Highlights from Gran Sasso

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External Buildings

Underground Site
Why are we going Underground?

Why don’t we see stars during the day?

To see a very weak signal (light of a star) we need to avoid interference from other light sources (like the sun).

To study rare nuclear events, we need an environment in which all the possible interferences are minimized.
Why are we going Underground?

Every second, at sea level, something around 200 particles (muons) per m² will interact with Earth.

In this conditions, Cosmic Rays become an unavoidable “noise” for every nuclear detector placed on the Earth surface.

Going underground we strongly suppress such interferences produced by Cosmic Rays on our apparatus.
• 1979: proposal by A. Zichichi to Italian Parliament
• 1982: Approval of LNGS construction
• 1987: Construction completed
• 1989: Start data taking of first large experiment (MACRO)
• 1991: GALLEX
• ........
LNGS characteristics

The largest and most important underground laboratory in operation

Shielded by 1400 m (3800 m.w.e.) of rock (Gran Sasso Mountains)

Muon flux reduction respect to sea level $10^6$

Easy access directly from the A24 highway

Area: 17.800 m$^2$

Volume: 180.000 m$^3$
An International Lab

TOTAL USERS: N. 981
ITALIAN USERS: N. 417
FOREIGN USERS: N. 564
The most sensitive laboratory for very low radioactivity measurements

3 main experimental halls 100 m long, 20 m width and 18 m height

Many small tunnels for lab facilities and small experiments

Actually there are 22 experiments in data taking or under construction
**LNGS experiments**

**Fundamental physics**
- **Neutrino astrophysics**
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova neutrinos
- **Nuclear astrophysics**
  - Astrophysical nuclear processes
- **Neutrino properties**
  - Neutrinoless Double Beta Decay
  - Search for relic neutrinos
- **Dark Matter**
  - Direct interaction of WIMPs with Nuclei

**...... but also**
- **Test on quantum mechanics**
  - Study on Planck invariance
  - Electron decay
- **Radiobiology**
  - Biological effects of low radioactive environment
- **Geophysics**
  - Earthquake monitoring and study
  - Analysis of water resources
- **Ultra Trace elemental analysis**
  - Low radioactivity tests and measurements
  - Cultural Heritage analysis
  - Advanced additive manufacturing
KEY words

- Rare events
- Background
- Radiopurity
- Screening
Every second our fingers are crossed by around **60 Billions** of neutrinos
Produced by many different sources
Neutrino Astrophysics Experiments

- **BOREXINO**
  - solar neutrinos
  - geo-neutrinos
  - SN neutrinos

- **LVD**
  - SN neutrinos

- **LUNA**
  - Nuclear Astrophysics
Nuclear Fusion Processes in the Sun

- **pp chain (99%)**
- **CNO cycle (1%)**

**Borexino detector**
- Liquid scintillator
- Very high purity materials
- Very low radioactive background
  - U and Th $\sim 10^{-19}$-$10^{-20}$ g/g
Borexino results

Reconstruction of the Solar Neutrino Spectrum

Risultati:
- Catena PP
- CNO

Counts / (day × 100 ton × keV)

Energy [keV]
The most powerful scintillator telescope

Main features:
- Liquid Scintillator: $C_nH_{2n+2}$ $\langle n \rangle = 9.6 + 1 g/l$ PPO + 0.03 g/l POPOP, $\rho = 0.8 \text{ g/cm}^3$ total 1 kt
- 840 stainless steel, 1.5 m$^3$, counters total 0.85 kt
- (FEU49b or FEU125) 15 cm diameter 2520 PMTs

STAND ALONE
- $<1$ fake event/100 years
- $E_{\text{cut}} = 7 \text{ MeV}$
- $E_{\text{cut}} = 10 \text{ MeV}$

$\Rightarrow$ full sensitivity up to 25 kpc for active mass $> 300 \text{ t}$
Nuclear Astrophysics - LUNA400

