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Novel concepts of light sensors and light detection techniques for neutrino physics

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FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

CNPq

Light detection in neutrino physics

- **Light detection** plays a *central role in neutrino physics*
- Light production is ***one of the mechanisms through which the energy deposited by a charged particle is transformed spontaneously into a detectable signal*** (as ionization, phonons, acoustic, heat,…)
- Light signal can be produced through **different processes**: *scintillation, Cherenkov radiation, transition radiation, ...*
- Light signals carry **a lot of information about the incoming particle**: *time of arrival, type, direction, energy loss (related to dE/dx and LET)*
- Enough reasons to justify **the enormous effort that experimental particle physicists have done to detect them** with high efficiency to extract as much as information as possible

Photomultiplier tube

- The ***first demonstration of a photomultiplier*** (PMT) dates back to about 90 years ago. The floor for the invention had been set up by the discovery (H. Hertz, 1887) and theoretical explanation (A. Einstein, 1905) of the **photoelectric effect** and by the discovery of the **secondary electron emission** (Villard, 1902);
- PMTs enabled many of the discoveries done in neutrino physics since the beginning;
- **...and still play a central role in current and next generation experiments.**

Photomultiplier tube

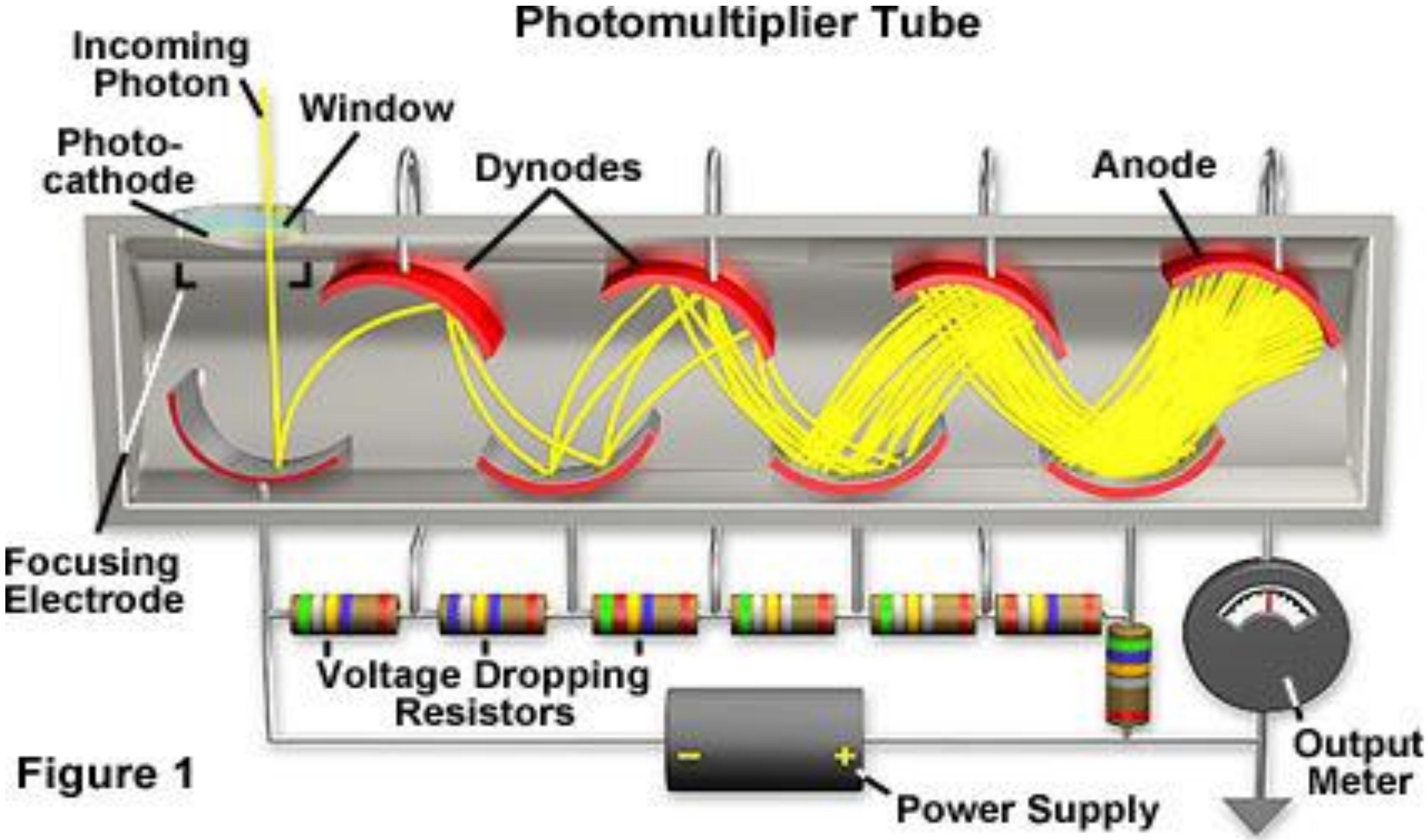
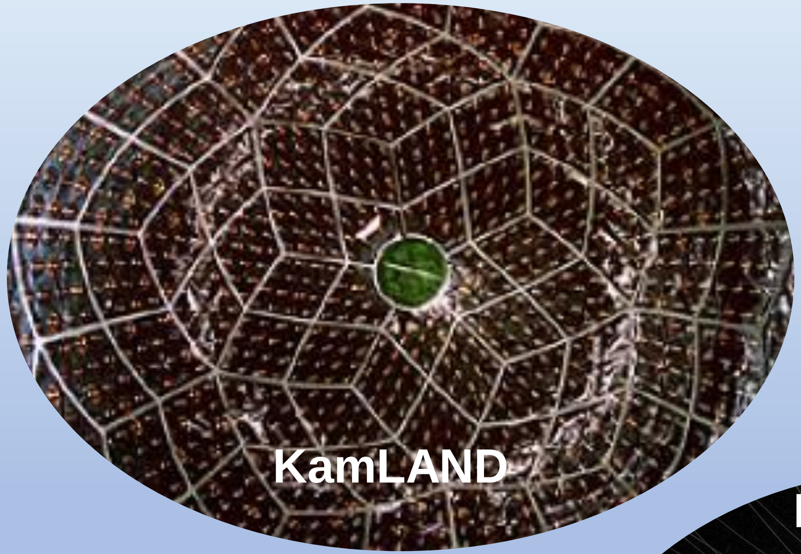
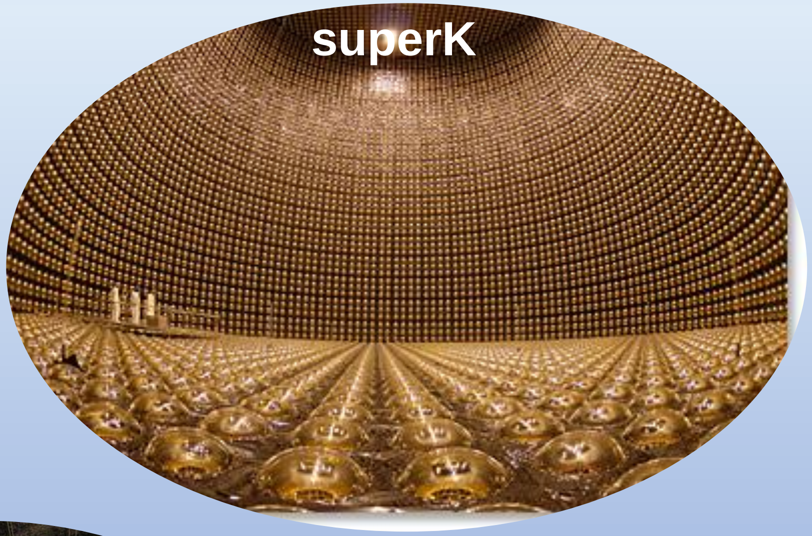
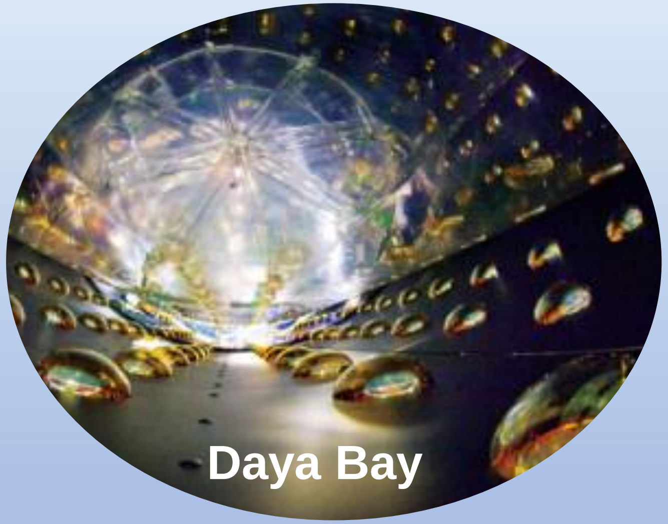
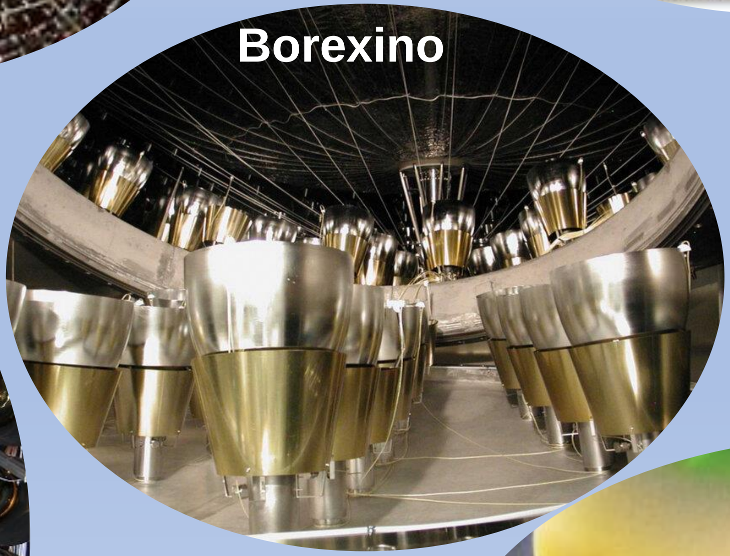


