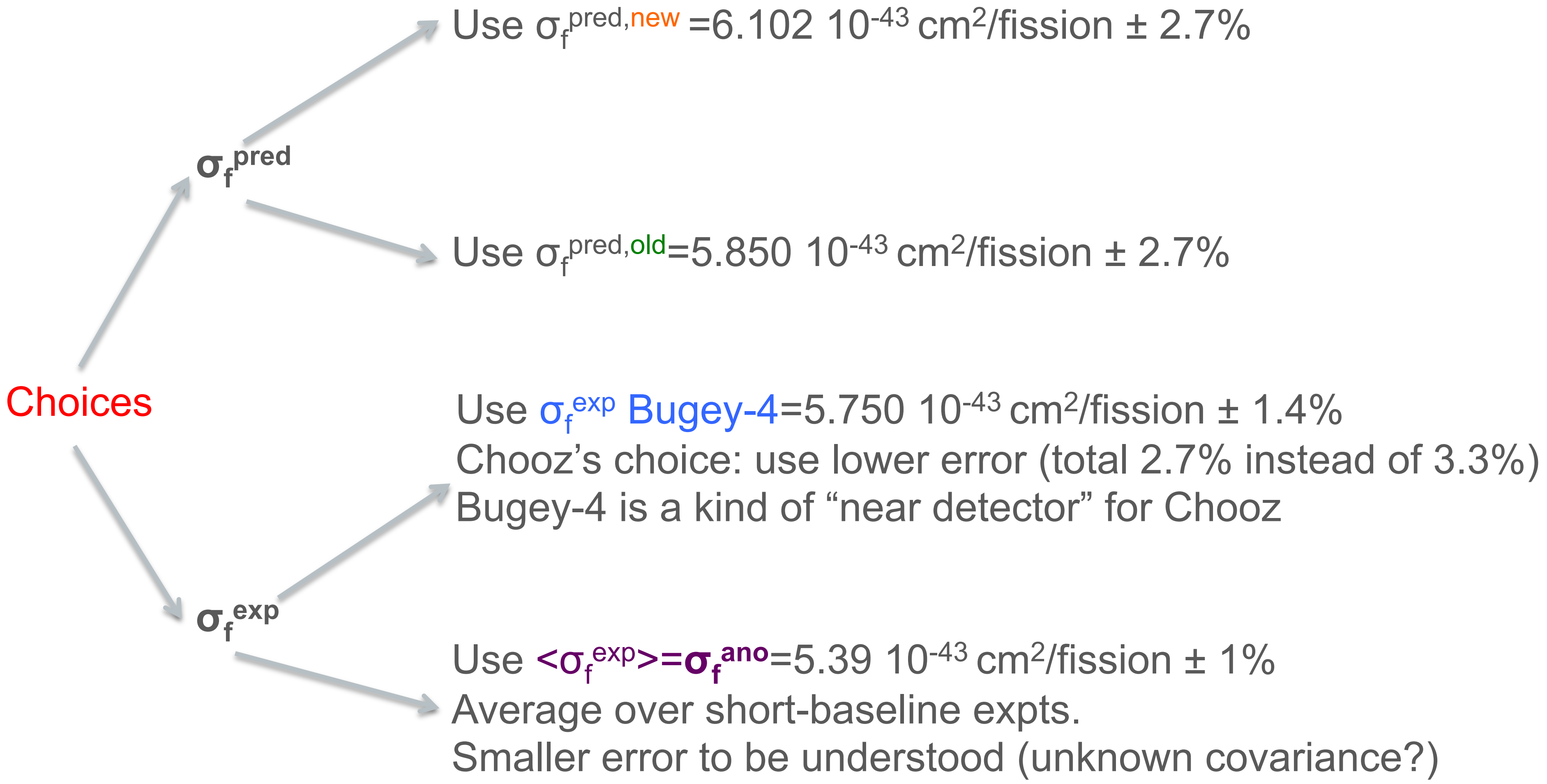
- Experiments without near detector monitoring equally each core may be effected by the reactor antineutrino anomaly (Double Chooz Phase I, RENO?)

- Experiments with a comprehensive monitoring of the core at close distances are not affected by the anomaly (Double Chooz PhaseIII, Daya Bay final configuration)

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.



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

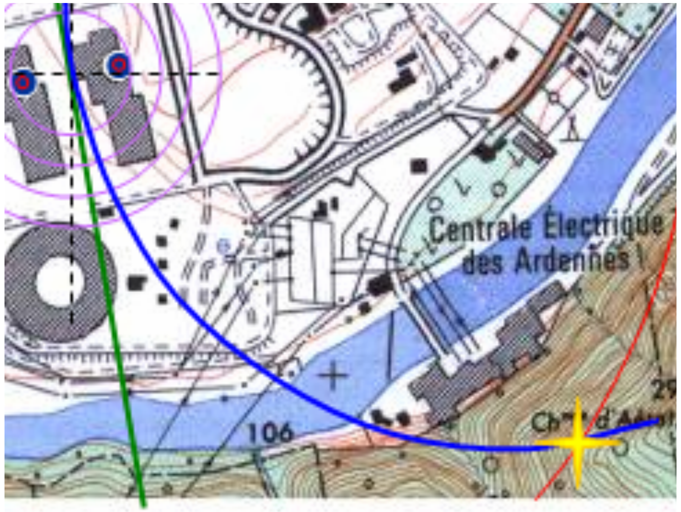
Use $<\sigma_f^{exp}>=\boldsymbol{\sigma_f^{ano}}$=5.39 10^{-43} cm^2/fission ± 1%
Average over short-baseline expts.
Smaller error to be understood (unknown covariance?)

