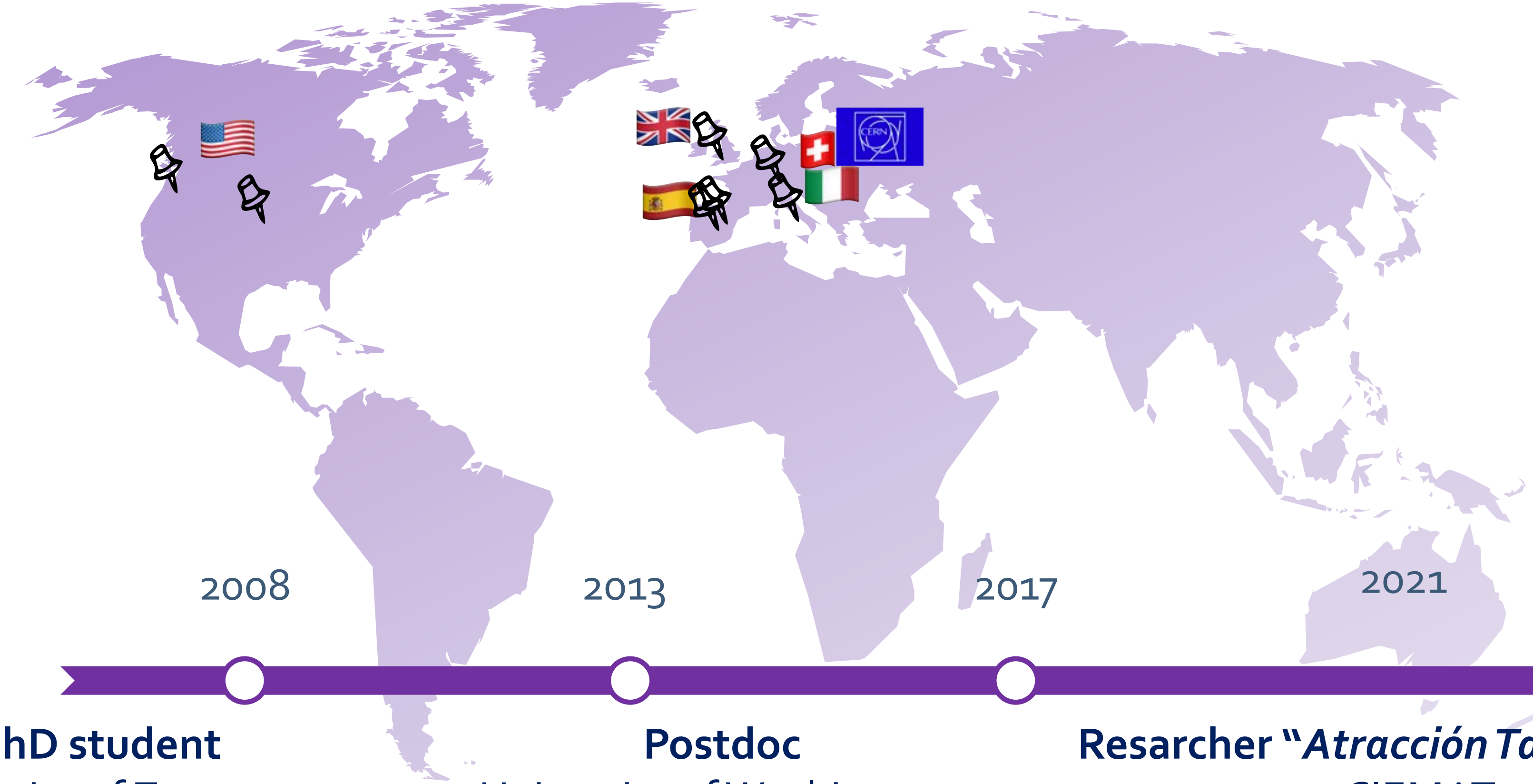
Neutrino Experiments

Clara Cuesta

Seminar at PRISMA$^+$
Johannes Gutenberg University Mainz
June, 22nd 2022

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

Scientific career



Participation in different experiments at all phases: design, validation, data analysis, results

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

2008 — 2013 — 2017 — 2021

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

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

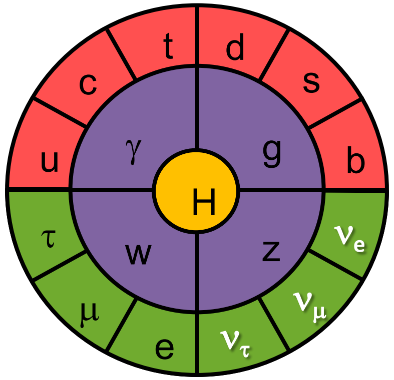
Resarcher "*Atracción Talento CAM*"
CIEMAT
(Madrid, Spain)
Study of neutrinos
(ProtoDUNE, DUNE, SBND, MAJORANA)

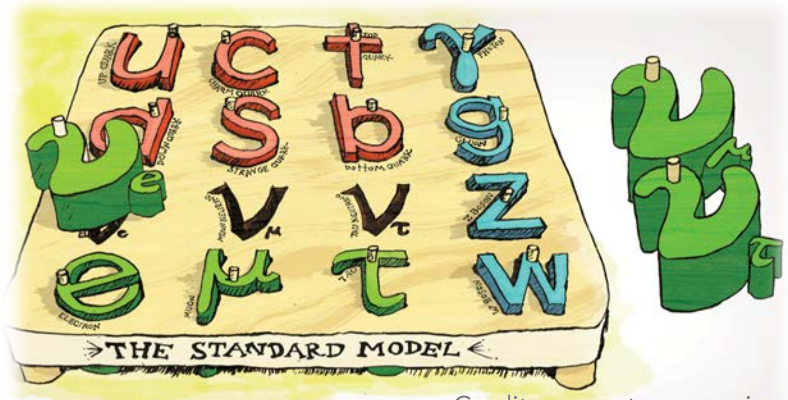
NEUTRINOS

Why do we study neutrinos?

Particles of the Standard Model

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





Credit: symmetry magazine

Credit: symmetry magazine

Neutrinos are abundant, but the most elusive particles.

Enigmatic particles, not fully understood

Provide answers to our understanding of the universe

Where are neutrinos coming from?

Neutrino sources

Sun

Terrestrial

Atmospheric

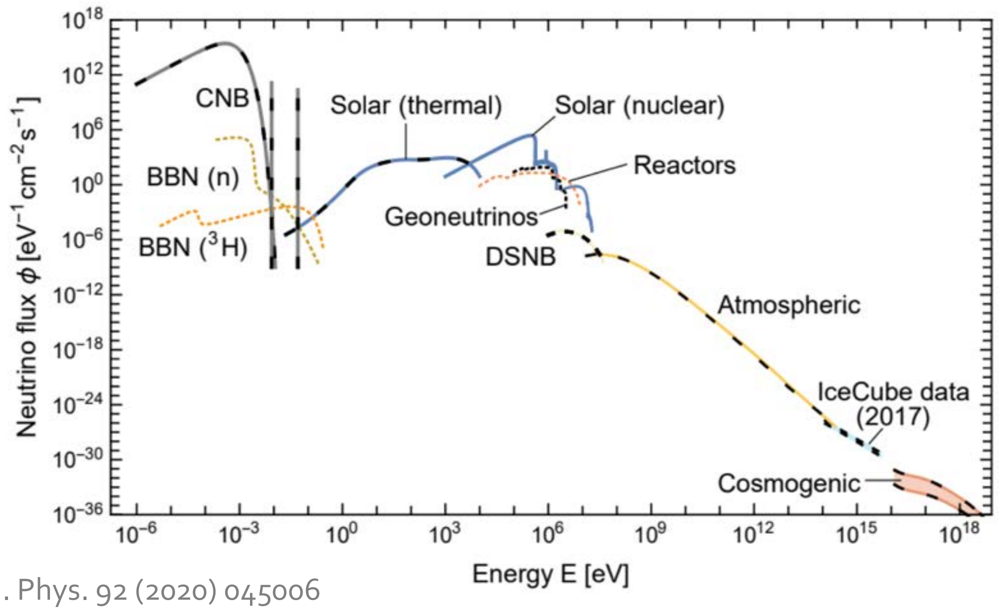
galactic & extragalactic

Supernova

Big bang

Reactor

Accelerator



Rev. Mod. Phys. 92 (2020) 045006

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 (ν_e) was directly observed by Cowan & Reines. — Reines - 1995

1962 - First experiment with accelerator ν's in Brookhaven (USA): ν_μ observation. — Lederman, Schwartz, Steinberger - 1988

1968 - Solar ν detection by Davis $\rightarrow \nu_e$ rate smaller tan expected. — Davis - 2002

- 1957 - Pontecorvo postulated oscillation theory of $\nu \rightarrow \bar{\nu}$.
- 1962 - Maki, Nakagawa y Sakata proposed a two-flavor mixing theory and latter built a general model.

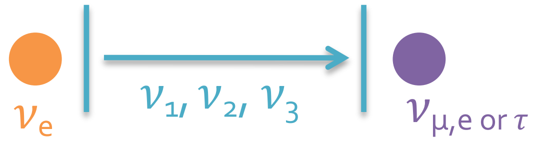
1998: Super-K detected atmospheric neutrino oscillations

2001: SNO detected solar neutrino oscillation measuring the total neutrino flux — McDonald, Kajita -2015

Flavor oscillations imply that neutrinos are massive $\rightarrow$

Physics Beyond the Standard Model

Neutrino oscillations



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

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{-i\alpha 1} & 0 & 0\\ 0 & e^{-i\alpha 2} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

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 0νββ

Oscillation probability:

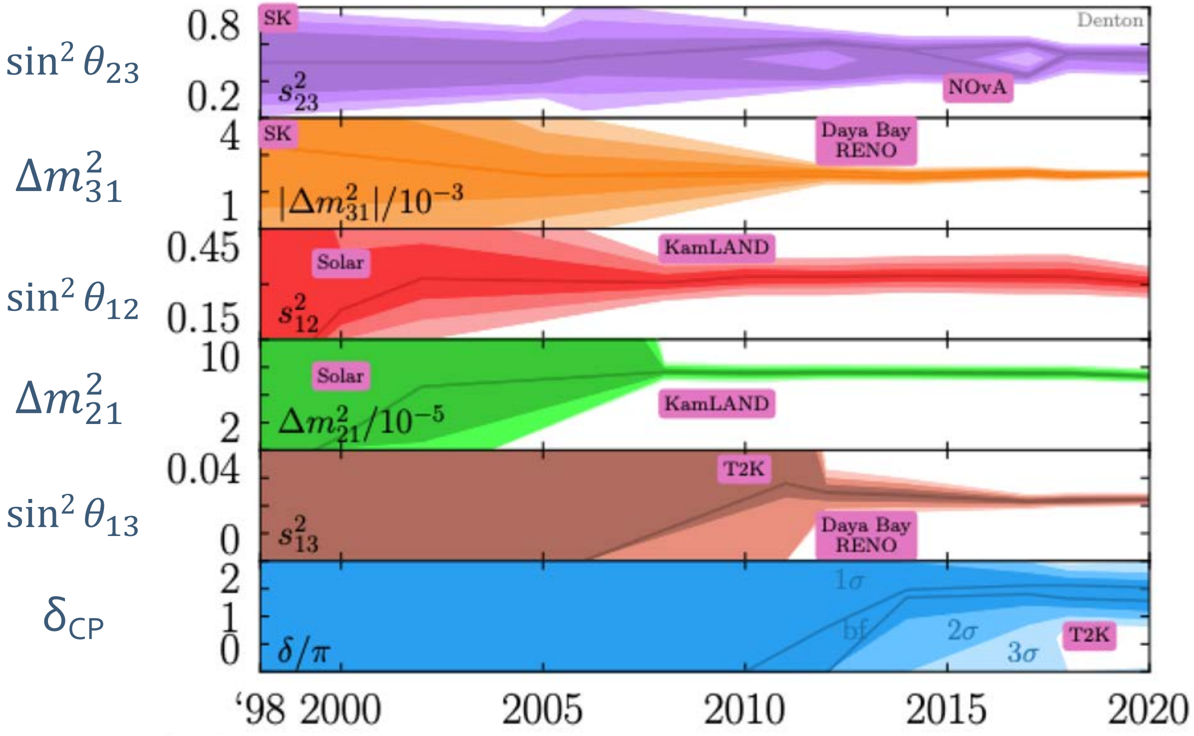
$$P_{\nu_\alpha\rightarrow\nu_\beta}(L,E) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) - 2\sum_{i>j} Im\left[U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right]\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Experimental approaches sensitive to 6 oscillation parameters.

Neutrino oscillation parameters

Evolution of experimental measurements

From P. Denton, Neutrino22

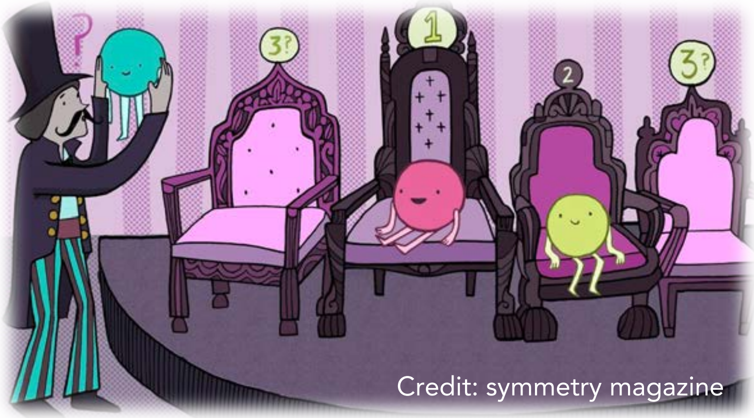


✓ Experimentally measured parameters: θ_{12}, Δm^2_{12} , θ_{23}, θ_{13}, Δm^2_{31}

? Unknown parameters: mass ordering (sing of Δm^2_{31}), δ_{CP}, θ_{23} octant

Neutrino unknowns

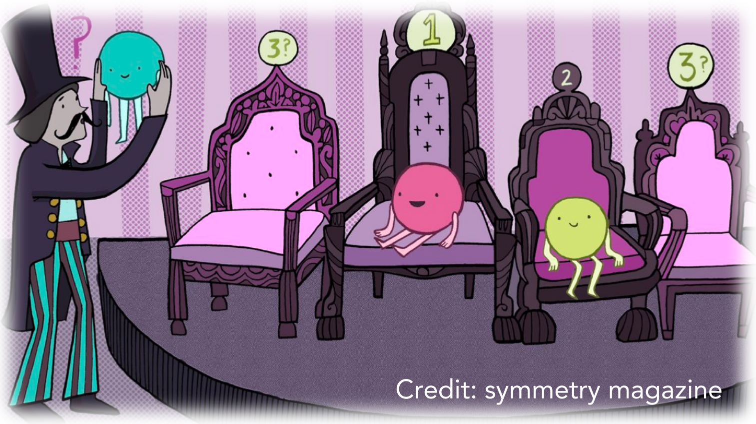
1. **Neutrino nature**
   Is the neutrino its own antiparticle? Are neutrinos Majorana particles?
2. **Neutrino mass scale**
   What is the absolute scale of neutrino masses?
3. **Neutrino mass spectrum**
   How are the three neutrino mass states ordered from lightest to heaviest (neutrino "mass ordering")?
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?



Credit: symmetry magazine

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?

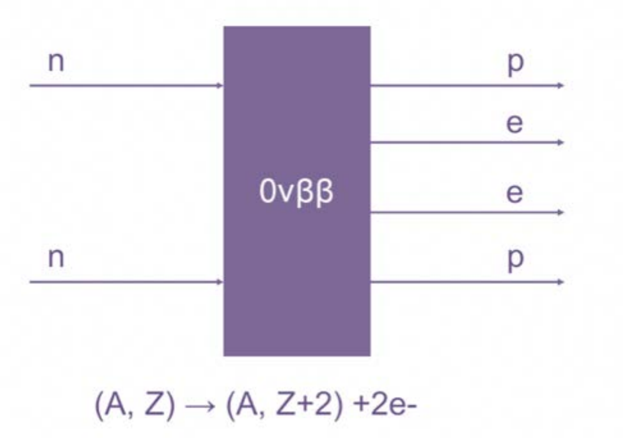


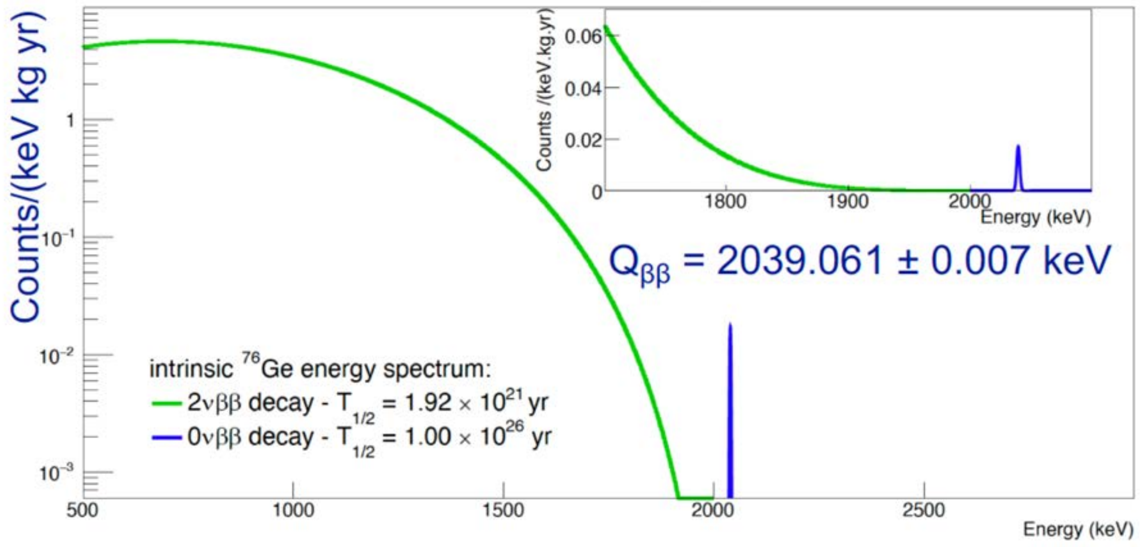
Credit: symmetry magazine

1. Neutrino nature

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

- 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 2ν process





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 **neutrinoless double beta decay (0νββ)**.

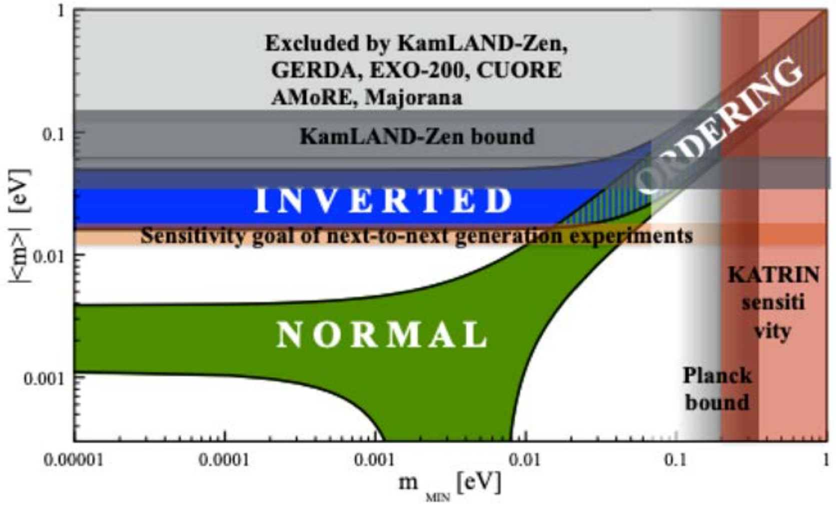
- Present best limits $T_{1/2} > 10^{26}$ y

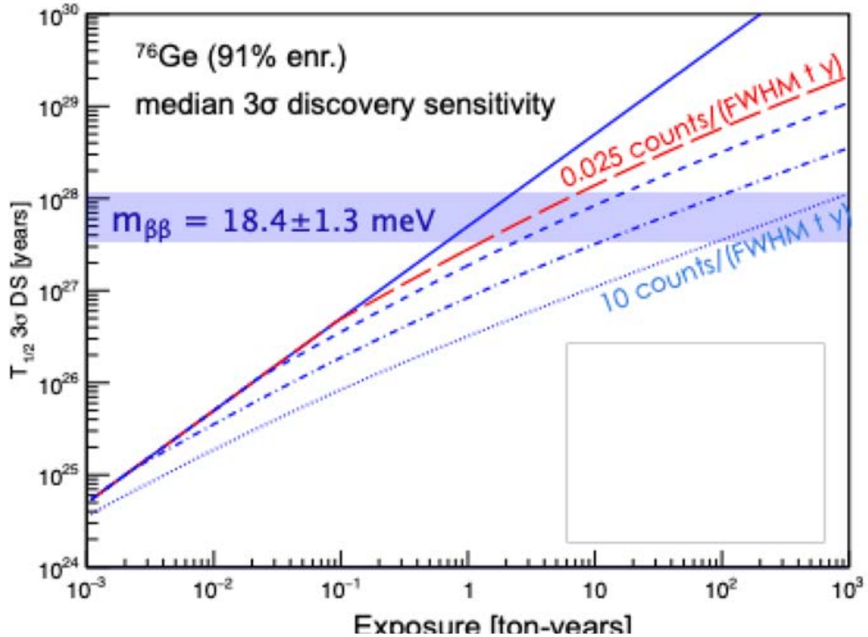
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Phase space

Nuclear matrix elements

$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U^2_{ei} m_i|$$



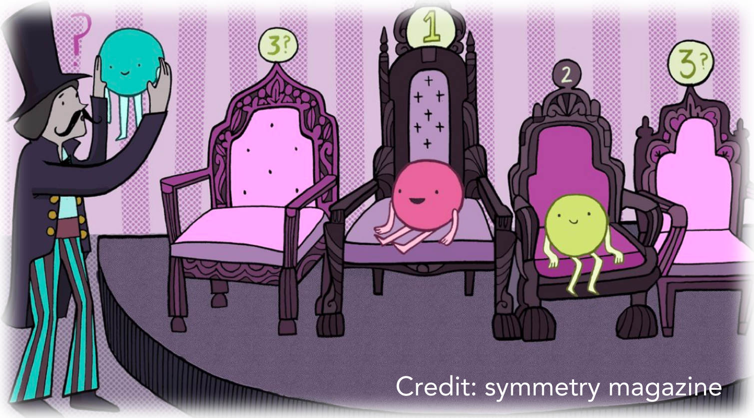


- Future goal ~2 OoM improvement in $T_{1/2}$ covering Io and up to 50% NO*.
  - Only observable: energy
  - Sensitivity rises with exposure, but strongly depends on backgrounds

* PRD 96 (2017) 053001

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?

