For CUORE and CUPID, I referred
Stefano Pirro and Andrea Giuliani’s presentation at NDM2018
CUORE collaboration, EPJC 77, 543 (2017)
Observation of $0\nu\beta\beta$

- **will confirm**
  - Neutrinos are Majorana particles and have Majorana masses.
  - Lepton number non-conservation.
- **will support on**
  - See-Saw model of the neutrino mass.
  - Leptogenesis to account for the baryon asymmetry of the universe.

$$m_\nu \approx \frac{m_D^2}{m_N}$$
Neutrino mass from $0\nu\beta\beta$ experiment

- Half-lives of $0\nu\beta\beta$ inversely proportional to (effective neutrino mass)$^2$ by theory.
- To discover a sharp peak @ Q-value, we need a good energy resolution and extremely low background at that energy.

\[
\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \left( \frac{m_{\beta\beta}}{m_e} \right)^2
\]

for light neutrino exchange model.
Current best results for $0\nu\beta\beta$

<table>
<thead>
<tr>
<th>Nucl.</th>
<th>$Q$ (keV)</th>
<th>Abun. (%)</th>
<th>$T_{1/2}^{2\nu}$ ($10^{20}$ Y)</th>
<th>Exp</th>
<th>$T_{1/2}$ ($10^{24}$ Y)</th>
<th>$M$ (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>4270.0</td>
<td>0.187</td>
<td>0.44</td>
<td>CANDLES</td>
<td>&gt; 0.058</td>
<td>&lt;3.1-15.4</td>
<td>PRC 78 058501 (2008)</td>
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<tr>
<td>$^{76}$Ge</td>
<td>2039.1</td>
<td>7.8</td>
<td>15</td>
<td>GERDA-II</td>
<td>&gt;53</td>
<td>&lt;0.15-0.33</td>
<td>Nature 544, 47 (2017)</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2997.9</td>
<td>9.2</td>
<td>0.92</td>
<td>CUPID-0</td>
<td>&gt; 2.4</td>
<td>&lt;0.38-0.77</td>
<td>PRL120, 232502 (2018)</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3034.4</td>
<td>9.6</td>
<td>0.07</td>
<td>NEMO-3</td>
<td>&gt;1.1</td>
<td>&lt;0.33-0.62</td>
<td>PRD 89, 111101 (2014)</td>
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<tr>
<td>$^{116}$Cd</td>
<td>2813.4</td>
<td>7.6</td>
<td>0.29</td>
<td>AURORA</td>
<td>&gt; 0.19</td>
<td>&lt;1-1.8</td>
<td>nulc-ex/1601.05578.</td>
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<tr>
<td>$^{130}$Te</td>
<td>2527.5</td>
<td>34.5</td>
<td>9.1</td>
<td>CUORE</td>
<td>&gt; 15</td>
<td>&lt;0.11-0.52</td>
<td>PRL120, 132501 (2018)</td>
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<tr>
<td>$^{136}$Xe</td>
<td>2458.0</td>
<td>8.9</td>
<td>21</td>
<td>KamLAND-Zen</td>
<td>&gt; 107</td>
<td>&lt;0.06-0.16</td>
<td>PRL117, 082503 (2016)</td>
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<tr>
<td>$^{150}$Nd</td>
<td>3371.4</td>
<td>5.6</td>
<td>0.08</td>
<td>NEMO-3</td>
<td>&gt; 0.02</td>
<td>&lt;1.6-5.3</td>
<td>PRD 94 072003 (2016)</td>
</tr>
</tbody>
</table>

Cryogenic experiments
Backgrounds are most critical!

- If “zero” backgrounds in ROI (Region of Interests), the half-life limits are proportional to the detector mass and DAQ time. If finite backgrounds, \( \sqrt{MT} \).

\[
T_{1/2}^{0\nu} \propto MT \quad \text{(for zero backgrounds)} \\
T_{1/2}^{0\nu} \propto \sqrt{\frac{MT}{b\Delta E}} \quad \text{(for finite backgrounds)}
\]

**Background Unit**: \( \text{ckky} : \text{counts/ (keV kg year)} \)

**ROI (Region of Interests)**

![Graph showing the relationship between Mass*Time and Half-life](image)
Identify critical radioactivity

- Go through all known nuclei decaying $\beta$ with $Q > 3.02\text{MeV}$ in NNDC database.
- $^{110m}\text{Ag}(3010.5\text{ keV})$ doesn’t contribute for Mo experiment.
- Cosmogenic excitation is negligible after 1 year at underground.
- Only Thorium and Uranium natural radioactivity are critical for $Q > 3.02\text{MeV}$. Great advantage to run high $Q$-value nuclei!

