Precision measurements with neutrinos from nuclear reactors: new results, anomalies and perspectives

Julia Haser, MPIK Heidelberg

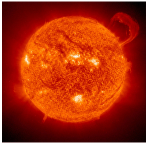
Kaffeepalaver, 2015/05/21

Contents

Neutrinos from reactors and the oscillation phenomenon

Neutrino sources

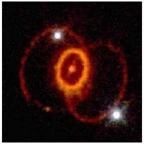
natural sources



solar ν

ν_e

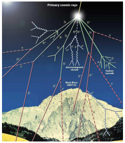
MeV



cosmic ν

$\overset{(-)}{\nu}_e\ \overset{(-)}{\nu}_\mu\ \overset{(-)}{\nu}_\tau$

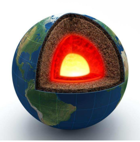
MeV- PeV



atmospheric ν

$\overset{(-)}{\nu}_e\ \overset{(-)}{\nu}_\mu$

GeV



geo ν

$\overset{(-)}{\nu}_e$

MeV

artifical sources

reactors

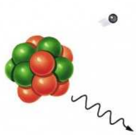
$\bar{\nu}_e$

MeV

accelerators

$\overset{(-)}{\nu}_e\ \overset{(-)}{\nu}_\mu$

MeV- GeV

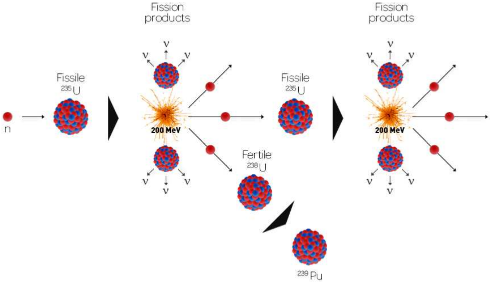


radioactive sources

$\overset{(-)}{\nu}_e$

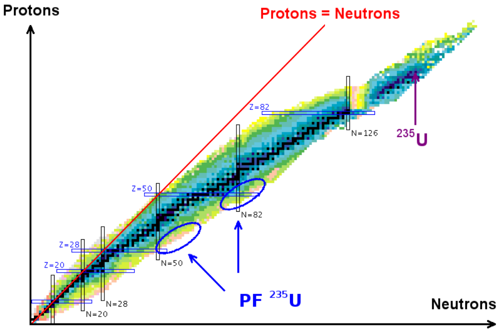
MeV

Reactors as source of $\bar{\nu}_e$



- nuclear reactors rely on fission chain
- 1 fission: $\sim$200 MeV and 6 neutrinos
- light water reactor: few $GW_{th} \rightarrow 10^{20}\ \bar{\nu}_e/s$

Reactors as source of $\bar{\nu}_e$

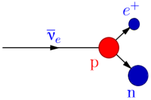


- fission products are neutron rich nuclei
- **pure and intense** source of $\bar{\nu}_\mathrm{e}$ through β^- decays
- 99.9 % of $\bar{\nu}_\mathrm{e}$ flux: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U

Detection of $\bar{\nu}_e$

- inverse beta decay (IBD) reaction on hydrogen nuclei (H_2O, $-CH_2$)

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



- ^{3}He detectors: neutron counting
- Organic scintillator detectors: **coincidence signal**

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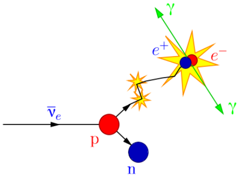
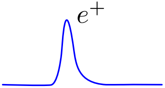


- ^{3}He detectors: neutron counting
- Organic scintillator detectors: **coincidence signal**
  - prompt: e^+ annihilation + kinetic energy



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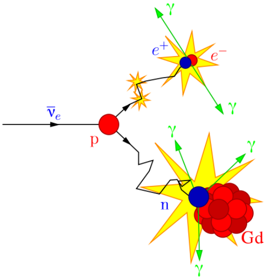
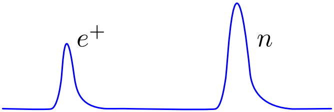


- ^{3}He detectors: neutron counting
- Organic scintillator detectors:
  coincidence signal
  - prompt: e^+ annihilation + kinetic energy
  - delayed: neutron capture
    - H: $E_\gamma \approx 2.2\,\text{MeV}$, $\tau \sim 200\,\mu\text{s}$
    - Gd: $E_\gamma \approx 8\,\text{MeV}$, $\tau \sim 30\,\mu\text{s}$



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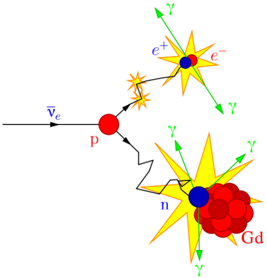

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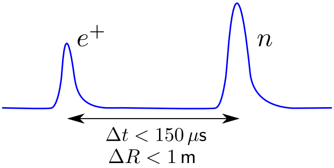
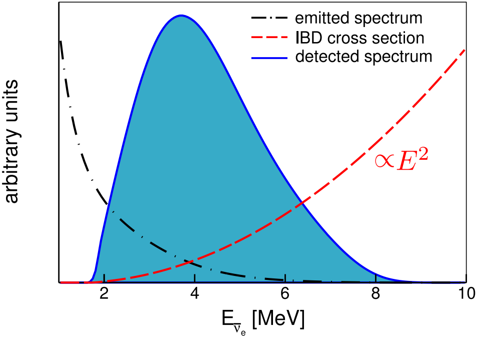


Detectable $\bar{\nu}_e$ spectrum

interaction spectrum



energy threshold = 1.8 MeV

energy of the e^+ event: $E_{vis} \approx E_\nu - 0.8\,\text{MeV}$

Neutrino mixing

flavour eigenstates		mass eigenstates
ν_e, ν_μ, ν_τ	$\neq$	ν_1, ν_2, ν_3
(creation/detection)		(propagation)

- linked via mixing matrix U (3 angles, 1 phase):

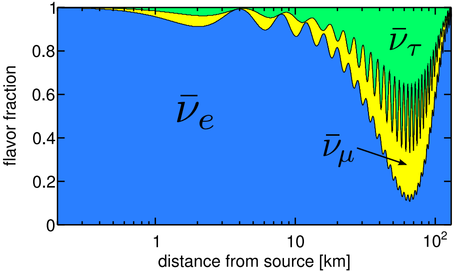
$s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric	small mixing angle	solar
$\theta_{23} \sim 45^\circ$	$\theta_{13} \sim 9^\circ$	$\theta_{12} \sim 33^\circ$

- mass splittings: $\Delta m_{ij}^2 = m_i^2 - m_j^2\,; \quad i,j = 1,2,3$

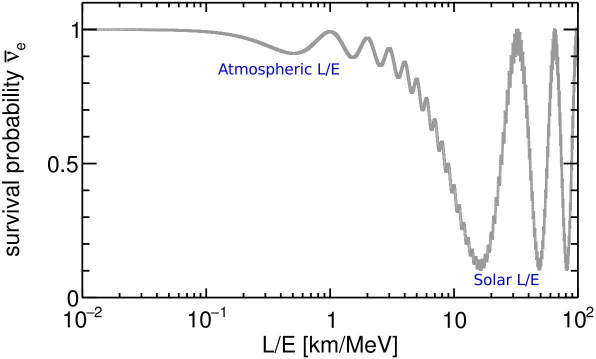
Reactor $\bar{\nu}_e$ & neutrino oscillation



E_ν = 4 MeV

- flavor content of the reactor neutrino flux **changes during flight**
- mixing parameters responsible for oscillation pattern

