Origin and Status of the Gran Sasso INFN Laboratory

Lucia Votano - LNGS
Why Underground Laboratories

- The physics of the earliest state of our Universe, when the fundamental forces were unified and the particles were interacting at energy not accessible to present accelerators, can be assessed by searching for very rare phenomena in matter and weak effects of elusive particles.

- Searches for rare events like $0\nu$DBD or proton decay, the study of weak interactions from cosmic or artificial neutrinos, the direct detection of dark matter candidates and nuclear astrophysics require low-background environments.

- Thanks to the rock coverage and the corresponding reduction in the cosmic ray flux and c.r.-spallation induced neutrons, underground laboratories provide the necessary low background environment to investigate these processes.

- Underground Laboratories are the main infrastructures for astroparticle and neutrino physics.
Gran Sasso Laboratory

- **Largest underground laboratory** in the world
  - Run by **INFN** under the **Gran Sasso Mountain**, Italy
  - 120 km far from Rome, completed **1987**
  - International scientific community (**1000 users per year**)
  - Permanent staff: **82 + 19 temporary positions**

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**Non Italian users 2010 = 550**

![Graph showing user distribution](image)
Gran Sasso Laboratory

Muon Flux

\[ 3.0 \times 10^{-4} \, \mu m^{-2} s^{-1} \]

Neutron Flux

\begin{align*}
\text{Neutron Flux} & \quad \text{Depth: 1400 m (3800 m w.e.)} \\
2.92 \times 10^{-6} \, n \, cm^{-2} \, s^{-1} & \quad (0-1 \, keV) \\
0.86 \times 10^{-6} \, n \, cm^{-2} \, s^{-1} & \quad (>1 \, keV) \\
\end{align*}

3 main halls A B C ~100 x 20 m² (h 20 m)

Depth: 1400 m (3800 m w.e.)
Surface: 17800 m²
Volume: 180000 m³
Rn in air: 20-80 Bq/m³
ISO 14001
Ventilation: 1 Lab volume/3 h
Electrical power: 1300 kW
Access: horizontal

external facilities
A brief history of Gran Sasso National Laboratory

1979 → Submission to the Italian Parliament of the proposal of the Gran Sasso Underground Laboratory, conceived by Antonino Zichichi

1982 → Approval of the Parliament

1987 → The Underground Laboratory completed

1989 → The first experimental apparatus, MACRO, begins the data taking.
First generation experiments

- Solar Neutrinos
  - GALLEX/GNO

- Supernova Neutrinos
  - LVD

- Dark Matter
  - GENIUS-TF
  - HDMS
  - DAMA

- Cosmic rays, Monopoles
  - EAS-Top
  - MACRO
  - LVD

- Double Beta Decay
  - DBA, D-BGS
  - MIBETA
  - HM$\beta\beta$
  - CUORICINO
Research activities:

- Neutrino physics
- Dark matter searches
- Nuclear Astrophysics

Associate Sciences:
Environmental Radioactivity for Earth Sciences, Geophysics, Fundamental Physics, Biology
Neutrino Physics: open questions

- The accurate determination of the intrinsic properties of neutrino is of prime interest in particle physics.
- Solar, atmospheric, accelerator and reactor neutrino experiments show that flavour mixing concerns not only the hadronic sector, but the leptonic sector as well.
- The main goals of neutrino physics for the next decade:
  ① The full measurement of the leptonic mixing matrix
    New scenarios opened by the recent $\theta_{13}$ measurements
  ② The measurement of their absolute mass scale
  ③ The discrimination of the Dirac/Majorana nature of neutrinos,
  ④ Beyond 3 $\nu$ ??
- Neutrinos from cosmos are very important messengers for our comprehension of the stars and of the Universe evolution.
Basic neutrino properties
- $0\nu$DBD

Solar neutrinos (Borexino)
- $^7\text{Be}$ the main target
- $^8\text{B}$, pep first evidence, CNO limit, and possibly pp

Geo anti-neutrinos (Borexino)

CNGS neutrinos
- OPERA and ICARUS

SuperNova neutrinos
- LVD, Borexino and ICARUS
- LVD and Borexino are in the SNEWS network
Oscillation experiments have clearly demonstrated that:

- Neutrinos \( \nu_e, \nu_\mu, \nu_\tau \) do oscillate
- Neutrinos \( \nu_1, \nu_2, \nu_3 \) are massive

