Neutrino Experiments

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Seminar at PRISMA+
Johannes Gutenberg University Mainz
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Scientific career

2008

PhD student
University of Zaragoza (Zaragoza, Spain)
Direct dark matter search (ANAIS)

2013

Postdoc
University of Washington, (Seattle, EE.UU.)
Study of neutrinos (MAJORANA & COHERENT)

2017

Resarcher “Atracción Talento CAM”
CIEMAT (Madrid, Spain)
Study of neutrinos (ProtoDUNE, DUNE, SBND, MAJORANA)

2021

L’Oréal-UNESCO For Women In Science 2020 Award (Spain)

Participation in different experiments at all phases: design, validation, data analysis, results
NEUTRINOS
Why do we study neutrinos?

Particles of the Standard Model
- Standard Model Leptons
- Neutral charge
- 3 neutrino flavors
- Weak interaction
- Strictly massless

Neutrinos are abundant, but the most elusive particles.

Enigmatic particles, not fully understood
Provide answers to our understanding of the universe

Credit: symmetry magazine
Where are neutrinos coming from?

Neutrino sources

- Sun
- Terrestrial
- Atmospheric
- galactic & extragalactic
- Supernova
- Big bang
- Reactor
- Accelerator

Many neutrino sources with covering a broad energy range!
History highlights of neutrinos

1930 - Pauli proposed the ν: a light, spin ½, neutral particle to solve the β-decay problem: E and momentum conservation in β-decay

1956 - The neutrino (νₑ) was directly observed by Cowan & Reines.

1962 - First experiment with accelerator ν’s in Brookhaven (USA): νₑ observation.

1968 - Solar ν detection by Davis: νₑ rate smaller than expected.

1957 - Pontecorvo postulated oscillation theory of ν → ¯ν.

1962 - Maki, Nakagawa y Sakata proposed a two-flavor mixing theory and latter built a general model.

1998: Super-K detected atmospheric neutrino oscillations

2001: SNO detected solar neutrino oscillation measuring the total neutrino flux

Flavor oscillations imply that neutrinos are massive → Physics Beyond the Standard Model
Neutrino oscillations

- $\nu$'s generated in definite flavor states.
- Propagate as mass states. $\nu_m = U \nu_f$
- Experimentally detected in states or definite flavor: project back onto flavor basis at detector

**Pontecorvo, Maki, Nakagawa, Sakata (PMNS) mixing matrix**

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13} e^{-i\delta} \\
    0 & 1 & 0 \\
    -s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    e^{-i\alpha_1} & 0 & 0 \\
    0 & e^{-i\alpha_2} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

\begin{align*}
\nu_1 &= \cos \theta_{12} \\
\nu_2 &= 0 \\
\nu_3 &= 0
\end{align*}

- Atmospheric + LBL: $\nu_\mu \rightarrow \nu_\tau$
- Reactors + LBL: $\nu_\mu \rightarrow \nu_e$
- Solar + KamLAND: $\nu_e \rightarrow \nu_\mu, \tau$
- [Majorana]
- Not accessible in osc. exp. only $0\nu\beta\beta$

**Oscillation probability:**

\[
P_{\nu_\alpha \rightarrow \nu_\beta}(L, E) = \delta_{\alpha \beta} - 4 \sum_{i \neq j} \text{Re} \left[ U_{\alpha i}^* U_{\beta j} U_{\alpha j} U_{\beta i}^* \right] \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) - 2 \sum_{i \neq j} \text{Im} \left[ U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right] \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)
\]

Experimental approaches sensitive to 6 oscillation parameters.
Neutrino oscillation parameters

Evolution of experimental measurements

✓ Experimentally measured parameters: $\theta_{12}, \Delta m_{12}^2, \theta_{23}, \theta_{13}, \Delta m_{31}^2$

? Unknown parameters: mass ordering (sign of $\Delta m_{31}^2$), $\delta_{CP}, \theta_{23}$ octant
Neutrino unknowns

1. Neutrino nature
   Is the neutrino its own antiparticle? Are neutrinos Majorana particles?

2. Neutrino mass scale
   What is the absolute scale of neutrino masses?

3. Neutrino mass spectrum
   How are the three neutrino mass states ordered from lightest to heaviest (neutrino “mass ordering”)?

