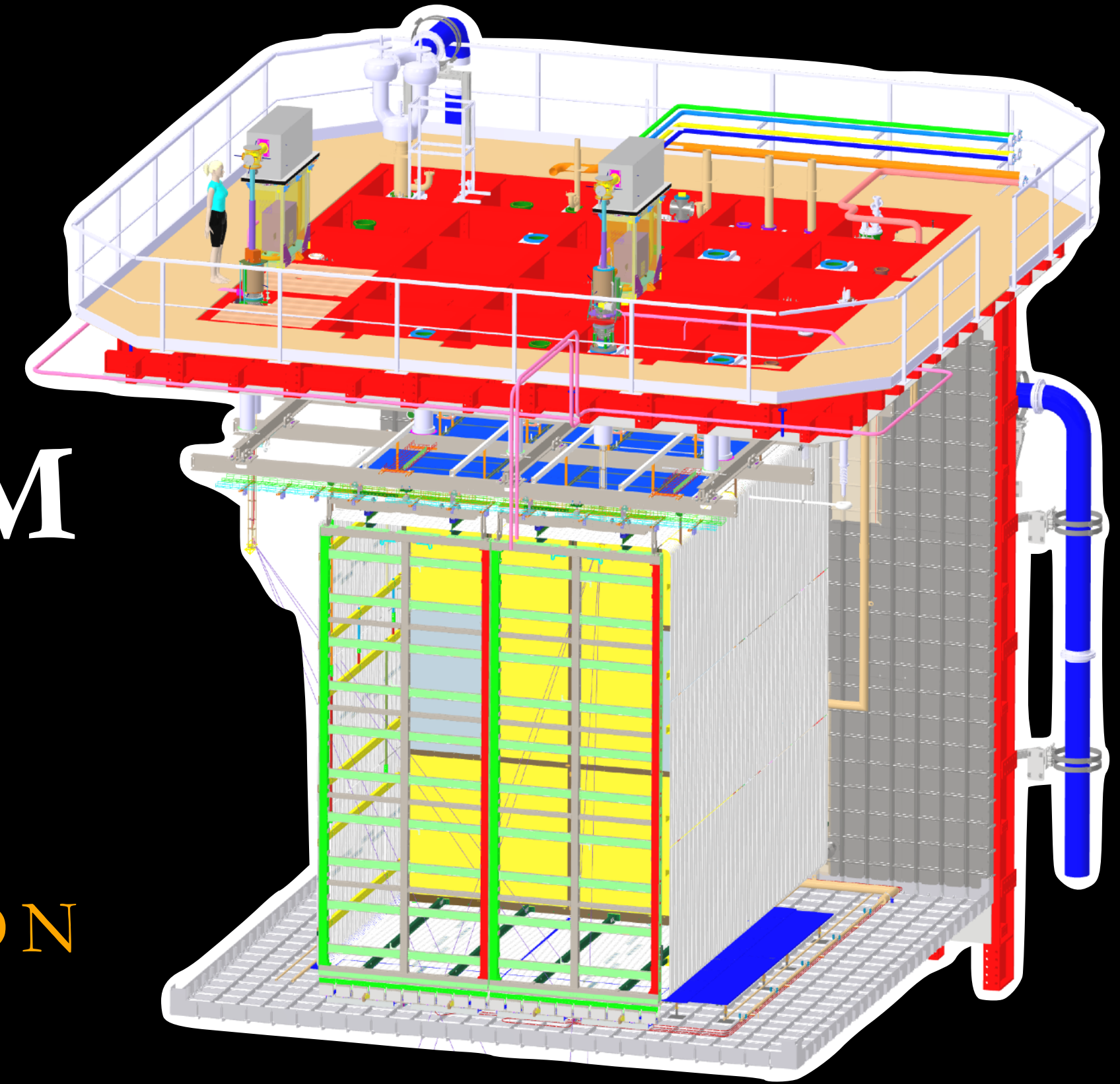


# IONIZATION LASER CALIBRATION SYSTEM FOR DUNE

JOSÉ MANEIRA, LIP LISBOA  
ON BEHALF OF THE DUNE COLLABORATION



23RD INTERNATIONAL WORKSHOP ON NEXT GENERATION  
NUCLEON DECAY AND NEUTRINO DETECTORS (NNN24)

CENTRO BRASILEIRO DE PESQUISA FÍSICAS (CBPF)  
RIO DE JANEIRO, BRAZIL

OCTOBER 31, 2024

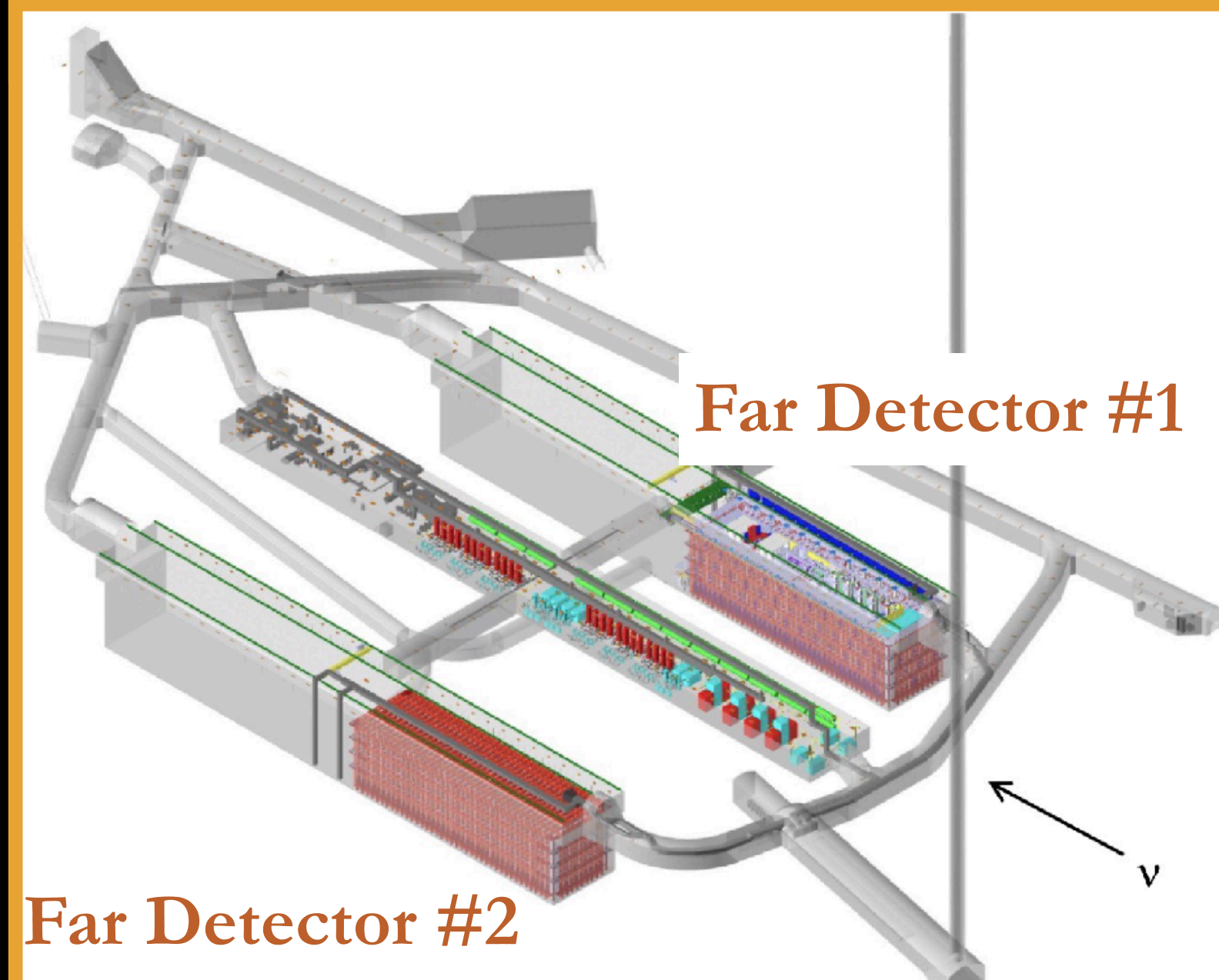
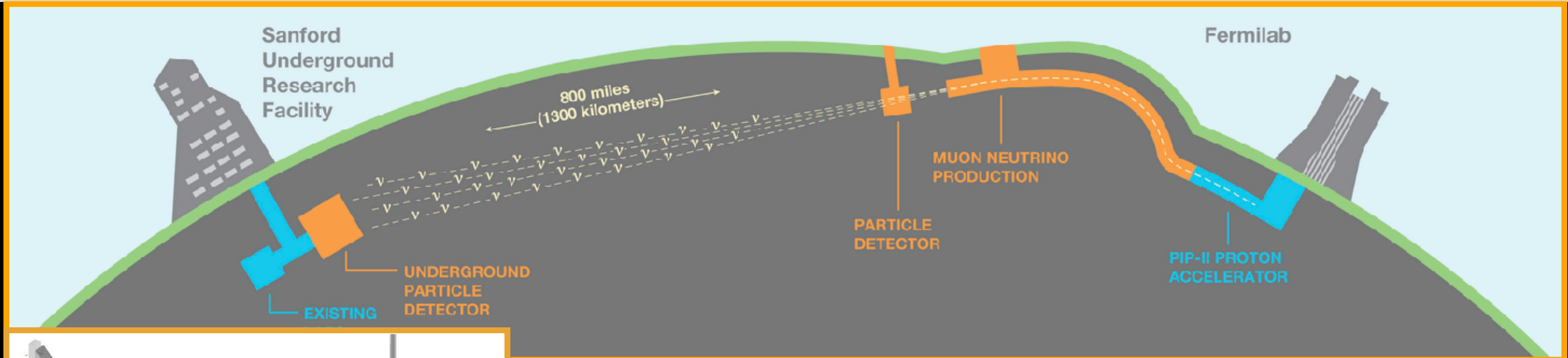
- DUNE requirements for physics
- Calibration of Liquid Argon TPCs with natural sources
- Design of DUNE ionisation laser calibration system
- Construction and commissioning of system for ProtoDUNE at CERN
- Initial performance checks and results





# REQUIREMENTS FOR PHYSICS

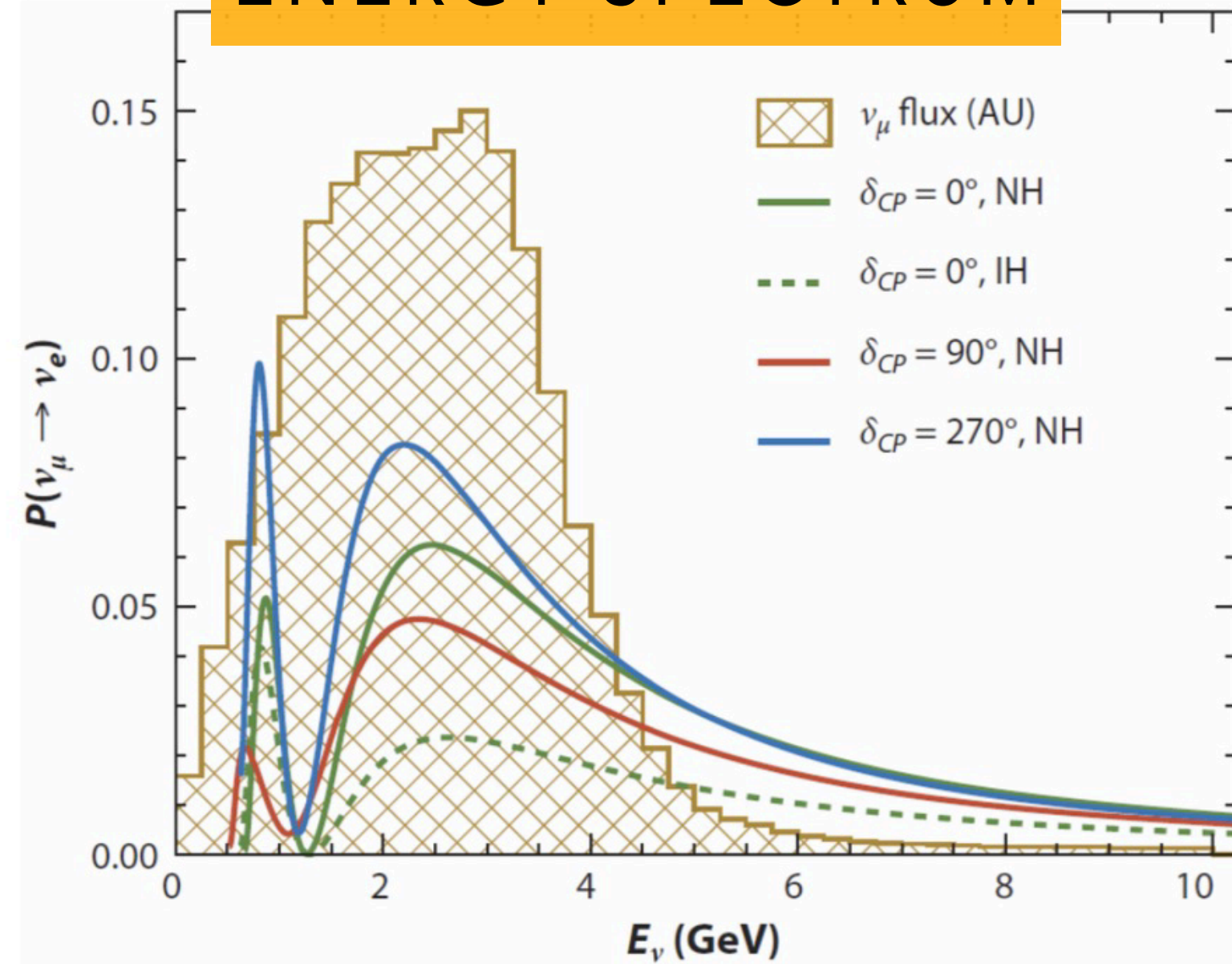
# DUNE OVERVIEW



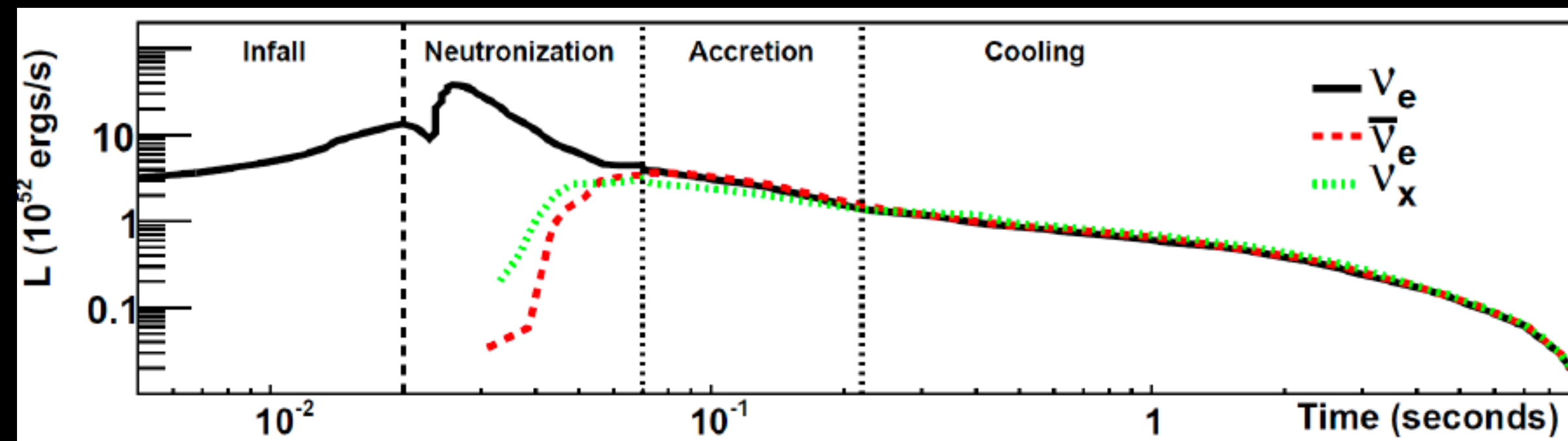
- Other talks in this conference:
  - DUNE Overview, Gustavo Valdivieso
  - LAr Near Detectors, Zoya Vallari
  - DUNE Far Detectors, André Steklain Lisbôa
  - LAr purification for DUNE, Pascoal Pagliuso, Dirceu Norlier
  - Photon Detectors, Ettore Segreto



## ENERGY SPECTRUM



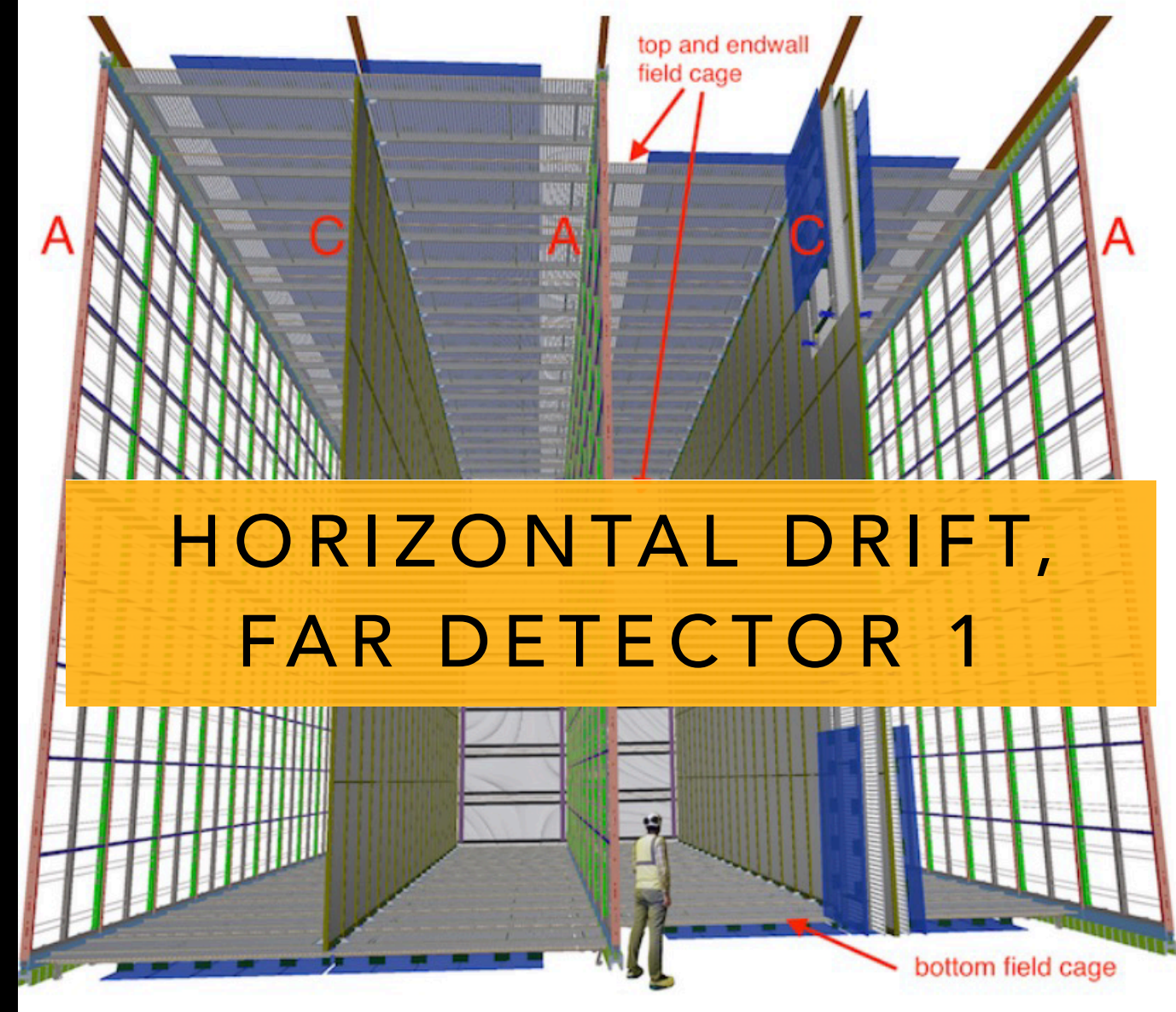
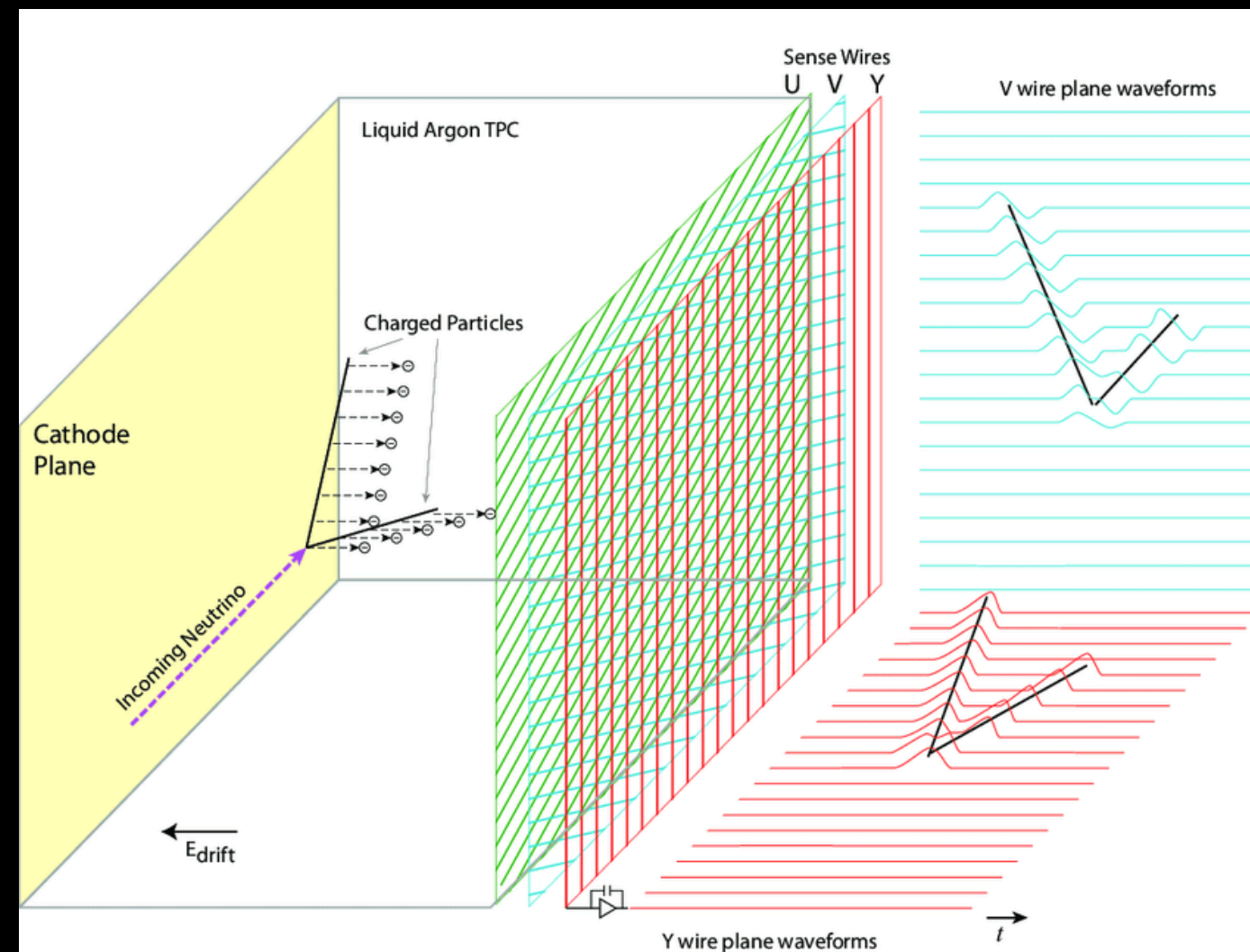
- Oscillation physics: CP-violation and neutrino mass ordering (MO); Energies O(GeV)
- MO,  $\delta_{CP}$ , and  $\theta_{23}$  all impact the spectral shape → need to resolve the different effects
- After some years, systematics become important, and among them, energy response
- Uncertainty on energy scale < 2% (5%) for leptons (hadrons)



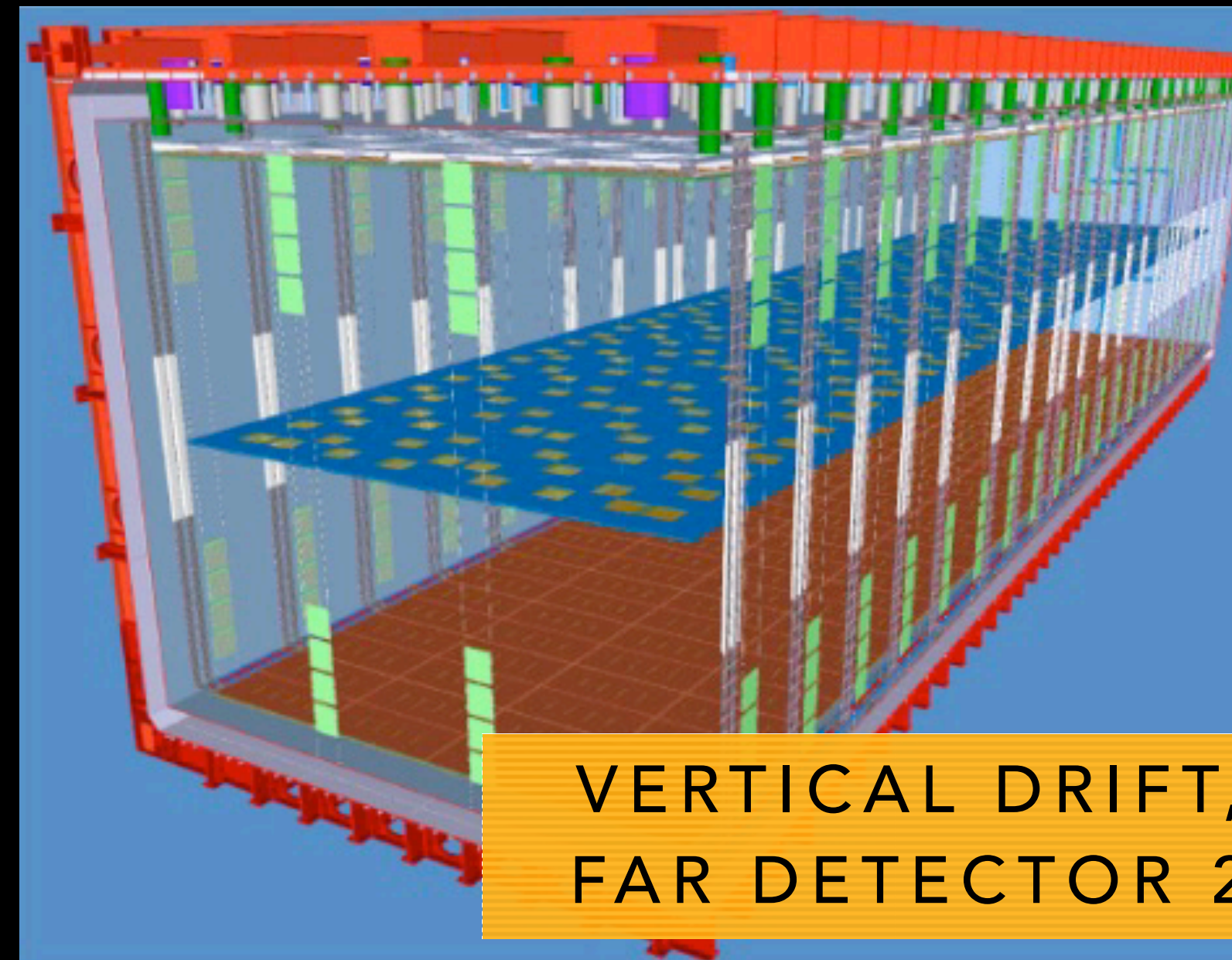
- Supernova neutrino burst
- Energies O(MeV)
- Energy resolution 20-30%



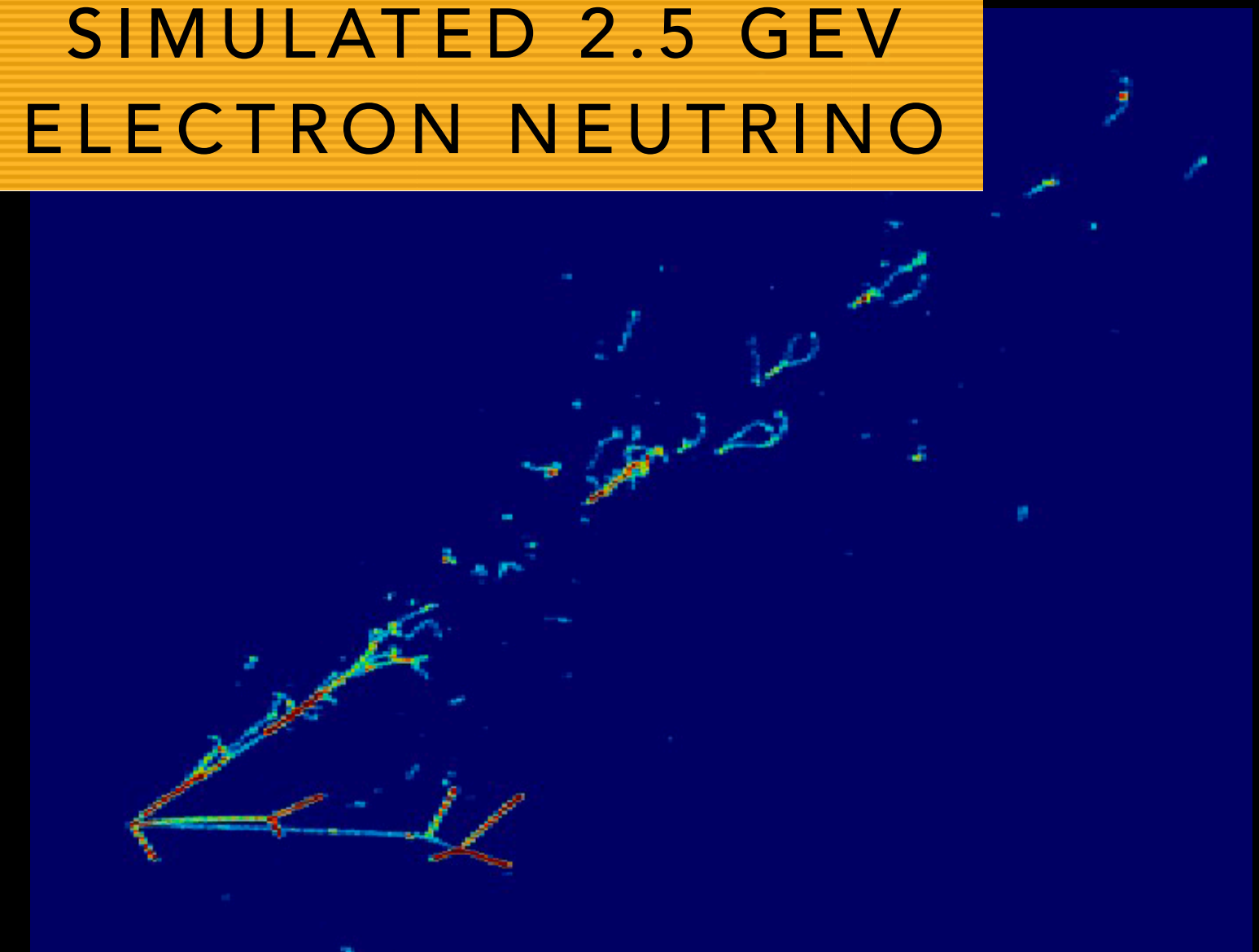
# LIQUID ARGON TPC



- LAr Time Projection Chambers
- Technology invented by C. 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 reconstruction (particle ID, energy)



