DUNE

Physics program and prototyping

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On behalf of the DUNE Collaboration

La Thuile – 11/03/2025

DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

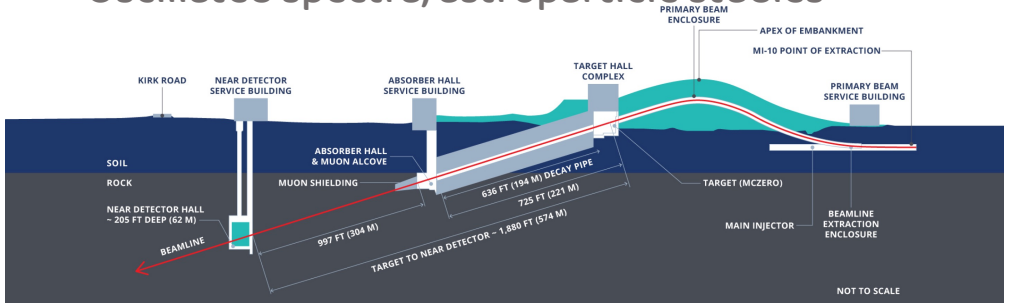
INFN MILANO BICOCCA

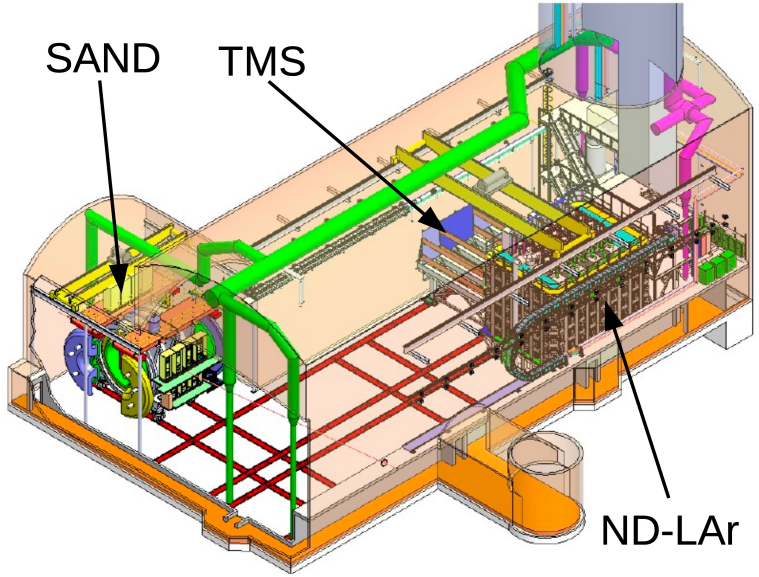
The experiment

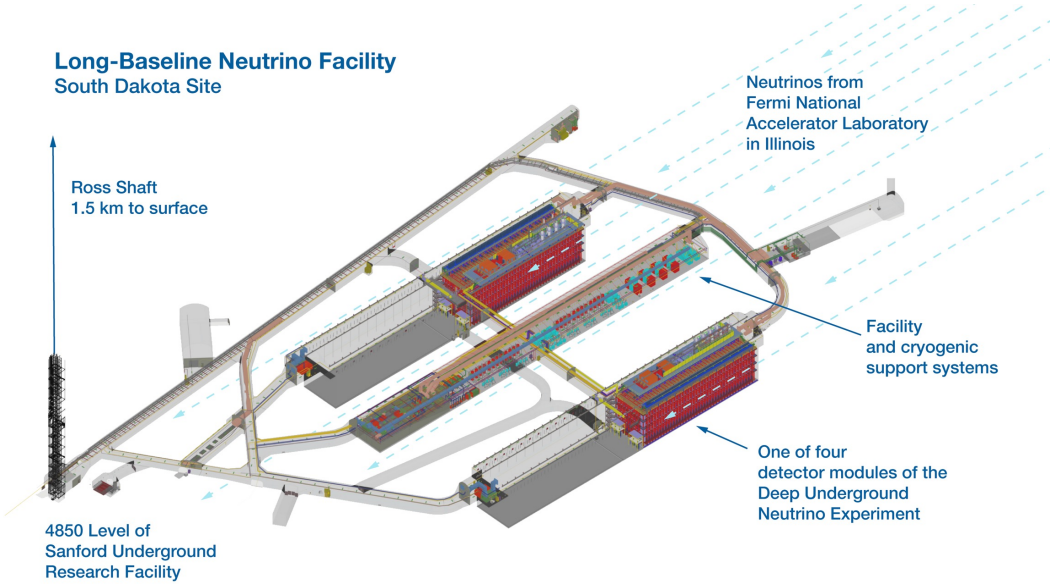
A next-generation neutrino experiment

The long-baseline scheme [1]

- Powerful (anti)neutrino beam
  - Wide spectrum, peak ~ 3 GeV
  - Intensity > 2 MW
- Near Detector
  - Argon target and movable detectors
  - Pixelated readout and optical modularity
  - Flux constraints (spectra and composition)
- Far Detector
  - Massive underground LAr-TPCs
  - Charge and light readouts
  - Oscillated spectra, astroparticle studies







Physics program

Not to scale :)

Supernova neutrinos

Multi messanger astronomy

Mass hierarchy

Normal or inverted ordering?

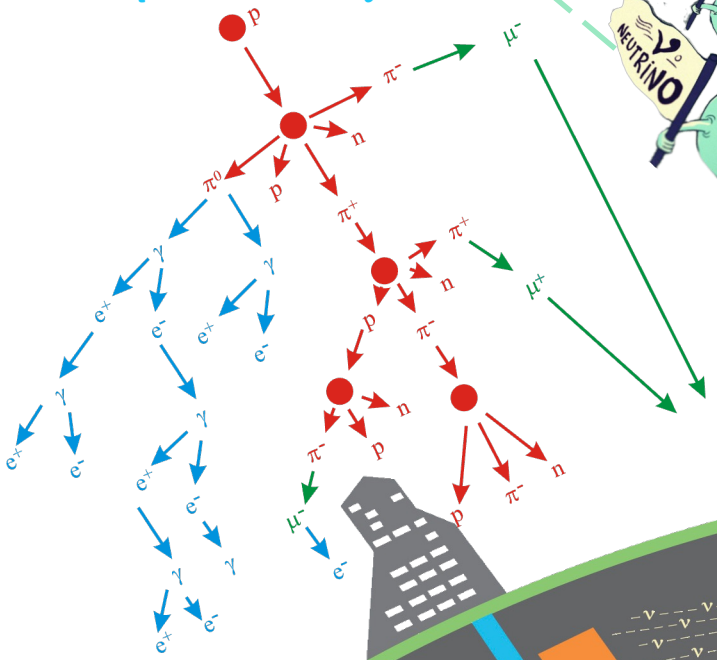
Solar neutrinos

Day-night asymmetry

hep-chain

Barion number violation

Do protons dacay?

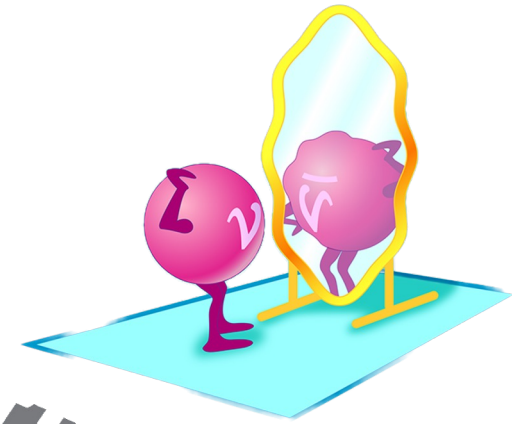


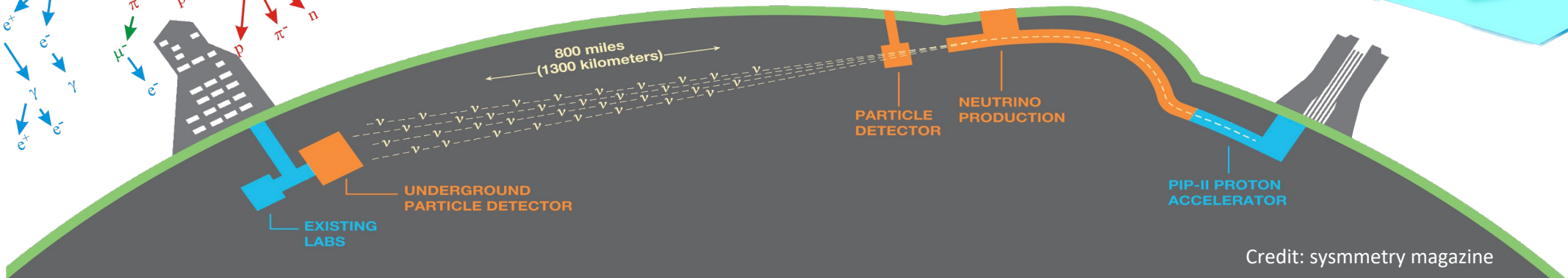
CP violation

Do neutrinos and antineutrinos oscillate the same?

Atmospheric neutrinos

A single detector, infinite baselines





Credit: sysmmetry magazine

Beam program

Complete the three-flavour frame

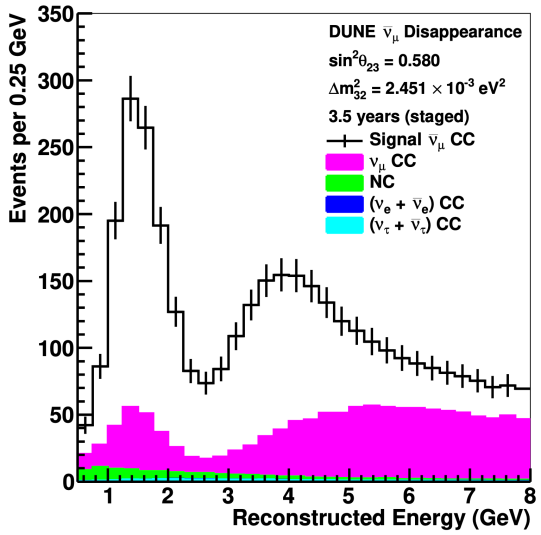
Analysis of the (dis)appearence spectra:

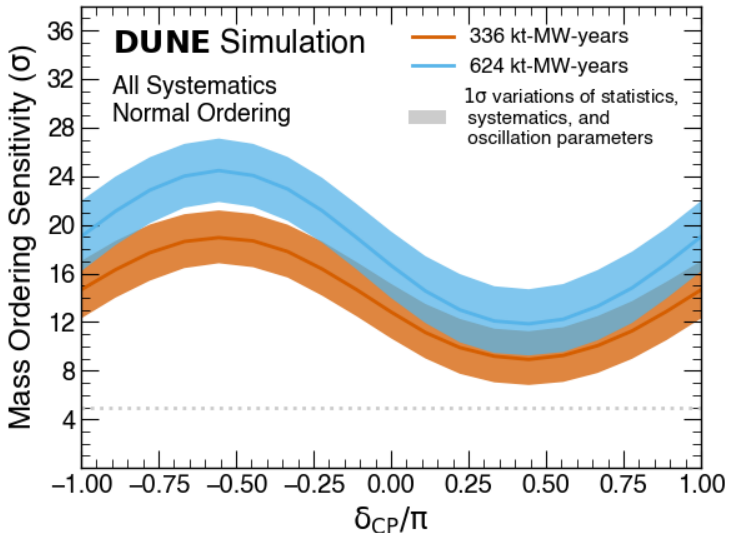
$$\nu_\mu \rightarrow \nu_\mu \qquad \nu_\mu \rightarrow \nu_e$$

