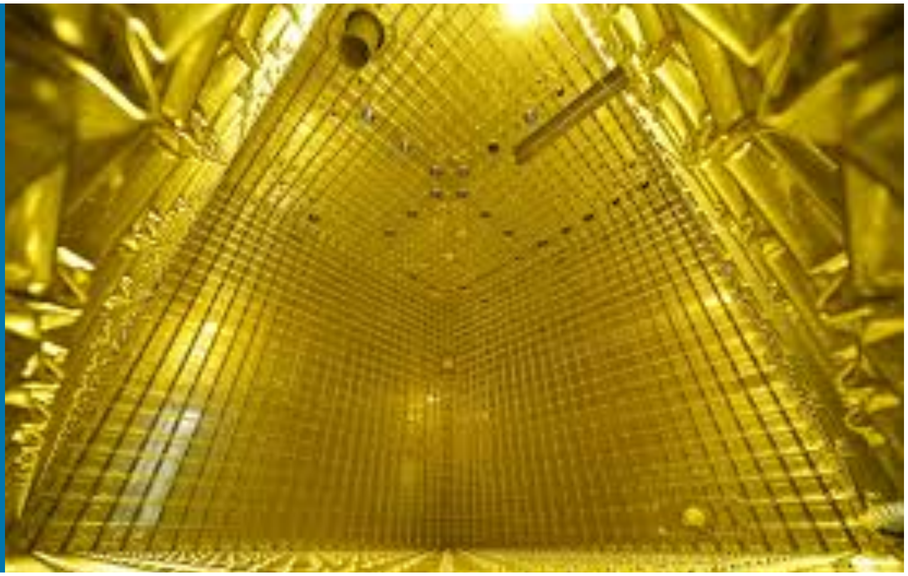
# LIGHT DETECTION IN DUNE LAr TPC



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High Energy Physics
Argonne National Laboratory

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN18), November 1-3, 2018 Vancouver, Canada

# Outline of Talk

- DUNE Experiment Introduction
- Brief Overview of DUNE Far Detector Designs

  -Liquid Argon Scintillation Light

  -Photon Detection System Motivation

  -Photon Detection System Motivation
- Focus on DUNE Far Detector Photon-Detector System (PDS)

  -Design and Light Collection

  -Photosensors and Readout Philosophy

  -Mechanical Design
- DUNE/ProtoDUNE-SP Photon Detection System

  -Readout Design

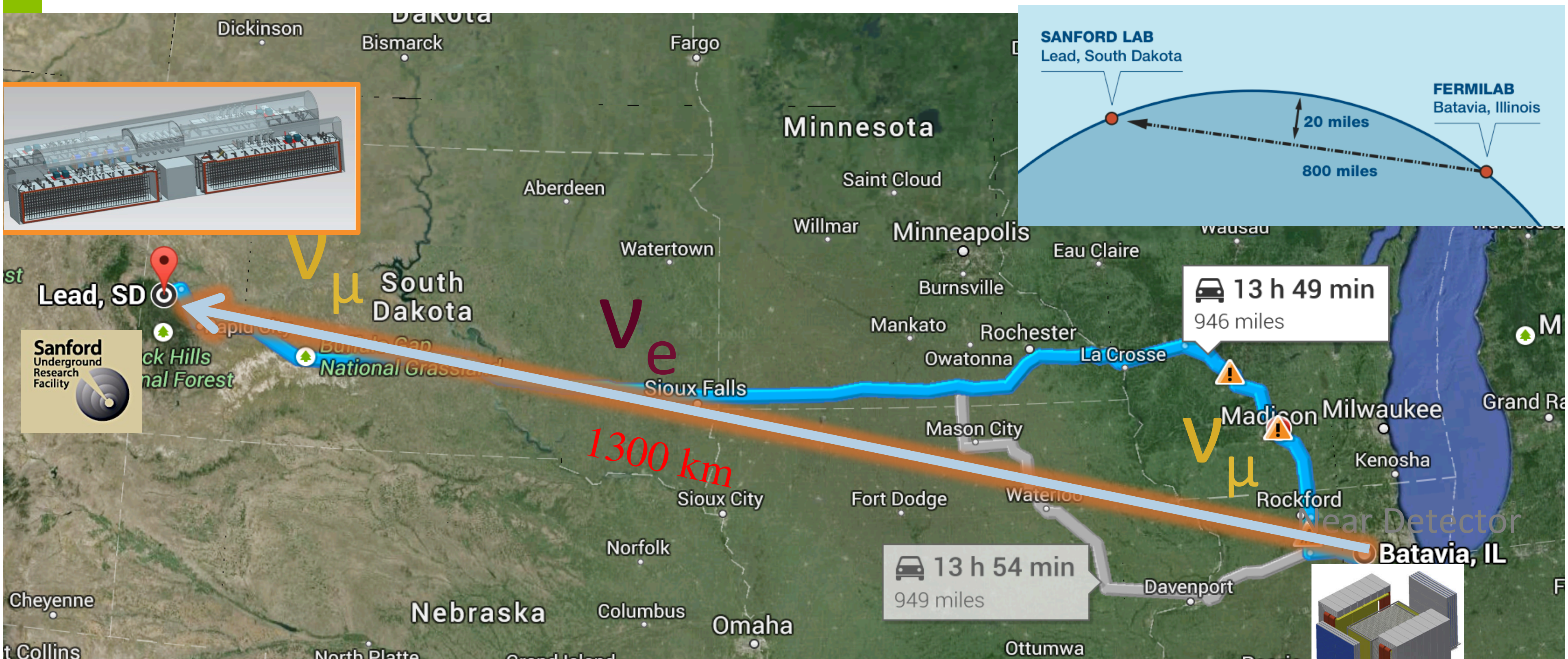
  -Photon-Detector Calibration System

  -Photon Detector Performance
- Going to DUNE

  -Simulation Effort

  -Development Plans
- Summary

# Deep Underground Neutrino Experiment (DUNE)




Major features of the DUNE experiment are:

- *A high-intensity wide-band neutrino beam originating at FNAL*
  -1.2 MW proton beam upgradable to 2.4 MW
- *A highly capable near detector to measure the neutrino flux*
- *A 40 kt fiducial mass liquid argon far detector*
  -Located 1300 km baseline at SURF's 1.5 km underground level (2300 mwe)
  -Staged construction of four ~10 kt detector modules. First module to be installed starting in 2022.

# Deep Underground Neutrino Experiment (DUNE)


DUNE/LBNF Conceptual Design Report (CDR):
Volume 1: The LBNF and DUNE Projects, arXiv:1601.05471
Volume 2: The Physics Program for DUNE at LBNF, arXiv:1512.06148
Volume 4: The DUNE Detectors at LBNF, arXiv: 1601.02984

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# The Goals of DUNE Experiment

- Primary focus of the DUNE science program is on fundamental open questions in particle physics and astro-particle physics:

1) Neutrino Oscillation Physics
   - -CPV in the leptonic sector

     "Our best bet for explaining why there is matter in the universe"
   - -Mass Hierarchy
   - -Precision Oscillation Physics & testing the 3-flavor paradigm

2) Nucleon Decay
   - -Predicted in beyond the Standard Model theories [but not yet seen]

     e.g. the SUSY-favored mode, $p \rightarrow K^{+}\overline{\nu}$

3) Supernova burst physics & astrophysics
   - -Galactic core collapse supernova, sensitivity to $\nu_e$

     Time information on neutron star or even black-hole formation

Any would be a major discovery

- DUNE Ancillary Science Program

  -Other LBL oscillation physics with BSM sensitivity

  -Oscillation physics with atmospheric neutrinos

  -Neutrino Physics in the near detector

  -Search for signatures of Dark Matter

Please see A. Sousa "DUNE" talk

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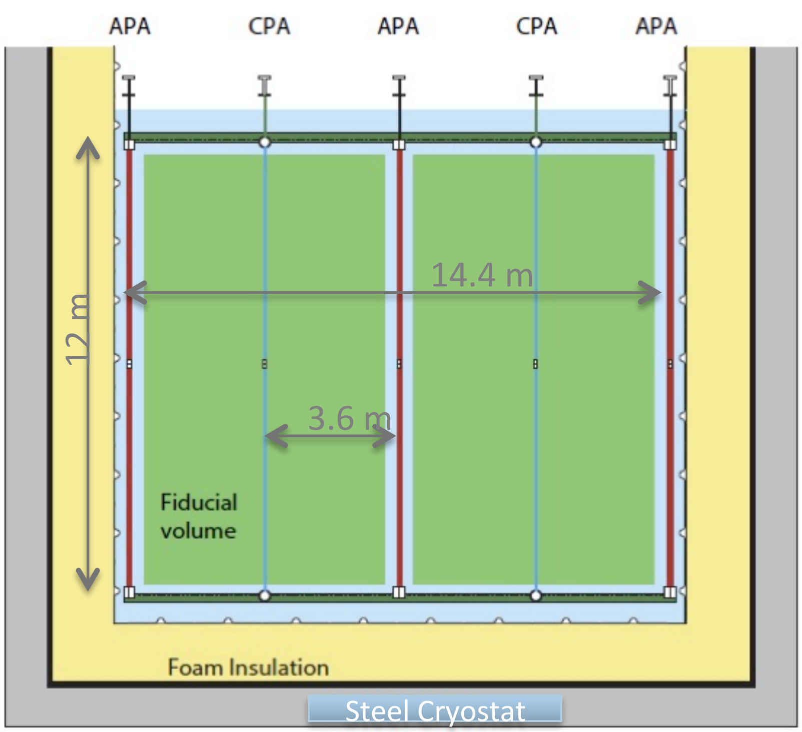
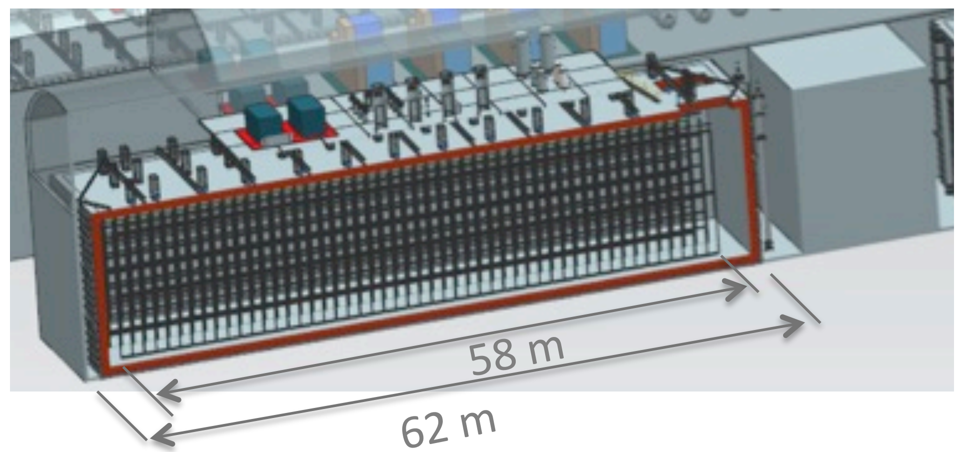
# DUNE Far Detector

- Four 10-kt (fiducial) liquid argon TPC modules
  - *Liquid Argon Time projection chamber with both charge and optical readout*
- Single and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection (need wavelength shifting to visible)
- Modules will not be identical




Single-phase: charge drifts to wire planes (APAs)




- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  -Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  -3.6 m drift length

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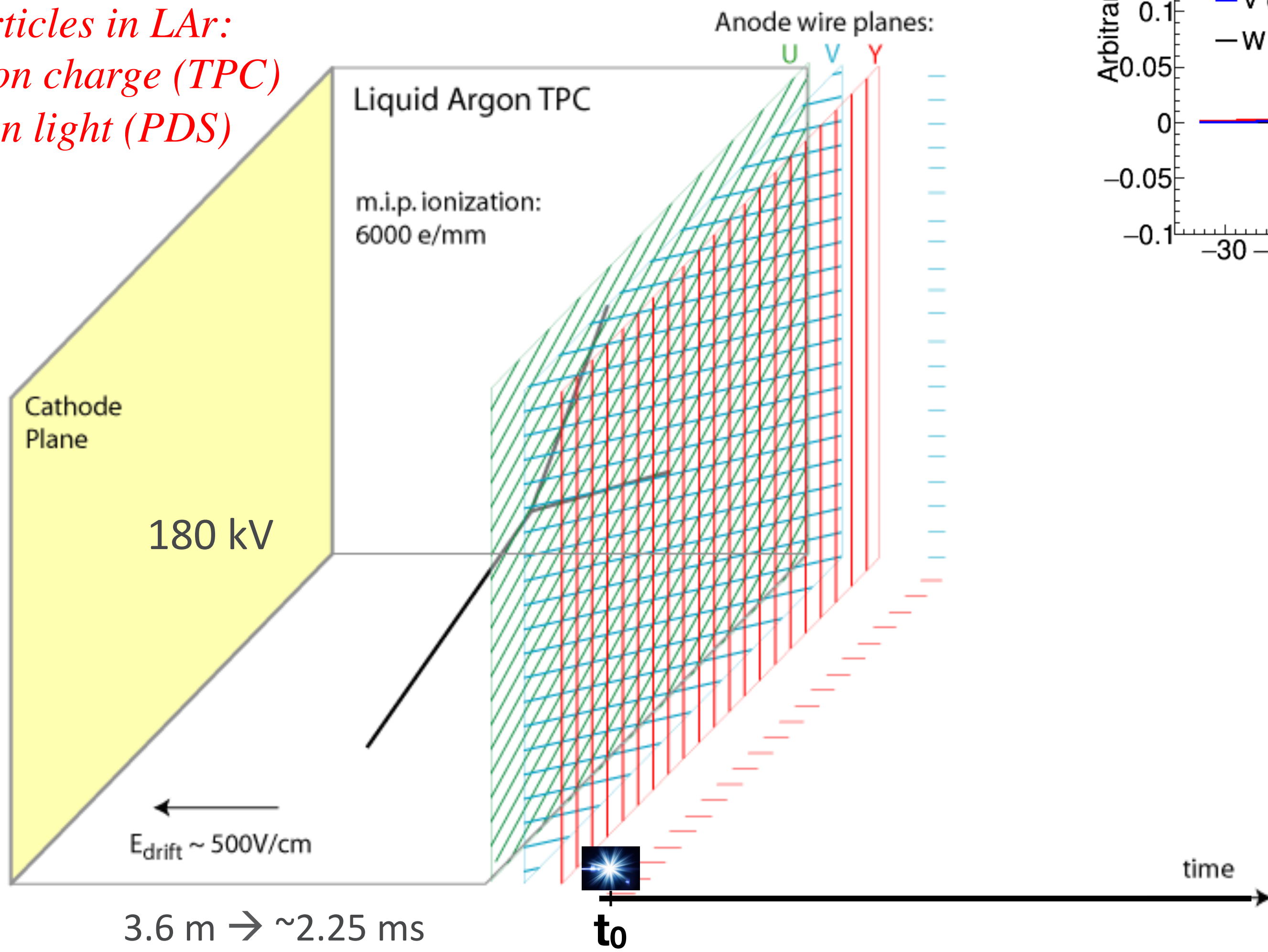
# DUNE Far Detector: SINGLE Phase Concept

- *Energy release from charged particles in LAr:*
  *-free electron charge (TPC)*
  *-scintillation light (PDS)*



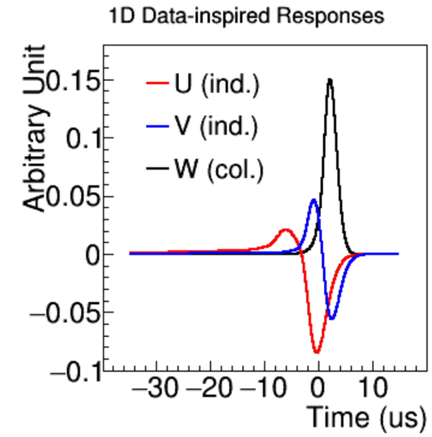
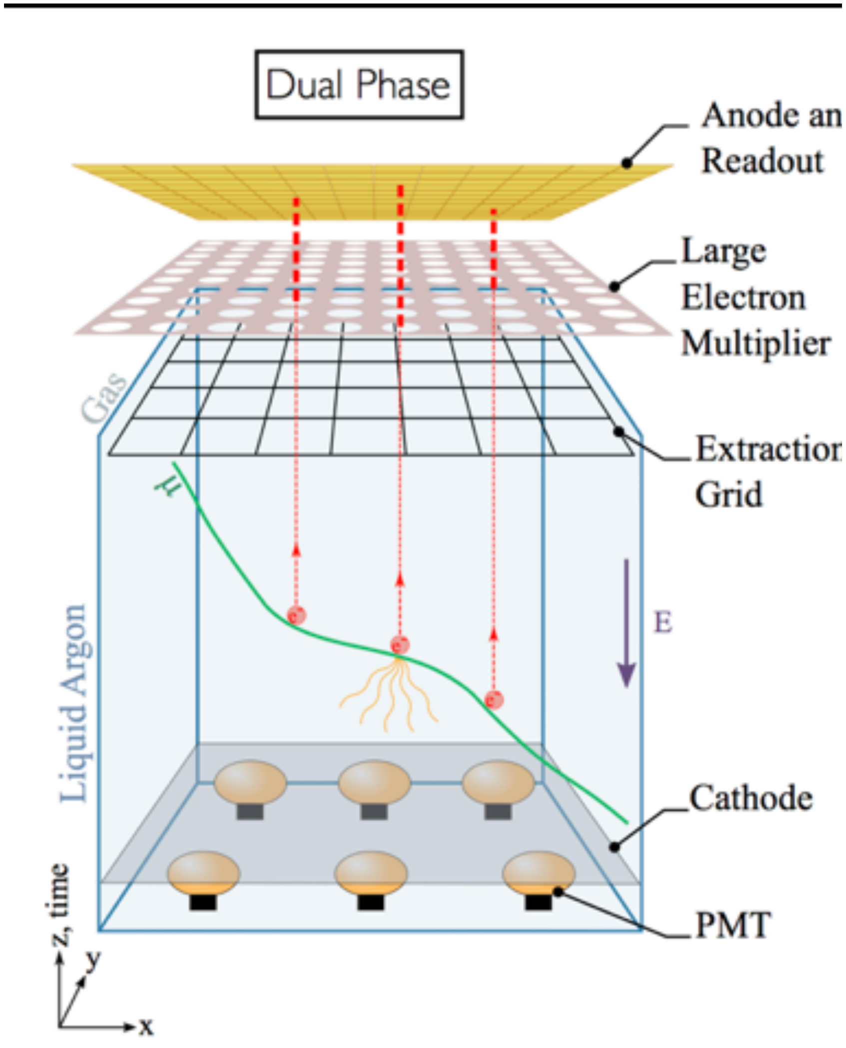
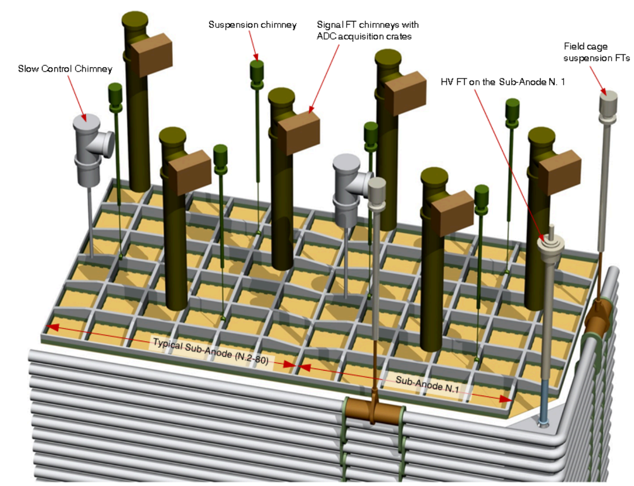




