Low-energy neutrinos

Solar
Geo
Sources

Livia Ludhova
Istituto Nazionale di Fisica Nucleare, Milano, Italy
Outline

Solar  Geo  Sources

few MeV

1.5 x 10^{11} m  < 1.27 x 10^{7} m  ~m

1. Motivation to study them today
2. Latest experimental results
3. Future perspectives
Which experiments? Underground laboratories

**Liquid scintillator**

- **Borexino**
  - Italy
  - 280 ton

**Water Cherenkov**

- **SuperKamiokande**
  - Japan
  - 50 kton

- **KamLAND**
  - Japan
  - 1 kton
Nuclear reactions in the Sun

**pp-cycle**

- $p + p \rightarrow ^2H + e^+ + \nu_e$
- $p + 2^2H \rightarrow ^3He + \gamma$
- $^3He + ^3He \rightarrow ^4He + p + p$
- $^3He + ^4He \rightarrow ^7Be + \gamma$
- $^7Be + e^- \rightarrow ^7Li + \nu_e$
- $^7Li + p \rightarrow ^4He + ^4He$
- $^8B \rightarrow ^8Be + e^- + \nu_e$
- $^8Be \rightarrow ^4He + ^4He$

**CNO-cycle**

- Sun: should contribute <1%
- Heavy stars: should be dominant!
- Never observed until now
Energy spectrum of solar neutrinos

Flux on Earth (\(\nu/\text{cm}^2\text{s}\))

- \(10^{12}\)
- \(10^{11}\)
- \(10^{10}\)
- \(10^{9}\)
- \(10^{8}\)
- \(10^{7}\)
- \(10^{6}\)
- \(10^{5}\)
- \(10^{4}\)
- \(10^{3}\)
- \(10^{2}\)
- \(10^{1}\)

Energy [MeV]

- \(0.1\)
- \(1\)
- \(10\)

- \(^{13}\text{N}\)
- \(^{15}\text{O}\)
- \(^{17}\text{F}\)

- pp ± 0.8%
- \(^{7}\text{Be} ± 9.4\%\)
- pep ± 2%
- \(^{8}\text{B} ± 20\%\)

Real-Time Liquid Scintillator Borexino

- Real-Time
- Water Cherenkov Detectors
- SuperK + SNO

Integral Flux/Radiochemistry

Ga exps

Cl exp
Standard Solar Model and metallicity problem

**INput:**
- Nuclear parameters;
- Luminosity
- Mass
- Radius
- Surface metals (C, N, O, Ne, Mg, Si, Ar, Fe)—to-hydrogen ratio \((Z/X = \text{metallicity})\)
- Equations of state
- Chemical elements abundance
- Radiation opacity

**OUTput:**
- Neutrino fluxes
- Helioseismology (sound-waves speed profiles)

Older High-Metallicity: \(Z/X = 0.0229\) SSM GS98, 1D SSM
Newer Low-Metallicity: \(Z/X = 0.0178\) SSM AGS05, AGSS09/ph, 3D SSM

Better spectroscopy and 3D SSM is spoiling the previous agreement of the SSM predictions with helioseismology data

**WHY?**
Short history of solar $\nu$ experiments in 1 slide

70’s-80’s: **Homestake** (R. Davies): Radiochemistry: $E_\nu > 814$ keV
- $^{37}$Cl + $\nu$ $\rightarrow$ $^{37}$Ar + e$^-$
- **THE FIRST DETECTION!** deficit in the observed flux, skepticism
- final triumph, **Nobel prize 2002**
- **J. Bahcall** continues the development of the Standard Solar Model

80’s-90’s: **(super)Kamiokande:** Water Cherenkov: $E_\nu > 5$ MeV
- confirms deficit on $^8$B-$\nu$ and with real-time technique
- first neutrino picture of the Sun (directionality)
- neutrinos from other stars observed (supernova SN1987-A)

90’s: **Gallex (GNO) and Sage:** Radiochemistry: $E_\nu > 233$ keV
- $\nu_e + ^{71}$Ga $\rightarrow ^{71}$Ge + e$^-$
- deficit observed also at low energy, but is energy dependent!

