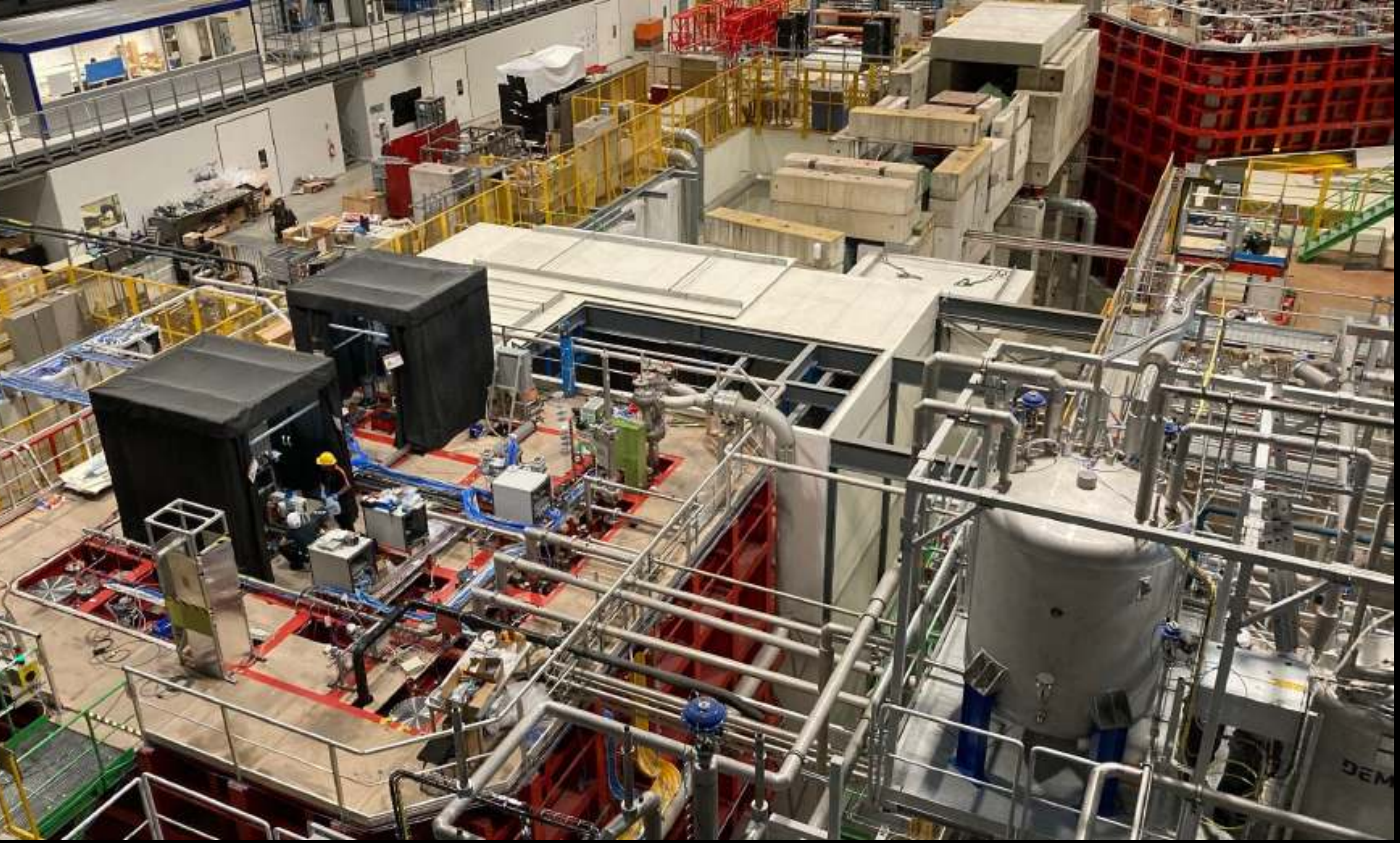


PORTUGUESE HEP RESEARCH AT CERN: DUNE

Ciências ULisboa

LIP

JOSÉ MANEIRA

CLAF SYMPOSIUM: OPPORTUNITIES FOR LATIN-AMERICAN COOPERATION IN HIGH ENERGY PHYSICS WITH CERN
CBPF, NOVEMBER 14, 2025

OUTLINE

- Open question in neutrino physics
- The Deep Underground Neutrino Experiment
- Portugal in DUNE
- Calibration systems for ProtoDUNE at CERN
- DUNE future prospects
- Collaboration with Brazil

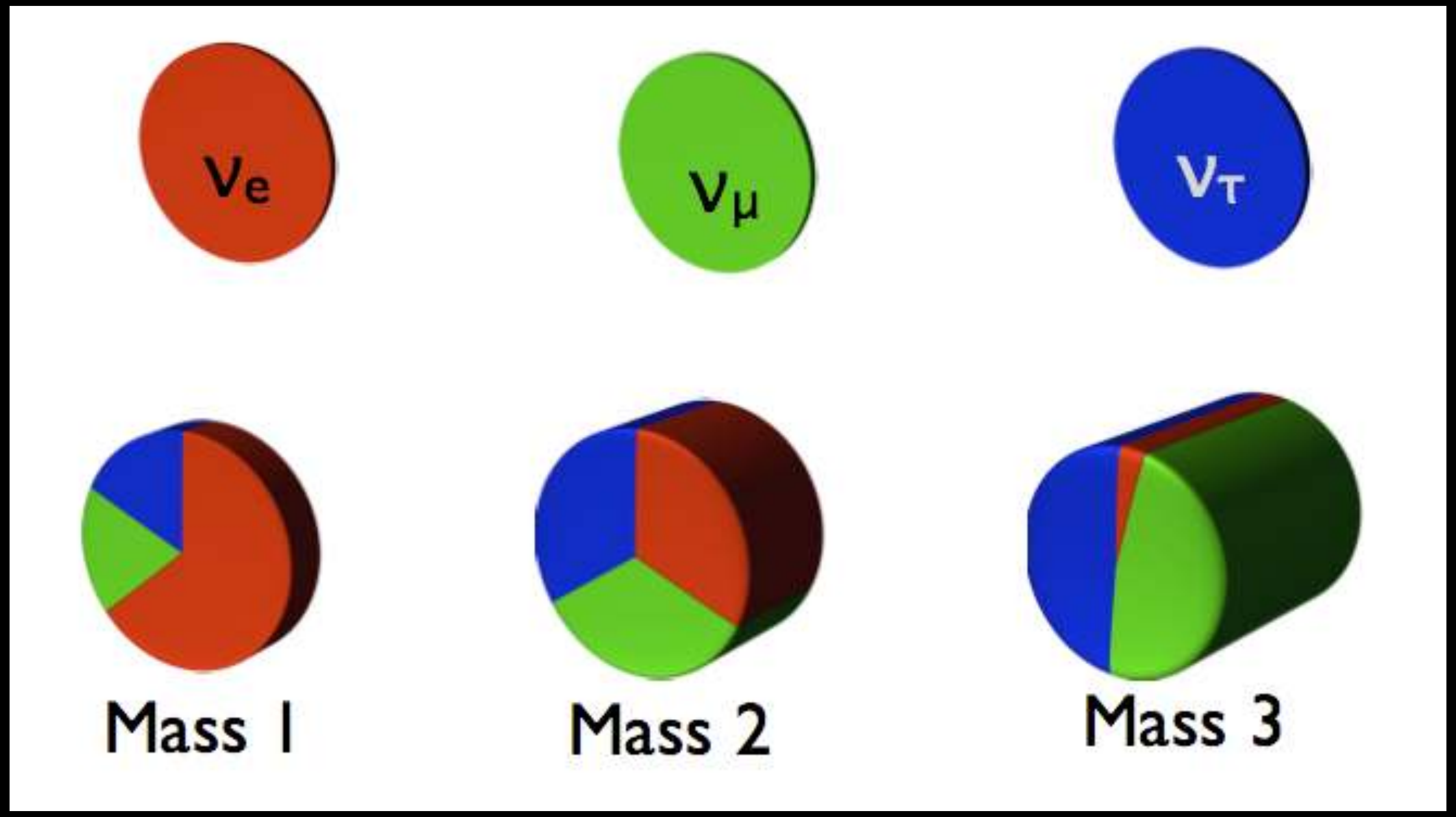
NEUTRINO PHYSICS

NEUTRINO MASS AND MIXING

flavor states
$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

mass states
$\nu_k = \nu_1, \nu_2, \nu_3$



$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$

$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3} eV^2$

3x3 mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

$\theta_{23} \approx 43°(NO)$ *or* $\approx 48°(IO)$

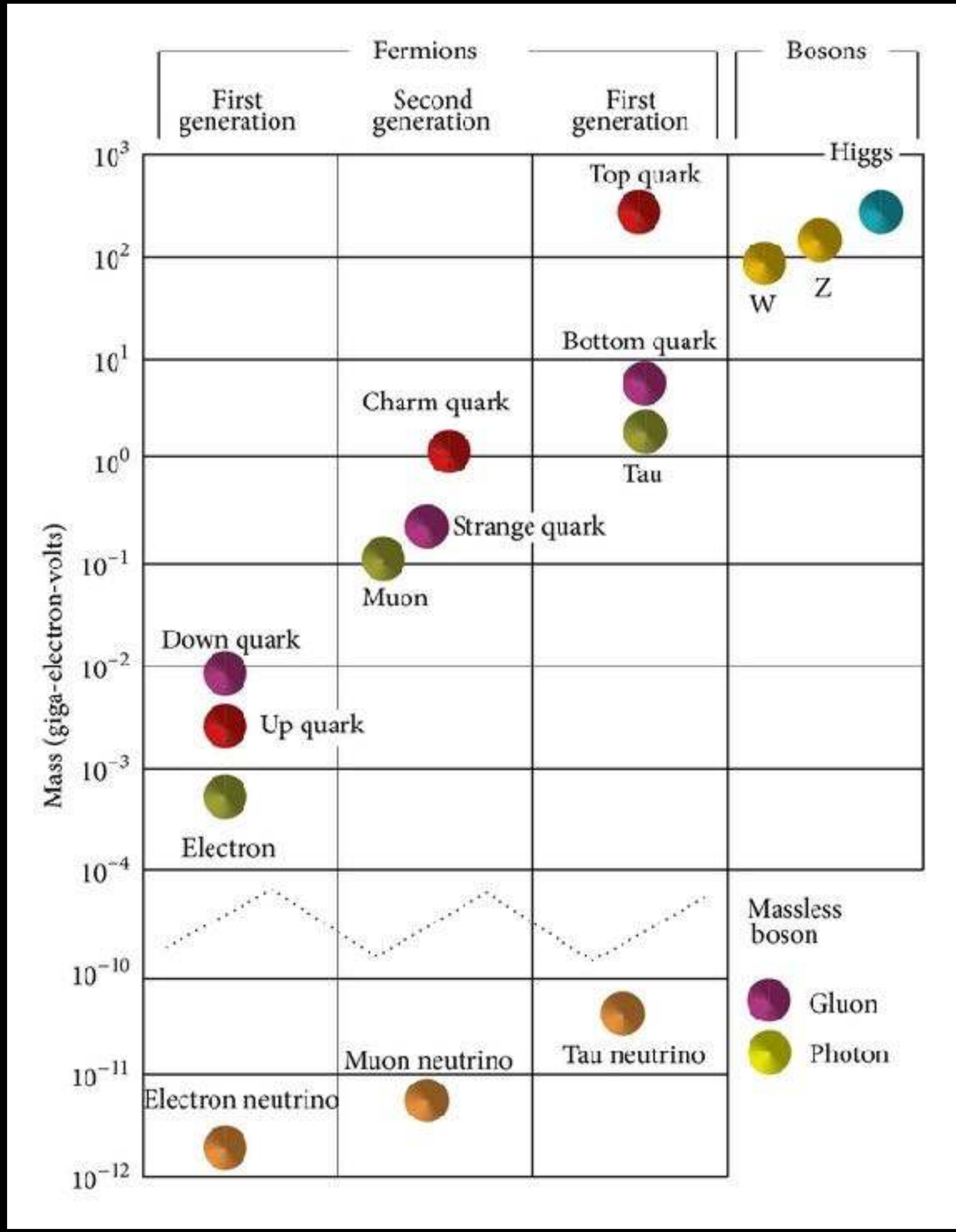
$\theta_{13} \approx 8.6°$

$\theta_{12} \approx 33.7°$

no effect on oscillations

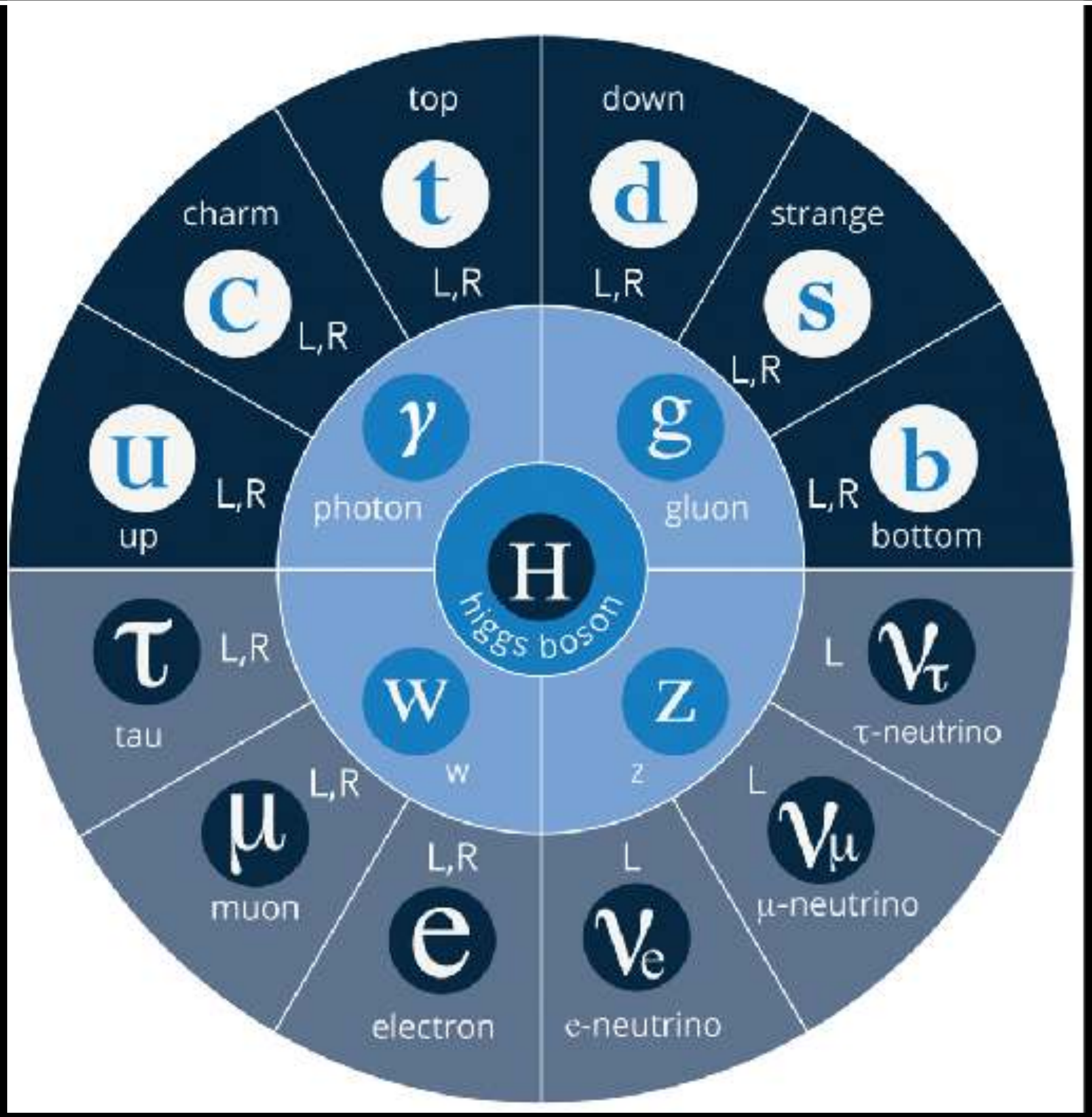
THERE IS A LARGE AND CONSISTENT AMOUNT OF EVIDENCE FOR NEUTRINO MASSES AND 3-FLAVOR MIXING FROM SOLAR, REACTOR, ATMOSPHERIC AND BEAM NEUTRINOS

WHAT WE KNOW AND DON'T



Very, very small masses.
Why so small? Due to Higgs or See-saw?

Coupled to e, μ, τ via charged weak interactions.
Flavor mixing (oscillations) due to non-zero mass.
Are oscillations the same for neutrinos and antineutrinos?



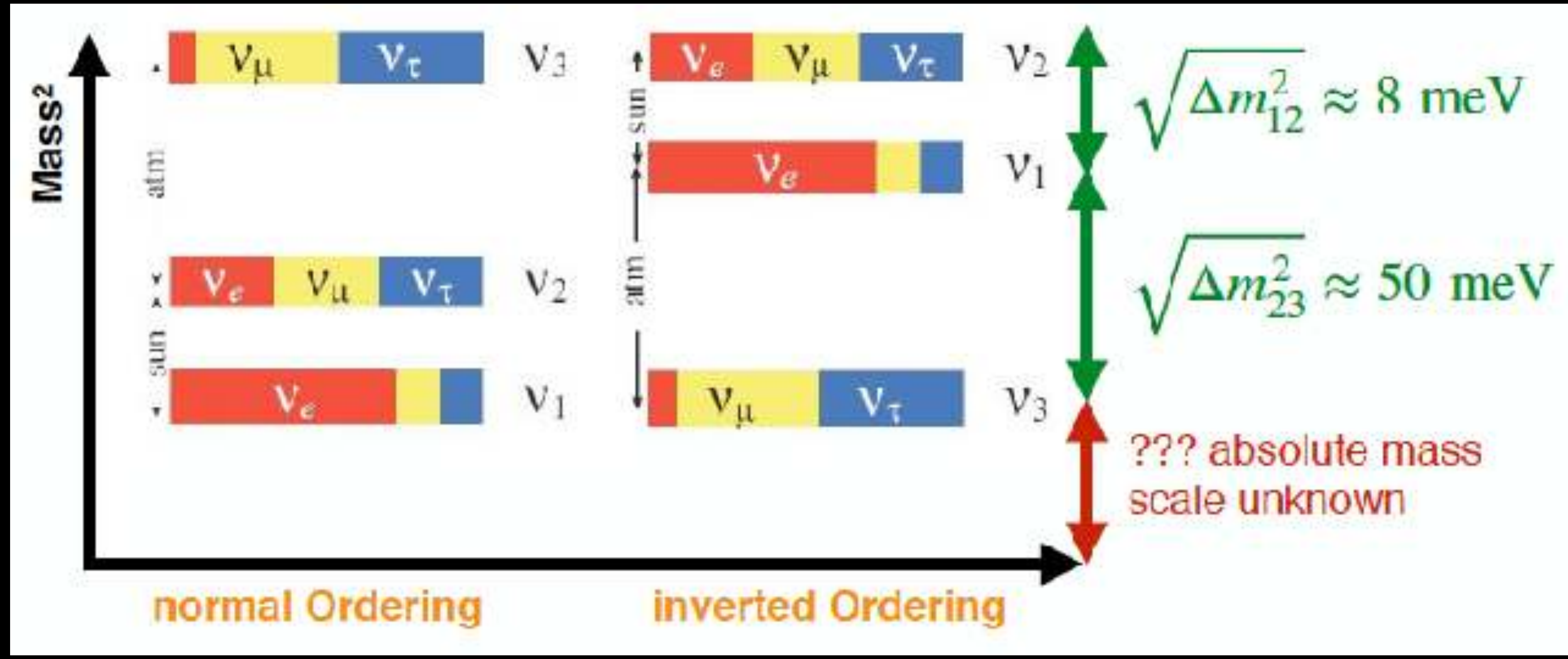
The only neutral elementary fermion.
Can it be its own antiparticle?

Neutrino abundance in the Universe similar to photons (10^9 x baryons)
What role did they play in Big Bang?
Matter/antimatter asymetry?

THE NEXT BIG QUESTIONS ?

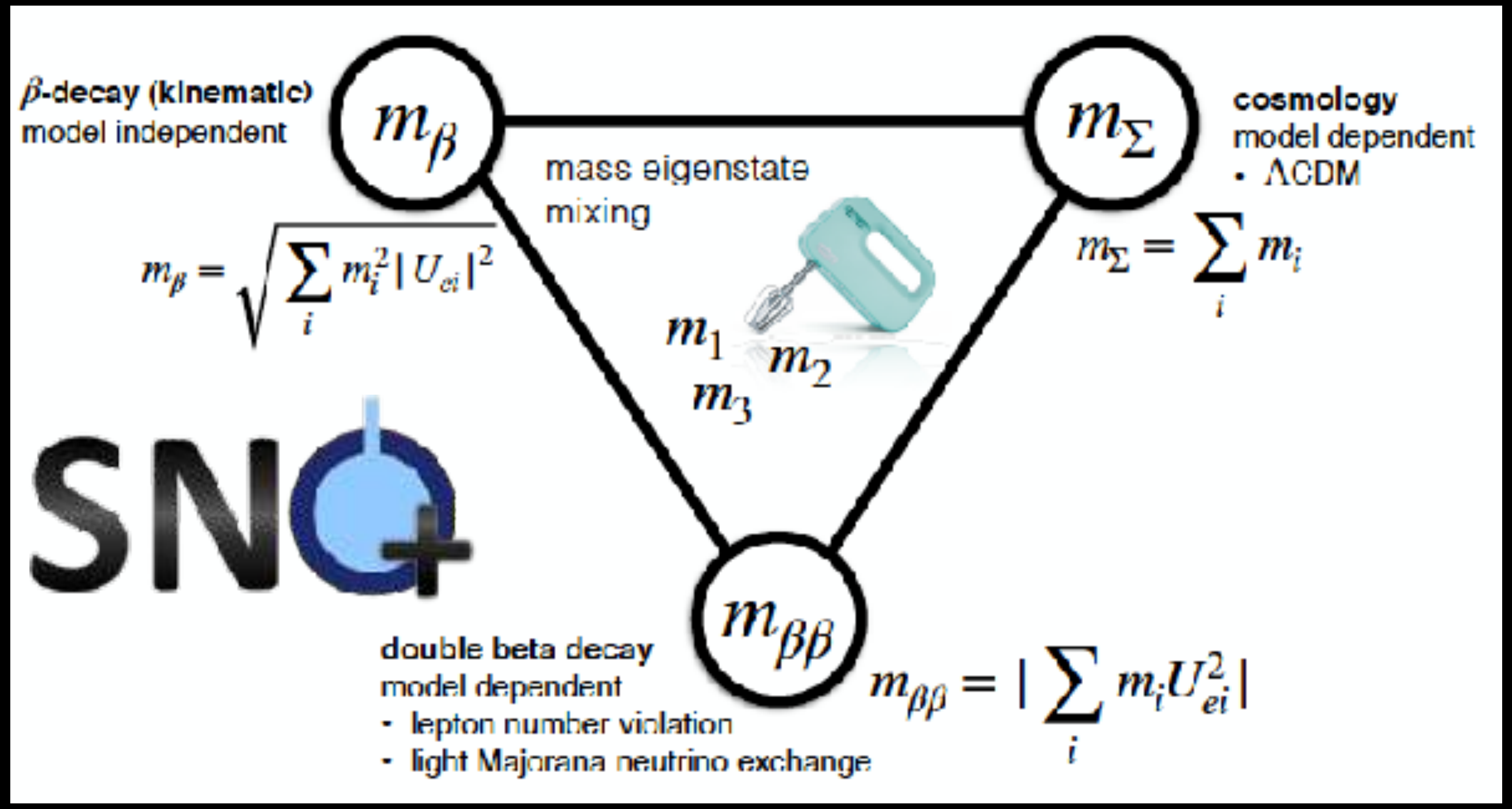
What is the ordering of the neutrino masses?