*Photo-Detector*
*for triggering and*
*t0 determination*

# DUNE Far Detector: DUAL Phase Concept




- Larger drift distance (12 m) – higher fields
- Potentially better signal to noise
- Readout/HV access through chimneys on top.
- Photon-Detector for Triggering and t0




- 153,600 channels
  -80 3x3 $m^2$ Charge Readout Planes

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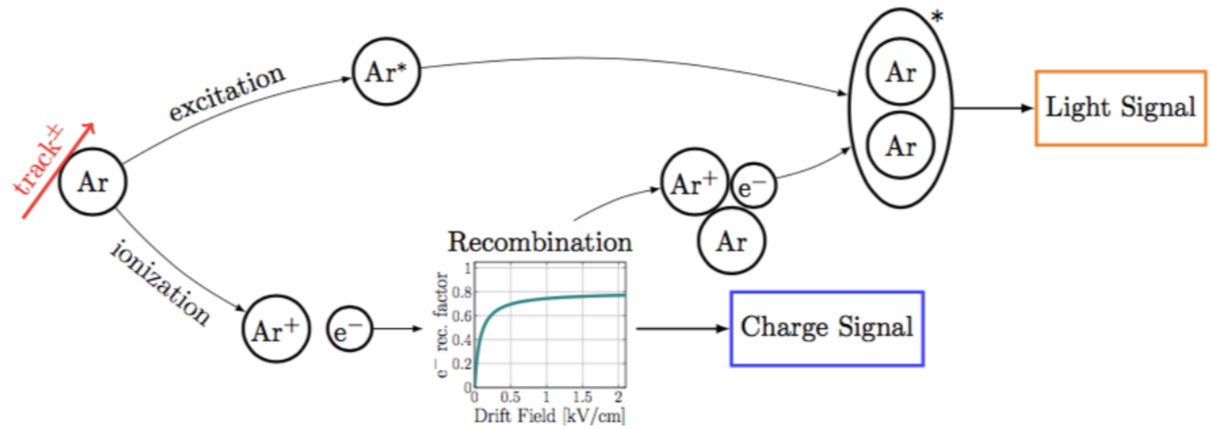
# Liquid Argon Scintillation Light

- LAr is a scintillator that emits about 40,000 ph/MeV (E = 0) when excited by MIP
  -at nominal DUNE SP E = 500 V/cm the yield is approximately 24,000 ph/MeV (reduced due to recombination)




- Ionization radiation in LAr results in formation of excited dimer $Ar_2^*$
  -photon emission follows through de-excitation of singlet $^1\Sigma$ and triplet $^3\Sigma$ states
  -photons emitted in a narrow band around 128 nm (VUV region)
  -de-excitation from $^1\Sigma$ is fast with $\tau_{fast} \approx 6$ ns
  -de-excitation from $^3\Sigma$ is slow with $\tau_{slow} \approx 1.3$ µs
  -ratio of fast and slow components dependent on the ionizing particle through ionization density of LAr (0.3 for $e^-$; 1.3 for $\alpha$; 3 for n)
  => basis for PID capability



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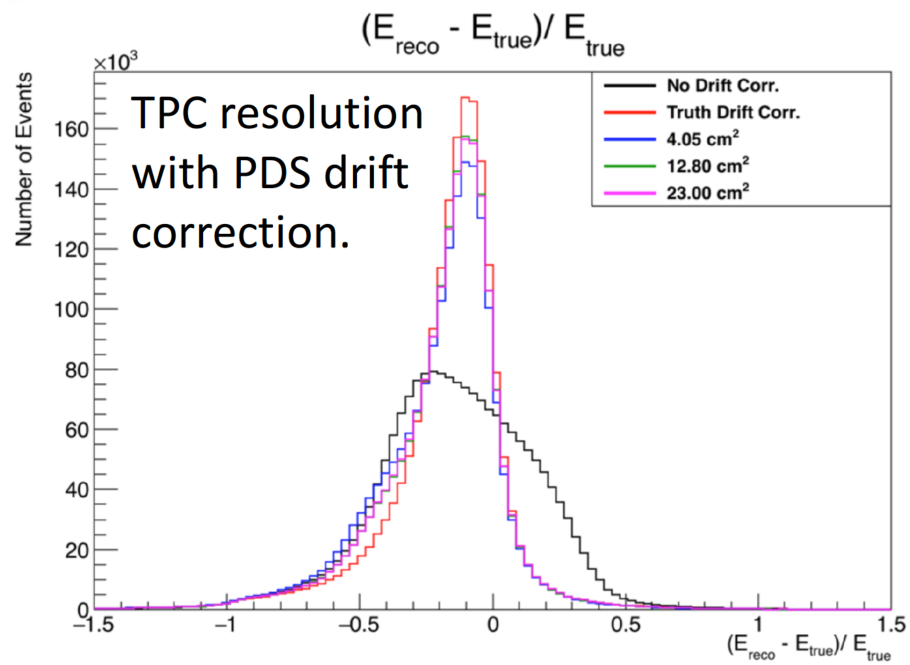
# Photon Detection System Motivation

- Detect (prompt) LAr scintillation light
  - ➢ Extract information from LAr scintillation light to enhance physics reach of LArTPC




- Photon detection used for event trigger and interaction time (t0) determination for underground physics
  - ➢ Provides triggering on non-beam events (SNB, proton-decay, atmospheric ν's)
  - ➢ Enables correction of charge losses, important for the reconstruction of the energy deposited by the ionizing event

- Potential for improved energy measurements in combination with TPC charge.



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# PDS Performance Requirements

- Performance requirements considered to achieve the primary science objectives

| **Requirement** | Rationale |
|---|---|
| The far detector (FD) PDS shall detect sufficient light from events depositing visible energy >200 MeV to efficiently measure the time and total intensity. | This is the region for nucleon decay and atmospheric neutrinos. The time measurement is needed for event localization for optimal energy resolution and background rejection. |
| The FD PDS shall detect sufficient light from events depositing visible energy <200 MeV to provide a time measurement. The efficiency of this measurement shall be adequate for SNB events. | Enables low energy measurement of event localization for SNB events. The efficiency may vary significantly for visible energy in the range 5 MeV to 100 MeV. |
| (Proposed) The FD PDS shall detect sufficient light from events depositing visible energy of 10 MeV to provide an energy measurement with a resolution of 10%. | Enables energy measurement for SNB events with a precision similar to that from the TPC ionization measurement. |
| The FD PDS readout electronics shall record time and signal amplitude from the photosensors with sufficient precision and range to achieve the key physics parameters. | The resolution and dynamic range needs to be adjusted so that a few-photoelectron signal can be detected with low noise. The dynamic range needs to be sufficiently high to measure light from a muon traversing a TPC module. |

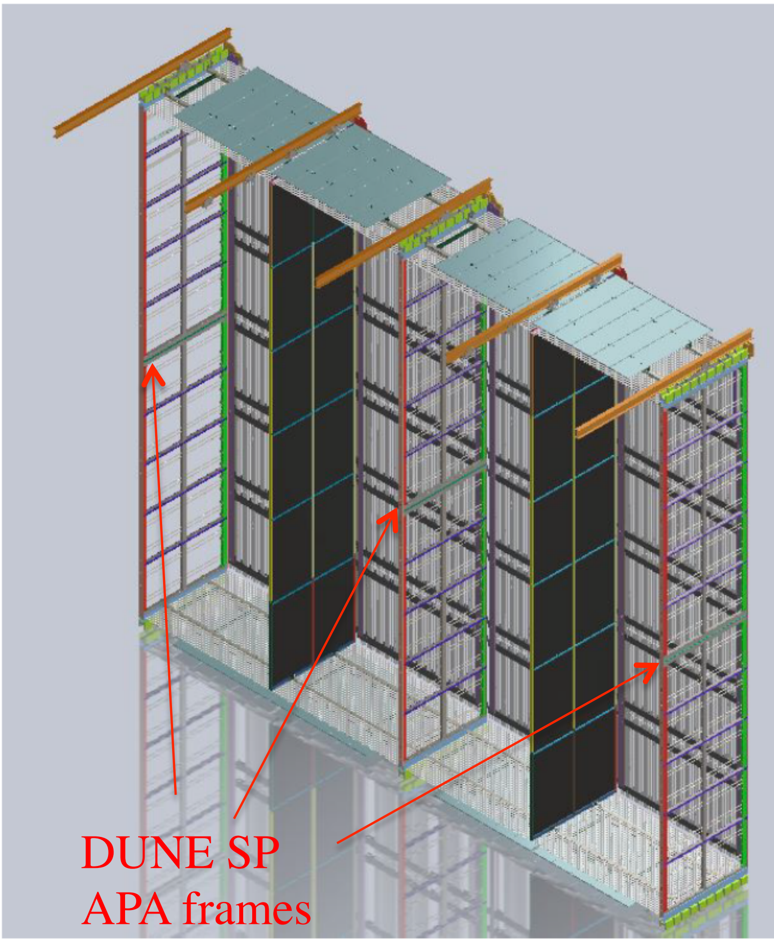
# PDS Performance Requirements (cont.)

- The photon detectors in both single and dual Phase have the potential to improve the physics reach of all of DUNE's physics goals.

| | | Supernova Bursts | Nucleon Decays | Atm. Neutrinos | Beam Neutrinos |
|---|---|---|---|---|---|
| T0 for | fiducial volume | | X | X | |
| | TPC drift correction | X | X | X | |
| | sub-ms timing | X | | | |
| | Triggering | X | X | X | |
| | Direct calorimetry | X | X | | X |
| | Position Reconstruction | X | X | X | |
| | Michel *e* Detection | | X | X | X |

- There is ongoing R&D program to investigate methods that maximize the photon detection efficiency of the PDS within the constraints of the SP TPC design
  - Focus is to quantify what physics impacts are, and what they require the system performance to be
- Concentrate in this talk on Photon-Detector in **DUNE Single Phase Far Detector**

# Photon Detection System Design in DUNE Single Phase




- Photon-system must detect / measure LAr scintillation light produced by ionizing particles

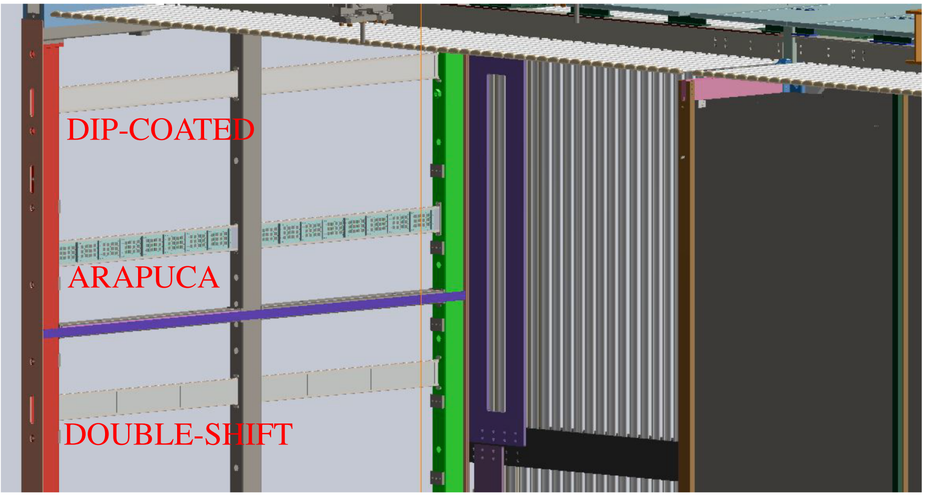
- First detection stage is **Photon Collector**
  - A unit that captures VUV photons produced in the TPC volume
  - Converts VUV photons to visible range to be converted into electrical signals by photo-sensors
  - Light collectors must fit within APA frames

- Second detection stage is **Photosensor**
  - Silicon photomultiplier (SiPM) performs the final stage conversion of visible photons to electrical signals
  - Use cost-effective SiPMs solution with peak response in > 400 nm range

# Photon Detection System Design in DUNE Single Phase (cont.)

- Photon-collector must optimize cost of various components (readout electronics channel and signal cable count, SiPM count), and still meet the performance requirements

- At the time of the interim design report there are three photon collector options under consideration:
  - -ARAPUCA concept
  - -Dip-Coated Light Guides
  - -Double-Shift Light Guide




- Interim Design Report details
  - ➢ The DUNE Far Detector Interim Design Report Volume 1: Physics, Technology and Strategies, arXiv:1807.10334
  - ➢ The DUNE Far Detector Interim Design Report, Volume 2: Single-Phase Module, arXiv:1807.10327
  - ➢ The DUNE Far Detector Interim Design Report, Volume 3: Dual-Phase Module, arXiv:1807.10340

- Interim Design Report not yet a detailed technical document, no costing
  - ➢ Important milestone on the way to the TDR in 2019

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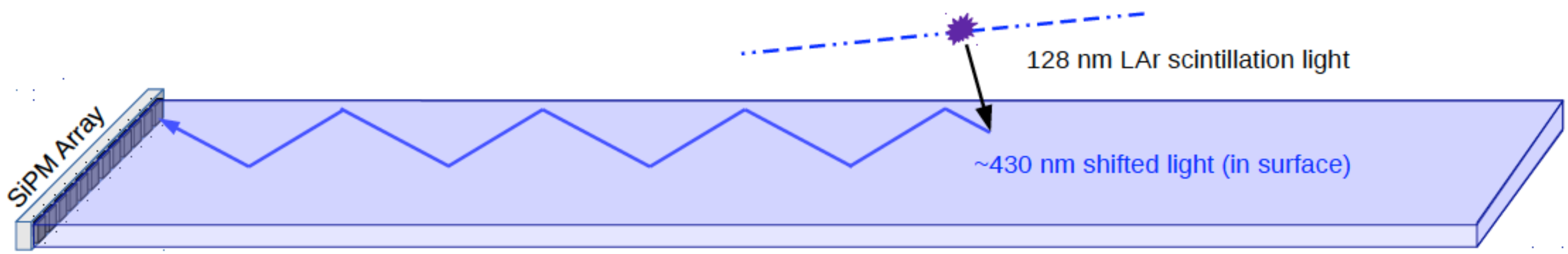
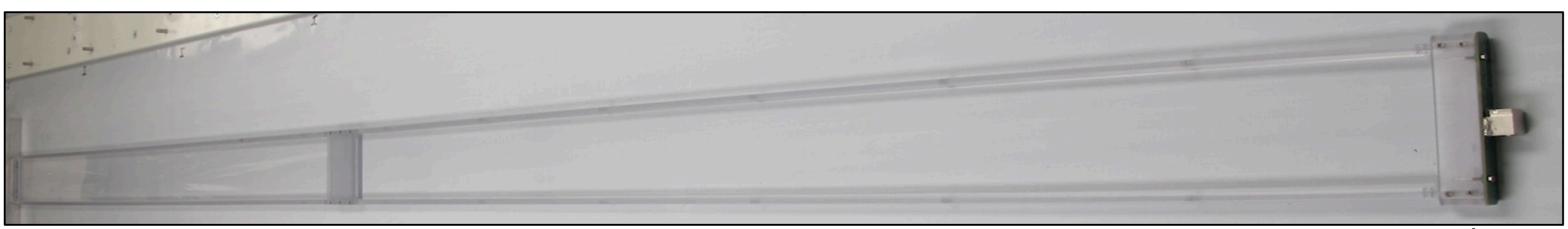
# Dip-Coated Light Guide

- VUV photons (128 nm) are absorbed and wavelength-shifted to blue (430 nm) by TPB-based coating on the surface of the bar
  - Pre-treated commercially-cut acrylic
  - Acrylic dip-coated with TPB + acrylic + toluene solution
  - Wavelength-shifted light is captured and guided via total internal reflection where it is detected by SiPMs