4. Neutrino mixing
   Is the CP symmetry violated in the neutrino sector? CP-violation is one of the ‘Sakharov conditions’ to explain the matter-antimatter asymmetry in the Universe.

5. Neutrino species
   Are there sterile neutrino species in addition to the three active ones participating in the weak interactions?
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1. Neutrino nature

The experimental way to determine the neutrino nature is the discovery of neutrinoless double beta decay ($0\nu\beta\beta$).

- Matter creation process!
- Lepton number is not conserved
- The neutrino is a fundamental Majorana particle
- Must measure summed electron kinetic energy to distinguish from Standard-model $2\nu$ process

$$Q_{\beta\beta} = 2039.061 \pm 0.007 \text{ keV}$$

Need a good signal-to-background ratio to get statistical significance
- Very low background event rate
- The best possible energy resolution
1. Neutrino nature

The experimental way to determine the neutrino nature is the discovery of \textit{neutrinoless double beta decay} (0νββ).

- Present best limits $T_{1/2} > 10^{26}$ y

\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M_{0\nu}|^2 \left( \frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2
\]

Phase space
Nuclear matrix elements

\[
\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} U_{ei}^2 m_i
\]

- Future goal $\sim$2 OoM improvement in $T_{1/2}$ covering Io and up to 50% NO*:
  - Only observable: energy
  - Sensitivity rises with exposure, but strongly depends on backgrounds

* PRD 96 (2017) 053001
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3. Neutrino mass scale

Measuring the masses requires:

<table>
<thead>
<tr>
<th>Beta decay</th>
<th>0νββ</th>
<th>Cosmology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observable</td>
<td>$m_{\nu}^2 = \sum_i</td>
<td>U_{ei}</td>
</tr>
<tr>
<td>Model dependence</td>
<td>Direct measurement</td>
<td>Neutrino nature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Matrix elements</td>
</tr>
</tbody>
</table>

Absolute mass scale

$m_{\nu} < 0.8$ eV

Upper bound from direct measurements

Lower bound from oscillation experiments

T. Lasserre, Neutrino’22
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3. Neutrino mass spectrum

Measuring the masses requires:

- T2K and NOvA show mild preference for normal ordering
- Need next generation experiments: neutrino oscillations in matter (DUNE, atmospheric neutrinos) or in vacuum (JUNO)

mass ordering $\rightarrow$ oscillation experiments

Upper bound from direct measurements
Lower bound from oscillation experiments

$\Delta m^2_{12}$ solar

$\text{sing of } \Delta m^2_{31}$
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4. Neutrino mixing

- Is there leptonic CP violation?
  - Hints from T2K and NOvA, but tension for NO. Combined analysis may give more preference, but not stable yet.
  - Need next generation experiments: DUNE, T2HK
- The angle $\theta_{23}$ is still not known very well.
- Next experiments: DUNE, T2HK, JUNE will measure precisely mixing parameters.
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5. Neutrino species

Is the standard 3-neutrino picture correct?

- An active area with a lot of experiments and anomalies:
  - Reactor neutrino fluxes
    - most likely solved
  - Reactor spectra: NEUTRINO-4
  - Gallium anomaly: BEST
    - recently confirmed
  - LSND anomaly
  - MiniBooNE excess, non explanation, non-confirmation by MicroBooNE. Short Baseline Neutrino Program (Fermilab) will solve it.

Sterile neutrinos? Simplest 3+1 model seems in tension to cover all anomalies.
  - Some anomalies seems real, but maybe not related to sterile neutrinos.
  - An extra neutrino species is in severe tension with cosmology.
Neutrinos also provide answers

Neutrinos and neutrino experiments are excellent probes to explore the Universe and provide insight of new Physics

• **Neutrinos as messengers**
  - Neutrinos bring raw information from the source as barely interact along the way.
  - The observation of the **SN1987A** was the beginning of neutrino & multi-messenger astronomy.
  - Astrophysical neutrinos firstly observed by IceCube.
  - **Multi-messenger astronomy** provides complementary information from neutrino detector, gravitational waves, cosmic-rays, γ-rays, X-rays.
  - Bright new era coming!