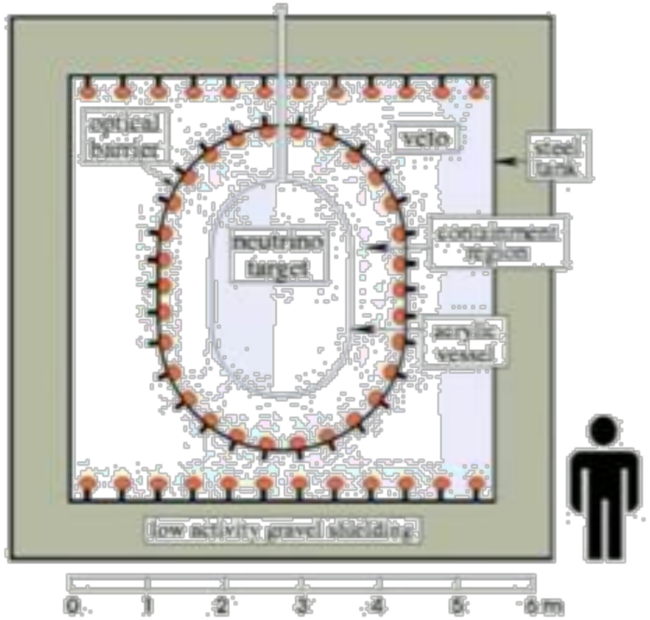
CHOOZ

- 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

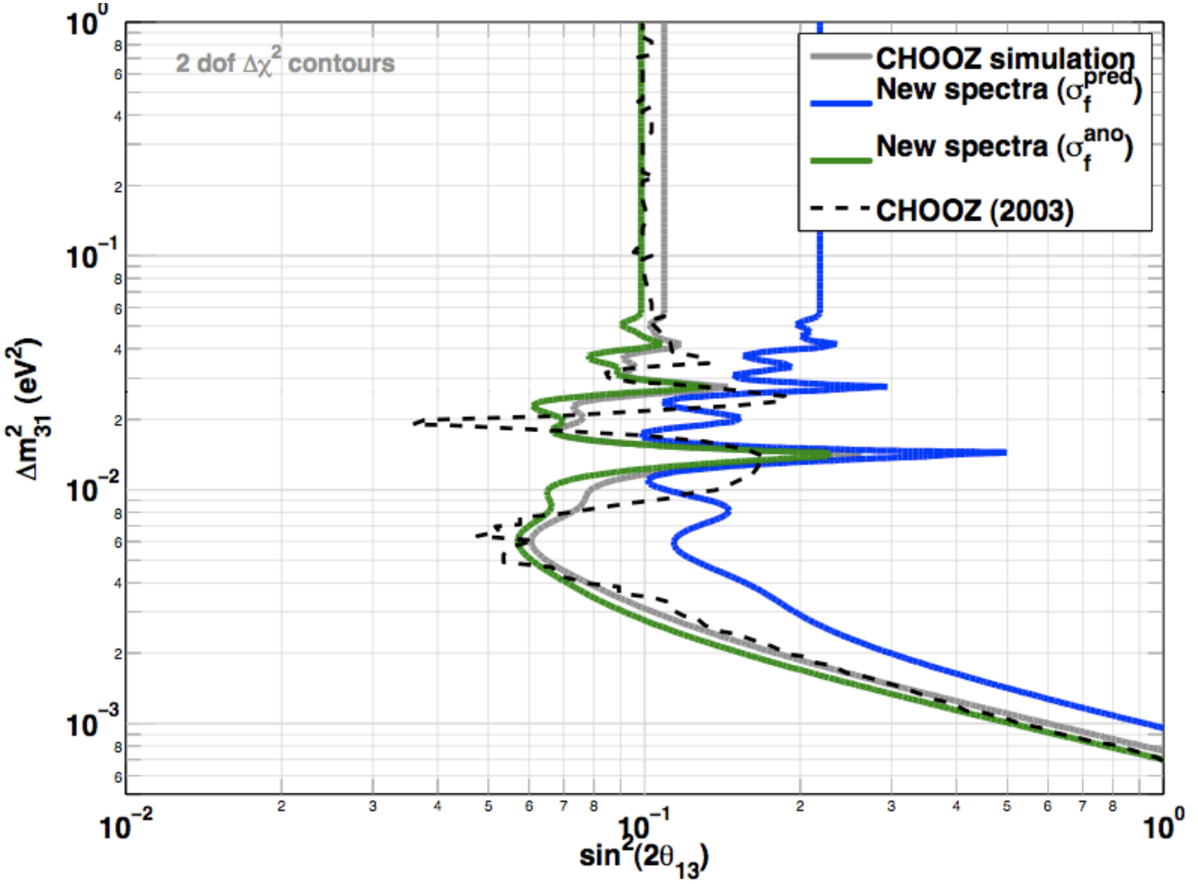
  θ_{13} mixing angle sensitivity, or more…
- Fuel composition typical of starting PWR – 57.1% ^{235}U, 29.5% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- Neutron lifetime used in original paper: 886.7 s
- **Published ratios:**
  1.01±0.043
- **Revised ratios with new spectra:**
  0.954±0.041
- Uncertainties: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





CHOOZ reanalysis

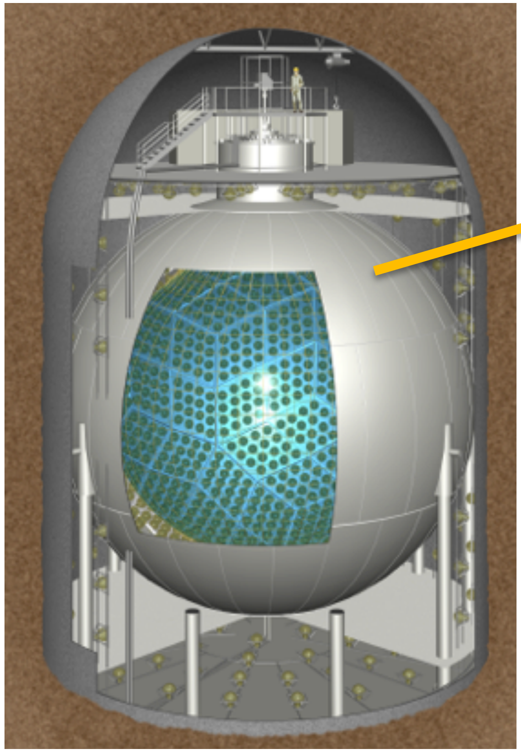
- The choice of σ_f changes the limit on θ_{13}
- Chooz original choice was σ_f^{exp} from Bugey-4 with low error
- If $\sigma_f^{pred,new}$ is used, limit is worse by factor of 2
- If σ_f^{ano} is used with 2.7%, we obtain the original limit
- If $\sigma_f^{ano,}$ which error should be used? → need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