2001: **SNO:** Water Cherenkov: $E_\nu > 5$ MeV
- oscillation of solar neutrinos proved
- CC (electron flavor) and NC (all flavors) interactions separately in $D_2O$
- total flux agrees with Standard Solar Model!

2002: **KamLAND:** Liquid scintillator
- observes and measures oscillations of electron anti-neutrinos from reactors;

2007: **Borexino:** Liquid scintillator of extreme radiopurity: $E_\nu > 303$ keV
- First real-time observation of $^7$Be, pep, pp neutrinos
- best limit on CNO
- Low-energy $^8$B neutrinos ($> 3$ MeV recoiled e$^-$)

First detection
Solar-neutrino puzzle
Solution: Neutrino oscillations!
Real-time precision spectroscopy
Why to measure solar neutrinos today?

1) Solar and stellar physics:
   a) metallicity problem

Low and High metallicity SSMs predict different neutrino fluxes!

Fluxes given in units of $\nu$ cm$^{-2}$ s$^{-1}$ x $10^{10}$ (pp), $10^9$ ($^7$Be), $10^8$ (pep, $^{13}$N, $^{15}$O), $10^6$ ($^8$B, $^{17}$F), $10^3$ (hep)

Currently no power to resolve low/high metallicity problem

<table>
<thead>
<tr>
<th>SOLAR NEUTRINO FLUXES - SHP11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ Flux</td>
</tr>
<tr>
<td>pp</td>
</tr>
<tr>
<td>pep</td>
</tr>
<tr>
<td>hep</td>
</tr>
<tr>
<td>$^7$Be</td>
</tr>
<tr>
<td>$^8$B</td>
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<td>$^{15}$O</td>
</tr>
<tr>
<td>$^{17}$F</td>
</tr>
</tbody>
</table>

Why to measure solar neutrinos today?

1) Solar and stellar physics:
   
   \textit{b) testing energy production/loss mechanism}

- Neutrinos are THE proof that nuclear fusion powers the Sun
- Is the optical and neutrino luminosity in agreement?
- Neutrinos promptly escape from the Sun’s core, while for photons it takes \(\text{cca} 10^5\) years to escape! By comparing optical and neutrino luminosities… testing Solar stability at \(10^5\) time scale!

![Graph showing pp-ν flux](image)

\(\chi^2/\text{d.o.f.} = 172.3/147\)

- \(pp \nu\): 144 ± 13 (free)
- \(^7\text{Be} \nu\): 46.2 ± 2.1 (constrained)
- \(\text{pep} \nu\): 2.8 (fixed)
- CNO \(\nu\): 5.36 (fixed)
- \(^{214}\text{Pb}\): 0.06 (fixed)
- \(^{210}\text{Po}\): 583 ± 2 (free)
- \(^{14}\text{C}\): 39.8 ± 0.9 (constrained)
- Pile-up: 321 ± 7 (constrained)
- \(^{210}\text{Bi}\): 27 ± 8 (free)
- \(^{85}\text{Kr}\): 1 ± 9 (free)

Borexino, Nature 512 (2014) 383

\(pp-\nu\) flux

Physics World:
Top 10 Physics Breakthroughs of 2014

1. Spectral observation of solar \(pp-\nu\) (extreme radiopurity, synthetic pile-up, independent measurement of \(^{14}\text{C}\) rate, low energy threshold 164 keV)

\(R_{pp} = 144 \pm 13\) (stat) \(\pm 10\) (sys) c.p.d/100 ton

Borexino: \(\Phi_{pp} = 6.6 \times (1 \pm 0.106) \times 10^{10}\) cm\(^{-2}\) s\(^{-1}\):
SSM: \(\Phi_{pp} = 5.98 \times (1 \pm 0.006) \times 10^{10}\) cm\(^{-2}\) s\(^{-1}\)

2. Direct prove that \(pp\)-cycle provides \(~99\)% of Solar power

Borexino parallel talk of Gemma Testera
Why to measure solar neutrinos today?

