eV scale sterile neutrino searches at reactor

European Neutrino Town meeting
CERN - 23/10/2018

Thierry Lasserre
CEA-Saclay – APC – TUM
Reactor experiments provide the most precise $\theta_{13}$ value

$\Delta m^2$ 1.4 %
$\delta m^2$ 2.2 %
$\sin^2 \theta_{13}$ 3.8 %
$\sin^2 \theta_{12}$ 4.4 %
$\sin^2 \theta_{23}$ ~ 5 %

(1 $\sigma$ uncertainty)
Double Chooz

2 detectors Gd-volume: 20 m³

Daya Bay

8 detectors Gd-volume: 200 m³

Reno

2 detectors, Gd-volume: 40 m³

S/B>100 – Fully contained events (calorimeters) – ultra-low systematics: <O(1%)

⇒ High-resolution reactor neutrino spectroscopy with high statistics
2011: Reevaluation of the $e - \nu$ conversion procedure – Flux reevaluated at + 3.5%! – 3% systematics
Reactor Antineutrino Anomaly - 2011

\[ \frac{L}{E} \sim 1 \text{ m MeV} \]


3σ anomaly

Lasserre – 22/10/2018
Several statistically ‘moderate’ Anomalies

Triggered a lot of projects, since 2011
2014: 4-6 MeV spectral distorsion still unexplained...

Reactor $\nu$-spectra?  
Bias? Underestimated systematics?

Detector response?  
E-scale non-linearity?

G. Mention (CEA)
Concept: relative measurement, not relying on reactor neutrino spectra

\[ \Delta m^2_{\text{new}} = 2.3 \]
\[ \sin^2(2\theta_{\text{new}}) = 0.17 \]
Stéréo – 50 MW ILL compact core – France

- Overburden: 15 mwe - under water channel
- Baseline: 9-11m
- Pure $^{235}\text{U}$ fission spectrum
- 6 identical cells filled with LS-Gd – 1.5 ton
- Oscillation analysis independent of the prediction
- High external background mitigated by Heavy shielding and PSD capability on delayed IBD
- 400 IBD/day – S/B ~ 1
- 66 days of data analyzed
Stéréo Results – Exclusion of part the RAA domain

Final sensitivity (2020):
- Covers the whole RAA domain
- Factor 4 variation in L/E
- Test the 5 MeV bump ($^{235}$U)

Projected sensitivity to $^{235}$U spectrum shape

Robust oscillation analysis based on:
- Ratios of cell spectra
- Extensive background characterization (reactor OFF 50% time)

Thierry Lasserre – 22/10/2018
Prospect – 85 MW HFIR compact core - USA

- **At the surface.** Overburden < 1 mwe!
- **Baseline:** 7 to 12 m
- **Pure** $^{235}$U fission spectrum
- **4t** $^{6}$Li-doped liquid scintillator segmented detector
  - $\sim 4.5%/\sqrt{E}$ energy resolution
- **High external background mitigated by heavy shielding** – Prompt/Delayed IBD PSD capability and event localization
- **750 IBD/day – S/B ~ 1.36**
  Best S/B achieved at the surface
Prospect Results – Exclusion of part the RAA domain

- 5σ neutrino detection achieved in < 2hr
- Oscillation analysis independent of the prediction
- 33 days of data analyzed – Accepted PRL
- RAA best-fit disfavored at > 95%
- Neutrino-4 best-fit disfavored at > 95%

Next Steps
- Improved oscillation search with higher statistics
- $^{235}\text{U}$ reactor neutrino spectrum measurement (test the 5 MeV bump)
- Detailed modeling of near-surface backgrounds for future experiments
NEOS – 2.8 GW extended core - Korea

- overburden ≥ 20 m.w.e.
- Baseline: 24 m
- Homogeneous liquid scintillator detector of 1 ton 0.5 % Gd loaded, PSD discrimination for n-signal
- Shieldings: 10 cm B-Pe, 10 cm Pb, muon counter
- 2000 IBD evts/day - S/N ~ 22
- Phase 1 - completed: 180 d ON & 46 OFF
  Phase 2 - starting: Origin of the 5 MeV bump
- Exclusion of part of the reactor anomaly region
- Oscillation expected @E>4 MeV: rely on Daya Bay Bump subtraction
- Caveat: RENO/Daya Bay bumps look different...
Caveat concerning low mixings best-fits – NEOS (2016)

Oscillation signal:
- dominant in the region of the Daya Bay bump subtraction
- washed out since source is extended

PRL 118 (2017) 12, 121802

sin^2(2\theta) = 0.05
- <2% amplitude in NEOS (extended source)
- Embedded by %-ish systematic effects
DANSS – Kalinin 3 GW extended core – Russia

- Overburden ~ 50 m w.e.