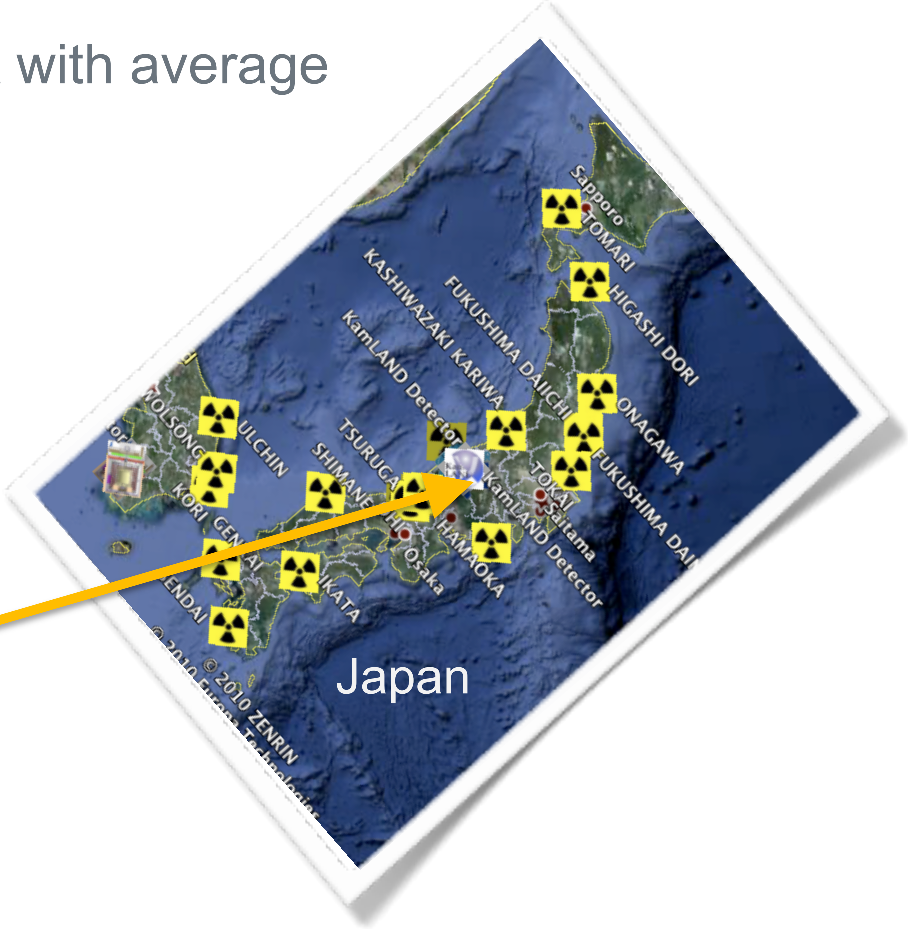


KamLAND experiment

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

~ 1kt liquid scintillator detector





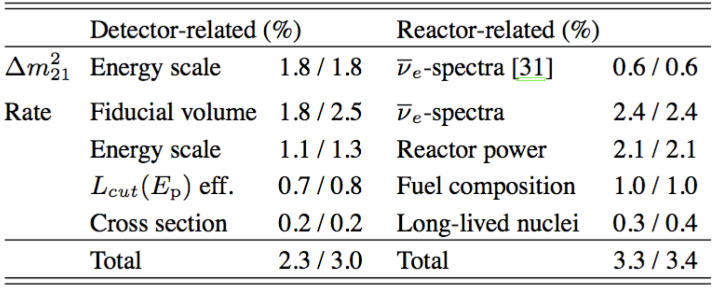
~ 4% syst. uncert. on normalization
~ 1-2% syst. on energy scale.

arXiv:1009.4771v2 [hep-ex]

Reanalysis of KamLAND's 2010 results

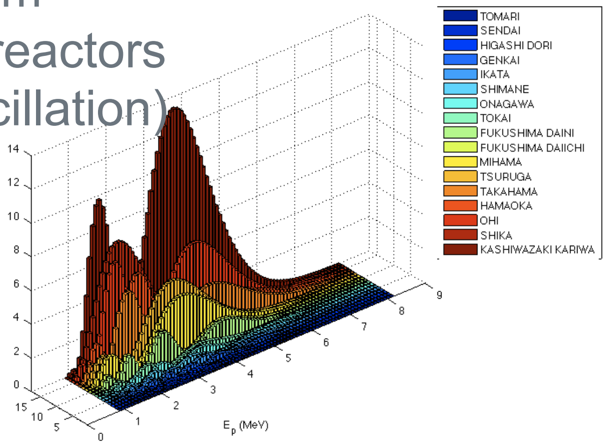
arXiv:1009.4771v2 [hep-ex]

Systematics

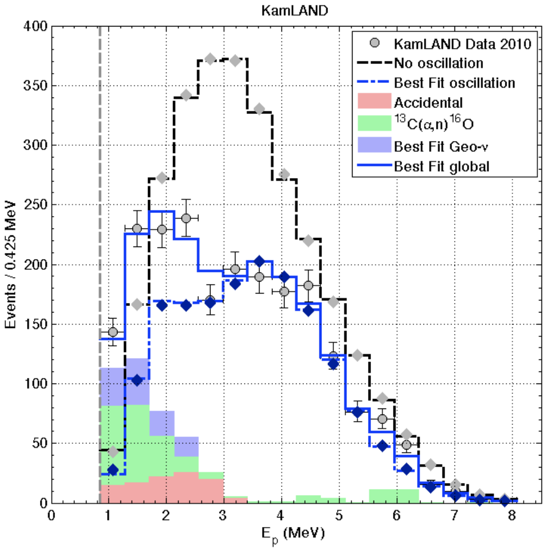


	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [31]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	2.4 / 2.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_p)$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section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

