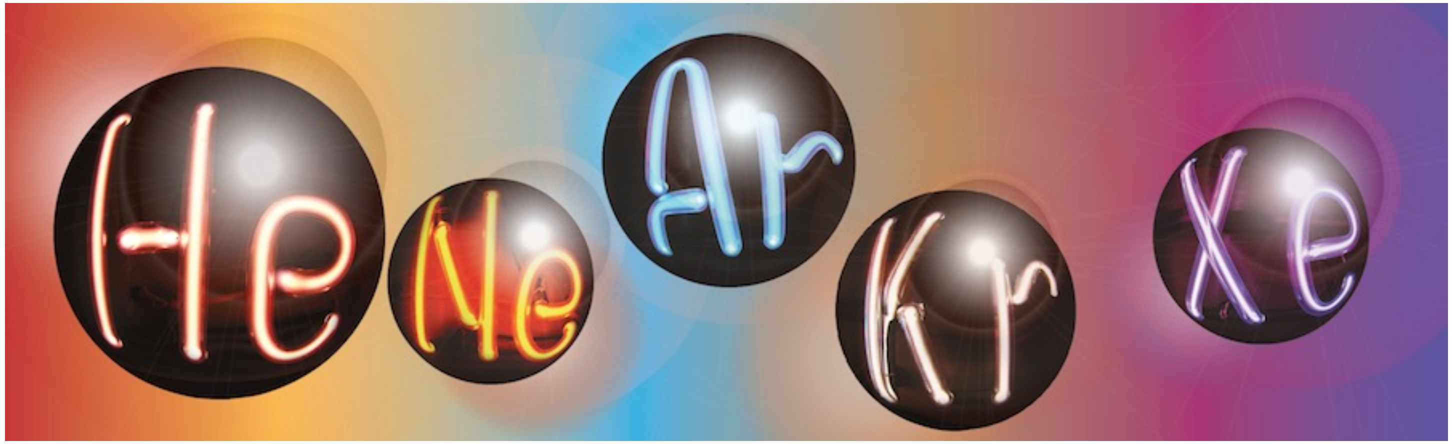
Absolute Photon Collection Efficiency for Photon Detection System of Vertical Drift far detector module



Madrid 20/09/2023

F. Di Capua - **Università di Napoli and INFN**

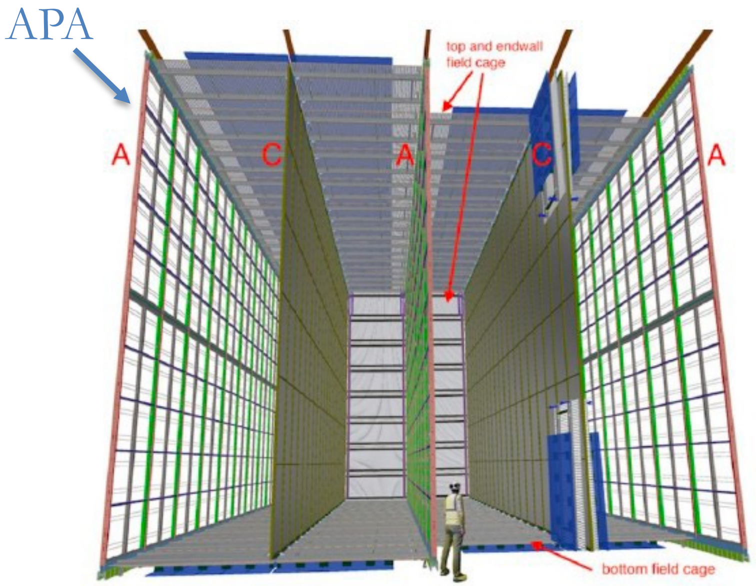
on Behalf of the DUNE Collaboration

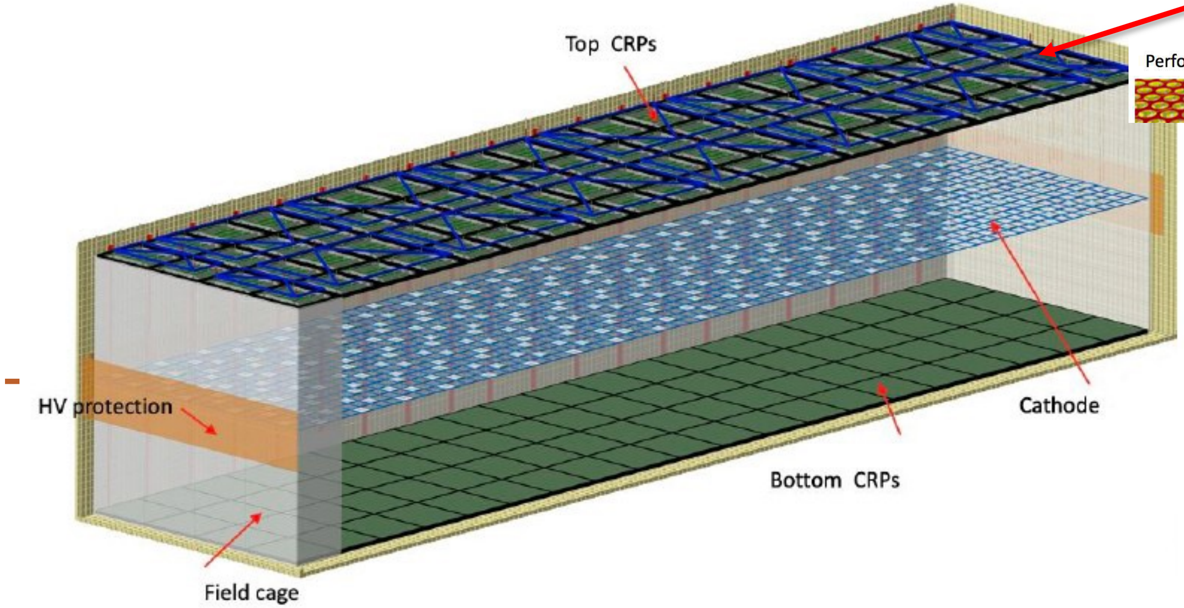
Overview

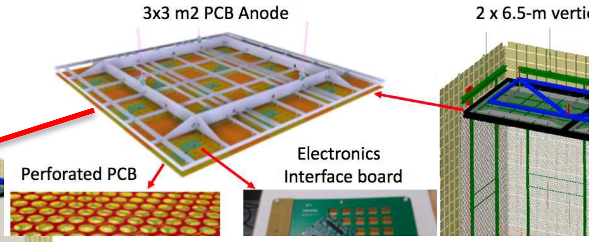
- Photon Detection System in the second DUNE Far Detector module (FD-2)
- Setup in Naples cryogenic laboratory
- Detector calibration and purity monitoring
- Source signal and Photon Collection Efficiency measurement

DUNE Far Detector: HD & VD

- First FD module will use Horizontal Drift technology: four 3.5 m drift regions, charge readout with wires in Anode Planes Assembly (APA). Similar to ICARUS, MicrobooNE, SBND.
- Second FD module will use Vertical Drift technology (two volumes 13.5 m x 6.5 m drift x 6.0 m), readout with strips (perforated PCB). Larger active volume, cheaper than FD-1 and similar performances



