The DUNE Photon Detection System

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DUNE

DUNE IN A NUTSHELL

Long-Baseline Neutrino Oscillation Experiment

A leading-edge international experiment for neutrino science and proton decay studies

① Neutrino beam

- 1.2 MW beam power
- Upgradeable up to 2.4 MW

② Near Detector (ND)

- 574m from the beam
- Unoscillated flux monitoring (energy spectra & composition)
- νAr cross-section measurements

③ Massive Far Detector (FD)

- 1300 km from the ND
- Measurement of oscillated neutrinos
- Technology: LArTPC

DUNE PHYSICS

Long-Baseline Neutrino Oscillation Experiment

A leading-edge international experiment for neutrino science and proton decay studies

Details about DUNE physics in L. Perez-Molia talk

Measurement of ν_e appearance and ν_μ disappearance for a wide range of neutrino energies [0-10 GeV]

- 5σ measurement of the neutrino mass ordering
- Discovery potential for CP violation (wide range of δ_{CP})
- Precise measurements of neutrino mixing parameters

No Beam Physics:

- Proton Decay $p \rightarrow K^+ \bar{\nu}$
- Supernova Neutrino Bursts (SNB)
- Solar neutrinos & BSM physics

DUNE FAR DETECTOR (FD)

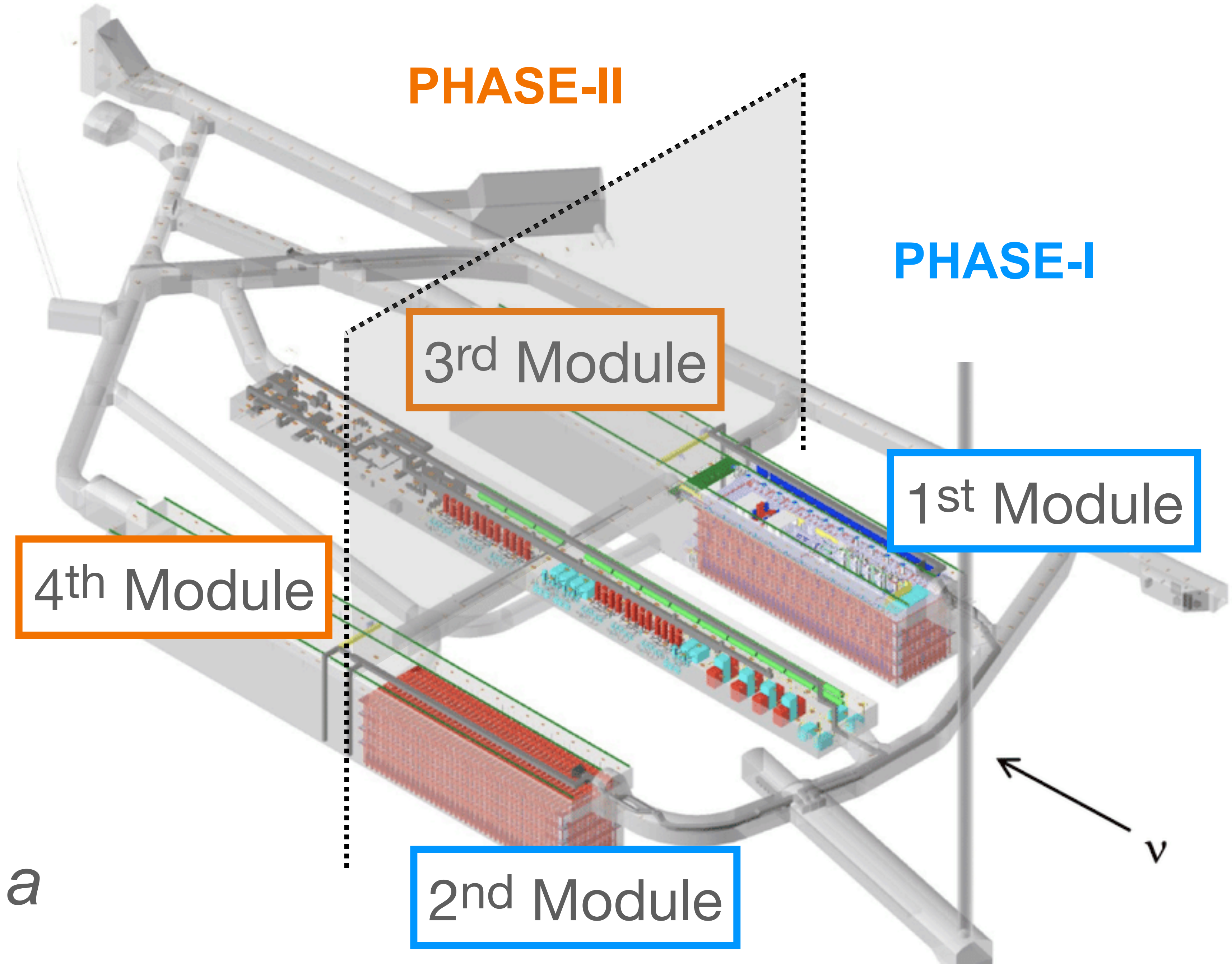
LArTPCs: liquid argon time projection chambers
— 4 modules: 70 kton total mass —

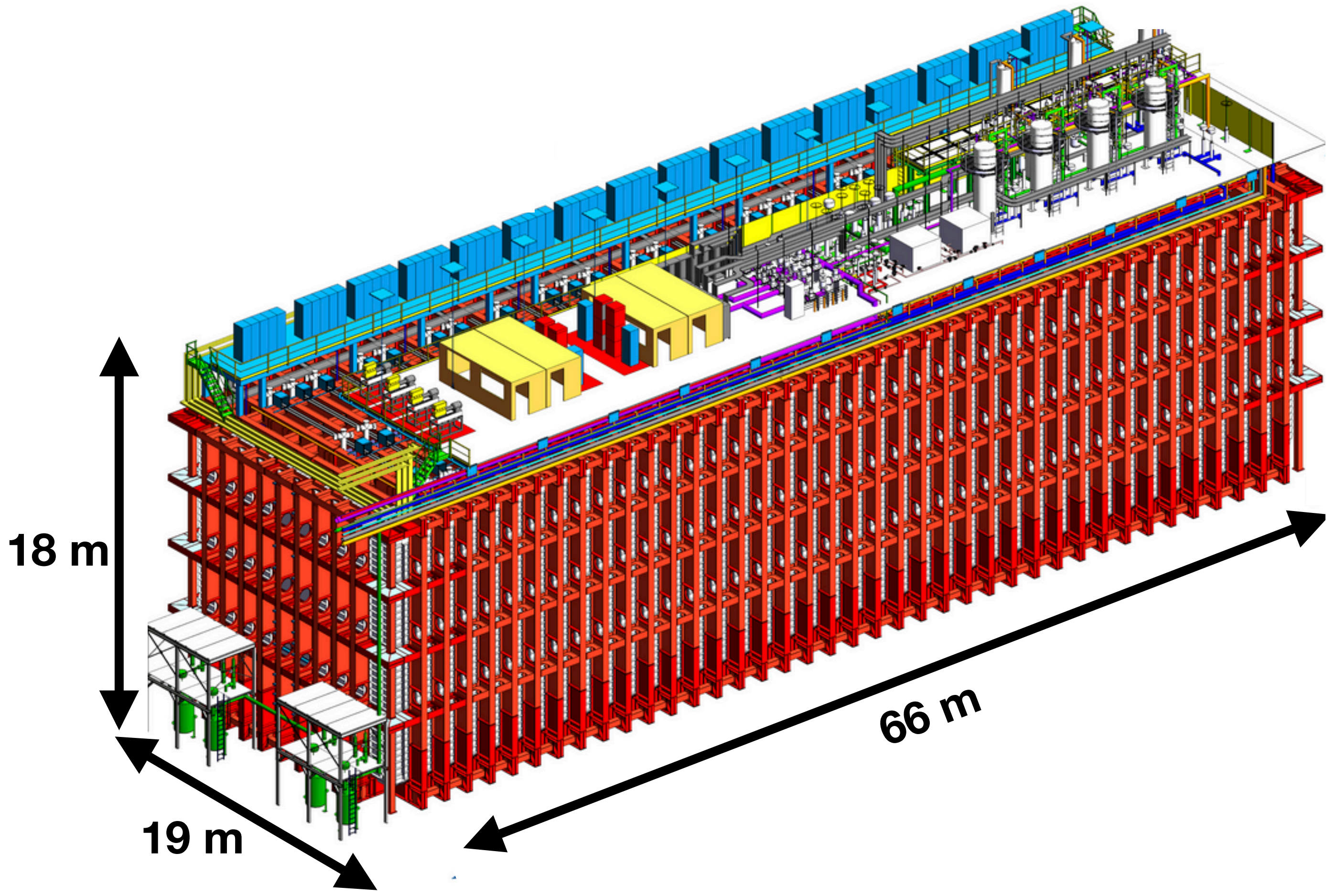
- Sanford Underground Research Facility (SURF)
- 1500 m underground (4300 m.w.e.)
- 4 detectors in 2 caverns
- Detector deployment in stages:

  - DUNE PHASE-I (Modules 1 & 2)

  - DUNE PHASE-II (Modules 3 & 4)

The two-phase approach will allow implementation of improvements in the technology during PHASE-II