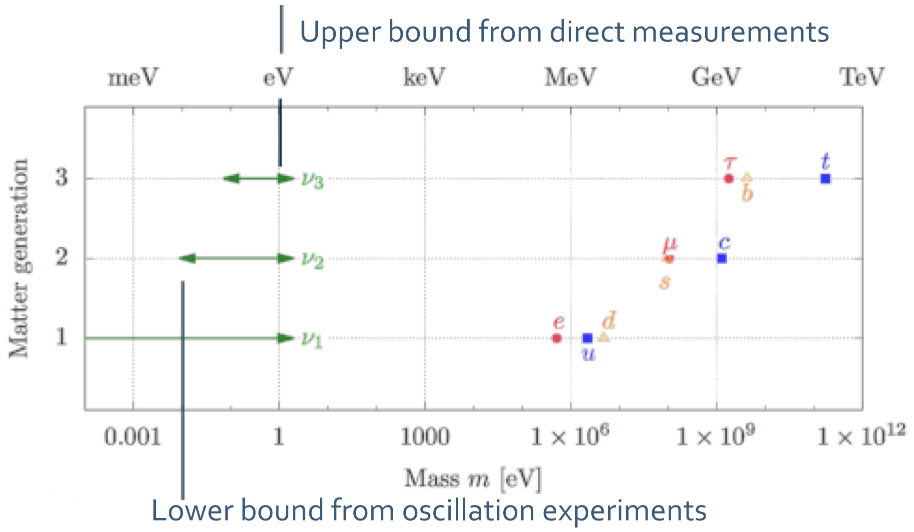


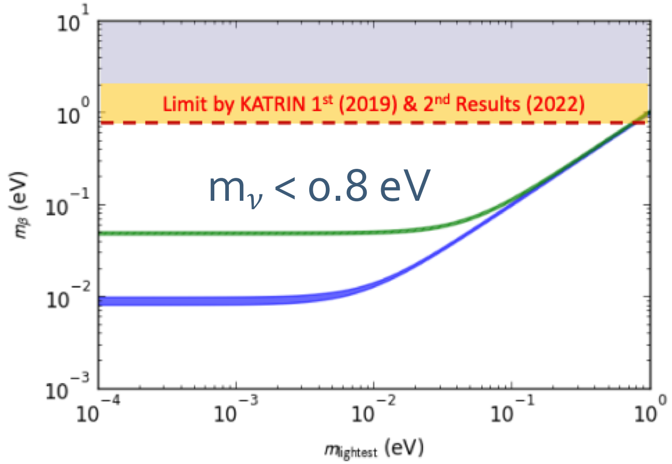
Credit: symmetry magazine

3. Neutrino mass scale

Measuring the masses requires:

Absolute mass scale



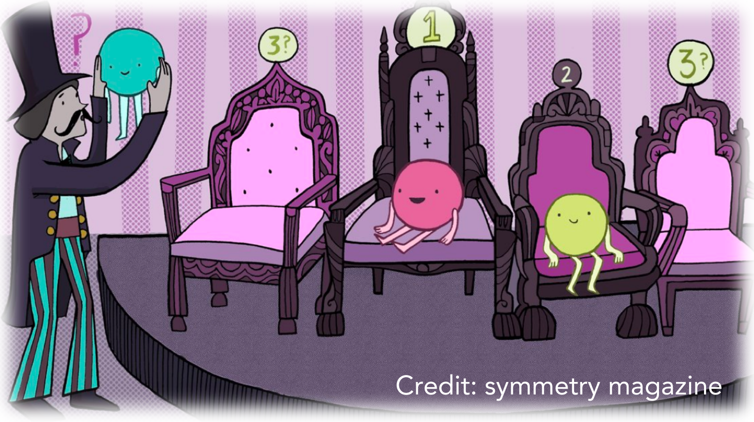


T. Lasserre , Neutrino'22

	Beta decay	0νββ	Cosmology
Observable	$m^2_{\nu_e} = \sum_i \lvert U_{ei}\rvert^2 \cdot m^2_{\nu_i}$	$m_{\beta\beta} = \left\lvert \sum_i U^2_{ei} \cdot m_{\nu_i} \right\rvert$	$\sum m_\nu$
Model dependence	Direct measurement	Neutrino nature Matrix elements	Cosmological model

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?

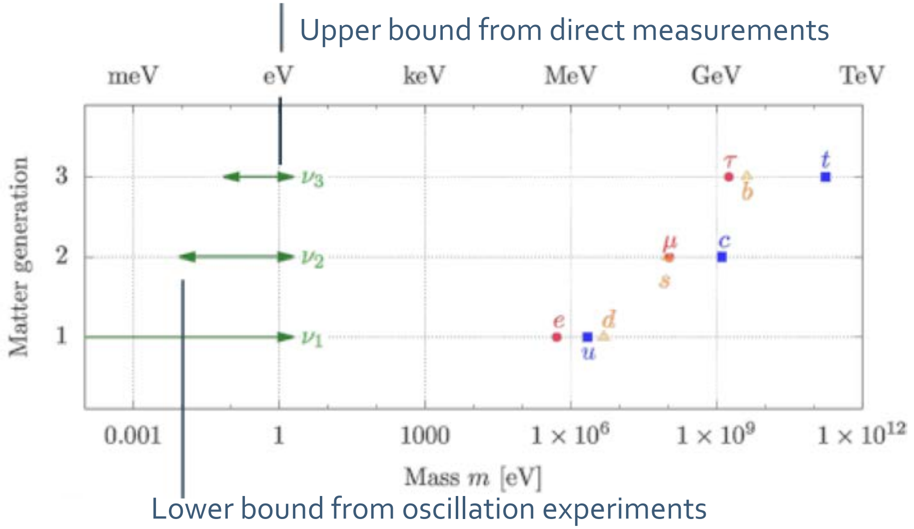


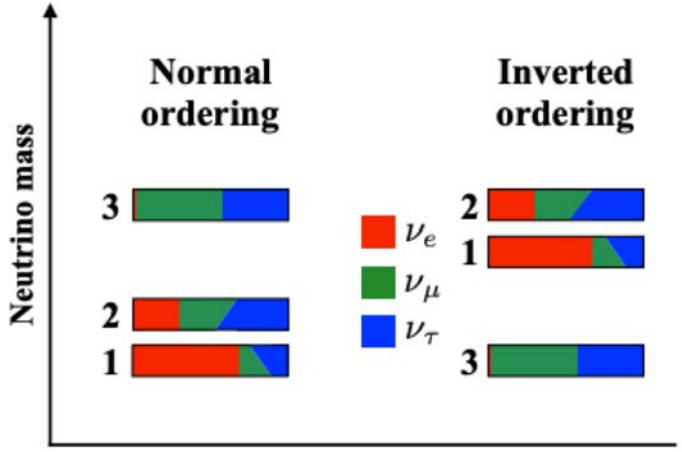
Credit: symmetry magazine

3. Neutrino mass spectrum

Measuring the masses requires:

mass ordering → oscillation experiments





✓ Δm_{12}^2 solar

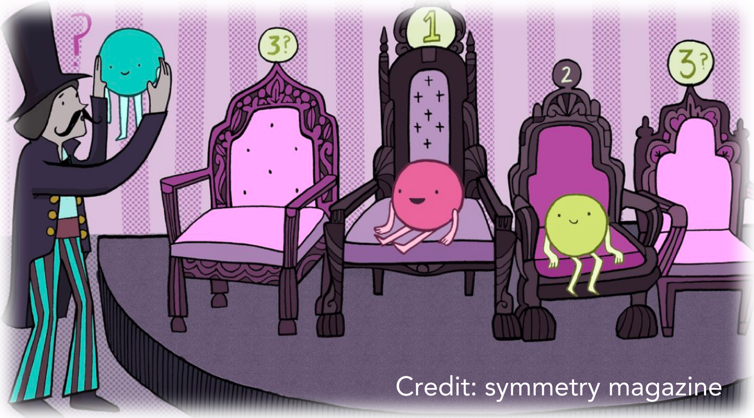
? sing of Δm_{31}^2

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

Neutrino unknowns

Q

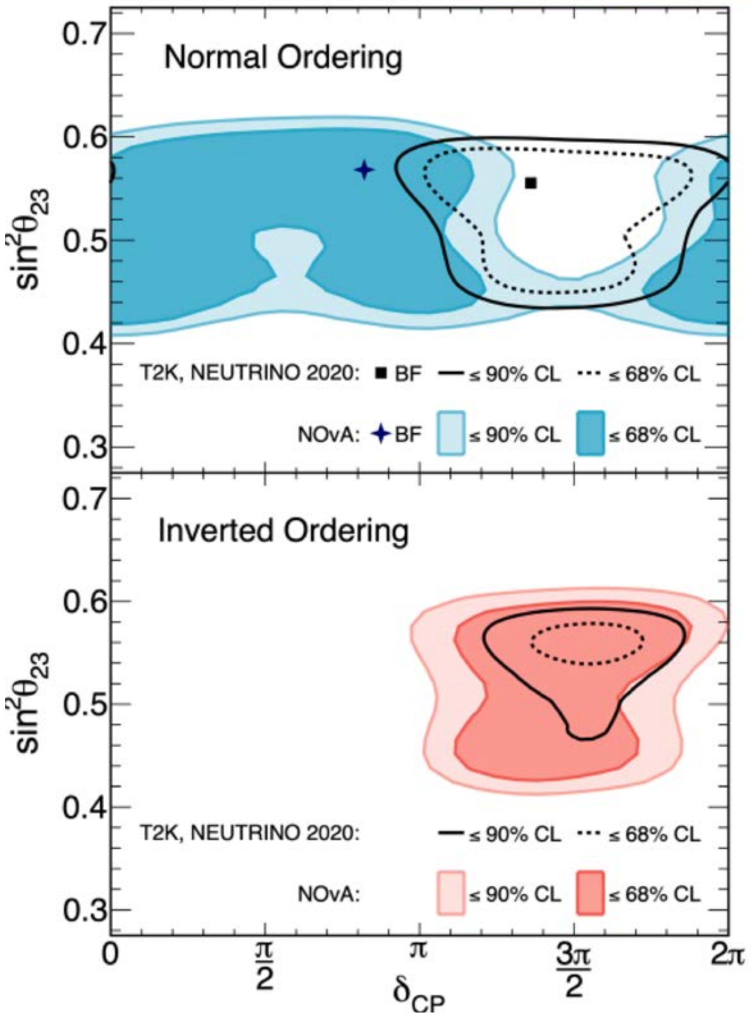
1. **Neutrino nature**
   Is the neutrino its own antiparticle? Are neutrinos Majorana particles?
2. **Neutrino mass scale**
   What is the absolute scale of neutrino masses?
3. **Neutrino mass spectrum**
   How are the three neutrino mass states ordered from lightest to heaviest (neutrino "mass ordering")?
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?



4. Neutrino mixing

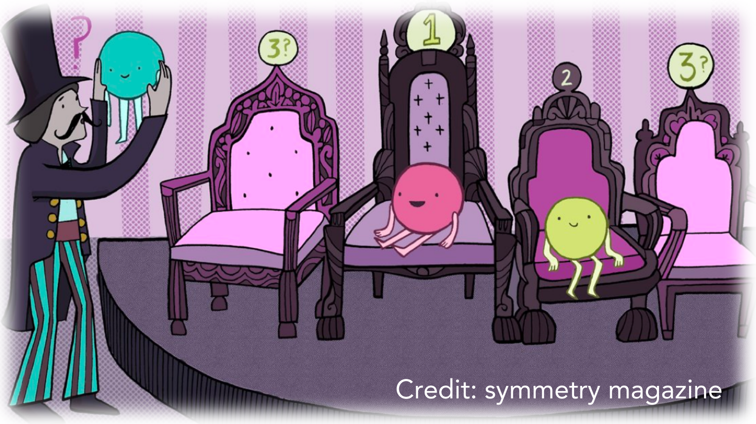
- Is there leptonic CP violation?
  - Hints from T2K and NOvA, but tension for NO. Combined analysis may give more preference, but not stable yet.
  - Need next generation experiments: DUNE, T2HK
- The angle θ_{23} is still not known very well.
- Next experiments : DUNE, T2HK, JUNE will measure precisely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

2020 data set: https://arxiv.org/abs/2108.08219



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?



Credit: symmetry magazine

5. Neutrino species

Is the standard 3-neutrino picture correct?

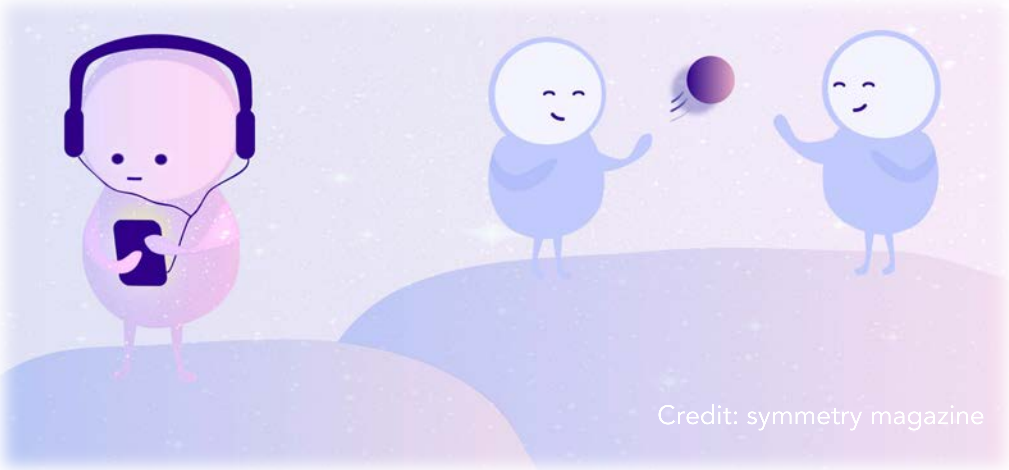
- An active area with a lot of experiments and anomalies:
  - ✓ **Reactor neutrino fluxes**
    - most likely solved

    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

A

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

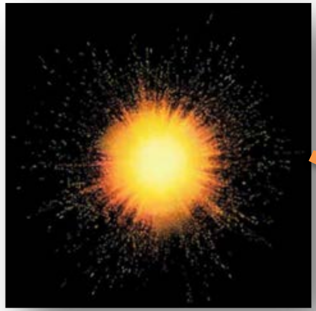
- **Neutrinos as messengers**
  - Neutrinos bring raw information from the source as barely interact along the way.
  - The observation of the SN1987A was the beginning of neutrino & multi-messenger astronomy.
  - Astrophysical neutrinos firstly observed by IceCube.
  - Multi-messenger astronomy provides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

A

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

This is key to understand the matter - antimatter asymmetry:



Big Bang
Matter + antimatter

?

Universe today
Matter

1967: Sakharov conditions for matter and antimatter to be produced at ≠ rates:

- Interactions out of thermal equilibrium
- Baryon number violation (baryogenesis)
- Charge-parity (CP) violation

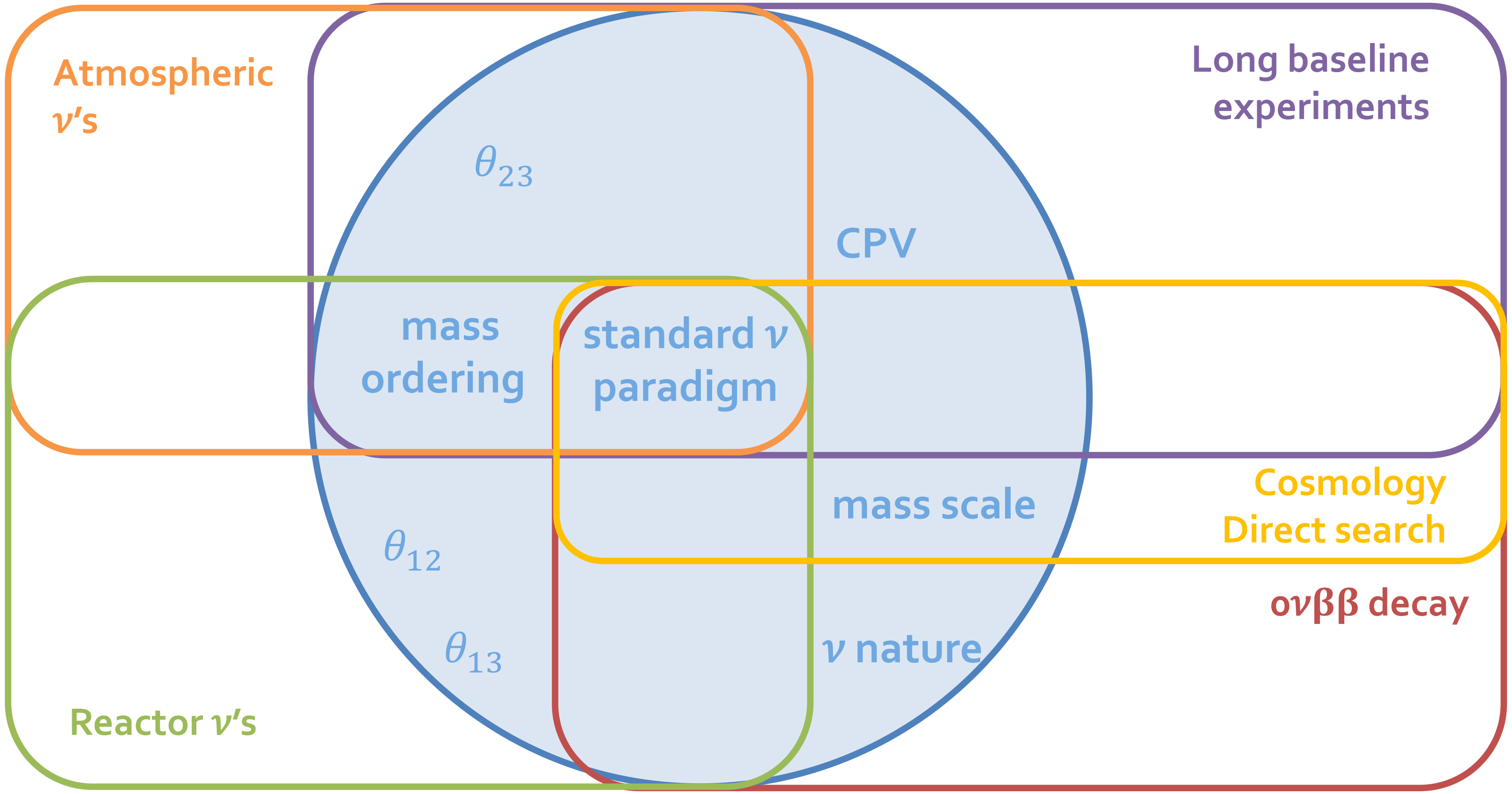
- If the oscillations of ν's are fundamentally different from $\bar{\nu}$'s, CP symmetry is broken.
  → Experimental measurement of ν and $\bar{\nu}$ oscillation parameters.
- **1937** Majorana: ν's & $\bar{\nu}$'s are not distinct particles, can transform into each other → neutrinoless double beta decay.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

Complementarity

Next generation experiments able to answer ν unknowns!

Q A

ν's can answer fundamental questions



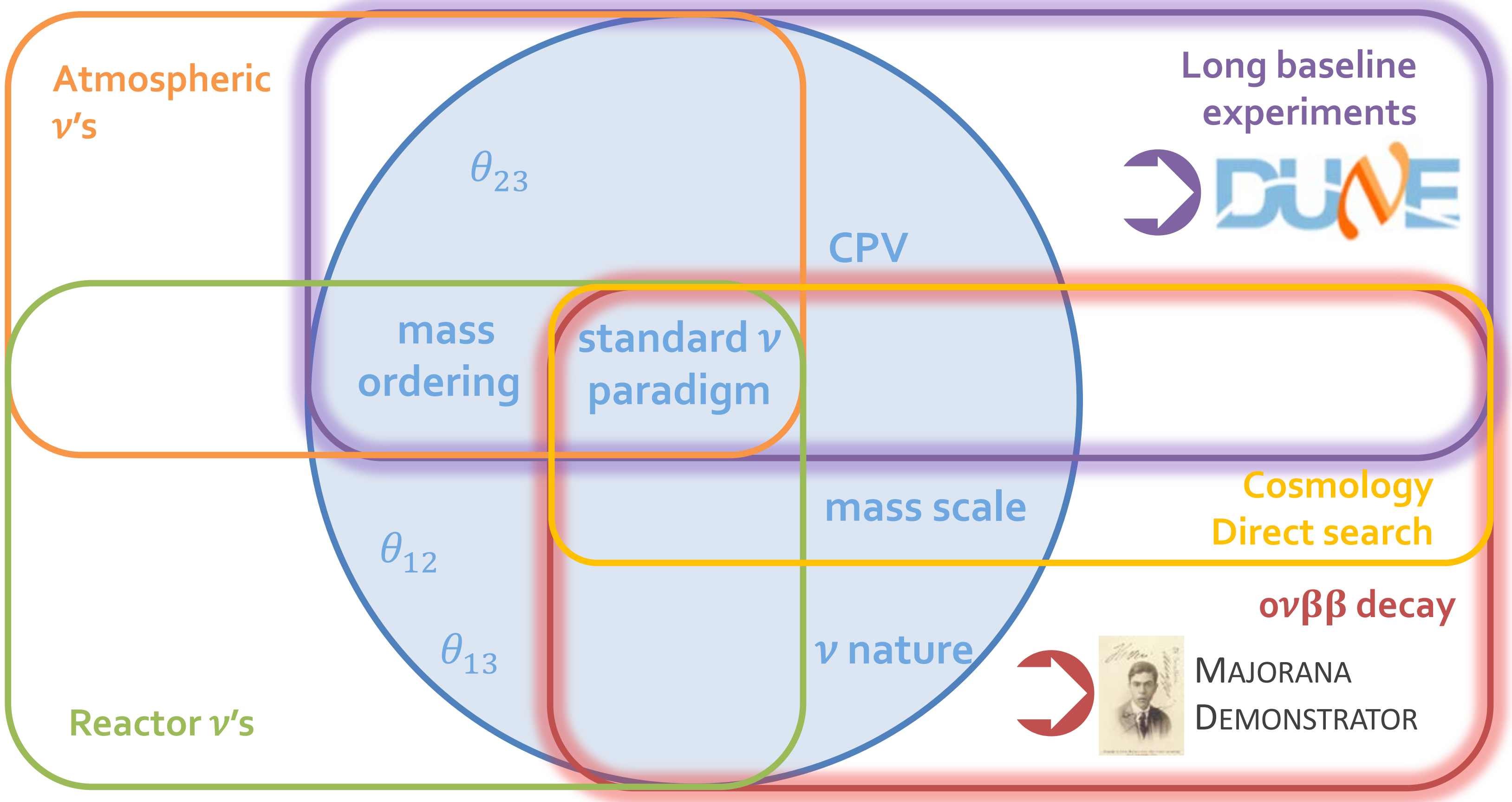
Adapted form S. Pascoli

Complementarity

Next generation experiments able to answer ν unknowns!