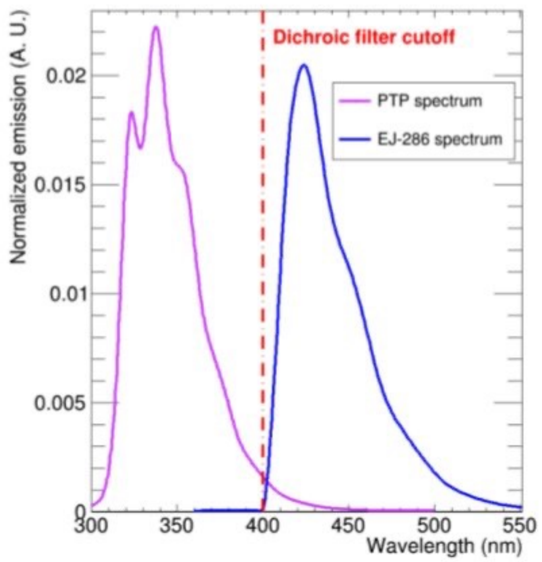


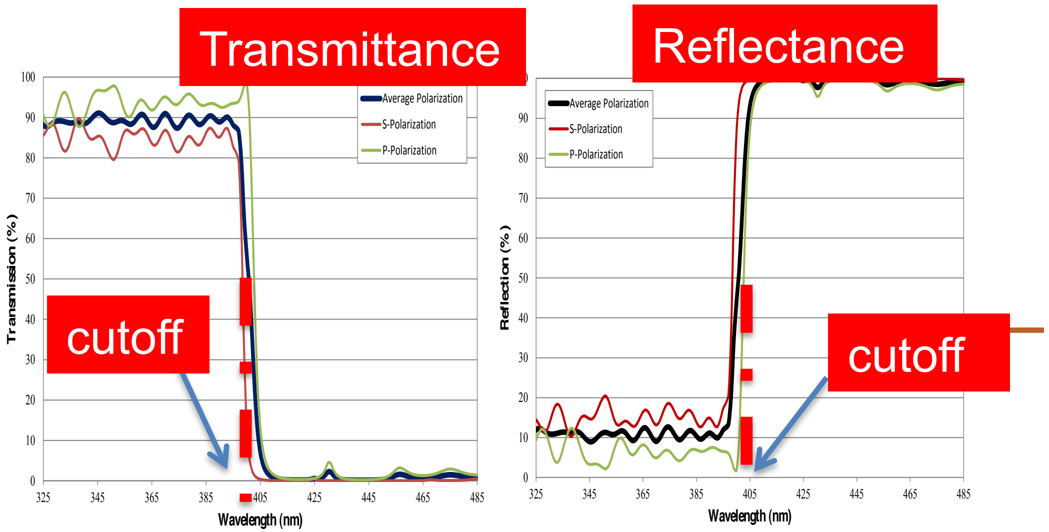


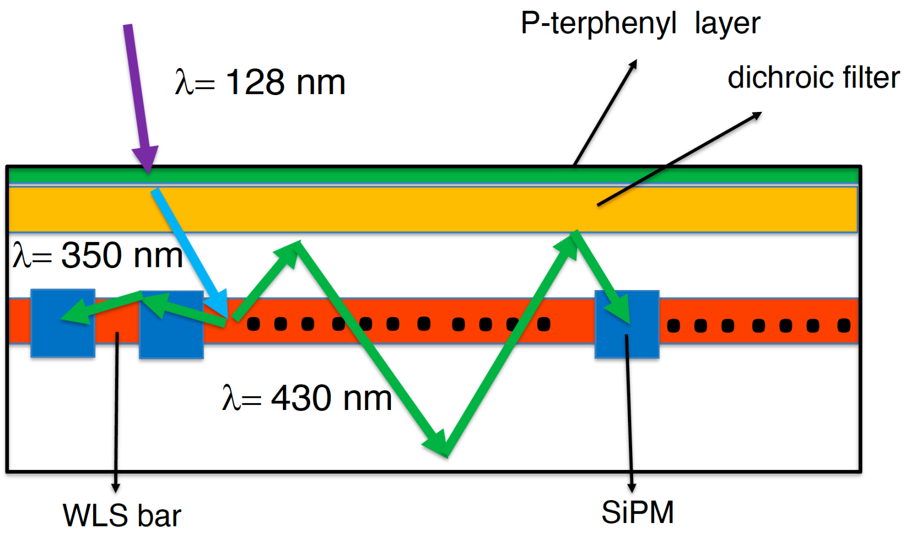
Charge Readout Planes (CRP)

Photon Detection System: the X-ARAPUCA concept

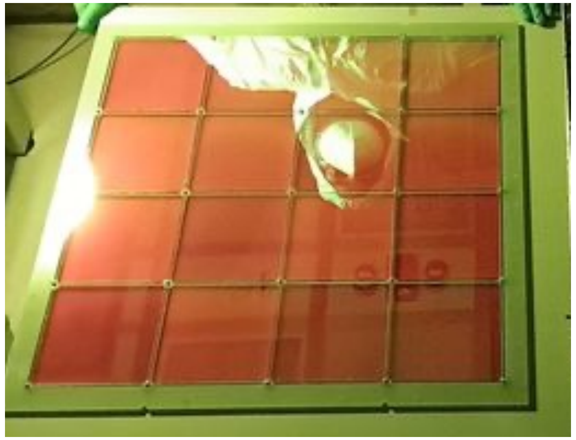
- VUV scintillation light produced in LAr
- PTP shifter deposited on the dichroic external side converts VUV light to a wavelenght (350 nm) < dichroic cutoff **(light transmitted)**
- The internal WLS bar converts the primary shifted photons to a wavelenght (430 nm) > dichroic cutoff **(light is trapped)**
- After reflections the photons can be detected by SiPM positioned laterally with respect to the WLS plane

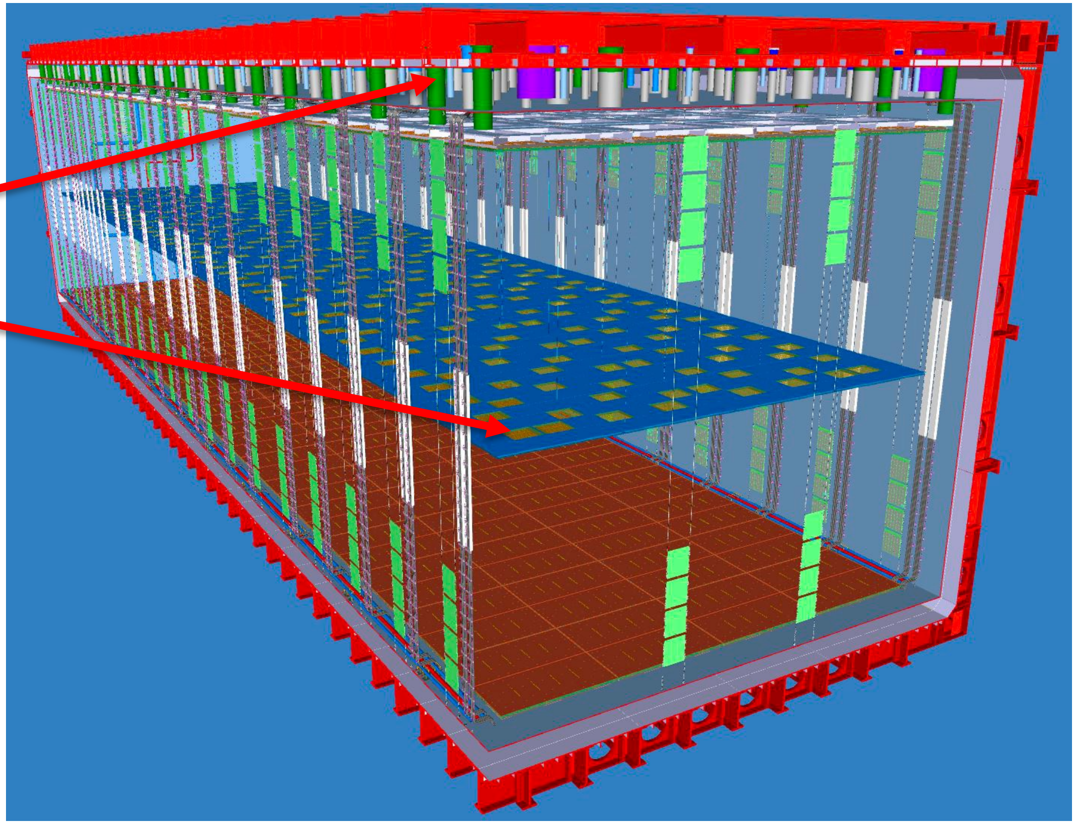






Photon Detection System in VD Detector

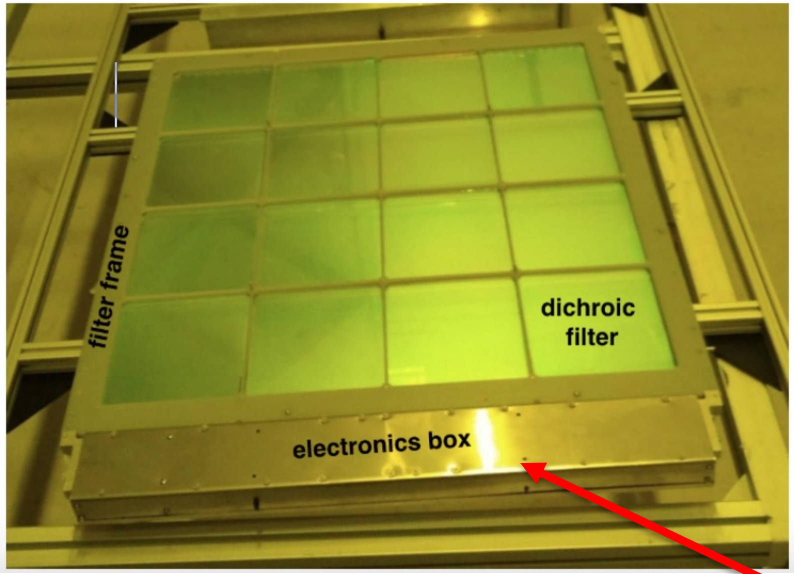


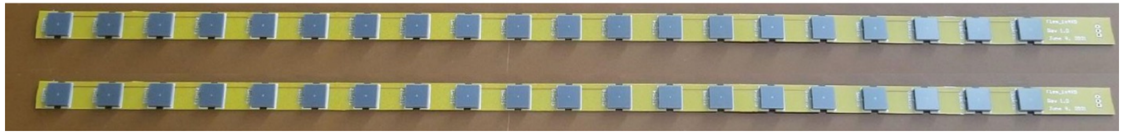


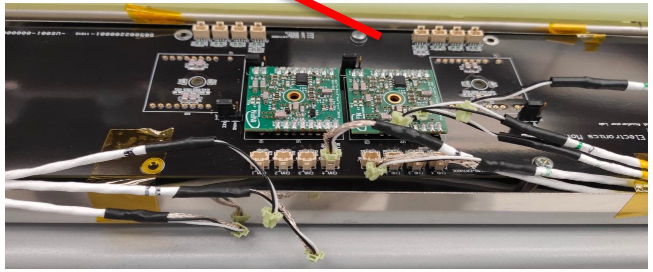
- **PD modules** mounted on the cathode (at 300 kV) and on the cryostat walls (membrane) behind the transparent (70%) field cage
- 320 double side (cathode) + 352 single side (membrane)