SIMULATED 2.5 GEV  
ELECTRON NEUTRINO

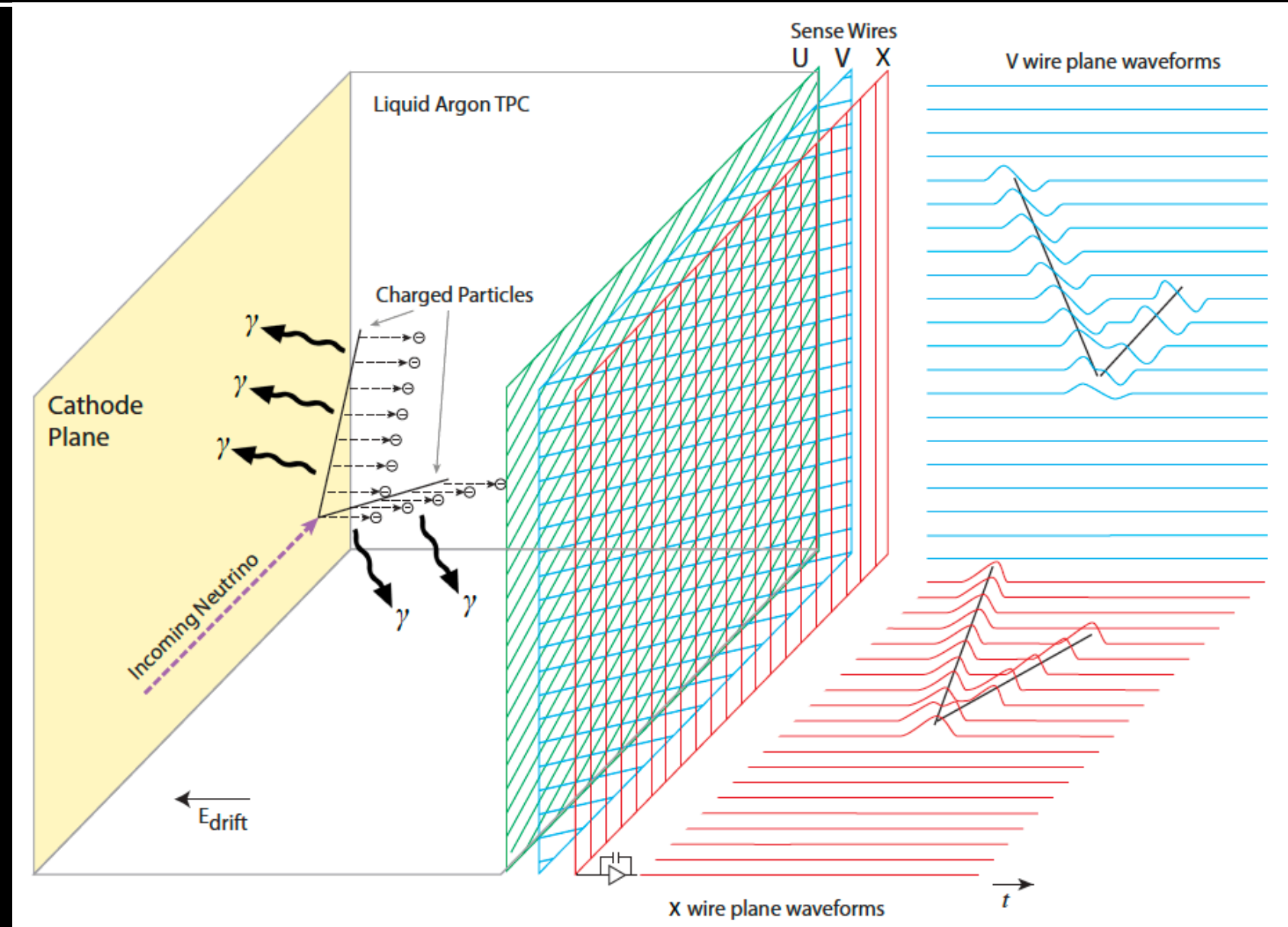




# LIQUID ARGON TPC CALIBRATIONS



## LOW LEVEL: MEASURE MODEL PARAMETERS

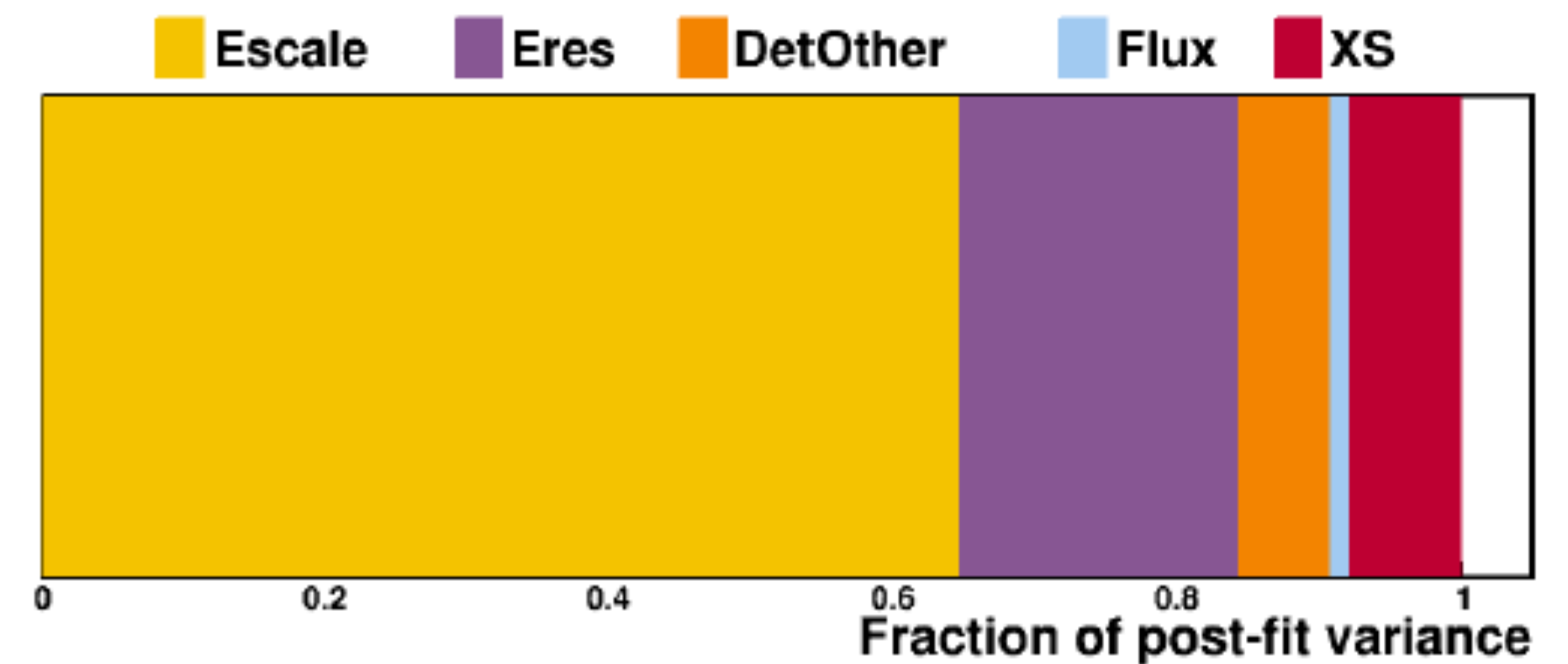


- Wire collection efficiency, etc.
- HV system and readout planes geometry
- Drift velocity/E-field maps
- Purity/lifetime/diffusion
- Recombination model
- Work function, dQ/dE scale

## HIGH LEVEL: CHECK RECONSTRUCTION PERFORMANCE

- Overall energy scale factor
- Energy/momentum scale and resolution
- Position offsets/resolution
- Particle ID algorithm biases
- Correlations and systematics

### Contributions to $\delta_{CP}$ systematic:





# DUNE CALIBRATION STRATEGY



Best source for this  
Some limitations

IoLaser = Ionisation Laser System, to be described next  
Pulsed Neutron Source, based on external deuterium-tritium generator  
Bi207 = Fixed location conversion electron source (1 MeV)

| Goal                       | Measurement                             | Natural sources                                   | Deployed sources                               |
|----------------------------|-----------------------------------------|---------------------------------------------------|------------------------------------------------|
| Determine parameters       | Detector defects, alignment             | Cosmics (low stats)                               | IoLaser                                        |
|                            | Drift velocity/ E-field                 | Cosmics (low stats)                               | IoLaser                                        |
|                            | Electron lifetime, diffusion            | Cosmics (low stats), Ar39                         | Purity Monitors (lim. cov.),<br>IoLaser, Bi207 |
|                            | Recombination                           | Cosmics, beam                                     | IoLaser (angular dependence ?)                 |
| Reconstruction Performance | High energy: $\mu$ track $dE/dx$        | Cosmics, beam: muon tracks                        | X                                              |
|                            | High/Mid energy $e/\gamma$              | Cosmics, beam: $\pi^0$ decays, Michels (low stat) | X                                              |
|                            | Low energy “standard candle” $e/\gamma$ | X                                                 | Pulsed Neutron Source, Bi207 (lim. cov.)       |
|                            | Neutrons                                | X                                                 | Pulsed Neutron Source                          |

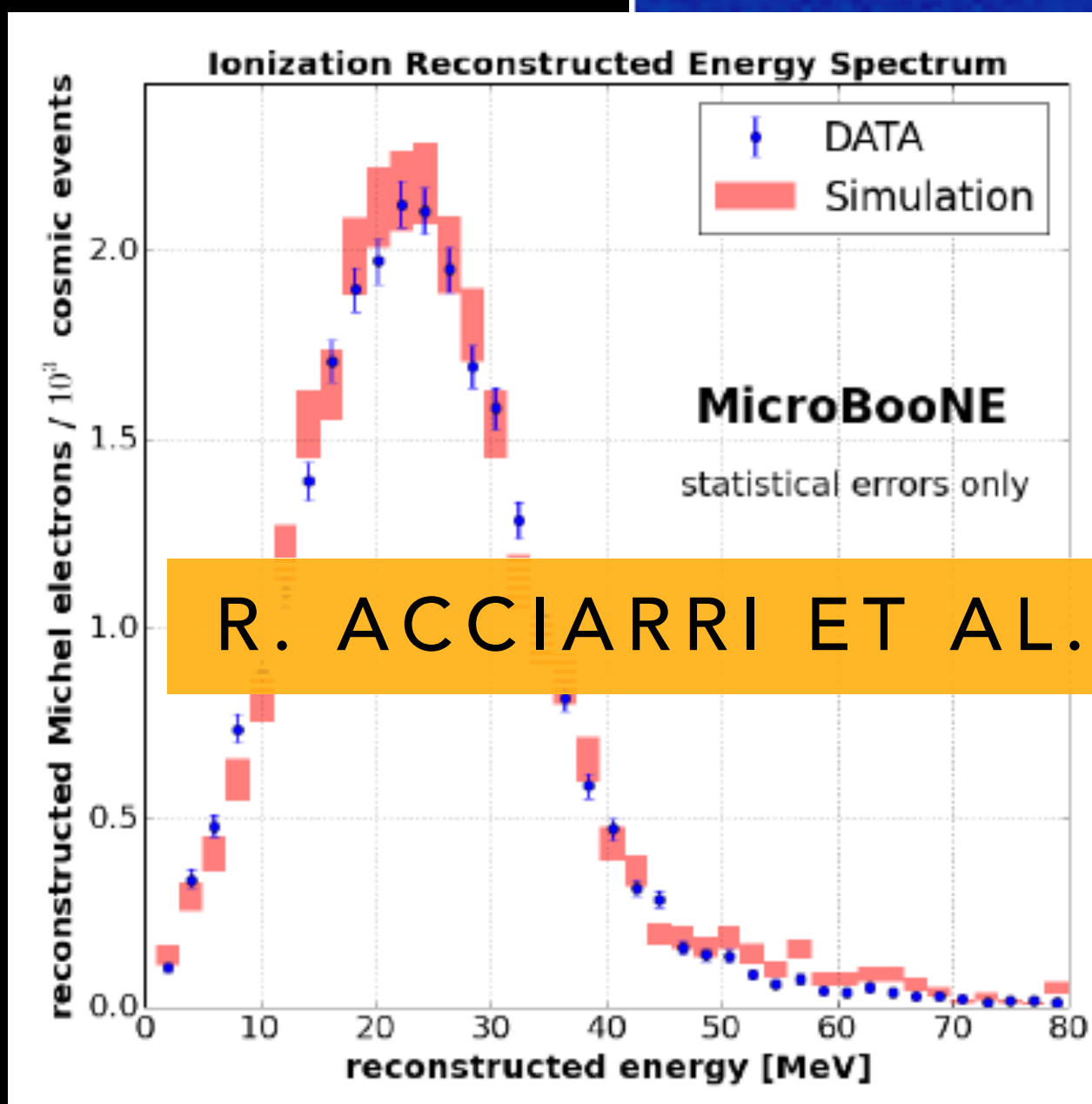
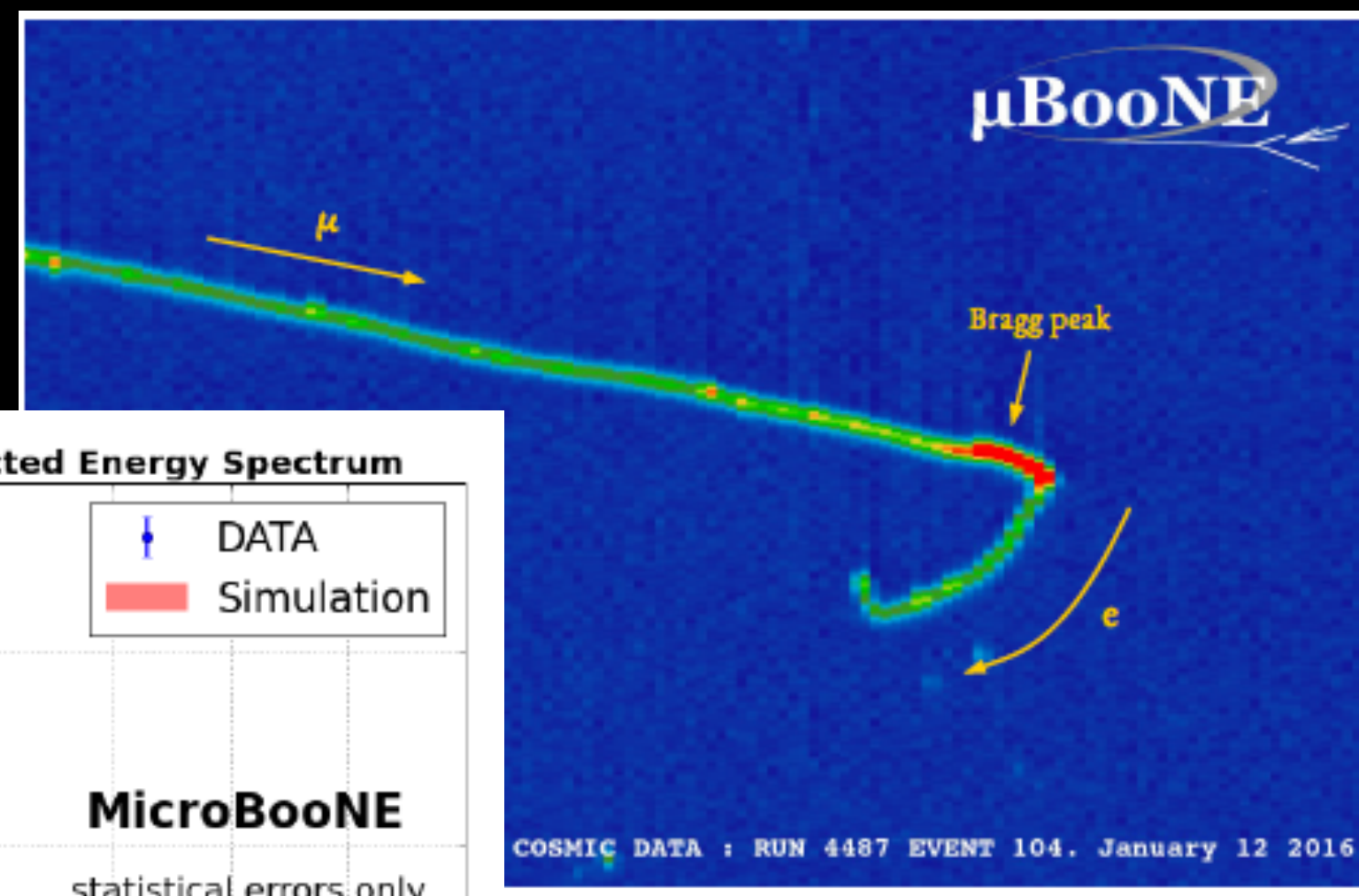
CALIBRATION OF LIQUID  
ARGON TIME PROJECTION  
CHAMBERS  
WITH NATURAL SOURCES



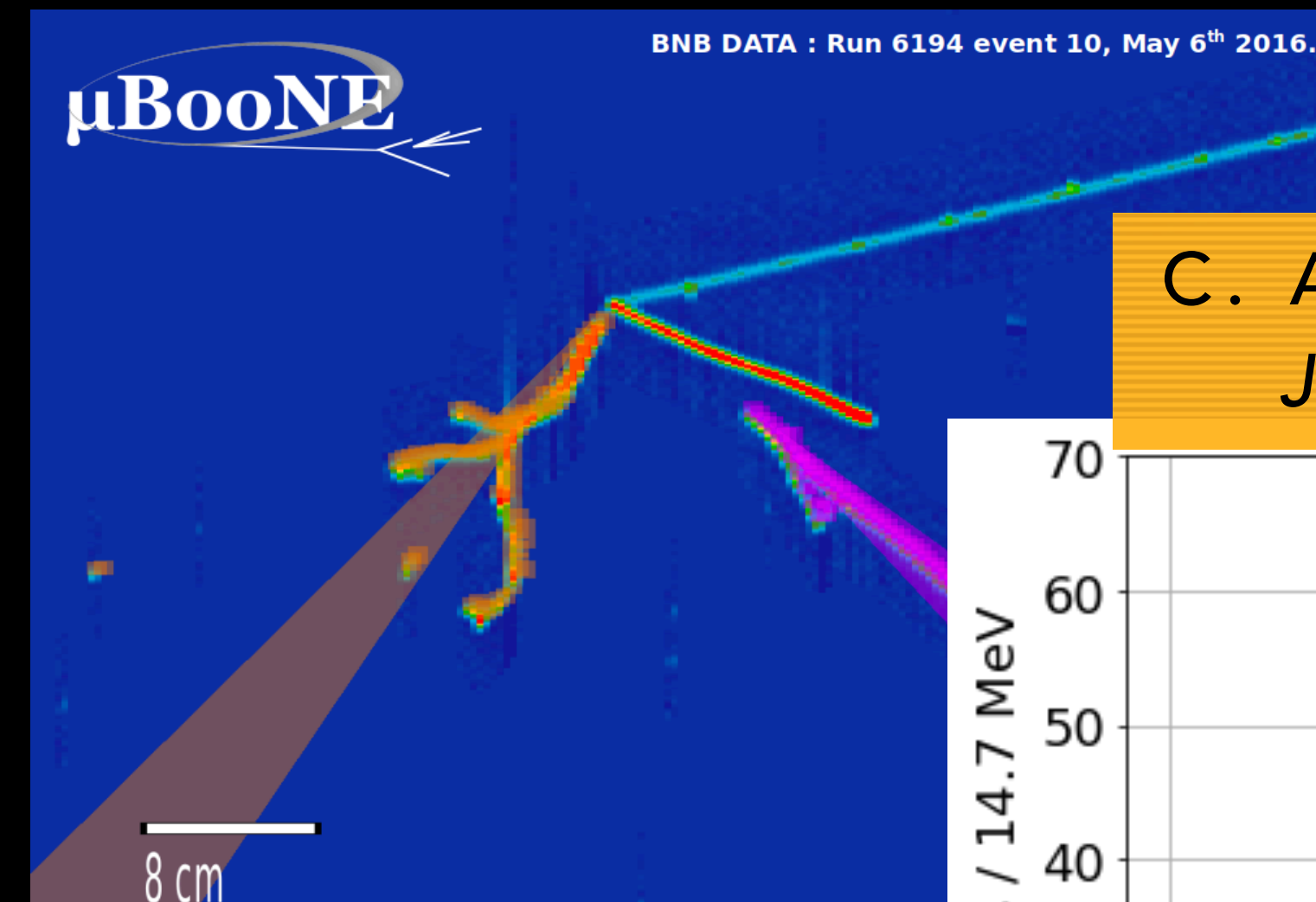
# RECONSTRUCTION PERFORMANCE



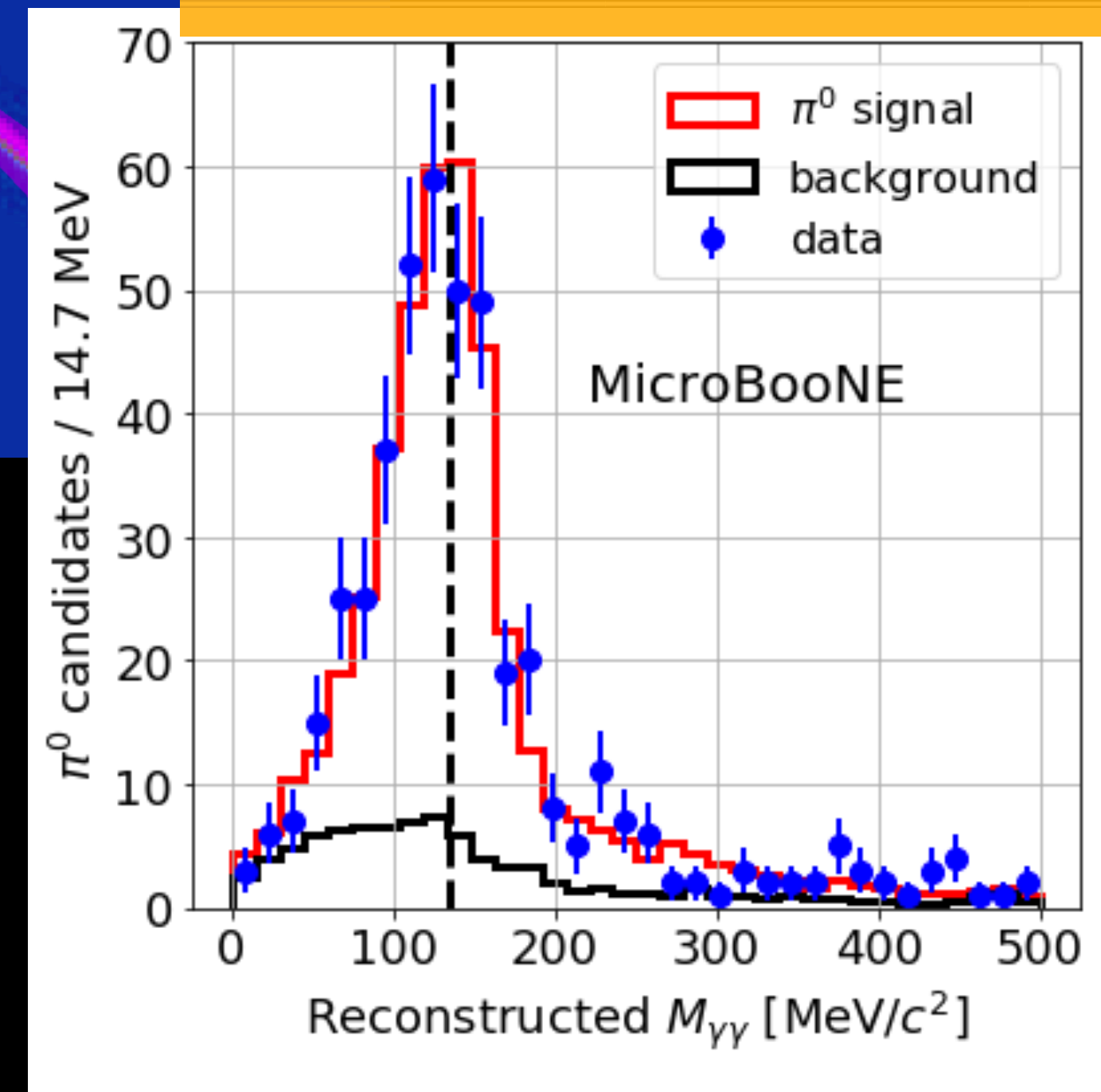
- Michel electrons provide energy scale at low energies
- $\pi^0 \rightarrow 2\gamma$  provide energy scale at intermediate energies



R. ACCIARRI ET AL. 2017 JINST 12 P09014



C. ADAMS ET AL 2020  
JINST 15 P02007



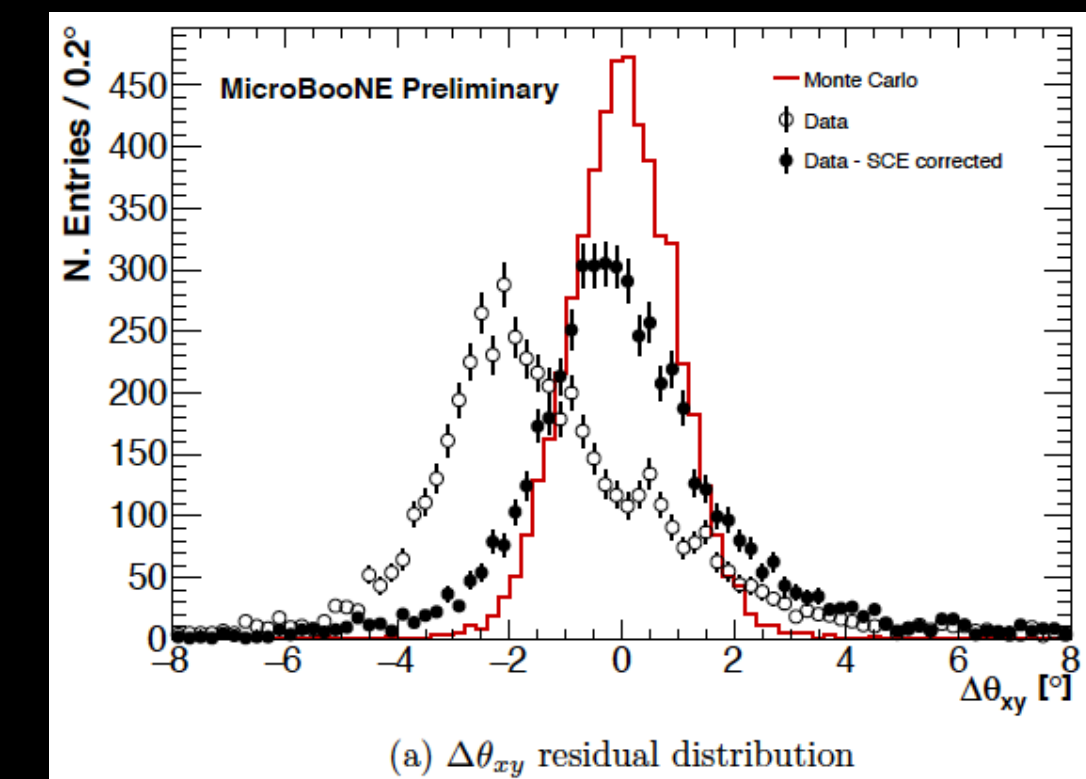
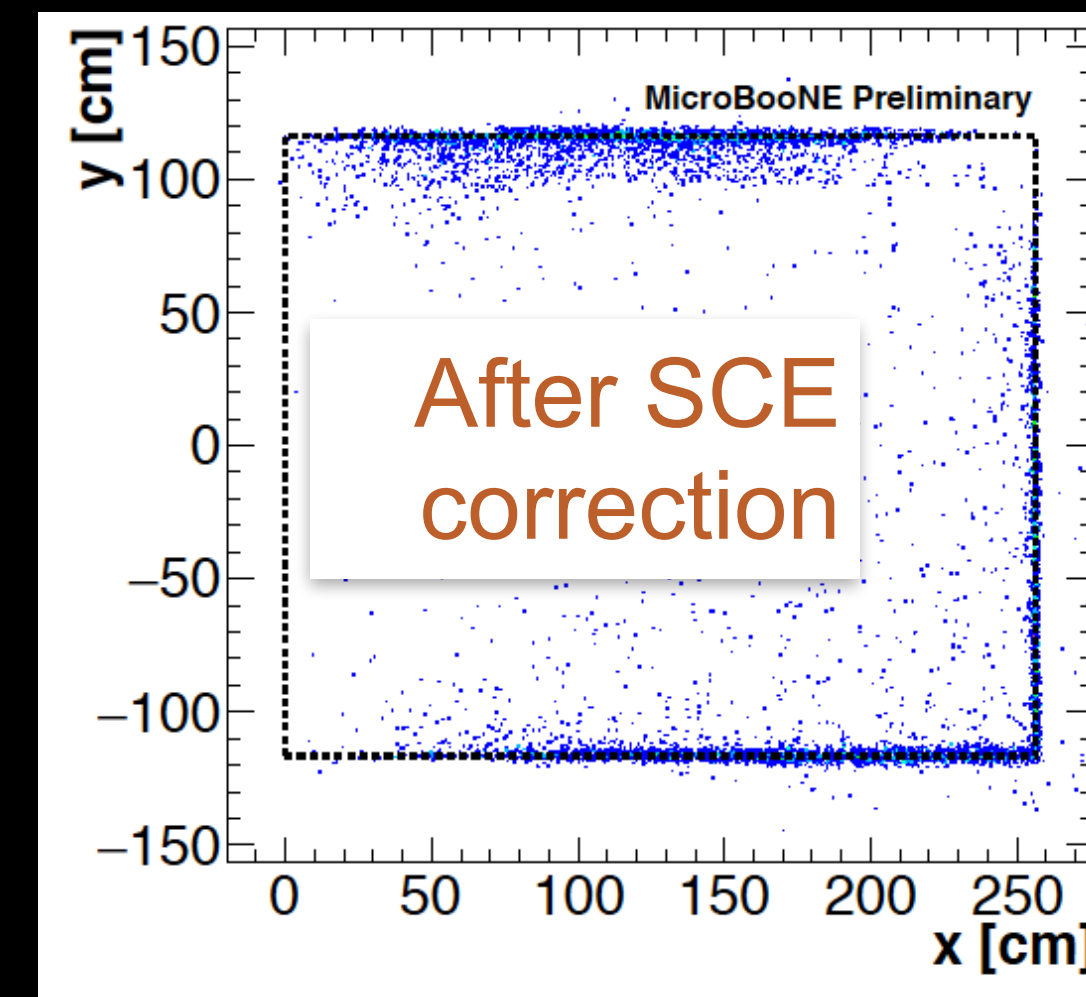
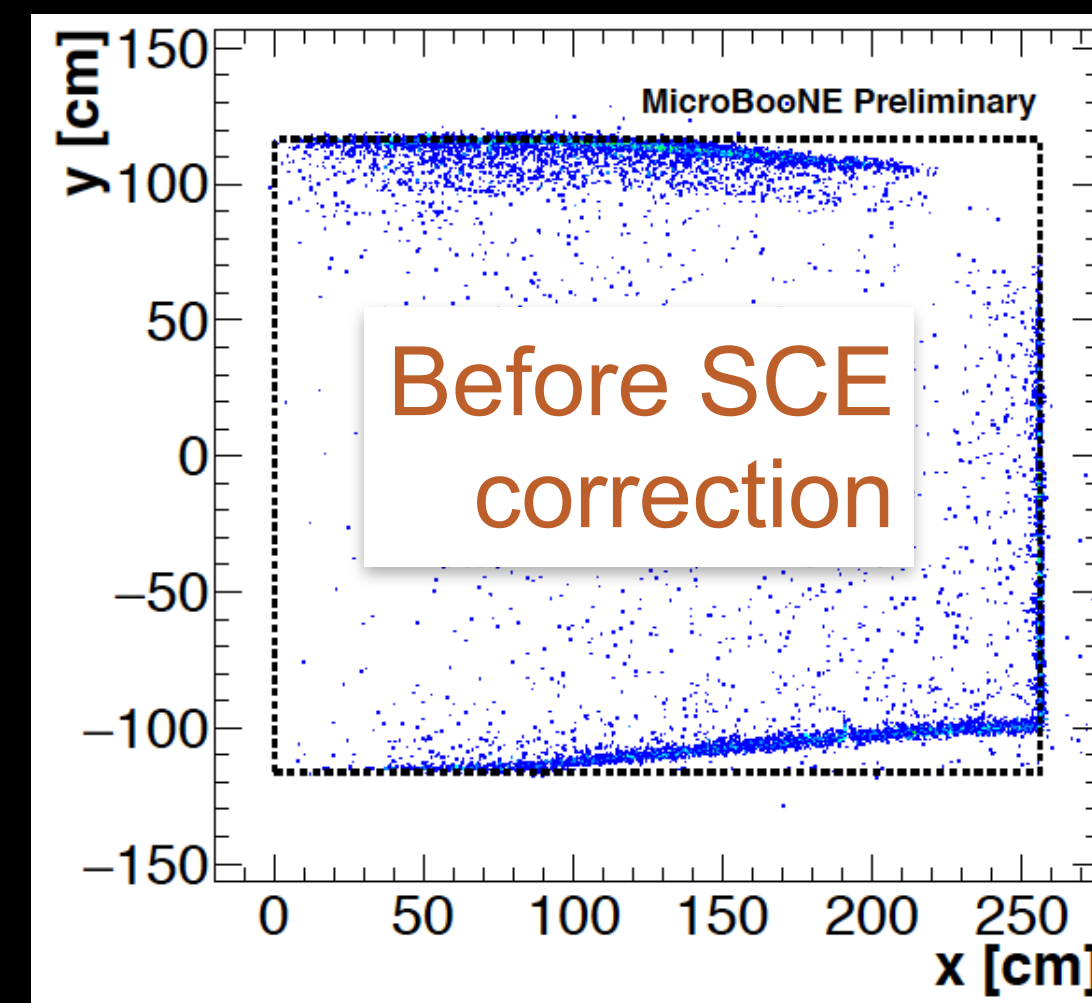
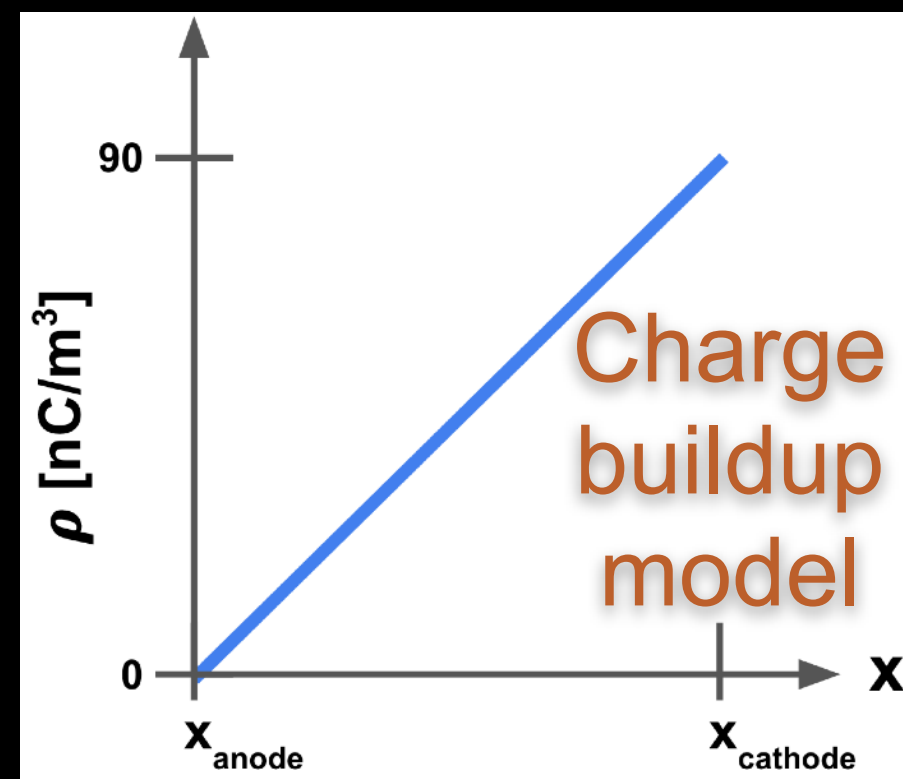
COSMICS AND BEAM EVENTS  
IRREPLACEABLE FOR THESE  
MEASUREMENTS