2) **Neutrino physics:**

   a) *Searching for new physics:*

   *searching for deviations from MSW-LMA scenario of solar ν oscillations, especially in the transition region of $P_{ee}$ (e.g. mass-varying neutrinos or non-standard interactions models)*

   ![Diagram](image)

   **Examples of suggested new-physics models:**

   - Mass varying neutrinos  
     (Gonzales-Garcia & Maltoni 2008)
   - Non-Standard Interactions/flavour changing NC  
     (Friedland, Lunardini, Pena-Garay, 2008)
   - Sterile Neutrinos  
     (Holanda & Smirnov 2011)
Electron-neutrino survival probability

Testing MSW-LMA

Borexino only data

MSW-LMA with oscillation parameters:
- Solar (nu) + KL (antinu) best fit
- Solar best fit
- SK best fit

SK gives the world's strongest constraints on the shape of the survival probability in the transition region between vacuum oscillations and the MSW resonance.

Extended Data Figure 2
Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun.

All the numbers are from Borexino (this paper for pp, ref. 17 for 7Be, ref. 18 for pep and ref. 19 for 8B with two different thresholds at 3 and 5 MeV).
7Be and pep neutrinos are mono-energetic. pp and 8B are emitted with a continuum of energy, and the reported $P(n_e R_{n_e})$ value refers to the energy range contributing to the measurement. The violet band corresponds to the 61 prediction of the MSW-LMA solution. It is calculated for the 8B solar neutrinos, considering their production region in the Sun which represents the other components well. The vertical error bars of each data point represent the 61 interval; the horizontal uncertainty shows the neutrino energy range used in the measurement.
Why to measure solar neutrinos today?

2) Neutrino physics:

b) Confirming MSW: energy-dependent matter resonant conversion

observation ($^8$B) or exclusion ($^7$Be) of a **day-night effect** for different neutrino energies according to MSW predictions!

First direct indication at $\sim$3σ level for matter enhanced neutrino oscillations.

More precise measurement of $\Delta m^2_{12}$

**Paralel talk of Hiroyuki Sekiya**
Why to measure solar neutrinos today?

2) Neutrino physics:

c) Oscillation analysis and global fits

Determination of $\Delta m^2_{12}$, $\sin^2 \theta_{12}$, $\sin^2 \theta_{13}$ and comparison with the values obtained including also reactor antineutrino data.

SuperKamiokande: Parallel talk of Hiroyuki Sekiya
What’s next for solar neutrinos?

Running experiments

• **Borexino (Italy) Phase II** *(almost complete removal of $^{85}$Kr and a strong reduction of $^{210}$Bi)*:
  - more precise measurement of pep, $^7$Be, pp
  - the first detection of CNO (?)
• **SuperKamiokande (Japan)** continues to take data
  - further tests of the transition region of the MSW-LMA

Near future experiments:

• **SNO+** (Canada, 780 ton of liquid scintillator, ready for fill in 1 year)
  - $^8$B-ν also with Te-loaded scintillator (main goal – 0νββ decay)
  - > 1 order of magnitude less cosmogenic bgr than Borexino – ideal for CNO and pep neutrinos
• **JUNO** (China, **20 kton scintillator**, DAQ planned for 2020) and **RENO-50** (Korea, 18 kton scintillator, if DAQ planned for 2021)
  - close to reactors – main goal is the neutrino mass hierarchy: 3% @ 1 MeV
  - the solar neutrino program depends on final radiopurity

Far future experiments:

• **Hyper-Kamiokande** *(MEGATON SCALE) = 20 x SuperKamiokande;*
• **LENA** - 50 kton liquid scintillator…. Unclear future
• **LENS** - Unclear future;
Geoneutrinos: antineutrinos from the decay of $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$ in the Earth

- **Main goal:** determine the contribution of the radiogenic heat to the total surface heat flux, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;
- **Further goals:** tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth’s formation…..