New Physics beyond SM must exist

Oscillation experiment cannot answer:

1. Are neutrinos Dirac or Majorana particles?
2. What is the absolute mass scale?

\( \nu_\beta \beta \) experiments can shed light on 1. and 2.
2ν2β decay:
(A,Z) → (A,Z+2) +2e^- +2ν

SM allowed & observed on several isotopes with forbidden single-β. Conserves lepton number, but long half-life because 2nd order (10^{19} ÷ 10^{21} y)

0ν2β decay:
(A,Z) → (A,Z+2) +2e^-

Violates lepton number by two units.
Possible only if ν Majorana and <m_{ββ}> >0.
\( 0^{\nu} 2\beta \) decay

If mediated by the exchange of massive Majorana neutrinos:

\[
\frac{1}{\tau} = G(Q, Z) |M_{\text{nucl}}|^2 <m_{\beta\beta}>^2
\]

\[
|\Sigma_i U_{ei}^2 m_i |
\]

Experimental signatures:

- peak at \( Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e \)
- two electrons from vertex
- production of grand-daughter isotope

\( 2^{\nu} \beta\beta \) background (resolution)
- nuclear backgrounds
# Double Beta Decay Candidates

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Q(MeV)</th>
<th>Abund(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}\rightarrow^{48}\text{Ti}$</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}\text{Ge}\rightarrow^{76}\text{Se}$</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}\text{Se}\rightarrow^{82}\text{Kr}$</td>
<td>2.995</td>
<td>9.2</td>
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<tr>
<td>$^{96}\text{Zr}\rightarrow^{96}\text{Mo}$</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}\text{Mo}\rightarrow^{100}\text{Ru}$</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}\text{Pd}\rightarrow^{110}\text{Cd}$</td>
<td>2.013</td>
<td>11.8</td>
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<tr>
<td>$^{116}\text{Cd}\rightarrow^{116}\text{Sn}$</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}\text{Sn}\rightarrow^{124}\text{Te}$</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}\text{Te}\rightarrow^{130}\text{Xe}$</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}\text{Xe}\rightarrow^{136}\text{Ba}$</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}\text{Nd}\rightarrow^{150}\text{Sm}$</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

### 2$\nu\beta\beta$ decay

\[
\begin{array}{c}
\text{n} \\
\text{e}^-
\end{array} \rightarrow \begin{array}{c}
p \\
\nu \\
\bar{\nu}
\end{array}
\]

\[
(Z,A) \rightarrow (Z+2,A)+2e^-+2\bar{\nu}
\]

\[T_{1/2} \sim 10^{21} \text{y}\]

### 0$\nu\beta\beta$ decay

\[
\begin{array}{c}
\text{n} \\
\text{e}^-
\end{array} \rightarrow \begin{array}{c}
p \\
\text{e}^-
\end{array}
\]

\[
(Z,A) \rightarrow (Z+2,A)+2e^-
\]

\[T_{1/2} > 10^{25} \text{y}\]
LNGS program: complementary approaches concerning isotopes and techniques

- GERDA: HPGe detectors enriched in $^{76}\text{Ge}$
  - running
- CUORE: $\text{TeO}_2$ bolometers ($^{130}\text{Te}$)
  - construction phase.
- Lucifer R&D to further suppress background: scintillating bolometers
- COBRA R&D: CdZnTe room temperature detectors
GERDA 2νββ preliminary results
Summed electron energy spectrum

exposure: 6.1 kg yr

our result:

$T_{1/2}^{2ν}(^{76}\text{Ge}) = (1.88 \pm 0.10) \times 10^{21}$ yr

preliminary!
GERDA $2\nu\beta\beta$ preliminary results
Summed electron energy spectrum

exposure: 6.1 kg yr

$2\nu\beta\beta$

$^{76}\text{Ge}$

$T_{1/2}^{2\nu} = (1.88 \pm 0.10) \times 10^{-21}$ yr
The aim of CUORE experiment is to study $0\nu\beta\beta$ from $^{130}$Te by using cryogenic detectors made of TeO$_2$ crystals. The prototype CUORICINO, operated at LNGS up to 2008, demonstrated the feasibility of the large scale detector CUORE.
closely packed array of 988 detectors
19 towers - 13 modules/tower - 4 detectors/module
\[ M = 741 \text{ kg} \Rightarrow \sim 10^{27} \; ^{130}\text{Te} \text{ nuclides} \]
200 kg \(^{130}\text{Te}\)