• **Neutrino experiments** are such a powerful tools that allow to perform searches beyond the standard model: dark matter searches, proton decay, etc.
Neutrinos and antineutrinos

Do $\nu$ and $\bar{\nu}$ behave the same way?

This is key to understand the matter - antimatter asymmetry:

- If the oscillations of $\nu$'s are fundamentally different from $\bar{\nu}$'s, CP symmetry is broken.
  - Experimental measurement of $\nu$ and $\bar{\nu}$ oscillation parameters.
- 1937: Majorana: $\nu$'s & $\bar{\nu}$'s are not distinct particles, can transform into each other $\rightarrow$ neutrinoless double beta decay. This can imply leptogenesis and baryogenesis.
  - Experimental measurement of neutrinoless double beta decay.

1967: Sakharov conditions for matter and antimatter to be produced at $\neq$ rates:
- Interactions out of thermal equilibrium
- Baryon number violation (baryogenesis)
- Charge-parity (CP) violation
Complementarity

Next generation experiments able to answer $\nu$ unknowns!

$\nu$'s can answer fundamental questions

Adapted form S. Pascoli
Complementarity

Next generation experiments able to answer n unknowns!

ν’s can answer fundamental questions

Atmospheric ν’s

mass ordering

standard ν paradigm

Long baseline experiments

Cosmology

Direct search

νββ decay

MAJORANA DEMONSTRATOR

Adapted from S. Pascoli
The Deep Underground Neutrino Experiment (DUNE)
Deep Underground Neutrino Experiment (DUNE)

DUNE aims at answering fundamental questions related to:
• The matter-antimatter asymmetry – Long baseline neutrino oscillations
• The Grand Unification of forces – Physics beyond the Standard Model
• The supernova explosion mechanism – Low energy physics

- New neutrino ($\nu_\mu$ or $\bar{\nu}_\mu$) beam facility at Fermilab (LBNF), US.
- A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints.
- 4 x 17 kton liquid argon time-projection chambers (LArTPC) modules deep underground at SURF (Lead, SD, 1300 km baseline).

Instruments 5 (2021) 31
JINST 15 (2020) T08008
JINST 15 (2020) T08010

EPJC 80 (2020) 978
EPJC 81 (2021) 322
EPJC 81 (2021) 423
The DUNE Collaboration

~1400 collaborators from
~200 institutions in
>30 countries + CERN

DUNE Collaboration Meeting,
Fermilab, May 2022
DUNE Collaboration Organization

Detector construction consortia:

Physics working groups:
Long-baseline oscillations

Precision measurement of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0-5+ GeV
- At 1,300 km the oscillation probability has a strong dependence on the $\delta_{CP}$ and the mass ordering.
- The beam energy will cover two oscillation maxima improving the sensitivity.
Long-baseline oscillations

**Precision measurement** of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with the goal of

- Measuring the CP violating phase ($\delta_{CP}$)
- Determining neutrino mass ordering ($\Delta m^2_{31}$ sign)
- Precision tests of the 3 flavor neutrino oscillation paradigm ($\theta_{23}$ and octant)

**CP violation sensitivity**

Significance with which $\delta_{CP}$ can be determined

**Mass ordering sensitivity**

Discriminating power between the two mass ordering hypotheses

EPJC 80 (2020) 978
DUNE can probe a rich and diverse BSM phenomenology including searches for:

- **Dark matter** at the ND, including searches for axion-like particles and low-mass dark matter, and boosted dark matter particles at the FD.

- **Sterile neutrino** mixing by looking for disappearance of charged-current and neutral-current $\nu$ interactions over the long distance between the ND and FD, and the short baseline of the ND.

- **Non-standard neutrino interactions**, affecting neutrino propagation through the Earth, can significantly modify the data to be collected by DUNE as long as the new physics parameters are large enough.

- **CPT violation**: Using beam neutrinos, DUNE can improve the present limits on Lorentz and CPT violation by several orders of magnitude, a very important test of these fundamental assumptions underlying quantum field theory.

