Reactor Anti-Neutrinos: Anomalies, Interpretations and new Experiment

Manfred Lindner

Selected puzzles in particle physics

chaired by Gennaro Corcella (LNF), Giuseppe Degrassi (ROMA3), Barbara Mele (ROMA1), Enrico Nardi (LNF)

from Tuesday, 20 December 2016 at 10:00 to Thursday, 22 December 2016 at 13:00 (Europe/Rome)
at Laboratori Nazionali di Frascati (High Energy Building, Seminar Room)
Directions in Neutrino Physics

3 massive $\nu$’s only: determine masses and mixings
- oscillations
- absolute mass $\leftrightarrow$ how precise should we know?
- Dirac or Majorana

more than 3 neutrinos
- sterile neutrinos
- L-violation $\leftrightarrow$ any one of them a major discovery!
- NSIs
- large magnetic moments
- ...

methods: precision $\Rightarrow \theta_{ij}, m_1, \Delta m_{ij}^2$, over-constraining
 MH, CP $\Rightarrow$ enough precision to extract it
 other $\Rightarrow 0\nu\beta\beta$, coherent scattering, ...

physics goals:
precise flavour information $\leftrightarrow$ origin of mass/flavour?
lever arm to other new physics $\Rightarrow$!
learn about sources $\Rightarrow$
Learning from Neutrino Sources

- Sun
- Cosmology
- Atmosphere
- Earth
- Reactors
- Accelerators
- Astronomy: Supernovae, GRBs, UHE n’s, β-Sources
The Status of Neutrino Parameters (3f)

M. Lindner, MPIK

See e.g. Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz

<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 0.83$)</th>
<th>Any Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bfp ±1σ</td>
<td>3σ range</td>
<td>3σ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.306$^{+0.012}_{-0.012}$</td>
<td>0.271 → 0.345</td>
<td>0.271 → 0.345</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>33.56$^{+0.77}_{-0.75}$</td>
<td>31.38 → 35.99</td>
<td>31.38 → 35.99</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.441$^{+0.027}_{-0.021}$</td>
<td>0.385 → 0.635</td>
<td>0.385 → 0.638</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>41.6$^{+1.5}_{-1.1}$</td>
<td>38.4 → 52.8</td>
<td>38.4 → 53.0</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.02166$^{+0.000075}_{-0.000075}$</td>
<td>0.01934 → 0.02392</td>
<td>0.01934 → 0.02397</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>8.46$^{+0.15}_{-0.15}$</td>
<td>7.99 → 8.90</td>
<td>7.99 → 8.91</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>261$^{+51}_{-59}$</td>
<td>0 → 360</td>
<td>0 → 360</td>
</tr>
<tr>
<td>$\Delta m_{21}^2/10^{-5}$ eV$^2$</td>
<td>7.50$^{+0.19}_{-0.17}$</td>
<td>7.03 → 8.09</td>
<td>7.03 → 8.09</td>
</tr>
<tr>
<td>$\Delta m_{32}^2/10^{-3}$ eV$^2$</td>
<td>+2.524$^{+0.039}_{-0.040}$</td>
<td>+2.407 → +2.643</td>
<td>[+2.407 → +2.643]</td>
</tr>
</tbody>
</table>

Absolute mass limits from Mainz and Troitsk: $m_1 < 2.2$ eV

Limits from cosmology: 0.17-0.2 eV

Future:

KATRIN ➔ just started operation ➔ 0.2 eV

Project8, ...
Precision with Reactor Neutrino Experiments

Identical detectors $\Rightarrow$ many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E_{\nu}}\right) - \left(\frac{\Delta m^2_{21} L}{4E_{\nu}}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

Clean & precise $\theta_{13}$ measurements $\leftrightarrow$ beams

3 flavour effect
- no degeneracies
- no correlations
- no matter effects

$E=4\text{MeV} \Rightarrow 1\text{km} \quad 180\text{km}$

$\Rightarrow$ Double Chooz
$\Rightarrow$ Daya Bay
$\Rightarrow$ Reno

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Anti-Neutrino Detection

Oscillations:
- affect rate & shape

Earlier reactor experiments:
- calculated spectrum
- rate normalized by $P_{\text{thermal}}$
- event rate = flux * x-section

- uncertainties in x-sections?

