0νββ decay search in 2013: Status and advancements

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Searching for the rare neutrinoless double beta decay

Towards the valley of stability:
- **Second-order nuclear transition** that can occur between two odd-odd isobars:
  - $\rightarrow$ single $\beta$ decay **energetically forbidden**
  - $\rightarrow$ Among partly competing alternatives ($\beta^-\beta^-, \beta^+\beta^+, \text{EC}\beta^+, \text{ECEC}$) $\beta^-\beta^-$ has highest rates
- **35 candidates** in Nature; Examples: $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{96}\text{Zr}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$, $^{130}\text{Te}$, $^{136}\text{Xe}$

Role of neutrinos in $\beta\beta$ decay:
1. **$2\nu\beta\beta$ decay**
   - **Allowed by Standard Model**
   - **Signature**: $\beta$ -like spectrum
   - **Observed in 12 candidates**: $\mathcal{O}(T_{1/2})=10^{18}$-10$^{24}$ yr (Longest-lived decay processes observed in Nature)

2. **$0\nu\beta\beta$ (or $0\nu\chi^0(\chi^0)\beta\beta$) decay**
   - **Signature**: Full energy peak at $Q_{\beta\beta}$
   - **Lepton-number violation ($\Delta L=2$)**, thus not allowed by Standard Model
   - **Note**: One claim (in $^{76}\text{Ge}$) by subgroup of Heidelberg-Moskow Collaboration

Expected experimental signature from $2\nu\beta\beta$ and $0\nu\beta\beta$ decays
Motivations for $0\nu\beta\beta$ decay search

Observation of $0\nu\beta\beta$ decay helps answering 3 fundamental questions:

1. **Is lepton number conservation violated?** Are neutrinos their own anti-particles?
   → If yes, physics beyond the Standard Model of Elementary Particles with impact up to cosmology

2. **What is the absolute neutrino mass scale?**
   → Neutrino-oscillations reveal only squared mass-differences of neutrino mass eigenstates

3. **Is the neutrino mass spectrum degenerate, normal or inverted?**
   → Atm./solar/reactor neutrino oscillation experiments allow different scenarios (Hierarchy problem)
   → Measurement of 'effective' neutrino mass which is very rich of information:

$$\langle m_{ee} \rangle = \left| \sum |U_{ei}|^2 m_i e^{i\alpha_i} \right|$$

with $U_{ei}$ neutrino mixing matrix, $m_i$ neutrino mass eigenstate, $\alpha_i$ CP-violating Majorana phases

**Observable:** $0\nu\beta\beta$ decay rate at $Q_{\beta\beta}$, i.e. half-life $T_{1/2}$. If not observed, then quoting a lower limit of $T_{1/2}$ (90%C.L).

- **Best limit in the past** obtained by HdM (2001):
  $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr; $\langle m_{ee} \rangle \leq 0.35$ eV

- **KKDC claim** (2004):
  $T_{1/2}^{0\nu} = 1.17 \times 10^{25}$ yr; $\langle m_{ee} \rangle \sim (0.23-0.59)$ eV
0νββ decay formalism

Half-life correlation with effective Majorana neutrino mass

\[
(T_{1/2})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{ee}\rangle^2
\]

with \(G^{0\nu}\): phase space factor, \(M^{0\nu}\): nuclear matrix element, \(\langle m_{\beta\beta}\rangle = \sum_j m_j U^2_{ej}\)

- \(M^{0\nu}\) Calculations:
  - Improvements for NSM and QRPA:
    - Most QRPA discrepancies solved
    - Progress in understanding source of spread of NSM values
  - New methods IBM, EDF, pHFB

- \(Q_{\beta\beta}\) values:
  - Penning-traps (e.g. \(^{130}\)Te: 5% shift)

- Cross sections for neutron reactions:
  (e.g. \(^{207}\)Pb(n,n'\gamma): DEP of 3062 keV \(\simeq Q_{\beta\beta}\) of \(^{76}\)Ge)

Request: Larger number of measurement with different isotopes

- Avoid (not well) known rare background events at \(Q_{\beta\beta}\)
- NME uncertainties \(\leq 30\%\) for neutrino mass spectrum & CP violating phases
- Mechanisms: Light vs. heavy Majorana neutrino exchange, RHC,...
Progresses in experimental techniques

Determination of the half-life

\[ T_{1/2} \propto \begin{cases} 
  a \cdot \epsilon \cdot M \cdot T, & \text{background-free} \\
  a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, & \text{if background is present}
\end{cases} \]

with \( a \): Abun./Enrich.; \( M \): Mass; \( \epsilon \): act.volume; \( \Delta E \): e-res.; \( T \): life-time; \( B \): bkgd