- \( L \approx 10.7-12.7 \text{ m} \) – Evolution of the neutrino flux and spectrum with distance via lifting platform (top/middle/down every 2.5 days)

- Segmented plastic scintillator - 3D-information about each event

- IBD count rate \( 4000 \text{ IBD} / \text{day} \)
  High signal / background ~ 40

- Status: 2 y data taking – \( \frac{1}{2} \) data analyzed

JINST 11 (2016) no.11, P11011
DANSS – The strongest RAA exclusion

- Reactor modeling independent analysis based on spectral ratio (down / up) \(\rightarrow\) robust
- Exclude most the reactor antineutrino anomaly region – systematics treatment?

\[
\chi^2 = \sum_{i=1}^{N} \frac{(R_{i}^{\text{obs}} - k \times R_{i}^{\text{pre}})^2}{\sigma_i^2}
\]
Neutrino-4 – 100 MW SM-3 compact core – Russia

- Overburden: 3-5 mwe
- Baseline: 6-12m
- Pure $^{235}$U fission spectrum
- 5x10 identical cells filled with LS-Gd
- Oscillation analysis independent of the prediction
- High external background mitigated by
  - Heavy shielding - PSD capability
- 200 IBD/day – S/B ~ 0.5
- 480 days of data analyzed

Thierry Lasserre – 22/10/2018
Neutrino-4: claim for a $3\sigma$ sterile neutrino signal

- Coherent sum of E-spectra from 10 cells at 24xL, binned in L/E
- Model independent analysis

\[
R_{i,k}^{\text{exp}} = \frac{N(E_i^\nu, L_k) L_k^2}{K^{-1} \sum_k N(E_i^\nu, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m^2_{14}[L_k/E_i^\nu])]}{K^{-1} \sum_k [1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m^2_{14}[L_k/E_i^\nu])]} = R_{i,k}^{\text{th}}
\]
Neutrino-4: claim for a « 3σ » sterile neutrino signal

- Analysis
  - Correlations not included (considered small)
  - Systematics considered as negligible

- No-oscillation rejected@3σ (see arXiv:1809.10561)

- Best fit
  - $\Delta m^2 = 7.3 \text{ eV}^2$
  - $\sin^2(2\theta) = 0.44$ (17% deficit)

- Large mixing solution!
  - Tension with DC/DB/Reno Stéréo/Prospect/DANSS...

\[ R_{i,k}^{\text{exp}} = \frac{N(E^i_i, L_i) L_k^2}{K^{-1} \sum_k N(E^i_i, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_i 4 \sin^2 (1.27 \Delta m^2 L_k / E^i_i)]}{K^{-1} \sum_k [1 - \sin^2 2\theta_i 4 \sin^2 (1.27 \Delta m^2 L_k / E^i_i)]} = R_{i,k}^{\text{th}} \]
Conclusion and Outlook

- eV-scale sterile neutrinos hypothesis being tested by short baselines reactor expts Chandler, DANSS, NEOS, Neutrino-4, Prospect, Stéréo, Solid, ...

- **1st Objective achieved:** exclusion of part of the RAA Domain. Will improve.

- **2nd Objective:** Improve knowledge on reactor neutrino spectra
  - Understand the 5 MeV Bump (pure $^{235}$U ν-spectra) – Not yet completed
  - Reactor Applications
Conclusion and Outlook

- eV-scale sterile neutrinos hypothesis being tested by short baselines reactor expts Chandler, DANSS, NEOS, Neutrino-4, Prospect, Stéréo, Solid, ...

Caveat: Oscillation signal(s)

- $\sin^2 2\theta \geq 0.1$: Neutrino-4 claim for sterile $\nu$ (3$\sigma$)
  - Not confirmed by others. Background/analysis/systematics to be discussed.
- $\sin^2 2\theta \ll 0.1$: NEOS, DANSS best-fits
  - Oscillation signal amplitude comparable to systematics (underestimated?)
  - Difficult to address at high-significance with current SBL reactor experiments!
Conclusion and Outlook

- eV-scale sterile neutrinos hypothesis being tested by short baselines reactor expts Chandler, DANSS, NEOS, Neutrino-4, Prospect, Stéréo, Solid, ...