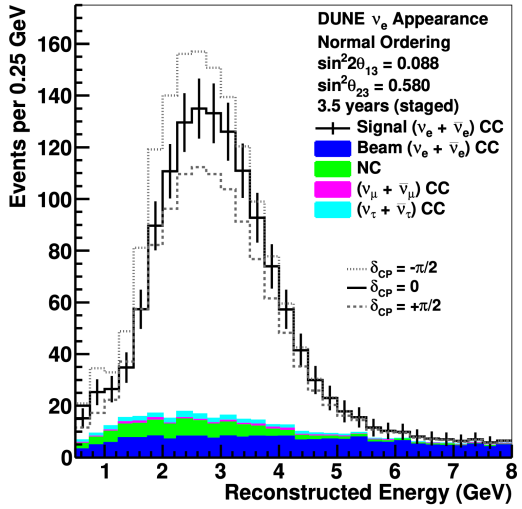
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \qquad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

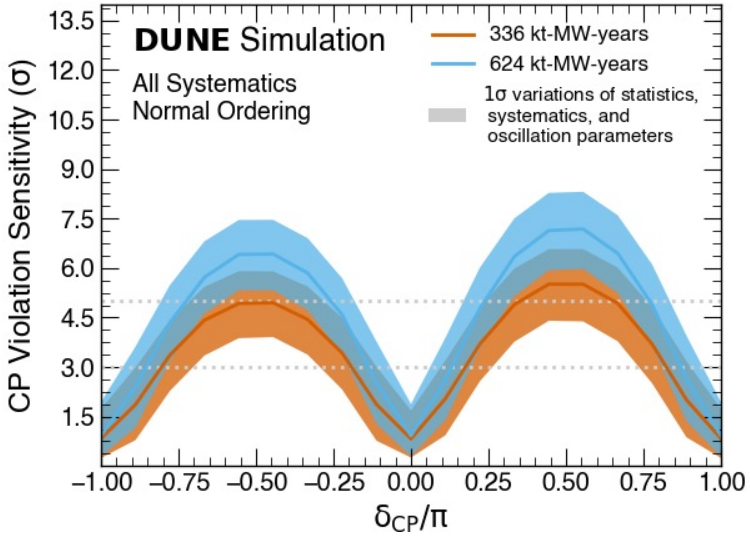
- Mass Ordering
  - > 5σ sensitivity for any δ_{CP} value
  - From 1 to 3 years according to the scenario
  - Exploit the matter effect
- CP-violation
  - Exp 5σ for 50% of values in ~10 years
  - Sub-leading distortion in the oscillated spectra

Ref: [2]







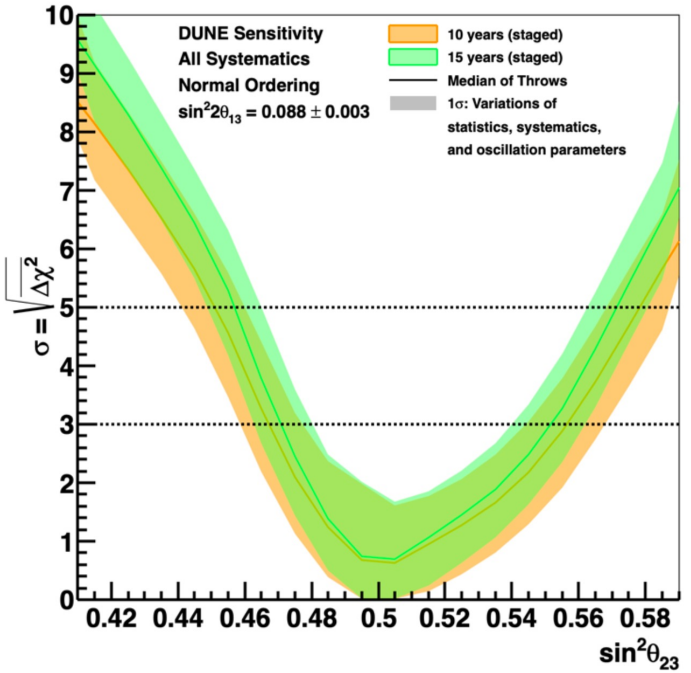


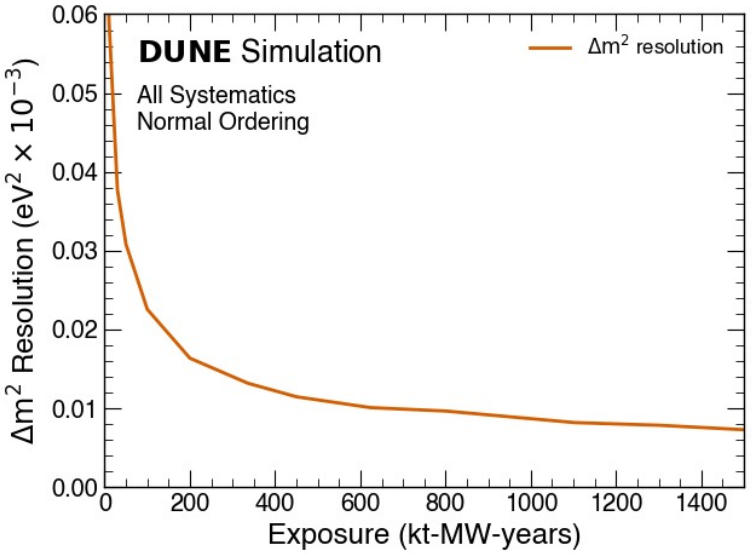
Beam program

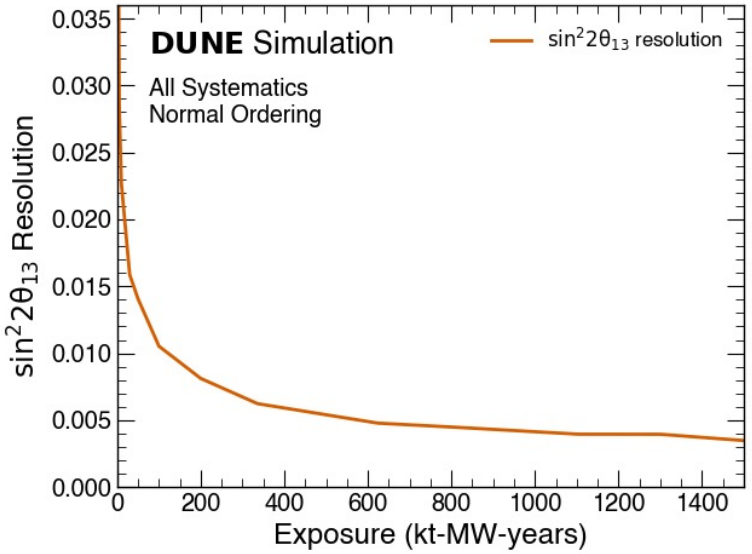
Constraint the three-flavour frame

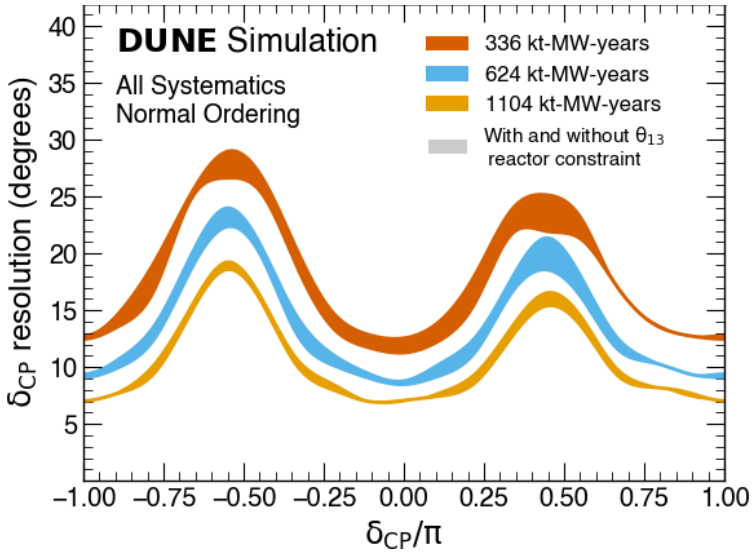
Precise measurements [3]

- Δm^2 resolution $\sim 10^{-5}$ eV^2
- δ_{CP} within to 6°-16° (depending on true value)
- θ_{13} comptetive with reactor experiments
- θ_{23} octant determination







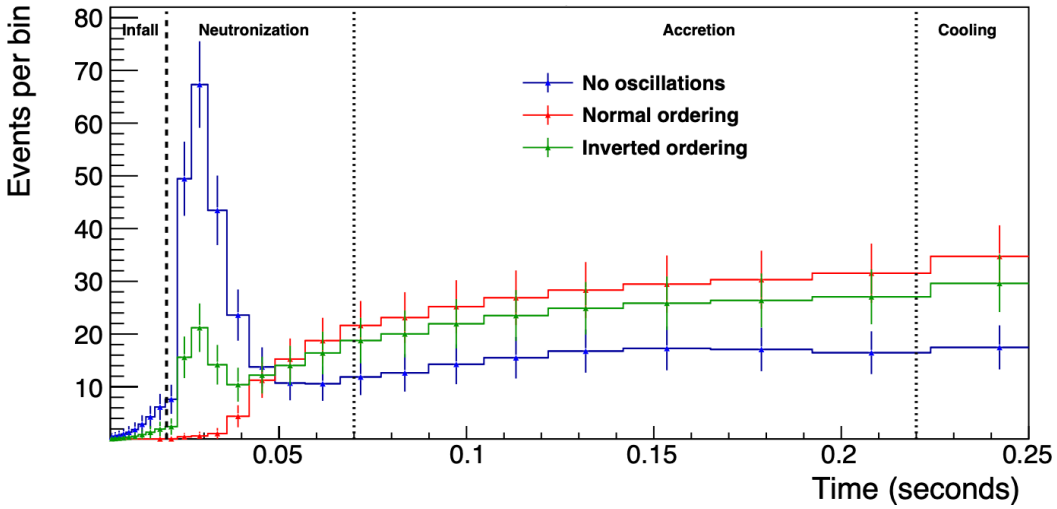


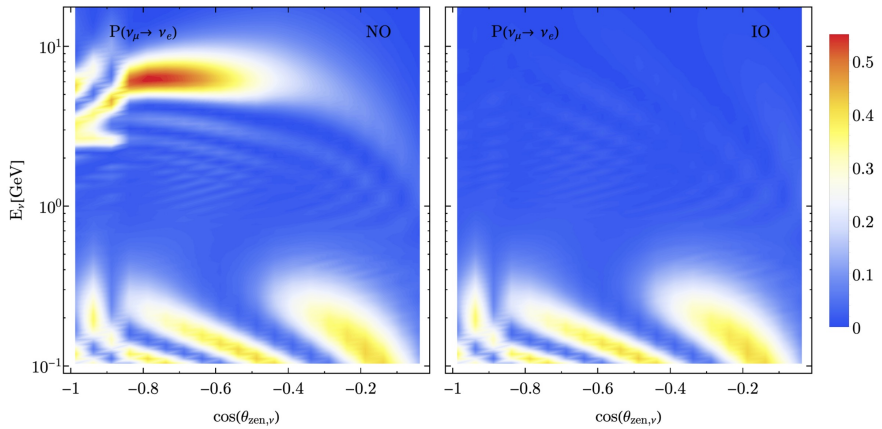
Natural sources

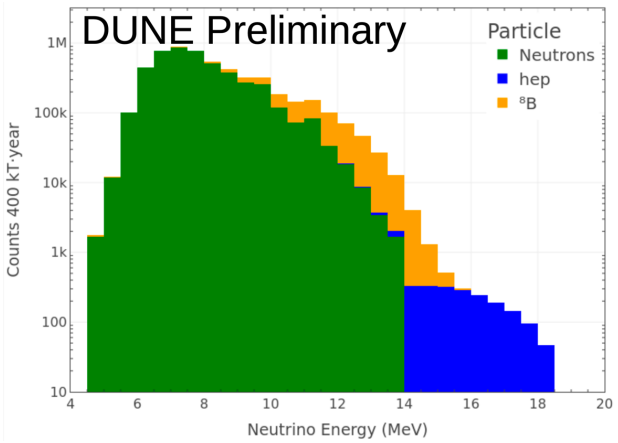
Atmospheric, solar and supernova neutrinos