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( Q_{\beta\beta} ) [keV]</th>
<th>nat. Abun. [%]</th>
<th>Experiment ((\text{oper./funded}))</th>
<th>FWHM/E @ ( Q_{\beta\beta} ) [%]</th>
<th>Mass [kg]</th>
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<tr>
<td>( ^{48} \text{Ca} )</td>
<td>4273.7</td>
<td>0.19</td>
<td>Candles</td>
<td>0.35</td>
<td></td>
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<td>( ^{76} \text{Ge} )</td>
<td>2039.1</td>
<td>7.8</td>
<td>GERDA</td>
<td>0.1-0.2</td>
<td>15→35</td>
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<tr>
<td>( ^{82} \text{Se} )</td>
<td>2995.5</td>
<td>9.2</td>
<td>Majorana Dem.</td>
<td>0.1-0.2</td>
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<tr>
<td>( ^{100} \text{Mo} )</td>
<td>3035.0</td>
<td>9.6</td>
<td>SuperNEMO</td>
<td>7→100</td>
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<tr>
<td>( ^{116} \text{Cd} )</td>
<td>2809.1</td>
<td>7.6</td>
<td>Lucifer</td>
<td>–</td>
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<tr>
<td>( ^{130} \text{Te} )</td>
<td>2530.3</td>
<td>34.5</td>
<td>MOON</td>
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<td>( ^{136} \text{Xe} )</td>
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<td>8.9</td>
<td>AMoRe</td>
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<tr>
<td>( ^{150} \text{Nd} )</td>
<td>3367.3</td>
<td>5.6</td>
<td>Cobra</td>
<td>64</td>
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</tbody>
</table>

Request: Larger number of measurement with different isotopes

→ Avoid natural radioactivity: stay above \( ^{208} \text{Th} \) and \( ^{214} \text{Bi} \) lines
→ Advantages of single isotopes: better \( \Delta E \), scalability/enrichment of isotope mass
→ Measurements: independent techniques with \( \leq 30\% \) precision
Isotopes and experimental techniques for $0\nu\beta\beta$ decay search

Selected best isotope candidates: 8 out of 35 (← nat. abundance, $Q_{\beta\beta}$, $G^{0\nu} \propto (Z, Q_{\beta\beta}^5$, chem. properties)

Techniques and their advantages:

- **Source=Detector**: large isotopic masses possible and scalable (10-100 kg now, 1 ton near future)
- **Source≠Detector**: tracking particle momenta → topology of events and mechanisms
- **Liquid scintillator detectors**: multi-functional, largest target masses, purification strategies
- **Solid state detectors** achieve the best energy resolution: FWHW/E at $Q_{\beta\beta} = 0.15\%$
The CUORE experiment

Location: LNGS, Assergi, Italy

Detectors, cryostat, and shield

- TeO$_2$ crystals cooled down to $\sim$10 mK with He within a multi-layer copper cryostat
- Isotopic nat. abundance of $^{130}$Te: 34.1% (no enrichment!)
- Energy resolution: 0.2% in ROI!
- Inner Roman lead layer and outer lead layer
- Ra barrier and neutron shield
- 1400 m overburden, corresponding 3500 m w.e.

Concept: DBD Source = Absorber

Bolometric technique

- TeO$_2$ absorbs energy deposition $E$ by particle
- Energy deposition $E$ registered by a thermistor (NTD Ge) as temperature increase:
  Signal: $\Delta T = E/C$, C: capacity
  Time constant $= C/G$; G: thermal coupling
  Need: $\rightarrow$ low-heat C $\rightarrow$ mK $+$ diele.diamagn.mat.
- Very good energy resolution achievable:
  $\sim$5 keV @ $Q_{\beta\beta}$ (2527 keV), corr. FWHM/E = 0.2%

W. Maneschg (MPI-K)

$0\nu\beta\beta$ decay search in 2013

April 11, 2013
Installation of Cuore-0
(spring/summer 2012)

- **Cuoricino** (2003—2008):
  - 12 kg 130Te
  - Main purpose: identify and disentangle backgrounds (cryostat, copper/crystal surfaces)