![Diagram](image.png)

- **Abundance of radioactive elements**
- **Distribution of radioactive elements (models)**
- **Geoneutrino flux**
- **Radiogenic heat (Main goal)**

**Nuclear physics**

- $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\alpha + 8\ e^- + 6\ \text{antineutrinos} + 51.7\ \text{MeV}$
- $^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\alpha + 4\ e^- + 4\ \text{antineutrinos} + 42.8\ \text{MeV}$
- $^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + 1\ \text{antineutrino} + 1.32\ \text{MeV}$
Earth’s interior

Dynamical picture

Compositional layers

- Continental crust: 10-70 km
- Oceanic crust: 5-7 km

Mechanical layers

- Lithosphere: 10-200 km
- Asthenosphere
- Mantle
- Mesosphere
- Core
- Outer core
- Inner core

U, Th, K: refractory lithophile elements

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper continental crust</td>
<td>2.5 ppm</td>
</tr>
<tr>
<td>middle continental crust</td>
<td>1.6 ppm</td>
</tr>
<tr>
<td>lower continental crust</td>
<td>0.63 ppm</td>
</tr>
<tr>
<td>oceanic crust</td>
<td>0.1 ppm</td>
</tr>
<tr>
<td>upper mantle</td>
<td>6.5 ppb</td>
</tr>
<tr>
<td>core</td>
<td>nothing</td>
</tr>
</tbody>
</table>

http://www.skepticalscience.com/heatflow.html
Earth’s profile in time

http://www.ess.sci.osaka-u.ac.jp/english/3_research/groups/g05kondo.html
Seismology

Discontinuities in the waves propagation and the density profile, but no info about the chemical composition of the Earth

P – primary, longitudinal waves
S – secondary, transverse/shear waves
Geo-chemistry

1) **Direct rock samples**
   * surface and bore-holes (max. 12 km);
   * mantle rocks brought up by tectonics
   **BUT:** POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**
   rock samples + meteorites + Sun
   **Bulk Silicate Earth** (BSE) models
      medium composition of the “re-mixed” crust + mantle,
      *i.e.*, **primordial mantle** before the crust differentiation and after the Fe-Ni core separation

**Compositional (relative to Si) correlation**
Sun vs Chondrites
Surface heat flux

Bore-hole measurements

Sources

Radiogenic heat:
(Geoneutrinos)!!!!!

BSE models predictions:

- Geochemical BSE: 17-21 TW
- Cosmochemical BSE: 11 TW
- Geodynamical BSE: > 30 TW

Other sources:

1) Residual heat from the past
2) $^{40}$K in the core?
3) Nuclear reactor in the core?
4) Very minor (phase transitions, tidal etc..)

47 ± 2 TW
(Davies & Davies 2010)
Geoneutrinos spectrum and detection

\[ \nu + p \rightarrow n + e^+ \]

**Inverse Beta Decay**

- **Prompt signal**
  - e\(^+\): energy loss \(T_{e^+}\) annihilation \((2 \times 0.511 \text{ MeV})\)
  - \(E_{\text{prompt/visible}} = E_{\text{geonu}} - 0.784 \text{ MeV}\)

- **Delayed signal**
  - Thermalisation and neutron capture on protons, emission of 2.2 MeV \(\gamma\)

**1.8 MeV kinematic threshold**

- Geoneutrinos spectrum and detection
- Scintillator
- Prompt signal
- Delayed signal

Livia Ludhova: Low-energy neutrinos: solar, GEO, sources

TAUP 2015, Torino, 11\(^{\text{th}}\) September
Geoneutrino experimental results

KamLAND (Japan)

- **The first investigation in 2005**
  CL < 2σ
  *Nature* 436 (2005) 499

- **Update in 2008**
  73 ± 27 geonu’s
  *PRL* 100 (2008) 221803

- **99.997 CL observation in 2011**
  106 $^{+29}_{-28}$ geonu’s
  (March 2002 – April 2009)
  3.49 x $10^{32}$ target-proton year
  *Nature Geoscience* 4 (2011) 647

- **Latest result in 2013**
  116 $^{+28}_{-27}$ geonu’s
  (March 2002 – November 2012)
  4.9 x $10^{32}$ target-proton year
  0-hypothesis @ 2 x $10^{-6}$
  *PRD* 88 (2013) 033001

Borexino (Italy)

- **99.997 CL observation in 2010**
  9.9 $^{+4.1}_{-3.4}$ geonu’s
  small exposure but low background level
  (December 2007 – December 2009)
  1.5 x $10^{31}$ target-proton year
  *PLB* 687 (2010) 299