# SPACE-CHARGE WITH COSMIC MUONS



MICROBOONE-  
NOTE-1018-PUB

- Ion drift velocity much lower ( $2 \times 10^5$ ) than for electrons
- Charge buildup (cosmics) distorts E-field and drift velocity, impacts position reconstruction and charge collection (due to recombination)
- Distortions of tracks observed with end-points of externally tagged muons, can use that to extract correction



- What if the detector is underground (UG)? The effect is smaller, but harder to measure
- Alternatively can use ionization laser system



# CHARGE RESPONSE

JINST 15 (2020) P12004

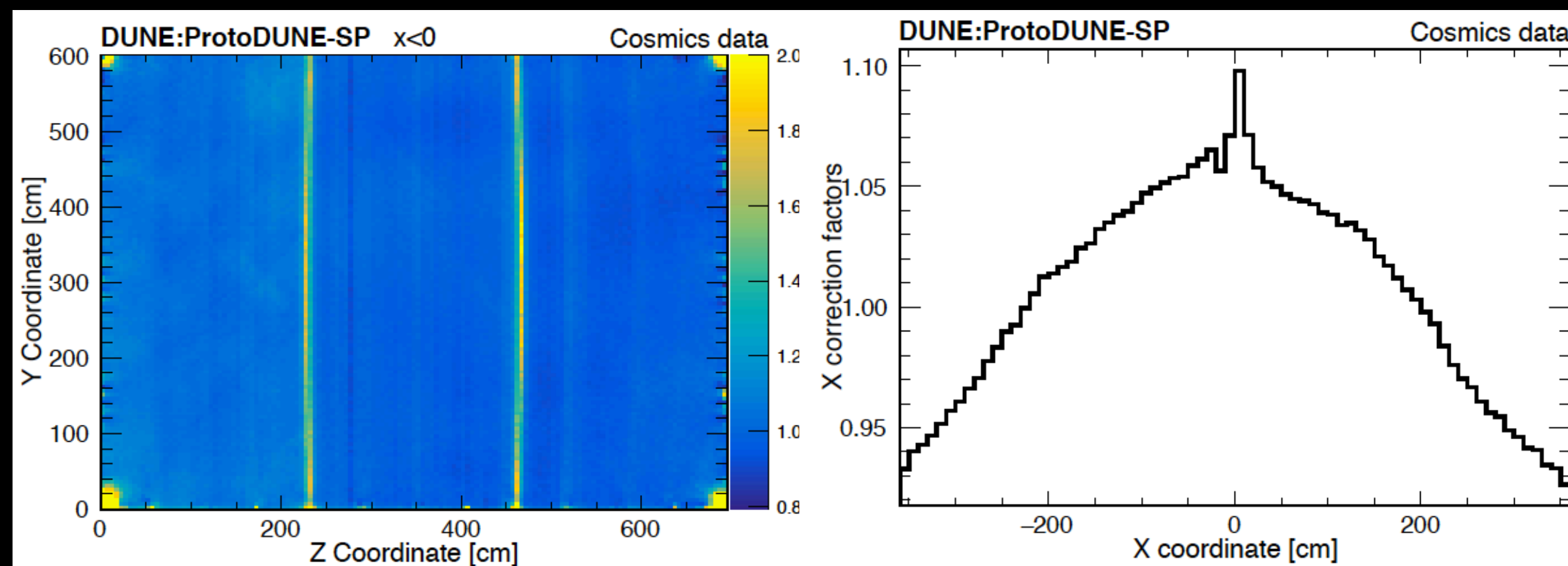
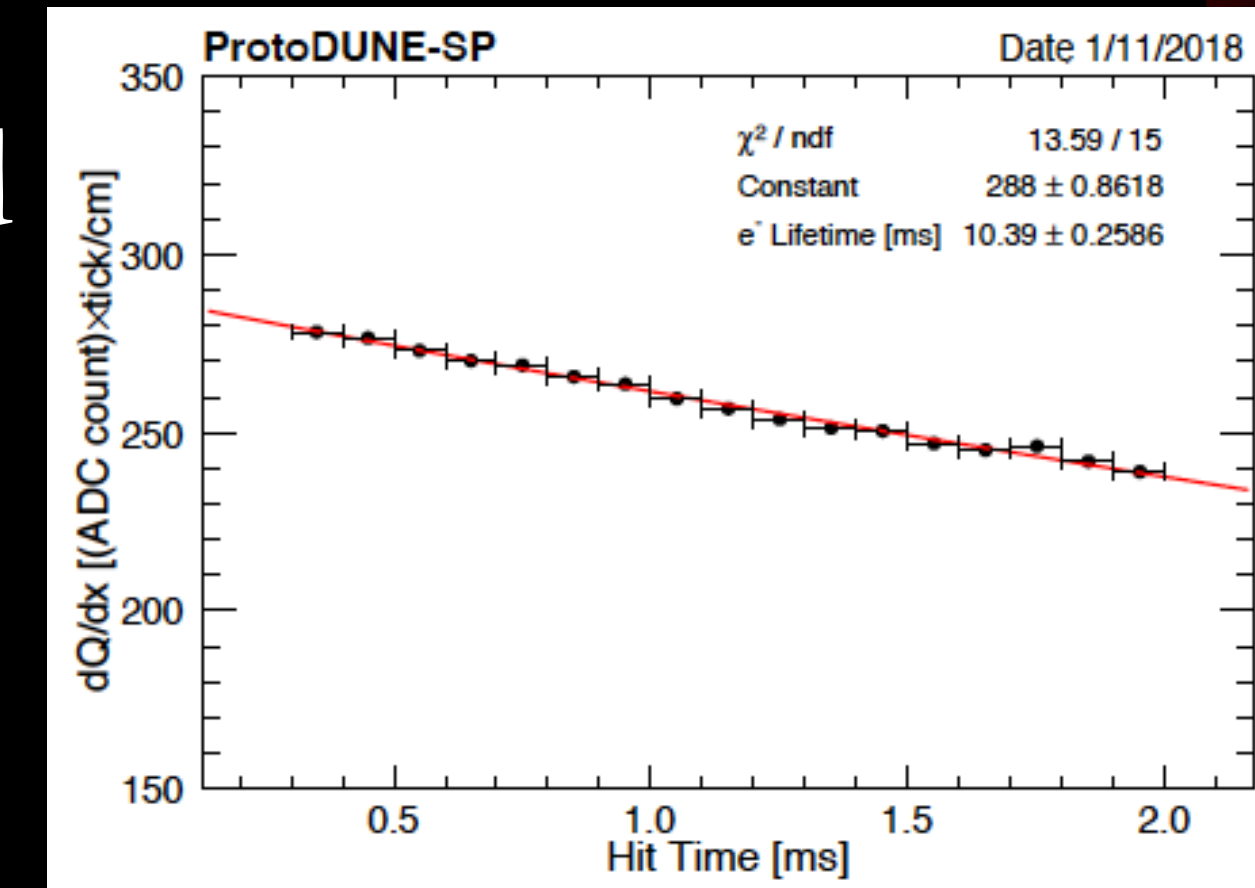


$$dQ'_e = dQ_e e^{-t/\tau}$$

$$N_{O_2} = \frac{1}{k_a \tau} = \frac{300 \text{ ppt ms}}{\tau}$$

NO<sub>2</sub>: Oxygen contamination

- ProtoDUNE measured electron lifetime with tagged cosmics, high stats.
- Precision of 0.5% in Q ratio achieved
- However, directly related to purity, so can change fast and be non-uniform across detector

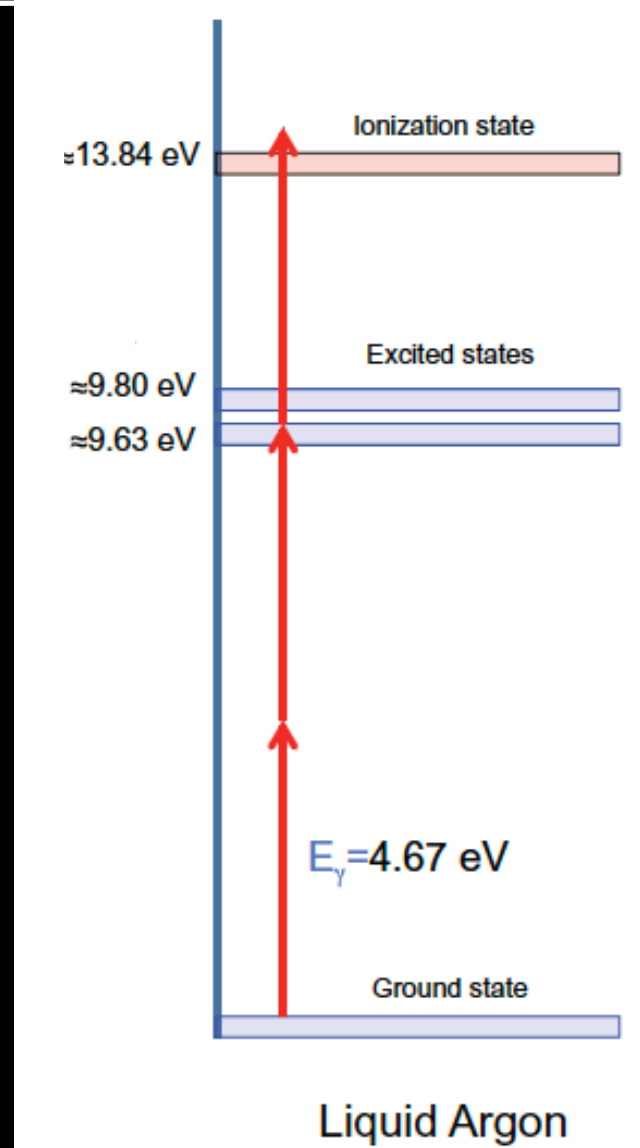


- Energy response maps require 100k tracks for 2% precision, fine map
- With anode-crossing tracks, it would take 15 yrs to do the same UG.

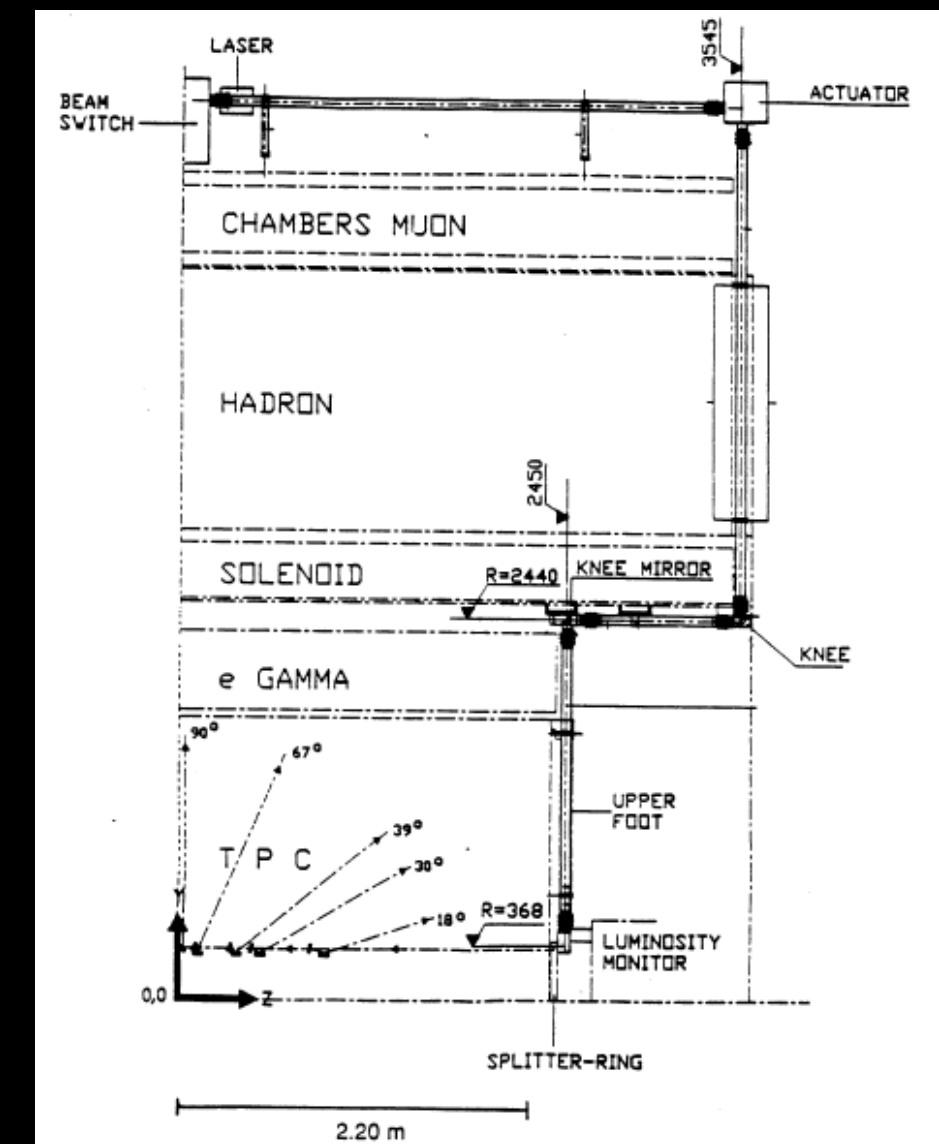
DESIGN OF DUNE  
IONISATION LASER  
CALIBRATION SYSTEM



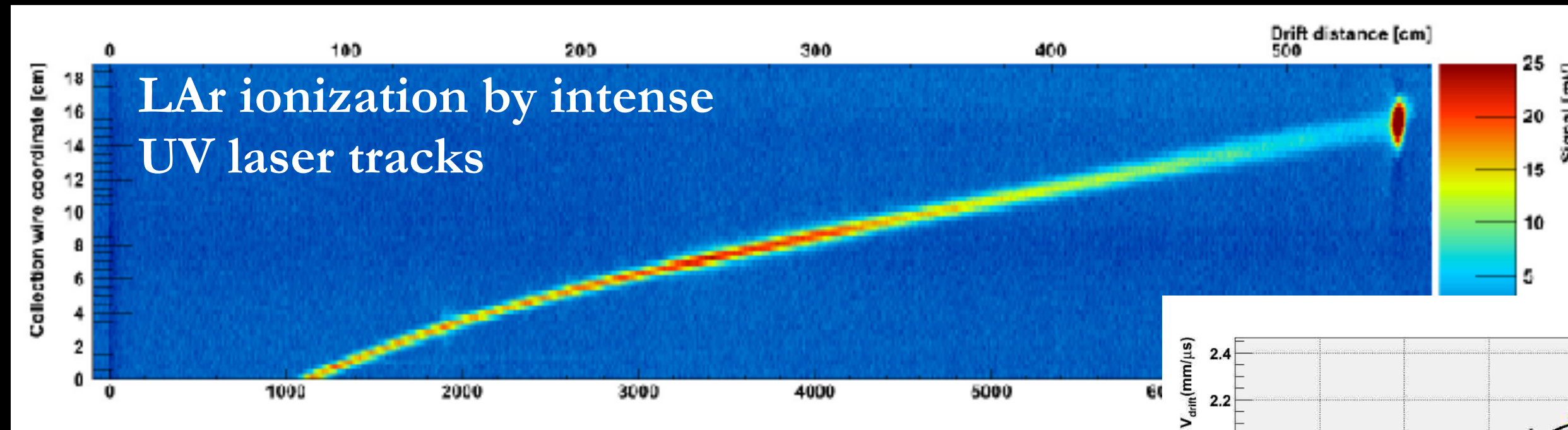
# IONIZING ARGON WITH LASER



- Since 1980's: Lasers used to create tracks and calibrate gas detectors. Ex.: TPC of ALEPH.  $\longrightarrow$
- Tune gas mixtures so only 2 photons needed to ionize.
- Moderate laser intensity  $\sim 1 \mu\text{J}/\text{mm}^2$
- R&D on LAr ionization @CERN, Napoli, Bern.
- 3-photon process  $\sim 500 \mu\text{J}/\text{mm}^2$
- Requires more intense, Nd-YAG ultra-violet laser



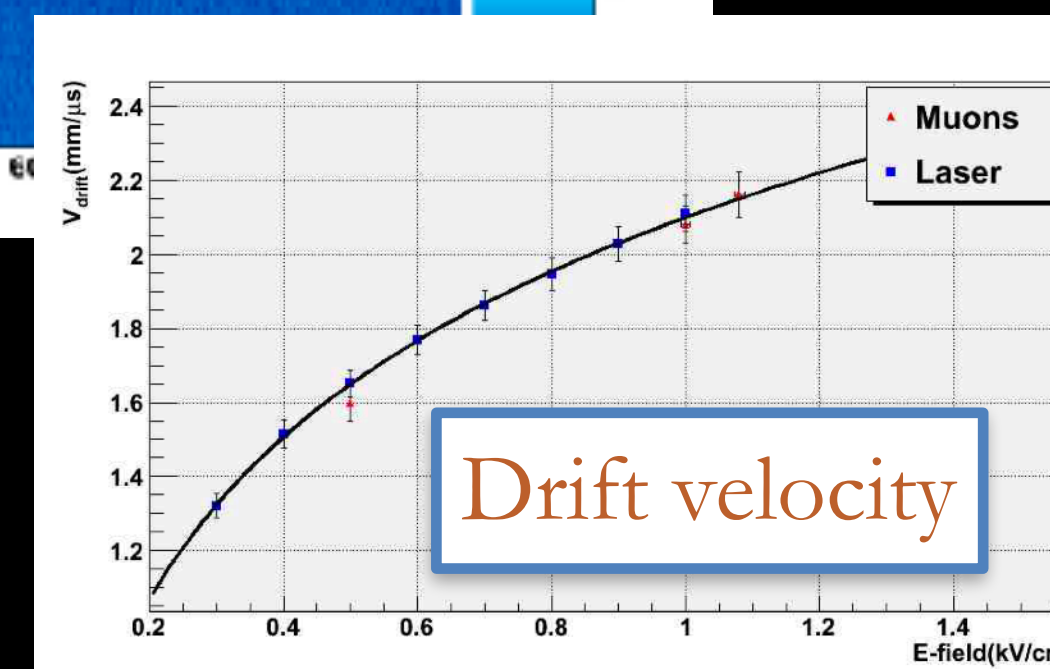
ARGONTUBE,  
LEP BERN



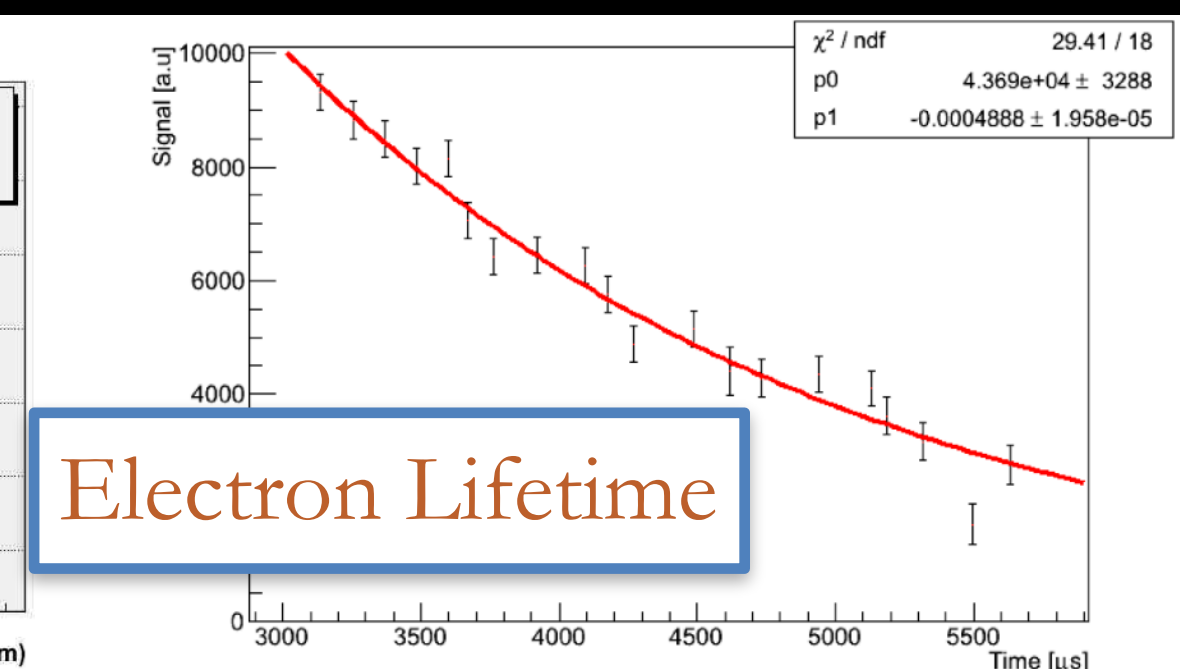
LAr ionization by intense  
UV laser tracks

I. BADHREES ET AL. 2010  
NEW J. PHYS. 12 113024

B ROSSI ET AL 2009  
JINST 4 P07011  
A EREDITATO ET AL  
2013 JINST 8 P07002



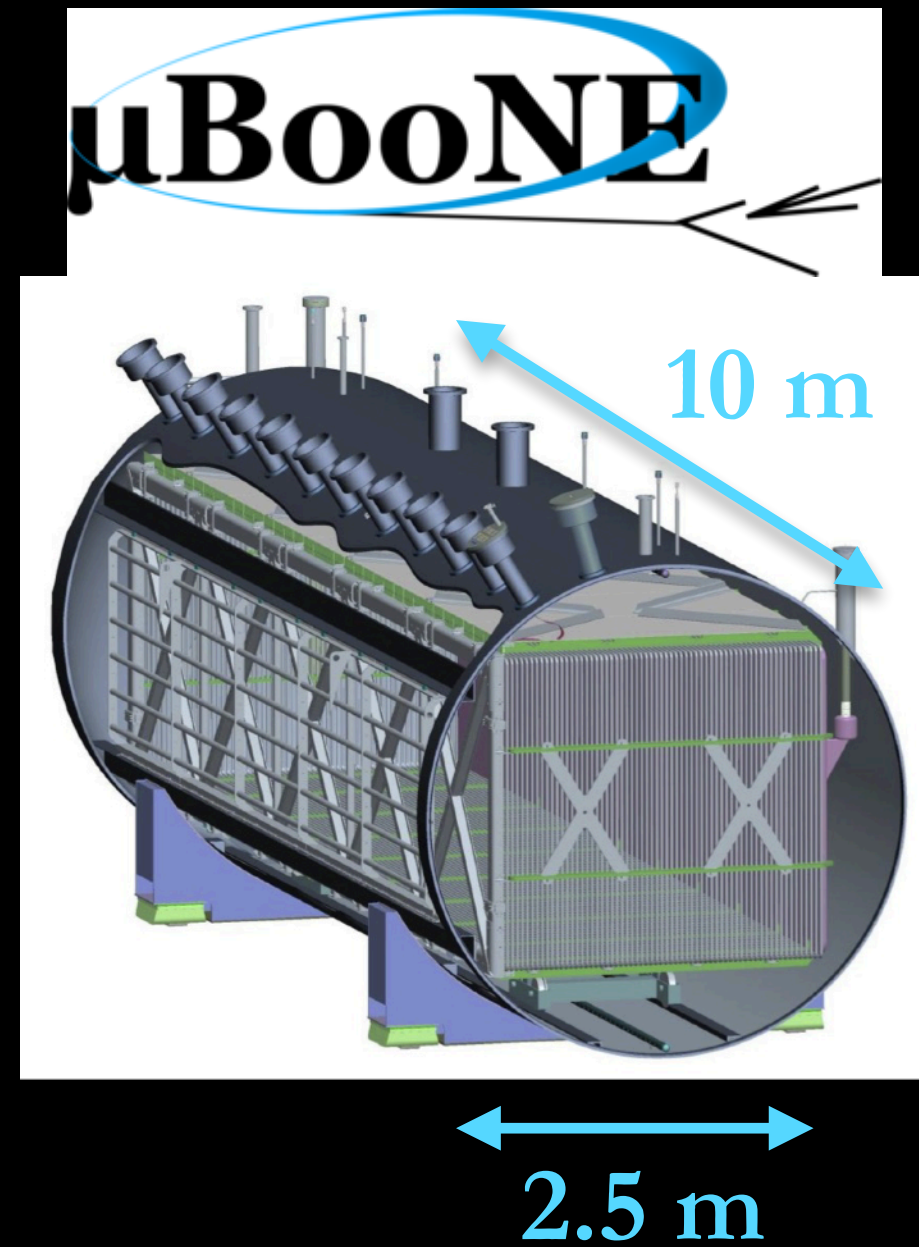
Drift velocity



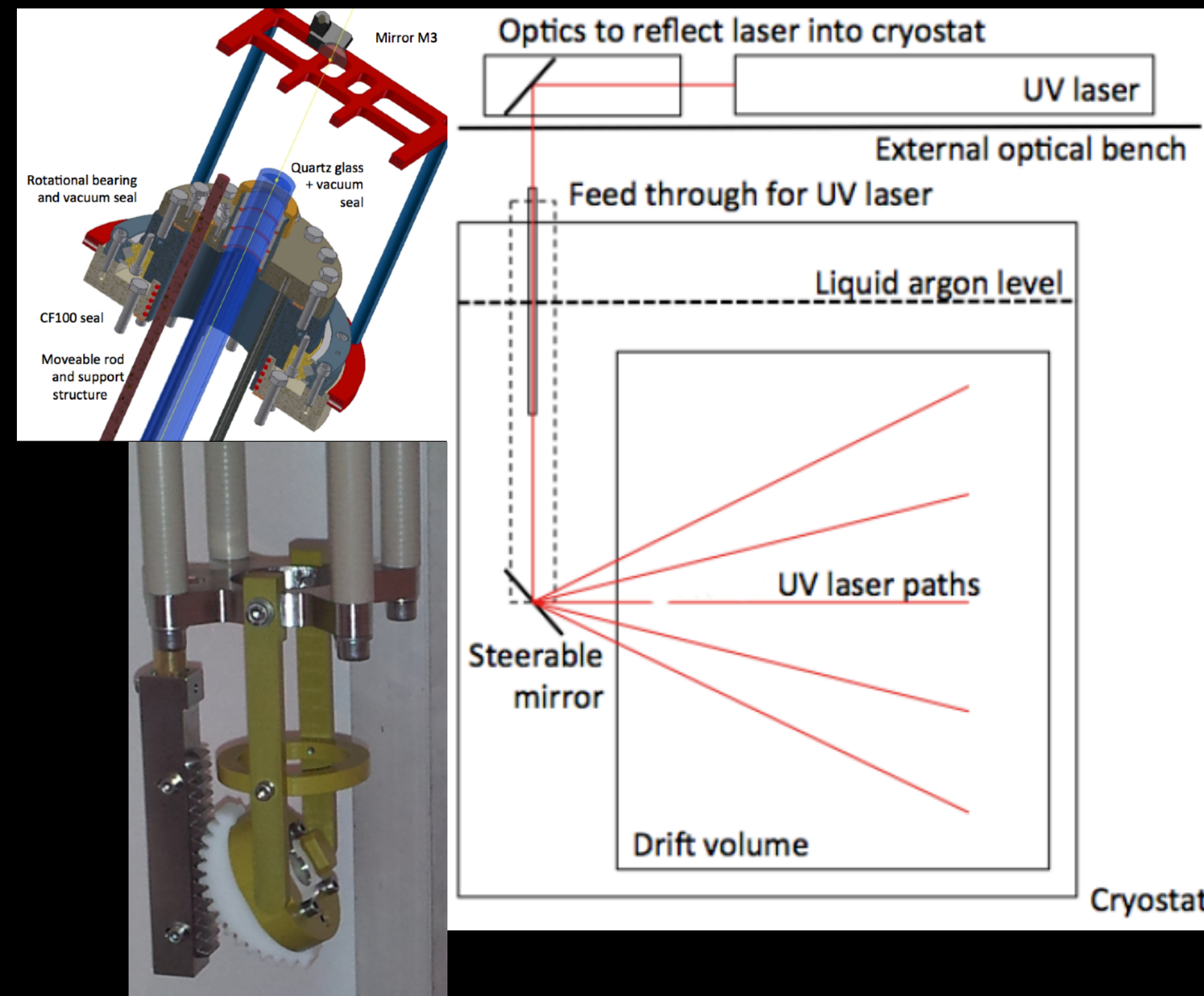
Electron Lifetime



# MICROBOONE'S LASER SYSTEM



MicroBooNE @  
FNAL  
90 tons (active)  
at surface



- MicroBooNE: first large detector with a ionization laser system
- Intense (60 mJ) UV(266 nm) laser
- Steerable cold mirrors in inverted periscopes
- Two periscopes in opposite sides, to get crossing tracks