<table>
<thead>
<tr>
<th>El</th>
<th>Decay</th>
<th>$T_{1/2}$</th>
<th>$Q$  MeV</th>
<th>Mother</th>
<th>Chain</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{26}\text{Al}$</td>
<td>EC</td>
<td>$7.4\times10^5\text{y}$</td>
<td>4.004</td>
<td>N/A</td>
<td>N/A</td>
<td>Long lifetime</td>
</tr>
<tr>
<td>$^{56}\text{Co}$</td>
<td>EC</td>
<td>0.21y</td>
<td>4.567</td>
<td>N/A</td>
<td>N/A</td>
<td>Short lifetime</td>
</tr>
<tr>
<td>$^{88}\text{Y}$</td>
<td>EC</td>
<td>0.29y</td>
<td>3.623</td>
<td>$^{88}\text{Zr}$ (0.23 y)</td>
<td>$^{106}\text{Ru}$ (1.02y)</td>
<td>Short lifetime</td>
</tr>
<tr>
<td>$^{106}\text{Rh}$</td>
<td>B-</td>
<td>30s</td>
<td>4.004</td>
<td>$^{126}\text{Sn}$ (2.3x10$^5$y)</td>
<td>$^{146}\text{Gd}$ (0.13 y)</td>
<td>Long lifetime</td>
</tr>
<tr>
<td>$^{126}\text{Sb}$</td>
<td>B-</td>
<td>12.5d</td>
<td>3.670</td>
<td>$^{128}\text{Sn}$ (2.3x10$^5$y)</td>
<td>$^{146}\text{Gd}$ (0.13 y)</td>
<td>Short lifetime</td>
</tr>
<tr>
<td>$^{146}\text{Eu}$</td>
<td>EC</td>
<td>4.61d</td>
<td>3.878</td>
<td>$^{228}\text{Th}$ (1.91 y)</td>
<td>$^{228}\text{Th}$ (1.91 y)</td>
<td>Th232</td>
</tr>
<tr>
<td>$^{208}\text{Tl}$</td>
<td>B-</td>
<td>3.05m</td>
<td>4.999</td>
<td>$^{228}\text{Th}$ (1.91 y)</td>
<td>$^{228}\text{Th}$ (1.91 y)</td>
<td>Main</td>
</tr>
<tr>
<td>$^{209}\text{Tl}$</td>
<td>B-</td>
<td>2.16m</td>
<td>3.970</td>
<td>$^{233}\text{U}$ (159200y)</td>
<td>$^{233}\text{U}$ (159200y)</td>
<td>U233</td>
</tr>
<tr>
<td>$^{210}\text{Tl}$</td>
<td>B-</td>
<td>1.3m</td>
<td>5.482</td>
<td>$^{226}\text{Ra}$ (1600y)</td>
<td>$^{226}\text{Ra}$ (1600y)</td>
<td>U238</td>
</tr>
<tr>
<td>$^{214}\text{Bi}$</td>
<td>B-</td>
<td>19.9m</td>
<td>3.269</td>
<td>$^{226}\text{Ra}$ (1600y)</td>
<td>$^{226}\text{Ra}$ (1600y)</td>
<td>U238</td>
</tr>
</tbody>
</table>

+ high energy gammas from (n,g) and muon induced high energy gammas
Principle of low temp detector

Bolometric approach: the source is embedded in a crystal, which is cooled down to 10-20 mK and works as a perfect calorimeter.

Advantages:
- High energy resolution (~5 keV FWHM)
- High efficiency (~70 – 90 %)
- Large flexibility in the isotope choice: $^{130}$Te, $^{82}$Se, $^{100}$Mo, $^{116}$Cd
Alpha background rejection

Scintillating Bolometric approach: Both heat and scintillation are measured and alphas are separated.

Thermometer

Scintillation sensor

Scintillating Crystal Absorber
CUORE (Cryogenic Underground Observatory for Rare Events)

- Search for $0\nu\beta\beta$ of $^{130}$Te and other rare events
- 988 TeO$_2$ crystals run as a bolometer array
  - 19 Towers, 13 floors
  - 4 modules per container
  - 741 kg total mass; 206 kg $^{130}$Te
  - $10^{27}$ $^{130}$Te nuclei
- 10 mK base temperature in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy
Setup

NTD
Absorber
Weak Thermal coupling
CUORE Backgrounds

- Significant reduction in the gamma region with respect to CUORE-0 (earlier version)
- $^{210}$Po excess appears to be from shallow contamination in copper around the detectors.
Background Index of CUORE