matter effects in oscillations @DUNE

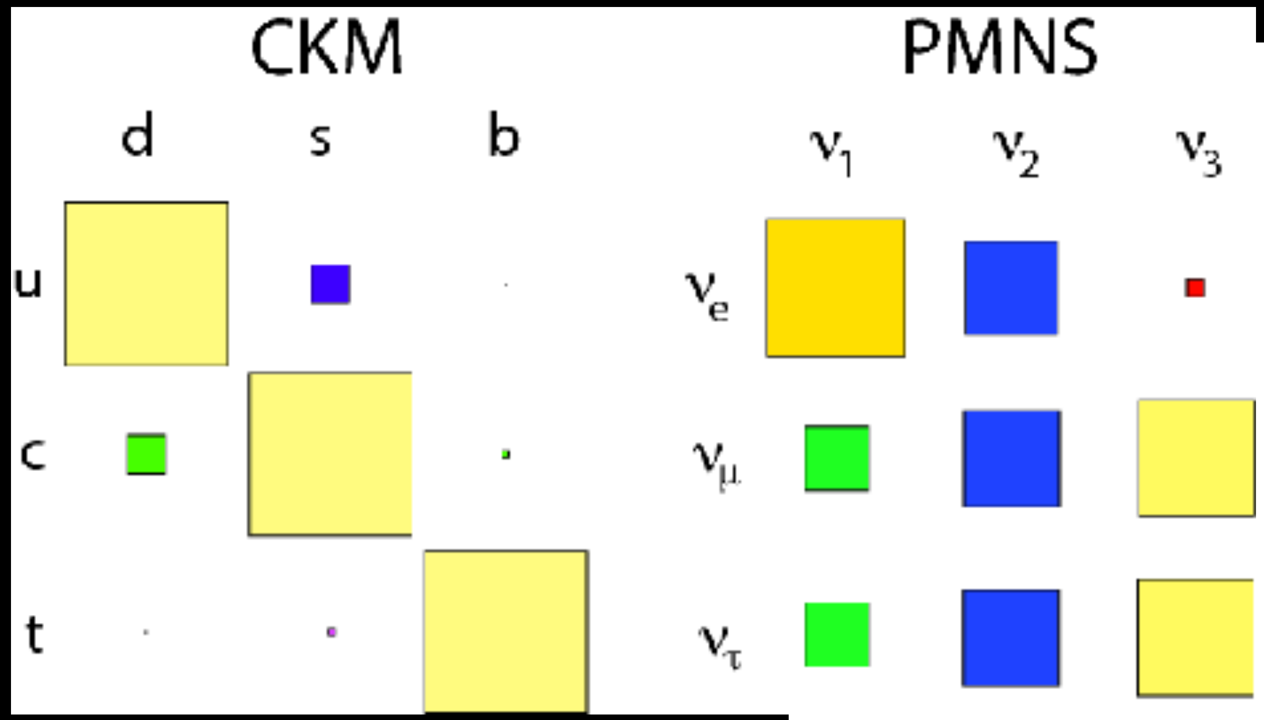


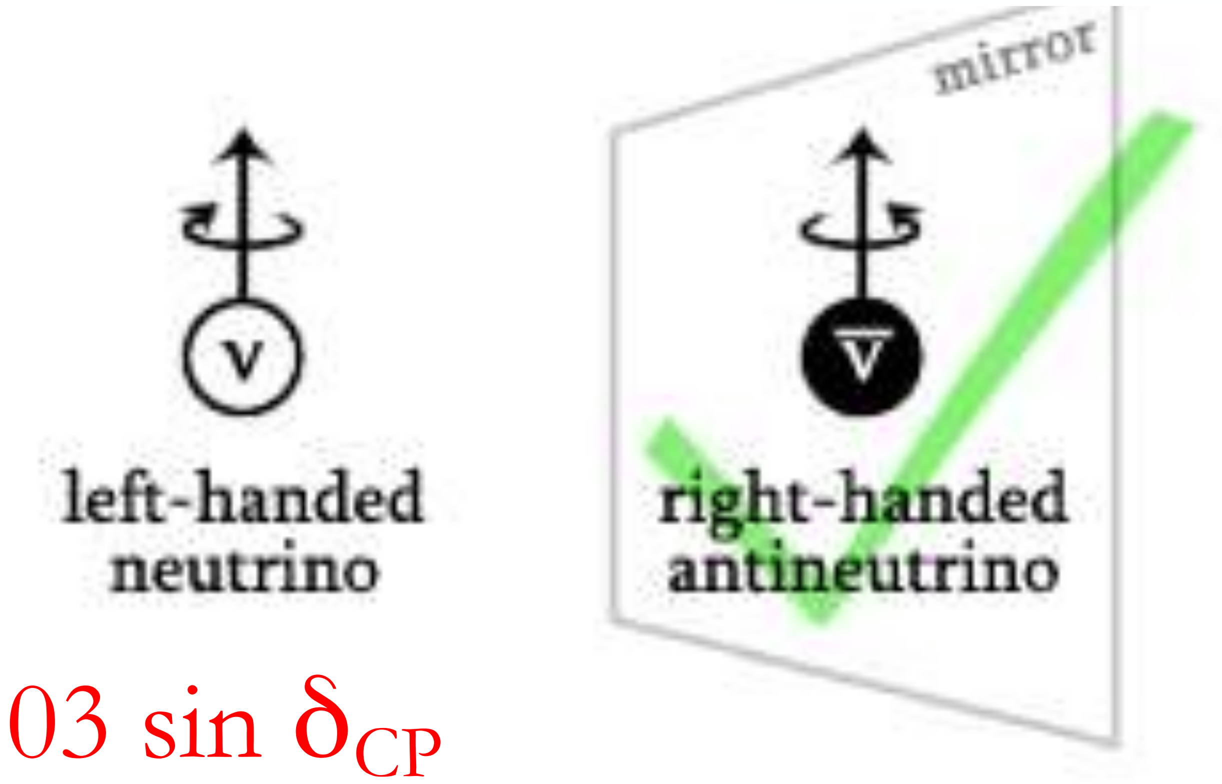
Are neutrinos Majorana? What is the effective $m_{\beta\beta}$?

Many upcoming Neutrino-less Double Beta Decay Experiments (SNO+, …)



$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$





$J_{quarks} = 3\text{x}10^{-5}$ $J_{leptons} = 0.03 \sin \delta_{CP}$

Is the PMNS matrix unitary?

Is there CP violation in leptons? Is it enough to explain the dominance of matter?

precision oscillations

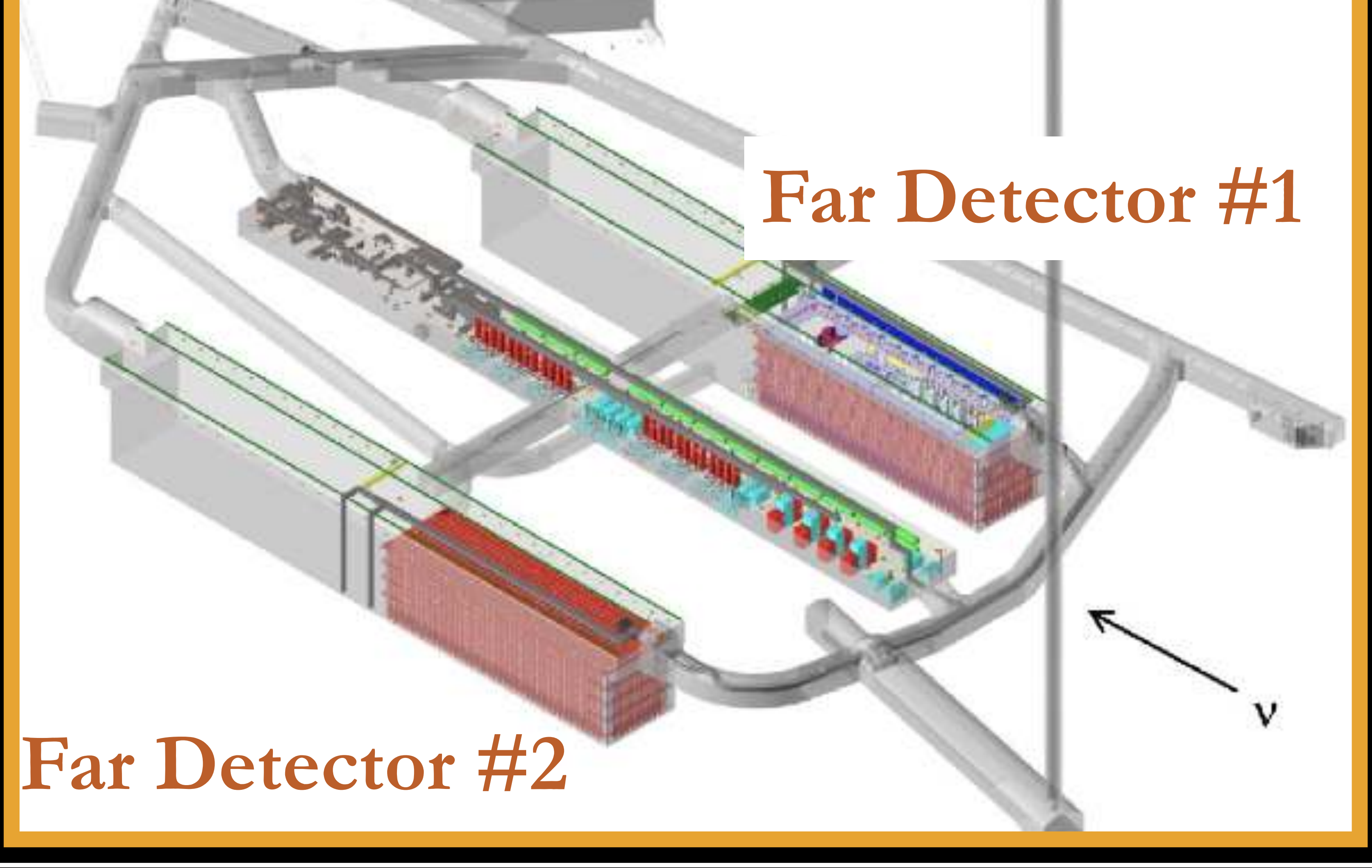
ν vs anti-ν @DUNE

DUNE

DUNE OVERVIEW

Near detector Movable LAr + GAr tracker + beam monitor

Beamline Powerful new proton injector

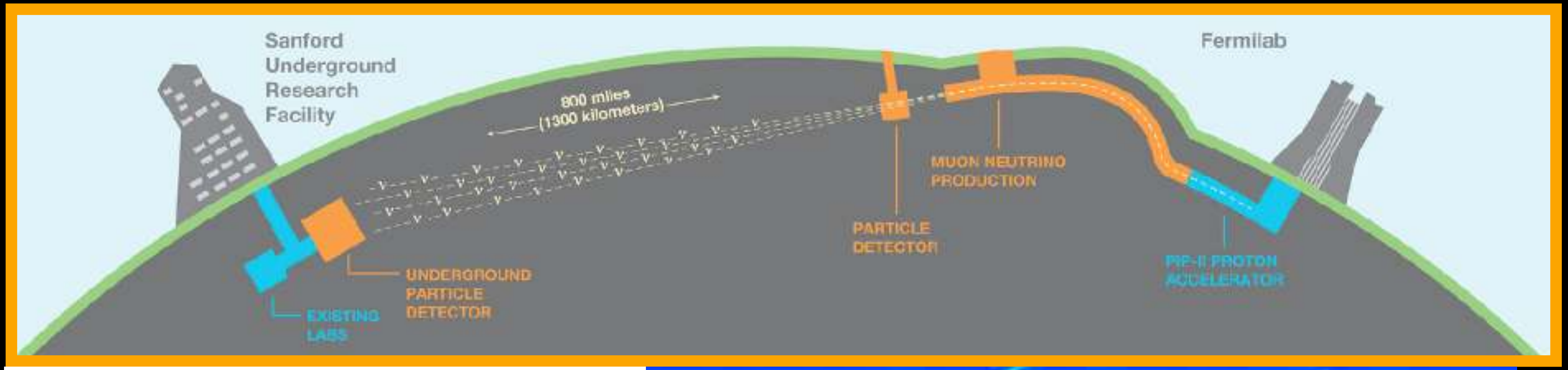


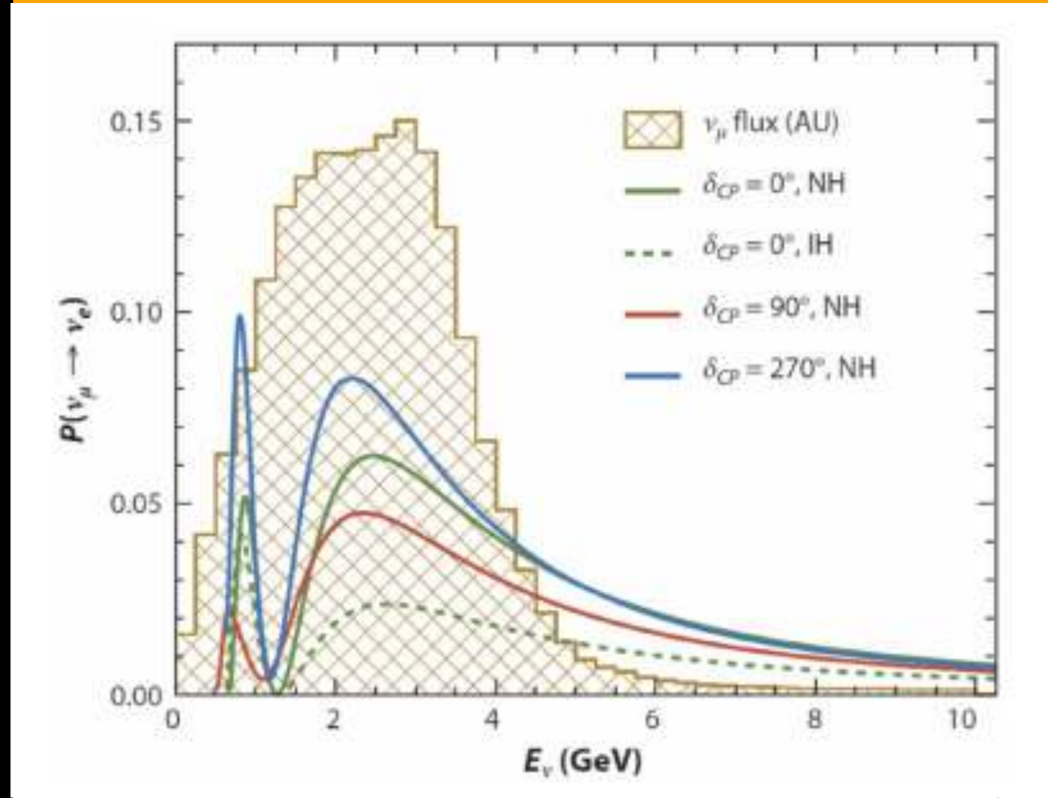
Far Detector #1

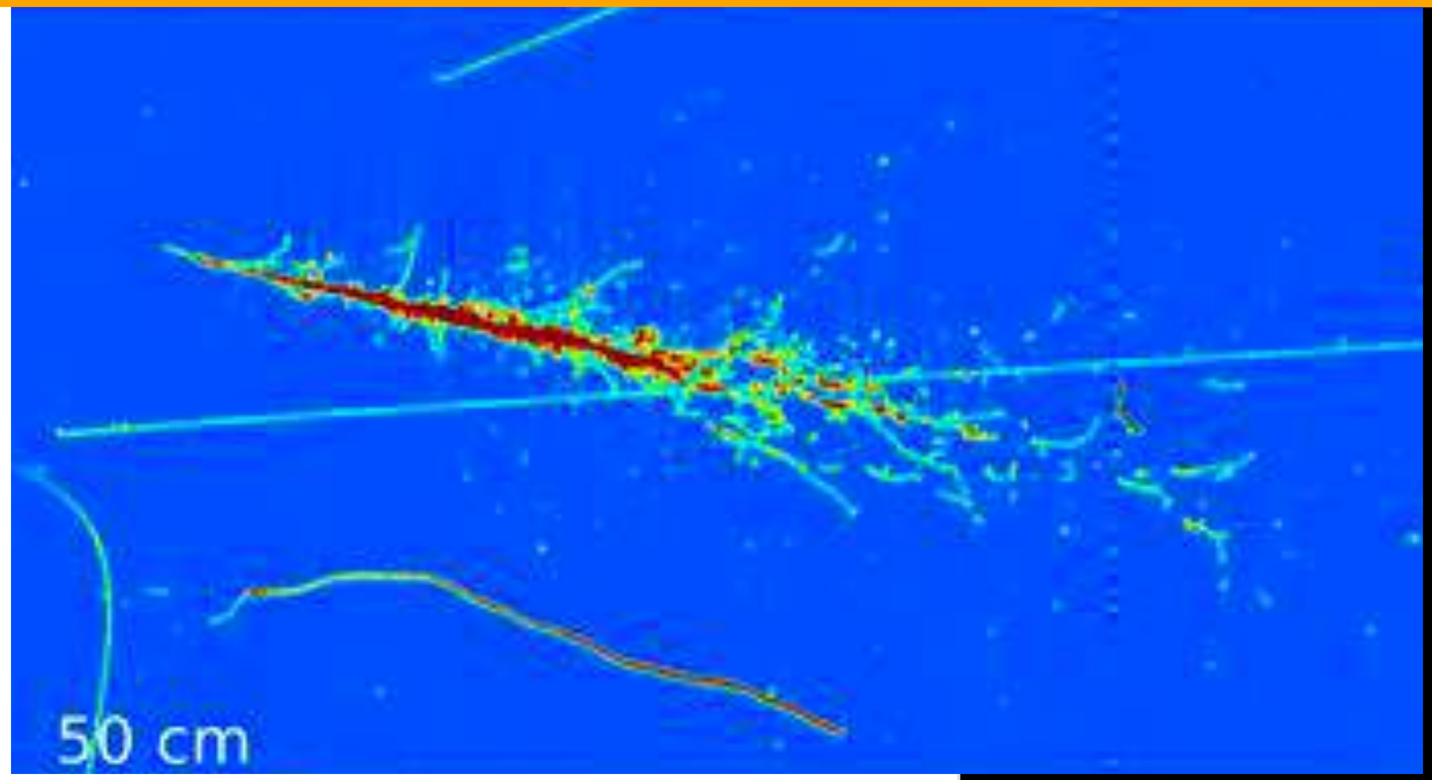
Far Detector #2

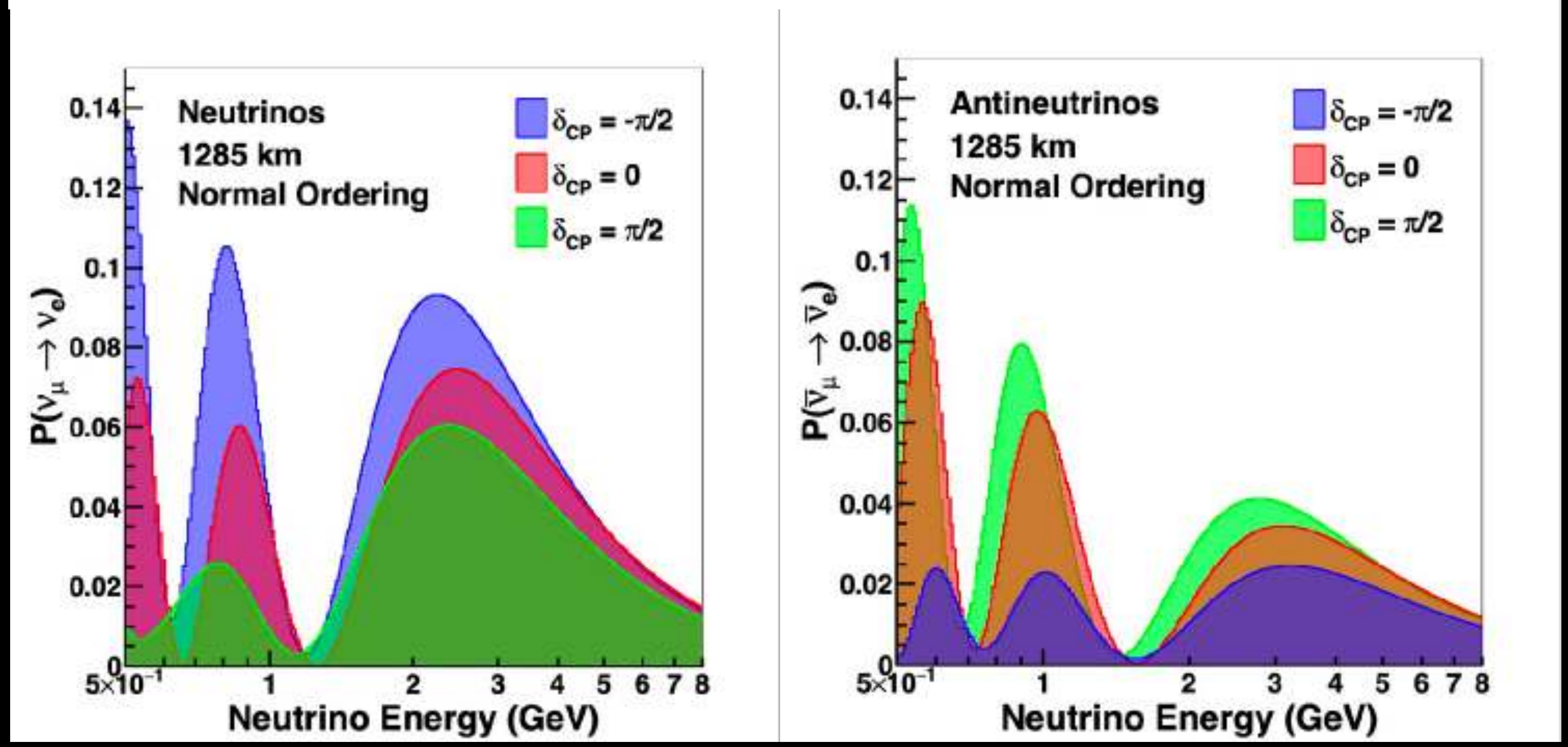
- Fermilab makes intense, wideband, ν_μ and $\bar{\nu}_\mu$ beams
- Near Detector characterizes cross sections, beam flux, energy
- Beams reach Sanford lab, 1285 km away, 1.5 km underground
- 70 kt Far Detector, divided in 4 modules, at least 3 of which use LArTPC technology

DUNE APPROACH







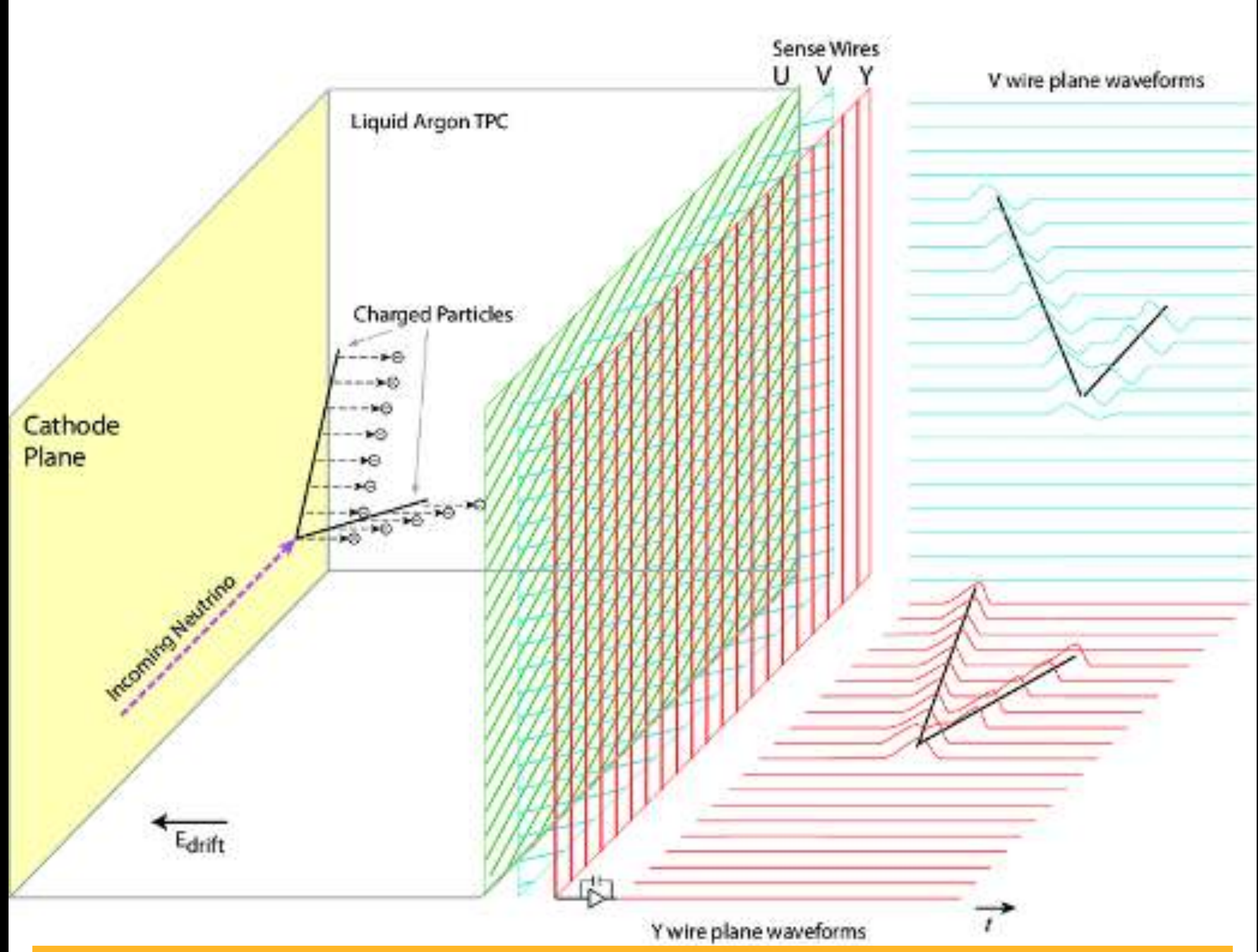


- DUNE has a unique approach
  - wide energy → measure oscillations over >1 full period
  - long baseline → sensitive to mass order
- Measure everything in one experiment