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

prompt $e^+$ signal

delayed $n$ capture
$\Rightarrow$ Gd doping
$\Rightarrow$ delayed $\gamma$ (30 $\mu$s)

\[ \Sigma \gamma \sim 8 \text{ MeV} \]

• position & time correlation
• delayed energy information
  $\Rightarrow$ background reduction!
Gd loaded liquid scintillator
  $\Rightarrow$ stability, transparency, WLS, ...
DC: 2,1,0 reactors on $\Rightarrow$ bg

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an extra (sterile) neutrino with a small mixing angle and a mass $O(eV)$ or heavier could have oscillated @ 10-100m averaged out: reduction by $\frac{1}{2} \sin^2(\theta_s) \sim 0.06$

$\leftrightarrow$ active $\nu$-unitarity tested @ few % $\rightarrow$ consistent $\rightarrow$

$\rightarrow$ check with a new experiment at shorter baseline
Surprise 2: A Bump in the Spectrum

Double Chooz, RENO and Daya Bay:

→ all see unexpected bump in near and far spectrum
→ $\theta_{13}$ measurement robust
→ expectations are Huber (235U, 239, 241Pu) and Mueller (238U)
→ RENO has largest bump
→ Double-Chooz used Huber and Haag (238U) for expected flux

High energy $\nu$'s $\leftrightarrow$ short lived isotopes ... little known

Nuclear theory:
theory errors ... maybe explainable...
better $\Rightarrow$ experimental test
Anti-Neutrino Event Rates

- cross-section is safe $\sim E^2$
- event rate emphasizes medium energies
- uncertainties in $\nu$-flux?
  $\Rightarrow$ HE tail has reduced weight
- BUT: more than 800 nuclides from the fission of $^{235}\text{U}$ and others: $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$, ...
  $\Rightarrow$ many instable fission products
  $\Rightarrow$ reactor is during steady operation in a flow equilibrium

$\text{event rates} = \text{flux} \times x\text{-section}$
Nuclear Reactors as Antineutrino Source

- Reactors like Chooz A+B \(\Rightarrow 8.5 \text{ GW}_{\text{th}}\)
- Few percent of the released energy \(\Rightarrow\) escapes with anti-neutrinos
  \(\Rightarrow\) \(2 \times 10^{21} \bar{\nu}/s \leftarrow \rightarrow O(1 \text{ kW/m}^2) @\text{fence}\)

- measured e\(^-\) spectrum of U\(^{235}\), Pu\(^{239}\), Pu\(^{241}\)
  \(\Rightarrow\) calculate \(\nu_e\) spectrum \(\Rightarrow\) certain precision
  \(\Rightarrow\) two “identical” detectors...

example: fission of U\(^{235}\)
\[
\overset{\text{92}}{\text{U}} + n \rightarrow X_1 + X_2 + 2n
\]

most likely A
\(\Rightarrow\) on average:
- 6 neutrons \(\beta\)-decay to 6 protons to reach stable matter
- 1.5 \(\nu_e\) emitted with E > 1.8 MeV

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Calculating Reactor Neutrino Spectra

\[ ^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n \]

Involves poorly known \(\beta\)-emitters

Protons

Neutrons

Decay

- \(\beta^+\)
- \(\beta^-\)
- \(\alpha\)
- Fission
- Proton
- Neutron
- Stabiles Nuklid
- Unbekannt

Short lived \(\leftrightarrow\) high energy \(\Rightarrow\) spectral uncertainties?
Reactor Spectrum Predictions

outcome:
- reactor flux anomaly unexplained
- most impressive proof of existence of dark sectors
  \[ P = 4 \text{GW}_\text{th} \at 15\text{m from core} \implies 150\text{kW/m}^2 \text{ in anti-neutrinos} \]
The ILL β-Spectra

Expected ν-fluxes originally determined from measurements of electrons (β-spectra) at ILL → inversion: ν-spectra from β-decays

