SP PHOTON DETECTION CONSORTIUM

ETTORE SEGRETO

30% READINESS REVIEW

NOVEMBER 12, 2018

UNICAMP

FAPESP

CNPq
Conselho Nacional de Desenvolvimento
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Consortium Membership

Pretty International Consortium

42 Participating Institutions ***equally distributed among Latin America (13) , North America (15) and Europe (14) as in the spirit of DUNE Colllaboration***

USA	Brookhaven National Lab
USA	California Institute of Technology
USA	Colorado State University
USA	Duke University
USA	Fermi National Accelerator Lab
USA	Idaho State University
USA	Indiana University
USA	University of Iowa
USA	Louisiana State University
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USA	University of Michigan
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Italy	University of Lecce Aand INFN
Italy	INFN Milano
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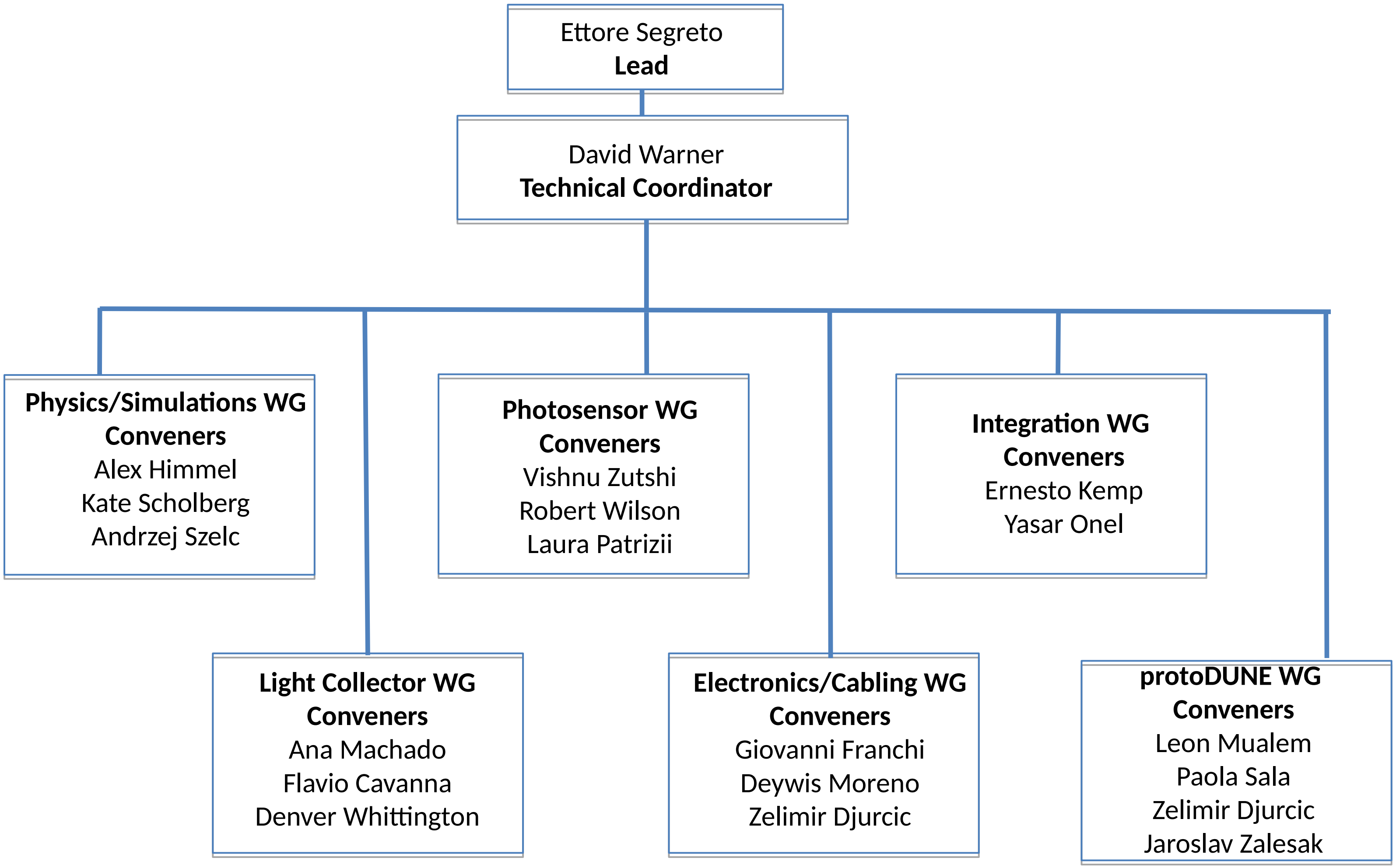
PD Consortium Management Table of Organization



SP PD Scope

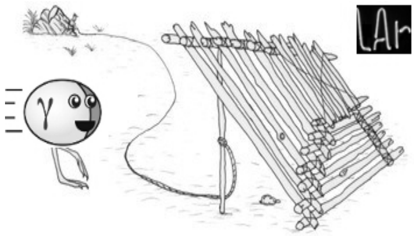
The scope of the photon detector (PD) system for the DUNE far detector reference design includes design, procurement, fabrication, testing, delivery and installation of the following components:

- ***Light collection system***
  - ✓ Collects photons from a large area and drives them towards the active sensors (SiPMs). **X-ARAPUCA** – an evolution of the ARAPUCA - is the baseline design.
- ***Silicon photomultipliers (SiPMs)***
  - ✓ **Hamamatsu MPPCs are currently the baseline choice**. Collaboration with **FBK** (Fondazione Bruno Kessler, Italy) is being strongly persued.
- ***Readout electronics***
  - ✓ Mu2e adapted electronics is the current baseline choice for the Front End. Exploring low cost alternatives to waveform high frequency digitization (including signal integration). Two SiPM active ganging circuits available.
- ***Related infrastructure (***APA mounting, cabling, cryostat flanges, etc.)

- **The final design of the SP PD will appear very similar to the protoDUNE one:**
-
- **Bar shaped modules** slided inside the APA frame between wire planes
- Each photon collector module will have approximate linear dimensions of 200 cm x 10 cm
- 10 modules per APA