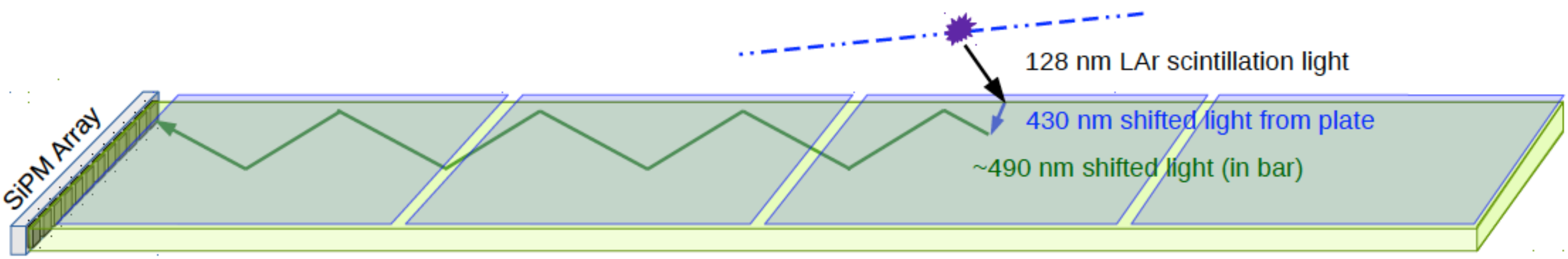



- Example of light guide in ProtoDUNE: 209.3 cm x 8.47 cm x 0.60 cm
- Used an array of 12 0.6 cm x 0.6 cm SensL C-series MicroFC-60035-SMT SiPMs

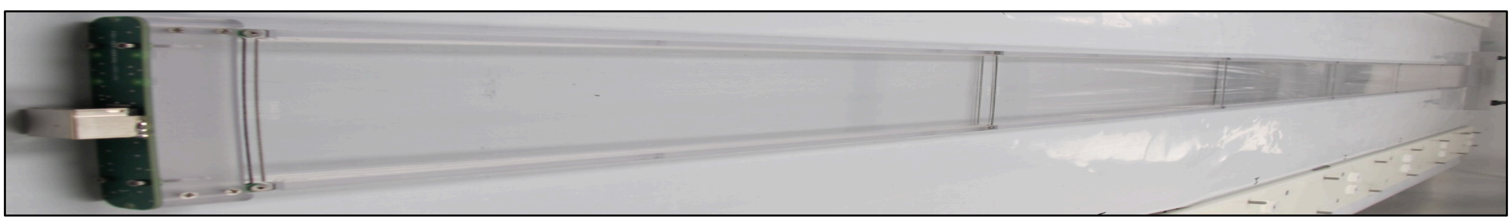


# Double-Shift Light Guides

- Idea is to decouple the process of converting VUV photons to optical wavelengths from the transportation of photons along the bars
  - Spray-coated TPB wavelength-shifting plates convert VUV (128 nm) to blue (430 nm)
  - Commercially-fabricated wavelength-shifting light guide coverts blue to green (490 nm)
  - Green photons captured and guided via total internal reflection where it is detected by SiPMs




- Example of light guide in ProtoDUNE: double-shift light collector with six radiator plates mounted on each face of the wavelength-shifting light guide
- A 210 cm x 8.6 cm light guide is fabricated by Eljen Techs and consists of a polystyrene bar doped with the EJ-280 wavelength shifter.



SensL C-series MicroFC-60035-SMT SiPMs

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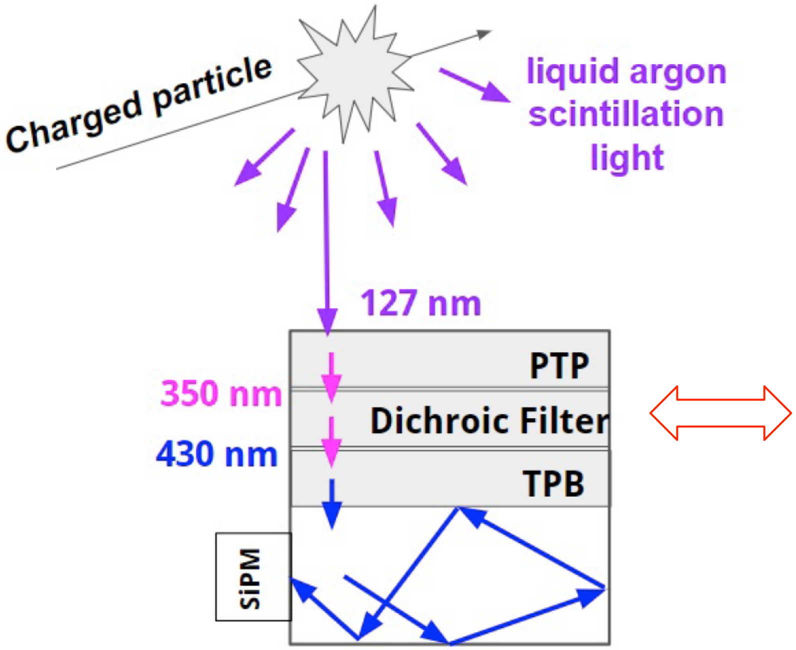
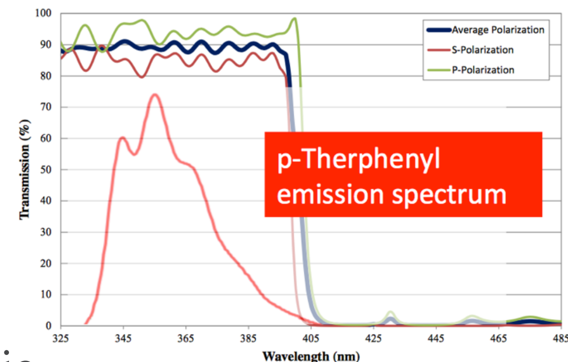
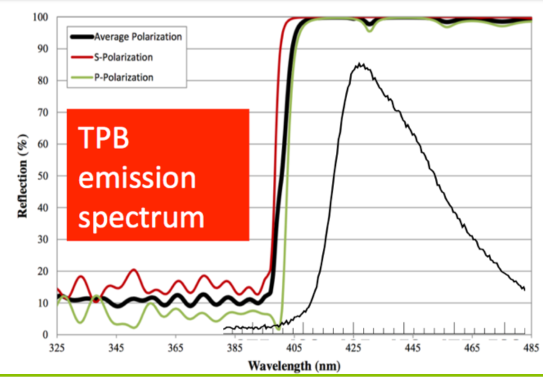
# ARAPUCA concept

- ARAPUCA is the light trap
  - Dichroic (short-pass) filter to trap wavelength-shifted light inside ARAPUCA reflective cell
  - p-TerPhenyl on outer surfaceTPB on inner surface (trapped)
  - Provides segmentation along beam direction




Dichroic Glass



# ARAPUCA concept (cont.)

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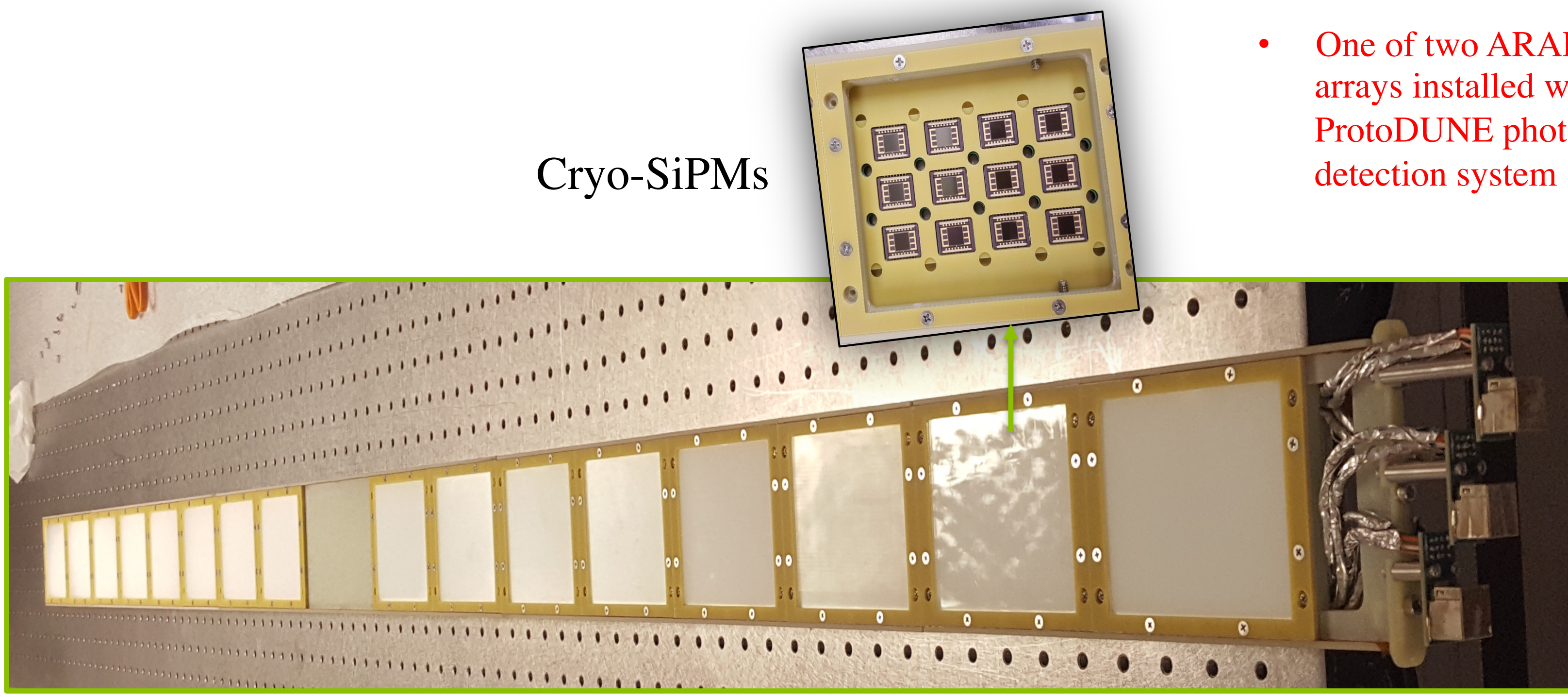
Cryo-SiPMs

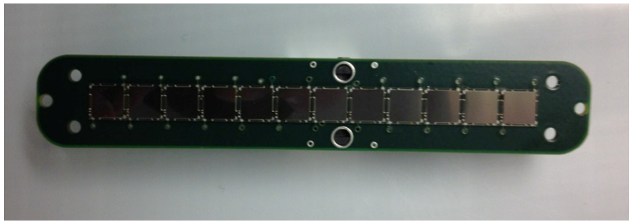


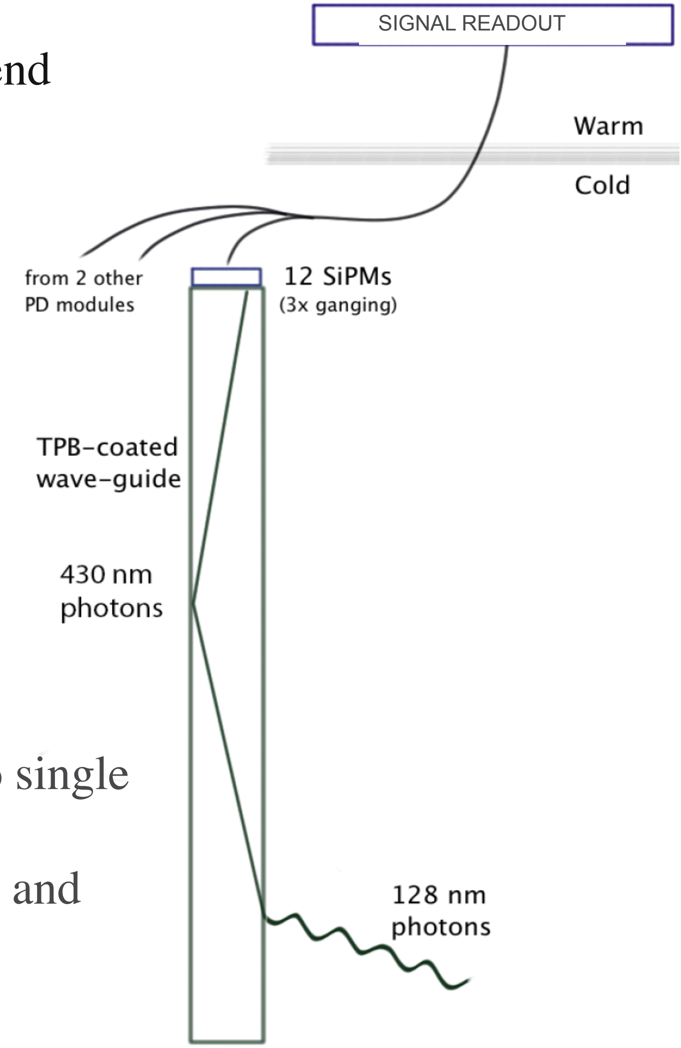
- One of two ARAPUCA arrays installed with ProtoDUNE photon-detection system

# Photon Conversion with SiPMs and Readout Philosophy

- After the light collection and the wave-length shift
  -fraction of photons internally reflected to light guide's end
  -blue/green photons detected by silicon photomultipliers (SiPMs).

SiPM board with array of 12 SiPMs and RJ-45





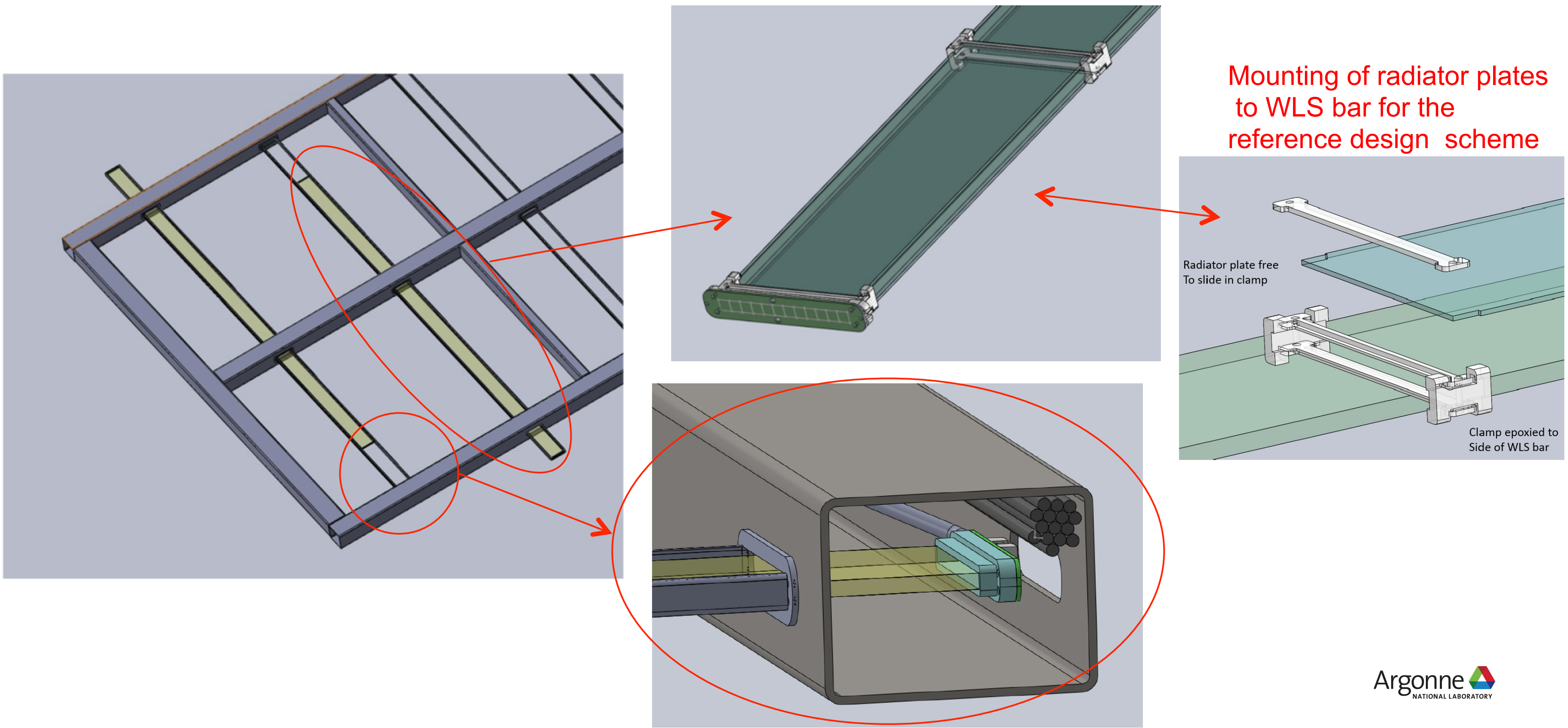

- PD signal is extracted in two stages:

1) Summing ("ganging") the output of multiple SiPMs into single cable pair to reduce number of readout channels
2) Digitization of resulting electrical signal to provide time and amplitude of light signal

➢ ProtoDUNE example: A passive summing scheme with three SiPMs together was chosen for the light guides (4 SSP channels for each bar) and groups of 12 SiPMs are passively ganged for the two ARAPUCA modules (12 SSP channels per module).

