ARAPUCA ARRAYS IN PROTODUNE

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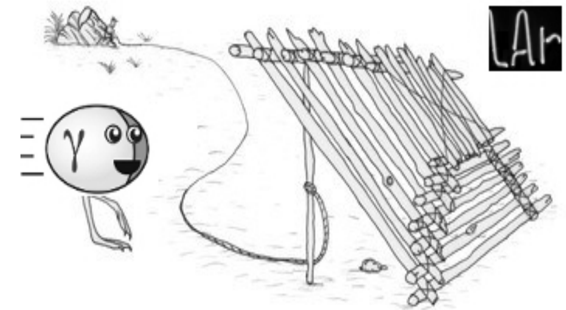
ARAPUCA a brief review



- **ARAPUCA** in the language of *native Brazilian* means ***trap*** for birds

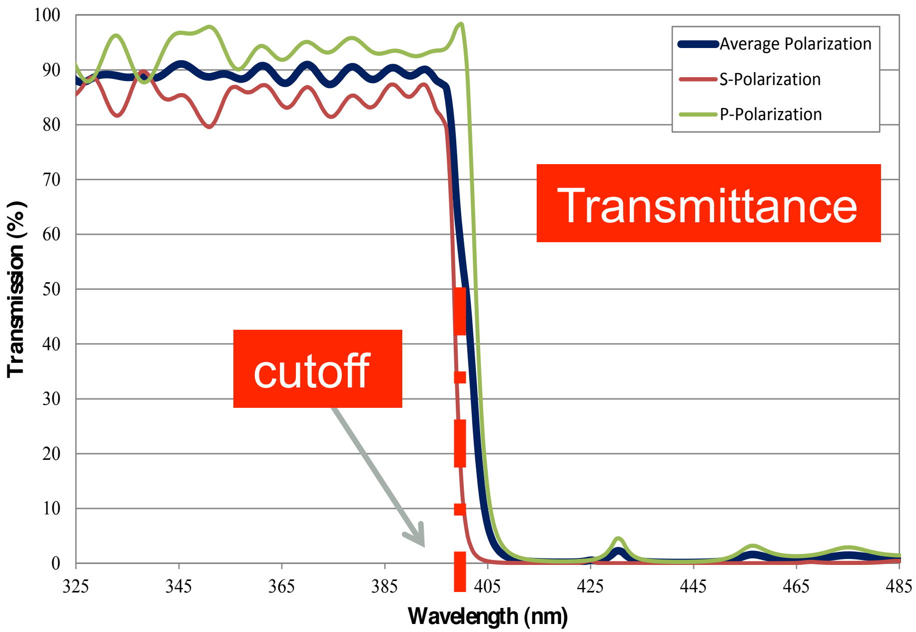
- The idea at the basis of the ARAPUCA is to **trap photons** inside a **box with highly reflective internal surfaces**, so that the detection efficiency of trapped photons is high even with a limited active coverage of its internal surface

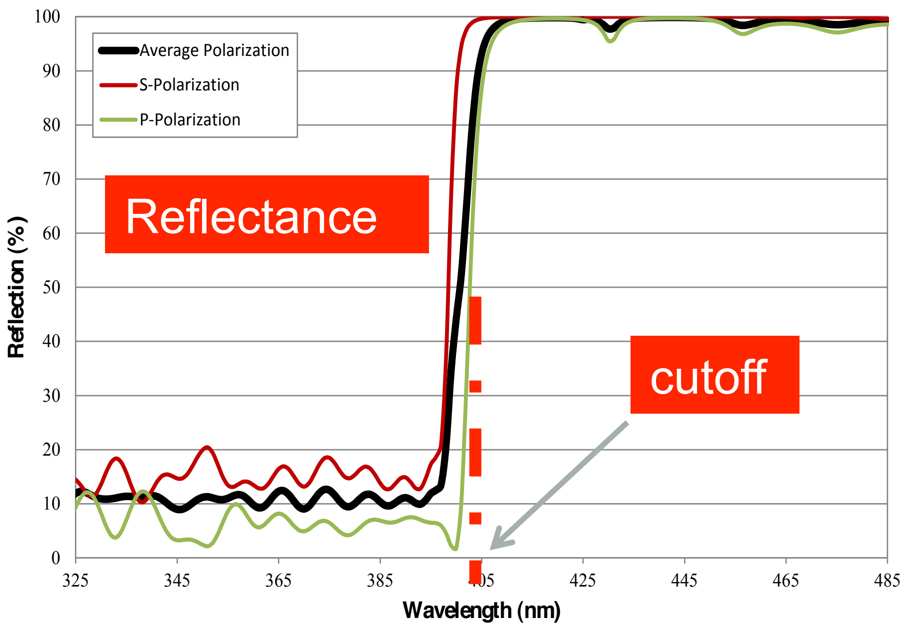
- **New concept for light detection in liquid argon** (LAr)

- **High efficiency light collector** + **silicon devices (SiPM)** → good detection efficiency on **large**

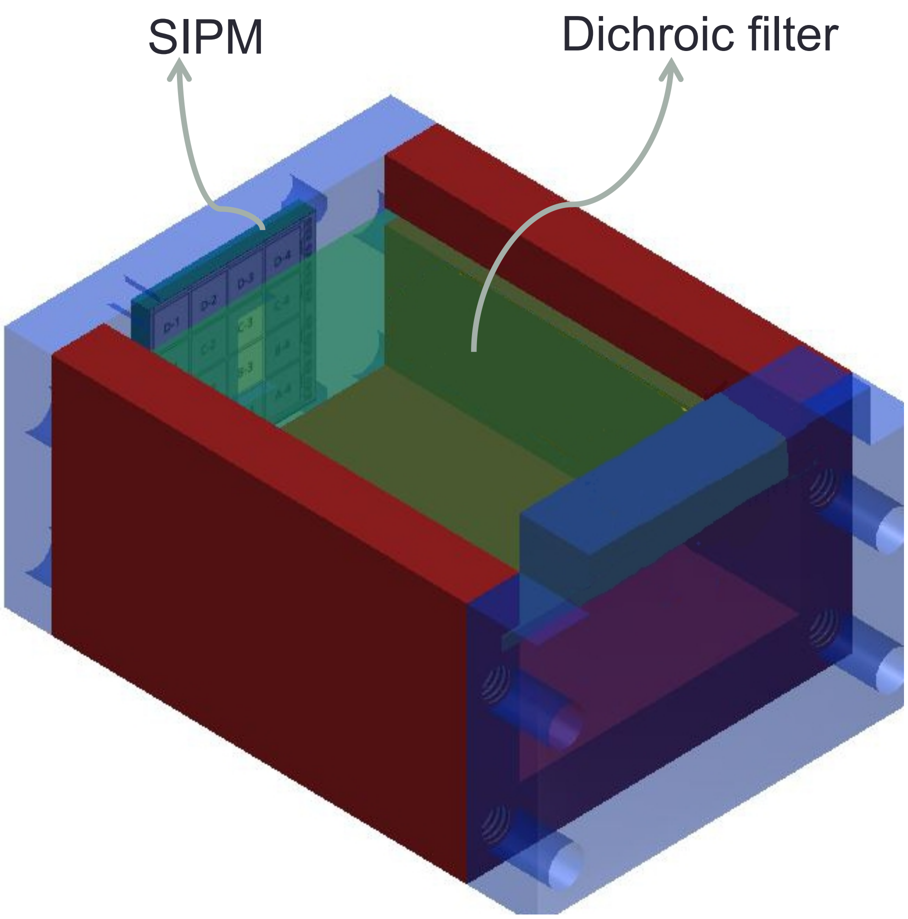
The dichroic filter I

- The core of the device is a **dichroic filter**. It is a **multilayer acrylic film** - same technology used to produce reflective plastic foils like 3M VIKUITI or VM2000.
- It has the property of being **highly transparent** for wavelength **below a cutoff** and **highly reflective above it**.