- **Update in 2013**
  14.3 ± 4.4 geonu’s
  (December 2007 – August 2012)
  3.69 x $10^{31}$ target-proton year
  0-hypothesis @ 6 x $10^{-6}$
  *PLB* 722 (2013) 295–300

- **NEW in June 2015: 5.9σ CL**
  23.7 $^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu’s
  (December 2007 – March 2015)
  5.5 x $10^{31}$ target-proton year
  0-hypothesis @ 3.6 x $10^{-9}$
  *PRD* 92 (2015) 031101 (R)
Latest Borexino geoneutrino results

Unbinned maximal likelihood fit:
- Geoneutrinos free
- Reactor antineutrinos free
- Other backgrounds ($0.78^{+0.78}_{-0.10}$ events total) constrained

Two types of fits:
1) $\text{Th/}U$ mass ratio fixed to chondritic value of 3.9

$$N_{\text{geo}} = 23.7^{+6.5}_{-5.7} \text{(stat)}^{+0.9}_{-0.6} \text{(sys)}$$ events

$$S_{\text{geo}} = 43.5^{+11.8}_{-10.4} \text{(stat)}^{+2.7}_{-2.4} \text{(sys)} \text{ TNU}$$

2) $U$ and $\text{Th}$ free fit parameters

Non antineutrino background is almost invisible!

Non antineutrino background is almost invisible!
Geological implications of the new Borexino results

Radiogenic heat

The Earth is not fully radiogenic

Mantle signal

- $S_{\text{Mantle}} = S_{\text{measured}} - S_{\text{Crust}}$
- Crustal signal at LNGS “known”
  $S_{\text{Crust}} = (23.4 \pm 2.8)$ TNU
- Non-0 mantle signal at 98% CL
  $S_{\text{mantle}} = 20.9^{+15.1}_{-10.3}$ TNU

More details in Borexino parallel talk of Aldo Ianni
Latest KamLAND geoneutrino results

- After Fukushima, Japanese reactors off
- Plan to refurbish outer detector in Jan’ 16.
  new update expected then!

116 $^{+28}_{-27}$ geonu’s
Geoneutrino future

- **Borexino** will switch to SOX (see later) in late 2016 – closure of geoneutrino dataset;
- **KamLAND**: possible next update with low reactor-background data after the end of 2015;
- **SNO+** (Canada): 780 ton & DAQ start in 2017; detector should be able to provide geoneutrino results;
- **JUNO** (China): 20 kton & DAQ start in 2020; If non antineutrino background low and under control, JUNO will soon beat the precision of existing measurements;
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution: “THE” GEONU DETECTOR: MISSING FUNDING!

- New interdisciplinary field established: **NEUTRINO GEOSCIENCE** conference every two years
- Power of combined analysis and importance of multi-site measurements at geologically different environments
Livia Ludhova: Low-energy neutrinos: solar, geo, sources

TAUP 2015, Torino, 11th September
Neutrino anomalies: hints for sterile neutrino?

\[ \nu_e, \text{anti-}\nu_e \text{ DISAPPEARANCE} \]

Reactor anomaly \(~2.5\sigma\)
Re-analysys of data on anti-neutrino flux from reactor short-baseline (L\(~10-100\) m) shows a small deficit of R=0.943 ±0.023

\[ \nu_e, \text{anti-}\nu_e \text{ APPEARANCE} \]

Gallex/SAGE anomaly \(~3\sigma\)
Deficit observed by Gallex in neutrinos coming from a \(^{51}\text{Cr}\) and \(^{37}\text{Ar}\) sources
\[ R = 0.76^{+0.09}_{-0.08} \]

Accelerator anomaly \(~3.8\sigma\)

Confirmed by miniBooNE (which also sees appearance of \(\nu_e\) in a \(\nu_\mu\) beam) A. Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)

Possible explanation: mixing of the active flavours with a sterile neutrino \(\Delta m^2 \sim 1 \text{ eV}^2\)

- 3-flavor scenario cannot accommodate these anomalies, at least one sterile neutrino needed
- No strong preference for \((3+1), (3+2), (3+1+1)\) scenarios
- In \((3+1)\) scenario: \(0.82 < \Delta m^2_{41} < 2.19 \text{ eV}^2\) \(3\sigma\)
- To probe this region: MeV (anti)neutrinos at short distances of few meters!