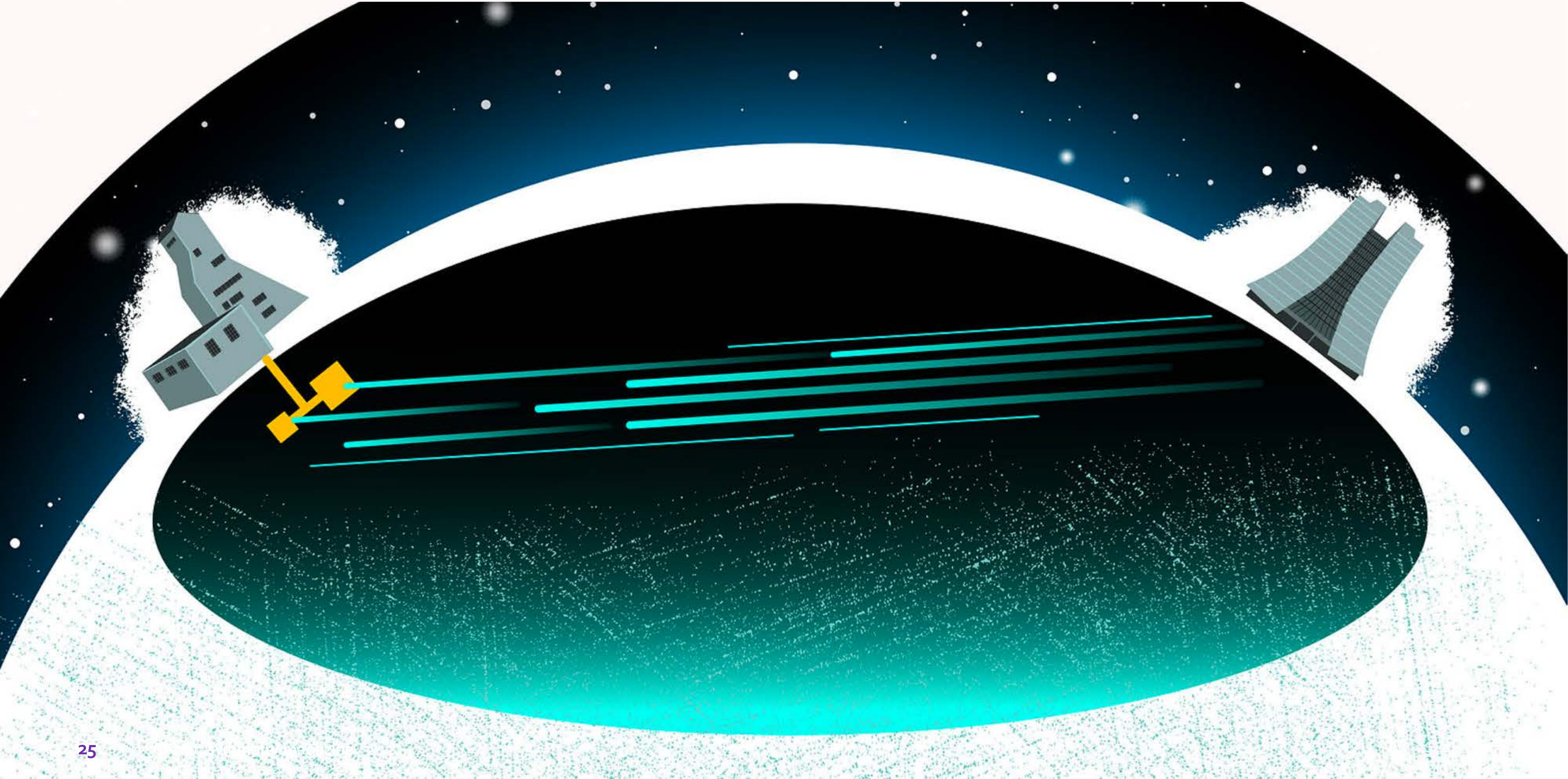
Q A

ν's can answer fundamental questions



Adapted form S. Pascoli

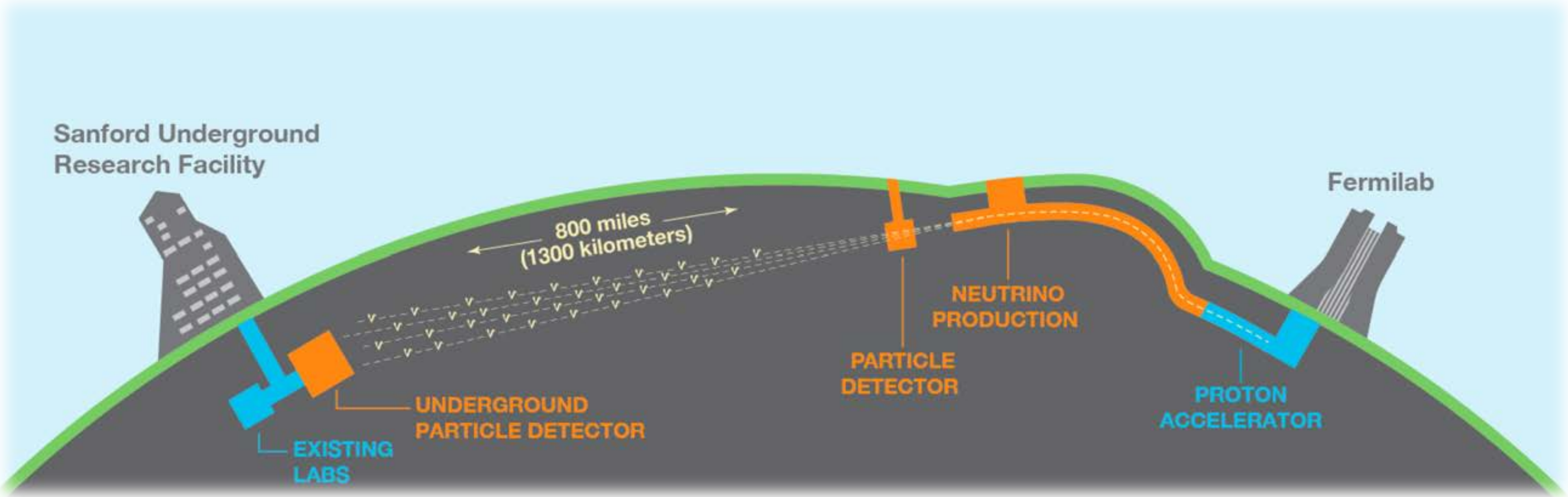
The Deep Underground Neutrino Experiment (DUNE)



Deep Underground Neutrino Experiment (DUNE)

DUNE aims at answering fundamental questions related to:

- The matter-antimatter asymmetry – Long baseline neutrino oscillations EPJC 80 (2020) 978
- The Grand Unification of forces – Physics beyond the Standard Model EPJC 81 (2021) 322
- The supernova explosion mechanism – Low energy physics EPJC 81 (2021) 423



- New neutrino (ν_μ or $\overline{\nu}_\mu$) 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).

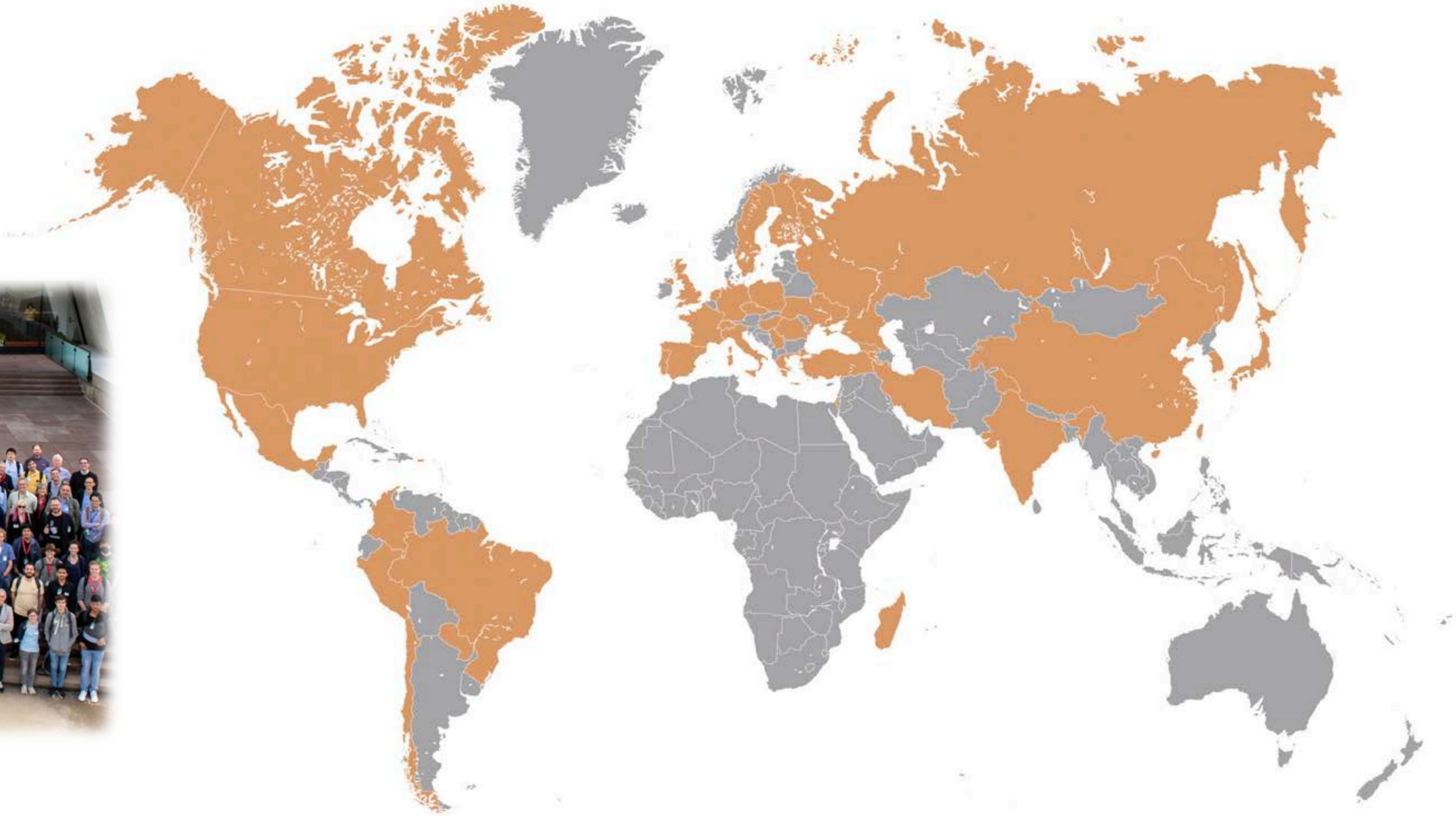
Instruments 5 (2021) 31

JINST 15 (2020) T08008
JINST 15 (2020) T08010

The DUNE Collaboration

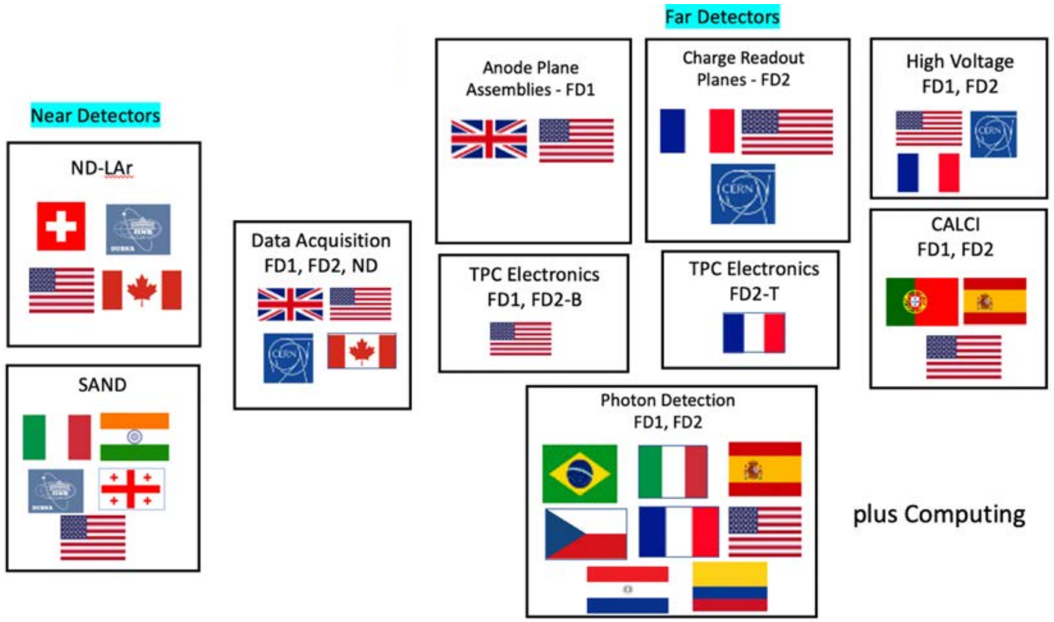
~1400 collaborators from
~200 institutions in
>30 countries + CERN

DUNE Collaboration Meeting,
Fermilab, May 2022



DUNE Collaboration Organization

Detector construction consortia:



Physics working groups:

Physics Coordination Inés Gil-Botella Chris Marshall	**Long-baseline** Callum Wilkinson Luke Pickering	**High energy** Lisa Koerner Yun-Tse Tsai	**FD sim/reco** Chris Backhouse Dom Brailsford
DUNE Physics Working Groups	**Neutrino Interactions** Cheryl Patrick Mateus Carneiro	**BSM** Justo Martin-Albo Alex Sousa	**ND sim/reco** Linda Cremonesi Mat Muether
Liaisons Dan Cherdack (ND) Tom Junk (computing)	**Low Energy** Clara Cuesta Dan Pershey	**Calibration** David Caratelli Mike Mooney	**protoDUNE analysis** Leigh Whitehead Tingjun Yang

DUNE Physics Goals

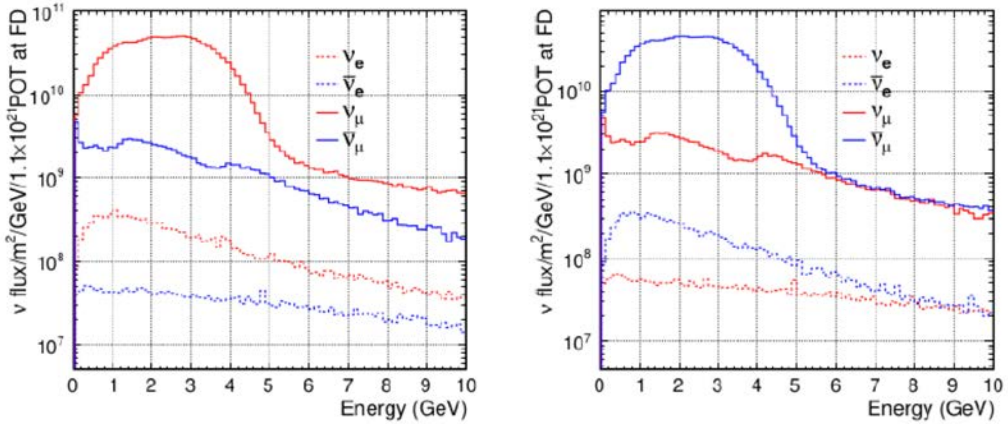
Credit: symmetry magazine

Long-baseline oscillations

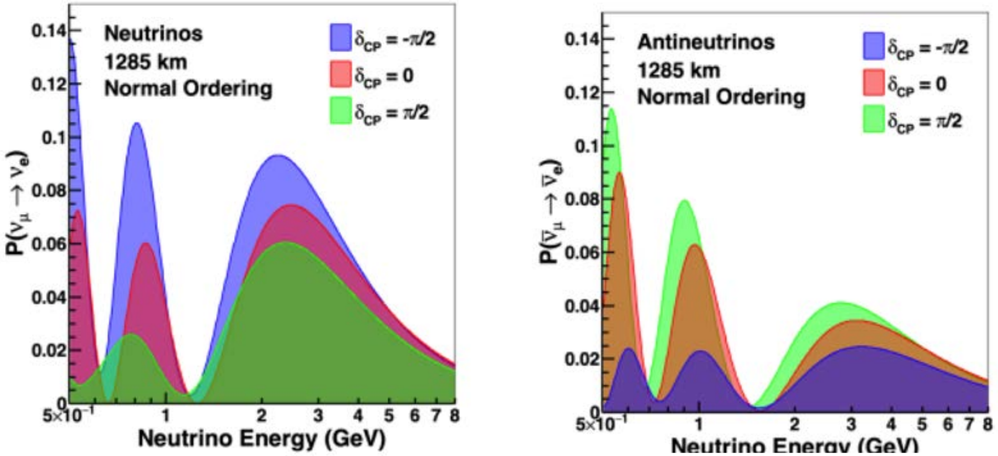
Precision measurement of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

- 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 δ_{CP} and the mass ordering.
- The beam energy will cover two oscillation maxima improving the sensitivity.

Neutrino beam energy spectrum



Neutrino oscillation probability at a baseline of 1300 km



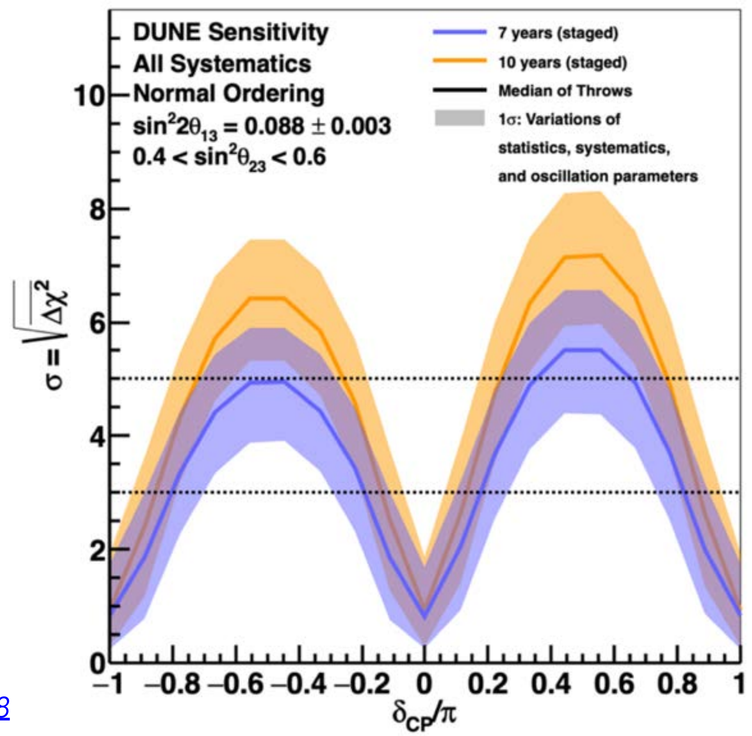
Long-baseline oscillations

Precision measurement of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillations with the goal of

- Measuring the CP violating phase (δ_{CP})
- Determining neutrino mass ordering (Δm^2_{31} sign)
- Precision tests of the 3 flavor neutrino oscillation paradigm (θ_{23} and octant)

CP violation sensitivity

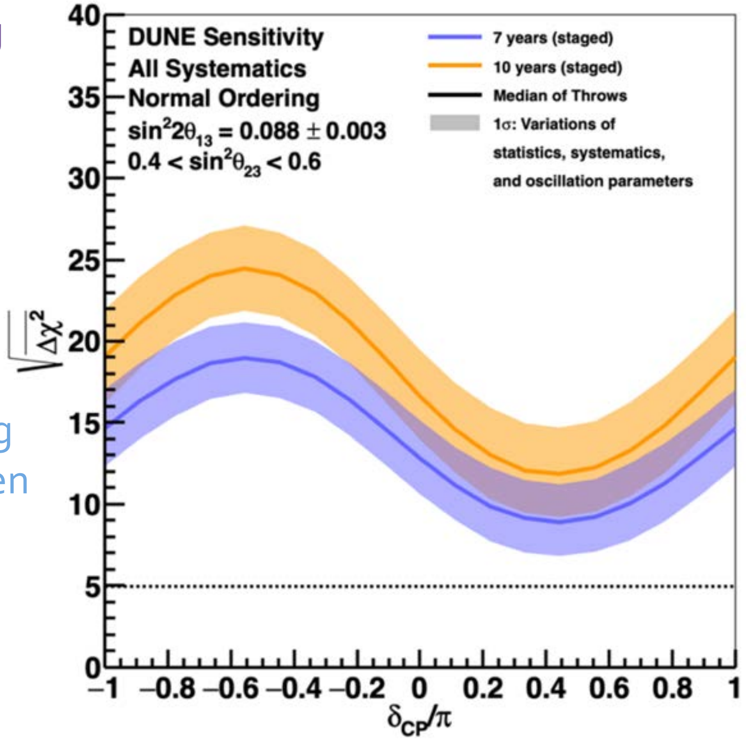
Significance with which δ_{CP} can be determined



EPJC 80 (2020) 978

Mass ordering sensitivity

Discriminating power between the two mass ordering hypotheses



Physics Beyond the Standard Model

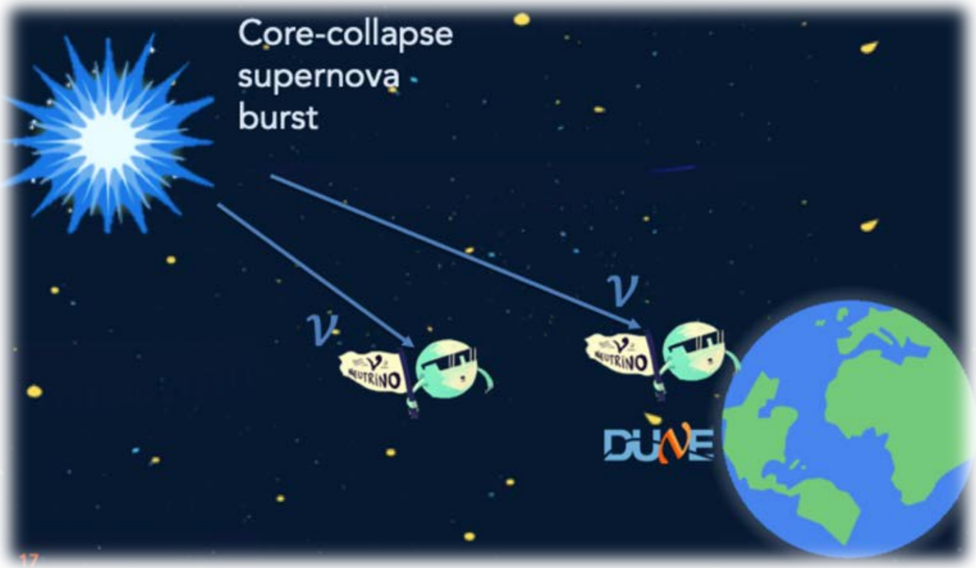
DUNE can probe a rich and diverse BSM phenomenology including searches for:

- 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 ν 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 ν, 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.

EPJC 81 (2021) 322

Low Energy Physics

The DUNE FD is sensitive to ν's produced by the Sun and in core-collapse supernovae with E ~ 5-100 MeV.



- **Core-collapse supernovae** are a huge source of ν'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 ν's will provide information about:
    - **Supernova physics**: Core collapse mechanism, SN evolution in time, black hole formation.
    - **Neutrino physics:** ν flavor transformation, ν absolute mass, other ν properties (sterile ν's, magnetic moments, extra dimensions…).
- **Solar and diffuse background supernova ν's** are also potentially detectable.

