Experiments for double beta decay and dark matter

- Historically close connection both from the strictly scientific and technical point of view:
  - Neutrinoless DBD $\Rightarrow$ lepton number conservation $\Rightarrow$ $<m_\nu>$ and $m_\nu$ as possible component of DM
  - Many experimental common problems (operation underground, reduction of the background, choice of detectors, hybrid techniques)
  - Searches for WIMPs. started as a sub-product of DBD (Drukier, Avignone) Even now Synergy with $\beta\beta$ experiments
Evidence for DM in a *spiral galaxy, superclusters* etc.
WMAP!

(now three years of measurements)
<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Density</td>
<td>$\Omega_{\text{tot}}$</td>
<td>1.02±.02</td>
</tr>
<tr>
<td>Dark energy Density</td>
<td>$\Omega_{\Lambda}$</td>
<td>.73±.04</td>
</tr>
<tr>
<td>Baryon Density</td>
<td>$\Omega_{\text{bar}} \cdot h^2$</td>
<td>.0224±.0009</td>
</tr>
<tr>
<td>Baryon Density</td>
<td>$\Omega_{\text{bar}}$</td>
<td>.044±.004</td>
</tr>
<tr>
<td>Baryon Density (cm⁻³)</td>
<td>$N_{\text{bar}}$</td>
<td>(2.5±1) x 10⁻⁷</td>
</tr>
<tr>
<td>Matter Density</td>
<td>$\Omega_{\text{m}} \cdot h^2$</td>
<td>.135+.008⁻.009</td>
</tr>
<tr>
<td>Baryon Density</td>
<td>$\Omega_{\text{m}}$</td>
<td>.27±.04</td>
</tr>
<tr>
<td>Light Neutrino Density</td>
<td>$\Omega_\nu \cdot h^2$</td>
<td>&lt; .0076 =&gt; $\Sigma m_\nu &lt; .7$ eV</td>
</tr>
<tr>
<td>CMB Temperature (K)</td>
<td>$T_{\text{CMB}}$</td>
<td>2.725 ± .002</td>
</tr>
<tr>
<td>CMB Photon Density</td>
<td>$N_\gamma$</td>
<td>410.4 ± .9</td>
</tr>
<tr>
<td>Baryon to Photon Ratio</td>
<td>$\eta$</td>
<td>(6.1+.3⁻.2) x 10⁻¹⁰</td>
</tr>
<tr>
<td>Hubble Constant</td>
<td>$h$</td>
<td>.71 +.04⁻.03</td>
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<tr>
<td>Age of the Universe (Gy)</td>
<td>$T_0$</td>
<td>13.7 ± .2.04</td>
</tr>
<tr>
<td>Age at Decoupling (ky)</td>
<td>$T_{\text{dec}}$</td>
<td>378+9⁻.7) x 10⁻¹⁰</td>
</tr>
</tbody>
</table>
How to search for WIMPS

By rude force (reduction of the background in the energy region expected for recoils induced by WIMPs)

- **Seasonal modulation** due to the orbital motion of our observatory with respect to the Sun
- **Directionality**
- **Pulse shape** and time discrimination
- **Position** reconstruction
- Hybrid techniques (heat+ light or ionization)
- Double phase liquid detectors - “Bubble chambers” etc.
Events/kg/d for spin independent interaction with $m_{\text{WIMP}} = 100\text{GeV}$ and $\sigma = 4.0 \times 10^{-43} \text{ cm}^2$ ($\sim 10^7 \text{ ev/kg/d in an unshielded detector}$)