- ILL fission β-spectra for $^{235}$U, $^{239}$Pu, $^{241}$Pu
- converted to antineutrino β-spectra by fitting to 30 end-point energies
- originally, used ENDF nuclear database

→ beware of uncertainties...

$$S_\beta(E) = \sum_{i=1,30} a_i S^i(E,E^i_0)$$

$$S^i(E,E^i_0) = E_\beta p_\beta (E^i_0 - E_\beta)^2 F(E, Z)(1 + \delta_{\text{corrections}})$$

$Z \to Z_{\text{eff}}$ and $\delta$ are parametrizations!
Conversion of ILL $\beta$-Spectra requires Input

\[ S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1 + \delta_{\text{corrections}}) \]

1) Z of the fission fragments
\( \rightarrow \) $Z_{\text{eff}}$ which determines the Fermi function

On average, higher end-point energy correlates with lower $Z$

$\leftrightarrow$ different nuclear binding energies

2) sub-dominant corrections $\delta_{\text{corrections}}$

\[ \delta_{\text{correction}}(E_e, Z, A) = \delta_{FS} + \delta_{WM} + \delta_R + \delta_{\text{rad}} \]

3) Contributing $\beta$-branches: 30 $\rightarrow$ ?

$Z_{\text{eff}} \sim a + b E_0 + c E_0^2$

$\delta_{FS} = \text{Finite size correction to Fermi function}$

$\delta_{WM} = \text{Weak magnetism}$

$\delta_R = \text{Recoil correction}$

$\delta_{\text{rad}} = \text{Radiative correction}$
Finite Size and Weak Magnetism Corrections

\[
S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e e (E_0 - E_e)^2 F(E_e, Z, A)(1 + \delta_{corr}(E_e, Z, A))
\]

\(\delta_{FS} = \) Finite size correction to Fermi function
\(\delta_{WM} = \) Weak magnetism

Original approximation by parametrization:
\[
\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4 MeV)
\]

In the updated spectra, both corrections were applied on a state-by-state basis.
An approximation was used for each:

\[
\delta_{FS} = -\frac{10Z\alpha R}{9\hbar c} E_\beta; \quad R = 1.2A^{1/3}
\]

\[
\delta_{WM} = +\frac{4(\mu_\nu - 1/2)}{3M_n} 2E_\beta
\]

\(\Rightarrow\) leads to a systematic increase of in the antineutrino flux above 2 MeV
\(\Rightarrow\) might account for half of the anomaly…
Forbidden Transitions

Forbidden transitions introduce a shape factor $C(E)$:

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 C(E) F(E_e, Z, A)(1 + \delta_{\text{corr}}(E_e, Z, A))$$

 Corrections for forbidden transitions: uncertainties or unknown

Forbidden transitions are part of the uncertainty in the calculated expected spectrum

⇒ Might account for up to 30% increase (while being consistent with ILL $\beta$-spectra)
Improvement with optimized $Z_{\text{eff}}$

- Simultaneous fit to Daya Bay and $\beta$-spectra, with improved description of $Z_{\text{eff}} \Rightarrow$ significantly reduced anomaly
  Hayes, et al.

- New fit is within the Daya Bay $1\sigma$ error bars

- DC+RENO+DB combined?
The Bump and improved $Z_{\text{eff}}$

what happens to the bump with the optimized $Z_{\text{eff}}$?

→ better!

→ The bump depends on how the ‘expected’ spectrum was derived
→ Shape differences partly reflect assumption in the conversion of β-spectra
→ But: Beware of collecting effects that go in the right direction…
Other Directions to explain the Bump

- Forbidden transitions – unlikely; effect $\sim < 1\%$

- Harder neutron spectrum
  conceivable, but so far no indication from theory and any data

- Dominant from $^{238}\text{U}$
  conceivable; would fit to the fact that RENO has biggest effect.
  ➔ clarification required

- Errors in the ILL $\beta$-spectrum measurements
  possible, initially considered likely, now unlikely

- ...?
Why not the ILL Spectra?