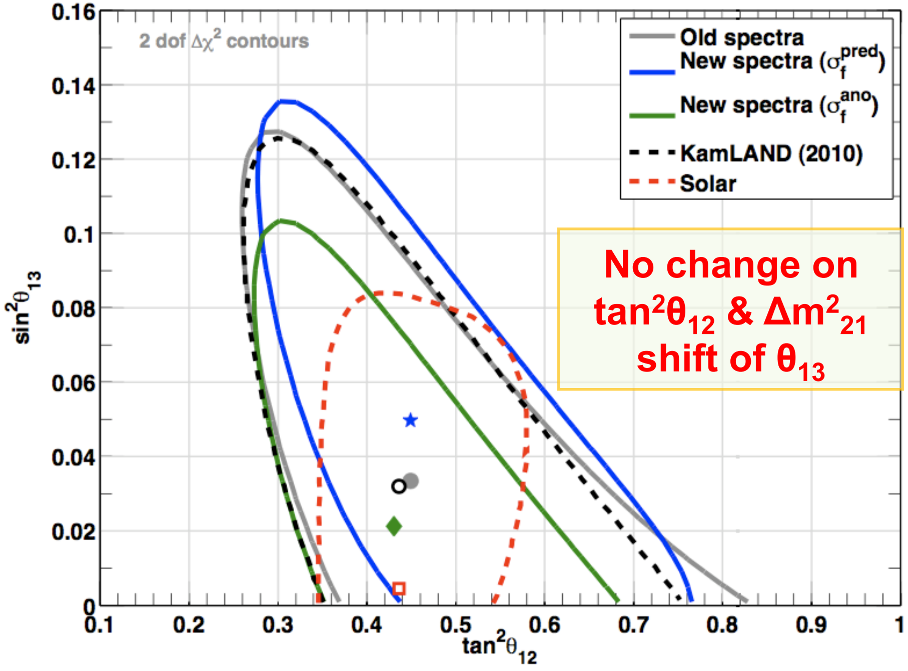
Spectra from Japanese reactors (with ν_e oscillation)



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



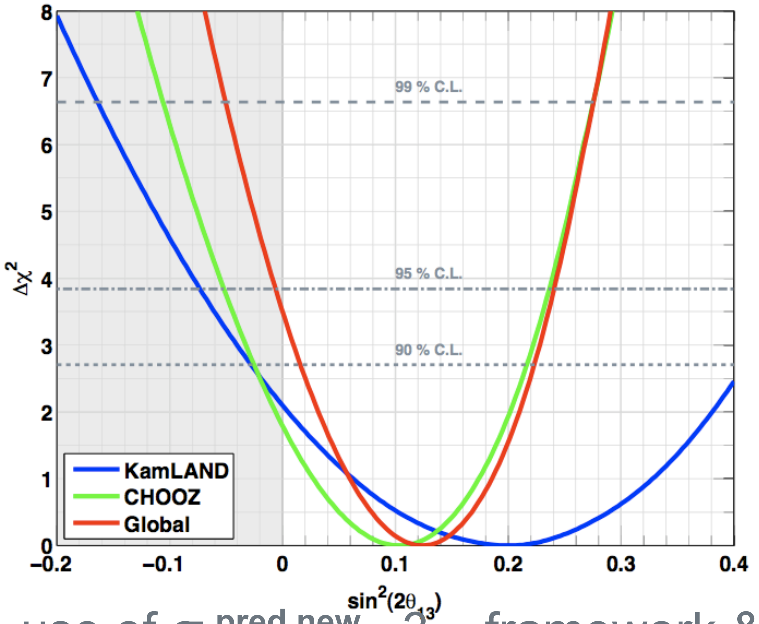
With new spectra predictions



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

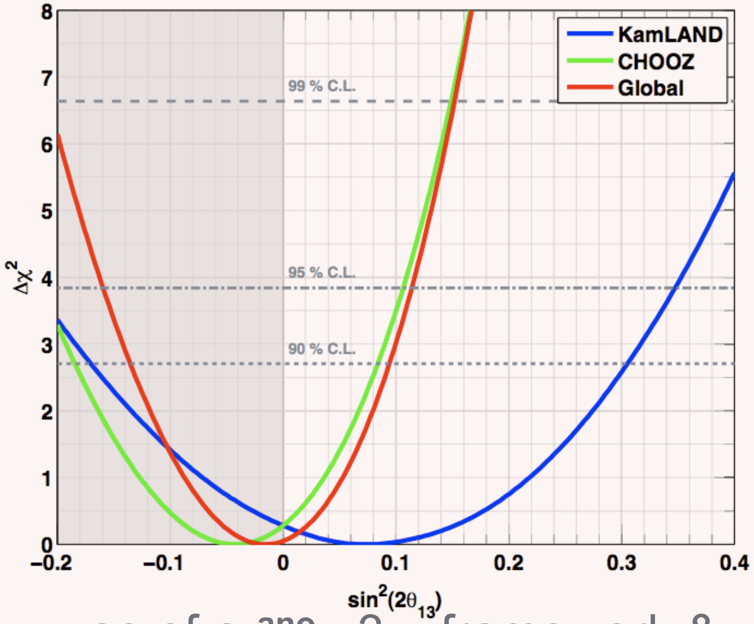
CHOOZ and KamLAND combined limit on θ_{13}

