Recent results from STEREO
Reactor Anti-ν Anomaly

\[ \nu_e \rightarrow \nu_1, \nu_2, \nu_3, \nu_4 ? \]

propagation (mass states)

\[ \nu_e \ ? \nu_\mu \ ? \nu_\tau \ ? \nu_s ? \]

Phys. Rev. D83 (2011) 073006

RAA best fit
\[ \Delta m_{new}^2 = 2.4 \text{ eV}^2 \]
\[ \sin^2(2\theta_{ee}) = 0.14 \]
• Compare 6 target cells to measure oscillation-driven distortions in the $E_{\bar{\nu}_e}$ spectrum.
• Mitigate sensitivity to predicted spectrum.

**Liquid Scintillator**

**Target:** 6 identical cells
- Gd-loaded (0.2% in mass)
- $V_{\text{tot}} = 2.2 \times 0.9 \times 0.9 \, \text{m}^3$

**Gamma catcher** (unloaded):
- Vetos ext. background
- Captures escaping $\gamma$'s

<table>
<thead>
<tr>
<th>sin$^2(2\theta)$=0.14, $\Delta m^2$=2.4 eV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No oscillation</td>
</tr>
<tr>
<td>Furthest cell $L \approx 11 , \text{m}$</td>
</tr>
<tr>
<td>Closest cell $L \approx 9 , \text{m}$</td>
</tr>
</tbody>
</table>

Spectra (arbitrary normalization)

20 cm thick acrylic buffers for homogeneous detector response. PMT coupling via oil bath.

$\nu$ detection through Inverse Beta Decay (prompt + delayed coincidence)

$\Delta t \approx 16 \, \mu s$

$\Sigma_\gamma \approx 8 \, \text{MeV}$
Reactor ν spectrum

- Bump at around 5 MeV
- Problem in reactor ν prediction? Bias? Underestimated systematics?
- Experiment calibration problem? 1% bias in E scale suffices…

⇒ Measurement of ~pure $^{235}$U useful


ILL Site

Institut Laue-Langevin, Grenoble, France

- 57 MW_thermal
- Ø40 cm × 80 cm
- Highly enriched: 93% $^{235}$U (fissions > 99% $^{235}$U)
- 3-4 cycles/yr x 50 days/cycle
- $10^{19}$ s$^{-1}$ pure $\nu_e$ flux

Challenging mitigation of the background generated by:
- Cosmic-rays
- Neighboring experiments
ILL Site

Institut Laue-Langevin, Grenoble, France

Heavy passive shielding added around detector and on front and side walls:

- > 100 tons Pb
- > 9 tons Borated PE
- B₄C rubber
- (soft iron)

Challenging mitigation of the background generated by:
- Cosmic-rays
- Neighboring experiments

- 57 MW_thermal
- Ø40 cm × 80 cm
- Highly enriched: 93% $^{235}$U (fissions > 99% $^{235}$U)
- 3-4 cycles/yr x 50 days/cycle
- $10^{19}$ s⁻¹ pure $\bar{\nu}_e$ flux
ILL Site

Institut Laue-Langevin, Grenoble, France

- 57 MW_thermal
- $\varnothing 40 \text{ cm} \times 80 \text{ cm}$
- Highly enriched: 93% $^{235}\text{U}$ (fissions > 99% $^{235}\text{U}$)
- 3-4 cycles/yr x 50 days/cycle
- $10^{19} \text{s}^{-1}$ pure $\nu_e$ flux

Challenging mitigation of the background generated by:
- Cosmic-rays
- Neighboring experiments

Overburden only ~15 m.w.e.

NEUTRINO DETECTOR AT SURFACE IS CHALLENGING!!

~300 $\nu_e$/day induced by cosmics
Dataset

Phase I
ON → 66 days  OFF → 22 days

Phase II
ON → 119 days  OFF → 211 days

Good background understanding thanks to long reactor OFF period

+ calibration runs (hourly LEDs, weekly $^{54}$Mn, monthly AmBe, bi-annual $^{68}$Ge, $^{137}$Cs, $^{60}$Co, $^{24}$Na)
Dataset

Phase I
ON → 66 days  OFF → 22 days

Phase II
ON → 119 days  OFF → 211 days
Good background understanding thanks to long reactor OFF period.