Figure 1


KamLAND


superK


Daya Bay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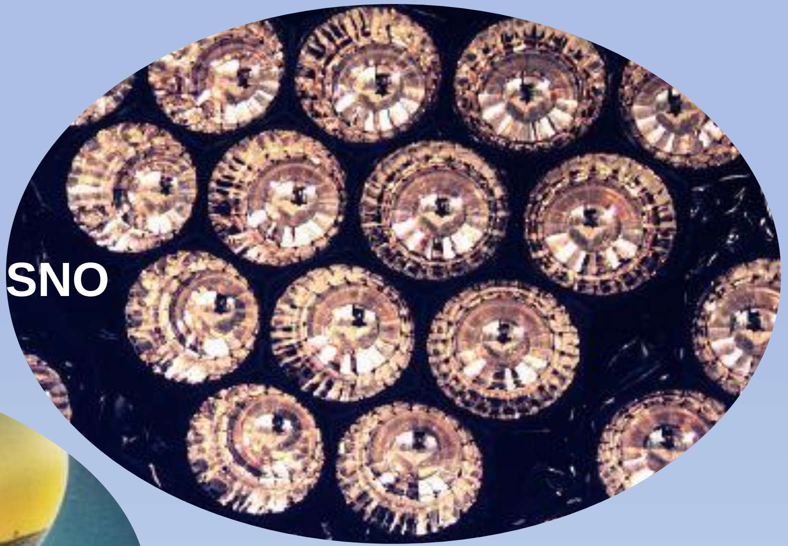
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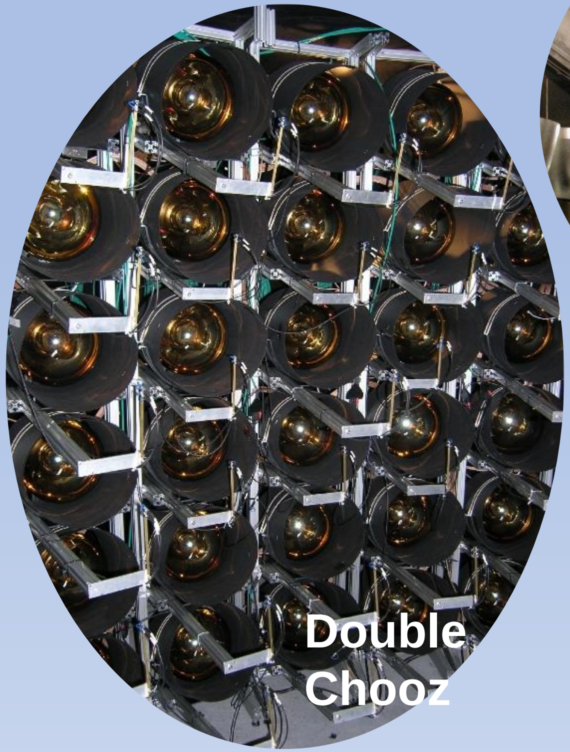
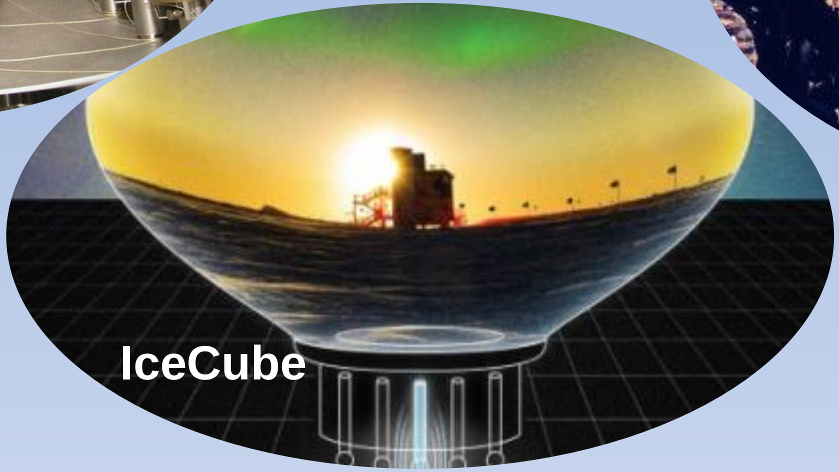
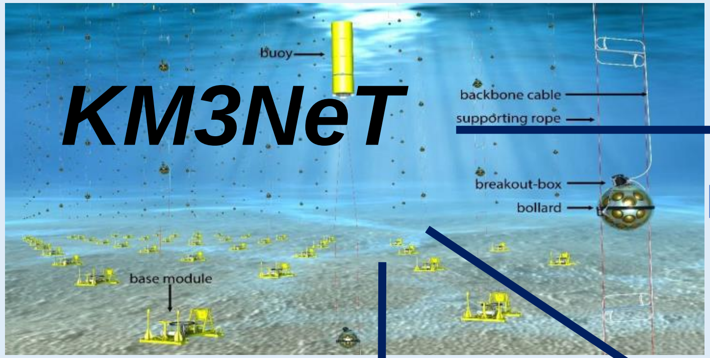