Supernova neutrino emission

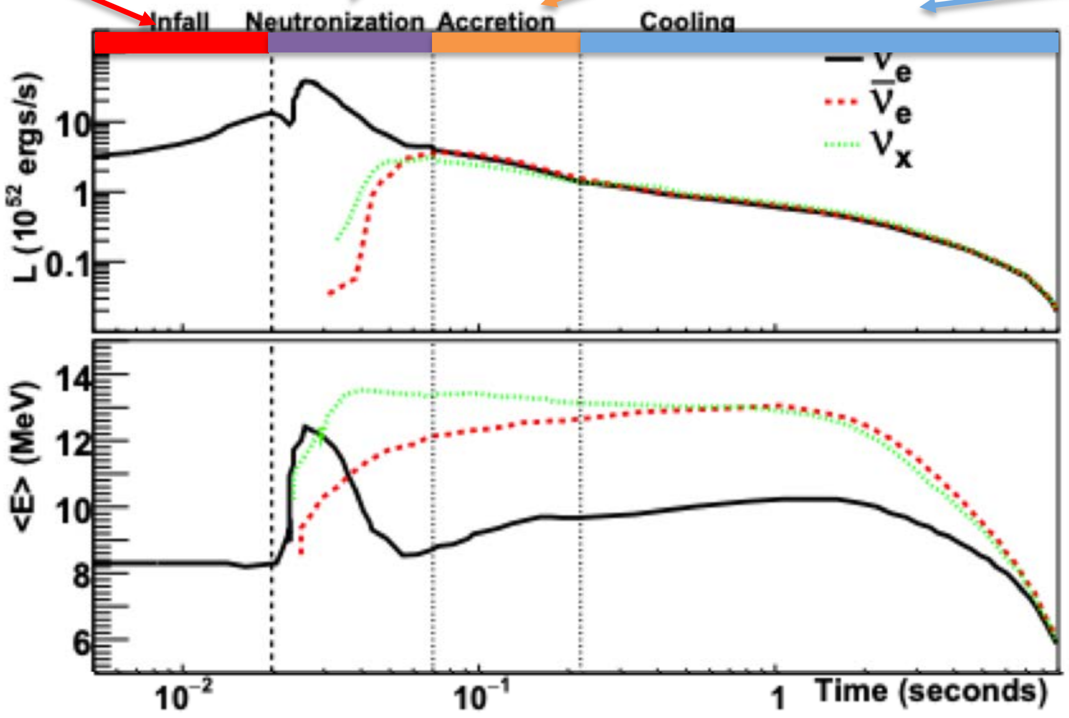
Infall — Core collapses, and a shock wave is formed. The medium is opaque even for neutrinos.

Neutronization — Primarily ν_e escape, as messengers of the shock front breaking.

Accretion — (<1s) ν's powered by infalling matter.

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

For a supernova at 10 kpc from Earth.



A lot of information about the supernova in this profile: flavor content and spectra of the ν's emitted change throughout these phases, and the supernova's evolution can be followed with the ν signal.

Supernova neutrino signal in LAr

1. Charged-current (CC) interaction on Ar

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

Dominant interaction

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

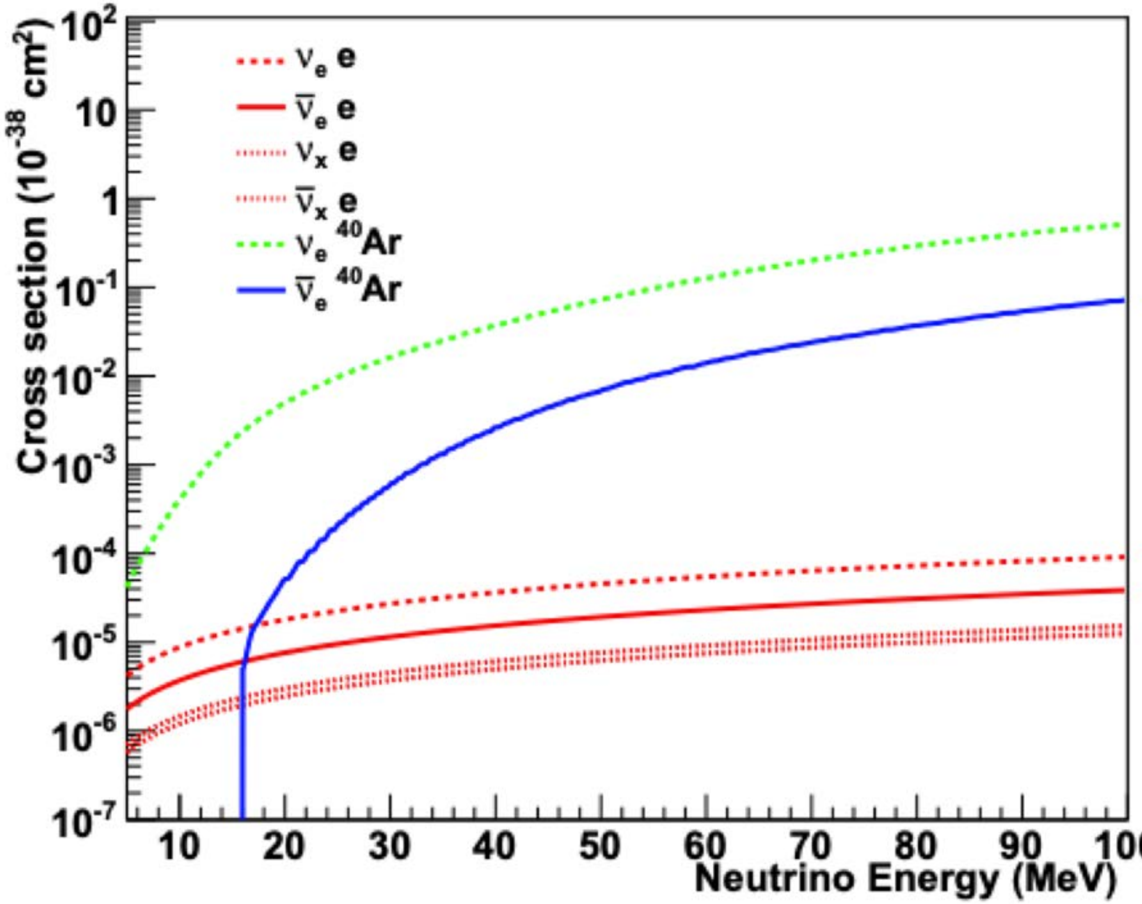
2. Elastic scattering on electrons (ES)

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

3. Neutral current (NC) interactions on Ar

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

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)



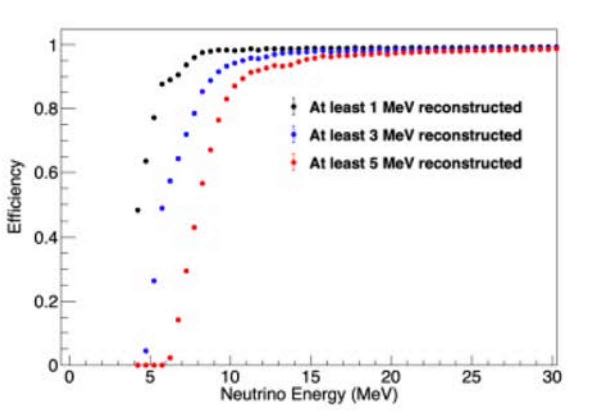
Supernova event simulation and reconstruction in DUNE

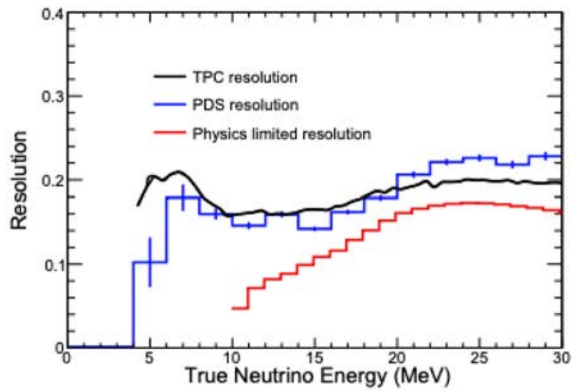
MARLEY simulates tens-of-MeV ν-nucleus interactions in LAr

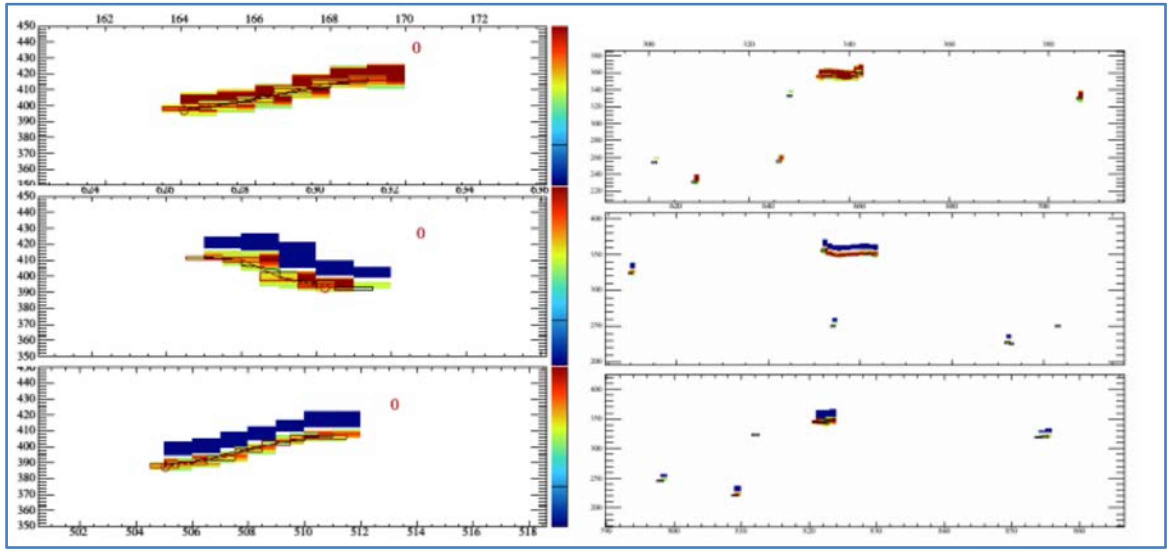
Reconstruction: **LArSoft** to identify interaction channel, ν flavor in CC events, & incoming neutrino 4-momentum

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

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







ν-e$^-$ **ES event** (10.25 MeV e$^-$) ν_e**CC event** (20.25 MeV ν)

EPJC 81 (2021) 423

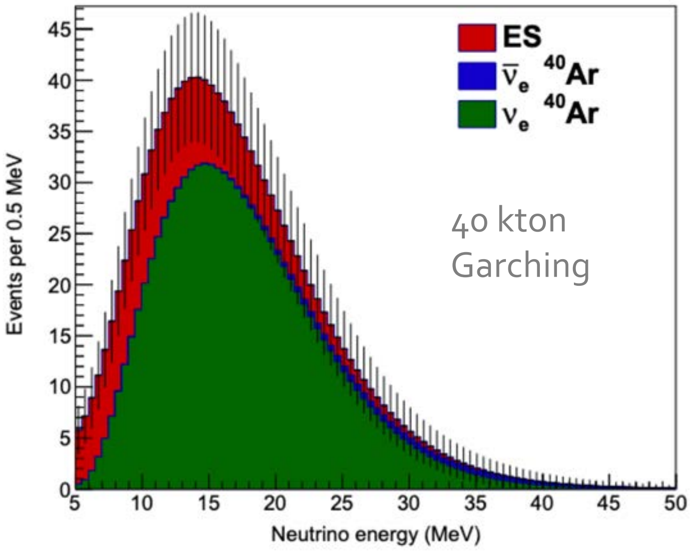
Expected Supernova burst signal in DUNE

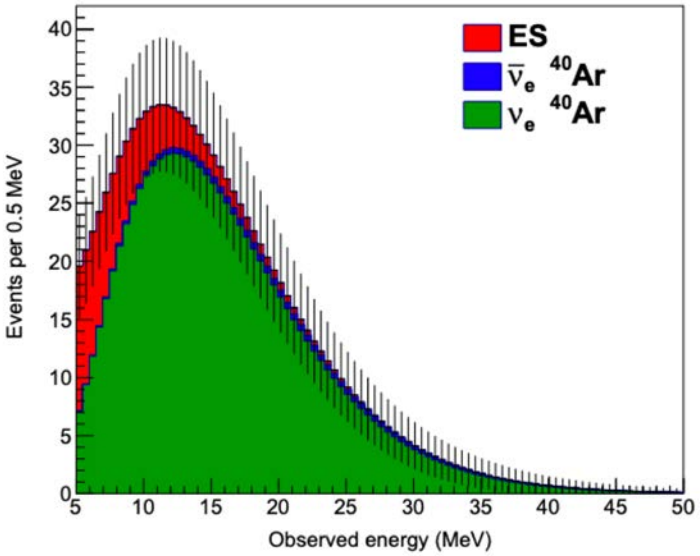
Channel	Liver-more	GKVM	Garching
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2648	3295	882
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

ν_e flavor dominates.

LAr only future prospect for a large, cleanly tagged SN ν_e sample

40 kton LAr & 10 kpc SN

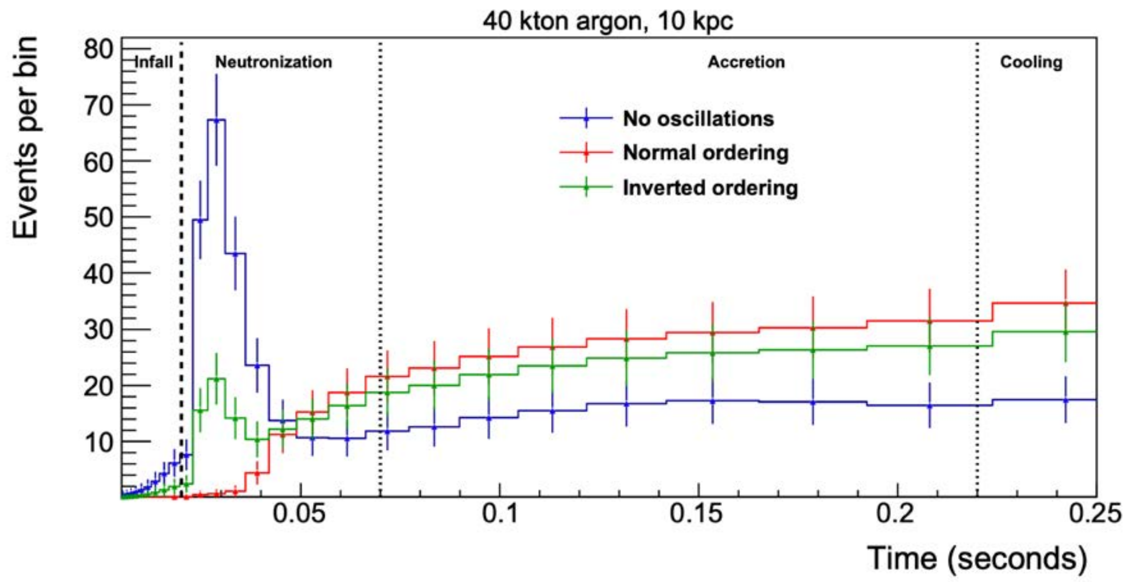


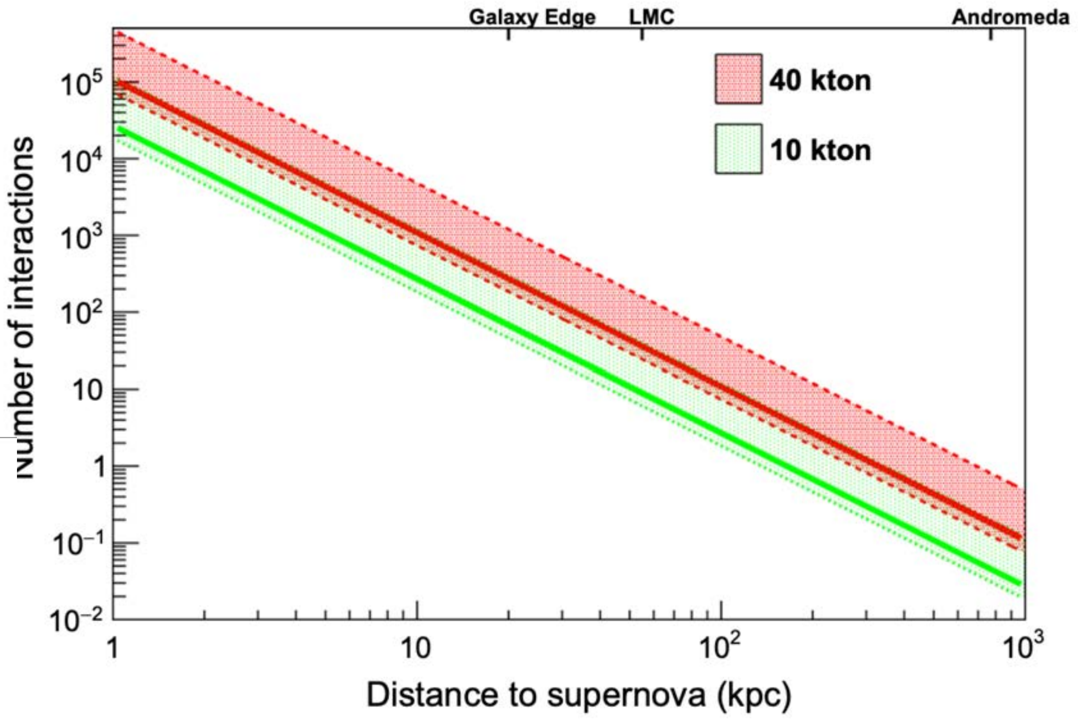


EPJC 81 (2021) 423

Expected Supernova burst signal in DUNE

- Number of SN ν 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.

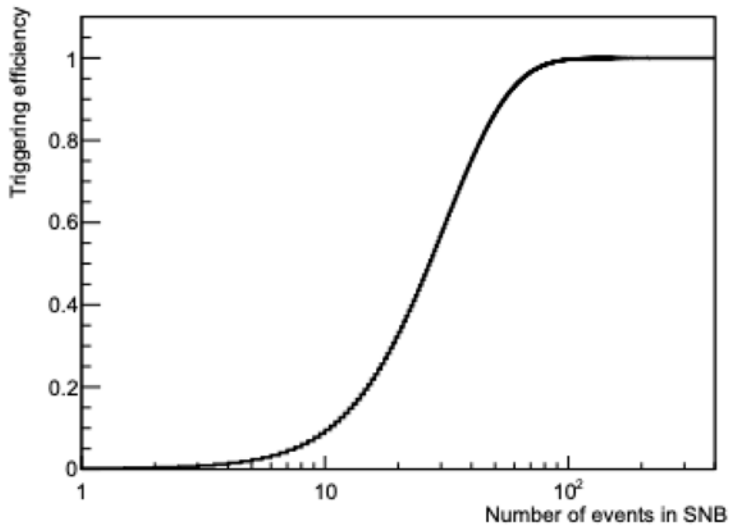
EPJC 81 (2021) 423

Low Energy Physics

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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)

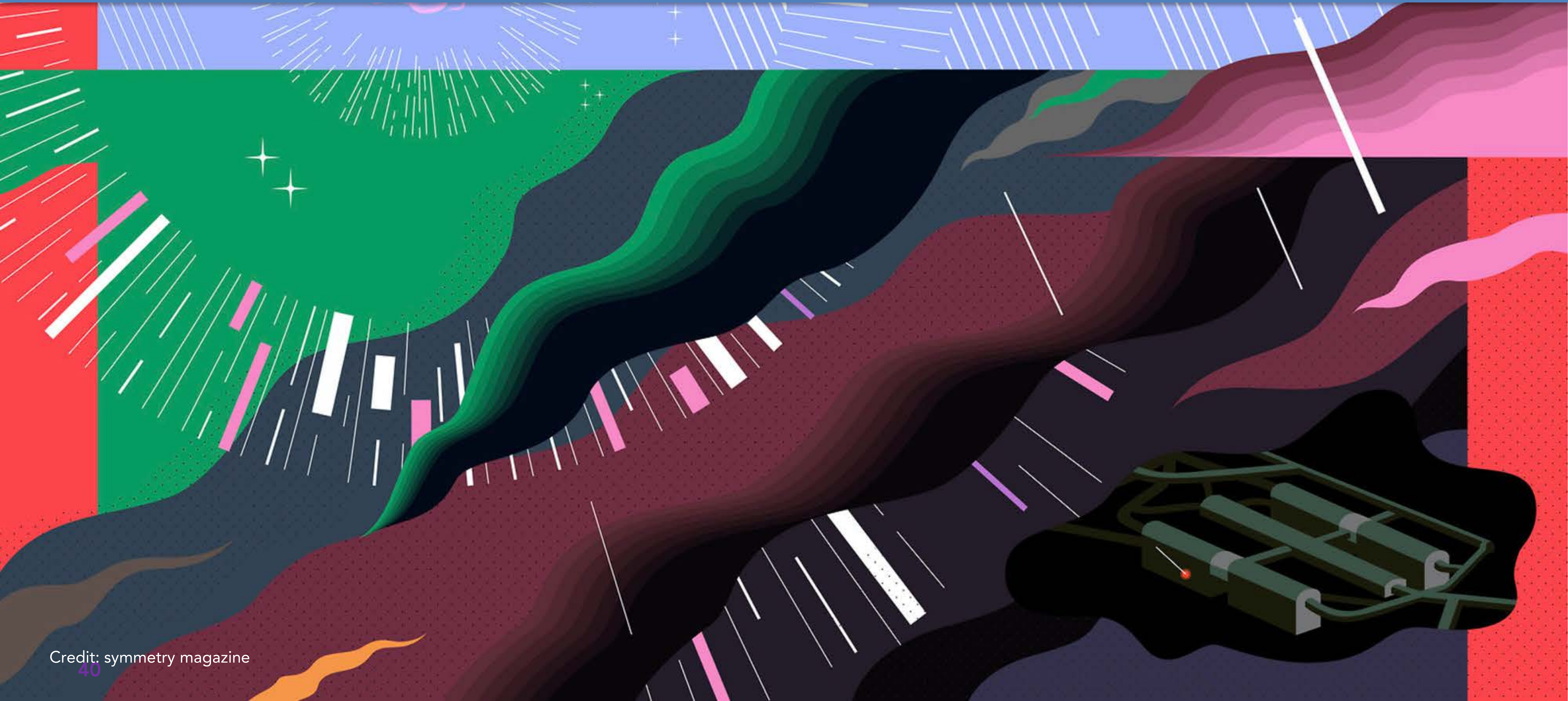


Example: Photon detection system in dual-phase far detector.

- 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.

