Recent results and future prospects from Super-Kamiokande

Yasuhiro Nakajima (ICRR, the University of Tokyo) on behalf of the Super-Kamiokande collaboration

The XXIX International Conference on Neutrino Physics and Astrophysics (NEUTRINO2020) June 30, 2020
The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy

INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea

University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, Japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~190 collaborators from 49 institutes in 10 countries
Super-Kamiokande

- 50-kton water Cherenkov detector located at Kamioka, Japan
- Overburden: 2700 mwe
- Inner Detector covered by > 11000 20-inch PMTs
- Studying neutrinos from wide variety of sources
  - Solar neutrinos
  - Supernova neutrinos
  - Atmospheric/Accelerator neutrinos
- Operational since 1996, transitioning to SK-Gd

SK-I  SK-II  SK-III  SK-IV  SK-V  SK-Gd

- Photo coverage 40%
- 20%
- 40%
- 40%
- 40%
- 40%

Accident  Full reconstruction  Replace electronics & DAQ system  Tank refurbishment
Super-Kamiokande Gadolinium Project (SK-Gd)

- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from $\nu$ interactions
  

- Aiming for the first observation of Diffuse Supernova Neutrino Backgrounds

- Also aiming for:
  - Improving pointing accuracy for galactic supernova
  - Precursor of nearby supernova by Si-burning neutrinos
  - Reducing proton decay background
  - Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric neutrinos)
  - Reactor neutrino measurements

- As the first step, loading 0.02% of Gd$_2$(SO$_4$)$_3$ in 2020
  
  $\sim$50% n-capture on Gd
**R&D Challenges (RI in Gd powder)**

- Radio impurities in Gd power could introduce additional backgrounds to solar and supernova neutrinos

- Stringent requirement for RI imposed

- Developed methods to evaluate low concentration RI

- Screened at multiple sites
  - ICP-MS: Kamioka
  - HPGe: Canfranc, Boulby and Kamioka
  - Worked with production companies and achieved the required purity

<table>
<thead>
<tr>
<th>Chain</th>
<th>Isotope</th>
<th>SK-Gd requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>For solar</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{238}\text{U}$</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td></td>
<td>$^{226}\text{Ra}$</td>
<td>$&lt; 0.5$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{228}\text{Ra}$</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td></td>
<td>$^{228}\text{Th}$</td>
<td>$&lt; 0.05$</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>$^{227}\text{Ac}$/$^{227}\text{Th}$</td>
<td>$&lt; 30$</td>
</tr>
</tbody>
</table>

*Radioactive impurities for Gd$_2$(SO$_4$)$_3$ powder [mBq/kg]*

- **U contamination (ICP-MS)**
  - Requirement: $^{238}\text{U} < 400$ ppt

- **Th contamination (ICP-MS)**
  - Requirement: $^{232}\text{Th} < 13$ ppt
R&D Challenges (water purification)

- Challenge: remove impurities without removing Gd
- Two systems developed and tested with a 200 m³ tank (EGADS)
  - “Band-pass” system with nano-filter
  - Special resin-based system
    - Both successfully kept water transparency at the current SK level without losing Gd

Both successfully kept water transparency at the current SK level without losing Gd


- Constructed a dedicated Gd-dissolving and Gd-water purification system for Super-Kamiokande

200 m³ tank (EGADS)

Water transparency

Gd concentration

Blue band: SK-III and SK-IV water transparency values

Black dashed line: final Gd sulfate concentration

Sampling position:
- Bottom
- Centre
- Top

Gd concentration
SK detector preparation

• Major refurbishment work 2018-2019:
  • Stopped water leak: < 1/200 of before (~1 m³/d)
  • Many other improvements and cleaning

• SK-V operation (2019-):
  • The new Gd-water purification system tested with the real SK detector
    • Successfully kept water transparency at a level similar to previous phases
  • Water flow tuning: Suppressed convection and expanded low-background region

Event rate at 3.5-4.0 MeV
Ready, Set, …

• 14 tons of $\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O}$ powder for initial loading produced and screened

• The new water system is ready to process Gd-loaded water
Gd dissolving

- Commissioning of the new Gd dissolving system just started!
- Gd loading to Super-K will start **VERY** soon!
Recent results from Super-Kamiokande

