SOLAR NEUTRINOS

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INFN-LNGS and Borexino Collaboration,
European Neutrino “Town” meeting
and ESPP 2019 discussion
CERN, April 22-24, 2018
### Solar Neutrino Experiments: past and present

<table>
<thead>
<tr>
<th>Detector</th>
<th>Target mass</th>
<th>Threshold [MeV]</th>
<th>Data taking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>615 tons $\text{C}_2\text{Cl}_4$</td>
<td>0.814</td>
<td>1967-1994</td>
</tr>
<tr>
<td>Kamiokande II/III</td>
<td>3kton $\text{H}_2\text{O}$</td>
<td>9/7.5 / 7.0</td>
<td>1986-1995</td>
</tr>
<tr>
<td>SAGE</td>
<td>50tons molted metal Ga</td>
<td>0.233</td>
<td>1990-2007</td>
</tr>
<tr>
<td>GALLEX</td>
<td>30.3tons GaCl$_3$-HCl</td>
<td>0.233</td>
<td>1991-1997</td>
</tr>
<tr>
<td>GNO</td>
<td>30.3tons GaCl$_3$-HCl</td>
<td>0.233</td>
<td>1998-2003</td>
</tr>
<tr>
<td>SNO</td>
<td>1kton $\text{D}_2\text{O}$</td>
<td>6.75/6/3.5</td>
<td>1999-2006</td>
</tr>
<tr>
<td>Borexino</td>
<td>300ton $\text{C}<em>9\text{H}</em>{12}$</td>
<td>0.2 MeV</td>
<td>2007-present</td>
</tr>
<tr>
<td>KamLAND</td>
<td>1kton LS</td>
<td>0.2 MeV</td>
<td>2009-present</td>
</tr>
<tr>
<td>SNO+</td>
<td>1kton $\text{H}_2\text{O}$</td>
<td>5 MeV</td>
<td>2018</td>
</tr>
</tbody>
</table>
## Solar Neutrino Experiments: future

<table>
<thead>
<tr>
<th>Detector</th>
<th>Target mass</th>
<th>Threshold [MeV]</th>
<th>Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borexino</td>
<td>300ton C$<em>9$H$</em>{12}$</td>
<td>Sub-MeV</td>
<td>present-???</td>
</tr>
<tr>
<td>KamLAND</td>
<td>1kton LS</td>
<td>Sub-MeV</td>
<td>Main goal DBD</td>
</tr>
<tr>
<td>Super-Kamiokande-Gd</td>
<td>22.5 kton H$_2$O</td>
<td>3.5/4.5</td>
<td>1/2019 resume data taking w/ pure water</td>
</tr>
<tr>
<td>SNO+</td>
<td>780 ton LAB</td>
<td>sub-MeV</td>
<td>2018 LS filling</td>
</tr>
<tr>
<td>JUNO</td>
<td>20 kton</td>
<td>Sub-MeV</td>
<td>2021 data taking</td>
</tr>
<tr>
<td>Hyper-Kamiokande</td>
<td>258 kton H$_2$O</td>
<td>3.5/4.5</td>
<td>2020 start construction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2027 start operation</td>
</tr>
<tr>
<td>DUNE</td>
<td>40 kton LAr</td>
<td>7-10</td>
<td>2024 (10kton 1st module)</td>
</tr>
<tr>
<td>Jinping LS</td>
<td>2 kton LS FV</td>
<td>sub-MeV</td>
<td>Prototype under construction</td>
</tr>
<tr>
<td>Theia</td>
<td>H$_2$O based LS at SURF</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>LAr / LXe</td>
<td>GADM or DARWIN size</td>
<td>--</td>
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</tr>
</tbody>
</table>
The Solar Neutrino Problem viewed by Borexino

$\nu$ fluxes: Solar models (B16-GS98) vs. Borexino

SNP solved in the framework of MSW-LMA
sub-leading effect still possible

Vinyoles et al. 2016
http://www.ice.csic.es/personal/aldos
To be the chain, and, to a minor extent, in the alternative three-body theoretical solar models. Their intuition was correct and neutrinos are that the detection of solar neutrinos could be a direct way of testing can be found in ref.