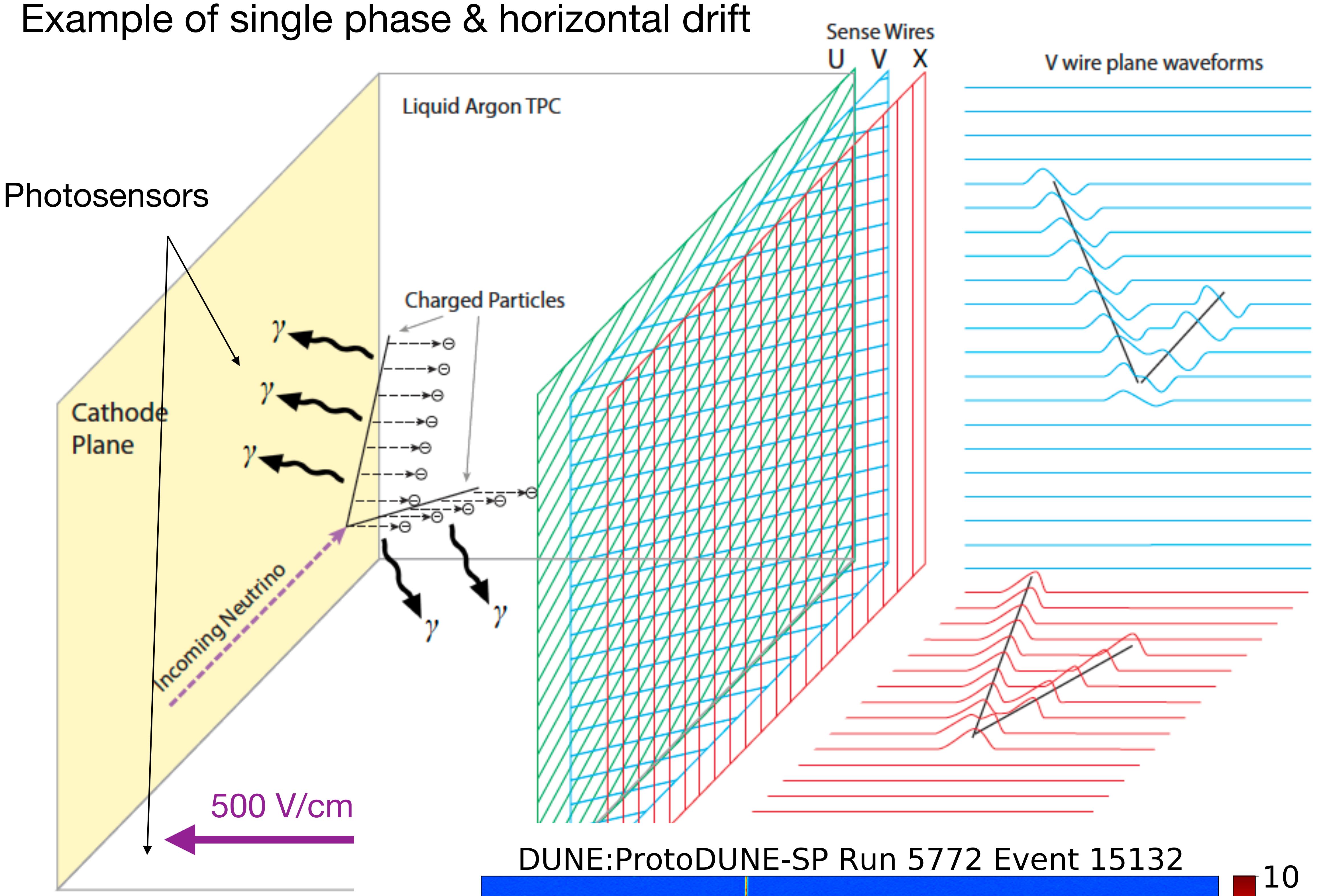


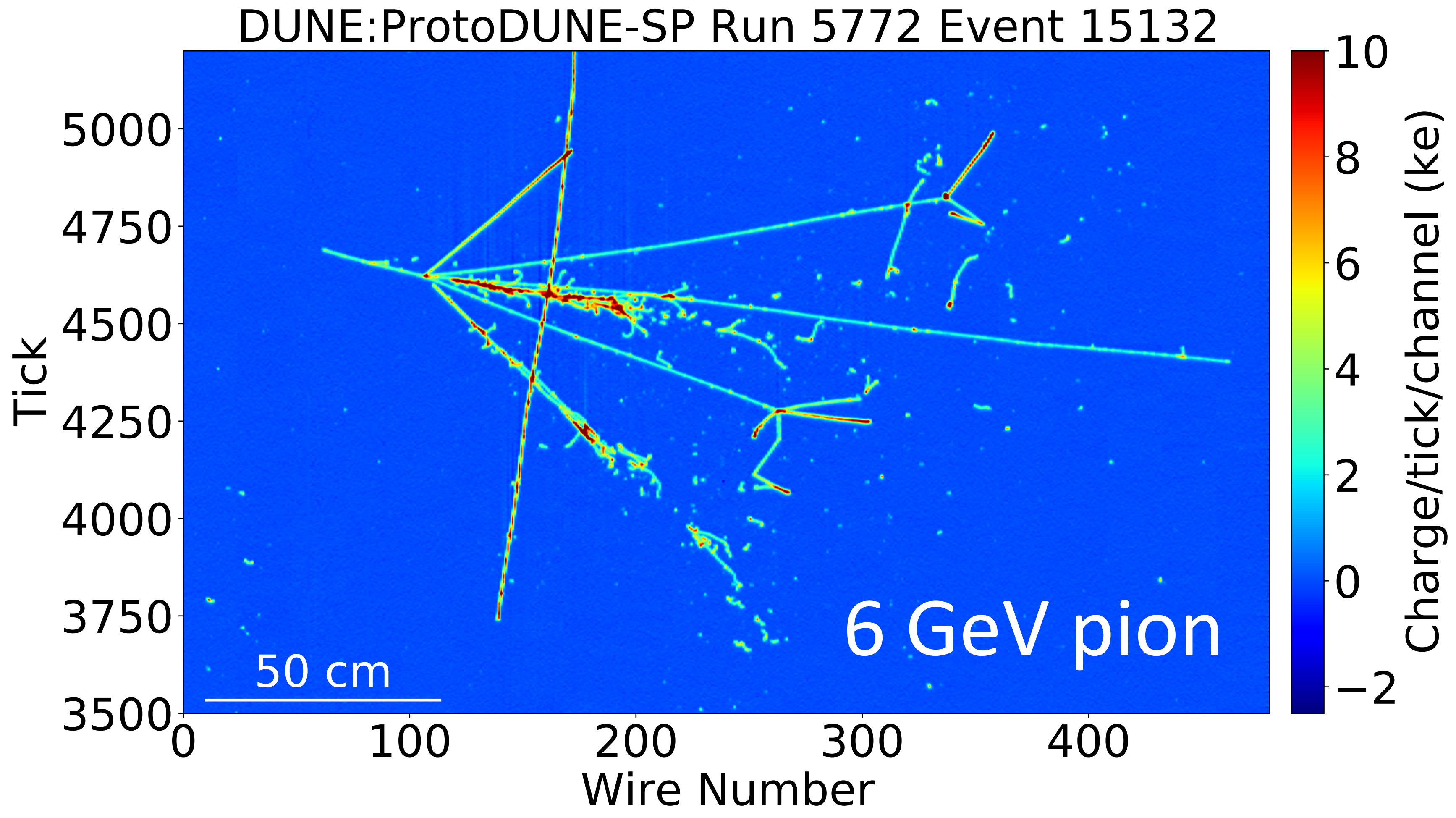


Phase-II also includes a 2.4 MW beam and a full ND (LArTPC + GArTPC + tracker)

WORKING PRINCIPLE OF A LArTPC

Example of single phase & horizontal drift





Interactions in a LArTPC

two signals proportional to the energy deposit

ionisation electrons	scintillation photons
~27000 e- / MeV	~24000 γ / MeV

For 500V/cm drift field

Drifted and collected in charge readout planes → Precision tracking and calorimetry

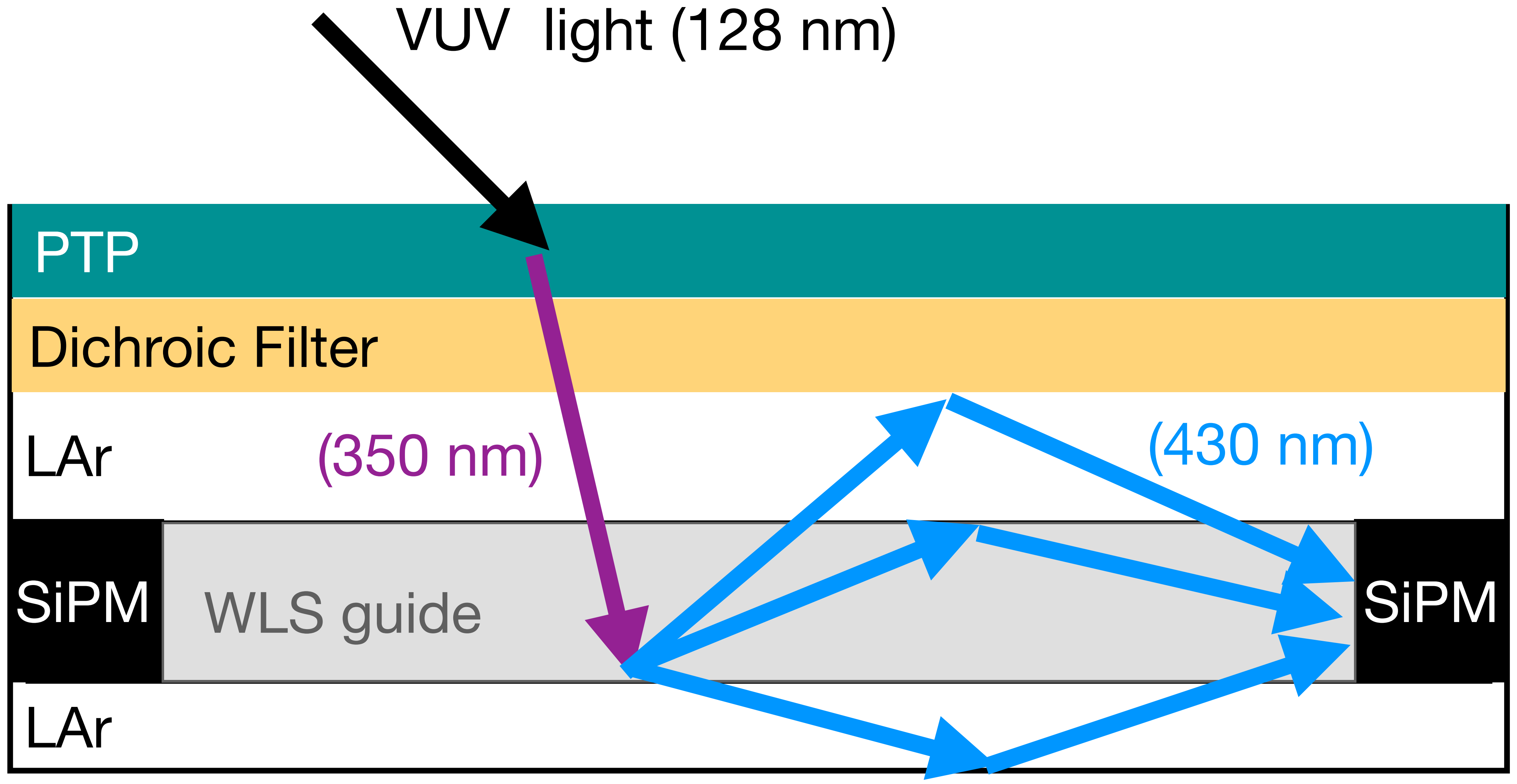
observed by the **photon detection system** → Time zero (t_0) and complementary calorimetry

DUNE PHOTON DETECTION SYSTEM: X-ARAPUCA

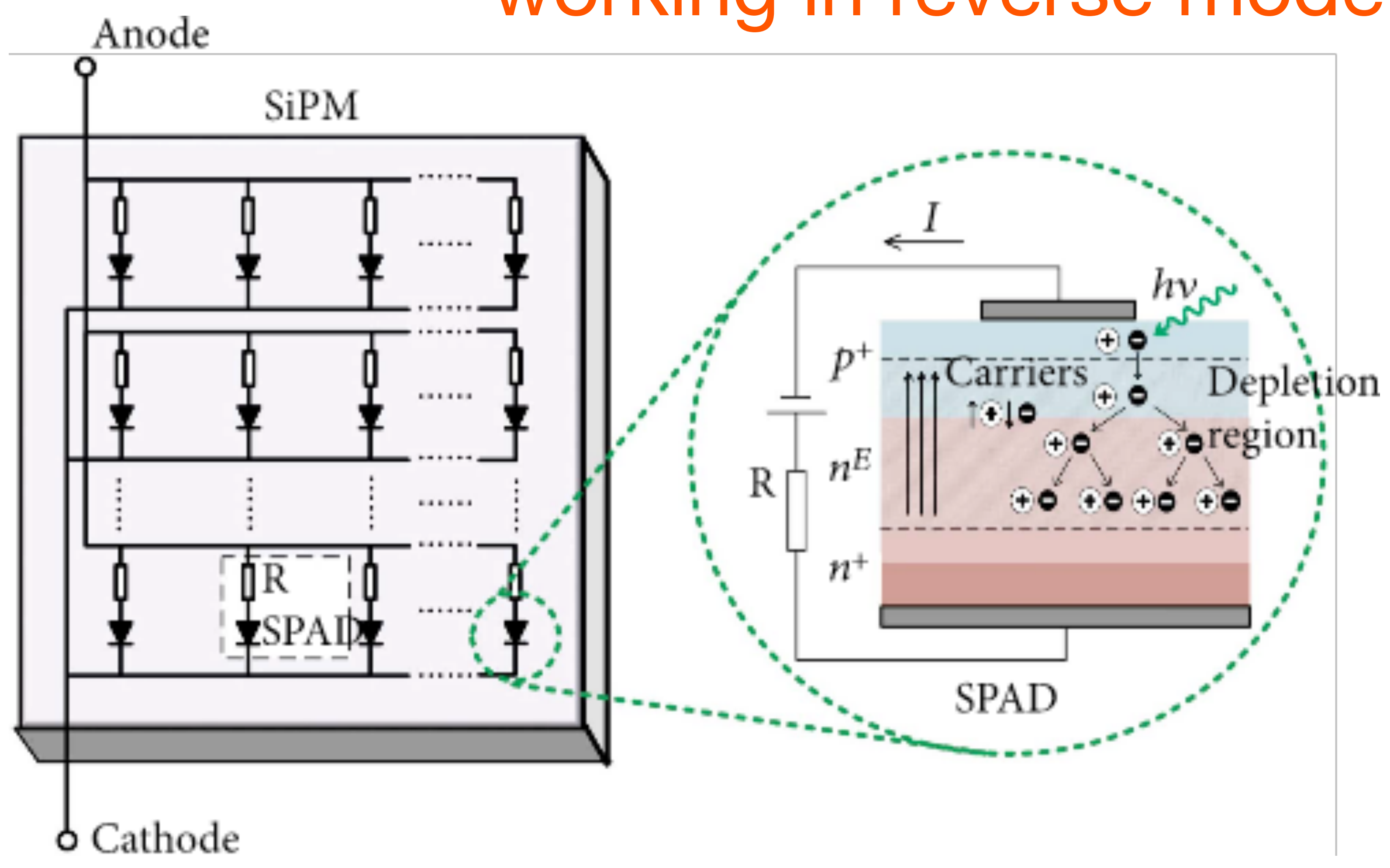
X-ARAPUCA system based on SiPMs

The idea is to maximise the collection of photons by trapping them in a box

1) PTP converts VUV light to a wavelength < dichroic cutoff (128 nm -> 350 nm)
2) The dichroic filter allows the pass of the 350 nm photons.
3) Wavelength shifter bars (WSB) shift the light above the dichroic cutoff (350 nm -> 430 nm)
4) The light is trapped and after several reflections reaches the SiPMs