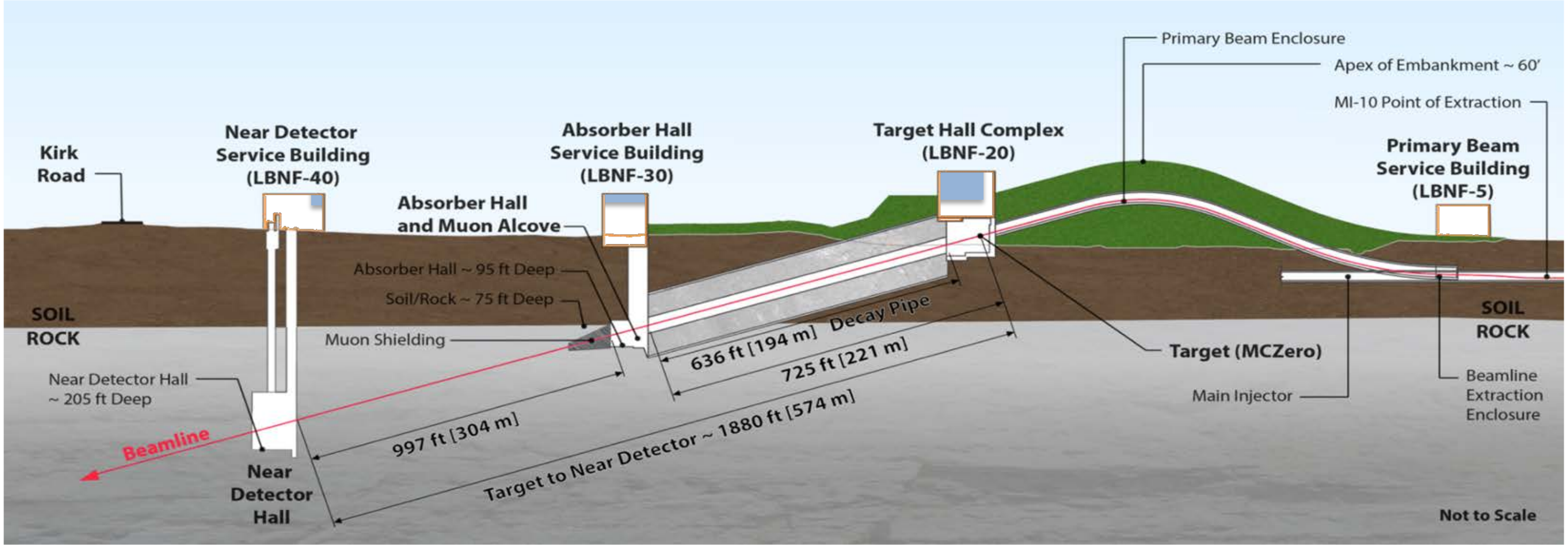
A. Gallego-Ros (CIEMAT) PhD Thesis

DUNE
Neutrino beam, Near and Far Detectors



Credit: symmetry magazine

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

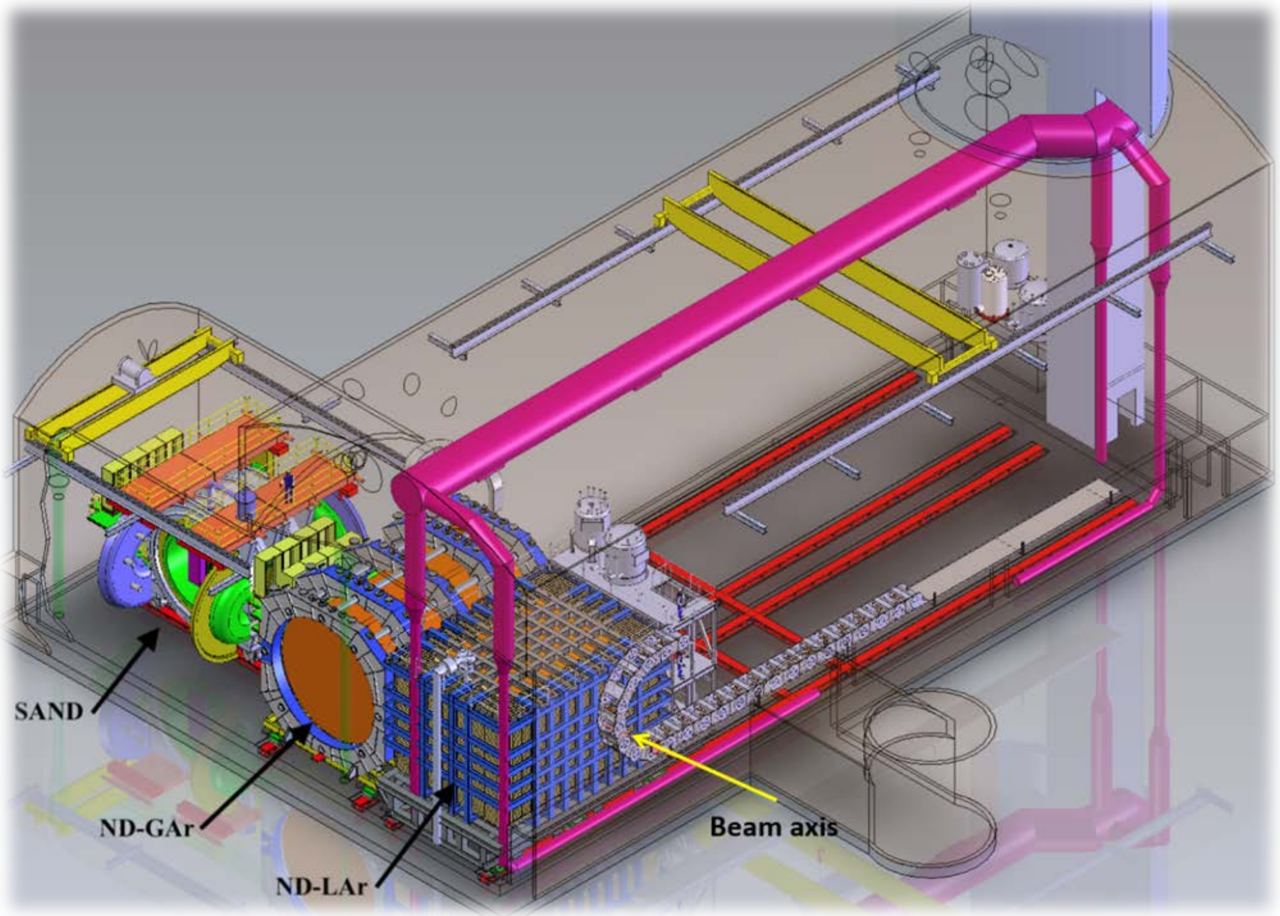
Roles:

- 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 ν source.

Components:

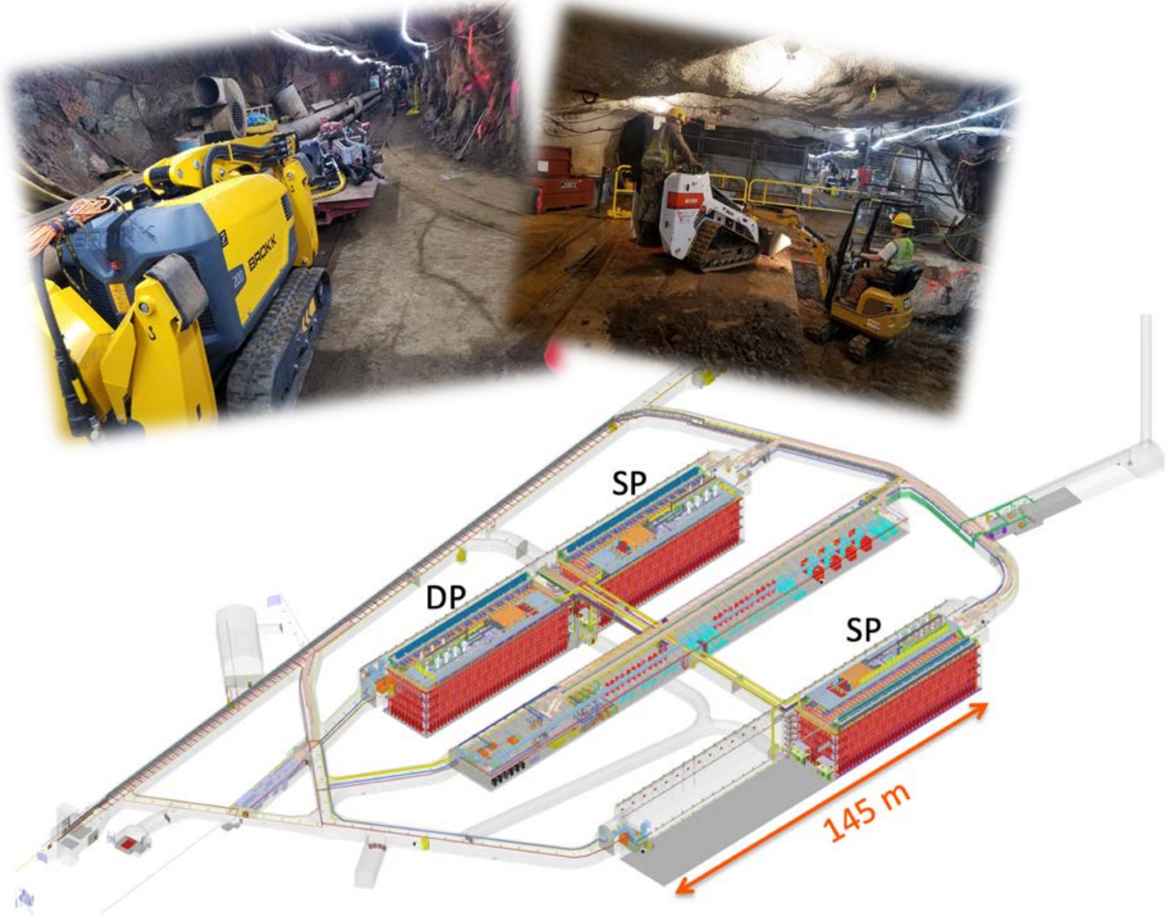
- Highly modular LArTPC (**ND-LAR**).
- Magnetized gaseous argon TPC (**ND-GAr**).
- Magnetized beam monitor (**SAND**).

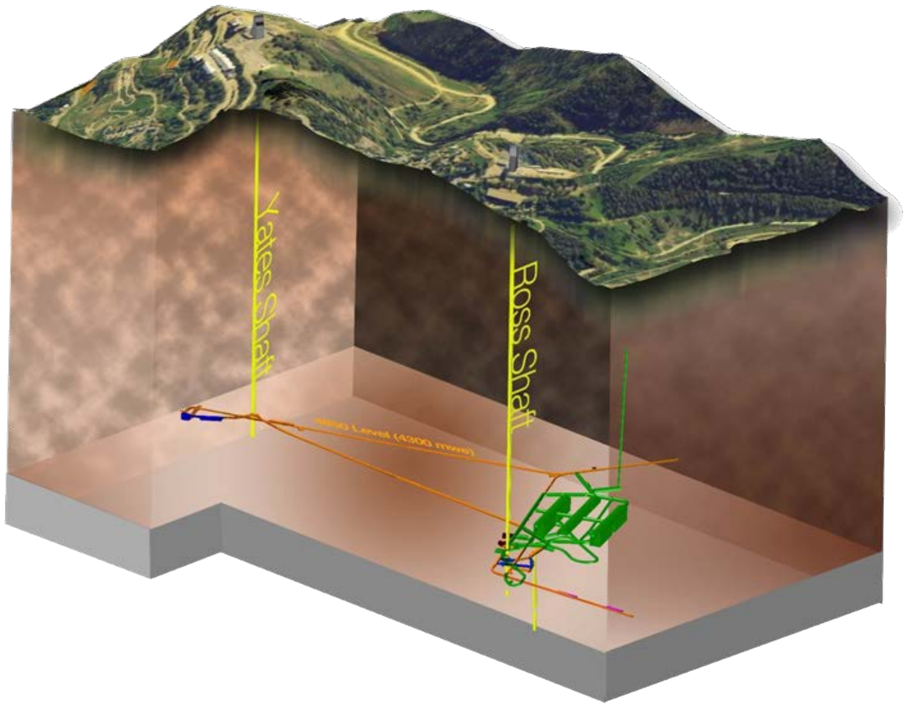


Instruments 5 (2021) 31

Far Detector

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





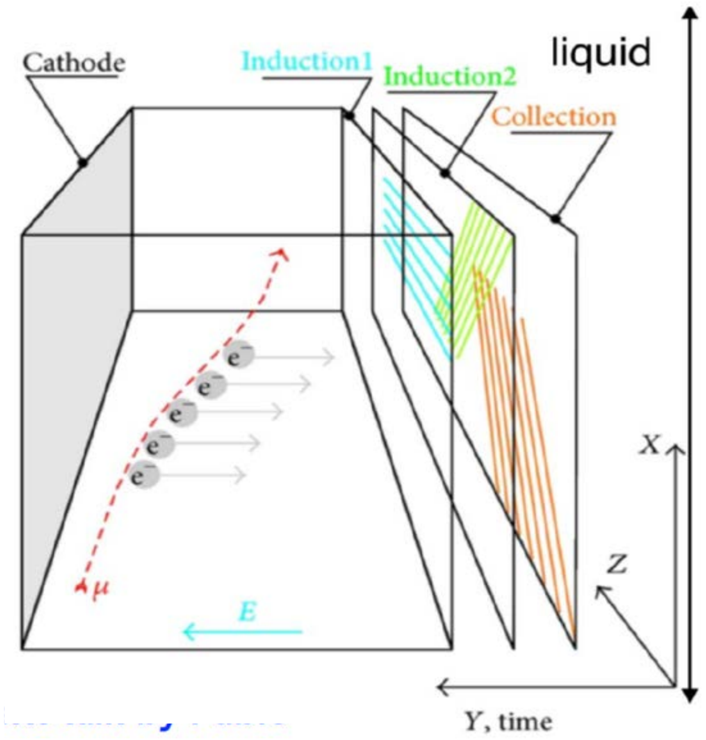
Four 10-kt Fiducial LAr TPC modules

"2+1+1" model:

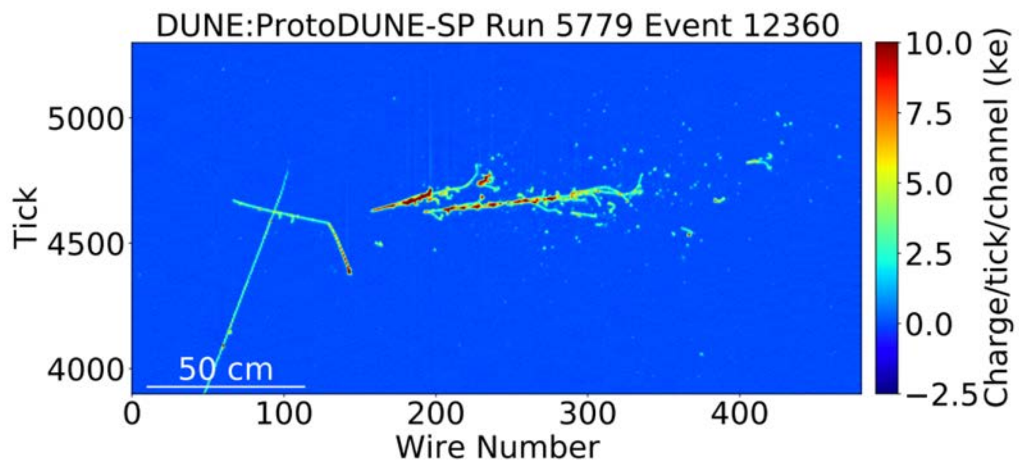
- 2 modules horizontal drift
- 1 vertical drift module
- 1 "opportunity" module

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.

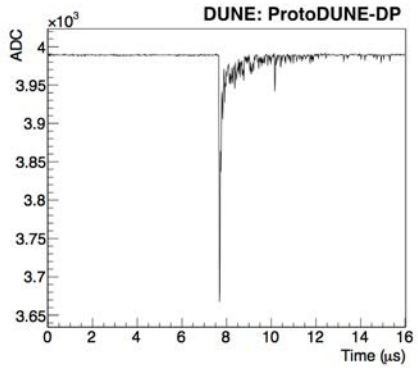


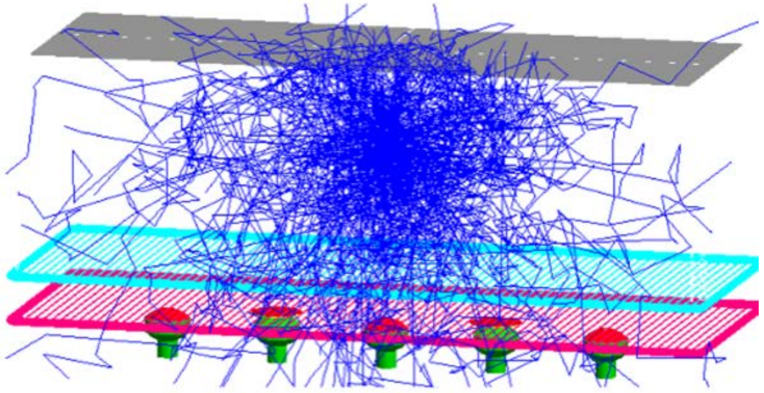
Scintillation light in LArTPC

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

- **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. λ_{Abs}= 20 m (~3 ppm N_2).
  - Reflections and absorption in the detector.
- **Detection** is challenging:
  - Wavelength shifting usually required
  - Maximizing photon detection efficiency