C. ADAMS ET AL  
2020 JINST 15  
P07010

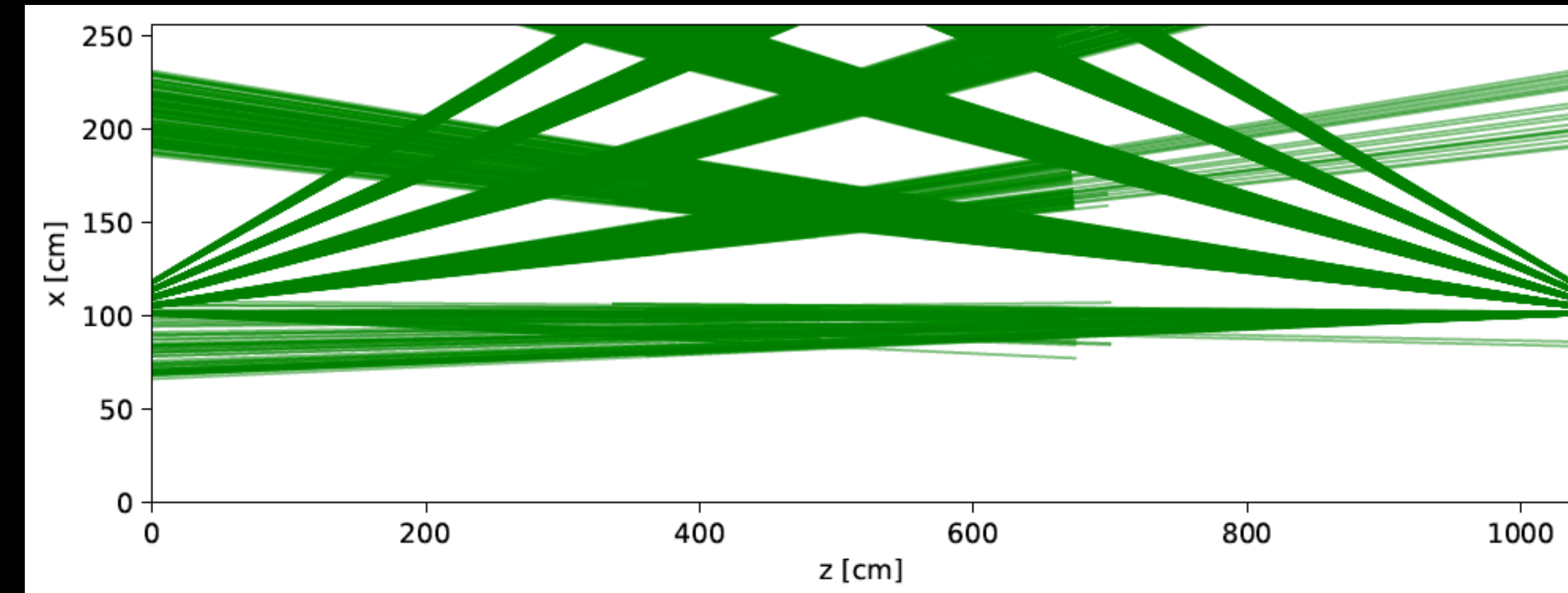
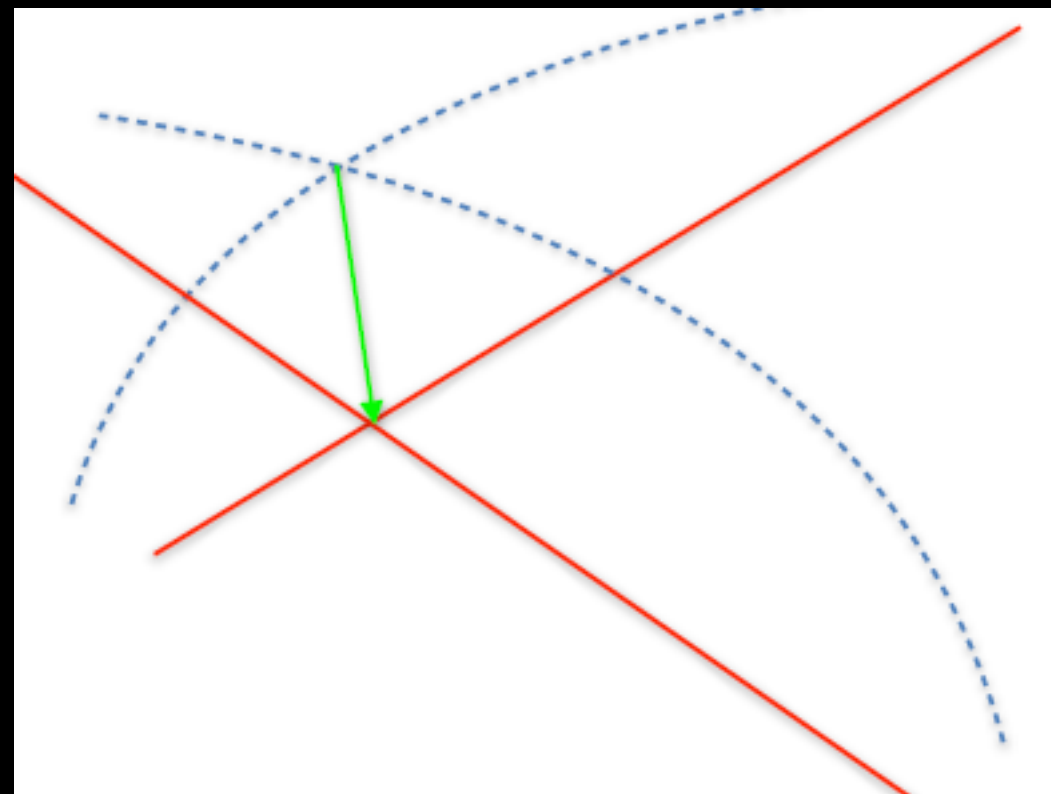
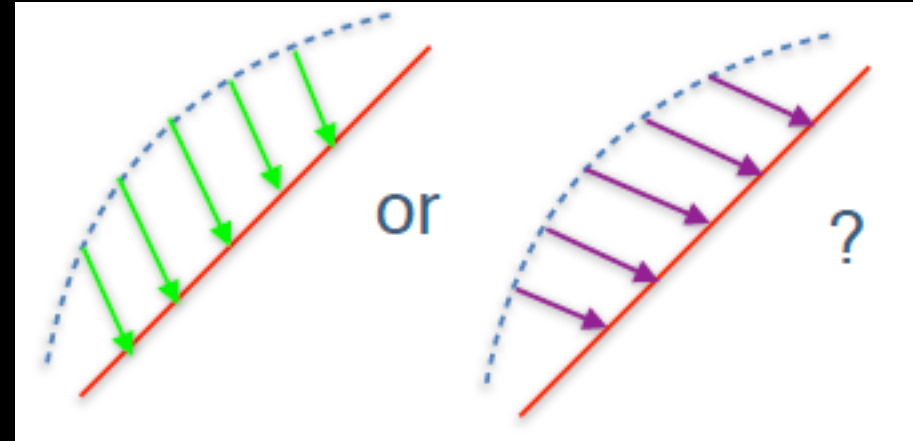
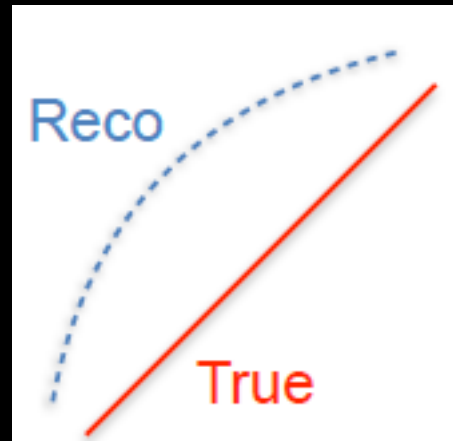
Also at SBND



# MICROBOONE'S LASER CALIBRATION

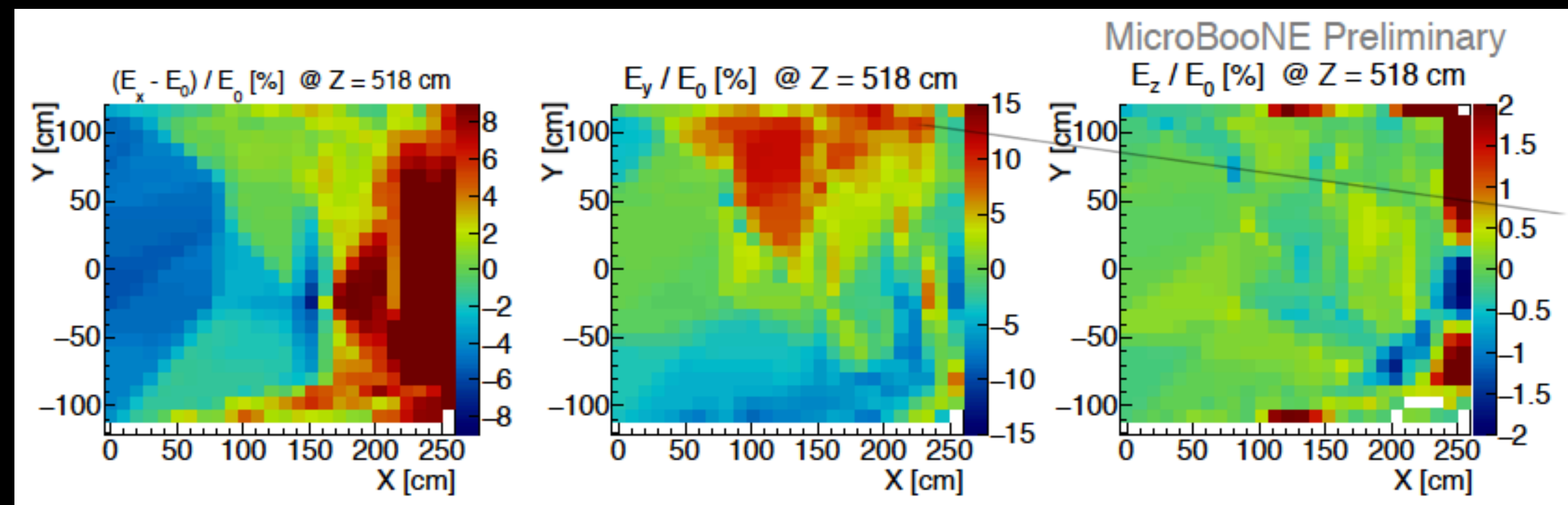


- MicroBooNE's laser track directions
- Limited by field cage shadowing
- Crossing tracks



- Compare true and reconstructed track → measured E-field distortions with 2% precision

Crossing tracks remove ambiguity about apparent displacements



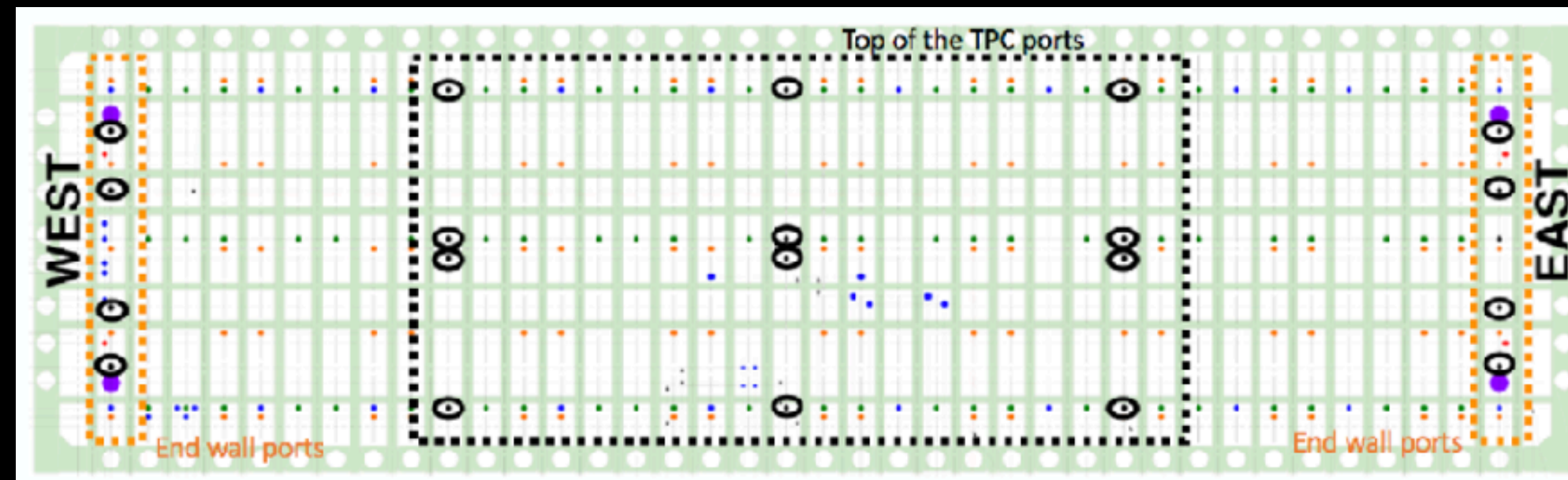
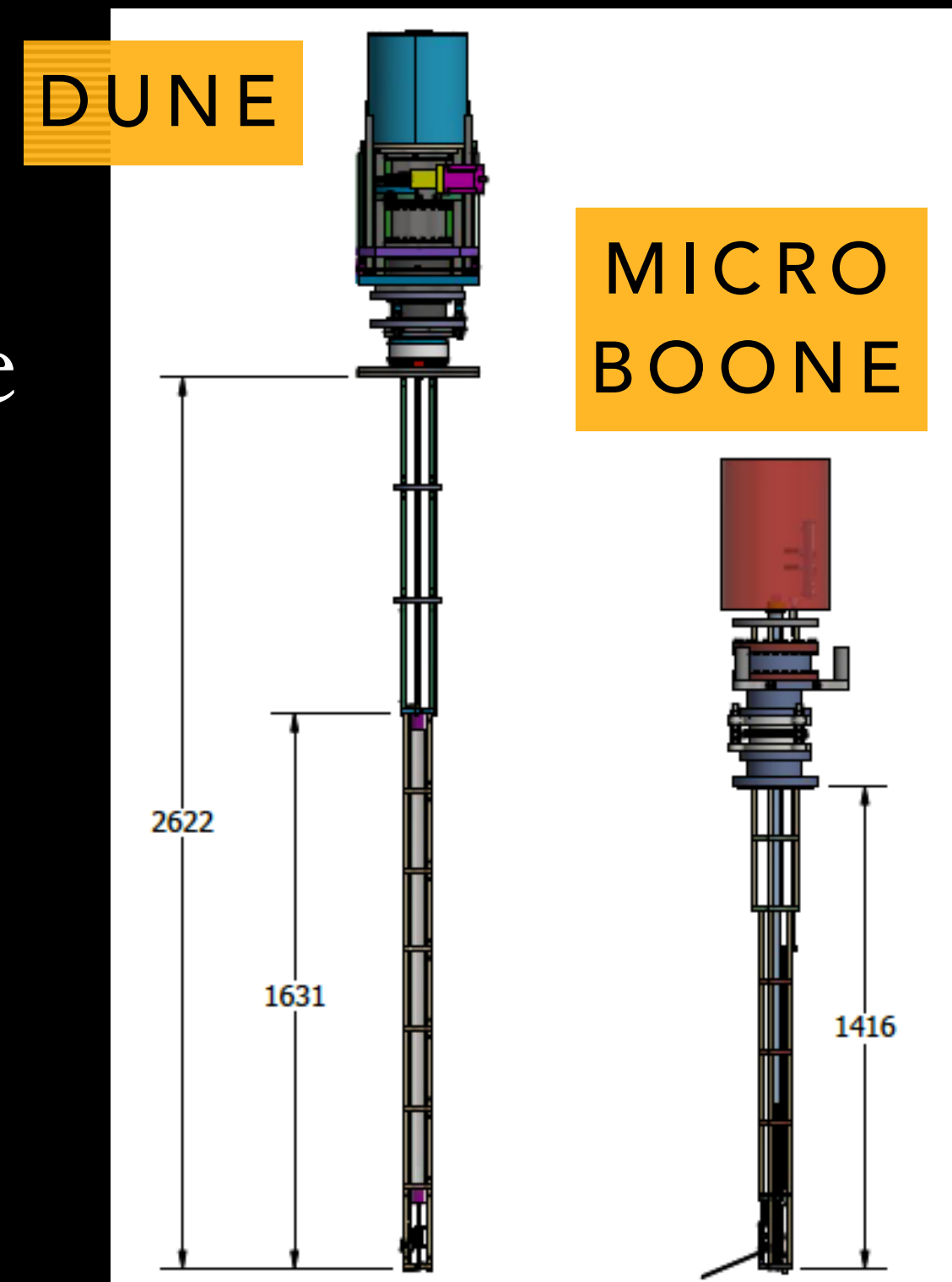
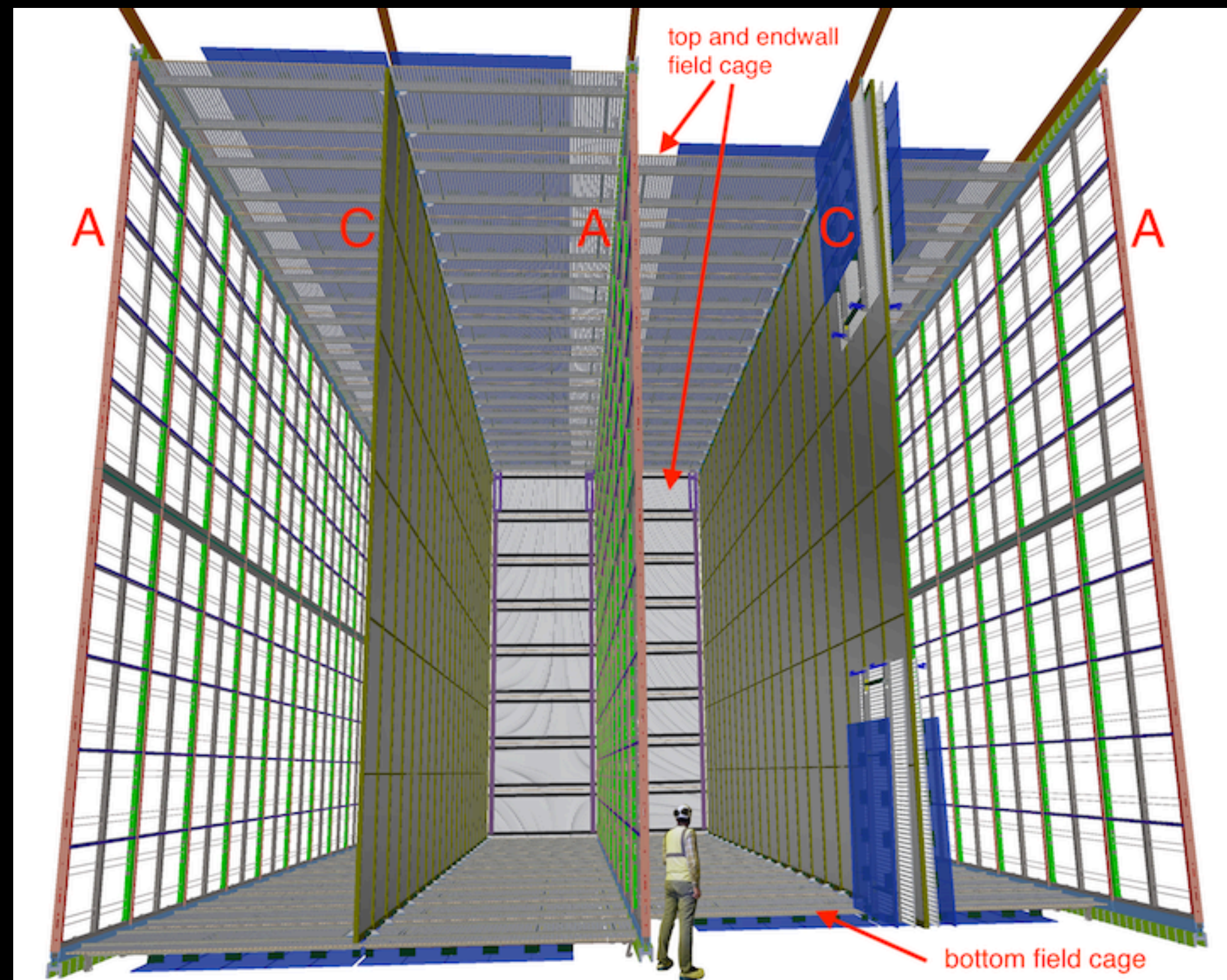


# NEW ASPECTS IN DUNE SYSTEM

- Much bigger detector
- Segmented detector
- Need better coverage
- Need better precision



- Longer periscopes
- More periscopes
- New designs improve coverage
- DAQ integration to improve automatization
- New systems to check-alignment in-situ





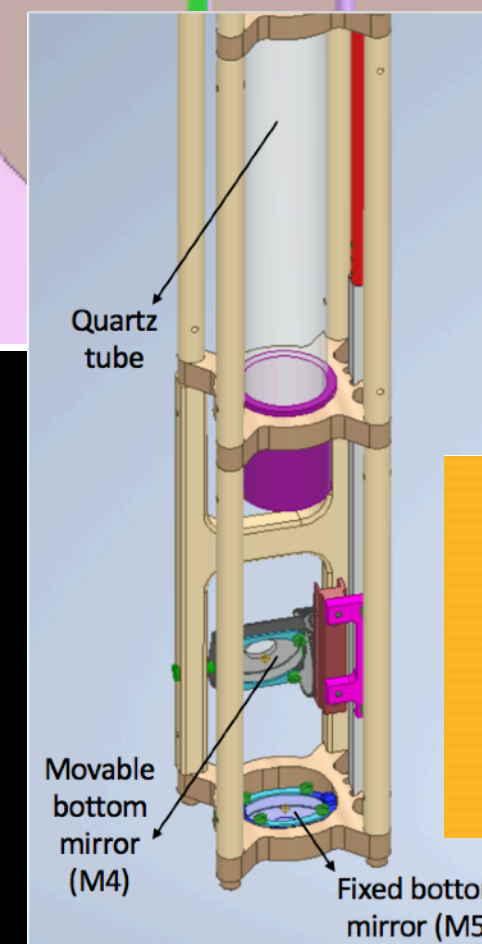
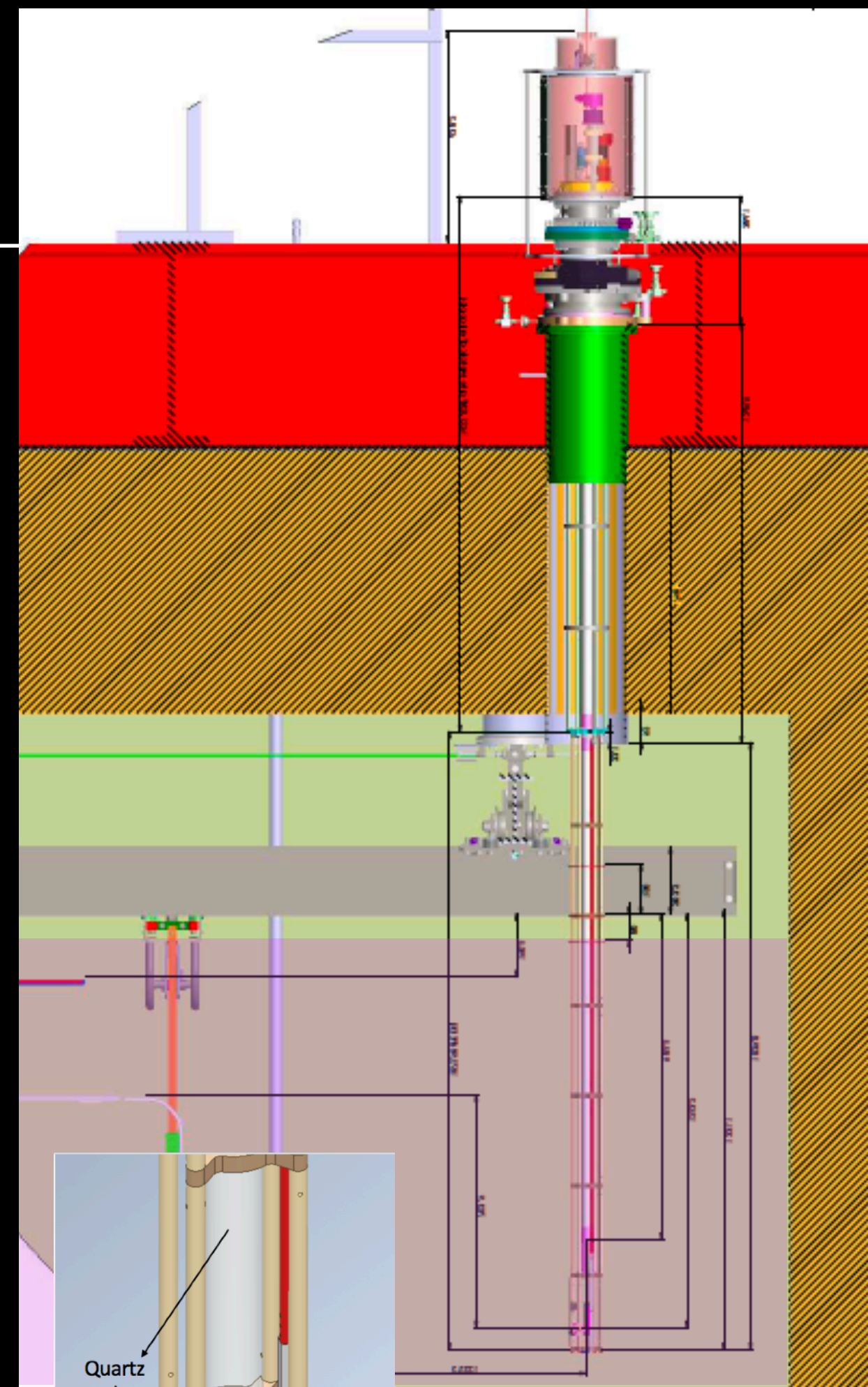
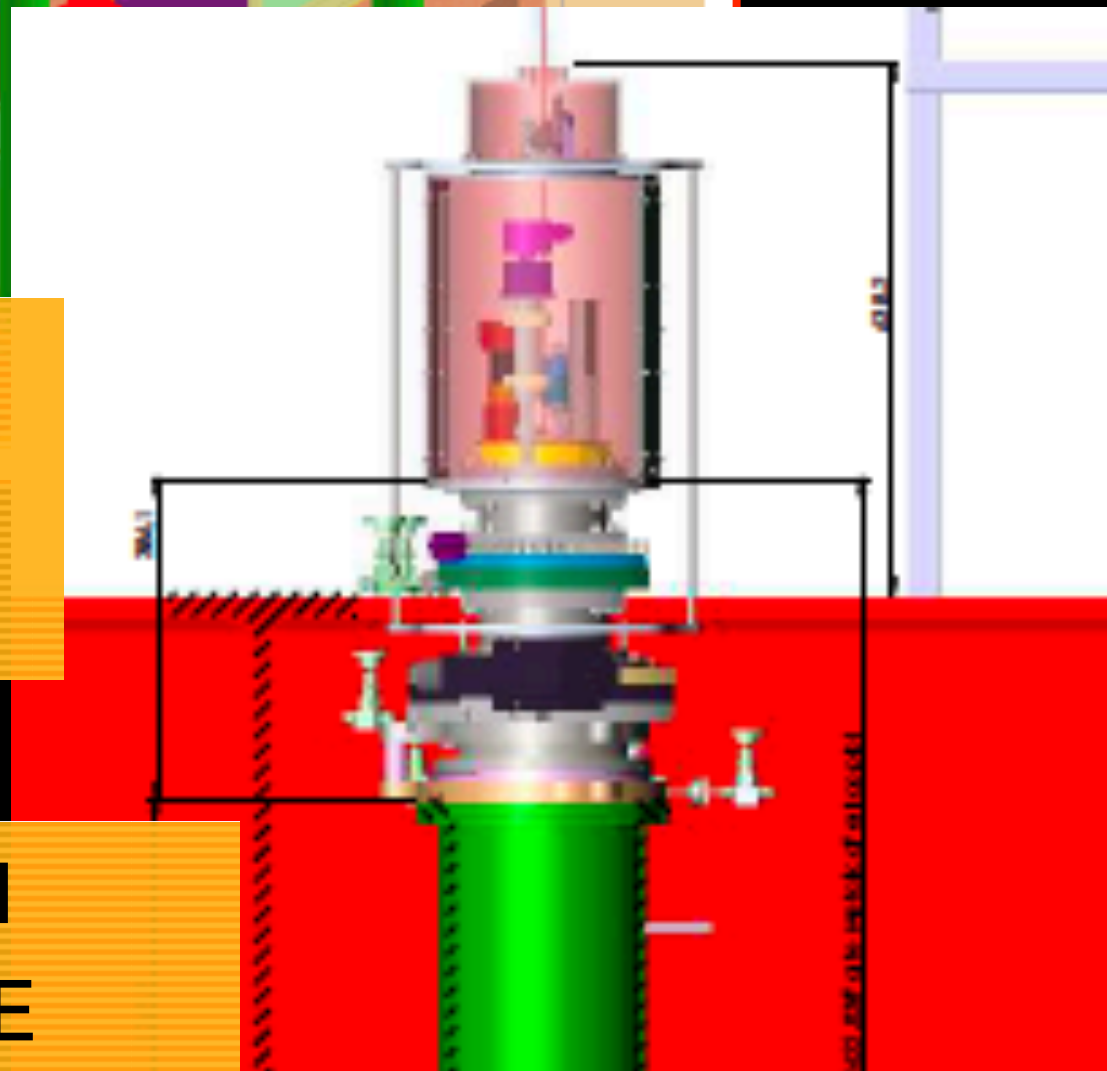
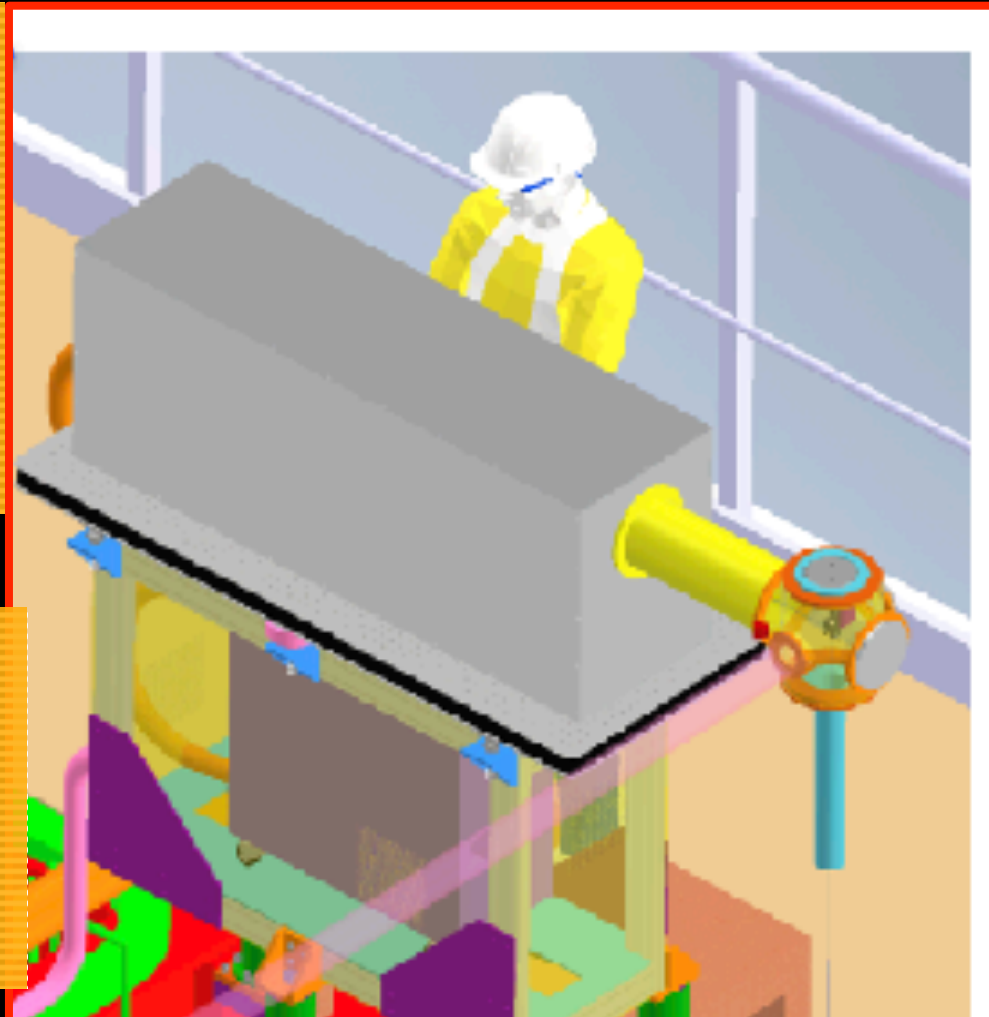
# BASE DESIGN

