The science and technology of DUNE

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Univ. of Milano Bicocca and INFN

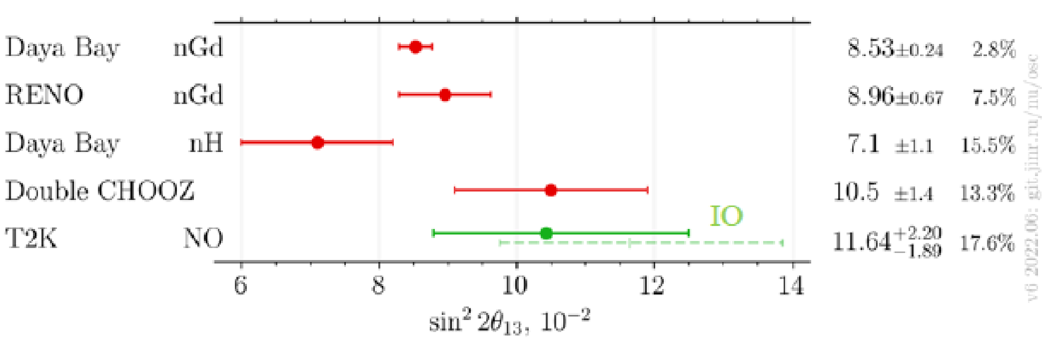
CERN Colloquium - Thursday 26 January 2023

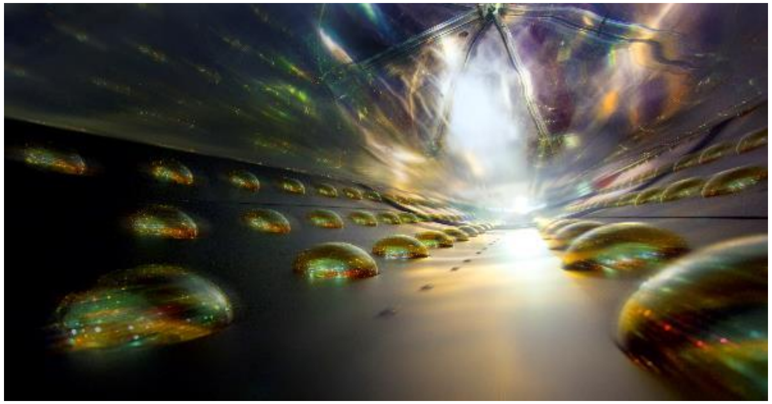
Why DUNE

A large mass, high precision, Deep-Underground accelerator Neutrino Experiment is the soundest choice to reap the "most unexpected opportunity in neutrino physics since the discovery of neutrino oscillation"

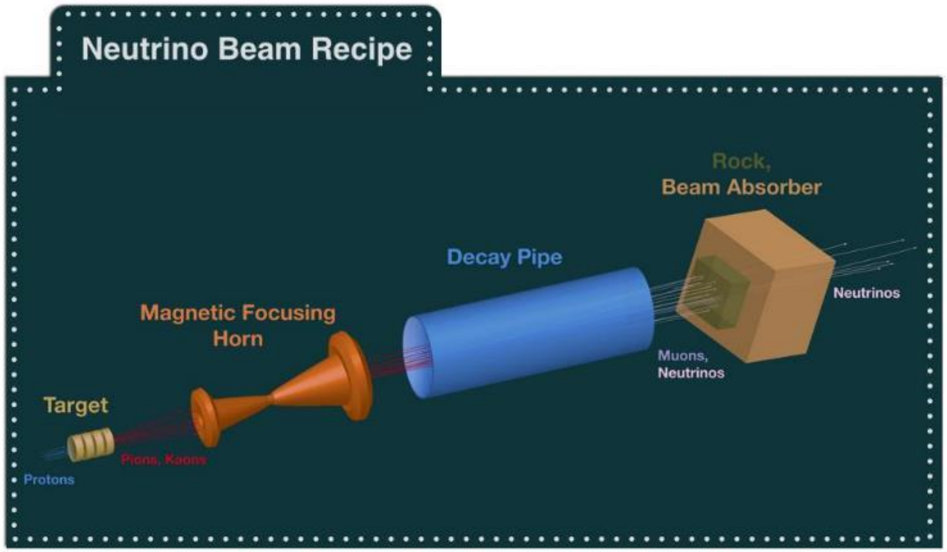
It sounds like a bold statement ("DUNE is just the right thing to do after the discovery of ϑ_{13}") but it is a claim that turned out to be well grounded both from the physics and technology point of view

2012: all neutrino mixing angles are "large" compared with the CKM matrix and we can observe sizable oscillations at distances and energies that can be produced on earth by particle **accelerators** and **reactors**





Best-in-class: accelerator neutrino beams



$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} \simeq\; & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& - \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

$\Delta \equiv \Delta m^2_{31} L/(4E)$ — Year 2005 → «**oscillation phase**» It is O(1) for E= O(1 GeV) and L= O(500 km). Cool, we can build experiment on Earth ☺

$\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$ — Year 2003 → Must be <1. The larger the better. We know now that is 0.03

$\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$ ~1

$\sin^2 2\theta_{13}$ ~0.1 — Year 2012 → The larger the better! It is O(1) in neutrinos! (it is tiny in quarks..)

One ring to rule them all

A large mass, high precision, Deep-Underground accelerator Neutrino Experiment can reconstruct **the whole lepton Yukawa sector of the Standard Model** except for one parameter (m_1)

Large source to detector distance (“baseline”): mass hierarchy through matter effects

Wide band beam and superior particle identification capability to suppress systematic uncertainties

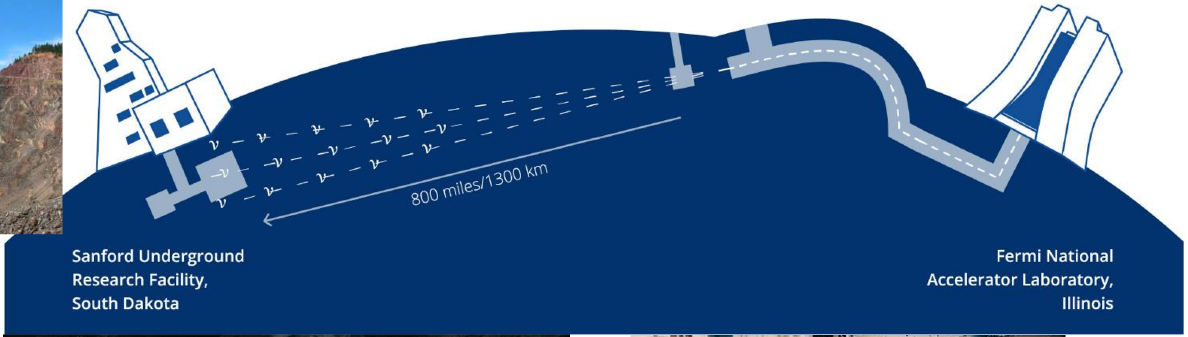
A single experiment to test the entire three neutrino paradigm

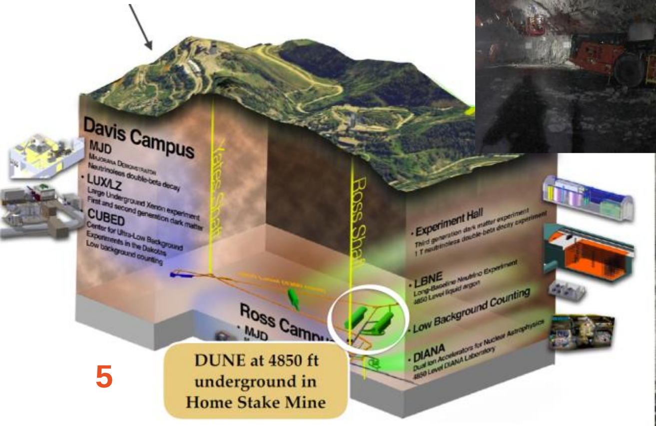
Large exposure to pin down CP asymmetry and perform high precision measurements of known parameters (octant ϑ_{23})

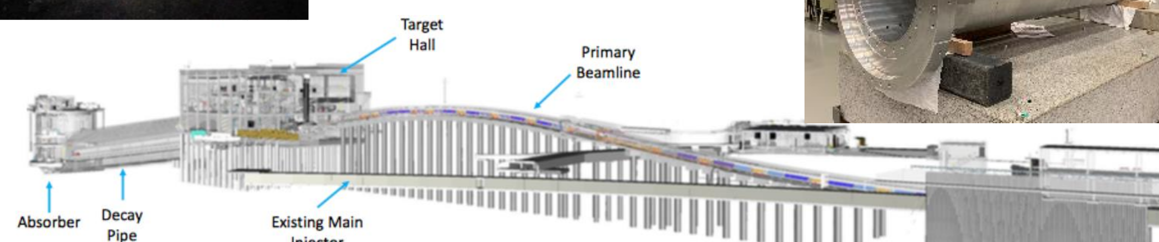
Deep underground location to complement beam with natural sources

The Long Baseline Neutrino Facility and SURF

The implementation of the DUNE science require two major facilities: a broad-band neutrino beam with 1.2 MW power upgradable to 2.4 MW power and the SURF laboratories in South Dakota. **These long-lasting facilities are going to play in neutrino physics a role similar to the Simon observatory or the LHC**. They are aimed at feeding a broad, top-class programme in neutrino physics, astroparticle and multi-messenger astronomy, rare event search and physics beyond the standard model for several decades.





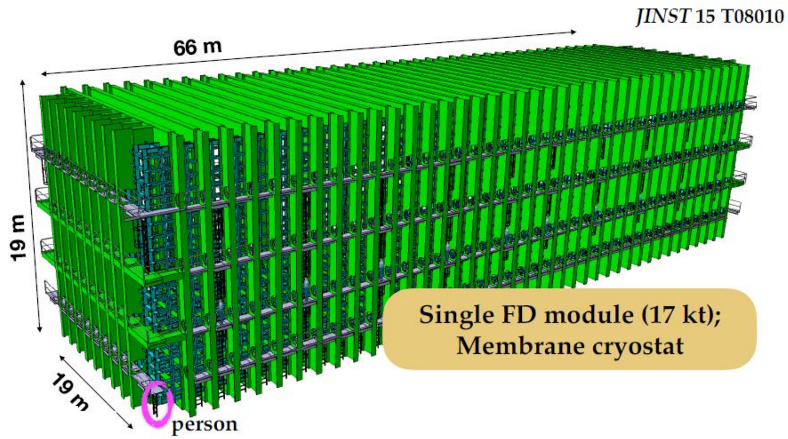


Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

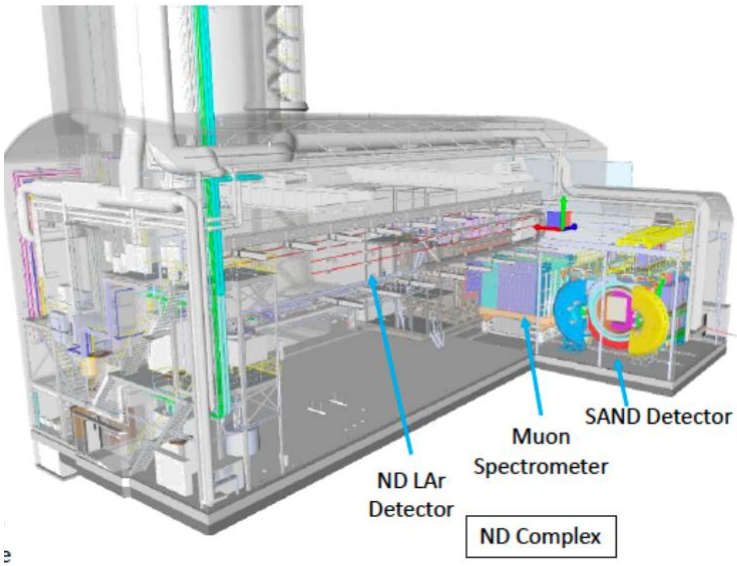
DUNE in a nutshell

Mass: the DUNE far detector comprises 4 modules of liquid argon for a **total fiducial mass of 40 kton** (full mass **70 kton**).