X-Arapuca Vertical Drift module

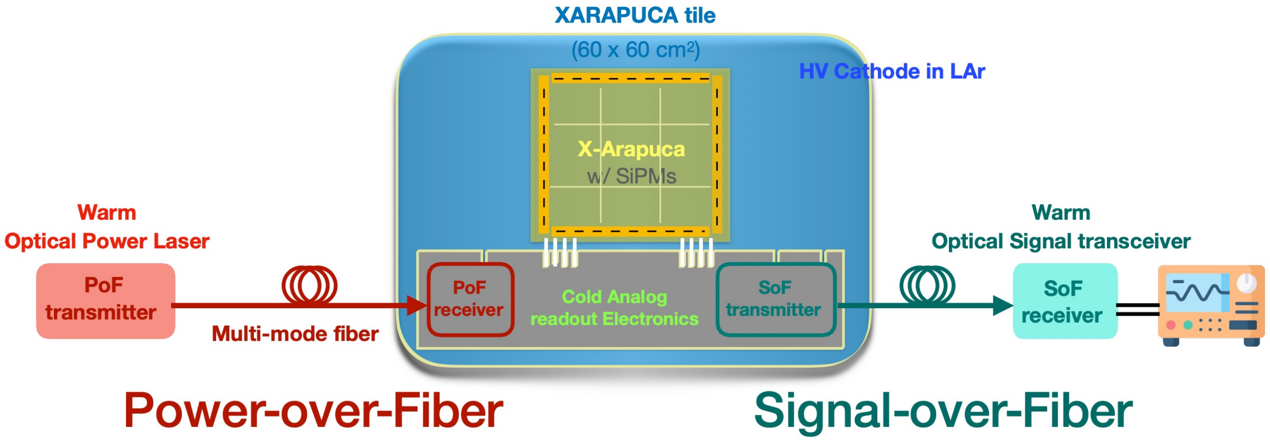
- **Square geometry**: dimension 60 x 60 cm^2
- 16 dichroic filters
- A single large **WLS light guide** slab
- Light readout by **160 SiPMs** mounted on flexible strips
- SiPMs 6 x 6 mm^2

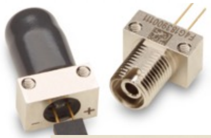




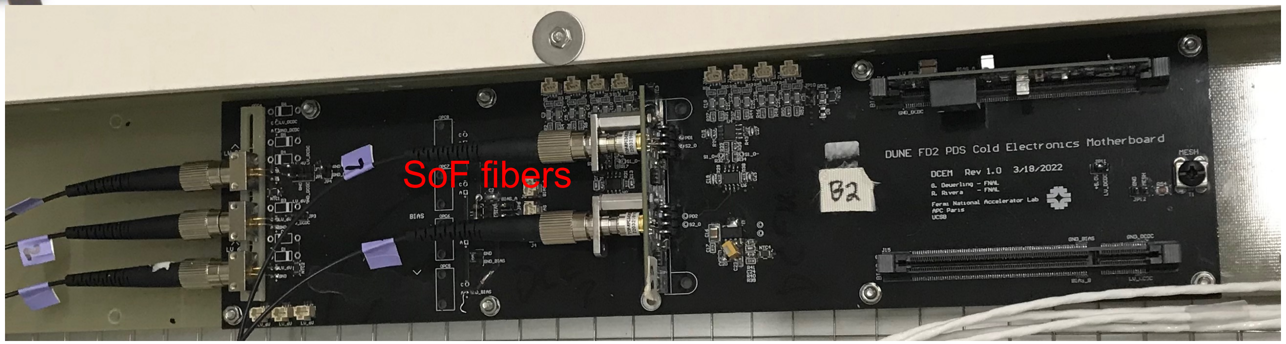


PDS-VD Electronics (Power over Fiber and Signal over Fiber)

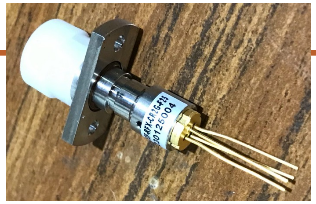




PoF: High efficiency GaAs OPC

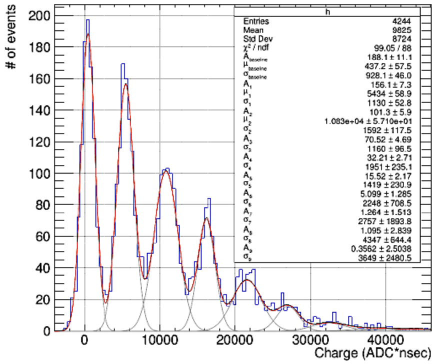


PoF fibers

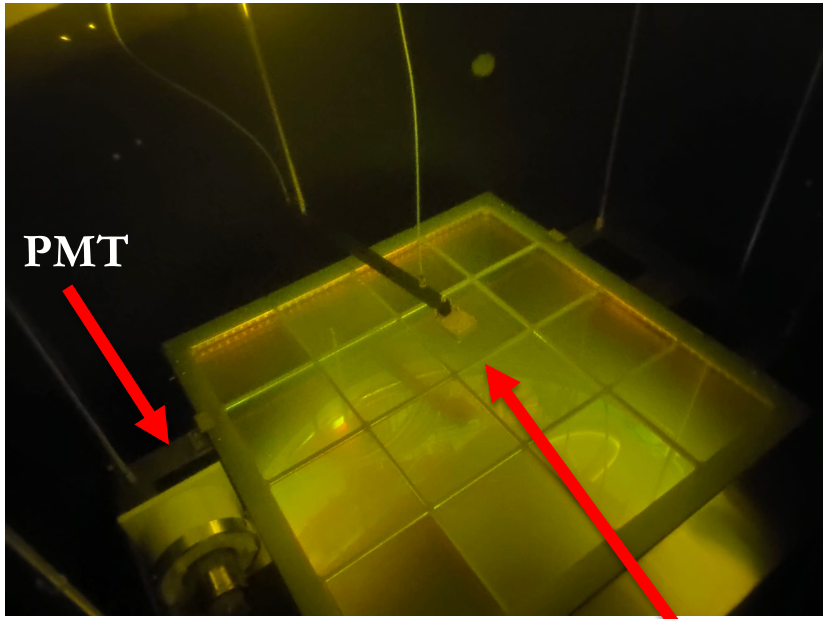


SoF defocused FP laser diode

- **Membrane** modules have standard electronics
- 4 groups of 20 SiPM passively-ganged in two stages, two output channels
- For **Cathode** modules a dedicated R&D has been carried out
- **Power over Fiber:** Laser toward a Photovoltaic Power Converter (PPC)
- **Signal Over Fiber:** analog signal transmission using IR laser light



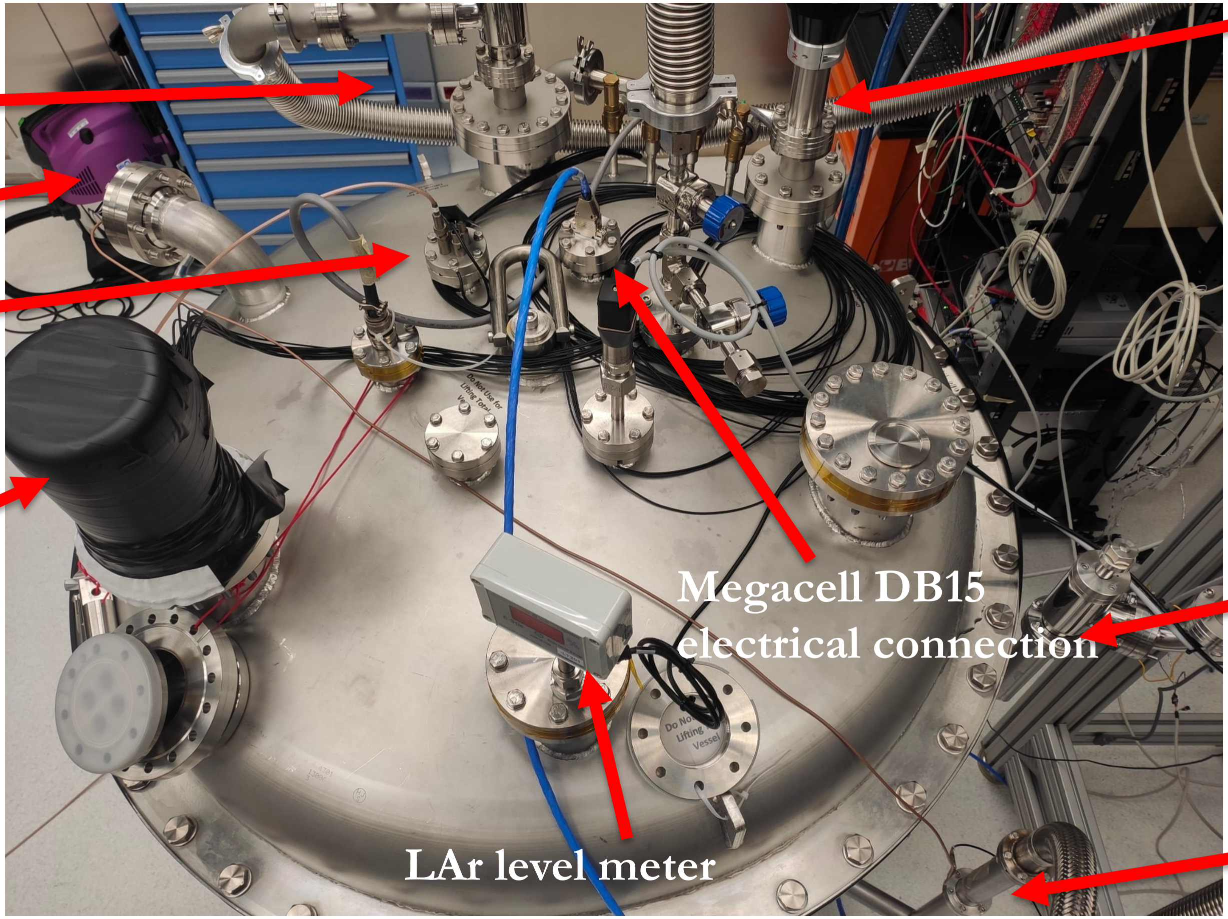
Photon Collection Efficiency estimation of X-Arapuca Megacell at Naples cryogenic laboratory



