Detector R&D
non-Accelerator Physics

10-17 July 2019 - Ghent, Belgium

Ezio Previtali
University and INFN of Milano Bicocca
...in the sky, on the earth and almost everywhere...

...I will do my best but...
Main experimental challenges

Physics challenges

Neutrino physics
- Neutrinoless Double Beta Decay
- Neutrino Oscillation
- Direct Neutrino Mass Measurements

Direct Dark Matter Search
- Low and high mass WIMPs
- Axions

High Energy Cosmic Rays

Gravitational Waves

Detector challenges

Increase signal
- Large mass
- High intensity sources

Detector performances
- Energy resolution
- Time resolution
- Position/Angular resolution

Low background
- Underground labs
- Very high purity materials
- Large radioactive shields
- Signal/Background discrimination
$\beta\beta$ decay sensitivity

**Approach:**

SOURCE = DETECTOR

- Detector mass [kg]
- Measuring time [y]
- Detector efficiency
- Isotopic abundance
- Atomic number
- Energy resolution [keV]
- Background [c/keV/y/kg]

**Experimental sensitivity related**

$\Delta E \text{ BI} \quad M \text{ } t_{\text{meas}}$

$\tau_{1/2}^{0\nu}$ sensitivity

$S(\tau_{1/2}^{0\nu}) \propto \frac{a.i.}{A} \frac{M t_{\text{meas}}}{\Delta E \cdot BI}$

**Background Index vs Detector Mass**

$\Delta E = 10$ keV

$t_{\text{meas}} = 10$ years
$0\nu\beta\beta$ – GERDA, HPGe background rejection

Novel HPGe detectors allow for efficient PID

Thanks S. Shoenert
$0\nu\beta\beta$ – GERDA, HPGe background rejection

 Novel HPGe allow for efficient PID

Thanks S. Shoenert

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
$0\nu\beta\beta$ - GERDA background achievements

GERDA experiment operates in a real $0$ background conditions

Thanks S. Shoenert

Ezio Previtali
From GERDA to LEGEND

LEGEND-200 (first phase):
- up to 200 kg of detectors
- BI < 2E-4 cts/(keV kg yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t yr
  - Sensitivity $10^{27}$ yr
  - Isotope procurement ongoing
  - Start in 2021

LEGEND-1000 (second phase):
- 1000 kg of detectors (deployed in stages)
- BI < 1E-5 cts/(keV kg yr)
- Location tbd
- Design exposure ~ 10 t yr
  - $1.2 \times 10^{28}$ yr

LEGEND.
To increase the experimental mass a new HPGe detector configuration will be adopted

Inverted Coaxial Detector guaranties the same rejection capability as BEGe detector with a detector mass of 2 kg

Inverted coaxial detectors:
R. Cooper, D. Radford, P. Hausladen, K. Lagergren

Pulse shape discrimination performance of Inverted Coaxial Ge detectors

Thanks S. Shoenert
$0\nu\beta\beta$ – NEXT, High Pressure Gas-Xe TPC

Gas-Xe TPC with two readout planes

Energy resolution at $Q_{\beta\beta} < 1\%$ FWHM

High Energy Resolution
Topological event reconstruction

Talk P. Novella

Topological signature: 2nu candidates

Topological signature:
92\% signal efficiency 92\% background rejection

Thanks J.J. Gomes Cadenas

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
$0\nu\beta\beta$ – NEXT, High Pressure Gas-Xe TPC

NEXT – 100 detector under preparation

Energy resolution at $Q\beta\beta < 1\ %$ FWHM

Expected BI: $< 4.09 \times 10^{-4}$ cts / (keV kg year)

Topological signature: 2nu candidates

Talk P. Novella

Thanks J.J. Gomes Cadenas

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
$0\nu\beta\beta$ – NEXT, Ba$^{++}$ tagging