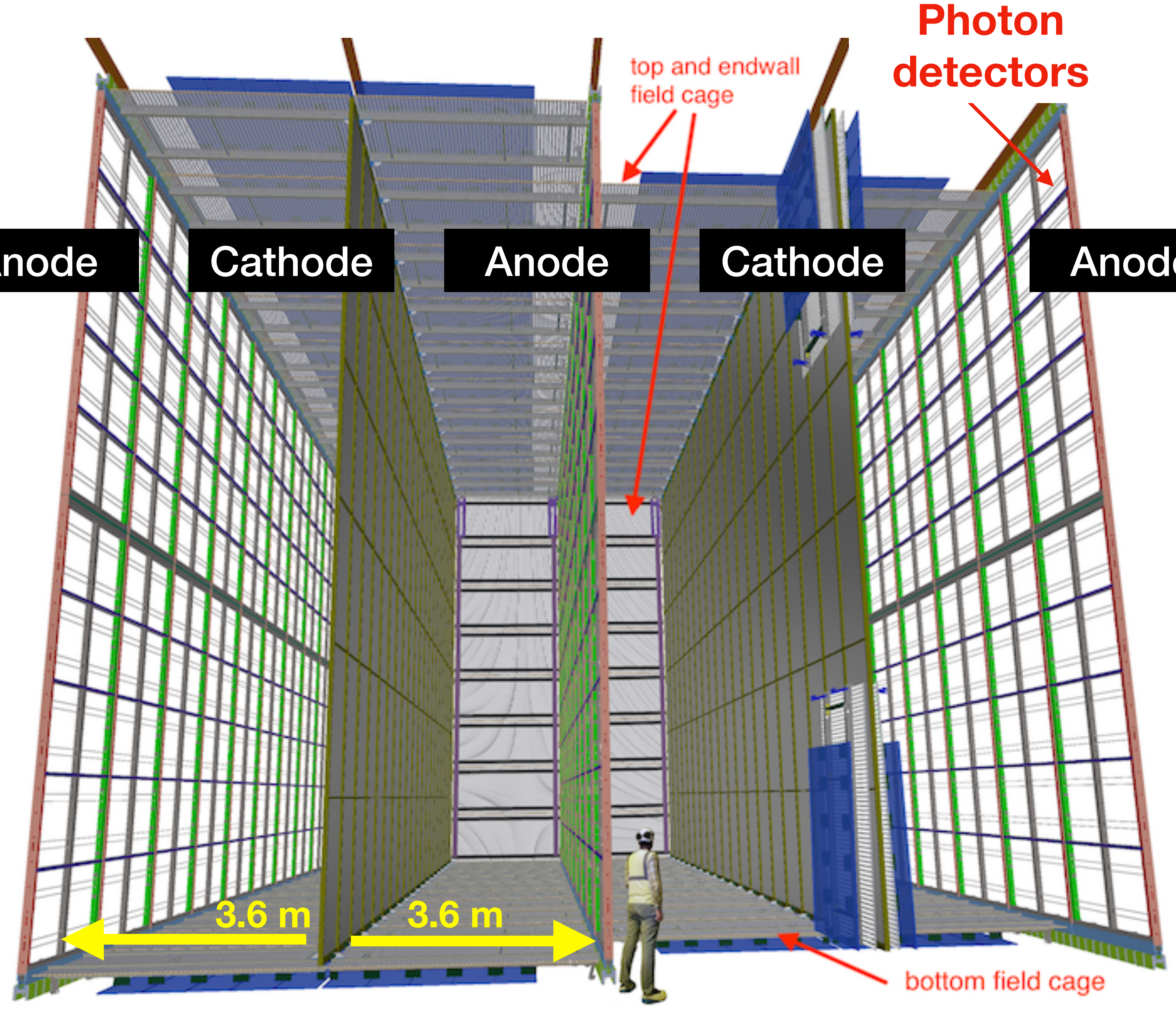


A SiPM is a p-n junction working in reverse mode



DUNE SINGLE PHASE LArTPCs (FD-HD & FD-VD)

FD-HD (Horizontal Drift)



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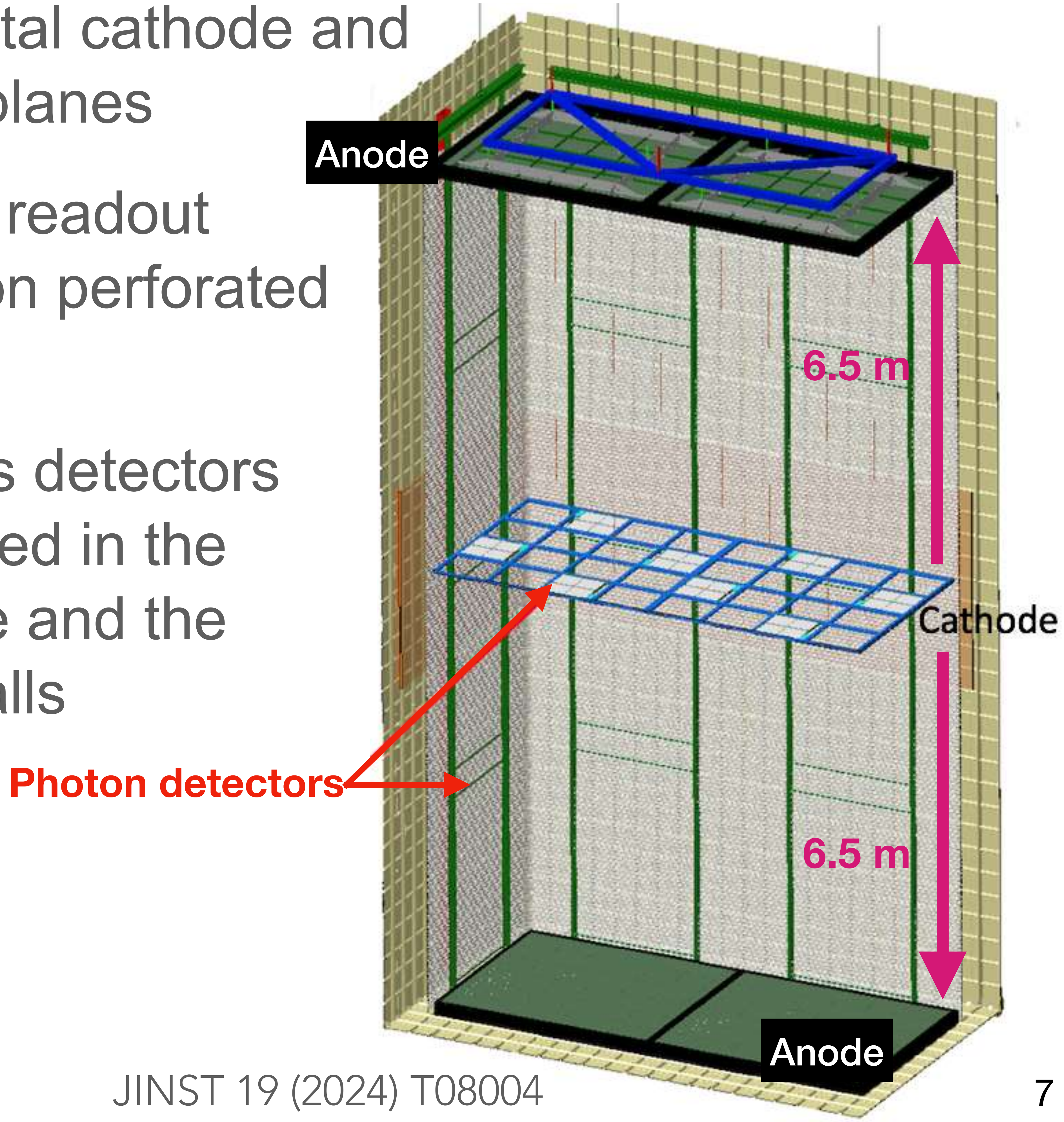
- 4 horizontal drift regions (3.6 m)
- Vertical cathode and anode planes
- Charge readout based on wires
- Photons detectors integrated in the anode planes

FD-VD (Vertical Drift)

- 2 vertical drift regions (6.5 m)
- Horizontal cathode and anode planes
- Charge readout based on perforated PCBs
- Photons detectors integrated in the cathode and the TPC walls



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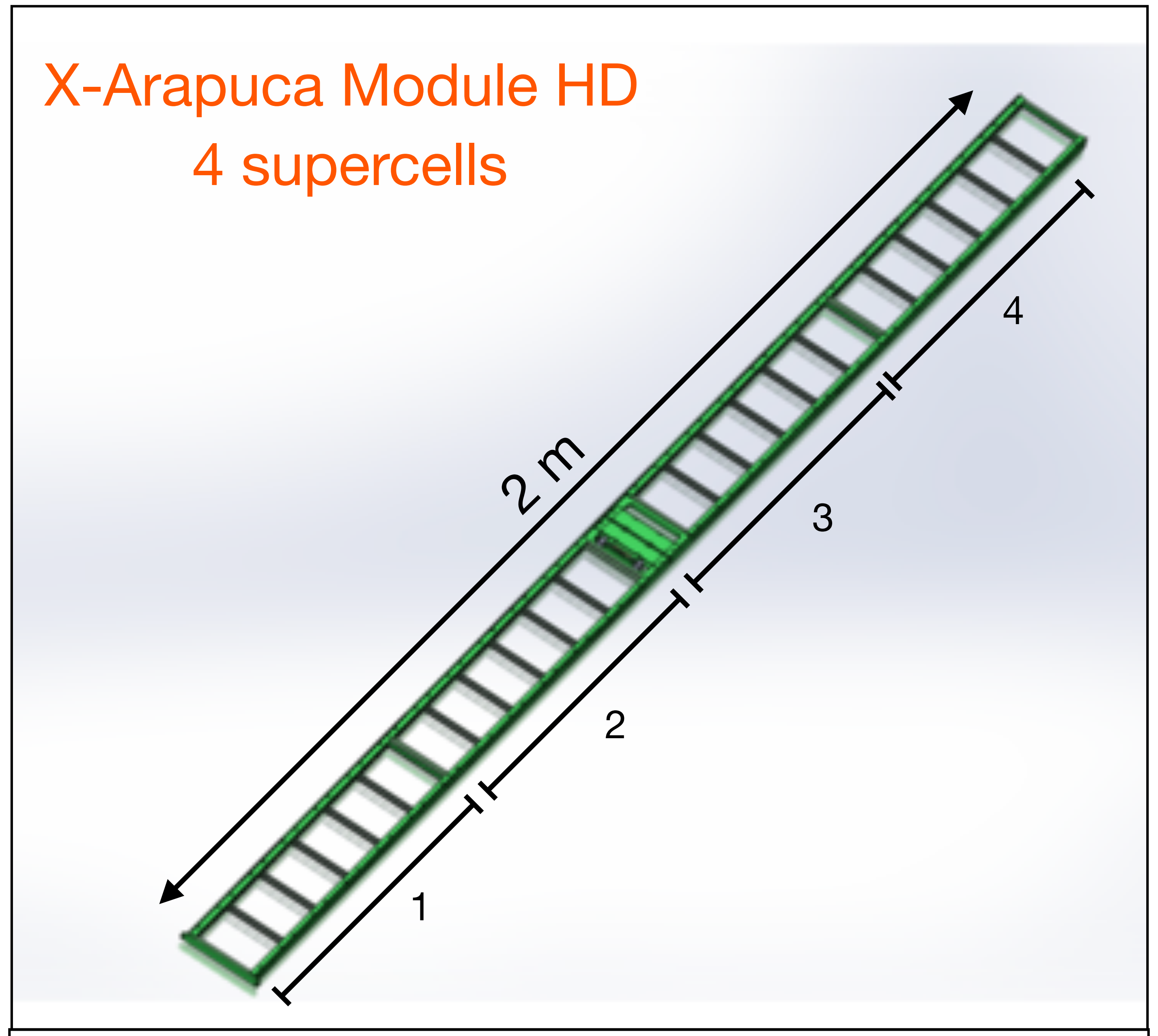
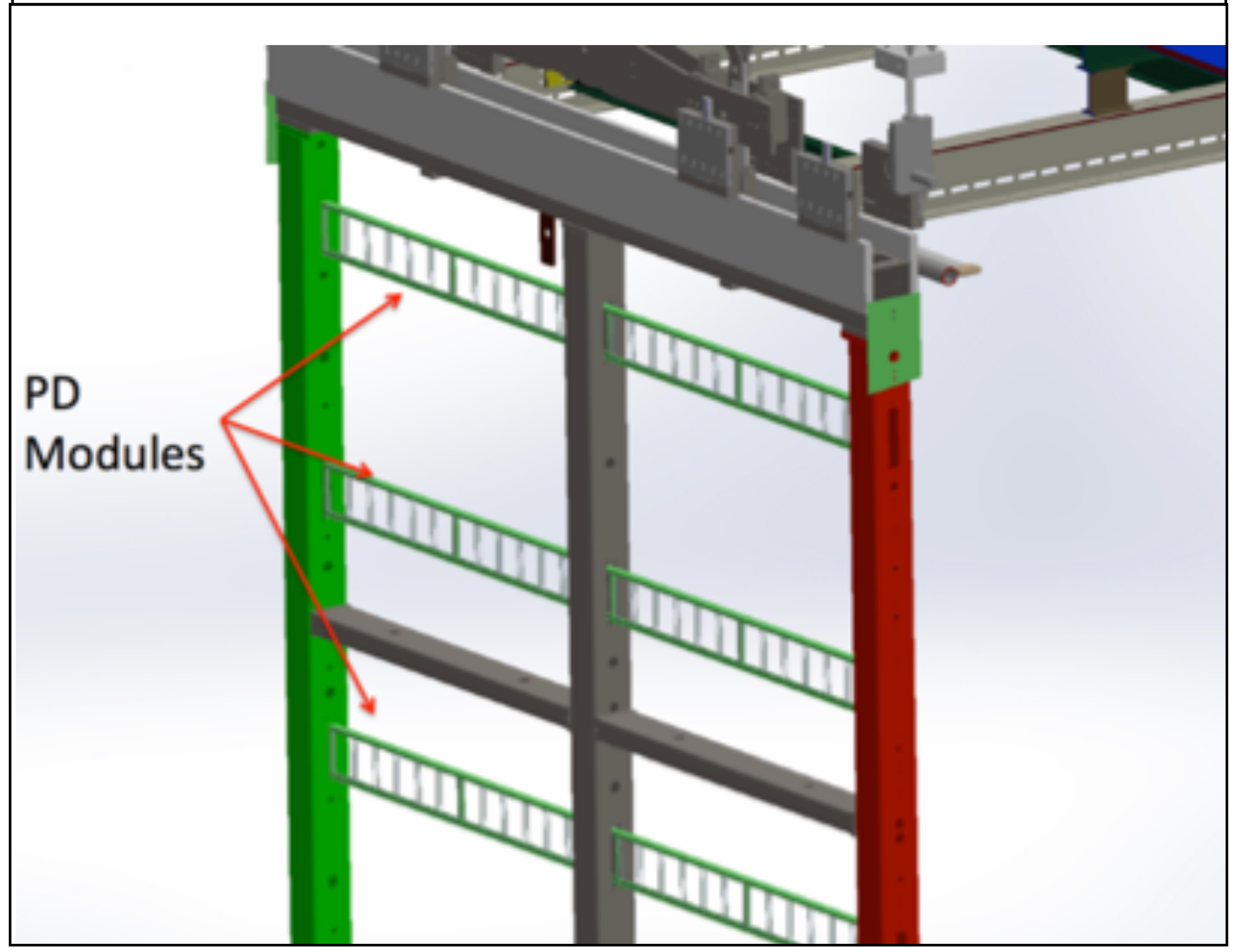
PHOTON DETECTION SYSTEM FOR THE FD-HD