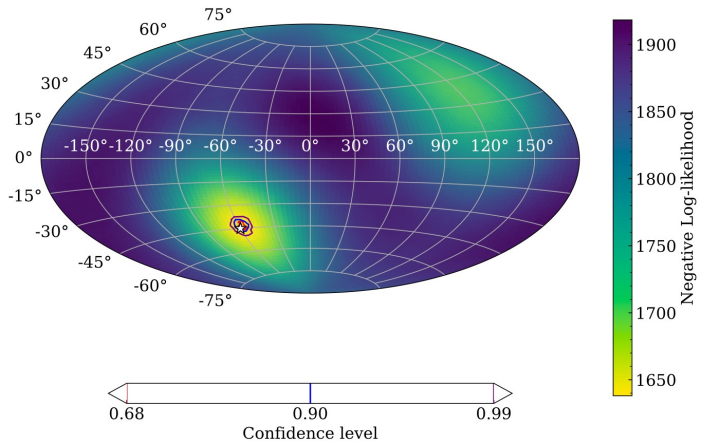
Far Detector as standalone experiment for astroparticle studies

- Supernova neutrinos
  - Trigger, pointing, mass ordering [4]
- Solar neutrinos
  - hep chain and day-night asymmetry [5]
- Atmospheric neutrinos







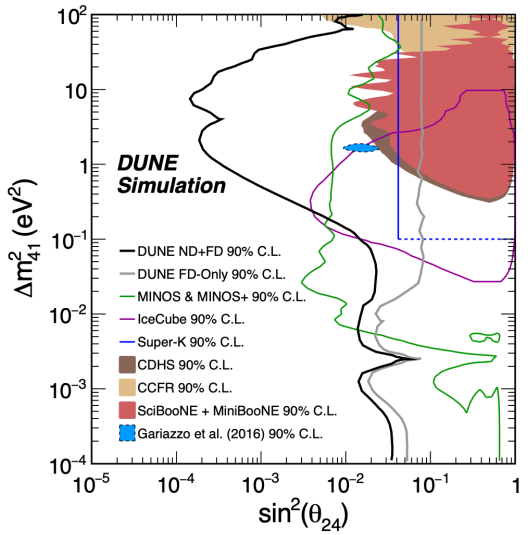


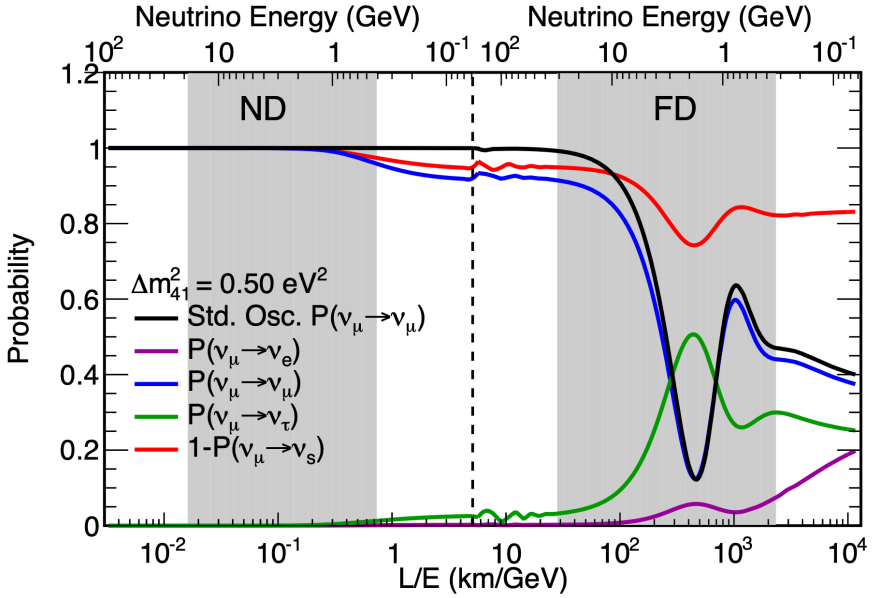
BSM program

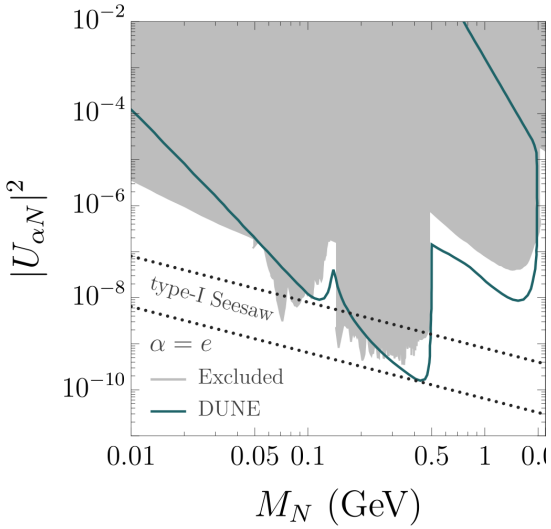
… and beyond!

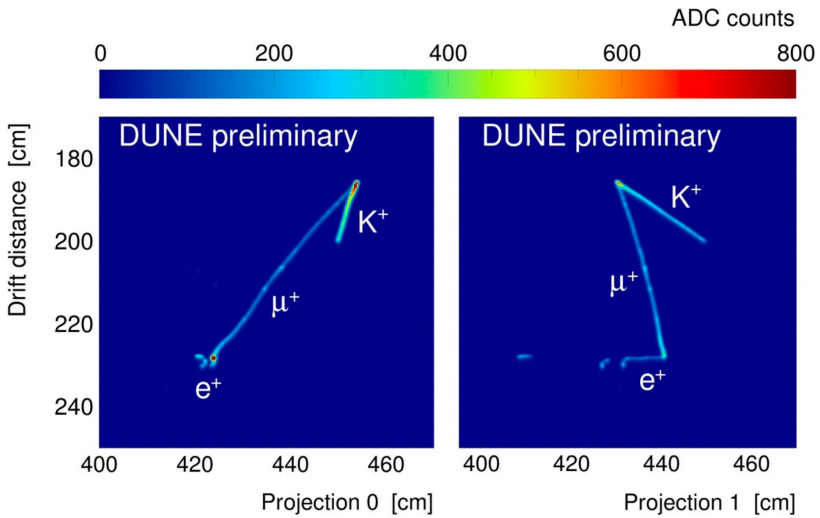
- Non-standard oscillation
  - Sterile neutrino mixing
  - PMNS non-unitarity
  - CPT violation
  - ν_τ appearance
- Baryon number violation
  - Proton decay
  - Golden channel $p^+ \to K^+ \bar{\nu}$
  - $n \to \bar{n}$
- Dark matter searches
  - Heavy Neutral Lepton

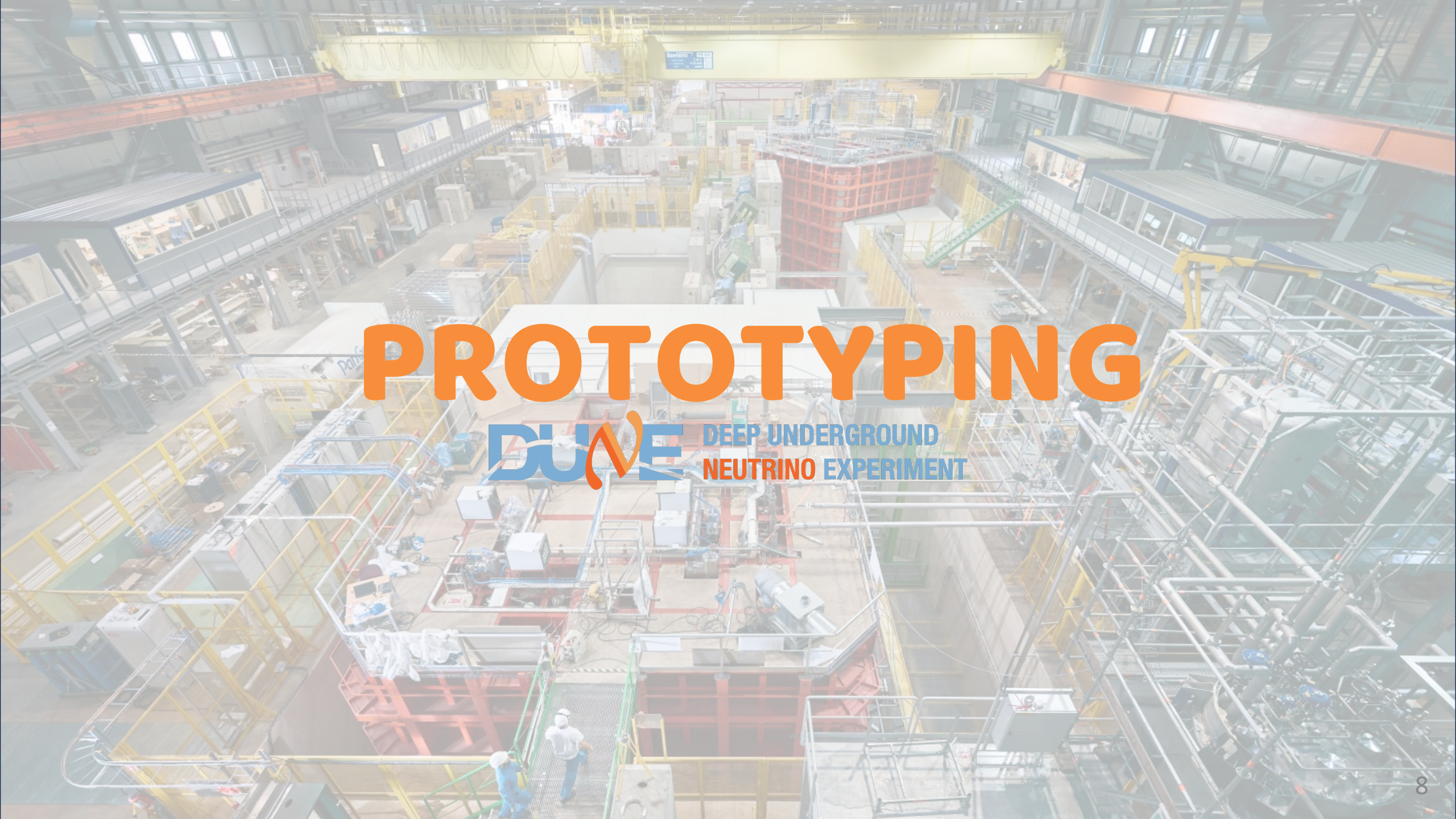
Ref: [6]