Resolution: DUNE is based on the technique with **the best particle imaging capability** available at kton scale: the Liquid Argon TPC (C. Rubbia, 1977)



Precision: DUNE employs a **near detector complex** for beam characterization based on a movable (NDLAr, TMS/NDGar) + on-axis (SAND) detector.

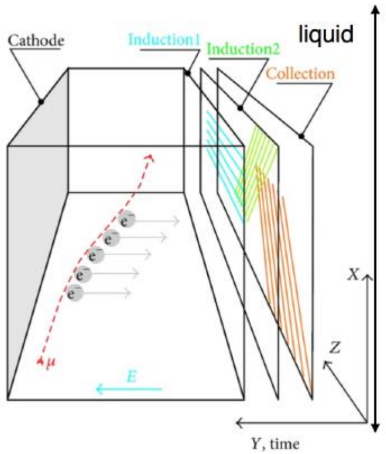


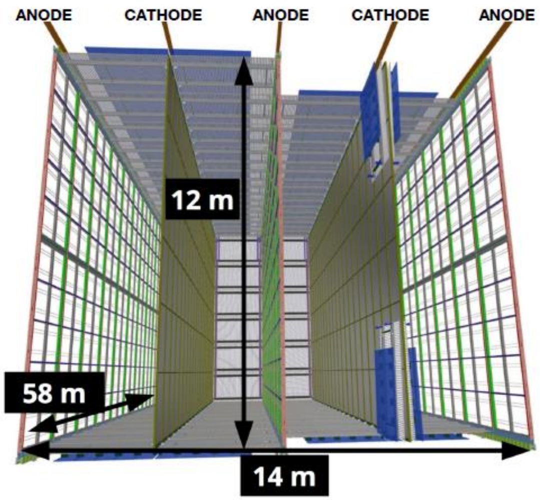
Beam observables: $\nu_\mu \rightarrow \nu_e$ oscillations and its CP conjugate $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$; ν_μ survival probability at the far detector. **Natural sources**: atmospheric and solar neutrinos. Transient sources like supernove neutrinos. Forbidden decays like $p \rightarrow K\nu$ proton decay

The DUNE Far detector modules

The four DUNE modules are **not** a clone of a single system because they reap the advances of the R&D that is ongoing - as soon as it is mature for a large-scale implementation

FD1-HD ("Horizontal drift")

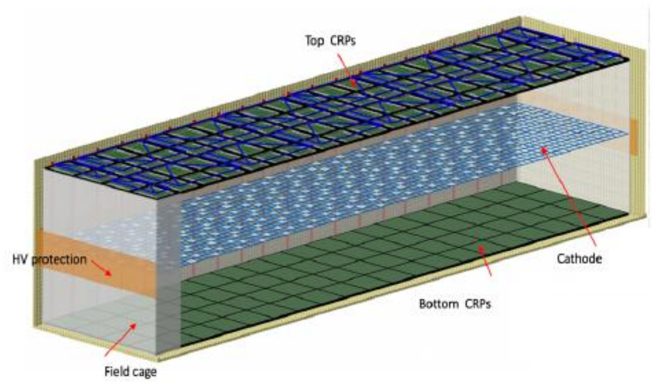




JINST 15 T

- 12 m x 14 m x 58 m active volume
- Each Anode-Cathode chamber has 3.5 m drift
- Cathode at -180 kV
- 150 Anode Plane Assemblies (APAs) with 384,000 readout wires
- Anode planes have wrapped wires (readout on both sides)
- 6000 photon detection system (PDS) channels for light readout

FD2-VD ("Vertical drift")



- Charge readout units at the top and bottom
- Cathode in the middle
- Photon detectors integrated on cathode and on cryostat walls
- Two 6.5 m drift chambers
- -300kV on cathode; 450 V/cm field

The science of DUNE

Discovery of yet unknown parameters of the lepton Yukawa sector:

- Determination of the mass ordering
- Discovery of CP violation

Measurements of PMNS parameters:

- ϑ_{23} and its octant
- Δm^2_{13}
- Precision measurement of CP phase delta

Observation of atmospheric, solar and SNB neutrinos:

- First observation of HEP neutrinos from the sun
- Galactic SN explosion
- Best measurement of ϑ_{12}

Physics beyond the standard model

- Sterile neutrinos at LBNF
- Dark matter candidates at the near detector
- Proton decay
- Boosted dark matter at far detector

Phase I: 20 kton, 1.2 MW beam

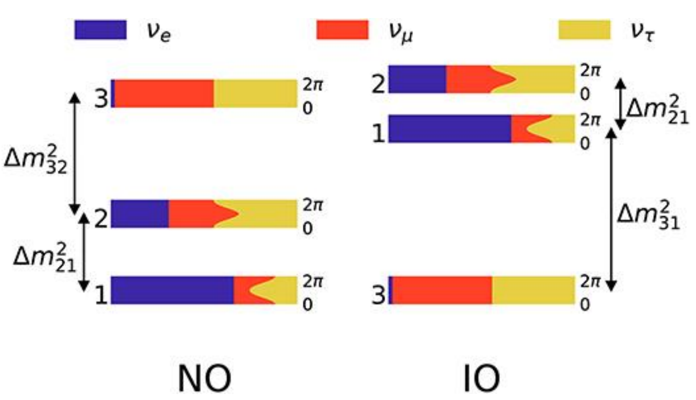
Phase II: 40 kton, 1.2 MW beam

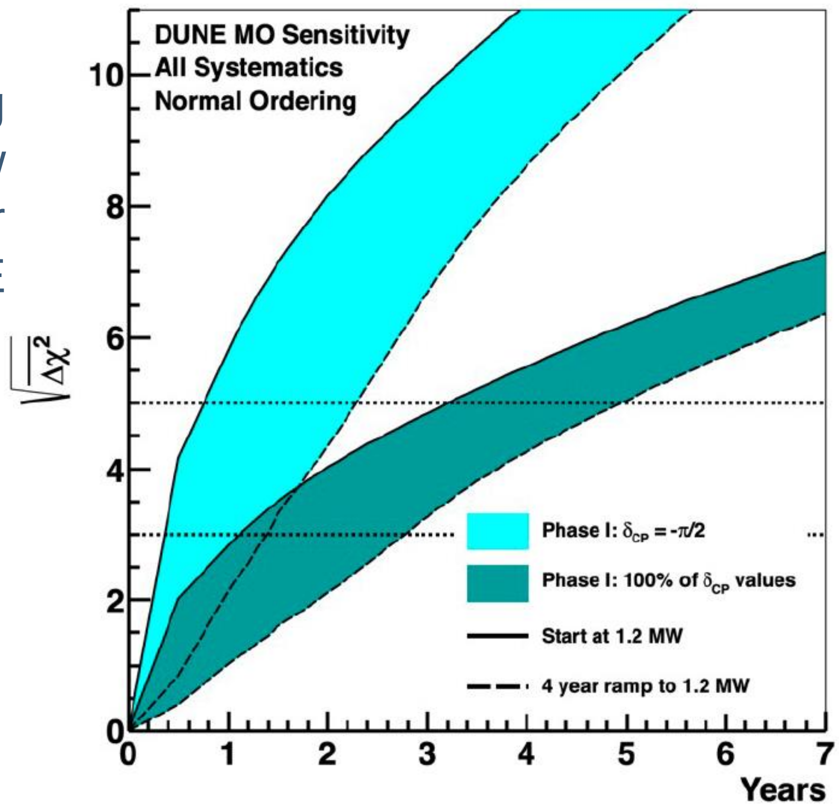
Phase II: 40 kton, 2.4 MW beam

Early science: mass ordering

Mass ordering (normal or inverted ordering) plays a pivotal role in the search of neutrinoless double beta decay, laboratory measurements of absolute neutrino mass (m_1), cosmology and model building (origin of flavor in SM). There are several experiments currently in construction that may address this parameter at 2.5-4 sigma level, depending on the final systematic budget (JUNO, ORCA, SK/HyperK).

The measurement of DUNE is very strong from statistic and systematic point of view and can provide a definitive answer already at the early stage of the DUNE data taking (2030-32).





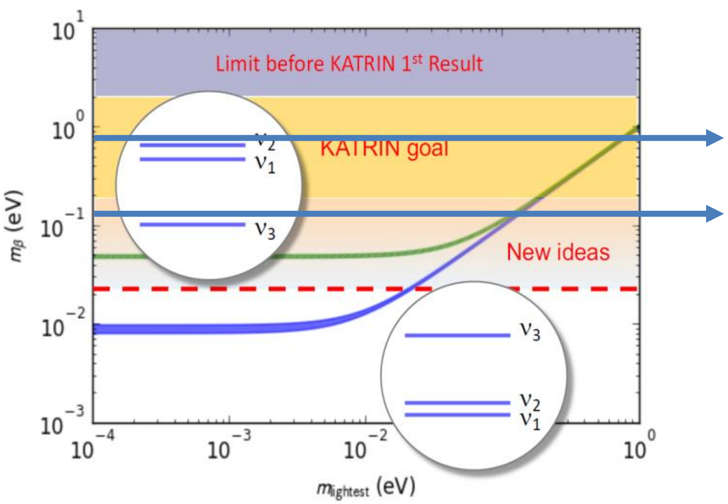
The impact of such a measurement

It is difficult to anticipate what will be the global scenario in 2030:

- Most optimistic: evidence from JUNO and ORCA sum up consistently. A famous example: pre-2012 hints of "large ϑ_{13}" G. Fogli et al, Phys.Rev.D 84 (2011) 053007 (400 citations!)
- Most pessimistic: tensions among experiment makes the combined fit inconclusive. Most famous example: T2K+NoVA circa 2022

Whatever is the situation, the DUNE measurement will have a tremendous impact because it comes when the next generation of neutrino mass and neutrinoless double beta decay exhaust its potential and:

T. LAsserre, Talk at Neutrino 2022



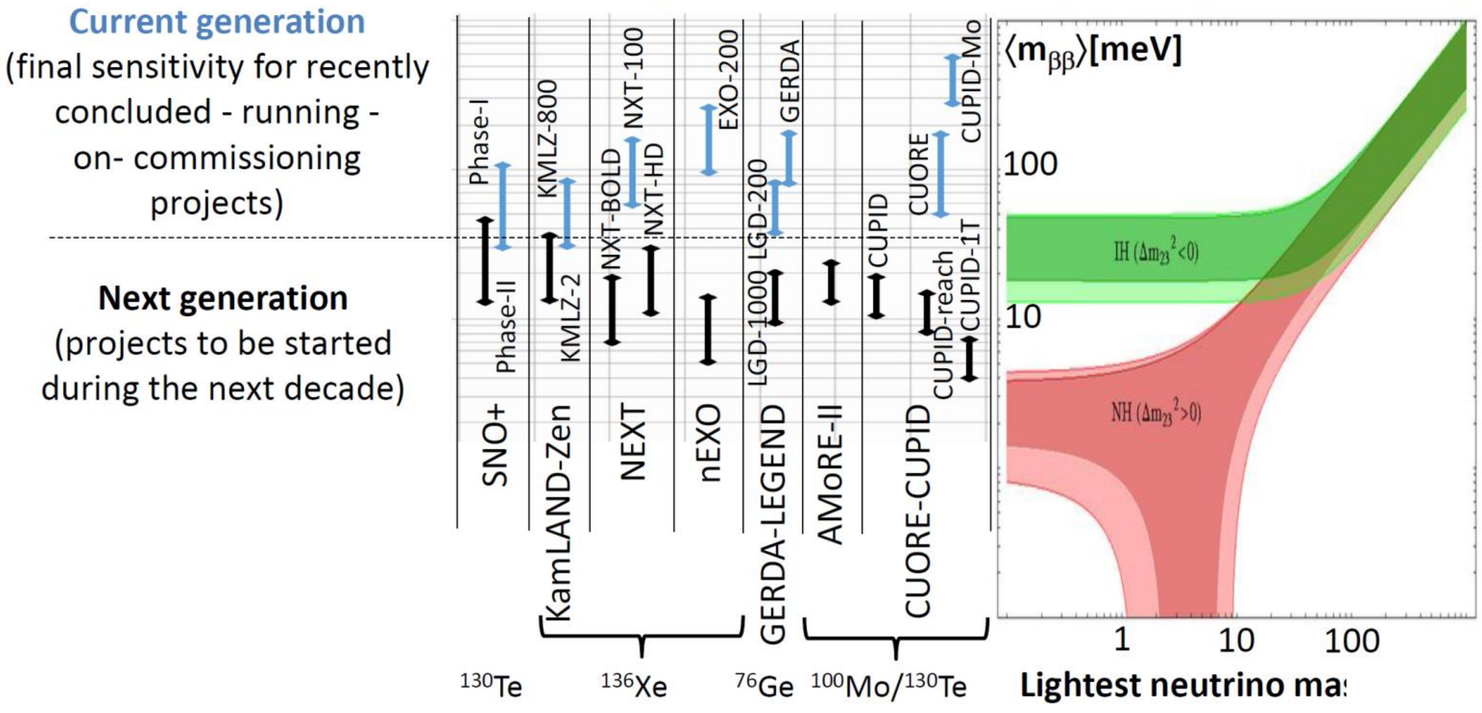
We are here

We will be here around 2030

The impact of such a measurement (II)

- Major investments will be needed to access smaller region of m_1 ("lightest neutrino mass eigenstate if ordering is normal") in case of null results
- A new strategy will have to be devised to constrain m_1 and Majorana phases in case of positive results
- We may need to check the overall consistency of SM and LCDM in case cosmologists cannot find a hint of $m_1+m_2+m_3>0$ (expected around 2030-35)

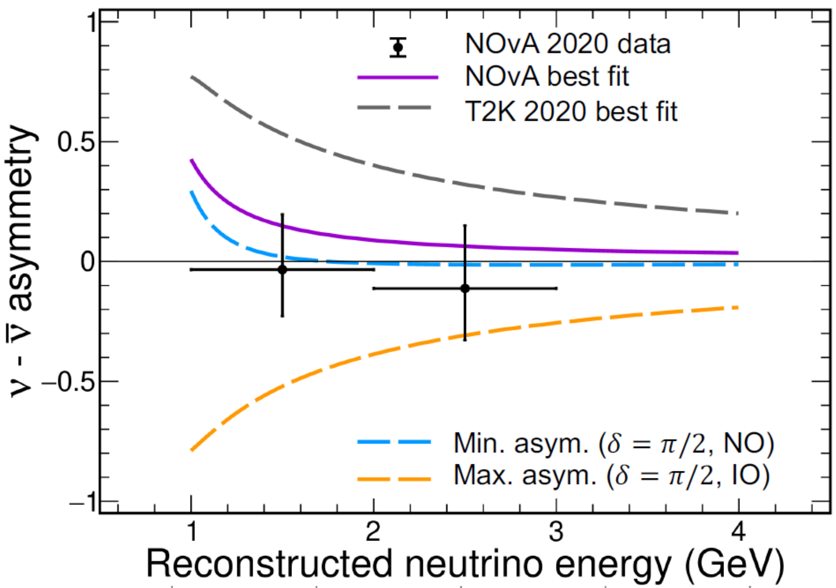
A. Giuliani, Talk at NOW2022



CP violation

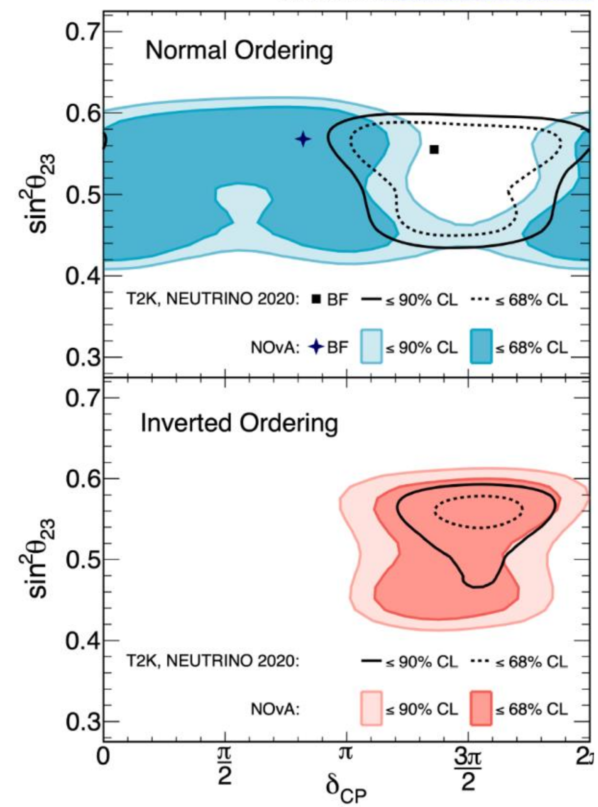
This is a fundamental measurement, and the long-lasting impact of DUNE strongly depends on the implementation of Phase II

Current status: some experiments may have hints for CP violation at 2-3 sigma in a short timescale although neither the $\nu_\mu \rightarrow \nu_e$ / $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ asymmetry nor the multiparameter fit uniquely point toward a well-defined value



J. Hartnell, Talk at Neutrino2022

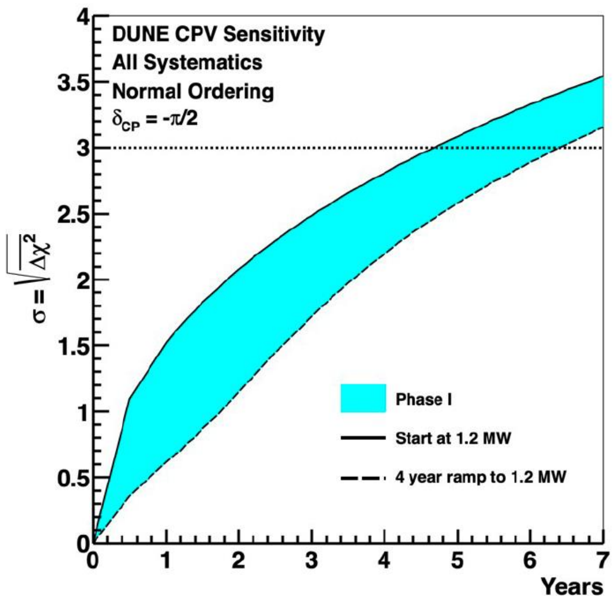
2020 data set: https://arxiv.org/abs/2108.082



CP violation in DUNE

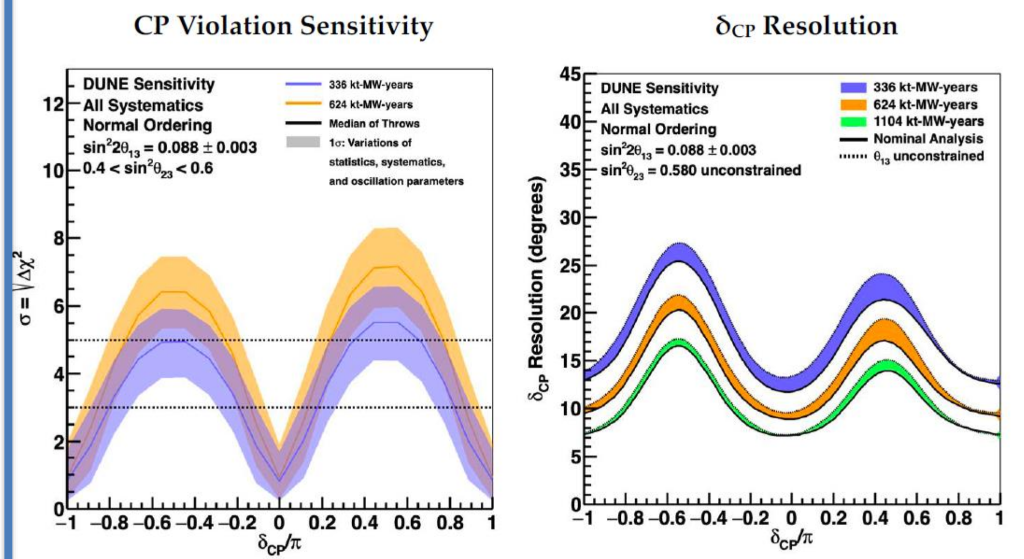
In addition, DUNE has a powerful competitor in this field: HyperKamiokande – whose setup relies on a shorter baseline and coarser detector but a much larger mass.

Phase I: DUNE is able to clarify current tensions at 3 sigma level but…



Phase II: DUNE has a tremendous impact on CP discovery and δ resolution

EPJC 80 (2020) 978



5σ CPV sensitivity for 50% of δ_{CP}

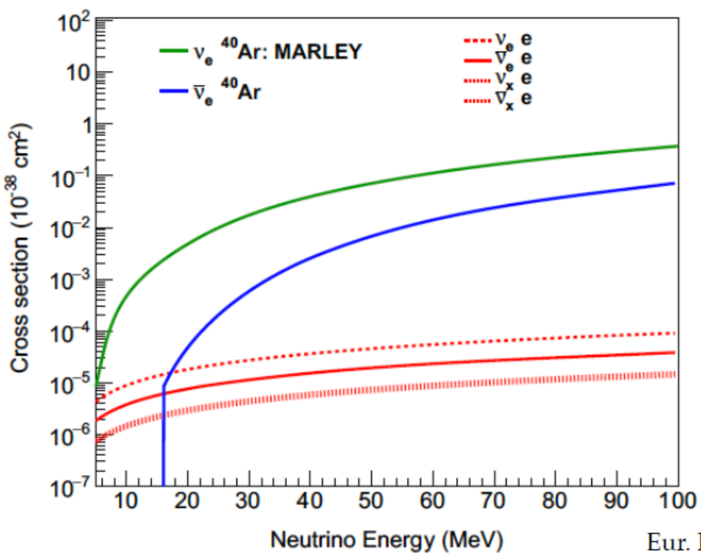
7–16° δ_{CP} resolution regardless of true values

The science of DUNE: natural sources

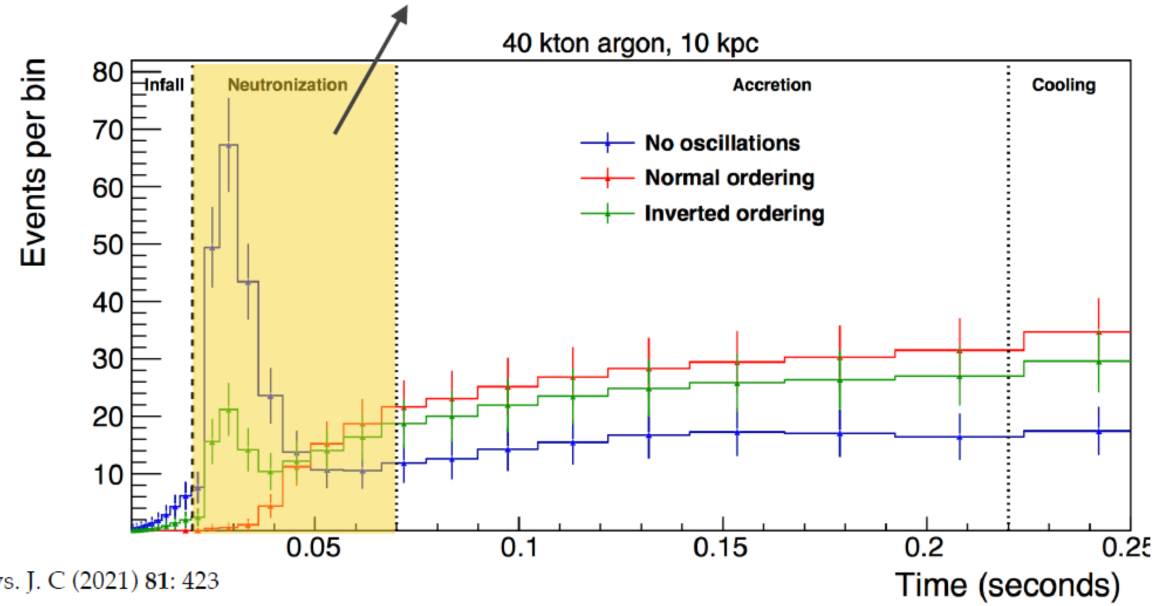
DUNE will be the most precise underground observatory in the world thanks to the exploitation of liquid argon TPC. Are we benefiting from such an asset?