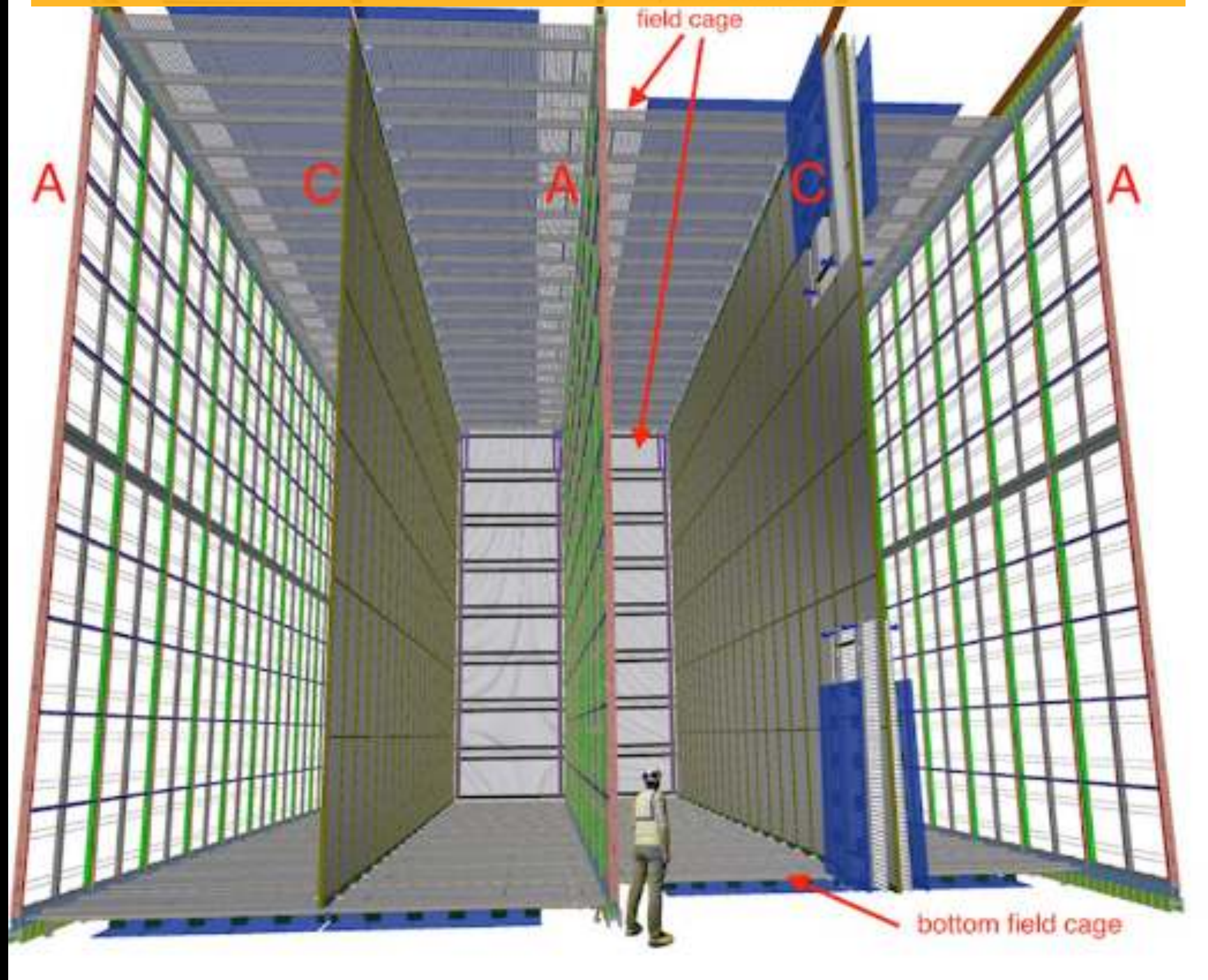
- Many advantages (over HK)
  - Robust to parameter degeneracies
  - Better long-term precision
  - Much better sensitivity to new physics in neutrino oscillations

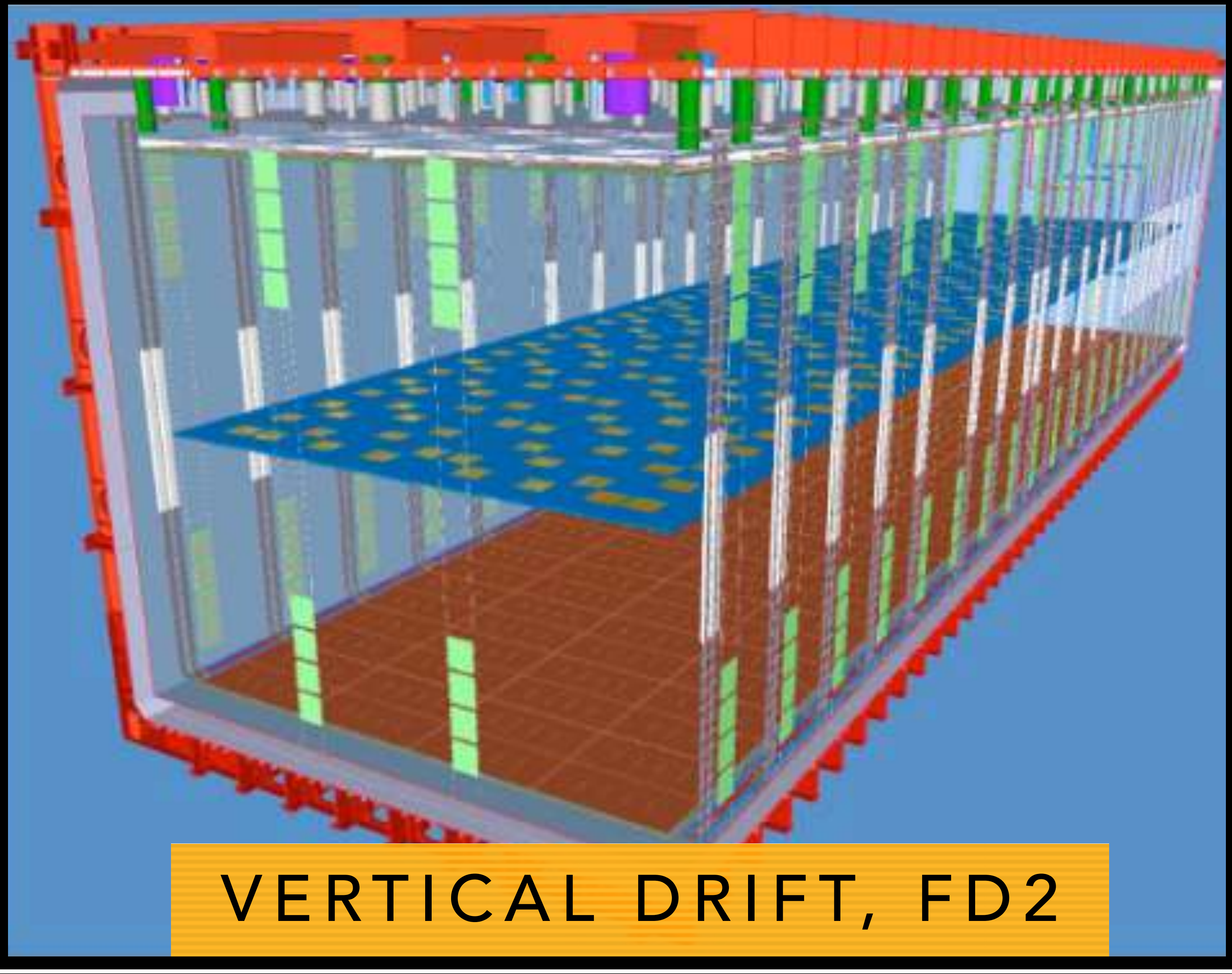
LIQUID ARGON TPC

- LAr Time Projection Chambers
  - Technology invented by Carlo Rubbia at CERN
  - Main developers at large scale: ICARUS, MicroBooNE
- Detection capabilities
  - Precision tracking (5 mm wire pitch)
  - Detects all charges → full calorimetry
  - Full event (ν ID and energy) reconstruction



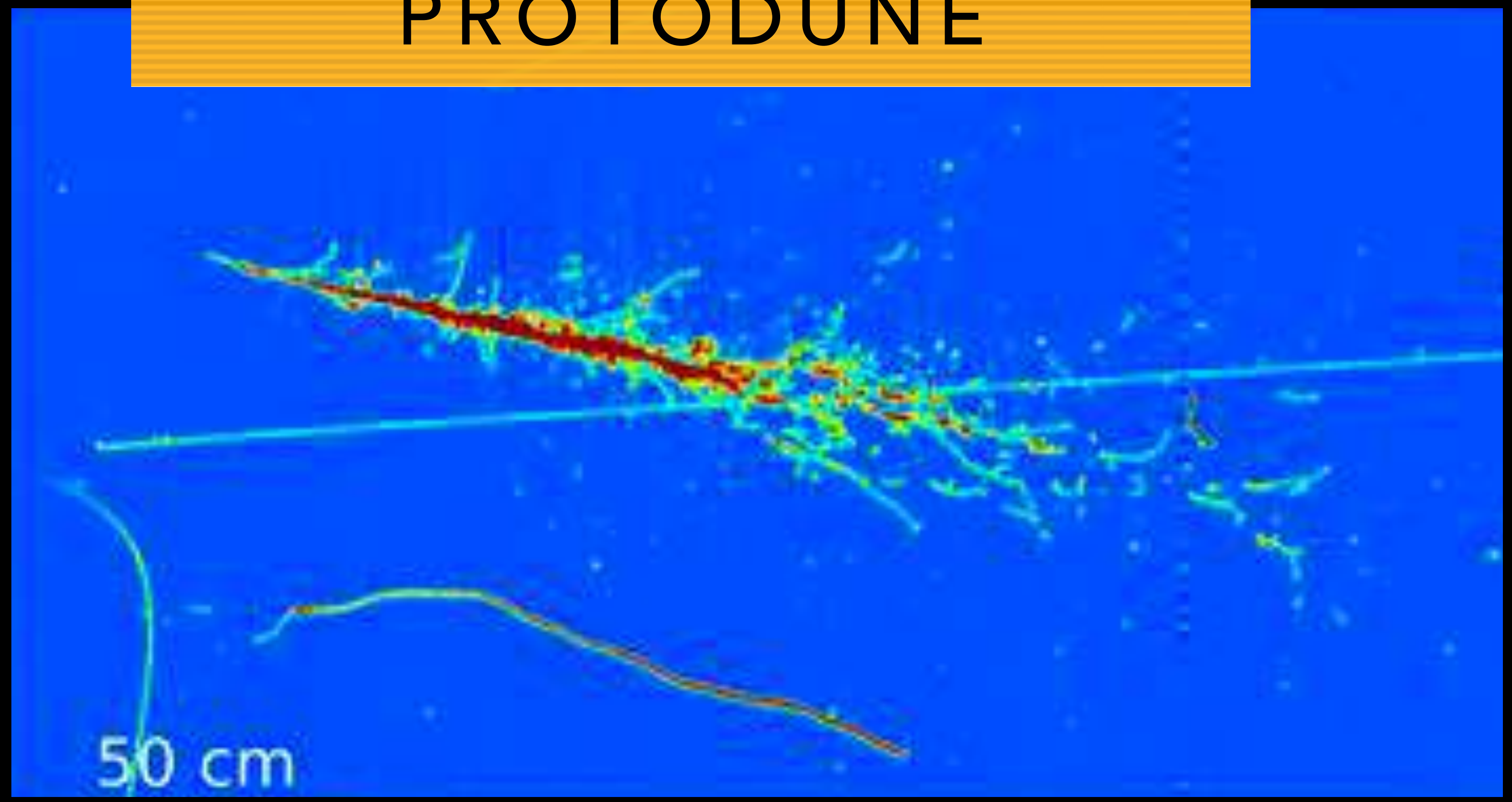
HORIZONTAL DRIFT, FD1





VERTICAL DRIFT, FD2

6 GEV POSITRON, PROTODUNE



PORTUGAL IN DUNE

PORTUGUESE DUNE GROUP

Senior Researchers

Sofia Andringa

Fernando Barão

Nuno Barros

Amélia Maio

José Maneira

Francisco Neves

Vladimir Solovov

Cristóvão Vilela

Students

Wallison Campanelli

Joana Vences

Leonor Gonçalves

- All LIP members
- Other experiments we participate on (listed alphabetically):
  - AMS, ATLAS, LZ, SND@LHC, SNO+, SWGO, XLZD

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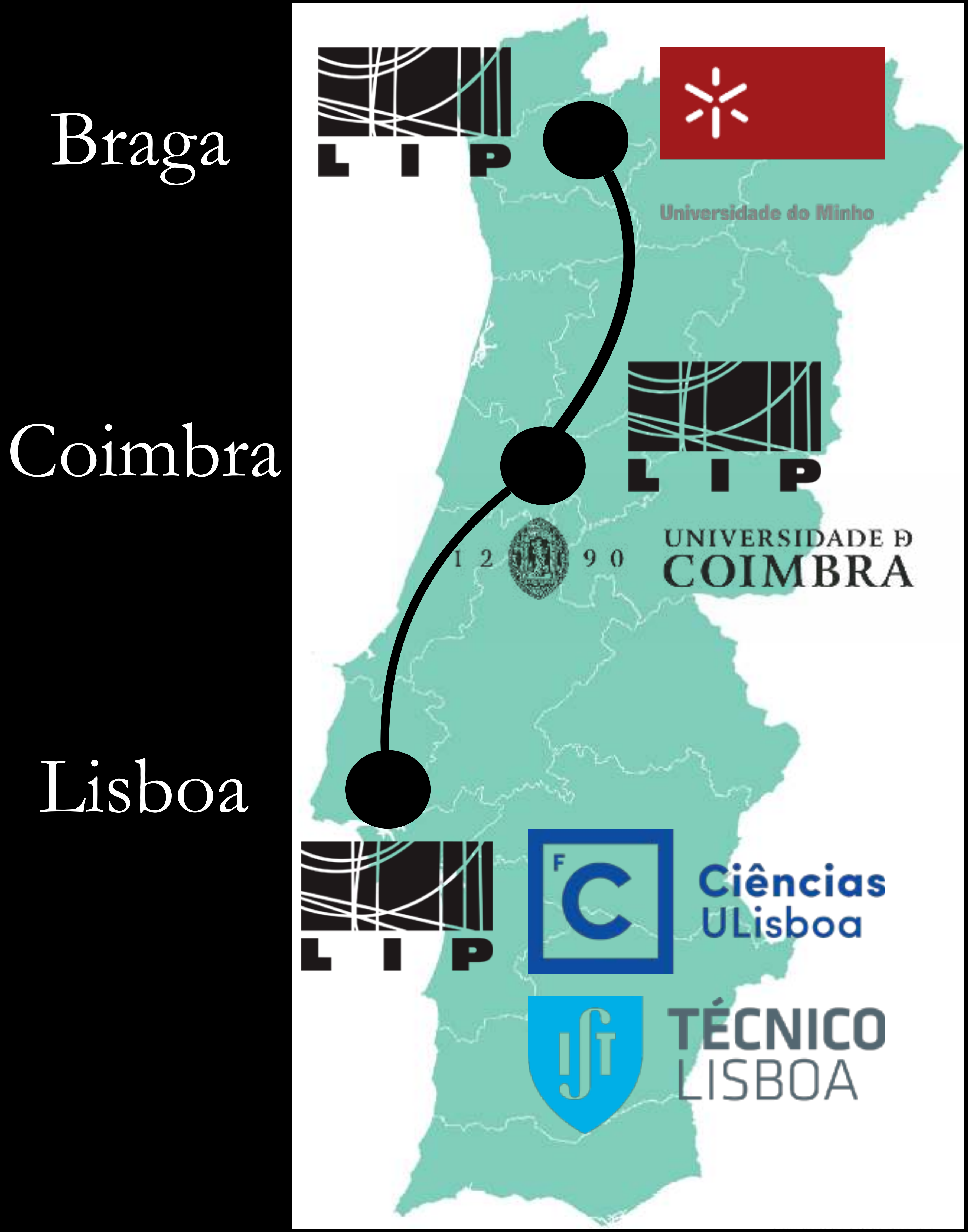
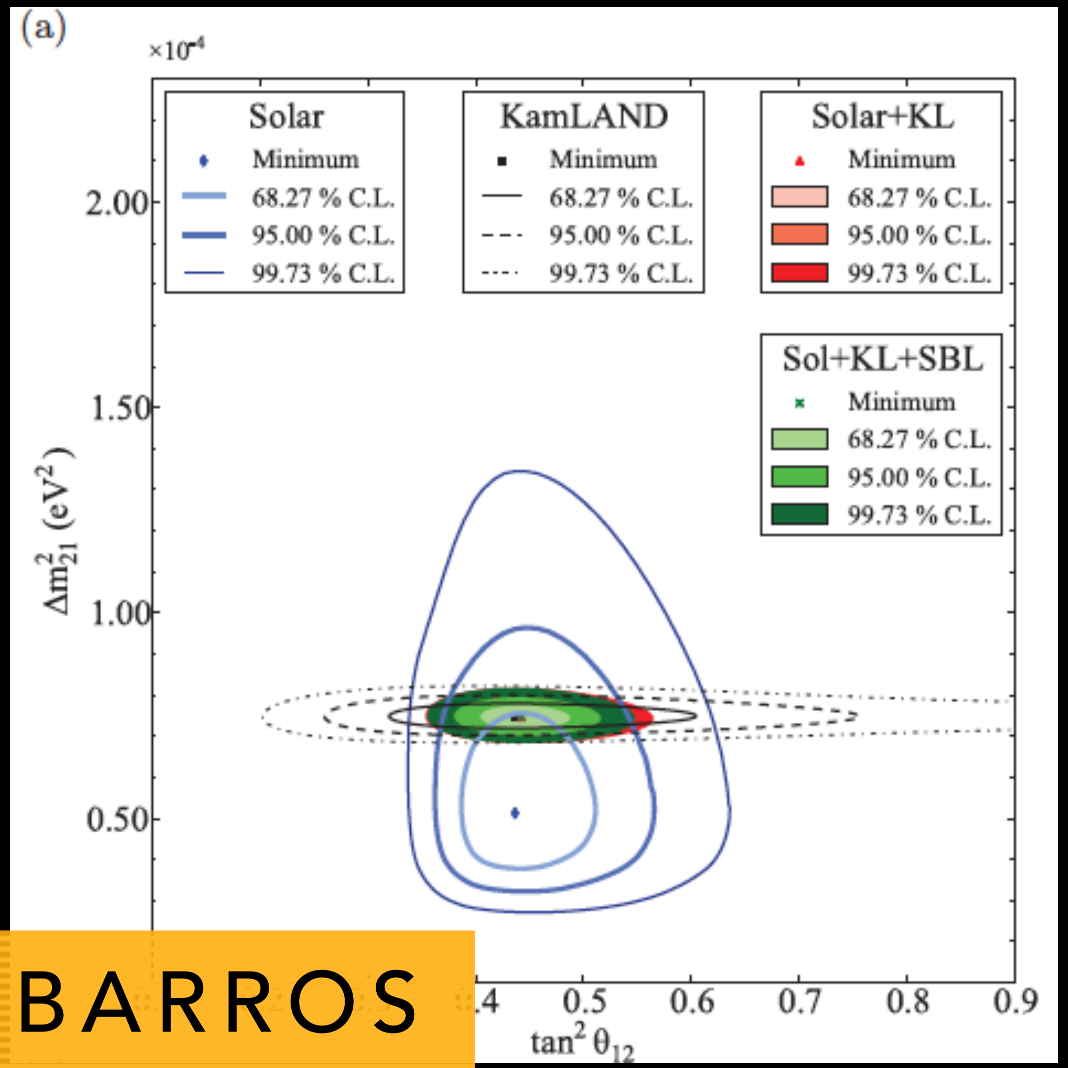


LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

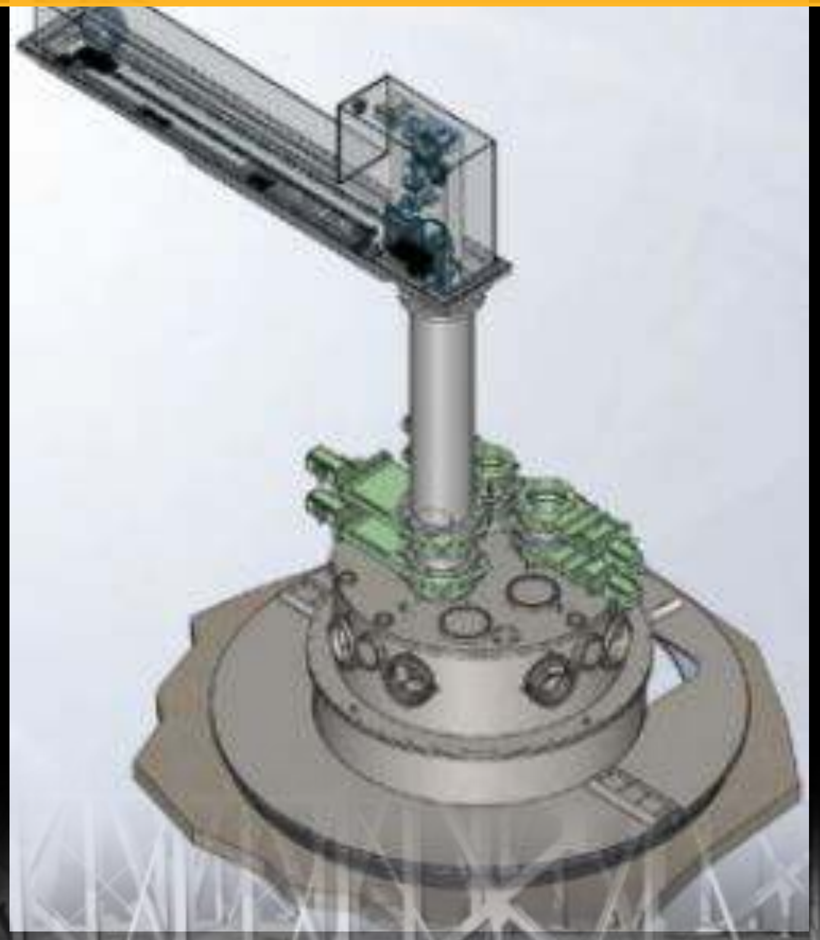
- LIP is the single portuguese institute participating in DUNE
  - coordination, institutional representation, researchers, technicians, labs, computing
  - we work as a single group present in the 3 poles: Lisboa, Coimbra and Braga
  - close connection to the local universities, where some of us are professors, and the students are enrolled

HOW WE JOINED DUNE

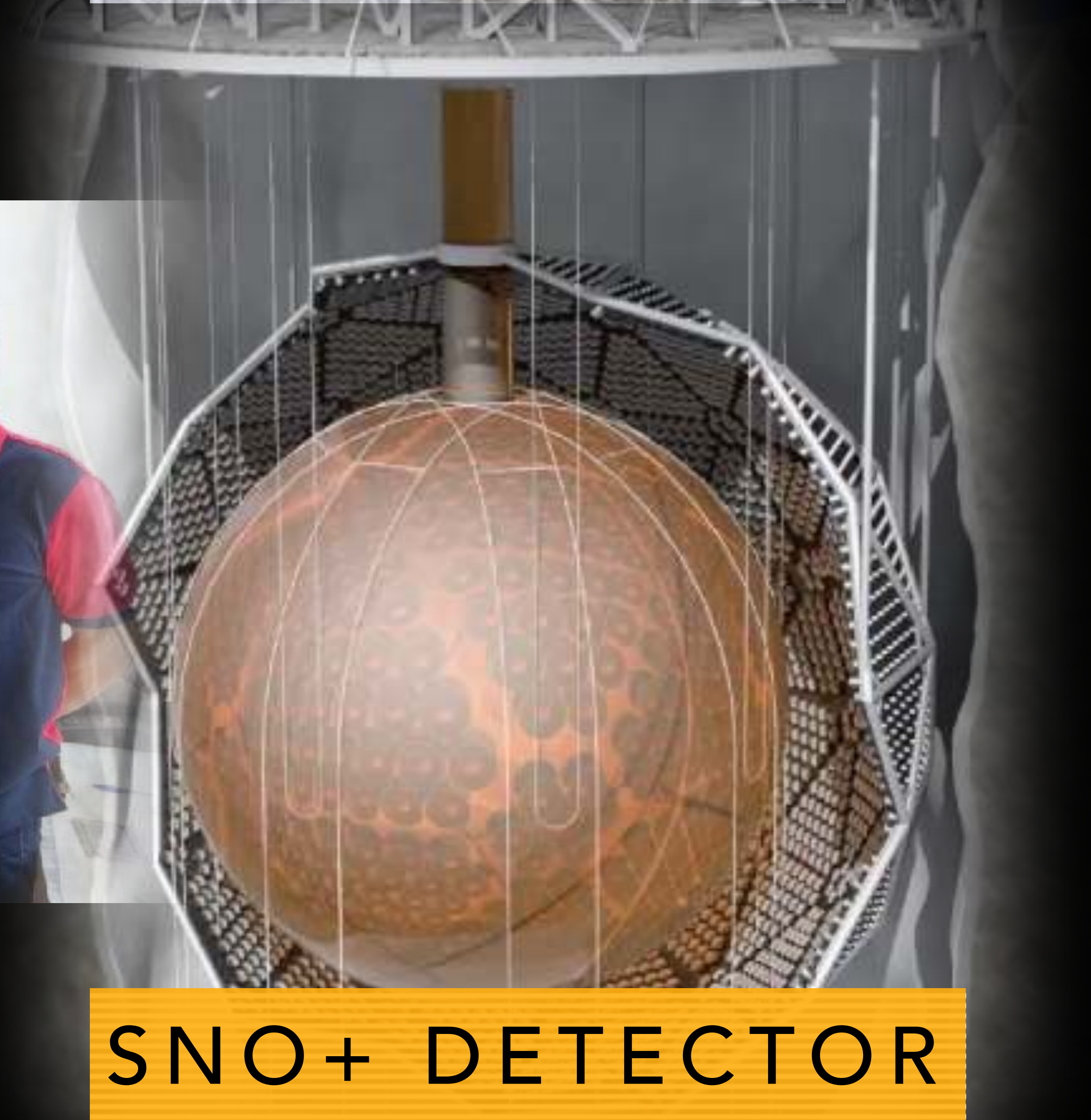


N. BARROS PHD THESIS

CALIBRATION SYSTEM



ART MCDONALD (2015 NOBEL) VISIT



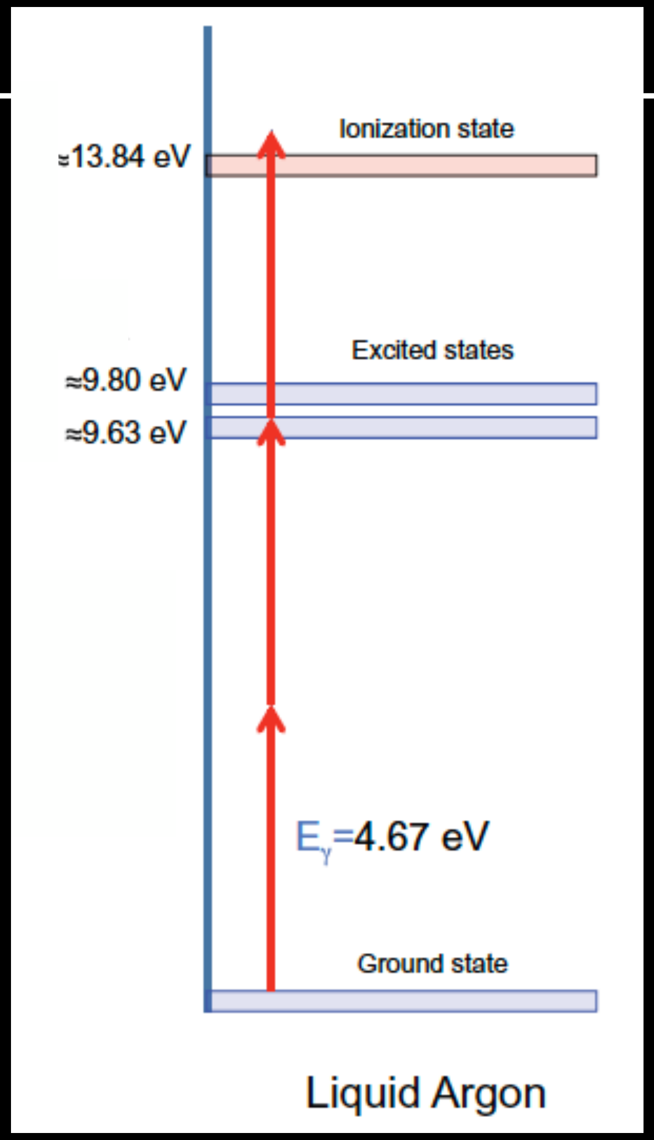
SNO+ DETECTOR

- LIP joined SNO (Sudbury Neutrino Observatory) in 2005
  - Optical calibration and neutrino oscillations analysis
- LIP was a founding member of the successor experiment, SNO+, in 2007
  - Construction of two different calibration systems, both working at SNOLAB
  - One of the largest groups, many responsibilities in data analysis
- We applied to join DUNE in 2018
  - CERN connection was a strong motivation
  - Our track record in SNO+ opened many doors and led to our leadership of the DUNE Calibration and Cryogenic Instrumentation Consortium