$0\nu\beta\beta$ of $^{136}$Xe

In the final state there are:
- 2 electrons
- 1 Ba$^+$ ion

$^{136}$Xe $\rightarrow$ $^{136}$Ba + 2 e$^-$

Electrons are detected by the TPC

Identification of Ba$^{++}$ ions will strongly suppress the background

A more clear determination of the Ba detection efficiency is needed

Thanks J.J. Gomes Cadenas

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

0νββ – From EXO200 to nEXO

5 ton LXe enriched in $^{136}$Xe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nEXO</th>
<th>EXO-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Mass (kg)</td>
<td>4780</td>
<td>98.5</td>
</tr>
<tr>
<td>Enrichment (%)</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>Data taking time (yr)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Energy resolution @Q_{ββ} (keV)</td>
<td>58</td>
<td>88 (58)</td>
</tr>
<tr>
<td>Background in ROI (ev/yr/mol$^{136}$)</td>
<td>$6.1 \times 10^{-4}$</td>
<td>0.022 (0.0073)</td>
</tr>
<tr>
<td>Background in ROI inner 3000kg (ev/yr/mol$^{136}$)</td>
<td>$1.6 \times 10^{-4}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Thanks G. Gratta

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium

Ezio Previtali
$0\nu\beta\beta$ – nEXO R&D to finalize detector design

New charge collection tiles


Prototype charge collection tile

New SiPM


Thanks G. Gratta

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium

Ezio Previtali
$0\nu\beta\beta$ – CUPID: CUORE Upgrade with Particle IDentification

- CUORE cryostat: **most powerful cryostat** ever realized
- **Tens of ton of materials** cooled at 10 mK
- Cryogenic detectors are **reliable**

CUORE alpha background
BI $\sim 10^{-2}$ 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**
0νββ – CUPID scintillating bolometer background rejection

- Scintillating crystals and light detectors operated @ 10 mK
- Grown from various ββ emitters (multi-isotope approach)
- Excellent energy resolution @Q_ββ (<1%)
- Possibility to high Q_ββ (3 MeV) for ^82Se and ^100Mo
- L_yα ≠ L_yβ/γ → Particle ID
- LShape_α ≠ LShape_β/γ → Particle ID
- HShape_α ≠ HShape_β/γ → Particle ID
$0\nu\beta\beta$ – CUPID Conceptual Design

- Re-use **CUORE cryogenic infrastructure** at LNGS
- Li$_2^{100}$MoO$_4$ scintillating crystals
- $\sim$1500 crystals for **250 kg of $^{100}$Mo**
- Active background rejection using light and heat signals
- Options for **multiple isotopes**.
- TDR and **construction readiness in 2021**

Expected BI $\sim 1 \times 10^{-4}$ cts / (keV kg year)

**CUPID CDR available soon**

**Talk L. Pattavina**
$0\nu\beta\beta$ – CUPID-CROSS surface background rejection

Numerous above-ground tests (CSNSM, Orsay) with $20\times20\times10$ mm Li$_2$MoO$_4$ and TeO$_2$ crystals and recently with a large (75 g) Li$_2$MoO$_4$ crystal

10-μm-thick Al film

75 g Li$_2$MoO$_4$ crystal

Alphas impacting on the film side are clearly discriminated.

Next test: fully coated crystal

Thanks A. Giuliani
Direct neutrino mass measurement with $^3$H

$$\beta: \frac{dN}{dE} = K F(E,Z) \rho E_0 \sum |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m(\nu_i)^2}$$

essentially phase space:

- $p_e$  
- $E_e$  
- $E_\nu$  
- $p_\nu$

very tiny signature!

Talk S. Pascoli
KATRIN - Direct neutrino mass measurement

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium

Thanks C. Weinheimer
KATRIN – Many technological challenges

- 10 kg/a tritium throughput
- $10^{-3}$ stability of tritium source column density
- $10^{-3}$ isotope content in source
- $10^{-5}$ non-adiabaticity in electron transport
- $10^{-5}$ monitoring of HV-fluctuations
- $10^{-8}$ remaining ions after source
- $10^{-14}$ remaining flux of molecular tritium
- $10^7$ dynamic rate range
- $10^{-2}$ background rate envisaged
- $10^{-11}$ mbar ultrahigh vacuum

- huge circulation and purification system, special TMPs
- temp. regulation by dual phase Ne
- laser Raman spectroscopy
- novel computational code KASSEIPEIA, pulsed angular-defined electron gun
- ultra-precision HV divider, novel e\(^{-}\) source
- dipole drift electrodes, FT-ICR
- 3K cryopumping section with Ar snow
- electronics and DAQ
- huge cold-baffles to catch radon
- huge getter pumps and TMPs

KATRIN, the film: http://www.youtube.com/watch?v=cnu79iC0C1M

Thanks C. Weinheimer

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
KATRIN – Background from the spectrometers

Penning trap at spectrometer entrance/exit
Mitigation: „Colani-shaped“ electrodes

Secondary electrons from walls
Mitigation: air coils & wire electrodes

Rydberg atoms due to $^{212}$Pb in wall
Mitigation: still working ...