New results at Neutrino 2020

- **Search for Diffuse Supernova Neutrino Backgrounds**
- **Solar neutrino oscillation measurements**
- **Atmospheric neutrino oscillation measurements**
- Multi-messenger astronomy:
  - Gravitational-wave event follow-up
    [Poster #161: M. Lamoureux]
  - Gamma-ray burst follow-up
    [Poster #85: M. Harada]
- Search for supernova bursts
  [Poster #136: M. Mori]
- Search for neutron-antineutron oscillation
  [Poster #43: L. Wan]

Recent publications (2019-)

- **Phys. Rev. D 101, 052011 (2020)**, “Search for proton decay into three charged leptons in 0.37 megaton-years exposure of the Super-Kamiokande”
Supernova Neutrinos
Diffuse Supernova Neutrino Backgrounds

a.k.a Supernova Relic Neutrinos (SRN)

• Supernova burst neutrinos:
  • Rich physics observables once detected
  • No detection since 1987A. Most recent search in [Poster #136: M. Mori]

• Diffuse Supernova Neutrino Backgrounds (DSNB):
  • Neutrinos produced from all the SN bursts and diffused in the current universe.
    ~ a few SN explosions every second
    \( O(10^{18}) \) SNe so far in this universe
  • Can study history of SN bursts with neutrinos
    \[
    \frac{dF_\nu}{dE_\nu} = c \int_0^{z_{\text{max}}} R_{\text{SN}}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} (1 + z) \frac{dt}{dz} \]
    \( z_{\text{max}} \sim 1 \) for SK energy range
  • Many astrophysics and particle physics implications:
    • Contribution of failed supernova
    • Neutrino oscillation effect in dense medium
    • Galaxy evolution
    • Supernova burst mechanism

Adapted from Y. Ashida Ph.D. Thesis, Kyoto University 2020
DSNB: Signal and Backgrounds

Rare event search: a few interactions / year / SK

- Primary signal: Inverse Beta Decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
  
  Detecting both position and neutron is the key to reduce backgrounds

- Backgrounds that mimic $e^+ + n$ pair:
  - $^9\text{Li}$ (from cosmic $\mu$ spallation)  
    $[E < \sim 15 \text{ MeV}]$
  - Atmospheric neutrinos  [Poster #175: S. Sakai]
    
    - $\nu_\mu$ CC  
      $[E < \sim 50 \text{ MeV}]$
    - $\nu_e$ CC $[E > \sim 20 \text{ MeV}]$
    - NC(QE)  $[E < \sim 20 \text{ MeV}]$
  - Accidental coincidence (mostly spallation products + fake-neutrons)  $[E < \sim 15 \text{ MeV}]$
  - Reactor neutrinos  $[E < \sim 10 \text{ MeV}]$  [Poster #221: A. Goldsack]

\[\text{ICRR research Joint meeting, December 14th, 2019}\]
Analysis method

- Employed neutron tagging:
  - Neutron signal in SK (pure water): 2.2 MeV γ from n-H capture
    - Very small (typically ~ 7 PMT hits) signal
    - Buried in radioactivity from the detector
  - Developed a neutron selection algorithm based on Boosted Decision Tree
    - 20-30% signal efficiency with 0.2-3% fake-tag rate
- Two methods for testing DSNB signal
  - Spectrum fit: Fit spectrum shape assuming a DSNB model
  - DSNB-model independent search: Test event excess for each reconstructed energy bin

Analysis strategy

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Overall efficiencies for our analysis

- Preliminary

Figure: Neutron tagging performance

- Preliminary

Graph: Timing resolution event/20 μs

- Preliminary

[Preliminary]

[Poster #231: S. El Hedri]

[Analysis method]

Spectrum fit result

SK-IV data

DSNB region

Spectrum shape from [Ando et al (NNN05)]

No significant excess observed

Combined limit: $\phi < 2.7 \text{ cm}^{-2}/\text{s} (90\% \text{ CL})$ for $E_p > 16 \text{ MeV}$

Model prediction: $\phi = 1.7 \text{ cm}^{-2}/\text{s}$ [Ando et al (NNN05)]

Limit within a factor two of this prediction!
DSNB-model independent search

- No significant excess found
- Set one of the most stringent limits above 13.3 MeV
- Many model predictions are within several factors from the current limit
- Sensitivity limited by small statistics and backgrounds

