THE ASPECT I LIKE MOST
THE IDEA OF COSMIC SILENCE

from dream to reality!
A SHORT HISTORY

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.
GRAN SASSO
A WONDER OF NATURE
LNGS is (by far) the largest, the easiest to access and deep enough.
OUTLINE

Introduction

Neutrino Physics

Dark Matter

more science....

Summary
Muon Flux

3.0 \times 10^{-4} \mu \text{m}^{-2} \text{s}^{-1}

Neutron Flux

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Flux Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0-1 keV)</td>
<td>2.92 \times 10^{-6} \text{n cm}^{-2} \text{s}^{-1}</td>
</tr>
<tr>
<td>(&gt; 1 keV)</td>
<td>0.86 \times 10^{-6} \text{n cm}^{-2} \text{s}^{-1}</td>
</tr>
</tbody>
</table>

3 main halls A B C \sim 100 \times 20 \text{ m}^{2} (h 20 \text{ 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
High Energy Neutrinos

Solar and Cosmogenic Neutrinos

Double $\beta$ decay
FIRST TAU NEUTRINO CANDIDATE EVENT

Muonless event 9234119599, taken on 22\textsuperscript{nd} August 2009
LOOKING AT WHAT THE EMULSIONS ARE GOOD AT
INTERPRETATION

careful visual inspection of the films behind/in front of the secondary vertex:

no “black” or “evaporation” tracks. Support topological hypothesis of a particle decay
ICARUS-T600 @ LNGS

0.77 kton LAr-TPC
Primary vertex (A):
very long $\mu$ (1), e.m. cascades (2), $\pi$ (3)

Secondary vertex (B):
longest track (5) is a $\mu$ from stopping K (6)
$\mu$ decay is observed
ICARUS result strongly limits parameters for LSND anomaly

\[ (\Delta m^2 - \sin^2 2\theta) = (0.5 \text{ eV}^2 - 0.005) \]
NEUTRINO PHYSICS

- High Energy Neutrinos
- Solar and Cosmogenic Neutrinos
- Double $\beta$ decay
SOLAR NEUTRINOS

Sun is a precious source of neutrinos. They are studied thoroughly on Earth!
BOREXINO @ LNGS
BOREXINO CONTRIBUTION TO SOLAR NEUTRINO UNDERSTANDING

Graphs showing neutrino flux and survival probability against energy.
The Earth shines in anti-$\nu$

$^{238}\text{U}$ $\rightarrow$ $^{206}\text{Pb} + 8\alpha + 8\ e^- + 6\ \nu_e + 51.7\ \text{MeV}$

$^{232}\text{Th}$ $\rightarrow$ $^{208}\text{Pb} + 6\alpha + 4\ e^- + 4\ \nu_e + 42.8\ \text{MeV}$

$^{40}\text{K}$ $\rightarrow$ $^{40}\text{Ca} + e^- + 1\ \nu_e + 1.32\ \text{MeV}$

Uranium & Thorium contribution disentangled
anti-neutrino sources

- **SOX-A**
  - $^{51}$Cr neutrino source (external)
  - Tentative schedule: 2015/2016

- **SOX-B**
  - $^{144}$Ce anti-neutrino source (external)
  - Tentative schedule: 2015-2016 (TBD)

- **SOX-C**
  - $^{144}$Ce anti-neutrino source (internal)
  - No schedule (>2016)
High Energy Neutrinos
Solar and Cosmogenic Neutrinos
Double $\beta$ decay
WHAT IS A NEUTRINO?
NEUTRINOLESS DBD
INVERTED OR DIRECT?

Three region:
1) Degenerate: few 100meV
2) Inverse: few 10meV
3) Direct: few meV
THE NASTY PROBLEM

Sensitivity

\[ \propto K \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \]

\[ m \propto \sqrt{\frac{1}{\tau}} \]

To gain a factor 10 you need 10000!

GERDA: 15 kg, i.a. = 1, B=0.01, 300 meV @ 2 year

what are the achievable limits?

i.a. =1 ? $$$$$$$$$$$$$
B=0.0001 ideas!
M= kT on does it go with energy resolution?