• ENDF database predicts an analogous bump in the beta-spectrum relative to Schreckenbach Dwyer, Langford, PRL 114, 012502 (2014)

• The European database JEFF does not predict the bump Hayes, et al. PRD, 92, 033015 (2015)

• The bump in ENDF is largeley a mistake in the database for fission yields at mass A=86. Plus other shortcomings of ENDF Corrected: ENDF no longer predicts a bump Sonzogni, et al. PRL, March 2016
More experimental Tests needed

Do sterile neutrinos exist?
Understand / explain reactor anomaly
Understand / expplain the bump
use well understood reactor spectra
- improved analysis of experiments
- new experiments…
### Sterile Hints & Plans for Tests

| Project          | | | | | |
|------------------|---|---|---|---|
|                 | neutrino | source | $E$ (MeV) | $L$ (m) | status       |
| SAGE [166]      | $\nu_e$   | $^{51}$Cr  | 0.75       | $\lesssim$ 1 | in preparation |
| CeSOX [167, 168]| $\bar{\nu}_e$ | $^{144}$Ce | 1.8 – 3   | 5 – 12 | in preparation |
| CrSOX [167]     | $\nu_e$   | $^{51}$Cr  | 0.75       | 5 – 12  | proposal     |
| Daya Bay [169, 170]| $\bar{\nu}_e$ | $^{144}$Ce | 1.8 – 3   | 1.5 – 8 | proposal     |
| JUNO [171]      | $\bar{\nu}_e$ | $^{144}$Ce | 1.8 – 3   | $\lesssim$ 32 | proposal |
| LENS [172]      | $\nu_e, \bar{\nu}_e$ | $^{51}$Cr, $^6$He | 0.75, $\lesssim$ 3.5 | $\lesssim$ 3 | abandoned   |
| CeLAND [173]    | $\bar{\nu}_e$ | $^{144}$Ce | 1.8 – 3   | $\lesssim$ 6 | abandoned |
| LENA [174]      | $\nu_e$   | $^{51}$Cr, $^{37}$Ar | 0.75, 0.81 | $\lesssim$ 90 | abandoned |

#### Source experiments

<table>
<thead>
<tr>
<th>Project</th>
<th>$P_{th}$ (MW)</th>
<th>$M_{target}$ (tons)</th>
<th>$L$ (m)</th>
<th>Depth (m.w.e.)</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucifer (FRA) [175]</td>
<td>70</td>
<td>0.8</td>
<td>7</td>
<td>13</td>
<td>operating</td>
</tr>
<tr>
<td>Stereo (FRA) [176]</td>
<td>57</td>
<td>1.75</td>
<td>9 – 12</td>
<td>18</td>
<td>running</td>
</tr>
<tr>
<td>DANSS (RUS) [177]</td>
<td>3000</td>
<td>0.9</td>
<td>10 – 12</td>
<td>50</td>
<td>running</td>
</tr>
<tr>
<td>SoLid (BEL) [178]</td>
<td>45 – 80</td>
<td>3</td>
<td>6 – 8</td>
<td>10</td>
<td>in preparation</td>
</tr>
<tr>
<td>PROSPECT (USA) [179]</td>
<td>85</td>
<td>3, 10</td>
<td>7 – 12, 15 – 19</td>
<td>few</td>
<td>in preparation</td>
</tr>
<tr>
<td>NEOS (KOR) [180]</td>
<td>16400</td>
<td>1</td>
<td>25</td>
<td>10 – 23</td>
<td>in preparation, withdrawn</td>
</tr>
<tr>
<td>Neutrino-4 (RUS) [181]</td>
<td>100</td>
<td>1.5</td>
<td>6 – 11</td>
<td>10</td>
<td>proposal</td>
</tr>
<tr>
<td>Poseidon (RUS) [182]</td>
<td>100</td>
<td>3</td>
<td>5 – 8</td>
<td>15</td>
<td>proposal</td>
</tr>
<tr>
<td>Hanaro (KOR) [183]</td>
<td>30</td>
<td>0.5</td>
<td>6</td>
<td>few</td>
<td>proposal</td>
</tr>
<tr>
<td>CARR (CHN) [184]</td>
<td>60</td>
<td>$\sim$ 1</td>
<td>7, 11</td>
<td>few</td>
<td>proposal</td>
</tr>
</tbody>
</table>

#### Reactor experiments

- $\Rightarrow$ tensions with cosmology…
- $\Rightarrow$ $N_{\text{eff}} = 3.x < \sim 4$
- BBN...
- Nevertheless: $\Rightarrow$ lab tests important
- Also important: $\Rightarrow$ keV sterile $\nu = \text{WDM}$. .