**BBN**

\[
p + p \rightarrow ^2\text{H} + e^+ + \nu \quad \text{(p,p)}
\]

\[
p + e^- + p \rightarrow ^2\text{H} + e^+ + \nu \quad \text{(p,e)}
\]

\[
^2\text{H} + p \rightarrow ^3\text{He} + q
\]

\[
^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p
\]

\[
^3\text{He} + ^4\text{He} \rightarrow ...
\]

\[
Q_{\text{eff}} = 19.67 \text{ MeV}
\]

\[
Q_{\text{eff}} = 25.66 \text{ MeV}
\]

\[
Q_{\text{eff}} = 26.20 \text{ MeV}
\]

\[
Q_{\text{eff}} = 16.84 \text{ MeV}
\]

**pp chain**

\[
p + p \rightarrow ^2\text{H} + e^+ + \nu \quad \text{(p,p)}
\]

\[
p + e^- + p \rightarrow ^2\text{H} + e^+ + \nu \quad \text{(p,e)}
\]

\[
^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu
\]

\[
^7\text{Be} + p \rightarrow ^8\text{Li} + \gamma
\]

\[
^7\text{Be} + p \rightarrow ^8\text{B} + e^+
\]

\[
^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu
\]

\[
^8\text{Be} \rightarrow 2^4\text{He}
\]

**CNO cycle**

**NeNa cycle**

**MgAl cycle**
Neutrinoless Double Beta Decay

CUPID

GERDA

CUORE
From the Table of Isotopes

- 35 isotopes with double beta decay transitions
- 9 promising for sensitive measurements
- most promising candidates: $Q_{\beta\beta} > 2$-3 MeV
- isotope enrichments are needed

Considering a calorimetric approach (Source == Detector)

- **isotope enrichments** are needed
- **very clean materials** have to be identified
Background interferences

It is necessary to strongly reduce background events:

- Cosmic Rays
- Radioactivity

**Possible Calorimetric Approaches**

**Fluid or diluted in a fluid**
- Container size
- Concentration of the source

**Source**

**Scalability**
- Size of a single crystal
- Number of crystals

**Integral part of a crystal**

**Large volumes of fluid**
- Diluted source in liquid scintillatol
- TPC
- High-pressure gas
- Liquid

**Crystal arrays**
- Inorganic Scintillators (Candles)
- Semiconductor detectors
- Bolometers
- Pure bolometer

**Evolved detectors**
- Germanium diodes
- CCD to Se (SELENA)
- CdZnTe (COBRA)
- PSD (CROSS)

**Detectors**
- Inorganic Scintillators (Candles)
- Semiconductor detectors
- Bolometers
- Pure bolometer

**Detectors**
- Inorganic Scintillators (Candles)
- Semiconductor detectors
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- Pure bolometer

**Detectors and their configurations**
- Without balloon (SNO+)
- With balloon (KamLAND-Zen)
- With balloon+Cherenkov (Theia)
- Opaque scintillator (LiquidO)
- Cylindrical (Xe: Next, PandaX, Axel; SeF6:N\nuDEx)
- Spherical (R2D2)
- Single phase (Xe: EXO-200, nEXO)
- Double phase (Xe: Darwin, LZ)

**Detectors and their configurations**
- Immersed in LAr (GERDA, LEGEND)
- Conventional cryostats (MJD)
- Opaque scintillator (LiquidO)
- Cylindrical (Xe: Next, PandaX, Axel; SeF6:N\nuDEx)
- Spherical (R2D2)
- Single phase (Xe: EXO-200, nEXO)
- Double phase (Xe: Darwin, LZ)
## Present and Future experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Status</th>
<th>Laboratory</th>
<th>Moles of isotope</th>
<th>Isotopic abundance</th>
<th>B (events/kg.eV)</th>
<th>Fiducial isotope mass (kg)</th>
<th>Active fraction (%)</th>
<th>Efficiency</th>
<th>FWHM (keV)</th>
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Double beta decay experiments

Current situation

**T_{1/2} > 10^{24} y 90\% C.I. restricted club**

- **GERDA**
  - $T_{1/2} > 1.8\times10^{26}$ y

- **KamLAND-Zen 400**
  - $T_{1/2} > 1.07\times10^{26}$ y

- **EXO-200**
  - $T_{1/2} > 3.5\times10^{25}$ y

- **MAJORANA dem.**
  - Phys. Rev. C 100, 025501
  - $T_{1/2} > 2.7\times10^{25}$ y