- Photon Collector based on the X-ARAPUCA
- **Light read-out based on SiPM**

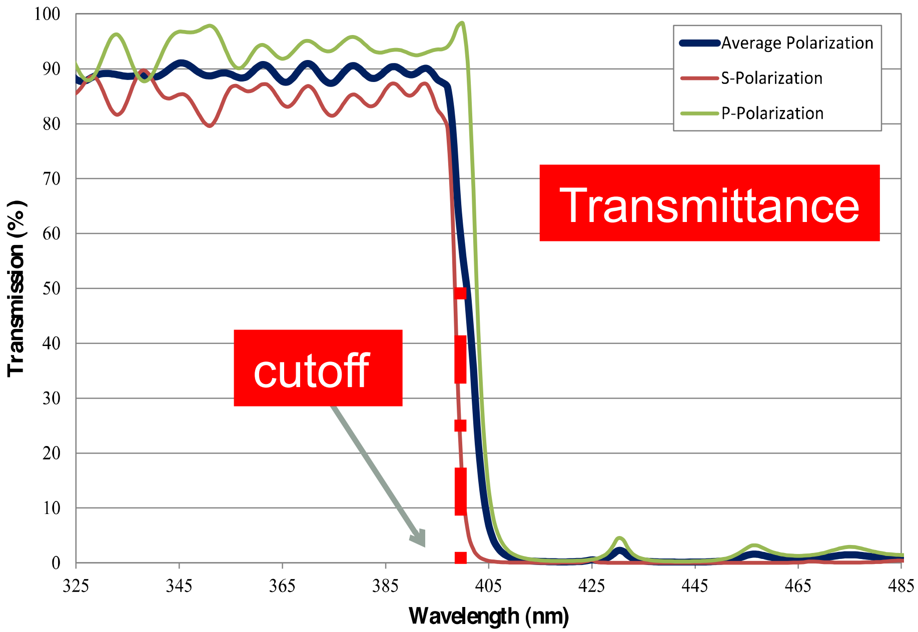
ARAPUCA concept

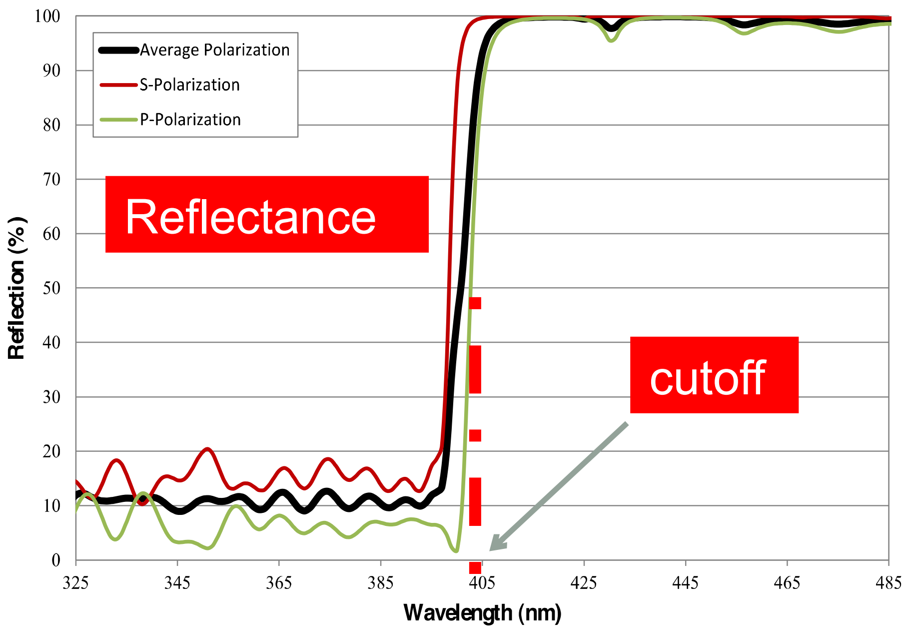


- **ARAPUCA** in the language of *native Brazilian* means ***trap*** for birds
- The idea is to **trap photons** inside a **box with highly reflective internal surfaces**, so that the detection efficiency of trapped photons is high even with a limited active coverage of its internal surface → Allows to reduce the number of active device and electronic channels.
- Detection efficiency can be tuned by varying the number of SiPMs (ratio between acceptance window and SiPM areas).
- LAr tests performed at ***Fermilab*** and in ***Brazil*** demonstrated a detection efficiency at the 1% level. ProtoDUNE design, with an increased number of SiPM is expected to be in the range of 2% to 3%. See F. Cavanna talk.
- DUNE design, based on ***X-ARAPUCA*** is expected to do better than this.

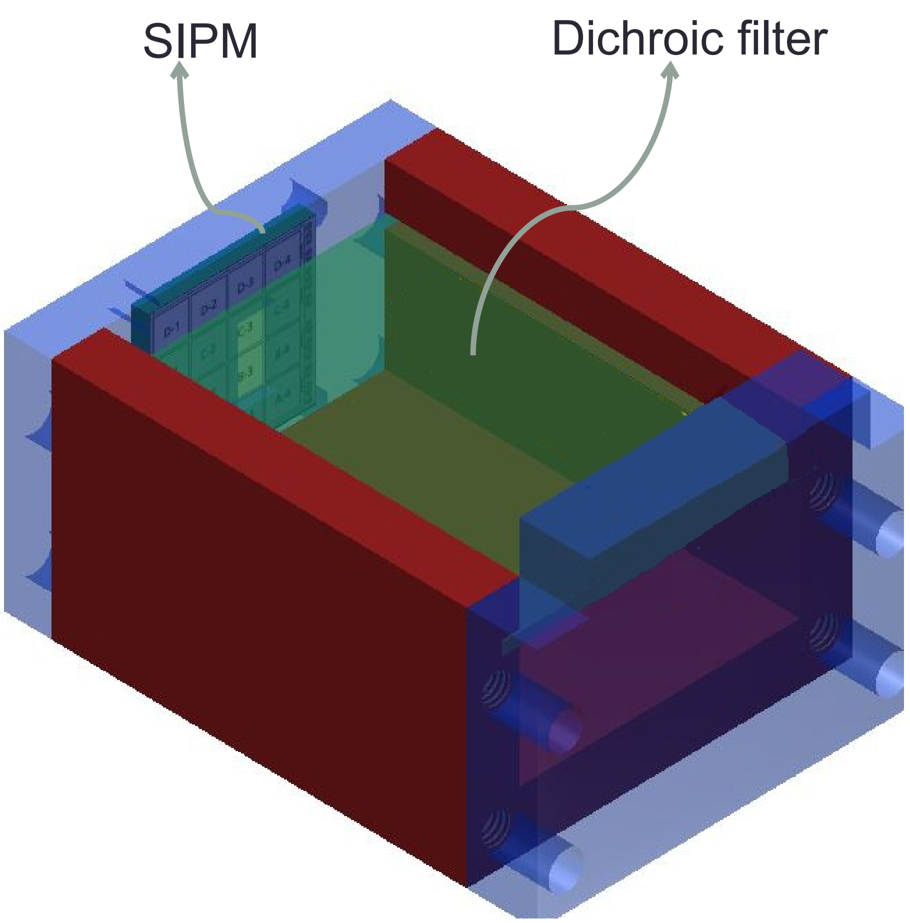
Dichroic filter

- The core of the device is a **dichroic filter**. It is a dielectric interference **film** deposited on a fused silica substrate.
- It has the property of being **highly transparent** for wavelength **below a cutoff** and **highly reflective above it**.