*Giunti 1512.04758*
burnup in LEU reactors changes isotope fraction

- effect on spectrum?
- not yet significant
- use HEU+LEU

• what if cosmology ($N_{\text{eff}}$) conflicts with sterile $\nu$’s?
  - check assumptions/errors on both sides
  - or new/extra physics on one side
SOX: Radioactive Source @ BOREXINO

large detector combined with 100-150 kCi Ce-144 source
goal 1% normalization uncertainty ➔ met & ready (TUM)
precise shape & rate measurement
authorizations in Italy OK
contract between CEA and Mayak settled
⇒ delivery scheduled for fall/end of next year ➔ data taking
STEREO @ ILL Reactor (HEU)

57 MW, compact core < 1m
~8–11 m from core
15 mwe overburden

Segmented detector with Gd loaded LS

400 ν per day
Spectral distortions in identical cells

HEU: burn only 235U ➔ compare pwr stations
Comparing different Reactor Fuels

Combine STEREO (HEU) and Double Chooz ND (LEU)

Buck, Collin, Haser, ML
→ can realistically be done (also with other results)
Timeline for Source and Reactor Experiments

- **NEOS**
  - 1st result → withdrawn

- **DANSS**
  - 1st data interrupted – continue running

- **STEREO I**

- **SOX @ Borexino**

- **SoLid Phase I & II**

- **PROSPECT Phase I**

- **2016**
- **2017**
- **2018**
- **2019**
- **2020**

→ Very interesting results as of next year
Coherent Neutrino Scattering

The Standard Model has six different interactions of neutrinos with matter:

- 5 have already been detected:
  - inverse muon (tau) decay
  - elastic electron scattering
  - (quasi) - elastic nucleon scattering
  - nuclear excitation and resonant production
  - Deep inelastic scattering and jet production

- 1 has so far not been detected:
  - Coherent neutrino-nucleus scattering: CvS
    - conceptually important
    - useful method to test new physics

Coherent Neutrino Scattering

Z-exchange of a neutrino with nucleus
- nucleus recoils as a whole
- coherent up to $E_\nu \sim 50$ MeV

$$Q_w = N - (1 - 4 \sin^2 \theta_w)Z$$

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left( 1 - \frac{MT}{2E_\nu^2} \right) F(Q^2)^2 \sim N^2$$

Important: Coherence length $\sim 1/E$
- need neutrinos below $O(50)$ MeV for typical nuclei
- low energy $E_\nu \leftrightarrow$ lower cross sections $\leftrightarrow$ flux!
The Neutrino Spectrum

10 GW at a distance of 150 km

reactor neutrinos:
ca. 4% of the thermal power P
3.9 GW → ca. 150 MW in ν’s
dilution by distance R
flux \( \Phi \sim \frac{P}{R^2} \)
ca. 7 kW/m² at 15m distance

But: Interaction is
- extremely weak
- grows with neutrino energy

<table>
<thead>
<tr>
<th>source</th>
<th>flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>reactor neutrinos (3 GW, at 10m distance)</td>
<td>5 x 10^13 /cm²/s</td>
</tr>
<tr>
<td>solar neutrinos (on Earth)</td>
<td>6 x 10^10 /cm²/s</td>
</tr>
<tr>
<td>supernova (50 kpc Abstand, for O(10) seconds)</td>
<td>~ 10^9 /cm²/s</td>
</tr>
<tr>
<td>geo-neutrinos (on the Earth’s continental surface)</td>
<td>6 x 10^6 /cm²/s</td>
</tr>
</tbody>
</table>
Two main Paths