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



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

Normalization using σ_f^{ano}

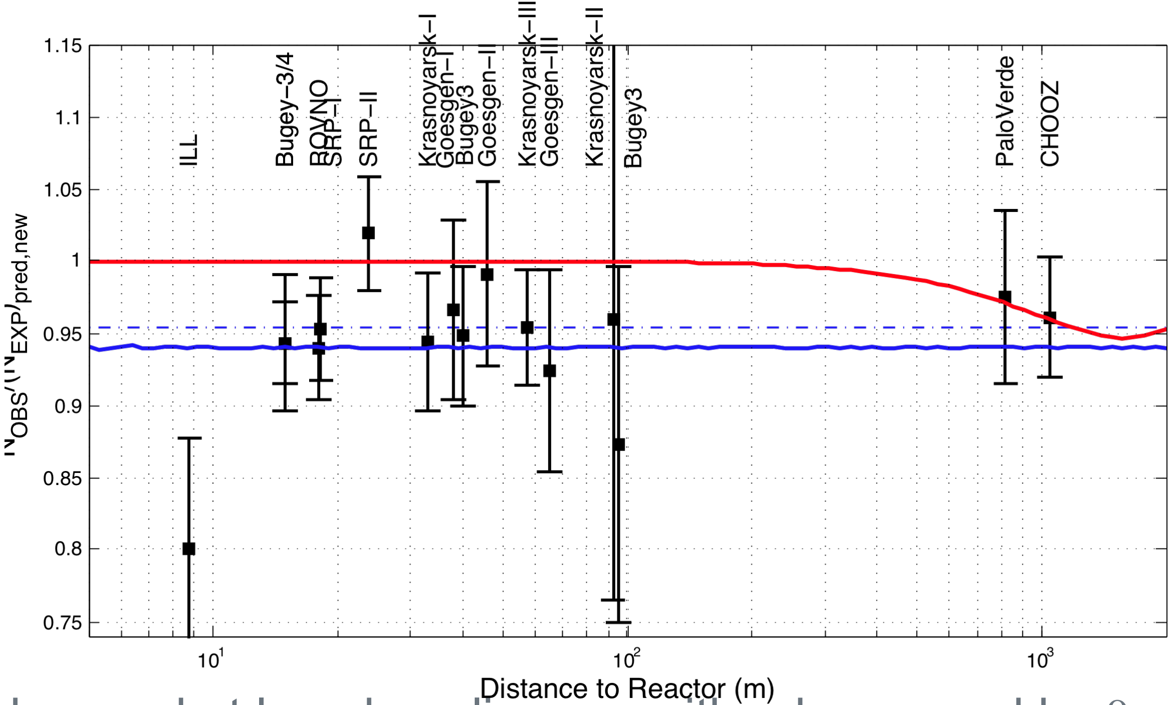


use of σ_f^{ano} , 3-ν framework & 2.7% uncertainty (arbitrary…)

- **Our interpretation:**
  - No more hint on $\theta_{13}>0$ from reactors
  - Global 90 % CL limit stays identical to published values

The reactor anti-neutrino anomaly and θ_{13}

- The choice of normalization is crucial for reactor experiments looking for θ_{13}

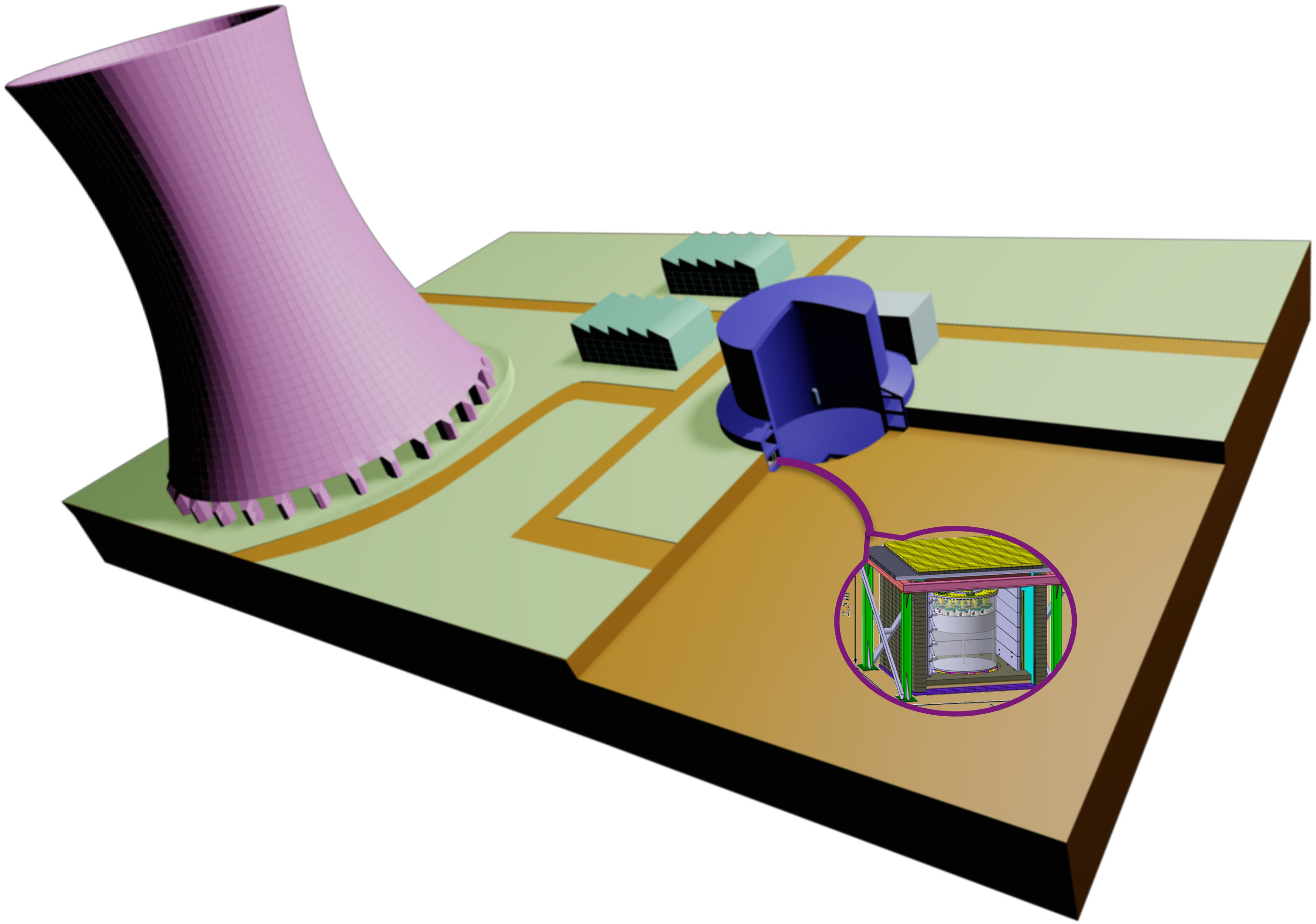


- A deficit observed at long baseline can either be caused by θ_{13} or by new physics closer to the core (oscillation towards a 4th neutrino, θ_{new})