PROTOTYPING

DEEP UNDERGROUND NEUTRINO EXPERIMENT

ProtoDUNE-I

Single- and dual-phase era

The first Far Detector prototipes run

- ProtoDUNE-SP
  - Multiwire chamber technology, confirmed for the Horizontal Drift module
  - Explored different Photon Detection System technologies

  Articles:

  Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora

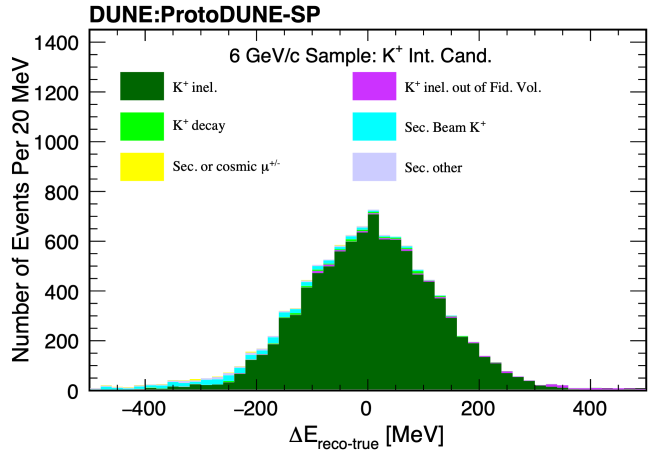
  Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector

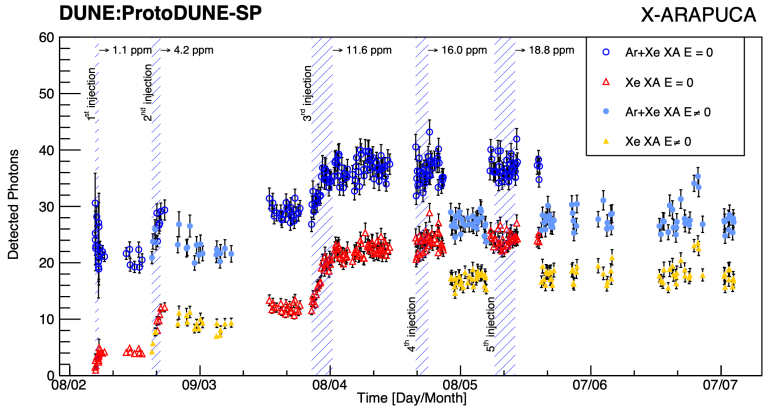
  Doping liquid argon with xenon in ProtoDUNE Single-Phase: effects on scintillation light

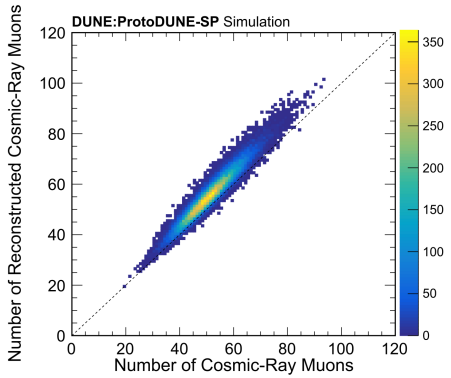
  First Measurement of a Positively Charged Kaon on Argon Total Inelastic Cross Section at Total Energies of Approximately 5 to 7.5 GeV
- ProtoDUNE-DP
  - Single drift volume, liquid and gaseous phases
  - Xenon doping effects

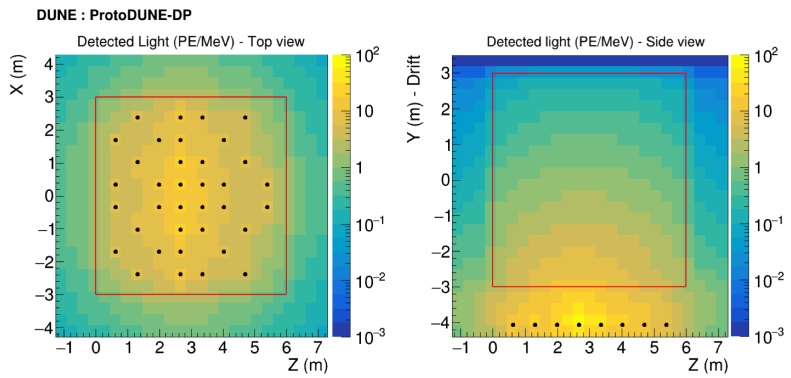
  Articles:

  Scintillation light detection in the 6-m drift-length ProtoDUNE Dual Phase liquid argon TPC





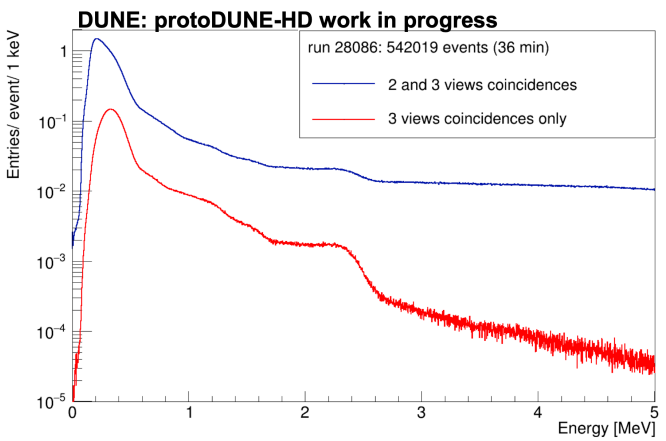


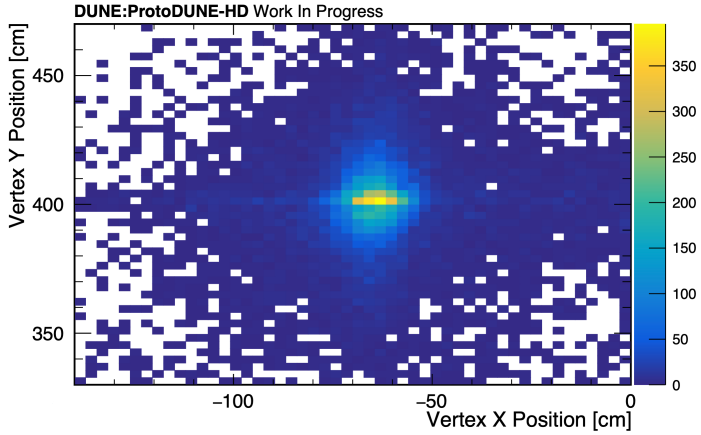


ProtoDUNE-II

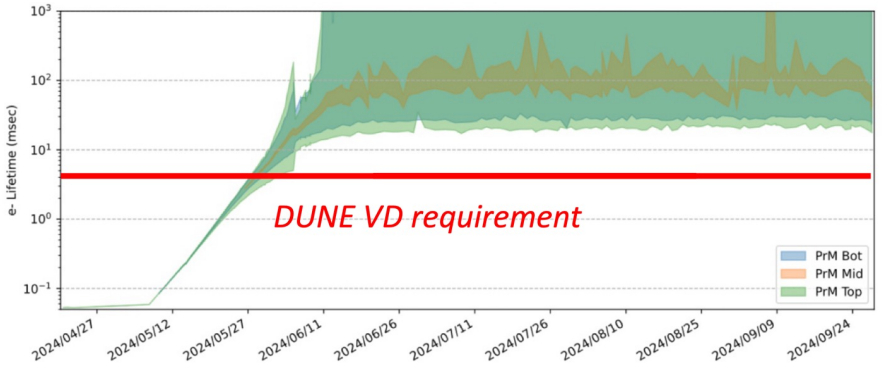
The DUNE-FD now

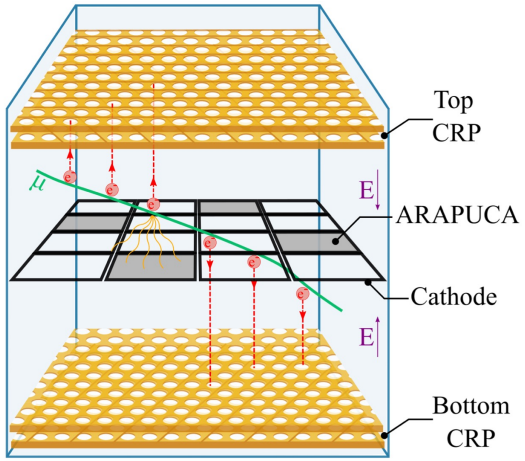
- ProtoDUNE-HD
  - Operation in 2024, April-October
  - 10 weeks of beam: ± 1, 2, 3, 5, 7 GeV
  - New CE, PDS, and DAQ
- ProtoDUNE-VD
  - Commissioning
  - Completely re-designed
  - Two drift-volumes, one phase, CRPs as anodes
  - X-ARAPUCA with Signal and Power Over Fiber

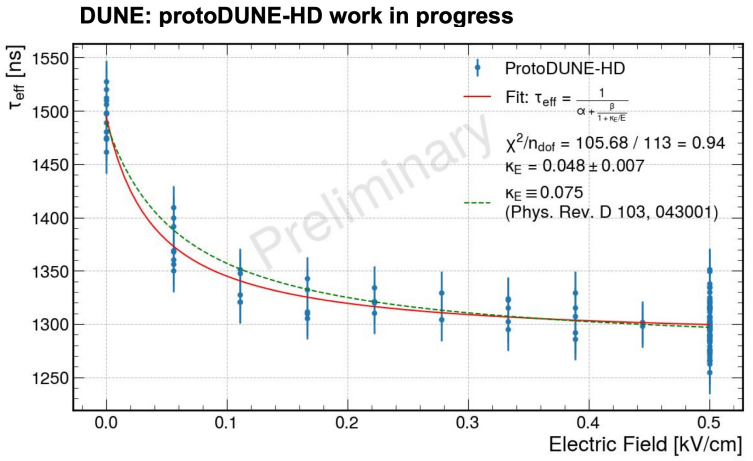




Beam spot reconstruction







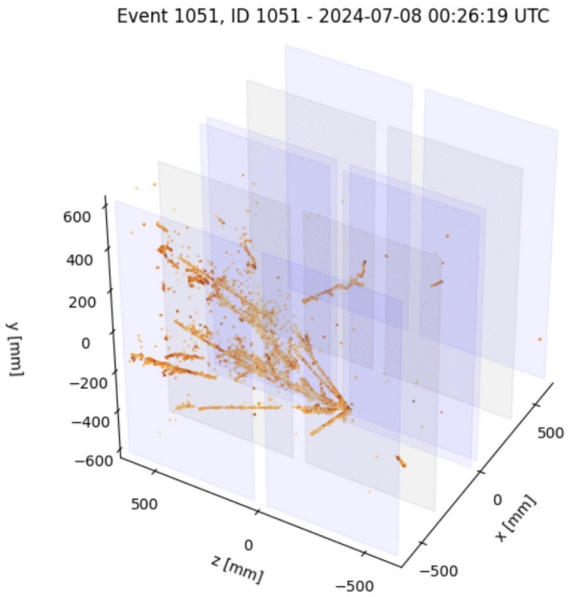
Refs: [7] [8] [9]