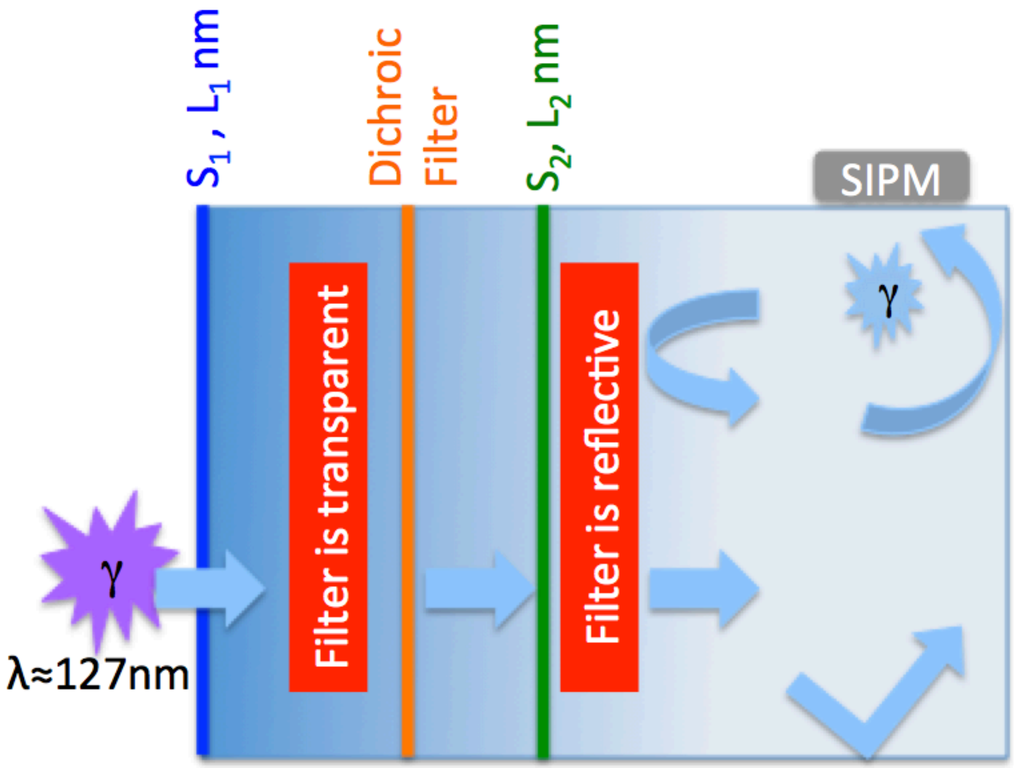
Operating principle I



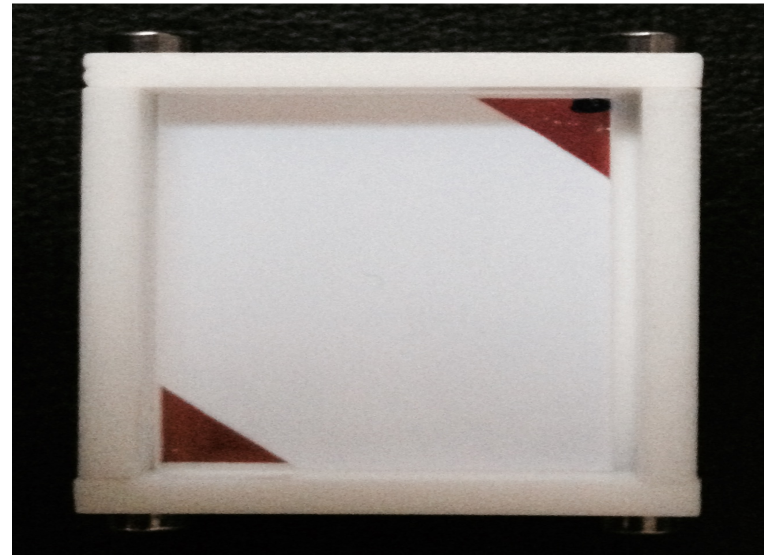
- The simplest geometry is a **flattened box** with highly reflective internal surfaces (Teflon, VIKUITI, VM2000) with an open side.
- The open side hosts the **dichroic filter** that is the acceptance window of the device
- The filter is deposited with **TWO SHIFTERS** – **one on each side**
- The shifter on the **external side**, S1, converts LAr scintillation light 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 II

- 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



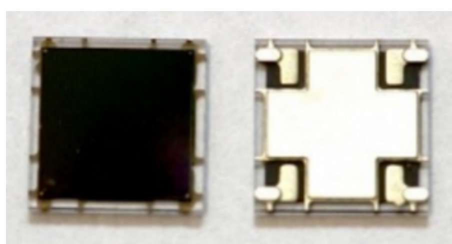
How to compare their photon detection capabilities ?



ARAPUCA

Light guide bar

SIPM



… calculating the equivalent surface

$$\mathcal{S}_{eq} = \varepsilon \times S_w$$

Quantum efficiency

Surface area of acceptance Window

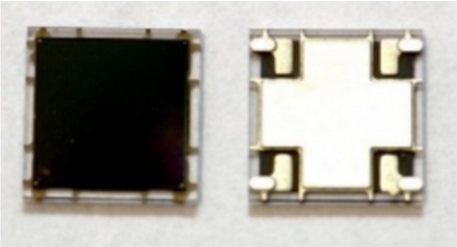
Case of Guidinging Bars – TPB coated

$\mathcal{S}_{eq} = \varepsilon \times S_w =$ **1.7 cm²**

Bar surface = 1700 cm^2,
Efficiency = 0.1 %.

Case of SIPM – TPB coated

SIPM



$\mathcal{S}_{eq} = \varepsilon \times S_w =$ **5.4 x 10^{-2} cm^2**

SIPM of 0.6 cm X 0.6 cm – SensL C60035
Efficiency = 0.3 (PDE) X 0.5 (TPB) = 0.15

An array of ~ 30 SiPM => S_{eq} = 1.7 cm^2

Case of 3" PMT - TPB coated

$\mathcal{S}_{eq} = \varepsilon \times S_w =$ **6.8 cm^2**

PMT area of 45.6 cm^2 (3"),
Efficiency = 0.3 (PDE) X 0.5 (TPB) = 0.15

Equivalent to ~ 4 times one bar

Case of ARAPUCA

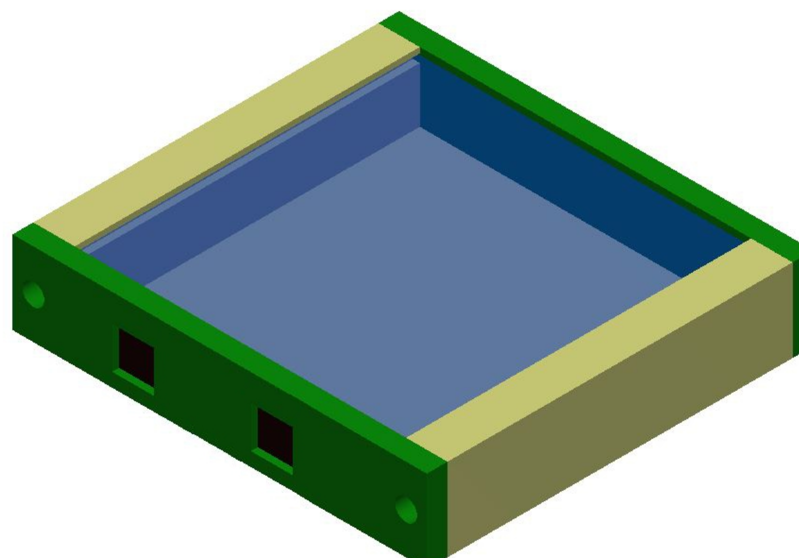
- Substantial saving of active devices
- **Amplification of the SiPM** equivalent surface of a factor 10 can be realistically obtained (main constrain: reflectivity of internal surface => 95%)
- An equivalent surface of **1.7 cm^2** can be reached with an array of 3/4 SiPM (coupled to an ARAPUCA) ***instead of 30***. The ARAPUCA surface would be of the order of 40/45 cm^2 (a 6.5 cm x 6.5 cm square).