DUNE is sensitive to ν_e CC events by $\nu_e\ {}^{40}Ar \rightarrow {}^{40}K\ e^+$ thanks to the LArTPC technology and to e-ν scattering thanks to its unprecedented mass.

CC events play a unique role in the occurrence of a galactic supernova explosion



Early neutrino burst is sensitive to the neutronization phase of the supernova and to mass ordering!



Eur. Phys. J. C (2021) 81: 423

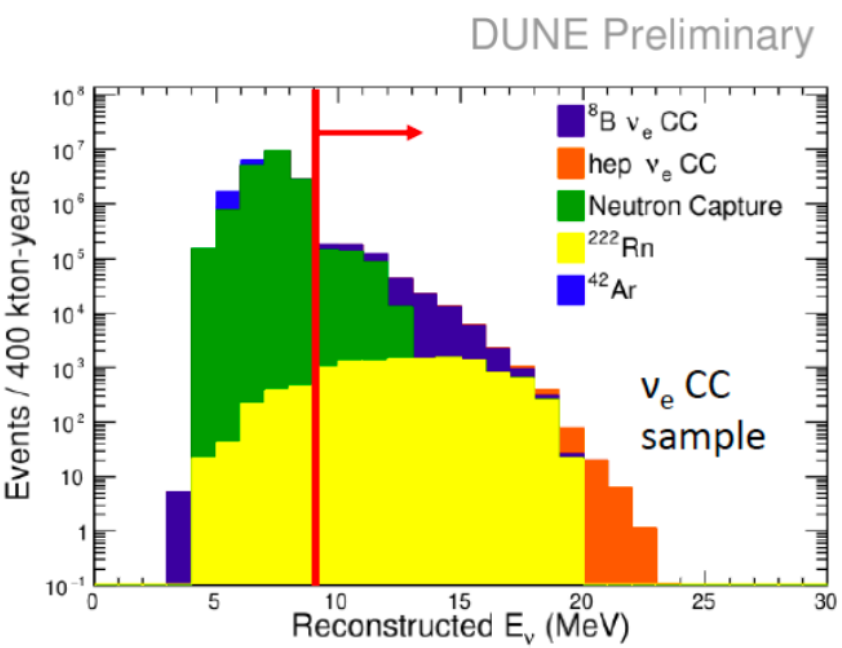
Solar neutrinos in DUNE

DUNE is sensitive to ν_e CC events by $\nu_e\ {}^{40}Ar \rightarrow {}^{40}K\ e^+\ e$ thanks to the LArTPC technology and to e-ν scattering thanks to its unprecedented mass.

This feature gives its best with solar neutrinos where we have an observable only sensitive to electron flavor and another observable sensitive to all flavors. DUNE has features that resembles the “good old” SNO experiment but with an unprecedented mass (*)

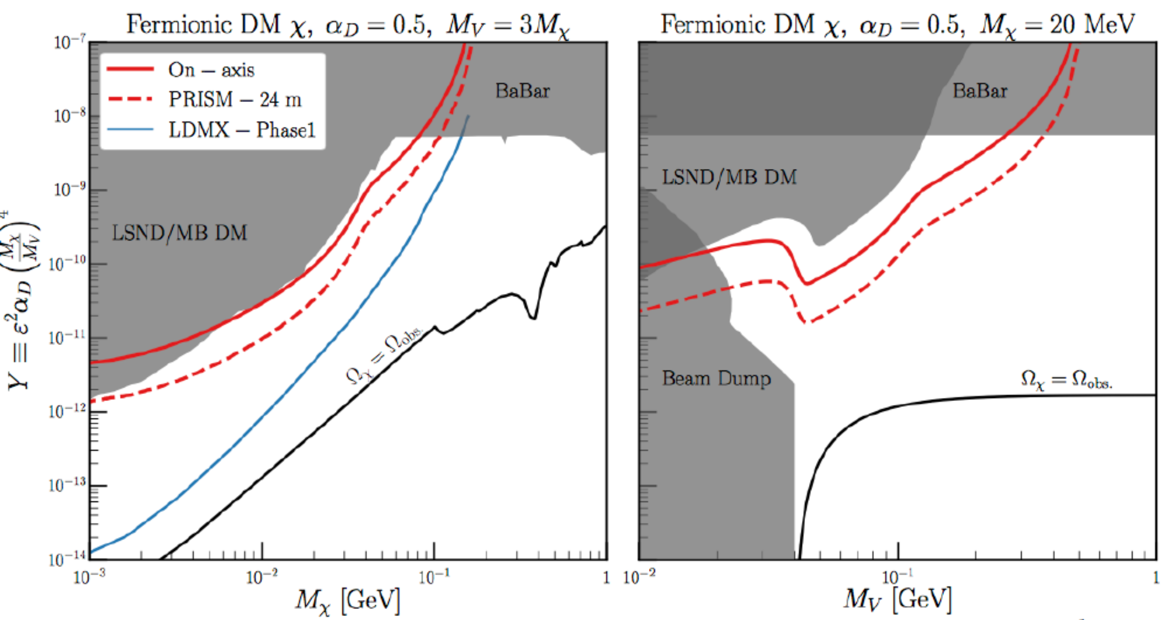
(*) F. Capozzi et al PRL 123 (2019) 13

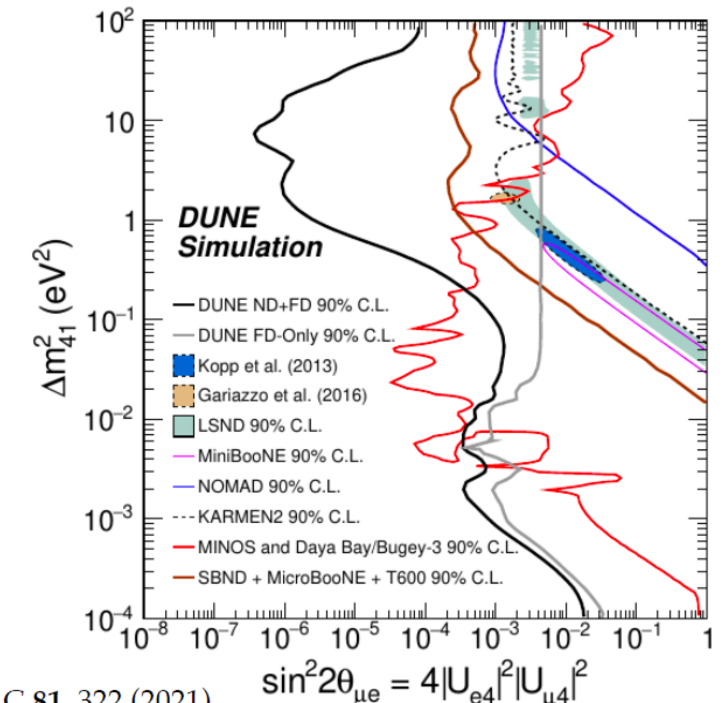
DUNE has not been optimized for low energy (<10 MeV) physics in neither granularity nor radiopurity. Still the mass and background rejection capability may provide the first evidence of neutrinos from He-p fusion (“hep”) even using the technology of the “Phase I” modules.
Again “Phase II” and the “Module of Opportunity” (see below) may represent a breakthrough



Physics beyond the Standard Model

- DUNE will be able to probe many potential BSM searches such as
  - Sterile neutrino mixing
  - Dark Matter (beam induced and cosmogenic origin)
  - Heavy neutral leptons (HNL), neutrino trident production
  - Non-standard interactions (NSIs)
  - CPT symmetry violation

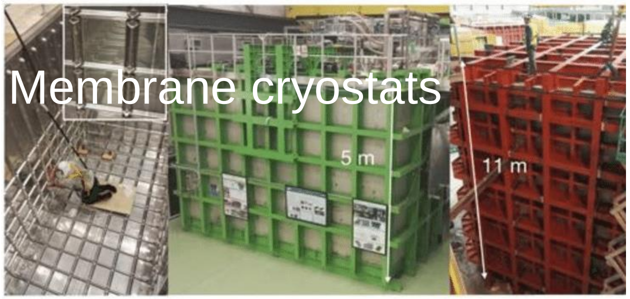


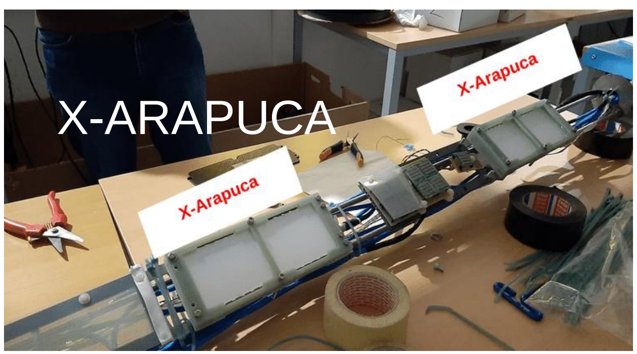


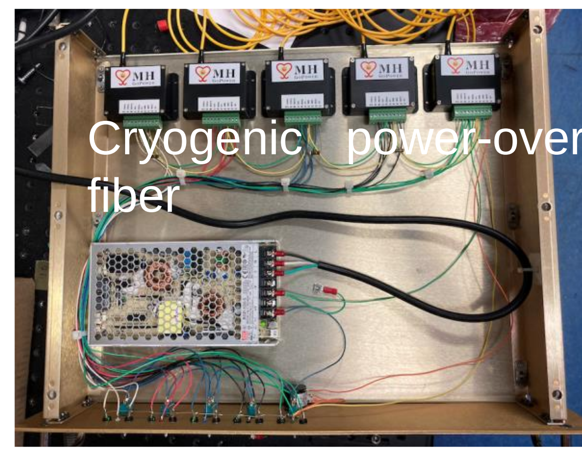
Eur. Phys. J. C **81**, 322 (2021)

The technology of DUNE

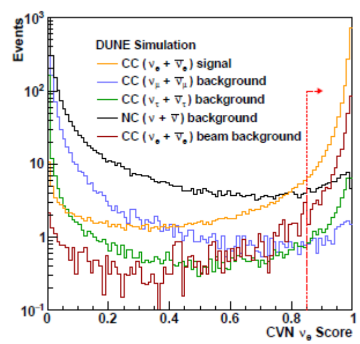
Even in its prototyping phase, DUNE achieved a wealth of results that have advanced neutrino detector science at unprecedented pace. CERN - and in particular, the CERN neutrino platform - was the hub of such an advancement. And still it is.