C. Giunti, M. Laveder, Y. F. Li, H.W. Long
Sterile neutrino search using nuclear decays

<table>
<thead>
<tr>
<th>ν type</th>
<th>Source type</th>
<th>Life τ</th>
<th>Decay mode</th>
<th>Energy [MeV]</th>
<th>Production mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>νe</td>
<td>⁵¹Cr</td>
<td>40 d</td>
<td>EC</td>
<td>0.75 (90%) 0.43 (10%)</td>
<td>Neutron irradiation of ⁵⁰Cr in reactor ( \Phi_n \geq 5 \times 10^{14} \text{cm}^{-2} \text{s}^{-1} )</td>
</tr>
<tr>
<td></td>
<td>³⁷Ar</td>
<td>35 d</td>
<td>EC</td>
<td>0.811</td>
<td>Fast neutron irradiation of Ca oxide in reactor</td>
</tr>
<tr>
<td>( \overline{\nu}_e )</td>
<td>¹⁴⁴Ce-¹⁴⁴Pr</td>
<td>411 d</td>
<td>β⁻</td>
<td>&lt;2.997</td>
<td>Chemical extraction from spent fuel</td>
</tr>
<tr>
<td></td>
<td>⁹⁰Sr</td>
<td>40 y</td>
<td>β⁻</td>
<td>&lt;2.27</td>
<td>RHS (RadioNuclide Heat Source)</td>
</tr>
<tr>
<td></td>
<td>⁸Li</td>
<td>868 ms</td>
<td>β⁻</td>
<td>&lt;12.9</td>
<td>Beam of neutrons on a ⁷Li target (ISODAR facility)</td>
</tr>
</tbody>
</table>

Look for:

1) **Dissapearance** of (anti)neutrinos emitted from the source

2) **Oscillometry** in (L, E) parameter space

Gaffiot et al. PRD 91 (2015) 072005

\[ \Delta m_{31}^2 = 2 \text{eV}^2 \rightarrow \text{oscillations within detector} \]

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{ee}) \sin^2 \frac{\Delta m_{31}^2 L}{4E} \]
### Candidates and ideas around the world

#### Large Liquid scintillator detectors

<table>
<thead>
<tr>
<th>Technique</th>
<th>Detector</th>
<th>Sources</th>
<th>Reaction</th>
<th>Activity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Liquid scintillator detectors</td>
<td>SOX (Borexino)</td>
<td>$^{51}$Cr, $^{144}$Ce-$^{144}$Pr</td>
<td>$\nu+e \rightarrow \nu+e$, $\nu+p \rightarrow e^-+n$</td>
<td>10MCi</td>
<td>JHEP08(2013)038, Phys. Rev. Lett. 107, 201801 (2011)</td>
</tr>
<tr>
<td>KamLAND</td>
<td>$^8$Li (ISODAR)</td>
<td>$^{144}$Ce(CeLAND)</td>
<td>$\nu+p \rightarrow e^-+n$, $\bar{\nu}+p \rightarrow e^-+n$</td>
<td>$8.2 \times 10^{14}$ $\nu$/sec</td>
<td>arXiv:1205.4419, arXiv:1310.3857</td>
</tr>
<tr>
<td>Daya-Bay</td>
<td>$^{144}$Ce-$^{144}$Pr</td>
<td>$^{8}$Li (ISODAR)</td>
<td>$\nu+p \rightarrow e^-+n$</td>
<td>100kCi</td>
<td>arXiv:1312.0896</td>
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<tr>
<td>LENS</td>
<td>$^{51}$Cr</td>
<td>$^{144}$Ce-$^{144}$Pr</td>
<td>$\nu+^{115}$In $\rightarrow ^{115}$Sn$^*$+e</td>
<td>10MCi</td>
<td>Phys.Rev.D75 093006(2007)</td>
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<tr>
<td>JUNO</td>
<td>$^{8}$Li (ISODAR)</td>
<td>$^{51}$Cr</td>
<td>$\nu+^{70}$Ga $\rightarrow ^{71}$Ge+e</td>
<td>3MCi</td>
<td>arXiv:1204.5379</td>
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#### Radiochemical