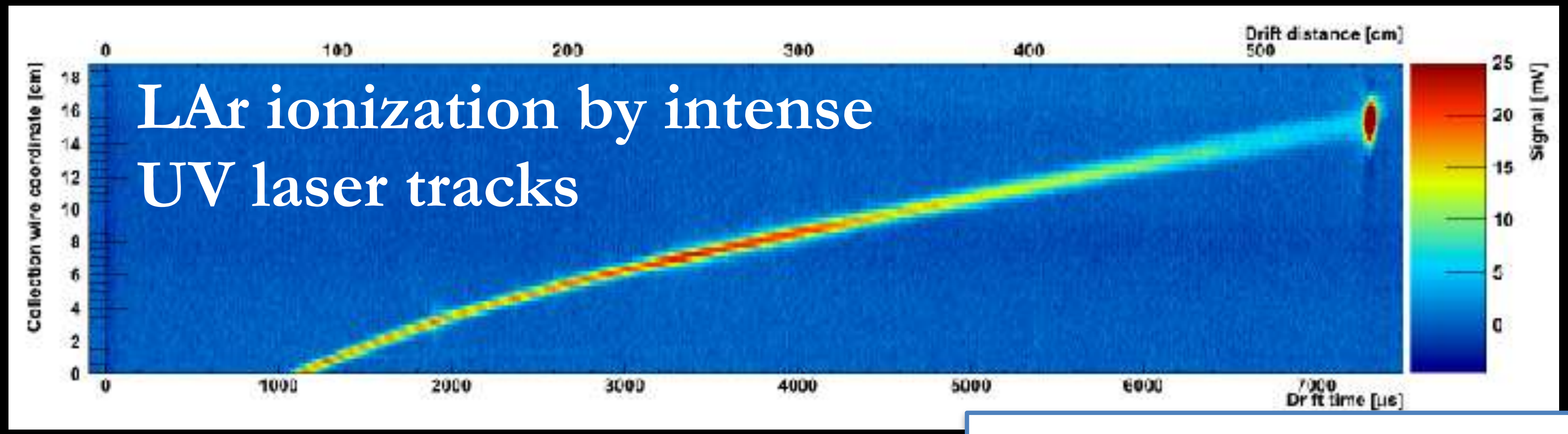
CALIBRATION SYSTEMS FOR PROTODUNE AT CERN

IONIZATION TRACKS WITH LASER

- Since 1980's: Lasers used to create tracks in gas detectors
  - 2-photon process ~ 1µJ/mm^2
- Higher intensity needed in liquid
  - 3-photon process ~ **500 µJ/mm^2**

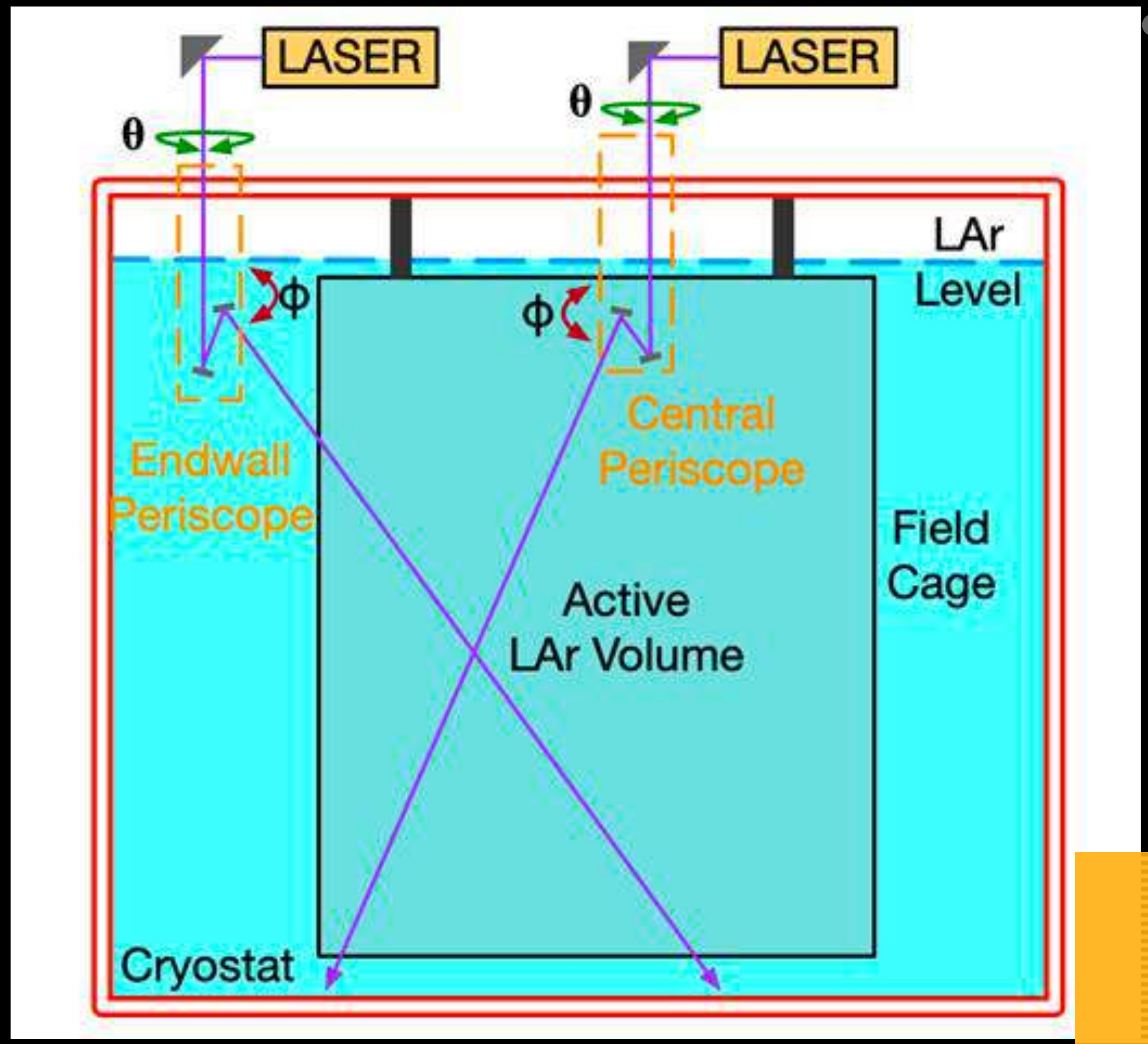


5 m long!



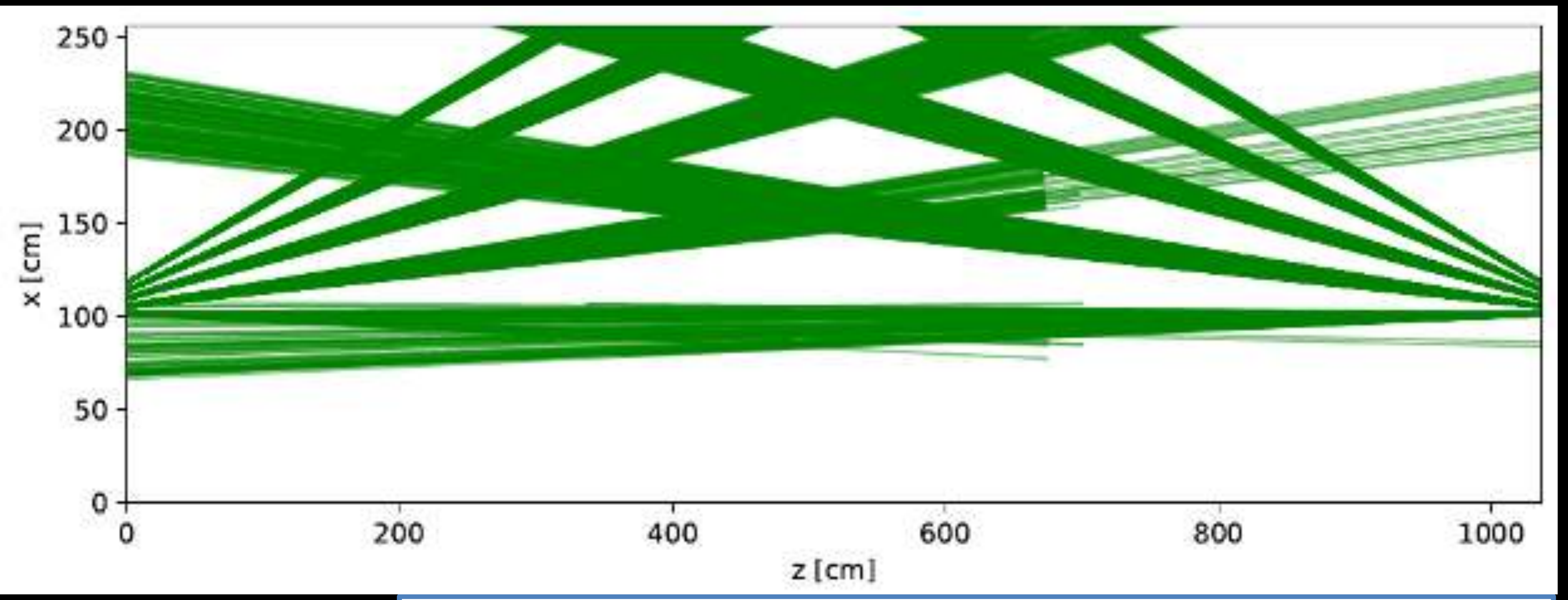
R&D @ BERN

I. Badhrees et al. 2010 *New J. Phys.* **12** 113024



- Basic concept
  - Intense (60 mJ) UV(266 nm) laser
  - Steerable cold mirrors in inverted periscopes
  - Compare true and reconstructed track → MicroBooNE measured E-field distortions with 2% precision

10 m

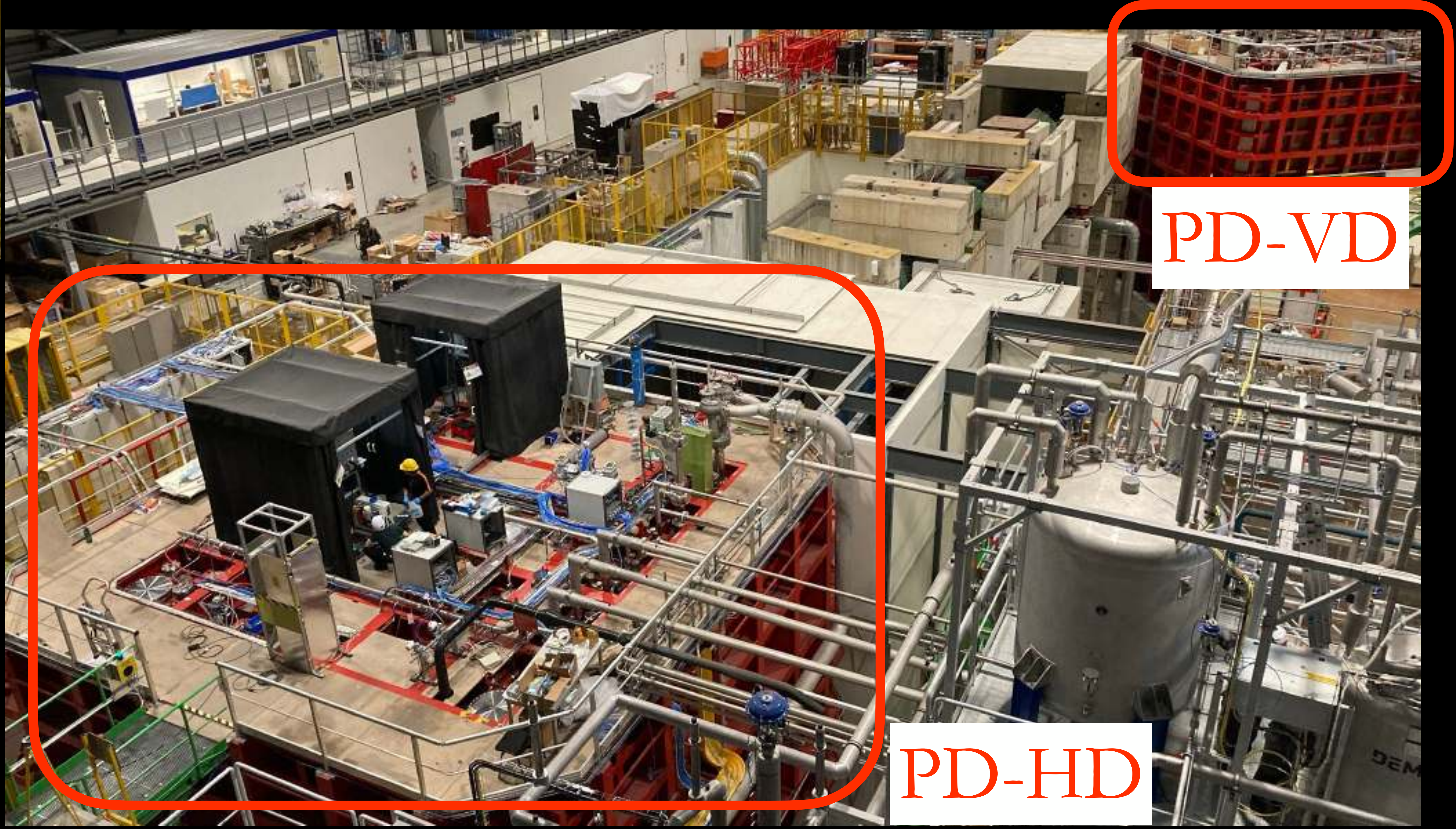


C. Adams et al 2020 JINST 15 P07010

SYSTEM FOR DUNE BASED ON MICROBOONE @ FNAL BUT BIGGER!

PROTODUNE(S) @ CERN

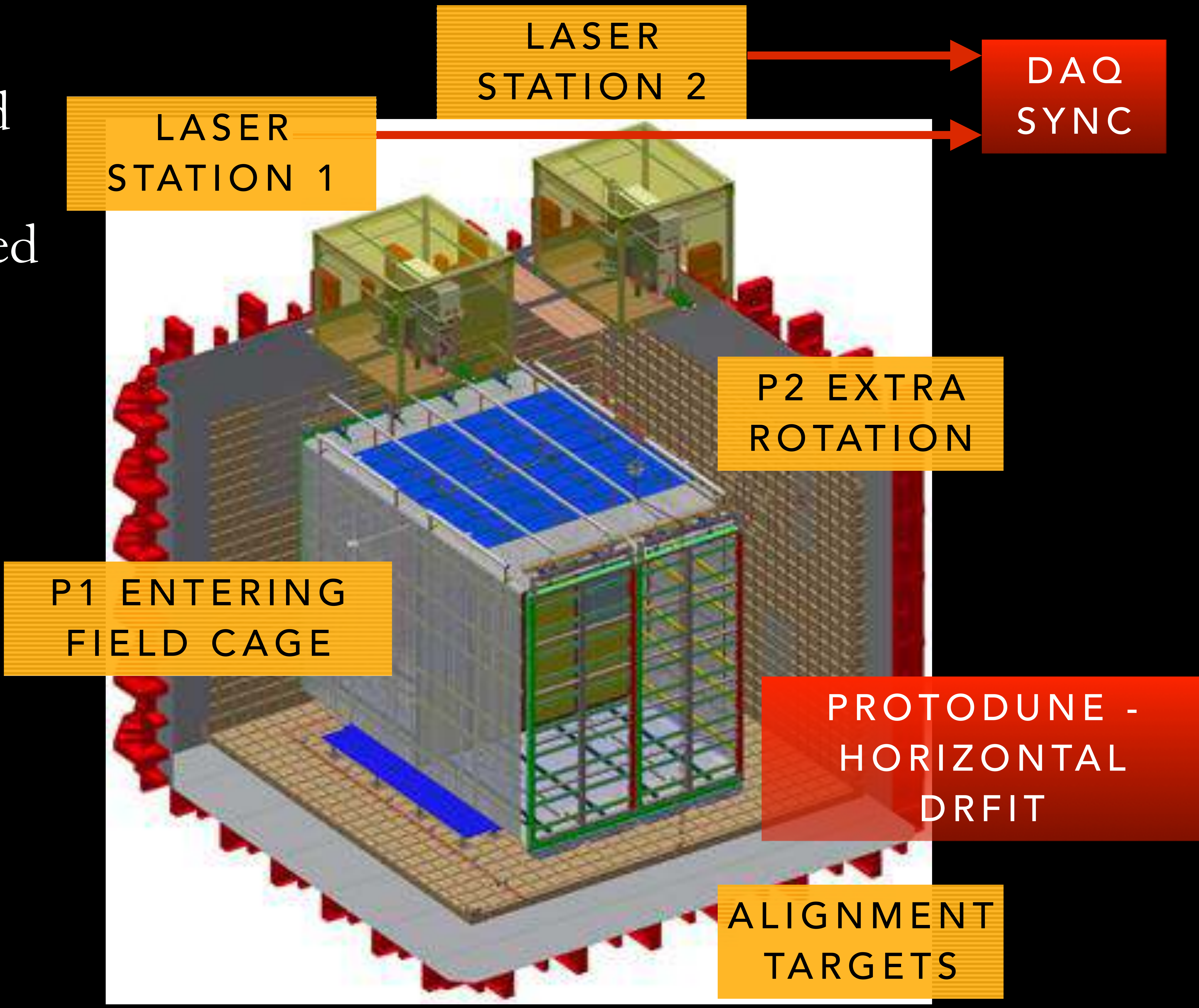
- Neutrino Platform at CERN
  - New (~2015) large experimental area
  - Beam (charged particles) from SPS
  - Infrastructure for large cryogenic detectors



- ProtoDUNEs
  - 2017-2019: Develop single phase and dual phase designs
  - 2023-2026: Test production modules of horizontal and vertical drift (both single phase)

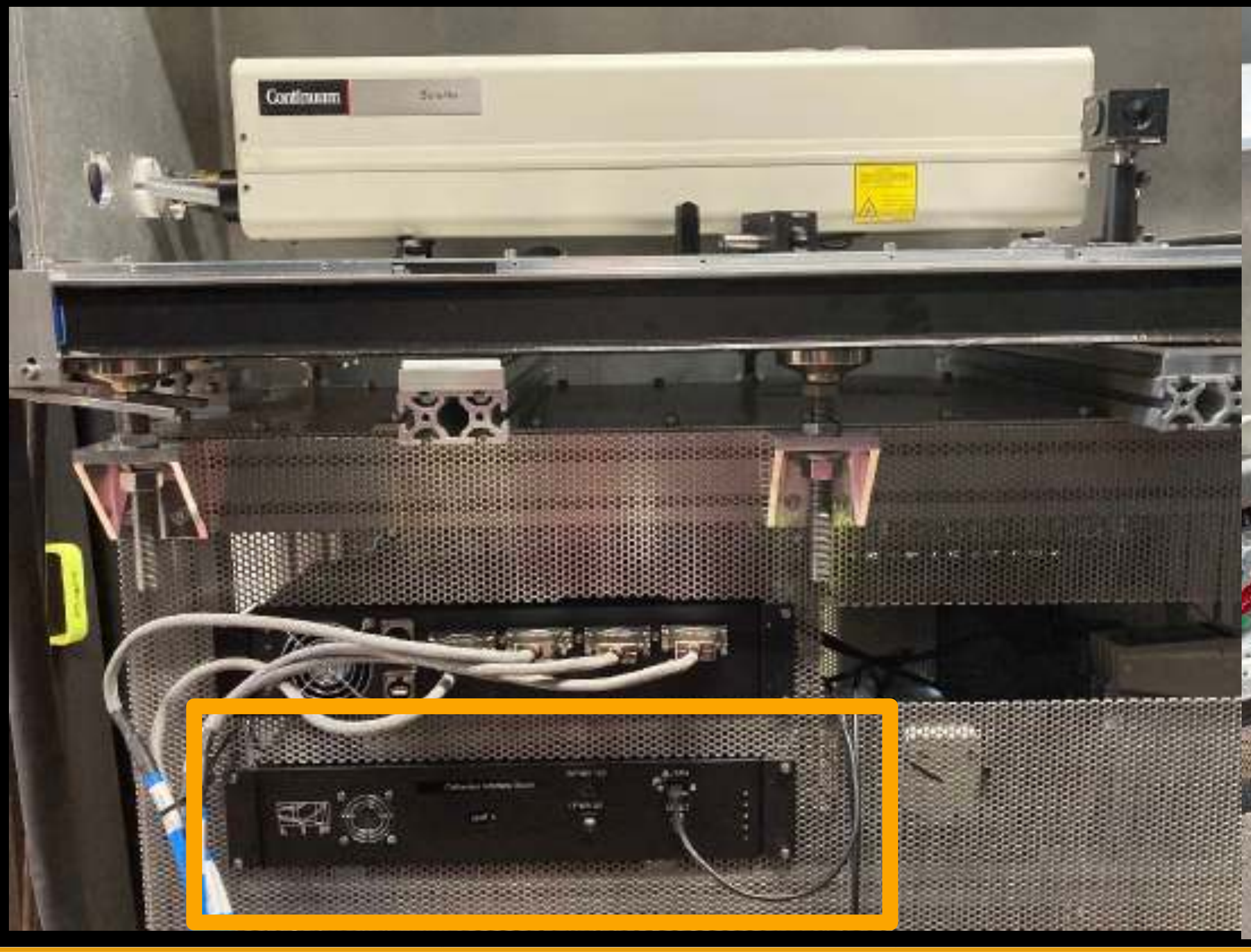
LASER CALIBRATION AT PROTODUNE

- All systems for DUNE need to be tested first in ProtoDUNE
- Laser systems designed, built and installed by the teams of LIP and Los Alamos
  - PD-HD 2024
  - PD-VD 2025 completing commissioning
- Laser system designs
  - Different periscope geometries
  - Alignment targets
  - Integration with DAQ
- Goals
  - Map space-charge distortions
  - Characterize charge collection in APAs
  - Characterize electron lifetime