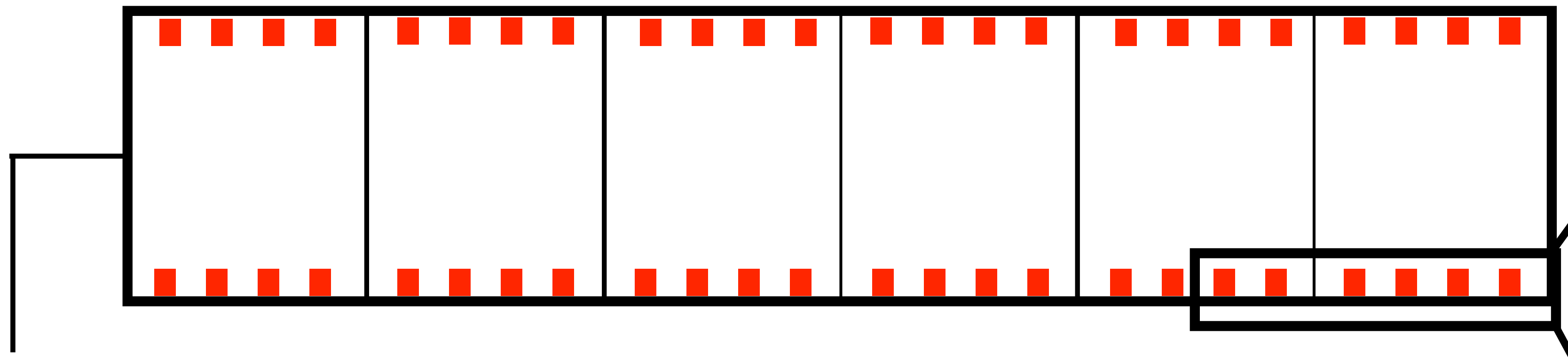




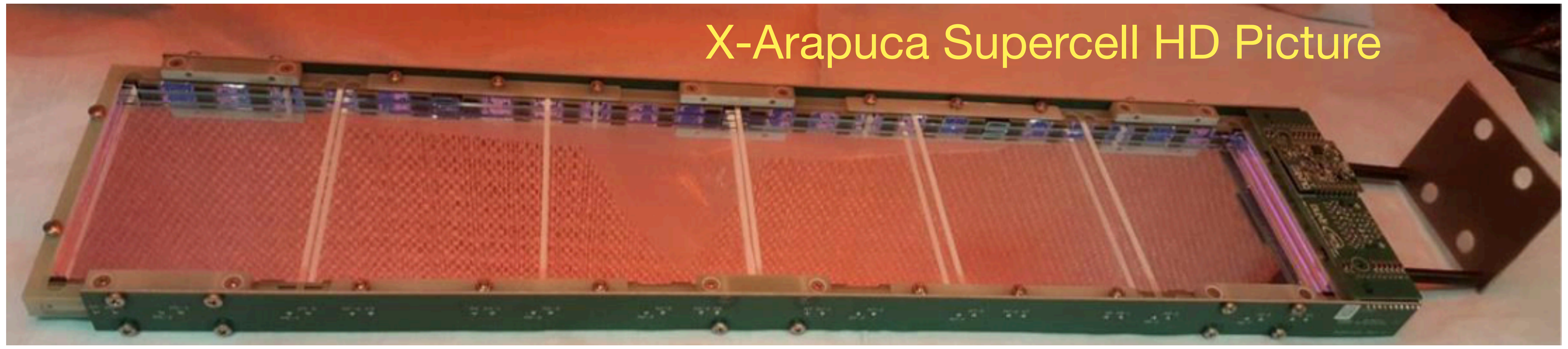
X-Arapuca - Horizontal Drift

Rectangular arrangement for easier integration in the anode planes

X-Arapuca Supercell HD

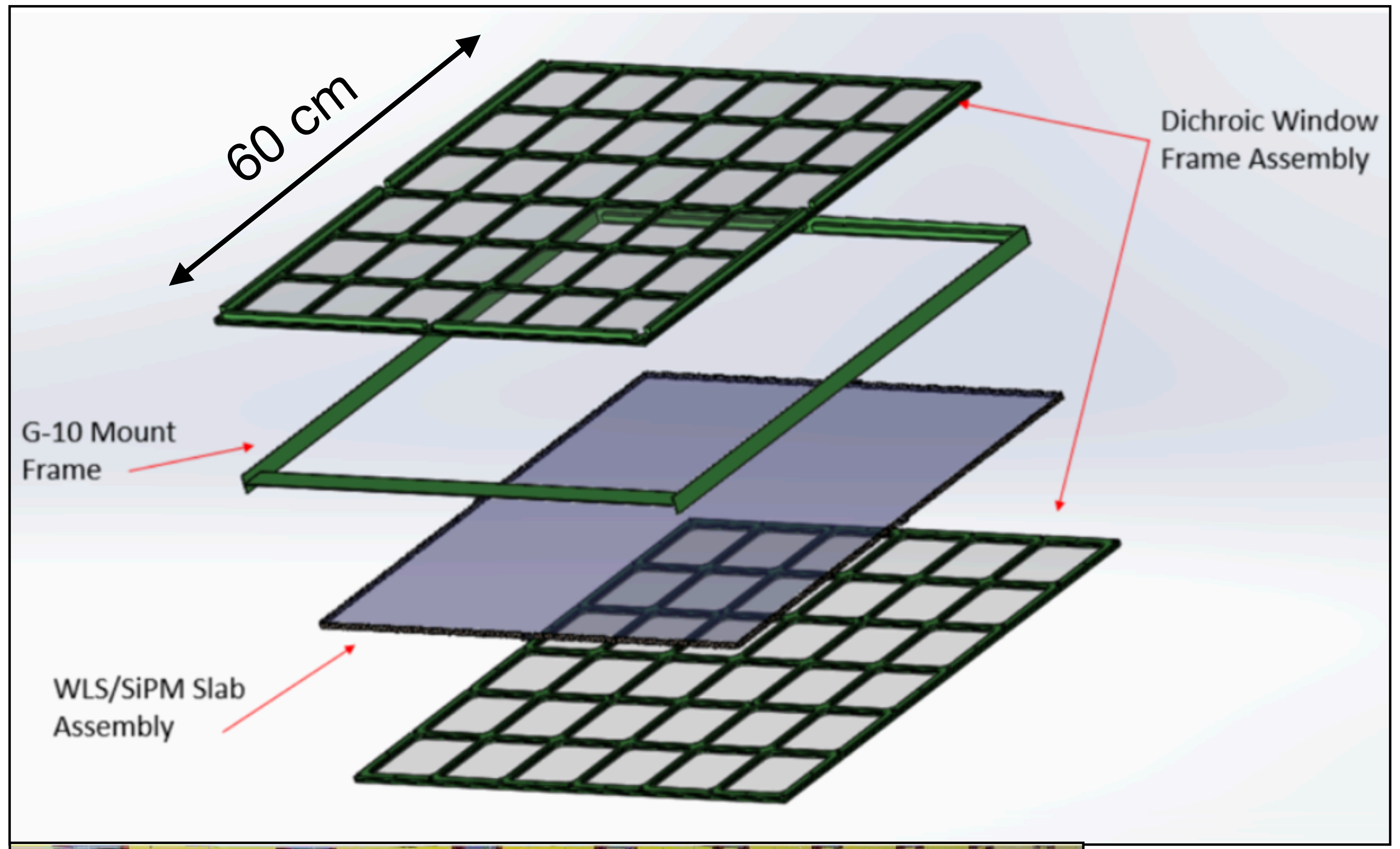


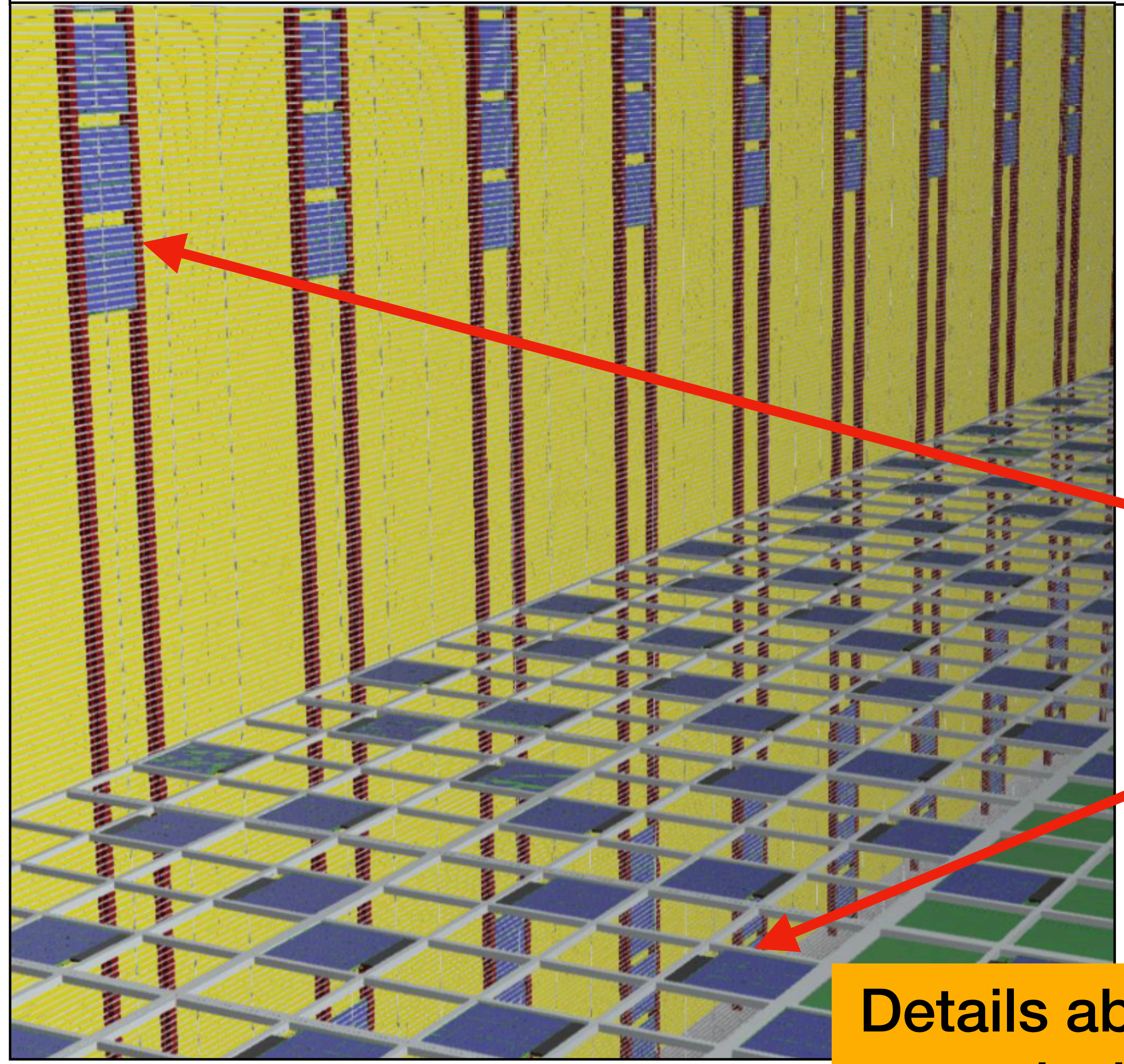
- 50 x 10 cm²
- 6 dichroic filters
- 48 SiPMs in total (8 strips)
- Strips with 6 SiPMs
- SiPMs 6x6 mm²
- One readout channel only