Stored electrons in specs
Mitigation: electric dipole & magnetic pulses

Intrinsic Penning trap between specs
Mitigation: $10^{-11}$ mbar backed up by „wiper“

Radon emanating from NEG pumps:
Mitigation: LN2-cooled baffles

M. Beck et al., EPJ A44 (2010) 499
F. M. Fränkle et al., APP 35 (2011) 128
S. Mertens et al., APP 41 (2013) 52
F.M. Fränkle et al., JINST 9 (2014) P07028

G. Drexlin et al., Vacuum 138 (2017) 165
M. Arenz et al., arXiv:1805.01163
M. Arenz et al., arXiv:1805.12173

Thanks C. Weinheimer

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
Criogenic detector for direct neutrino mass measurement

\[
\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \left[1 - \frac{m_v^2}{(Q_{EC} - E_C)^2}\right] \sum_H B_H \phi_H^2(0) \frac{\Gamma_H}{2\pi} \frac{1}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}
\]

Statistics in the end point region
- \( N_{ev} > 10^{14} \rightarrow A \approx 1 \text{ MBq} \)

Unresolved pile-up \((f_{pu} \sim a \cdot \tau_r)\)
- \( f_{pu} < 10^{-5} \)
- \( \tau_r < 1 \mu\text{s} \rightarrow a \approx 10 \text{ Bq} \)
- \( 10^5 \) pixels

Precision characterization of the endpoint region
- \( \Delta E_{FWHM} < 3 \text{ eV} \)

Background level
- \(< 10^{-5} \) events/eV/det/day


Thanks L. Gastaldo

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
Criogenic detector high energy resolution technologies

Low temperature microcalorimeters

- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- Very sensitive temperature sensor

\[ \Delta T \approx \frac{E}{C_{\text{tot}}} \]

\[ \tau = \frac{C_{\text{tot}}}{G} \]

Resistance at superconducting transition, TES


Magnetization of paramagnetic material, MMC


Thanks L. Gastaldo

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
Criogenic detector performances

Fast risetime $\rightarrow$ Reduction un-resolved pile-up

Extremely good energy resolution $\rightarrow$ Reduced smearing in end point region

Excellent linearity $\rightarrow$ precise definition of the energy scale

A. Fleischmann et al., AIP Conf. Proc. 1185 (2009) 571

Thanks L. Gastaldo
DM – CRESST: scintillating bolometers for dark matter search

CaWO₄ iSticks (with holding clamps & TES)

reflective and scintillating housing

light detector (with TES)

block-shaped target crystal (with TES)

TES – Transition Edge Sensor

log scale

WIMP - ⁷⁸Ge nucleon scattering

Talk J. Schieck
Thanks F. Petricca

©T. Dettlaff/MPP

©Ezio Previtali

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
DM – CRESST: very low threshold scintillating bolometer

Detector layout optimized for low-mass dark matter

Radical reduction of dimension (300→25g)

- Cuboid crystals of \((20\times20\times10)\text{mm}^3\) (≈24g)
- With self grown crystals ≈4 counts/(keV kg day)
- Threshold design goal <100 eV (best achieved 30 eV)
- Fully scintillating housing
- Instrumented sticks

Eff. ≈ 65%

Threshold \(E_{\text{th}} = 30.1\) eV (cross-check by fitting error function)

Talk J. Schieck
### DM – XENON, dual phases LXe TPC

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
<th>XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>25 kg – 15 cm drift</td>
<td>161 kg – 30 cm drift</td>
<td>3.2 t – 1 m drift</td>
<td>8 t – 1.5 m drift</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>~10^{-43} cm²</td>
<td>~10^{-45} cm²</td>
<td>~10^{-47} cm²</td>
<td>~10^{-48} cm²</td>
</tr>
</tbody>
</table>

Talk A. Brown

Thanks C. Weinheimer

**EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium**
DM – XENON, dual phases LXe TPC

Drift time:
\[ \Delta t = t_{s2} - t_{s1} \]