Double
Chooz


IceCube



Hyper-K

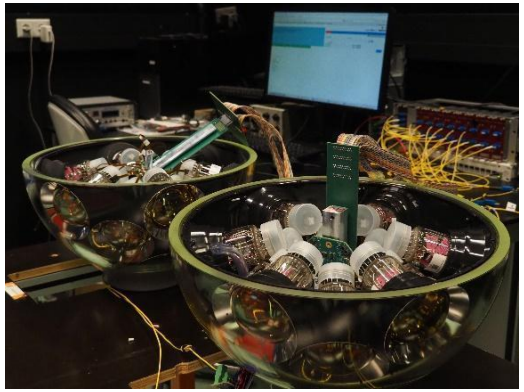
Multi-PMT concept

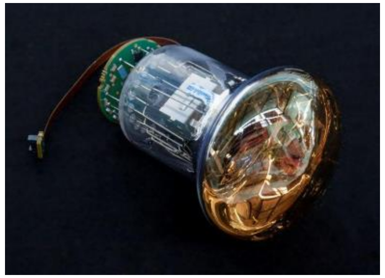
ICECUBE

SWGO

The Southern Wide-field Gamma-ray Observatory

Multi-PMT - KM3Net

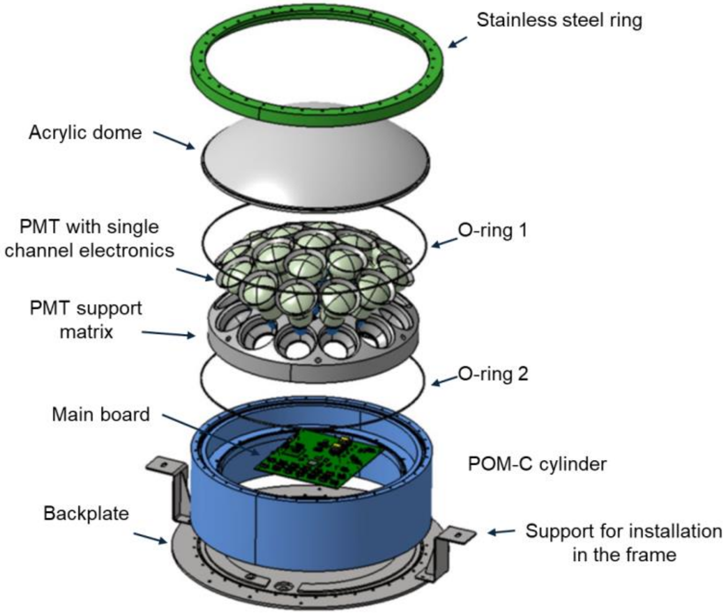




Glass sphere containing 31 3” PMTs, onboard *calibration and and readout electronics*

- ***Photocathode area of about 1300 cm^2*** (three 10” PMT)
- Nanosecond time resolution
- **Uniform angular coverage**
  - *Sensitivity to the incoming direction of detected photons*
  - *Allows to reconstruct charged particle direction*
- Very efficient tool to discard ^{40}K and bioluminescence background through multiple coincidences
- Possibility to define **local triggers** (implemented onshore) **based on the pattern of PMT signals**
- Reduced impact of single PMT failures

mPMT - HyperK

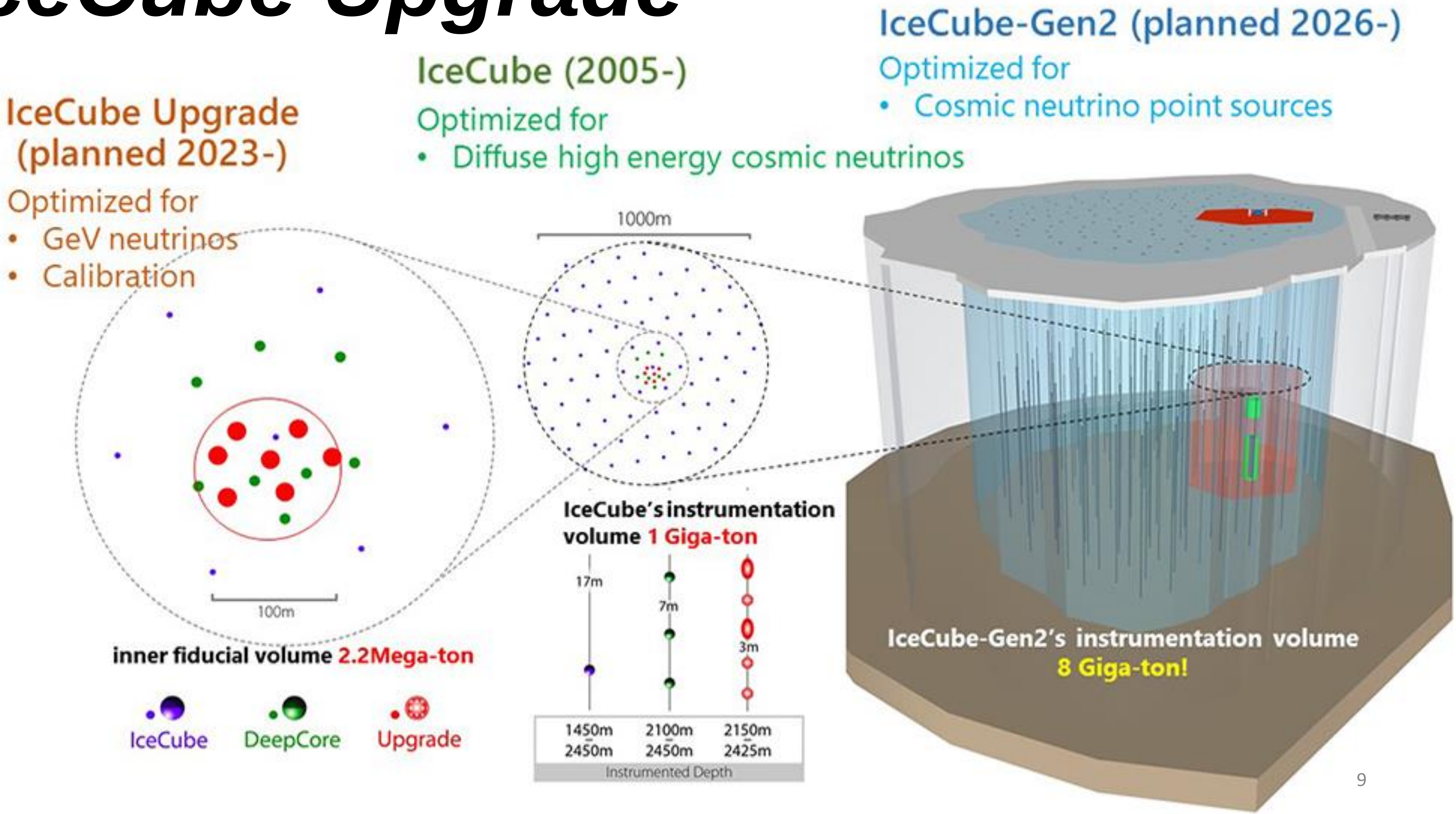


MultiPMT module inspired by the KM3NeT design.