<table>
<thead>
<tr>
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<th>Activity</th>
<th>Reference</th>
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<tr>
<td>Radiochemical</td>
<td>BEST</td>
<td>$^{51}$Cr</td>
<td>$\nu+^{70}$Ga $\rightarrow ^{71}$Ge+e</td>
<td>3MCi</td>
<td>arXiv:1204.5379</td>
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#### Bolometers

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<th>Activity</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Bolometers</td>
<td>Richochet</td>
<td>$^{37}$Ar</td>
<td>$\nu+N \rightarrow \nu+N$</td>
<td>5MCi</td>
<td>Phys. Rev. D85, 013009, (2012)</td>
</tr>
</tbody>
</table>
SOX: Short-distance neutrino oscillation with Borexino

Aim: Clear and unambiguous discovery or definitive disproof of the anomalies

Also under discussion:
- $^{51}$Cr source underneath the detector
- $^{144}$Ce source inside the water tank or in the center

Counts per 0.10 m MeV$^{-1}$ bin

No oscillations

$\sin^2(2\theta_{\text{new}}) = 0.10,$ $\Delta m^2_{\text{new}} = 0.5 \text{ eV}^2$

$\sin^2(2\theta_{\text{new}}) = 0.10,$ $\Delta m^2_{\text{new}} = 2 \text{ eV}^2$

Livia Ludhova: Low-energy neutrinos: solar, geo, SOURCES

TAUP 2015, Torino, 11th September
**144\(^{\text{Ce}}\)-144\(^{\text{Pr}}\) antineutrino source**

- 3.7 PBq (in 144\(^{\text{Ce}}\)(\(\beta\)), 100 kCi)
  > 10\(^{15}\) antineutrinos/s
  (CHALLENGE technical and bureaucratic)

- Long lifetime of 285 days
- 2.2 MeV gammas difficult to handle

**Inverse Beta Decay**

\(\nu + p \rightarrow n + e^+\)

**Background suppression!**

Detection of \(~ 500\) pe/MeV

Energy resolution \(\sigma_E/E \sim 5\%\) (@1MeV)

Position resolution \(\sigma_x \sim 10\) cm (@1MeV)
144Ce-144Pr source production

- From fresh (< 2 years) nuclear spent fuel
- Chemical form CeO₂

Purity requirements
- Content of any others REE (γ-emitters) \( \leq 10^{-3} \text{ Bq} / \text{Bq of } 144\text{Ce} \)
- Content of Pu and TPE (actinides) \( \leq 10^{-5} \text{ Bq} / \text{Bq of } 144\text{Ce} \)

Image: Radiochemical Plant
- Standard radiochemical re-processing of SNF (Purex)
- Separation of CeO₂
- Primary encapsulation
- Activity measurement (~5%)

Image: Radioisotope Plant
- Source manufacture
- Certification ISO 9978
- Loading into W-shield
- Loading into transport cask

Arrival to LNGS: 2nd half of 2016
**Additional physics challenges**

- \(^{144}\text{C}-{^{144}\text{Pr}}\) \(\beta/\nu\) spectra needed with 5% precision: BUT forbidden transitions and shape factors with 10% error! Ongoing developments of new spectroscopic measurements (CEA, TUM)!

- **Activity has to be known with < 1.5% precision: Calorimetry!** (CEA, TUM + Genova)

  - **Fighting all other systematic errors down to 1-2% precision!**
    - the “whole” scintillator volume of Borexino will be used (similar to geoneutrino studies)
    - A few months-long calibration campaign with external (gamma’s, AmBe-neutron) sources planned for early 2016
    - Upgrade of the trigger system
    - New Geant-based Monte Carlo development
    - Source-induced background study
    - Adding PPO to the internal buffer region?
Sensitivity studies

More details in Ce-SOX parallel talk of Matthieu Vivier
Sensitivity studies

100 kCi source at 8.5 m from detector center (1% norm. uncertainty)

- shape-only
- rate-only
- rate+shape

More details in Ce-SOX parallel talk of Matthieu Vivier

Stay tuned in 2017!
Thank you!