Daring

isn’t it?
GERDA

clean room – rdy

phase I lock – under test

status

cryo-mu-lab

control room

water plant Rn monitor

phase I array rdy (scaled:)

FE electronics under test

μ veto rdy

cryostat - rdy

water tank - rdy

GERDA bldg - rdy

LAr fill : Oct/Nov 09
Energy resolution at $Q_{\beta\beta}$ (FWHM, mass weighted average):

- 4.5 keV for coaxial detectors
- 3 keV for BEGe detectors
Average background index values in $Q_{\beta\beta}$ ± 100 keV (excluding central 40 keV):

- $2.2^{+0.3}_{-0.3} \times 10^{-2}$ cts/(keV·kg·yr), enriched Ge coaxials, 13.6 kg·yr
- $1.7^{+0.3}_{-0.3} \times 10^{-2}$ cts/(keV·kg·yr), enriched Ge coaxials, 12.3 kg·yr (w/o run 34/35, 8% exp)
- $4.1^{+1.5}_{-1.2} \times 10^{-2}$ cts/(keV·kg·yr), enriched BEGe’s, 1.5 kg·yr
- $2.4^{+0.3}_{-0.3} \times 10^{-2}$ cts/(keV·kg·yr), natural Ge coaxial, 4.7 kg·yr

Previous experiments:
- HdM: $B_I = 0.17$ cts/(keV·kg·yr)
- IGEX: $B_I = 0.17$ cts/(keV·kg·yr)

Background contributions at $Q_{\beta\beta}$:
- $\gamma$: TI-208 and Bi-214
- $\beta$: K-42 and Bi-214
- $\alpha$: Po-210, Rn-222 chain
eagerly awaiting for neutrinoless DBD results. To compare to HdM.
Searching for neutrinoless double beta decay of $^{130}\text{Te}$

Expected 5 Years sensitivity:

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

background counting rate

$10^{-2} \text{ c/keV/kg/y}$
A couple of hundred ingots for the CUORE shielding

$^{210}\text{Pb}$ free (22.3 y half-life)

2000 y shielded by sea water
CUORE PRINCIPLE

heat sink \((T_0)\)

(thermal conductance \(G\))

thermometer

\(\beta \beta\) atom x-tal

Basic Physics: \(\Delta T = \frac{E}{C}\)

\[
C(T) = \beta \frac{m}{M} \left( \frac{T}{\Theta_D} \right)^3
\]

\[
\Delta T(t) = \frac{\Delta E}{C} \exp \left( -\frac{t}{\tau} \right)
\]

\(T_0 \sim 10\) mK

\(C \sim 2\) nJ/K \(\sim 1\) MeV/0.1 mK

\(G \sim 4\) pW/mK
CUORE FIRST PHASE
CUORE-0

CTAL (CUORE Tower Assembly Line)
radioactivity control
reproducible protocols

Assembled in N₂ atmosphere
uses equipment developed for CUORE
e.g. new CUORE gluing semi-automatic machine

1 CUORE-like tower of 13 planes - 4 crystals each

52 TeO₂ 5x5x5 cm³ crystals

Detector Mass: 39 kg TeO₂

¹³⁰Te mass (natural i.a.): 11 kg of ¹³⁰Te

Ch. # 45 calibration spectrum
(²³²Th source)

E (@2615 keV) = 5.3 keV (FWHM)
CUORE SENSITIVITY

\[ T^{00}_{1/2} \] vs Live time [y]

- **Cuoricino**
- CUORE-0 - bkg: 0.05 cts/(keV kg y)
- CUORE - bkg: 0.01 cts/(keV kg y)
AN OPTION FOR A BRIGHT FUTURE

- Tower of 32-40 ZnSe scintillating bolometers at Gran Sasso, enriched in $^{82}\text{Se}$, ~10 kg of $^{82}\text{Se}$.

- Background free: $\alpha$ background identified via the scintillation signal, $\beta/\gamma$ radioactive background below the $^{82}\text{Se}$ Q-value (2997 keV).

• 431g Zn$^{nat}$Se crystal operated for 22 days.
  ‣ $\Delta E@2615$ keV = 13 keV FWHM
  ‣ $\alpha$ background entirely identified via light pulse shape.

• One $\beta/\gamma$ event above 2615 keV, in coincidence with several hits in nearby detectors ($\mu$-spallation).
• Easily to tag via coincidence analysis in an array, or via a $\mu$-veto.
LVD

Search for $\nu$ from Core Collapse Supernovae
Run from 1992
1 kT
100% duty cycle
90% U.L. of gravitational collapses (for D<20kpc)
R<0.12 events /year
**OPERA-LVD MUONS**

a solution to the fast neutrino problem at hand!