<table>
<thead>
<tr>
<th>Threshold (keV)</th>
<th>Xe</th>
<th>Ge</th>
<th>Ar</th>
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<tbody>
<tr>
<td>no</td>
<td>.3</td>
<td>.05</td>
<td>.006</td>
</tr>
<tr>
<td>10</td>
<td>.03</td>
<td>.02</td>
<td>.004</td>
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<tr>
<td>20</td>
<td>.008</td>
<td>.008</td>
<td>.003</td>
</tr>
<tr>
<td>30</td>
<td>.0025</td>
<td>.004</td>
<td>.002</td>
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<td>40</td>
<td>.0015</td>
<td>.0035</td>
<td>.0015</td>
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<tr>
<td>50</td>
<td>.0006</td>
<td>.0025</td>
<td>.001</td>
</tr>
<tr>
<td>60</td>
<td>.00015</td>
<td>.0015</td>
<td>.0008</td>
</tr>
<tr>
<td>70</td>
<td>.00006</td>
<td>.0008</td>
<td>.0006</td>
</tr>
</tbody>
</table>
- More techniques for DM than for searches on DBD. Some adopted for both searches and more should be
DAMA results

107731 kg d a 6.3 $\sigma$ effect

At present no running “conventional” experiment with similar mass, threshold and background, but many being planned including massive $\beta$ $\beta$ experiments.

New => Korea Invisible Mass Search with CsI in the place of NaI
Thermal Detectors

\[ \Delta T = \frac{Q}{C_V} \]

\[ C_V = 1944 \frac{V}{V_m} \left( \frac{T}{\Theta} \right)^3 \text{ J/K} \]

Excellent resolution

\(<1 \text{ eV} \quad \sim 3 \text{ eV} \quad @ \ 6 \text{ keV} \)

\(~10 \text{ eV} \quad \sim \text{keV} \quad @ \ 2 \text{ MeV} \)
Hybrid techniques

Heat + ionization or heat + scintillation
Gamma calibration

Neutron calibration

Nuclear recoil discrimination down to 20 keV threshold
γ-ray rejection > 99.99 %
CRESST II: Phonons and Scintillation

Results from 20.5 kg-d exposure of two 300-g CaWO₄ prototypes

- No neutron shielding
- Observe low-yield events consistent with neutron rates and oxygen cross section & light yield
- Claim no tungsten recoils in light yield region below oxygen yield (not distinct from noise)

The “bubble chamber”

- 2 kg CF$_2$ bubble chamber – Chicago group (Collar, Sonnenschiøn, Crisler)
- Tune thermodynamic parameters
  - Existence proof: principle challenge of stability met
  - Time between events consistent with laboratory neutron background

![Diagram of a bubble chamber]

Installed at 300 mwe depth at FNAL.
Future experiments for direct detection of WIMPS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>Technique</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperCDMS</td>
<td>Ge, Si</td>
<td>cryogenic</td>
<td>Pulse shape inform. =&gt; localization</td>
</tr>
<tr>
<td>Eureka</td>
<td>Ge, CaWO₄</td>
<td>cryogenic</td>
<td>Improved suppr. of low $\beta$ backgr.</td>
</tr>
<tr>
<td>Zeplin</td>
<td>Xe</td>
<td>two phase</td>
<td>Scintillation + ionization</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>two phase</td>
<td>Scintillation + ionization</td>
</tr>
<tr>
<td>Warp</td>
<td>Ar</td>
<td>two phase</td>
<td>Scintillation + ionization</td>
</tr>
<tr>
<td>Xmass</td>
<td>Xe</td>
<td>1/2 phase</td>
<td>Also for $\beta\beta$ decay</td>
</tr>
<tr>
<td>Deap</td>
<td>Ar</td>
<td>one phase</td>
<td>Cryogenic scintillator</td>
</tr>
<tr>
<td>Clean</td>
<td>Ar, Ne</td>
<td>one phase</td>
<td>Cryogenic scintillator</td>
</tr>
<tr>
<td>Drift</td>
<td>CS₂</td>
<td>TPC</td>
<td>Directiona</td>
</tr>
<tr>
<td>Sign</td>
<td>Ne</td>
<td>S and I</td>
<td>Scintillation and ionisation in gas</td>
</tr>
<tr>
<td>COUPP</td>
<td>CF₃I</td>
<td>Bubble Chamber</td>
<td>Insensitive to minimum ionizing particles</td>
</tr>
</tbody>
</table>
Spin independent