Test in LAr @ FERMILAB (I)

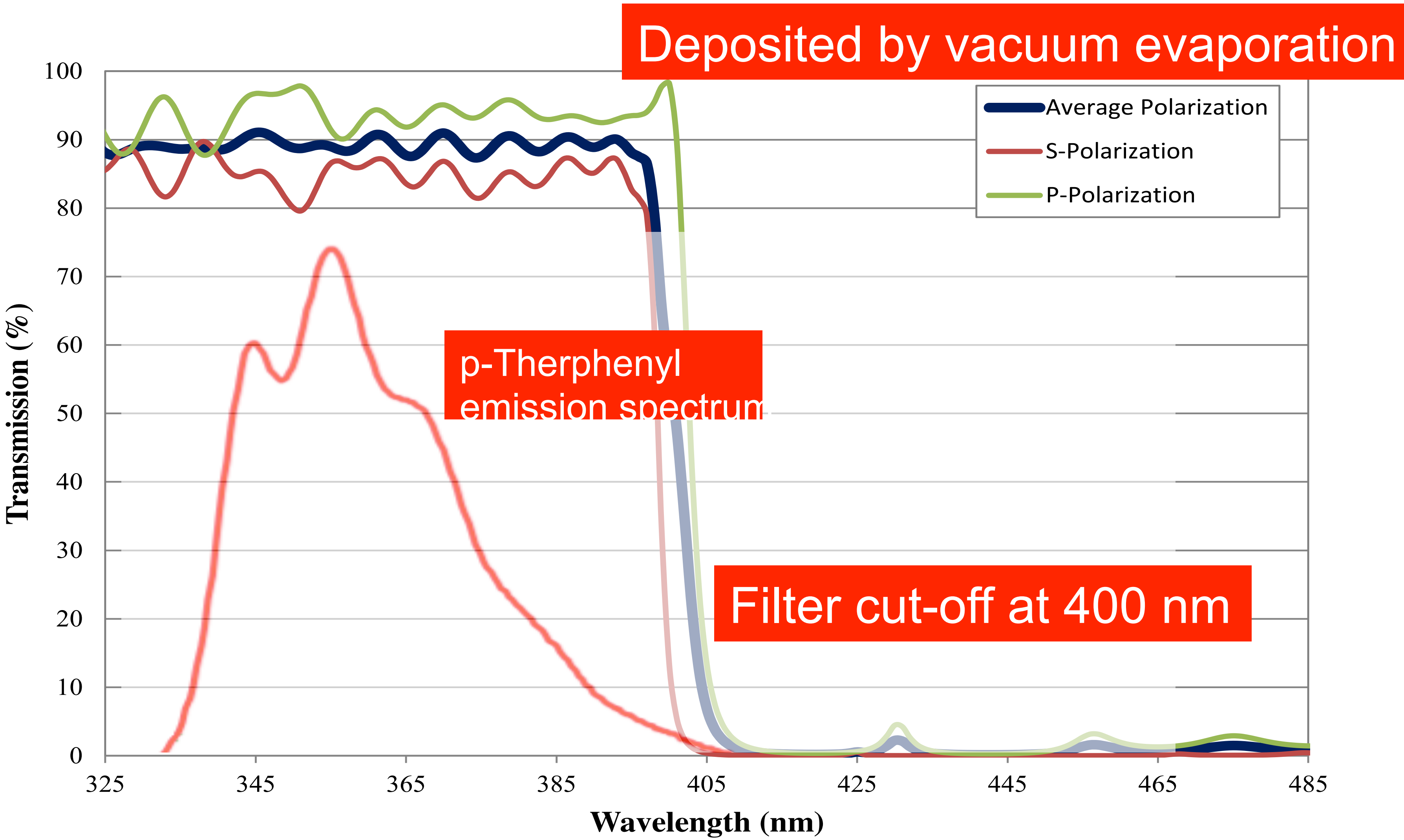
- Arapuca with **5x5 cm^2** acceptance window;
- **Box** with dimensions **5x5x0.6 cm^3**
- Read-out by **2 SiPM** 0.6cm X 0.6cm active area each

SensL MicroFC-60035-SMT (courtesy of **Cormac Campbell** - SensL Technologies Ltd.)

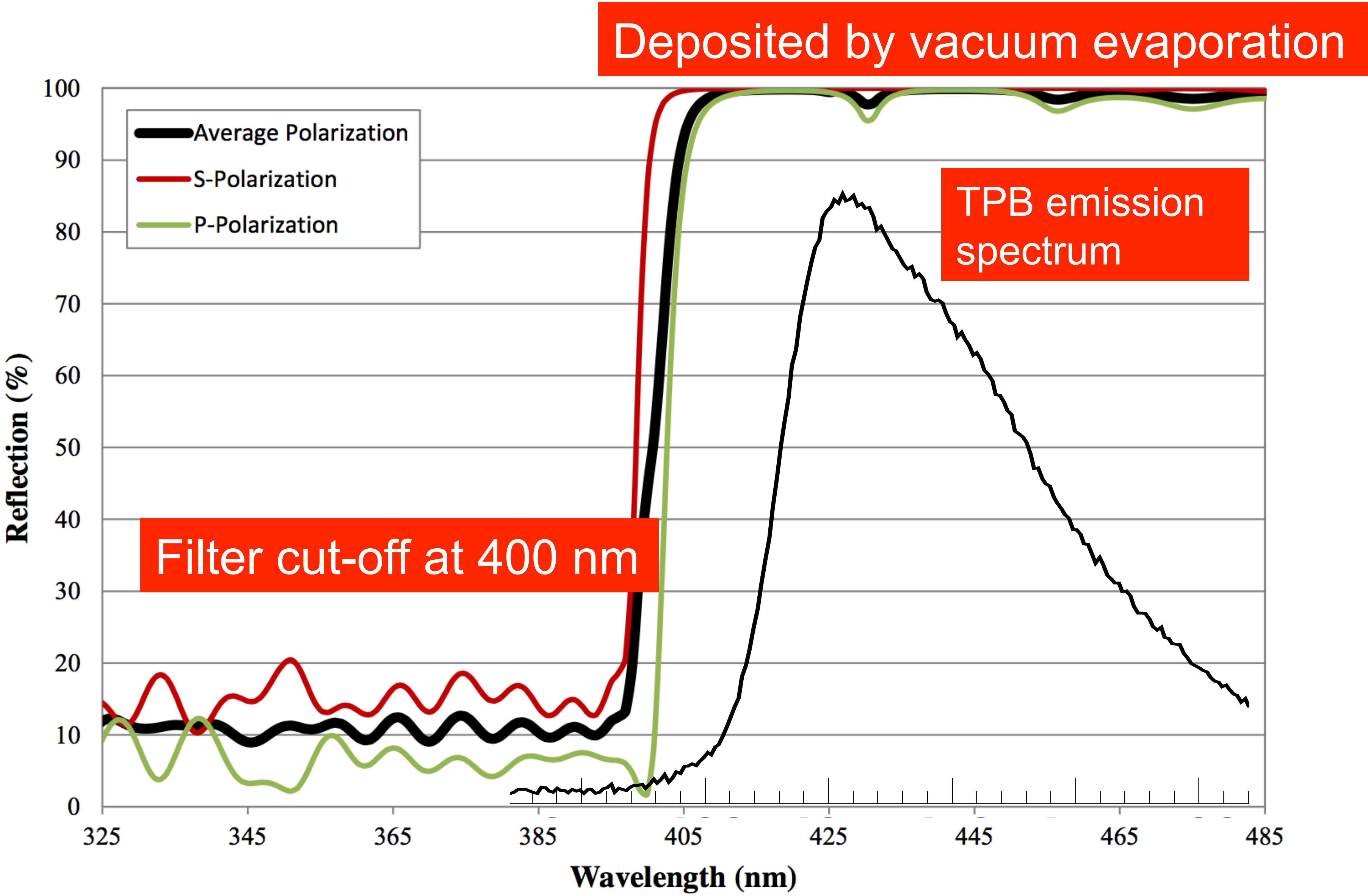
- **Dichroic filter** (Quantum Design- cutoff @ 400 nm – substrate fused silica)