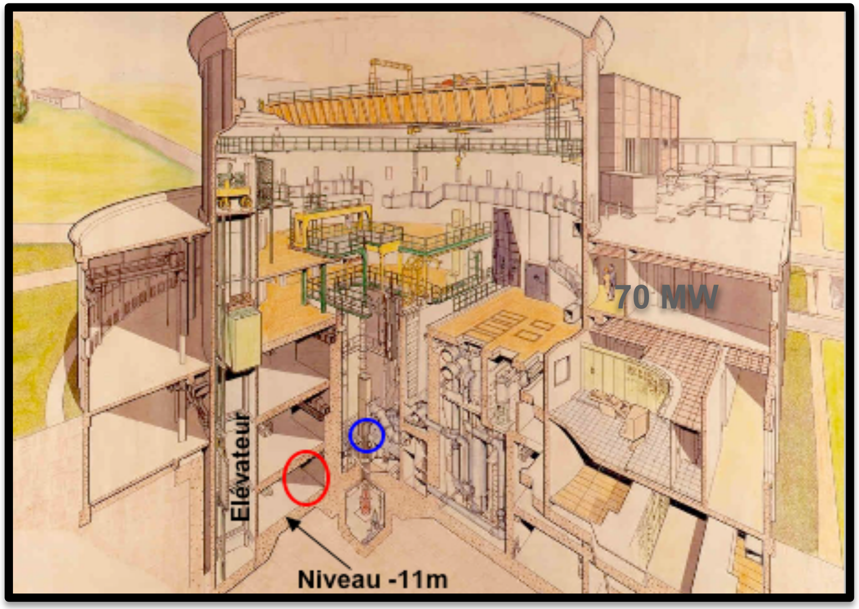
- If the sterile hypothesis from this work is proven, then using $\sigma_f^{pred,new}$ with 2.7% error is justified, together with a 3+N neutrino framework

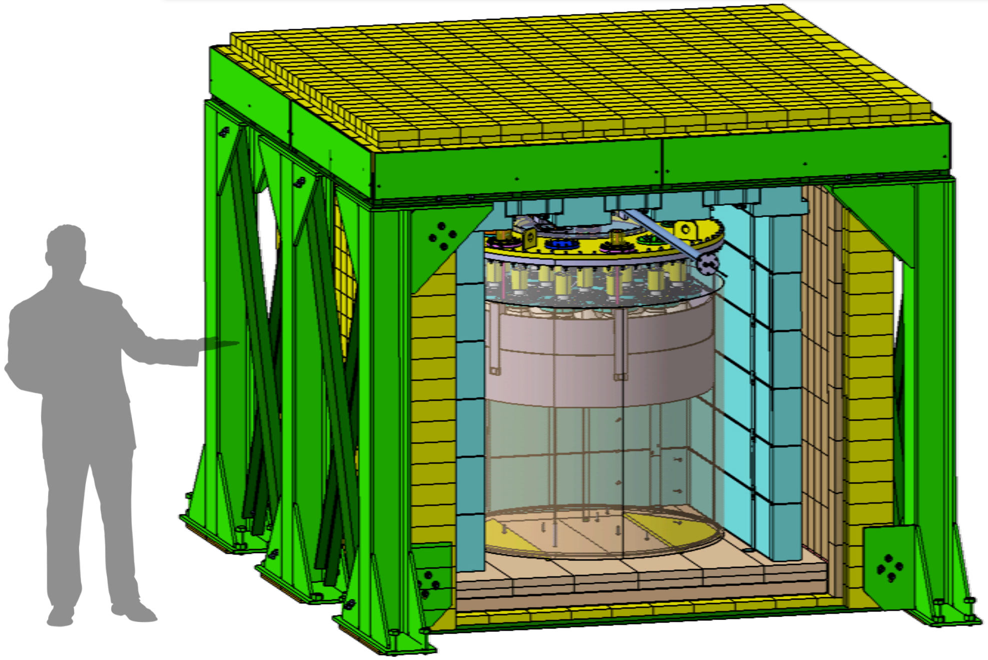
- Using σ_f^{ano}, effects at short distances are absorbed
  - 3 neutrino framework
  - Error budget : weighted standard deviation of experimental errors ~1-2%?