UV LASER (266  
NM, 60 mJ)  
+ MODULATING  
OPTICS

ELECTRONICS FOR  
AUTOMATIZATION  
AND DAQ SYNC

QUARTZ WINDOW  
FOR BEAM TO  
ENTER CRYOSTAT

MOUNTED ON  
ROTARY STAGE  
(AZIMUTHAL ANGLE)



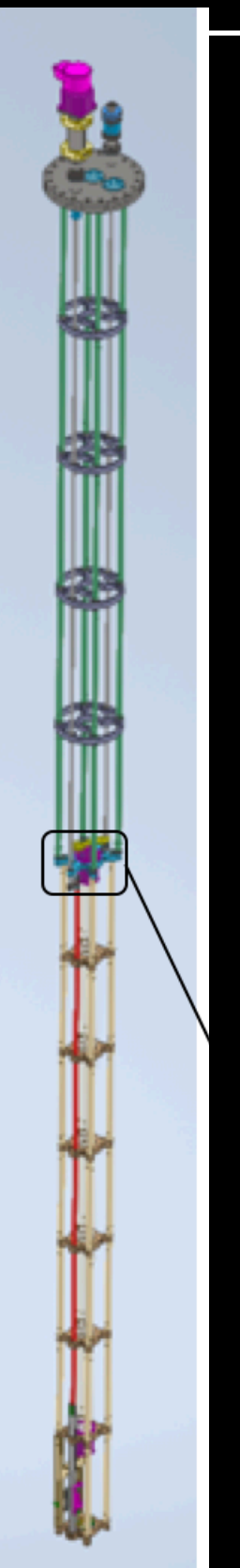
LONG 2-STAGE  
PERISCOPE

GAS

LIQUID

COLD MIRROR  
MOVABLE IN  
POLAR ANGLE

QUARTZ TUBE  
INSIDE PERISCOPE  
IMPOSES A STABLE  
OPTICAL PATH



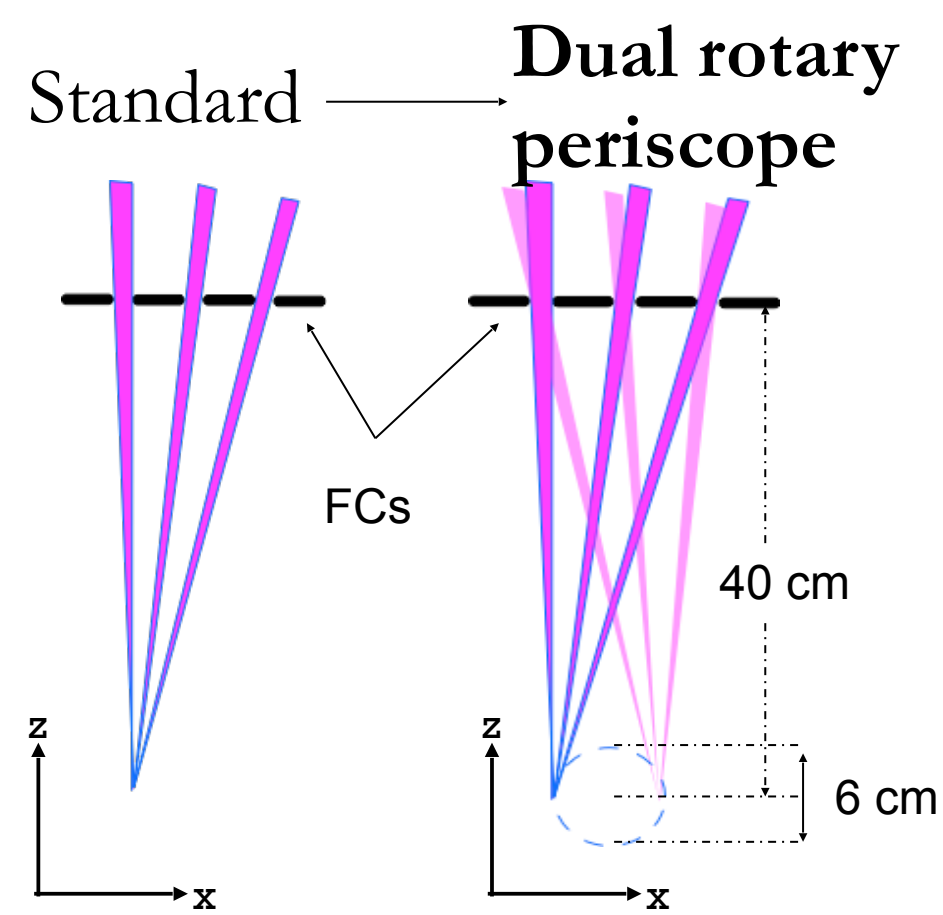
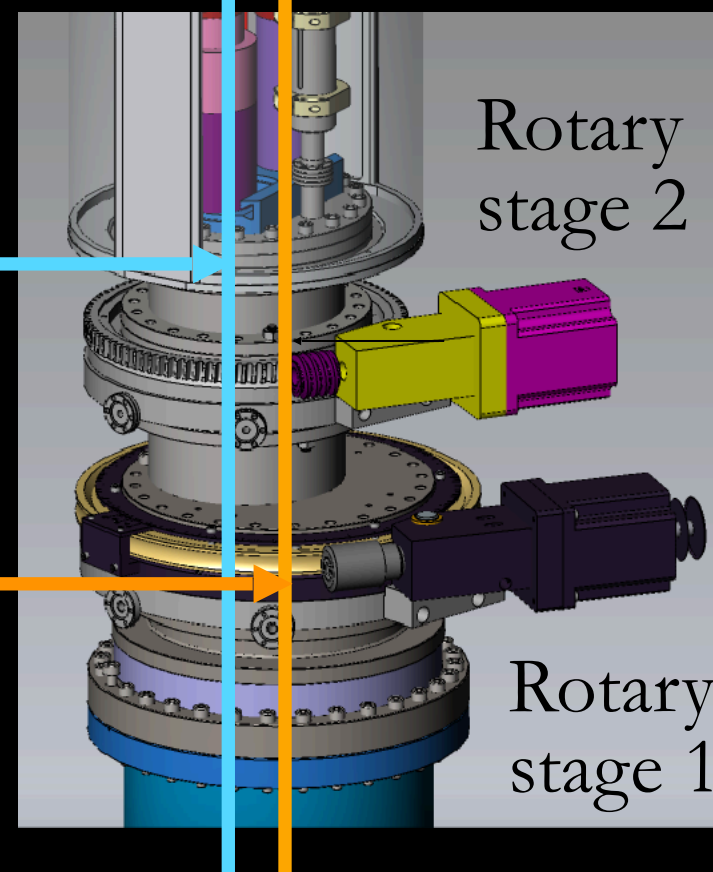


# NEW PERISCOPES FOR BETTER COVERAGE

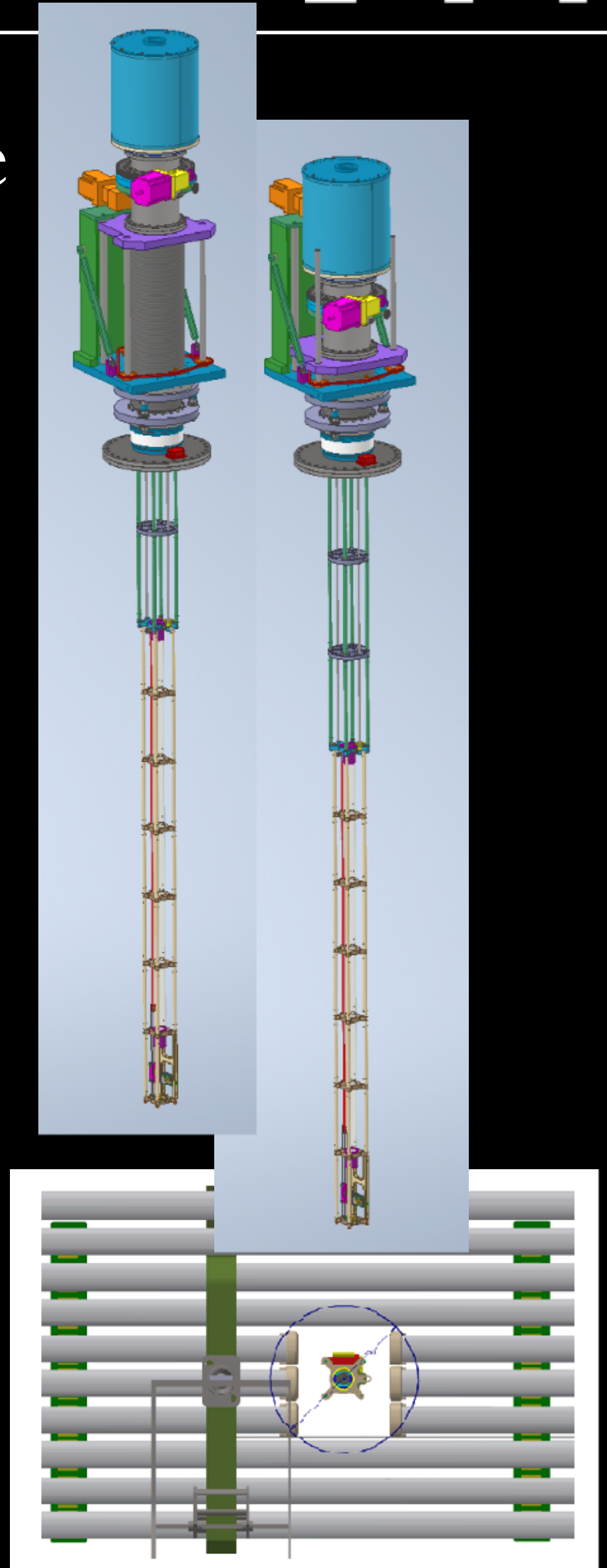
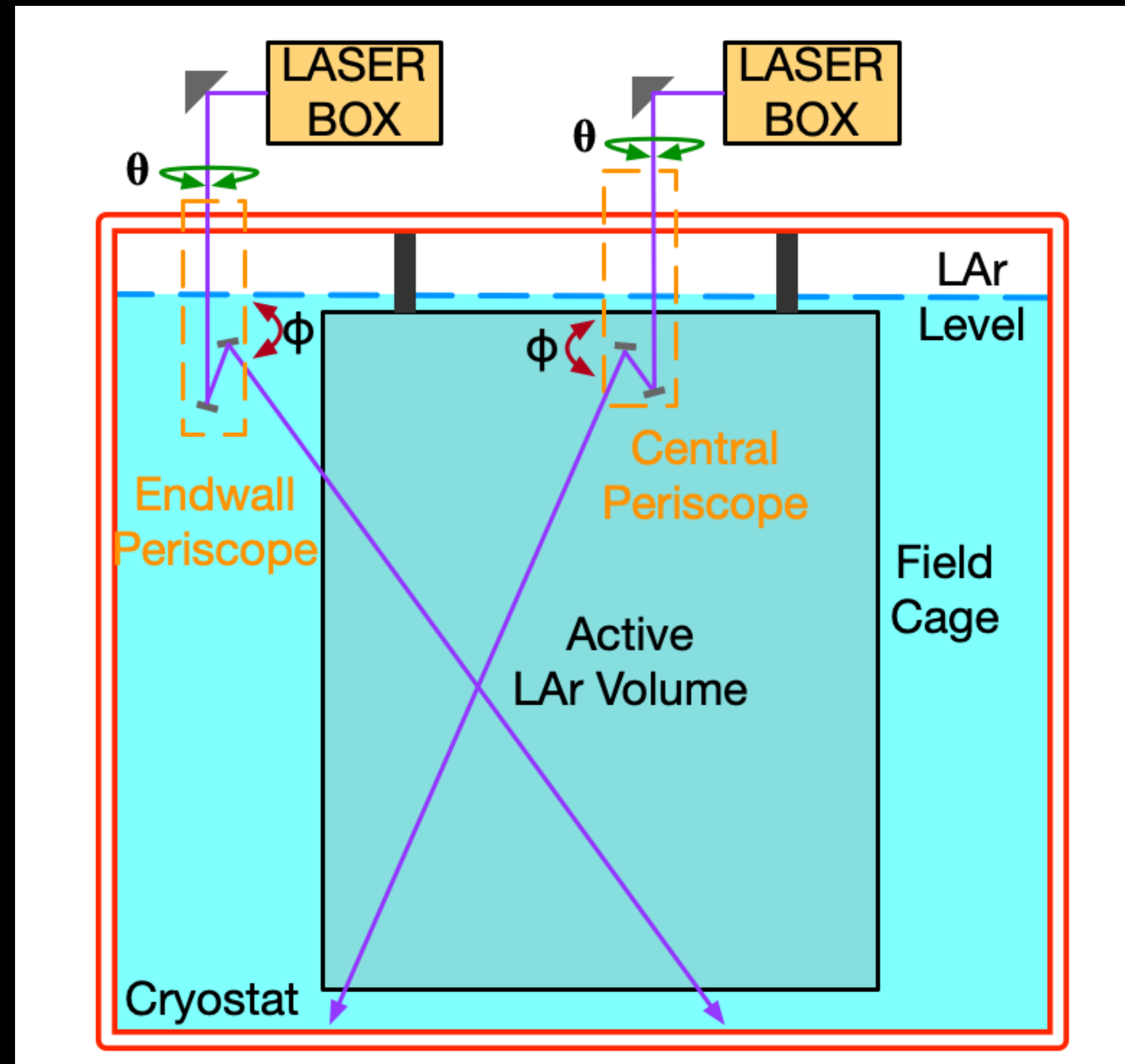


Rotation  
axis 2

Rotation  
axis 1



- Dual rotation for ports outside field cage
- Vertical retraction for ports entering openings in field cage



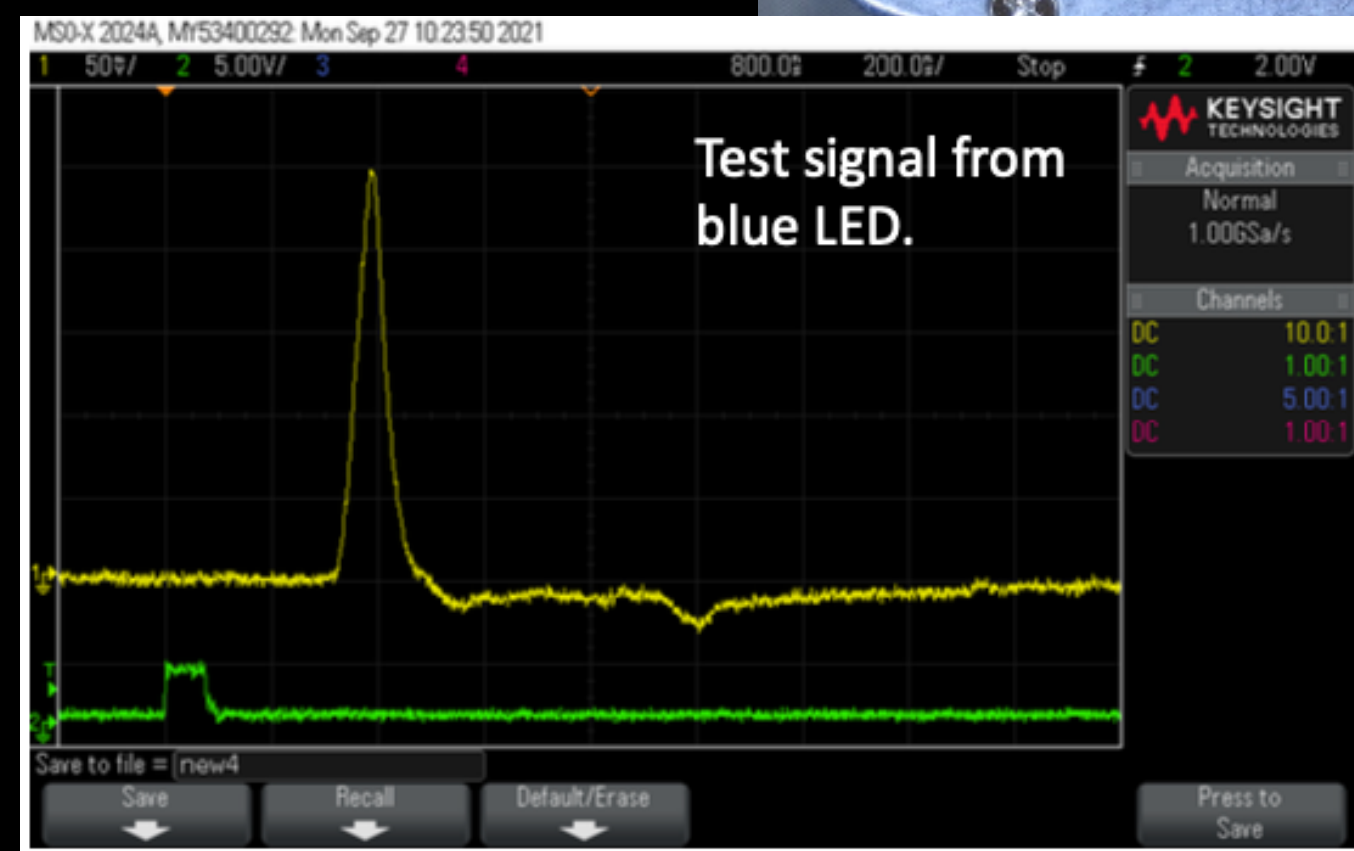


# LASER BEAM LOCATION SYSTEMS



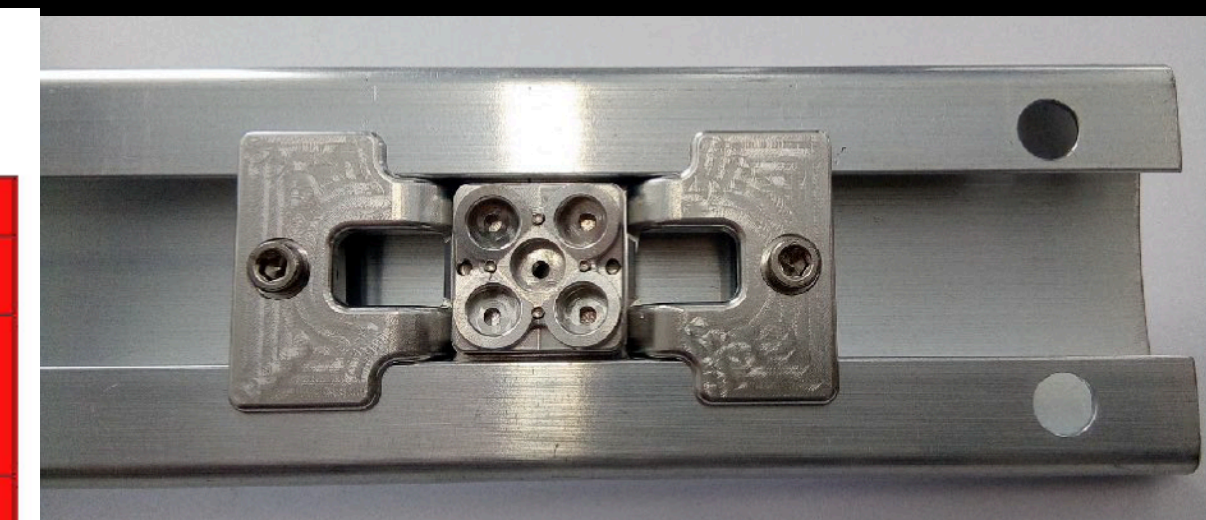
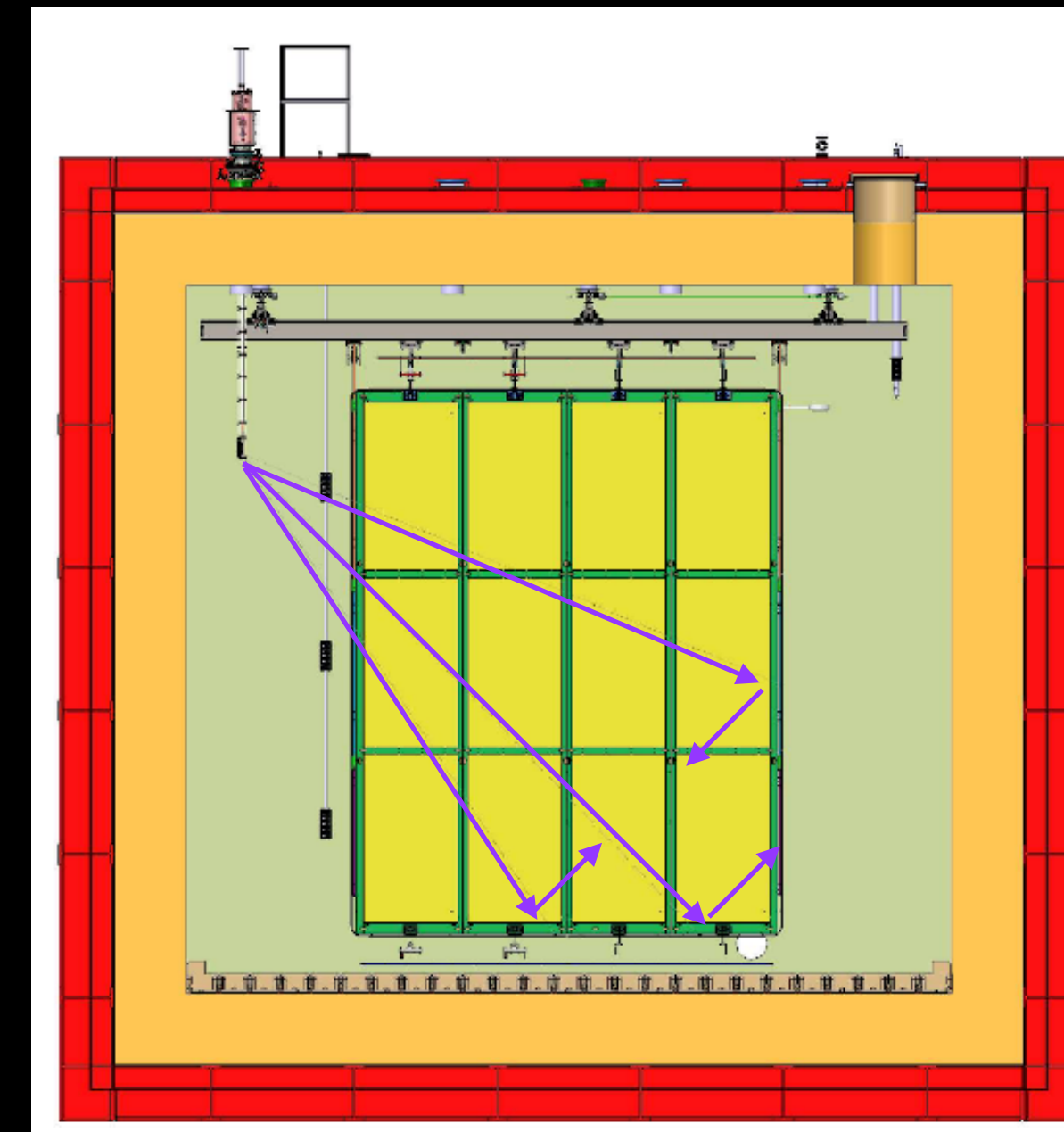
- The laser beam direction is given by encoders in the motors driving the periscope
- Accurate to a few mm at many meters, but there are offset uncertainties
- Beam targets inside detector for 5 mm accurate location

## ACTIVE SYSTEM: PIN DIODES



- independent of TPC data
- cannot be placed inside field cage

## PASSIVE SYSTEM: MIRRORS



- reflection angle identifies mirror
- can be placed inside field cage



CONSTRUCTION AND  
COMMISSIONING OF  
SYSTEM FOR  
PROTODUNE AT CERN

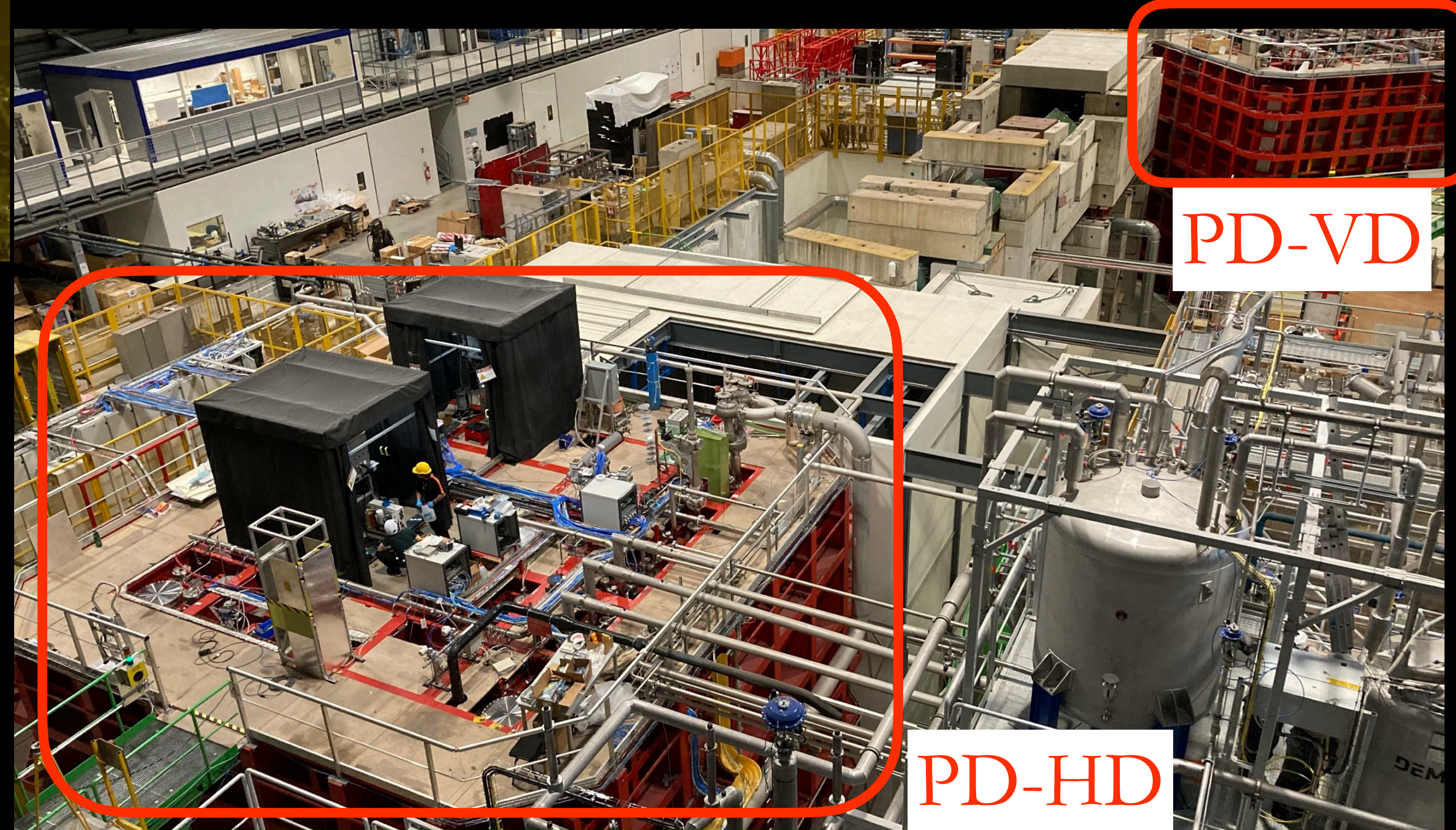


# PROTODUNE(S) @ CERN



- ProtoDUNES
  - 2017-2019: Develop single phase and dual phase designs
  - 2023-2025: Test production modules of horizontal and vertical drift (both single phase)

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

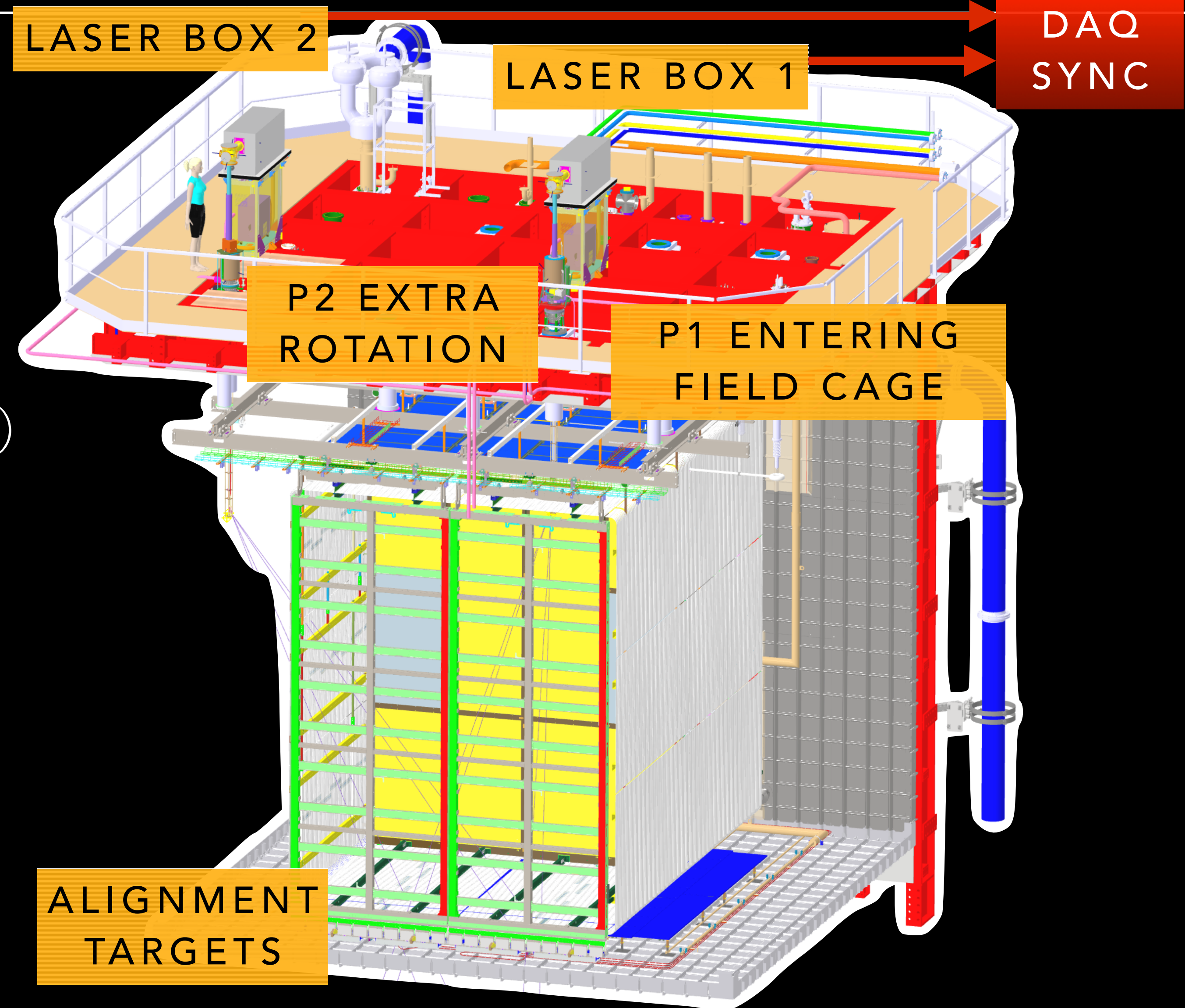




# LASER CALIBRATION AT PROTODUNE



- All systems for DUNE need to be tested first in ProtoDUNE
  - PDHD now
  - PDVD next year
- Ionisation laser calibration system designs
  - Periscope entering opening in field cage (P1)
  - External periscopes with extra rotation (P2)
  - Simple external periscope (P3 - VD)
  - Alignment targets: PIN diodes, mirrors
  - Integration with DAQ
- Goals
  - Map space-charge distortions
  - Characterize charge collection in APAs
  - Characterize electron lifetime