Compact structure, ideal for active shielding

Expected 5 Years sensitivity:

\[ T_{1/2} = 2.1 \times 10^{26} \text{ y}, \; m_{\beta\beta} = 41\text{-}95 \text{ meV} \]

background counting rate
\[ 10^{-2} \text{ c/keV/kg/y} \]

The start of the first tower CUORE-0 is foreseen in July

Custom dilution refrigerator
Neutrinoless Double Beta Decay

From Vissani, Strumia
hep-ph/0606054v2
Roman lead for CUORE @LNGS

- 120 ingots of Roman Lead (4 tons) from an ancient ship that sunk off the Sardinia coast have arrived in LNGS and are safely installed underground. With the previous 170 they are sufficient for the internal shield of CUORE.
BOREXINO: a real-time liquid scintillator detector for solar neutrinos
- 278 tons of PC+PPO in a nylon bag
- 2200 photomultipliers
- 2500 tons ultrapure water

**Diagram:**
- Stainless steel sphere 13.7 m diameter
- Nylon sphere 8.5 m diameter
- 2200 photomultipliers
- 300 tons of liquid scintillator
- Stainless steel water tank with 2400 tons of ultrapure water 18m diameter
Importance of Borexino precise low-energy measurements: 
\(^7\)Be, DayNight asymmetry, \(^8\)B, pep, CNO, ….

- Independently confirm the MSW-LMA scenario or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying \(\nu\)'s
- Solve the tension between the High and Low metallicity solar model
- Prove CNO cycle in the Sun.
**BOREXINO**

Low-level background record

\[
210\text{Bi rate} = 16 \pm 4 \text{ cpd/100tons} \\
85\text{Kr rate} = 7 \pm 5 \text{ cpd/100tons}
\]

From delayed coincidence analysis (95% C.L.)
- \(238\text{U} < 9.7 \times 10^{-19} \text{ g/g};\)
- \(232\text{Th} < 4.3 \times 10^{-18} \text{ g/g};\)
- The BX scintillator has never been so clean!

- The possibility to perform further purification steps is being evaluated;
- Collect few more months of data (good data!) to precisely evaluate \(210\text{Bi} \) level
NEW: BX pep and CNO measurements

pep V measurement motivations

pep neutrino flux predicted with high precision: 1.2% SSM uncertainty

pep neutrino energy (1.44 MeV) in $P_{ee}$ transition region, sensitive to Physics beyond Standard Model

Allows for more stringent tests of oscillation models

![Graph showing neutrino energy distribution](image)
FIRST DETECTION OF PEP NEUTRINOS

- Rate: $3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}} \text{ cpd/100 t}$

- No oscillations excluded at 97% c.l.

- Absence of pep solar $\nu$ excluded at 98%

- Assuming MSW-LMA:
  - $\Phi_{\text{pep}} = 1.6 \pm 0.3 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$

- CNO limit obtained assuming pep @ SSM

- CNO rate $< 7.1 \text{ cpd/100 t} (95\% \text{ c.l.})$

Courtesy M. Pallavicini
Solar neutrino oscillations before Borexino

![Graph showing survival probability of neutrinos as a function of energy. The graph compares different neutrino types and their survival probabilities.](image-url)
Solar neutrino oscillations after Borexino
Geo-ν: a unique direct probe of the Earth interior

The radioactive isotopes inside the Earth generate heat.

The Earth shines in anti-ν

\[ {}^{238}\text{U} \rightarrow {}^{206}\text{Pb} + 8\alpha + 8\,\text{e}^- + 6\,\nu_e + 51.7\,\text{MeV} \]
\[ {}^{232}\text{Th} \rightarrow {}^{208}\text{Pb} + 6\alpha + 4\,\text{e}^- + 4\,\nu_e + 42.8\,\text{MeV} \]
\[ {}^{40}\text{K} \rightarrow {}^{40}\text{Ca} + \text{e}^- + 1\,\nu_e + 1.32\,\text{MeV} \]

Only two detectors (Kamland, Borexino) are presently able to detect Geo-ν

Relevance of geoneutrinos: a new probe of the Earth interior

The movement of the heat within the Earth is central in the theory of plate tectonics