For CUORE, by far the most dominant backgrounds are

1. CuNOSV copper holder \(\sim 10^{-2}\)  
2. TeO2 crystal \(\sim 10^{-3}\)  
3. SI & Rods & Muons \(\sim 10^{-4}\)

\[\text{Surface} > \text{Bulk}\]
CUPID

**CUORE Upgrade with Particle IDentification**


It is clear from CUORE that we need alpha background rejection.
CUPID-0 represent the first enriched bolometer $\beta\beta$-experiment that is demonstrating the background rejection achievable for hybrid $\beta\beta$ scintillating bolometers.
**ββ-0ν Results**

**Background Level:** $3.6 \times 10^{-3}$ ckky

$$T_{1/2}^{82\text{Se}} \rightarrow ^{82}\text{Kr} > 2.4 \times 10^{24} \text{y} (90\% \text{C.I.}) \Rightarrow 4.0 \times 10^{24} \text{y} (2018)$$

This results overcomes by 1 order of magnitude the results of Nemo recently republished (https://arxiv.org/abs/1806.05553)
**CUPID-Mo (LUMINEU)**

**EDELWEISS-III cryogenic facility at LSM (France)**

**Laboratoire Souterrain de Modane**
- 1.7 km rock overburden (~4.8 km w.e.)
- 5 μ/day/m²; 10⁻⁶ n/day/cm² (>1 MeV)
- Deradonized air flow (~30 mBq/m³)

**EDELWEISS set-up**
- Clean room (ISO Class 4)
- \(^3\)He/\(^4\)He inverted wet cryostat
- Passive shield
  - Modern lead (18 cm)
  - Roman lead (2 cm; 14 cm at 1 K plate)
  - Polyethylene (external ~ 50+5 cm and 10 cm at 1 K plate)
- Background monitors
  - Muon veto (98.5% covering)
  - Neutron counter
  - Radon counter
- Electronics, DAQ (Samba)
  - Low noise cold electronics
  - AC bias, modulation (100 kHz) → demodulation (up to 1 kHz)
  - 16-bit or 14-bit ADC
  - Trigger and/or Stream data

Tests of Li$_2^{100}$MoO$_4$ scintillating bolometers

- LUMINEU 12/04/2017, 17.0 mK
- CUPID-Mo 10-12/2017, 21-19.3 mK

- LMO1b, Ge LD 204 g
- LMO2b, Ge LD 207 g
- LMO2t, Ge LD 213 g
- enrLMO-2, T1 186 g

+ enrLMO-2 was tested at LNGS 05/2016, 12 mK
+ a tower T2 with enrLMO-1

ZMO nat-2, FID211, enrLMO-1, enrLMO-3, enrLMO-4, enrLMO-2, enrLMO-15
Background index in the CUPID-Mo precursor $\rightarrow b = 0.06(3) \text{ cky}$

This value is due to $^{232}\text{Th}$-contaminated connectors close to the detectors.

Full estimation of the background is in progress

Reasonable expectation: $b \sim 10^{-2} - 10^{-3} \text{ cky}$
CUPID-Mo Phase I (20 crystals):

- 20 $^{100}$Mo-enriched (97%) Li$_2$MoO$_4$
  
  ($\varnothing$ 44x45 mm, 0.21 kg each; 4.18 kg total)
  
  $\Rightarrow$ 2.5 kg of 100Mo

- 20 Ge light detectors ($\varnothing$ 44x0.175 mm)+SiO
- **EDELWEISS** set-up @ LSM (France)

**START DATA TAKING:** in the next weeks

CUPID-Mo Phase II (20+26 crystals):

- Additional 26 cubic Li$_2$100MoO$_4$
  
  (45x45x45 mm, 0.28 g each)
  
  $\Rightarrow$ 5 kg of 100Mo

- **CUPID-0** set-up @ LNGS (Italy)

**PLANNED START DATA TAKING:** June 2019
CUPID-Mo Modane (Phase I)

Evolution of the Majorana mass sensitivity

Current results
- CUPID-0
- NEMO-3
- CUORE
- \(^{82}\text{Se}\)
- \(^{100}\text{Mo}\)
- \(^{130}\text{Te}\)
- \(^{76}\text{Ge}\)
- \(^{136}\text{Xe}_{39}\)

Graph showing the evolution of sensitivity over live time.
Overview of AMoRE Project

Detector schematics of AMoRE

- Use Mo containing Scintillating Bolometer: \((^{40}\text{Ca},X)^{100}\text{MoO}_4 + \text{MMC}\)
- For Each crystal, phonon and photon sensors made of MMCs, SQUIDs to separate alphas (background) and betas. -- Fully covered by Yong-Hamb’s presentation.
Plan of AMoRE Project

- 100 kg $^{100}$Mo double beta decay experiment, largest experiment $Q > 2614$ keV
- One of two $^{100}$Mo DBD projects.