...Neutrinos are copiously emitted in the primary chain (see Fig. 1) fusion with the highest precision so far achieved, and the boron-8 (B) beta decay with the lowest threshold. We measure the interaction rates of neutrinos produced by four reactions...
### Astrophysics with Solar Neutrinos

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux [cm$^{-2}$s$^{-1}$] SSM-HZ</th>
<th>Flux [cm$^{-2}$s$^{-1}$] SSM-LZ</th>
<th>Flux [cm$^{-2}$s$^{-1}$] Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>$5.98(1\pm0.006)\times10^{10}$</td>
<td>$6.03(1\pm0.005)\times10^{10}$</td>
<td>$6.1(1\pm0.10)\times10^{10}$ w/o luminosity constraint</td>
</tr>
<tr>
<td>pep</td>
<td>$1.44(1\pm0.009)\times10^{8}$</td>
<td>$1.46(1\pm0.009)\times10^{8}$</td>
<td>$1.27(1\pm0.17)\times10^{8}$ (HZ CNO)</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>$4.93(1\pm0.06)\times10^{9}$</td>
<td>$4.50(1\pm0.06)\times10^{9}$</td>
<td>$4.99(1\pm0.03)\times10^{9}$</td>
</tr>
<tr>
<td>$^8$B</td>
<td>$5.46(1\pm0.12)\times10^{6}$</td>
<td>$4.50(1\pm0.12)\times10^{6}$</td>
<td>$5.35(1\pm0.03)\times10^{6}$</td>
</tr>
<tr>
<td>CNO</td>
<td>$4.88(1\pm0.11)\times10^{8}$</td>
<td>$3.51(1\pm0.10)\times10^{8}$</td>
<td>$&lt;7.9\times10^{8}$ (2σ)</td>
</tr>
<tr>
<td>p-value (pp, Be, B)</td>
<td>0.96</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>
Summarizing, the "known" oscillation parameters $m^2$, $\sin^2 \theta_{12}$, $\sin^2 \theta_{13}$ and $\sin^2 \theta_{23}$ are currently measured at the few % level. Concerning the "unknown" oscillation parameters, interesting indications emerge in favor of NO at a global 3$\sigma$ level. At the same level one can also determine upper and lower limits for the phase $\delta$, with preference for nearly maximal CP violation. CP conservation is generally disfavored, but remains allowed at $\pm 2\sigma$ in NO. The octant of $\theta_{23}$ is unresolved at the $\pm 2\sigma$ level in both NO and IO. If these trends are confirmed, the mass spectrum ordering and the CP phase might be the first "unknowns" to become "known" (at $>3\sigma$) with further data; assessing the octant and excluding CP conservation might instead require more effort.

We conclude this section by comparing our results with other recent global analyses [31, 32, 33]. If we exclude SK atmospheric data as advocated in [31, 32], our results agree well with theirs on both known and unknown parameters. In particular, we obtain very similar $\delta m^2$ curves for $\theta_{12}$ and for $\theta_{23}$, including a comparable set between IO and NO (not shown). Given this agreement, we surmise that the authors of [31, 32] would also obtain results very similar to ours (Fig. 3 and Table 1) by adding the $\delta m^2$ map from the latest SK atmospheric neutrino data [176] in their recent fit [32]. Concerning the analysis in [33], we observe qualitative agreement with their hints on the mass ordering and the CP-violating phase. However, at the level of details, a comparison with [33] is not obvious: their data set is based on earlier T2K and NOvA data, and it also includes the $\delta m^2$ map of older SK atmospheric data [175], that was derived in the approximation $m^2 = 0$. By construction, this approximation switches CP-violation effects (and may bias other subleading effects) in atmospheric neutrinos, preventing a proper and detailed comparison of global fit results.

4 Results on oscillation parameter pairs

In this Section we show the allowed regions in various planes charted by pairs of oscillation parameters. We discuss covariances related to $m^2$-driven oscillations, to $m^2$-driven oscillations, and to the CP-violating phase $\delta$. We always take NO and IO as two isolated cases, without marginalizing over the mass ordering.

A) Longstanding tension at 2$\sigma$ level on best-fit for $\delta m^2$ between solar and KamLAND oscillation analysis
1. CPT invariance?
2. Physics beyond the SM
3. Subtle unknown effect in present analysis?

B) Day-Night (DN) asymmetry in SuperKamiokande is $-3.3\pm1.1\%$ with $DN = 2(D-N)/(D+N) \propto E/\delta m^2$ DNA for KL best-fit it should be $-1.7\%$
Solar Neutrinos and neutrino oscillations

Future ROI

Neutrino energy [MeV]

Survival Probability

BX
SNO+SK
SNO-LETA
LMA global
LMA Solar
LMA KL
NSI $\varepsilon = -0.16$
NSI $\varepsilon = -0.25$
What physics from solar Neutrinos in the future?