Drift velocity:
\[ v \approx 2 \text{ mm/\mu s} \approx 7200 \text{ km/h} \]

Depth (z - position):
\[ z = v \cdot \Delta t \]

Concentric PMT array on top
\[ \rightarrow \text{S2 signal local} \]
\[ \rightarrow \text{x} - \text{and y - position} \]

\[ \rightarrow \text{3D position reconstruction} \]
\[ \rightarrow \text{Self - shielding} \]
\[ \rightarrow \text{Inner + radio-pure volume} \]

Thanks C. Weinheimer
DM – XENON, dual phases LXe TPC

Figure in courtesy: L. Althüser

Thanks C. Weinheimer

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
DM – XENON, dual phases LXe TPC

Particle identification

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

Figure in courtesy: L. Althüser

Thanks C. Weinheimer
**DM – Online krypton removal for XENON1T**

**Event Rate in TPC (ER):** Data give direct „online“ insight to innermost 700 kg of LXe

**Rare Gas Mass Spectrometer (RGMS):** Samples extracted from LXe for off-site analysis at MPIK Heidelberg

First RGMS point scaled to ER rate
- Direct comparison at all times possible
- Allows for absolute calibration of ER

At the beginning:
- Krypton dominated

At the end:
- Radon dominated

- Reached sufficient krypton concentration for first science run
- Lowest background so far

\[
\text{natKr/Xe} = (360 \pm 60)\text{ppq}
\]

M. Murra, PhD thesis, 2019


---

**M. Murra, PhD thesis, 2019**

**Ezio Previtali**

**EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium**
DM – XENONnT Radon mitigation

TPC + Cryostat emanate 19% of total budget
→ Reduce with a new Radon Distillation System
→ Expect less radon due to lower surface to volume ratio by factor $3^{1/3} \sim 1.4$

Cryo-pipe/cables/CRY system emanate 46% of total budget
→ Reduce with online distillation

PUR system emanates 35% of total budget
→ Reduce by pump exchange

Thanks C. Weinheimer
DM – LAr TPC

For LAr TPC
Pulse shape discrimination on S1 signal shape (Talk T. Pollman – DEEP)

Electroluminescence of S2:
- Additional γ/n discrimination (S2/S1)
- Radial fiducialization
  (Talk A. Caminata – Dark Side)
DM – DS20k development on SiPM

- **Silicon-based 3” PMT** equivalent
- The basic photo-detector element in DS-20k
  - One read-out analog channel per PDM
    - Aggregating **24x 1cm² SiPM**
- Integrates the SiPMs and the electronics in a plastic cage

**NUV-HD-LF – Dark Rate**

The NUV-HD technology was selected

- Peak sensitivity **at ~ 420 nm**
- High density SPAD with high PDE

NUV-HD Low field variant:

- **DCR ~ 5 \(10^{-3}\) cps/mm² at 80 K**

FBK developed the NUV-HD-Cryo variant for extended gain at cryogenic temperature

- It is based on NUV-HD-LF with different (higher) doping
- It allows operation of NUV-HD at 14 Volt over-voltage

Thanks G. Fiorillo

IEEE Trans. Electron Dev. 64 2, 2017
DM – DS20k SiPM performances

Finger plot of a full PDM
- 25 cm$^2$ @ 77 K
- SNR > 20
- Gain disuniformity < 3%

Amplitude vs Time (1 pe)
- 25 cm$^2$ @ 77 K
- Jitter 3-4 ns

- 2 Motherboards were produced and tested
- A motherboard 25 PDM = 600 SiPM 1 cm$^2$ large
  - For a total gross surface of 625 cm$^2$
- The tests demonstrated a very high uniformity of the signal-to-noise ration of the PDMs

Thanks G. Fiorillo
Detection principle

1. Ionization induced by a particle
   - 2.6 eV band gap
2. Electrons trapped at a lattice defect on the crystal surface
   - Attract interstitial silver ions
   - Produce a “latent image” = $\text{Ag}_n$
3. Chemical amplification of signal
   - Development $\rightarrow$ silver filaments
   - $10^7 - 10^8$ amplification
4. Dissolve crystals
5. Observe it at optical microscopes

Grain as seen by a sensor of an optical microscope

Crystal size
NIT: nano imaging tracker

- 40 nm
- 25 nm

Thanks G. Galati
DM – NEWs, Plasmon resonance, nanometric imaging


• Sensitive to the shape of nanometric grains: being silver grains non-spherical, the resonant response depends on the polarization of the incident light.
• Each grain is emphasized at different polarization values

Thanks G. Galati

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium

Ezio Previtali
DM – NEWS, Very high resolution analysis

Taking multiple images over the whole polarization range produces a displacement of the barycentre of the cluster.