- What is radiogenic contribution to the Earth energy budget (50%??)?
- What is the distribution of the radiogenic elements?
- How much in the crust and how much in the mantle?
BOREXINO  Continental crust

Different contribution from the crust and sediment; regional geology needed

KamLand  Oceanic crust

Data sample almost doubled since 2010
Not yet released

Null hypothesis disfavored at 4.2 $\sigma$ in both cases

Geov: $9.9^{+4.1}_{-3.4}$

Geov: $111^{+45}_{-43}$
Borexino Phase II (3-4 years) Physics goal

- Improve significance of pep signal
- Improve limit (or observation?) of CNO
- Search for pp neutrinos
- Improve precision on $^7$Be neutrinos
- Improve significance of geo-antineutrinos

What’s next?

A proposal for a short baseline sterile neutrino search experiment has been submitted to the LNGS SC in April 2012

- $\nu^{51}$Cr Source under the detector
- $\bar{\nu}^{144}$Ce-$^{144}$Pr inside the detector
CNGS beam: CERN Neutrino to Gran Sasso

Energy: optimized for $\nu_\tau$ appearance mode
Goal: prove definitely the neutrino oscillations

Project INFN-CERN: approved in 1999, started in 2006
$\nu_\mu$ beam produced at CERN and detected at LNGS
Experimental halls designed in the CERN direction

OPERA running since 2006
ICARUS running since 2010
• Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the appearance of $\nu_\tau$ in a pure $\nu_\mu$ beam
• Search for the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations for $\Theta_{13}$ measurement
• Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the appearance of $\nu_\tau$ in a pure $\nu_\mu$ beam
• Search for the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations for $\Theta_{13}$ measurement

<table>
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<tr>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$</td>
<td>0.75</td>
</tr>
<tr>
<td>Counts for 22.5x10^{19} pot</td>
<td>10.4</td>
</tr>
</tbody>
</table>
In 2010 at LNGS

the first evidence of direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode
Neutrino Oscillations: OPERA

- In June 2012 presented at Kyoto Neutrino Conference
  - the second evidence of direct detection of $\nu_\mu \rightarrow \nu_\tau$
  - oscillation in appearance mode
Neutrino Oscillations: OPERA

- In June 2012 presented at Kyoto Neutrino Conference
  the second evidence of direct detection of $\nu_\mu \rightarrow \nu_\tau$
  oscillation in appearance mode

Schematics of the event

Interaction Vertex
in Lead plate
With one Nuclear fragment

Primary Track

Decay point
**In Plastic Base**
No Nuclear fragment
Flight length 1.54mm

Secondary Interaction
**In Emulsion**
With four Nuclear fragments

Beam View
$\Phi=167^\circ$
Two identical modules
3.6 x 3.9 x 19.6 ≈ 275 m³ each
Liquid Ar active mass: ≈ 476 t

Conceived as a Multi-purpose detector: atmospheric, solar (>8 Mev), supernovae neutrinos, nucleon decay searches in “exotic” channels, CNGS beam

The most important Milestone towards a multi-kton LAr detector with unique imaging capability, and spatial/calorimetric resolutions

CNGS neutrino events
1000 tons liquid scintillator in 3 towers

300 $\nu$ from a SN in the center of Galaxy (8.5 kpc)

Early warning of neutrino burst important for astronomical observations with different messengers (Gravitational Waves)

SNEWS = Supernova Early Warning System
LVD, SNO, SuperK
Kamland, BOREXINO
The neutrino velocity issue using CNGS and OPERA
CNGS-OPERA Synchronisation

Already existing system (not enough accurate)

CERN

already existing system (not enough accurate)

LNGS

new system

Common View Mode

PolaRx2e  →  Cs

Time-transfer equipment

Cs  →  PolaRx2e

Time-transfer equipment

XLi

GPS

GMT

CNGS

ESAT 2000 GPS

Offline event selection

New system installed in 2008
After the September 2011 OPERA announcement, a test of the 8.3 Km long optical fiber brought to the discovery of a faulty connection of an optical cable reducing the amount of light received by the optical/electrical converter of the Master Clock and thus increasing artificially the neutrino velocity by $\approx 74$ ns.