→ Will be significantly improved with better neutron tagging in SK-Gd

**Search Results & Integrated SRN Electron Antineutrino Flux [cm²/sec.]**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>SK-IV 2970 days</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Expected)</td>
<td>9.48</td>
<td>1.35</td>
<td>0.82</td>
</tr>
<tr>
<td>(Observed)</td>
<td>9.08</td>
<td>2.22</td>
<td>0.35</td>
</tr>
<tr>
<td>Horiuchi+18</td>
<td>1.583</td>
<td>0.553</td>
<td>0.173</td>
</tr>
<tr>
<td>($E_{\nu,\text{rec}} = 0.1$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horiuchi+18</td>
<td>1.108</td>
<td>0.252</td>
<td>0.050</td>
</tr>
<tr>
<td>($E_{\nu,\text{rec}} = 0.5$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nakazato+15</td>
<td>0.798</td>
<td>0.236</td>
<td>0.081</td>
</tr>
<tr>
<td>(Maximum, IH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nakazato+15</td>
<td>0.337</td>
<td>0.089</td>
<td>0.026</td>
</tr>
<tr>
<td>(Minimum, NH)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horiuchi+09</td>
<td>2.534</td>
<td>0.887</td>
<td>0.314</td>
</tr>
<tr>
<td>(6 MeV, Maximum)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunardini09</td>
<td>1.032</td>
<td>0.321</td>
<td>0.098</td>
</tr>
<tr>
<td>(updated at NNN05)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Ando+03</td>
<td>2.652</td>
<td>0.796</td>
<td>0.261</td>
</tr>
<tr>
<td>(updated at NNN05)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malaney97</td>
<td>0.469</td>
<td>0.125</td>
<td>0.034</td>
</tr>
<tr>
<td>Hartmann+97</td>
<td>0.947</td>
<td>0.297</td>
<td>0.093</td>
</tr>
</tbody>
</table>

: Models within a factor of 3

**Preliminary**
Solar Neutrinos
Solar Neutrinos

- Intense neutrinos from nuclear fusion in the Sun’s core
  - Majority (99%) from pp-chain with subdominant contribution from CNO cycle
- What’s left in solar neutrinos?
  - Help understanding solar interior
- Precision test of the MSW oscillation model
  - Precise measurement of spectrum at the vacuum-to-matter transition region
  - Measurement of Day/Night asymmetry
- Super-K’s measurement of solar neutrinos
  - Detecting recoil electrons from elastic scattering
  - Robust signal extraction using angular correlation with the Sun
  - Current threshold for analysis: $E_{\text{kin}} > 3.5$ MeV

Super-K has been continuously improving analysis with more statistics
Analysis Improvements

• Detector simulation improvements  [Poster #350: Y. Nakano]
  • Improved PMT hit timing simulation
  • Improved modeling of water quality non-uniformity
• Analysis improvements  [Poster #350: Y. Nakano]
  • Correction for PMT gain drift (introduced in 2017)
  • Improved correction for non-uniform energy response
    E-scale non-uniformity (MC) 1.7% → 0.5%
• Improved spallation cut  [Poster #166: S. Locke]
  • 12% more signal efficiency while keeping spallation rejection efficiency at a similar level (~90%)
    Gained ~1 year worth statistics

Energy scale stability (decay-e from cosmic μ)

Energy scale non-uniformity (MC)

Additional events w/ new spallation cut

Gained ~1 year worth statistics
Solar neutrino flux

- Analysis using all the data up through SK-IV presented today
- 5805 live days from all (SK-I ~ SK-IV) period (2970 days in SK-IV)
- More than 100k $^8$B (and HEP) solar neutrino interactions collected