Reactor $\bar{\nu}_e$ & survival probability

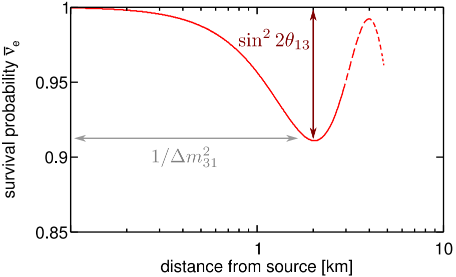


- $\overset{(-)}{\nu}_e$ deficit:
  - amplitude $\propto \sin^2 2\theta$
  - frequency: terms with $\sin^2\left(1.27 \cdot \Delta m^2 \cdot L/E\right)$
- "large" oscillation: θ_{12}, $\Delta m^2_{21} = 7.60 \cdot 10^{-5}\text{eV}^2$
- "fast" oscillation: θ_{13}, $\Delta m^2_{31} = 2.48 \cdot 10^{-3}\text{eV}^2$

$\Rightarrow$ size of the measured deficit varies wrt distance L and E_ν

Measuring the mixing angle θ_{13} with Double Chooz

Reactor neutrinos and θ_{13}

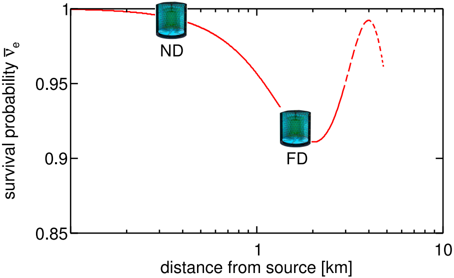


$E_\nu = 4\,\text{MeV}$

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2_{31} L}{E}\right)$$

- θ_{13} measurement w/o parameter degeneracies
- short baseline, low energy → no matter effects

Reactor neutrinos and θ_{13}



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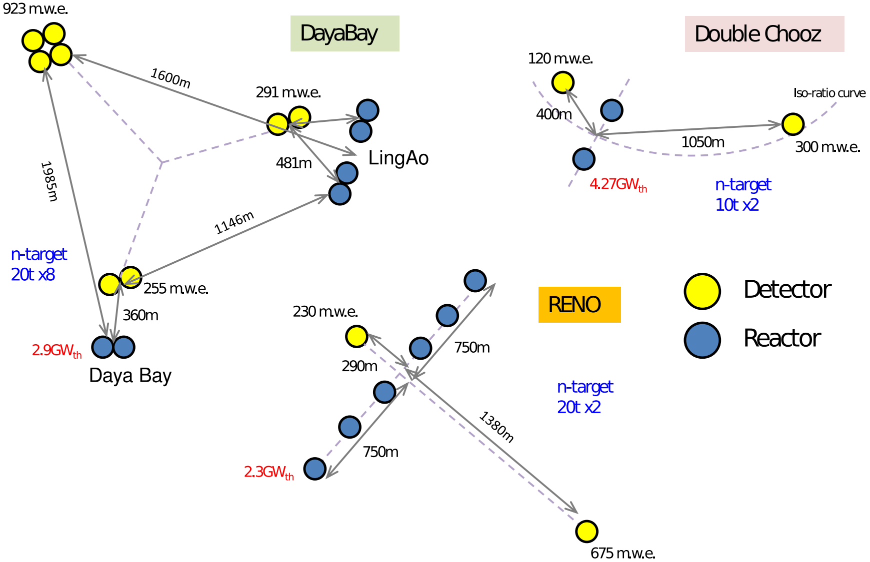
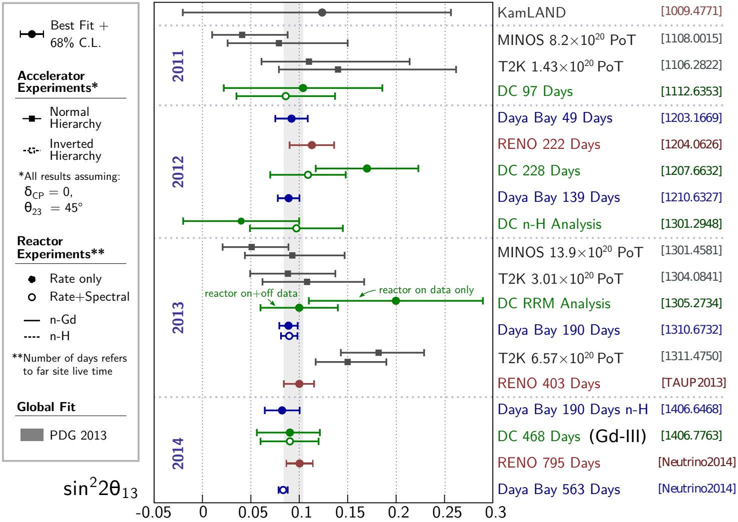
- θ_{13} measurement w/o parameter degeneracies
- short baseline, low energy → no matter effects
- multi detector principle (cancel systematics)

Recent reactor neutrino experiments

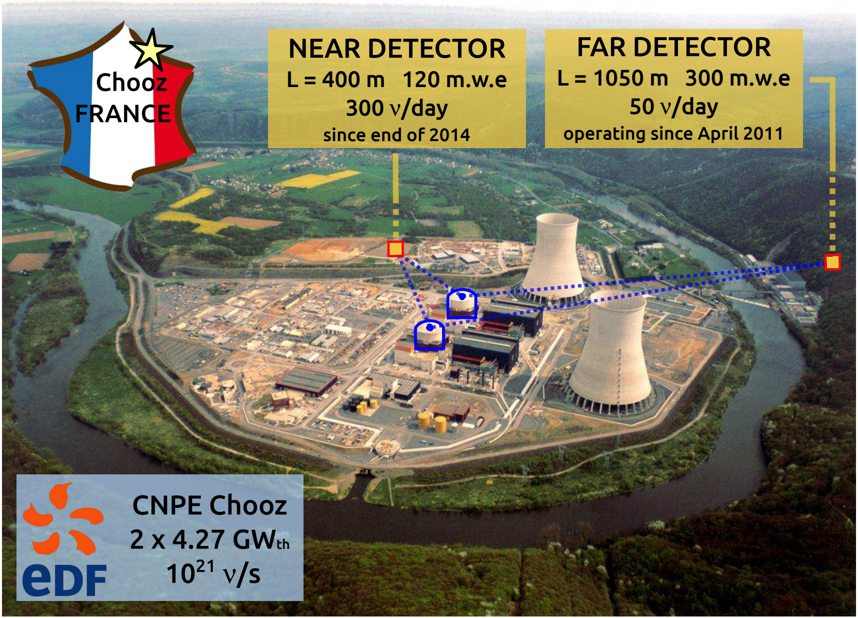


θ_{13} measurements

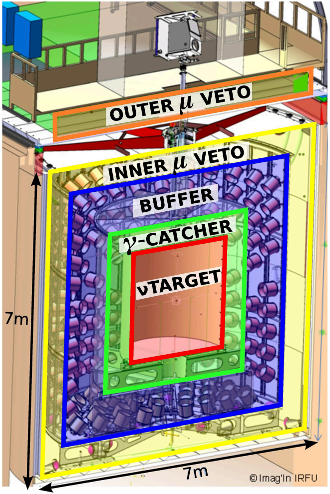


"Gd-III" publication: Double Chooz Collaboration, JHEP10(2014)086

Chooz reactor site



Double Chooz Detector



μ VETOES

- Outer Veto: plastic scintillator strips
- Inner Veto: liquid scintillator (LAB)
  with 78 x 8" PMTs

INNER DETECTOR

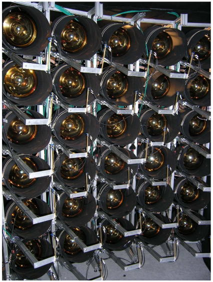
- ν-Target: liquid scintillator PXE + Gd (1 g/l)
- γ-Catcher: liquid scintillator PXE (no Gd)
- Buffer: transparent mineral oil
  with 390 x 10" PMTs

Calibration

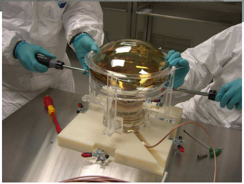
- source deployment in ν-Target & γ-Catcher
- light injection system
- background events