How stable was this condition? The period of time when “anomalous” conditions occurred during data taking and stability of these conditions were subjected to ‘special investigations’.
The neutrino velocity issue: a joint LVD-OPERA analysis

Coincidences using horizontal cosmic muons through the “Teramo anomaly”

An unambiguous indication of an instrumental bias of OPERA at Gran Sasso
The neutrino velocity issue

The bunched proton beam

2009-2011

- statistical method for $\text{TOF}_\nu$ extraction
- $\sim 10^{20}$ pot

October 22 to November 6 (2011)

- $\text{TOF}_\nu$ for each detected neutrino
- $4 \times 10^{16}$ pot

and May 2012

Courtesy S. Bertolucci
The neutrino velocity issue

After the September 2011 OPERA announcement, all the big experiments at LNGS besides OPERA BOREXINO, ICARUS and LVD set up a campaign to repeat the measurement with:

• Improved timing resolution
• Reduction of systematics
• Improved and redundant time stamp:
  1. White Rabbit System at LNGS
  2. Borexino new high precision GPS system (in collaboration with INRIM and ROA)
• Independent geodesy

CNGS bunched beam campaign in May 2012
The neutrino velocity issue: THE END

- All experiments consistent with no measurable deviation from the speed of light for neutrinos:
  - **Borexino**: $\delta t = 2.7 \pm 1.2 \text{ (stat)} \pm 3 \text{(sys)}$ ns
  - **ICARUS**: $\delta t = 5.1 \pm 1.1 \text{(stat)} \pm 5.5 \text{(sys)}$ ns
  - **LVD**: $\delta t = 2.9 \pm 0.6 \text{(stat)} \pm 3 \text{(sys)}$ ns
  - **OPERA**: $\delta t = 1.6 \pm 1.1 \text{(stat)} \pm [+6.1, -3.7] \text{(sys)}$ ns

- Very preliminary analyses, more refinements to be expected soon

- A paradigmatic example of collaboration and competition!

*Courtesy S. Bertolucci*
The dark side of the Universe...
Evidence of large abundance in the Universe of non-baryonic and non-relativistic 'dark matter' comes from gravitational effects, also supported by measurements of the cosmic microwave background anisotropy.

Stable, Weakly Interacting Massive Particles, predicted by a number of theories beyond the SM, are candidates for DM. WIMPs could have been produced thermally in the early Universe and persist to the present day. Under this hypothesis the Earth is embedded within a WIMP gas.

Direct detection of DM aims to observe the scattering of DM particle off target nuclei. WIMPs-target nuclei interactions produce exponentially falling differential energy spectra with energy deposition up to several- to several tens-of KeV.

Very low rates expected
(a few counts/kg/day- to a few counts/kg/year)

Uglabs, low background and ways to distinguish signals from bkg
Dark Matter @ LNGS

Different methods and techniques towards a 'smoking gun' signature

**Ionization**

*Noble liquids*
- XENON100
- XENON 1t
- DarkSide 50

**Scintillation**

*Crystals NaI 250 kg*
- DAMA/LIBRA

**Heat**

*Bolometric
Cryogenic CaWO$_4$
CRESST*
Rich experimental program at LNGS in the next years: many complementary techniques and target materials available

- Ultrapure scintillating NaI Crystals
  - DAMA/LIBRA: continues observations on annual modulation with improved set-up (lower energy threshold)

- Liquid XENON
  - Xenon 100: Running, new results expected by 2012
  - XENON 1T: approved by INFN and LNGS SC, location: Hall B, MOU signed, installation will start by fall 2012

- Liquid Argon Technology
  - Pioneered by Warp, continues with DarkSide 50

- CRESST
  - Results shown last year; it will resume Data Taking with low bkg
  - precursor of the next-generation dark matter project EURECA
DAMA/LIBRA: Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)  Total exposure: 425428 kg·day = 1.17 ton·yr

Experimental single-hit residuals rate vs time and energy

\[ A = (0.0183 \pm 0.0022) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 75.7/79 \quad 8.3 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof}=147/80 \rightarrow P(A=0) = 7 \cdot 10^{-6} \]

2-4 keV

\[ A = (0.0144 \pm 0.0016) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 56.6/79 \quad 9.0 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof}=135/80 \rightarrow P(A=0) = 1.1 \cdot 10^{-4} \]

2-5 keV

\[ A = (0.0114 \pm 0.0013) \text{ cpd/kg/keV} \]
\[ \chi^2/\text{dof} = 64.7/79 \quad 8.8 \sigma \text{ C.L.} \]