P-Terphenyl on the external side

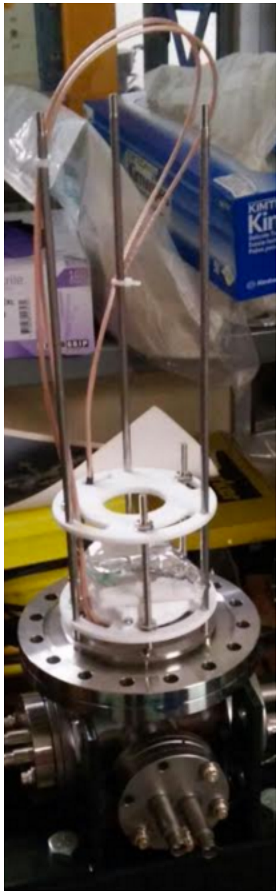


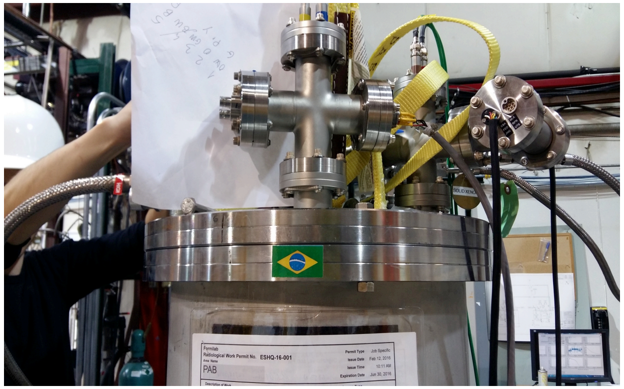
TPB on the internal side

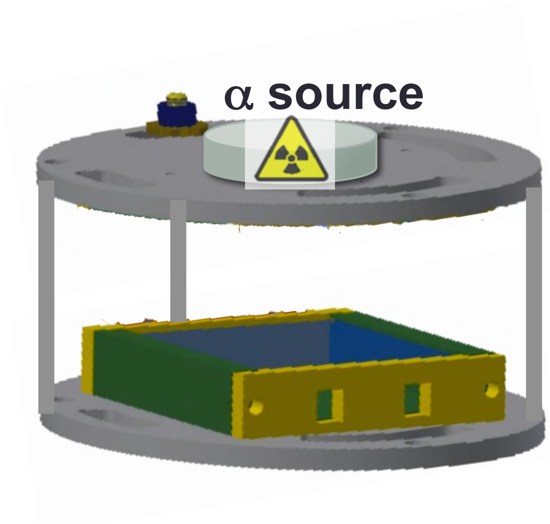


Test in LAr @ FERMILAB (II)

- The device has been installed inside a **liquid argon cryostat** and exposed to an alpha source.
- Alpha source is ^{241}**Am** that produces 5.4 MeV monochromatic particles
- Two different runs have been performed and two different read-out electronics have been tested



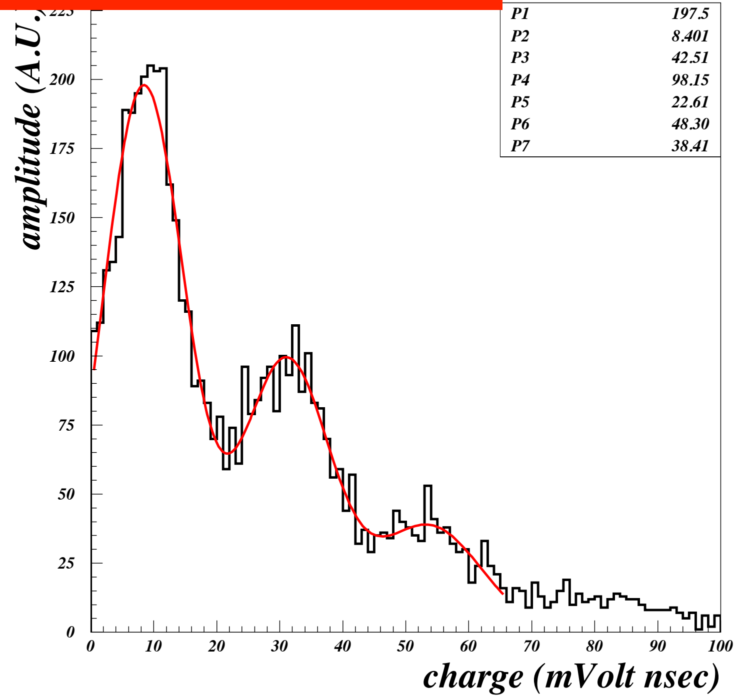




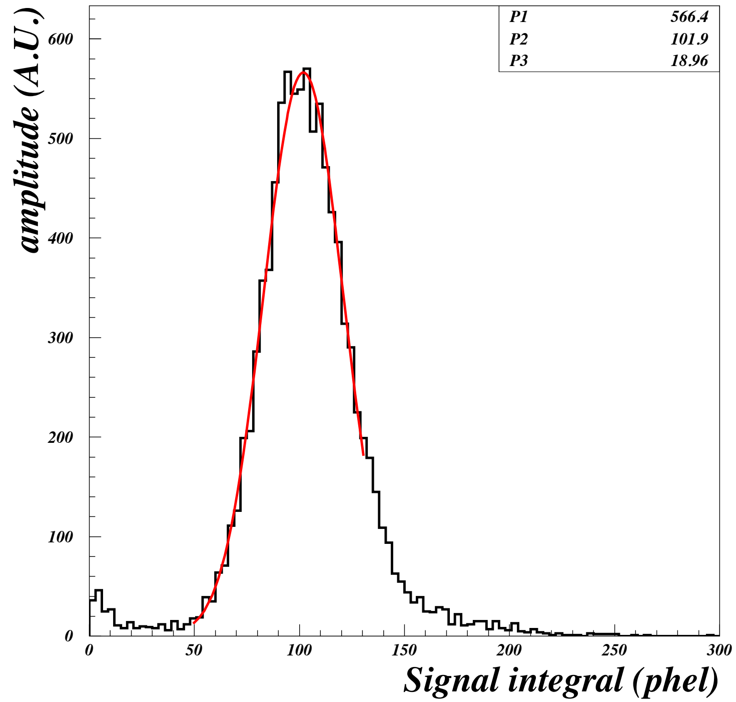
Test in LAr @ FERMILAB (III)

- Encouraging results: we measured an efficiency of ~1% (S_{eq} ~ 0.25 cm^2) in this first test
- It can be significantly improved considering that:
  - ✓ Low quality of the evaporations
  - ✓ Thicknesses of the films non-optimized
  - ✓ Internal reflectivity probably not at its maximum (cleanliness, quality of the material, thickness of the box walls)