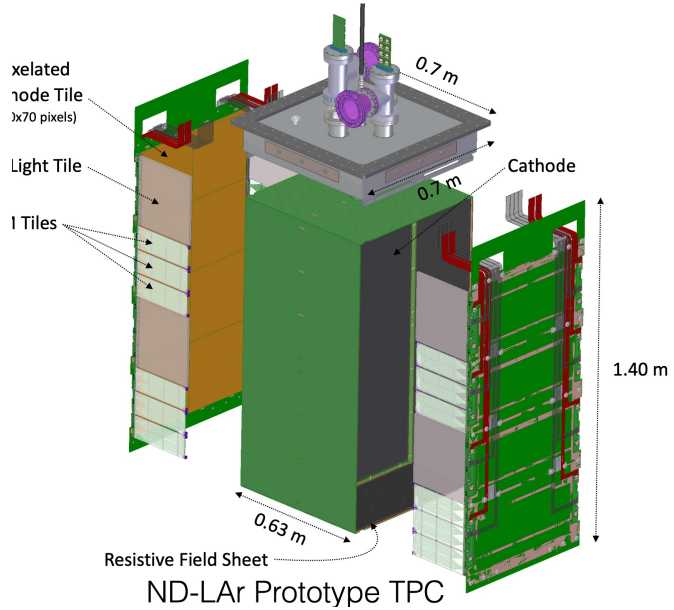
ND-LAr 2x2

First neutrino canidate!

The first detector in a neutrino beam

- Modularised LAr-TPC to sustain high rate
  - Module dimensions: 0.5 m x 1 m x 3 m
- Pixelated charge readout
  - 4mm granularity
  - Native 3D imaging
- High-performance light readout
  - 25% photocoverage
  - WLS materials coupled with SiPMs

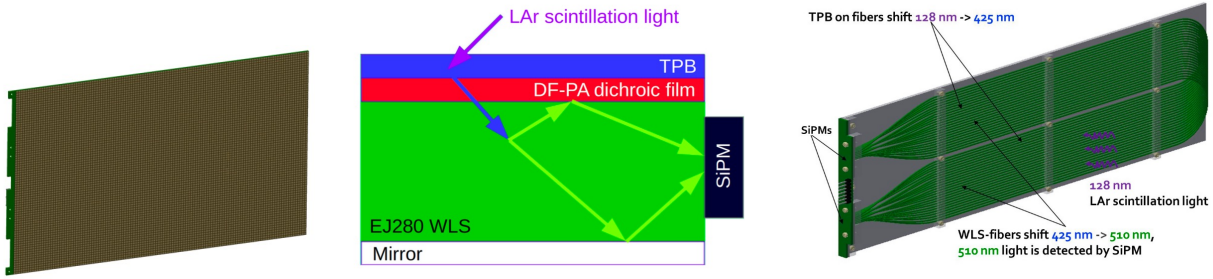




First accelerator neutrino record on July 8th!

- 5 days of Physics data-taking ~1k CC evt/day

Ref: [10]



Anode plane, and two light guide technologies employed

DUNE Phase-II

Forseen upgrades

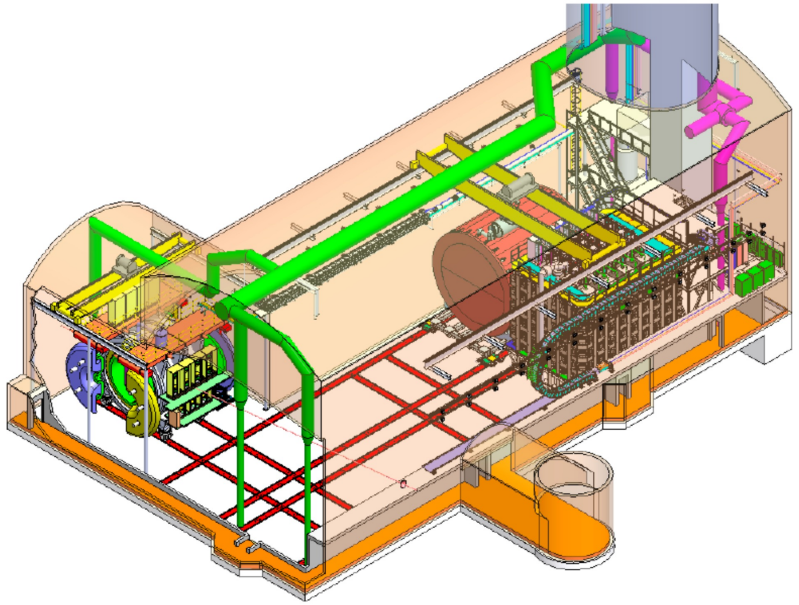
Near Detector

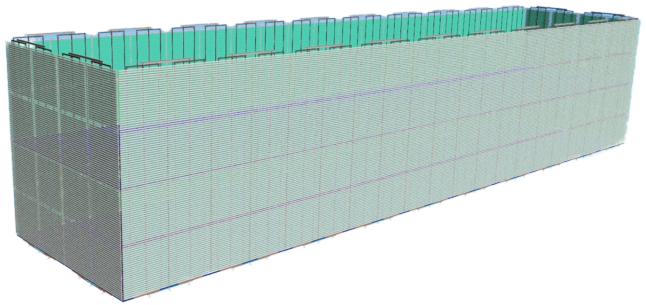
- ND-Gar: a new high-pressurized gas Argon TPC

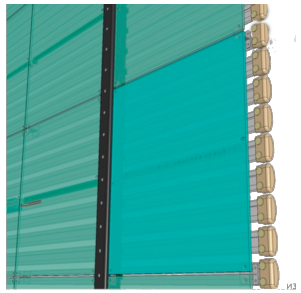
Far Detector

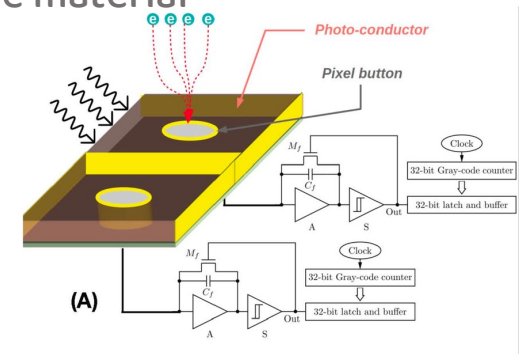
- FD3: APEX
  - CRP optimization, pixel base option
  - PDS embedded into the field cage
- FD4: Moldule of Opportunity
  - SoLAr: light-charge pixel readout on anode
    - VUV SiPMs
  - Q-Pix: light-charge readout through photo-conductive material

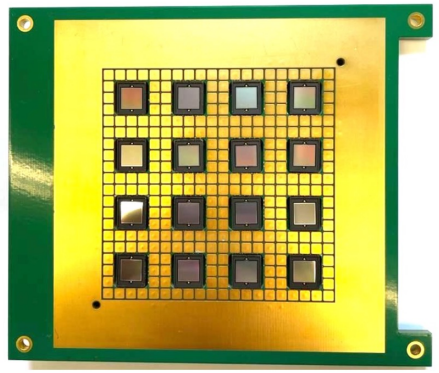
Refs: [11] [12] [13] [14] [15]

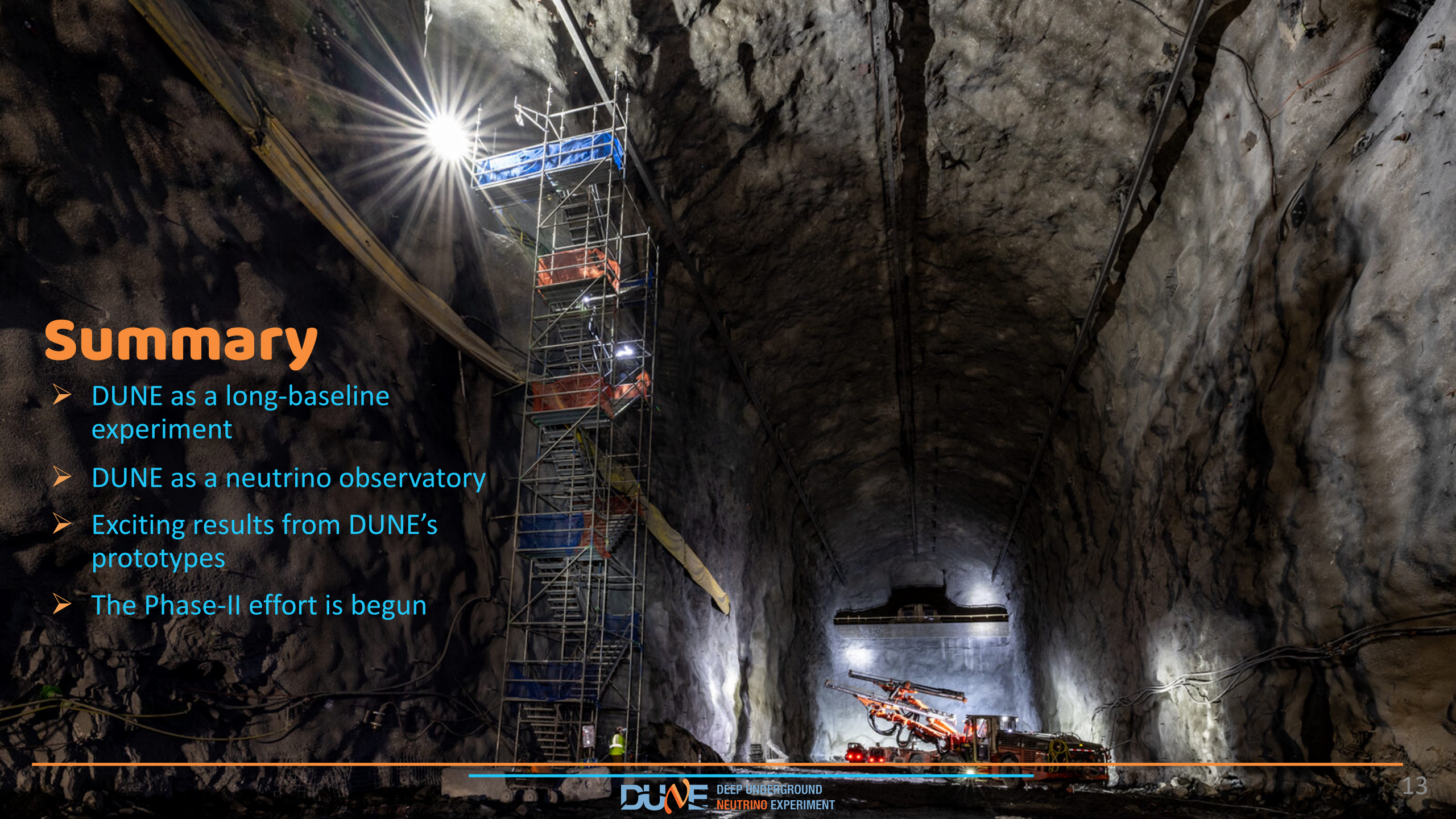












Summary

- DUNE as a long-baseline experiment
- DUNE as a neutrino observatory
- Exciting results from DUNE's prototypes
- The Phase-II effort is begun