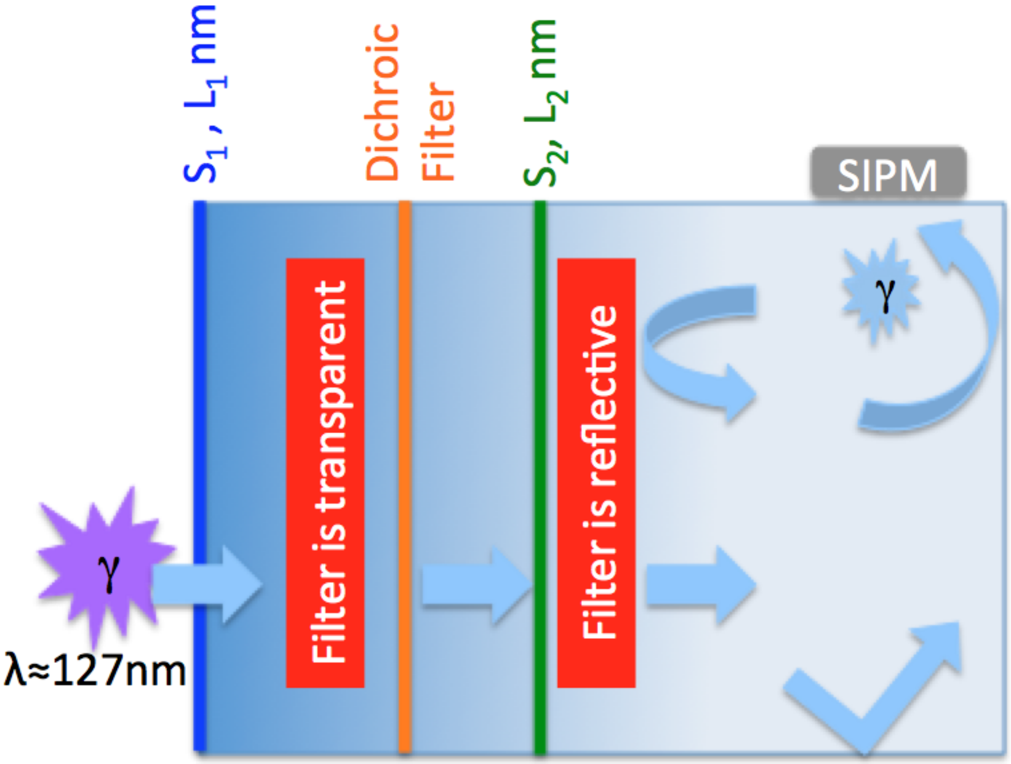
Operating principle



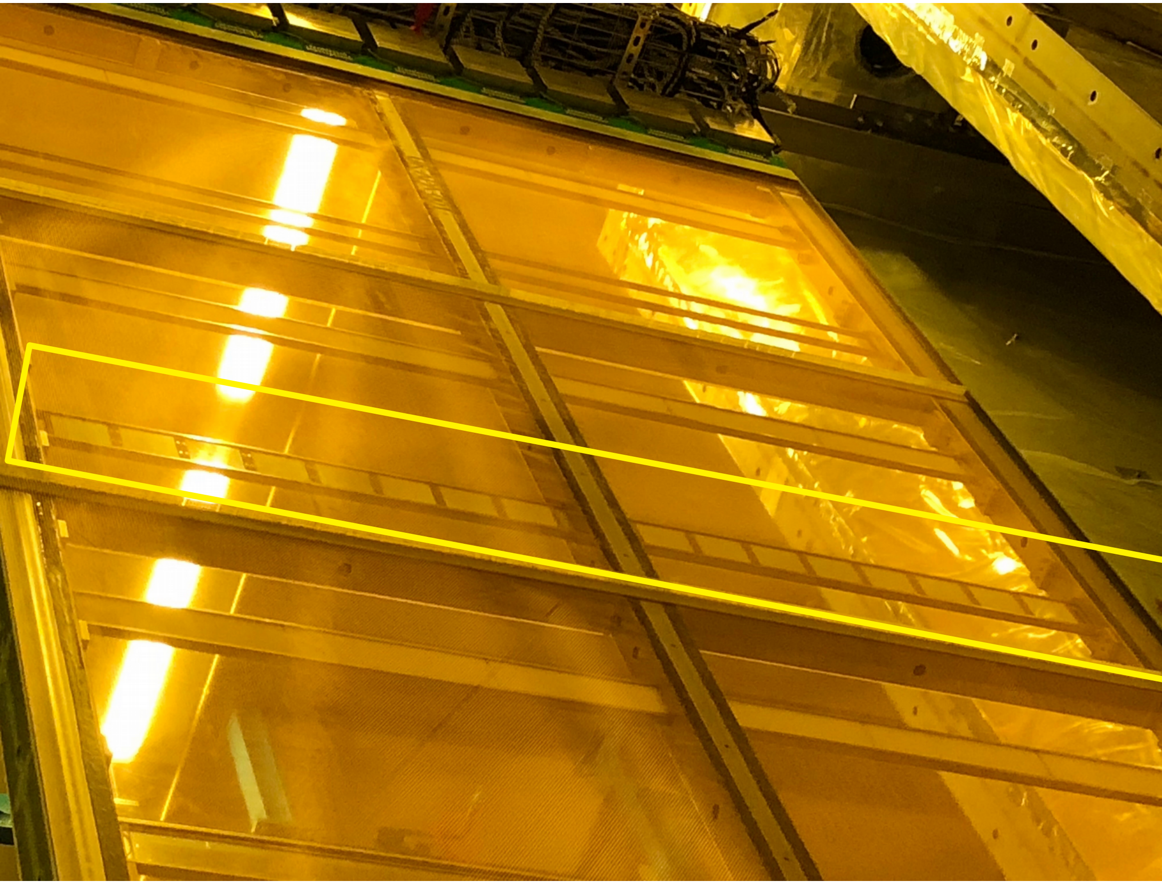
- The simplest geometry is a **flattened box** with highly reflective internal surfaces (Teflon, VIKUITI, VM2000) with an open side.
- The open side hosts the **dichroic filter** that is the acceptance window of the device
- The filter is deposited with **TWO WAVELENGTH SHIFTERS (WLS)** – **one on each side**
- The shifter on the **external side**, S1, converts LAr scintillation light (128 nm) to a wavelength L1, with **L1 < cutoff**
- The shifter on the **internal side**, S2, converts S1 shifted photons to a wavelength L2, **with L2 > cutoff**
- **The internal surface** of the ARAPUCA is observed by **one or more SiPM**

The Operating Principle cont.

- After the **first shift** the light enters the ARAPUCA since **the filter is transparent**
- After the **second shift** the **photon gets trapped inside the box** because the filter turns to be **reflective**
- Photons are **detected by the SiPM** after some reflections