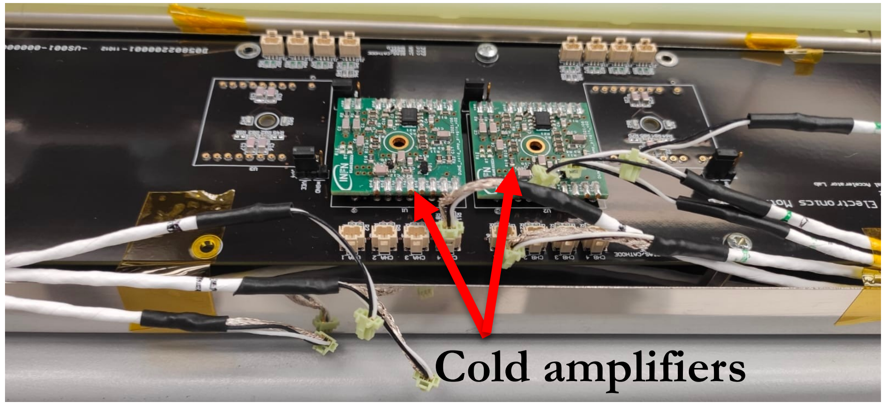
^{241}Am source (250 Bq)

- PDS module mechanical structure connected to cryostat dome
- ^{241}Am source connected to rototranslator
- Cryostat internal surfaces lined up with black delrin light shield

XA-VD measurement setup

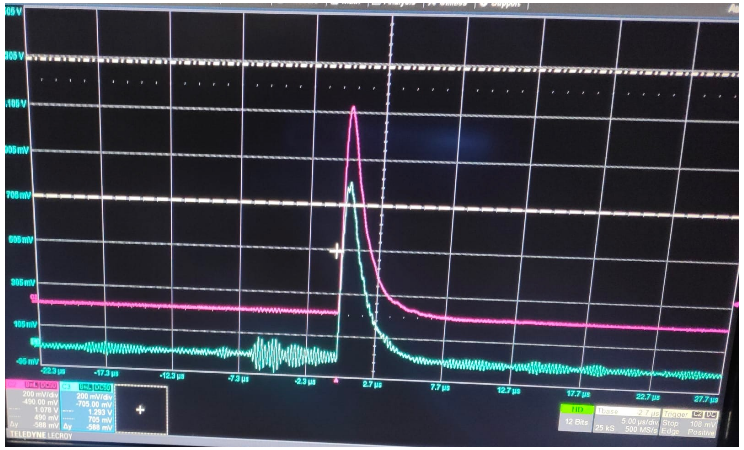


Electrical connection and DAQ



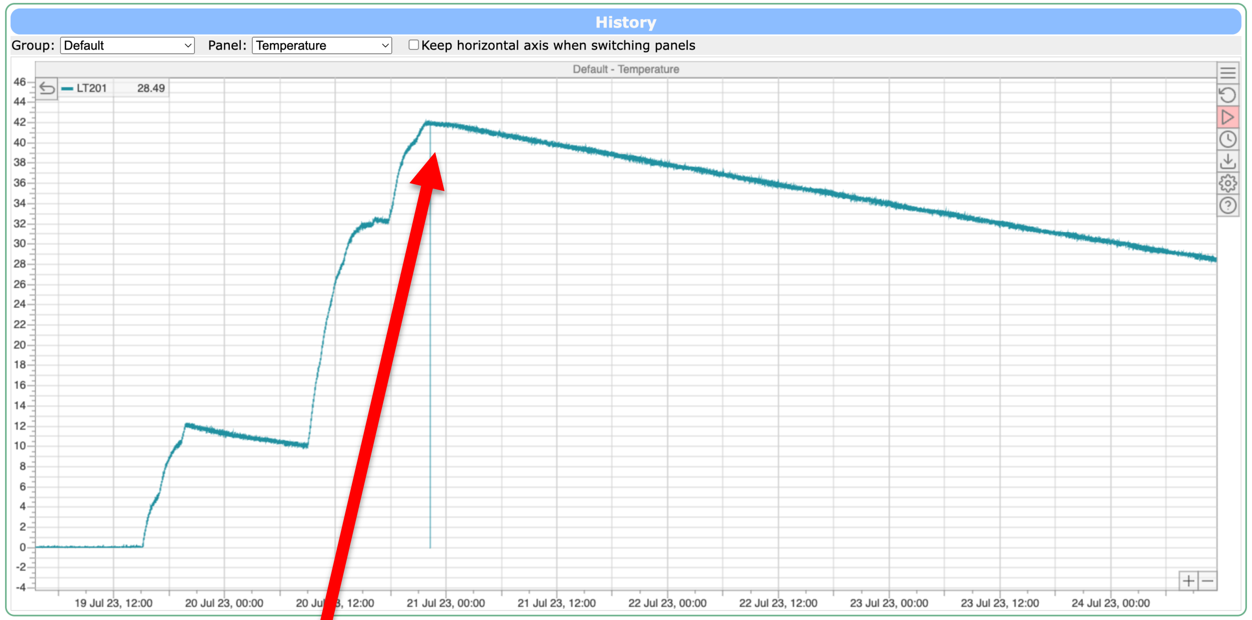
- Cold amplifiers: each of them readout the signal from 4 SiPM strips (80 SiPMs)
- Warm second stage amplifier convert the differential outputs in single-ended
- Output signals from second stage amplifier sent to CAEN V1725B digitizer and/or oscilloscope

Warm second stage amplifier

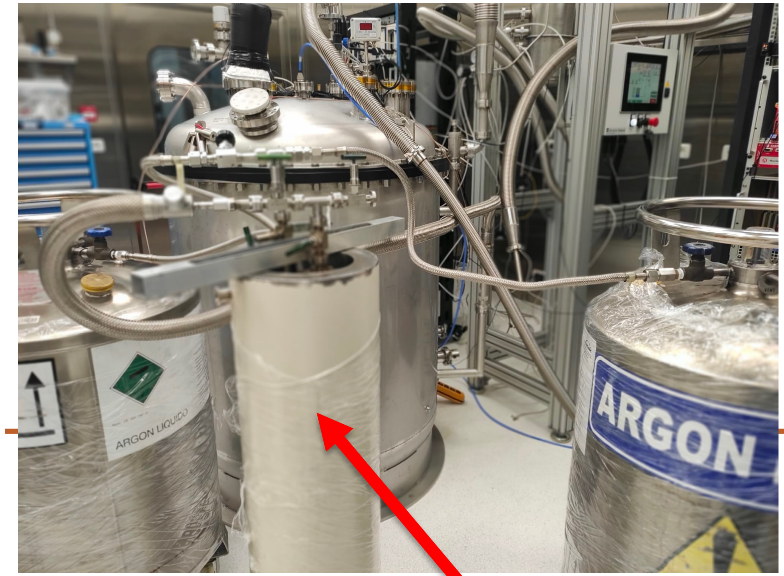


Vacuum operations and LAr filling

- Pump and purge cycles before filling
- Due to large amount of materials vacuum level not better than 10^{-4} mbar
- The cryostat has been filled with LAr5.0 filtered by an in-line Trigon (Engelhard Q5-Cu0226)
- During all measurement operations cryostat is in overpressure (1.2 atm) with respect to external pressure