MPIK Double Chooz activity

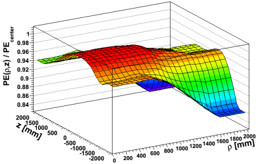
Liquid Scintillators:
developement
large scale production
filling

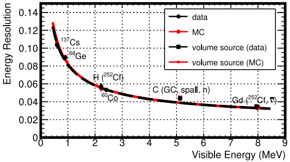


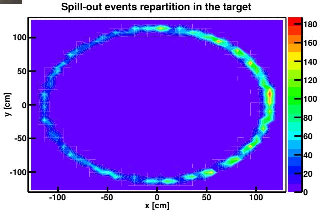
PMTs:
testing
installation



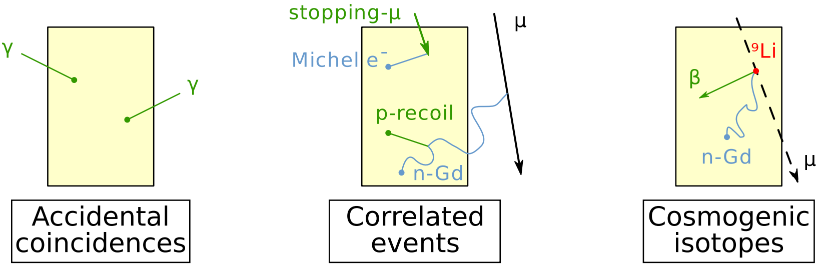
Analysis:
MC optical model
energy scale
detection efficiency







Double Chooz backgrounds



natural radioactivity

- 0.070 ± 0.003 /day

fast neutrons, stopping-μ

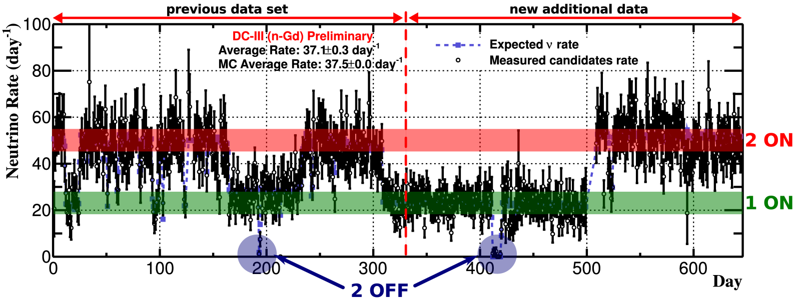
- 0.60 ± 0.05 /day

β-n emitter (mainly ^{9}Li)

- $0.97^{+0.41}_{-0.16}$ /day

background expectation: $1.6^{+0.4}_{-0.2}$ events/day

Far Detector analysis: Neutrino candidates



April 2011 – Jan 2013

- live-time: 460.7 days
- IBD candidates: 17351 – prediction: 18290 ± 350
- **unique to DC:** 7.24 days of all reactors off!!
  (7 candidates)

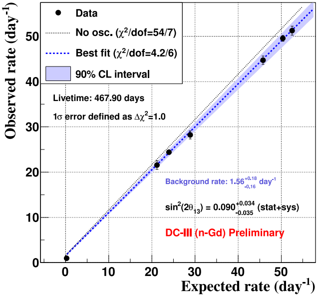
Far Detector analysis: Normalization uncertainties

source	uncertainty (%)	improvement wrt DC-II
reactor flux	1.7	–
signal detection	$\sim$ 0.6	-40 %
statistics	0.8	-30 %
backgrounds	0.8	-50 %
total	2.1	-20 %

uncertainty relative to signal prediction

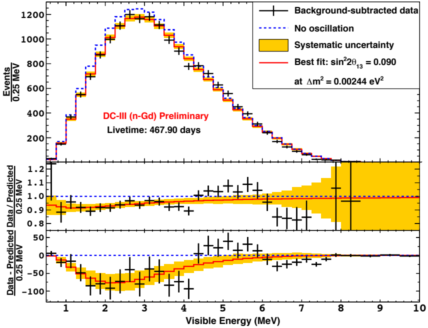
- Far Detector (FD) only analysis: compare data to MC prediction
- Bugey-4 “anchor” point reduces reactor normalization uncertainty from 2.8 to 1.7 %

Reactor Rate Modulation results



- measure θ_{13} (slope) and BG rate (intercept) at the same time
  - **background model independent** θ_{13} analysis possible
  - unique to DC: additional reactor off data point
- result:
  - $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$ (stat+sys)
  - $B = 1.56^{+0.18}_{-0.16}$ day^{-1}

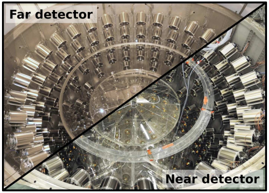
Rate + Shape results



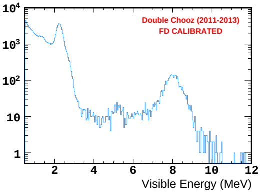
$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$ (stat+sys) $\chi^2_{\mathrm{min}}/\mathrm{dof} = 52.2/40$ (p = 9.4 %)

BG rate after fit: 1.38 ± 0.14 day^{-1}

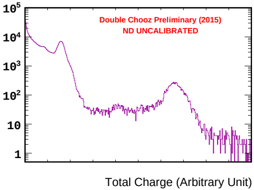
Near+Far detector outlook



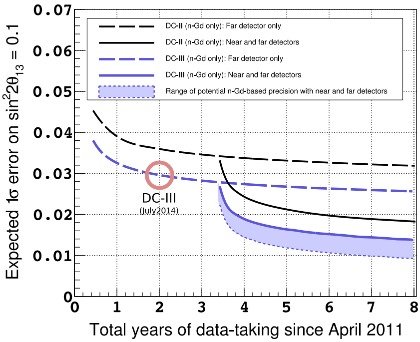
spallation neutrons **FD** (calibrated)



spallation neutrons **ND** (**uncalibrated**)



- near detector running since end of 2014
- 1σ within [0.015,0.010] after 3 years of ND+FD
  - BG uncertainty dependent → statistics dominated!



Prediction of the reactor $\bar{\nu}_e$ flux

Reactor flux prediction

of expected IBD events:

$$\frac{dN^{\nu}(t)}{dt} \propto \frac{1}{L^2} \times \frac{P_{th}}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

number of fissions

geometrical scaling

cross section per fission

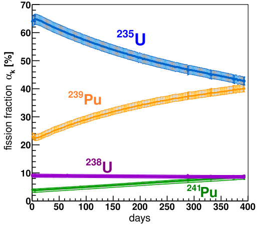
f = fission

fission fraction

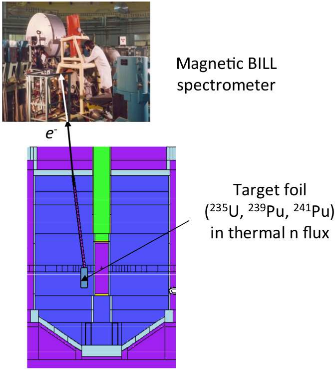
$$\langle \sigma_f \rangle = \sum_{k=U,Pu} \alpha_k \int_0^{\infty} S_k(E) \cdot \sigma_{IBD}(E)\, dE$$

ν spectrum

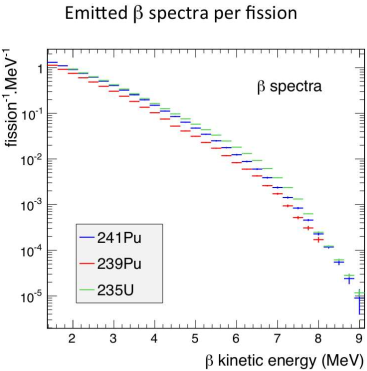
- $S_k(E)$ contain normalization and spectral information



ILL data: reference β-spectra



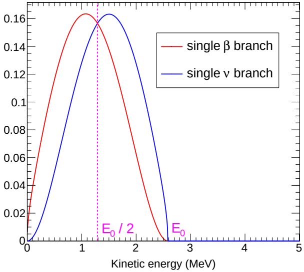
ILL research reactor
(Grenoble, France)