DAMA
IGEX
CRESST II
CDMS I
EDELWEISS
ZEPLIN I
CDMS II
Many attempts (not only by DAMA) to reconcile DAMA with exclusion plots => **annual modulation of spin dependent interaction on Na, anisotropic galactic halos, steams of WIMPS etc., many uncertain astrophysical and nuclear parameters**
Spin dependent
DOUBLE BETA DECAY

1. \((A,Z) \Rightarrow (A,Z+2) + 2 \, e^- + 2 \, \nu_e^-\)
2. \((A,Z) \Rightarrow (A,Z+2) + 2 \, e^- + \chi \, (\ldots 2,3 \, \chi)\)
3. \((A,Z) \Rightarrow (A,Z+2) + 2 \, e^-\)

Oscillations have been found in solar, atmospheric and reactor neutrino experiments, but only indicate that \(\Delta m^2 \neq 0\) to determine \(< m_\nu >\) \(\Rightarrow\) neutrinoless double beta decay
Two neutrino $\beta \beta$ decay has been detected in ten nuclei also into exited states.
\[ \frac{1}{\tau} = G(Q,Z) |M_{\text{nucl}}|^2 \langle m_\nu \rangle^2 \]

Rate of DDB-0ν

Phase space

Nuclear matrix elements

Effective Majorana neutrino mass

Need to search for neutrinoless DBD in various nuclei

A pick could be due to some unforeseen background peak

\begin{align*}
\text{Source} &= \text{detector} \\
\text{(calorimetric)}
\end{align*}

\begin{align*}
\text{Source} &\neq \text{detector}
\end{align*}
\[
\begin{align*}
\Delta m^2_{\text{atm}} & \quad \sin^2 \theta_{13} \\
\nu_3 & \quad \nu_1 \\
\Delta m^2_{\text{sol}} & \quad \{ \Delta m^2_{\text{sol}} \}
\end{align*}
\]

Normal

Inverse

Quasi-degenerate: \( m_{\text{low}}^2 \gg \Delta m^2_{\text{atm}} \gg \Delta m^2_{\text{sol}} \)

\( m_{\text{low}} \approx \)
Recent calculation by S. Pascoli and S.T. Petkov
### Present experimental situation

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Experiment</th>
<th>%</th>
<th>$Q_{\beta\beta}$</th>
<th>Enr</th>
<th>Technique</th>
<th>$T_{0\nu\gamma}$ (y)</th>
<th>$\langle m_\nu \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>Elegant IV</td>
<td>0.19</td>
<td>4271</td>
<td>scintillator</td>
<td>$&gt;1.4 \times 10^{22}$</td>
<td>7-45</td>
<td></td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>Heidelberg-Moscow</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>ionization</td>
<td>$&gt;1.9 \times 10^{25}$</td>
<td>.12 – 1</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>IGEX</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>Ionization</td>
<td>$&gt;1.6 \times 10^{25}$</td>
<td>.14 – 1.2</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>Klapdor et al</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>ionization</td>
<td>$1.2 \times 10^{25}$</td>
<td>.44</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>NEMO 3</td>
<td>9.2</td>
<td>2995</td>
<td>97</td>
<td>tracking</td>
<td>$&gt;1.0 \times 10^{23}$</td>
<td>1.8-4.9</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>NEMO 3</td>
<td>9.6</td>
<td>3034</td>
<td>95-99</td>
<td>tracking</td>
<td>$&gt;4.6 \times 10^{23}$</td>
<td>.7-2.8</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>Solotvina</td>
<td>7.5</td>
<td>3034</td>
<td>83</td>
<td>scintillator</td>
<td>$1.7 \times 10^{23}$</td>
<td>1.7 - ?</td>
</tr>
<tr>
<td>$^{128}\text{Te}$</td>
<td>Bernatovitz</td>
<td>34</td>
<td>2529</td>
<td>geochem</td>
<td>$&gt;7.7 \times 10^{24}$</td>
<td>1-4</td>
<td></td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>Cuoricino</td>
<td>33.8</td>
<td>2529</td>
<td>bolometric</td>
<td>$&gt;2.4 \times 10^{24}$</td>
<td>.2-1.</td>
<td></td>
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<tr>
<td>$^{136}\text{Xe}$</td>
<td>DAMA</td>
<td>8.9</td>
<td>2476</td>
<td>69</td>
<td>scintillator</td>
<td>$1.2 \times 10^{24}$</td>
<td>1.1 -2.9</td>
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<tr>
<td>$^{150}\text{Nd}$</td>
<td>Irvine</td>
<td>5.6</td>
<td>3367</td>
<td>91</td>
<td>tracking</td>
<td>$&gt;1.2 \times 10^{21}$</td>
<td>3 - ?</td>
</tr>
</tbody>
</table>
HM collaboration subset (KDHK): claim of evidence of 0ν-DBD