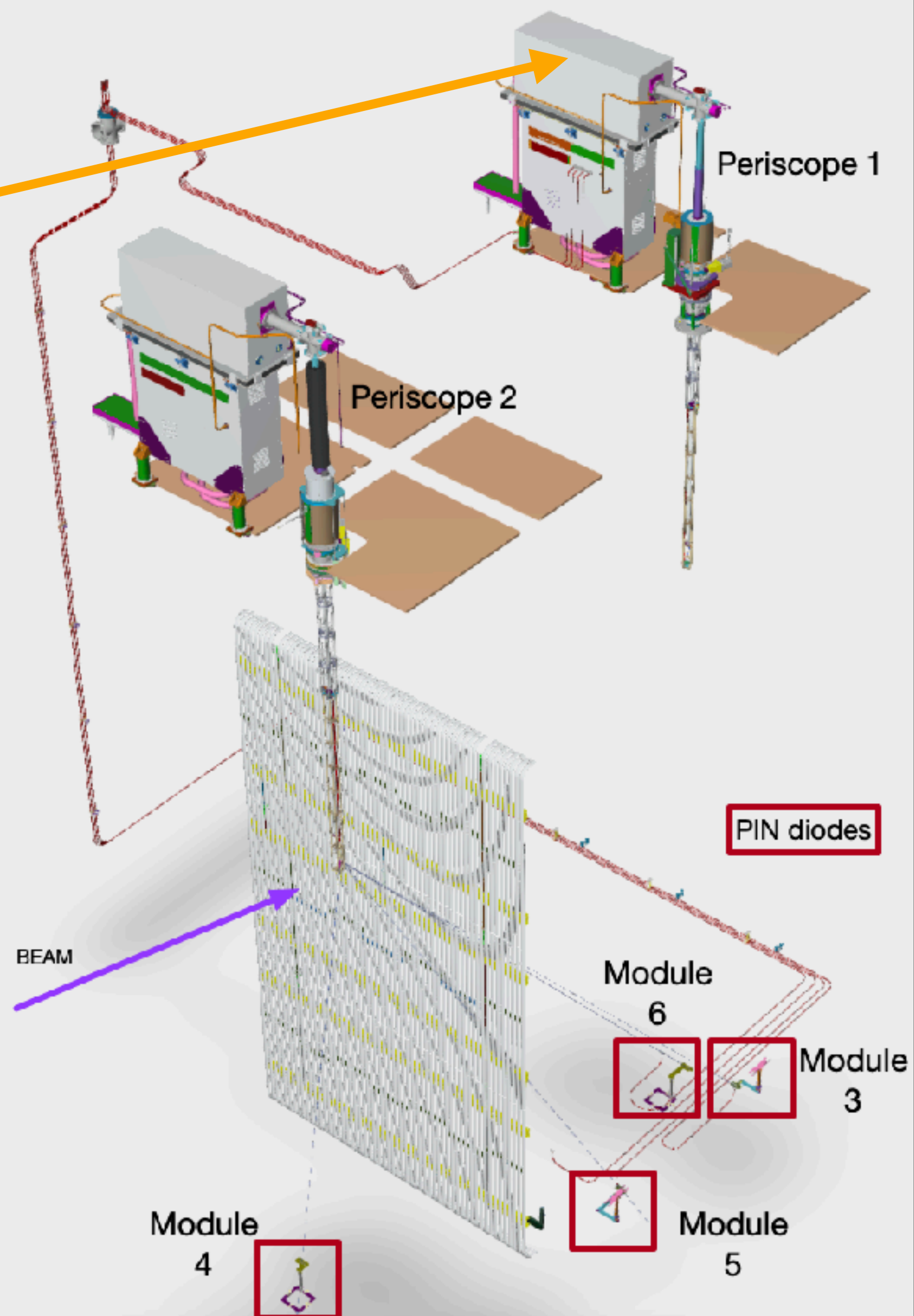




# SYSTEM COMPONENTS

LASER + HARMONIC GENERATOR

ELECTRONICS





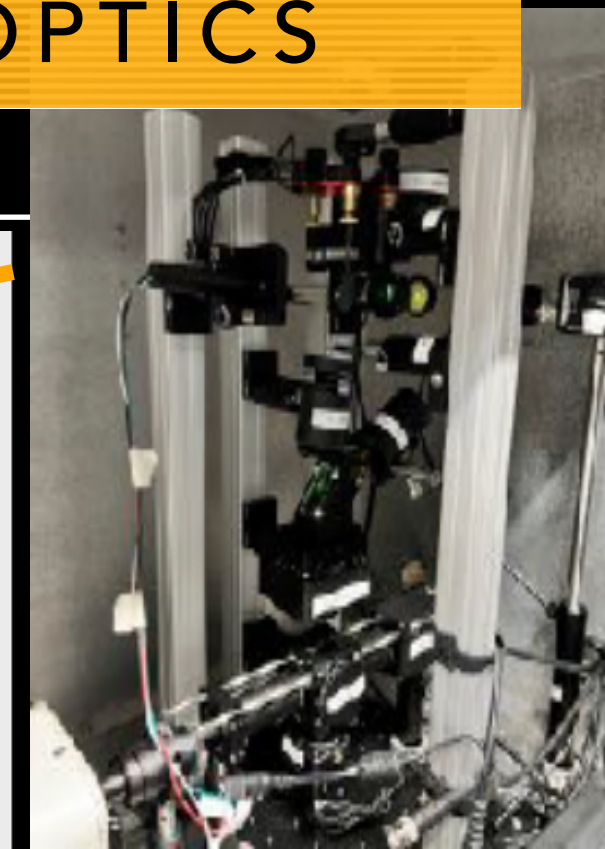
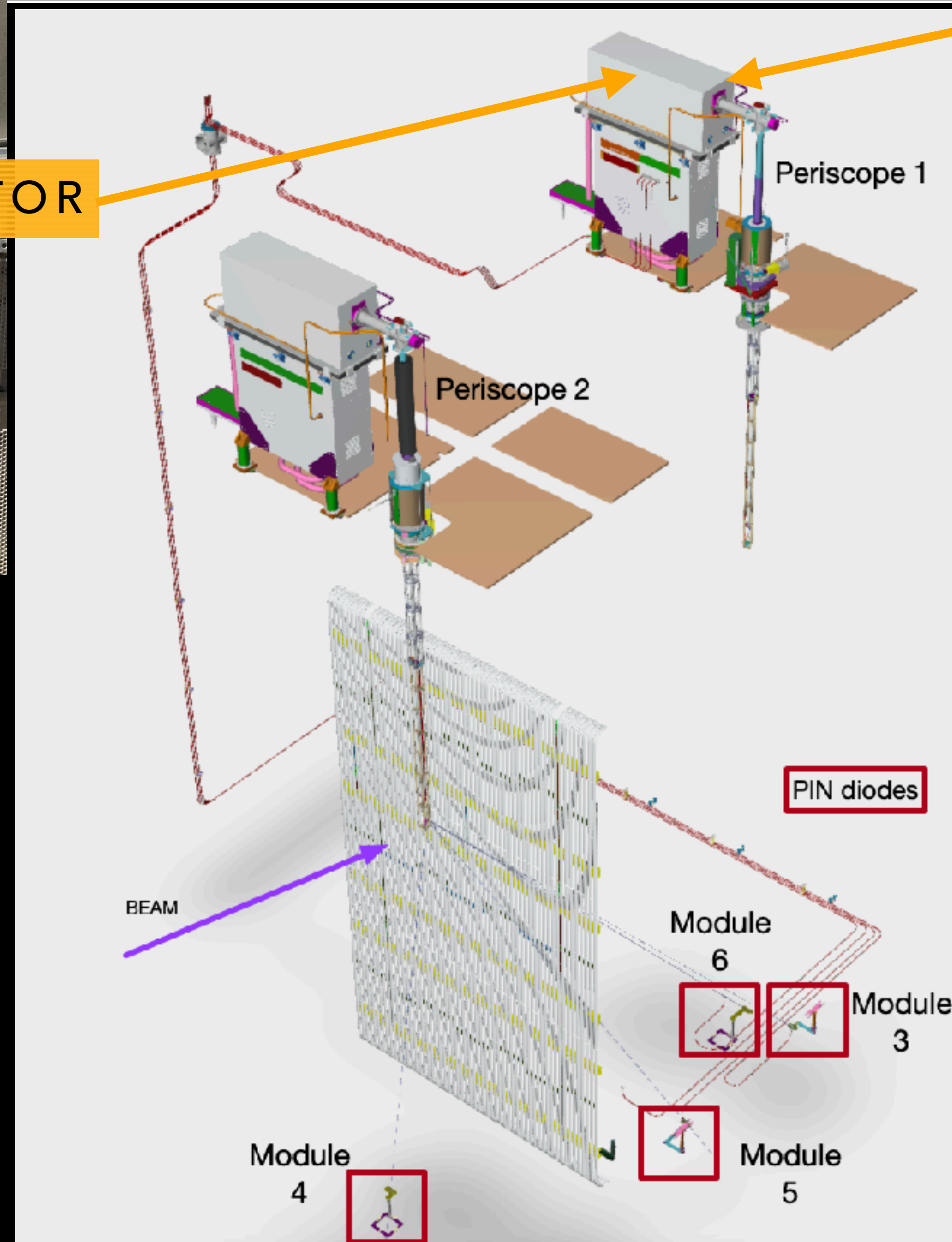
# SYSTEM COMPONENTS

ATTENUATOR,  
OPTICS



LASER + HARMONIC GENERATOR

ELECTRONICS





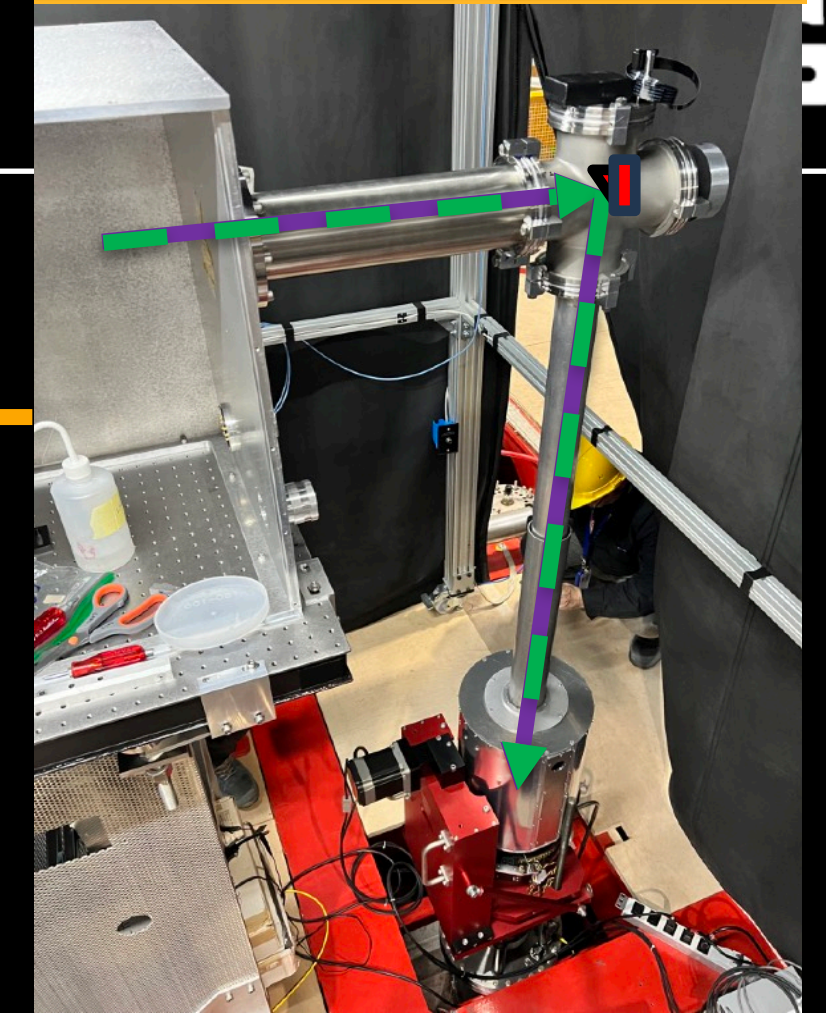
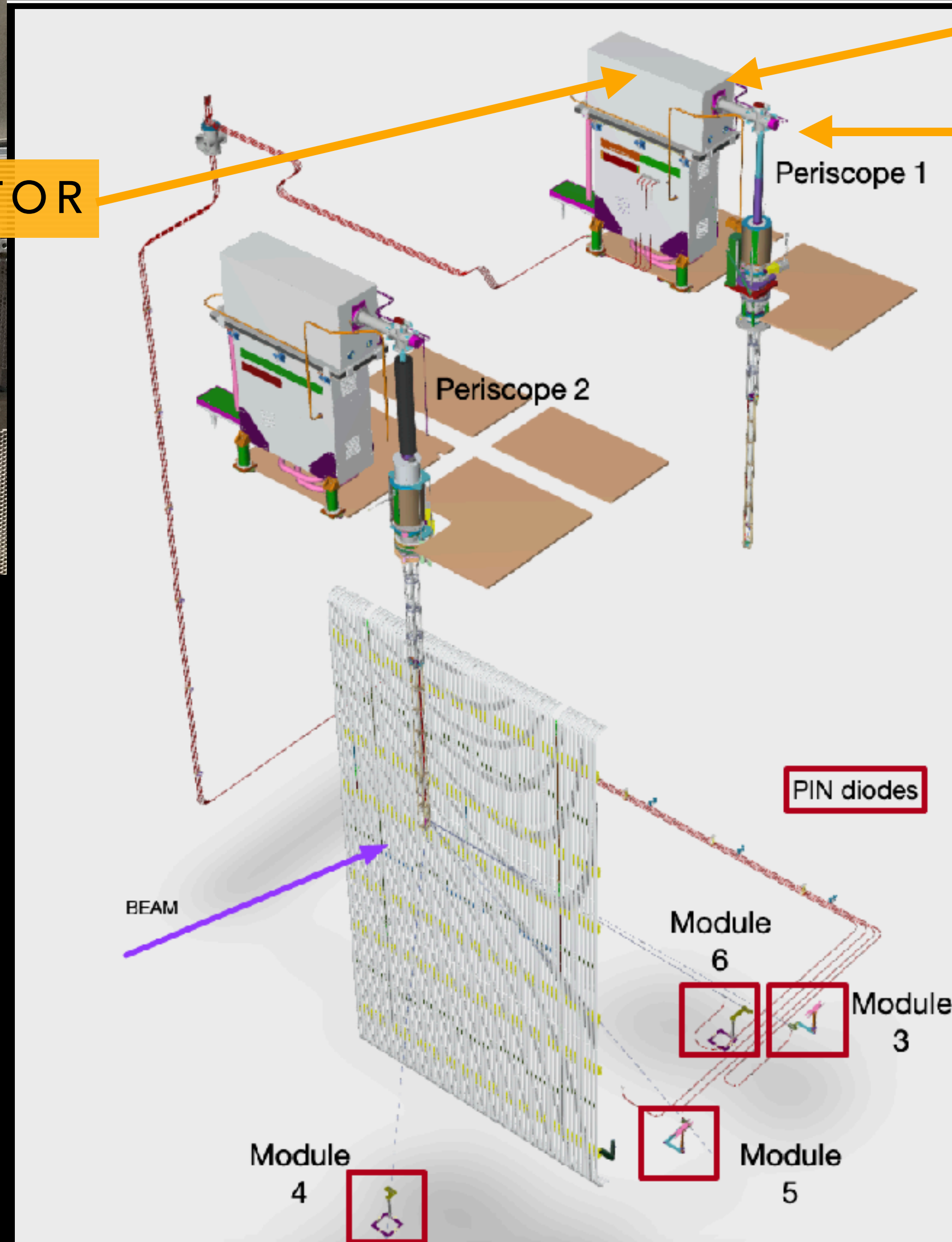
# SYSTEM COMPONENTS

ATTENUATOR,  
OPTICS

CONNECTION

LASER + HARMONIC GENERATOR

ELECTRONICS





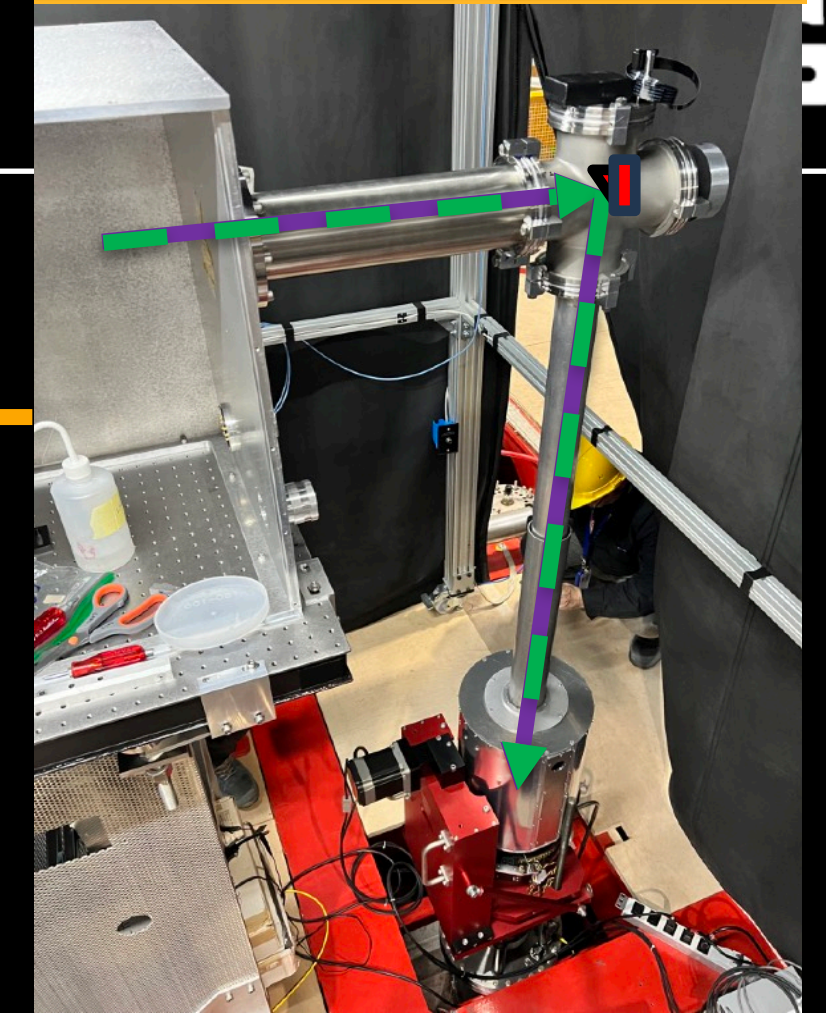
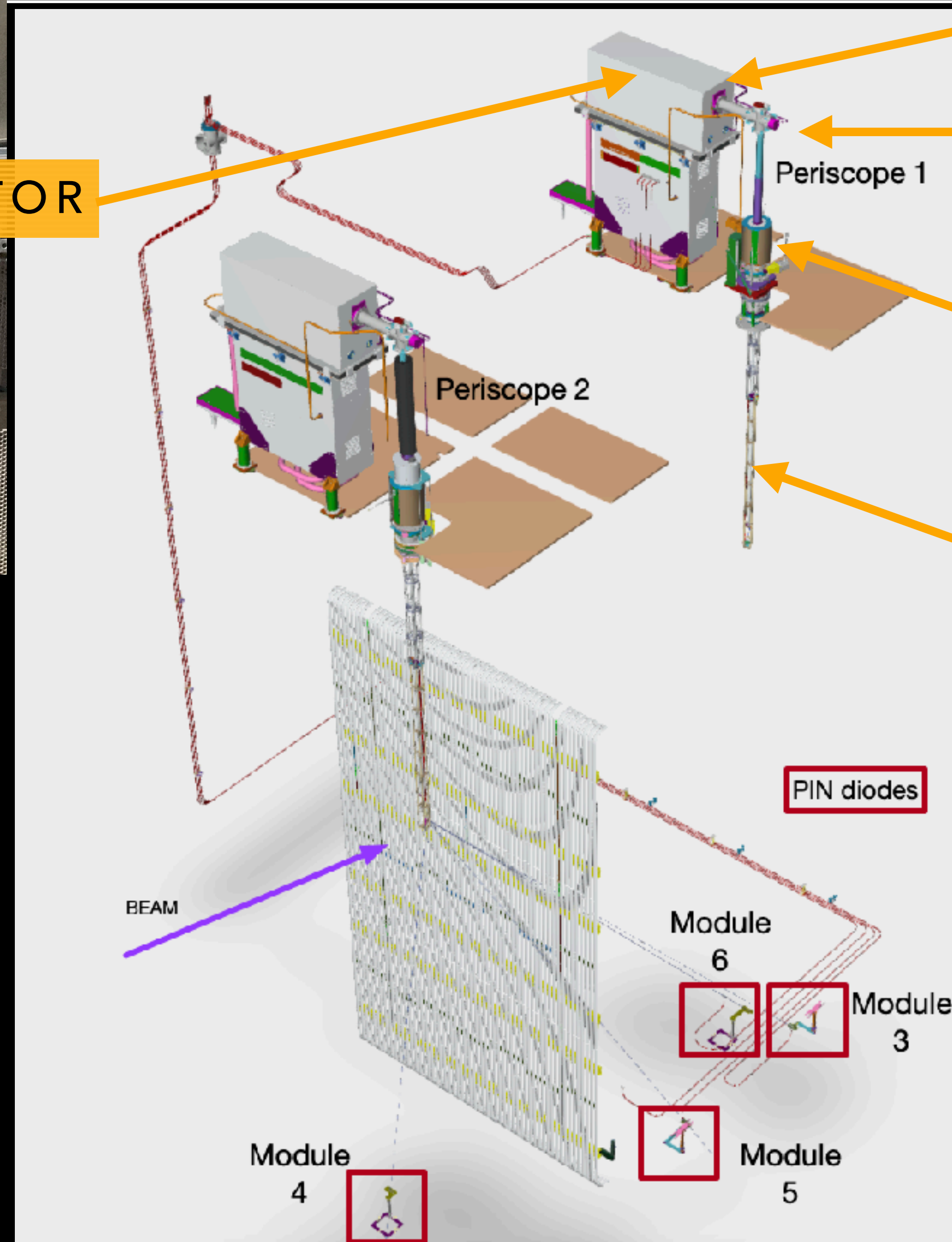
# SYSTEM COMPONENTS

ATTENUATOR,  
OPTICS

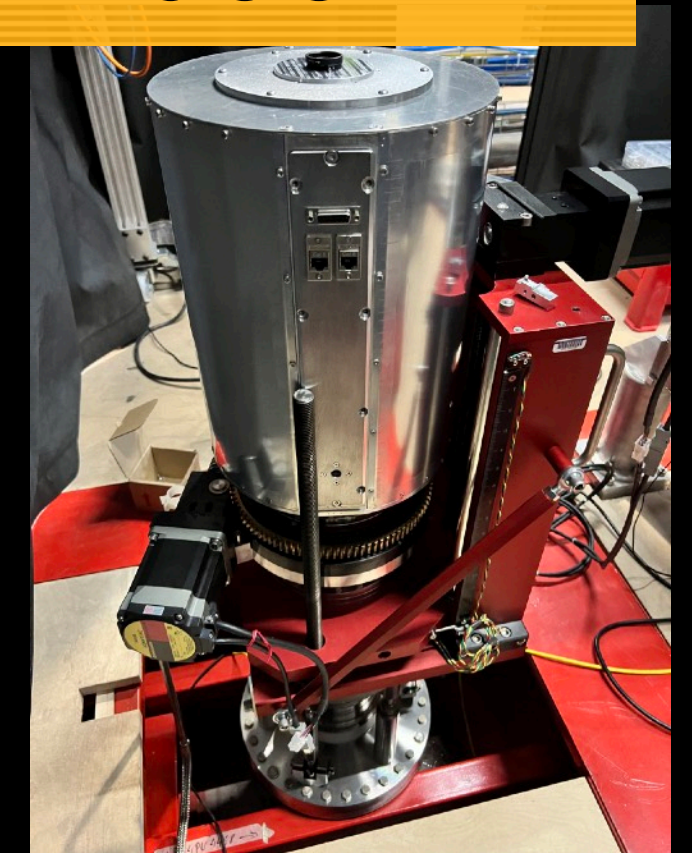
CONNECTION

LASER + HARMONIC GENERATOR

ELECTRONICS



PERISCOPE 1





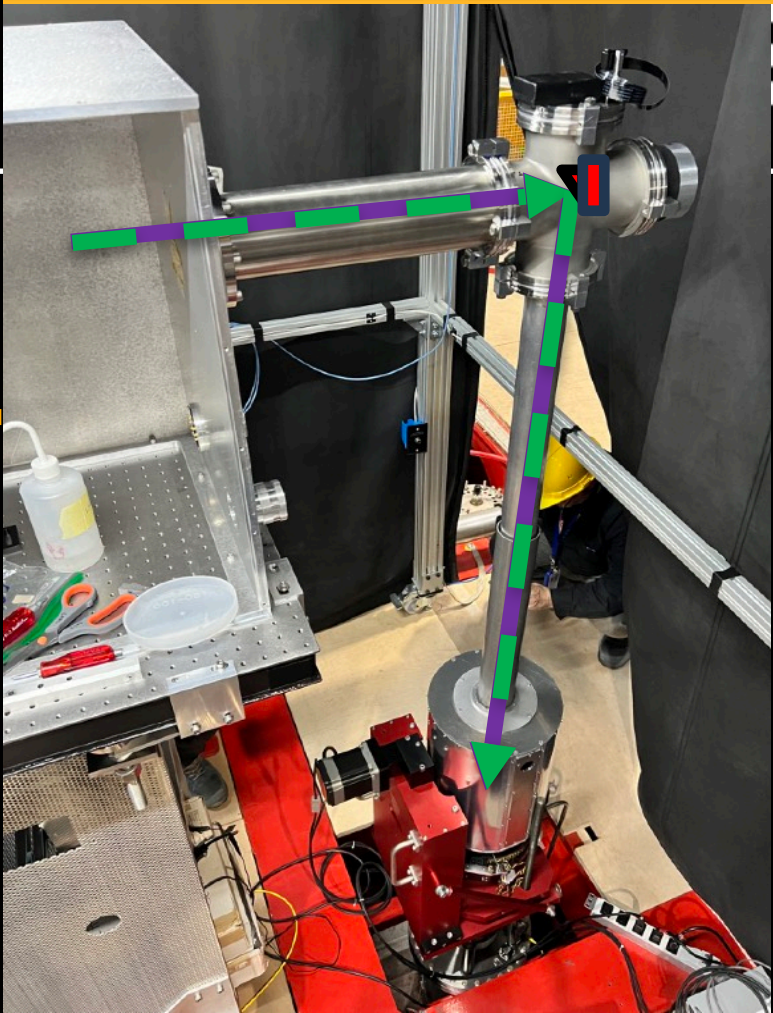
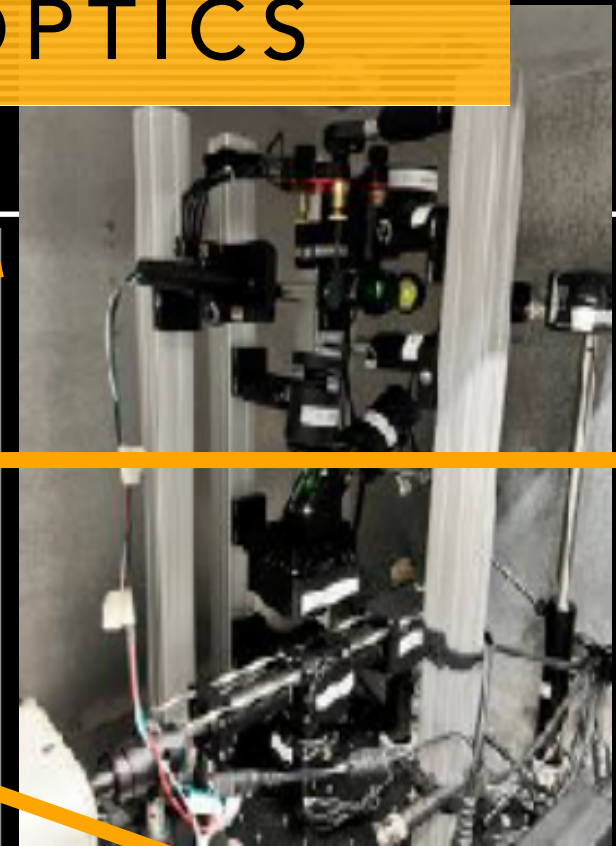
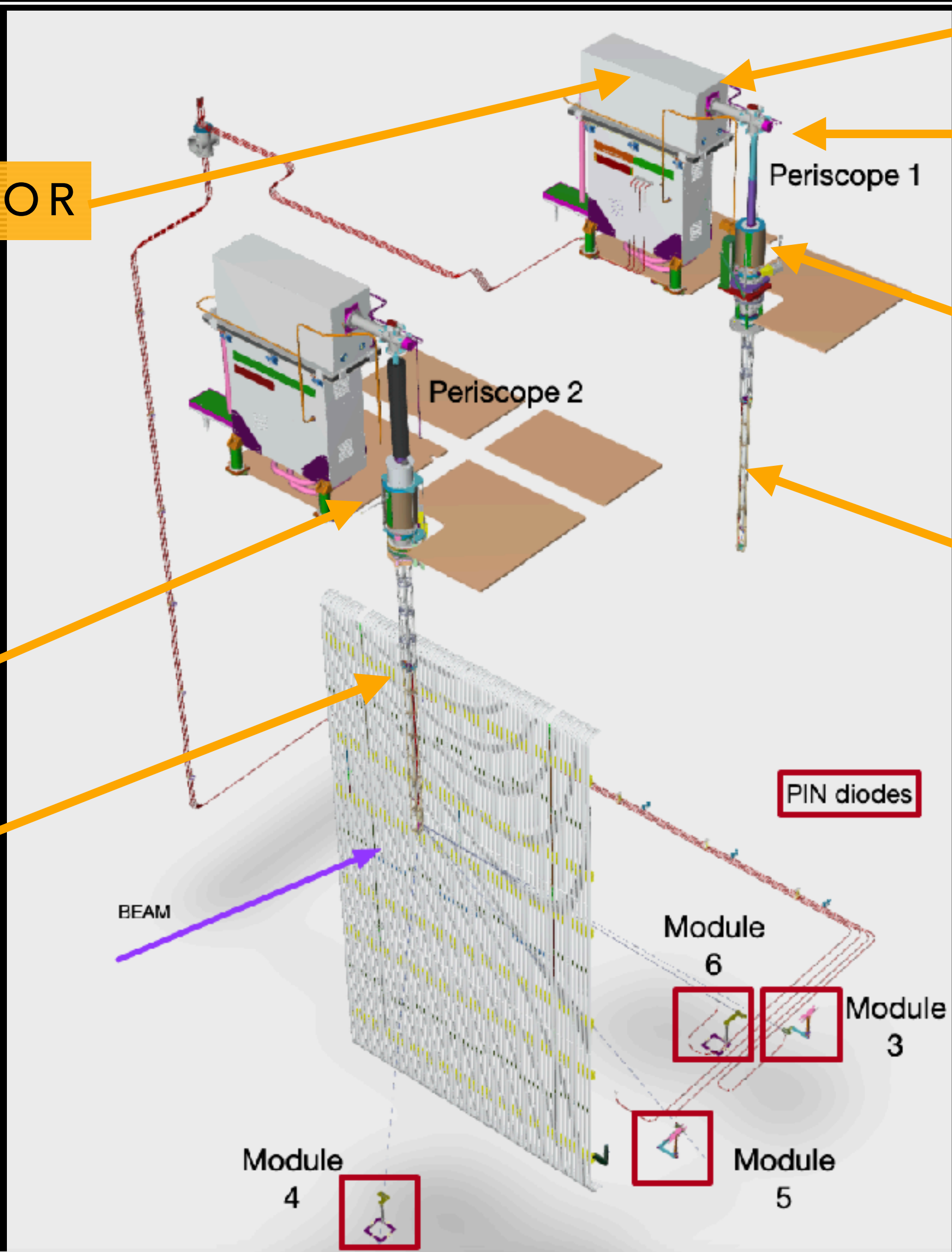
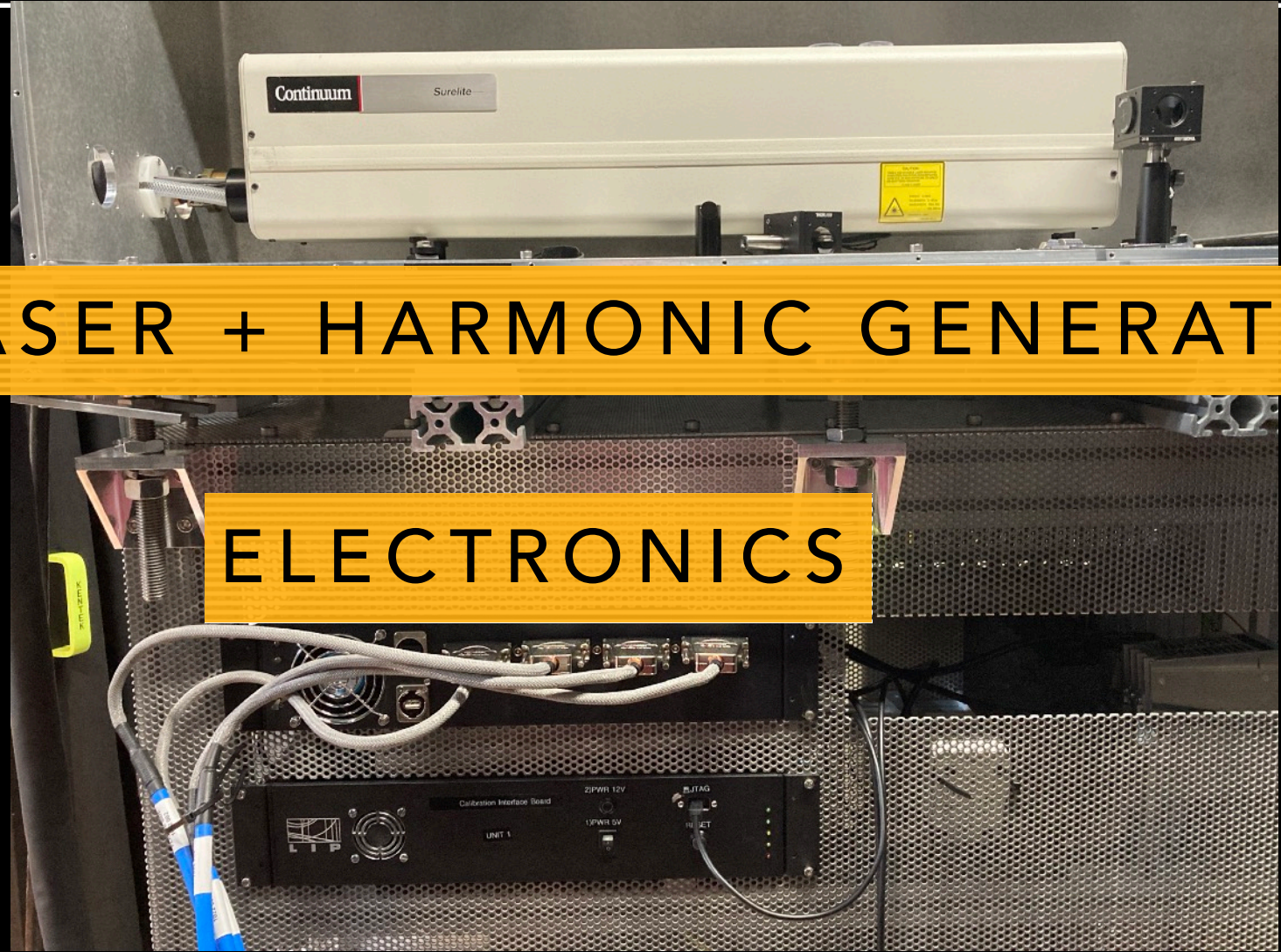
# SYSTEM COMPONENTS