Single grain

Barycenter of the cluster

Signal-like events (100 keV C ion)

Max barshift

Talk G. Galati
DM – NEWs, very high position accuracy

- 10keV C-ions vertical ⇒ single clusters ⇒ no displacement ⇒ position accuracy

Unprecedented accuracy of 6 nm achieved on XY coord

Future R&D will demonstrate if a large detector mass will be realizable

Talk G. Galati

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
JUNO – High sensitive neutrino oscillation experiment

a huge liquid scintillator detector

2 Key parameters:

LARGE & PRECISE

<table>
<thead>
<tr>
<th>DETECTOR</th>
<th>TARGET MASS</th>
<th>RESOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND</td>
<td>1000 t</td>
<td>6%/√E</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>8 t</td>
<td></td>
</tr>
<tr>
<td>RENO</td>
<td>16 t</td>
<td>8%/√E</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>20 t</td>
<td></td>
</tr>
<tr>
<td>Borexino</td>
<td>300 t</td>
<td>5%/√E</td>
</tr>
<tr>
<td>JUNO</td>
<td>20000 t</td>
<td>3%/√E</td>
</tr>
</tbody>
</table>

Talk M. Grassi
JUNO – High sensitive neutrino oscillation experiment

Talk M. Grassi

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium
LiquidO – Opaque-liquid-scintillator

novel opaque-liquid-scintillator technology
(unprecedented $\nu$ detection potential)

$e^+ \leftrightarrow \text{anti-}\nu(e)$  $e^- \leftrightarrow \nu(e)$  $p$-recoil

[IBD interaction]  $^{12}$C/new interaction] [cosmogenic background]

CERN seminar (https://indico.cern.ch/event/823865/) & publication (within days!)

**powerful PID capability (i.e. imaging) + large loading**

$\Rightarrow$ new physics capabilities?

Collaborators+Cooperators
(Brasil, Chile, France, Germany, Italy, Japan, Spain, UK, USA)
[contact: anatael@in2p3.fr & suekane@awa.tohoku.ac.jp]
Conclusions

• Many R&Ds on non-accelerator detectors are ongoing

• Different technologies were developed with the aim of
  • Increasing the detector masses
  • Lowering the detector backgrounds
  • Improving the detector performances

• New generation detectors is under design/construction

• Specific efforts will be needed to
  • Enriched isotope productions ($0
  • Very pure material selections
  • Suitable underground infrastructures

• Strong improvements in the experimental sensitivities is expected soon
...and what else...

Neutrino physics
SNO+
SuperNEMO
AMoRE
Project8
......

Direct Dark Matter Search
Edelweiss
LZ
COSINE
COSINUS
......

... thank you ...
Cryogenic multiplexing readout

... → ΔΦ → ΔL → Δf₀ → (ΔA, Δφ) → (ΔI, ΔQ)

Thanks A. Nucciotti
JUNO – High sensitive neutrino oscillation experiment

— By changing the constructor of the focusing electrode, using the flower-like one, the TTS of the PMTs is improving from 20ns to 5ns, but the CE of the prototype is decreasing to 85%,
— By decrease the area of the photocathode for better TTS, the dark rate of the PMT also much better than the normal one, from 40KHz to 20KHz.

Thanks M. Grassi

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Normal focusing electrode</th>
<th>Flower-like focusing electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Efficiency (400nm)</td>
<td>~30%</td>
<td>~30%</td>
</tr>
<tr>
<td>Relativity Detection Efficiency</td>
<td>~100%</td>
<td>85%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td>~7</td>
<td>~5</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>~20ns</td>
<td>5 ns</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>~40KHz</td>
<td>~20KHz</td>
</tr>
</tbody>
</table>

EPS-HEP2019 - 10-17 July 2019, Ghent, Belgium