SYSTEM COMPONENTS, PD-HD

Laser box + Electronics



Connections

DAQ INTERFACE ELECTRONICS

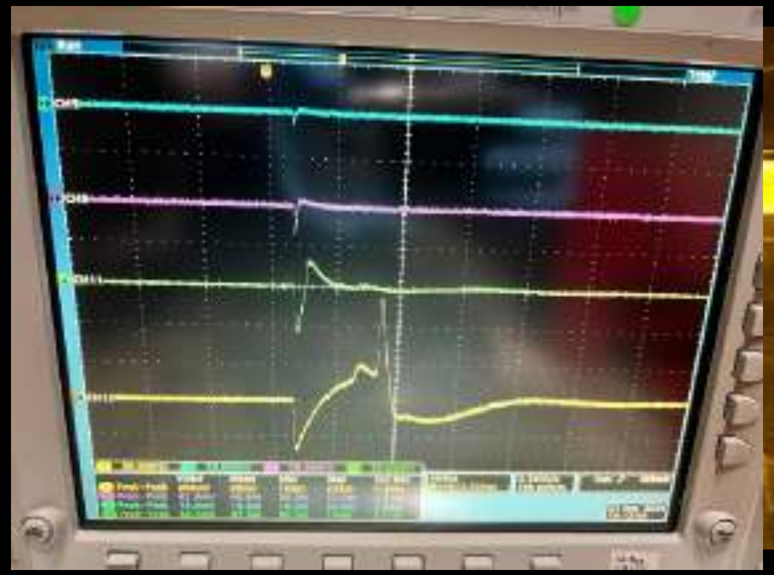
Cryostat feedthrough

Periscope

P1 enters top of field cage

P2 Outside field cage

Targets: PIN diodes



Mirror pads

DESIGN/CONSTRUCTION @LIP

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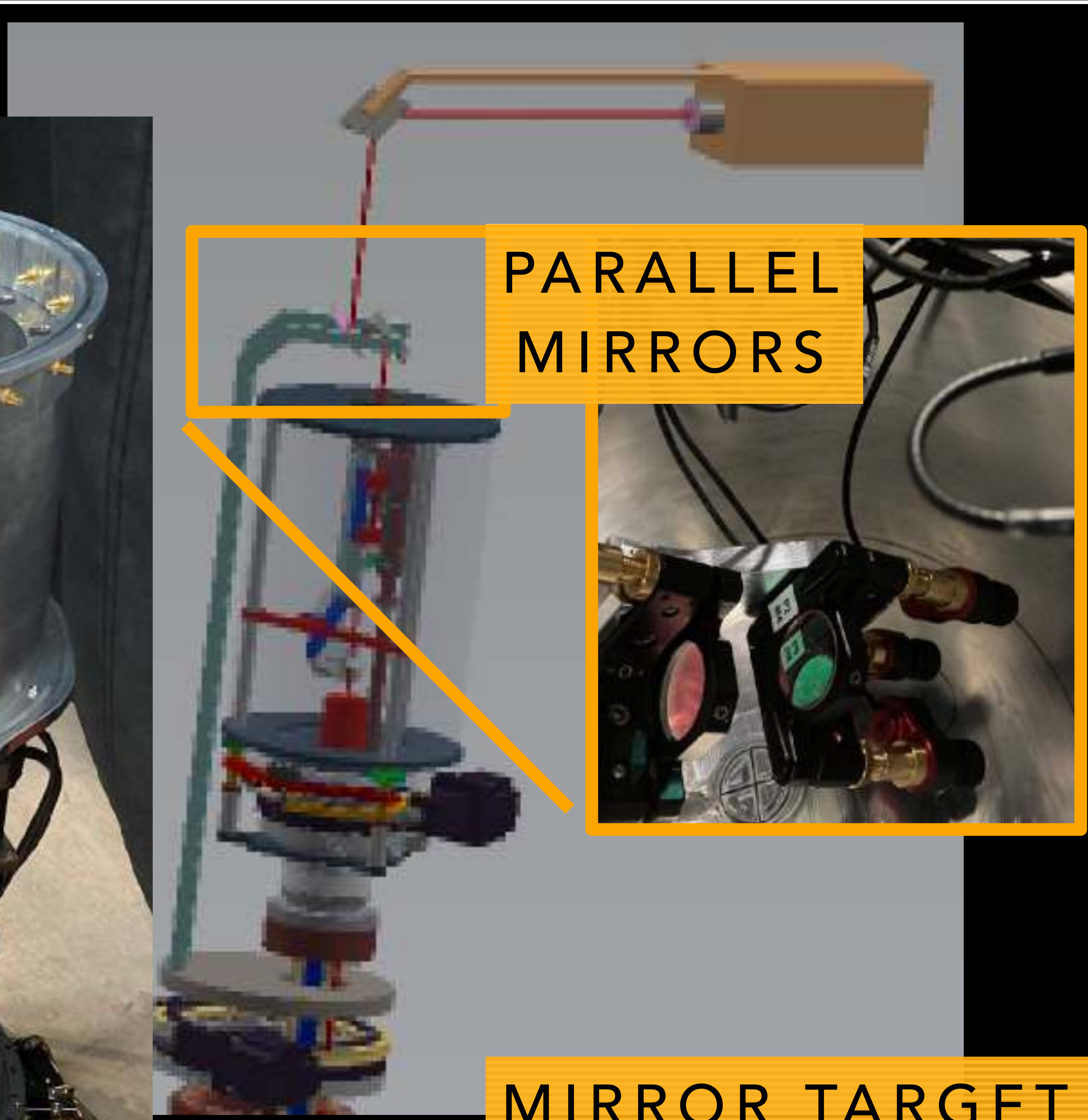
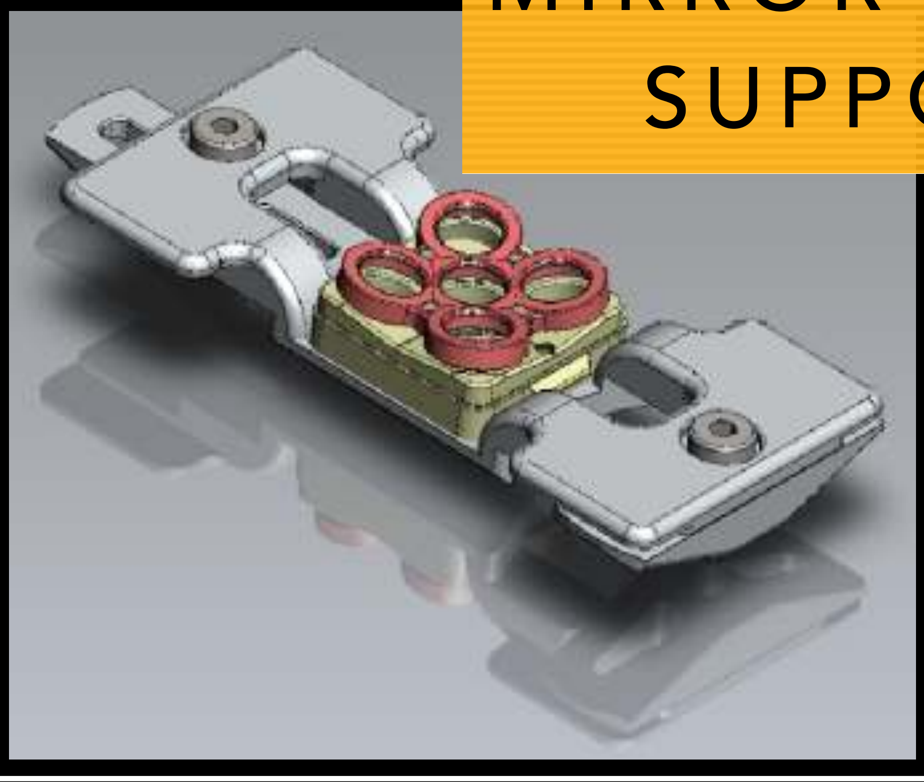
PERISCOPE 2

DUAL ROTATION

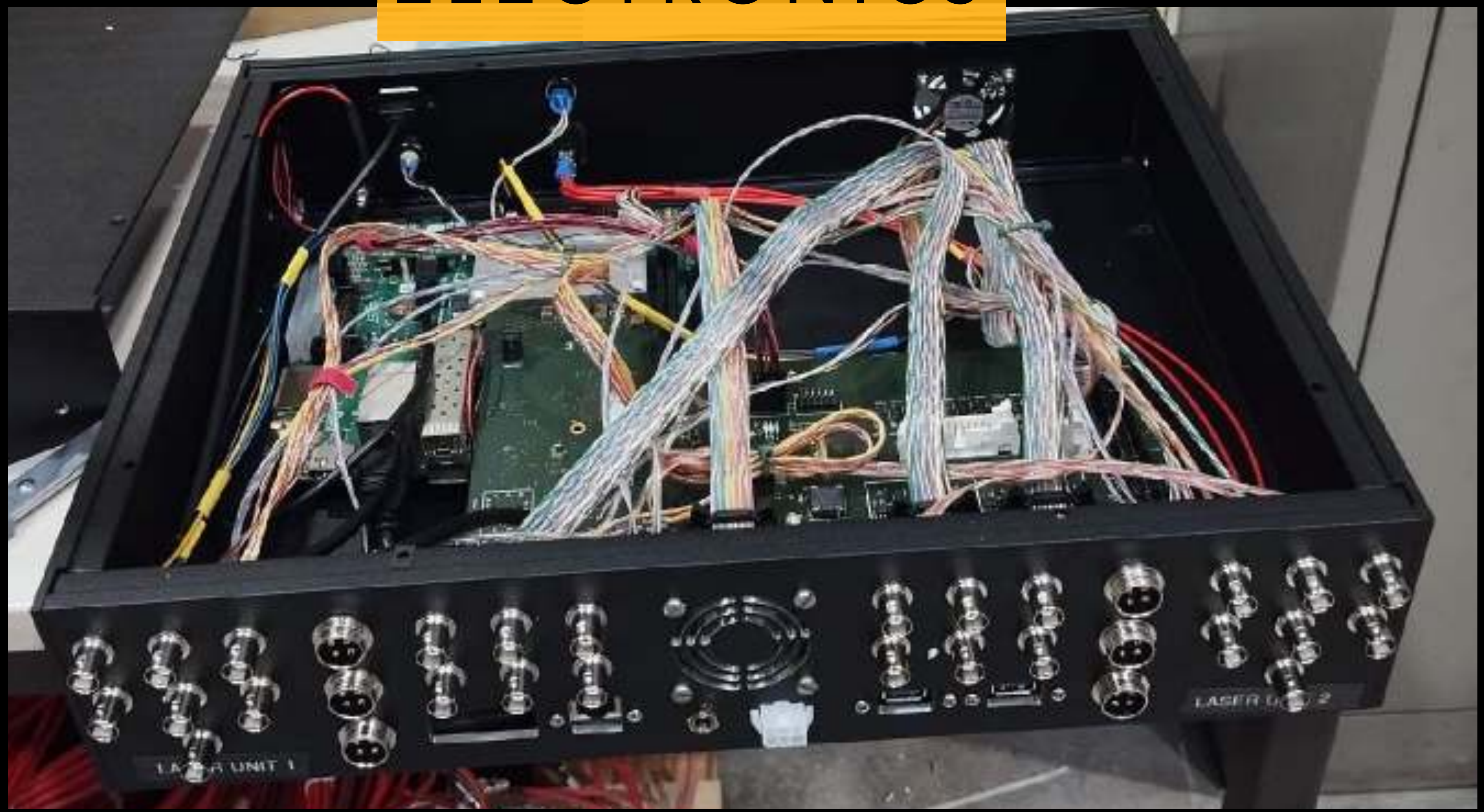


PARALLEL MIRRORS

MIRROR TARGET SUPPORTS



ELECTRONICS



ECCENTRIC FLANGE

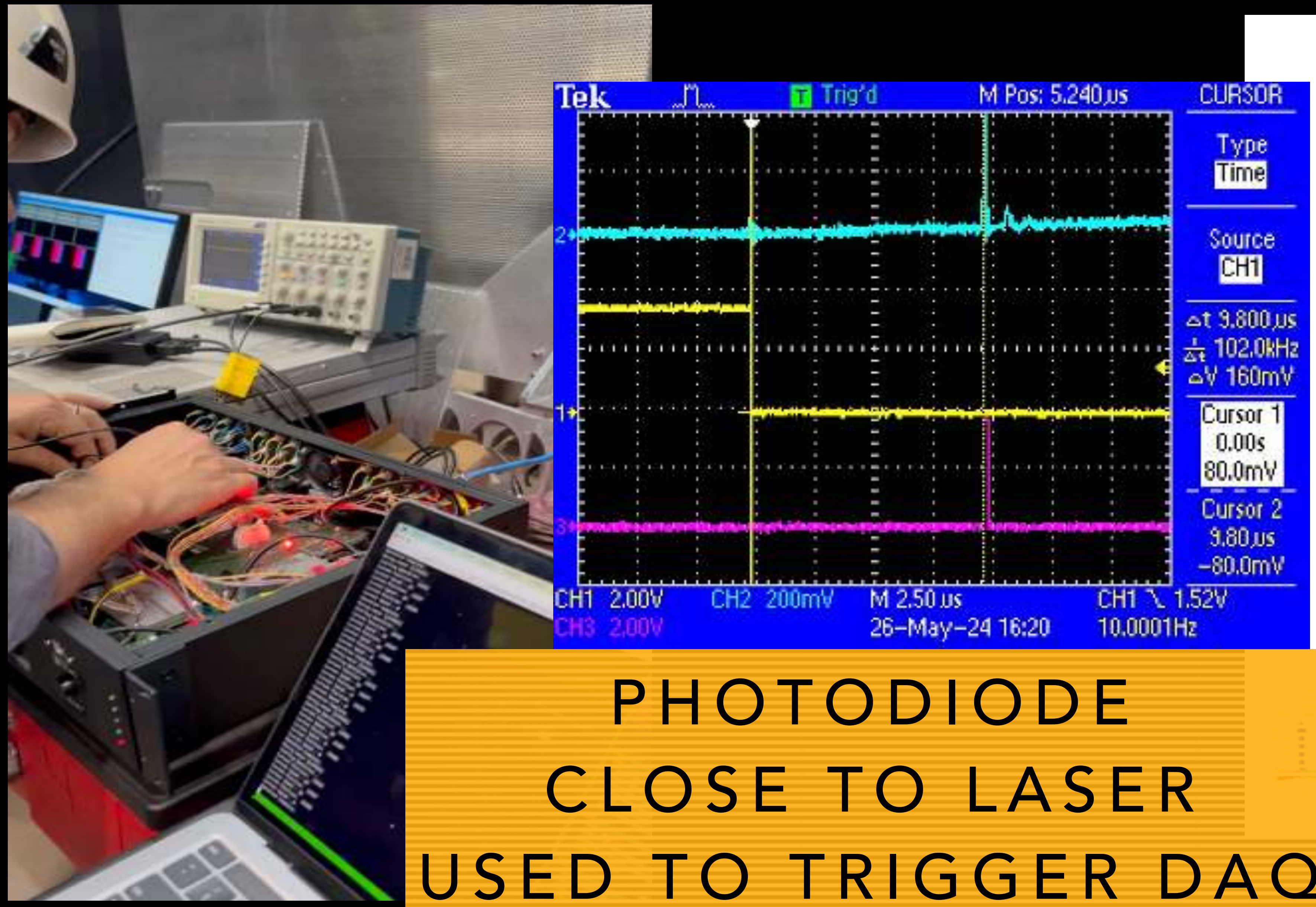
LARGE OPENING ELECTRICAL BREAK

PERISCOPE 3

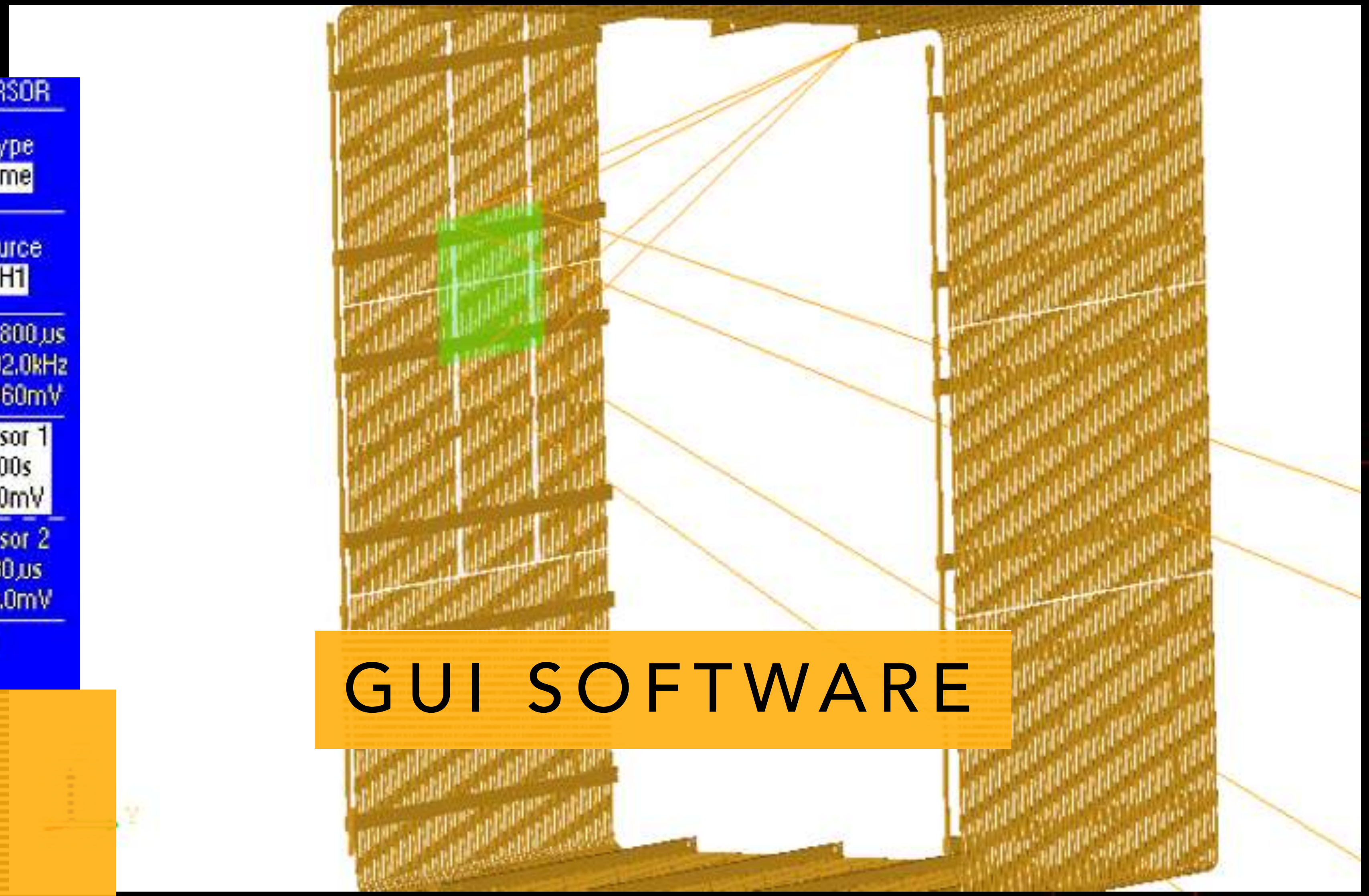
AND MORE...