# Photon Detection System Mechanical Design (ProtoDUNE-SP)

- PDS is configured as a set of modules that are mounted on the APA frames
  - APA frames hold ten PDS modules (2.2-m long, 86-mm wide and 6-mm thick)
  - PDS module is combination of a light guide  and SiPM array in the case of Dip-Coated and Double-Shift Light Guides
  - An ARAPUCA array have the dimension of light guide, but each encapsulates 16 ARAPUCA boxes with either 12 or 6 SiPMs in each box

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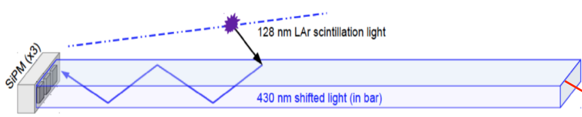
# Path to DUNE SP FD

- **Members of PDS Consortium performed a multi-year Photon-Detector R&D program**
  - ➢ Concepts described above results of multi-year R&D efforts at Universities and Labs
  - ➢ Example: DUNE 35-ton Prototype fabrication, operation, analysis (arXiv:1803.06379)

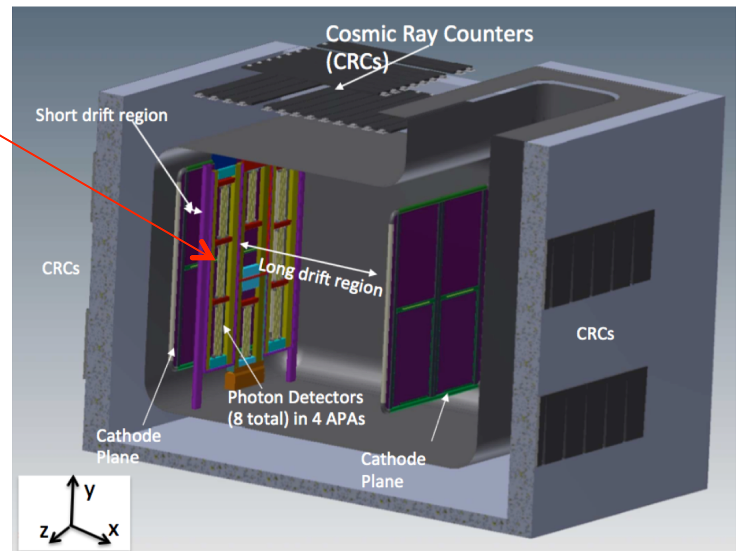
    -Implemented and tested several light-collection techniques

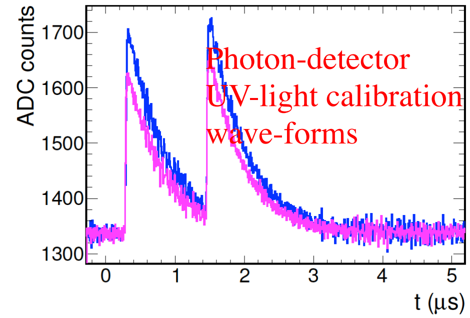
    -Full readout system: fast digitization and timing/trigger interfaces

    -Calibration system

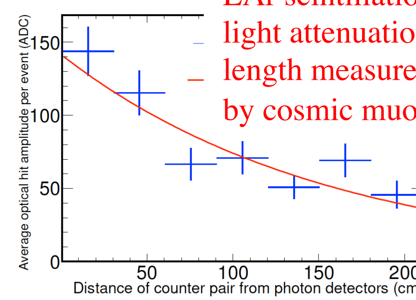



Photon-detector light collector


LAr scintillation light attenuation length measured by cosmic muons



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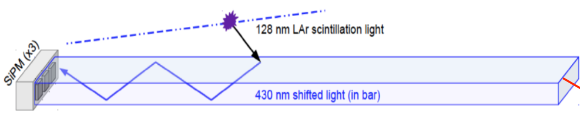
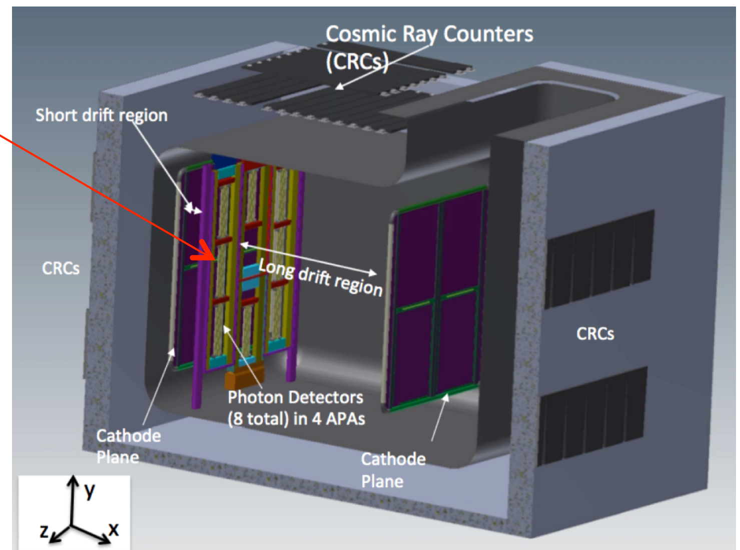
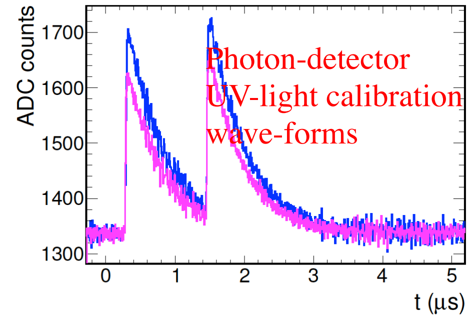
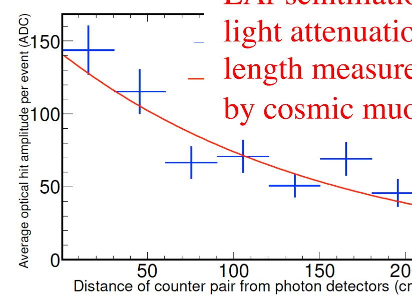



Photon-detector light collector


LAr scintillation light attenuation length measured by cosmic muons

- **Current PDS development focus is on ProtoDUNE-SP**
  - ➢ Critical component of DUNE SP FD Development

- **Additional R&D beyond ProtoDUNE is needed to lead to DUNE-SP Far Detector**
  - ➢ Intense simulation effort
  - ➢ Optimization of light collection, readout system, PDS uniformity response

# ProtoDUNE-SP

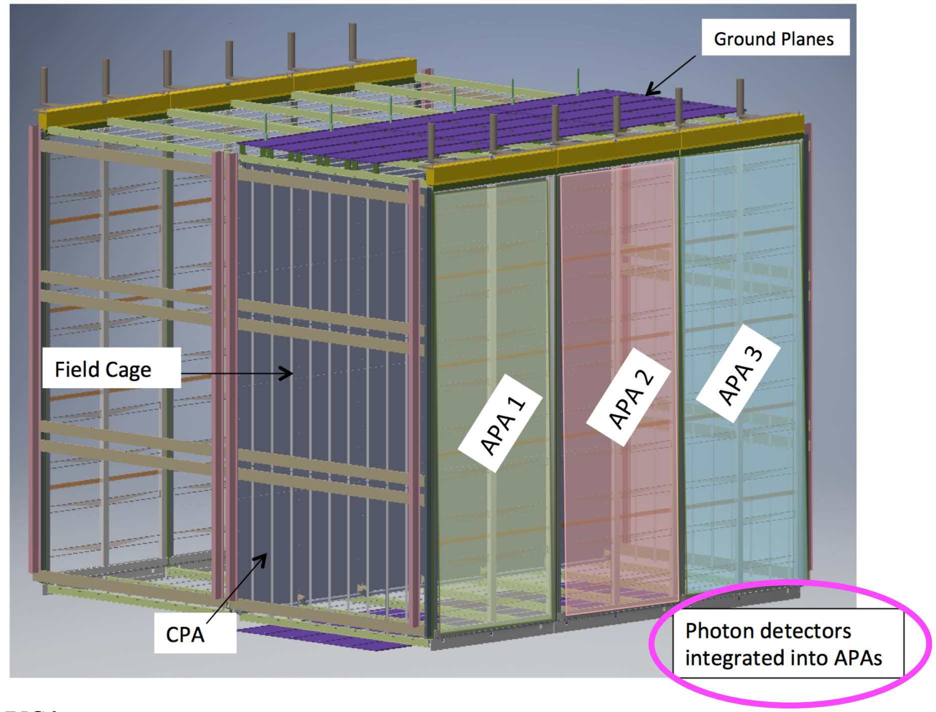
Please see F. Stocker "ProtoDUNE" talk

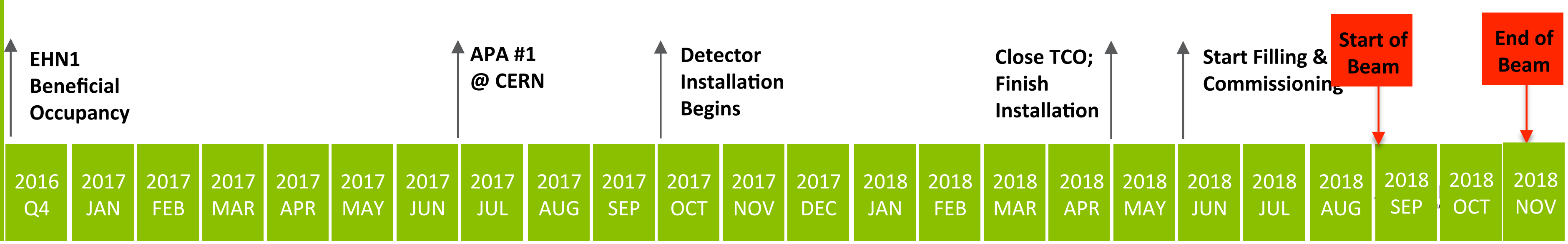
- LArTPC located in the EHN1 Hall @ CERN: 760 tons of liquid argon
  - ➢ Provides a full drift length of future DUNE SP Far Detector

- Main Detector Elements include:
  -Time Projection Chamber (TPC)
  -Front-end electronics
  -Photon Detector System

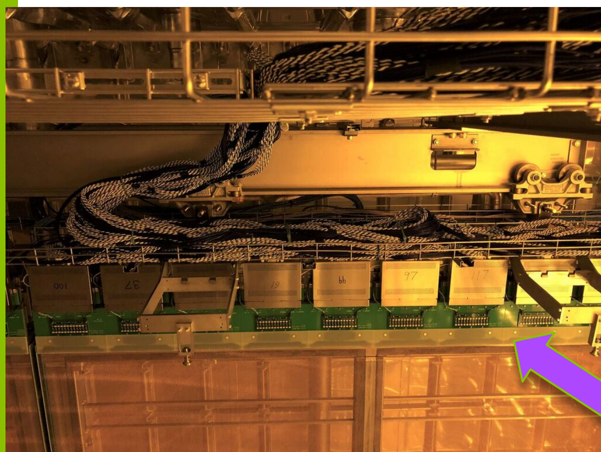
- ProtoDUNE-SP Goals:
  -Prototype the production and installation for SP DUNE Far Detector.
  -Validate detector performance with cosmic-rays; calibrate with different test-beam particle
  - ➢ Demonstrate photon-detector concept

ProtoDUNE-SP TPC



# ProtoDUNE (SP) Main Detector  Elements

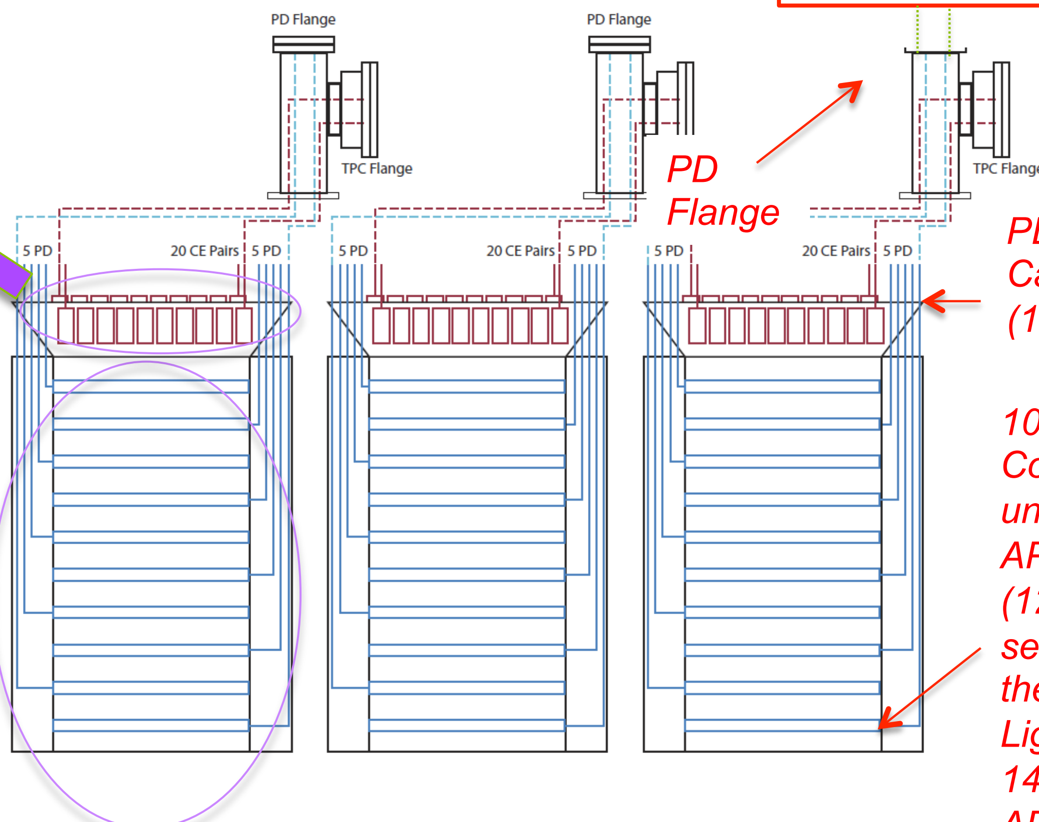



58 light guide and 2 ARAPUCA photon collectors

TPC Readout

DAQ

SSP (FEE readout)

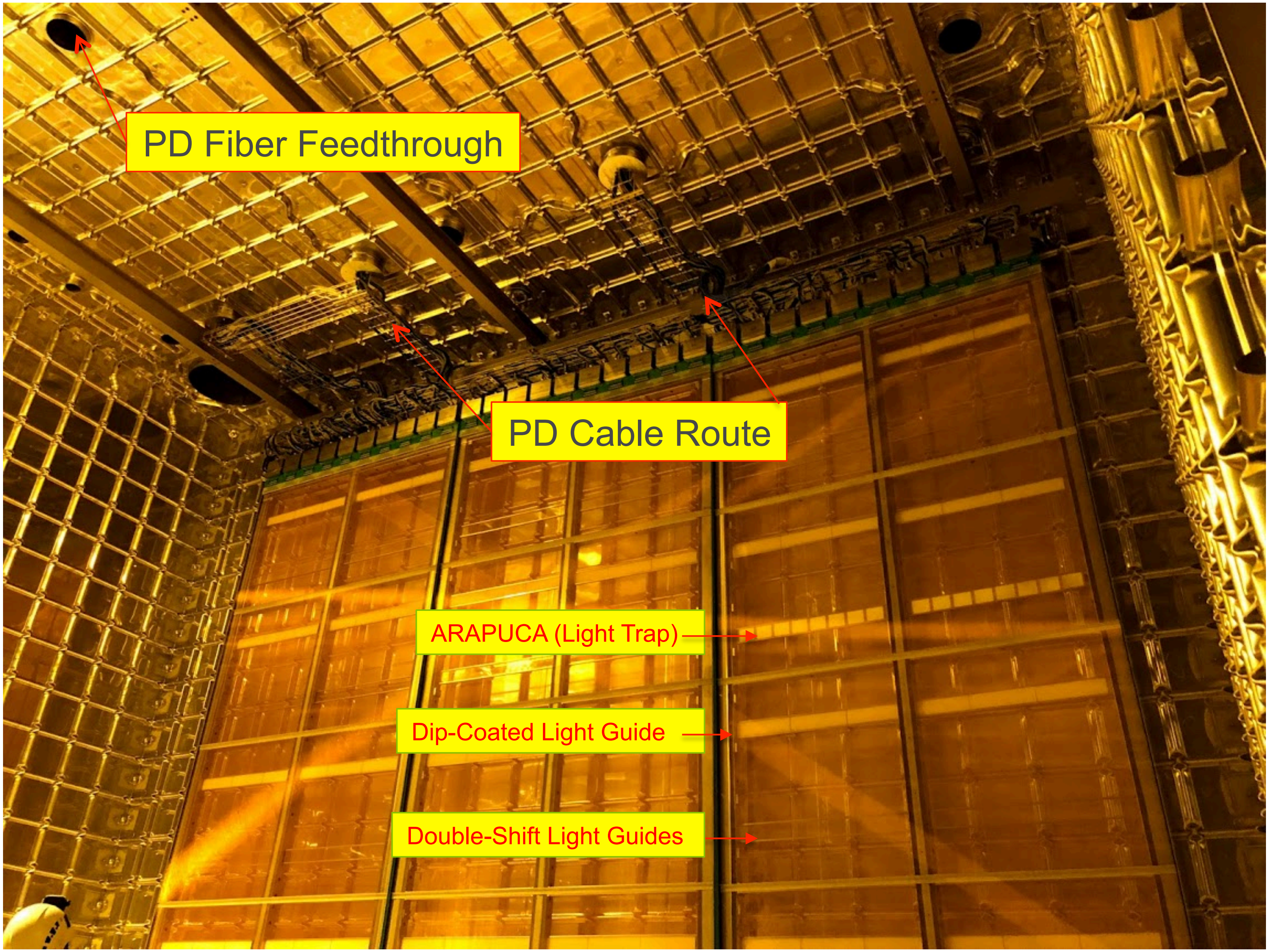



*PD Flange*

*PD Signal Cables (10 per Port)*

*10 PD Light Collection units per APA (12) SiPM sensors on the end of Light guides; 144 SiPMs in ARAPUCA array*