Single electron spectrum



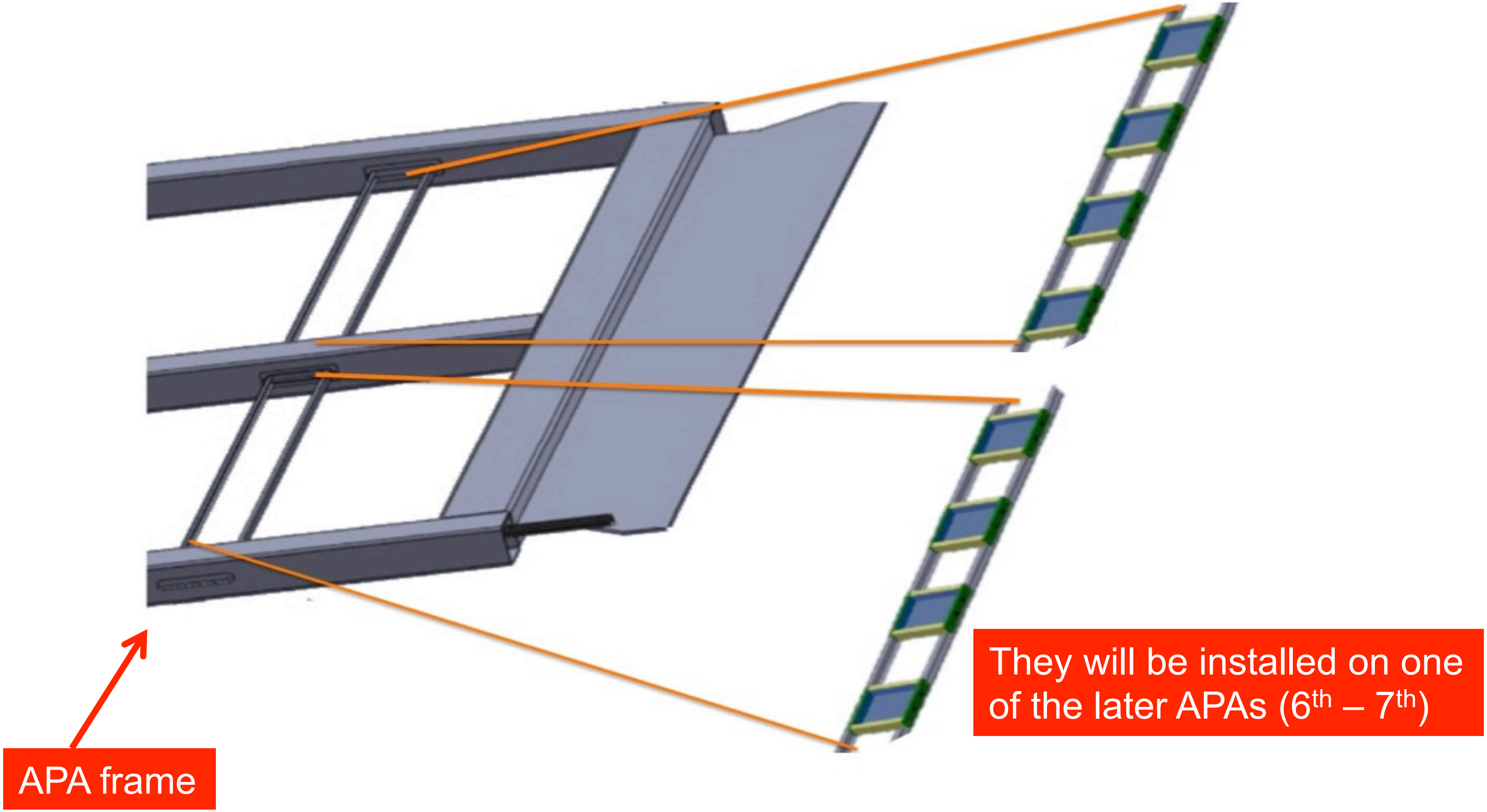
Source spectrum



- OUR PROPOSAL for protoDUNE -

- **Installing two arrays of ARAPUCAs** in place of two scintillating bars.
- **Each array** will be composed by **8 ARAPUCAs**
- Each ARAPUCA : equivalent surface of about **1cm²** (or more)
- The arrays will **be produced in BRAZIL** (project founded by FAPESP)
- Other devices could be produced at Fermilab
- No impact on the protoDUNE mechanical project
- **Read-out of the SiPM** : same board foreseen for the protoDUNE reference design and with the same number of channels
- **Arrays will be plug and play systems**, whose installation will be totally transparent to all the other sub-systems of the detector.

ARRAY - 8 ARAPUCAs

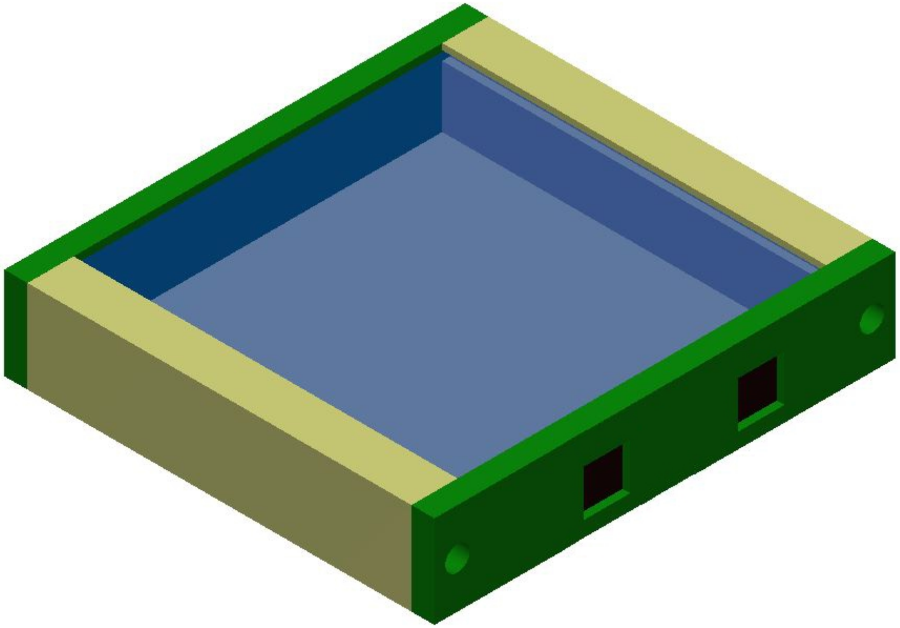


ARAPUCA basic cell

- **Design driven by the mechanical constraints of the reference solution**

- **5x5 cm^2 acceptance window**;
- **Box** with internal dimensions **5x5x0.6 cm^2**
- Read out by **2 SiPM (0.6cm x0.6cm – SensL C60035)**

- The target is reaching an equivalent surface of at least 1.0 cm^2 for each cell.



New LAr laboratory at UNICAMP

- A new laboratory for **R&D** studies on the detection of liquid argon scintillation light is being realized at **UNICAMP**, founded by FAPESP - São Paulo agency

- It will be **equipped with a brand new evaporator for organic materials, cryogenic facilities to test prototypes in a LAr environment, equipments to perform optical measurements** (pulsed and continuous laser/led, integrating sphere, vacuum monochromator with deuterium lamp,...)

- The laboratory will be **operative starting by the end of this year**.

- **The majority of the ARAPUCAs will be realized and tested in this lab** (production could start even before the completion of the Lab => evporator will be installed in two/three months)

- A fraction of the devices could be produced at Fermilab

Program of activities - Production

- **Start at the end of this year** and will be completed in three weeks:
  - ✓ Mechanical design including scheme for routing the cables
  - ✓ Evaporation of the filters (2 days)
  - ✓ Construction of the boxes (two weeks)
  - ✓ Assembly (one week)

- **Efficiency** of the evaporated filters will be individually measured inside the **vacuum monochromator.**

- **SiPM** will be tested at room & cryogenic temperature

- The integration of the arrays will be worked out with D. Warner for the mechanics and with T. Tope for the cabling and shielding

- E. Segreto and A.A. Machado will spend 6 month at CERN for the installation of the photon detection system

Conclusions

- A novel concept for liquid argon scintillation light detection has been developed
- The performances of the first prototypes are promising
- We propose the installation of two arrays of ARAPUCAs inside protoDUNE, in place of two guiding bars
- Their installation will be transparent to all the other sub-systems of the detector and without any additional costs for the collaboration

Back-up

Case of ARAPUCA – Gain

- The Gain is the ratio between the $S_{\text{ARAPUCA}}^{\text{eq}}$ and the $S_{\text{SiPM}}^{\text{eq}}$ of the SiPM that read out the ARAPUCA itself.

- It represents the effective amplification factor of the SiPM array surface.

$$G = \frac{S_{ARAPUCA} \times \varepsilon_{ARAPUCA}}{S_{SiPM} \times \varepsilon_{SiPM}}$$

Gain of an ARAPUCA

The Gain can be **analytically estimated** and results to be:
[E Segreto 2012 JINST 7 P05008]

$$G = \frac{1}{2}\left[\frac{1}{1 - R(1 - f/2)}\right]$$

Where ***f*** is the ratio between the surface of the SiPM and of the acceptance window of the ARAPUCA and **R** is the average reflectivity of the internal surface of the box.