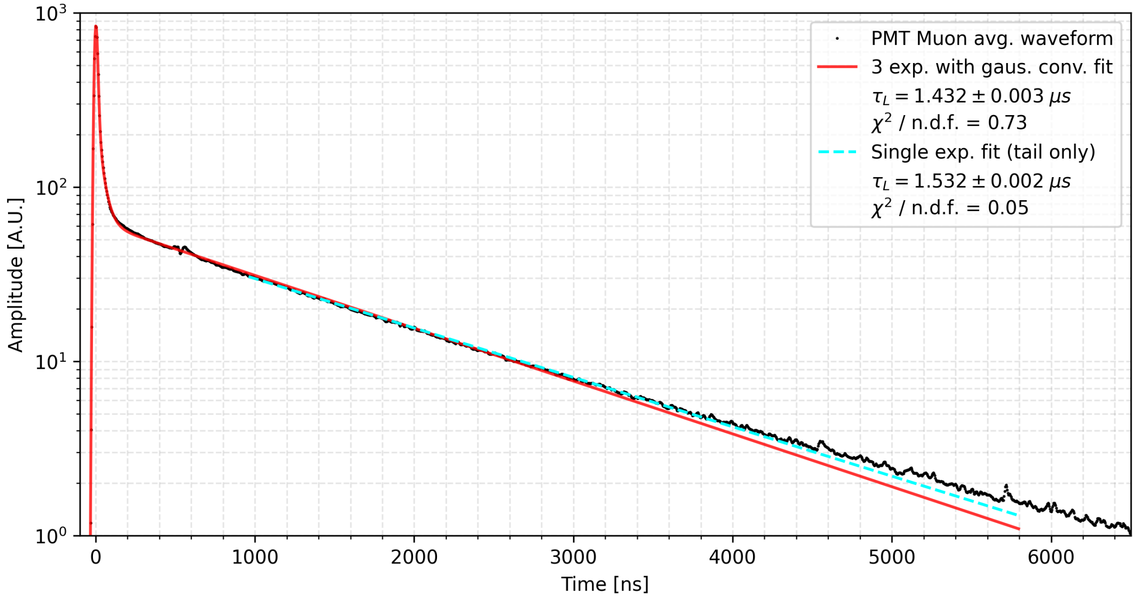


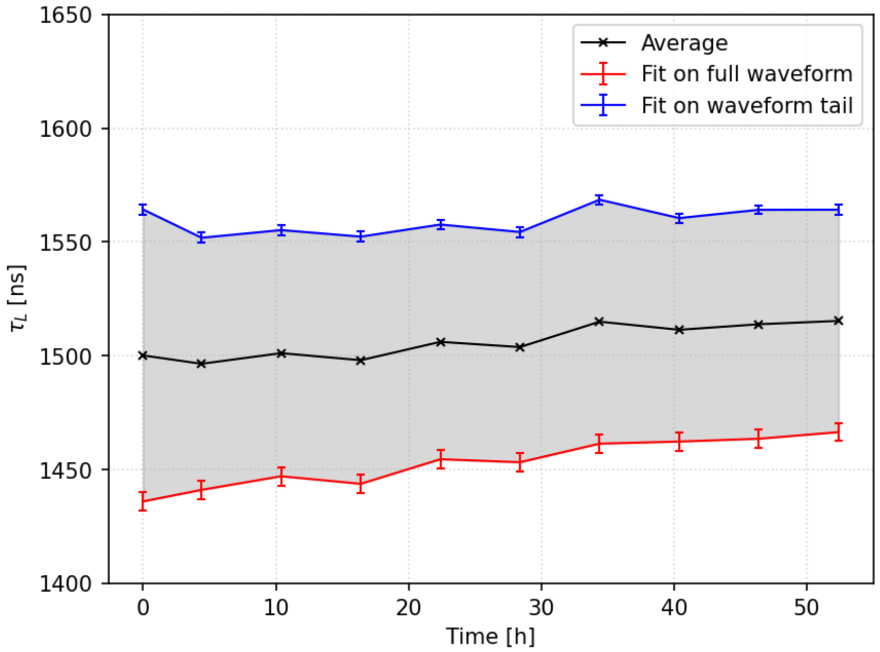
- Capacimeter level: the maximum correspond to 25 cm of LAr above the photon detector module
- Evaporation rate 4 cm/24h



Trigon filter in LAr open bath

LAr purity estimated with PMT





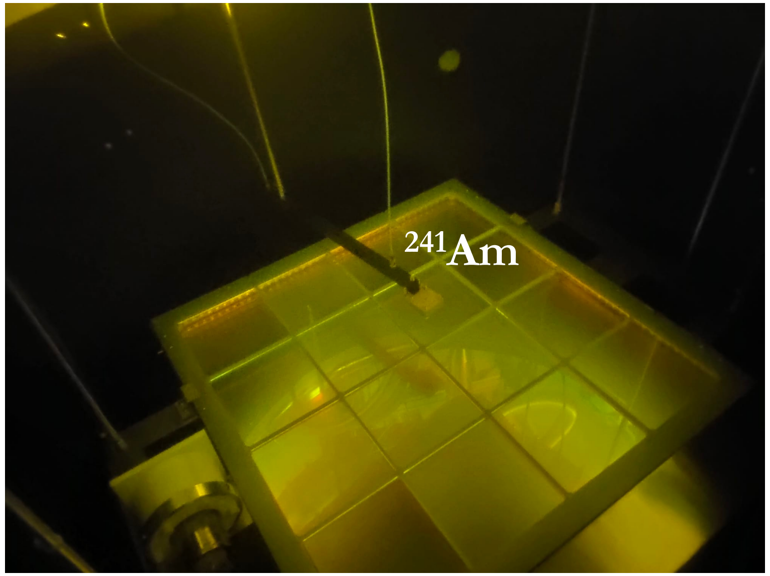
- Two fitting procedures_
  - 3 exp. + gaussian
  - Single exp (tail only)
- **Result of long tau component between 1.4-1.5 us**
- Fit executed on muon sample

- Purity is found stable in all the measurement period
- No purity correction to the measurement are required

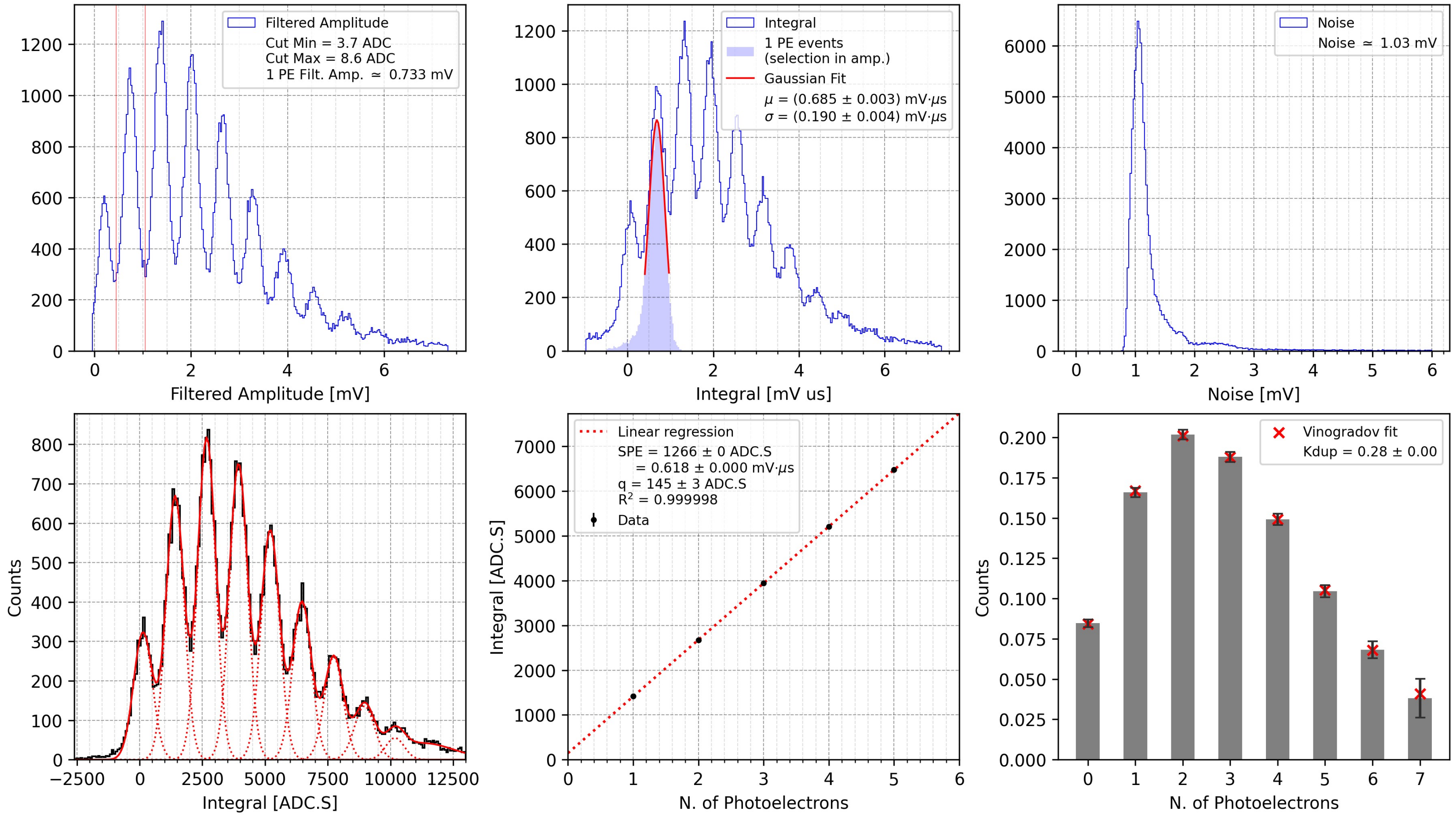
Steps for the Photon Collection Efficiency estimation

$$PCE = \frac{N^{PE}}{N^{Ph}{}_{SIM}}$$

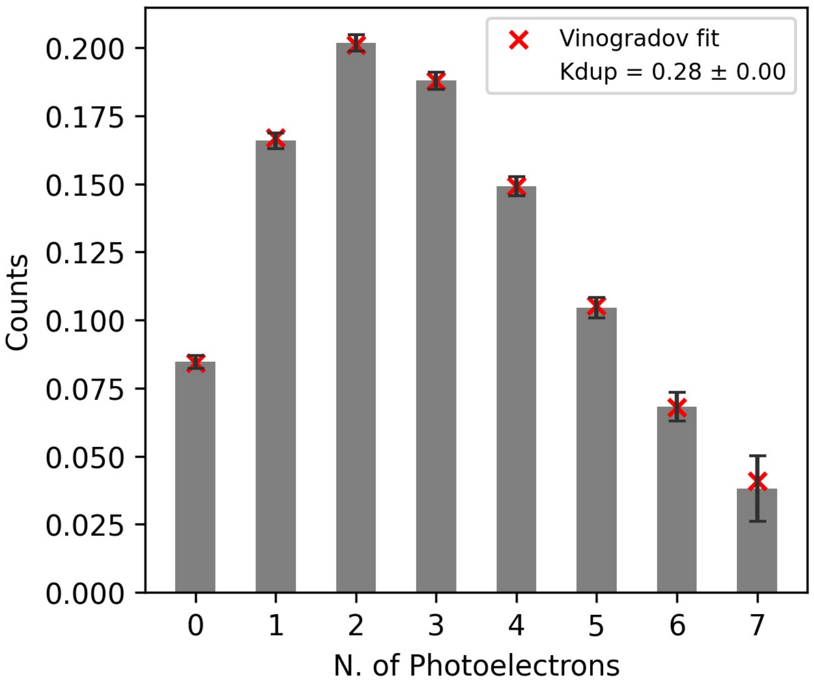
- Scintillation VUV photons produced by alpha source
- SPE response determined with pulsed laser
- Signal selection from alpha source and conversion in PEs
- N^{PE} given by detected photoelectrons produced by alpha particles (two channels summed)and corrected for SIPMs secondary pulses: afterpulse and cross-talk (AP/CT)
- $N^{Ph}{}_{SIM}$ given by full simulation of the experimental setup: number of photons produced from source and impacting the photon detection module