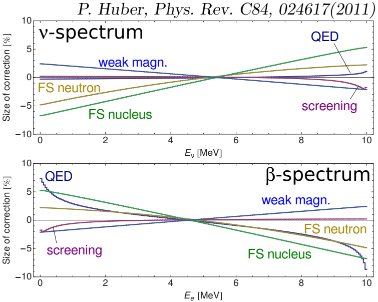


A. A. Hahn, K. Schreckenbach et al.,
Phys. Let. B218,365 (1989)+ refs therein

- total β-spectrum of each fissile isotope
- largest uncertainty: 1.8 % on normalization

Beta decay spectrum conversion



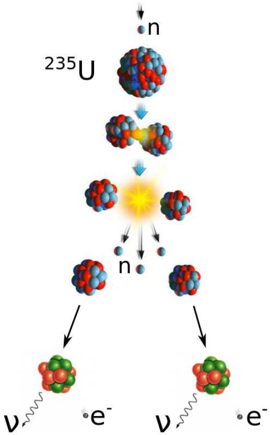


- neglect nucleus recoil
- endpoint energy: $E_0 = E_e + E_\nu$
- electron spectrum:

$$S(E) = N \cdot F(Z, A, E) \cdot \rho(E) \cdot C(E) \cdot (1 + \delta(Z, A, E))$$

- corrections:
  - radiative
  - finite size of nucleus and neutron
  - screening of e^-
  - weak magnetism

Contribution per isotope



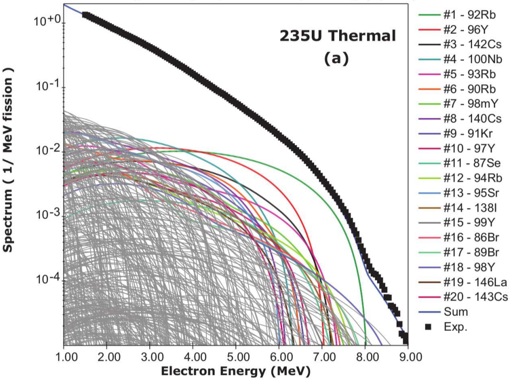
fission fragments: Z, A

fission fragment live-times

decay branching ratios
$(Q_\beta = E_0 + E_{ex})$

Realistic ^{235}U spectrum

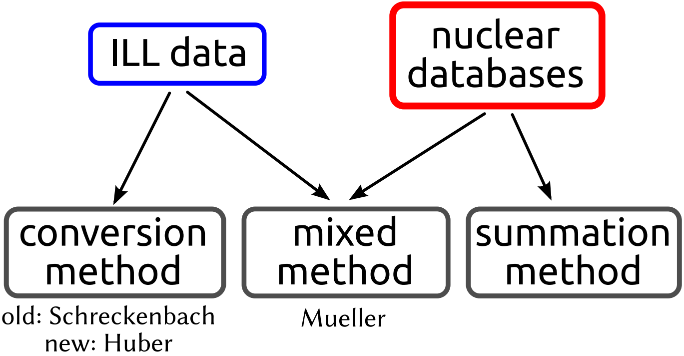
A. A. Sonzogni et al., Phys. Rev. C91, 011301(R) (2015)



built using the "summation method"

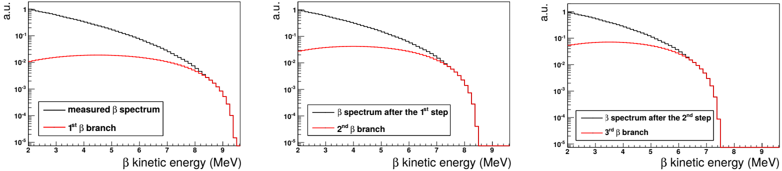
~1000 fission fragments with 10^4 β-branches

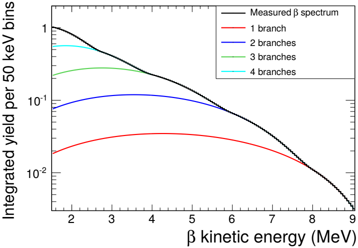
Prediciton of the $\bar{\nu}_e$ spectra



T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)
A. A. Hahn, K. Schreckenbach et al., Phys. Let. B218,365 (1989) + refs. therein

1) Conversion method

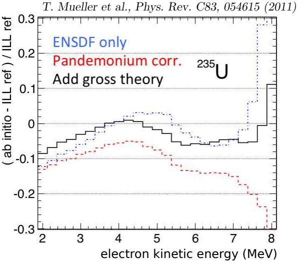




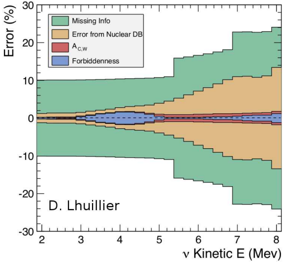
1. fit ILL data with 30 "virtual" β-branches
2. convert each β-branch into the corresponding ν-branch
3. sum the ν-branches to obtain the total spectrum

+ contraint on nuclear charge Z of fission fragments as a function of E_0 (retrieved from nuclear databases)

2) Summation method



- use information from nuclear databases
- includes new data from branching ratio measurements
- missing information: use theoretical predictions



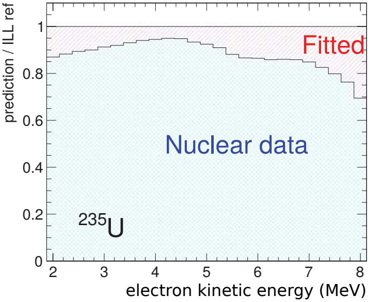
- agreement at the 10 % level with ILL data
- error of 10 to 20 %, dominated by missing info

3) Mixed method

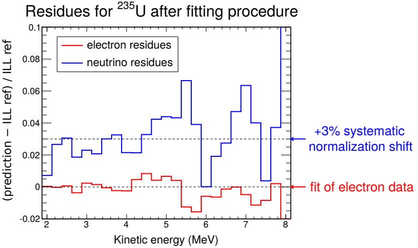
- maximize the use of measured data:
  90 % of the spectrum from nuclear databases

- missing 10 % compared to ILL data from fit with 5 virtual β-branches
- corrections applied on the single branch level
- error reduced compared to the pure summation spectrum (ILL data = only reference)

T. Mueller et al., Phys. Rev. C83, 054615 (2011)



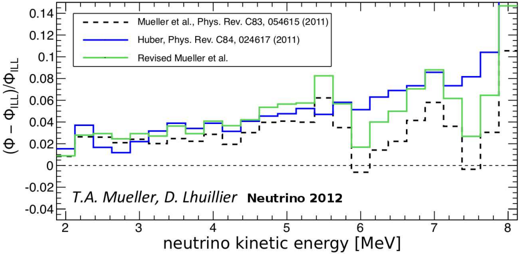
New antineutrino spectra of 2011



T. Mueller et al., Phys. Rev. C83, 054615 (2011)

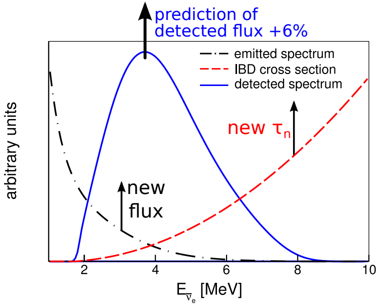
- uncertainties similar as for the old spectra (~3 %)
- mixed method results: +3.5 % total flux
  - low energy: corr. at branch level
  - high energy: true information on Z of fission fragments

- **mixed method and re-evaluation of conversion method in agreement**
  (Mueller et al.) (Huber)