For small values of *f* the maximum Gain is reached:

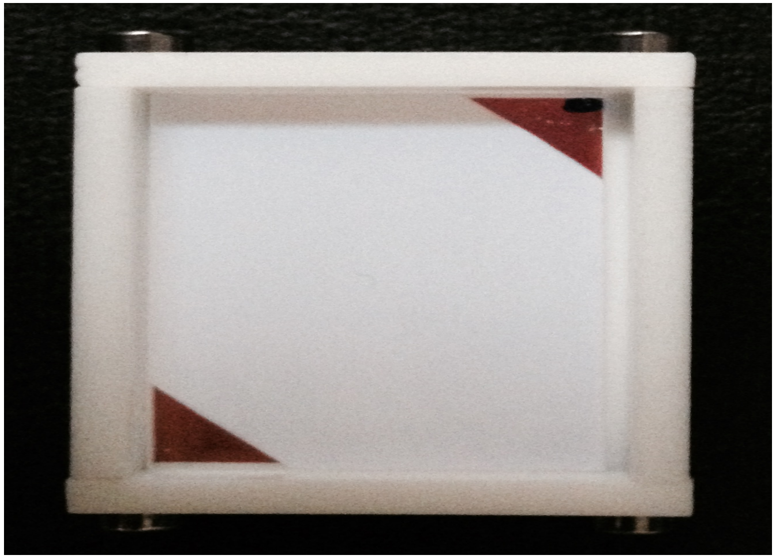
$$G_{\max} = \frac{1}{2(1 - R)}$$

Gain of an ARAPUCA (II)

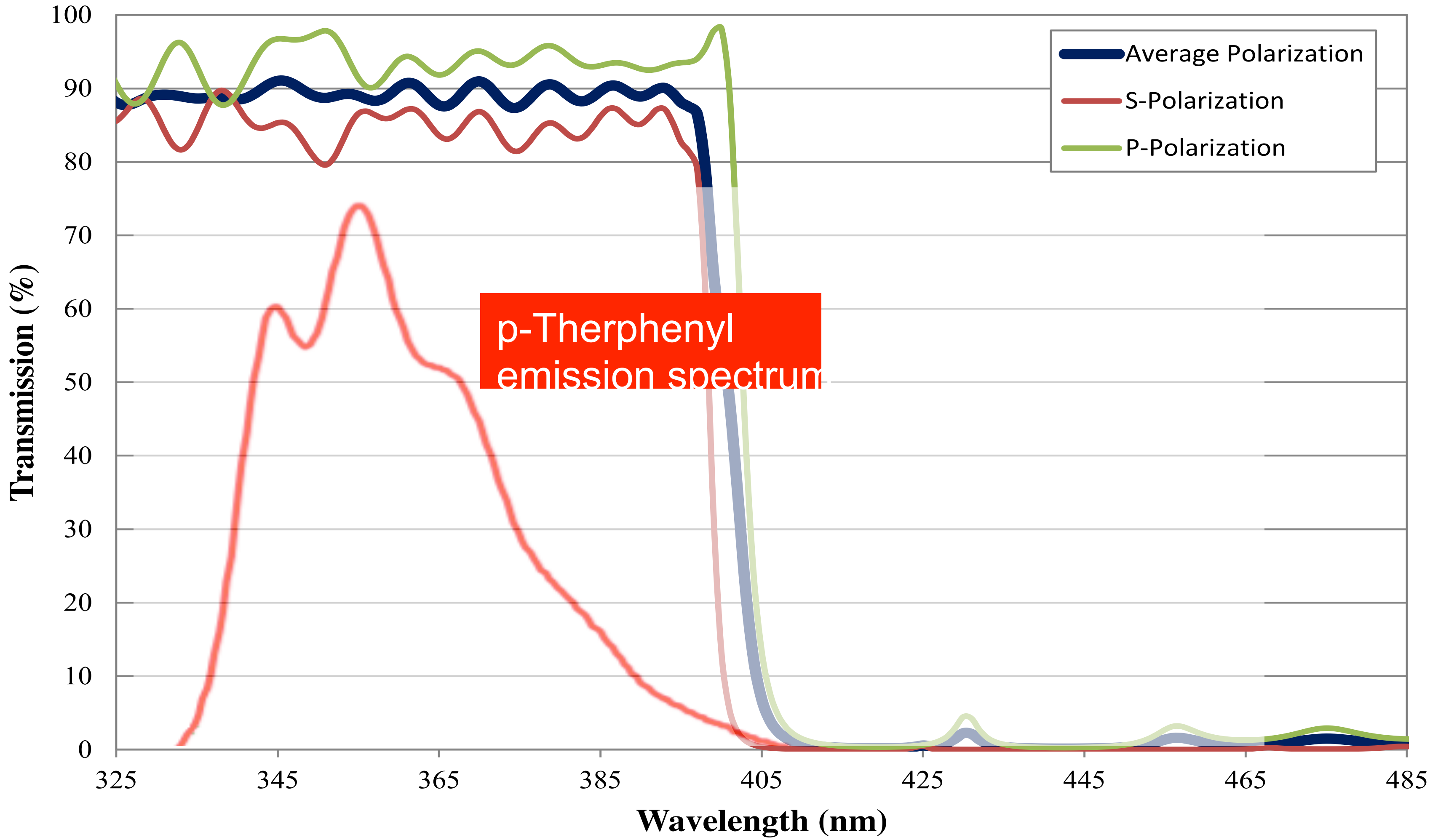
- To obtain a gain **G = 10** one needs to have **R = 0.95**
- This value of R can be reasonably reached (and very likely improved).
    - ➢ Reflectivity of the filter is high (~0.98)
    - ➢ Reflectivity of the internal surfaces of the box can be made arbitrarily high (teflon, VIKUITI, ...)
- If **G = 10** an equivalent surface of 1.7 cm^2 is reached with an array of 3/4 SiPM (coupled to an ARAPUCA) instead of 30. The ARAPUCA surface would be of the order of 40/45 cm^2 (a 6.5 cm x 6.5 cm square).

Test of trap effect of ARAPUCA

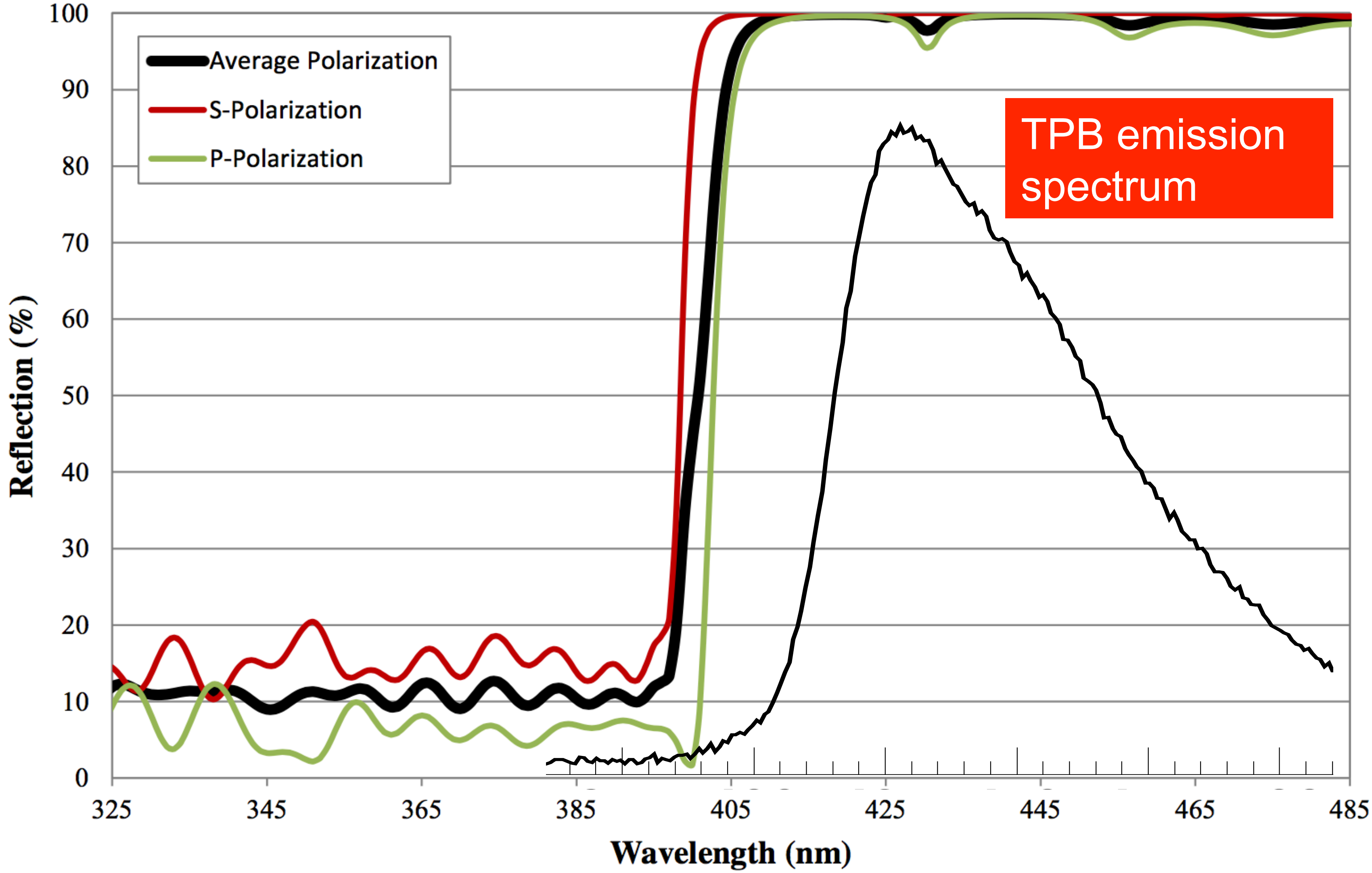
- Was used a **small prototype** with a window of **3.5 cm x 2.3 cm**
- The box is made of **teflon** and has an internal height of **1 cm**
- The cutoff of dichroic = **400 nm**
- We used as shifters **P-Terphenyl** (**λ ~ 350 nm**) for the external side and **TPB** (λ ~ **430 nm**) for the internal one.