Absence of modulation? No
\[ \chi^2/\text{dof}=140/80 \rightarrow P(A=0) = 4.3 \cdot 10^{-5} \]

The data favor the presence of a modulated behavior with proper features at 8.8\sigma \text{ C.L.}
The XENON Dark Matter Program

past (LNGS)  (2005 - 2007)

current (LNGS)  (2008-2011)

future  (2011-2015)

XENON10
Achieved (2007) $\sigma_{SI} = 8.8 \times 10^{-44} \text{ cm}^2$

XENON100
Achieved (2011) $\sigma_{SI} \approx 7 \times 10^{-45} \text{ cm}^2$

XENON1T
Projected (2015) $\sigma_{SI} \sim 10^{-47} \text{ cm}^2$

Achieved (2010) $\sigma_{SI} = 2.4 \times 10^{-44} \text{ cm}^2$

Approved by INFN and by the LNGS Scientific Committee
2011 Results: XENON100 Dark Matter Limit (90% CL)

Minimum at $7 \times 10^{-45}$ cm$^2$ and 50 GeV
**DarkSide-50**

- first implementation of new technologies
  - depleted argon, QUPIDs, organic-scintillator-based neutron veto
- dual-phase TPC à la WARP
- 50 kg DAr active mass

sensitivity $10^{-45} \text{ cm}^2$ in 3-yrs background-free operation

demonstrate potential of the technology for multi-ton year background-free sensitivity
Laboratory for Underground Nuclear Astrophysics

400 kV Accelerator:
- $E_{\text{beam}}$: 50 – 400 keV
- $I_{\text{max}} \approx 500 \mu\text{A}$ protons
- $I_{\text{max}} \approx 250 \mu\text{A}$ alphas

<table>
<thead>
<tr>
<th>reaction</th>
<th>Gamow energy (keV)</th>
<th>Lowest meas. Energy (keV)</th>
<th>LUNA limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{15}\text{N}(p,\gamma)^{16}\text{O}$</td>
<td>10-300</td>
<td>130</td>
<td>50</td>
</tr>
<tr>
<td>$^{17}\text{O}(p,\gamma)^{18}\text{F}$</td>
<td>35-260</td>
<td>300</td>
<td>65</td>
</tr>
<tr>
<td>$^{18}\text{O}(p,\gamma)^{19}\text{F}$</td>
<td>50-200</td>
<td>143</td>
<td>89</td>
</tr>
<tr>
<td>$^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$</td>
<td>100-200</td>
<td>240</td>
<td>138</td>
</tr>
<tr>
<td>$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$</td>
<td>50-300</td>
<td>250</td>
<td>68</td>
</tr>
<tr>
<td>$D(\alpha,\gamma)^{6}\text{Li}$</td>
<td>50-300</td>
<td>700(direct)</td>
<td>50</td>
</tr>
</tbody>
</table>

3 reactions still to be studied: probably 2-3 years from now
Nuclear astrophysics FUTURE: LUNA MV

key reactions of the He burning and neutron sources for the s-process

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}, \quad ^{13}\text{C}(\alpha,n)^{16}\text{O}, \quad ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}, \ (\alpha,\gamma) \text{ reactions on } \ ^{14,15}\text{N} \quad \text{and }\ ^{18}\text{O} \rightarrow$ reactions relevant at higher temperatures than reactions belonging to the hydrogen-burning studied so far at LUNA.

higher energy machine required: 3 MV

Location underground identified: interferometric area

n production could be an issue with the other experiments

no major impact in the foreseen position
CONCLUSIONS

- INFN-Gran Sasso laboratory is the largest underground laboratory in the world
  - Leadership in massive experiments with record performance and low-level background

- The present scientific program of LNGS includes a very broad spectrum of competitive experiments (astroparticle, particle and nuclear physics)
  - 16 experiments + R&D activities, including world-leading in the fields of solar neutrinos, accelerator neutrinos, double beta decay, dark matter and nuclear astrophysics

- Plan to maintain the scientific excellence in the next years by an extensive physics program (new experiments and upgrades of the present ones)

- After the end of the CNGS program (2013-2015), underground space (OPERA and ICARUS) could be made available
  - Laboratory still open to proposals for new and innovative experiments