<table>
<thead>
<tr>
<th></th>
<th>AMoRE Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Mass (kg)</td>
<td>1.9</td>
<td>6</td>
<td>200</td>
</tr>
<tr>
<td>Background Goal (ckky)</td>
<td>&lt;10$^{-2}$</td>
<td>&lt;10$^{-3}$</td>
<td>&lt;10$^{-4}$</td>
</tr>
<tr>
<td>$T_{1/2}$ (year)</td>
<td>1.0x10$^{24}$</td>
<td>8.2x10$^{24}$</td>
<td>8.2x10$^{26}$</td>
</tr>
<tr>
<td>$m_{bb}$ (meV)</td>
<td>380-719</td>
<td>130-250</td>
<td>13-25</td>
</tr>
</tbody>
</table>

$^{40}$Ca$^{100}$MoO$_4$ ~ 1.9 kg

$^{40}$Ca$^{100}$MoO$_4$ ($^{40}$Ca, X)$^{100}$MoO$_4$ ~ 6 kg

X = Li, Na, Pb…

$^{(40}$Ca, X)$^{100}$MoO$_4$ 200 kg

AMoRE-II
### AMoRE Collaboration

- **Total 105 members from 23 institutes at 8 countries.**

<table>
<thead>
<tr>
<th>Country</th>
<th>Institute</th>
<th>Collaborations</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea</td>
<td>CUP, Institute of Basic Science (CUP)</td>
<td>Simulation, Crystal Tests</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Kyungpook National University (KNU)</td>
<td>Theory</td>
<td>3</td>
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<tr>
<td></td>
<td>Soongsil University (SSU)</td>
<td></td>
<td></td>
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<td></td>
<td>Seoul National University (SNU)</td>
<td>Low Temp., Data Analysis</td>
<td>4</td>
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<td></td>
<td>Ehwa Womans University (EWU)</td>
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<td>Semyung University (SMU)</td>
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<td>KRISS</td>
<td>DR, Cryostat</td>
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<td>Sejong University (SJU)</td>
<td>Data Analysis, Muon</td>
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<td>Chung-Ang University (CAU)</td>
<td>Theory</td>
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<tr>
<td>Russia</td>
<td>JSC FOMOS-Materials (FOMOS)</td>
<td>CMO crystals</td>
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<td>Baksan Neutrino Observatory of INR RAS (BNO)</td>
<td>HPGe, Simulation</td>
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<td></td>
<td>National Research Nuclear University (NRNU)</td>
<td>Backgrounds, Crystals</td>
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<td>Nikolaev Institute of Inorganic Chemistry (NIIC)</td>
<td>Enriched Crystal</td>
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<td>Germany</td>
<td>Physikalisch-Technische Bundesanstalt (PTB)</td>
<td>SQUID</td>
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<td>Kirchhoff-Institute for Physics (KIP)</td>
<td>MMC, Photon Detector</td>
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<td>Ukraine</td>
<td>Institute for Nuclear Research (INR)</td>
<td>Simulation, Background</td>
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<td>China</td>
<td>Tsinghua University (THU)</td>
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<td>Thailand</td>
<td>Nakhon Pathom Rajabhat University (NPRU)</td>
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<tr>
<td>Indonesia</td>
<td>Institut Teknologi Bandung (ITB)</td>
<td>Muon Veto</td>
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<td>University of Mataram (UM)</td>
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<td>Pakistan</td>
<td>Abdul Wali Khan University (AWKUM)</td>
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<tr>
<td></td>
<td>Kohat University of Science and Technology (KUST)</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>
AMoRE-Pilot Setup

- 6 crystals making total mass 1.89 kg.
- Two vibration reduction systems are installed.

12 detector channels
(6 heat detectors + 6 light detectors)
Preliminary results

- Both photon/phonon ratio and rise time used to remove alpha background.
- Internal radioactivity is measured by alphas.

111 kg·day exposure
0.55 cky bkg.
$T^{0\nu} > 1 \times 10^{23} \, y$
Comparison of Data with MC simulation

Simulated spectra from the radioactivity measurements vs data.

Flux (thermal neutron) ~ $2 \times 10^{-5}$ /cm$^2$/sec
Active components & neutron capture dominant
Connectors, glue, and PCB boards were found highly radioactive and are removed for next runs in Pilot setup.