Laser calibration: SPE response



Secondary pulses estimated with Vinogradov model



$$f(n;\mu,p) = \frac{e^{-\mu}}{n!}\sum_{i=0}^{n} B_{i,n}[\mu\cdot(1-p)]^i \cdot p^{n-i}$$

$$B_{i,k} = \begin{cases} 1 & \text{when } i=0 \text{ and } k=0 \\ 0 & \text{when } i=0 \text{ and } k>0 \\ \frac{k!(k-1)!}{i!(i-1)!(k-i)!} & \text{otherwise} \end{cases}$$

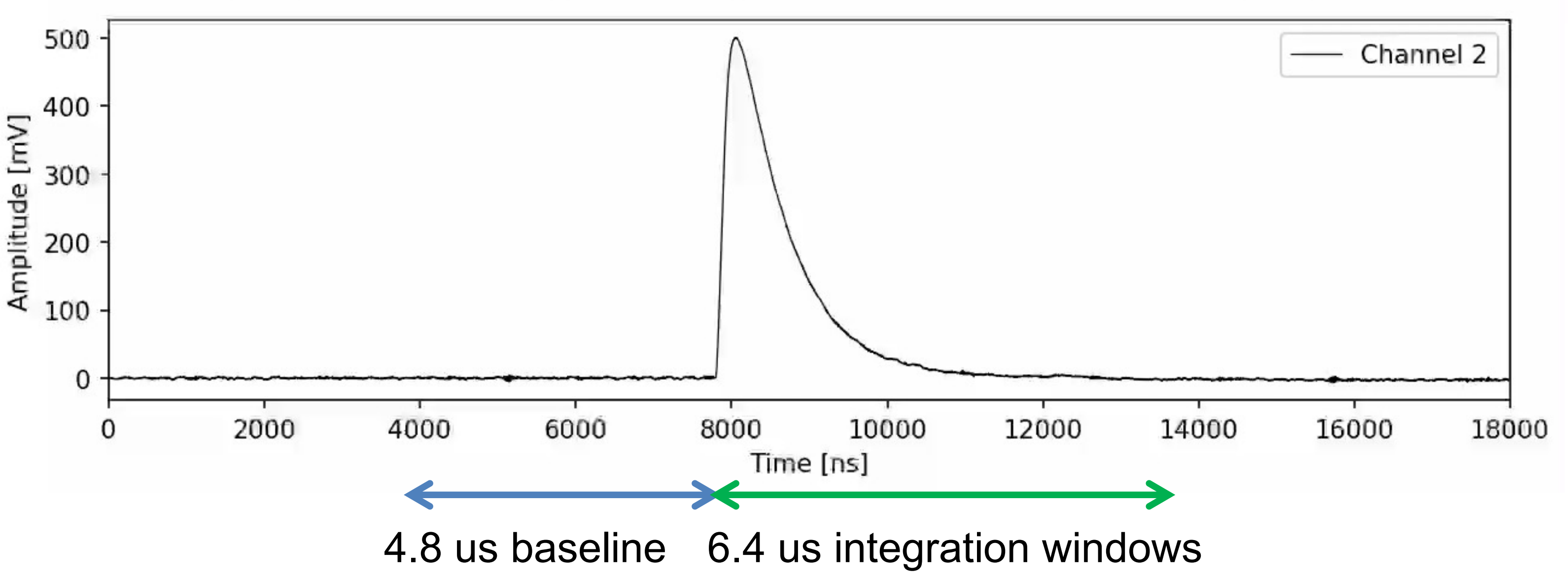
- **K_{dup} = 0.28**
- **p=22%**

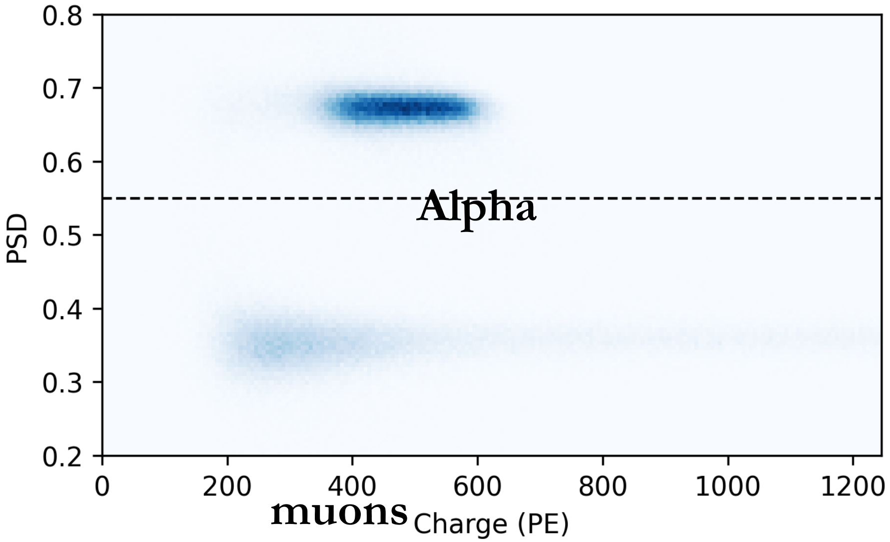
- Composite Poissonian to describes the joint effect of cross-talk and afterpulses
- Two parameters μ e *p*
  - *p:* probability to generate a secondary correlated avalanche
  - μ: poissonian mean
  - K_{dup} = p / (1-p) duplication factor

$$E[X] = \mu\cdot(1+K_{dup})$$
$$VAR[X] = \mu\cdot(1+K_{dup})\cdot(1+2\,K_{dup})$$

From independent FBK single SiPM characterization data we have: p=19% (PDE=45%)

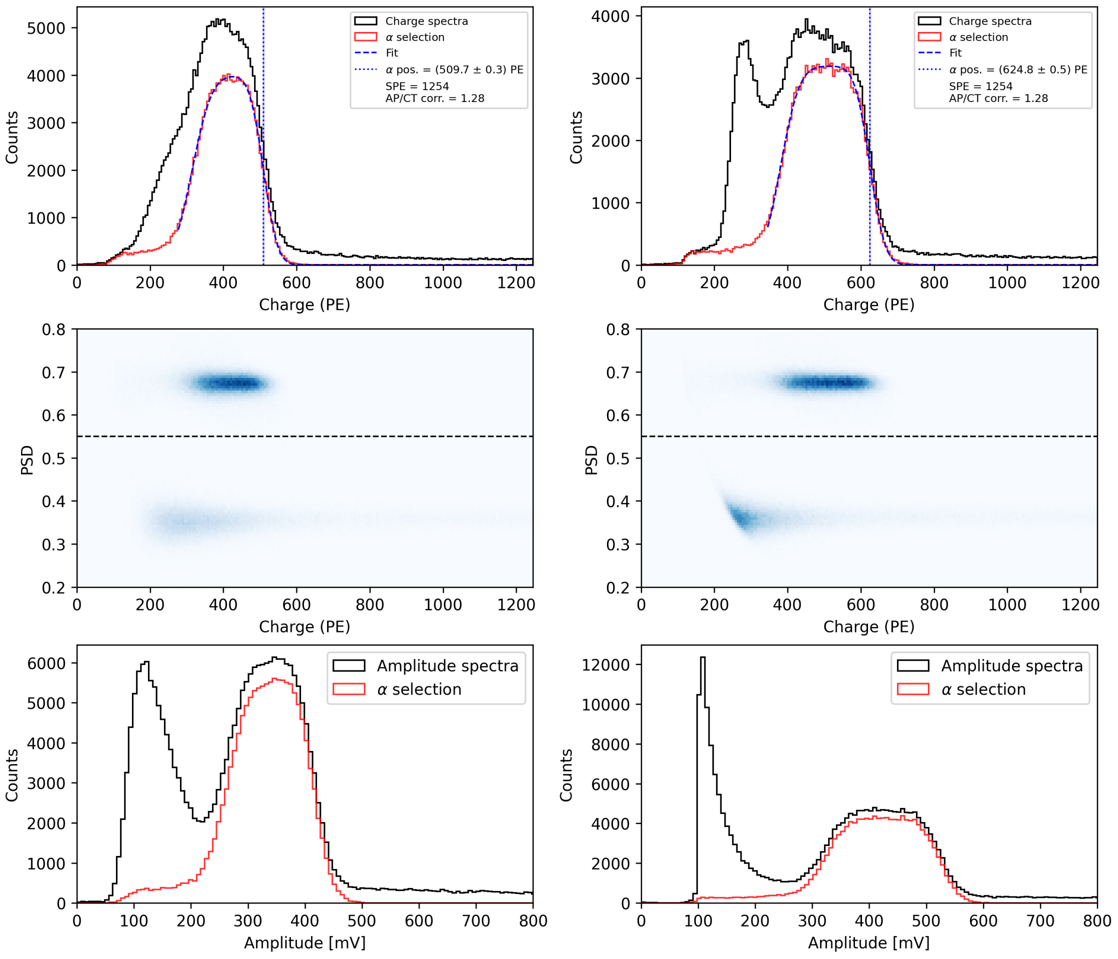
Alpha source signal





Pulse Shape Discrimination clearly allow to separate alpha signal from cosmic muons