Effect of the first shifter



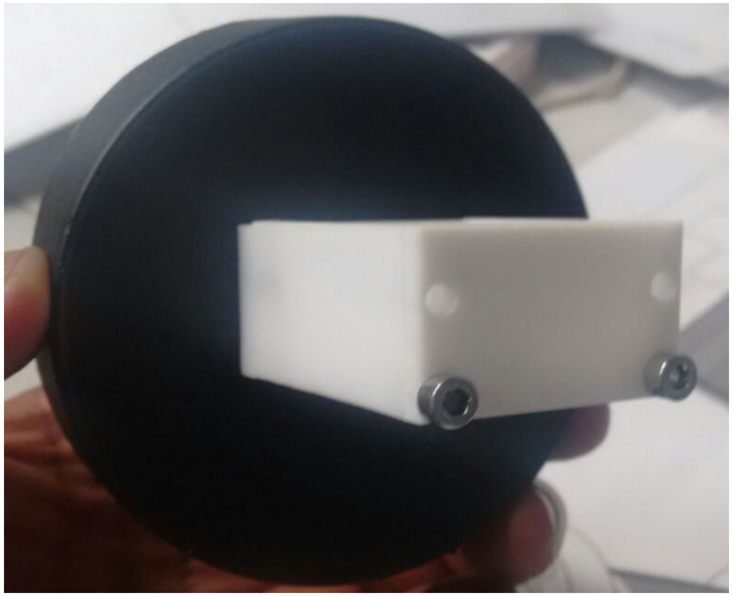
Effect of the second shifter



Verifying the trapping process

Experimental tests performed at room temperature in a black box @ **UNICAMP**

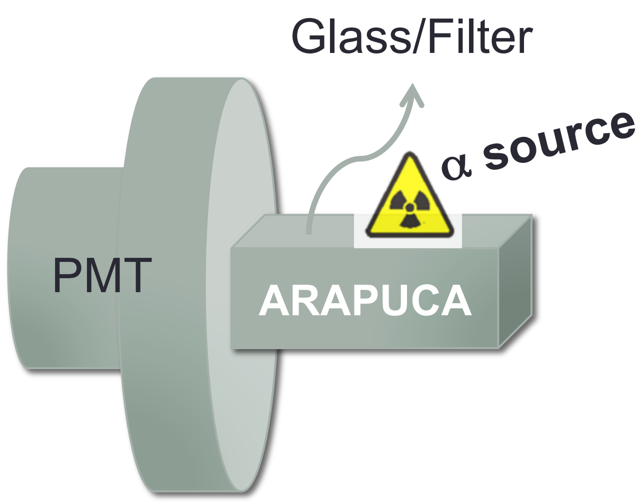
- Using an alpha source to excite scintillation of the external shifter
- Coupled the ARAPUCA to a PMT
- The dimensions of the slit ~ fit one side of the PTFE box (~1.8 x 0.9 cm^2)