# Photon-Detector in ProtoDUNE-SP



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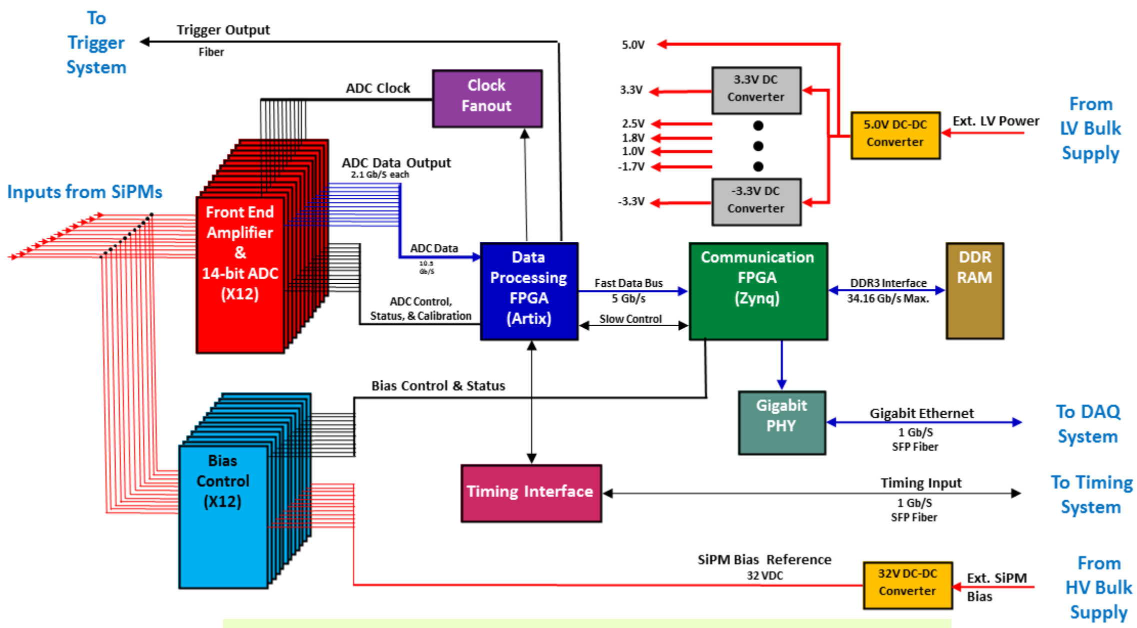
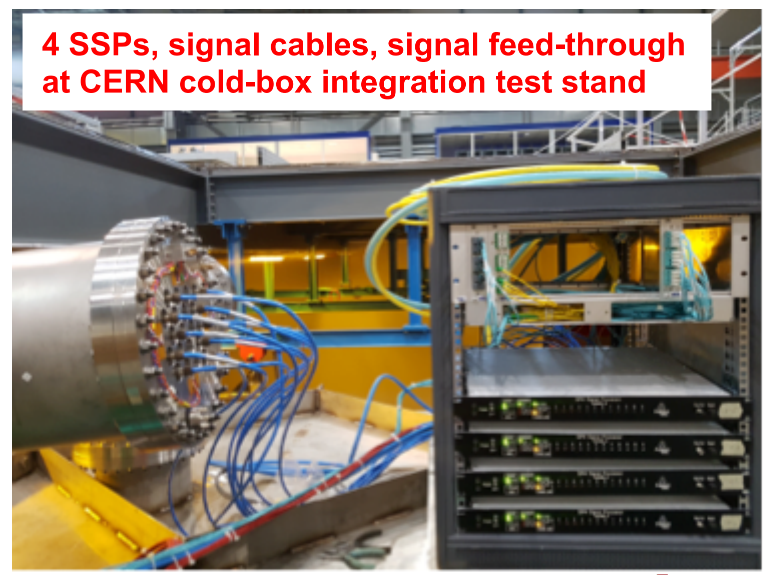
# Photon-Detector Readout in ProtoDUNE-SP

- A dedicated photon-detector readout system (SSP) was developed for ProtoDUNE




SSP (SiPM Signal Processor) Block Diagram

- ➢ Two units prototyped to test CERN DAQ integration schemes
- ➢ Four units produced for CERN "cold-box" integration test (see the figure below).




(details in backup slides)

- Twenty-four custom SiPM Signal Processor (SSP) units were produced to read out the 58 light guide and 2 ARAPUCAs photon collectors in final ProtoDUNE
- Development included custom SiPM PCB/ summing schemes, signal/power cables, signal feed-through

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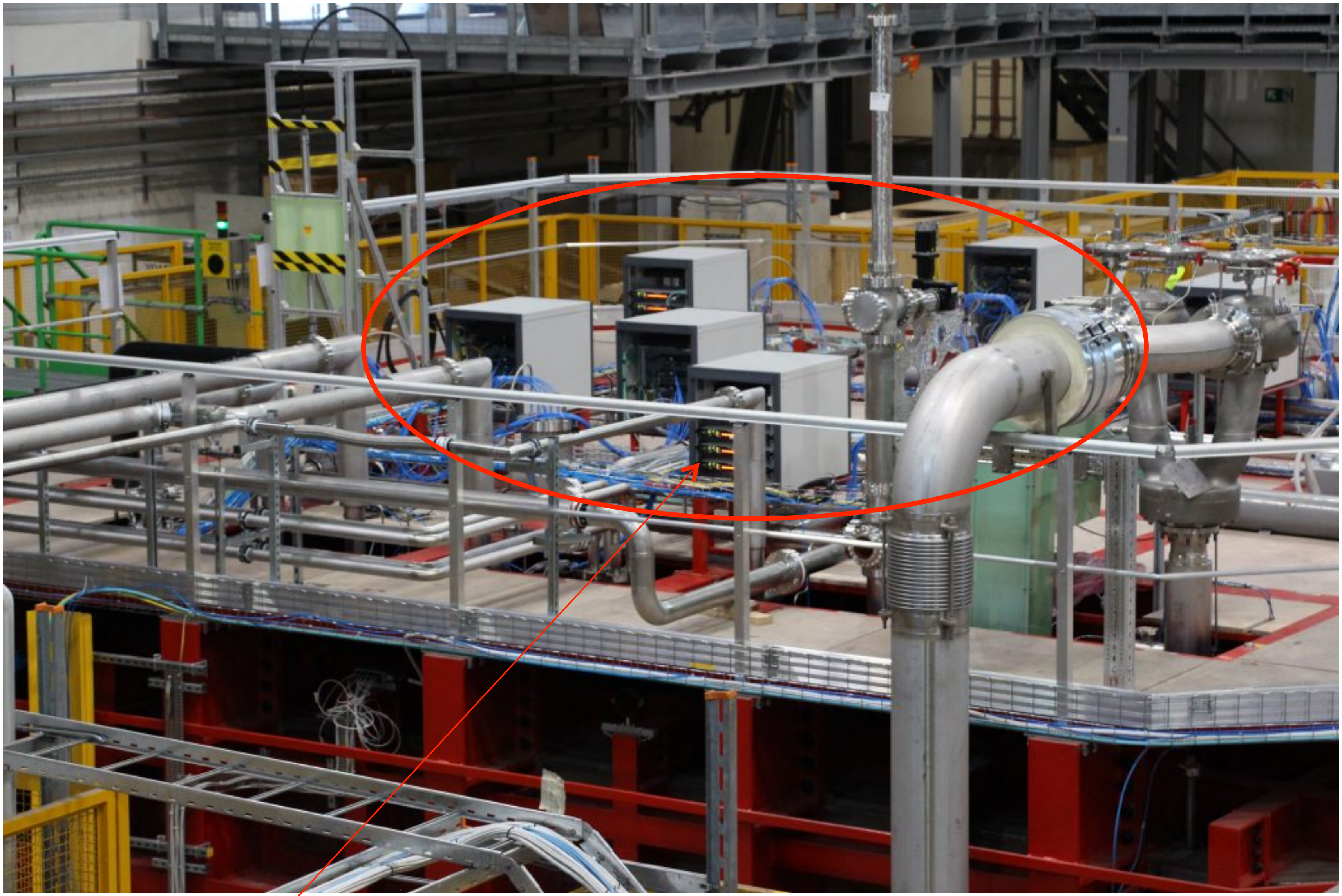
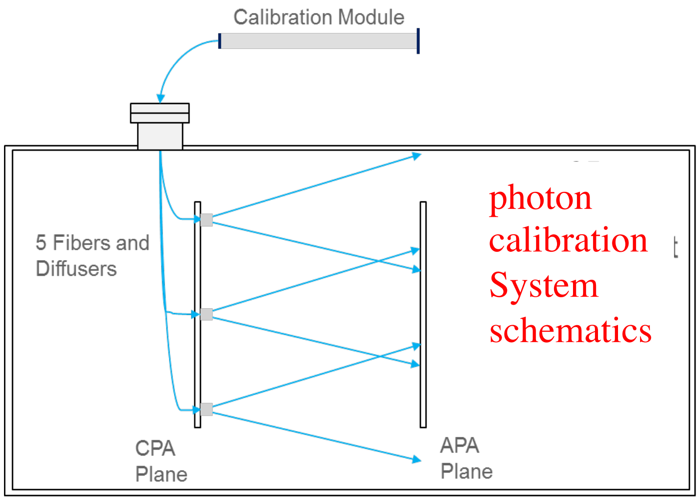
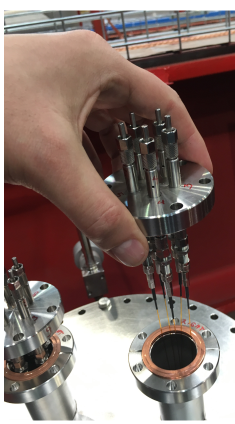


- The ProtoDUNE detector is filled with liquid argon, and is taking data
- The flashing lights in the crates on the top are the photon-detector readout boards

# Photon-Detector Calibration System

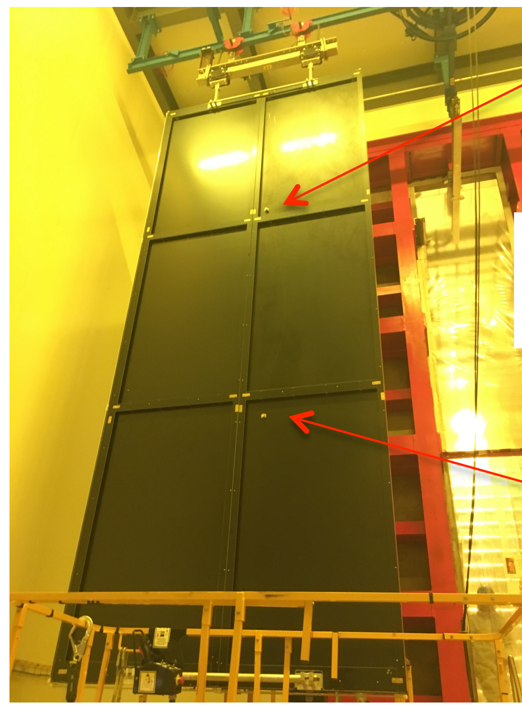
- UV-light system fabricated and installed to monitor health of the system, and to calibrate PDS gain and time resolution
- Calibration light pulses set by amplitude and pulse width, as a single pulse or as pulse pair

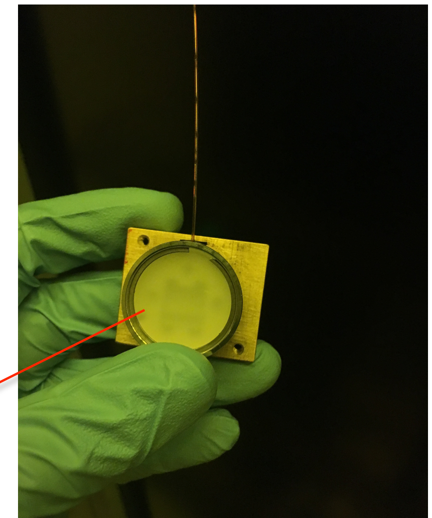


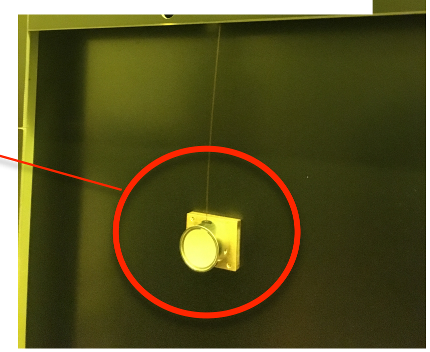



Optical fibers and feed-thruough

Two Calibration modules







Pictures of light diffusers and fibers integrated with one CPAs at CERN.

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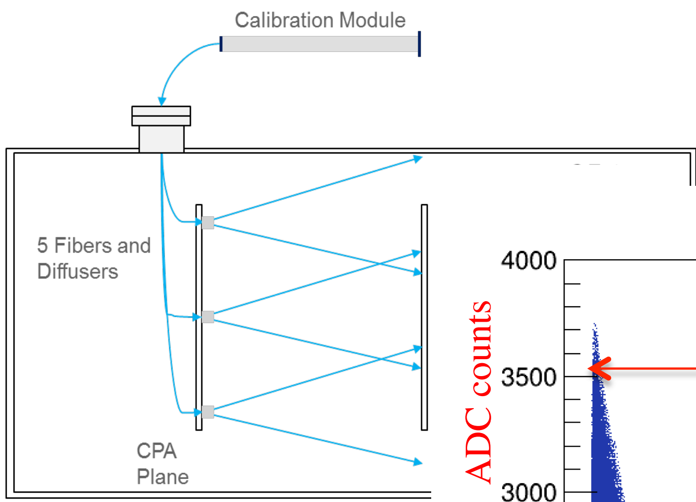
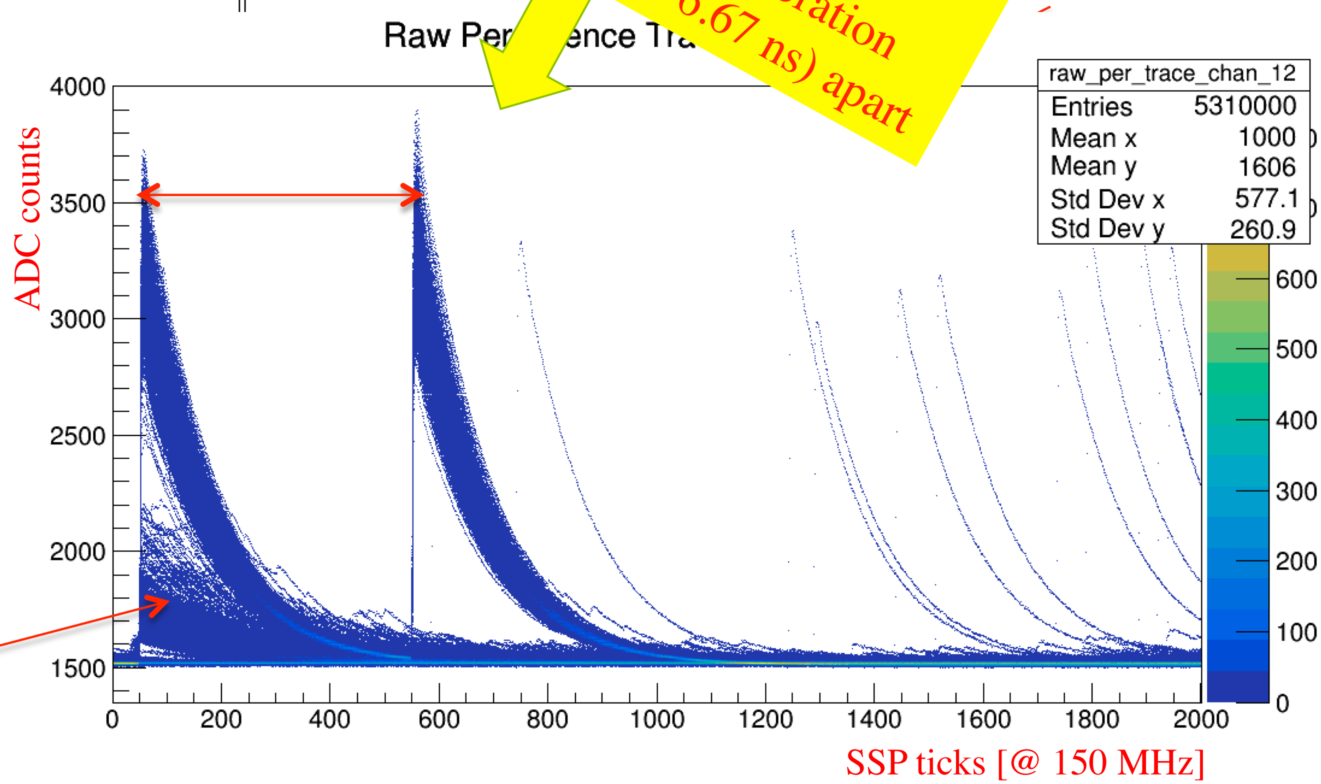
Typical photon-detector waveform as a response to a pair of calibration pulses at 500 ticks (500*6.67 ns) apart