**Time-shift in OPERA set-up**
high energy horizontal $\mu$
both LVD & OPERA


---

Class A
Class B
Class A

---

DARK MATTER SEARCHES
The mass inside an orbit can be found using the size of the orbit and the orbital speed. The arrows show the speeds for certain points on the rotation curve for this galaxy.
STRONG LENSING

YOU LOOK UP AT A GALAXY...

LIGHT FROM IT COMES ONE WAY...

AND GETS BENT BY THE DARK MATTER'S GRAVITY...

GALAXY

DARK MATTER

BUT IT ALSO COMES AROUND THE OTHER WAY...

YOU SEEM TO SEE A GALAXY IN TWO DIFFERENT DIRECTIONS...

YOU

BUT IT'S ACTUALLY THE SAME GALAXY!
DAMA/LIBRA

- Ultrapure Na(Tl)
  - Residual contamination
  - $^{232}$Th, $^{238}$U and $^{40}$K at level of $10^{-12}$ g/g
Comparison between single hit residual rate (red points) and multiple hit residual rate (green points):
$A = -(0.0006 \pm 0.0004) \text{cpd/kg/keV}$

Multiple hits events = Dark Matter particle “switched off”

$2-6 \text{ keV}$
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

Systematics or other processes do not explain quantitatively the measured modulation amplitude and simultaneously satisfy the signal characteristics.

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

→ phonon channel provides precise measurement of deposited energy
→ Light channel distinguishes types of interaction
→ Types of recoiling nuclei distinguished by different slopes in light energy plane
The latest CRESST run

Net exposure after cuts: 730 kg days

Assumes missing events due to WIMPs

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon/\gamma$-events</td>
<td>$8.00 \pm 0.05$</td>
<td>$8.00 \pm 0.05$</td>
</tr>
<tr>
<td>$\alpha$-events</td>
<td>$11.5^{+2.6}_{-2.3}$</td>
<td>$11.2^{+2.5}_{-2.3}$</td>
</tr>
<tr>
<td>neutrons events</td>
<td>$7.5^{+6.3}_{-5.5}$</td>
<td>$9.7^{+6.1}_{-5.1}$</td>
</tr>
<tr>
<td>Pb recoils</td>
<td>$15.0^{+5.2}_{-5.1}$</td>
<td>$18.7^{+4.9}_{-4.7}$</td>
</tr>
<tr>
<td>Signal events</td>
<td>$29.4^{+8.6}_{-7.7}$</td>
<td>$24.2^{+8.1}_{-7.2}$</td>
</tr>
<tr>
<td>$m_X$ [GeV]</td>
<td>$25.3$</td>
<td>$11.6$</td>
</tr>
<tr>
<td>$\sigma_{WN}$ [pb]</td>
<td>$1.6 \cdot 10^{-6}$</td>
<td>$3.7 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

Assumes missing events due to WIMPs
THE XENON FAMILY

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

Achieved (2011) $\sigma_{SI}=7.0 \times 10^{-45}$ cm$^2$

Achieved (2012) $\sigma_{SI}=2 \times 10^{-45}$ cm$^2$

Projected (2017) $\sigma_{SI} \sim 2 \times 10^{-47}$ cm$^2$
XENON100 SI RESULTS

The graph illustrates the WIMP-nucleon cross-section as a function of WIMP mass, with various experimental results and limits from different collaborations.

- **Observed Limit (90% CL)**
- Expected limits:
  - $\pm 1\sigma$ expected
  - $\pm 2\sigma$ expected

Collaborations and years mentioned include:
- DAMA/Na
- CoGeNT
- XENON100 (2011)
- SIMPLE (2012)
- XENON100 (2012)
- CRESST-II (2012)
- COUPP (2012)
- ZEPLIN III (2012)
- CDMS (2010/11)
- EDELWEISS (2011/12)
- XENON100 (2011)

The graph provides a visual comparison of these results, highlighting the observed and expected limits for WIMPs.
XENON100 SD RESULTS
DARKSIDE (LAR DARK MATTER SEARCH)
DARKSIDE INNER CHAMBERS
• DarkSide-50 ($2 \times 10^{-45}$ cm$^2$)
  - Funded by DOE, INFN, NSF
• DarkSide-G2 ($2 \times 10^{-47}$ cm$^2$)
  - R&D funded by NSF (May 1 2012)
• Detector requirements
  - Low energy nuclear recoils ($< 100$ keV)
  - Low rate (~1 event/ton/yr for $10^{-47}$ cm$^2$)
  - Background, background, background
• Detector designed for discovery
A LOT OF LIGHT