- **Neutrino trident production** is a weak process in which a $\nu$, scattering off the Coulomb field of a heavy nucleus, generates a pair of charged leptons. A sizable production rate of trident events is expected in DUNE ND. A deviation from the event rate predicted by the Standard Model could be an indication of new interactions mediated by new gauge bosons.

- **Baryon number violating processes** at the FD, like proton decay, thanks to the excellent imaging, as well as calorimetric and particle identification capabilities.
Low Energy Physics

The DUNE FD is sensitive to $\nu$’s produced by the Sun and in core-collapse supernovae with $E \sim 5$-100 MeV.

- **Core-collapse supernovae** are a huge source of $\nu$’s of all flavors in ~10 sec.
  - 1-3 SN/century in our Galaxy (10 kpc).
  - DUNE will participate in SuperNova Early Warning System (SNEWS).
  - Measurement of the SN $\nu$’s will provide information about:
    - **Supernova physics**: Core collapse mechanism, SN evolution in time, black hole formation.
    - **Neutrino physics**: $\nu$ flavor transformation, $\nu$ absolute mass, other $\nu$ properties (sterile $\nu$’s, magnetic moments, extra dimensions...).

- **Solar and diffuse background supernova $\nu$’s** are also potentially detectable.
Supernova neutrino emission

For a supernova at 10 kpc from Earth.

**Infall**
Core collapses, and a shock wave is formed. The medium is opaque even for neutrinos.

**Neutronization**
Primarily $\nu_e$ escape, as messengers of the shock front breaking.

**Accretion**
(<1s) $\nu$’s powered by infalling matter.

**Cooling**
(~10s) main part of the signal, the proto-neutron star sheds its trapped energy.

A lot of information about the supernova in this profile: flavor content and spectra of the $\nu$’s emitted change throughout these phases, and the supernova’s evolution can be followed with the $\nu$ signal.
Supernova neutrino signal in LAr

1. Charged-current (CC) interaction on Ar
   \[ \nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^- \]
   \[ \bar{\nu}_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{Cl}^* + e^+ \]

2. Elastic scattering on electrons (ES)
   \[ \nu_x + e^- \rightarrow \nu_x + e^- \]

3. Neutral current (NC) interactions on Ar
   \[ \nu_x + {}^{40}\text{Ar} \rightarrow \nu_x + {}^{40}\text{Ar}^* \]

Possibility to separate the various channels by a classification of the associated photons from the K, Cl or Ar deexcitation (specific spectral lines for CC and NC) or by the absence of photons (ES)
Supernova event simulation and reconstruction in DUNE

**MARLEY simulates** tens-of-MeV $\nu$-nucleus interactions in LAr

**Reconstruction:** LArSoft to identify interaction channel, $\nu$ flavor in CC events, & incoming neutrino 4-momentum

**SNOwGLoBES:** computation tool of the predicted event rate from a SNB

**Backgrounds** will have a minor impact on reconstruction, but can affect triggering

$v$-e \cdot ES event (10.25 MeV $e^-$)  \hspace{1cm}  $\nu_e$ CC event (20.25 MeV $\nu$)

*EPJC 81 (2021) 423*
Expected Supernova burst signal in DUNE

<table>
<thead>
<tr>
<th>Channel</th>
<th>Livermore</th>
<th>GKVM</th>
<th>Garching</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + ^{40}$Ar $\rightarrow e^- + ^{40}$K$^*$</td>
<td>2648</td>
<td>3295</td>
<td>882</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{40}$Ar $\rightarrow e^+ + ^{40}$Cl$^*$</td>
<td>224</td>
<td>155</td>
<td>23</td>
</tr>
<tr>
<td>$\nu_X + e^- \rightarrow \nu_X + e^-$</td>
<td>341</td>
<td>206</td>
<td>142</td>
</tr>
<tr>
<td>Total</td>
<td>3213</td>
<td>3656</td>
<td>1047</td>
</tr>
</tbody>
</table>

$\nu_e$ flavor dominates.

LAr only future prospect for a large, cleanly tagged SN $\nu_e$ sample

40 kton LAr & 10 kpc SN
Expected Supernova burst signal in DUNE

- Number of SN $\nu$ interactions scales with mass and inverse square of distance.
- At 10 kpc, DUNE will observe hundred-thousand events and just a few events for a collapse in the Andromeda galaxy.