PHOTON DETECTION SYSTEM FOR THE FD-VD

X-Arapuca Supercell VD





Hanging from the membrane

Embedded in the cathode (-300 kV)

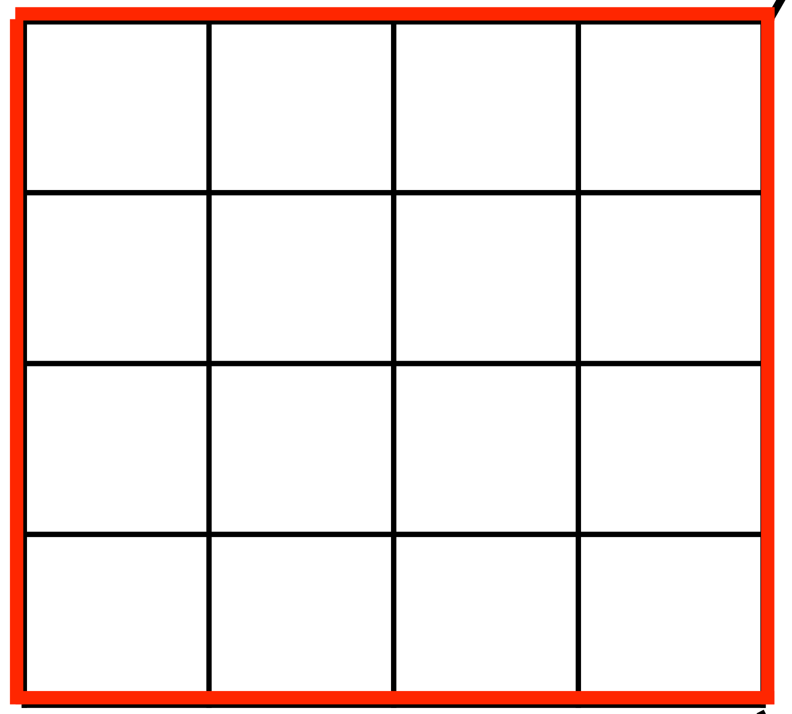
Details about signal and power transmission in S. Sacerdoti talk

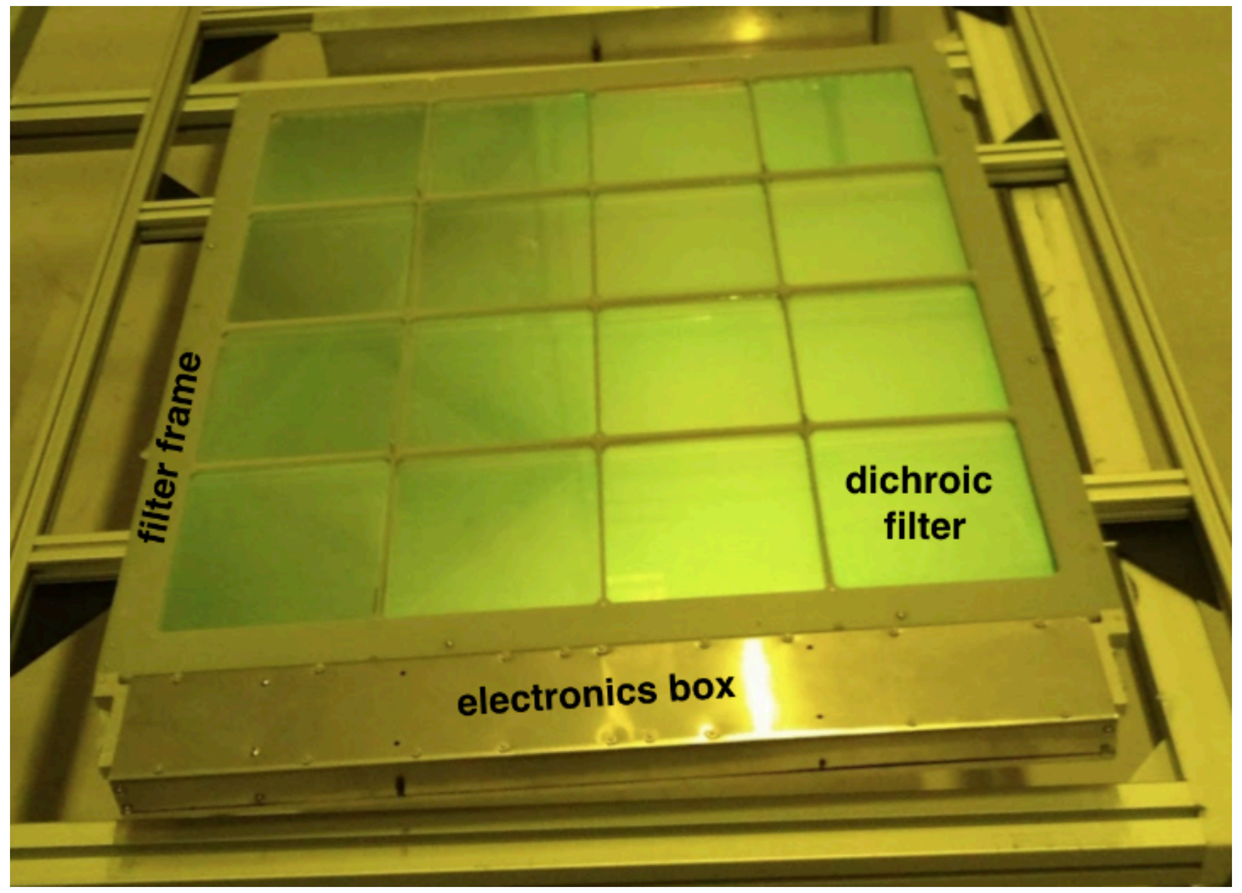
X-Arapuca - Vertical Drift

Square arrangement for easier integration in the cathode plane and the walls

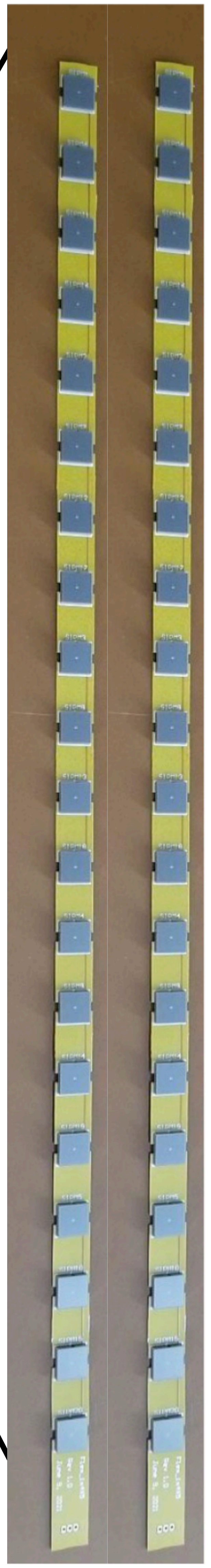
- 60 x 60 cm^2
- 160 SiPMs in total (8 strips)
- Flex strips with 20 SiPMs
- SiPMs 6x6 mm^2
- Two readout channels

X-Arapuca VD



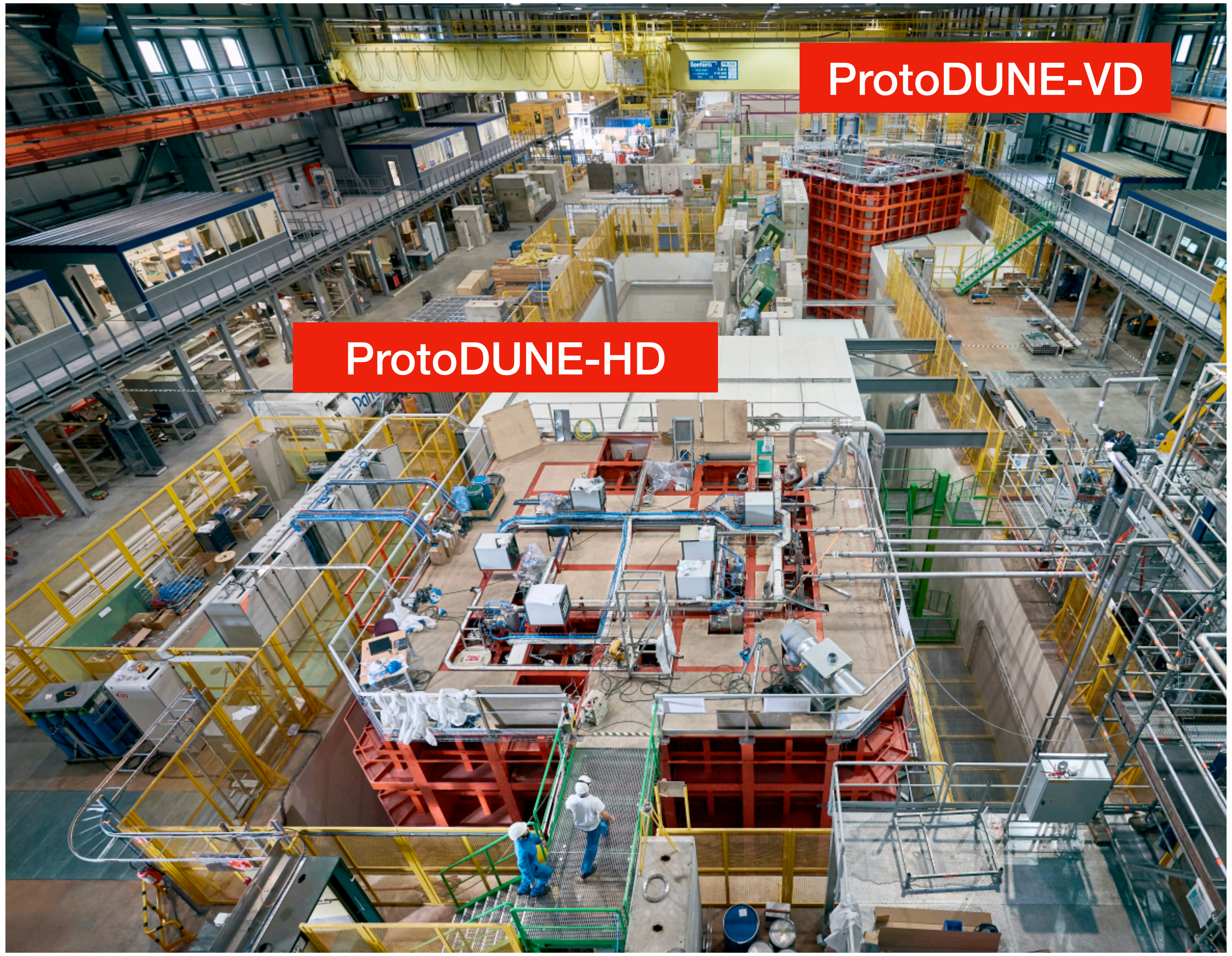


X-Arapuca cell VD



ProtoDUNEs at CERN

Technology choices based on the performance of the ProtoDUNEs at CERN



DUNE. JINST 15 (2020) P12004

- Size: 800 t LAr total (1/20 of a total FD module)
- Successful run in 2018 - 2020

NEW Runs:

- ProtoDUNE-HD run in summer 2024: ✅

Goal: Test upgraded components in their final design and take more beam data

- Test of 40 X-Arapuca modules

- ProtoDUNE-VD run in summer 2025: ⌛

Goal: Test the VD concept for the first time at large scale

- Test of 16 X-Arapuca modules

DUNE SiPMs

DUNE PHASE-I will have an enormous amount of SiPMs
- FD-HD (~300.000 SiPMs)
- FD-VD (~100.000 SiPMs)

- Two different vendors:
  - **Hamamatsu Photonics K.K (HPK)** - Japan
  - **Fondazione Bruno Kessler (FBK)** - Italy

HAMAMATSU
PHOTON IS OUR BUSINESS

FONDAZIONE BRUNO KESSLER

- Different SiPM technologies proposed (cell pitch, high/low resistance, packaging, design…)

- A thorough down-selection campaign among different labs identified the best models to be operated in DUNE