<table>
<thead>
<tr>
<th>Phase</th>
<th>Livetime [days]</th>
<th>Energy [MeV]</th>
<th>DATA/MC</th>
<th>Flux w/ systematic error [$^{+}10^{-6}$/cm$^2$/sec]</th>
<th>Extracted Signal (Statistical only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1496</td>
<td>4.5-19.5</td>
<td>0.453 $\pm$ 0.005 $^{+0.016}_{-0.014}$</td>
<td>2.38 $\pm$ 0.02 $\pm$ 0.08</td>
<td>22443 $^{+227}_{-225}$</td>
</tr>
<tr>
<td>SK-II</td>
<td>791</td>
<td>6.5-19.5</td>
<td>0.459 $\pm$ 0.010 $\pm$ 0.030</td>
<td>2.41 $\pm$ 0.05 $^{+0.16}_{-0.15}$</td>
<td>7210 $^{+153}_{-151}$</td>
</tr>
<tr>
<td>SK-III</td>
<td>548</td>
<td>4.0-19.5</td>
<td>0.459 $\pm$ 0.010 $\pm$ 0.030</td>
<td>2.40 $\pm$ 0.04 $\pm$ 0.05</td>
<td>8148 $^{+133}_{-133}$</td>
</tr>
<tr>
<td>SK-IV (Updated)</td>
<td>2970.08</td>
<td>3.5-19.5</td>
<td>0.443 $\pm$ 0.003 $\pm$ 0.006</td>
<td>2.33 $\pm$ 0.01 $\pm$ 0.03</td>
<td>63890 $^{+381}_{-379}$</td>
</tr>
<tr>
<td>Combined</td>
<td>5805</td>
<td>–</td>
<td>0.447 $\pm$ 0.002 $\pm$ 0.008</td>
<td>2.35 $\pm$ 0.01 $\pm$ 0.04</td>
<td>More than 100k events</td>
</tr>
</tbody>
</table>
Oscillation analysis

Energy spectrum fit (SK-IV)

Disfavors flat oscillation probability by $\sim 1\sigma$
Spectrum shape compatible with KamLAND $\Delta m^2_{21} (< 1\sigma)$

Day/Night amplitude fit (SK-IV)

$A_{DN}^{Fit} = (-2.1 \pm 1.1)\% \ [3.5 < E < 19.5 \ (MeV)]$
~$2\sigma$ preference of non-zero Day/Night asymmetry
Difference from the previous results

- Best fit value of solar $\Delta m^2_{21}$ changed from $4.8 \times 10^{-5} \text{eV}^2$ (2019) to $6.1 \times 10^{-5} \text{eV}^2$
- Spectrum analysis:
  - Data/MC ratio at $E < 6 \text{ MeV}$ slightly shifted upward
    - Shift of prediction due to improved detector simulation
    - Added statistics due to improved spallation cut
    - Event migration due to new reconstruction tool
  - Day/Night asymmetry:
    - $A_{\text{DN}}^{\text{Fit}} = (-3.6 \pm 1.6\ (\text{stat}) \pm 0.6\ (\text{syst}))\% \rightarrow A_{\text{DN}}^{\text{Fit}} = (-2.1 \pm 1.1)\%$
    - Event migration due to new reconstruction
    - Previous analysis used data up to Feb 2014 (SK-IV: 1664 days)
    - Added $\sim$1200 days of data fluctuated towards smaller D/N asymmetry
    - Both impacted to the shift of best fit $\Delta m^2_{21}$ value by roughly equal amount (in term of change of $\Delta \chi^2$)
Oscillation Parameter Extraction

- Oscillation parameters extracted by combining all SK data, as well as SNO and KamLAND data

<table>
<thead>
<tr>
<th></th>
<th>sin(^2(\theta_{12}))</th>
<th>(\Delta m^2_{21} \times 10^{-5} \text{ eV}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND</td>
<td>0.316(^{+0.034}_{-0.026})</td>
<td>7.54(^{+0.19}_{-0.18})</td>
</tr>
<tr>
<td>SK+SNO</td>
<td>0.306(^{+0.014}_{-0.012})</td>
<td>6.11(^{+1.21}_{-0.68})</td>
</tr>
<tr>
<td>Combined</td>
<td>0.306(^{+0.013}_{-0.012})</td>
<td>7.51(^{+0.19}_{-0.18})</td>
</tr>
</tbody>
</table>

- Consistent \(\theta_{12}\) values among experiments

- Solar best fit \(\Delta m^2_{21}\) lower than KamLAND, but difference is less than the previous analysis.