- **Particle physics (to be done)**
  - Measurement of expected matter-vacuum upturn
  - Measurement of day-night asymmetry

- **Astrophysics**
  - Solve the *solar abundance problem* by detecting CNO neutrinos (next future only Borexino, SNO+)
    - improved calculations of solar metallicity do not agree with data
  - Use solar neutrinos to understand the Sun (*inverse problem*)

- **The Sun in a unique laboratory!**
Borexino: next future

Main physics goal: CNO neutrinos

- Main challenge: constrain and reduce $^{210}$Bi background
  - ✓ Constrain by using tagging of $^{210}$Po and reduce convection inside the FV
  - Reduce by Water extraction purification

Underway activity and upgrade

- 2018-2019 improvement of thermal insulation system built in 2015 to reduce convection inside the LS
- 2018-2019 commissioning of fluid handling system for new Water Extraction purification
- 2019 commissioning of new water purification system (low $^{210}$Po water)
SuperKamiokande: next phase

Achievements

- SuperKamiokande has observed solar neutrinos for 22 years (2 solar cycles!)
  - Some 93,000 solar neutrinos detected
  - No correlation with solar activity observed
  - $\sim 3\sigma$ day-night asymmetry
  - Neutrino flux measured at 1.7% level

Underway upgrade

- Since June 2018 under refurbishment to be ready for operating with Gd salt
  - 0.2% Gd salt gives 90% neutron capture efficiency
  - Phase-I at 0.02%: 10ton of salt and 50% capture efficiency
- Resume data taking expected January 2019 with only water
- Critical point: radiopurity of Gd salt to keep current background level

Physics case

- Supernova relic neutrinos and electron anti-neutrino physics
- Day-Night asymmetry measurement at $3.9\sigma$ assuming systematics at 0.4%
- Upturn measurement at $3\sigma$ assuming $\Delta m^2$ from best-fit in KamLAND, 22.5kton and 3.5MeV threshold
  - At present: 22.5kton (>5MeV); 16.5kton (>4.5MeV); 8.8kton (>3.5MeV)
Solar Neutrinos in SNO+
Liquid Scintillator

Goals: precision measurement of pep (upturn); $^8$B (upturn+DN); CNO (SSM)

Solar neutrino-electron recoil energy spectrum
- simulated full spectrum
- no $\alpha/\beta$ PSD or Bi-Po coincidence cuts applied
- target background levels (w/slow $^{210}$Pb leaching)

$^8$B solar neutrinos down to 2 MeV
- simulated 6 months of data

Adapted from M. Chen
$^8\text{B}$ Solar Neutrinos in SNO+ Water

Measured with very low backgrounds!

Adapted from M. Chen
Hyper-Kamiokande detector

- 258 kt water
- 187 kt fid. vol. (1m from wall)
- OD: 1~2m thickness
- Photon detection efficiency: SK detector x 2
  - Better energy resolution
  - Better neutron tagging efficiency (~70%)
- Optional 2nd tank is under discussion.

Inner Detector (ID): ~40,000 of new 50-cm photo sensors
Outer Detector (OD): ~6,700 of new 20-cm photo sensors

Adapted from M. Shizowa
Solar neutrino measurements in HK

Day/Night sensitivity

- Sensitivity to no asymmetry
- Sensitivity to KamLAND

Sensitivity (sigma)

Day/Night (solar vs reactor): 4~5 sigma in 10 years
Spectrum upturn: ~3 sigma in 10 years

Solid: 0.3% syst. err.
Dotted: 0.1% syst. err.

Solid: 4.5 MeV threshold
Dotted: 3.5 MeV threshold
(at solar best parameters)

Adapted from M. Shizowa
Solar hep neutrino at HK

Integrated # of expected solar neutrino events

(100% signal efficiency)

<table>
<thead>
<tr>
<th>$E_{\text{total}}$ [MeV]</th>
<th>$^8\text{B}$ [1.9 Mt yr]</th>
<th>Hep [1.9 Mt yr]</th>
<th>Hep / $^8\text{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-25</td>
<td>0.56</td>
<td>6.04</td>
<td>10.6</td>
</tr>
</tbody>
</table>

First direct observation of hep solar $\nu$ could be done at 2~3 sigma with a few Mton year data