- Expected event rates during early stages – the neutronization burst and early accretion phases
- The effect of different mass orderings is observed.

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DUNE Supernova burst event triggering:

- It is essential to develop a redundant and highly efficient triggering scheme in DUNE.
- The trigger on a supernova neutrino burst can be done using either TPC or photon detection system information.
- Trigger scheme exploits the time coincidence of multiple signals over a timescale matching the supernova luminosity evolution.
- Preliminary trigger designs with maximum fake trigger rate (1/month).

**Example: Photon detection system in dual-phase far detector.**

- Real time algorithm provides trigger primitives by searching for PMT hits and optical clusters, based on time/spatial information.
- >90% efficiency on a SNB at a distance up to ≥25 kpc, so it would cover the entire Milky Way.

A. Gallego-Ros (CIEMAT) PhD Thesis
DUNE
Neutrino beam, Near and Far Detectors
LBNF Beam

- 120 GeV main injector proton beam
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Embankment allows target complex to be at grade and neutrino beam to be aimed to SURF
- Decay region followed by absorber
- Four surface support buildings
Near Detector

Roles:
- Characterization of the beam close to the source.
- Spectral beam monitor.
- Tuning the neutrino interaction model reducing systematics.
- Off-axis beam data to deconvolve beam and cross section models.

Located 574 m from the $\nu$ source.

Components:
- Highly modular LArTPC (ND-LAR).
- Magnetized gaseous argon TPC (ND-GAr).
- Magnetized beam monitor (SAND).
Far Detector

Located 1.48 km underground at Sanford Underground Research Facility in Lead, South Dakota

Four 10-kt Fiducial LAr TPC modules

“2+1+1” model:
- 2 modules horizontal drift
- 1 vertical drift module
- 1 “opportunity” module
LAr TPC technology

- Liquid argon is inert, dense and naturally abundant.
- Strong electric field applied across the TPC to collect $e^-$ produced by energy loss.
- LAr is transparent to its own scintillation light which can be used as an internal trigger and for complementary calorimetry measurement.

- Excellent 3D imaging capabilities – few mm scale over large volume detector.
- Excellent energy measurement capability – totally active calorimeter.
- Particle ID by $dE/dx$, range, event topology.
Scintillation light in LArTPC

- **Produced** by radiative decay of molecular argon excimers:
  - ~40k photons per MeV of deposited energy (at 0kV/cm)
  - Decay times: Fast (7 ns) and Slow (1.5 µs).
  - Wavelength of scintillation photons is 127 nm.
  - Quenched by impurities.

- **Propagation:**
  - Rayleigh scattering: The photon changes the phase and the direction.
  - Absorption: LAr is transparent, but impurities absorb photons.
    \( \lambda_{Abs} = 20 \text{ m} (~3 \text{ ppm N}_2) \).
  - Reflections and absorption in the detector.

- **Detection** is challenging:
  - Wavelength shifting usually required
  - Maximizing photon detection efficiency

**Goals**
- ✓ Provide the trigger for non-beam events.
- ✓ Add precise timing capabilities.
- ✓ Improve the calorimetry measurements.
Far Detector 1

Horizontal drift

- **3.6 m horizontal drift**
- Anode wires immersed in LAr vertical
- Anode and Cathode Plane Assemblies (APA, CPA)
- **Charge collected** on 3 views, pitch 5 mm
- **Photon detectors:** X-ARAPUCA light guides + SiPM, embedded in APAs
**Far Detector 2**

**Vertical drift**

- **6-m vertical drift** that maximizes active volume.
- **Printed Circuit Board**-based readout scheme makes detector assembly much simpler.
- **Photodetection system** deployed (X-ARAPUCA) on the central cathode plane + cryostat walls.
- Challenging technology.
ProtoDUNE at CERN

Construction and operation of 1 kton-scale SP and DP prototypes at CERN - critical to demonstrate viability of technology, and that the DUNE Collaboration can implement a major construction activity.