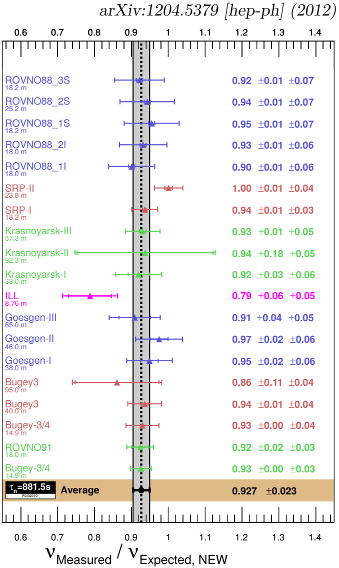
Reactor antineutrino anomalies

New reactor flux prediction



- **neutrino emission**
  - new reactor spectra: +3.5 %
    (2-8 MeV region)
  - accounting for long-lived isotopes: +1 %
- **neutrino detection**
  - re-evaluated σ_{IBD}: +1.5 %
    (new neutron life time measurement)

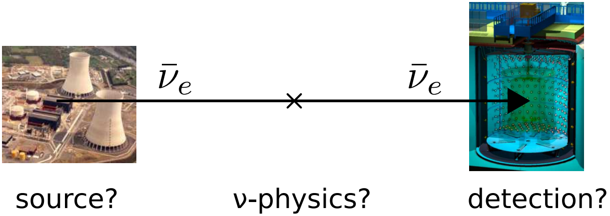
Reactor antineutrino anomaly



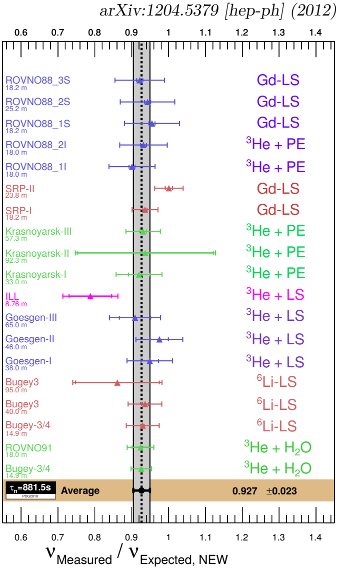
- 19 Short Baseline Experiments (SBL) $L < 100\,\mathrm{m}$
- observables: ratios of observed event rate to predicted rate of events

- before 2011:
  - average $\mu = 0.976 \pm 0.024$
- after 2011: (TAUP2013, T. Lasserre)
  - average $\mu = 0.936 \pm 0.024$
  - $2.7\,\sigma$ deviation from $\mu = 1$
  - includes km baseline experiments (Chooz, Double Chooz, PaloVerde, DayaBay)

Cause of the anomaly?



Experimental bias?



- IBD cross section well-known
- different experiments with different ...
  - ...reactor fuel compositions
  - ...detector technologies
  - ...efficiencies
  - ...backgrounds

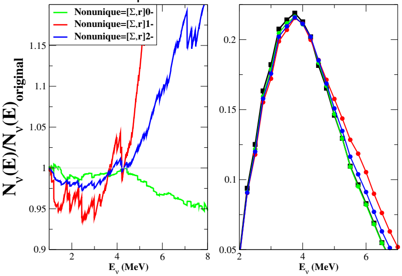
Limitations in the prediciton? (1)

- particle conservation: cancellation at low E adds up at high E
- corrections of the spectra of one beta branch depend on the **forbiddenness of the decay**

- Hayes et al.:
  - $\sim 25\,\%$ of the β-branches are forbidden
  - type of nuclear operator changes the spectral shape
  - 0-4 % change in the ν spectra → uncertainty underestimated?

ν interaction spectra for different treatment of the forbidden decays

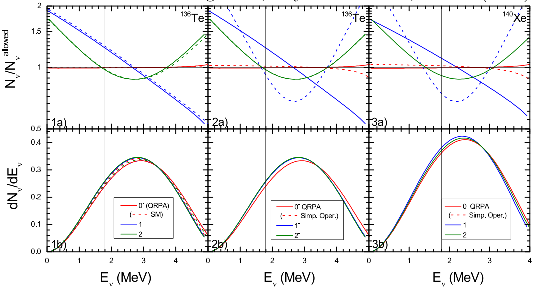
ratio of spectra



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

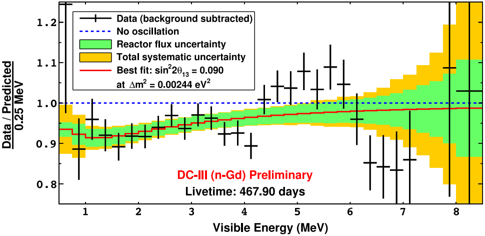
Limitations in the prediciton? (2)

D. Fang et al., Phys. Rev. C91 2, 025503 (2015)



- Fang et al.:
  - deviation in shape confirmed, but different correction terms
  - linear shape factor introduces larger spectral distortions than a parabola shape
  - average over all types of forbidden transitions: 1-2 % spectral change (smaller than Hayes)
- but: incomplete assumptions and extreme cases studied
- further realistic estimations are needed

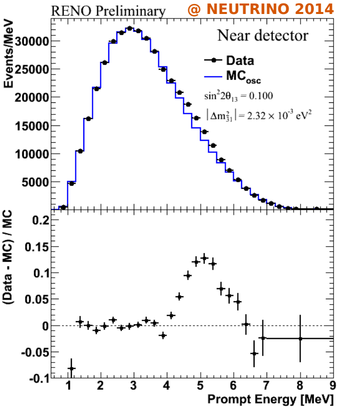
Neutrino spectrum distortion "Anomaly 2"

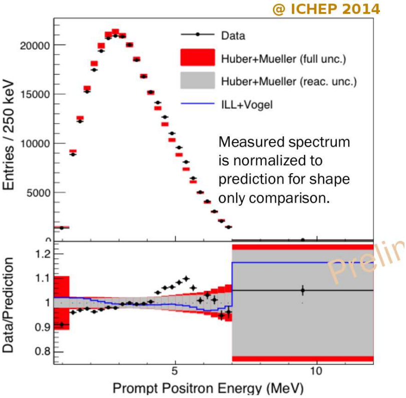


- spectral distortion above 4 MeV observed by the DC experiment in 2014
- several crosschecks have shown
  - θ_{13} measurement is not affected
  - energy scale at $E > 4$ MeV tested (n-^{12}C, ^{12}B) and as cause disfavoured
  - unknown background disfavoured
  - **correlation of excess with reactor power at $3\,\sigma$**

Spectral distortion in other experiments

- observation of DC of the distortion was confirmed by other reactor-ν experiments

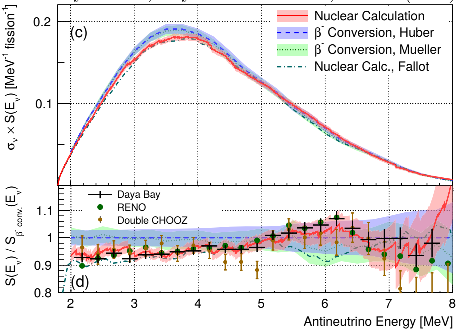




Spectral distortion in predicted spectrum

- bump in the summation method spectra of Dwyer et al. at 5-7 MeV
- at higher energies few decay branches contribute 40 % of the total spectrum

D. Dwyer et al., Phys. Rev. Lett. 114, 012502 (2015)



Note: Dwyer's spectrum is incomplete and dominant contributions to systematic errors are missing!

most prominent β-branches for $E > 4\,\mathrm{MeV}$

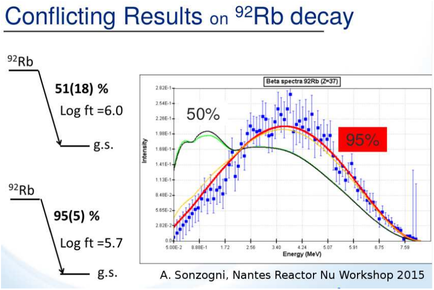
	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%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

M. Fallot et al., PRL 109, 20254 (2012)

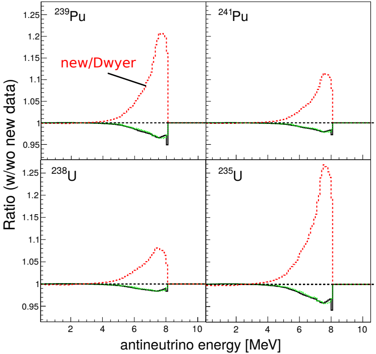
but: new data input on ^{92}Rb

- new data on ^{92}Rb leads to change in BR of GS → GS transition

A. Zakari-Issoufou et al., arXiv:1504.05812 [nucl-ex] (2015)

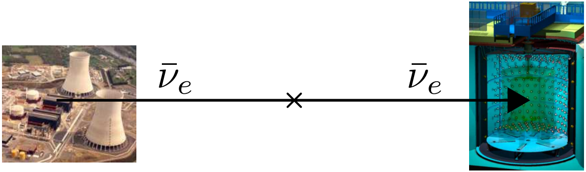


A. Sonzogni, Nantes Reactor Nu Workshop 2015



- bump in the Dwyer spectrum ratio will change with the new ^{92}Rb spectrum to a slope that rises wrt energy
- results very sensitive to database info → further measurements needed

Cause of the anomaly: new physics?