+ calibration runs (hourly LEDs, weekly $^{54}\text{Mn}$, monthly AmBe, bi-annual $^{68}\text{Ge}$, $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{24}\text{Na}$)

EPS HEP 2019 Ghent
Pablo DEL AMO SANCHEZ,
LAPP - IN2P3 - CNRS/ U. Savoie Mont Blanc
E reconstruction & calibration

- Correct for optical cross-talk among cells in energy reco algorithm:

\[ Q_j = R_{ji} \times E_i^{dep} \quad \text{where} \quad R_{ji} = C_i \times L_{ji} \quad \Rightarrow \quad E_{reco} = R^{-1} \times \overrightarrow{Q} \]

with

- \( R_{ji} \) response matrix
- \( C_i \) calib coeffs (collected photons in cell i from \(^{54}\text{Mn}\) calib runs \(\sim 220\) pe/MeV)
- \( L_{ji} \) optical crosstalk from cell i to cell j \(\sim 6 - 8\%\)

Monitoring of E reco stability with n-H 2.22 MeV gamma distributed over whole Target
Neutron efficiency

- Neutron efficiency, dominant uncertainty in neutrino selection efficiency
- Use AmBe gamma-neutron source that mimics IBD coincidence
- Build 3D model of Data/MC discrepancy

Good agreement in thermalisation time

![Graph showing data/MC model at y=0 with preliminary note]
**n-Gd γ cascade**

- Especially important for small detectors where higher energy γ more likely to escape
  - More higher energy γ than in GLG4sim
    (and slightly lower γ multiplicity)
n-Gd $\gamma$ cascade

- Especially important for small detectors where higher energy $\gamma$ more likely to escape
  \[ \rightarrow \text{More higher energy } \gamma \text{ than in GLG4sim} \]
  (and slightly lower $\gamma$ multiplicity)

<table>
<thead>
<tr>
<th></th>
<th>Cell 4 (central)</th>
<th>Cell 1 (border)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{Gd}} / \varepsilon_{\text{Gd}}$</td>
<td>GLG4sim 0.9744 ± 0.0003</td>
<td>0.9436 ± 0.0013</td>
</tr>
<tr>
<td></td>
<td>FIFRELIN 0.9918 ± 0.0003</td>
<td>0.9682 ± 0.0013</td>
</tr>
<tr>
<td>$\varepsilon_{\text{IBD}} / \varepsilon_{\text{IBD}}$</td>
<td>GLG4sim 0.9814 ± 0.0004</td>
<td>0.9957 ± 0.0018</td>
</tr>
<tr>
<td></td>
<td>FIFRELIN 1.0035 ± 0.0005</td>
<td>1.0091 ± 0.0019</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tot}} / \varepsilon_{\text{tot}}$</td>
<td>GLG4sim 0.9562 ± 0.0005</td>
<td>0.9396 ± 0.0025</td>
</tr>
<tr>
<td></td>
<td>FIFRELIN 0.9953 ± 0.0006</td>
<td>0.9770 ± 0.0022</td>
</tr>
</tbody>
</table>


- Good agreement in cell centre, disagreement in corners due to n mobility, corrected by map
Neutrino selection

- **IBD**
  - $E_{\text{prompt}} = 1.625 - 7.125$ MeV
  - $E_{\text{delayed}} = 4.5 - 10$ MeV
  - $\Delta t = 2 - 70 \mu s$ ($\tau_{n\text{ capture}} \sim 16 \mu s$)

Topography cuts:
- $E_{\text{prompt}}$ in neighbour cell $< 1.0$ MeV
- $E_{\text{prompt}}$ in other cells $< 0.4$ MeV
- $E_{\text{delayed}}$ in target $> 1$ MeV
- $D_{\text{prompt-delayed}} < 60$ cm

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

Mean signal cut eff: $61.4 \pm 0.9\%$

Background rejection (cosmic rays)

- Charge asymmetry per cell: $Q_{\text{max}} / Q_{\text{tot}} < 0.50$
- $\Delta t_{\text{last Veto}} \mu > 100 \mu s$
- Isolated prompt-delayed pair

- Stopping Muon
  - $\Delta t \sim 2.2 \mu s$

- Fast and/or multi $n$
  - $\tau_{n} = 2.2 \mu s$
Fit Pulse Shape Discrimination (PSD) to extract neutrino signal from correlated backgrounds (e.g. fast neutron from spallation by cosmics) in each cell and energy bin.