**Accelerators:**
\[\pi\text{-decay-at-rest (DAR) }\nu\text{ source}\]
Different flavors produced relatively high recoil energies ➔ close to de-coherence ➔ COHERENT project

**Reactors:**
Lower \(\nu\) energies than accelerators
Lower cross section
Different flavor content implications for probes of new physics ➔ Will follow this route
CvS Cross Section at different (reactor) $E_\nu$

This shows the importance of low thresholds.
Event Rates for a conceivable Experiment

Detector: BEGE or SAGE type germanium diode O(1kg)
Distance D=15m; 3.9GW ↔ flux = $3.12 \times 10^{13}$/cm$^2$/s
For a 1kg detector: Background ~ 1/kg/keV/day
Suitable shielding (not trivial!) a la GIOVE

<table>
<thead>
<tr>
<th>Pulser/Threshold [eV]</th>
<th>QF = 0.15</th>
<th>QF = best fit</th>
<th>QF = 0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 / 180</td>
<td>971 / 61 / 15.8</td>
<td>2173 / 85 / 25.6</td>
<td>9194 / 127 / 72.3</td>
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<tr>
<td>65 / 195</td>
<td>588 / 58 / 10.1</td>
<td>1488 / 81 / 18.4</td>
<td>6962 / 123 / 56.4</td>
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<tr>
<td>70 / 210</td>
<td>352 / 55 / 6.4</td>
<td>1014 / 78 / 13.0</td>
<td>5272 / 120 / 44.0</td>
</tr>
<tr>
<td>75 / 225</td>
<td>207 / 52 / 4.0</td>
<td>686 / 75 / 9.2</td>
<td>3989 / 117 / 34.2</td>
</tr>
<tr>
<td>80 / 240</td>
<td>120 / 49 / 2.5</td>
<td>460 / 71 / 6.5</td>
<td>3012 / 113 / 26.7</td>
</tr>
<tr>
<td>85 / 255</td>
<td>69 / 46 / 1.5</td>
<td>306 / 68 / 4.5</td>
<td>2269/110/20.7</td>
</tr>
</tbody>
</table>


⇒ Not trivial (reactor flux, detector threshold, background reduction)
⇒ but doable on a short time scale!
⇒ Even a 1kg detector would see CvS very soon
⇒ what then?

Maneschg, Rink, Salathe, ML
Why is CvS interesting: DM connections

1) DM experiments assume coherent DM scattering → test of CvS
2) Neutrino floor of direct DM experiments *IS* due to CvS
Upscaling to 100kg ➔ Interesting Potential