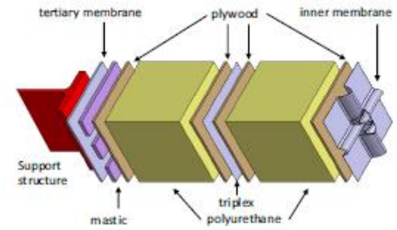
Automatic reconstruction of neutrino interactions



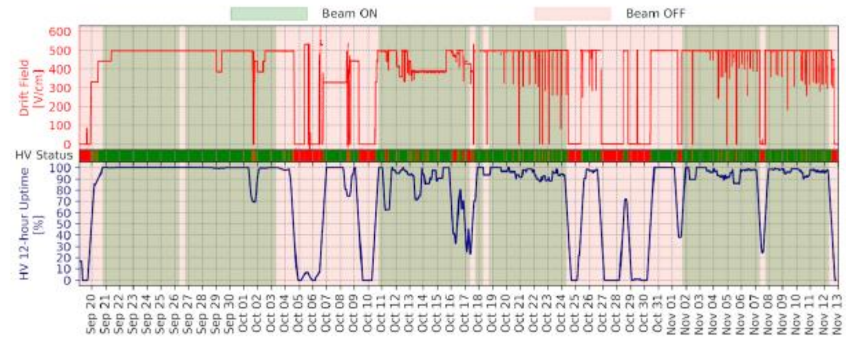
NP04/ProtoDUNE-SP

ProtoDUNE SP-HD

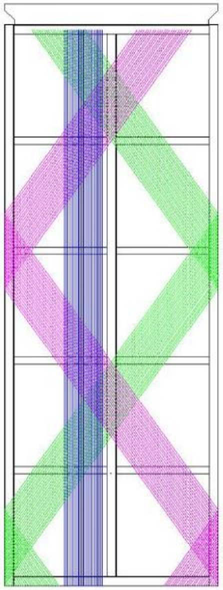
- *Largest LArTPC constructed to date!*
- Ran successfully from 2018-20 collecting over 4 million events!
- Charged particle beam and cosmic runs
- Low noise, stable HV, high purity, neutron calibration, Xe doping
- Calibration & detector physics; hadron-argon cross section measurement program



Large scale validation of membrane cryostat

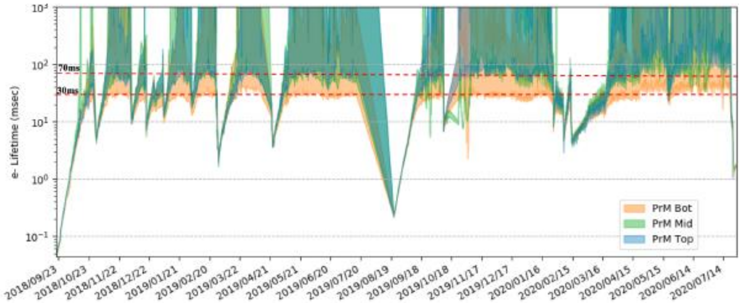


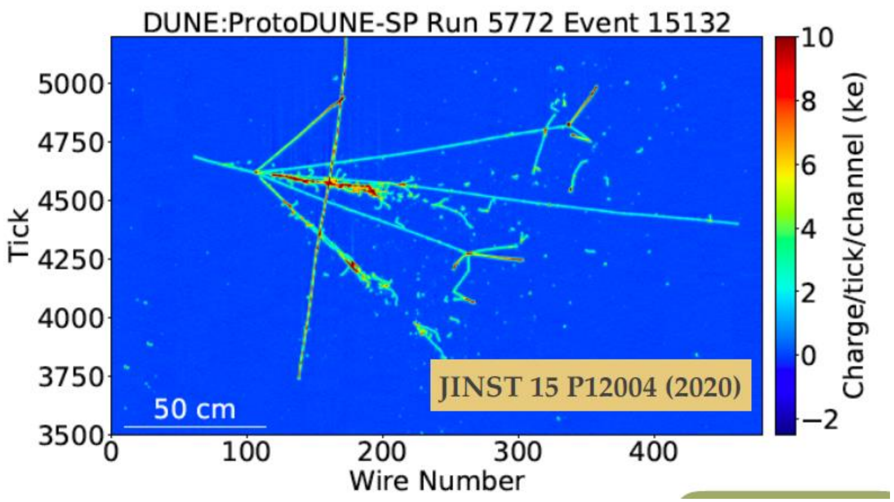
Flawless performance of the HV system

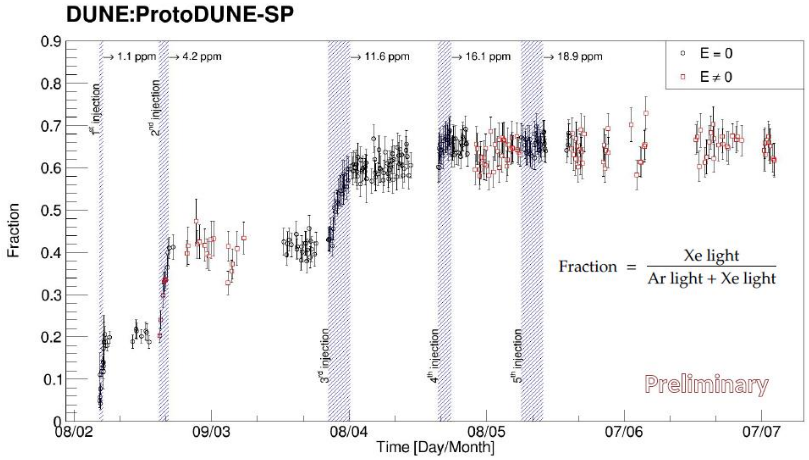


Large scale validation of APA

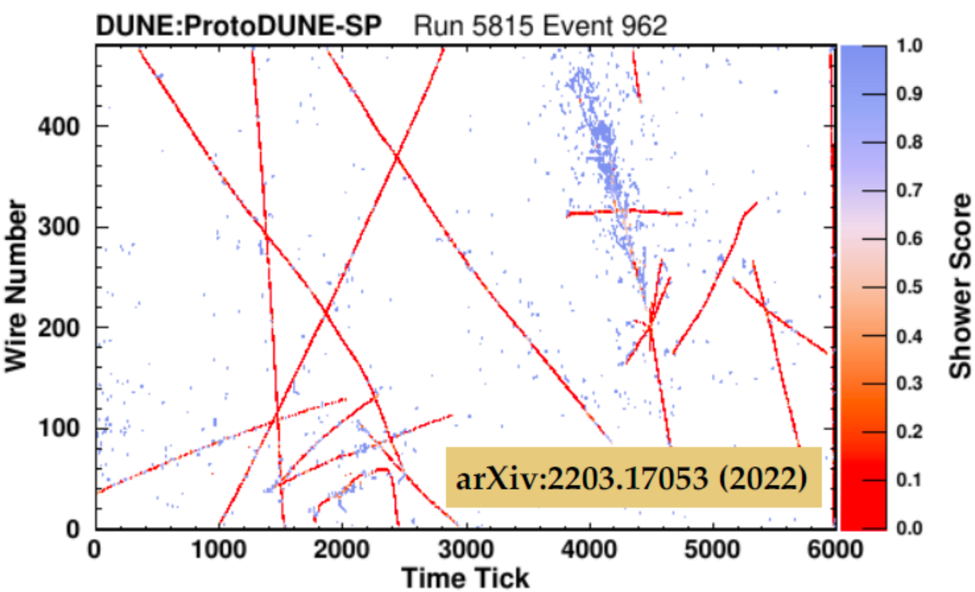
Validation of the purification system

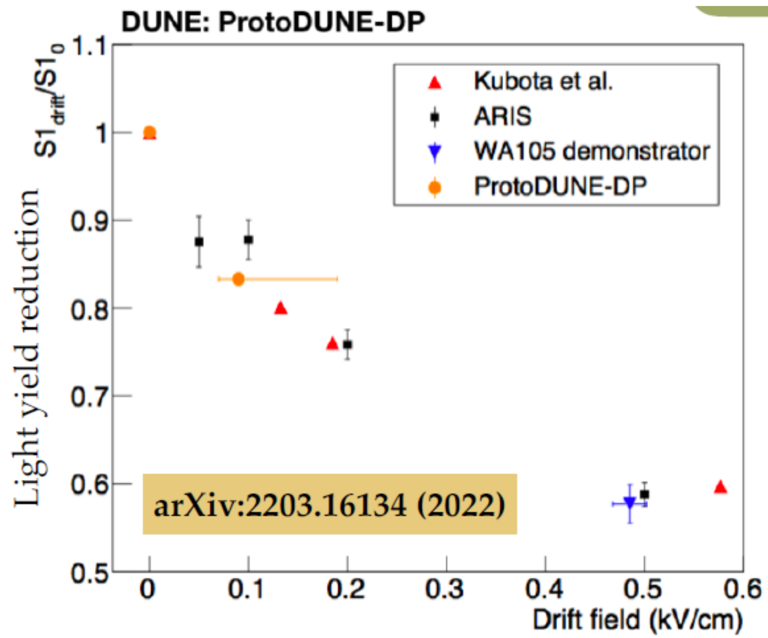






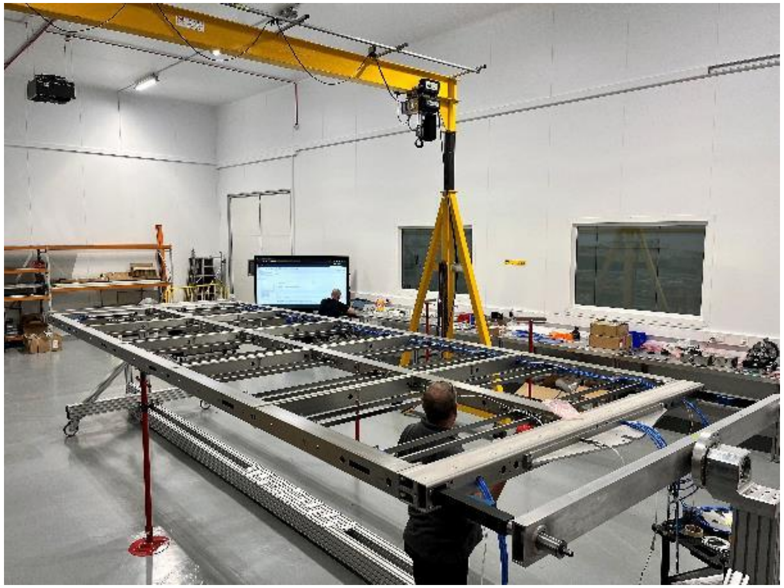
Xenon doping! N. Gallice @Lidine 2022

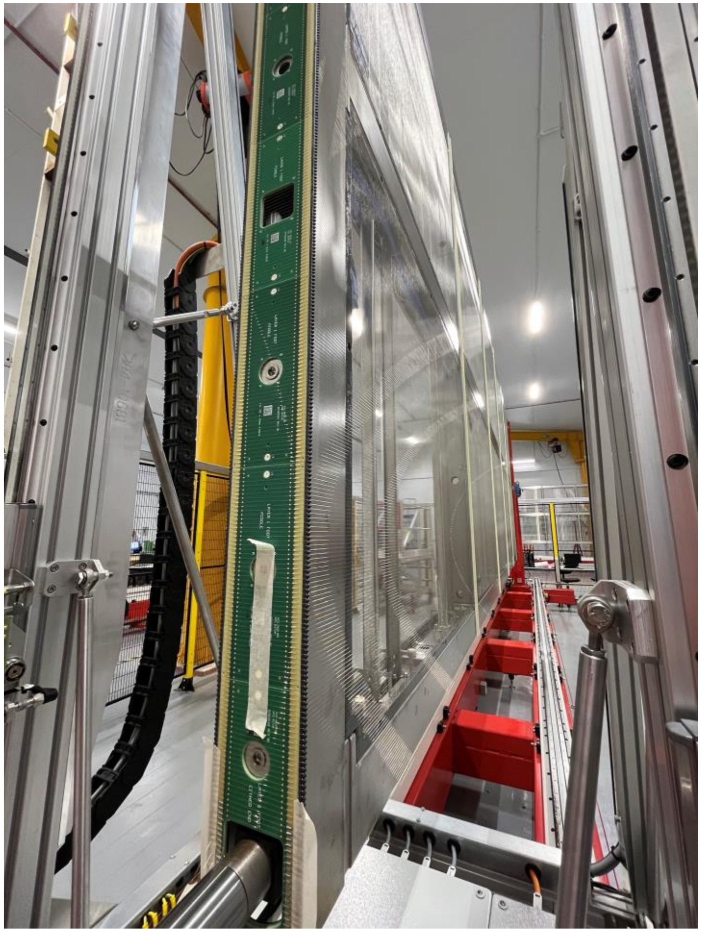




The impact of ProtoDUNE-SP

ProtoDUNE-SP tested most of the technology challenges of DUNE and it proved once for all that DUNE was “ready for construction”.