JINST 19 (2024) T08004

Results published at:
- *Cryogenic Characterisation of Hamamatsu HWB MPPCs for the DUNE Photon Detection System* (JINST **19** (2024) T01007)
- *Characterisation of FBK SiPM sensors for the DUNE Far Detector* (to be submitted soon)

DUNE SiPM CHARACTERIZATION

Every SiPM must be characterised prior its final installation in the detector

- Parameters to be studied:
  - Breakdown voltage (V_{BD})
  - Quenching resistance (R_Q)
  - DCR, after pulses (AP) and crosstalk (XT)

- Procedure:
  - IV curves
  - Dark measurements

before and after thermal stress to check reliability in LAr

DUNE STRATEGY

The V_{BD}, R_Q and DCR will be measured for each SiPM in dedicated facilities to guarantee that all the SiPMs installed in DUNE are operational

(Test ~400.000 SiPMs)

A sub-sample (~10%) will undergo a complete characterisation to identify damaged batches

DUNE SiPM MASS-TEST SETUP (I)

Cryogenic Apparatus for Control Tests Upon SiPMs

CACTUS allows for the characterisation of 120 SiPMs in parallel

- Characterisation both at room and LN_2 temperatures
- Automatic LN_2 refilling (55 L)
- Translator stage for controlling LN_2 immersions
- Custom low-noise cold and warm electronics
- FPGA based counter with programmable charge discriminator for DCR

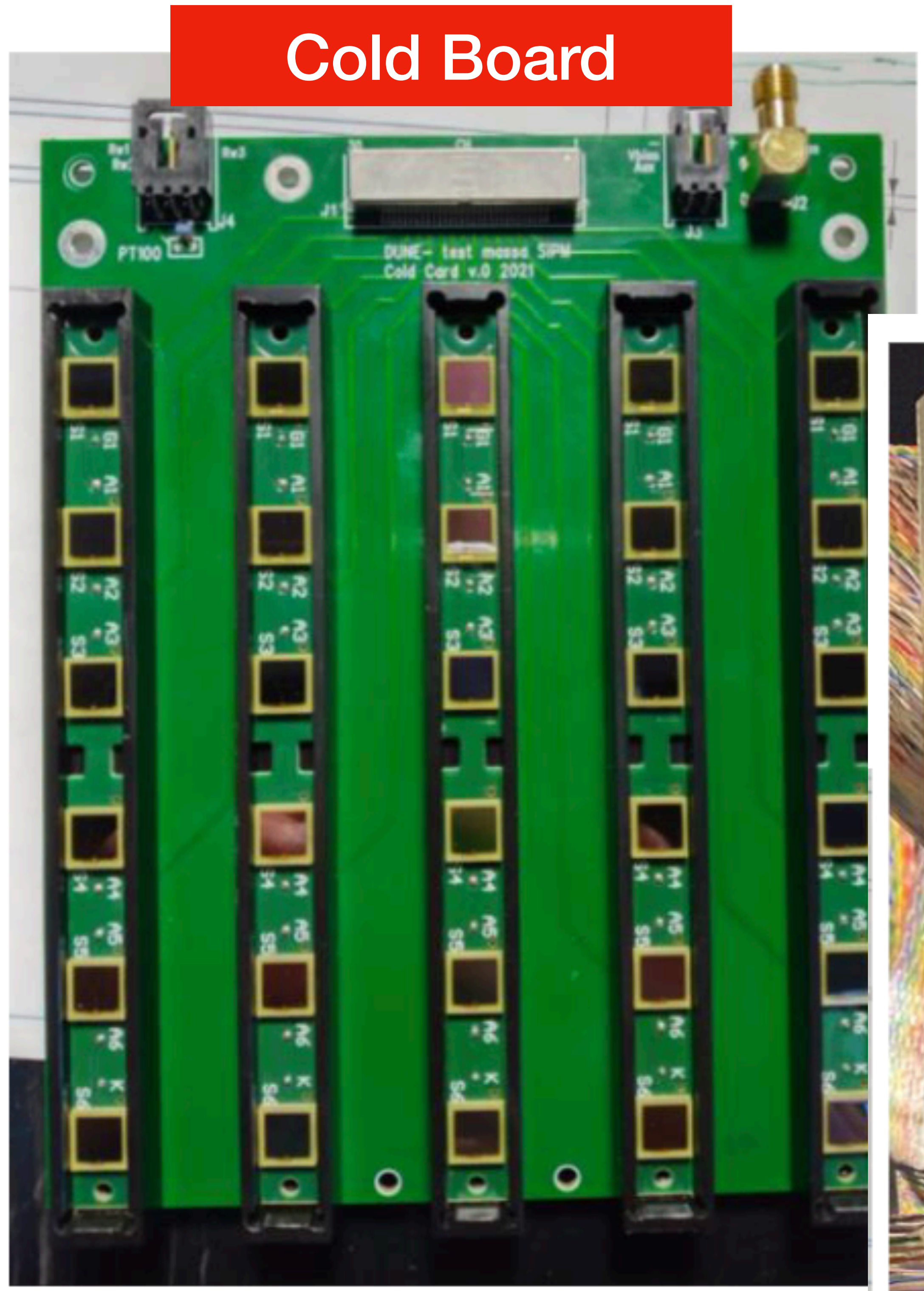
Developed by the Ferrara and Bologna Universities/INFN groups

DUNE SiPM MASS-TEST SETUP (II)

Cryogenic Apparatus for Control Tests Upon SiPMs

Electronics:

- Warm board: mother board + microcontroller unit (Arduino MKR Zero) + 15 daughter boards
- Cold board: connect SiPMs to the warm board
- A Raspberry SBC handles the IV characterisation
- Voltage precision 10 mV
- Dynamic range for IV curves [10nA - 3mA]



DUNE SiPM MASS-TEST SETUP (III)

Cryogenic Apparatus for Control Tests Upon SiPMs

5 CACTUS facilities in Europe

(Ferrara, Bologna, Granada, Milano Bicocca & Prague)

- All the labs taking data
- Two years of testing per site
- 2400 SiPMs per month
- Data uploaded to a common database

The CACTUS facility successfully tested the SiPMs already installed in both ProtoDUNEs at CERN

SUMMARY:

- The DUNE experiment will count on the LArTPC technology for its FD.
- Collection of VUV photons in the TPCs is crucial to fulfil the DUNE physics goals
- The DUNE photon detection system has the potential to enhance the experiment physics capabilities
- The light detection system will be the X-Arapuca device, based on SiPMs.
- The ProtoDUNEs (HD & VD) at CERN provide an opportunity to test the configuration of the X-Arapucas under real operation conditions.
- **The mass testing of DUNE SiPMs is on-going and it will last one year more, prior the final installation of the SiPMs in the detector.**

Back Up

DUNE SiPM MASS-TEST SETUP (I)

CACTUS

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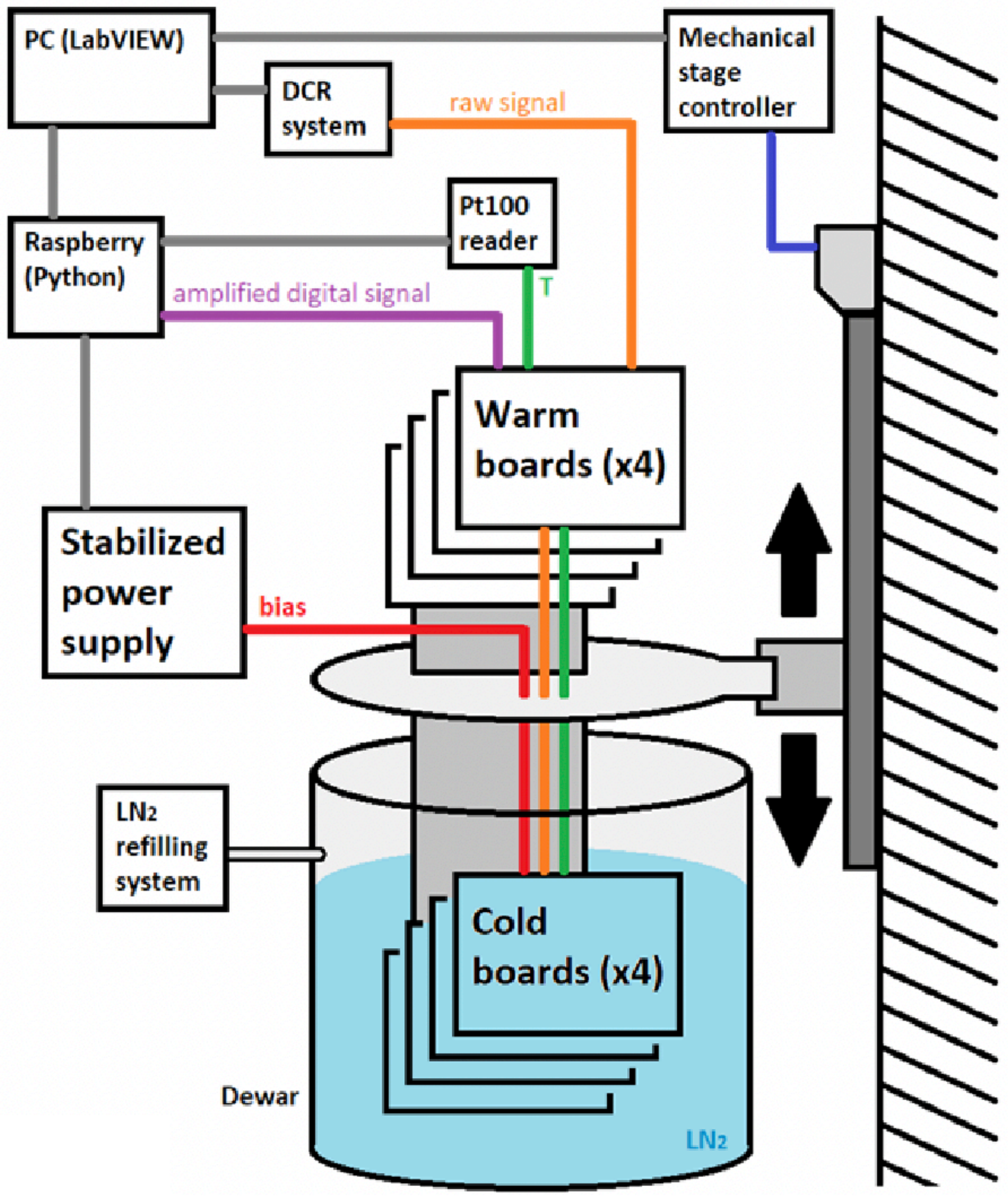

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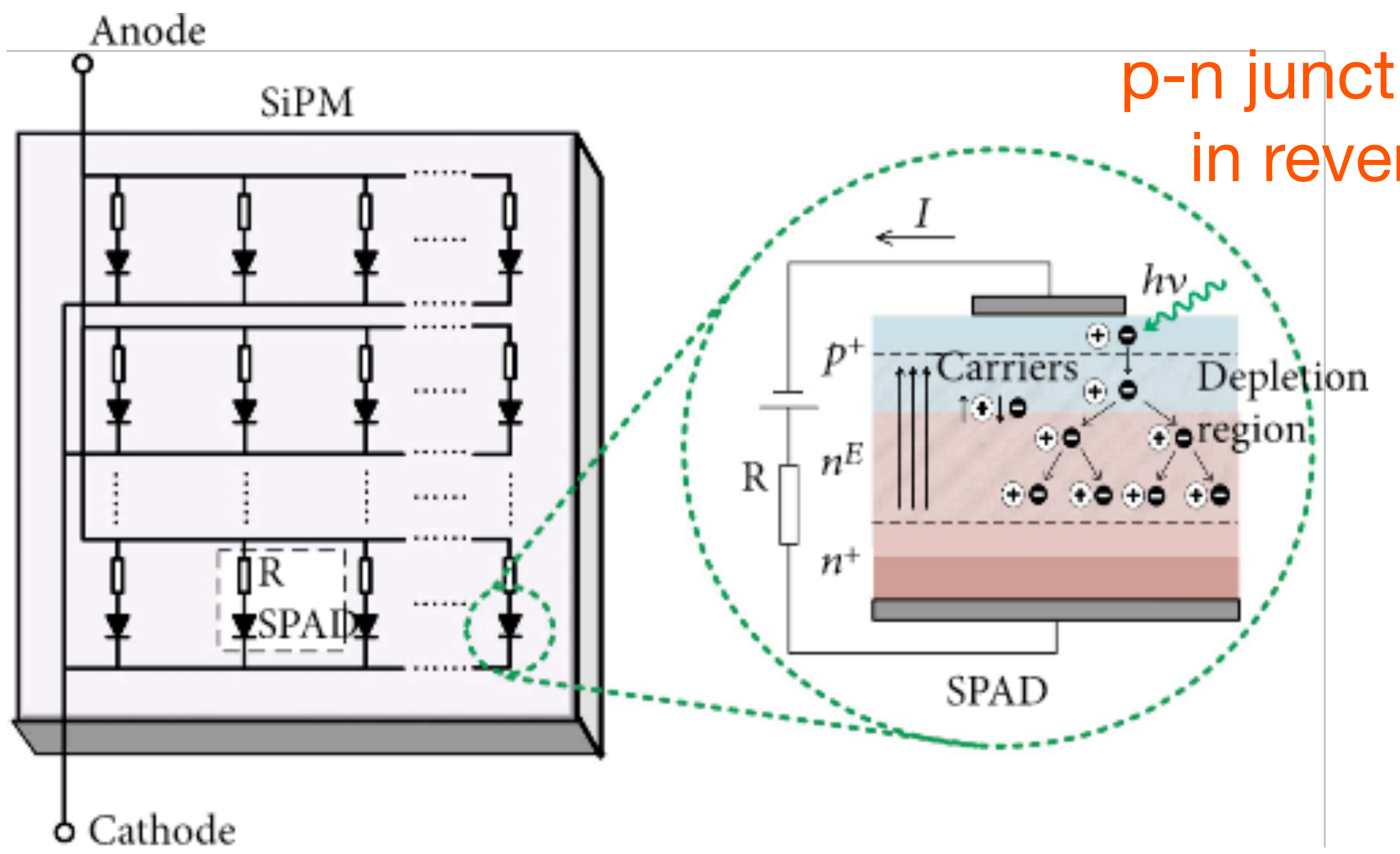
DUNE SiPMs