In December 2001, 4 authors (KDHK) of the HM collaboration announce the discovery of neutrinoless DBD

\[ \tau_{1/2}^{0\nu}(y) = (0.8 - 18.3) \times 10^{25} \text{y} (1 \times 10^{25} \text{y b.v.}) \]

\[ \langle M_{\beta\beta} \rangle = 0.05 - 0.84 \text{eV (95\% c.l.)} \]

54.98 kg\cdot y \quad 2.2 \sigma \quad \text{skepticism in DBD community in 2001}

71.7 kg\cdot y \quad 4 \sigma \quad \text{better results in 2004}
Two new experiments NEMO III e CUORICINO
$^{100}\text{Mo} \Rightarrow \tau_{1/2}^{0\nu} (y) > 4.6 \times 10^{23}$

$^{82}\text{Se} \Rightarrow \tau_{1/2}^{0\nu} (y) > 1.0 \times 10^{23}$

$\langle M_{\beta\beta} \rangle < 0.7 - 2.8 \text{ eV} \ (90\% \ c.l.)$

$\langle M_{\beta\beta} \rangle < 1.7 - 4.9 \text{ eV} \ (90\% \ c.l.)$
Searches with thermal detectors

CUORE (Hall A)

Cuoricino (Hall A)

CUORE R&D (Hall C)
Mass increase of bolometers

![Graph showing the mass increase of bolometers over time. The graph plots the total mass in kilograms against the year, with data points indicating mass increases at various intervals.]
✓ Search for the $2\beta|_{0\nu}$ in $^{130}$Te (Q=2529 keV) and other rare events
✓ At Hall A in the Laboratori Nazionali del Gran Sasso (LNGS)
✓ 18 crystals 3x3x6 cm³ + 44 crystals 5x5x5 cm³ = 40.7 kg of TeO₂
✓ Operation started in the beginning of 2003 => ~ 4 months
✓ Background $0.18\pm0.01$ c/keV/kg/a
✓ $T_{1/2}^{0\nu}(^{130}\text{Te}) > 2.4 \times 10^{24}$ y $<m_\nu> \geq 0.19 - 1$.

Klapdor 0.1 – 0.9

2 modules, 9 detector each, crystal dimension 3x3x6 cm³
Crystal mass 330 g
$9 \times 2 \times 0.33 = 5.94$ kg of TeO₂

11 modules, 4 detector each, crystal dimension 5x5x5 cm³
Crystal mass 790 g
$4 \times 11 \times 0.79 = 34.76$ kg of TeO₂
\[ \tau_{1/2}^{0\nu}(y) > 2.4 \times 10^{24} \text{ y} \]