- **1st Objective achieved:** exclusion of part of the RAA Domain. Will improve.

- **2nd Objective:** Improve knowledge on reactor neutrino spectra
  - Understand the 5 MeV Bump (pure $^{235}$U ν-spectra) – Not yet completed

- **Caveat: Oscillation signal(s)**
  - $\sin^2 2\theta \geq 0.1$: Neutrino-4 claim for sterile ν (3σ)
    - Not confirmed by others. Background/analysis/systematics to be discussed.
  - $\sin^2 2\theta \ll 0.1$: NEOS, DANSS best-fits
    - Oscillation signal amplitude comparable to systematics (underestimated?)
    - Difficult to address at high-significance with current SBL reactor experiments!
Conclusion and Outlook

- eV-scale sterile neutrinos hypothesis being tested by short baselines reactor expts Chandler, DANSS, NEOS, Neutrino-4, Prospect, Stéréo, Solid, ...

1st Objective achieved: exclusion of part of the RAA Domain. Will improve.

2nd Objective: Improve knowledge on reactor neutrino spectra
- Understand the 5 MeV Bump (pure $^{235}$U ν-spectra) – Not yet completed

Caveat: Oscillation signal(s)
- $\sin^2 2\theta \geq 0.1$: Neutrino-4 claim for sterile ν (3σ)
  - Not confirmed by others. Background/analysis/systematics to be discussed.
- $\sin^2 2\theta \ll 0.1$: NEOS, DANSS best-fits
  - Oscillation signal amplitude comparable to systematics (underestimated?)
  - Difficult to address at high-significance with current SBL reactor experiments!
### eV-sterile neutrino search results @SBL Reactor Experiments

<table>
<thead>
<tr>
<th>Expt</th>
<th>Reactor</th>
<th>Over-burden</th>
<th>L (m)</th>
<th>$\sigma_E / \sqrt{E}$</th>
<th>Detector / segmentation</th>
<th>IBD signal</th>
<th>S/N</th>
<th>syst</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEOS</td>
<td>Extended 2800 MW $^{235}\text{U}, ; ^{239}\text{Pu}$</td>
<td>20 mwe</td>
<td>24</td>
<td>5%</td>
<td>Gd-LS 1 cell</td>
<td>2000/d day</td>
<td>22</td>
<td>few %</td>
<td>Partial exclusion of RAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PSD: delayed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stéréo</td>
<td>Compact 50 MW $^{235}\text{U}$</td>
<td>15 mwe</td>
<td>9-11</td>
<td></td>
<td>Gd-LS 6 cells</td>
<td>400/day</td>
<td>1</td>
<td>2.3%</td>
<td>Partial exclusion of RAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PSD: delayed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Neutrino-4| Compact 100 MW $^{235}\text{U}$ | surface    | 6-12  |                       | Gd-LS 10 cells           | 200/day     | 0.5 | few % | Claim for a signal $\Delta m^2 = 7.3 \text{ eV}^2$  \\
|           |                          |             |       |                       |                         |             |     |      | $\sin^2(2\theta) = 0.44$           |
|           |                          |             |       |                       |                         |             |     |      |                                   |
| DANSS     | Extended 3000 MW $^{235}\text{U}, \; ^{239}\text{Pu}$ | 50 mwe      | 11-13 |                       | PS+WLS 2500 strips       | 4000/d day  | 40  | few % | Largest exclusion of RAA           |
|           |                          |             |       |                       |                         |             |     |      |                                   |
| Prospect  | Compact 85 MW $^{235}\text{U}$ | surface    | 7-12  | 4.5%                  | $^6\text{Li-LS}$ 154 cells  \\
|           |                          |             |       |                       | PSD: prompt/delayed     | 750/day     | 1.4 | few % | Partial exclusion of RAA           |

*Prospect*: Compact 85 MW $^{235}\text{U}$ surface 7-12 4.5% $^6\text{Li-LS}$ 154 cells  \\
| PSD: prompt/delayed | 750/day | 1.4 | few % | Partial exclusion of RAA |
Reactor Neutrino Spectra (Daya Bay)

Claim for a mismatch concerning $^{235}$U $\nu$-flux in reactor models?

$\sim 2.2 \times 10^6$ neutrino candidates

PRL 118, 251801 (2017)