Background shape from OFF data

Accidentals from displaced-time window

\[ \text{PSD} = \frac{Q_{\text{tail}}}{Q_{\text{tot}}} \]

Cell 2 -- \( E = [2.125 - 2.625] \) MeV

-2 \( \ln \lambda \) \( \min \) /ndf = 50.1/63
prob = 0.88

Fit model: \( G(A,\mu,\nu,\sigma) \)
\[ N_\nu^{Fitted} = 10.37 \pm 0.52 \text{ /day} \]

\[ \chi^2 / \text{ndf} = 8.12 / 9 \]
Mean = 0.004 ± 0.097
Sigma = 0.87 ± 0.10

Pablo DEL AMO SANCHEZ,
LAPP - IN2P3 - CNRS/ U. Savoie Mont Blanc
Oscillation fit

- Compare measured spectra of all cells via a MC prediction of the detector response:

\[ \chi^2 = \sum_{l} \sum_{i} \left( \frac{D_{l,i} - \phi_i M_{l,i}(\mu, \sigma, \bar{\alpha})}{\sigma_{l,i}} \right)^2 + \sum_{l} \left( \frac{\alpha_{l}^{\text{NormU}}}{\sigma_{l}^{\text{NormU}}} \right)^2 + \left( \frac{\alpha_{l}^{\text{EscaU}}}{\sigma_{l}^{\text{EscaU}}} \right)^2 + \sum_{l} \left( \frac{\alpha_{l}^{\text{EscaC}}}{\sigma_{l}^{\text{EscaC}}} \right)^2 \]

\[ M_{l,i}(\mu, \sigma, \bar{\alpha}) = M_{l,i}(\mu, \sigma) \times (1 + \alpha_{l}^{\text{NormU}} + (\alpha_{l}^{\text{EscaC}} + \alpha_{l}^{\text{EscaU}}) \times S_{l,i}^{\text{Esca}}(\mu)) \]

- \( \alpha \), nuisance parameters (norm, E scale)

For cell \( l \) and energy bin \( i \):
- \( D_{l,i} \) observed spectrum in data
- \( M_{l,i} \) MC prediction
- \( \phi_i \) factor common to all cells correcting the MC prediction to suit the observed spectrum in data

Independent of spectrum prediction
Phase II Oscillation results

- Do not reject the no oscillation hypothesis (p-value = 0.40)
- Raster scan in $\Delta m^2$
- RAA best fit point excluded at ~ 99% C.L.
- Non-normal $\Delta \chi^2$ distribution estimated from MC pseudo experiments
Conclusions

- 43.4 k nu detected in Phase II, 65.6 k in total
- STEREO rejects the RAA best fit point at > 99% C.L., excludes large part of the sterile neutrino oscillation parameter space
- Statistics to be doubled by mid-2020
- Systematics approaching < 1% level

- New work improving n-Gd γ cascade (arXiv:1905.11967 & zenodo/2653787)

- Stay tuned for STEREO’s upcoming papers on reactor spectrum and flux, and Phases I + II oscillation combination
Questions?

The STEREO Collaboration

Website: http://stereo-experiment.org
Background stability

- PSD background distribution the same for different atmos pressures, once norm corrected
- Norm correction in good agreement with expectations

\[ \Delta P = 10 \text{ hPa} \]

\[ \chi^2 / \text{ndf} \quad 310 / 265 \]
\[ \text{Slope (hPa}^{-1} R_{ref}^{-1}) \quad -0.00598 \pm 0.00049 \]

\[ \chi^2 / \text{ndf} \quad 374 / 265 \]
\[ \text{Slope (hPa}^{-1} R_{ref}^{-1}) \quad -0.00620 \pm 0.00020 \]
Background
• Detected neutrino rates corrected by detection eff in excellent agreement with $1/L^2$ law
• STEREO does not reject the no-oscillation hypothesis ($p = 0.40$)
• Fitted pull terms all $< 1 \sigma$
• Good agreement between Data and Non-oscillated Model
STereo calib systems