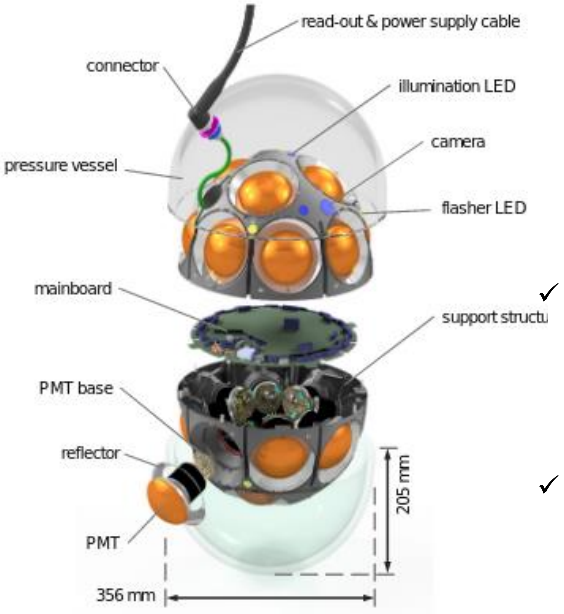
- 19 7,7 cm PMTs in a cylindrical vessel with a radius of 26 cm with acrylic cover and cylindrical body;
- Reflector cones added to each PMT to increase the effective photocathode area;
- Several attractive advantages compared to single PMT:
  - Superior photon counting, improved angular acceptance, extension of dynamic range
  - intrinsic directional sensitivity

Enhanced event reconstruction, in particular for multi-ring events and near wall events

IceCube Upgrade



mDOM and D-Egg



IceCube upgrade foresees the installation of 700 multiPMT devices
~400 mDOM and ~300 D-Egg

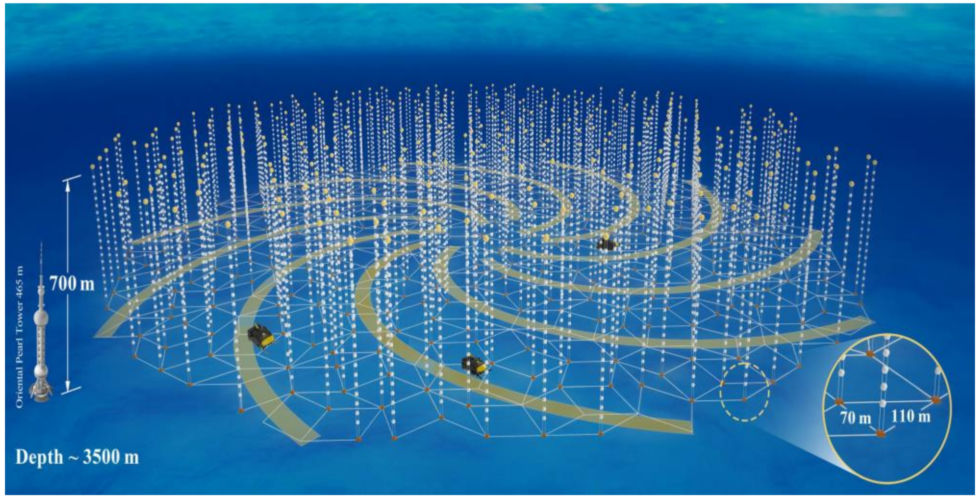
- ✓ *Improved atmospheric neutrino event selection efficiency and reconstruction at a few GeV*
- ✓ *Unique measurements of tau neutrino appearance with a high precision*

24 small (3”) Hamamatsu R15458-02 PMTs arranged in a spherical geometry

Two 8-inch high quantum efficiency PMTs installed back to back

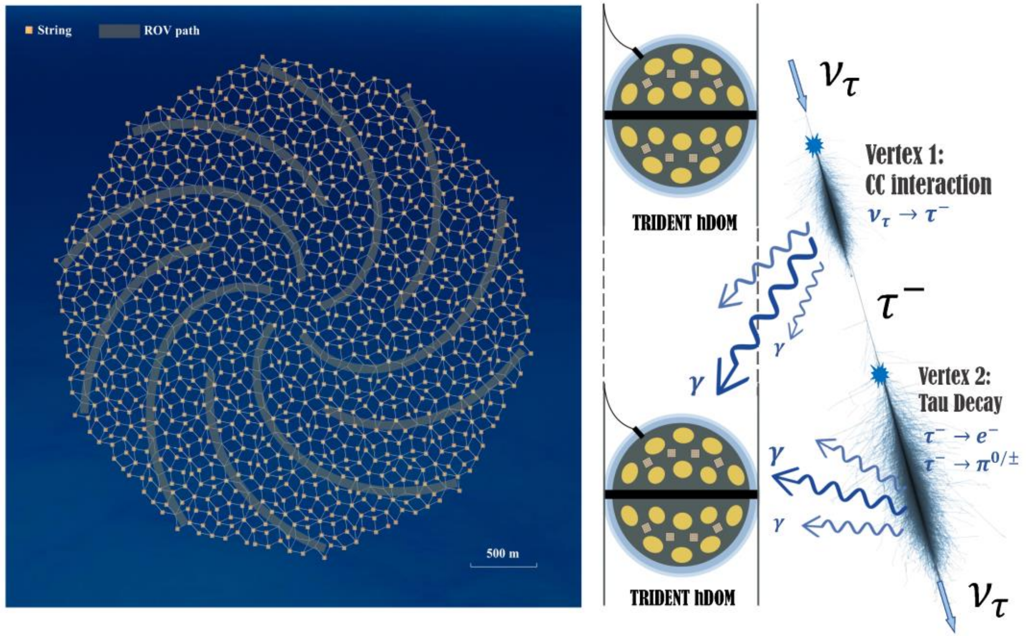
Rich suite of new calibration devices to study the optical properties of glacial ice and the detector response.

TRIDENT – hDOM

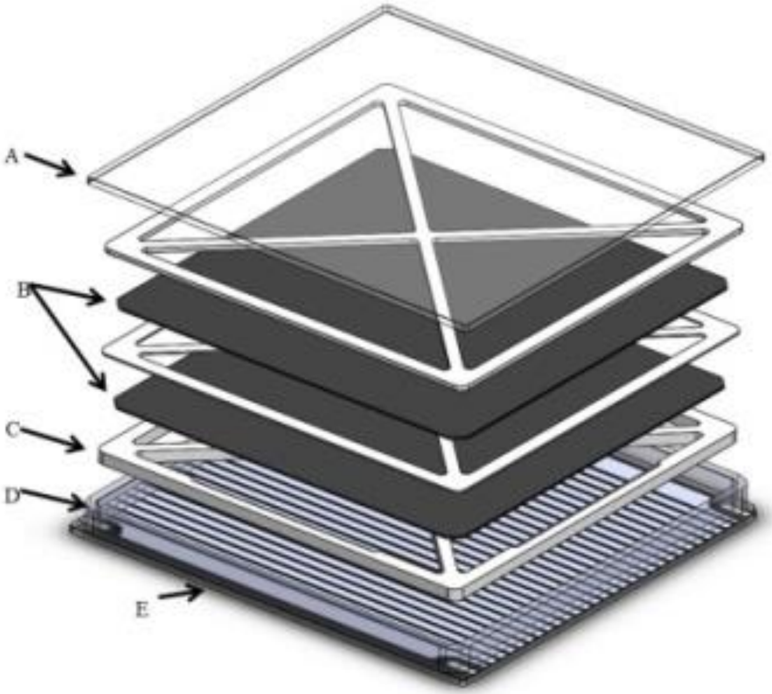


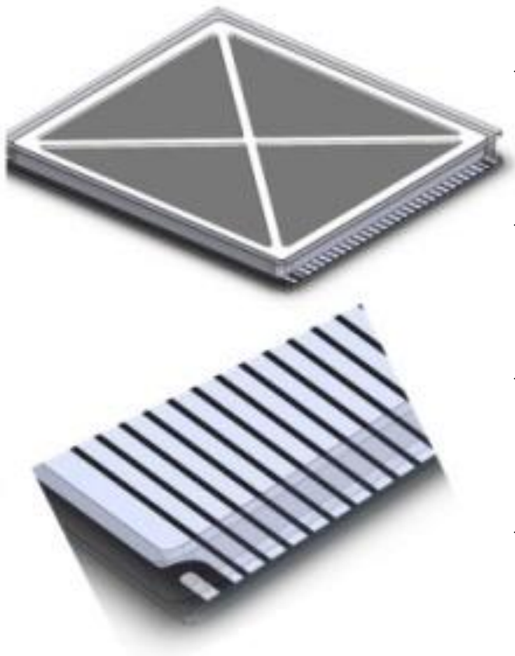
Similar (conceptual) design as KM3Net with SiPM arrays that fill the spaces between PMTs