high statistics ➔ precision ➔ various interesting topics…

Maneschg, Rink, Salathe, ML

### 100kg detector
4GW @ 15m
flux ~3*10^{13}/cm^2/s
background 1/kg/day

$$BSM_{sens} = \Delta S/S$$

<table>
<thead>
<tr>
<th>Puler/Thresh [eV]</th>
<th>QF=0.15</th>
<th>BSM_{sens}</th>
<th>QF=BF</th>
<th>BSM_{sens}</th>
<th>QF=0.25</th>
<th>BSM_{sens}</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 / 120</td>
<td>647 474/8291 / 78.1</td>
<td>1*10^{-3}</td>
<td>965 999/10 775/89.7</td>
<td>1*10^{-3}</td>
<td>2.9*10^{6}/15 158/189</td>
<td>6*10^{-4}</td>
</tr>
<tr>
<td>45 / 135</td>
<td>407 092/8 036 / 50.7</td>
<td>2*10^{-3}</td>
<td>664 316/10 519/63.2</td>
<td>1*10^{-3}</td>
<td>2.1*10^{6}/14 866/144</td>
<td>7*10^{-4}</td>
</tr>
<tr>
<td>50 / 150</td>
<td>254 745/7 780 / 32.7</td>
<td>2*10^{-3}</td>
<td>458 072/1 0264/44.6</td>
<td>1*10^{-3}</td>
<td>1.6*10^{6}/14 574/84.9</td>
<td>8*10^{-4}</td>
</tr>
<tr>
<td>55 / 165</td>
<td>158 109/7 524 / 21.0</td>
<td>3*10^{-3}</td>
<td>315 843/9 971/31.7</td>
<td>2*10^{-3}</td>
<td>1.2*10^{6}/14 318/84.9</td>
<td>9*10^{-4}</td>
</tr>
<tr>
<td>60 / 180</td>
<td>97 066/7 305 / 13.3</td>
<td>3*10^{-3}</td>
<td>217 277/9 716/22.4</td>
<td>2*10^{-3}</td>
<td>919 435/13 026/65.6</td>
<td>1*10^{-3}</td>
</tr>
<tr>
<td>65 / 195</td>
<td>58 827/7 049 / 8.3</td>
<td>4*10^{-3}</td>
<td>148 848/9 460/15.7</td>
<td>3*10^{-3}</td>
<td>696 196/13 770/50.6</td>
<td>1*10^{-3}</td>
</tr>
<tr>
<td>70 / 210</td>
<td>35 154/6 830 / 5.1</td>
<td>5*10^{-3}</td>
<td>101 386/9 204/11.0</td>
<td>3*10^{-3}</td>
<td>527 204/13 514/39.0</td>
<td>1*10^{-3}</td>
</tr>
<tr>
<td>75 / 225</td>
<td>20 711/6 575 / 3.2</td>
<td>7*10^{-3}</td>
<td>68 573/8 949/7.7</td>
<td>4*10^{-3}</td>
<td>398 867/13 222/30.2</td>
<td>2*10^{-3}</td>
</tr>
<tr>
<td>80 / 240</td>
<td>12 042/6 355 / 1.9</td>
<td>9*10^{-3}</td>
<td>46 008/8 730/5.27</td>
<td>5*10^{-3}</td>
<td>301 231/12 966/23.2</td>
<td>2*10^{-3}</td>
</tr>
<tr>
<td>85 / 255</td>
<td>6 924/6 136 / 1.1</td>
<td>1*10^{-2}</td>
<td>30 598/8 474/3.6</td>
<td>6*10^{-3}</td>
<td>226 910/12 711/17.9</td>
<td>2*10^{-3}</td>
</tr>
</tbody>
</table>

$$BSM_{sens} = \Delta S/S$$


M. Lindner, MPIK
Magnetic moment for minimal ν masses are very tiny:

\[
\mu^D_{\nu} \approx 3.2 \times 10^{-19} \left(\frac{m_{\nu}}{\text{eV}}\right) \mu_B
\]

\[
\mu^M_{\nu} \approx 4 \times 10^{-9} \mu_B \left(\frac{M^M_{\nu}}{\text{eV}}\right) \left(\frac{\text{TeV}}{\Lambda}\right)^2 \left|\frac{m_{\tau}^2}{m_l^2 - m_{\nu}^2}\right|
\]

New physics \(\Rightarrow\) detectable enhancements due to new physics:
SUSY, extra dimensions, …

At least new best limits:
e-scattering (GEMMA) and astrophysics:

\[
\mu_\nu < 3 \times 10^{-11} \mu_B
\]

Scattering on protons coherently enhanced: \(\Rightarrow\) detectable at low energy
(Vogel & Engel 1989)
Potential for Magnetic Moments

100kg * 5y = 500 kg-year ; low threshold ➔ one order of magnitude better
Searches for new Physics: NSI’s

NSI’s $\leftrightarrow$ new physics at high scales
Which are integrated out
$Z'$, new scalars, ... $\Rightarrow \epsilon_{ij}$

\[ L_{NSI} \simeq \epsilon_{\alpha\beta} 2 \sqrt{2} G_F (\bar{\nu}_L \beta \gamma^\rho \nu_{L\alpha}) (\bar{f}_L \gamma_\rho f_L) \]

\[
\frac{d\sigma}{dT}(E_\nu,T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{ \left[ Z(g_V^n + 2\epsilon_{ee}^V + \epsilon_{ee}^d) + N(g_V^n + \epsilon_{ee}^V + 2\epsilon_{ee}^d) \right]^2 + \sum_{\alpha=\mu,\tau} \left[ Z(2\epsilon_{\alpha\nu}^V + \epsilon_{\alpha\nu}^d) + N(2\epsilon_{\alpha\nu}^V + 2\epsilon_{\alpha\nu}^d) \right]^2 \right\}
\]