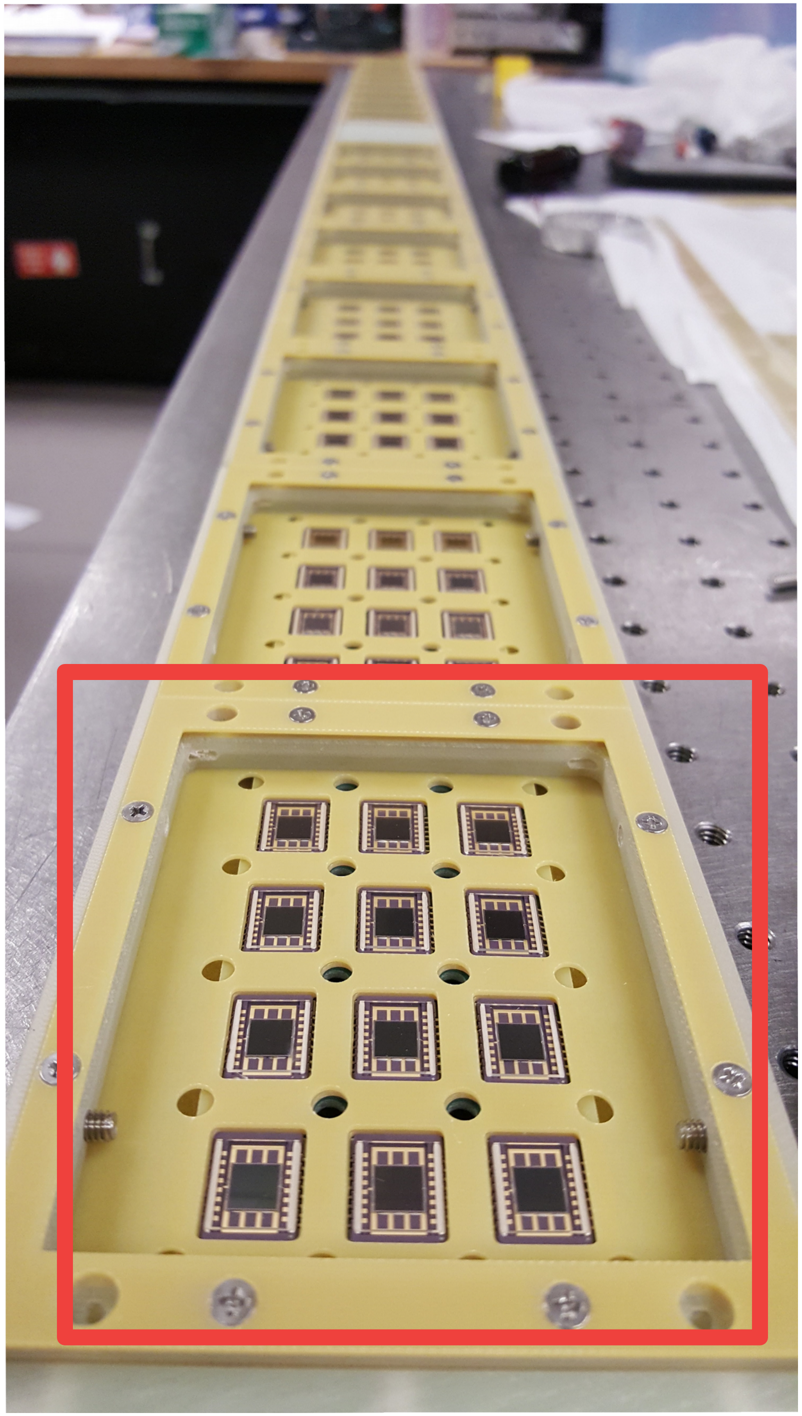
ARAPUCA modules in protoDUNE



Two ARAPUCA arrays installed in protoDUNE (**APA#3** – close to the beam and **APA#4** -opposite side)

Each array hosts ***16 ARAPUCA cells*** (10 cm x 8 cm) and each cell is *read-out by 12* (*6*) Hamamatsu SiPM passively ganged together.

ProtoDUNE ARAPUCA array assembled by CSU group



- Each cell is lined with **VIKUITI reflective** foils properly cut *(reflectivity > 98%)* - coated with a thin **TetraPhenyl-Butadiene** film *(TPB - emission wavelength 430 nm)*

- Acceptance window is a dichroic filter with **cut-off at 400 nm**

- Filters coated externally with **p-TerPhenyl** *(pTPemission wavelength 350 nm)*

- *ProtoDUNE ARAPUCAs are working (see F. Cavanna talk)*

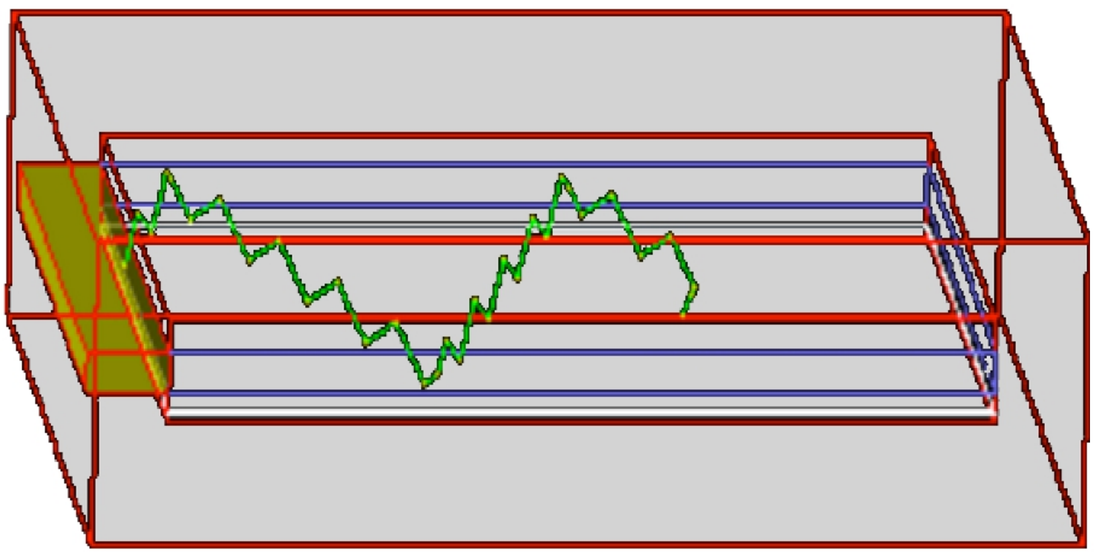
- ProtoDUNE represents an important part of the **ARAPUCA R&D** program

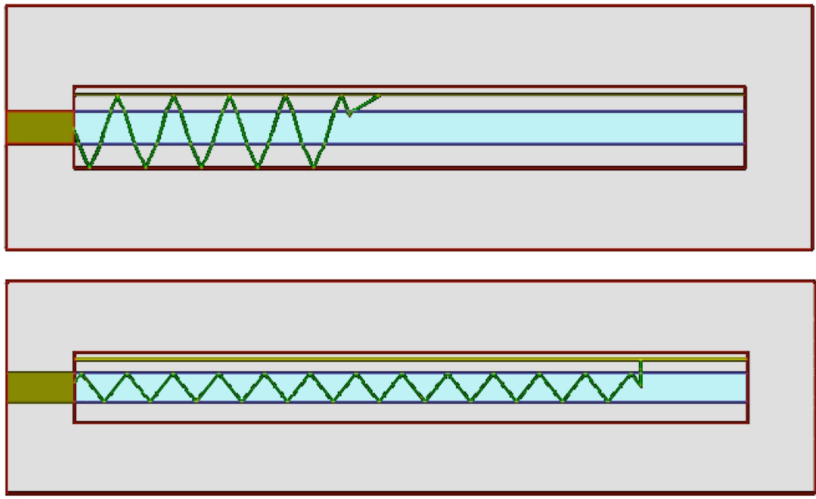
Expected protoDUNE outcomes

- Photosensors:
  - Characterize Hamamatsu devices (dark count rate, cross talk and afterpulsing, compare passive ganging of 3, 6 and 12 SiPM, single photoelectron response)
- Detector performance
  - Estimate the Detection Efficiency of ARAPUCA using beam and cosmic data
  - Compare to Monte Carlo Simulations
- Argon performance
  - Rayleigh scattering (hints of)
- CE/HV/PD interference studies
- Detector aging/monitoring system
  - stability in photosensor performance
  - monitoring changes in light collector system (loss of WLS performance)
  - Look for “MicroBooNE effect”: high rate of single photoelectrons, not compatible with the expectations based on background, dark counts and afterpulsing
  - Calibrate PD performance using Argon radioactive decays (^{39}Ar)

X-ARAPUCA concept

- The ***X-ARAPUCA*** represents a development and an optimization of the traditional *ARAPUCA*
- X-ARAPUCA is a *hybrid solution* between an ARAPUCA and a ***light guide***
- In an X-ARAPUCA the inner shifter is substituted by an ***acrylic slab*** which has the *WLS compound embedded*. The active photo-sensors are optically coupled to one or more ends of the slab itself