Need to calibrate every (small) active volume independently

3 different ways to expose active volumes to radioactive sources:
- internal calib tubes (Target only, 5 cells)
- outside steel vessel, around GC
- outside steel vessel, below central axis

<table>
<thead>
<tr>
<th>Source</th>
<th>$^{68}\text{Ge}$</th>
<th>$^{124}\text{Sb}$</th>
<th>$^{137}\text{Cs}$</th>
<th>$^{54}\text{Mn}$</th>
<th>$^{65}\text{Zn}$</th>
<th>$^{60}\text{Co}$</th>
<th>$^{24}\text{Na}$</th>
<th>AmBe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-ray energies (MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.511</td>
<td>0.603</td>
<td>0.662</td>
<td>0.835</td>
<td>1.11</td>
<td>1.17</td>
<td>1.37</td>
<td>2.22 (H(n,\gamma))</td>
<td></td>
</tr>
<tr>
<td>0.511</td>
<td>1.69</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.33</td>
<td>2.75</td>
<td>4.43</td>
</tr>
<tr>
<td>Initial Activity (kBq)</td>
<td>90</td>
<td>2.4</td>
<td>37</td>
<td>90</td>
<td>3.3</td>
<td>50</td>
<td>5.9</td>
<td>$250 \cdot 10^3$ ($^{241}\text{Am}$)</td>
</tr>
</tbody>
</table>
STERE calib systems

Need to calibrate every (small) active volume independently

3 different ways to expose active volumes to radioactive sources:
- internal calib tubes (Target only, 5 cells)
- outside steel vessel, around GC
- outside steel vessel, below central axis

<table>
<thead>
<tr>
<th>Source</th>
<th>$^{68}\text{Ge}$</th>
<th>$^{124}\text{Sb}$</th>
<th>$^{137}\text{Cs}$</th>
<th>$^{54}\text{Mn}$</th>
<th>$^{65}\text{Zn}$</th>
<th>$^{60}\text{Co}$</th>
<th>$^{24}\text{Na}$</th>
<th>AmBe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-ray energies (MeV)</td>
<td>0.511</td>
<td>0.603</td>
<td>0.662</td>
<td>0.835</td>
<td>1.11</td>
<td>1.17</td>
<td>1.37</td>
<td>2.22 (H(n,$\gamma$))</td>
</tr>
<tr>
<td>Initial Activity (kBq)</td>
<td>90</td>
<td>2.4</td>
<td>37</td>
<td>90</td>
<td>3.3</td>
<td>50</td>
<td>5.9</td>
<td>250 $\cdot$ 10$^3$ ($^{241}\text{Am}$)</td>
</tr>
</tbody>
</table>
Quenching

Precisely determined LS non-linearity (1% level)

Birks' law: $dL/dx = S \frac{dE/dx}{1 + K_{Birks} dE/dx}$

Very good Data/MC agreement after $k_B$ tuning

<table>
<thead>
<tr>
<th>Source</th>
<th>$^{68}$Ge</th>
<th>$^{124}$Sb</th>
<th>$^{137}$Cs</th>
<th>$^{54}$Mn</th>
<th>$^{65}$Zn</th>
<th>$^{60}$Co</th>
<th>$^{24}$Na</th>
<th>AmBe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-ray energies (MeV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.511</td>
<td>0.603</td>
<td>0.662</td>
<td>0.835</td>
<td>1.11</td>
<td>1.17</td>
<td>1.37</td>
<td>2.75</td>
<td>4.43</td>
</tr>
<tr>
<td>0.511</td>
<td>1.69</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.33</td>
<td>2.22</td>
<td>(H(n,\gamma))</td>
</tr>
<tr>
<td>Initial Activity (kBq)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>2.4</td>
<td>37</td>
<td>90</td>
<td>3.3</td>
<td>50</td>
<td>5.9</td>
<td>250 $\cdot$ 10$^3$</td>
<td>($^{241}$Am)</td>
</tr>
</tbody>
</table>