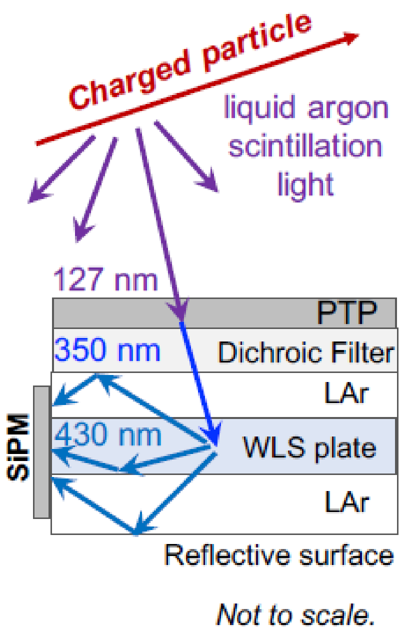


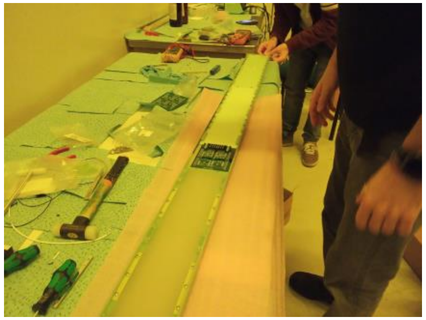


Still, a second run of ProtoDUNE-SP (now called “**ProtoDUNE-HD**”) is necessary to complete the validation. Prominent in ProtoDUNE-HD is the new Photon Detection System…

The DUNE Photon Detection System

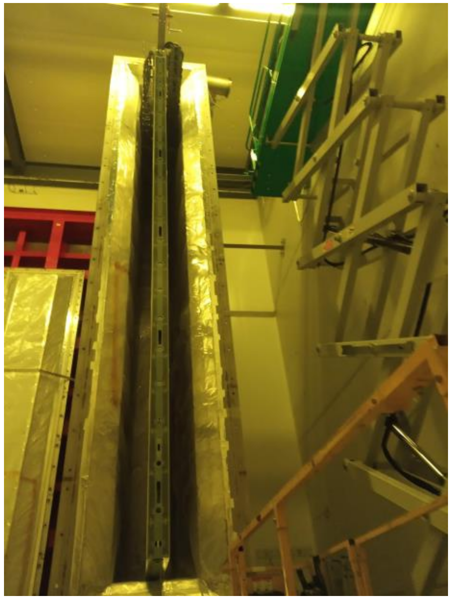
In the course of the construction of ProtoDUNE-SP, a new technology has emerged for the observation of the VUV (128 nm) scintillation light of liquid argon





The X-ARAPUCA

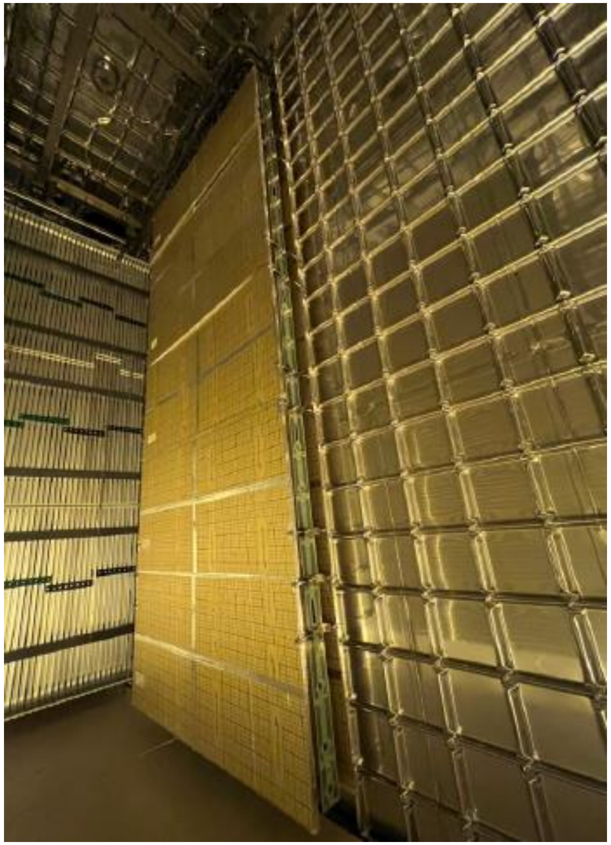
A.A. Machado, E. Segreto, JINST 11 (2016) 02, C02004



Compactness, low number of active detectors (SiPM), high efficiency (2-3%). A major effort to bring this technology at production level: the system was installed in ProtoDUNE-HD in Sep 2022

The Run II of ProtoDUNE-SP («protoDUNE-HD»)

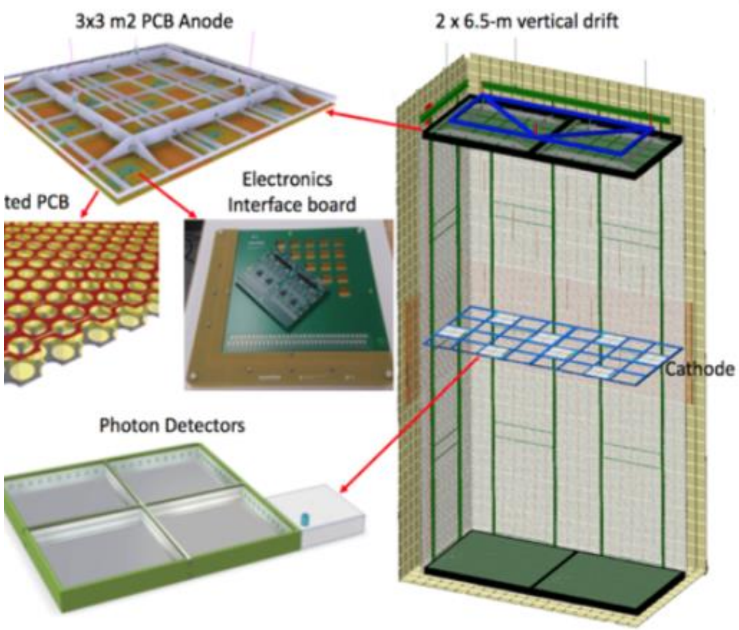
We are planning to validate the final version of APAs, Cold electronics, Photon Detection System, laser calibration system etc.) in the second run of ProtoDUNE (ProtoDUNE-HD – i.e. the "module-0" of the horizontal drift far detector). Detector ready for cool-down but run delayed due to LAr shortage (energy crisis due to Ukrainian war)



The second DUNE module: FD2-VD («vertical drift»)

The DUNE second module reaps the achievement of the dual phase R&D (NP02/ProtoDUNE-DP) but retains the single-phase concept. All readout anodes are in liquid argon but:

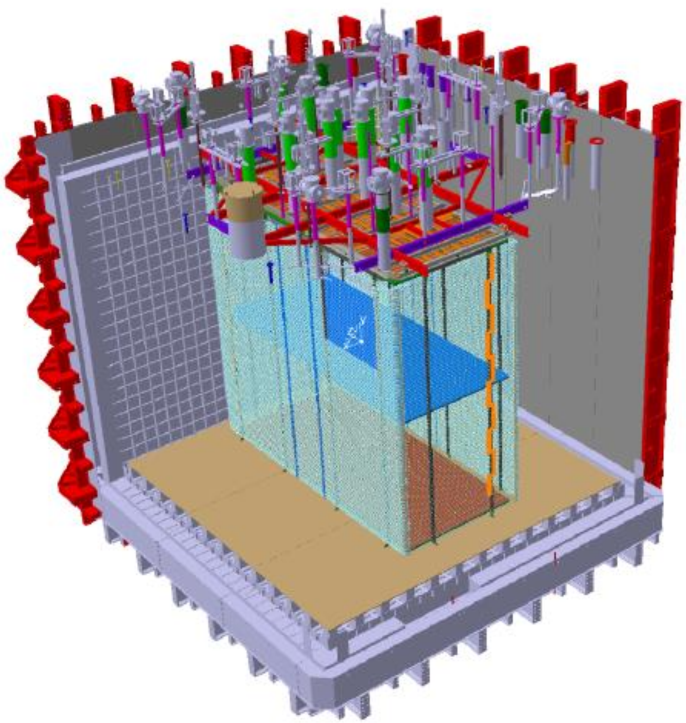
- The drift length is twice the length of the fist module (FD1-HD)
- The drift is vertical with the cathode in the middle.
- We exploit cold electronics and PCB readout removing the mechanical burden of wires
- The Photon Detection System is located in the cathode (300 kV!) and in the walls outside the field cage
- Light uniformity is restored using xenon doping

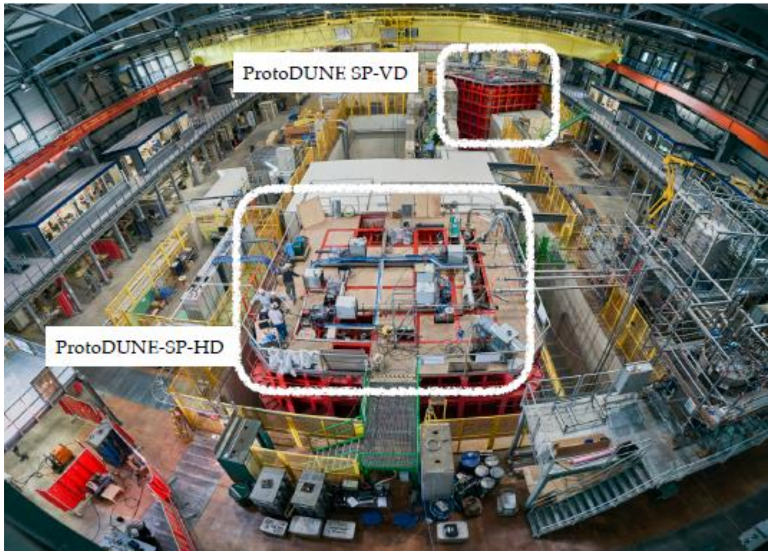


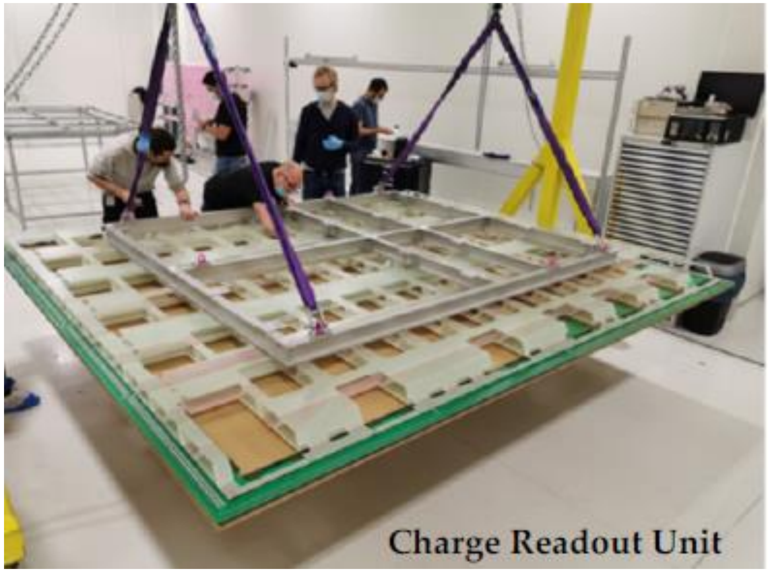
A module that is significantly cheaper than FD1-HD but retains the same physics performance