- **Cuore-0** (2012—2014):
  - Installation in cryostat completed, but cooling-down problems since May 2012
  - August 2012 first calibration, recently real data-acquisition started
  - With BI=0.05 cts/(keV·kg·yr), 2 yr run (90%C.L.):
    \[ T_{1/2}^{0\nu} > 5.9 \times 10^{24} \text{ yr}, \quad \langle m_{\beta\beta} \rangle < 0.17 - 0.39 \text{ eV} \]

- **Cuore** (2014—2019):
  - Crystals arrived at LNGS; first two towers should be glued in May 2013
  - Radiopurity of all crystals measured; extrapolation to BI for Cuore:
    \[ \text{from bulk: } 1.1 \times 10^{-4} \text{ cts/(keV·kg·yr)} \]
    \[ \text{from surface: } 4.2 \times 10^{-3} \text{ cts/(keV·kg·yr)} \]
  - With BI=0.01 cts/(keV·kg·yr), 5 yr run:
    \[ T_{1/2}^{0\nu} > 1.6 \times 10^{25} \text{ yr}, \quad \langle m_{\beta\beta} \rangle < 0.04 - 0.09 \text{ eV} \]
Concept: DBD source = Detector

Location: LNGS, Assergi, Italy

**Setup and background shielding:**

- **1.4 km overburden**, corresponding 3500 m w.e.
  - Reduction of cosmic-muon flux by six orders of magnitude down to \( \sim 1 \mu/(m^2 \cdot h) \) (PB)

- **Water tank and plastic scintillator**
  - R=5 m, h=9.0 m, 590 m\(^3\) ultra-pure water
  - water acts as neutron moderator/absorber (PB)
  - both components act as muon Cherenkov veto (AB)

- **Large volume cryostat:**
  - R=2 m, h=5.9 m, 64 m\(^3\) LAr
  - LAr acts as cooling medium for diodes
  - LAr attenuates external radiation (PB)
  - LAr scintillation light planned to be used as background rejection (AB)

- **GERmanium Detector Array:**
  - 1-string and 3-string arms with each 3 detectors (Phase I)
  - One 7-string arm (design for Phase II)
  - Accessible via a clean room (class 10000) (PB)
  - Operating bare diodes in LAr using low-mass holders (PB)
  - \( 0\nu\beta\beta \) source = Detector, enriched in \(^{76}\text{Ge}\)
  - coincidence mode and pulse shape tracing (AB)

PB = passive background rejection
AB = active background rejection
GERDA Phase I (November 2011 - summer 2013)

Data acquisition and handling, and detector performance:

- **Technology**: Refurbished co-axial HPGe detectors, 6 $^{76}$Ge enriched (HdM, IGEX) for $\sim 15$ kg, 3 natural (GTF)
- **Since July 2012**: added 5 enriched Phase II BEGe prototype detectors for $\sim 3.5$ kg
- **Energy resolution** of co-axial diodes: stable at 4.5-5.1 keV (FWHM) for 2614.5 keV
- **Background index (BI)** for co-axial diodes: $\sim 0.02$ cts/(keV·kg·yr)
  * BI := $Q_{\beta\beta}$=2039 keV of $^{76}$Ge ± 100 keV (minus 40 keV blinded region)
- **Collected statistics**: $\sim 19$ kg·yr (March 2013) (lifetime $\sim 90\%$)
- **Data blinding of $Q_{\beta\beta}$ region**: automatic blinding of $Q_{\beta\beta}$ region applied since January 11, 2012; → **Unblinding** planned for summer 2013!

String with co-axial HPGe diodes

String with BEGe diodes

BlI of Phase I co-axial detector

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Results from GERDA Phase I

Measurement of $2\nu\beta\beta$ half-life of $^{76}\text{Ge}$

- **Fit region**: (600-1800) keV; May 2011-Nov 2012; only enriched detectors
- **Fit method**: binned maximum likelihood method with free parameters: $^{40}\text{K}$, $^{42}\text{K}$, $^{214}\text{Bi}$, $T^{2\nu}_{1/2}$, active mass, enrichment
- **Background** is 'low': S/B~8/1!
- **High $^{42}\text{Ar}$ background**, however, due to ion collection through E-field of diodes from applied HV.