scintillation signal



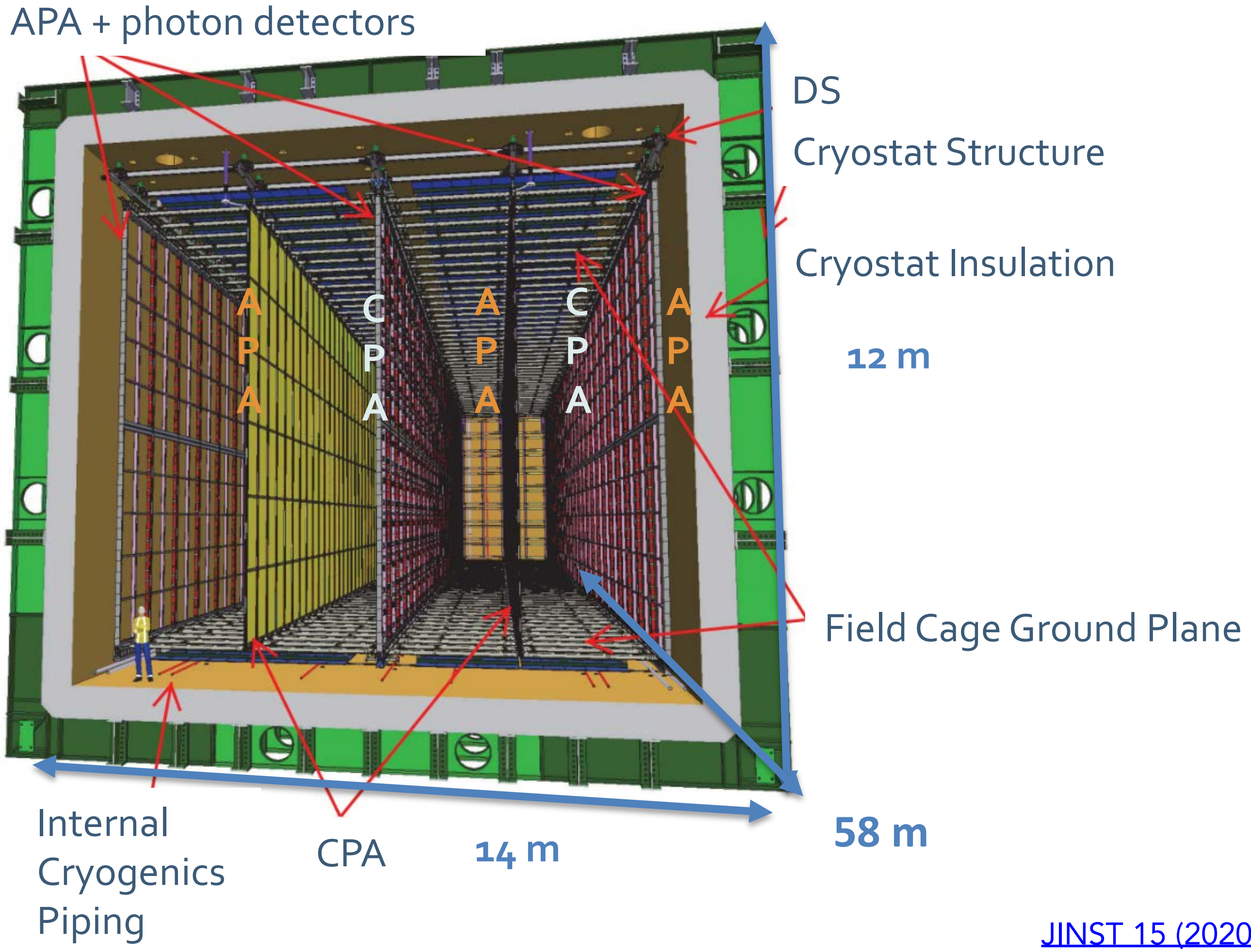


Photon trajectories for short λ_{RS}

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

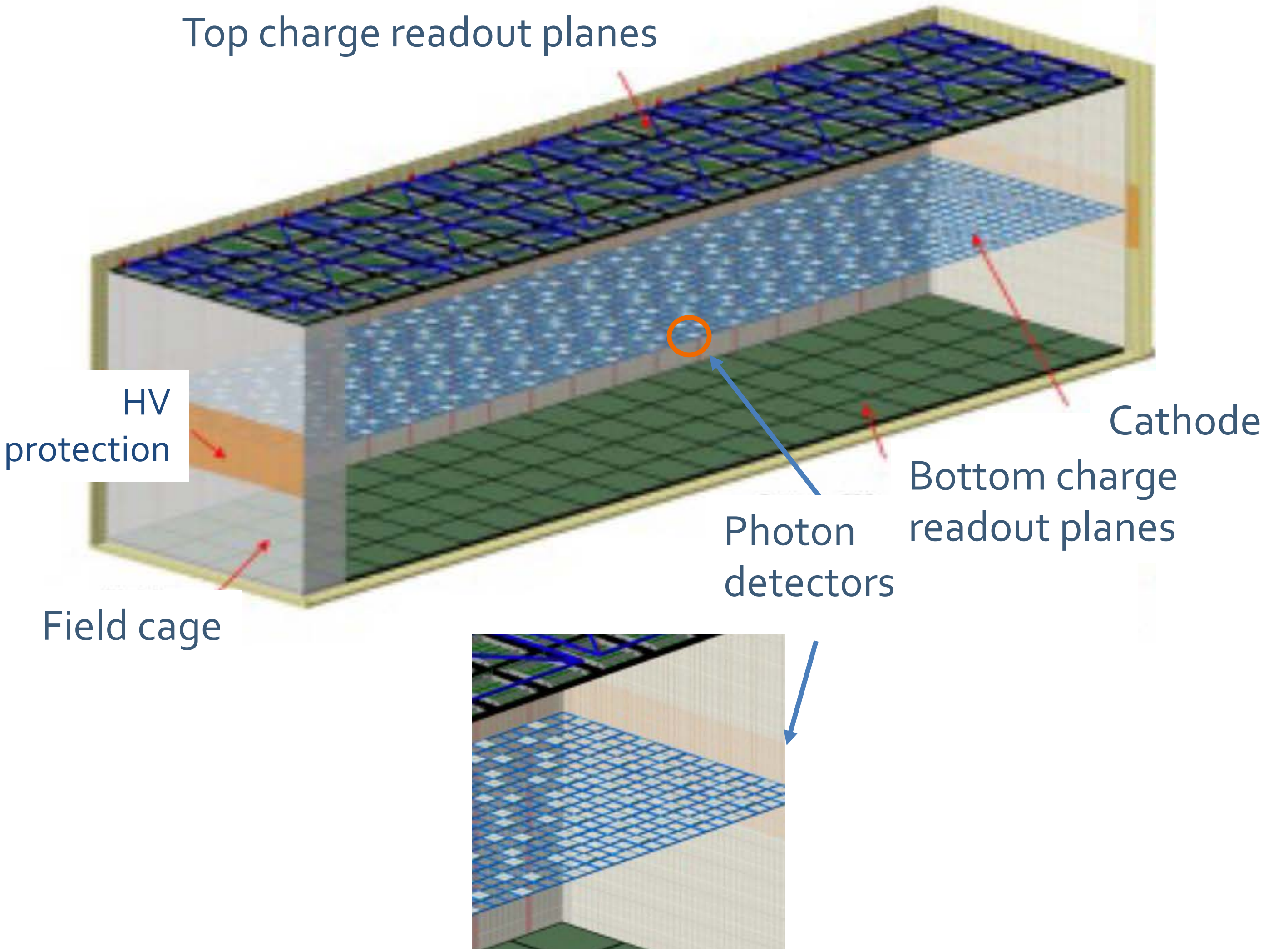


JINST 15 (2020) T08008
JINST 15 (2020) T08010

Far Detector 2

Vertical drift

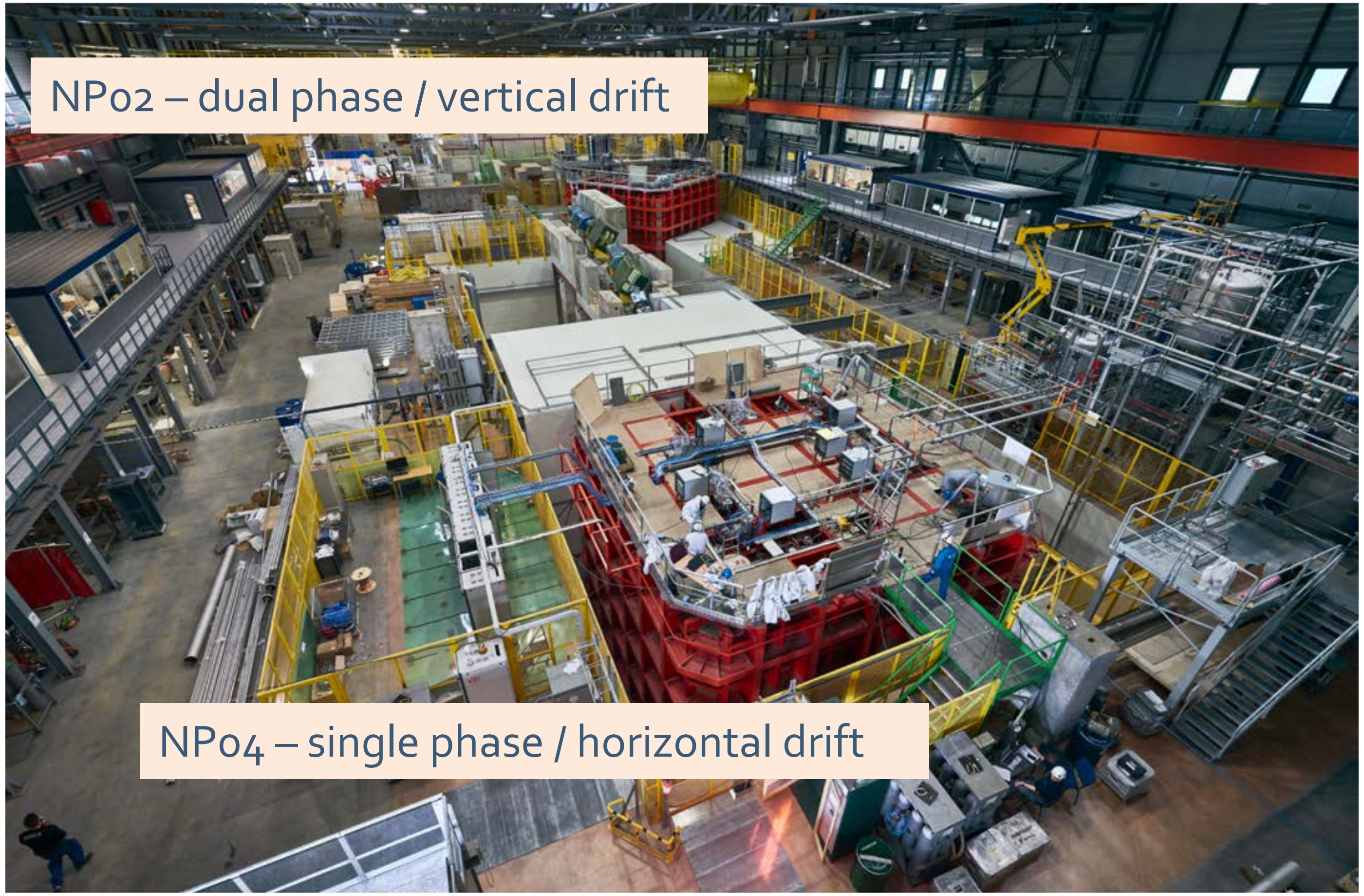
- **6-m vertical drift** that maximizes active volume.
- **Printed Circuit Board**-based readout scheme makes detector assembly much simpler.
- **Photodetection system** deployed (X-ARAPUCA) on the central cathode plane + cryostat walls.
- Challenging technology.



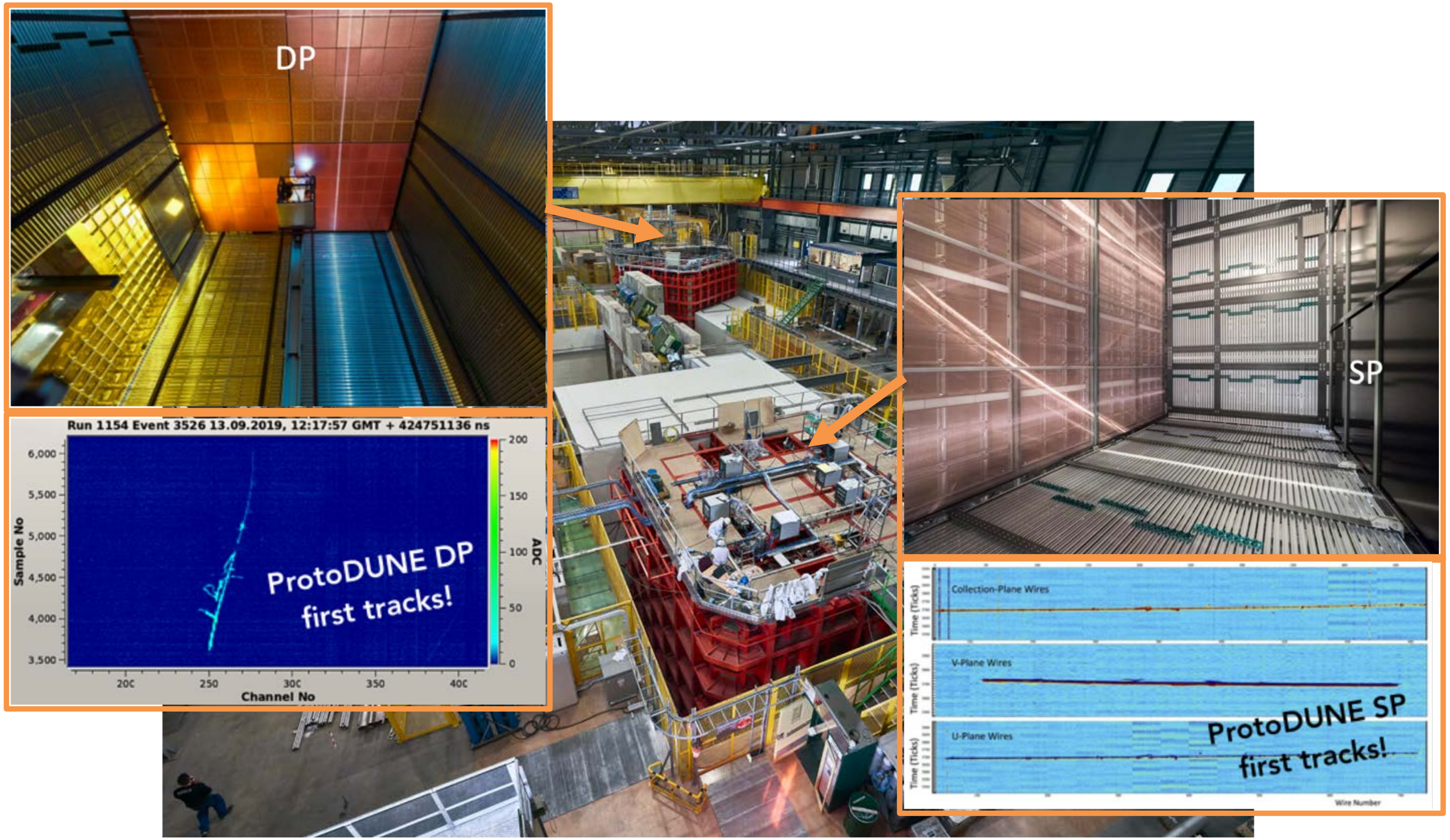

ProtoDUNE
Genie AWP-20S

ProtoDUNE at CERN

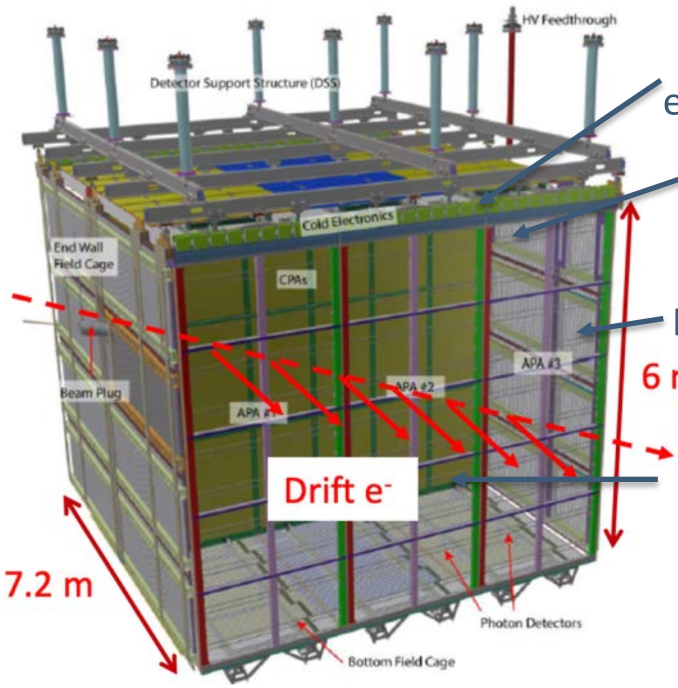
Construction and operation of 1 kton-scale SP and DP prototypes at CERN - critical to demonstrate viability of technology, and that the DUNE Collaboration can implement a major construction activity



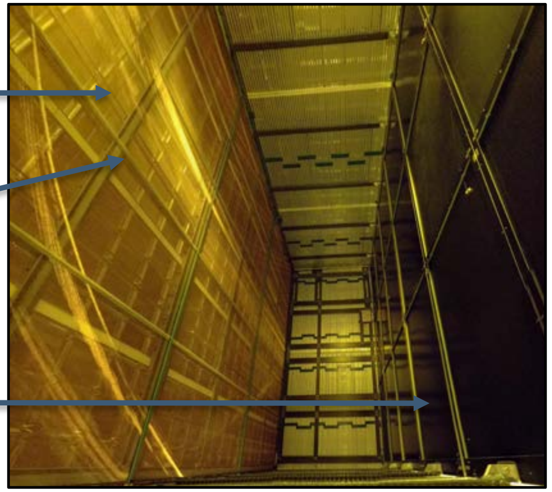
ProtoDUNE at CERN



NP04: ProtoDUNE Single Phase (Horizontal drift)



2 LAr volumes: 3.6 m drift length each TPC



[JINST 15 (2020) P12004](#)
[JINST 17 (2022) P01005](#)

Phase I

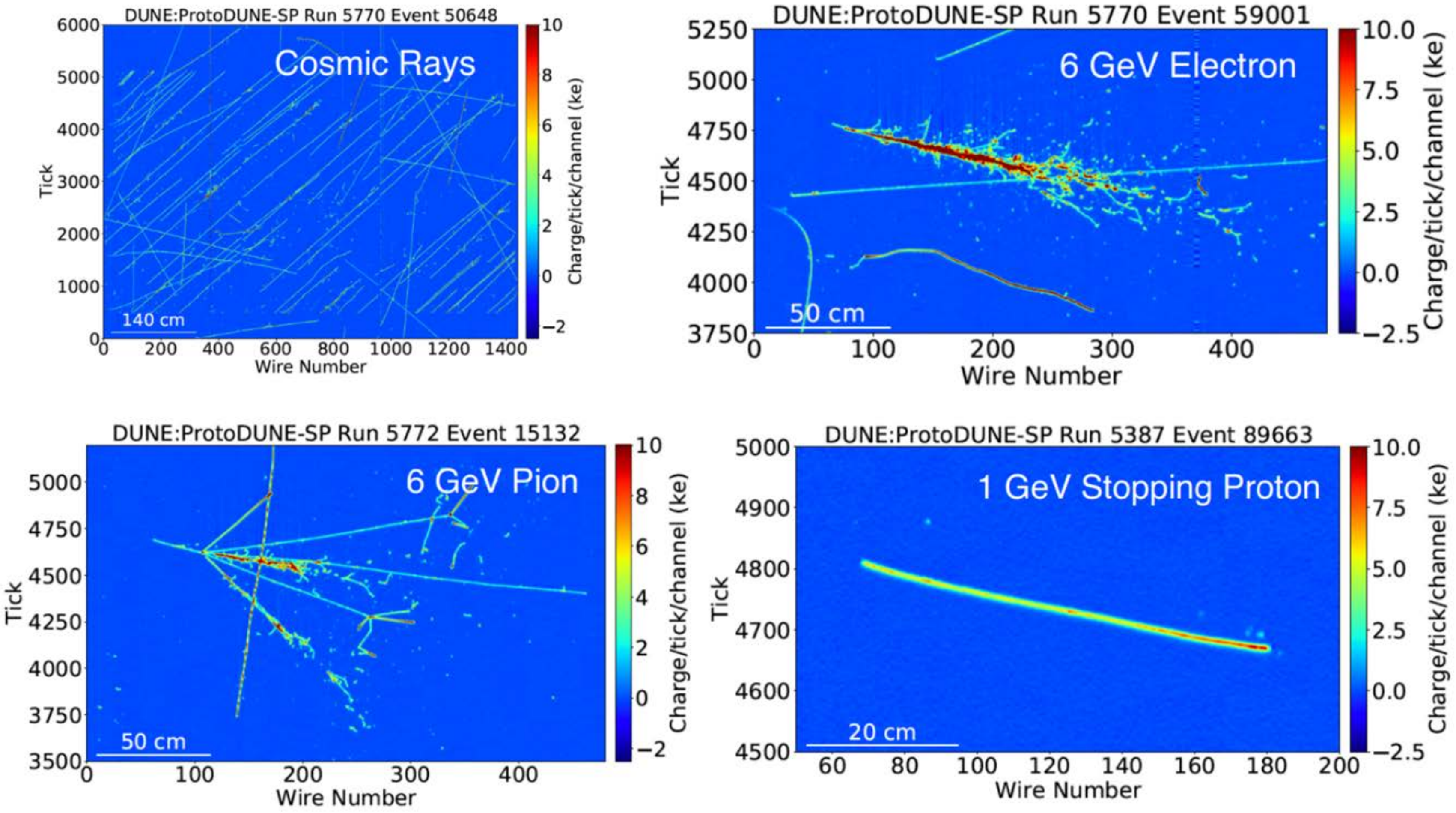
- Beam data taking (2018):
  - Collected >4M beam triggers,
  - 0.5 - 7 GeV particle beams (e, π, p, K)
- Cosmic-ray data taking (2018-2020):
  Excellent performance: HV, LAr purity, and signal-to-noise

Phase II

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

NP04: ProtoDUNE Single Phase (Horizontal drift)

Event display



NP04: ProtoDUNE Single Phase (Horizontal Drift)

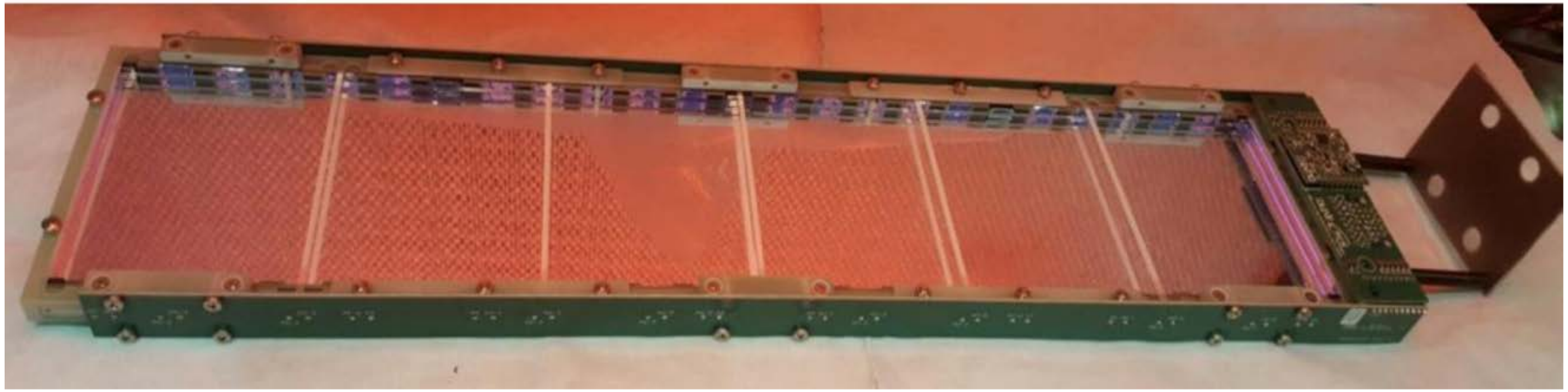
Photon detectors: X-ARAPUCAs

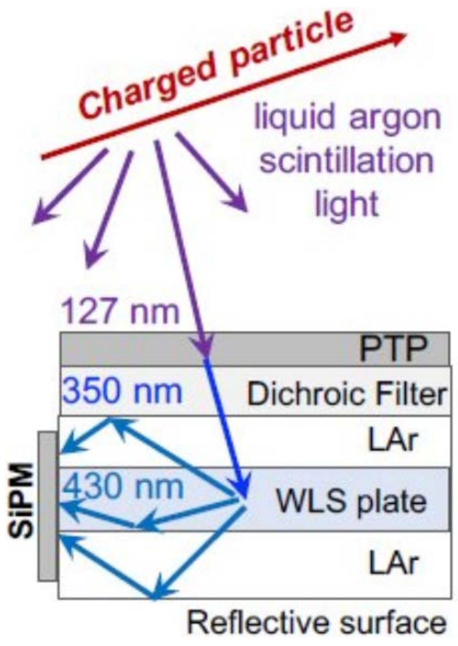
Challenges:

- 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.

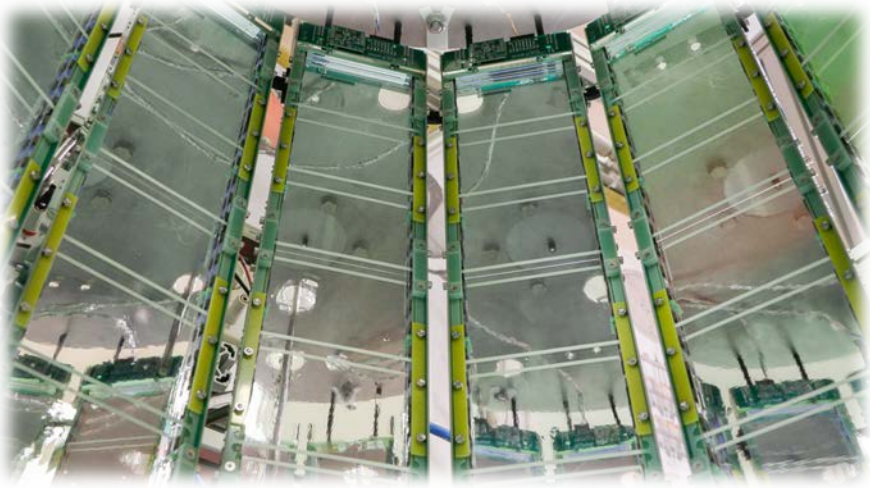




NP04: ProtoDUNE Single Phase (Horizontal Drift)

Photon detectors: X-ARAPUCAS

✓ Design, procurement, assembly, and characterization.



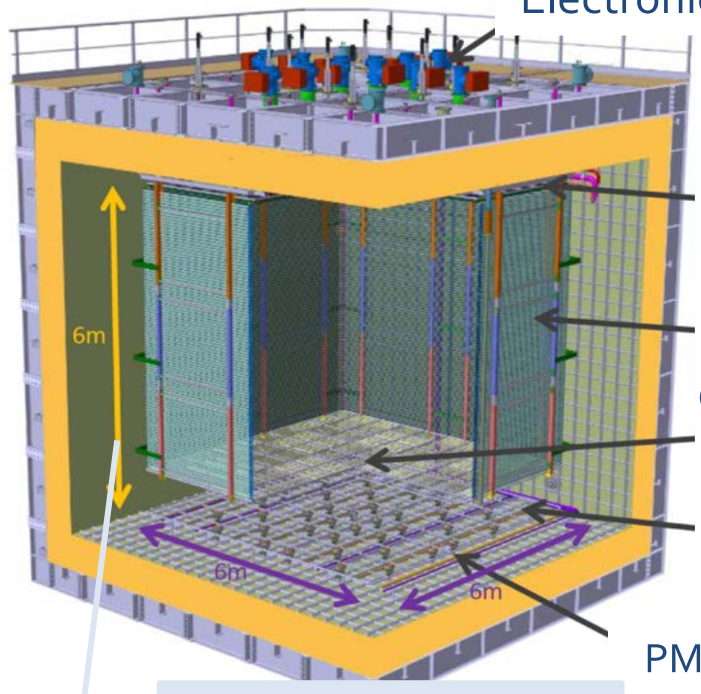
CIEMAT lab

✓ X-ARAPUCA Photon Detection Efficiency measured.
✓ Installation at ProtoDUNE APAs at CERN.