Grazie

References

[1] Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I: Introduction to DUNE (link)

[2] Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics (link)

[3] DUNE, *Chris Marshall* (link)

[4] Supernova Pointing Capabilities of DUNE (link)

[5] DUNE's low energy phyisics searches, *Sergio Manthey Corchado* (link)

[6] Prospects for Beyond the Standard Model Physics Searches at the Deep Underground Neutrino Experiment (link)

[7] ProtoDUNE Photon Detection System, *Jose Soto-Oton* (link)

[8] Analysis plans and preliminary results from the Proto-DUNE HD data taking, *Laura Zambelli* (link)

[9] Characterization and novel application of power over fiber for electronics in a harsh environment, *D. Leon Silverio et al.* (link)

[10] Overview and Status of the 2x2 NDLAr Demonstrator, *Karolina Wresilo* (link)

[11] Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report (link)

[12] DUNE Phase II: Scientific Opportunities, Detector Concepts, Technological Solutions (link)

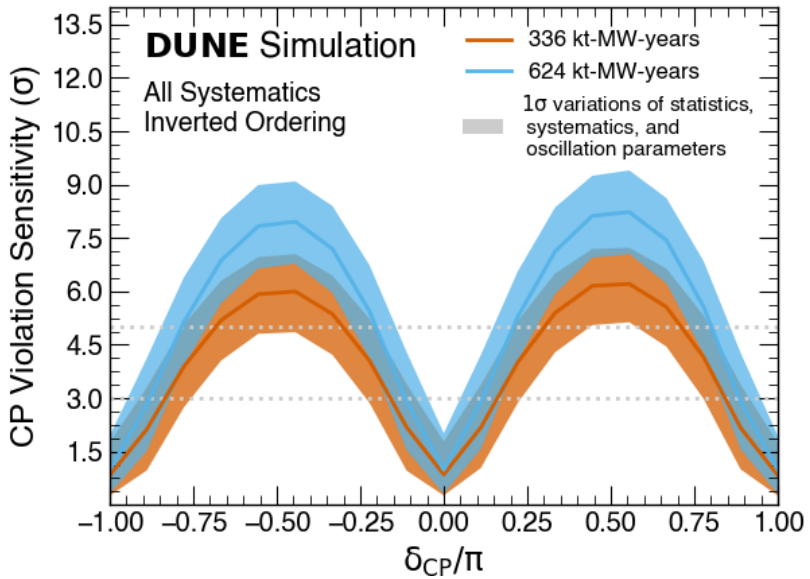
[13] Introducing APEX: a new concept for DUNE module 3 far detector photon detection system, *Franciole Marinho* (link)

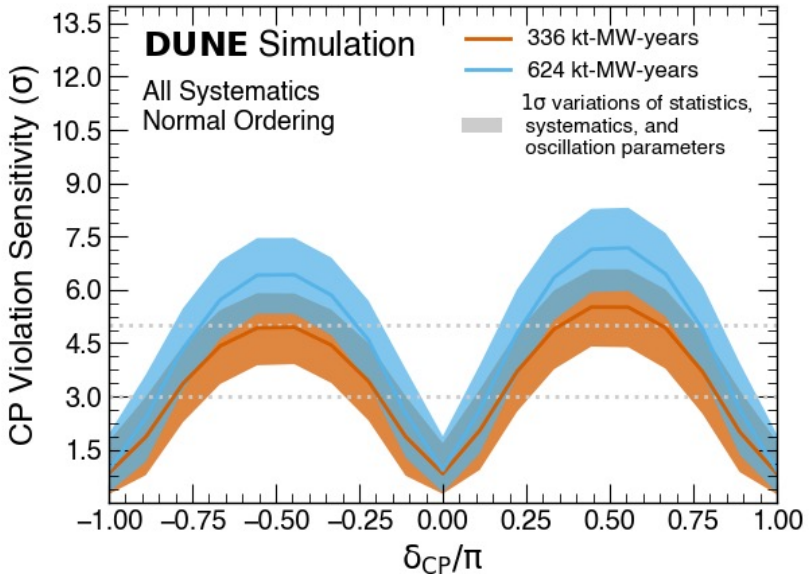
[14] SoLAr: Solar Neutrinos in Liquid Argon, *Saba Parsa et al.* (link)

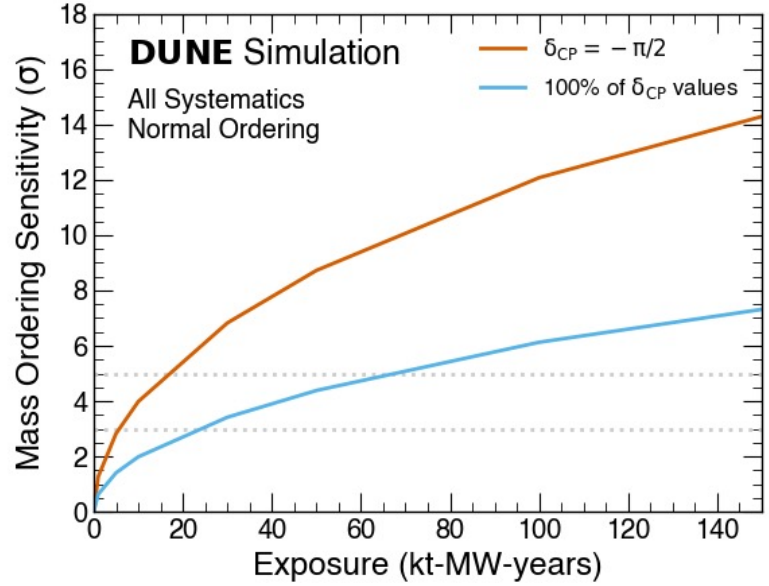
[15]QPIX, a novel pixel technology for large noble element detectors, *Austin McDonald* (link)

Back-up

Mass Ordering

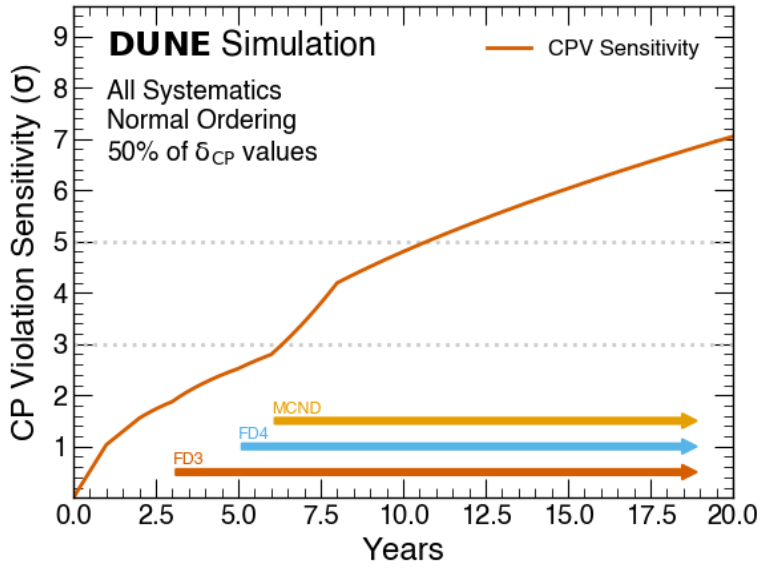


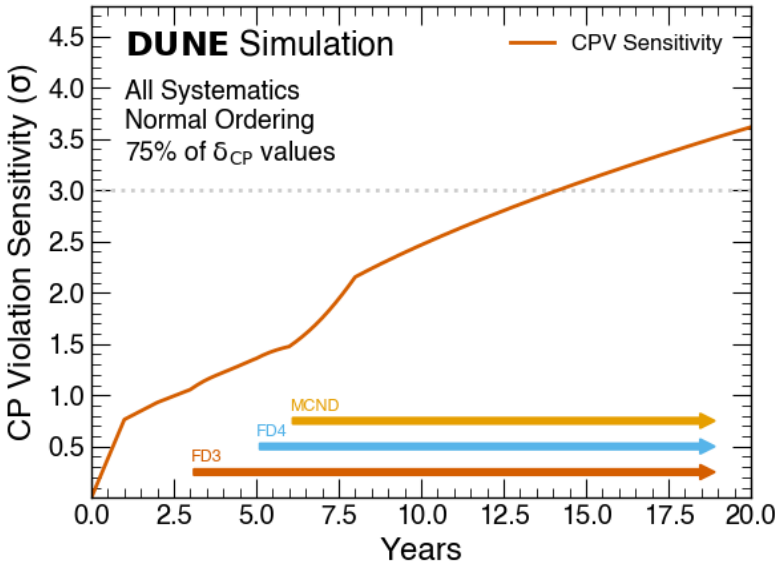


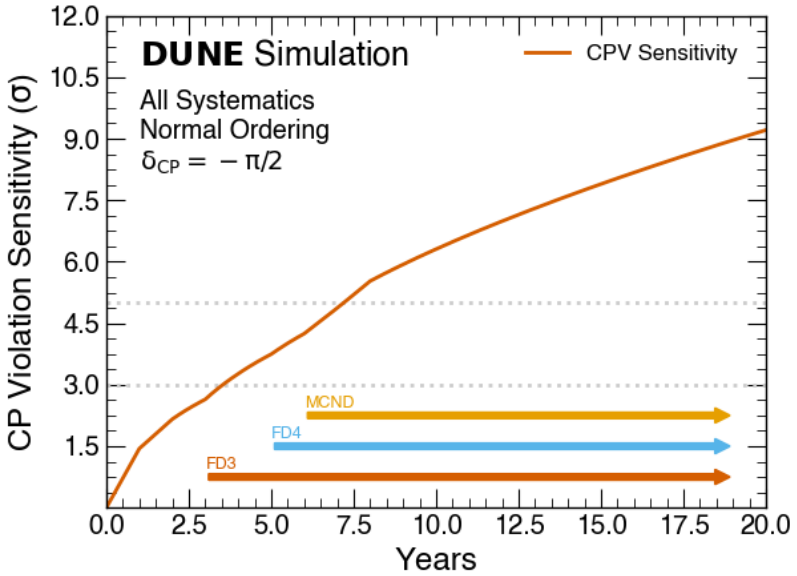


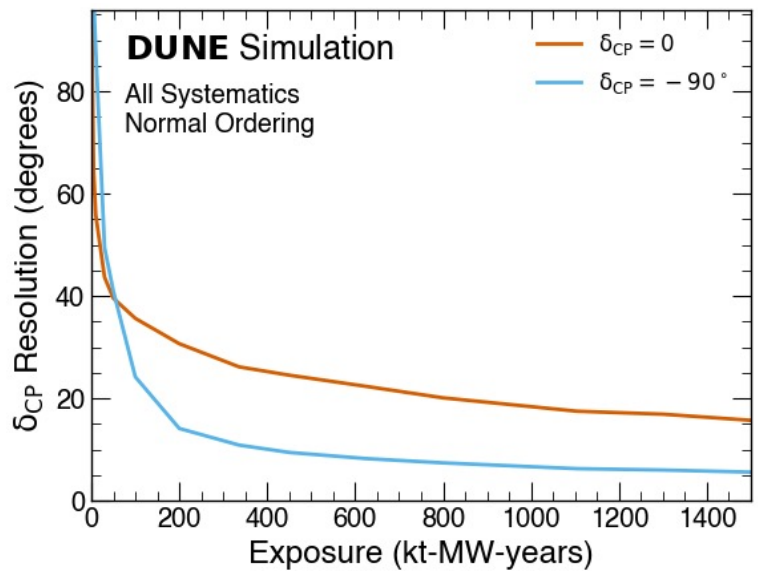
Back-up

CPV


DUNE Simulation
CPV Sensitivity
All Systematics
Normal Ordering
50% of δ_{CP} values
CP Violation Sensitivity (σ)
Years
MCND
FD4
FD3