X-ARAPUCA concept

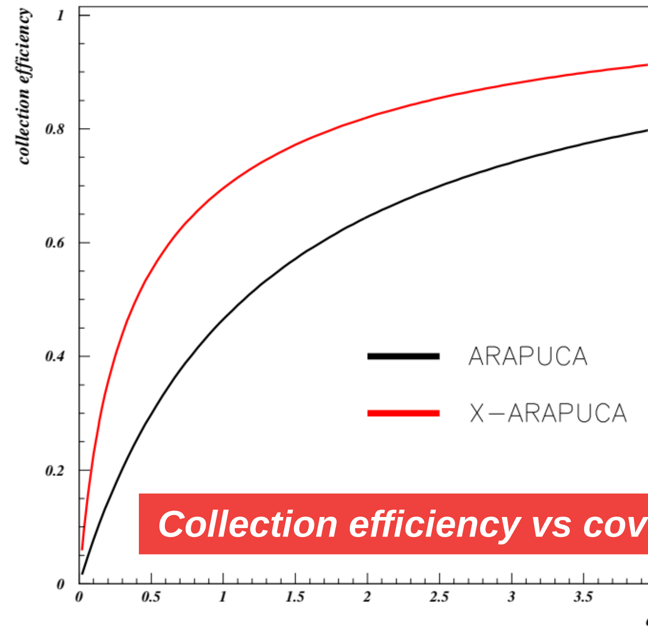
- There are ***two main mechanisms*** through which a photon can be detected by the X-ARAPUCA:
  - ***Standard ARAPUCA mechanism***. The photon, after entering the X-ARAPUCA box, is converted by the WLS of the inner slab, but is not captured by total internal reflection. In this case the photon bounces a few times on the inner surfaces of the box until when it is or detected or absorbed;
  - ***Total internal reflection***. The photon, converted by the filter and the slab, *gets trapped by total internal reflection*. It will be guided towards one end of the slab where it will be eventually detected. This represents an improvement with respect to a conventional ARAPUCA, which contributes to *reduce the effective number of reflections on the internal surfaces*. The sides of the slab where there are not active photo-sensors will be coated with a **reflective layer** which will allow to keep the photon trapped by total internal reflection.

X-ARAPUCA vs. ARAPUCA

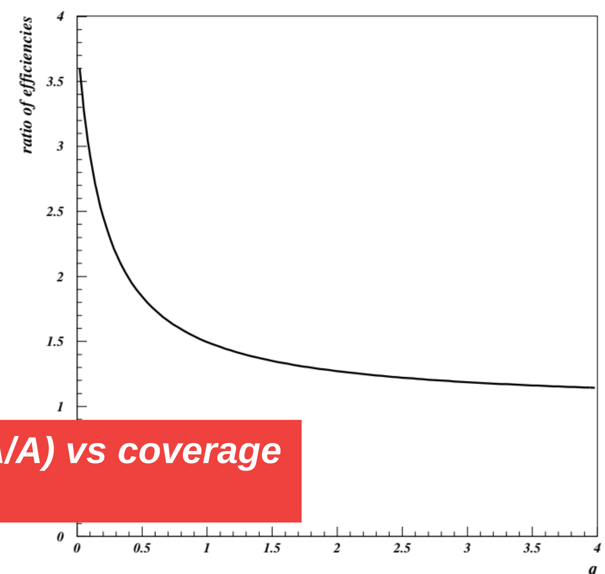
- **X-ARAPUCA is more efficient in trapping photons**:
  - ✓ Analytical calculations and MC simulations appoint to an enhancement *between 40% and 70%* wrt ARAPUCA

- **Simpler design:**
  - ✓ **No need of evaporating** the internal side of the filter or internal surfaces
  - ✓ Great advantage especially for double sided X-ARAPUCAs
  - ✓ Faster production

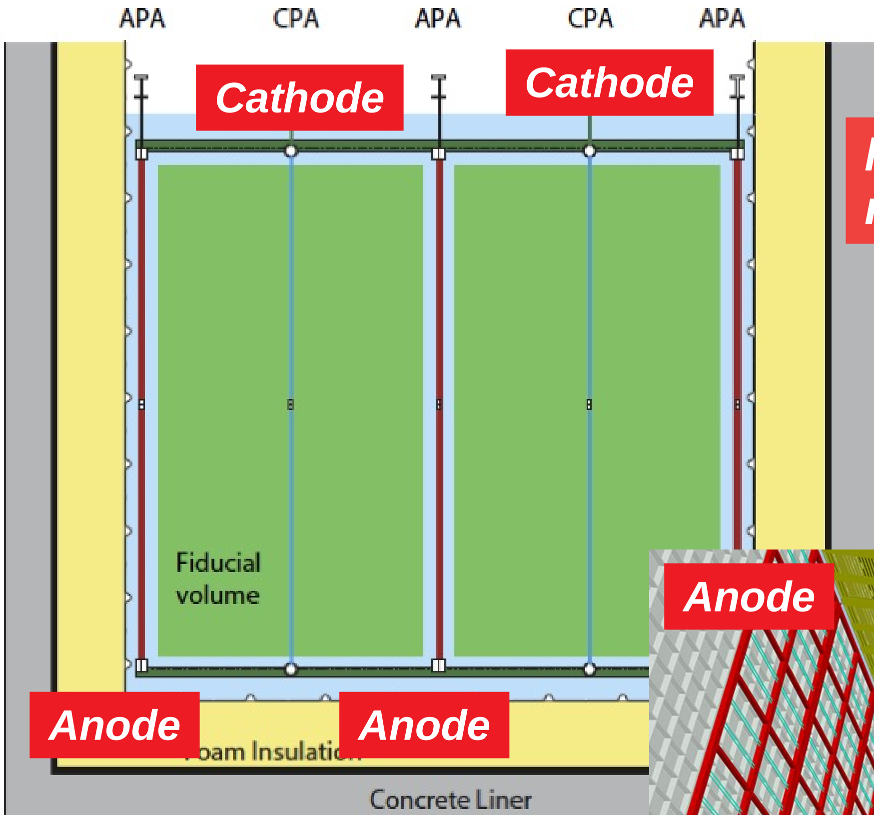
- **Risk reduction:**
  - ✓ Reduced adhesion issues → limited to the external shifter