Alpha source signal



- Trigger on ch2 due to lower noise
- Charge spectrum: integration
- Alpha events selected via prompt light (PSD)
  - Alpha distribution appears non-gaussian due to source holder shielding
  - Alpha yield = fitted tail with the convolution of constant + gaussian distributions=50% of the maximum on the right tail
- Measurement in six different locations for the source
- Error (systematic) estimated by varying cuts

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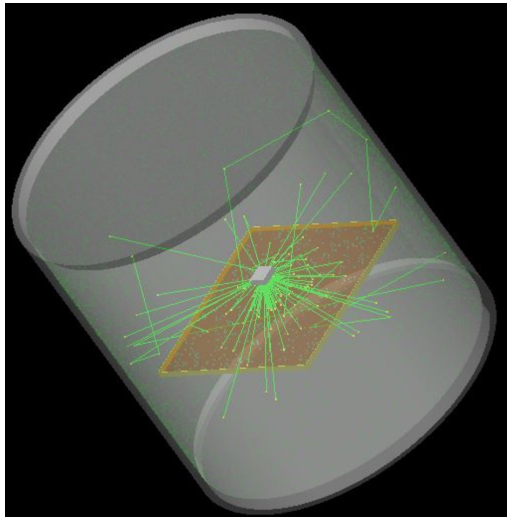
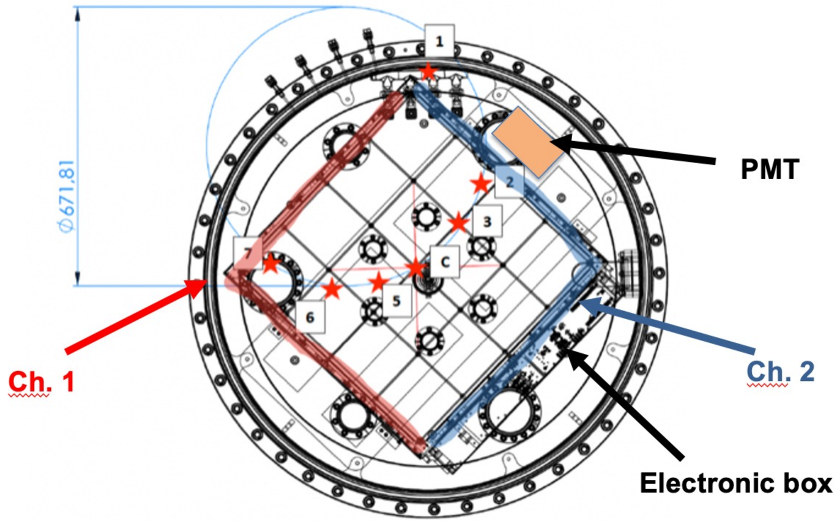
VERY PRELIMINARY

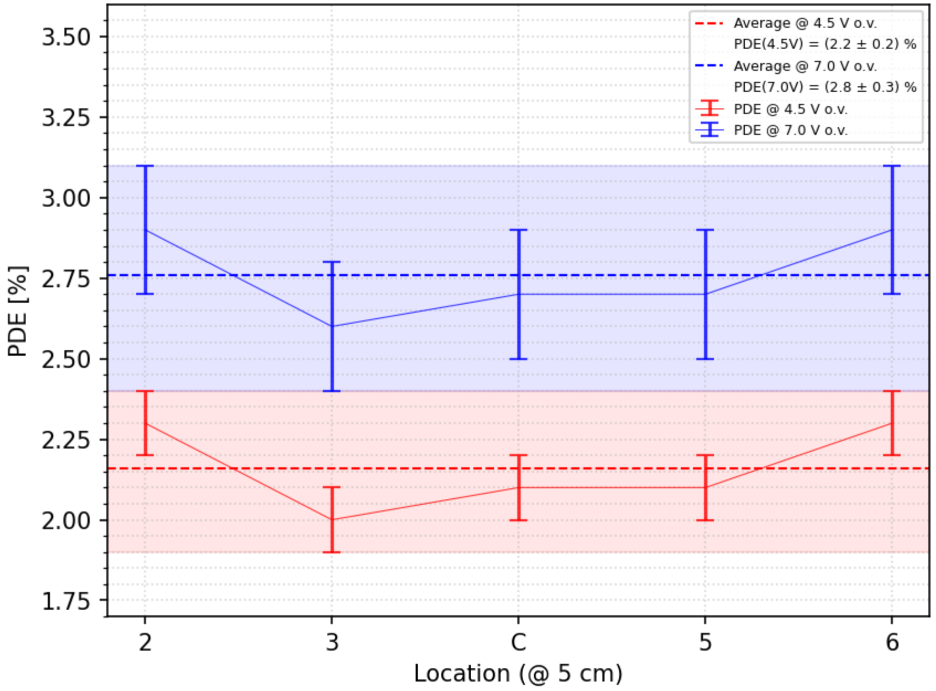
Photon Collection Efficiency

- N^{Ph}_{SIM} is the expected number of photons impacting on PD module estimated with G4 simulation: alpha LY + geometrical acceptance
- Measured efficiency in different detector locations and at 4.5 V and 7.0 V overvoltage
- A **very preliminary** PCE estimation is about $2.2 \pm 0.2\%$ at 4.5V overvoltage
- This value allows to infer an overall experiment LY of ~30 PE/MeV



$$PCE = \frac{N^{PE}}{N^{Ph}_{SIM}}$$





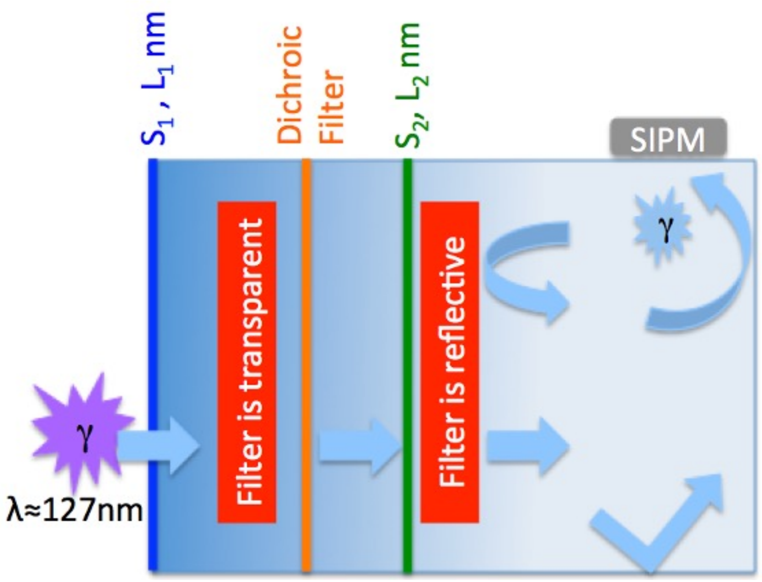
Conclusions

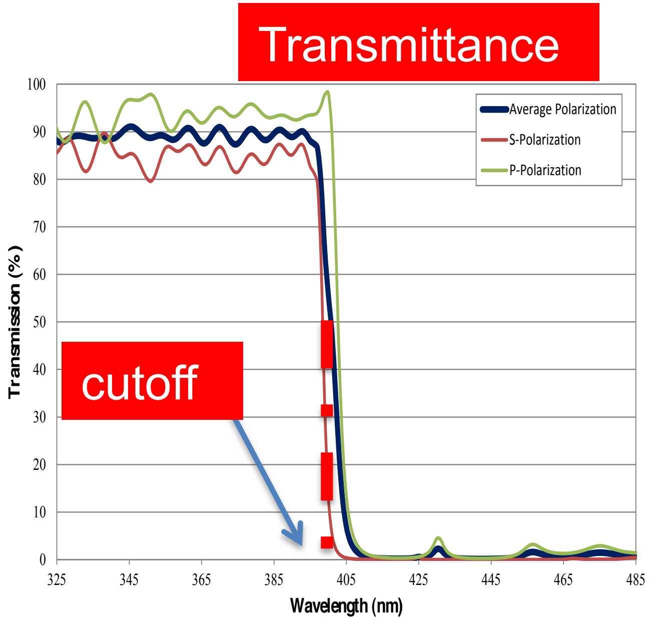
- DUNE Far Detector 2 will use Vertical Drift design
- Photon Detection System: conceptual design based on X-Arapuca light collector
- Naples clean room infrastructures used for PDS-VD module characterization
- First PCE measurement of the PDS-VD module