**Results for $T^{2\nu}_{1/2} \times 10^{21}$ yr**

- **Preliminary GERDA result**: $1.84^{+0.14}_{-0.10}$ (sys+stat)
- **Comparison** to previous measurements: superior signal-to-background ratio, trend towards higher $T^{2\nu}_{1/2}$, but in good agreement with the most recent results based on HDM data
Upgrade to GERDA Phase II (planned start within 2013)

Assembly of new detectors:

- **Novel technology**: 25 $^{76}$Ge enriched BEGe detectors for $\sim 17$ kg:
  - Better sensitivity due to: increased target mass, better energy resolution, and enhanced pulse shape discrimination of Multi-Site background Events (0νββ events are Single-Site Events)

Scintillation light instrumentation:

- **Technique**: Background rejection of external background events via detection of scintillation light in liquid argon ($\lambda = 128$ nm)
- **Options for read-out**: PMT, Wavelength-shifter glass-fibre, large area avalanche photodiodes or UV sensitive SiPMs
- **Envisioned BI (BEGe + Light instr)**: $\leq 0.001$ cts/(keV·kg·yr)
The Majorana Demonstrator

**Concept:** DBD source = Detector

Location: Sanford UG lab, Lead, SD, USA (1.480 m Overburden)

Detector setup and performance:

- **P-Type point contact Ge detectors** (also low noise, e-threshold below 1 keV → suitable for low-mass WIMP detection)
- 40 kg (out of them 30 kg enriched in $^{76}$Ge) germanium diodes in a large volume vacuum crystal within ultra-low background shield made of ultrapure electro-formed copper and lead.
- Full commissioning in 2013: after 1 year: $T_{1/2} > 4 \times 10^{25}$ yr, address KKDC $0\nu\beta\beta$ observation claim

GERDA-Majorana cooperation:

- Open exchange of knowledge and technologies
- Joint constant development of the Geant4-based simulation tool MaGe
- Common intention for 1-ton experiment; goal sensitivity: $\langle m_{\beta\beta} \rangle$: 0.04-0.12 meV (IH region)
The COBRA R&D project

**Concept:** DBD source = Detector

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**Location:** LNGS, Assergi, Italy

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**Solid state TPC**

- Large Array of CdZnTe semicond. detectors for 420 kg
  Goal sensitivity: $T_{1/2} > 10^{26}$ yr ($\langle m_{\beta\beta} \rangle$ $50$ meV)
- Containing: 5 $0\nu\beta\beta^-$, and 4 EC/$\beta^+$, EC/EC candidates
  Best candidate: $^{116}$Cd: $Q_{\beta\beta} = 2809$ keV; → enrichment
- Two modular designs (both oper. at room temp):
  - CoPlanar Grid Detectors (CPG): little 'location' info (with PSA), $\Delta E < 2\%$, and simple read-out
  - Pixelated Detectors (PD): 3D 'location', Particle ID if pixels small ($\sim 100 \: \mu m$), $\Delta E < 1\%$, but complex read-out

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**Status:**

- MC/test for shield options: multi-layer, liq. scint., water
- **Technical design report:** expected within 2013
- $2\nu\beta\beta$: 6 $T_{1/2}$ limits $> 10^{20}$ yr, 7 new upper limits
- $0\nu\beta\beta$: achieved background for:
  Colorless passivated CPG at $^{116}$Cd ROI: 5 cts/(keV$\cdot$kg$\cdot$yr)
  Large Volume PD in 2700-3000 keV: 0.9 cts/(keV$\cdot$kg$\cdot$yr)

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W. Maneschg (MPI-K)  0$\nu\beta\beta$ decay search in 2013  April 11, 2013  14 / 23
The EXO-200 experiment

**Concept:** DBD source = Detector

**Detector design and background reduction**
- LXe Vessel in ultra-radiopure copper cryostat filled with high-purity heat transfer fluid HFE7000
- Lead shield
- 4 plastic scintillators as active muon vetos
- 700 m overburden, corresponding 1600 m w.e.

**Location:** WIPP lab, Carlsbad, NM, USA

**Detection principle**
- **Medium:** 175 kg of LXe; $^{136}$Xe enrichment: 80.6%
- **Detection principle:**
  - Collection charge wires measure ionized electrons
  - Large Area Avalanche Photodiodes (APDs) measure 178 nm scintillation light
- **Gain information from:**
  - Drifttime:
    → Position reconstruction res.: X,Y: 18 mm; Z: 6 mm
    → Distinguish single $\beta/\beta\beta$'s from multiple $\gamma$-ray clusters:
  - Ionisation vs. Scintillation:
    → Discrimination of $\alpha$ from $\beta/\beta\beta/\gamma$
    → Improve energy resolution down to 1.67%
Measurement of $2\nu\beta\beta$ half-life of $^{136}\text{Xe}$