Recent upgrades
Clean PCB (tested)
no connectors

Also installed neutron shielding inside and outside of Pb shielding with Borated PE, PE blocks, and Boric Acids.
Preliminary Results

• Black (Red) : Before (After) replacing high activity materials.
• Currently we are getting data after installing neutron shielding.
Decision on crystals for AMoRE-II

- CMO (CaMoO$_4$) is a very good crystal with the largest light output, but CMO has a disadvantage that we need $^{48}$Ca depleted isotopes, expensive.
- LUMINEU group decided to use LMO (Li$_2$MoO$_4$), and we are working on LMO, PMO (PbMoO$_4$), & NMO (Na$_2$Mo$_2$O$_7$), crystals.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Emission (nm)</th>
<th>LightYield(10K)</th>
<th>Decay time (μs)</th>
<th>density</th>
<th>Mo Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMO(Ukra)</td>
<td>540</td>
<td>100</td>
<td>240</td>
<td>4.34</td>
<td>0.49</td>
</tr>
<tr>
<td>ZMO(NIIC)</td>
<td>614</td>
<td>63</td>
<td>280</td>
<td>4.36</td>
<td>0.536</td>
</tr>
<tr>
<td>LMO(KTI)</td>
<td>535</td>
<td>1</td>
<td>5</td>
<td>3.03</td>
<td>0.562</td>
</tr>
<tr>
<td>PMO(NIIC)</td>
<td>592</td>
<td>11</td>
<td>105</td>
<td>6.95</td>
<td>0.269</td>
</tr>
<tr>
<td>NMO(NIIC)</td>
<td>663</td>
<td>75</td>
<td>9</td>
<td>750</td>
<td>0.558</td>
</tr>
</tbody>
</table>

Publications:
- Pandey et al., Journal of Crystal Growth 480 (2017) 62-66
CUP and NIIC grow enriched molybdate crystals at CUP.

- Crystal group has been successful in growing molybdate crystals. Growing time ~ 1 week.
- The purity of the grown crystals are measured by ICP-MS → Promising results
- We have a campaign to grow an enriched LMO crystal in this summer at NIIC and CUP.

Unpurified Mo and Ca powders

Purified Mo and Li powders

Purified Mo and Na powder

Weight : 255.6 g, Height : 100 mm
After cut and polished
Impurity summary of molybdate crystals

- Low temperature crystal tests are critical and under preparation.
- We have a good progress toward AMoRE-II crystals.
- Enriched LMO crystals will be grown at CUP and NIIC (Russia) in this summer.

_ppb for Ba_
_ppt for U, Th_

Final decision of crystal will depend on background and particle identification power.
IBS is building a new underground lab.

- Will have an independent entrance (human vertical elevator) from mine activity.
- The construction starts this year and completed early of 2020.

Handuk mine, ~ 0.7 million tons iron ore a year

An Active Iron Mine

Mountain
(EL 998m)

Entrance Tunnel
(730m long)

IBS Elevator
600m long

Entrance of Rampway

Large (>2000m²), deeper (1100m depth)
## Comparison of cryogenic experiments

<table>
<thead>
<tr>
<th>Exp</th>
<th>Q (keV)</th>
<th>$\Delta E$ (keV)</th>
<th>Background ROI (ckky)</th>
<th>Comment (Mass of isotope)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE ($^{130}$Te)</td>
<td>2527.5</td>
<td>~5</td>
<td>0.01</td>
<td>Copper holder surface</td>
</tr>
<tr>
<td>CUPID-0 ($^{82}$Se)</td>
<td>2997.9</td>
<td>~23</td>
<td>0.0032</td>
<td>muons, neutron capture(?)</td>
</tr>
<tr>
<td>CUPID-Mo ($^{100}$Mo)</td>
<td>3034.4</td>
<td>~6</td>
<td>0.06</td>
<td>Active components</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5kg (2019)</td>
</tr>
<tr>
<td>AMoRE ($^{100}$Mo)</td>
<td>3034.4</td>
<td>~15</td>
<td>~0.5</td>
<td>Neutron capture, improving</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35 kg (2021) 100kg(2023)</td>
</tr>
</tbody>
</table>
Summary

- Cryogenic double beta decay experiments demonstrates the competence.
- Backgrounds can be reduced to confirm “zero background” reaching down to 10 meV scale.
- CUPIDs experiments are in progress towards next phases.
- AMoRE-Pilot & AMoRE-I is making progress in detector performance and reducing backgrounds.
- AMoRE-II will begin in 2021 at a new underground laboratory.