ProtoDUNE-VD

- 2 top CRPs + 2 bottom CRPs
- Cathode in the middle hanging from the top CRPs
- Field cages hanging independently from the cryostat roof
- ~3.2 m long drift, 300 kV capable HV system
- PDs on the cathodes and on the walls

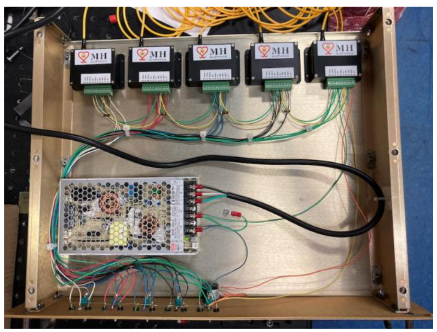


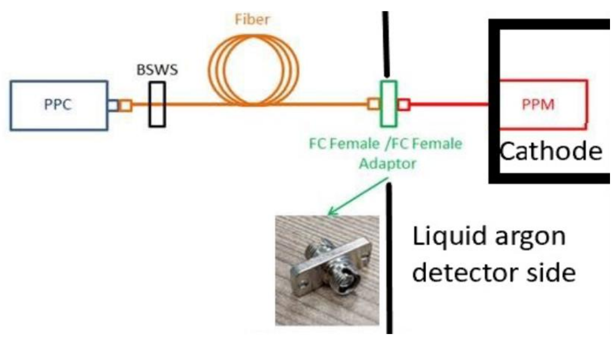


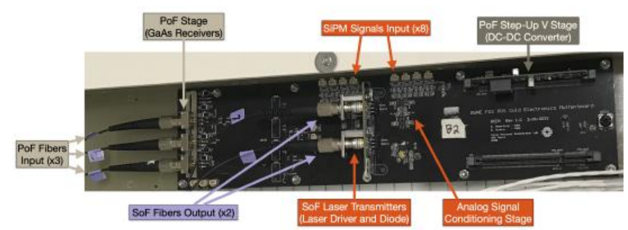


A case-study: cryogenic power-over-fiber

The Photon detection system for the Vertical Drift is worth a special mention. To overtake successfully the challenge of photon detection inside the TPC, DUNE exploits a technology breakthrough obtained by the R&D carried out in parallel with the construction of the first module and demonstrate the effectiveness of the modular approach. It give us the opportunity to benefit from new findings given the long construction time of DUNE.



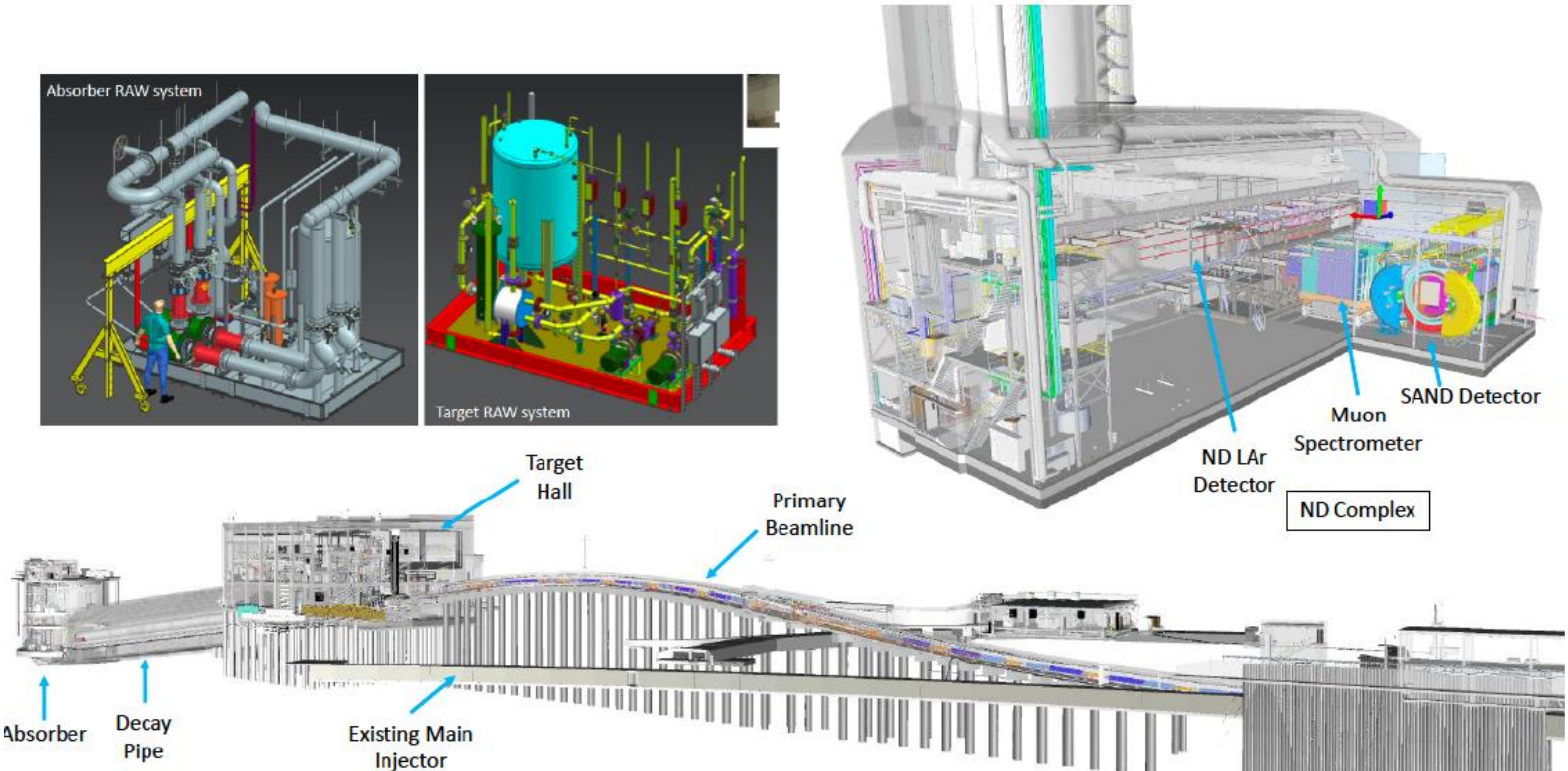




Based on GaAs laser and commercial system selected for operation at 87 K. It brings power through an optical fiber that is converted to electrical power (DC generator) at cold (B. Pellico, DUNE Coll meet. 2021)

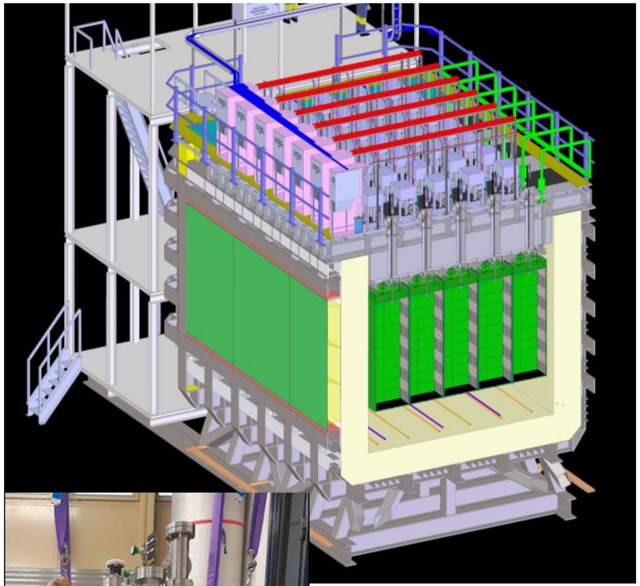
Gearing up for data taking: the DUNE near detector

Since the early physics of DUNE is compelling, we need to be prepared for an early commissioning and characterization of the beam and detector and pave the way for a sophisticated systematic mitigation program. In my opinion, the **DUNE near detector** will play here the leading role



Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

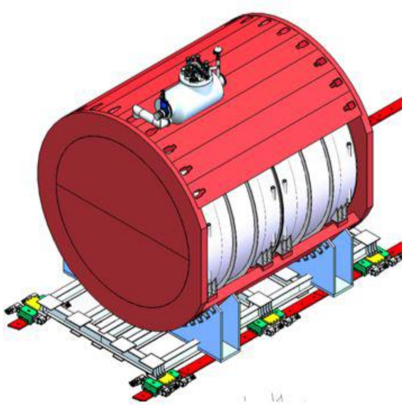
NDLar (movable)

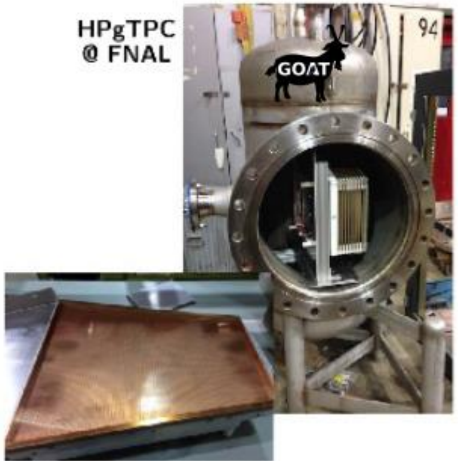


DUNE offers a sophisticated implementation of **the PRISM concept**:

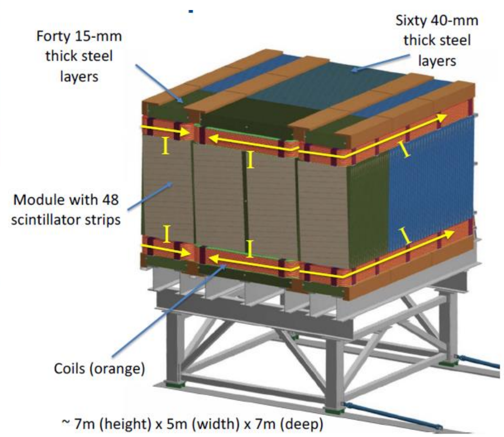
- A detector with the same target and particle imaging technology of the Far detectors (NDLar)
- Full particle containment (TMS)
- (phase II) High resolution gas argon TPC (NDGar)

NDGar (movable/phase II)