Testing the anomaly



NUCIFER

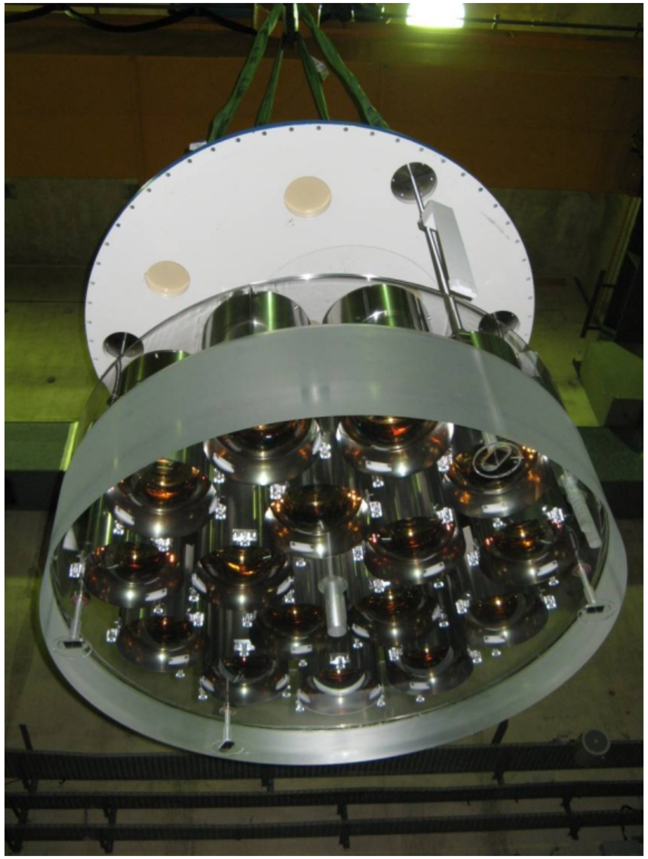


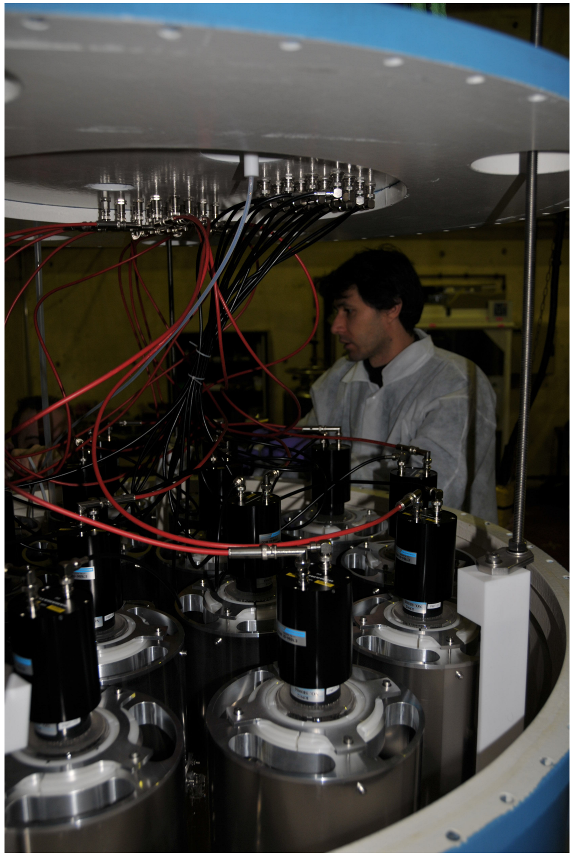


- First goal: validate the concept of neutrino for non proliferation for IAEA Safeguards
- 850 l of Gd-doped LS viewed by 16 PMTS on the top + Muon Veto + Low-Z and High-Z shielding
- Installed 7m away from the OSIRIS nuclear core in Saclay
- 500 antineutrino events/day expected
- Status: Detector & DAQ operational in Saclay ALS laboratory
- Integration at Osiris by June 2011

Test assembly in Saclay

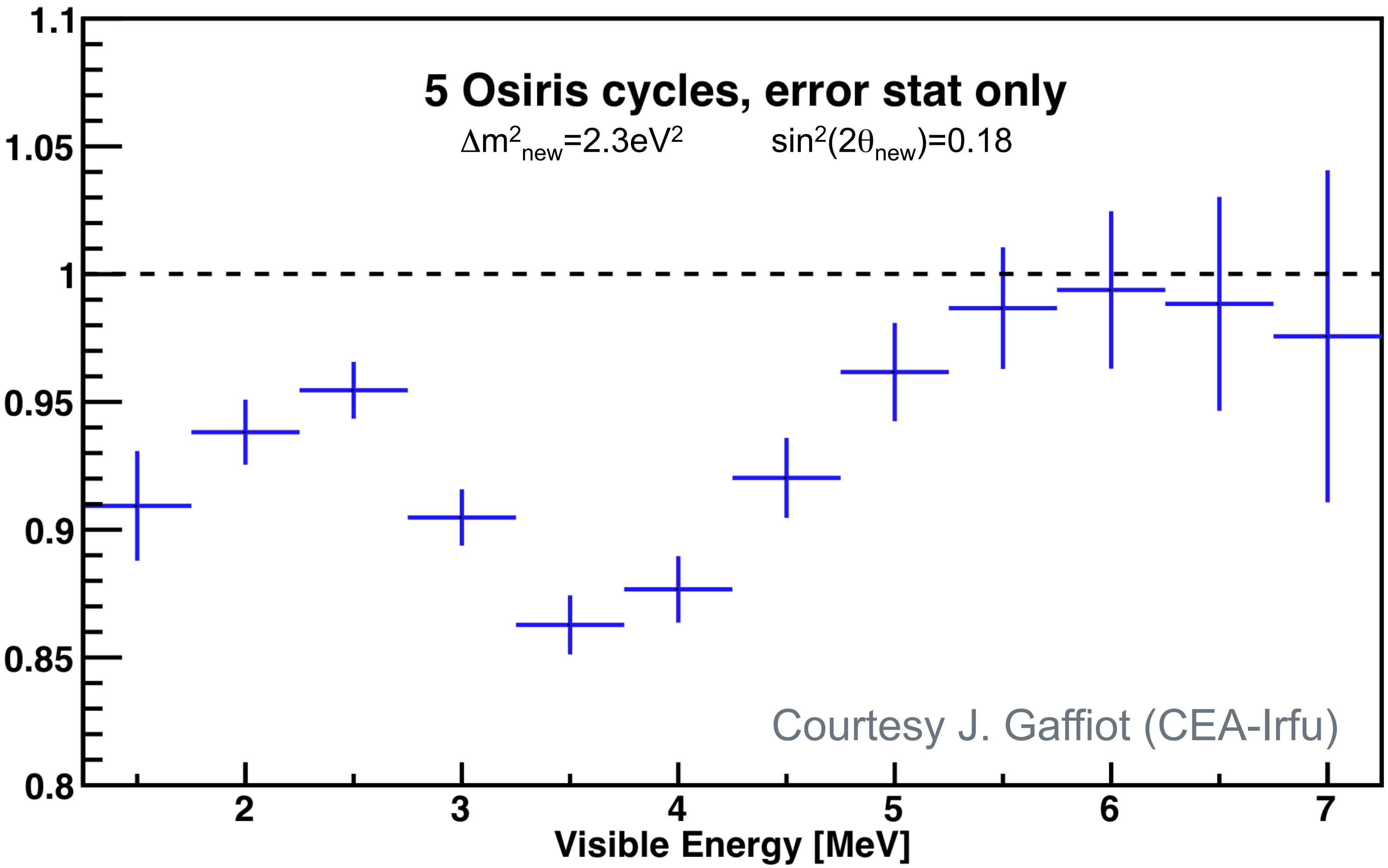
Detector ready to be integrated on the reactor site





Expected Signal in Nucifer

- 100 000 events (6 months of OSIRIS data, 5 cycles, 40% efficiency)
- 9% rate suppression expected at the best fit
- Significant spectrum distortion computed by folding the MC det. response