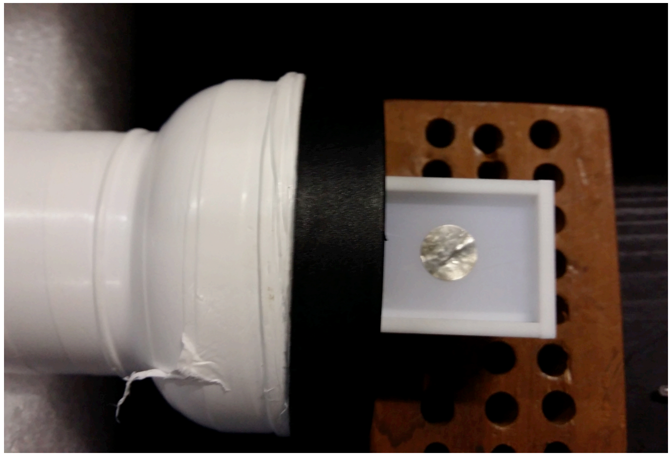


ARAPUCA with two different windows

1. Glass coated with TPB => NO TRAPPING EFFECT

2. Filter coated with pTP and TPB => TRAPPING EFFECT

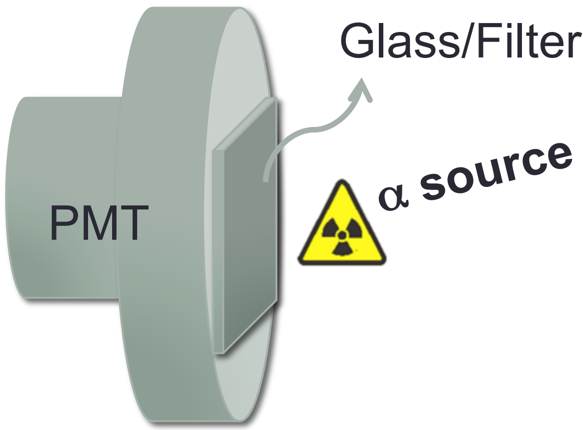


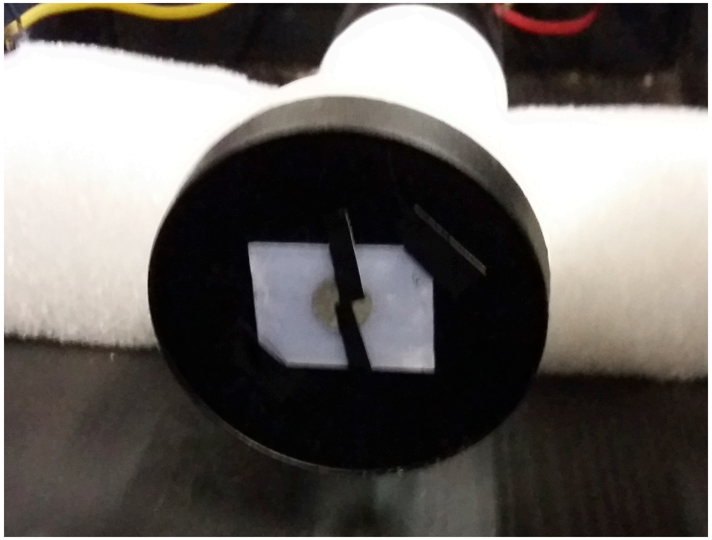


Normalize the input light

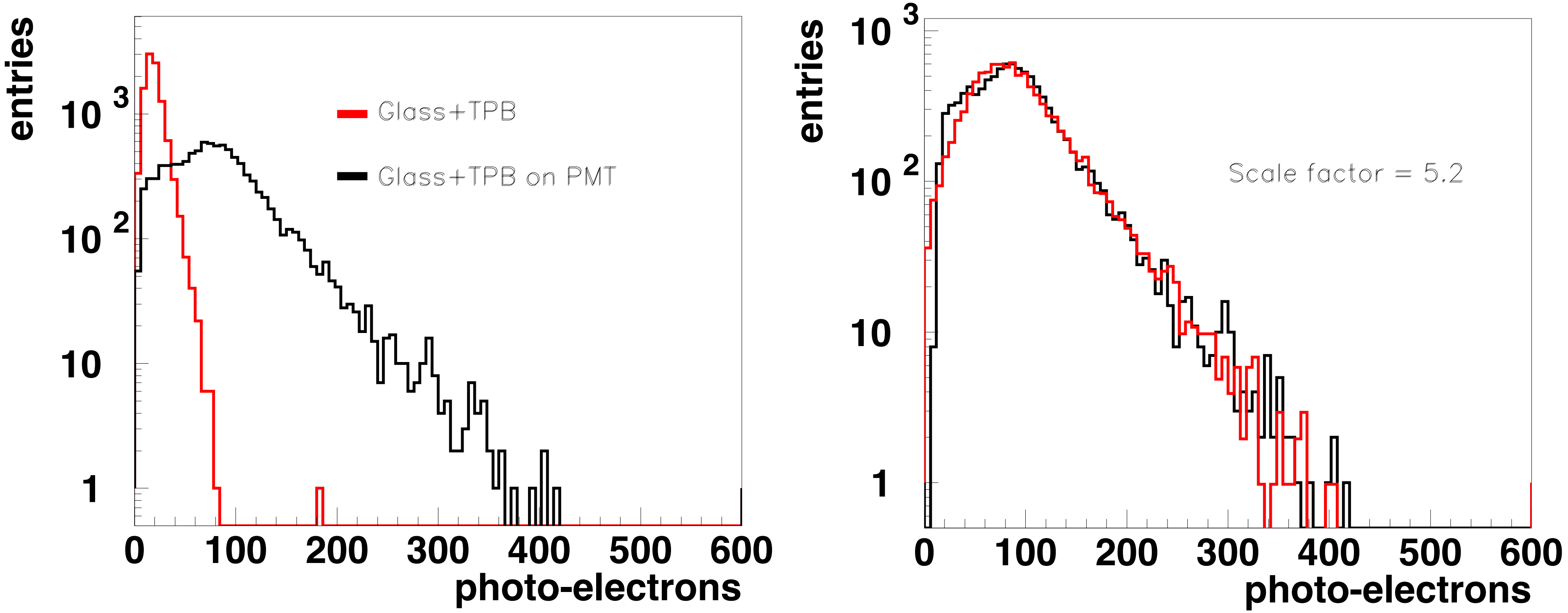
We measured the total amount of light produced by the alpha source gluing the glass or filter directly on the PMT.

The **comparison** of the measured spectra allows to determine the collection efficiency.



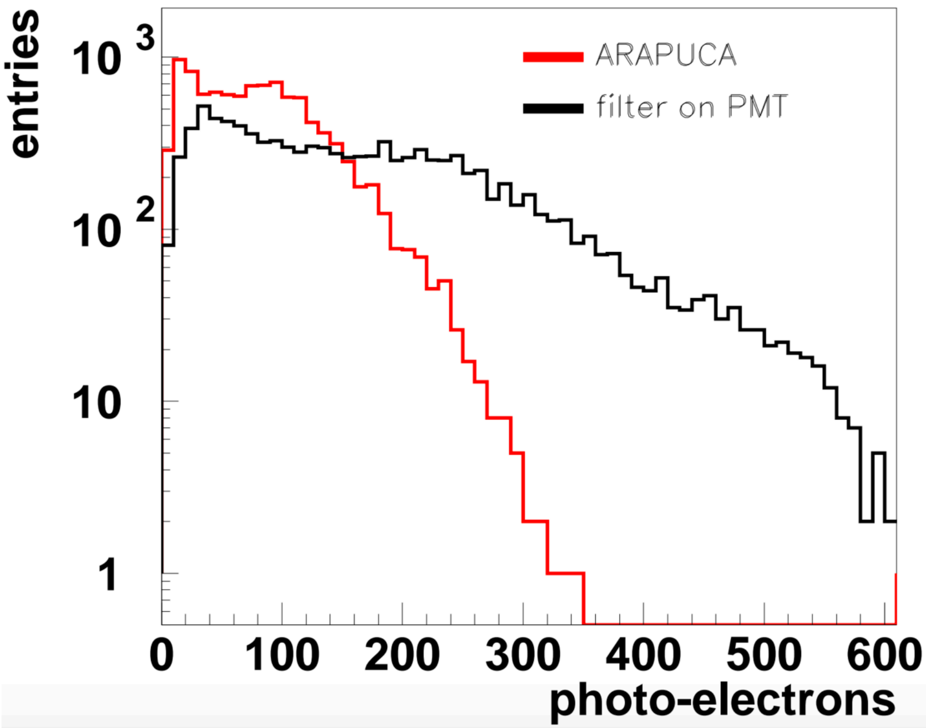


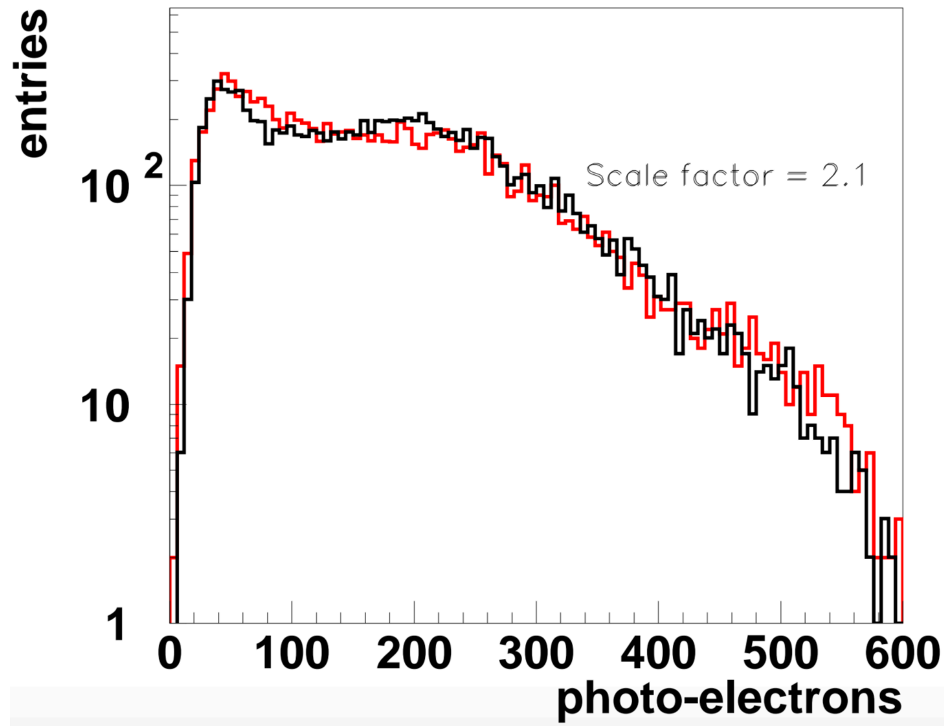
No trapping effect - TPB on glass



Collection efficiency ~ 20%

Trapping effect - ARAPUCA (filter)





Collection efficiency ~ 50%

The principle of ARAPUCA works!

Program of activities (II)

- Actually new prototypes are being realized in order to **optimize**:
  - ✓ Types of shifter to be used
  - ✓ Thickness of the films
  - ✓ Dichroic filter (from different vendors)
  - ✓ Internal geometry of the boxes.

- Measurements are being performed in few different laboratories:
  - National Laboratory of Synchrotron Light of Campinas (Brazil): the VUV line of the synchrotron can produce 128 nm photons (the same of LAr scintillation) that allows to study the properties of the shifters in a controlled way.
  - Fermilab: cryogenic tests of the ARAPUCAs using the PAB facilities. Measurements with TallBo in the near future.
  - A cryogenic set-up is being realized at the Campinas synchrotron. LAr measurement of the prototypes will be possible in 1 month.