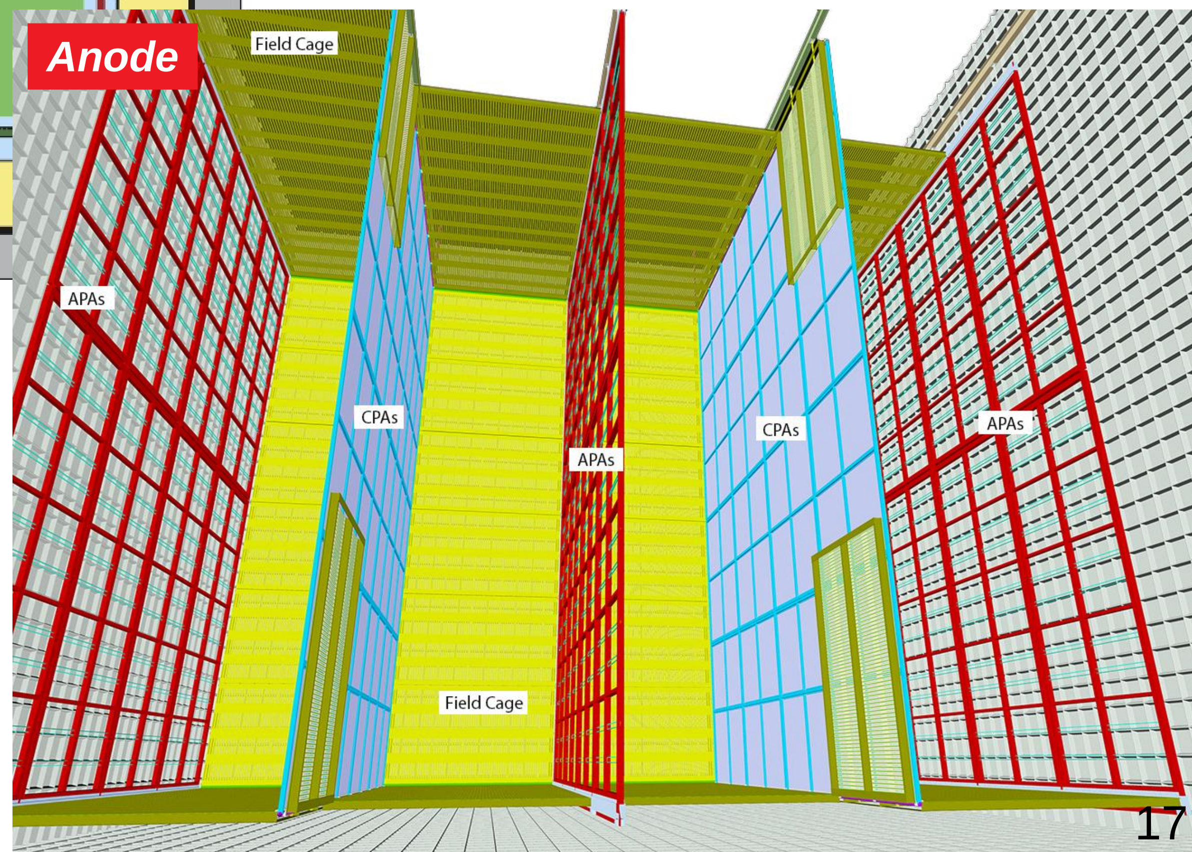
Collection efficiency vs coverage



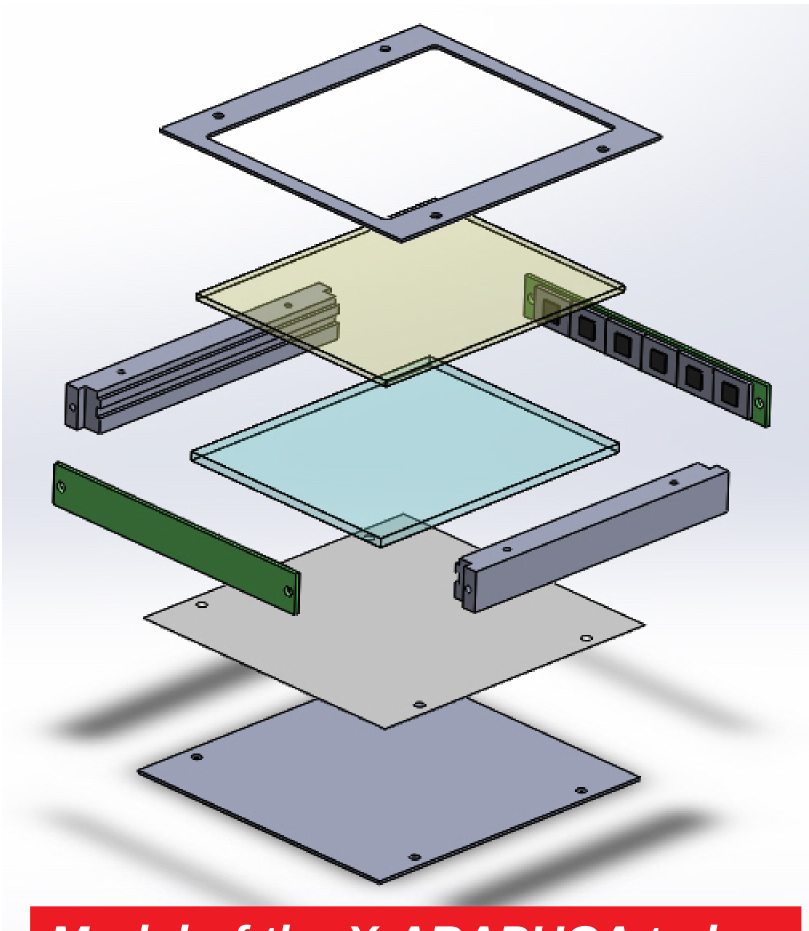
Ratio of efficiencies (XA/A) vs coverage



Modules installed on the central APAs need to be sensitive on two sides



X-ARAPUCA R&D program



Model of the X-ARAPUCA to be tested at UNICAMP

Two tests will happen on the short term (before the end of 2018):

- A small 10 cm x 8 cm X-ARAPUCA will be tested in LAr at **UNICAMP**
- **X-ARAPUCAs supecells** (basic unit of DUNE design) will be tested in the **ICEBERG** set-up at Fermilab *(joint test with Cold Electronics Consortium)*
- Main objectives of the tests are measuring *the X-ARAPUCA detection efficiency* (and comparing with MC expectations), *studying interferences with CE*, *test of the active ganging and read-out electronics*
- More details in D. Warner talk

X-ARPUCA design

- An **X-ARAPUCA module** for DUNE will have dimensions of approximately 210 cm x 12 cm, segmented into *four cells* **(supercells)**. Each supercell is an X-ARAPUCA and will host **48 SiPMs** read-out by one single electronic channel (D. Warner talk)

- We expect for these X-ARAPUCAs a detection efficiency *larger than 3%* (on the basis on analytical calculations, MC simulations and experimental tests). *Physics requirements should be (largely) met with such level of efficiency* (see A. Himmel).

- This result is outstanding, since large area (8") PMTs coated with wavelength shifter (TetraPhenyl Butadiene – TPB) are typically in the range of 5% - 7% in total detection efficiency. An X-ARAPUCA module is equivalent to **~3 large area PMTs**

- X-ARAPUCA design is expected to be >10 times more efficient than the most efficient light-guide bar installed in protoDUNE

Photosensors

- Current baseline is **Hamamatsu MPPC**

- **Two models** are being systematically investigated:
  - *S13360-6050VE*: 6x6mm MPPC with 50um pixel and *epoxy resin coating* in SMD package w/ TSV terminal

  - *S13360-6050CQ*: Uncoated 6x6mm MPPC with 50um pixel in ceramic package with *quartz window*

- Both sensors have been installed in protoDUNE: S13360-6050CQ on ARAPUCA modules and S13360-6050VE on a fraction of the guiding bars

- ***Both models resulted to be adequate to work at LAr temperature***. S13360-6050VE is our preferred option because of its *smaller packaging* which fits better into the X-ARAPUCA design where sensor are mounted on ***the lateral surface of the box***. They are cheaper.