- Rejection of peripheral background by Fiducial Volume cut:
  - Active mass of 98.5 kg of LXe ($^{136}\text{Xe}$: 79.4 kg)
  - LXe exposure after 120.7 d: 32.5 kg·yr

- SSE $2\nu\beta\beta$ spectrum:
  - Spectrum contains $\sim$22000 $2\nu\beta\beta$ events above 0.7 MeV
  - S/B ratio of $\sim10/1$!
  - SSE spectrum: 82.5% of $2\nu\beta\beta$ events (Fraction calculated via MC)

Results for $T_{2\nu}^{1/2} \times 10^{21}$ yr

- **EXO-200** (May 2012): $2.23 \pm 0.02 \pm 0.22$ (stat+sys) arXiv:1205.5608
- **Agrees** with **KamLAND-Zen** (May 2012): $2.30 \pm 0.02 \pm 0.12$ (stat+sys) arXiv:1205.6372
Limit for $0\nu\beta\beta$ half-life of $^{136}$Xe

0$\nu\beta\beta$ results after 120 d with 98.5 kg of LXe (May 2012):

- Observed background: 1(5) events within 1(2)$\sigma$ around $0\nu\beta\beta$ ROI
  $\rightarrow$ BI=$0.0015$ cts/(keV·kg·yr) $\rightarrow$ within specs!

- $T_{1/2}^{0\nu} > 1.6 \times 10^{25}$ yr, $\langle m_{\beta\beta} \rangle < 0.14-0.38$ eV (90% C.L.)
The KamLAND-Zen experiment

KamLAND-Zen is *embedded* within KamLAND using Xe-loaded LS

Location: Kamioka, Japan

**Overburden, 3.2 kt water tank, SSS**
- 1000 m overburden, corresponding 2700 m.w.e.
- Water tank: neutron moderator and muon Cherenkov detector
- SSS: 1879 PMTs detecting scintillation light

**1000 t KamLand LS (R=6.5 m)**
- Dodecane 80%, PC 20%, PPO 1.36 g/l
- **Active shield**: ext. $\gamma$s, int. $\gamma$s from IB/Xe-loaded LS

**Inner balloon (R=1.54 m, 25 $\mu$m thick)**
- 13 t of Xe-loaded LS:
  - Decane 82.3%, PC 17.7%, PPO 2.7 g/l
  - Xe $\sim$3 wt% (320 kg)
- $^{136}$Xe enrichment: 90.9%

**Advantages of using a) Xe-loaded LS b) in KamLAND**
- Xe: soluble in LS (Raghavan R., PRL72 1411 (1994))
- Xe: high isotopic enrichment, extraction and purification
- Use existing ultra-pure detector; low-energy anti-neutrino measurements can be continued
Measurement of $2\nu\beta\beta$ half-life of $^{136}\text{Xe}$

- **Fit region**: [0.5;4.8] MeV; includes 82% of the $2\nu\beta\beta$ spectrum
- **Data-sets and $2\nu\beta\beta$ rate** (February 2013: arXiv:1211.3863v2[hep-ex]):
  - DS-1: October 12, 2011 - filtration: $82.9 \pm 1.1\text{ (stat)} \pm 3.4\text{ (syst)}$ cts/(d·ton)
  - DS-2: filtration - June 14, 2012: $80.2 \pm 1.8\text{ (stat)} \pm 3.3\text{ (syst)}$ cts/(d·ton)
- **Exposure for $^{136}\text{Xe}$ alone (both data-sets together)**: $89.5 \text{ kg} \cdot \text{yr}$

KamLAND-Zen $2\nu\beta\beta$ half-life result (May 2012):

- $2\nu\beta\beta$ rate = $(80.9 \pm 0.7)$ cts/(d·ton)
- $T_{1/2}^{2\nu} = 2.30 \pm 0.02 \pm 0.12$ (stat+syst) $\times 10^{21}$ yr (arXiv:1205.6372)
Limit for $0\nu\beta\beta$ half-life of $^{136}$Xe

**Unexpected peak at 2.6 MeV**
- Rate stable in time, $\rightarrow$ non-shortlived radioisotopes
- Non-compatible with $Q_{\beta\beta}$ of $^{136}$Xe
- Check 'all' nuclei ($\mathcal{O}(10^3)$) and decay paths ($\mathcal{O}(10^6)$)
  $\rightarrow$ Remaining candidates: $^{110m}$Ar, $^{208}$Bi, $^{88}$Y, $^{60}$Co

**$T^{0\nu}_{1/2}$ result (February 2013)**

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

(EXO-200 result from 2012 ($\langle m_{\beta\beta} \rangle < 0.14$-$0.38$ eV (90% C.L.)) slightly improved)