Non-zero significance of hep $\nu$ detection from a spectrum analysis

(signal efficiency, spallation BG, major syst. uncertainties are estimated from SK-IV)

Black solid: at Tochibora site
Red solid: at Mozumi site
Red dotted: at Mozumi, no spallation BG

Adapted from M. Shizowa
JUNO

- Center Detector (3% energy resolution)
  - Acrylic sphere with LS
  - PMT in water tank (18k 20” + 25k 3”)
  - 20k LS with 78% PMT coverage

- Veto Detector
  - Water Cherenkov
  - Top tracker (adapted from OPERA)
  - Muon tagging and track reconstruction

- Calibration system
  - Covering various particle type, full energy range and position

- Timeline
  - 2018: surface buildings + acrylic sphere production + PMTs delivery
  - 2019-2020: detector construction + electronics production
  - 2021: ready for data taking
JUNO: solar neutrinos

- Precision measurement of pp-chain solar neutrino rates by ES
  - Borexino radiopurity assumed

- Precision measurement of $\Delta m_{21}^2$
  - will help solve tension between KL and solar fit (0.6% including systematics)

- $^8$B solar neutrinos in [2,3] MeV ROI to probe $P_{ee}$ upturn
  - $^{10}$C cosmogenic background tagging efficiency at 98% level assumed for $S/N \sim 1$
  - $\sim 6000$ events in 6 years

- Possibility to search for Day-Night asymmetry and CNO neutrinos under investigation (?)
Solar neutrinos in DUNE

Two detection channels:
1. CC on $^{40}$Ar
   \[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \]
2. ES
   This breaks the degeneracy between $\sin^2\theta$ and $\phi(8\text{B})$
   These channels can be separated exploiting the imaging capabilities

DN asymmetry can be probed

- new paper
  arXiv:1808.08232

Adapted from K. Scholberg
Capozzi et al. paper presents intriguing sensitivity with DUNE:

BUT: makes very optimistic assumptions
(7% energy resolution, 25% angular resolution, modest bg, no systematics, ...these may not be achieved*)

- Overall realistic sensitivity for solar vs still under study

Adapted from K. Scholberg

*~20% energy resolution more likely, e.g., µBooNE 1704.02927
Conclusions

- 50 years experimental activity on solar neutrino detection

- Achieved an important contributions to particle physics and astrophysics, background reduction

- Yet, more effort needed for
  - A definitive measurement of day-night asymmetry with $^8$B neutrinos
  - A definite measurement of the upturn energy region
  - Detection of CNO and pep neutrinos in upturn region
  - Probe possible sub-leading effects (NSI)

- The above program can be carried out in
  - Borexino, SuperKamiokande, SNO+ from present – 2027
  - Juno from 2021
  - DUNE and HyperKamiokande from 2024/2027 – 2037

- No long term solar neutrino detector in Europe
Acknowledgements

I would like to thank Masayuki Nakahata, Masato Shiozawa, Mark Chen, Kate Scholberg, Ding Xuefeng for providing information on SuperKamiokande, HyperKamiokande, SNO+, DUNE, and JUNO.
Solar neutrino spectra

Multivariate fit example

$L^{(11C_{sub})}$

$L^{(11C_{tag})}$

$L(...)$

$L(\text{Rad})$

$L(\text{PS})$
Borexino

- \( R(\,^7\text{Be}) + D/N \)
- \( R(\text{pep}) \) – first observation
- \( R(\,^8\text{B}) \) – first with LS
- \( R(CNO) \) – limit

Geo-\( \nu \) – first robust observation

Cosmic muons flux studies

Rare processes

- \( R(pp) \) first in real time
- Seasonal variations of \( R(\,^7\text{Be}) \)
- Simultaneous spectroscopy of \( pp, \,^7\text{Be} \) and pep \( \nu \)
- \( R(\,^8\text{B}) \) – improved
- Geo-\( \nu \)
- \( \nu \) magnetic moment
- NSI (under study)
- Rare processes

LS purification campaign
6 cycles of water extraction

External Tank insulation

CNO campaign

2007 \( \rightarrow \) 2010 \( \rightarrow \) 2012 \( \rightarrow \) 2015 \( \rightarrow \) 2017 \( \rightarrow \) 2018
CNO neutrino sensitivity

Depends on $^{210}\text{Bi}$ background.

We assume that $^{210}\text{Bi}$ will be measured with 10-20% accuracy.
Thermal insulation to reduce convection motion inside the FV

Thermal insulation (summer 2015)