- A sample of 400 units of S13360-6050VE was purchased a few months ago. It is undergoing an extensive series of tests at NIU and CSU (see next talk by V. Zutshi) in order to characterize their behavior at room and cryogenic temperature

Photo-sensors

- The SP PD Consortium is strongly investigating the possibility of using **FBK** *(Fondazione Bruno Kessler, Italy)* sensors
- FBK has successfully developed a sensor for ***LAr applications*** in collaboration with the *DarkSide experiment*
- Few arrays of FBK sensors have been tested inside the Consortium with positive results. *FBK manifested the interest in continuing the collaboration with the Consortium* on the development of a specific sensor for the DUNE experiment
- Recently several INFN (National Institute of Nuclear Physics - Italy) groups joined the Consortium and *proposed to follow this development*, also profiting of the strong relationship between INFN and FBK

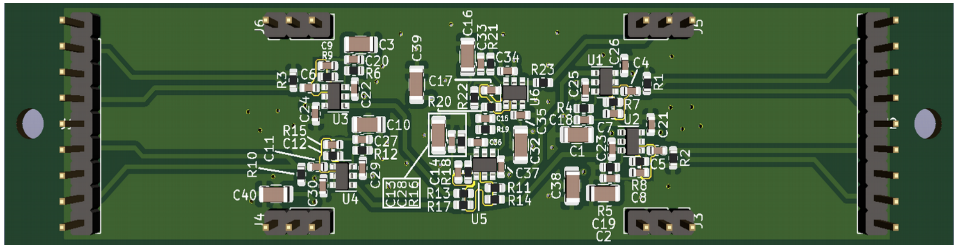
Electronics – Cold active ganging

Read out electronic is divided into ***two stages***: *Cold active ganging board* and *digitizing board*

- **Cold ganging (summing) board:**
  - SiPMs are small devices. They need to be ganged in order to contain the number of read-out channels. There is a limitation on the number of channels per ARAPUCA bar due to the space available to route the cables inside APA (see D. Warner talk). **There will be 4 readout channels per module** → *one channel per X-ARAPUCA supercell.*
  - **48 SiPMs will be ganged together**. The ganging is active, that is using active components (Operational Amplifier) → see G. Cancelo and J. Molina talks
  - The active ganging board is installed on the X-ARAPUCA module and *operates at LAr temperature* (D. Warner talk)

- *Two active ganging circuits developed by the Consortium*. With different degrees of maturity at this moment. Both **demonstrated LAr operation** and single photo-electron resolution

- G. Cancelo and J. Molina talks



Electronics – Digitizing board

Digitizing board:

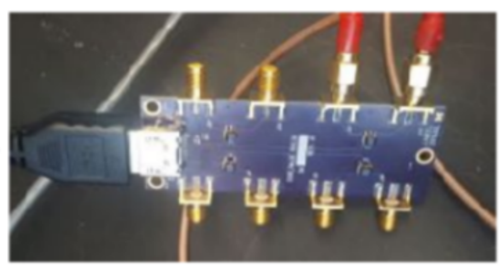
- It receives the signals from the ganged SiPM, performs digitization and communicates with the DAQ;

- Baseline design based on a commercial chip used for medical applications (board originally developed for the veto system of the ***Mu2e experiment***). *Cost/channel very favorable* (see J. Spitz talk);

- *Successfully tested in combination with G. Cancelo active ganging board*

- A second design is being developed in **Latin America** (Colmbia and Brazil). *Integration of the ganged signal followed by a (slow) digitization to detect the peak of the integrated signal.*

Gustavo's board



balun from Michigan

FEB

Options

- Consortium is investigating ***two options*** which can improve the performance of the PDS and *add features*, such as the *uniformity* in light collection, which are desirable for some of the ***Physics goals*** of the system (calorimetric measurements)

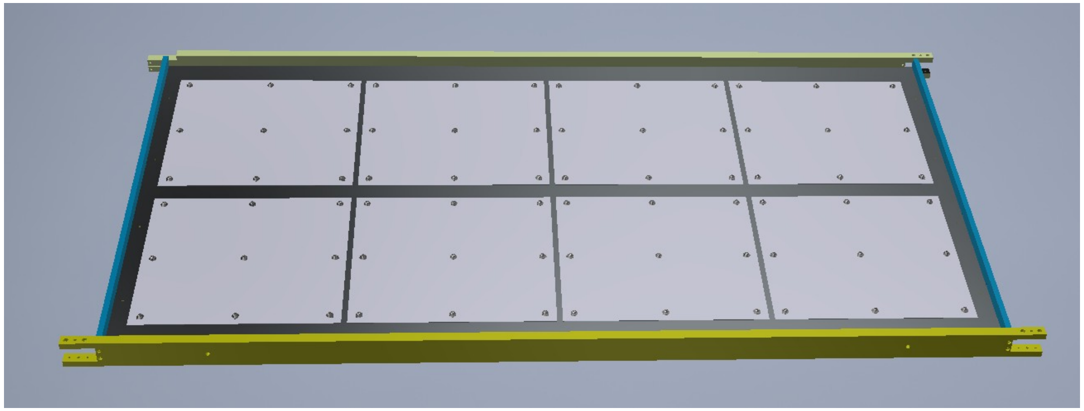
- Light collection suffers of huge non-uniformity for events near the anode (where the PD modules are located) with respect to those near the cathode, because of the **Rayleigh scattering length of LAr** scintillation light (λ = 128 nm ; $L_{Rayleigh}$ ~ 60 cm – 90 cm)

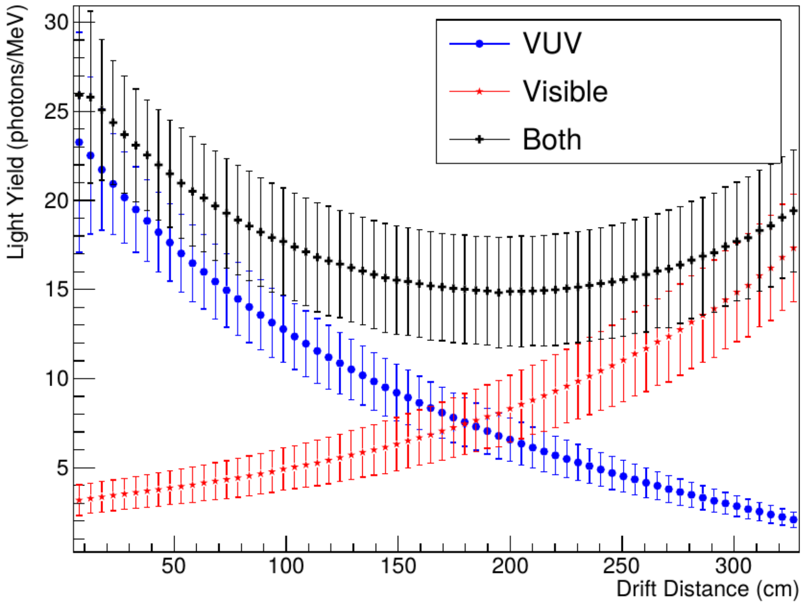
- *The two options are:*
  - *Installing reflective foils coated with wavelength shifter on the cathode*
  - *Doping LAr with Xenon*

- They add similar benefits but ***are not 100% overlapped***

Shifting/reflective foils

- Reflective foils coated with *WLS are installed on the cathode*
- Technique widely used in the past by **Dark Matter experiments** and in **LArIAT experiment**
- Approved for the **SBND experiment**





- Great improvements in the u**niformity of light collection**
- *Improvement in light yield*
- *Potentially enable x-position (drift direction) resolution with light*
- See A. Szelc talk

Xe Doping

- Concentrations of the order of tens of ppm of Xe in LAr allow to shift the **128 nm** scintillation of LAr to **174 nm**
  - ***Longer Rayleigh scattering length (6 times longer)***
  - ***Triplet component*** of LAr scintillation light ***gets much shorter***: hundred of ns instead of 1.5 μs
- *Uniformity significantly improves given the longer scattering length*
- **X-ARAPUCA design simplification**:
  - Potential to remove outer wavelength shifter from light collector modules (fused silica is transparent to 174 nm photons – Transmissivity ~ 80%)
  - *Increase Detection efficiency*
  - **Reduction of costs** for the production of PD modules
  - ***No risk of light exposure of the PD modules***. **X-ARAPUCA would not have any evaporated film, nor externally neither internally**
- See D.Whittington/C. Escobar talk

Issues raised at protoDUNE review 2-3 August 2016

1. Does the Photon Detector System design enable validation and refinement of the DUNE photon detector requirements ?

Optical system
Answer: Yes, but.