"Accidental" cosmic ray muons



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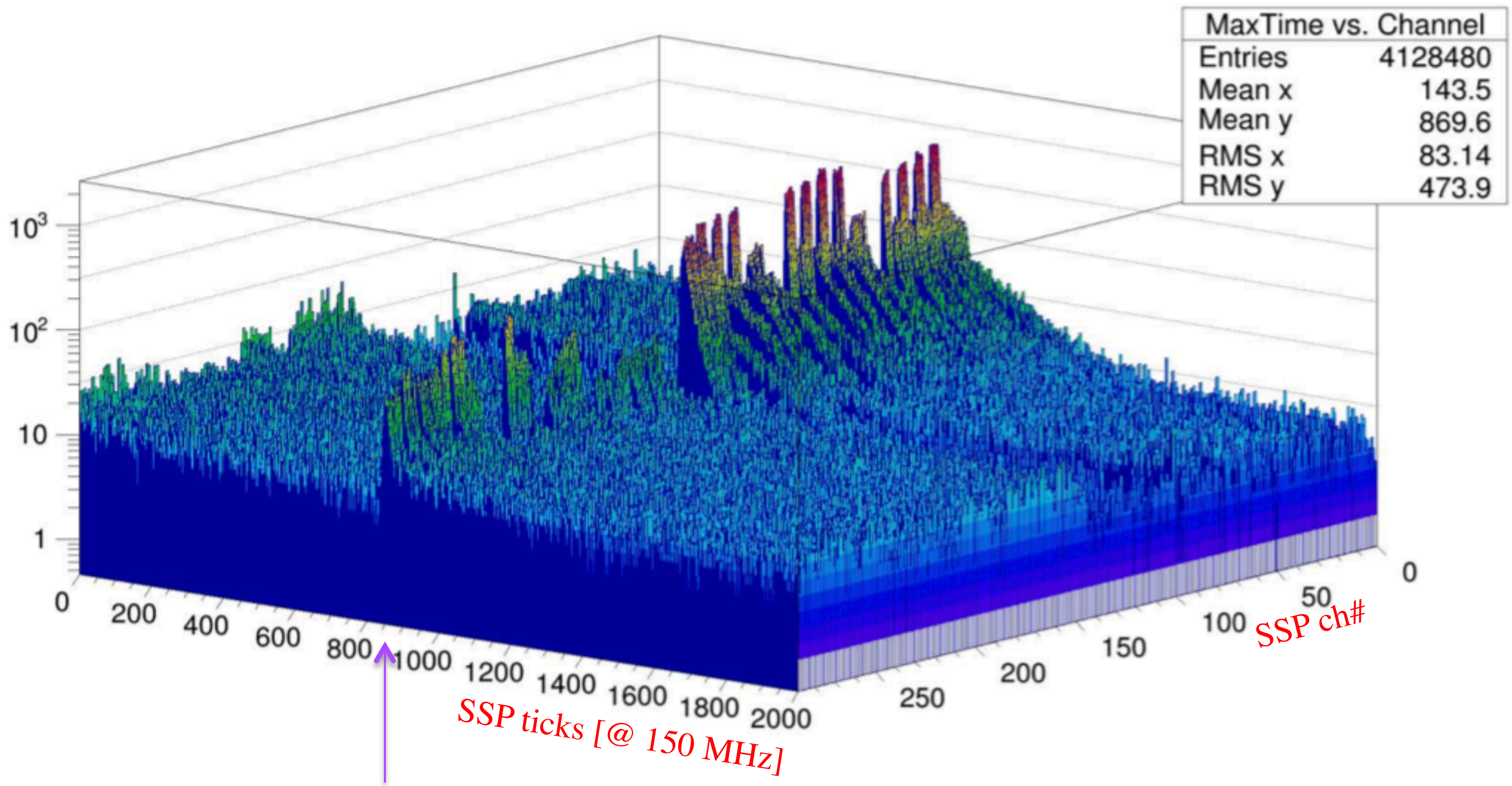
# Photon-Detector Performance

- ProtoDUNE is taking test-beam and comics data
  - ➢ Can separate photon signals from beam vs cosmics
  - ➢ Plot below shows photon-readout (SSP) waveforms for all 288 SSP channels for LAr light detected within Beam Trigger time window




Time of observed beam particles

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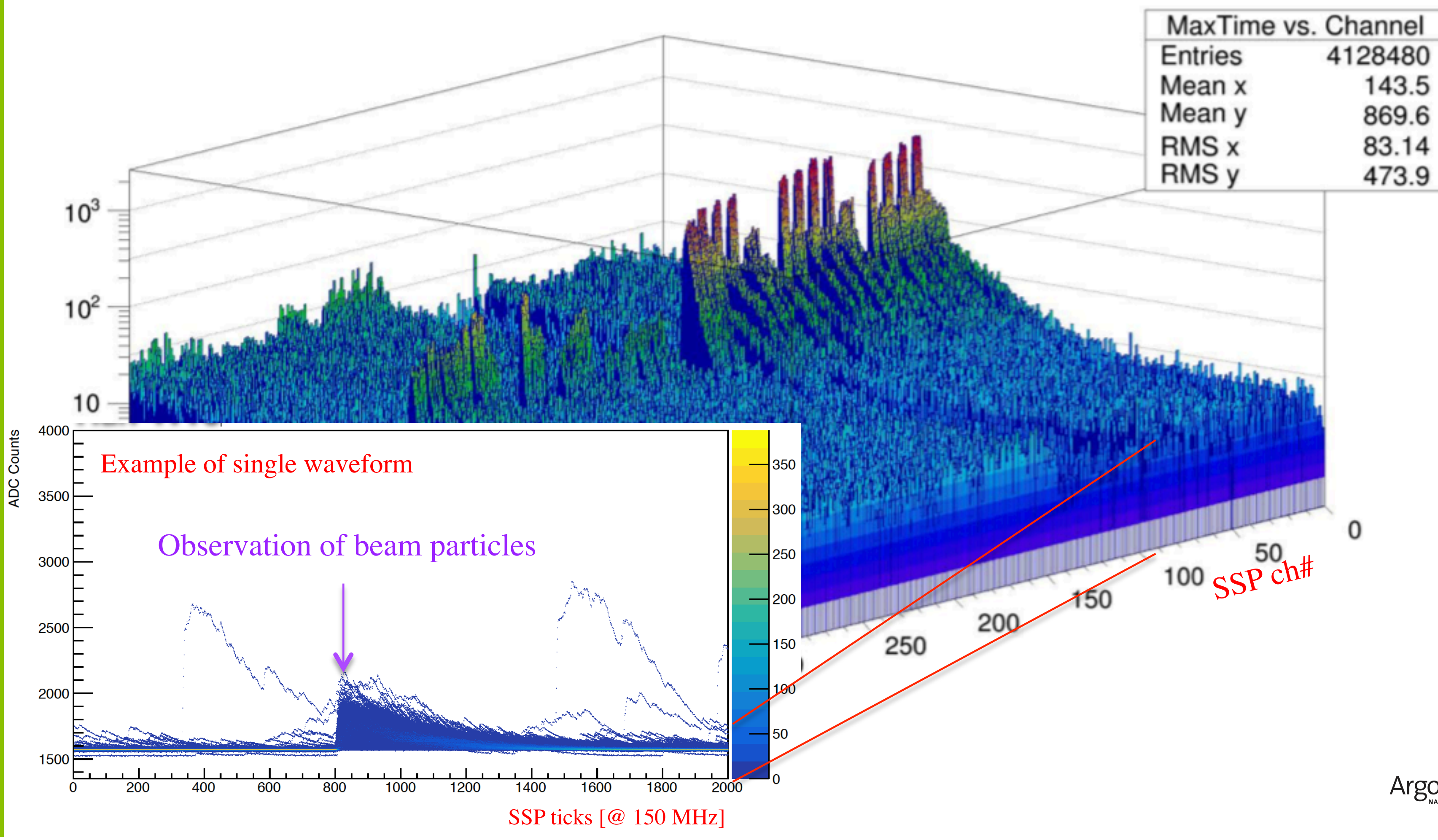

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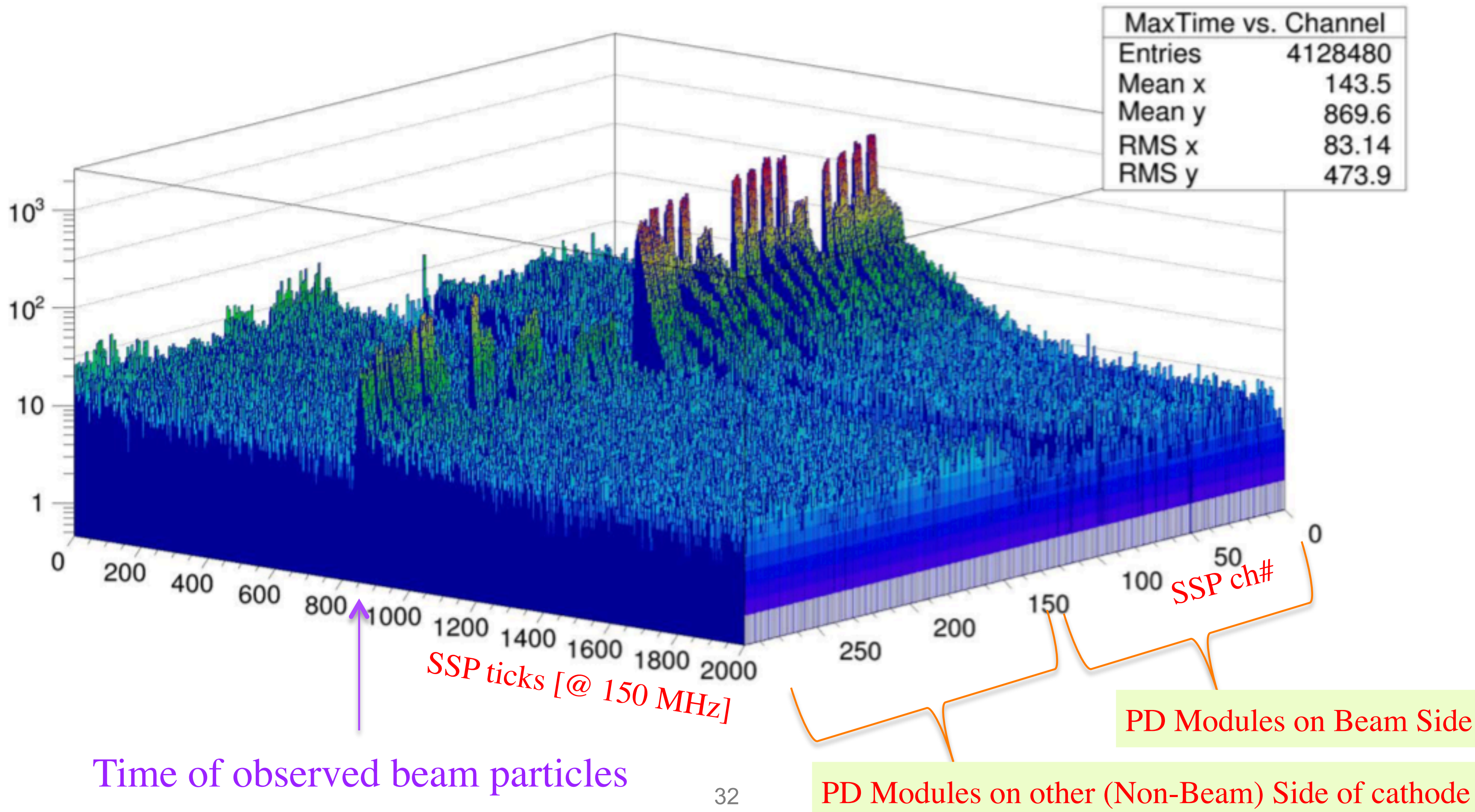


# ProtoDUNE Photon-Detector Status and Plans

- Initial data analysis demonstrates expected photon-detector performance
  - Already demonstrated triggering on Beam Events and on Cosmic muons
  - Successful demonstration of UV-light calibration system
  - Channel calibration is in progress with comic ray data and with calibration system
  - “t0” analysis is starting

- Next steps with ProtoDUNE PDS (needed as input to TDR)
  - Measure detection efficiency of three deployed light collection technologies
  - Verify “t0” capabilities
  - Explore possibility of pulse-shape discrimination through ratio of prompt to delayed light for different particle species

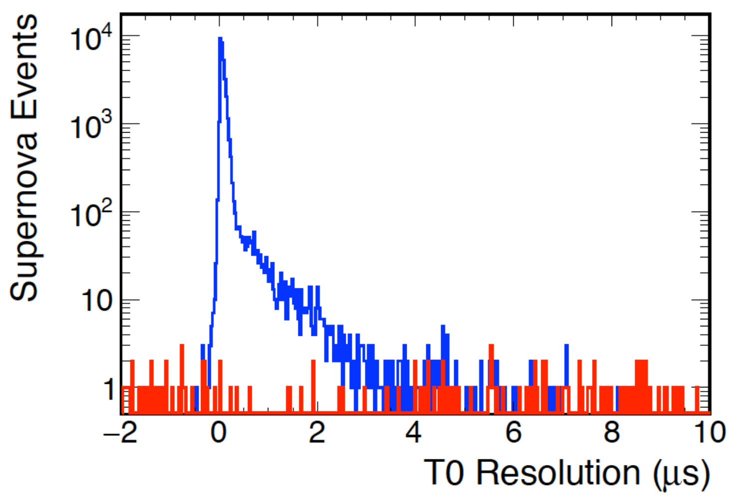
- Example of a longer term analysis topics
  - Explore Michel electron detection with combined PDS and TPC systems
  - Use PDS information to reject cosmic background in test-beam data reconstruction
  - Monitor PDS stability over time

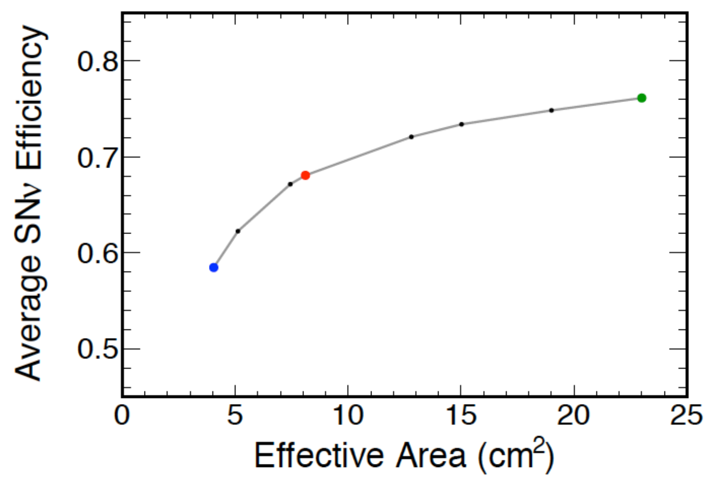
# Further DUNE PDS Optimization through Simulation Effort

- The anticipated physics performance of PD designs will be quantified using a full simulation, reconstruction, and analysis chain developed for the LArSoft framework.
  - ➢ Performance evaluation includes efficiency for determining the time of the event (t0), timing resolution, and calorimetric energy resolution for three physics samples: SNB neutrinos, nucleon decay events, and beam neutrinos.
  - ➢ Effort is underway

- Here we show one test case: **t0-finding efficiency for SNB neutrinos** versus the effective area of the photon collectors

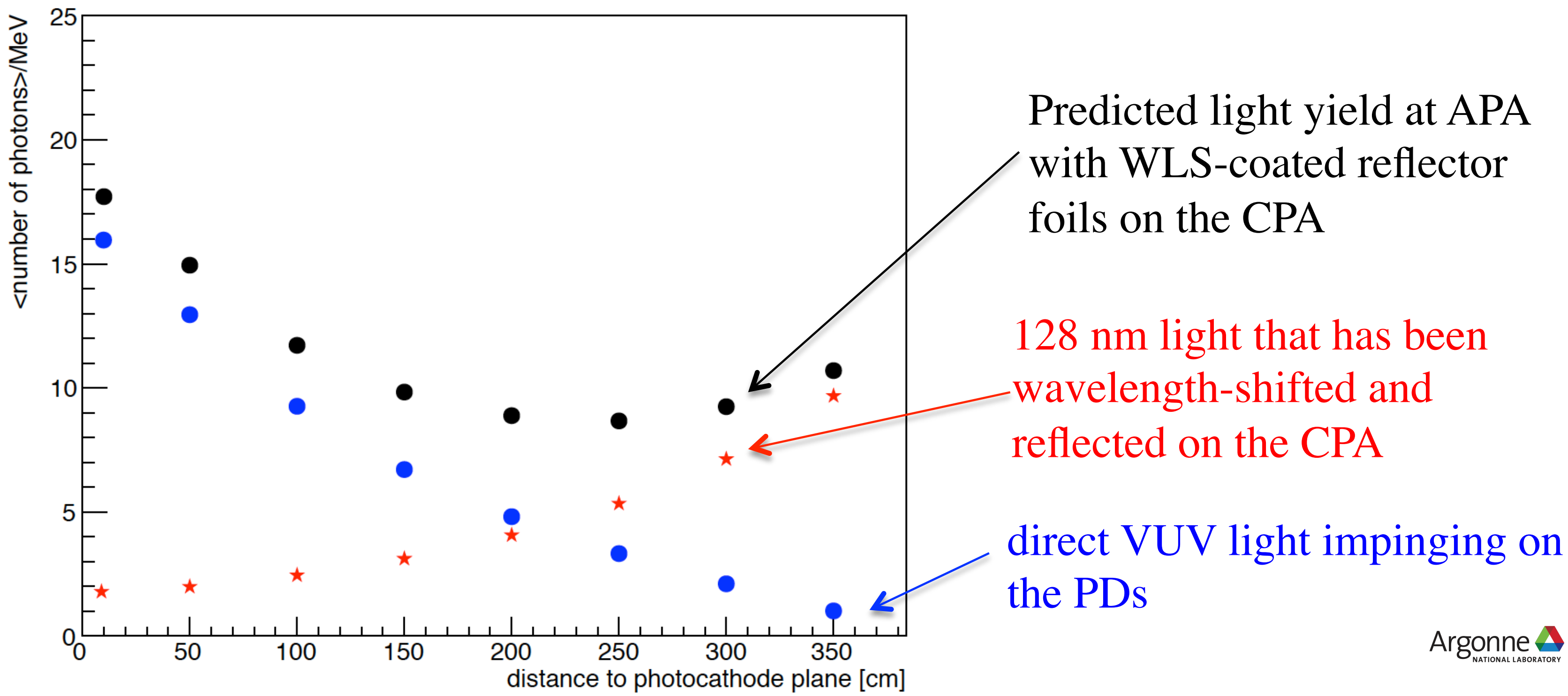
Effective area of a PD module is defined as photon detection efficiency multiplied by active photon collecting area of a PD module