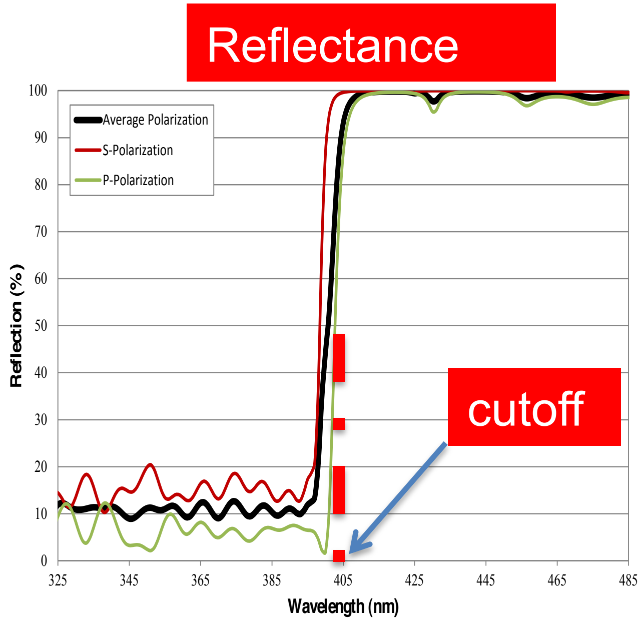
Backup Slides

Photon Detection System: the ARAPUCA concept

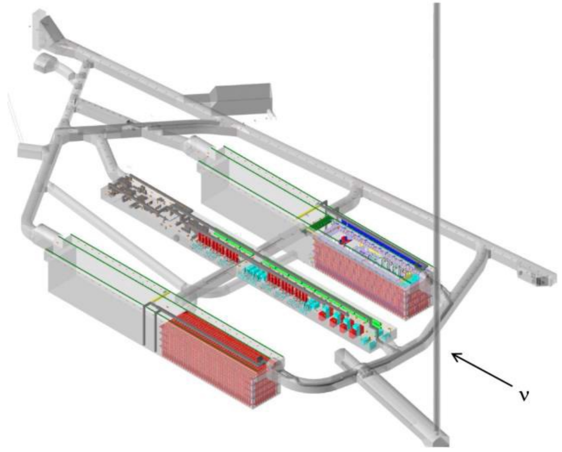
- Basic idea (Machado, Segreto) is to trap photons in a box with **highly reflective internal surfaces**
- Develop an **efficient photon collector** system which allows to increase the effective area of the active SiPM devices
- The core of the device is the **dichroic filter**: a multilayer interference film which is **highly transparent** for wavelength **below a cutoff** and **highly reflective above it**





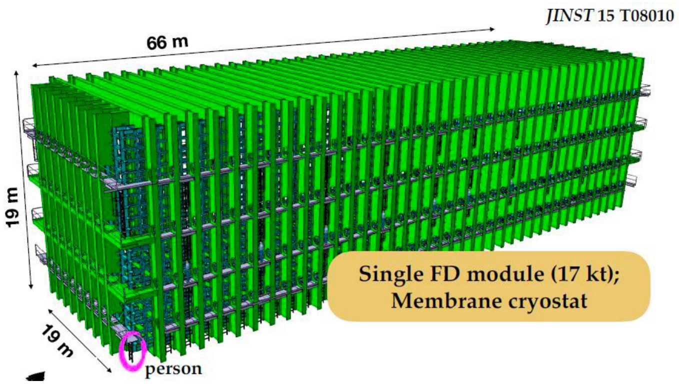


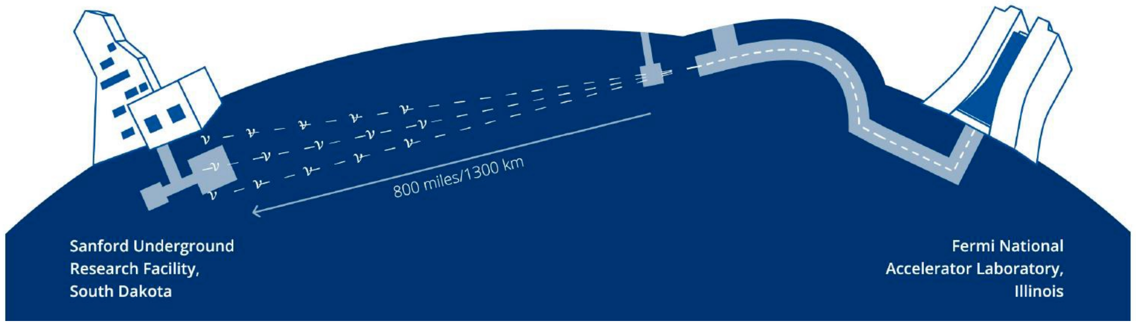
Deep Underground Neutrino Experiment (DUNE)

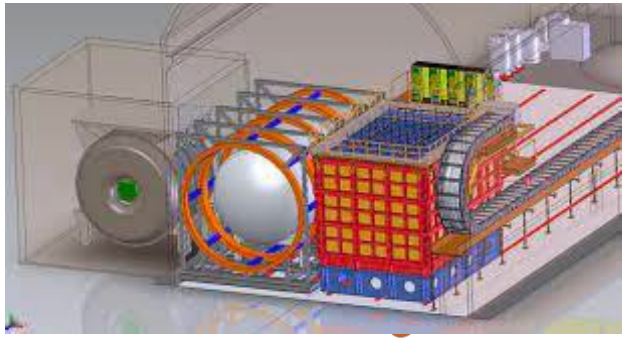


A new generation long-baseline neutrino oscillation experiment (1300 km – large matter effect):

- High power wide-band neutrino (ν_μ or $\overline{\nu}_\mu$) beam originating from the upgrade of the Fermilab accelerator complex (1.2MW in Phase I upgradable to 2.5MW in Phase II)
- Huge far detector volume(~70 kton) divided in 2 (Phase I) + 2 (Phase II) modules, 1.5 km underground
- Multi technology Near Detector (movable NDLAr, TMS + on axis SAND detector) for beam characterization and to constraint systematic uncertainties (same nuclear target)



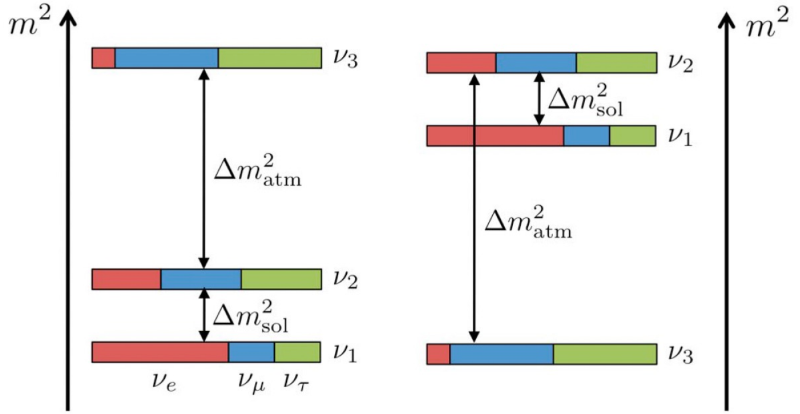




DUNE: A Wide Physics Program

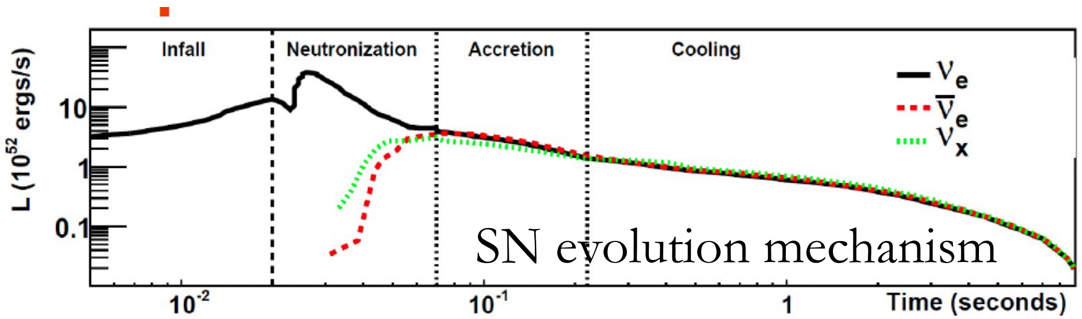
Beam Physics

- Discovery of *CP* violation phase δ_{CP}
- Determine neutrino mass hierarchy
- Precise measurement of neutrino oscillation parameters (ϑ_{23}, Δm_{13}^2)

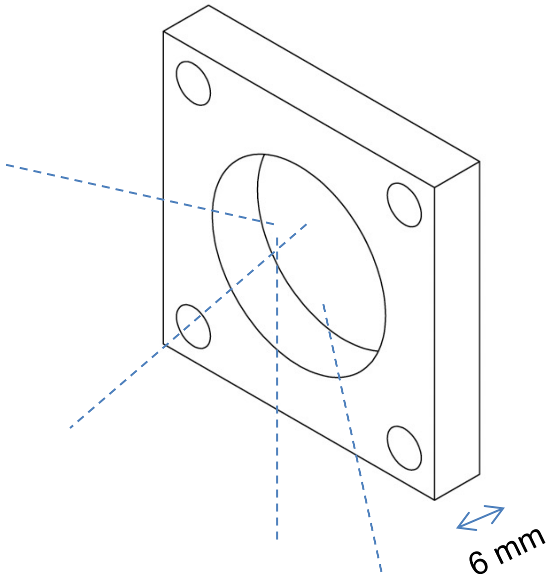


Astroparticle Physics

- Detection of low energy neutrinos bursts from galactic supernova (sensitive to ν_e)
- Detect solar neutrinos (first possible observ. hep neutrinos, best meas. ϑ_{12})
- BSM physics: proton decay…
- Dark matter



Source holder geometry



- Source holder window is 23 mm diameter
- Thickness of the holder edges is 6 mm: this induce a shielding of alpha particles
- Due to the holder shielding the alpha spectrum becomes flat
- **Charge spectrum** fitted with the convolution of a box function and a gaussian
- **Alpha yield: 50% of right tail**
- Alpha Spectrum has been corrected for secondary pulses (AP/CT)