ASSEMBLY, INSTALLATION

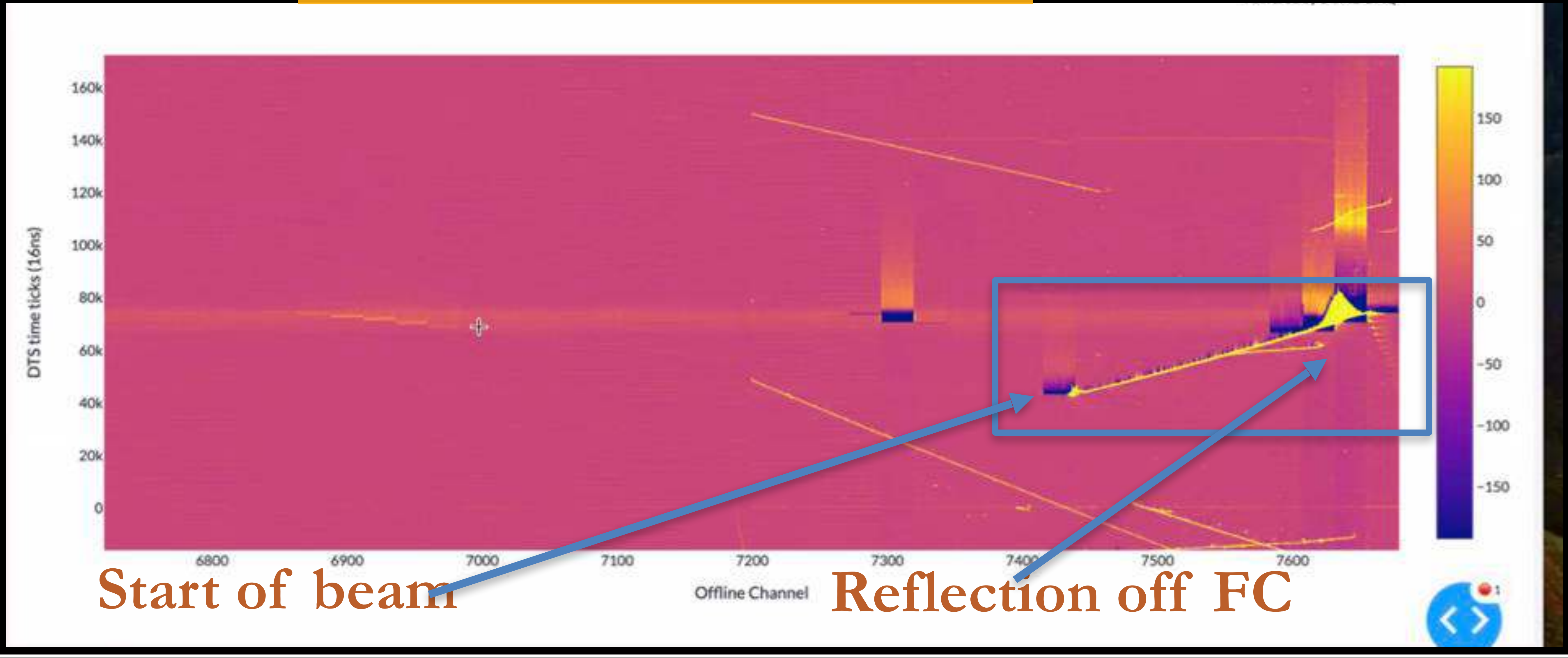
COMMISSIONING/LASER DATA

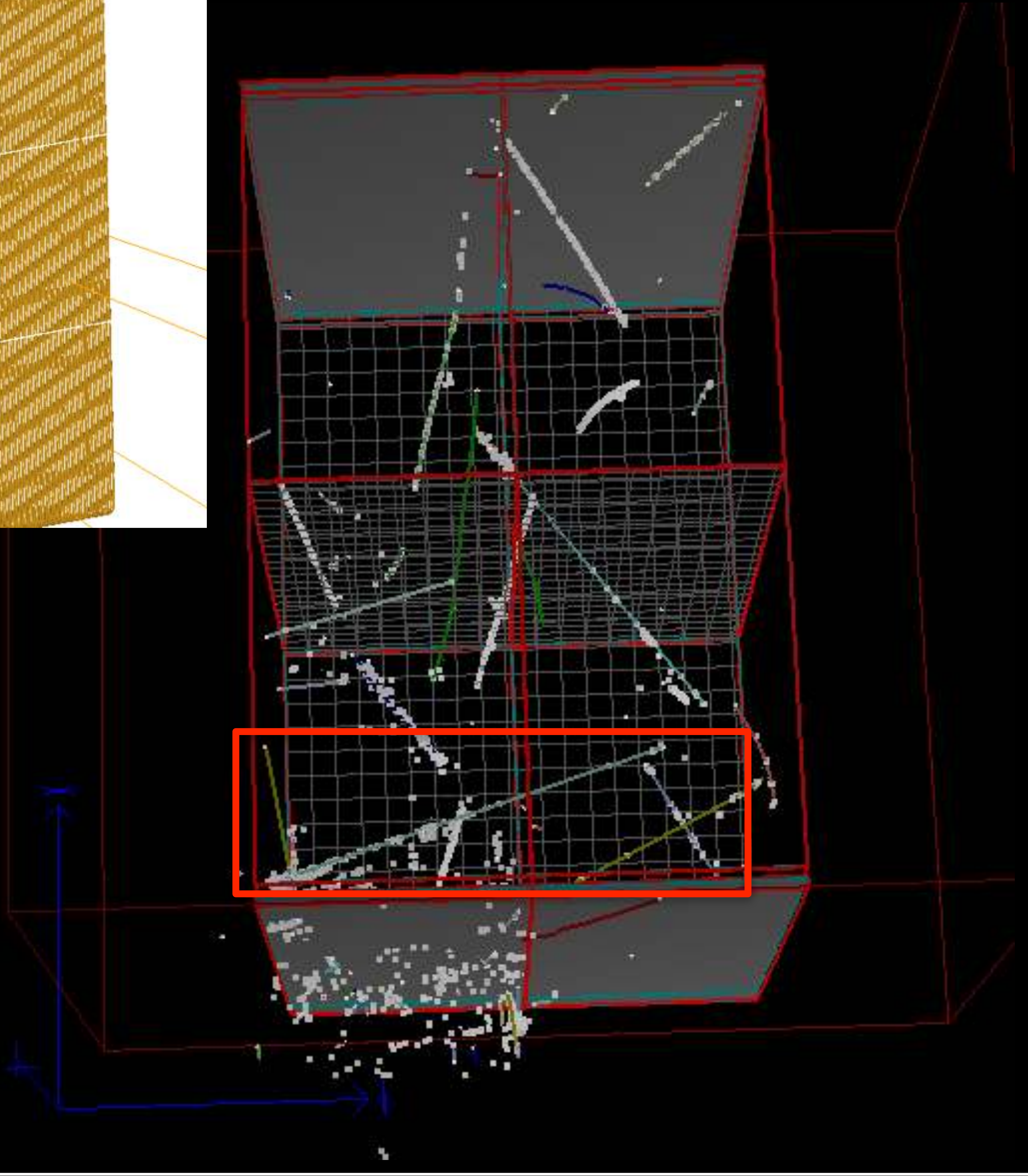


PHOTODIODE CLOSE TO LASER USED TO TRIGGER DAQ



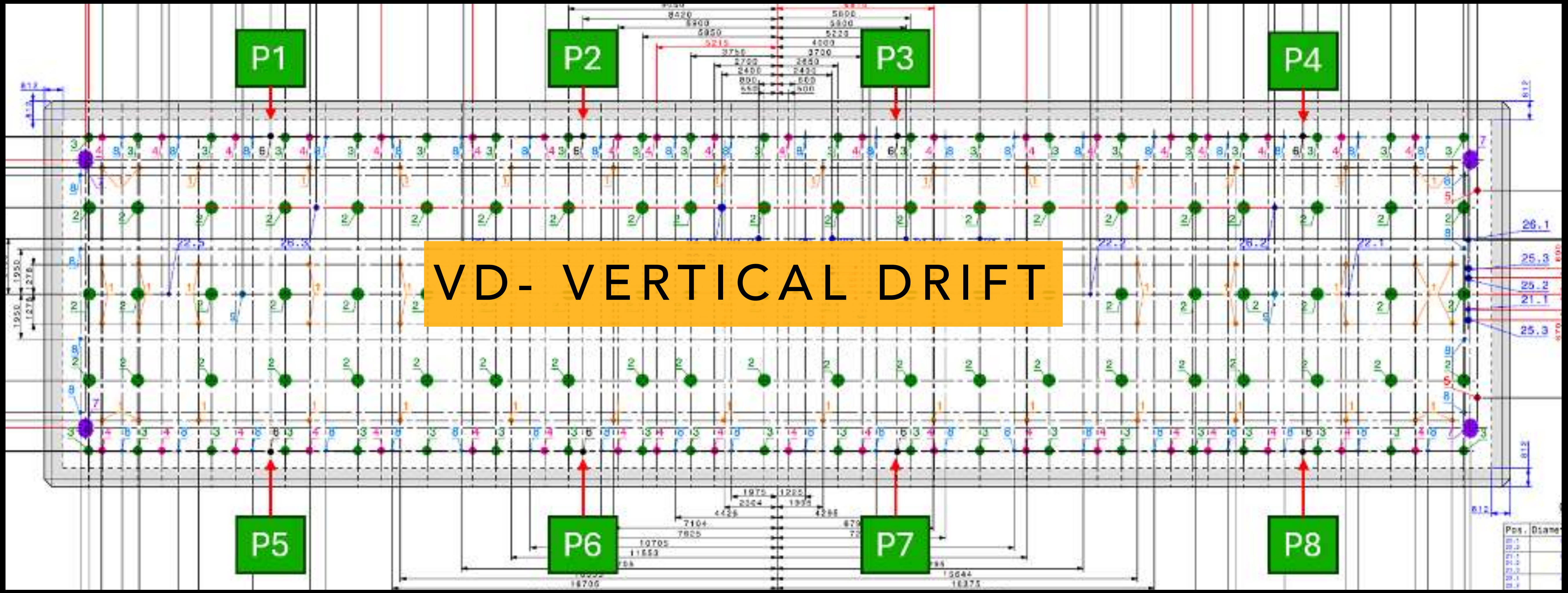
GUI SOFTWARE

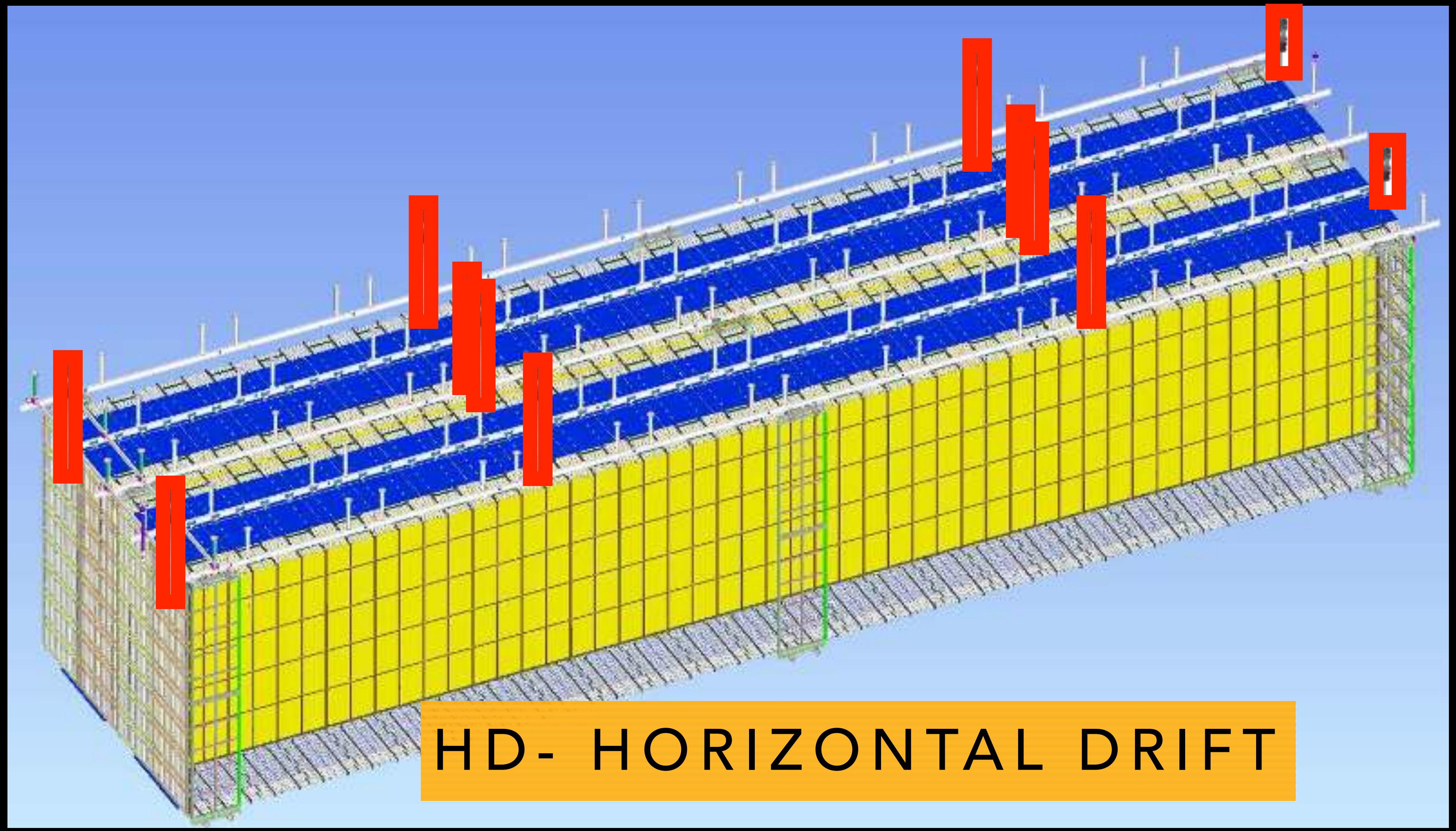




DUNE FUTURE PROSPECTS

CALIBRATION OF FAR DETECTORS





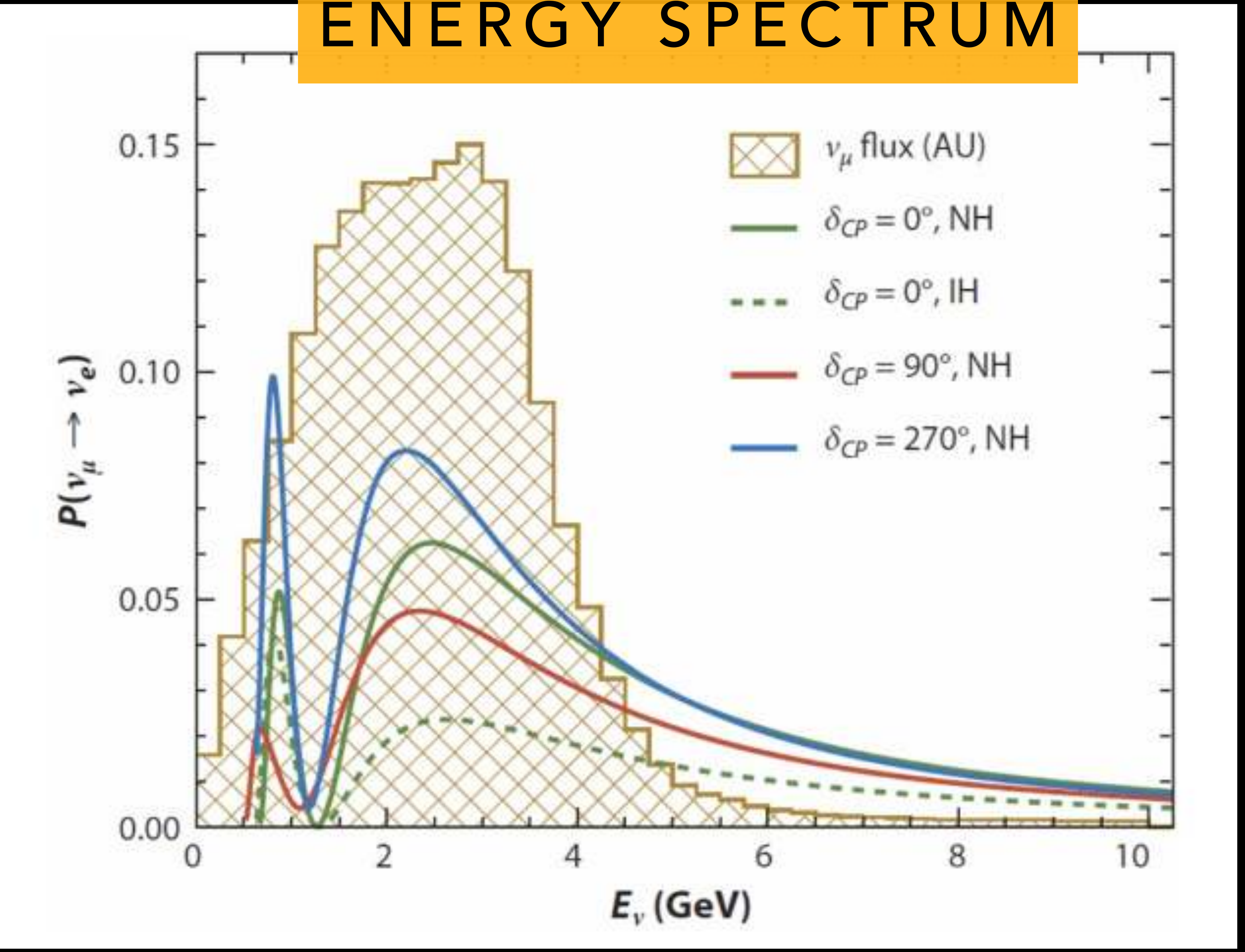
- Plan to build ionization laser system in DUNE far detector VD and HD
  - 20 periscopes total (8+12)
  - 8 lasers total (4+4)
- Installation 2028, 2029
- LIP mechanical workshop will produce a large part of the system

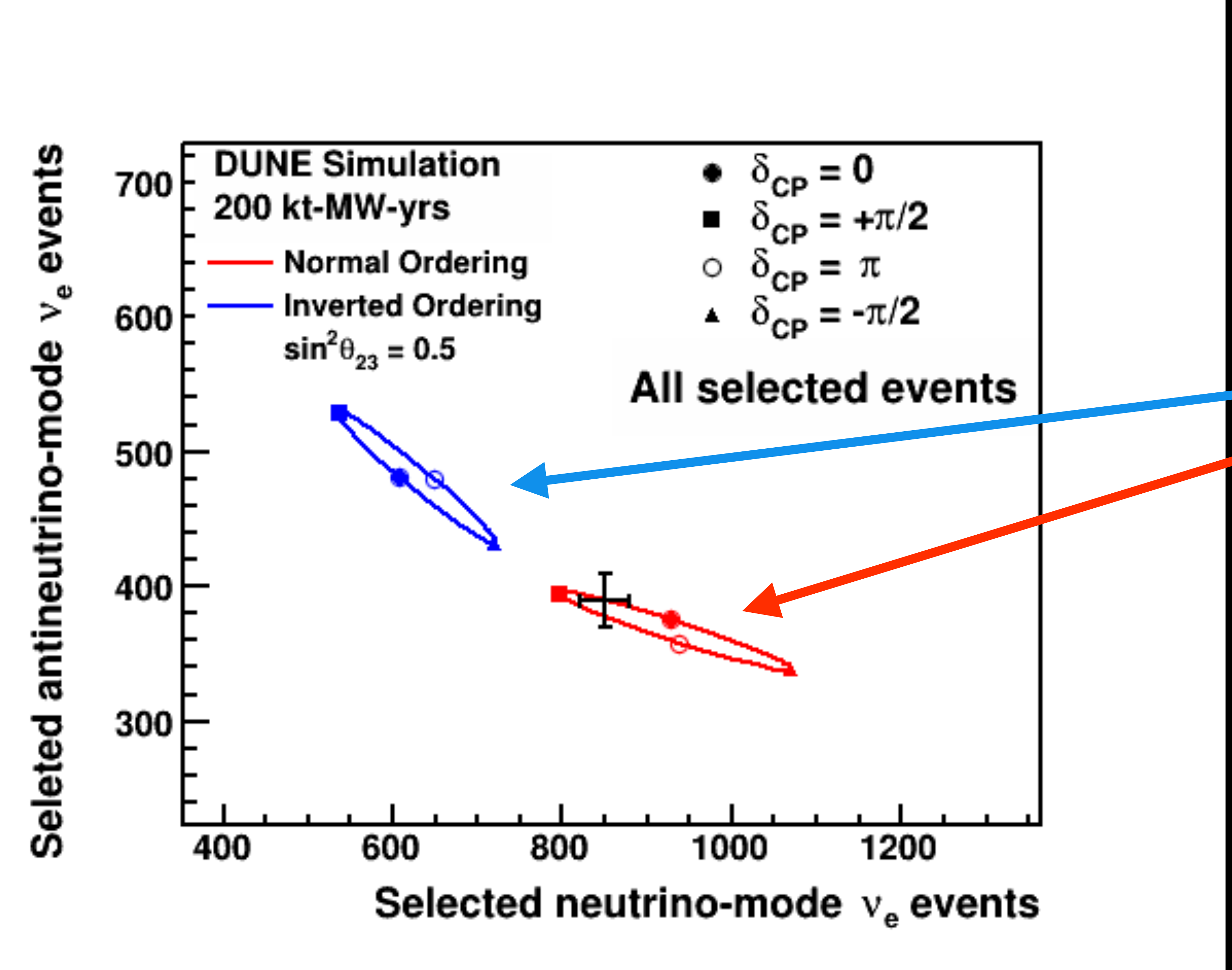
CONSTRUCTION STATUS

- Far Detector caverns excavation complete
- Vertical Drift detector
  - cryostat parts shipped from Spain to South Dakota, installation starts January 2026
  - Installation inside cryostats: 2027, 2028
- Beam upgrades, near detector civil construction started at Fermilab
- Physics start: 2029 / 2031 (with beam)

- Unique features of DUNE
  - Wide-band beams → observe **two** oscillation maxima
  - Long baseline gives sensitivity to mass ordering (MO) through matter effects
  - MO, δ_{CP}, and θ_{23} all affect spectra with different shapes → resolve degeneracies

ENERGY SPECTRUM

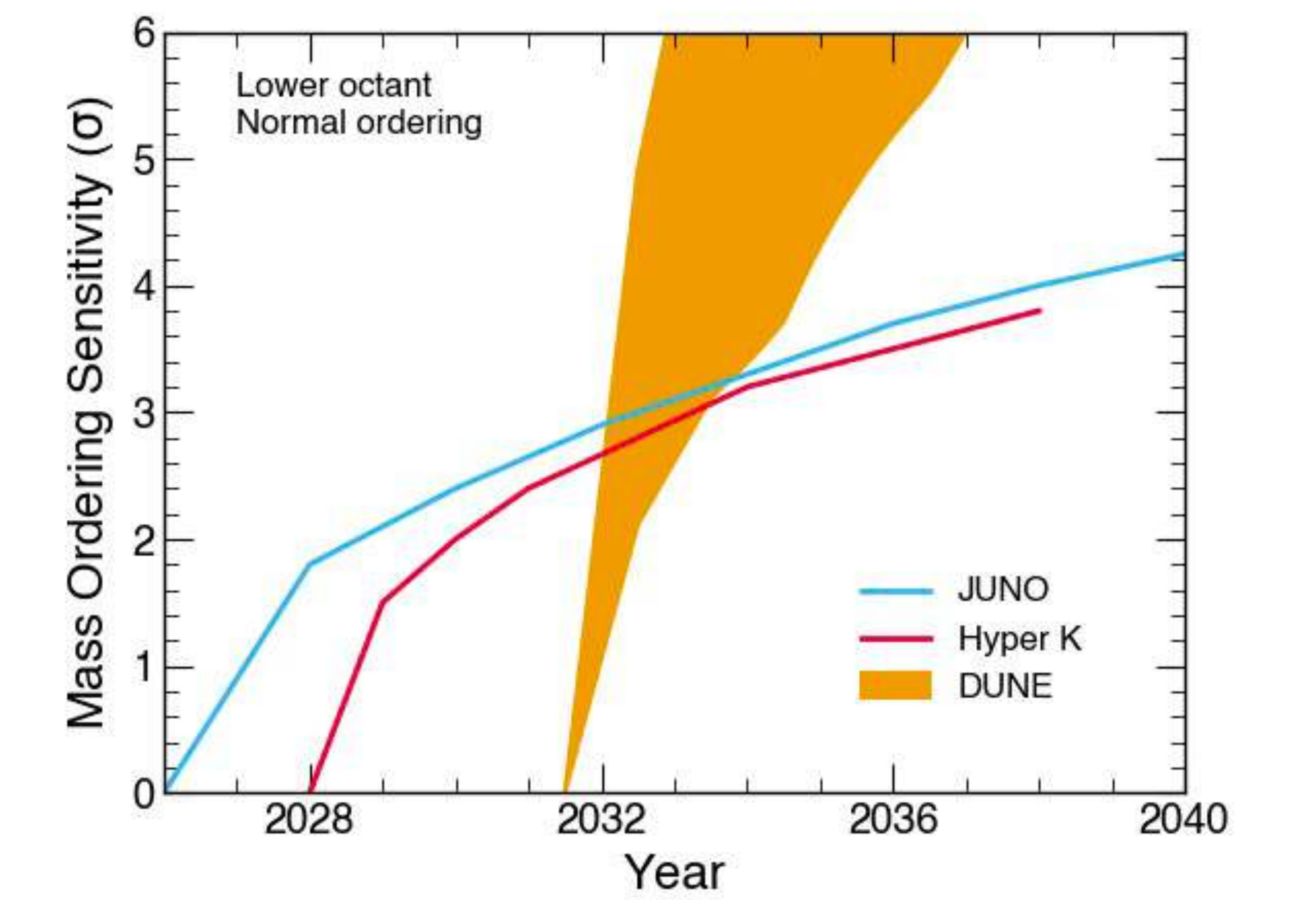




well-separated

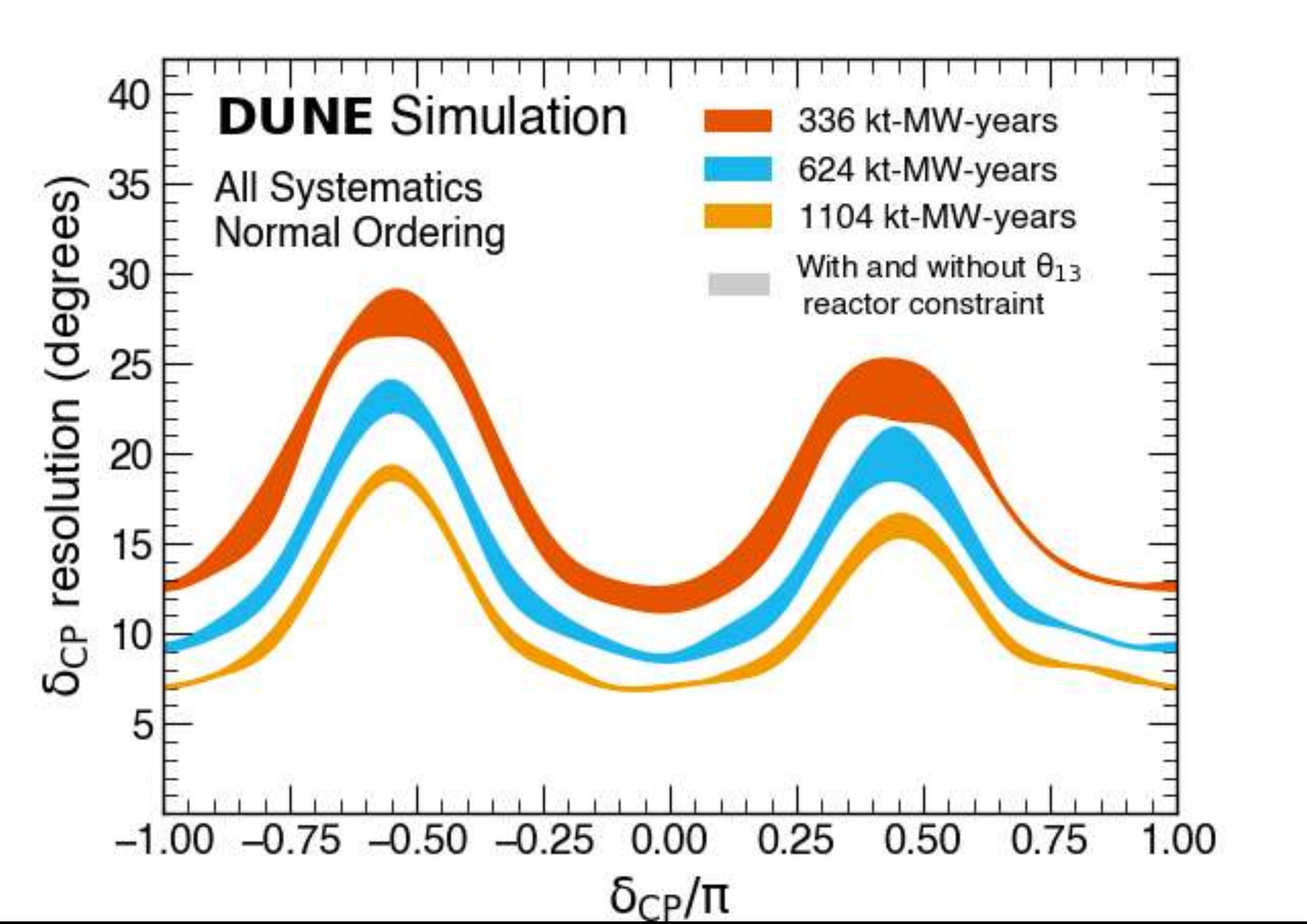
PHYSICS REACH

MASS ORDERING



- Even starting later, DUNE will quickly catch up and surpass other experiments

CP PHASE



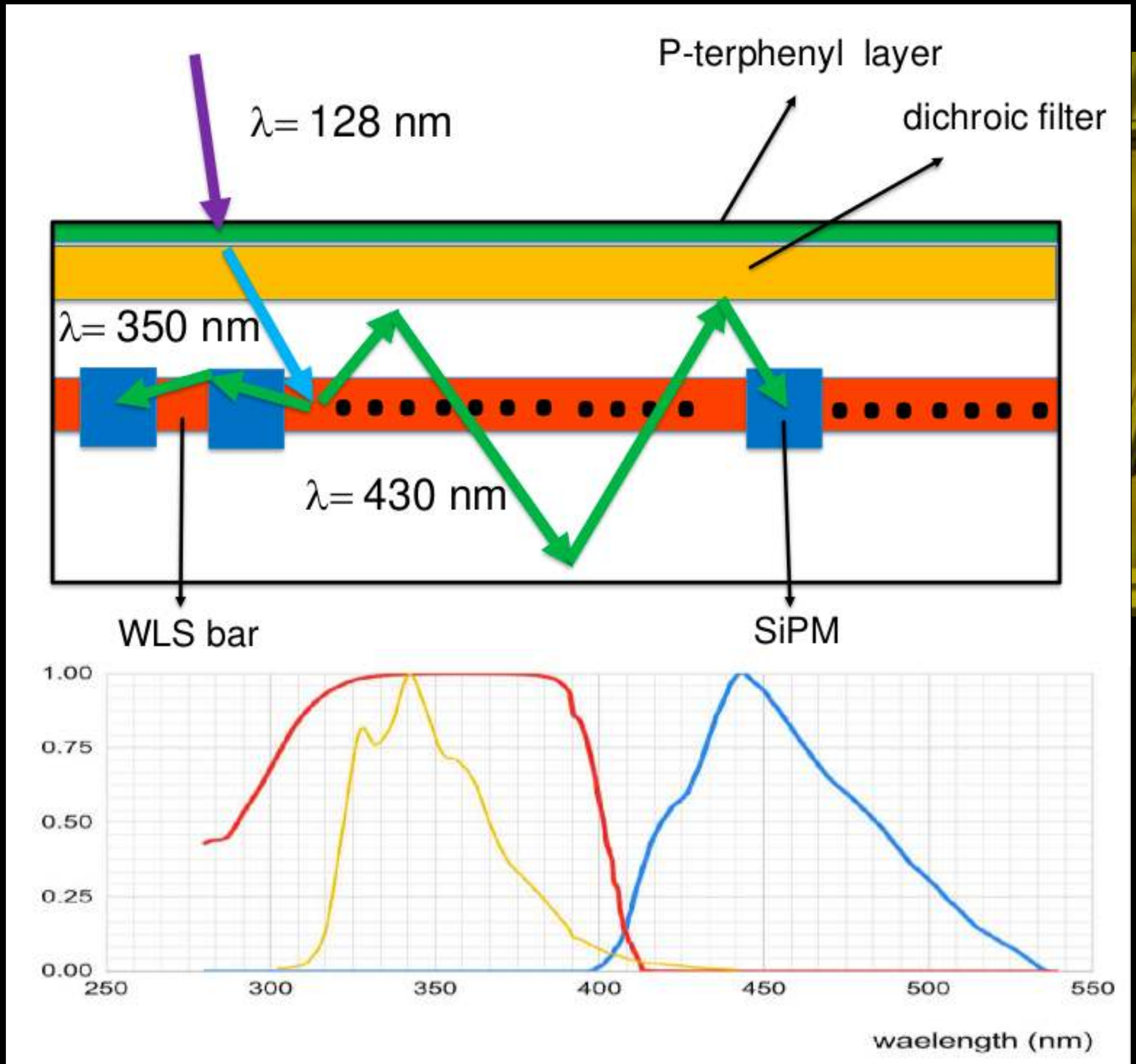
- Ultimate resolution for δ_{CP} measurement