SiPM: matrix of single-photon avalanche diodes (SPADs)

Properties:

- Mechanical robustness
- Reduced cost and size
- Magnetic field immunity
- High light sensitivity
- High dynamic range



p-n junction working in reverse mode

Dark Count Rate (DCR):

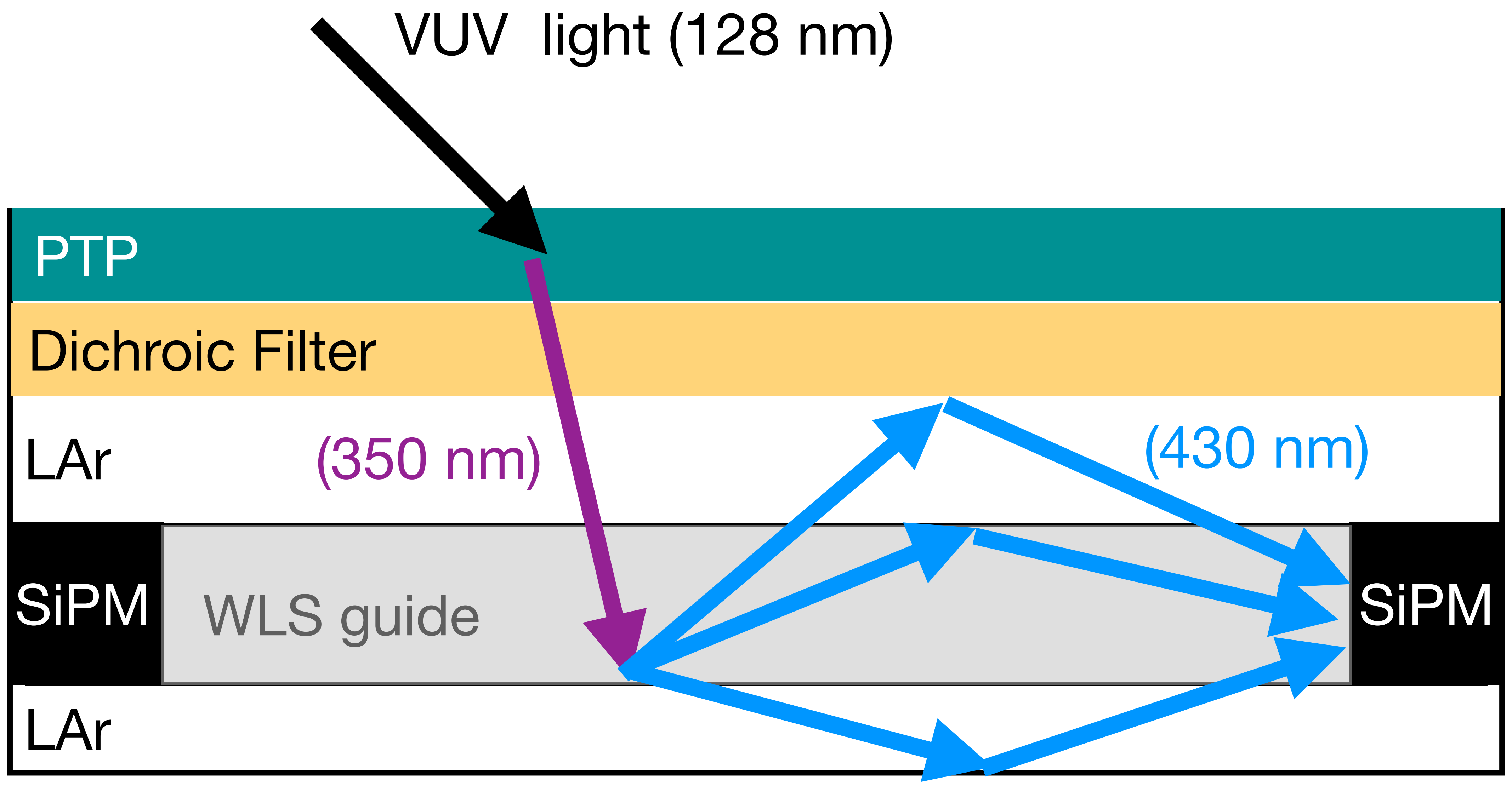
- Intrinsic background of the device happening also in absolute darkness
- Main disadvantage for low photon count applications
- DUNE requirement: DCR < 100 mHz/mm^2 at LAr temperature

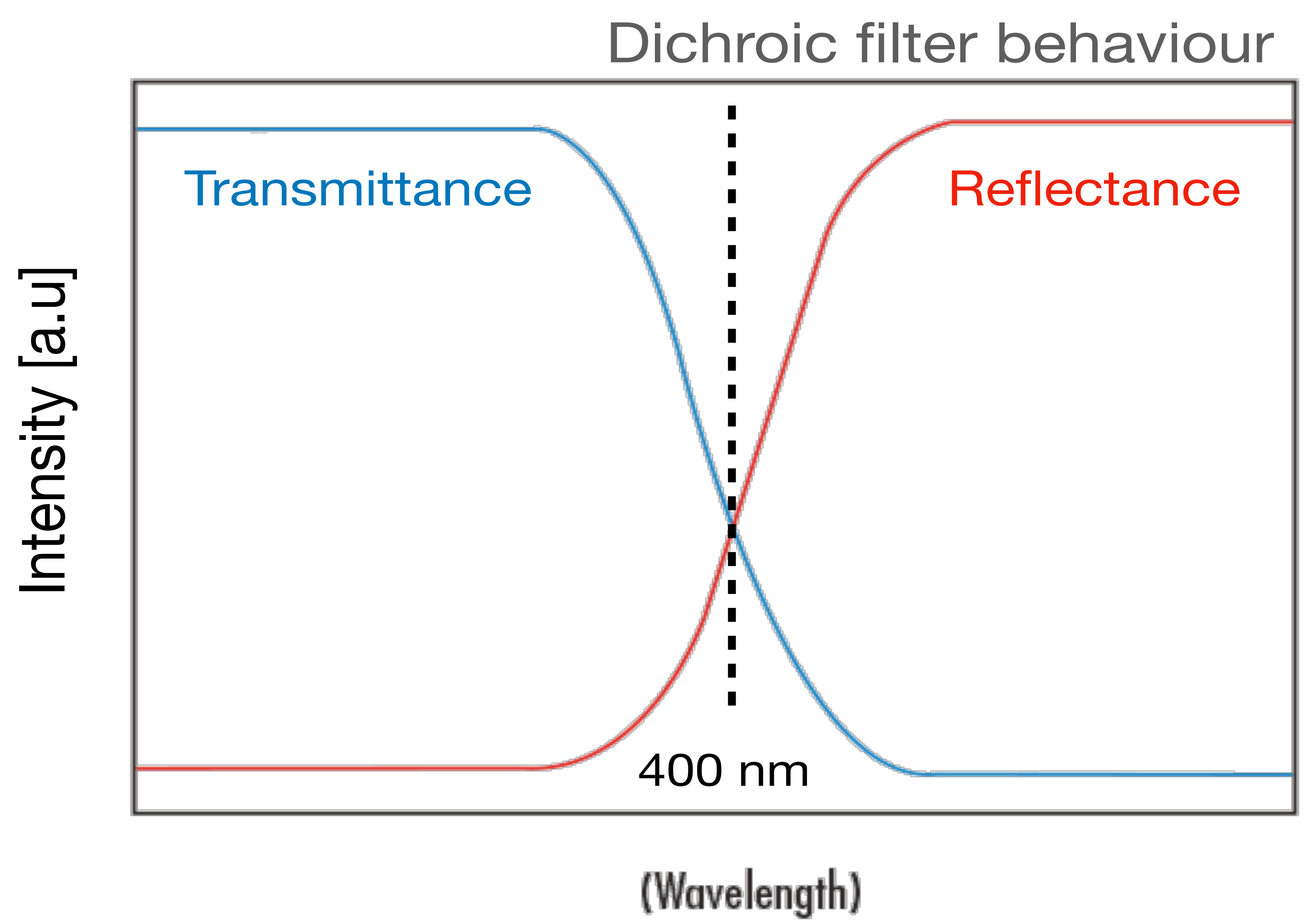
DUNE PHOTON DETECTION SYSTEM: X-ARAPUCA

X-ARAPUCA system based on SiPMs

The idea is to maximise the collection of photons by trapping them in a box

1) PTP converts VUV light to a wavelength < dichroic cutoff (128 nm -> 350 nm)
2) The dichroic filter allows the pass of the 350 nm photons.
3) Wavelength shifter bars (WSB) shift the light above the dichroic cutoff (350 nm -> 430 nm)
4) The light is trapped and after several reflections reaches the SiPMs





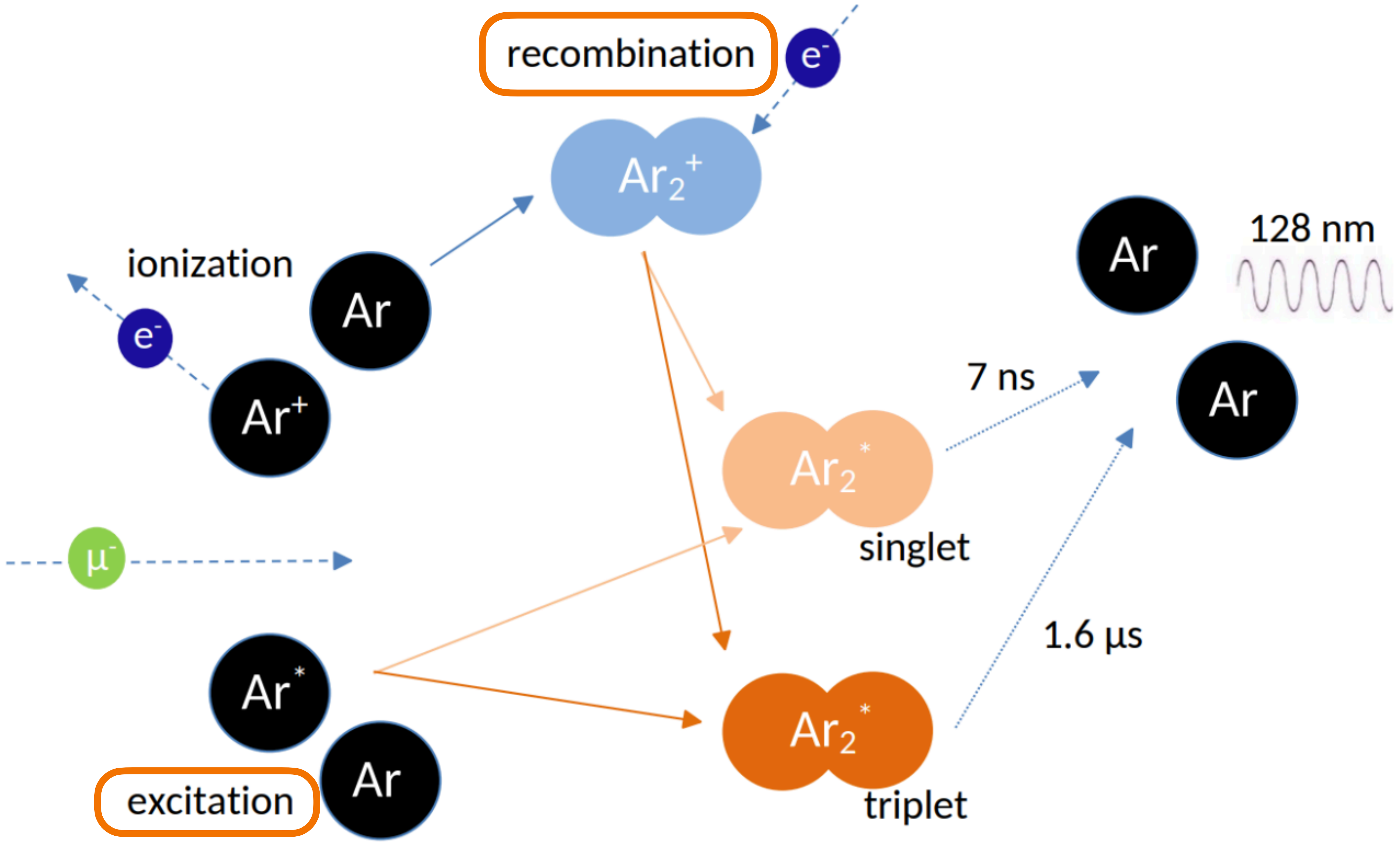
LAr LIGHT AND ITS IMPORTANCE IN DUNE

LAr VUV (vacuum ultraviolet) scintillation light: 128 nm

-> Luminescence mechanisms: recombination + self-trapped excitation

Time t_0

- Essential for proton decay searches
- Proper location of supernova event vertex
- Complementary trigger for supernova events