- ✓ *Maximize the photo-sensitive area*
- ✓ *Improve timing with SiPMs*
- ✓ *Waveform recording from individual PMTs allows for a power discrimination of ν_τ events*

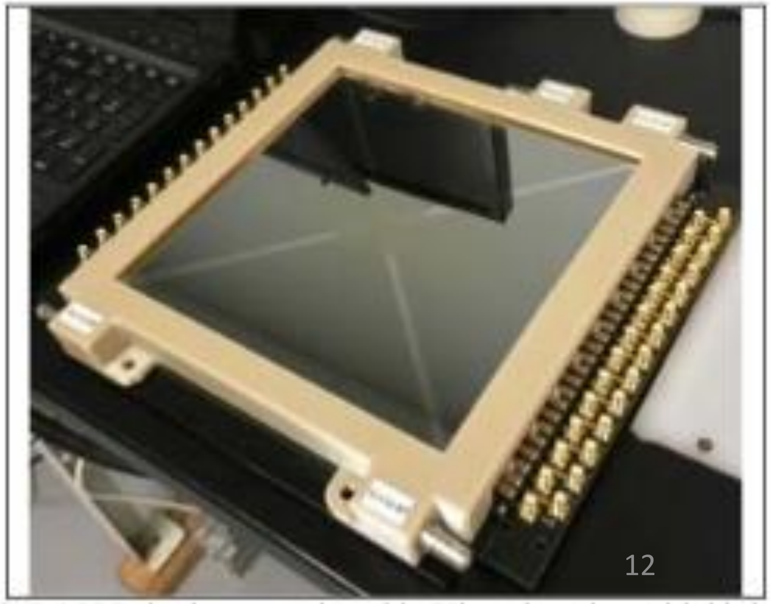


LAPPD Large Area Picosecond Photodetector





- **Large area** (20 cm X 20 cm) ***vacuum device***
- *Fused silica window with MultiAlkali photochatode on the inside*
- Two stage of electron multiplication through ***microchannel plates***
- **Strip anode** =>spatial reconstruction of the hit



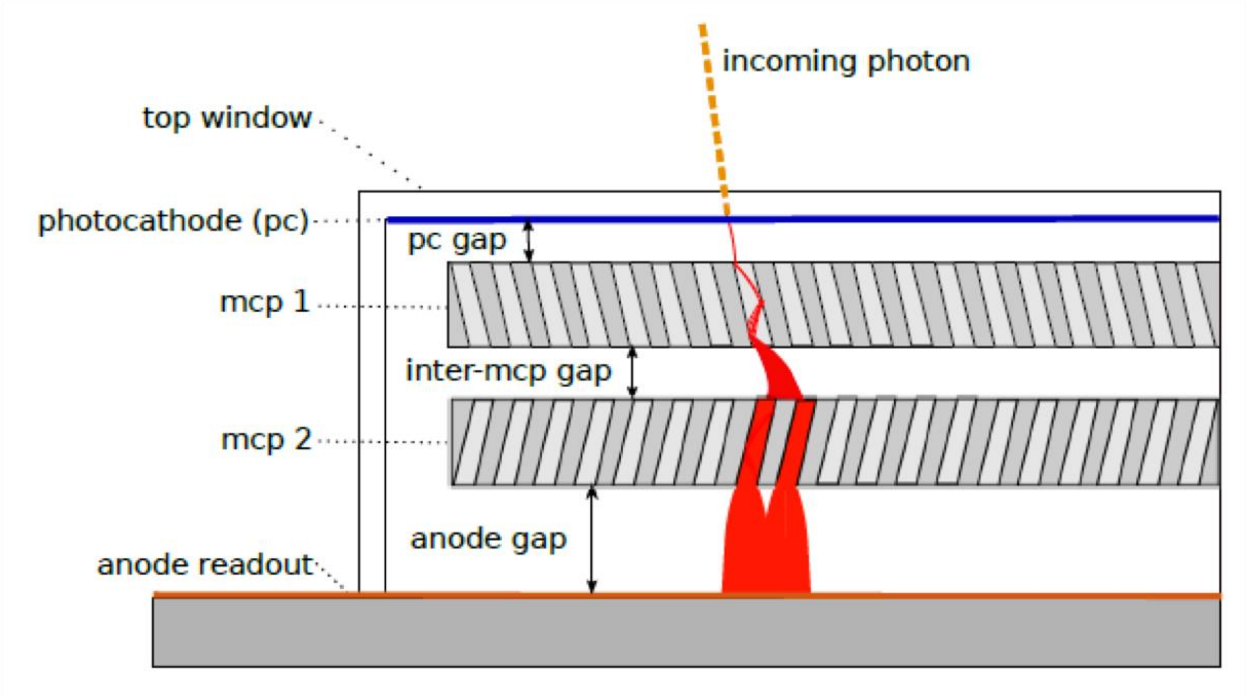
QE ~20%

Time resolution < 100 ps for single photon events

Space resolution < 1 mm in both directions

Gain ~ 10^7 and Dark noise ~20 Cts/s/cm^2

LAPPD Large Area Picosecond Photodetector



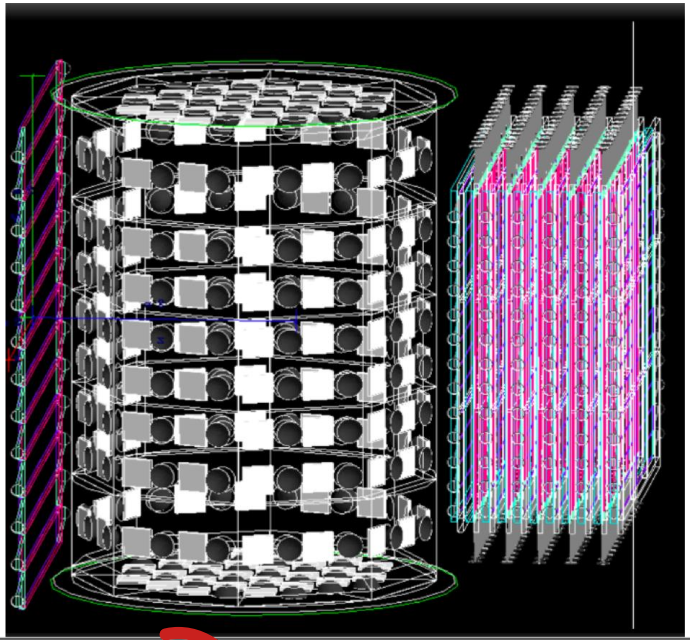
Enabling Technologies:

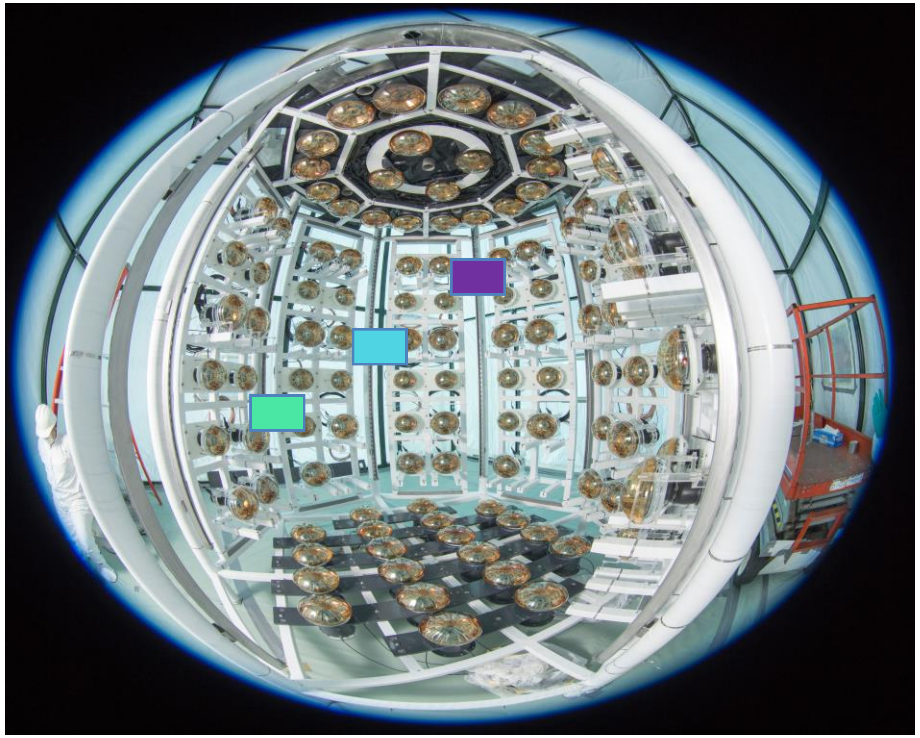
- ✓ Produce ***large blocks of low cost, hollow, glass capillary arrays with micron-sized*** pores **(Incom Inc)**. No need of chemical etching

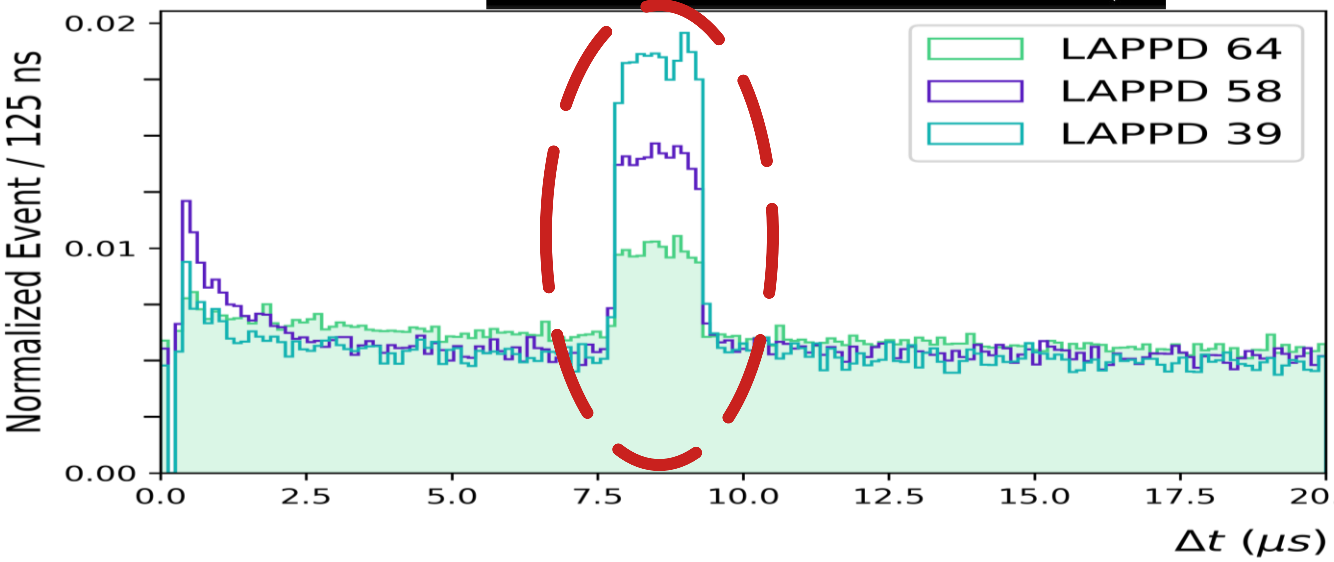
- ✓***Atomic layer deposition coating methods*** to impart the necessary **resistive and secondary emission properties** for high electronic gain and robust performance

LAPPD: ANNIE detector

- ***26-ton Gd-loaded water Cherenkov*** detector installed in the *BNB at Fermilab*
- **Study the neutron multiplicity** in *CC neutrino-nucleus interaction in water*
- **Demonstrate the use of LAPPD**

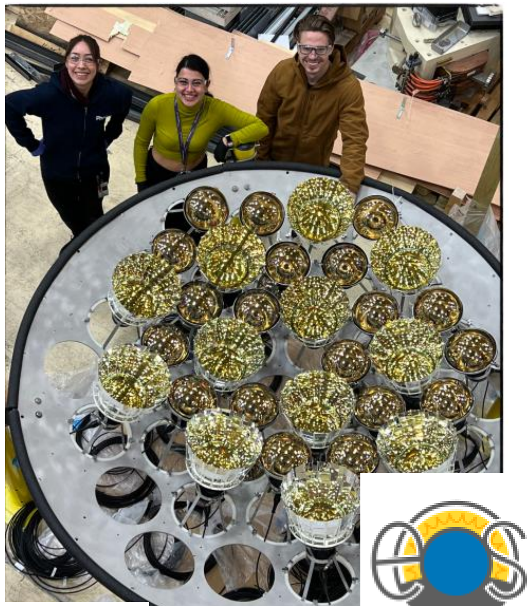






Neutrino events ***triggered with LAPPD***. Time distributions reproduces 1.6 μs BNB spill

Theia and EOS demonstrator

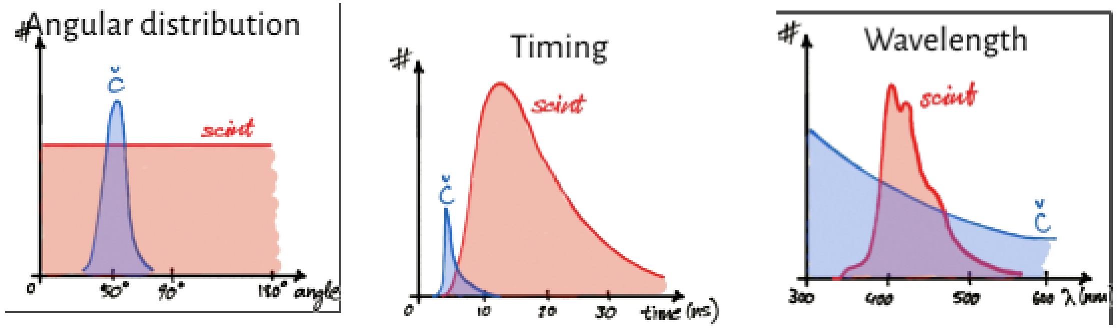


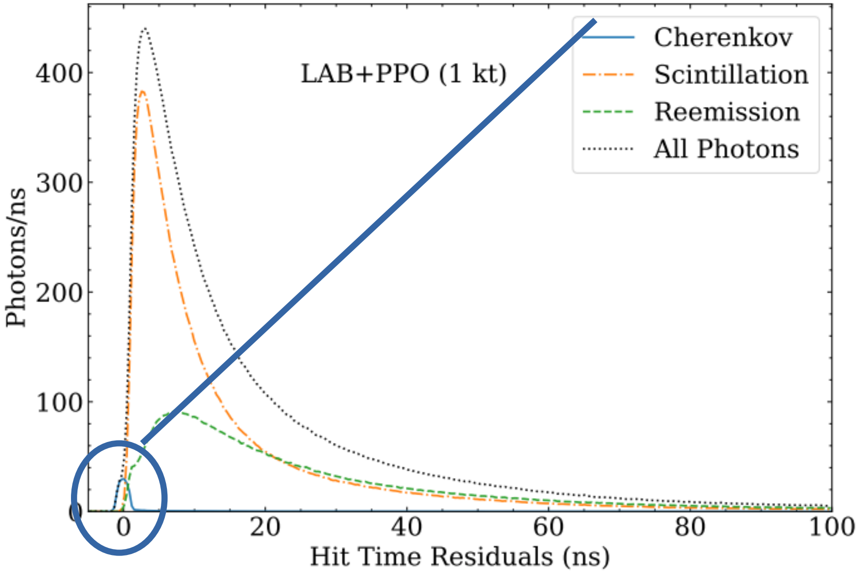
Hybrid multipurpose Cerenkov/scintillation detector with extremely rich physics program