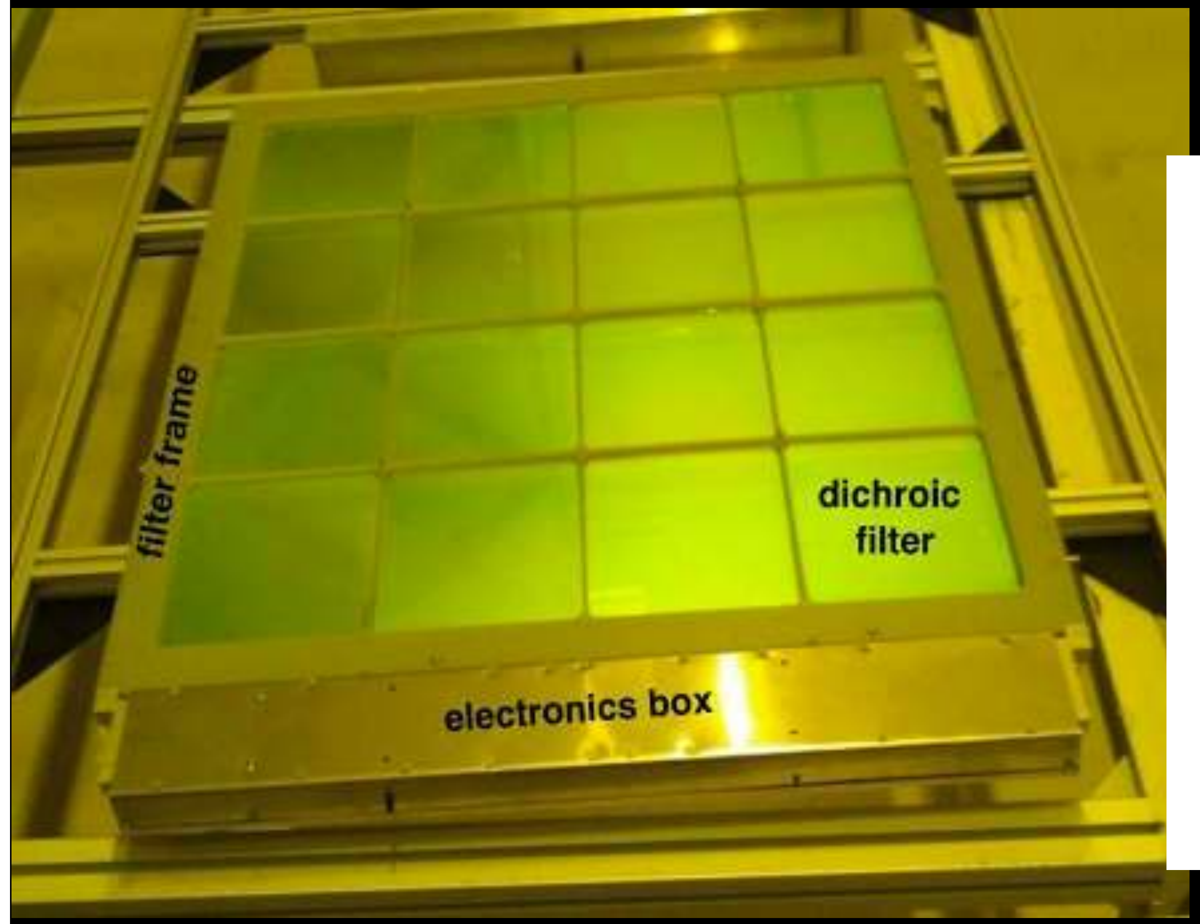
PLUS UNIQUE SENSITIVITY TO NON-UNITARITY OF MIXING MATRIX

COLLABORATION WITH BRAZIL

X-ARAPUCA

- Large Area Photon Detectors developed for LAr scintillation (128 nm)
- First use of dichroic filters, coupled to WLS and SiPM





X-ARAPUCAS IN DUNE

✓ Bar shaped modules ✓ 200 x 10 cm^2 ✓ 4 independent read-out channels ✓ 4 x 48 SiPMs ganged together	✓ Square modules ✓ 60 x 60 cm^2 ✓ 2 independent read-out channels ✓ 2 x 80 SiPMs ganged together

Efficiencies around 2% - 4%

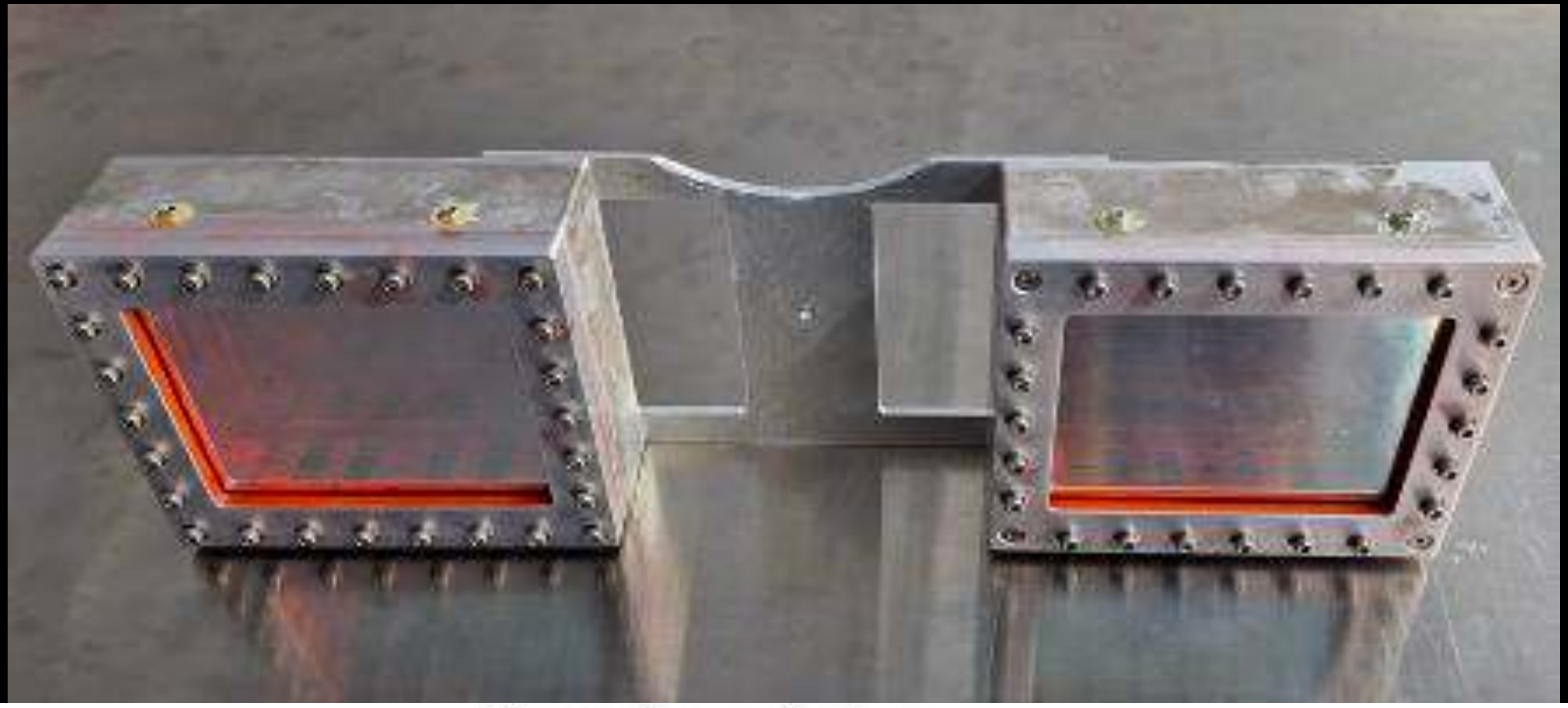
- Innovative technology for photon detection invented at Campinas. Major contribution to DUNE

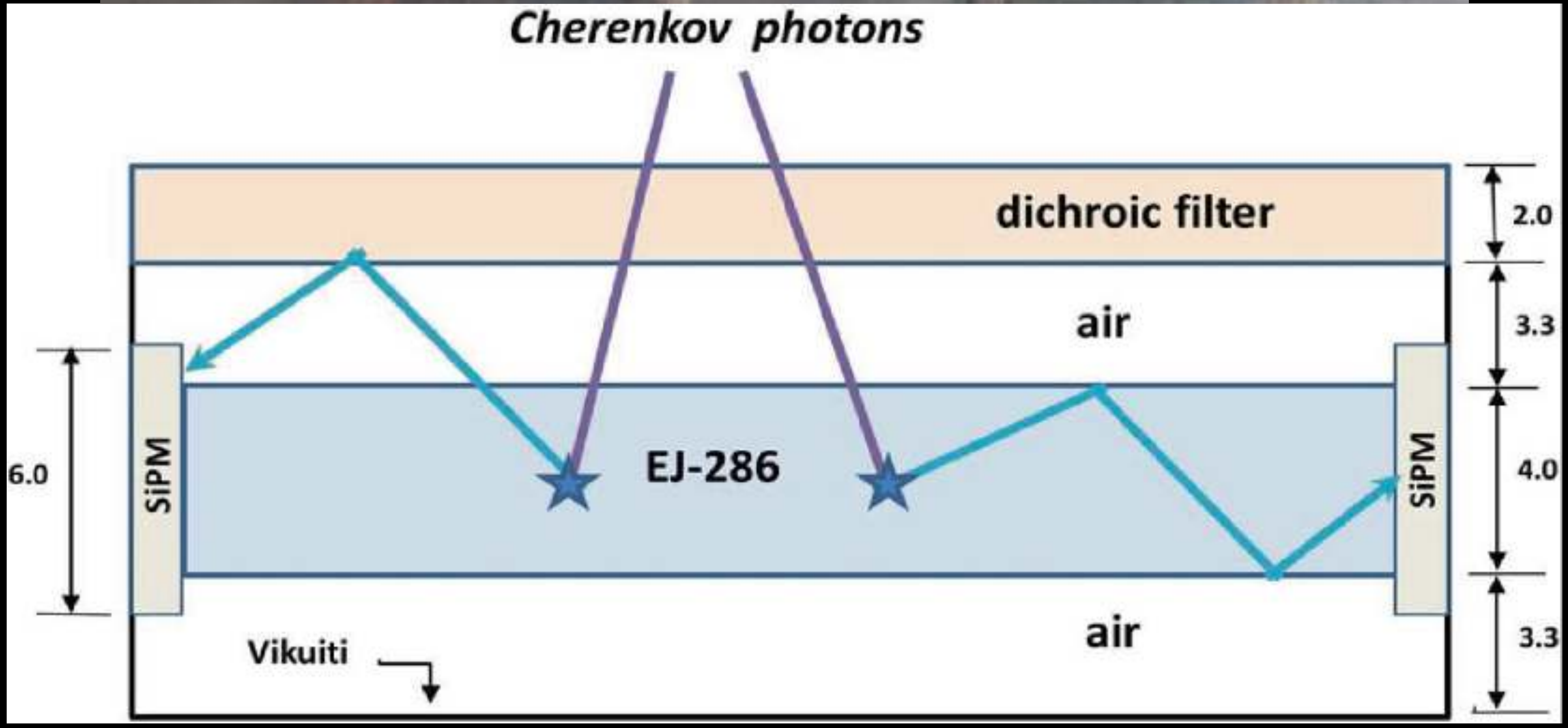
E. SEGRETO NNN24

A.A. MACHADO *ET AL* 2018 *JINST* 13 C04026

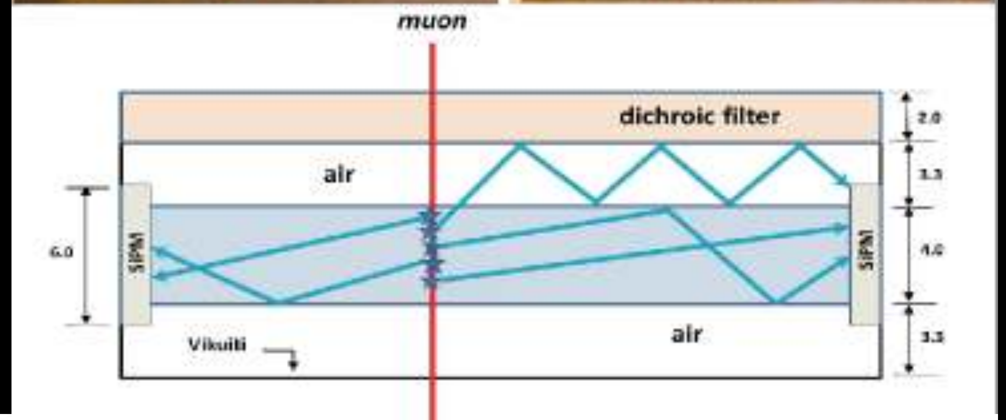
C-ARAPUCA

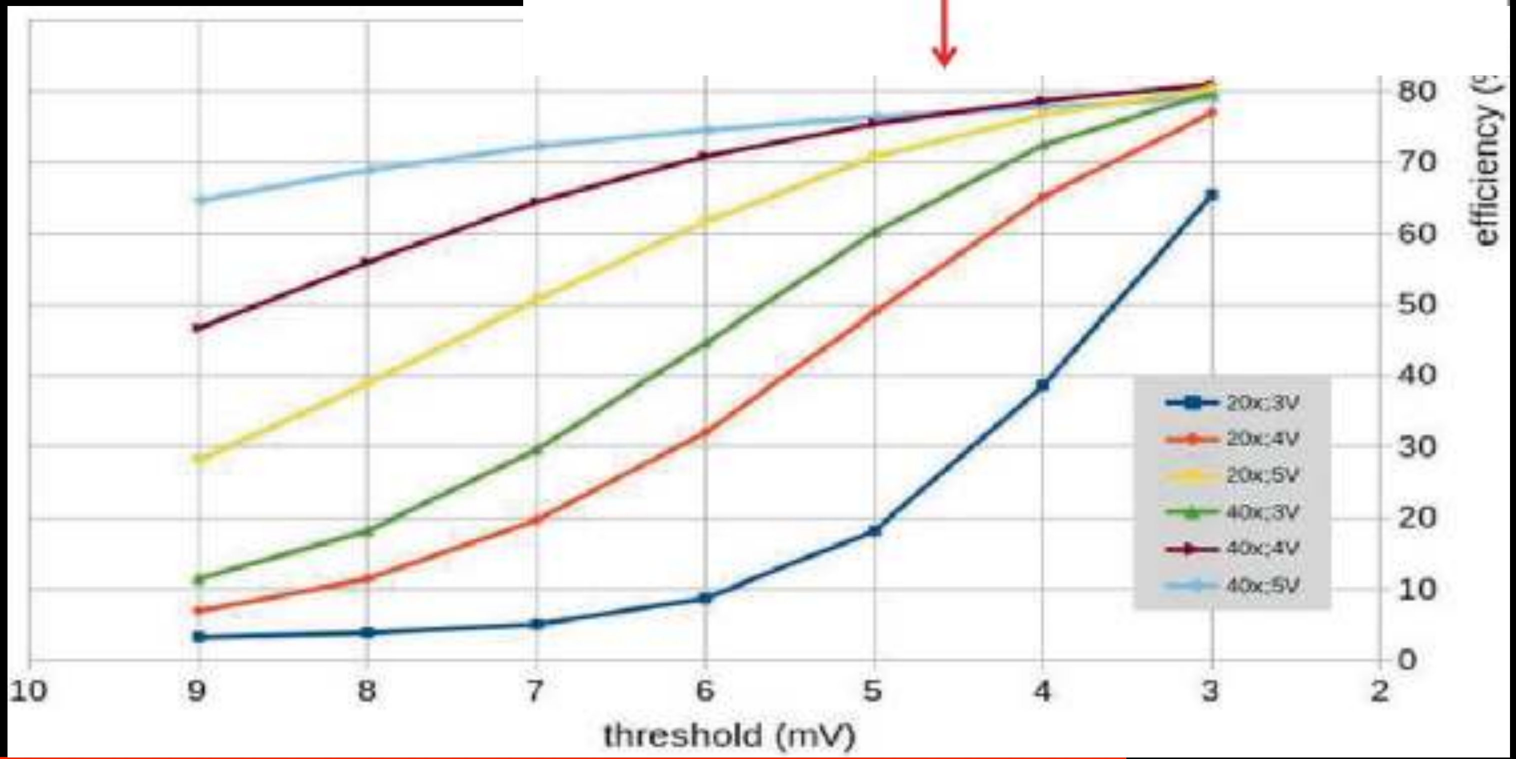
- Developed for water Cherenkov
- Simpler design (no PTB), low pass filters





Preliminary tests with muons and water tank at Campinas

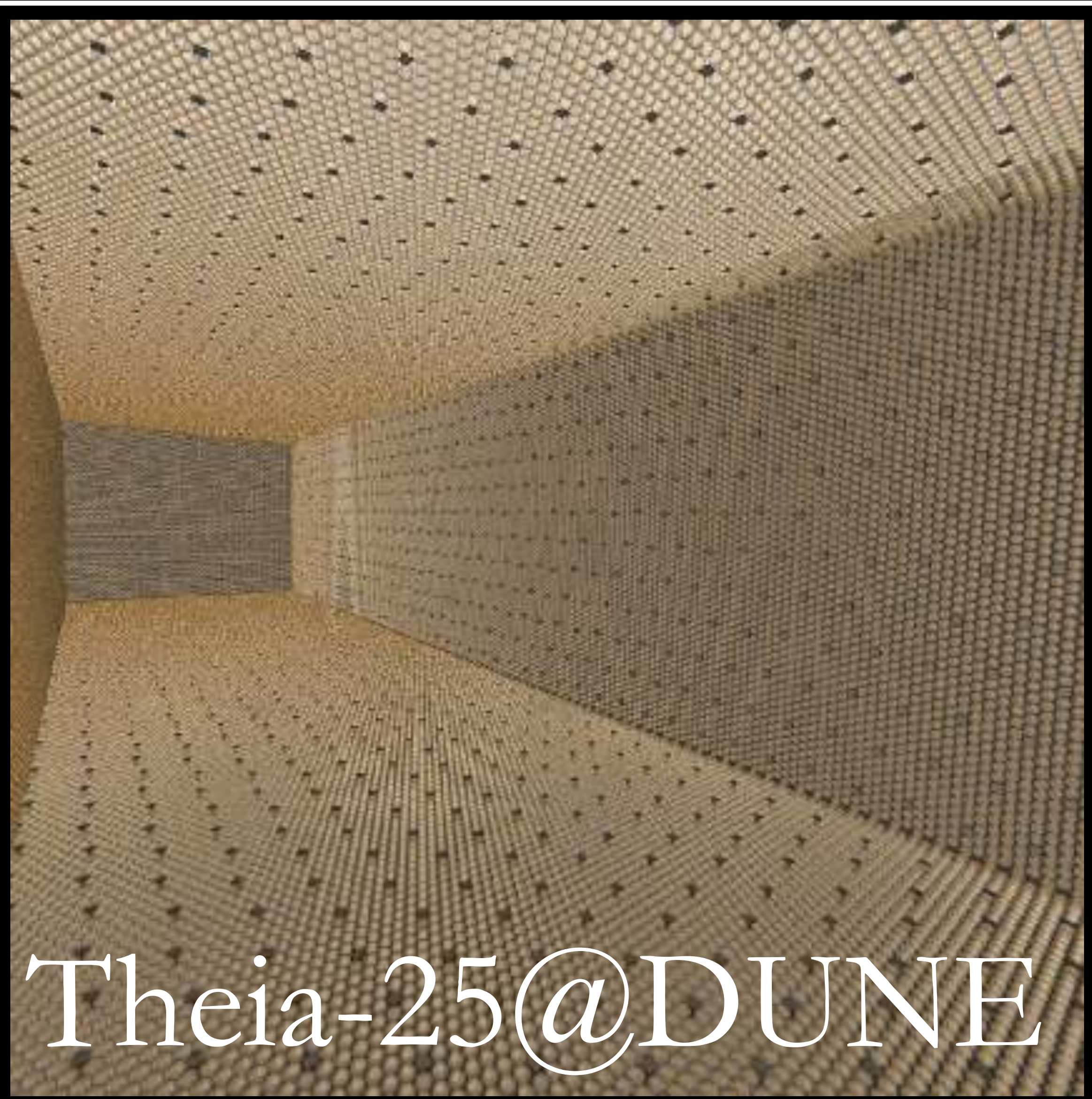




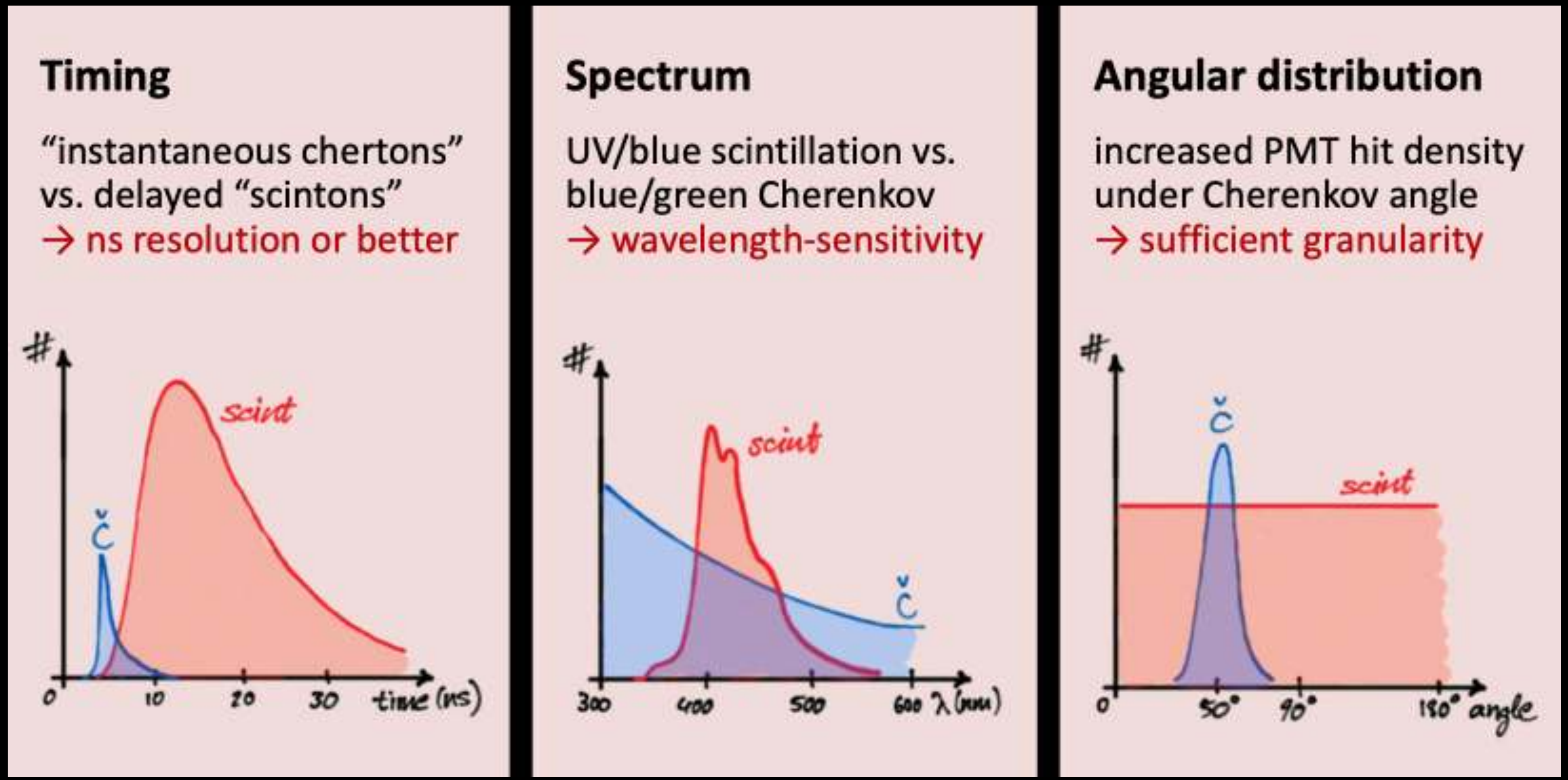
A. FAUTH, A. MACHADO ET AL.
HTTPS://DOI.ORG/10.1002/ASNA.20240123

COULD THIS BE USED FOR HYBRID CHERENKOV+SCINTILLATION DETECTORS?