Calorimetry

- Crosscheck for the charge signal
- Improved energy resolution (charge + light)

Further possibilities

- Enhance DUNE potential at few-MeV scale events

DUNE SiPM CHARACTERIZATION

Every SiPM must be characterised prior their final installation in the detector

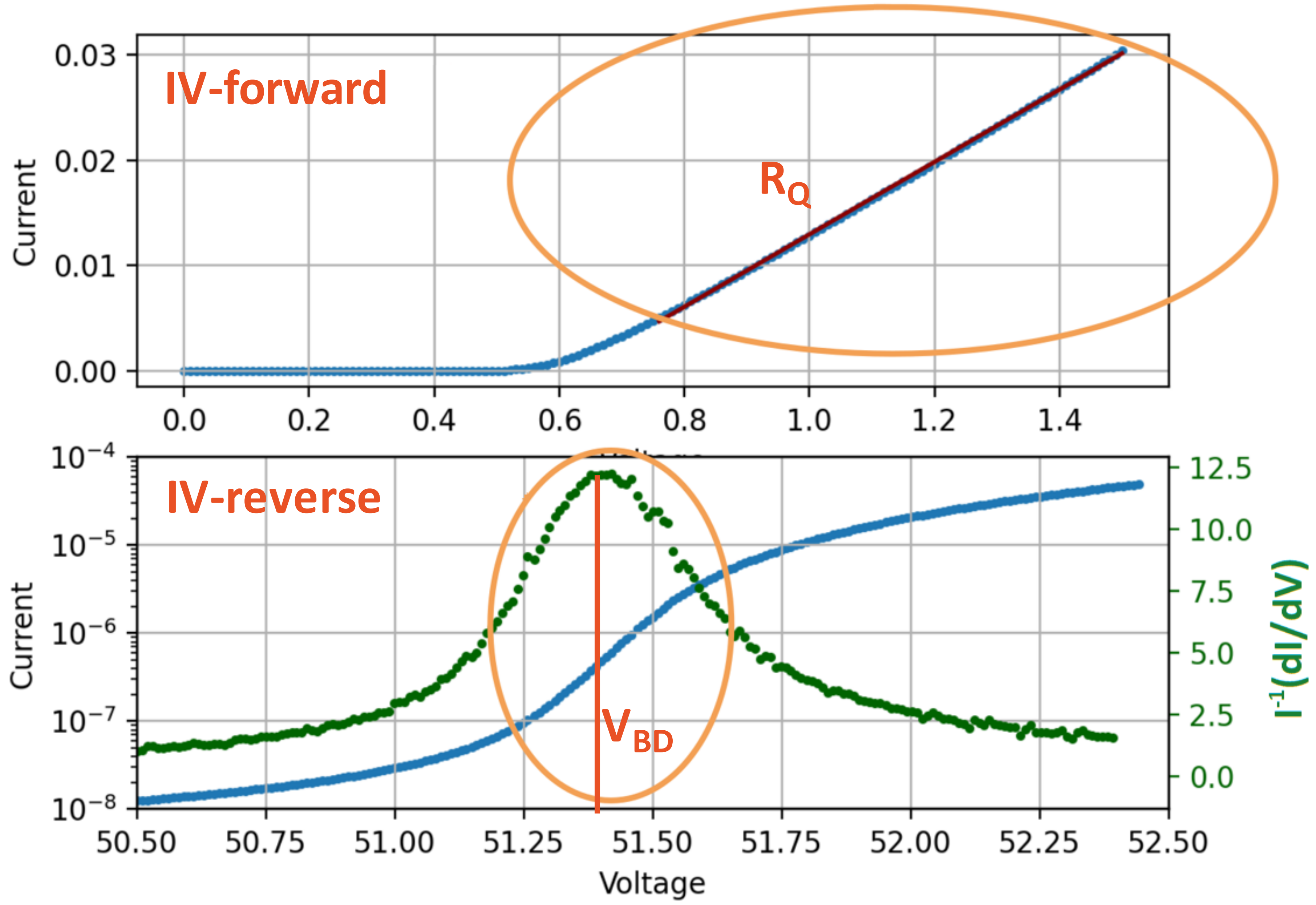
Parameters to be studied:

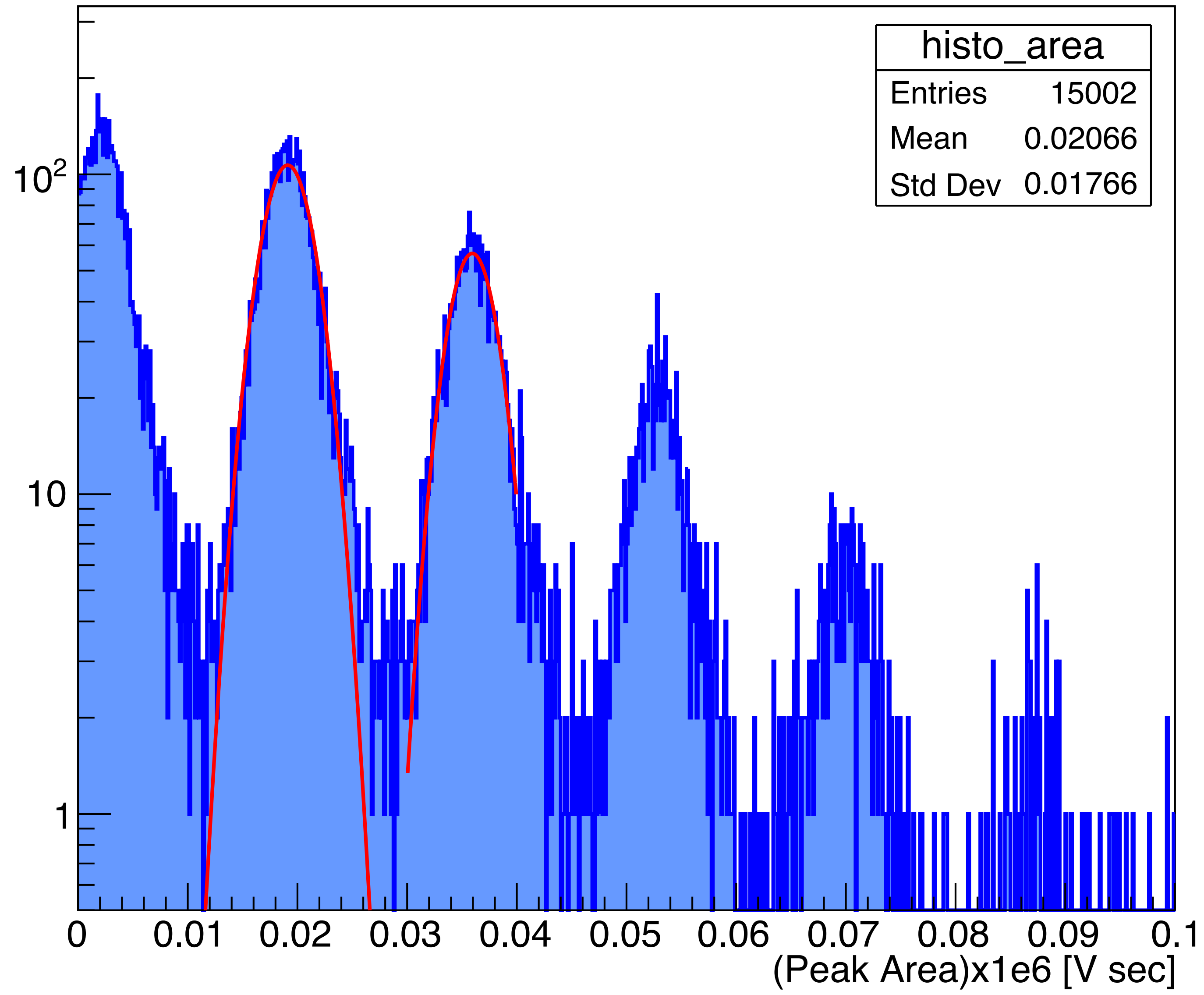
- Breakdown voltage (V_{BD})
- Quenching resistance (R_Q)
- DCR, after pulses (AP) and crosstalk (XT)
- Gain (G) and signal to noise ratio (SNR)

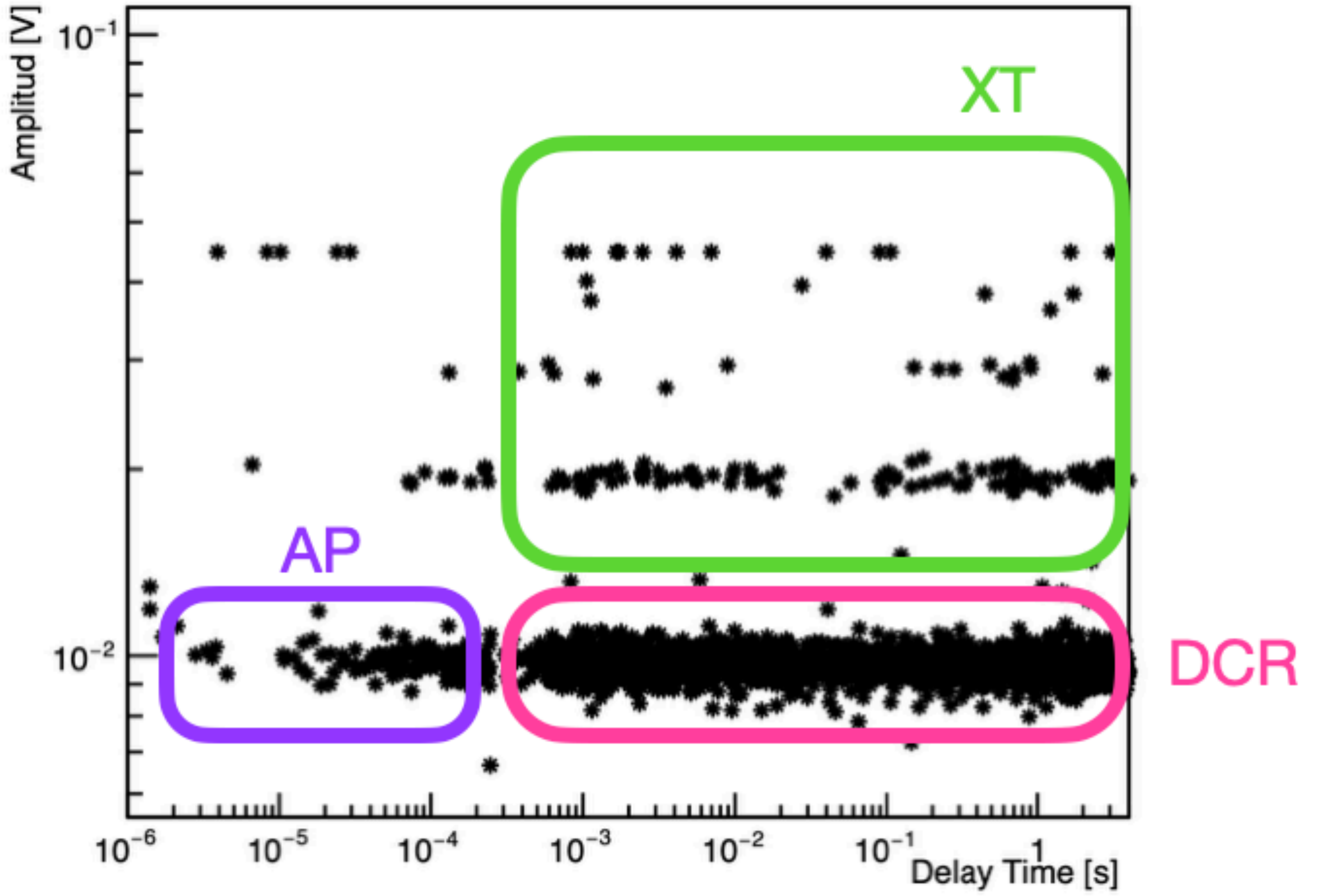
Procedure:

- IV curves
- Dark measurements
- LED acquisition

before and after thermal stress to check reliability in LAr







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