- **CUORE**
  - arXiv:1907.09376
  - $T_{1/2} > 2.2\times10^{25}$ y

- **CUPID-0**
  - L. Pagnanini, TAUP 2021
  - $T_{1/2} > 4.7\times10^{24}$ y

- **CUPID-Mo**
  - B. Welliver, TAUP 2021
  - $T_{1/2} > 1.8\times10^{24}$ y

- **NEMO-3**
  - $T_{1/2} > 1.1\times10^{24}$ y
Gerda Results

GERDA experiment operates in a real 0 background conditions

High purity germanium diodes immersed in LAr
- $\Delta E < 3$ KeV FWHM @ $Q_{\beta\beta}$
- Pulse shape analysis: multi/single site vs.
- anticoincidence with LAr
  - scintillating fibers (WLS) coupled to SIPMS
  - PMT above and below the detector

\[ \text{Counts} / (\text{keV/kg yr}) \]

Enriched coaxial - 23.1 kg yr
\[ \text{Counts} / (\text{keV/kg yr}) \]

Enriched BEGe - 30.8 kg yr

$Q_{\beta\beta} \pm 2 \sigma$

1 new event
(E - $Q_{\beta\beta} = 2.4 \sigma$)

Background index$^*$:
\[ (5.7^{+4.1}_{-2.6} \cdot 10^{-4}) \text{ counts/(keV-kg-yr)} \]

\[ (5.6^{+3.4}_{-2.4} \cdot 10^{-4}) \text{ counts/(keV-kg-yr)} \]

\*$^*$ in 1930-2190 keV excluding $\pm5$ keV at $Q_{\beta\beta}$

and lines at 2104 keV and 2119 keV

2 events in PRL
120 data set
Largest cryogenic particle detector ever realized

- **CUORE**
- **Largest cryogenic particle detector ever realized**

- **CUORE 2003**
- **CUORE 2012**
- **CUORE 2017**

- **CUORE**

- **LNGS**
  - 988 TeO$_2$ crystals arranged on 19 towers
  - Dedicated "dry" cryostat
  - 742 kg of natural TeO$_2$ (206 kg of $^{130}$Te)
  - FWHM: 7.7 keV FWHM (ROI)
  - Background: $(1.4 \pm 0.2) \times 10^{-2}$ cnts/(keV·kg·yr)
  - Total exposure: 1.8 tonne (TeO$_2$)·yr

- **$\beta\beta^{0v}$ result (1038.4 kg yr TeO$_2$, 288 kg yr $^{130}$Te):**
  - $T_{1/2}(0v) > 2.2 \times 10^{25}$ yr (90% C.L.)
  - $m_{\beta\beta} < 90-305$ meV

https://www.nature.com/articles/s41586-022-04497-4

- **$T_{1/2}(2v) = [7.71(0.08-0.06(stat.)+0.12-0.15(syst.))] \times 10^{20}$ yr**
• CUORE cryostat: most powerful cryostat ever realized
• Tens of ton of materials cooled at 10 mK
• Cryogenic detectors are reliable

CUORE alpha background
BI ~ $10^{-2}$ counts/(keV kg years)

CUPID - scintillating bolometers detector
Simultaneous read-out of Photons and Phonons
High energy resolution: as bolometer
High discrimination capability: as scintillator
CUPID detector

- Scintillating crystals and light detectors operated at 10 mK
- Grown from various $\beta\beta$ emitters (multi-isotope approach)
- Excellent energy resolution @ $Q_{Q\beta\beta}$ (<1%)
- Possibility to high $Q_{Q\beta\beta}$ (3 MeV) for $^{82}$Se and $^{100}$Mo
- $LY_\alpha \neq LY_{\beta/\gamma} \rightarrow$ Particle ID
- LShape $\alpha \neq$ LShape $\beta/\gamma \rightarrow$ Particle ID
- HShape $\alpha \neq$ HShape $\beta/\gamma \rightarrow$ Particle ID
Cosmological studies @ LNGS

Dark Matter Searches

...large part of our Universe is completely unknown...
Dark Matter Search Experiments@ LNGS