Comments:
The 0.1 pe/MeV requirement seems marginal for DUNE, and hence is a marginal design goalc for protoDUNE. Details of the SN burst trigger still need to be worked out. It seems likely that a TPC-based trigger, rather than a PDS trigger, will be developed.

A:Being investigated by DUNE Physics group and by PDS Physics and simulation WG. Requirements in the process of being formulated (see A. Himmel talk)

Recommendation:
Efforts should continue to improve both main light collection schemes and to develop the ARAPUCA scheme. Further R&D should continue in parallel with protoDUNE toward higher-light-yield schemes.
A:Done

Electronics
Answer: Maybe.

Comments:
Small scale tests demonstrate that the SSP digitizer system has low enough intrinsic noise to distinguish single PE signals from three SensL MicroFC-60035-SMT SiPMs ganged together. However, even with the TPC electronics turned off, the noise observed in the 35-ton test was at least 2 times higher than this level. One third of the SiPM channels had anomalous noise significantly higher than this. When the TPC was on and reading out, the noise in the SiPM waveforms was approximately 25 times the level present in small scale tests. ProtoDUNE-SP will operate approximately 3 times more SiPM readout channels than the 35-ton test. There is a significant risk that excessive noise will severely compromise the test of photon detectors in protoDUNE-SP. There is a serious risk that excessive noise in the SiPM readout will prevent the protoDUNE-SP test from providing a validation of the DUNE photon detector requirements or information that would lead to refinements to those requirements.

A:No excessive noise in protoDUNE. In any case the interference issue of PD with other subsystems (which will not be exactly the same of protoDUNE) will be invetigated in dedicated test at Fermilab (ICEBERG set-up) and in the protoDUNE SP Cold Box.

2. Are Photon Detector System risks captured and is there a plan for managing and mitigating these risks?

Optical system
Answer: Not completely.

Two risks are identified: FD-073 – Photon light yield too low; FD-098 – ProtoDUNE-SP Degraded Photon Detectors.
Estimates that predict meeting the 0.1 pe/MeV requirement are based on an estimate that 0.5% of the primary UV ends up wave-shifted and captured in the lightguide bars (Himmel, Slide 14). Actual measurements of this quantity with recent prototypes give ~0.1% (Whittington, Slides 14, 16), with recently-achieved improvements of about factor of 2 (Mufson, Slide 13).

MicroBooNE saw huge rates of single pe's.

Comments:
The Committee thanks the presenters for walking us through the capture efficiency issue.
While the light-yield risk is identified, neither current default scheme appears likely to meet the requirement.
The QA/QC plan presented to us should successfully mitigate the risk of degraded PD modules.
MicroBooNE is a different experiment, but efforts to understand the high photon rate and understand its origin are needed to know if the protoDUNE-SP's PDS will be crippled by the same effect.
A:X-ARAPUCA designs ensures a much higher efficiency which meets the current requirements (higher thatn those considered for the protoDUNE review)
MicroBooNE effect will be investigated in protoDUNE

Mechanical
Answer: Not completely.

Does not apply. Related to CERN operation.

Electronics
Answer: No.
Findings:
See Item 1.
Comments:
See Item 1. Chasing down noise issues can be very time-consuming. Even fixable noise problems could derail the already-tight schedule with respect to beam before the CERN Long Shutdown.
Recommendation:
Add to the risk registry the risk that the protoDUNE-SP photodetector system will not provide information of sufficient quality to inform the DUNE design because excess noise degrades the quality of waveform digitization. Pursue mitigation of this risk with an

Recommendation:
Add to the risk registry the risk that the protoDUNE-SP photodetector system will not provide information of sufficient quality to inform the DUNE design because excess noise degrades the quality of waveform digitization. Pursue mitigation of this risk with an aggressive attempt to understand the sources of noise in the 35-ton test (as is being done for the APA readout).
Add to the risk registry schedule risk from having to hunt down and fix noise. Mitigation strategies include prototype testing (described under Item 9) and early operation of electronics on assembled APAs, which could be interleaved with installation tasks.

A:Agreed, see previous answer.

3. Does the design lead to a reasonable production schedule, including QA, transport, installation and commissioning?

A:Does not apply.

4. Does the documentation of the Photon Detector System technical design provide sufficiently comprehensive analysis and justification for the Photon Detector System design adopted?

Answer: Not addressed by committee.
Comment:
The committee was not presented with discussion of alternate designs, except for the three to be implemented in protoDUNE-SP. At this point, it didn't seem useful to dig into this, as the designs presented to us will be implemented. However, as we have reservations about the light yield (both the requirement and that achieved so far) and have recommended (see Charge items 1 and 2) that variants be explored in parallel with protoDUNE, we present a recommendation anyway.
Recommendation:
Though we were shown (Himmel, slides 15-16) projected efficiencies vs. distance from anode plane for various thresholds (in pe), the impact of these efficiencies on the physics that can be extracted, especially from SN bursts, has not been studied in detail. A study should be performed documenting the impact of PDS light yield on SN physics, specifically at values of 0.1, 0.05, 0.02 pe/MeV at the CPA.A

A:Very important comment from the committee. SN requirement development is being studied in very details by the Physics Group. Translation of the physics requirements into detector requirements is one of the main commitments of the Consortium. X-ARAPUCA design seem to give enough guarantees that requirements can be met (even if not yet completely defined yet) given also the possibility of tuning the Detection Efficiency by increasing/ decreasing the number of SiPM

5. Is the Photon Detector system scope well defined and complete?
Answer: Yes, in all areas.

6. Are the Photon Detector System 3D model(s), top level assembly drawings, detail/part drawings and material and process specifications sufficiently complete to
demonstrate that the design can be constructed and installed?
Answer: Yes.

7. Are operation conditions listed, understood and comprehensive?

Comment:
The Committee never understood this part of the charge.

Is there an adequate calibration plan?
Answer: Partly.

Finding:
A UV-LED/optical fiber/diffuser system will have diffusers mounted on the CPAs.

Comment:
The design of the UV-LED system is nearing completion and was presented in detail to us. The LED system is more a monitoring system (devices working and stable) than a calibration system.
Recommendation:
A calibration plan, including, for example, channel-to-channel timing offsets, t0 timing for the TPC, light yield and resolution vs. 3D position, should be developed.

A:Agreed, Consortium is working on a detailed calibration plan for the PDS system. We will have led flasher also in DUNE. Calibration using ^{39}Ar will be tested in ICEBERG.

8. Are the Photon Detector System engineering analyses sufficiently comprehensive for safe handling, installation and operation at the CERN Neutrino Platform?

A:Does not apply.

9. Have applicable lessons-learned from previous LArTPC devices been documented and implemented into the QA plan?

Recommendation:
As part of the effort to avoid excess noise in the SiPM readout, we recommend tests of the readout of (even a partial) APA assembly including both TPC electronics and photon detectors. Either or both of the FNAL and BNL test systems could be modified to includeSiPM readout.

A:These tests will be done with the ICEBER set-up and possibly at CERN in the protoDUNE SP Cold Box.

Summary

- SP PD Consortium accounts from **40 Institutions** equally distributed in *Latin America*, *North America* and *Europe*
- Baseline design based on the **X-ARAPUCA concept**
- Two **well motivated SiPM candidates** are under evaluation and extensive tests are being carried *inside the Consortium*
- Two different flavors of ***active ganging electronics*** have been successfully developed
- *Low cost read-out electronics in a well advanced stage*
- **Two options** to improve the performances of the PDS are *under study*