- Pulse shape Discrimination
- Primary Scintillation
- Ionization/scintillation Ratio
- Sub-cm Spatial Resolution
- Underground argon

DS-10 Results
- \( \text{LY}=8.9 \text{ pe/keVee} \)
NUCLEAR

ASTROPHYSICS
nuclear fusion reaction cross sections

- Stars powered by nuclear reactions
- Key parameters to model stars: chemical composition, opacity...
- Reactions cross sections
- Determine the origin of elements
- Stellar evolution and dynamics
- Many reactions need high precision data.
LUNA ASTROPHYSICAL
MOTIVATION

- Solar neutrinos:
  \[ ^3\text{He}(^3\text{He},2p)^4\text{He}, \ ^3\text{He}(^4\text{He},\gamma)^7\text{Be}, \ ^{14}\text{N}(p,\gamma)^{15}\text{O} \]

- Age of globular cluster:
  \[ ^{14}\text{N}(p,\gamma)^{15}\text{O} \]

- Light nuclei nucleosynthesis
  \[ (^{17}/^{18}\text{O} \text{ abundances, } ^{19}\text{F} \text{ production, } ^{26}\text{Mg} \text{ excess, }...) \]
  \[ ^{15}\text{N}(p,\gamma)^{16}\text{O}, \ ^{17}\text{N}(p,\gamma)^{18}\text{O}, \ ^{25}\text{Mg}(p,\gamma)^{26}\text{Al} \]

- Big Bang Nucleosynthesis:
  \[ ^2\text{H}(\alpha,\gamma)^6\text{Li}, \ ^3\text{He}(^4\text{He},\gamma)^7\text{Be}, \ ^2\text{H}(p,\gamma)^3\text{He} \]

- Next:

- Light nuclei nucleosynthesis:
  \[ ^{17}\text{O}(p,\alpha)^{14}\text{N}, \ ^{22}\text{Ne}(p,\gamma)^{23}\text{Na}, \ ^{23}\text{Na}(p,\gamma)^{24}\text{Mg}, \ ^{18}\text{O}(p,\gamma)^{19}\text{F}, \ ^{18}\text{O}(p,\alpha)^{15}\text{N} \]

- He burning and stellar evolution:
  \[ ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \]

- s process nucleosynthesis:
  \[ ^{13}\text{C}(\alpha,n)^{16}\text{O}, \ ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]
Higher energy machine
- 3.5 MV single ended positive ion accelerator
- Now funded by Italian Research Ministry
  - 2.8 Million of Euros!
  - New collaborations highly welcome

Aim

key s-process reactions
- Helium burning
- neutron sources
  - $^{12}$C($\alpha,\gamma$)$^{16}$O
  - $^{13}$C($\alpha,n$)$^{16}$O
  - $^{22}$Ne($\alpha,n$)$^{25}$Mg
  - ($\alpha,\gamma$) reactions on $^{14,15}$N and $^{18}$O
- Relevant at higher temperatures than hydrogen-burning
HELPING BIOLOGY
LOW BACKGROUND RADIATION

- Test the “Linear No Threshold” model
  - No point in doubling the dose
  - Need to lower the dose
    - Is the damage to cells (DNA) $\propto$ dose
      - at low dose
    - or are low doses of radiation
      - more damaging ..... or ....
      - less damaging
      - than expected from the LNT model
  - *in vitro* studies done
  - with tantalising results
  - *in vivo* ?????
more.......
OTHER EXPERIMENTS

- Test of fundamental principles (Pauli, General Relativity)
- Environmental Sciences
<table>
<thead>
<tr>
<th>A great intuition</th>
<th>The Scientific Programme at Gran Sasso is world leading and addresses crucial scientific issues</th>
</tr>
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<td>A superb facility</td>
<td>Neutrino Physics</td>
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<tr>
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<td>Dark Matter</td>
</tr>
<tr>
<td>A brilliant future</td>
<td>Foundations of physics and cosmology</td>
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<td>potentially Environment and health</td>
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A national lab & international asset