Cryogenic Liquids
  XENON
  Dark Side

Bolometers
  CRESST

Ultrapure Scintillator
  DAMA/LIBRA
  SABRE

Ordinary Matter
  5%
Dark Matter Searches

- **Energía Oscura**
  - 68%
- **Materia ordinaria**
  - 5%

**Velocity in Milky Way Sun**

**December**

**June**

**Dark matter wind**

**Log scale**

**WIMP - $^{76}$Ge nucleon scattering**

**mediator**

**time**

**recoil Energy**
Dual Phase TPC

\[
\text{Drift time: } \quad \Delta t = t_{s2} - t_{s1} \\
\text{Drift velocity: } \quad v \approx 2 \, mm/\mu s \approx 7200 \, km/h \\
\text{Depth (z - position): } \quad z = v \cdot \Delta t 
\]

\[
\begin{align*}
\text{Concentric PMT array on top} & \quad \rightarrow \ S2 \text{ signal local} \\
\rightarrow \ x - \text{ and y - position} & \\
\rightarrow \ 3D \text{ position reconstruction} & \\
\rightarrow \ Self - shielding & \\
\rightarrow \ Inner + \text{radio-pure volume} & 
\end{align*}
\]
Dual Phase TPC

Particle identification

Electronic Recoil (ER)

Nuclear Recoil (NR)

Figure in courtesy: L. Althüser

Thanks C. Weinheimer
Xenon TPC

Particle identification

Reduction of ER-induced background up to 99.75% at 50% NR acceptance

Thanks C. Weinheimer
Dark Matter Searches

Figure created with the Dark Matter Limit Plotter by T. Saab and E. Figueroa

Created May 16, 2019
Possible future experiments @ LNGS
### Maximum beam intensity on target at different terminal voltage

<table>
<thead>
<tr>
<th>Ion specie</th>
<th>Terminal Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3 MV – 0.5 MV</td>
</tr>
<tr>
<td>$^1$H$^+$</td>
<td>500 μA</td>
</tr>
<tr>
<td>$^4$He$^+$</td>
<td>300 μA</td>
</tr>
<tr>
<td>$^{12}$C$^+$</td>
<td>100 μA</td>
</tr>
<tr>
<td>$^{12}$C$^{2+}$</td>
<td>60 μA</td>
</tr>
</tbody>
</table>

- Number of Beam Lines: 2
- Beam time / year: 7400h (308d)
- Max. admitted neutron flux at target: 2000 n/s
- Neutron level outside shielding: Below natural underground neutron flux at LNGS

**Literature reference:**

LUNA-MV mainly funded with a national grants
Double Beta Decay: Next Generation Experiments

- SNO+
- CUPID
- KamLAND-ZEN
- nEXO
- NEXT
- LEGEND
• Natural evolution of the GERDA principle
• Combines the best of Gerda and MJD
  ▶ from GERDA:
    - detector configuration
    - infrastructure@ LNGS
    - system improvements
  ▶ from MJD
    - selection of radio-pure materials
    - electronics
    - low threshold

• $^{76}$Ge:
  ▶ 35 kg from GERDA
  ▶ 30 kg from MJD
  ▶ 140 kg new materials

• New type of detector, already tested in GERDA
  ▶ ICPC $m > 2$ kg (0.7-0.9 kg previously)
  ▶ same energy resolution and PSD capability
Meeting between North American and European funding agencies

- Selection of future DBD experiments
  - Experimental sensitivities
  - Budget requested for each experiment
  - International collaborations
- Selection of possible underground laboratories
  - SNOLab/SURF – North America
  - LNGS - Europe

### Table: Double Beta Decay Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$T_{1/2}$ ($10^{28}$ years)</th>
<th>$m_{\beta\beta}$ (meV)</th>
<th>3σ Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excl. Sens.</td>
<td>3σ Discovery</td>
<td>Median</td>
</tr>
<tr>
<td>CUPID</td>
<td>0.14</td>
<td>0.10</td>
<td>15</td>
</tr>
<tr>
<td>LEGEND-1k</td>
<td>1.60</td>
<td>1.30</td>
<td>12</td>
</tr>
<tr>
<td>nEXO</td>
<td>1.35</td>
<td>0.74</td>
<td>11</td>
</tr>
</tbody>
</table>
A rich experimental program is actually in preparation:

- XENONnT
- Dark Side 20k
- COSINUS
- SABRE
- LIME/CYGNO
- ……

Specific LNGS facilities are under preparation

- NOA Clean Room for detector assembly
- New cryogenic plant for large LN production
- Screening facility for material selection
- ……