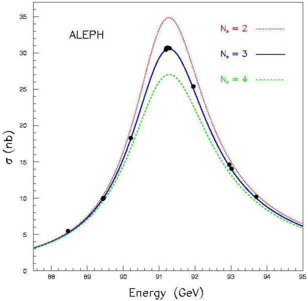
source? | ν-physics? | detection?

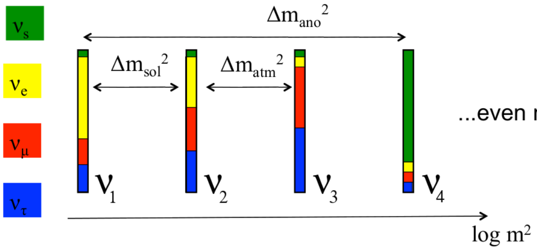
Future reactor experiments: search for a 4th neutrino eigenstate

Light sterile neutrinos

- Z decay measurements:
  3 active light ν flavors
  ($N_\nu = 2.984 \pm 0.008$)

$\Rightarrow$ new light neutrino eigenstate must be **sterile** (does not interact weakly)

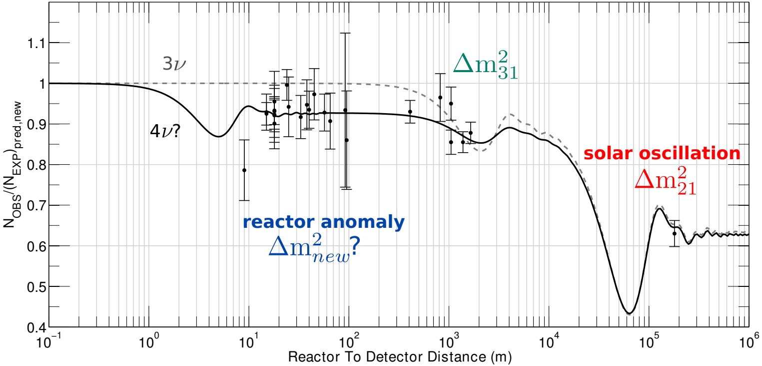




...even more?

Impact on $\bar{\nu}_e$ oscillation

New oscillation? $(|\Delta m^2_{\text{new}}| > 0.5\,\text{eV}^2,\ \sin^2 2\theta_{\text{new}} \approx 0.1)$



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

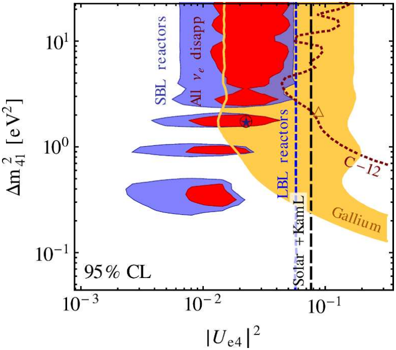
Other oscillation anomalies

Experiment	Neutrino source	Channel	Significance
LSND	Decay at rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8 σ
MiniBooNE	Short-baseline accelerator	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	3.0 σ
Reactor	β decay	$\bar{\nu}_e \to \bar{\nu}_e$	2.7 σ
Gallium	Electron capture	$\nu_e \to \nu_e$	2.7-3.0 σ

- LSND and MiniBooNE: observation of an excess in $\overset{(-)}{\nu}_e$
- Gallium anomaly: ν_e source measurements with ^{51}Cr and ^{37}Ar in the GALLEX and SAGE detectors

Sterile neutrino hypothesis

J. Kopp et al., JHEP05(2013)050



best fit (3 + 1 scenario)

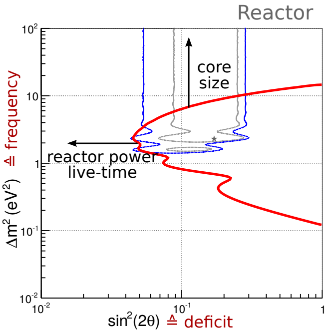
$|\Delta m^2_{\text{new}}| = 1.8\,\text{eV}^2$

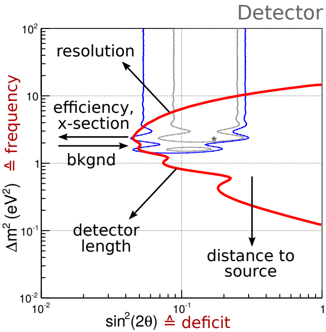
$\sin^2 2\theta_{\text{new}} = 0.09$

- combination of reactor (SBL, km-baseline, KamLAND), solar, Gallium source and ν_e scattering data
- data consistent with $\overset{(-)}{\nu}_e$ disappearance with $L/E \approx 1\,\text{m/MeV}$
- no-oscillation hypothesis excluded at 99.8 % CL

Sterile neutrino detector

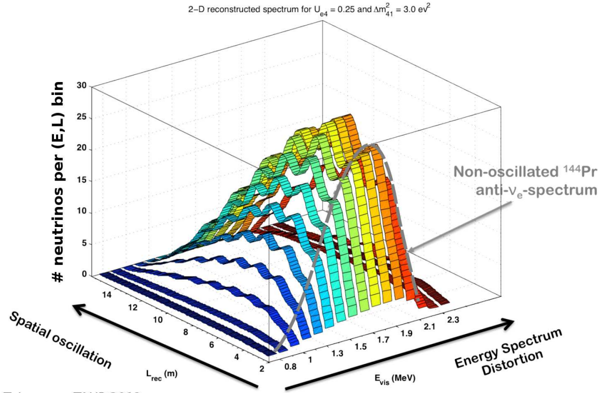
- influence of the ν source and detector parameters:





- $\Delta m^2 = 0.1 - 10\,\mathrm{eV}^2 \;\Rightarrow\; L_{\mathrm{osc}} = 0.1 - 10\,\mathrm{m}$
- experimental specifications:
  - compact source
  - good vertex and energy resolution
  - high statistics
  - low background

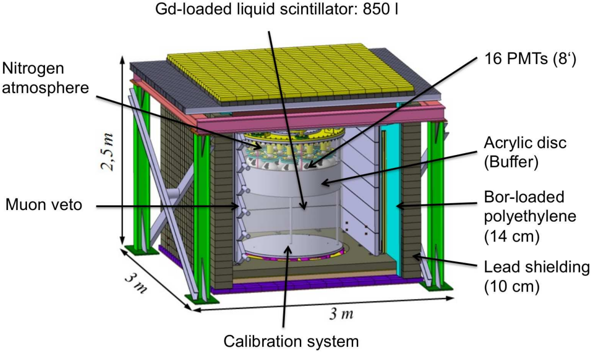
Sterile neutrino evidence



T. Lassere, TAUP 2013

- ν survival probability changes with L/E
- "smoking gun evidence": change in measured rate wrt to the distance to the source and energy