5 y sensitivity (with present performance):
5 \times 10^{24} \text{ y}
\[ \langle M_{\beta\beta} \rangle < 0.12 - 0.65 \text{ eV} \]

\[ \langle M_{\beta\beta} \rangle < 0.2 - 1.0 \text{ eV} \ (90\% \text{ c.l.}) \]

MT = 5.87 (kg \(^{130}\text{Te}\) x y
b = 0.18 \pm 0.02 \text{ c/keV/kg/y}
(Jul 2005)

Powerful test of KDHK
## Next generation experiments

<table>
<thead>
<tr>
<th>Name</th>
<th>Isotope</th>
<th>%</th>
<th>$Q_{\beta\beta}$</th>
<th>% E</th>
<th>B c/y</th>
<th>T (year)</th>
<th>Tech</th>
<th>$&lt;m&gt;$</th>
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</thead>
<tbody>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>34</td>
<td>2533</td>
<td>90</td>
<td>3.5</td>
<td>$1.8\times10^{27}$</td>
<td>Bolometric</td>
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<td>90</td>
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<td>.6</td>
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<td>GENIUS</td>
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<td>$210^{26}$</td>
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<td>EXO</td>
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<td>$1.3\times10^{28}$</td>
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<td>12-31</td>
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<td>Moon-3</td>
<td>$^{100}$Mo</td>
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<td>3034</td>
<td>85</td>
<td>3.8</td>
<td>$1.7\times10^{27}$</td>
<td>Tracking</td>
<td>13-48</td>
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<tr>
<td>DCBA-2</td>
<td>$^{150}$Nd</td>
<td>5.6</td>
<td>3367</td>
<td>80</td>
<td>1</td>
<td>$1\times10^{26}$</td>
<td>Tracking</td>
<td>16-22</td>
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<tr>
<td>Candles</td>
<td>$^{48}$Ca</td>
<td>.19</td>
<td>4271</td>
<td>-</td>
<td>.35</td>
<td>$3\times10^{27}$</td>
<td>Scintillation</td>
<td>29-54</td>
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<tr>
<td>CARVEL</td>
<td>$^{48}$Ca</td>
<td>.19</td>
<td>4271</td>
<td>-</td>
<td>3</td>
<td>$3\times10^{27}$</td>
<td>Scintillation</td>
<td>50-94</td>
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<tr>
<td>GSO</td>
<td>$^{160}$Gd</td>
<td>22</td>
<td>1730</td>
<td>-</td>
<td>200</td>
<td>$1\times10^{26}$</td>
<td>Scintillation</td>
<td>65-?</td>
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<td>COBRA</td>
<td>$^{115}$Cd</td>
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<td>2805</td>
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<td></td>
<td>Ionization</td>
<td></td>
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<td>SNOLAB+</td>
<td>$^{150}$Nd</td>
<td>5.6</td>
<td>3367</td>
<td></td>
<td></td>
<td></td>
<td>Scintillation</td>
<td></td>
</tr>
</tbody>
</table>
Two new $^{76}$Ge Projects:

- **GERDA**
  - Bare $^{76}$Ge array in liquid argon (nitrogen)
  - Shield: high-purity liquid Argon (N) / H$_2$O
  - Phase I: ~18 kg (HiDM/IGEX diodes)
  - Phase II: add ~20 kg new enr. Detectors; total ~40 kg

- **Majorana**
  - Array(s) of $^{76}$Ge housed in high-purity electroformed copper cryostat
  - Shield: electroformed copper / lead
  - Staged approach based on 60 kg arrays (50/120/180 kg)

**Physics goals:** degenerate mass range
**Technology:** study of bgds. and exp. techniques

**Lol**
- Open exchange of knowledge & technologies (e.g. MaGe MC)
- Consider to merge for $\Omega$ (1 ton) exp. (inv. Hierarchy)
The **CUORE** project
(approved by the S.C. of Gran Sasso Laboratory and by INFN)