- **Purification** ongoing: in late 2012 Xe removed from scintillator, LS being distilled, IB replacement
  $\rightarrow$ Expected lower background $^{110m}$Ar ($^{208}$Bi, $^{88}$Y) background by $100 \times$
- 600 kg Xe already in the Kamioka mine, $\rightarrow$ first $\beta\beta$ 1-ton experiment?
Combined results from the 136Xe experiments

- **Combination of the recent negative results** from KamLAND-Zen and EXO-200 (arXiv:1211.3863v2 [hep-ex]): $T_{1/2}^{0\nu} > 3.4 \times 10^{25}$ yr, $\langle m_{\beta\beta} \rangle < 0.12-0.25$ eV at 90%C.L.
  
  → refutes the $0\nu\beta\beta$ detection claim in $^{76}$Ge at >97.5% C.L. (for all NME, assuming light Majorana exchange mechanism)

- **Some remarks** about this result:
  - From QRPA calc.: $T_{1/2}(^{136}\text{Xe}) \sim 3.4-4.3 \times 10^{25}$ y needed for 90% C.L. to rule out $^{76}$Ge claim; however, some issues concerning the likelihood/$\chi^2$ functions non-available from experiments (A. Faessler et al., arXiv:1301.1587v1 [hep-ph])
  - Some issues concerning the 1.(4\sigma) and 2.(6\sigma) $^{76}$Ge KKDC claim (B. Schwingenheuer, arXiv:1210.7432 [hep-ex])

  → '...not yet the end of the story'
**SNO+**: a multipurpose experiment

**SNO+ 'recycles' upgraded SNO infrastructure**

filled with **Te-loaded LS**

**Location**: Sudbury, Ontario, Canada

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**Detector setup**

- 2000 m overburden, corresponding 6000 m w.e.
- Outer stainless steel frame \((D=17.8 \text{ m})\), carrying 9500 PMTs and acrylic vessel AV \((907 \text{ m}^3)\)
- Between PMTs and AV: 3 m thick ultrapure light water
- Upgrade of trigger/DAQ due to 45× more light
- **Scintillator**: 780 ton of acrylic-compatible linear alkylbenzene (LAB), hold down with ropes (buoyancy) installed in January 2013. Water filling (before scin. filling) starting in 9 days!

**Phase I**:
- Original idea with \(^{150}\text{Nd}\) rejected, March 2013 decision to pursue \(^{130}\text{Te}\) as prim. target isotope
- \(\sim0.3\%\) of nat. \text{Te} \((\% \text{^{130}Te }\text{800 kg})\) \(\rightarrow \langle m_{\text{eff}} \rangle=50 \text{ meV} \) (after \(\sim3 \text{ yr}\))

**Phase II**: \(\sim3\%\) of nat. \text{Te} \(\rightarrow \langle m_{\text{eff}} \rangle=15 \text{ meV} \) (full IH)
Current Status

- In 2012/2013, after a decade of R&D, we will have first results from several new generation $0\nu\beta\beta$ experiments: EXO-200, KamLAND-Zen, GERDA. Their sensitivities will be similar/better than the best former experiment: HdM.
- In the next years, other experiments using different techniques and $\beta\beta$ isotopes will become operational.
- A lot of progress in calculating the $0\nu\beta\beta$ nuclear processes were achieved.

Outlook: Possible scenarios

- If range $\langle m_{\beta\beta} \rangle = 0.1-0.5$ eV holds (if KK claim confirmed):
  - EXO-200, KamLAND-Zen ($^{136}$Xe) and GERDA ($^{76}$Ge) should observe the signal.
  - Other experiments that will be finalized in the next years will observed the $0\nu\beta\beta$ decay in other isotopes (SNO+, Phasel and Cuore in $^{130}$Te,...).
  - Precision-experiments (SuperNEMO-type) have to follow (to improve NME and understand exchange mechanisms $\rightarrow$ SuperNEMO-type detectors).

- If range $\langle m_{\beta\beta} \rangle = 0.02-0.05$ eV holds:
  - Necessity for large scale enrichment and lower background reduction.
  - Possible experiments: nEXO, Gerda Phase III and Majorana, Cuore marginally, KamLand-Zen(2),...
  - Discovery in 3-4 isotopes necessary to confirm the observation and to improve the calculations of nuclear processes.

2013+ will be exciting years for Lepton Number violating $\beta\beta$ decay search!