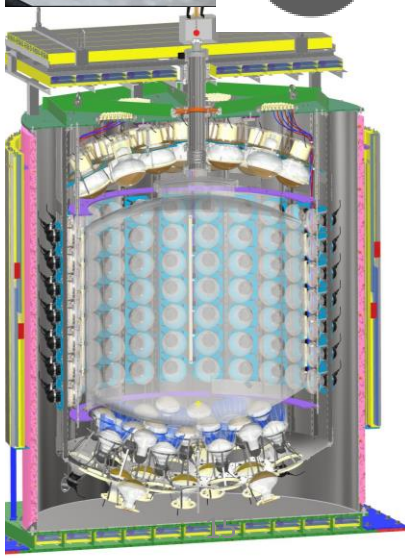
Enabling Technologies:

- ✓ ***Novel targets*** => water-based liquid scintillator (WbLS).
- ✓ **LAPPDs photon sensors**
- ✓ ***Dichroicons*** (“chromatic quantum sensing”). Cherenkov/scintillation separation via spectral sorting

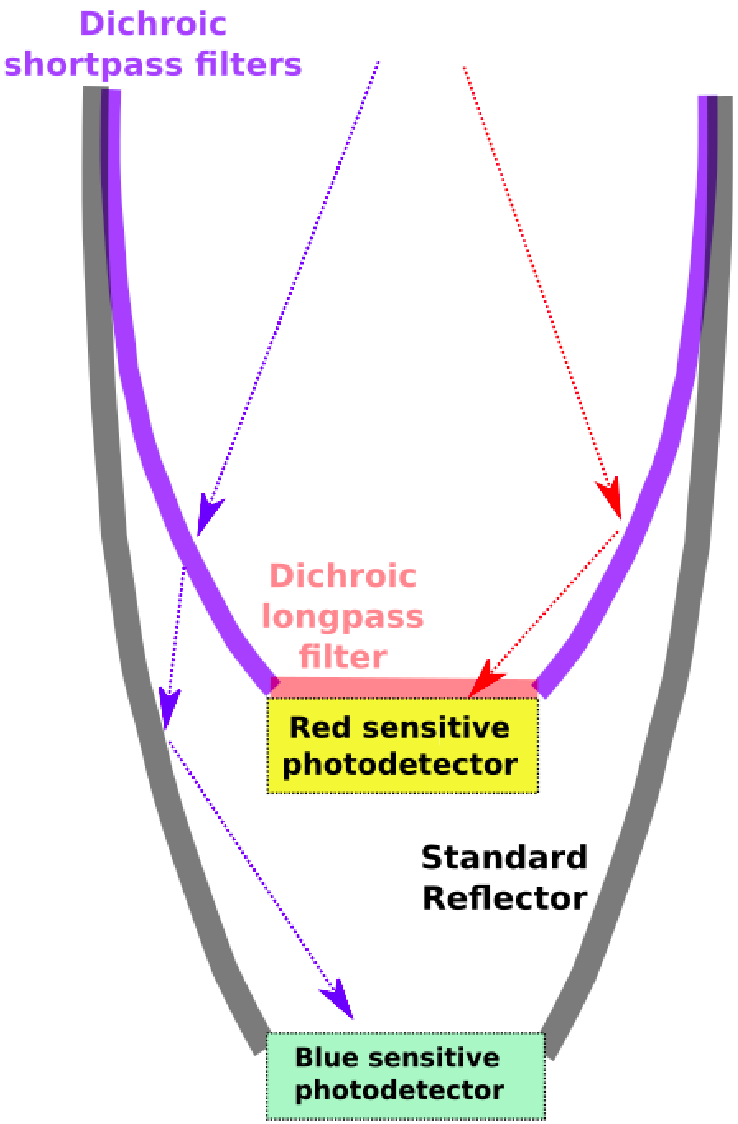
Preserve directional Cherenkov signature against more abundant scintillation yield