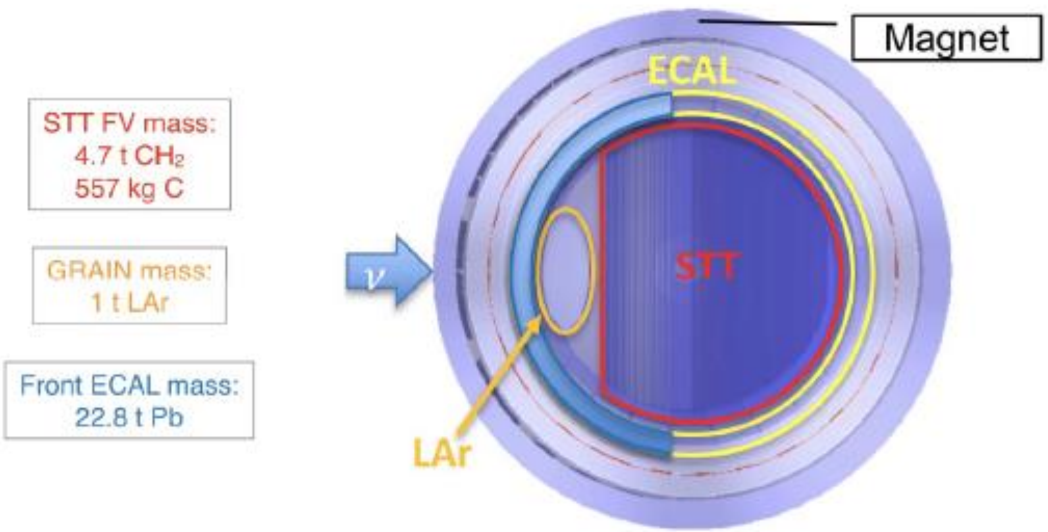
TMS (movable/phase I)

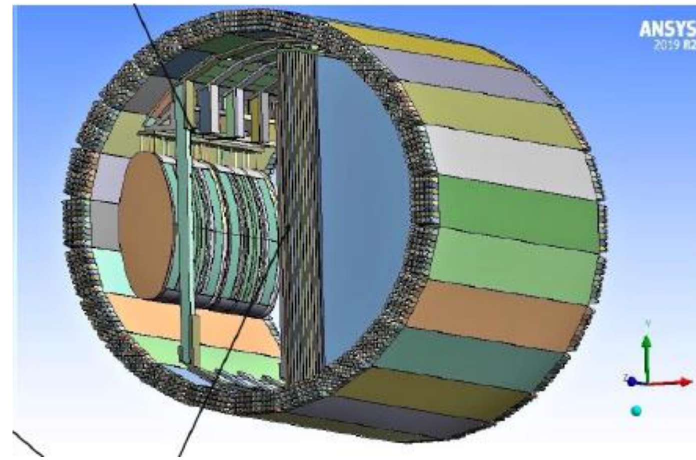


A. Abed Abud et al, Instruments 5 (2021)

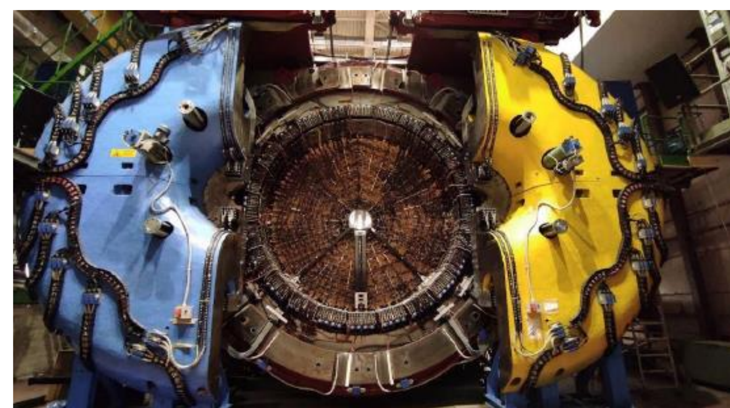
… and exploits a great opportunity!

The DUNE on-axis near detector is – by far – the most sophisticated on-axis monitor available today because it makes use of **SAND**: the former KLOE detector at INFN-LNF where we replaced the old KLOE tracker with straw tubes and a liquid argon standalone volume (GRAIN)





SAND, a multipurpose detector with an high-performant ECAL, light-targeted tracker, LAr target, all of them in a magnetic field

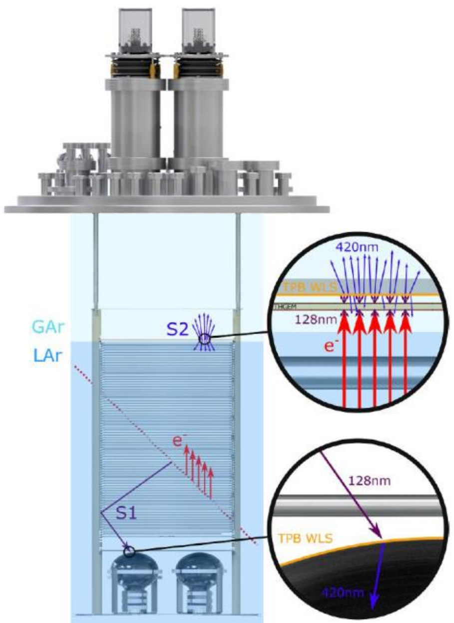


A module of Opportunities: technology

DUNE is pursuing the same strategy as FD1-HD and FD2-VD for FD3 and 4: exploit technology breakthrough as soon as they became scalable to large mass.

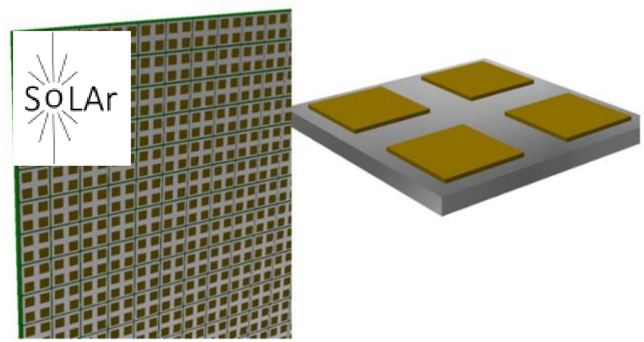
See the “DUNE Module of Opportunity Workshop”, Valencia 2-4 nov 2022

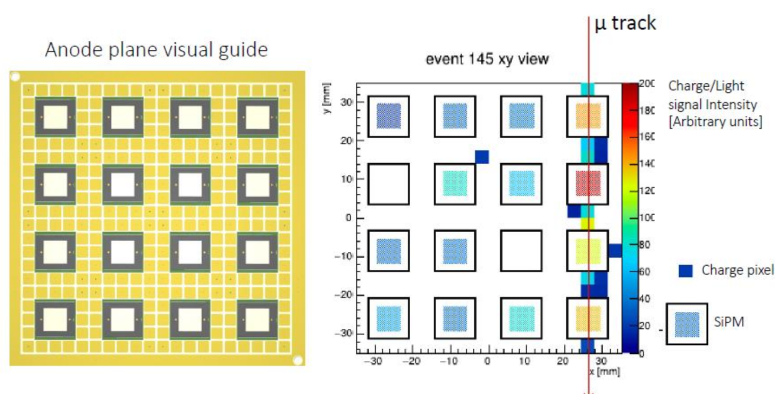
Optical readout of dual phase LArTPC



ARIADNE, A. Lowe et al., Instruments 4, 35 (2020)

Integrated light+charge readout

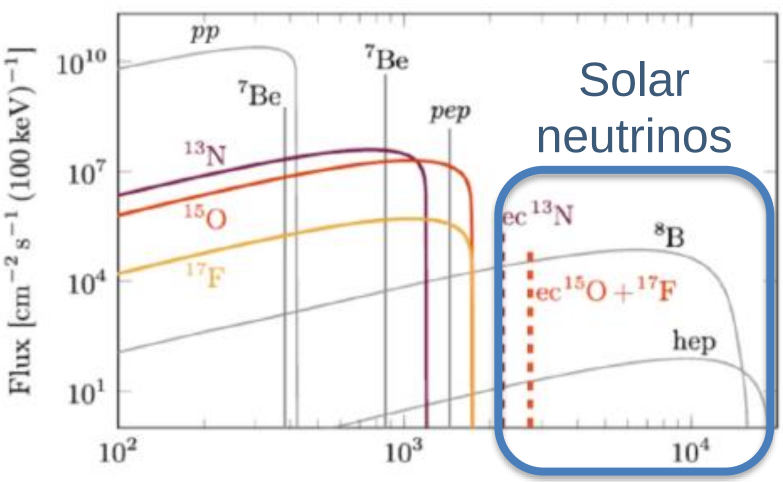


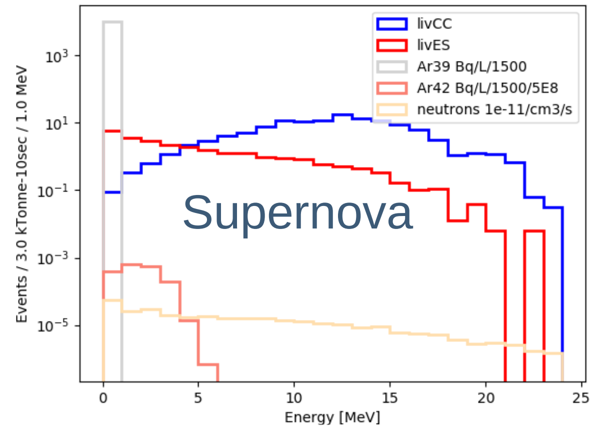


S. Parsa et al, Snomass, arXiv:2203.07501

A module of Opportunities: science

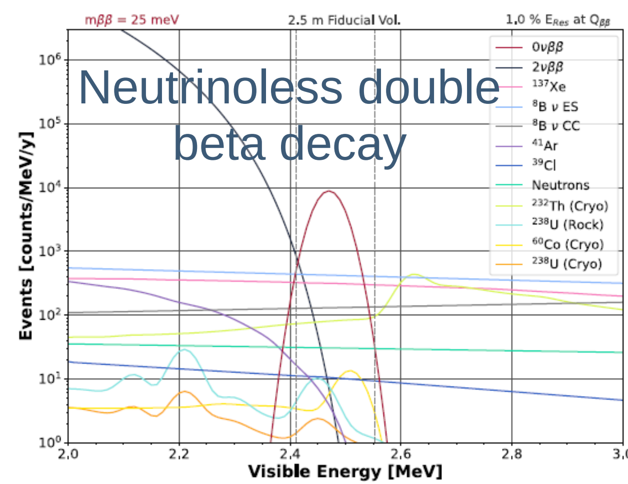
Low energy physics is the core of these R&Ds because DUNE was originally optimized for beam physics but its underground location and mass is an asset we must duly exploit See the "DUNE Module of Opportunity Workshop", Valencia 2-4 nov 2022





Radiopurity, neutron shielding, pulse shape discrimination, granularity, depleted argon

See e.g. A. Avashi et al, Snomass, arXiv:2203.08821,
D. Caratelli et al, Snowmass, 2203.00740
A. Mastbaum, et al,, PRD 106 (2022) 092002



Conclusions

DUNE is no more the “next generation project” for neutrino oscillation. We are now in construction phase and the DUNE experiment will provide major impact on neutrino physics starting from 2030

- Far site excavation is ongoing and the prototyping phase is over for most of the subsystem
- The strategy of modules based on the same underlying technology (liquid argon TPC) but reaping the latest advances in liquid argon technology has proven to be a smart approach for cost reduction and increase of the physics reach.
- We will pursue this strategy for module 3 and 4

The DUNE physics case is compelling both with artificial sources and natural sources. We now need to push toward a full exploitation of these opportunities:

- Complete validation at CERN with ProtoDUNE-HD and ProtoDUNE-VD
- Timely deployment of the DUNE Near Detector complex
- Full implementation of Phase II

CERN played a key role to have DUNE up and running and provided many technology breakthroughs in LArTPC over the last decade. We are grateful to you for such an impressive achievement!