ATTENUATOR,  
OPTICS

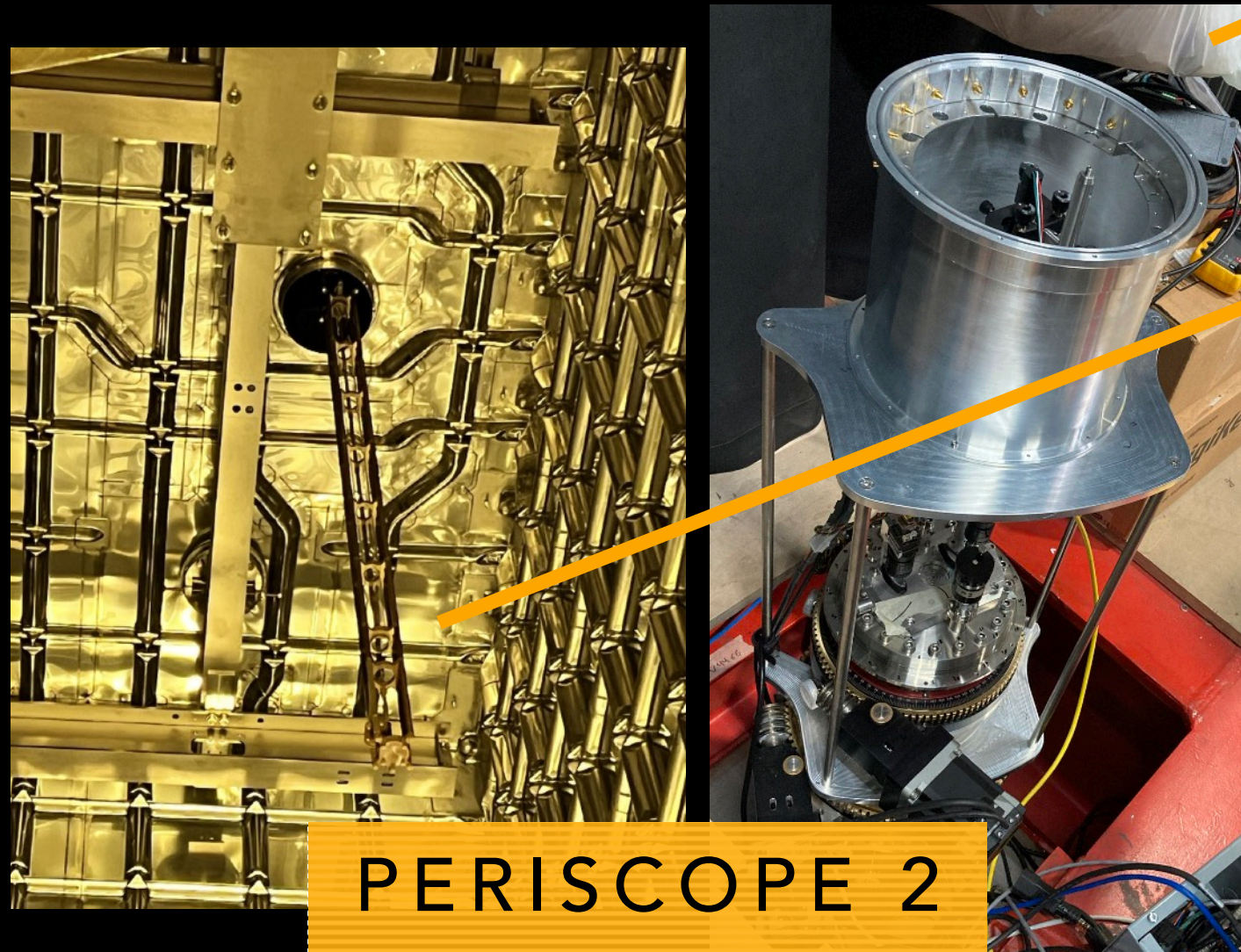
CONNECTION

LASER + HARMONIC GENERATOR

ELECTRONICS



PERISCOPE 1



PERISCOPE 2



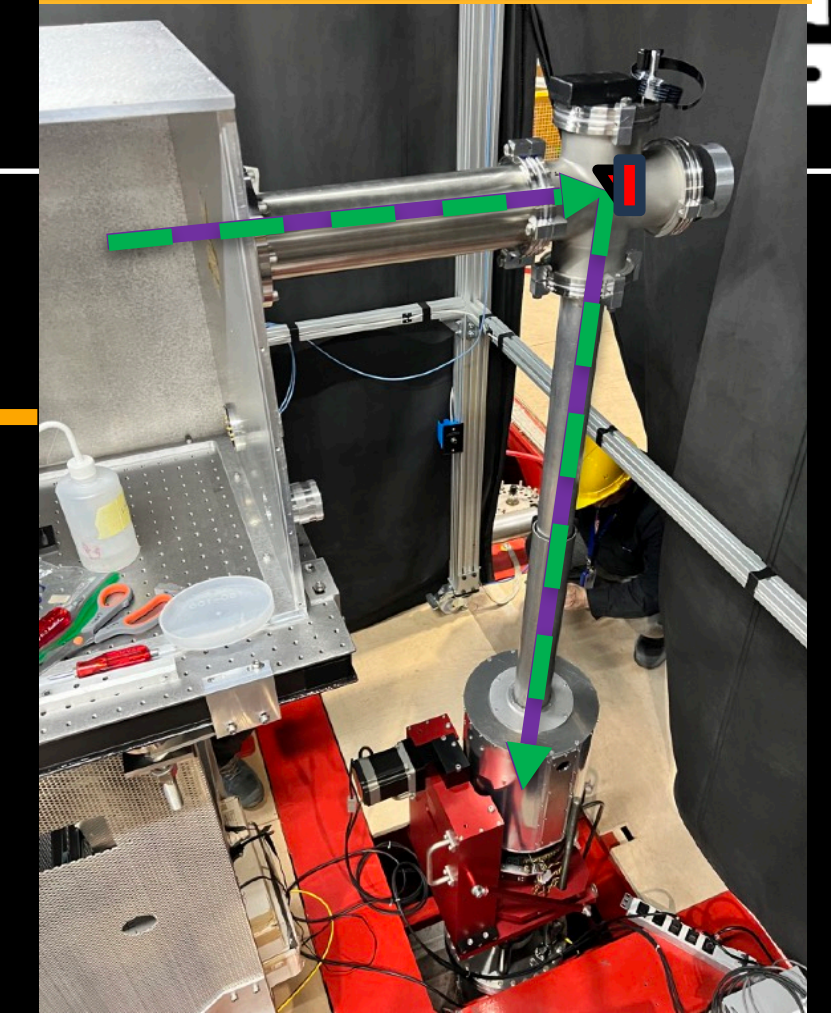
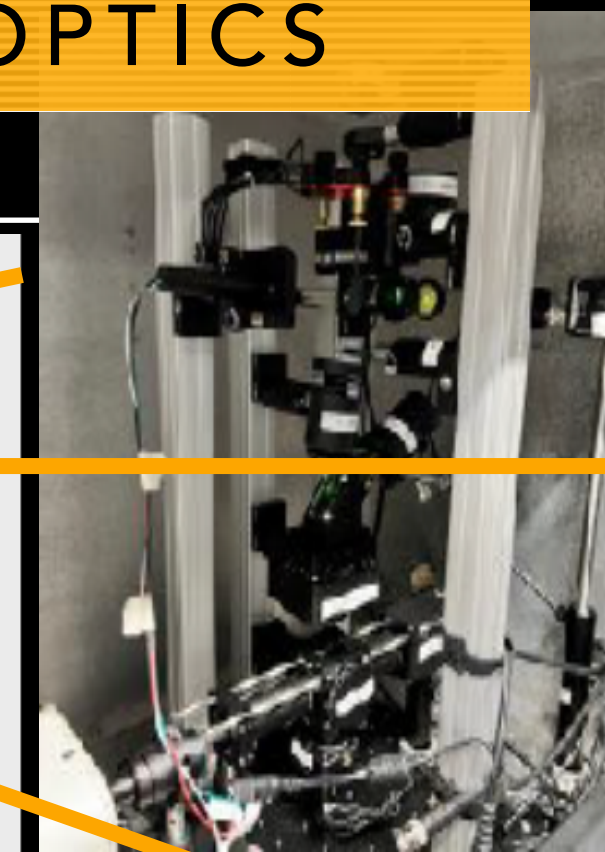
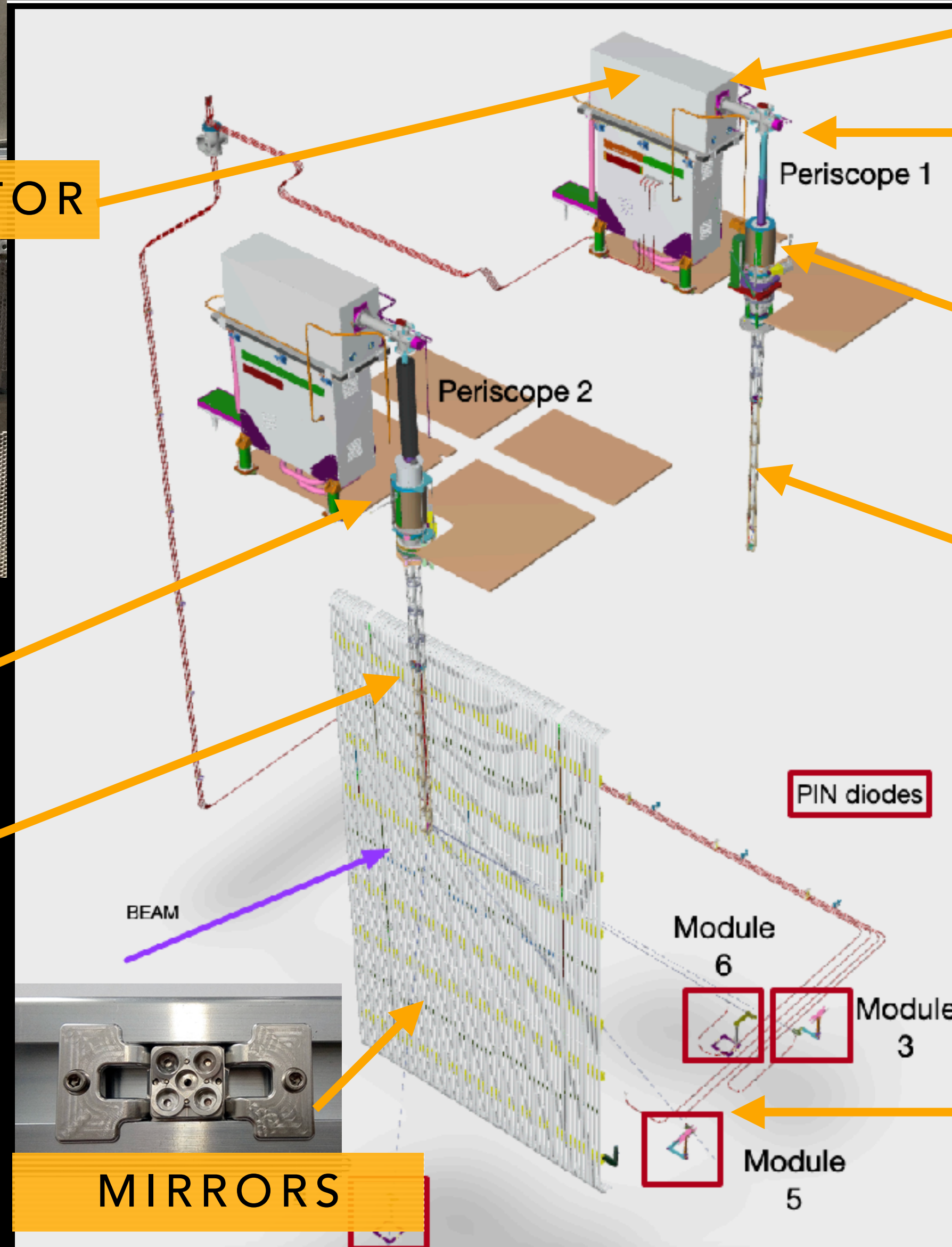
# SYSTEM COMPONENTS

ATTENUATOR,  
OPTICS

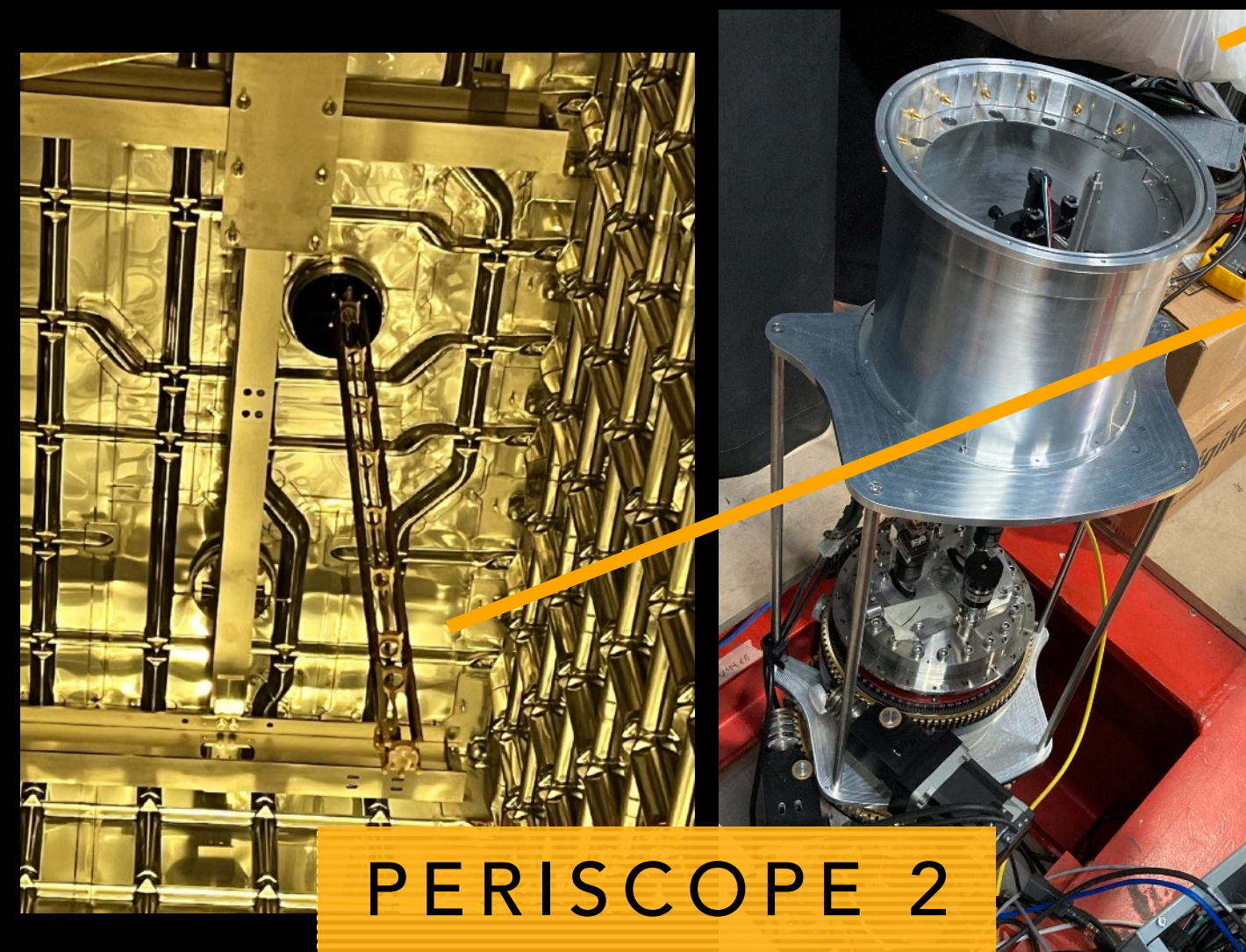
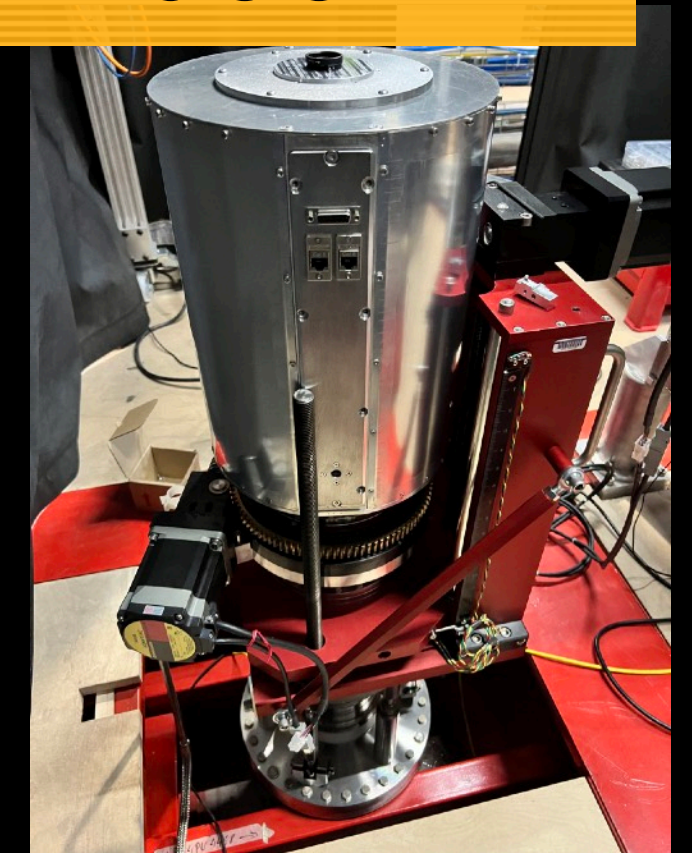
CONNECTION

LASER + HARMONIC GENERATOR

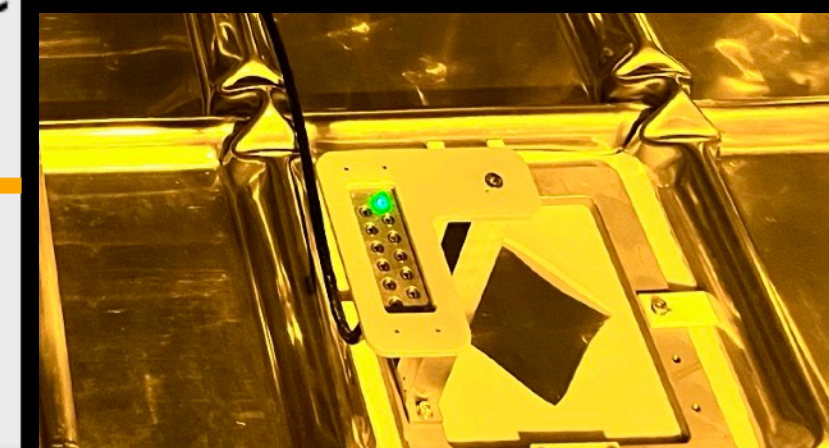
ELECTRONICS



PERISCOPE 1



PERISCOPE 2



PIN DIODES



# CONSTRUCTION AND TESTS

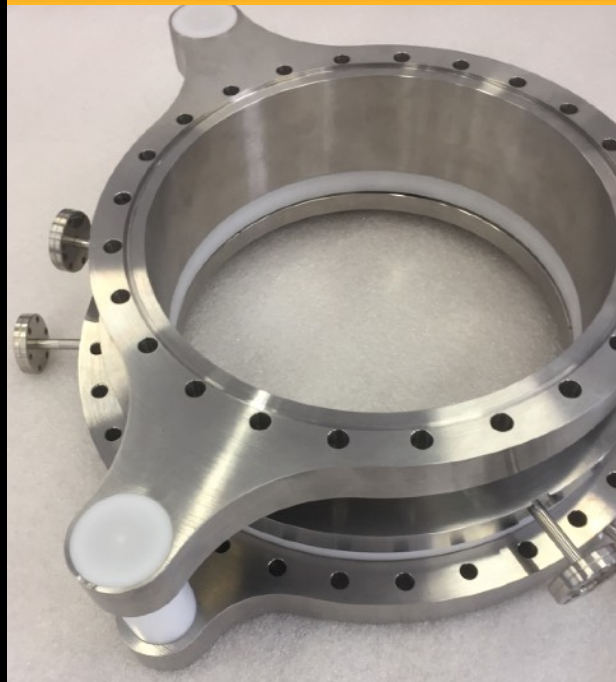


- Main components designed and fabricated at LANL and LIP, + PIN diode system at UHawaii
- Full assembly and cold tests @ LANL in 2022, then shipped to CERN

ECCENTRIC  
FLANGE



LARGE OPENING  
ELECTRICAL BREAK



HELIUM LEAK CHECKS  
INC. W/ ROTATION



PERISCOPE 3  
FOR PD-VD  
(STEEL)



ELECTRONICS



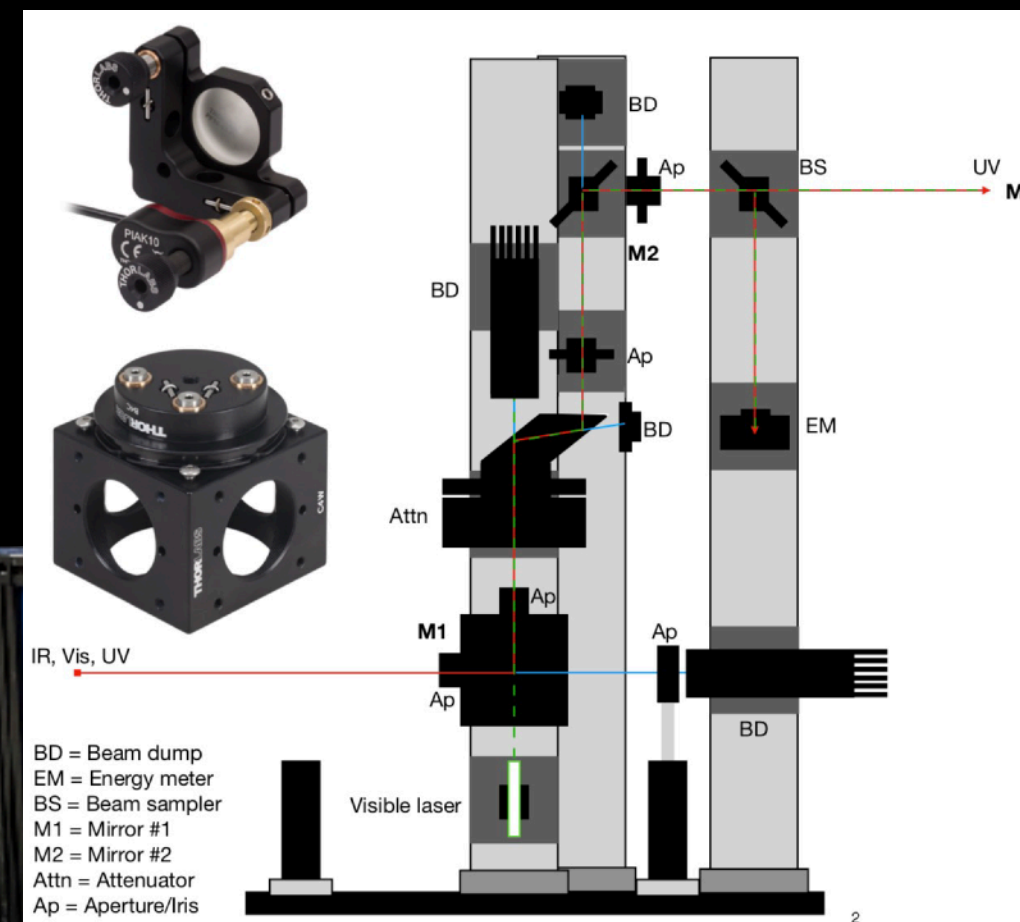
MIRROR PADS



# CONSTRUCTION AND TESTS



- Main components designed and fabricated at LANL and LIP, + PIN diode system at UHawaii
- Full assembly and cold tests @ LANL in 2022, then shipped to CERN



LASER  
CHARACTERIZATION  
DEVELOPMENT OF  
OPTICAL SETUP



FULL ASSEMBLY  
COLD TESTS

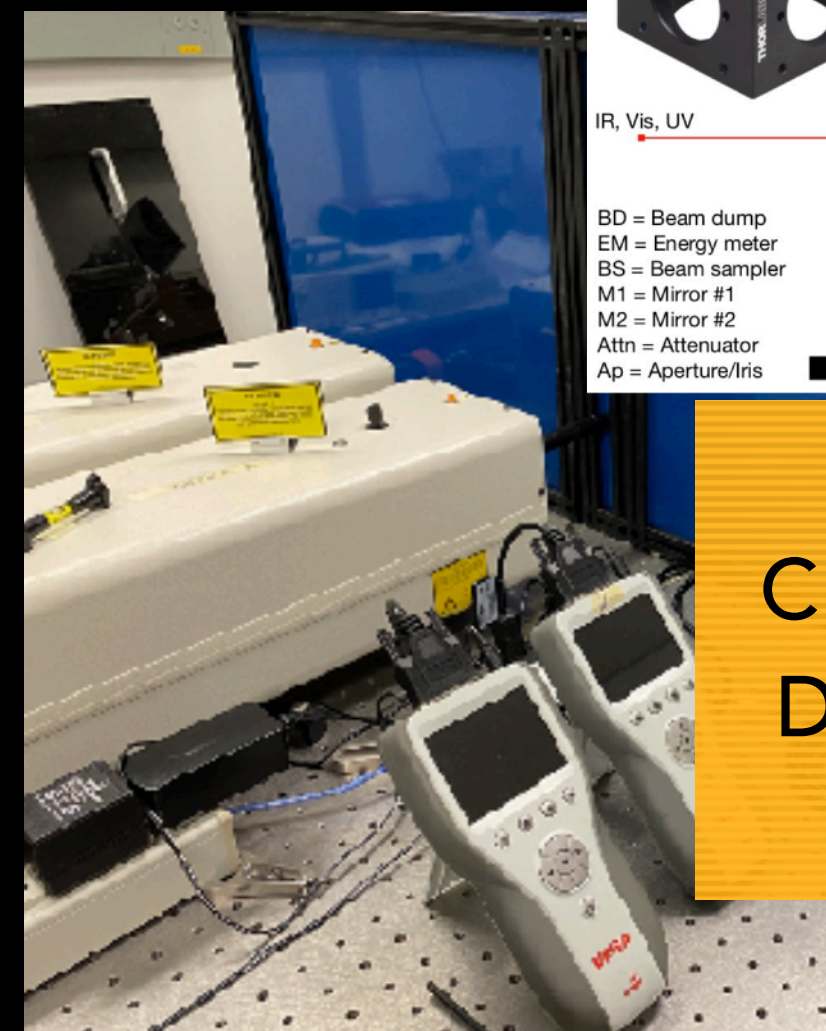


FEEDTHROUGH

PERISCOPE

QUARTZ  
TUBE

750 L DEWAR





# ASSEMBLY, INSTALLATION@CERN



INSERTION JUST BEFORE  
CRYOSTAT CLOSURE



NOISE GROUNDING



ASSEMBLY AND  
ALIGNMENT OF  
PERIOSCOPIES IN  
CLEAN ROOM



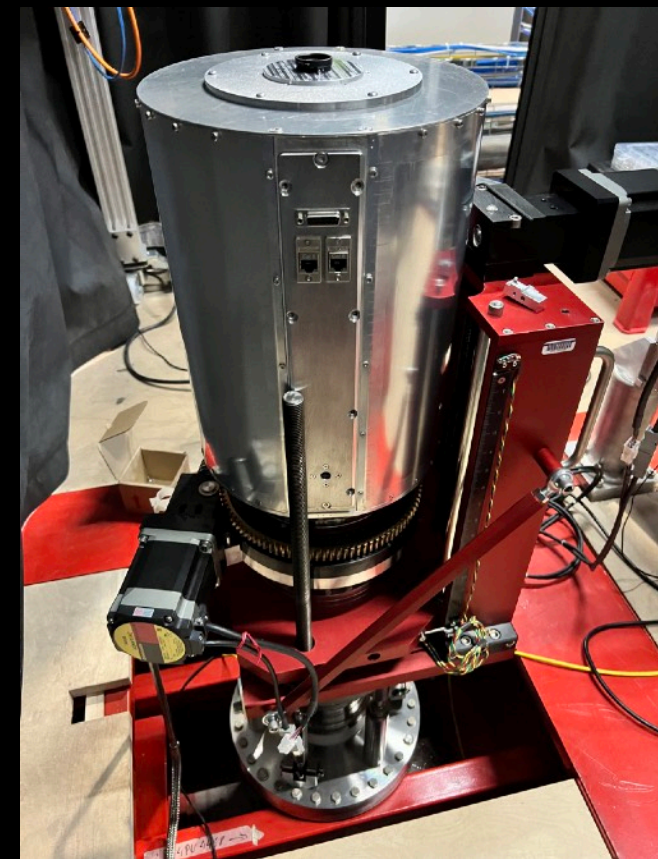
PD-HD ROOF WITH CLASS  
4 LASER SAFETY TENTS