SK+SNO fit disfavors the KamLAND best fit value at \(~1.4\sigma\) (was \(~2\sigma\)
Atmospheric Neutrinos
Atmospheric Neutrinos

- Neutrinos produced by cosmic-ray interactions in earth’s atmosphere
  - Baseline: O(10) km - O(10,000) km
  - Energy: peaks at several hundreds of MeV, extends to ~TeV
- Goals:
  - $\Delta m^2_{32}$ and $\theta_{23}$ measurements: primary through $\nu_\mu/\bar{\nu}_\mu$ disappearance
  - CP violation parameter $\delta$ and mass-ordering: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Atmospheric Neutrino Analysis at SK

- New results using the full data sets from SK-I to SK-IV
- Exposure: 364.8 kton-years (328 kton-years in Neutrino2018)
- Improvements in this analysis:
  - Neutron tagging ($\varepsilon \sim 25\%$) for $\nu/\bar{\nu}$ separation
  - New BDT-based event selection for multi-ring events
    - Increased signal efficiency and purity

Up: $\cos\theta < -0.4$, Down: $\cos\theta > 0.4$
Oscillation Parameter Measurement

<table>
<thead>
<tr>
<th>930 Bins</th>
<th>$\chi^2$</th>
<th>$\theta_{13}$</th>
<th>$\delta_{\text{CP}}$</th>
<th>$\theta_{23}$</th>
<th>$\Delta m_{23} \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK (NH)</td>
<td>1037.5</td>
<td>0.0218</td>
<td>4.36$^{+0.88}_{-1.39}$</td>
<td>0.44$^{+0.05}_{-0.02}$</td>
<td>2.40$^{+0.11}_{-0.12}$</td>
</tr>
<tr>
<td>SK (IH)</td>
<td>1040.7</td>
<td>0.0218</td>
<td>4.54$^{+0.88}_{-1.32}$</td>
<td>0.45$^{+0.09}_{-0.03}$</td>
<td>2.40$^{+0.09}_{-0.32}$</td>
</tr>
</tbody>
</table>

SK data disfavors Inverted Hierarchy at 71.4-90.3% CLs (was 81.9-96.1% in 2018)
Also prefers: 1st $\theta_{23}$ octant and $\delta_{\text{CP}}$$\sim$$3/2\pi$
$\Delta m^2_{32}$ vs $\sin^2 \theta_{23}$ constraints

- Normal Hierarchy, 90% C.L.
- Super-K 2020 (Preliminary)
- Super-K 2018
- T2K 2019
- NOvA 2019
- IceCube 2018
- MINOS

Preliminary
Summary

• The new era of Super-Kamiokande, SK-Gd, is about to start

• New results from Super-Kamiokande:
  • Diffuse supernova background search: New limit within a several factors of many models
  • Solar neutrino measurements: New spectrum and Day/Night asymmetry measurements to test MSW
  • Atmospheric neutrino measurements: New constraints on $\Delta m^2_{32}$, $\theta_{23}$, $\delta_{\mathrm{CP}}$ and MO

• Please also enjoy more results from Super-Kamiokande at the poster sessions:

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<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Presenter</th>
<th>Session</th>
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<td>43</td>
<td>Neutron-antineutron oscillation search at Super-Kamiokande</td>
<td>Linyan Wan</td>
<td>3</td>
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<tr>
<td>85</td>
<td>Search for astronomical neutrino from the Gamma-ray burst with Super-Kamiokande</td>
<td>Masayuki Harada</td>
<td>2</td>
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<td>136</td>
<td>Long time supernova simulation and supernova burst search at Super-Kamiokande</td>
<td>Masamitsu Mori</td>
<td>2</td>
</tr>
<tr>
<td>161</td>
<td>Follow-up of Gravitational Wave events with Super-Kamiokande</td>
<td>Mathieu Lamoureux</td>
<td>1</td>
</tr>
<tr>
<td>166</td>
<td>Spallation Studies in Super Kamiokande</td>
<td>Scott Locke</td>
<td>2</td>
</tr>
<tr>
<td>175</td>
<td>Study of the atmospheric neutrino background for Supernova Relic Neutrino search</td>
<td>Seiya Sakai</td>
<td>4</td>
</tr>
<tr>
<td>221</td>
<td>Reactor Neutrinos in Super-Kamiokande</td>
<td>Alexander Goldsack</td>
<td>1</td>
</tr>
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<td>231</td>
<td>The diffuse supernova neutrino background in Super-Kamiokande</td>
<td>Sonia El Hedri</td>
<td>3</td>
</tr>
<tr>
<td>350</td>
<td>Latest solar neutrino analysis results from Super-Kamiokande</td>
<td>Yuuki Nakano</td>
<td>4</td>
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</tbody>
</table>