**CUORE** is an array of 988 bolometers grouped in 19 columns with 13 flours of 4 crystals

\[
750 \text{ kg } \text{TeO}_2 \rightarrow 600 \text{ kg } \text{Te} \\
\rightarrow 203 \text{ kg } ^{130}\text{Te}
\]

Crystals are separated by a few mm, only, with little material among them
Other possible candidates for neutrinoless DBD

<table>
<thead>
<tr>
<th>Compound</th>
<th>Isotopic abundance</th>
<th>Transition energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{CaF}_2$</td>
<td>.0187 %</td>
<td>4272 keV</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.44 &quot;</td>
<td>2038.7 &quot;</td>
</tr>
<tr>
<td>$^{100}\text{MoPbO}_4$</td>
<td>9.63 &quot;</td>
<td>3034 &quot;</td>
</tr>
<tr>
<td>$^{116}\text{CdWO}_4$</td>
<td>7.49 &quot;</td>
<td>2804 &quot;</td>
</tr>
<tr>
<td>$^{130}\text{TeO}_2$</td>
<td>34 &quot;</td>
<td>2528 &quot;</td>
</tr>
<tr>
<td>$^{150}\text{NdF}_3$  $^{150}\text{NdGaO}_3$</td>
<td>5.64 &quot;</td>
<td>3368 &quot;</td>
</tr>
</tbody>
</table>

- $^{130}\text{Te}$ has high transition energy and 34% isotopic abundance => enrichment non needed and/or very cheap. Any future extensions are possible
- Performance of CUORE, amply tested with CUORICINO
- CUORE has been approved and has already an underground location Dilution refrigerator already funded
Recent results obtained with scintillating crystals of Cd WO4
Background: in DM => ionizing particles
in ββ => slow recoils eliminated with
=> Surface Sensitive Bolometers
=> scintillation vs. heat

A composite bolometer with a thin crystal of Ge, Si or TeO2
Germanium
How deep should we go, for DM and DBD?

Neutrons => Simulate DM
=> Background in the region of neutrinoless DBD
Depth Sensitivity Relation for Dark Matter

eg. Study for CDMS-II Detector
Depth Sensitivity Relation for DBD

eg. Study for 60 kg Majorana Module
Neutron background in CUORE (ββ region):

- Neutrons produced in the rock by radioactivity
  - Total: $8 \times 10^{-3}$ c/keV/kg/y
  - Anticoincidence: $2 \times 10^{-4}$ c/keV/kg/y
  - Can be reduced by neutron shield

- Neutrons produced in the rock by muon
  - Total: $6 \times 10^{-5}$ c/keV/kg/y
  - Anticoincidence: $1 \times 10^{-6}$ c/keV/kg/y
  - Negligible

- Neutrons produced in the lead shield by muon
  - Total: $2 \times 10^{-3}$ c/keV/kg/y
  - Anticoincidence: $1 \times 10^{-4}$ c/keV/kg/y
  - Can be reduced by muon veto

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No limit to CUORE sensitivity due to neutron flux @ LNGS

What about the background from the rocks: two tests were planned with weak neutron source
CONCLUSIONS

The interest of experiments on DM and neutrinoless $\beta\beta$ decay is obvious. Establishing the existence of DM particles, would support Supersymmetry and have far reaching consequences not only in astrophysics, but also in subnuclear physics. Oscillations exists and $\Delta m^2$ is finite. We need to determine the Majorana nature of the neutrino and the absolute value of $<m_\nu>$. Evidence has been presented in an experiment on the existence of WIMPs and in another on the existence of neutrinoless DBD. They are not yet confirmed by other experiments (somebody disagree on the term yet).

Fundamental physics has received in the last years great advantages from the “wedding” between nuclear and subnuclear physics and astrophysics. Searches on DM and DBD are, and much more will be in the future a beautiful example of synergy, but this synergy will be likely extended soon to other interesting subjects like solar and supernova neutrino physics. But this is not the end: in the fascinating field of astroparticle physics more results are expecting us and are probably beyond our imagination.