Barranco et al. 2005

$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$

$\Rightarrow$ Competitive method to test TeV scales
$\epsilon = 0.01 \leftrightarrow$ TeV scales
NSI-Potential of O(100kg) Detector

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu

\[ |\varepsilon^d_{\text{rel}}|, |\varepsilon^d_{\mu e}|, |\varepsilon^d_{e e}|, |\varepsilon^\mu_{\text{rel}}|, |\varepsilon^\mu_{\mu e}|, |\varepsilon^\mu_{e e}| \]

\[ \sim 10 \text{ TeV}, \sim \text{TeV} \]
Various indications / hints for sterile neutrinos with cosmology?
- eV hints with small mixing
- keV warm dark matter with tiny mixing $\leq 10^{-8}$

- Different mass ranges, but any sterile state would motivate others
- test if flux deviates from $1/R^2$
- time scales compared to other projects
Remember: DAR sources close to decoherence $\leftrightarrow$ combine with reactor measurements

we can start to explore nuclear form factors

K. Patton et al., PRC86 (2012) 024612

\[ \frac{d\sigma}{dT}(E, T) = \frac{G_F^2}{2\pi} M \left[ 2 - \frac{2T}{E} + \left( \frac{T}{E} \right)^2 - \frac{MT}{E^2} \right] \frac{Q_W^2}{4} F^2(Q^2) \]

Form factor: encodes information about nuclear (primarily neutron) distributions

Fit recoil **spectral shape** to determine the $F(Q^2)$ moments
(requires very good energy resolution, good systematics control)

Example:
tonne-scale experiment
at $\pi$DAR source

Ar-C scattering

+: model predictions

10% uncertainty on flux

$\langle R_n^4 \rangle^{1/4}$ (fm)
Precise Measurement of $\sin^2\theta_W$ at low $E$

Clean SM prediction for the rate $\rightarrow$ measure $\sin^2\theta_W^{\text{eff}}$; deviation probes new physics

$$\sigma \sim \frac{G_f^2 E^2}{4\pi} \left( N - (1 - 4\sin^2\theta_W) Z \right)^2$$

Example: hypothetical dark $Z$ mediator (explanation for $g$-$2$ anomaly)

BSMsens = $10^{-3} \Rightarrow \Delta\sin^2\theta_W = 0.006$

$10^{-4} \Rightarrow \Delta\sin^2\theta_W = 0.0006$

CEvNS sensitivity is @ low $Q$; need sub-percent precision to compete w/ electron scattering & APV, but new channel

slide adopted from K. Scholberg
Nuclear Safeguarding

P. Huber, talk at NA/NT workshop, Manchester, May 2015

Presence of **plutonium breeder blanket**
in a reactor has ν spectral signature

\[
^{238}\text{U} + n \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow ^{239}\text{Pu}
\]

ν spectrum is below IBD threshold
⇒ accessible with CEνNS, but require low recoil energy threshold

a) This is of interest to IAEA
b) Could be used as an extra “sensor” in reactors (close to core \(\leftrightarrow 1/R^2\)) ⇒ safety, optimal burn-up
Conclusions

• Neutrino physics was, is and will remain a hot field

• Important and unique insights into
  - fundamental interactions, important consequences: BAU...

• 3 neutrino flavours ➔ precision area
  - reactor neutrinos + neutrino beams ➔ origin of fermion masses?

• More than 3 neutrinos
  - Majorana masses, L-violation, sterile ν‘s, NSIs, large magnetic moments, ...
  ➔ any one of them would be a major discovery

• Coherent neutrino scattering will be a new tool
  - will contribute / make use of better β-spectra
  - will allow new experiments to test
  - coherent ν scattering ↔ DM & WIMP scattering
  - mag. Moments, NSIs, steriles, sin²θ_W, F(q^2), safeguarding, ...