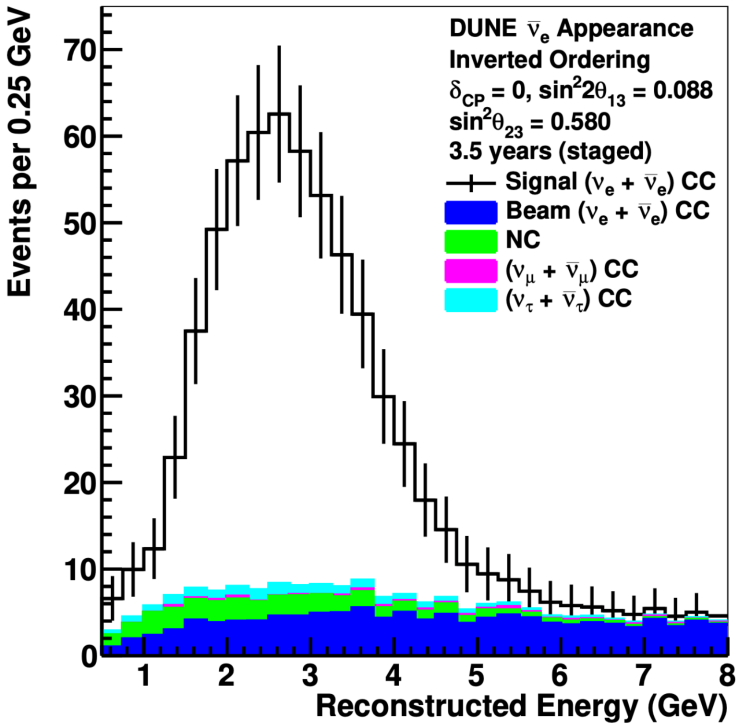

DUNE Simulation
CPV Sensitivity
All Systematics
Normal Ordering
75% of δ_{CP} values
CP Violation Sensitivity (σ)
Years
MCND
FD4
FD3

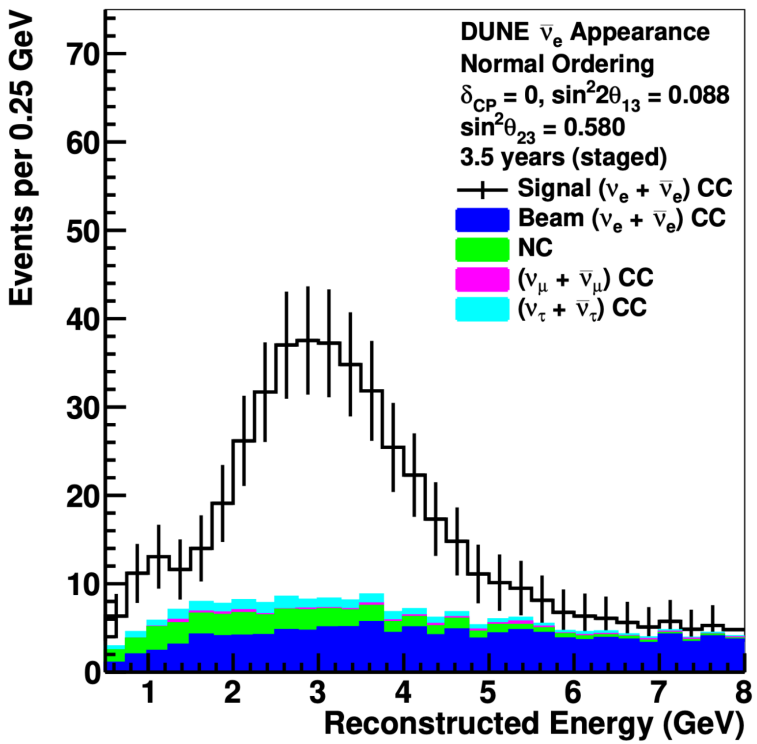

DUNE Simulation
CPV Sensitivity
All Systematics
Normal Ordering
$\delta_{CP} = -\pi/2$
CP Violation Sensitivity (σ)
Years
MCND
FD4
FD3


DUNE Simulation
All Systematics
Normal Ordering
$\delta_{CP} = 0$
$\delta_{CP} = -90°$
δ_{CP} Resolution (degrees)
Exposure (kt-MW-years)

Back-up

Nu_e appearance





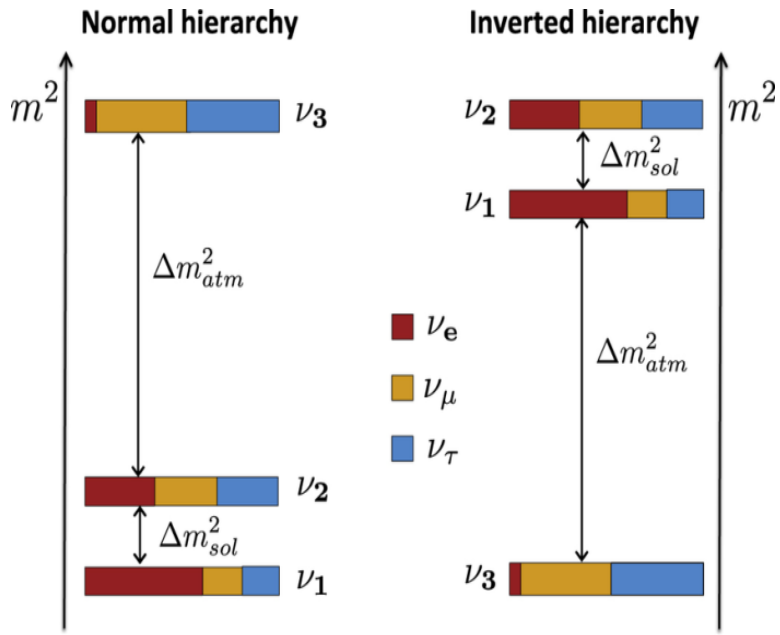
Back-up

PMNS

NuFIT 5.3 (2024)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
	$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
	$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
	$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

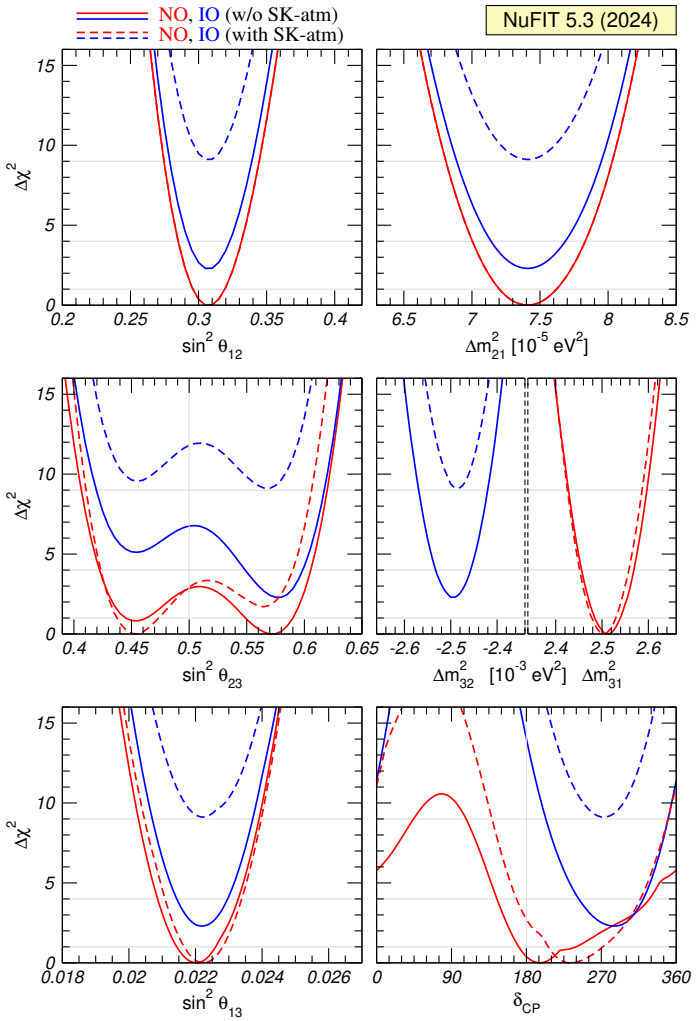


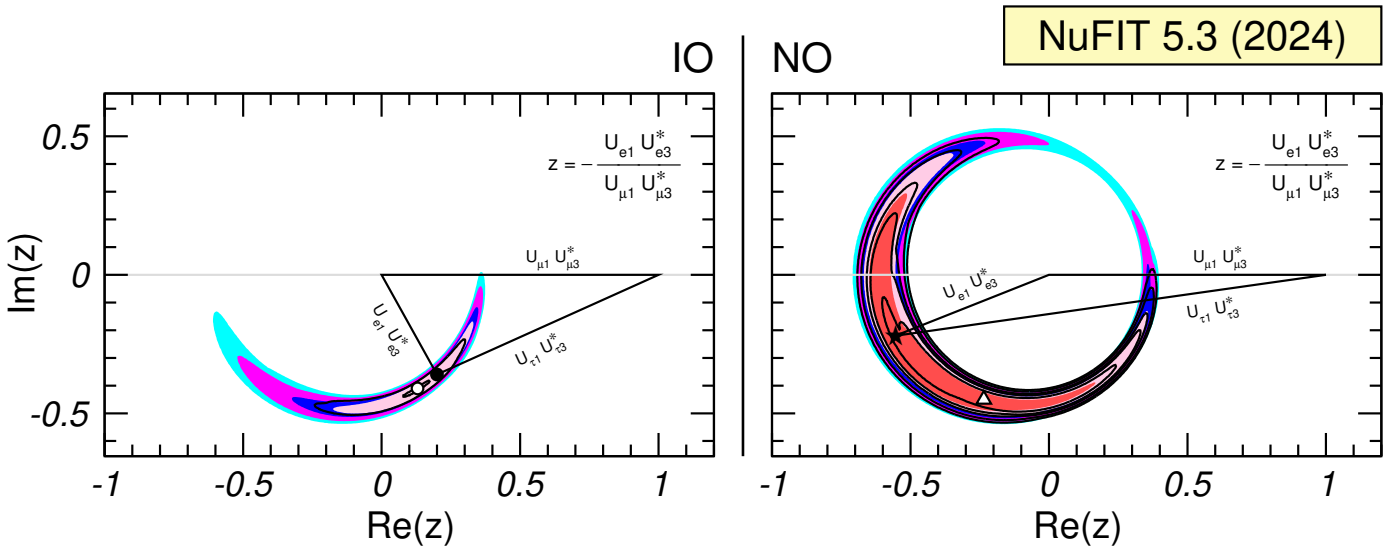
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric	Reactor/Interference	Solar
$\mu \to \tau$ 500 Km/GeV	$\mu \leftrightarrow e$ 500 Km/GeV	$\mu \to e$ 15,000 Km/GeV