# Further DUNE PDS Optimization through Simulation (cont.)

- Question of the uniformity of response away from APA
  - The baseline design (all PDS at APA) features a significant variation in the response to neutrino interactions occuring further from photon collectors towards the TPC cathode
  - One idea is to convert 128 nm light falling onto Cathode plane into the visible wavelengths using TPB-coated reflective foils, and detect the visible light by photon detectors within APA
  - Uniformity of the response would both increase the trigger efficiency and simplify the analysis for supernova neutrinos

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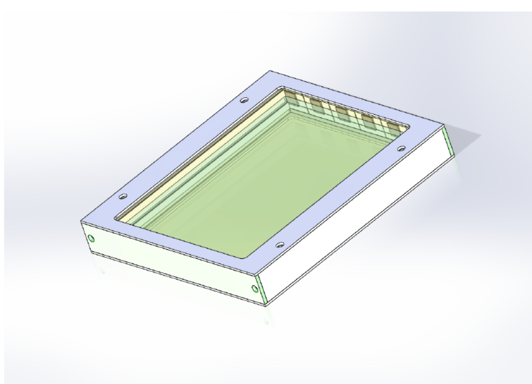
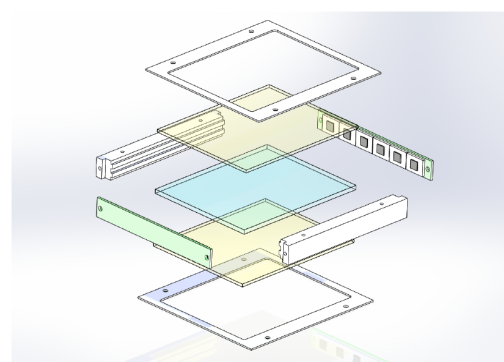
# DUNE Photon Detection System Baseline and Options

- Plans for preparation of the DUNE Technical Design Report (TDR):
  - ***Baseline*** describes a component of the system that will meet or exceed requirements (also needed to form a cost-estimate for the PDS)
  - ***Option*** provides a fallback (if the baseline is not met) or may present a more advanced solution to baseline in terms of performance specifications

- System Components
  1. **Photon Collector**
  - **Baseline**: Double-Window X-ARAPUCA (DWXA) is the baseline technology to meet or exceed DUNE performance specifications. Single-Window X ARAPUCA for side wall APAs.
  - **Option**: Use demonstrated ProtoDUNE-style single-window ARAPUCA, but enhance it with a larger window and with optimized (larger) number of photoelectrons

Double-Window X-ARAPUCA





A hybrid of ProtoDUNE ARAPUCA and light guide

# DUNE Photon Detection System Baseline and Options (cont.)

2. **Photosensors**
   - **Baseline**: The Hamamatsu Photonics K.K. (HPKK) device used in ProtoDUNE
   - **Option**: Investigate a photosensor based on the one developed by FBK (Fondazione Bruno Kessler) for the DarkSide collaboration

3. **Readout Electronics**

   (a) ganging the output of multiple photo-sensors
   - **Baseline**: Photosensor signal merging will be an active-ganging circuit based on the demonstrated Fermilab design
   - **Option**: Improvements in design will be pursued

   (b) digitization of the resulting electrical signal to provide the time and magnitude
   - **Baseline**: Use cost-effective digitization schemes (Mu2e cosmic-veto SiPM readout)
   - **Option**: Improvements in design will be pursued

4. **Uniformity of the response**
   - **Baseline**: None
   - **Option**: a) Cathode foils: Photons converted at a wavelength-shifter-coated reflecting foil mounted on the cathode planes
     b) Xenon doping of Lar: convert 128 to 175 nm photons, with 10-100 ppm

# DUNE-SP Far Detector Planning for Photon System

- Major development efforts prior to the TDR will focus on:
  - ➢ Operating the ProtoDUNE-SP and analyzing the PDS data
  - ➢ Further developing ARAPUCA system
  - ➢ Identifying and selecting reliable cryogenic photosensor (SiPM) candidates
  - ➢ Reducing cost and optimizing performance of FE electronics,
  - ➢ Solidifying PDS performance requirements from additional physics simulation efforts.

- Pre-TDR key milestones

| **Milestone** | Date |
|---|---|
| Preliminary PD technology selection criteria determined | 03/21/18 |
| Results from final prototype light collector studies available | 02/21/19 |
| Final PD technology selection criteria available | 02/21/19 |
| Down-select to primary (and potential alternate) light collector technology | 02/22/19 |
| Submit initial TDR draft for internal review | 03/29/19 |

- High-level post-TDR milestones

| **Milestone** | Date |
|---|---|
| PD pre-production review(s) complete | 03/2020 |
| Initial PD module fabrication begins | 09/2020 |
| Final PD production review based on initial production QA | 02/2021 |
| First PD modules delivered for installation | 05/2021 |
| Installation into anode plane assemblies begins | 06/2021 |
| PD fabrication complete (first SP module) | 07/2023 |

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# Summary

- Photon Detection System is used to capture scintillation light produced by charged particle interactions in the DUNE TPC.
    - Detected scintillation light is needed for event trigger and interaction time (t0) determination for underground physics (SNB, proton-decay, atmospheric ν's)
    - Energy response to low energy physics improved if sufficient light is detected
- The scintillation light of argon is VUV so the photon light collectors are designed to collect and shift this wavelength closer to the visible spectrum where conventional SiPMs with high efficiency are deployed
- Detector readout relies on summing outputs from multiple SiPMs into single channel to be processed to extract time and amplitude of detected light
- DUNE PDS prototypes are implemented in ProtoDUNE, test-beam experiment currently operational at CERN
    - Initial data demonstrate expected performance of PDS
- DUNE PDS baselined for TDR milestone (X-ARAPUCA with summed Hamamatsu SiPMs, digitized readout scheme, with potential improvements in uniformity response)
- DUNE PDS Physics Performance verification through simulation/reconstruction effort is underway
- PDS milestones constrained by DUNE FD schedule (TDR 2019; start of FD installation 2021; FD fabrication complete 2023; Physics from 2024)

# BACKUP SLIDES

# Selected DUNE Milestones

- May 2018: Decision on conceptual design of ND
- May 2018: Far Detector Interim Design Report
- July 2018: Completion of DUNE prototypes at CERN
- Jan 2019: Decision on staging of FD technologies
- Mar 2019: RRB to review status of funding matrix for first two FD modules
- April 2019: DUNE TDR submitted
- July 2019: LBNC and Cost Group Review of DUNE TDR
- Sep 2019: RRB to approve funding matrix for first two FD modules
- Oct 2019: CD2/3b Review of LBNF, US DUNE scope
- June 2020: LBNC and Cost Group Review of Near Detector TDR

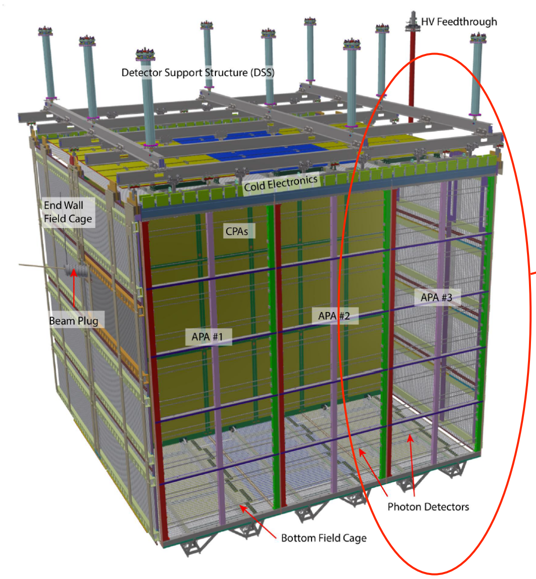
COMPLETED

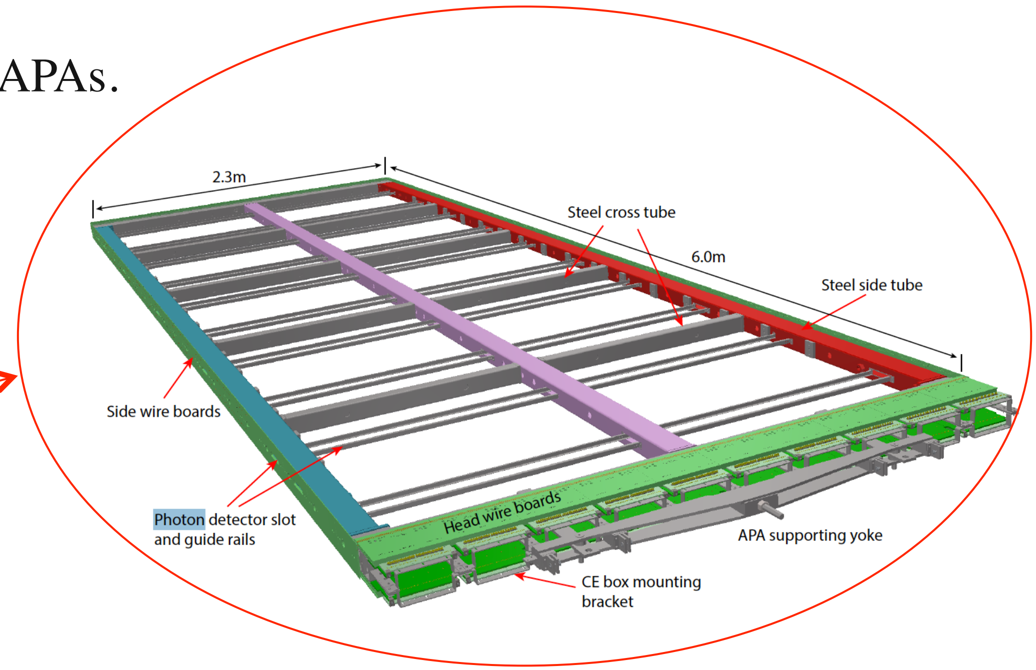
Slide from
Stefan Söldner-Rembold

| International Project Milestones | Date |
|---|---|
| Start Main Cavern Excavation | 2019 |
| Start Detector #1 Installation | 2022 |
| Beam on with two detectors | 2026 |

# DUNE/ProtoDUNE-SP Photon Detection System (PDS)

- Modular PDS is integrated into the APAs.



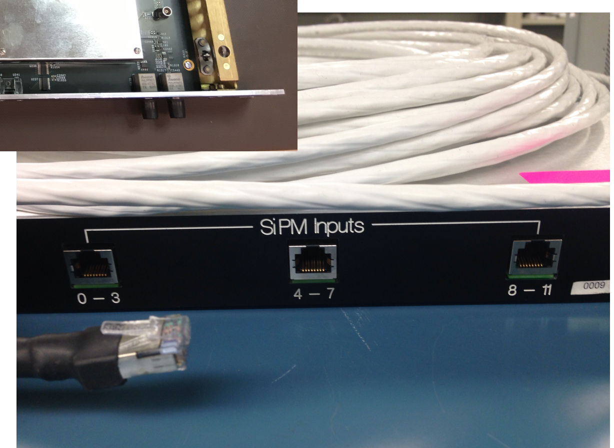




APA Frame with Photon Detector slots

- Each PDS module consists of
  - -bar-shaped light guide, and
  - -wavelength-shifting layer {
    - -surface-coating, or
    - -mounted radiator plate, or
    - ARAPUCA array
- Each APA frame is designed with ten bars into which PDs are inserted after the TPC wires have been strung.
  - =>allows for final assembly prior to installation inside the cryostat.

# Photon-Detector System Readout

- **The SSP module:**
  - High-speed waveform digitizer
  - ***Current sensitive, differential input amplifiers*** → Good noise performance over long cables
  - Each channel has a ***14-bit, 150 MSPS ADC***
  - ***Timing*** obtained using signal processing techniques on leading edge of SiPM signal (CFD)
  - 12 channels per module
  - Uses Artix FPGA for sig. proc.
  - Has ProtoDUNE Timing Interface
  - Has internal prog. SiPM bias (30V)
  - Trigger: self or external
  - ***Has Trigger Out signal***
  - Deep data buffering – 13 μsec
  - ***No dead-time*** (up to 30 KHz/ch)
  - Programmable DAQ interface
  - ***GbE communications***
  - Internal charge injection
  - Internal bias monitoring



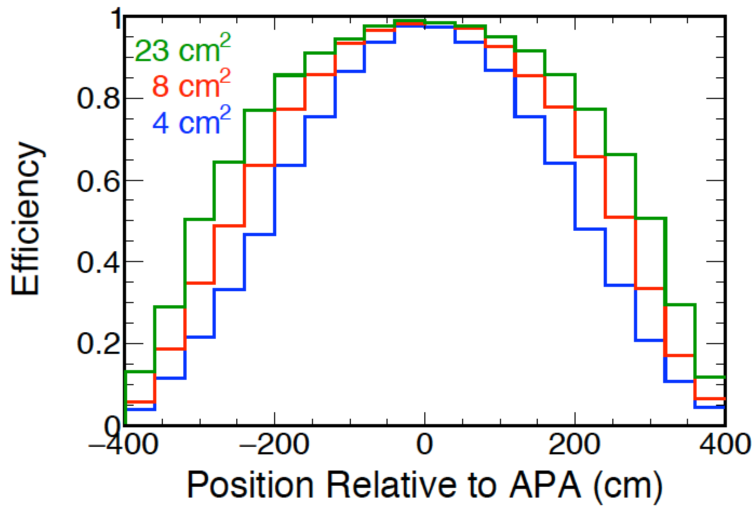

*=> SSP already integrated with ProtoDUNE DAQ*

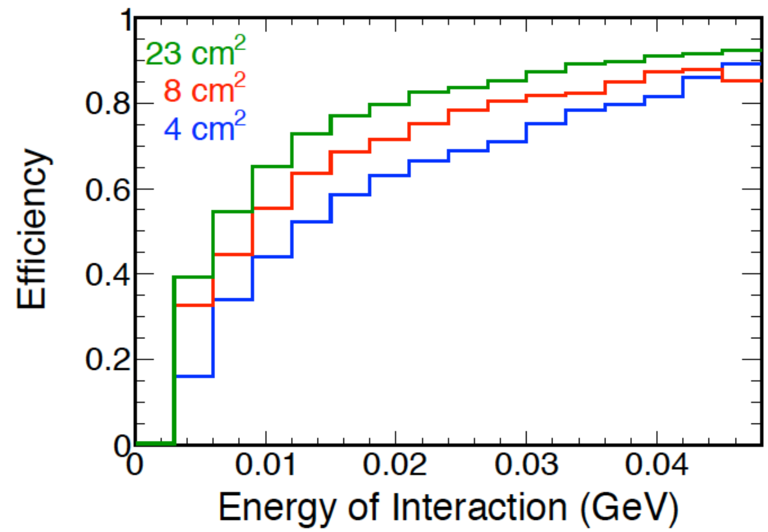
# Candidate Photosensors Characteristics

| | Hamamatsu | sensL | KETEK | Advansid |
|---|---|---|---|---|
| Series part # | S13360 | DS-MicroC | PM33 | NUV-SiPMs |
| Vbr range | 48 V to 58 V | 24.2 V to 24.7 V | 27.5 V | 24 V to 28 V |
| Vop range | Vbr + 3 V | Vbr +1 V to +3 V | Vbr+2V to +5 V | Vbr +2 V to +6 V |
| Temp. dependence | 54 mV/K | 21.5 mV/K | 22 mV/K | 26 mV/K |
| Gain | $1.7 \times 10^6$ | $3 \times 10^6$ | $1.74 \times 10^6$ | $3.6 \times 10^6$ |
| Pixel size | 50 $\mu$m | 10 $\mu$m to 50 $\mu$m | 15 $\mu$m to 25 $\mu$m | 40 $\mu$m |
| Sizes | 2x2 mm | 1x1 | 3x3 | 4x4 |
| | 3x3 mm | 3x3 | | 3x3 |
| | 6x6 mm | 6x6 | | |
| Wavelength | 320 to 900 nm | 300 to 950 nm | 300 to 950 nm | 350 to 900 nm |
| PDE peak wavelength | 450 nm | 420 nm | 430 nm | 420 nm |
| PDE @ peak | 40% | 24% to 41% | 41% at Vov=5 V | 43% |
| DCR @0.5PE | 2 to 6 MHz | 0.3 kHz to 1.2 MHz | 100 kHz at Vovr=5 V | 100 kHz/mm$^2$ |
| Crosstalk | $<$ 3% | 7% | 15% | $<$ 4% (correlated noise) |
| Afterpulsing | | 0.20% | <1% | <4% |
| Terminal capacitance | 1300 pF | 3400 pF | 750 pF | 800 pF |
| Lab experience | Good experiences from Mu2e and ARAPUCA | Crack at LN2 temps. after specifications change | | |

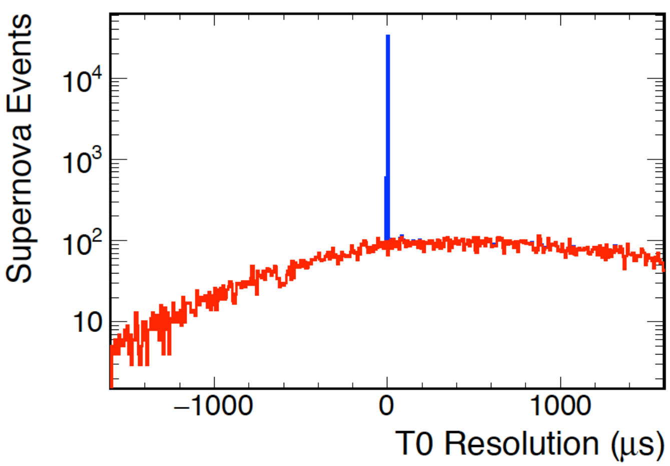
# Further DUNE PDS Optimization through Simulation (cont.)