An intense neutrino source inside a large detector

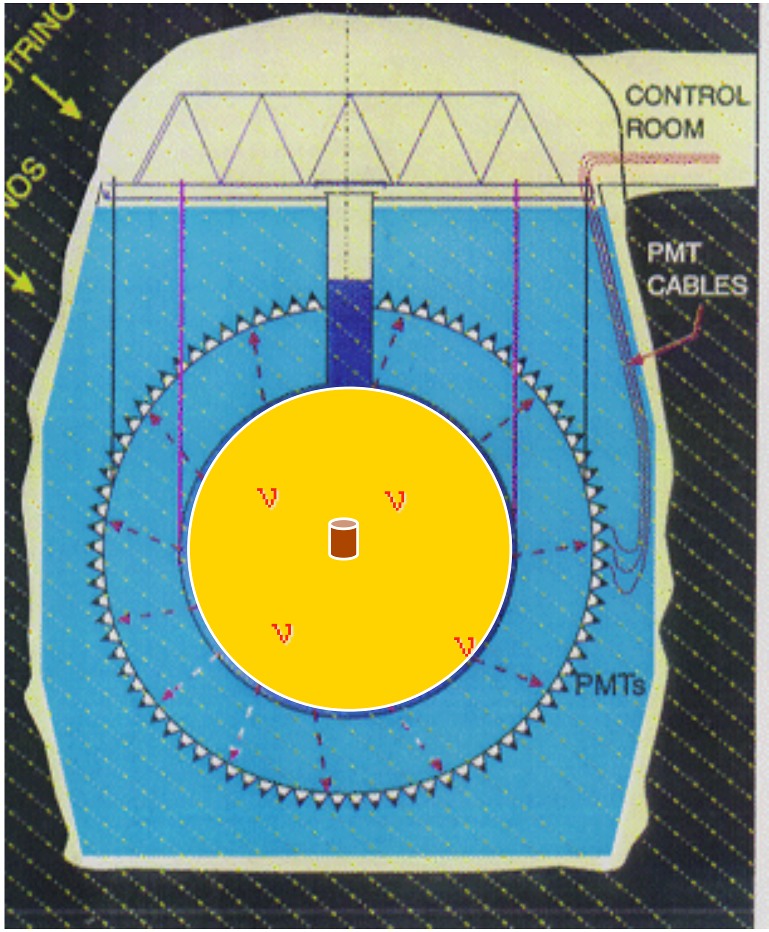
- MCi intensity source of ^{51}Cr or ^{37}Ar: Such sources have already been made several times for GALLEX & SAGE

- mono-E neutrinos emitted

- Large volume of scintillator

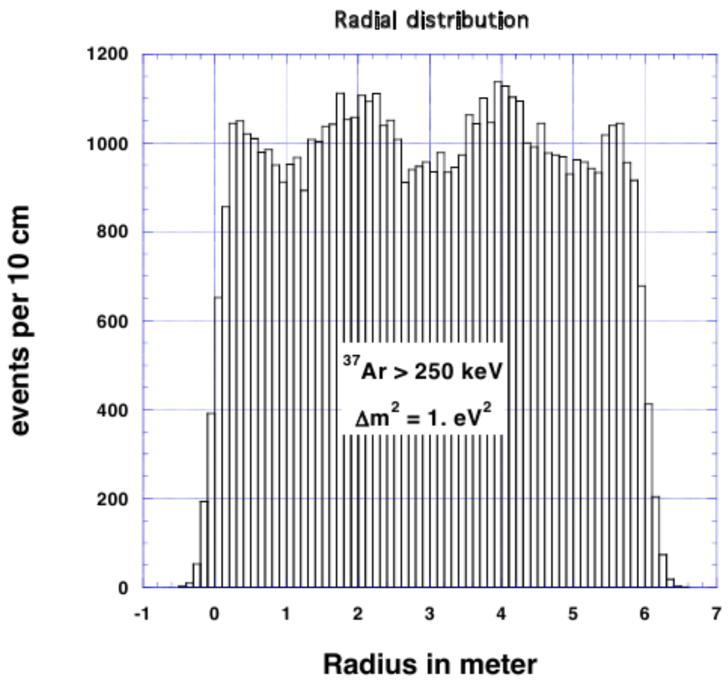
- Detect elastic scattering of ν_e on electrons

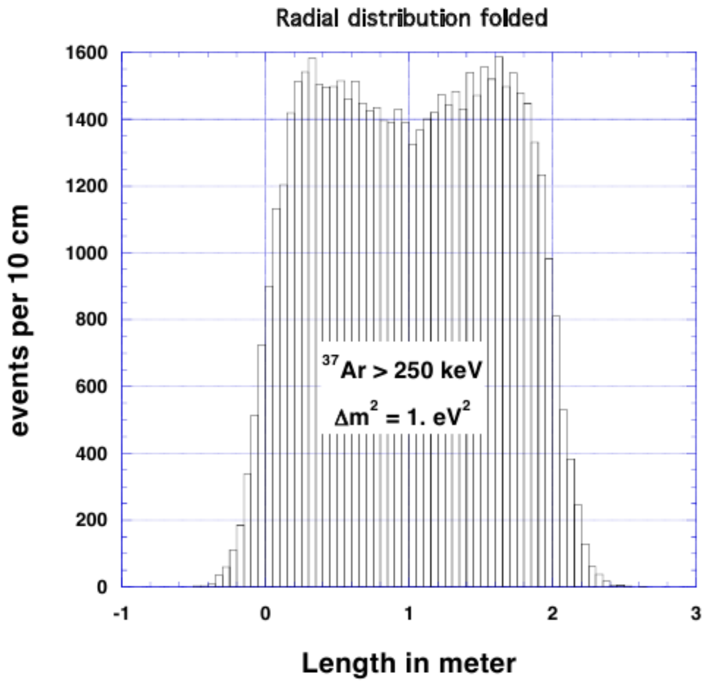
- ^{37}Ar is preferred for a deployment inside a detector:
- no cooling (14 W/MCi)
- BUT difficult to produced in a breeder reactor. Investigation on-going



Expected signal

- In a large detector like SNO+, with a ^{37}Ar source
- Threshold at 250 keV
- Clear oscillation pattern


Radial distribution


Radial distribution folded

- High statistics: about 60,000 events with 1MCi of ^{37}Ar in ~ 150 days, with threshold at 250 keV

- Need <u>very good</u> spatial resolution: σ~10 cm, only $\Delta m^2 < 3\ eV^2$ is visible

Conclusion

- New calculation of anti-ν_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 = 0.937 ± 0.027
  - 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 ν data
  - Overall, no-oscillation hypothesis disfavored at 99.84% CL
  - Data compatible with Δm^2 >~ 1 eV2 and $\sin^2 2\theta$~0.1
  - Seems compatible with LSND & Miniboone data (preliminary)

- Middle/Long-baseline reactor experiments: deficit from anomaly could be mis-interpreted as a hint for non-zero θ_{13}
  - Revised constraint: $\sin^2 2\theta_{13} < 0.095$ at 90%CL → 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 β spectrum measurements: within sensitivity of KATRIN

- If Majorana, the contribution of such a state would be of interest to future ββ0ν experiments

- Slightly favored by some cosmological models:
  - WMAP+BAO fit 4.34±0.87 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