Back-up

PMNS

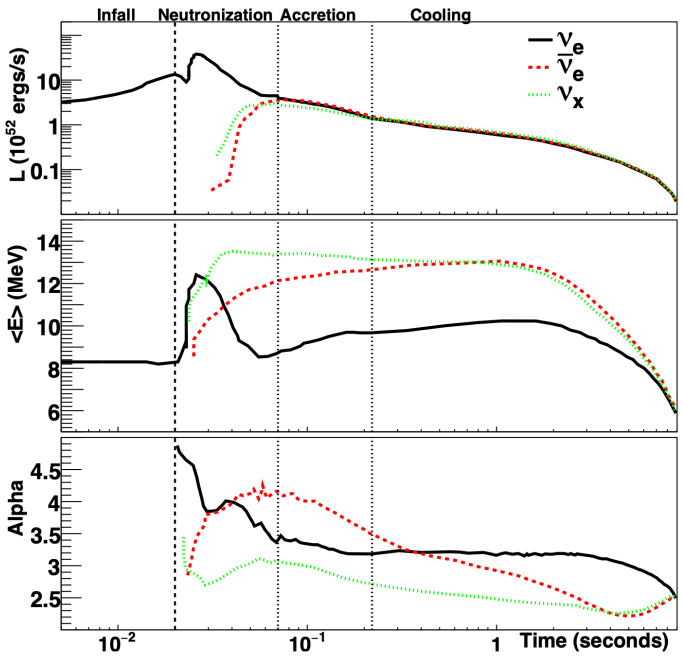

NO, IO (w/o SK-atm)
NO, IO (with SK-atm)
NuFIT 5.3 (2024)
Δχ²
sin² θ12
Δm²21 [10⁻⁵ eV²]
sin² θ23
Δm²32 [10⁻³ eV²]
Δm²31
sin² θ13
δCP

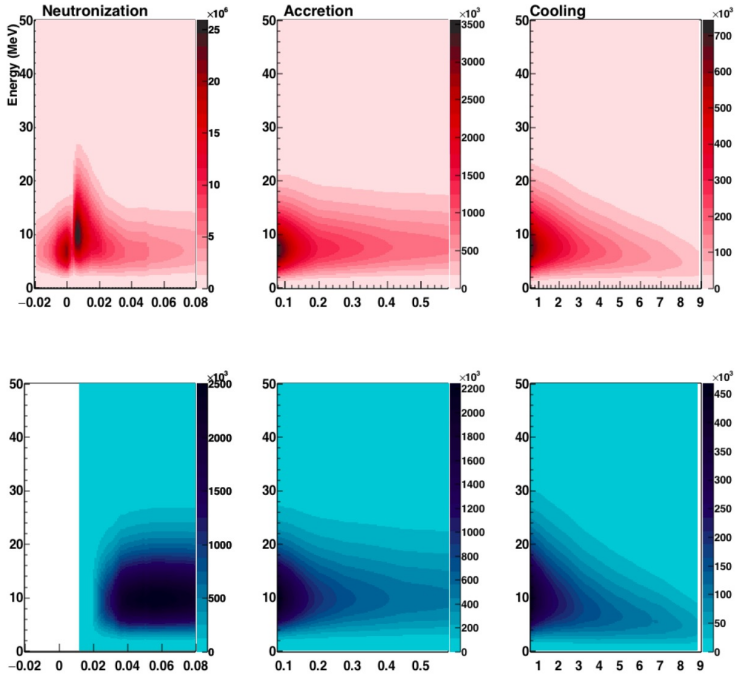

IO
NO
NuFIT 5.3 (2024)
Im(z)
Re(z)
z = − Ue1 Ue3* / Uμ1 Uμ3*
Uμ1 Uμ3*
Ue1 Ue3*
Uτ1 Uτ3*

Back-up

Supernovae

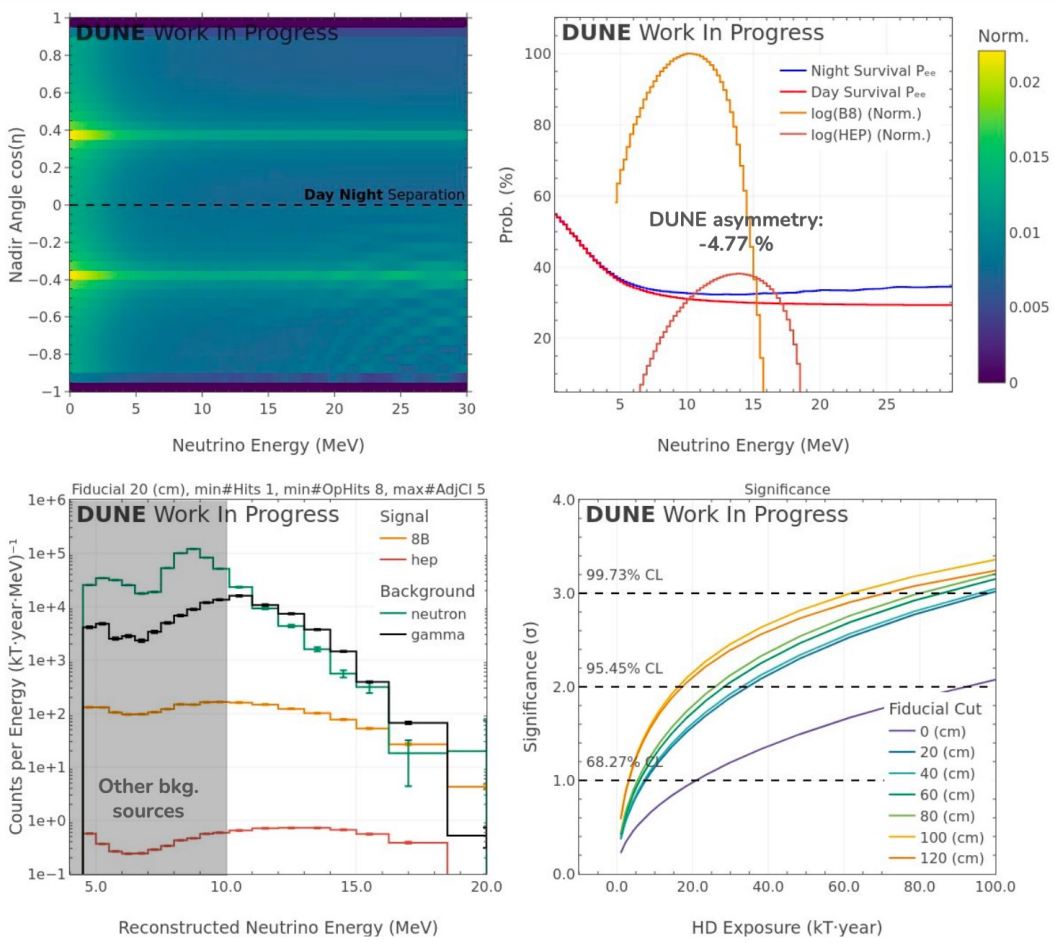
Channel	Liver-more	GKVM	Garching
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2648	3295	882
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

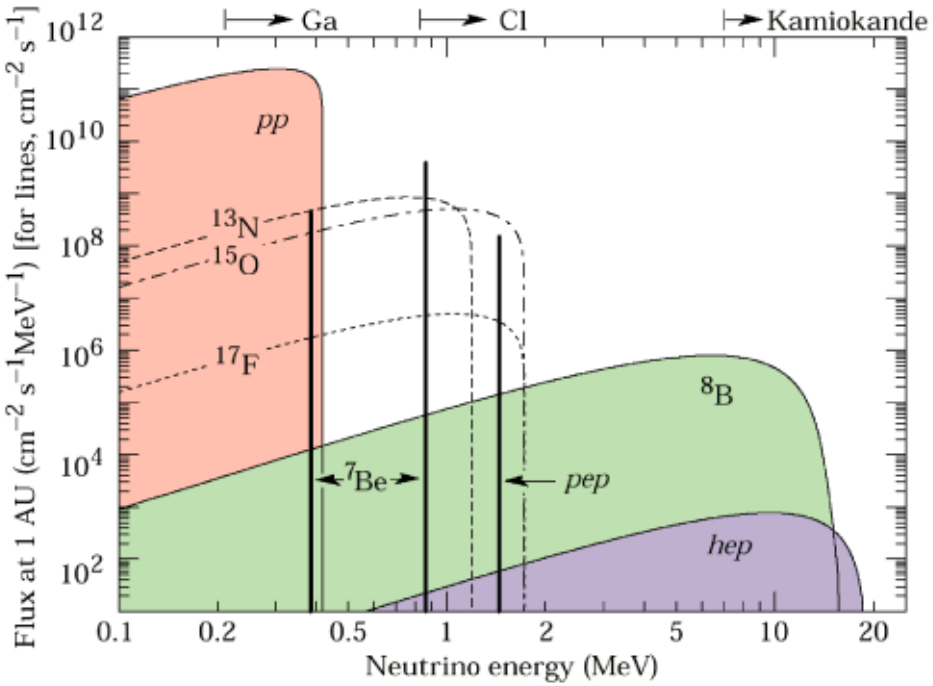




Back-up

Solar nu





Back-up

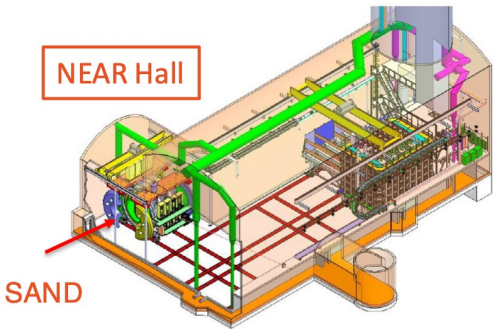
SAND

DUNE-SAND: prototyping activities

Luca Stanco

R&D for:

- ECAL electronics
- Tracker
- GRAIN

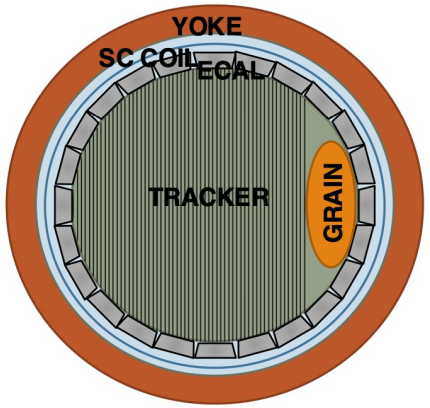


MAGNET – KLOE 0.6T superconductive coil + Fe Yoke

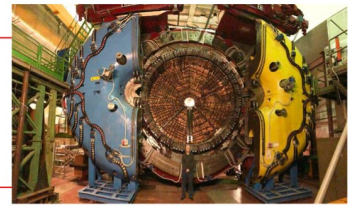
ECAL - KLOE Lead Scintillating Fibers calorimeter (Barrel ~85 t + EndCaps ~40 t)

TRACKER – STT: ~ 5 ton Straw-Tube tracker with "solid-H" target CH_2 and C interleaved foils (Drift Chamber, DCH, similar)

GRAIN – 1 ton liquid Argon target with VUV imaging system (fully optical read-out)



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



Our commitment: be ready to start installation as soon as ND hall available, and be ready as soon as Beamline ready

1 27/01/25

By Luca Stanco