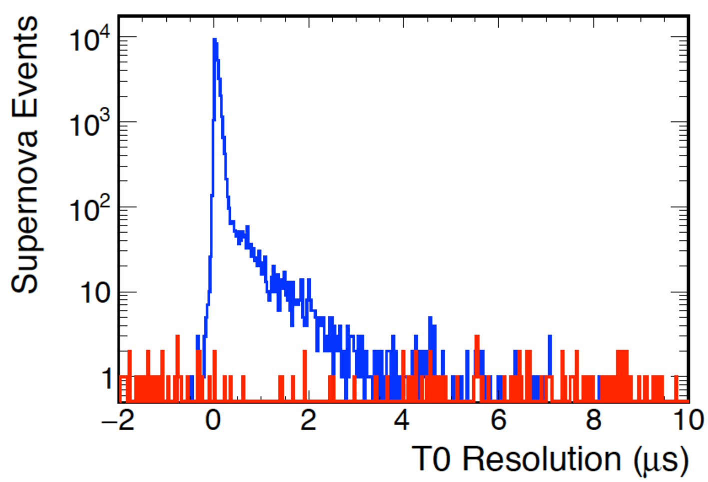
- **t0-finding efficiency for SNB neutrinos** versus the effective area of the photon collectors




- **Resolution on t0 for SNB events**




Results based on simulation with effective light collector area of 4 $cm^2$ (photon detection efficiency of 0.23%) measured for a double-shift light guide module

# Dedicated Integration Effort for DUNE PDS

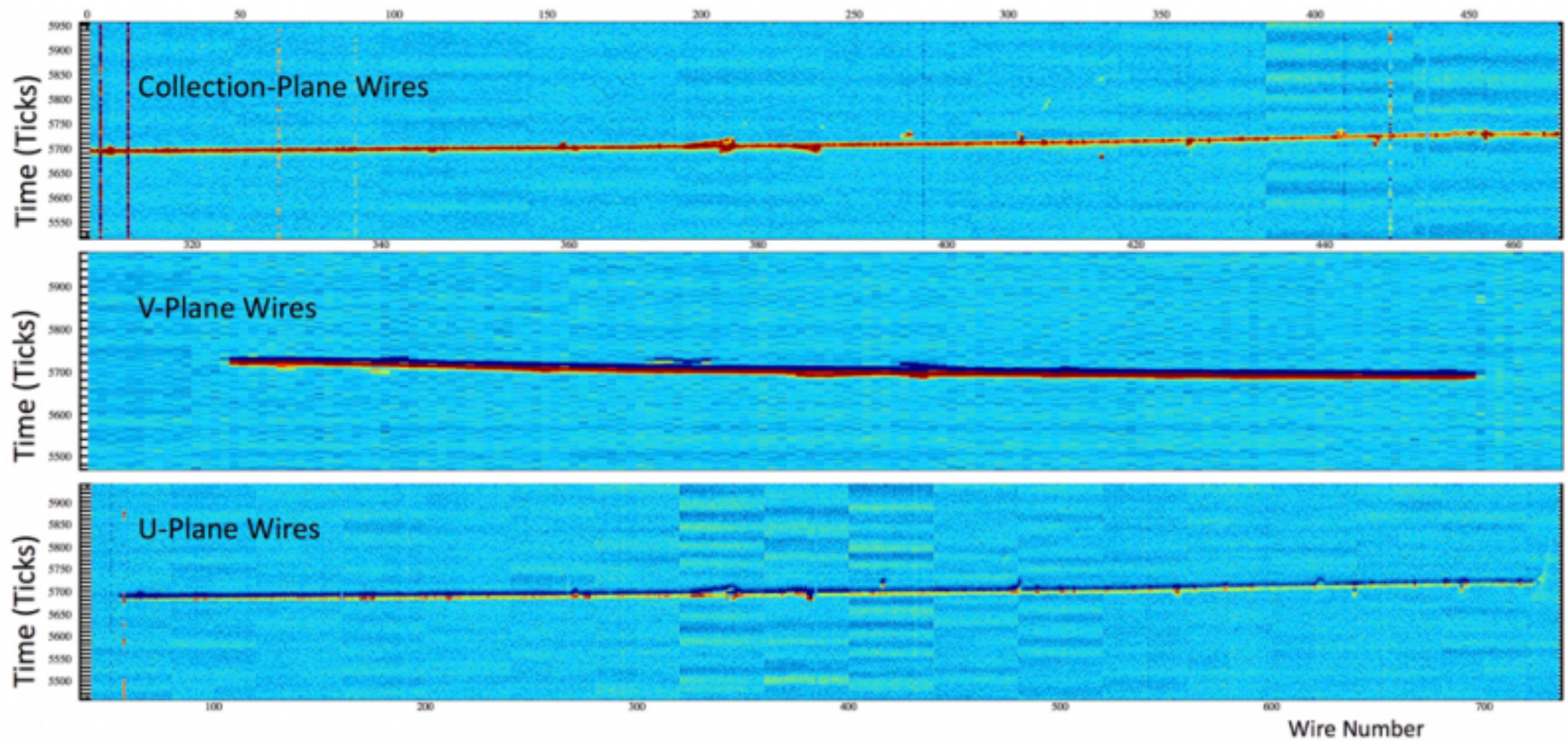
- Needs to incorporate Photon-Detector System Interfaces with other TPC system

- Interfaces exist between DUNE SP photon-detector system and other (sub)systems
  - ➢ Anode-Plane Assembly => integrates PDS light collectors and cables
  - ➢ Signal/Power cable feed-through => shared with Cold Electronics (CE)
  - ➢ TPC CE => Shared risk of signal interference, need "minimize cross-talk"
  - ➢ CPA / HV System => share components of PDS calibration/monitoring systems and (potentially) reflective foils in DUNE FD
  - ➢ DAQ => PDS data out; timing/trigger communication
  - ➢ Calibration and Monitoring => internal PDS system for commissioning and operation

- Integration process will be specified prior to the TDR.

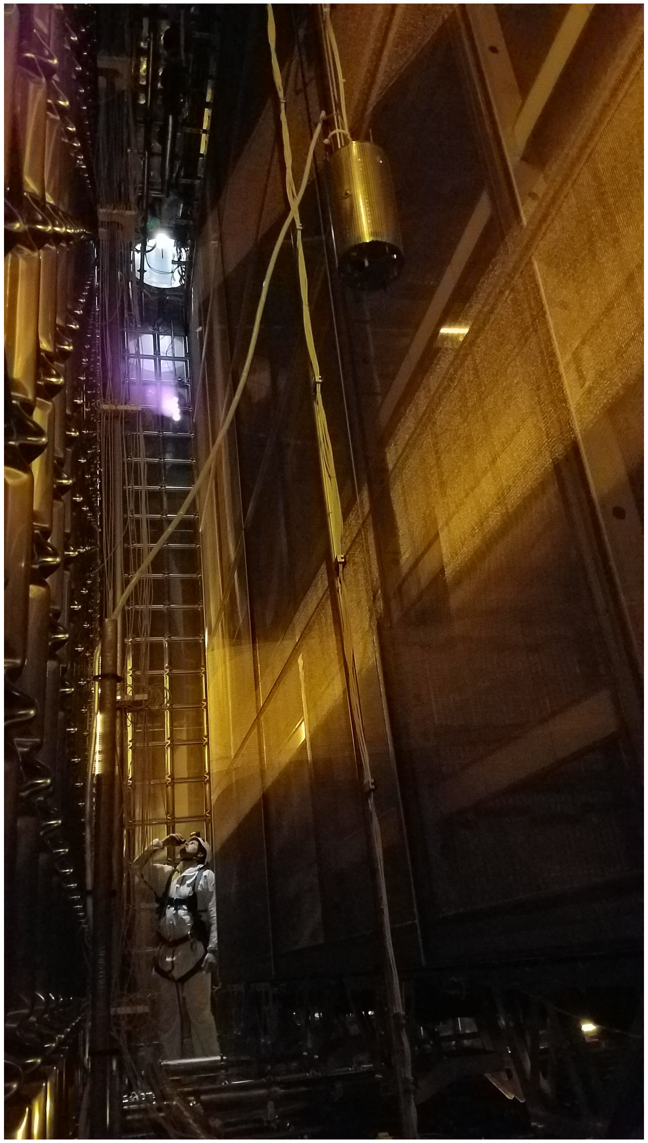
- An Integration and Test Facility (ITF) will be constructed by the collaboration/project for the integration of the PDs into anode plane assemblies.
  - -Transportation to and from ITF should be carefully planned.
  - -The PDS units will be shipped from the production area in quantities compatible with the APA transport rates.
  - -Other components will follow

# ProtoDUNE

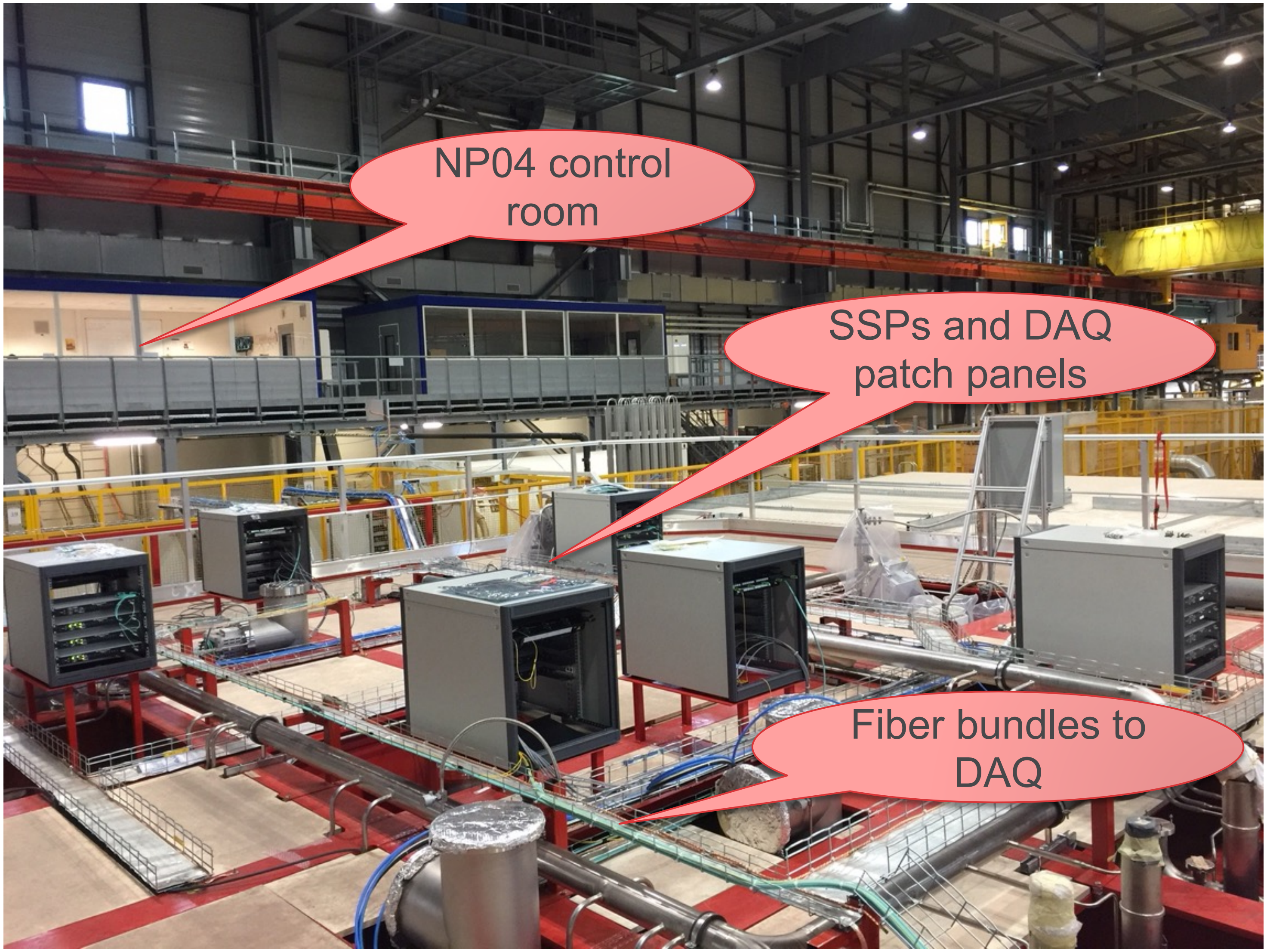

Collection-Plane Wires
V-Plane Wires
U-Plane Wires
Time (Ticks)
Time (Ticks)
Time (Ticks)
Wire Number

# ProtoDUNE

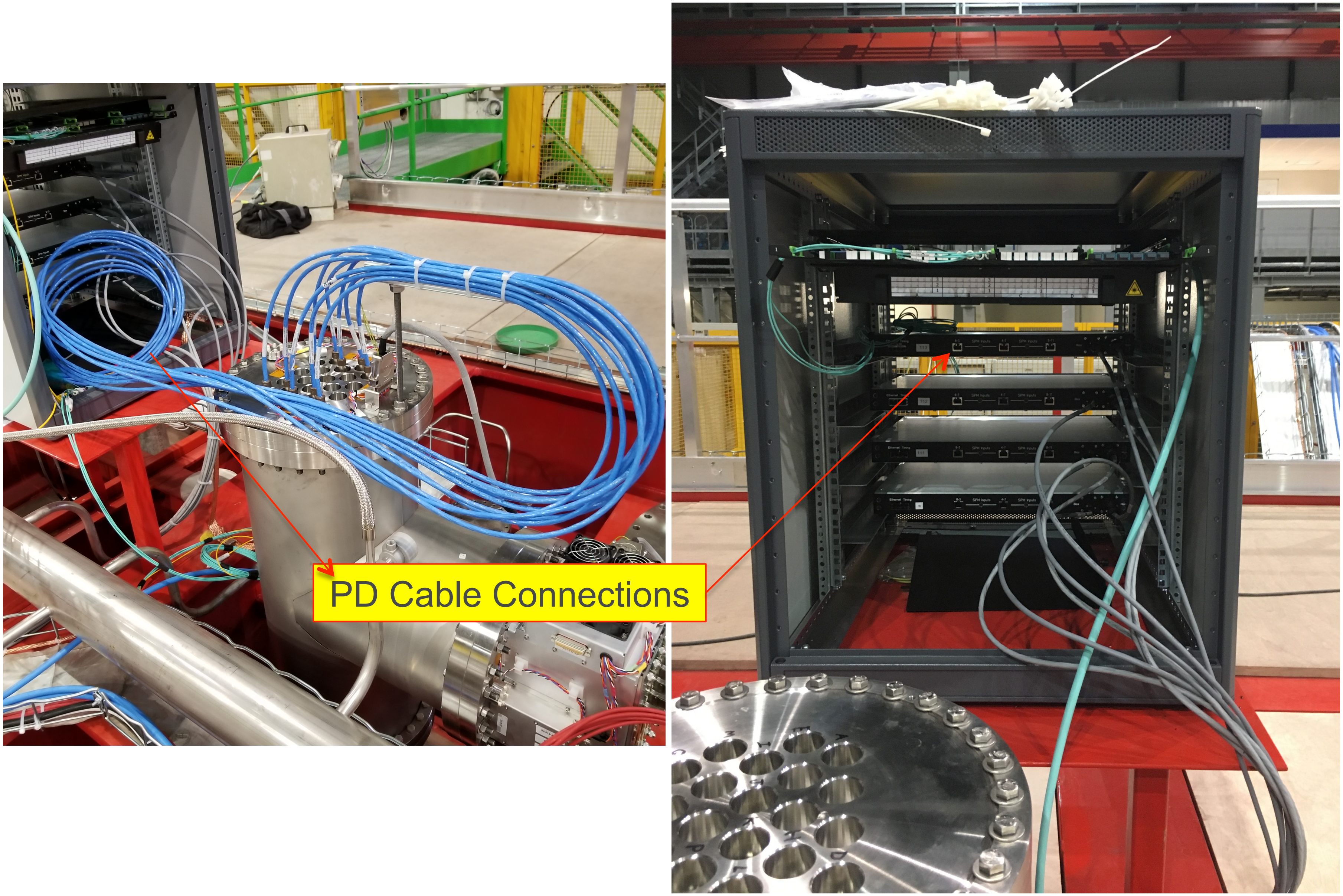
# ProtoDUNE



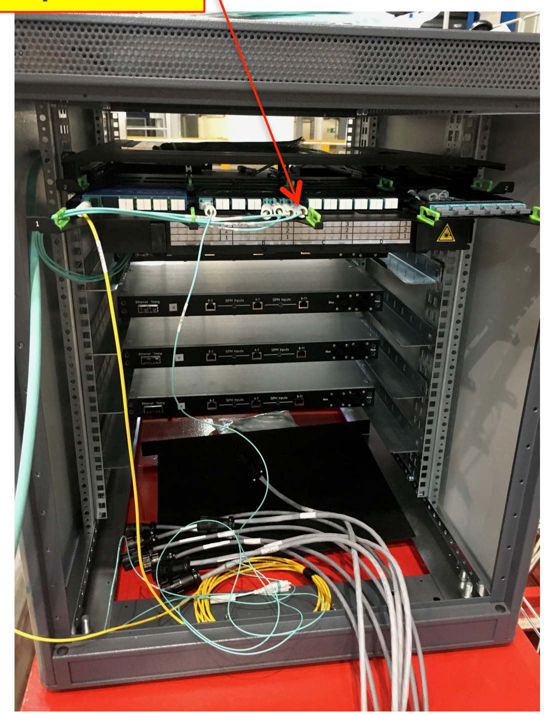
# ProtoDUNE


NP04 control room
SSPs and DAQ patch panels
Fiber bundles to DAQ

# ProtoDUNE



# More Details on SSPs



SSPs and DAQ patch panels

Fiber bundles to DAQ

# ProtoDUNE

-Fibers shown coming into the fiber feed-through