Medium/Long term activities on Dark Matter experiments are ongoing

Some LoIs for future experiments (Darwin, …) were received by LNGS

A 5/10 years plan on Dark Matter experiments is practically well established
A 20-tonnes fiducial argon detector filled with underground argon

TPC acrylic vessel surrounded by AAr + Gd-loaded acrylic shell as a neutron veto

21 m² of Cryogenic Silicon based Photo-Multipliers
LOW RADIOACTIVITY ARGON

URANIA

- Procurement of 50 tonnes of UAr from same Colorado source as for DS-50
- Extraction of 250 kg/day, with 99.9% purity
- UAr transported to Sardinia for final chemical purification at Aria

ARIA

- Big cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with $10^3$ reduction of all chemical impurities
- Ultimate goal is to isotopically separate $^{39}$Ar from $^{40}$Ar (at the rate of 10 kg/day in Seruci-I)
Cutting Edge Technologies

Advanced Additive Manufacturing
Copper 3D printing

Ultra-Trace elemental and isotopical analysis
Cultural Heritage
Environmental Studies
High Purity Material

Quantum Technology
Quantum Computing
Quantum Communication
Archeological Study

Ancient Roman Lead recovered from a Ship sunked in Sardegna (1 century b.C.)
Conclusions

• @LNGS a large number of experiments are actually taking data or are under construction

• LNGS international community involve many country around the world and large number of researchers

• LNGS play a leading role in many different field of researches (DBD, DM, NA ...) 

• Future scientific programs are under discussion at international level:
Prof. Enrico “Puccio” Bellotti
1940 - 2021
1st director of LNGS
President of Astroparticle Physics committee of INFN
Great scientist and great expert in DBD
Neutrino Oscillation

The CNGS beam along its five years of operation 2008 ÷ 2012

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam days</th>
<th>P.O.T. ($10^{19}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>123</td>
<td>1.74</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>3.53</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>4.09</td>
</tr>
<tr>
<td>2011</td>
<td>243</td>
<td>4.75</td>
</tr>
<tr>
<td>2012</td>
<td>257</td>
<td>3.86</td>
</tr>
<tr>
<td>Total</td>
<td>965</td>
<td>17.97</td>
</tr>
</tbody>
</table>
Neutrino Oscillation

\[ \nu_\mu \rightarrow \nu_\tau + N \rightarrow \tau^- + X \]

**The First \( \nu_\tau \) Candidate in the Brick**

\[ \tau^- \rightarrow \rho^- \nu_\tau \]
\[ \rho^- \rightarrow \pi^0 \pi^- \]
\[ \pi^0 \rightarrow \gamma \gamma \]
Sensitivities: a different view

Thanks to O. Cremonesi

Capri, September 12, 2022
Novel HPGe detectors allow for efficient PID
LUNA400: what can still be done

- $^{14}\text{N}(p,\gamma)^{15}\text{O}$ to decrease the uncertainty at solar temperature;
- $^{16}\text{O}(p,\gamma)^{17}\text{F}$ to determine the $^{16}\text{O}/^{17}\text{O}$ abundance ratio in red giant stars;
- $^{19}\text{F}(p,\alpha)^{16}\text{O}$ to constrain AGB star nucleosynthesis and to investigate spectroscopy of self-conjugate $^{20}\text{Ne}$ nucleus;
- $^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ to determine the production of $^{22}\text{Na}$ in Novae and Supernovae;
- $^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$ to understand the $^{23}\text{Na}$ production during H-burning both in stellar cores and shells;
- $^{24}\text{Mg}(p,\gamma)^{25}\text{Al}$ which is crucial to understand MgAl anticorrelation;
- $^{27}\text{Al}(p,\alpha)^{24}\text{Mg}$ which significantly affects the Mg and Al production;
- ……
LUNA400 2022-2024 new program

- $^{16}\text{O}(p,\gamma)^{17}\text{F}$ will be done using the solid target beam line setup together with the $\gamma$ detectors available, only minimal modifications are foreseen;

- $^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ will be done using the gas target beam line setup together with the $\gamma$ detectors available, only gas enriched in $^{21}\text{Ne}$ is needed;

- $^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$ & $^{27}\text{Al}(p,\alpha)^{24}\text{Mg}$ Edinburgh group will develop the $\alpha$ particle detection setup.