# INITIAL PERFORMANCE CHECKS AND RESULTS

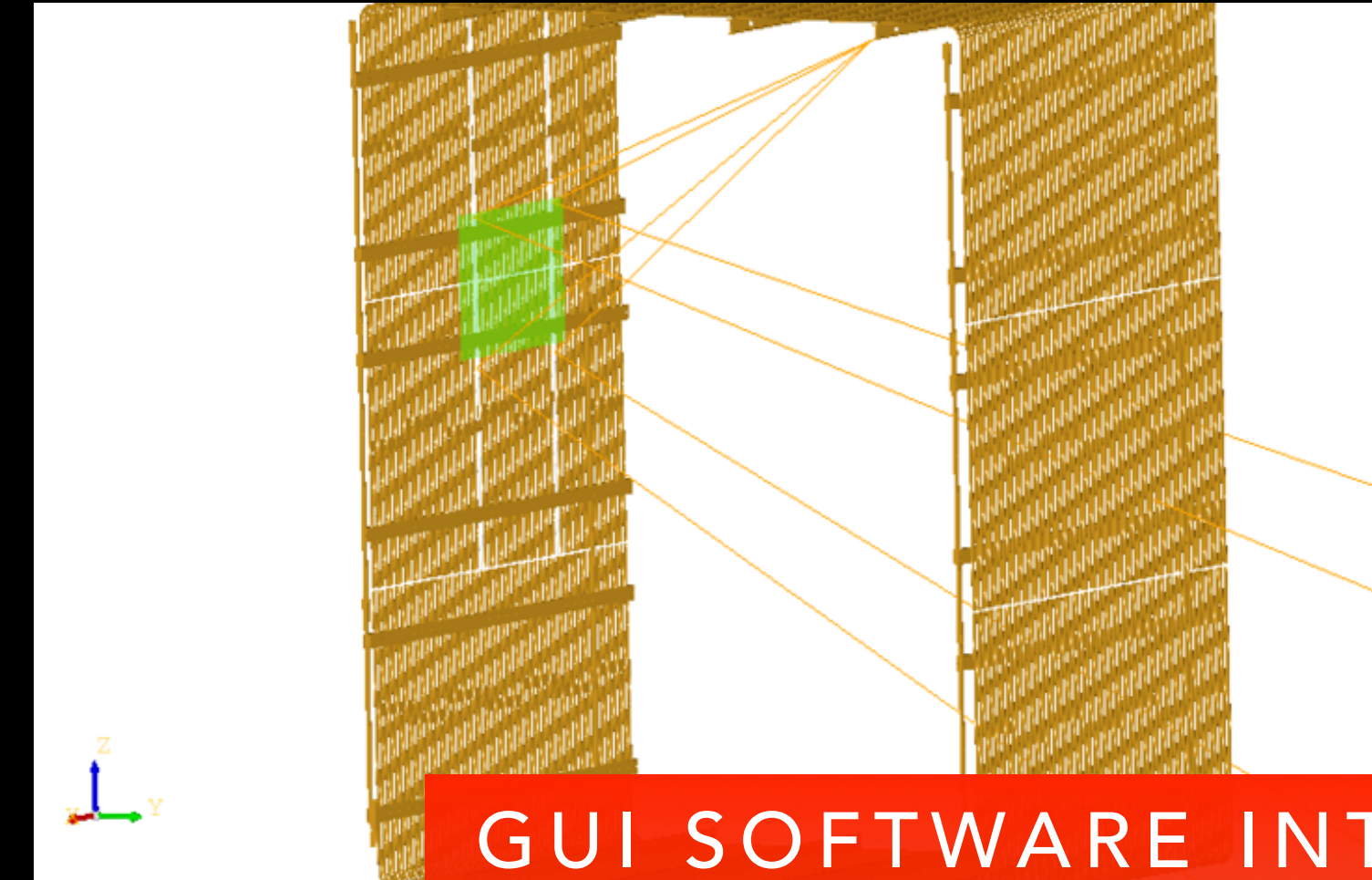


# DETECTOR INTEGRATION



PERISCOPE 1 INSERTION  
INTO FIELD CAGE OPENING  
NO HV OR NOISE ISSUES

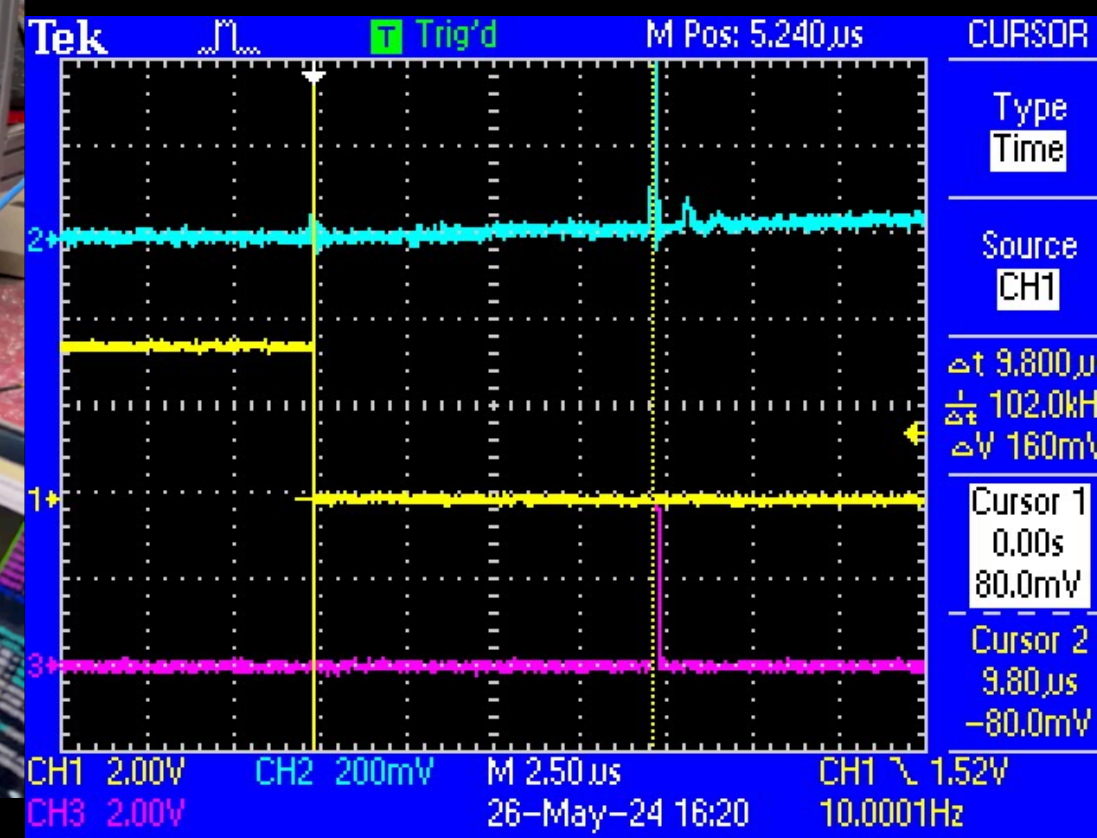
40 cm



GUI SOFTWARE INTEGRATED  
WITH CAD MODEL  
PREVENT LASER SHOTS IN  
SENSITIVE REGIONS



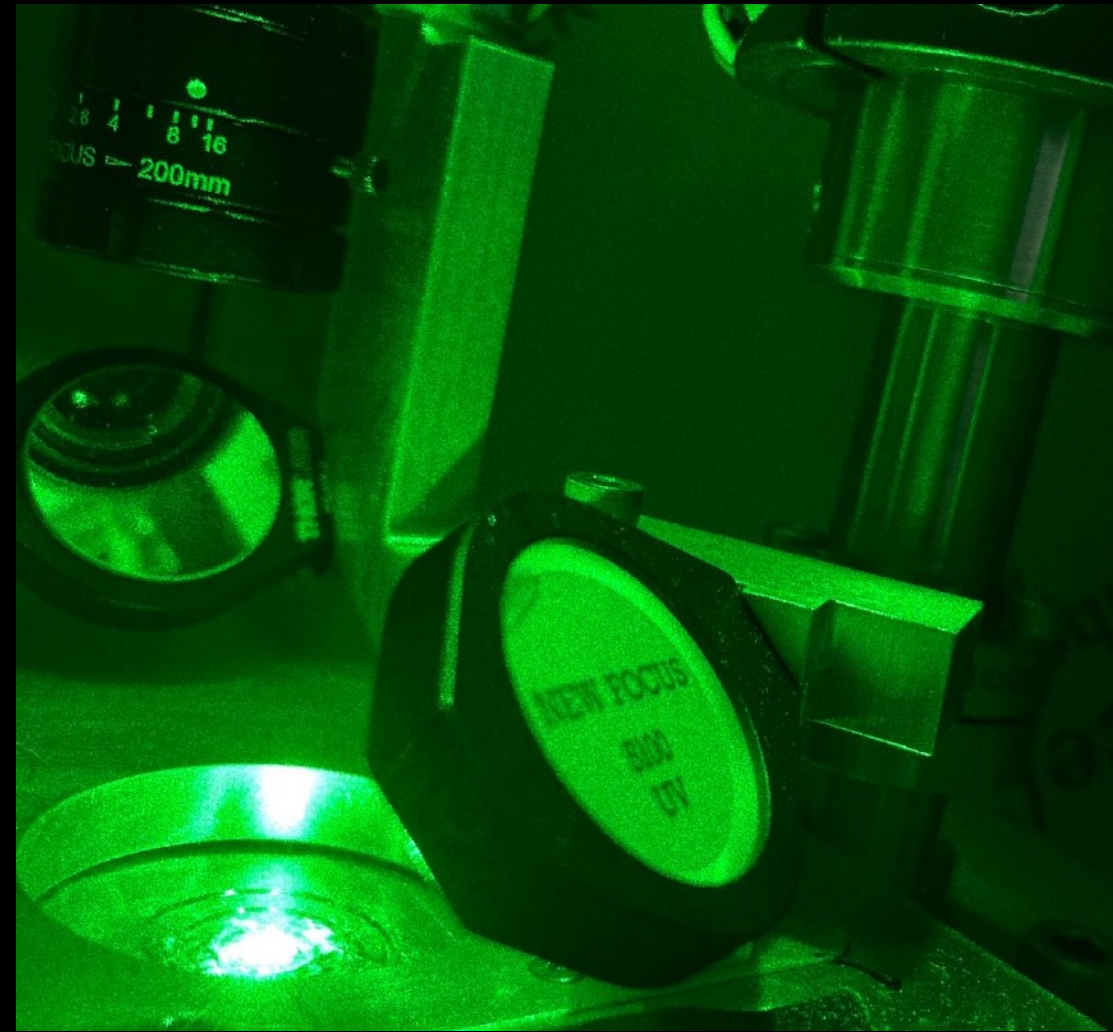
ELECTRONIC  
NOISE CHECKS



ELECTRONICS GENERATING  
DAQ TRIGGER BASED ON  
PHOTODIODE

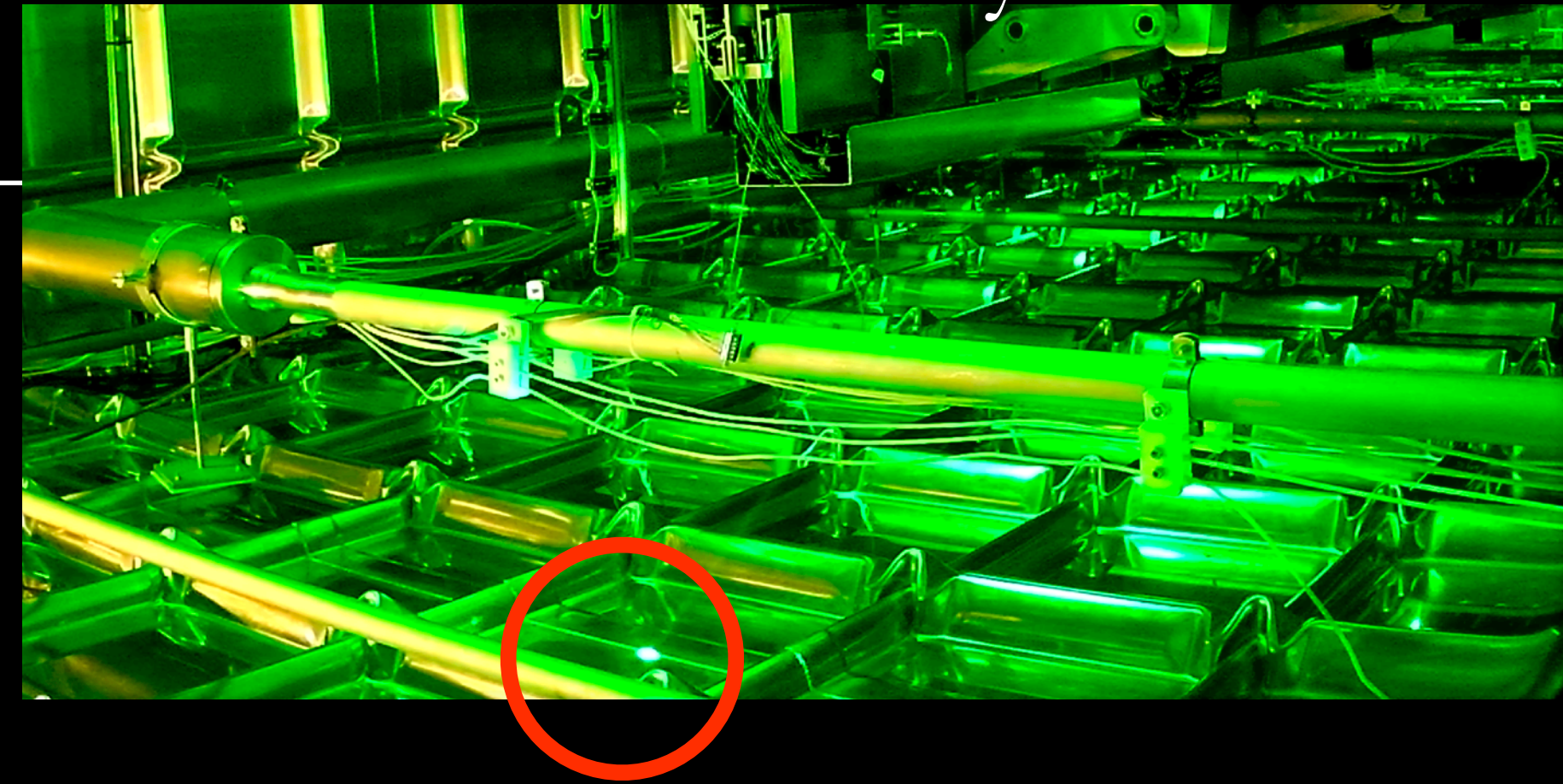


# ALIGNMENT



- Initially, with green laser
- A few targets and cameras within the system

- Camera inside cryostat



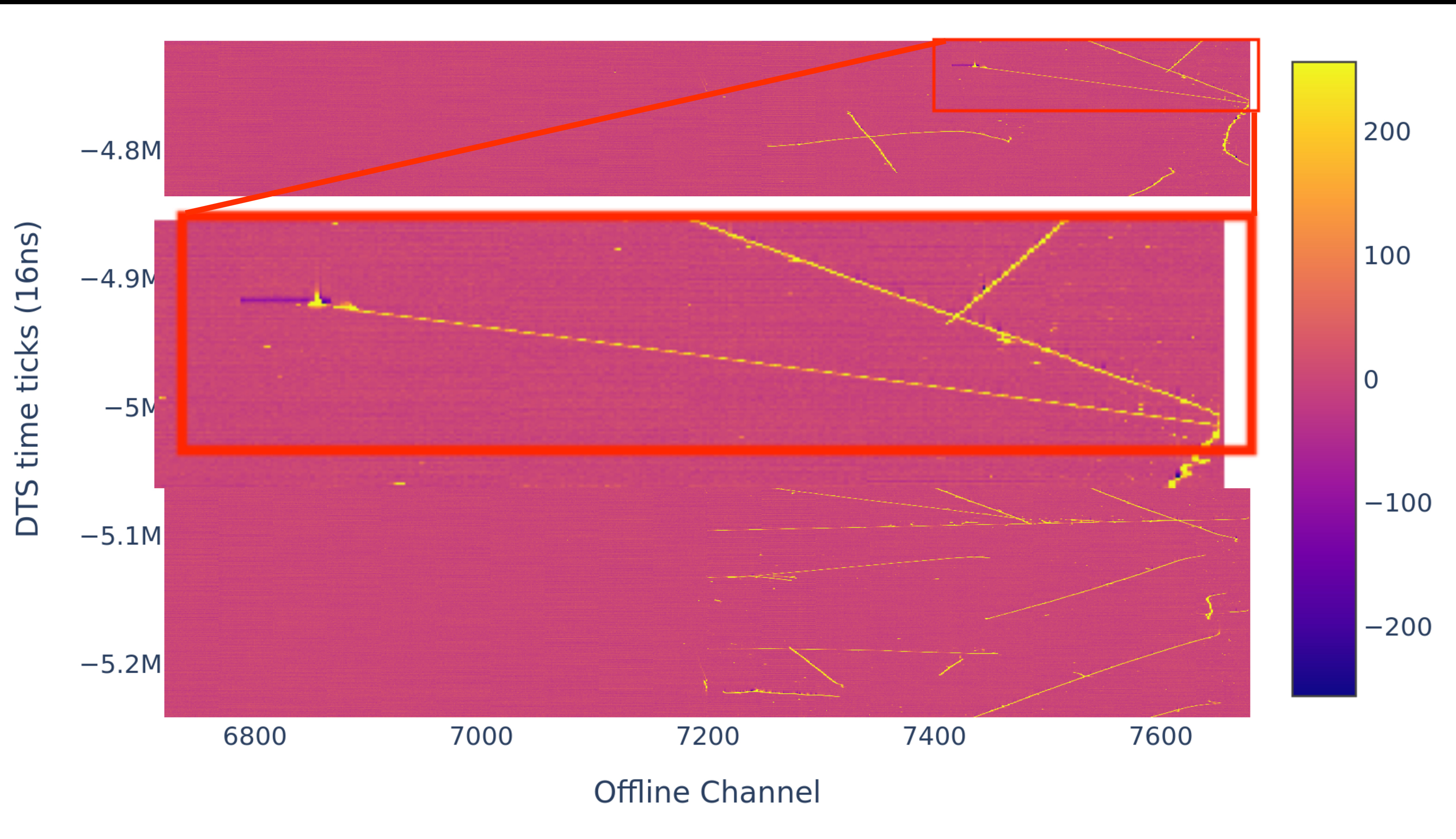
- Movable target within periscope
- Camera can tell when most light is passing through hole



- Hitting PIN diodes with UV laser!
- Next: mirror pads



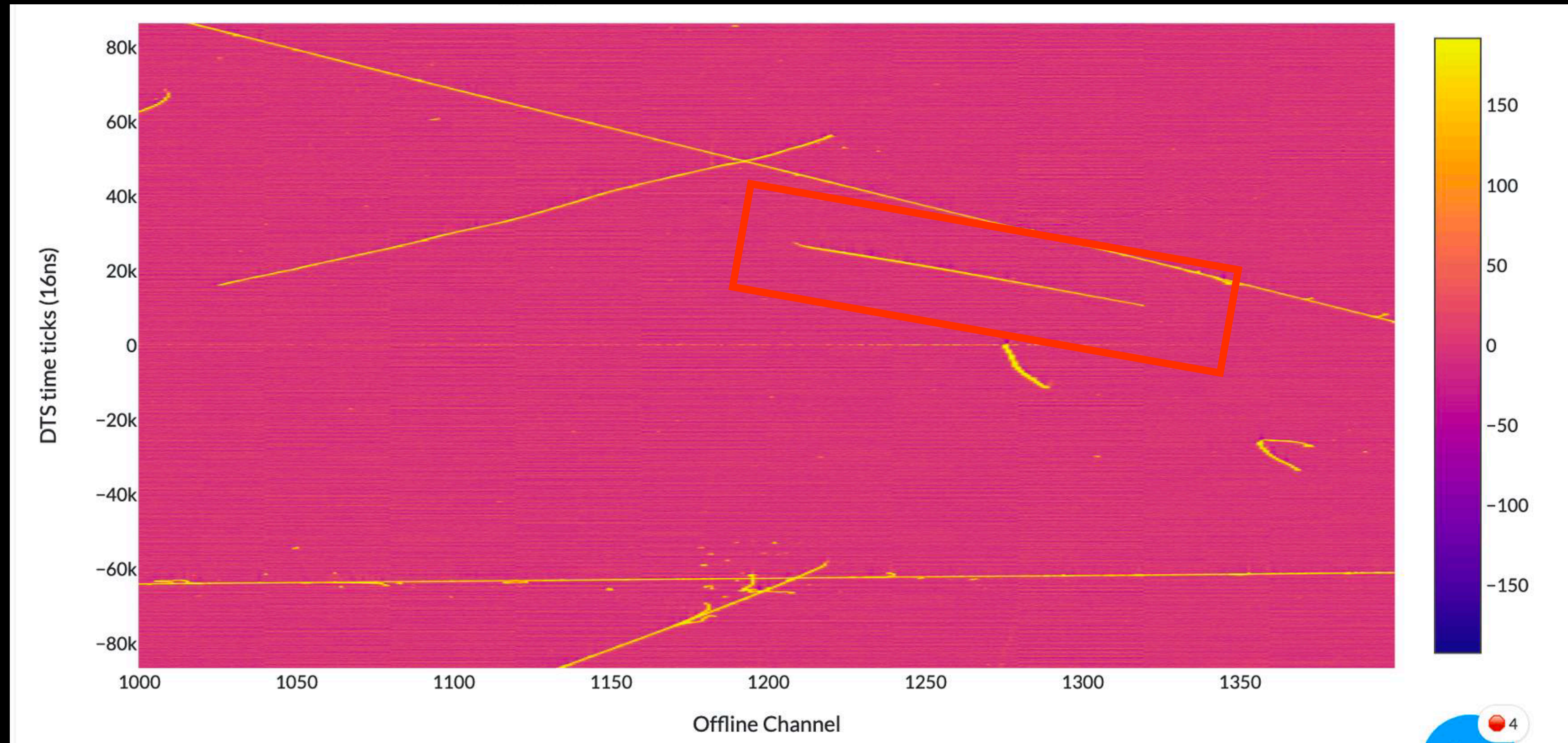
# COMMISSIONING/FIRST DATA



- First laser tracks in the detector in June
- No trigger then, using extra-wide time window
- Periscope 1. Track starts inside TPC
- Particle beam period started soon after
- Laser resumed in September, with DAQ trigger



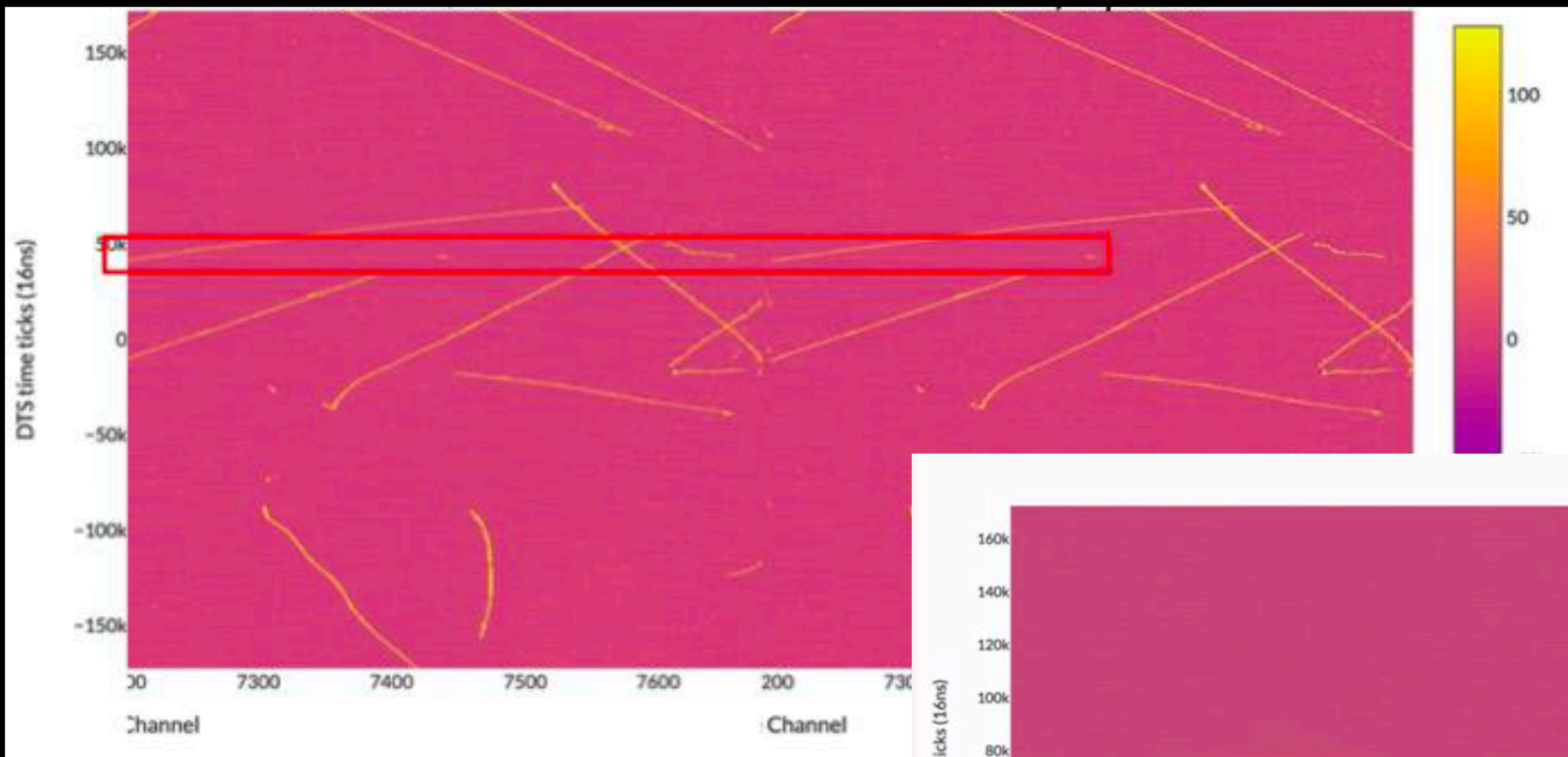
# PERISCOPE 2 TRACK



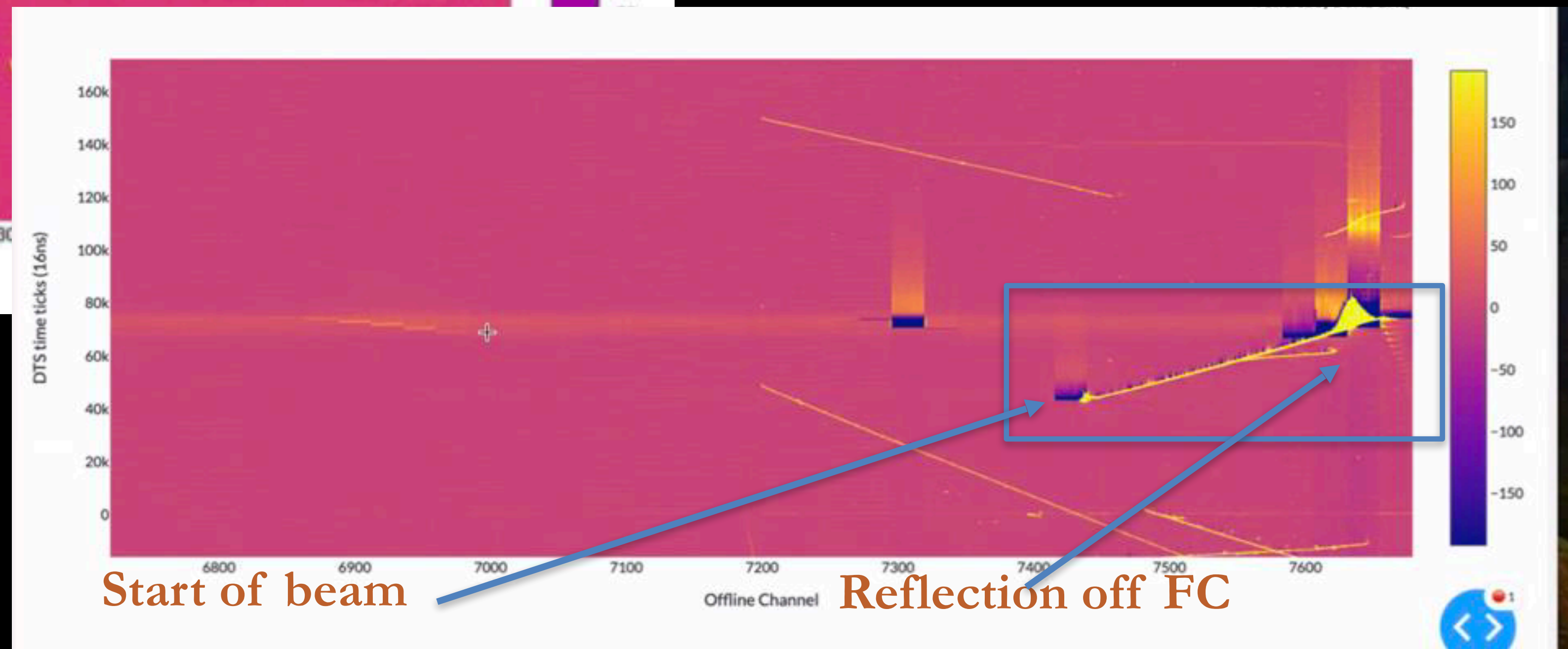
Beam making it within 1.4 cm field cage gap!



# MORE P1 TRACKS



- Parallel to anode, useful for channel checks
- High intensity, reflection off of field cage





# CONCLUSIONS



- DUNE measurements rely on a very good energy performance
- Calibrations will make use of several natural and deployed sources
- DUNE has proposed a series of improvements over the MicroBooNE laser system, that are being tested at ProtoDUNE
- Construction, installation and commissioning of PD-HD system completed at CERN. Taking data now!
- Next: PD-VD. And then... far detector construction!



EXTRA SLIDES