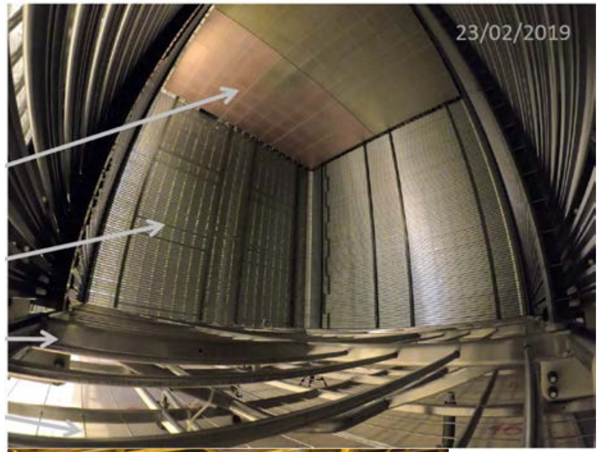
CERN Neutrino Platform

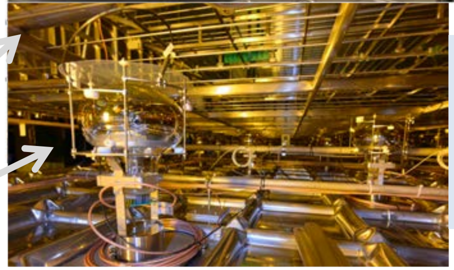
NP02: ProtoDUNE Dual Phase (Vertical drift)

6x6x6 m^3 DP LArTPC



Drift = 6 m
(~300 kV at cathode)





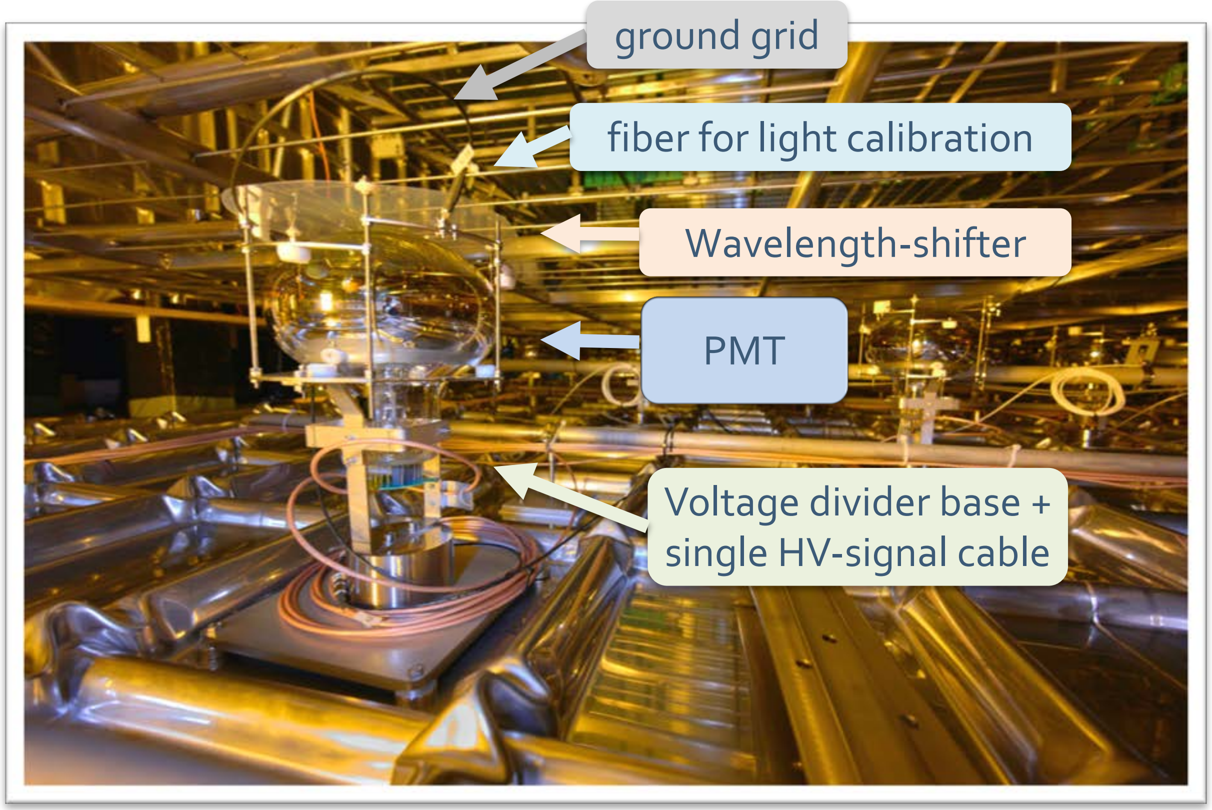
Dual phase: charge amplified in gas argon

Cosmic ray data taking (2019-2020)

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. Scie. 68 (2021) 2334

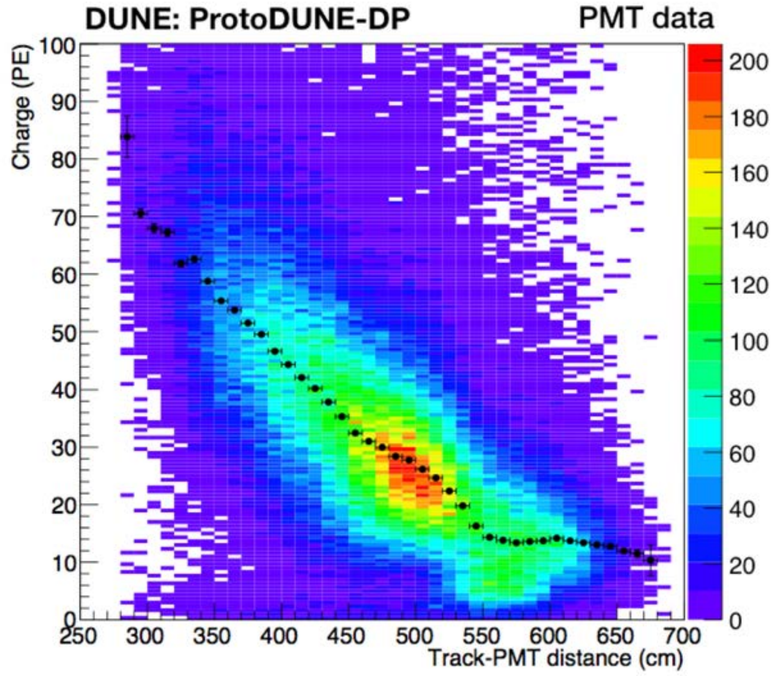
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
IFAE Institut de Física d'Altes Energies

NP02: ProtoDUNE Dual Phase (Vertical Drift)

Scintillation light results

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

- **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/m^2, 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

Duke University, Durham, NC, and TUNL:
Matthew Busch

Indiana University, Bloomington, IN:
Walter Pettus

Joint Institute for Nuclear Research, Dubna, Russia:
Sergey Vasilyev

Lawrence Berkeley National Laboratory, Berkeley, CA:
Yuen-Dat Chan, Alan Poon

Los Alamos National Laboratory, Los Alamos, NM:
Pinghan Chu, Steven Elliott, In Wook Kim, Ralph Massarczyk, Samuel J. Meijer, Keith Rielage, Danielle Schaper, Brian Zhu

National Research Center *'Kurchatov Institute' Institute of Theoretical and Experimental Physics, Moscow, Russia:*
Alexander Barabash

North Carolina State University, Raleigh, NC and TUNL:
Matthew P. Green, Ethan Blalock, Rushabh Gala

Oak Ridge National Laboratory, Oak Ridge, TN:
Vincente Guiseppe, Charlie Havener, José Mariano Lopez-Castaño, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan:
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, WA:
Isaac Arnquist, Maria-Laura di Vacri, Eric Hoppe, Richard T. Kouzes

Queen's University, Kingston, Canada:
Ryan Martin

South Dakota Mines, Rapid City, SD:
Cabot-Ann Christofferson, Jessica Peterson, Ana Carolina Sousa Ribeiro, Jared Thompson

Technische Universität München, and Max Planck Institute, Munich, Germany:
Susanne Mertens

Tennessee Tech University, Cookeville, TN:
Mary Kidd

University of North Carolina, Chapel Hill, NC, and TUNL:
Kevin Bhimani, Brady Bos, Thomas Caldwell, Morgan Clark, Aaron Engelhardt, Julieta Gruszko, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Aobo Li, Eric Martin, Gulden Othman, Anna Reine, Jackson Waters, John F. Wilkerson

University of South Carolina, Columbia, SC:
Franklin Adams, Frank Avignone, Thomas Lannen, David Tedeschi

University of South Dakota, Vermillion, SD:
C.J. Barton, Laxman Paudel, Tupendra Oli, Wenqin Xu

University of Tennessee, Knoxville, TN:
Yuri Efremenko

University of Washington, Seattle, WA:
Micah Buuck, Clara Cuesta, Jason Detwiler, Alexandru Hostiuc, Nick Ruof, Clint Wiseman

Williams College, Williamstown, MA:
Graham K. Giovanetti

*students

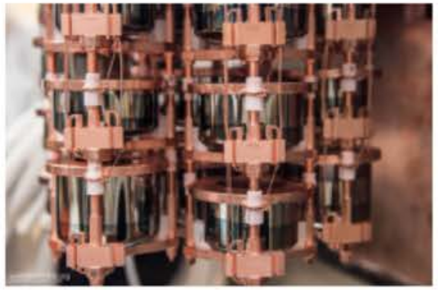
The MAJORANA DEMONSTRATOR

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

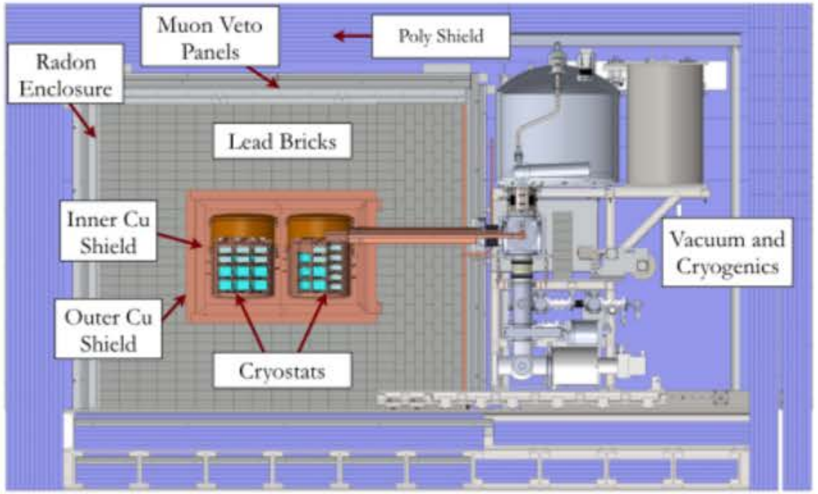
Source & Detector: Array of p-type, point contact detectors
- 29.7 kg of 87% enriched ^{76}Ge crystals
- Included 6.7 kg of inverted coaxial, point contact detectors in final run

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



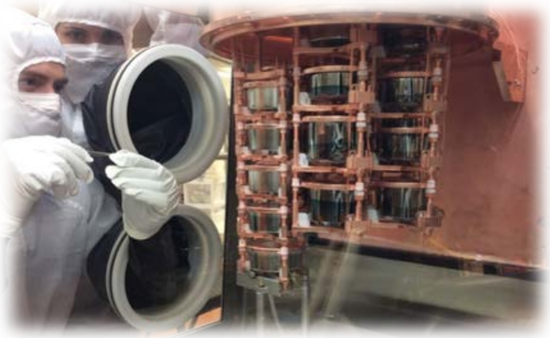
Background reduction

Ultra-pure materials

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

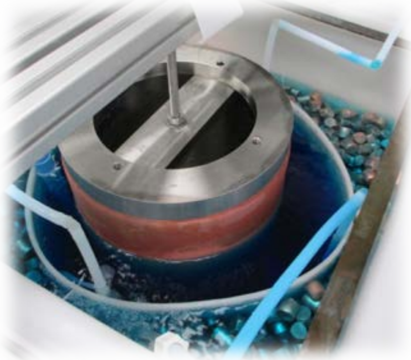
NIM A 828 22 (2016)

NIM A 775 93 (2015)



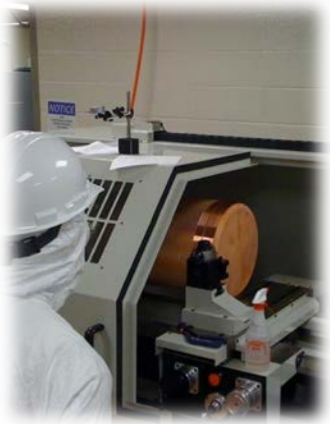
Machining, cleaning, and assembly

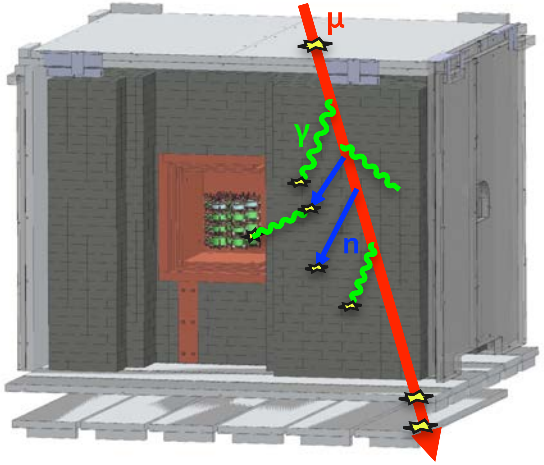
- Cu machining in an underground cleanroom
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts
- Dedicated glove boxes with a purged N_2 environment



Cosmogenic backgrounds

- Limit and track Ge above-ground exposure to prevent cosmic activation. NIM A 877 314 (2018) NIM A 779 52 (2015)
- Veto events coincident with muons Astropart. Phys. 93 70 (2017)

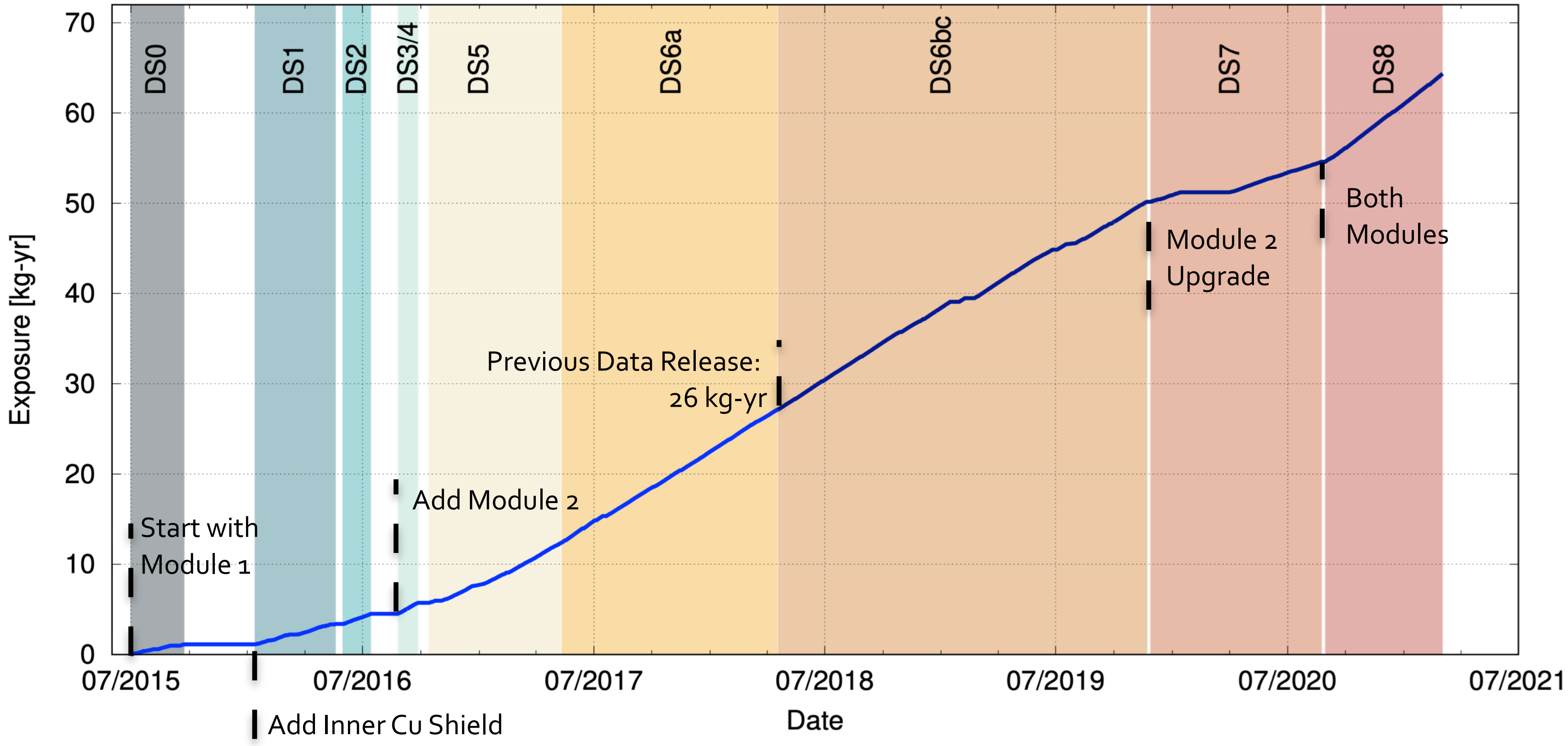




65 kg-yr of Exposure in Enriched Detectors

Total collected active exposure over time in enriched detectors.

Datasets (DSs) represent changes in experimental configuration



Energy resolution

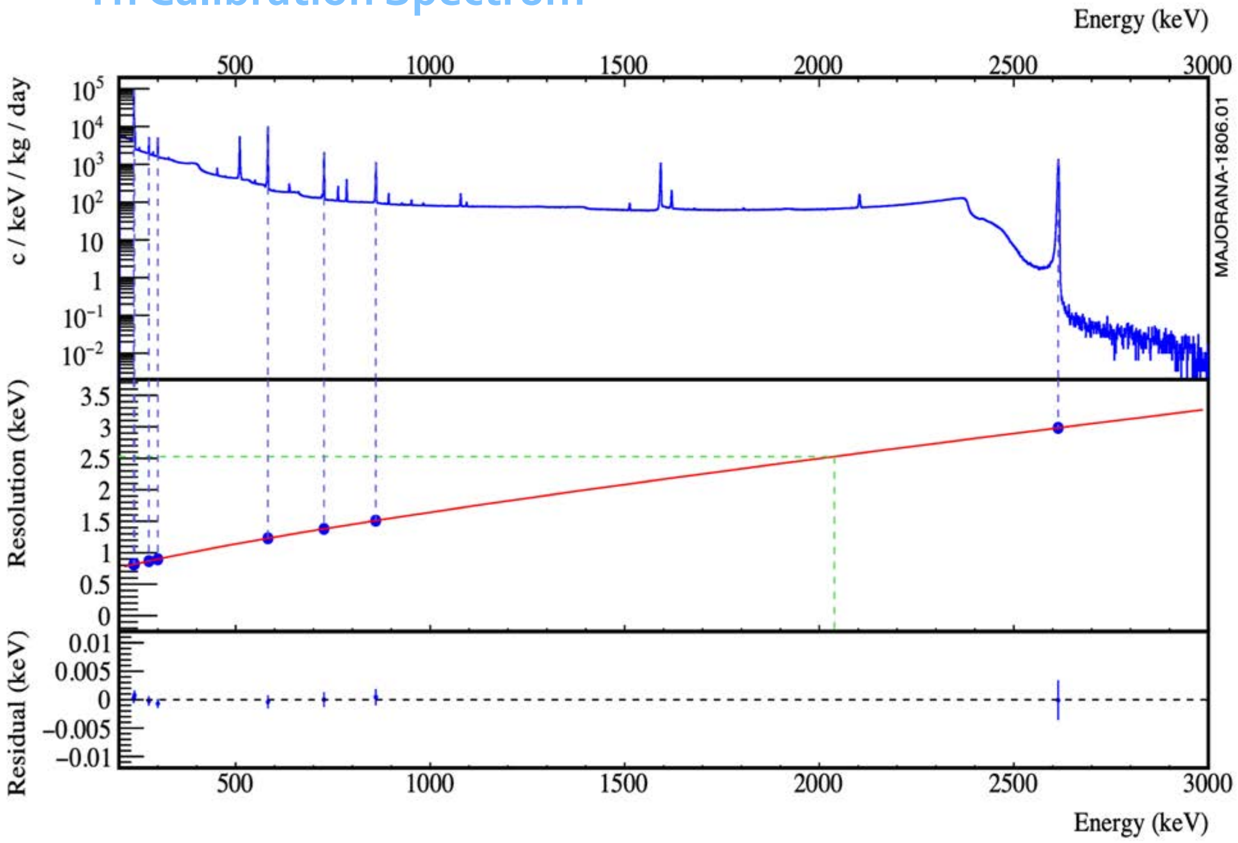
Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction.

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

^{228}Th line source deployed during calibration

FWHM of combined enriched detectors in the MAJORANA DEMONSTRATOR, measured using ^{228}Th calibration data

^{228}Th Calibration Spectrum



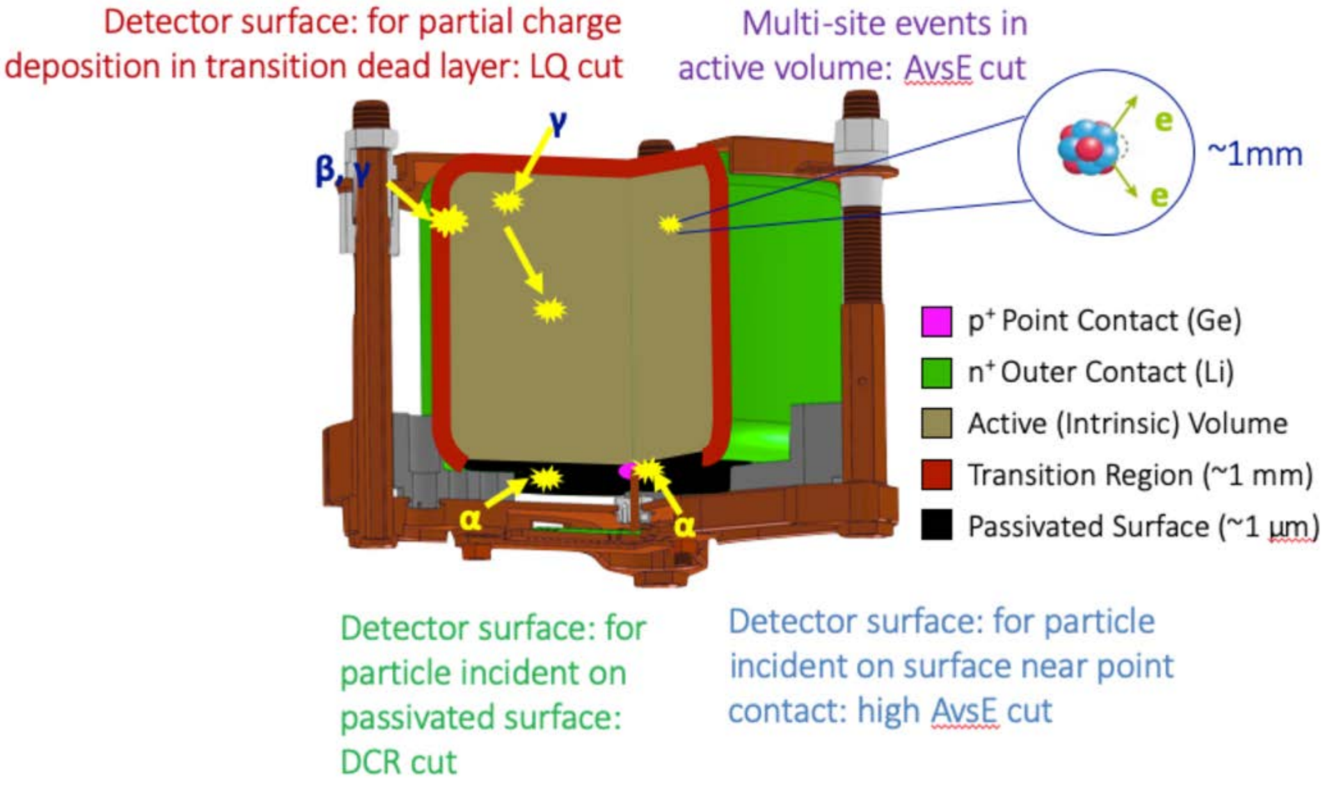
FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%) is a record for 0νββ searches

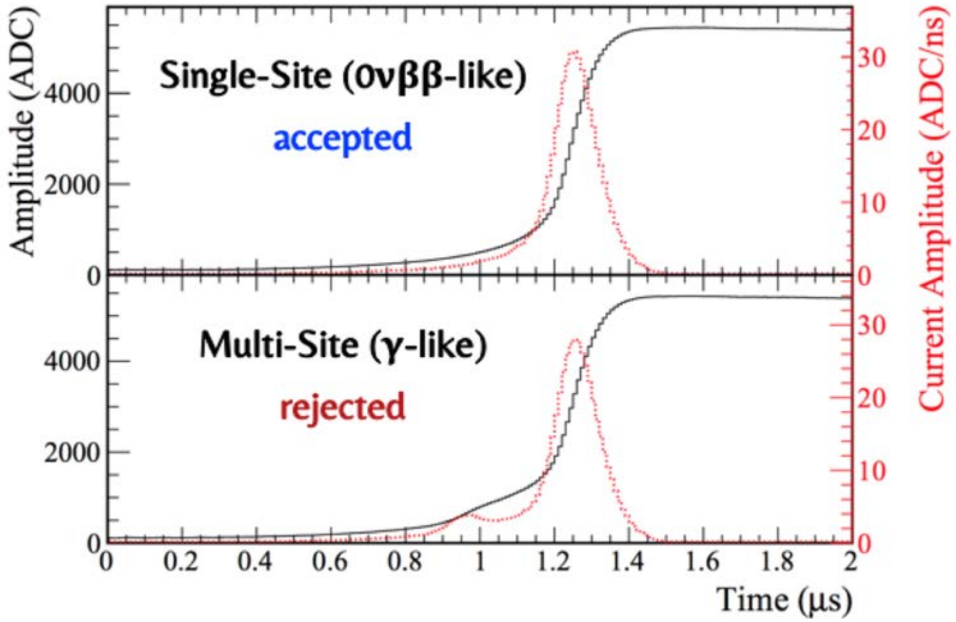
NIMA 872 (2017) 16

* IEEE Trans. on Nuc Sci 10.1109/TNS.2020.3043671

Analysis techniques for background rejection

0νββ 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.