HYBRID CHERENKOV/SCINTILLATION



- Hybrid photon detection combines the high light yield of scintillation with the directionality of Cherenkov light
- May be a breakthrough in neutrino detectors improving sensitivity to double beta decay, solar neutrinos, and performing well also at high energies.
- Ongoing R&D on fast sensors, slow scintillators, spectral separation, mostly in US, Germany. Theia 25 kton is a proposed design for DUNE far detector 4



OUR IDEA: MODIFY THE C-ARAPUCA DETECTOR TO SEPARATE CHERENKOV FROM SCINTILLATION

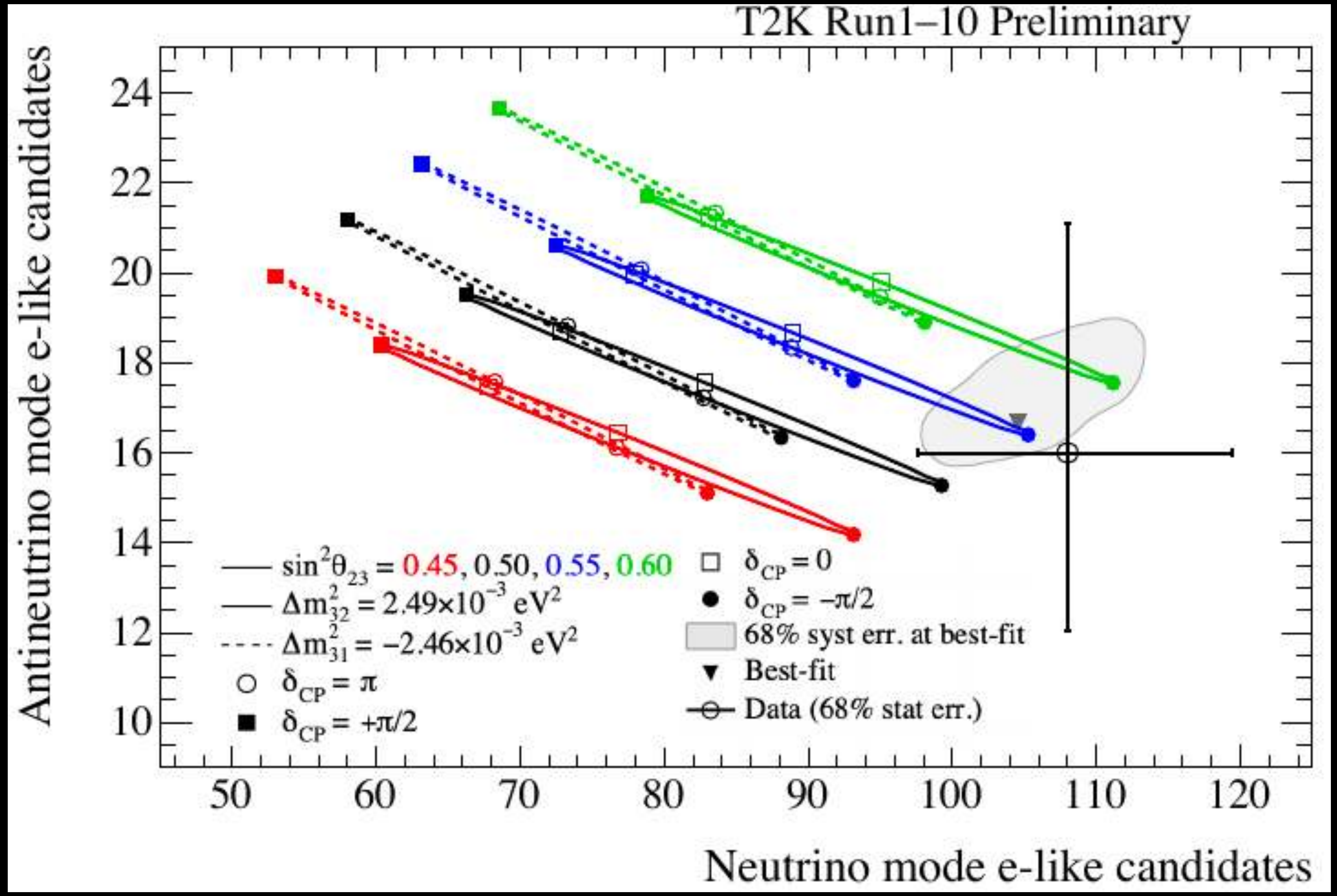
- Collaboration plans are starting:
  - 1 month visit (JM) to Campinas early 2026
  - simulation work at LIP
  - visit by Campinas colleague to LIP

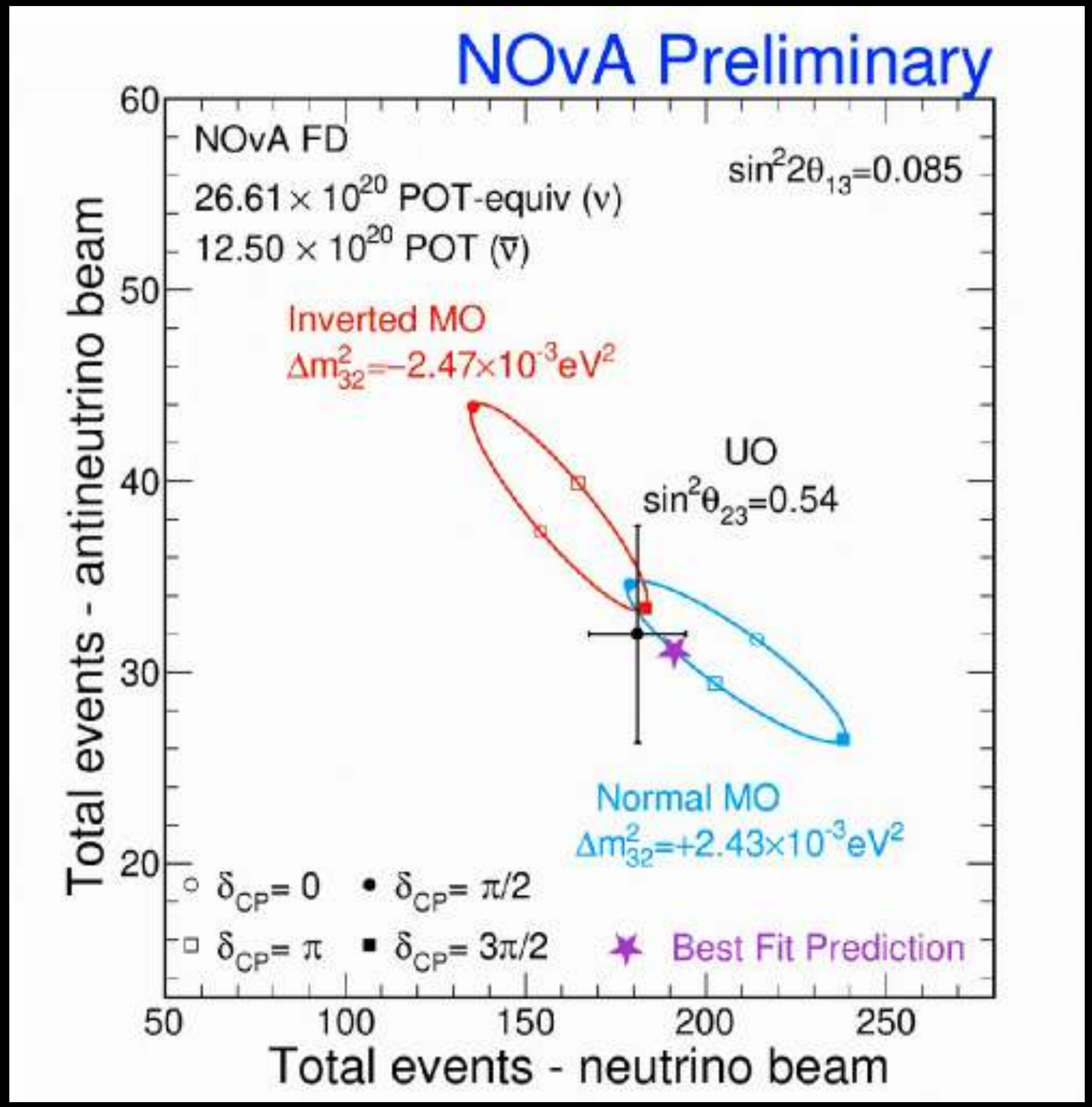
THANK YOU FOR YOUR ATTENTION!

EXTRA SLIDES

GLOBAL COLLABORATION

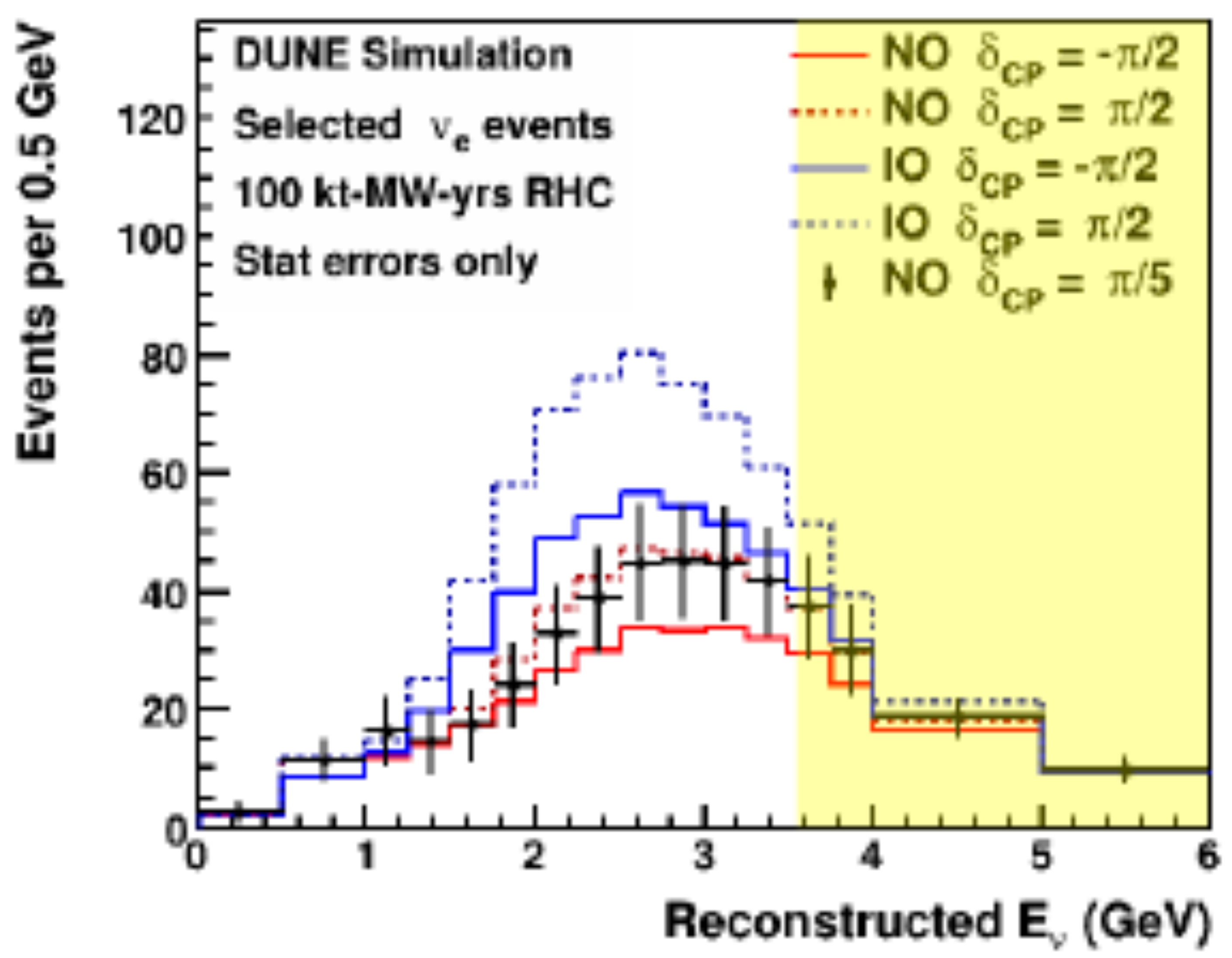
LIMITATIONS OF CURRENT DATA

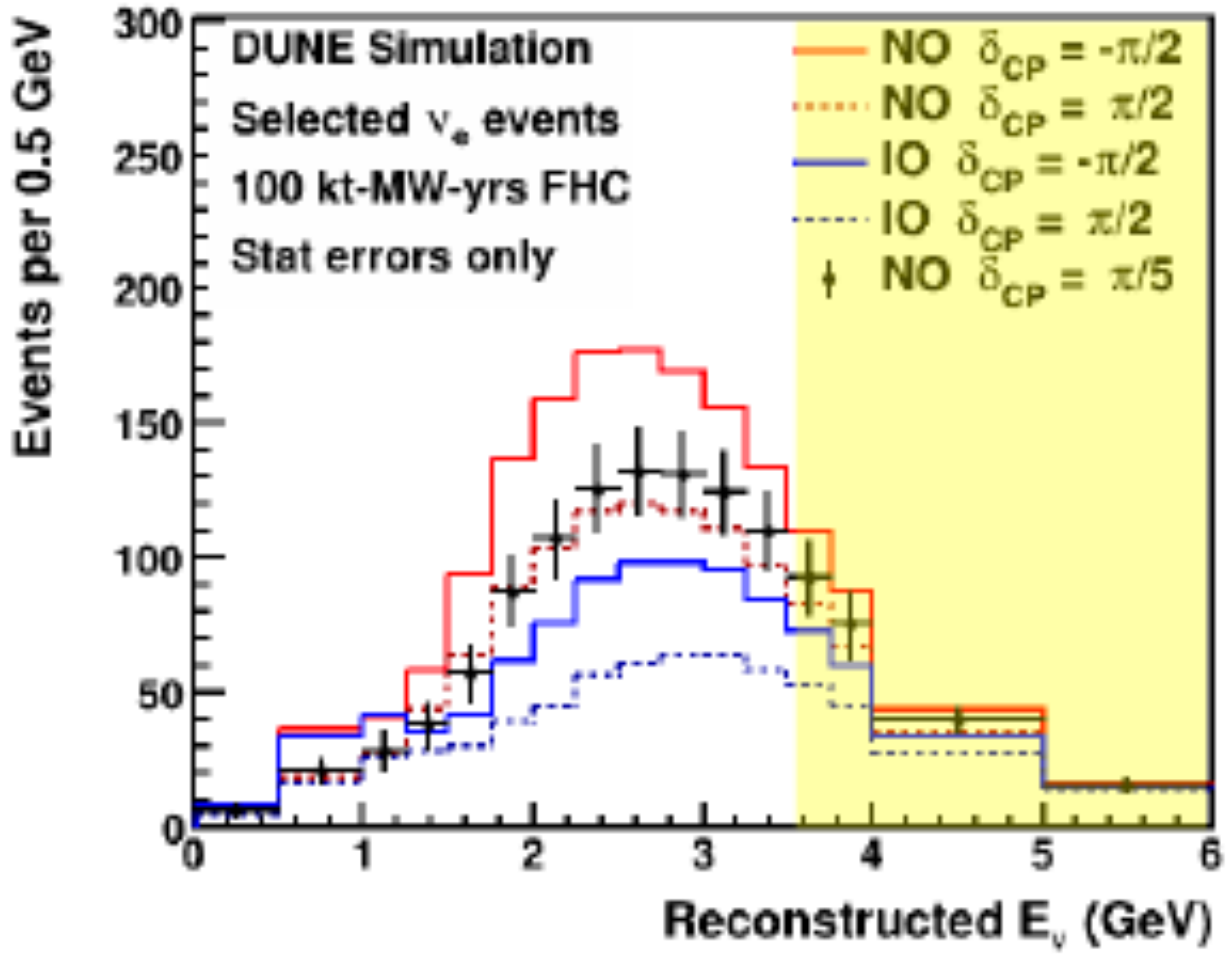


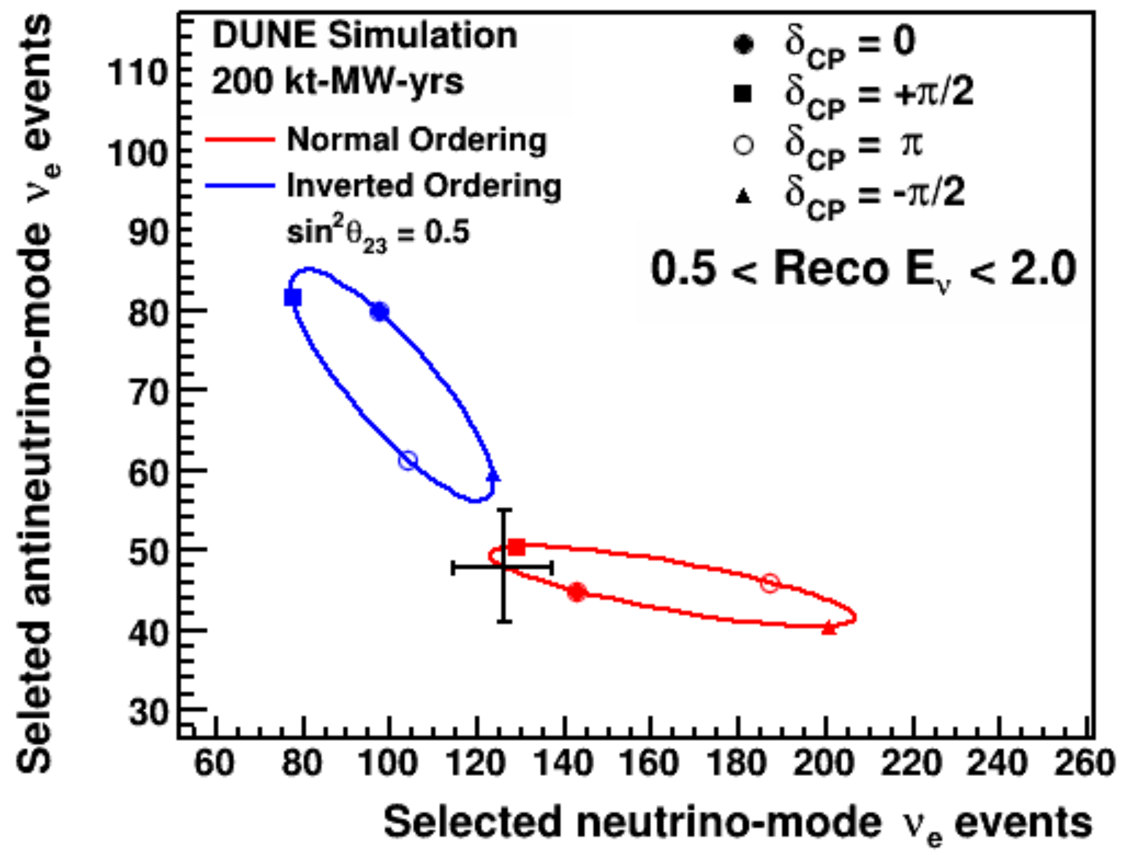


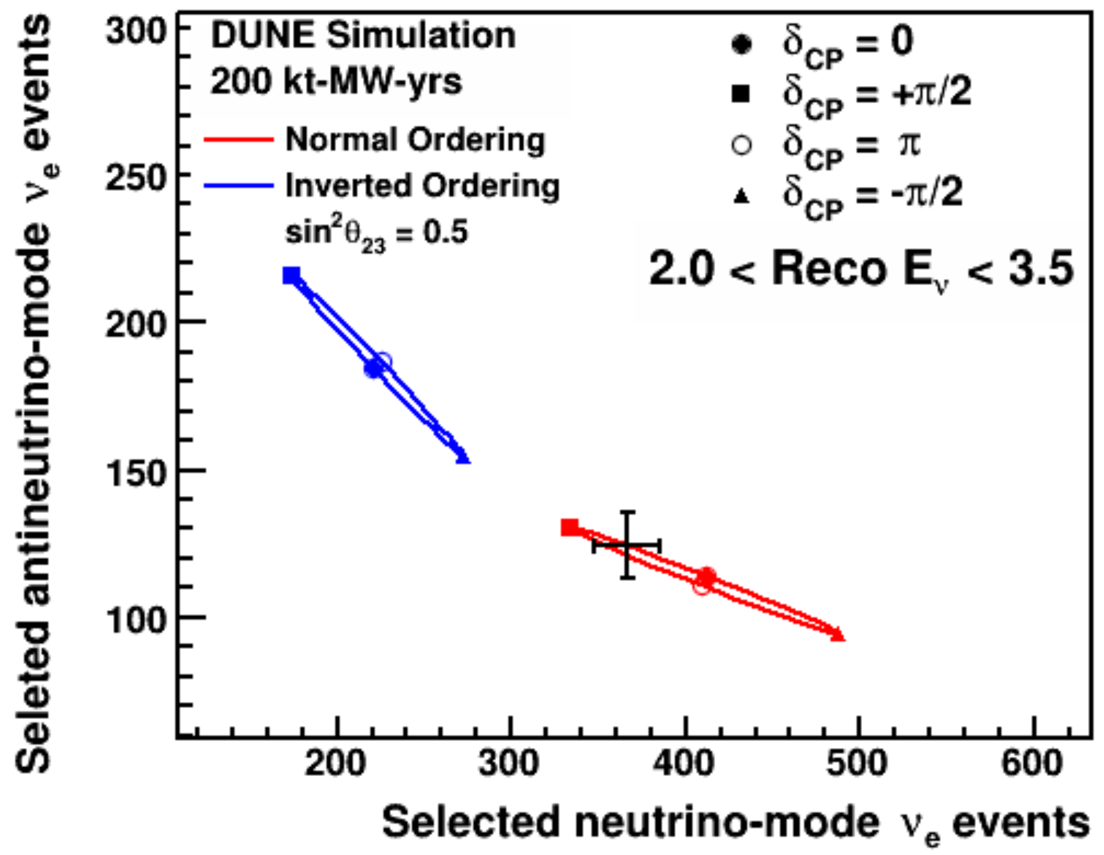
- Matter effect and CP violation are degenerate
- Statistical uncertainty is large compared to allowed parameter space:
  - There will always be a combination of standard parameters that agrees with the data → no sensitivity to new physics
- There will likely be many allowed combinations → degeneracies

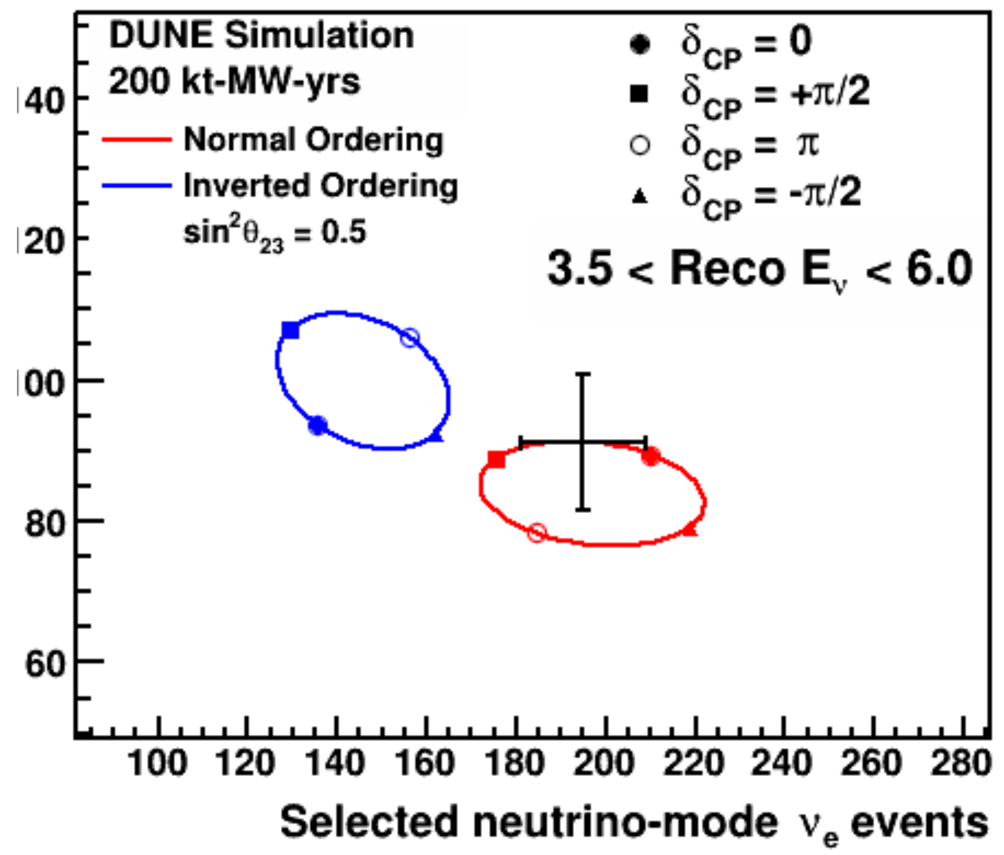
BUT DUNE CAN DO MORE











- DUNE can make a different bi-event plot in each energy bin, each of them with different sensitivity to CP, MO
- DUNE can measure oscillation parameters at each bin
- Data should prefer the same point in every bin, **if 3-flavor PMNS picture is correct**
  - **DUNE can probe this framework**