NP02 – dual phase / vertical drift

NP04 – single phase / horizontal drift
ProtoDUNE at CERN

ProtoDUNE DP first tracks!

ProtoDUNE SP first tracks!
NPo4: ProtoDUNE Single Phase (Horizontal drift)

**Phase I**
- Beam data taking (2018):
  - Collected >4M beam triggers,
  - 0.5 - 7 GeV particle beams (e, π, p, K)

**Phase II**
- Installation in summer 2022
- Spanish contribution photon detector system: X-ARAPUCAs characterization and photon detection efficiency measurement

2 LAr volumes: 3.6 m drift length each TPC
**NPo4: ProtoDUNE Single Phase (Horizontal drift)**

**Event display**

- **Cosmic Rays**
- **6 GeV Electron**
- **6 GeV Pion**
- **1 GeV Stopping Proton**

The images show event displays from different runs, illustrating various types of events, including cosmic rays, 6 GeV electrons, 6 GeV pions, and 1 GeV stopping protons.
Photon detectors: X-ARAPUCAs

Challenges:
• The emitted photons’ wavelength is 128 nm (VUV) and typically photosensors are not sensitive.
• Large detection area is needed, but available space is limited.

X-ARAPUCA clever design:
• Trap the light and shift photons’ wavelength to ~400 nm.
• More light opens additional physics opportunities like calorimetry and triggering.
NPO4: ProtoDUNE Single Phase (Horizontal Drift)

Photon detectors: X-ARAPUCAS

- Design, procurement, assembly, and characterization.
- X-ARAPUCA Photon Detection Efficiency measured.
- Installation at ProtoDUNE APAs at CERN.
The Vertical Drift technology arose as an evolution of the Dual Phase technology.
NP02: ProtoDUNE Dual Phase (Vertical Drift)

Photon Detection System

- **36 8” cryogenic photomultipliers (PMTs)**
  - JINST 13 (2018) T10006
  - JINST 15 (2020) P09023

- **Wavelength-shifter**: PEN / TPB coating on PMT

- **Voltage divider base** + single HV-signal cable + splitter (external)

- **Light calibration system**: LED (external) & fiber based
  - JINST 14 (2019) T04001

- **DAQ system (external)**
  - IEEE Trans Nucl. Sci. 68 (2021) 2334
Scintillation light results

- **Stable performance** → design validation.
- **Pioneering** use in a large scale experiment of:
  - **PEN as wavelength shifter**: possible alternative, although TPB is x3 more efficient.
  - **Xe doping**: Improvement of the light detection efficiency. 5.8 ppm of Xe double the collected light at large distances (3-5 m from the PMTs).
- **Unprecedented study of the light propagation**:
  - Good agreement data –MC for 99 cm **Rayleigh scattering length**.
  - The electroluminescence light, S2, produced in the gas phase ~7 m away from the PMTs was observed for the first time.
- **Cosmic muon flux** at ground level is $148^{+8}_{-11}$ Hz/m², from the S1 signal rate detected by the PMTs and a cosmic-muon light simulation sample.

Light collected by a PMT vs the distance to the light production

**arXiv:2203.16134**
DUNE project timeline

2018-2020 **ProtoDUNE** Phase I detectors (single and dual phase) online **at CERN**

2019 Excavation of the large caverns in South Dakota housing the DUNE Far Detector

2020 Far Detector I (Horizontal Drift) **Technical Design Report**

2022 **ProtoDUNE** Phase II detectors (horizontal and vertical drift) installation **at CERN**

2022 Far Detector II (Vertical Drift) **Technical Design Report**

2023 **ProtoDUNE** phase II beam and cosmic-ray data taking **at CERN**

2029 **DUNE** Far Detector I and II **constructed**
   DUNE Physics begins! Supernova, proton decay and atmospheric neutrinos

2031 **Neutrino beam operational with near detector and two far detectors online**
   Start of oscillation physics!
The MAJORANA DEMONSTRATOR

Fig: Courtesy M. Kapust
The MAJORANA Collaboration

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The MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of $^{76}$Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

Source & Detector: Array of p-type, point contact detectors
29.7 kg of 87% enriched $^{76}$Ge crystals
Included 6.7 kg of inverted coaxial, point contact detectors in final run

Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV
and Analysis Threshold: 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an ultimate exposure of ~65 kg-yr before removal of enriched detectors for the LEGEND-200 experiment at LNGS
Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics
Background reduction

Ultra-pure materials
- Low-mass design
- Custom cable connectors and front-end boards
- Selected plastics and low-mass Cu coax cables
- Underground electroformed copper

Cosmogenic backgrounds
- Limit and track Ge above-ground exposure to prevent cosmic activation.
- Veto events coincident with muons

Machining, cleaning, and assembly
- Cu machining in an underground cleanroom
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts
- Dedicated glove boxes with a purged N₂ environment
65 kg-yr of Exposure in Enriched Detectors

Total collected active exposure over time in enriched detectors.

Datasets (DSs) represent changes in experimental configuration.
Energy resolution

Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction.

Calibrated on weekly $^{228}$Th calibration data, retuned on full data set

FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%) is a record for 0νββ searches

* IEEE Trans. on Nuc Sci 10.1109/TNS.2020.3043671
Analysis techniques for background rejection

$0\nu\beta\beta$ is most likely single-site and located in the bulk of the detector. Many backgrounds are multi-site or located near detector surfaces. Pulse-shape discrimination is used to distinguish between these event topologies.
Operated in a low background regime, benefiting from excellent energy resolution

Final enriched detector active exposure:

\[ 64.5 \pm 0.9 \text{ kg yrs} \]

Background Index at 2039 keV in lowest background config:

\[ 15.7 \pm 1.4 \text{ cts/(FWHM t yr)} \]

Module 1:

\[ 18.6 \pm 1.8 \text{ cts/(FWHM t yr)} \]

Module 2:

\[ 8.4^{+1.9}_{-1.7} \text{ cts/(FWHM t yr)} \]

J. Gruszko, Neutrino’22
Majorana Demonstrator 0νββ results

- Background Index: $(6.2 \pm 0.6) \times 10^{-3}$ cts/(keV kg yr)
- Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$
- Frequentist Limit: Median $T_{1/2}$ Sensitivity: $8.1 \times 10^{25}$ yr (90% C.I.)
  65 kg-yr Exposure Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.)
- Bayesian Limit: (flat prior on rate) 65 kg-yr Exposure Limit: $T_{1/2} > 7.0 \times 10^{25}$ yr (90% C.I.)

$m_{\beta\beta} < 113 - 269$ meV

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Beyond the $0\nu\beta\beta$ search

Tests of Fundamental Symmetries and Conservations
- Lepton number violation via neutrinoless double beta decay
- Baryon number violation
- Pauli Exclusion Principle violation

Standard Model Physics
- In situ cosmogenics
- $(\alpha, n)$ reactions
- $\beta\beta$-decay to excited states

BSM Physics
- Low-mass dark matter signatures
  - Pseudoscalar dark matter
  - Vector dark matter
  - Fermionic dark matter
  - Sterile neutrino
  - Primakoff solar axion
  - 14.4-keV solar axion

Exotic Physics
- Quantum Wavefunction collapse
- Lightly ionization particle

Standard Model Physics, particular backgrounds
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References:
- PRC 105 014617 (2022)
- arXiv:2203.14228 (2022)
- PRC 103 015501 (2021)
- PRL 120 211804 (2018)
- arXiv:2202.01343 (2022)
- C. Wiseman, NDM’22

C. Wiseman, NDM’22
From the current generation to the ton scale

MJD: New final exposure results

GERDA: Final 0νββ results published
PRL 125, 252502 (2020)

LEGEND-200: Now in commissioning at LNGS

LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462
Conclusions
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**Neutrino experiments** in the next decades will shed light on the open questions about neutrino nature, mass scale, mass spectrum, mixing, and species.

**DUNE** will be a crucial experiment for precise oscillation parameter measurements, supernova electron neutrinos, and physics beyond the standard model.

DUNE will also be an enormous technological challenge. **ProtoDUNE** program on-going is key to validate the technology.

**Majorana demonstrator** performed a neutrinoless double beta decay search in $^{76}\text{Ge}$ with unprecedented energy resolution.
Thanks

Credit: Randall Munroe