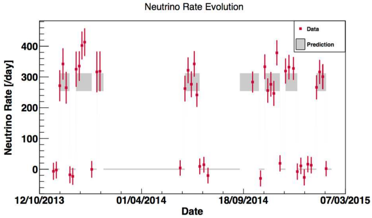
The Nucifer Experiment

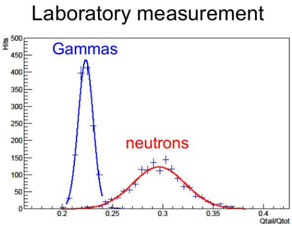


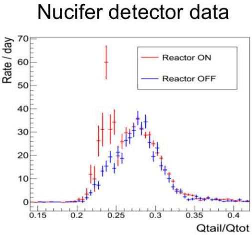
- 0.7 ton Gd-LS, 5 mwe overburden
- 7 m distance to Osiris research reactor at CEA/Saclay, France (70 MW, 20 % ^{235}U, 60x60x60 cm^3 core)
- designed for safeguard applications: ν rate measurement
- challenging: muon-induced bkg, γ-bkg from reactor

Nucifer data

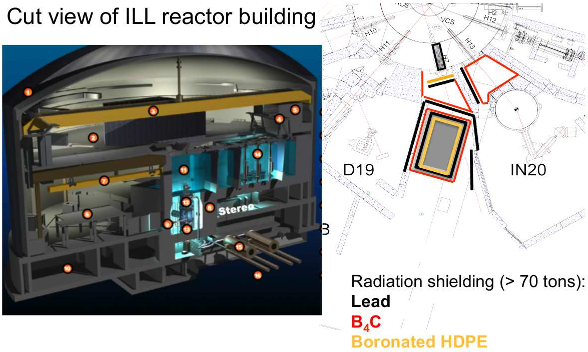
- clear signal of reactor antineutrinos
- optimized Gd-LS:
  pulseshape discrimination for background reduction
- no significant contribution from reactor induced fast neutrons







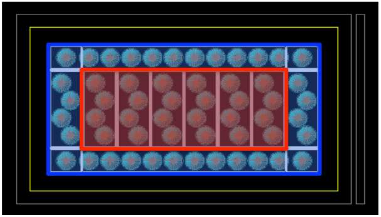
The Stereo project

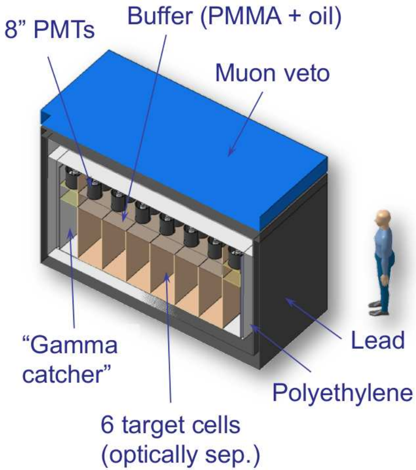


- 2 ton Gd-LS, 10 mwe overburden
- 8-11 m distance to ILL research reactor at Grenoble, France
  (57 MW, highly enriched in ^{235}U, core height = 80 cm, Ø= 40 cm)
- 500 $\bar{\nu}_e$ per day
- 70 tons γ and n shielding

Stereo detector

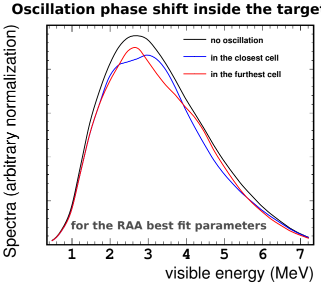
- size: 3x1.5x1 m^3
- Target: Gd-loaded liquid scintillator (MPIK)
- Gamma Catcher: Gd-free scintillator (MPIK)
- 8 inch PMTs at top (MPIK)

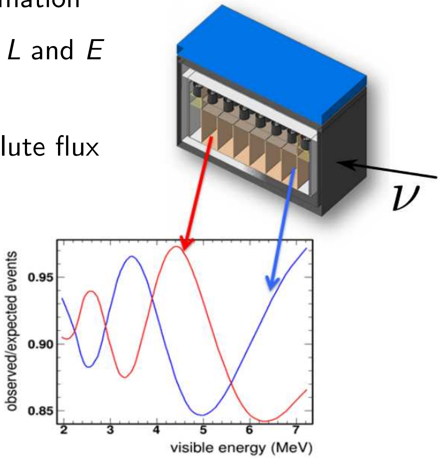




Sterile ν signature in Stereo

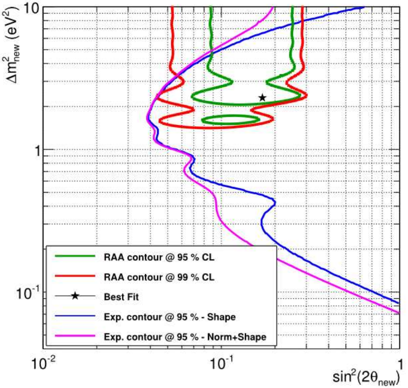
- **relative** measurement in 6 separate cells
- baseline dependent spectral deformation
- reminder: oscillation changes wrt L and E
- movable detector: $\pm$1-2 m
- measurements completed by absolute flux info





Stereo sensitivity

- finish detector construction this year
- assumptions:
  - $\sigma_{\text{e-scale}} = 2\,\%$
  - $S/B = 1.5$
  - 300 days reactor on
  - one position
  - 4 % normalization uncertainty
- two positions: improvement at low Δm^2



Conclusion

- the Double Chooz experiment measures the mixing angle θ_{13} using reactor anti-neutrinos
- R+S: $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$, BG rate: $1.38 \pm 0.14\ \text{day}^{-1}$
- targeted $1\,\sigma \approx 0.01$ uncertainty on $\sin^2 2\theta_{13}$

- re-evaluation of the reactor $\bar{\nu}$ spectra led to a +3.5 % shift in flux
- reactor $\bar{\nu}$ anomaly: short baseline reactor experiments detect deficit in flux
- combination with other exp.: no-oscillation hypothesis excluded at 99.8 % CL
- spectral distortion observed by 1 km baseline experiments

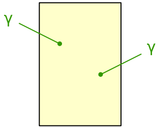
- reactor flux prediction is an active topic
  - treatment of forbidden decays has an impact on the spectral shape
  - summation method is extremely sensitive to the choice of database
  - further studies as well as measurements needed

- $\overset{(-)}{\nu}_e$ disappearance anomalies could be explained by a light sterile neutrino
- measurements with Nucifer and Stereo will test favoured parameter range

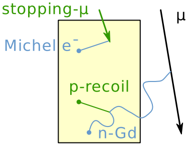
Thank you for your attention!

Appendix

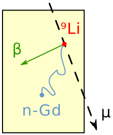
Double Chooz backgrounds



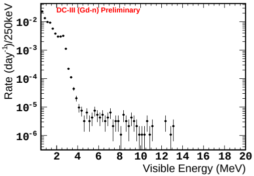
Accidental coincidences

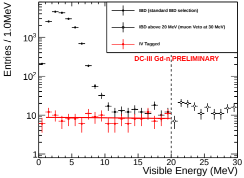


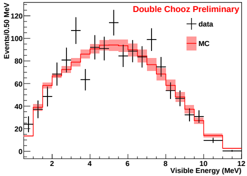
Correlated events



Cosmogenic isotopes







natural radioactivity

- 0.070 ± 0.003 /day
- DC-III/DC-II: **0.3**

correlation distance cut

fast neutrons, stopping-μ

- 0.60 ± 0.05 /day
- DC-III/DC-II: **0.5**

OV and IV veto + reconstruction likelihood veto

β-n emitter (mainly ^{9}Li)