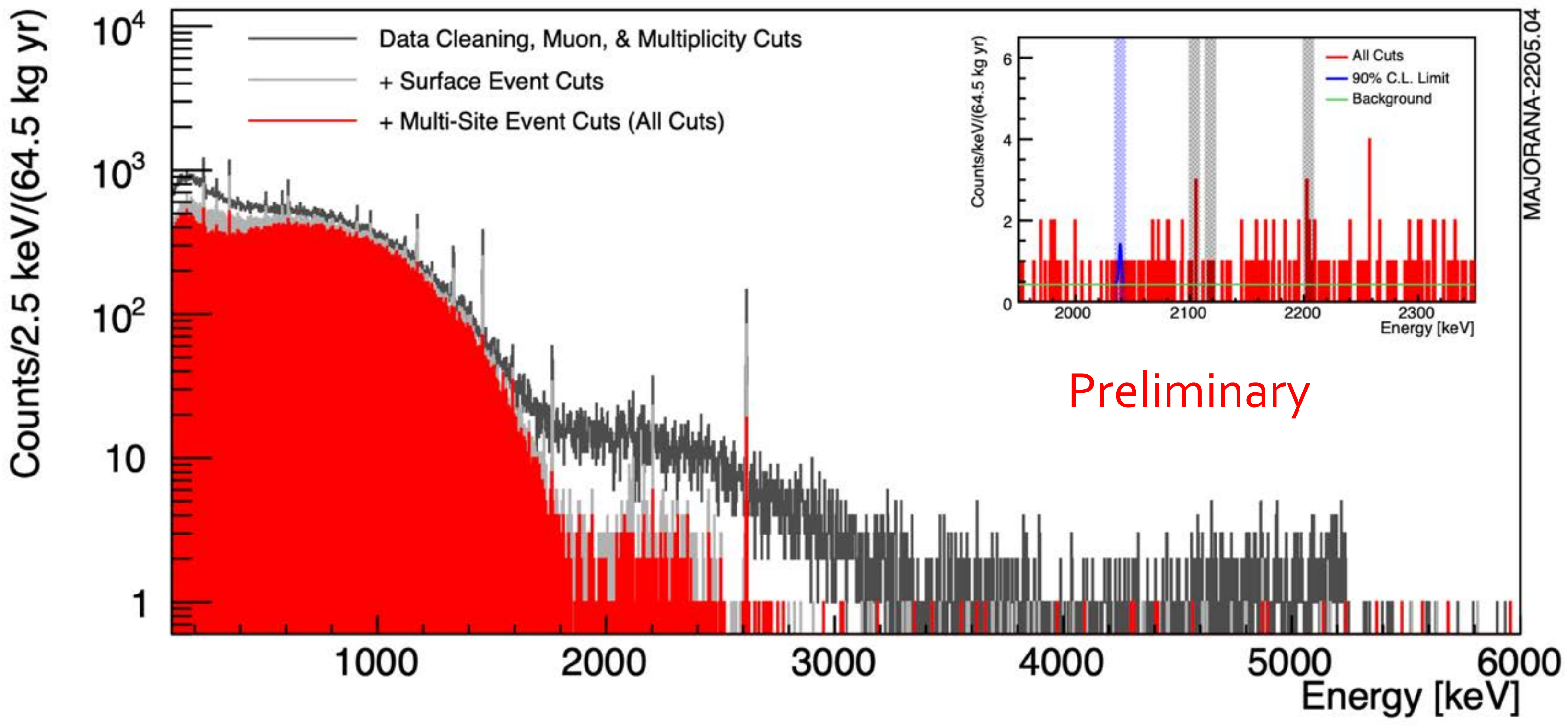


PRC 99 065501 (2019)

EPJC 82 (2022) 226

Final-exposure spectrum

Operated in a low background regime, benefiting from excellent energy resolution



Full spectrum with combined total of 65 kg-yr.

Final enriched detector active exposure:

64.5 ± 0.9 kg yrs

Background Index at 2039 keV in lowest background config:

15.7 ± 1.4 cts/(FWHM t yr)

Module 1:

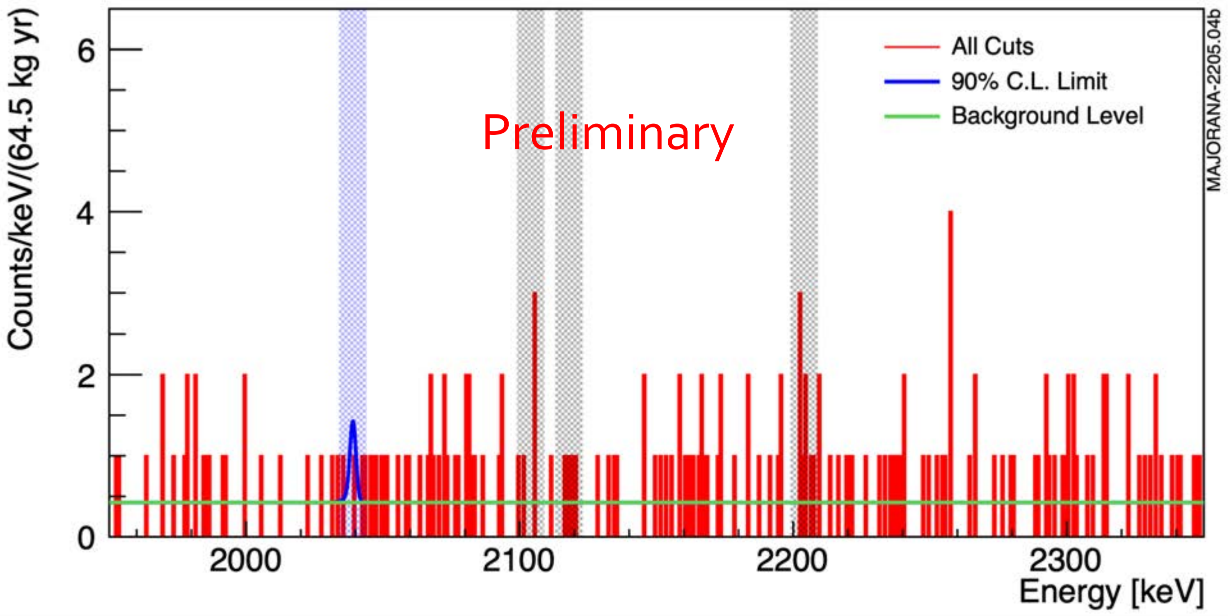
18.6 ± 1.8 cts/(FWHM t yr)

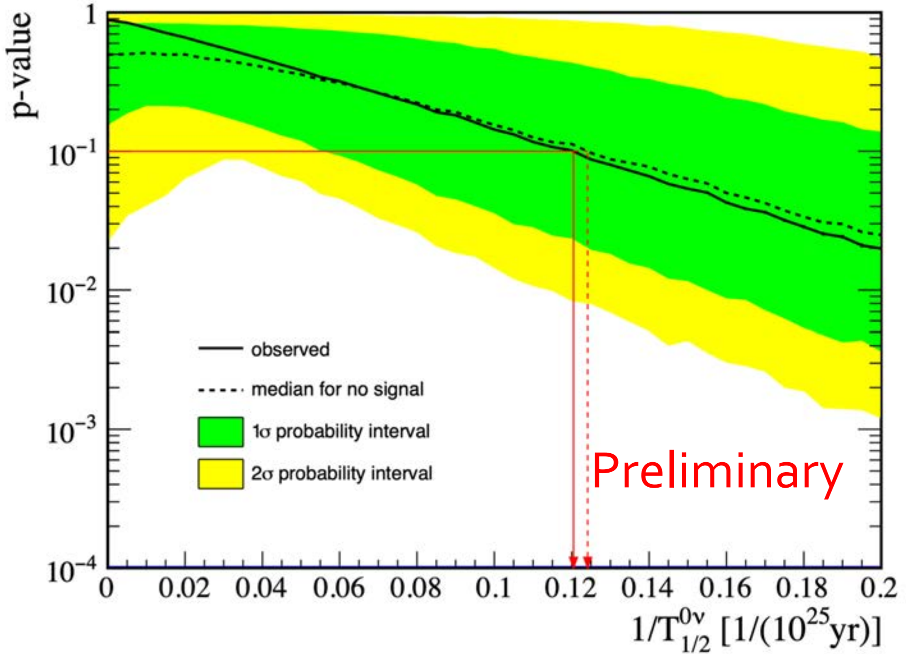
Module 2:

$8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

J. Gruszko, Neutrino'22

MAJORANA DEMONSTRATOR $0\nu\beta\beta$ results





- Background Index: (6.2 ± 0.6) × 10-3 cts/(keV kg yr)
- Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$
- Frequentist Limit: Median $T_{1/2}$ Sensitivity: 8.1 × 10^{25} yr (90% C.I.)

  65 kg-yr Exposure Limit: T1/2 > 8.3 × 10^{25} yr (90% C.I.)
- Bayesian Limit: (flat prior on rate) 65 kg-yr Exposure Limit: T1/2 > 7.0 × 10^{25} yr (90% C.I.)

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

J. Gruszko, Neutrino'22

Beyond the 0νββ search

Tests of Fundamental Symmetries and Conservations

- Lepton number violation via neutrinoless double beta decay
- Baryon number violation
- Pauli Exclusion Principle violation

PRC **100** 025501 (2019)
PRC **103** 015501 (2021)
PRD **99** 072004 (2019)
arXiv:2203.02033 (2022)

Standard Model Physics

BSM Physics

MAJORANA DEMONSTRATOR
excellent energy performance
Low backgrounds in broad energy regions

Standard Model Physics, particular backgrounds

- In situ cosmogenics
- (alpha, n) reactions
- ββ-decay to excited states

PRC **105** 014617 (2022)
arXiv:2203.14228 (2022)
PRC **103** 015501 (2021)

Low-mass dark matter signatures

- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Primakoff solar axion
- 14.4-keV solar axion

PRL 118 161801 (2017)
C. Wiseman, NDM'22

Exotic Physics

- Quantum Wavefunction collapse
- Lightly ionization particle

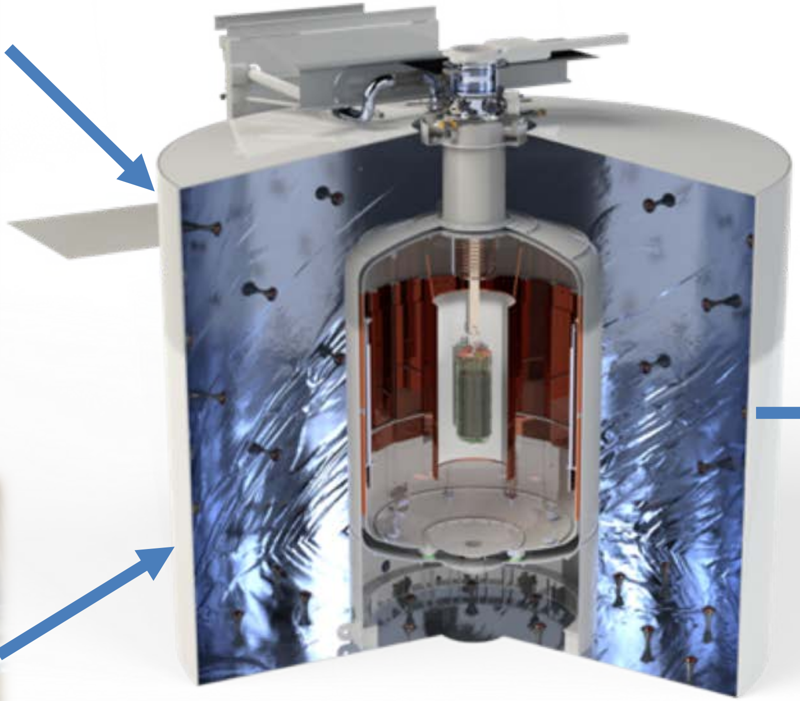
arXiv:2202.01343 (2022)
PRL 120 211804 (2018)

From the current generation to the ton scale

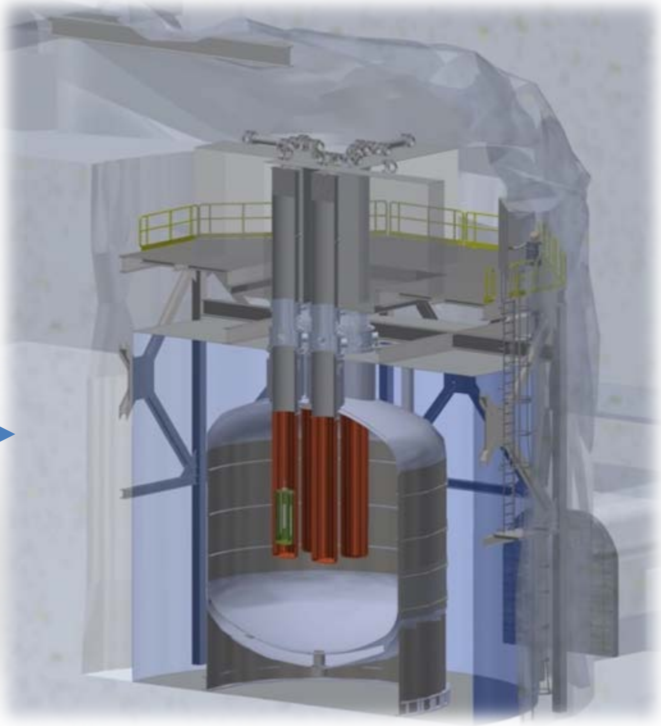
MJD: New final exposure results

GERDA: Final $0\nu\beta\beta$ results published

PRL 125, 252502 (2020)

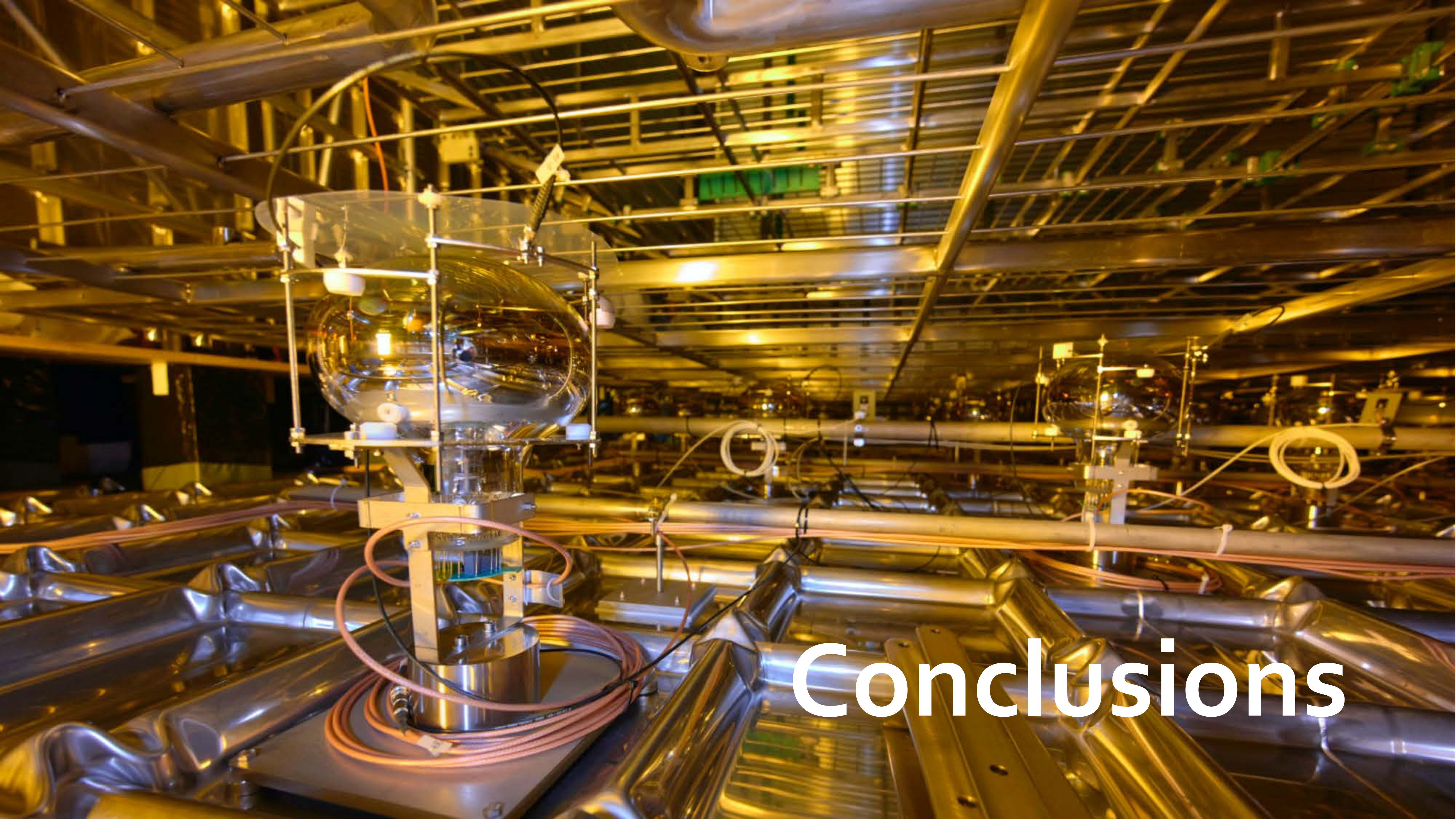


LEGEND-200: Now in commissioning at LNGS



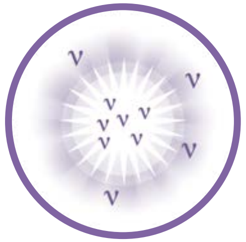
LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462



Conclusions

Conclusions



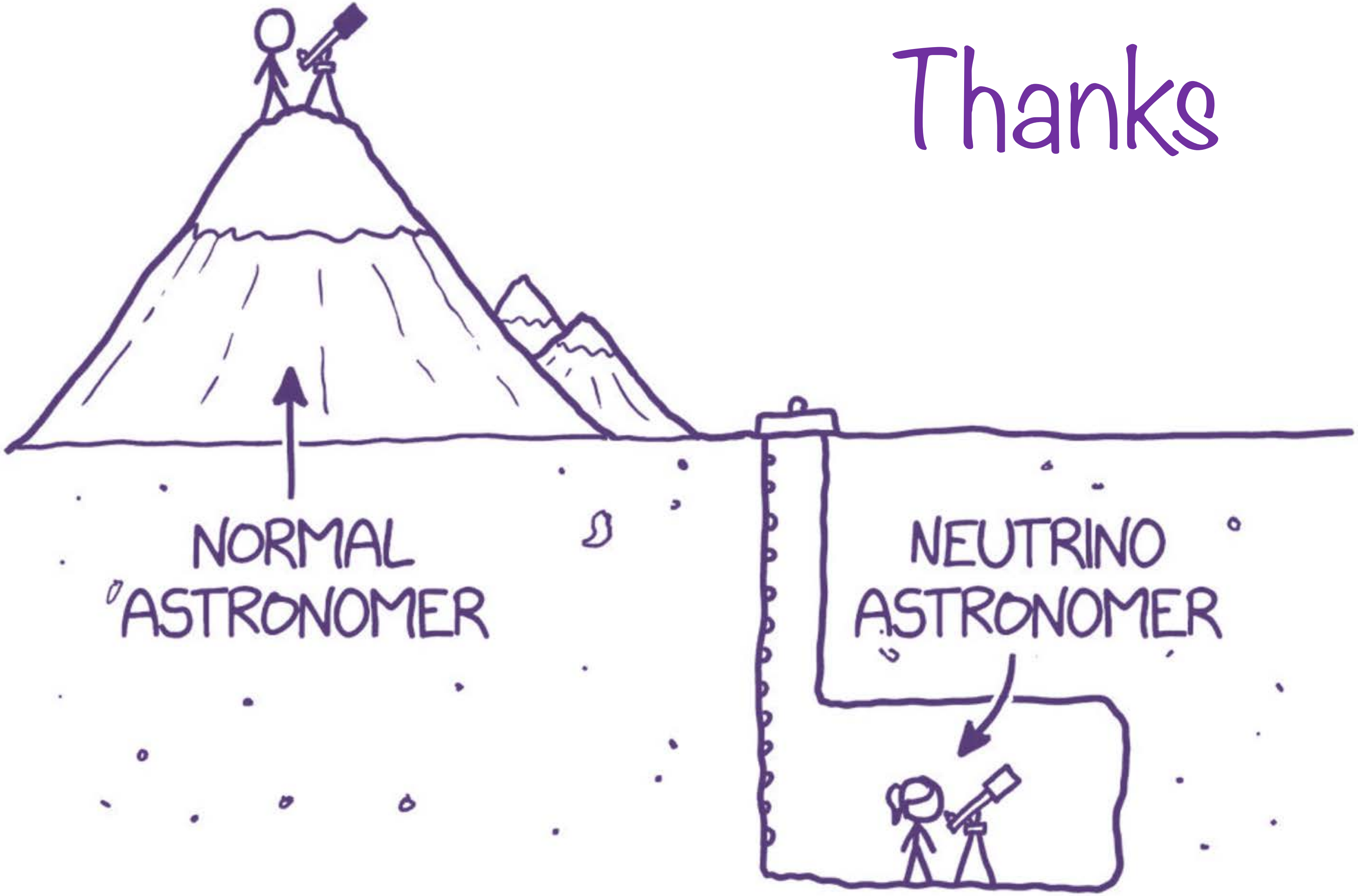
Neutrino experiments in the next decades will shed light on the open questions about neutrino nature, mass scale, mass spectrum, mixing, and species.

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}Ge with unprecedented energy resolution.

Thanks



Credit: Randall Munroe