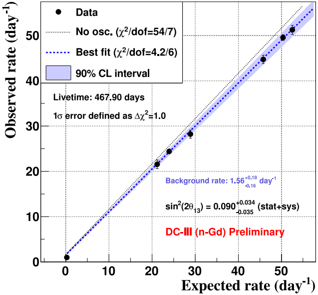
- $0.97^{+0.41}_{-0.16}$ /day
- DC-III/DC-II: **0.8**

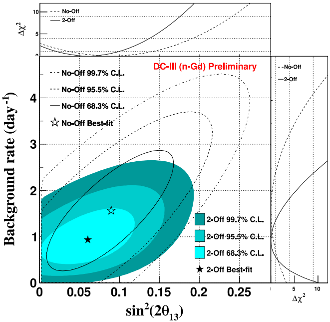
Li+He likelihood veto

DC-II: 2012

DC-III: 2014

Reactor Rate Modulation results



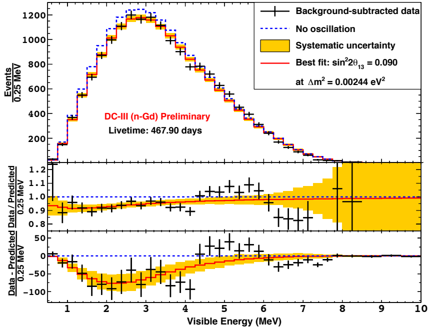


- measure θ_{13} (slope) and BG rate (intercept) at the same time
  - **background model independent** θ_{13} analysis possible
  - unique to DC: additional reactor off data point

- **result:**
  - $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$ (stat+sys)
  - $B = 1.56^{+0.18}_{-0.16}$ day^{-1}

- **w/o BG rate constraint result:**
  - $\sin^2 2\theta_{13} = 0.060 \pm 0.039$ (stat+sys)
  - $B = 0.93^{+0.43}_{-0.36}$ day^{-1}

Rate + Shape results



- innovations:
  - improved energy scale
  - all background assumptions from data
  - reduced uncertainties (bkg, ε, E-scale)
  - range from 0.5-20 MeV
  - measured ^{238}U spectrum in prediction
  - Δm^2 from MINOS 2013
  - includes 2 reactors off

$$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029} \text{ (stat+sys)}$$ $\chi^2_{\mathrm{min}}/\mathrm{dof} = 52.2/40$ (p = 9.4 %)

BG rate after fit: 1.38 ± 0.14 day^{-1}

Final Fit

- 40 energy bins with:

$$N_i^{\text{pred}} = \sum_{R=1,2}^{\text{Reactors}} P(\bar{\nu}_e \to \bar{\nu}_e) \cdot N_i^{\nu,R} + \sum_{b}^{\text{Bkgnds}} N_i^b$$

- binned rate + spectral shape fit:

$$\chi^2 = \sum_{i,j}^{\text{Bins}} (N_i - N_i^{\text{pred}}) \underbrace{(M_{ij})}_{\text{covariance matrix}}{}^{-1} (N_j - N_j^{\text{pred}})^T + \underbrace{\sum_{k=1}^{\text{Pulls}} \frac{(P_k - P_k^{\text{CV}})}{(\sigma_k^P)^2}}_{\text{pulled terms}}$$

Bugey-4 “Anchor” Point

- cross section per fission of each reactor R:

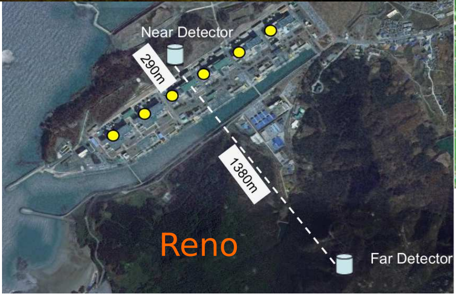
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{\text{Bugey}} + \sum_k (\alpha_k^{\text{DC}} - \alpha_k^{\text{Bugey}}) \langle \sigma_f \rangle_k$$

α_k = fractional fission rate of the k^{th} isotope

$$\text{while } \langle \sigma_f \rangle_k = \int_0^\infty dE \, S_k(E) \, \sigma_{\text{IBD}}(E)$$

$S_k(E)$ = reference spectrum

Other Experiments (1)

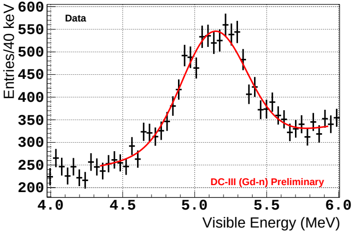


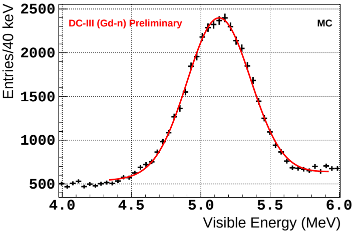
Other Experiments (2)

recent reactor experiments' results

	$\sin^2(2\theta_{13})$	
Double Chooz	$0.090^{+0.032}_{-0.029}\,(\text{stat.} + \text{syst.})$	10.1007/JHEP10(2014)086
Daya Bay	$0.090^{+0.008}_{-0.009}\,(\text{stat.} + \text{syst.})$	10.1103/PRL.112.061801
RENO	$0.101 \pm 0.013\,(\text{stat.} + \text{syst.})$	Neutrino2014

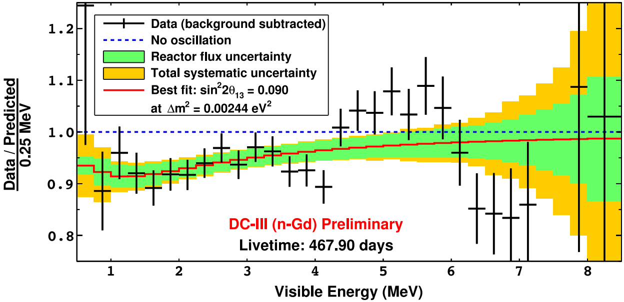
Carbon-12 n-captures





- n-C peak in Gamma-Catcher with $\Delta(\text{data,MC}) < 0.5\,\%$

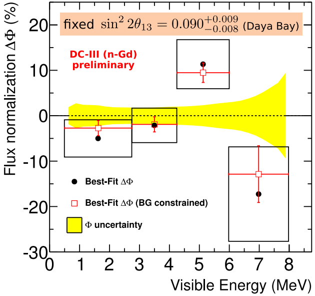
Spectrum distortion (1)



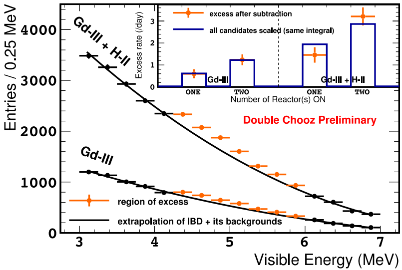
- spectral distortion above 4 MeV observed
- several crosschecks have shown
  - θ_{13} measurement is not affected
  - energy scale at $E > 4\,\mathrm{MeV}$ tested (e.g. n-^{12}C) and as cause disfavoured
  - unknown background disfavoured

Spectrum distortion (2)

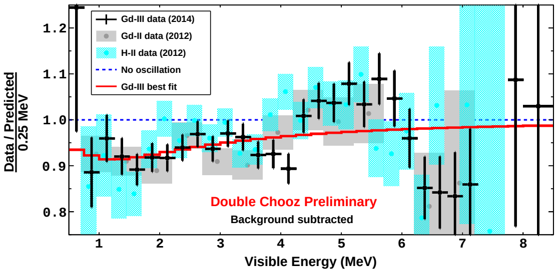
- RRM fit with free reactor normalization performed for different energy ranges
- excess at 4.25 – 6 MeV consistent with an unaccounted reactor flux
  - the significance wrt flux prediction is 3 σ with BG constraint from our estimation



- data-driven study of this energy region:
  - correlation of excess with reactor power
  - not only limited to n-Gd sample



Spectrum distortion (3)



- same pattern observed in DC-II results with different detection channels (Gd, H) and detector volumes (Target and Gamma-Catcher)
- better resolved with DC-III (more statistics, better energy scale and less background)