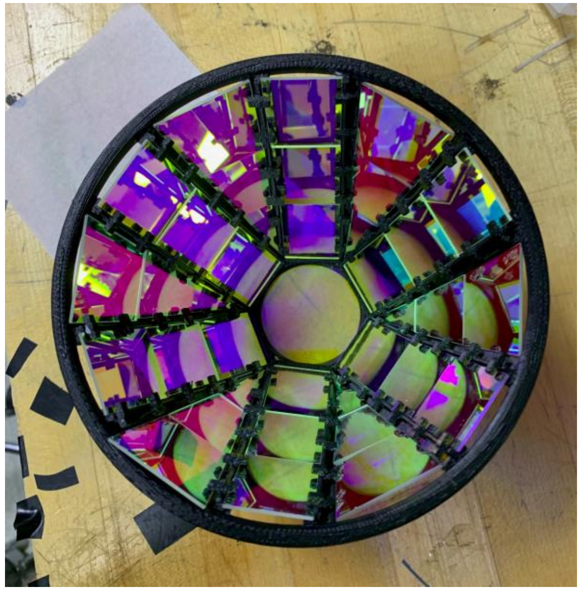


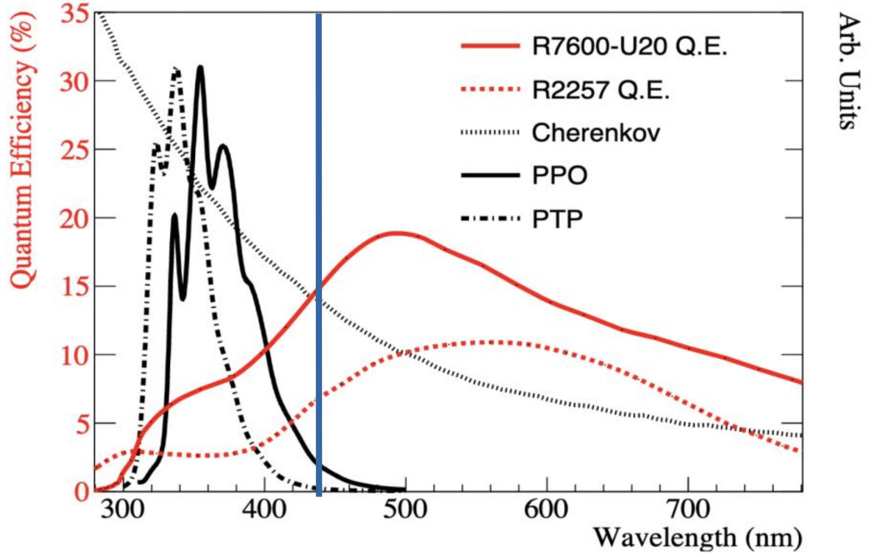


Dichroicon: sorting photons’ wavelengths

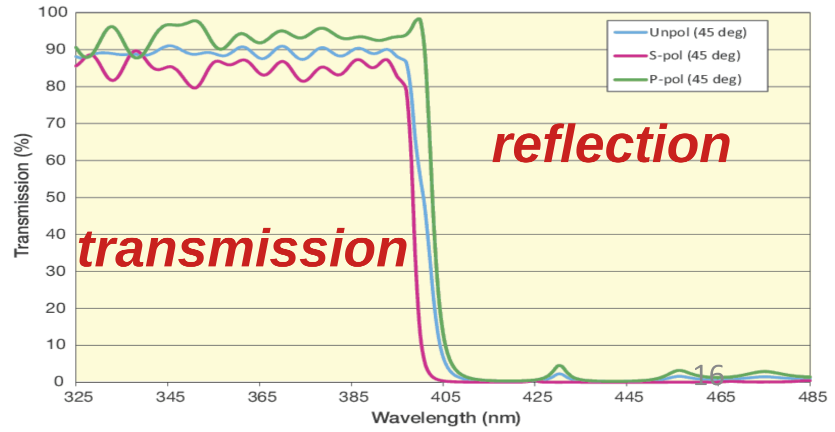


Enabling technologies:
Winston cones and dichroic filter

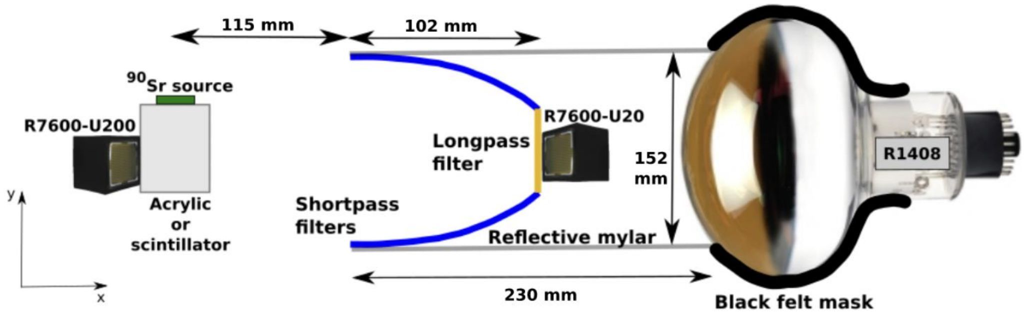


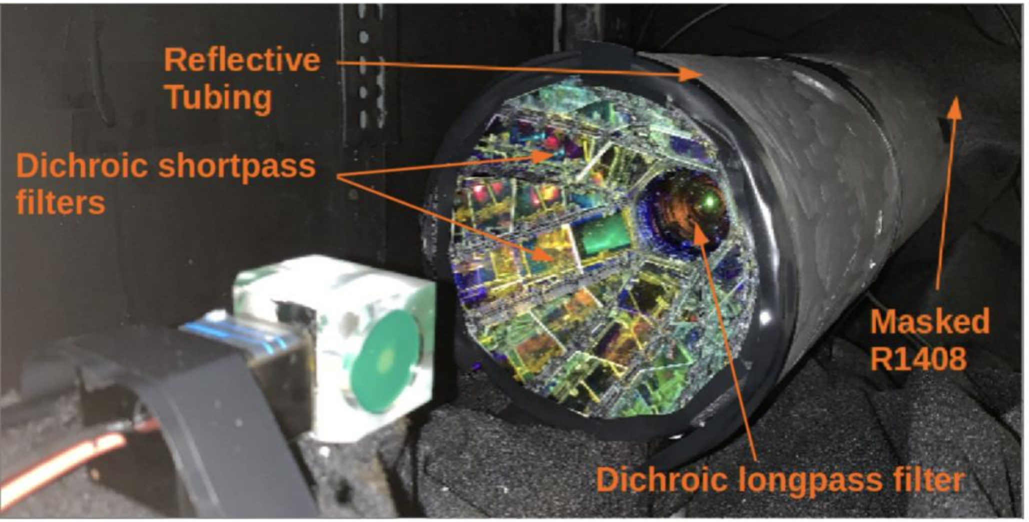


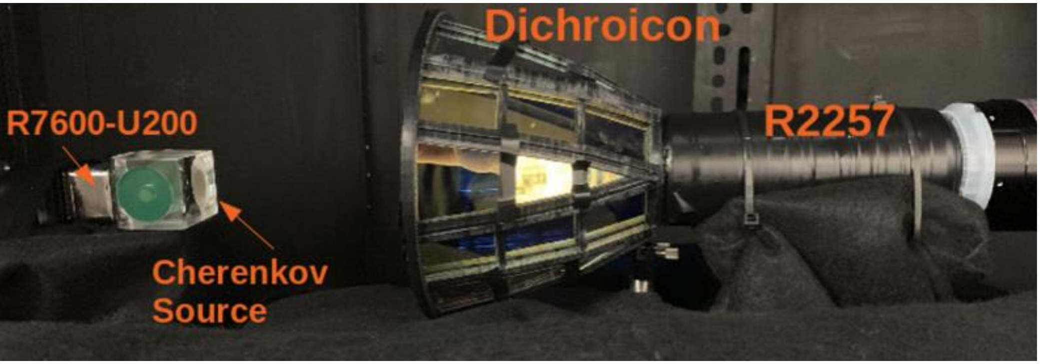
Winston cone *made of* ***flat dichroic filters*** *=> concentrate long wavelenrgths and pass short wavelength*

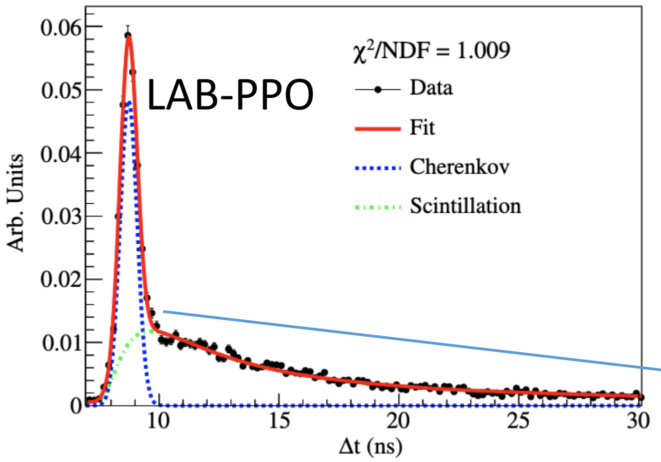


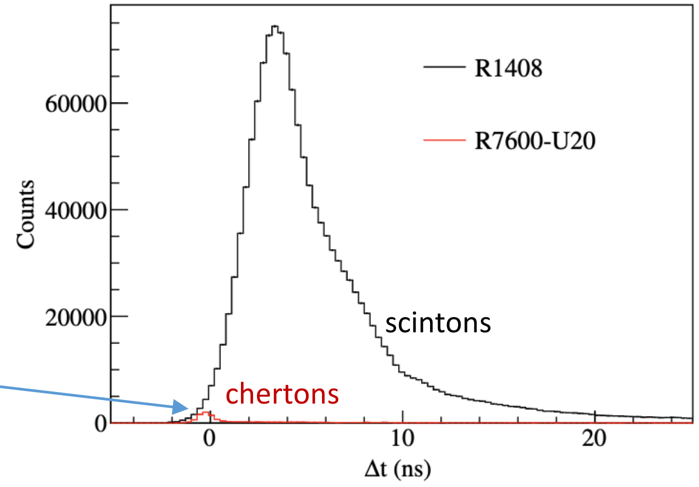
Dichroicon: sorting photons' wavelengths

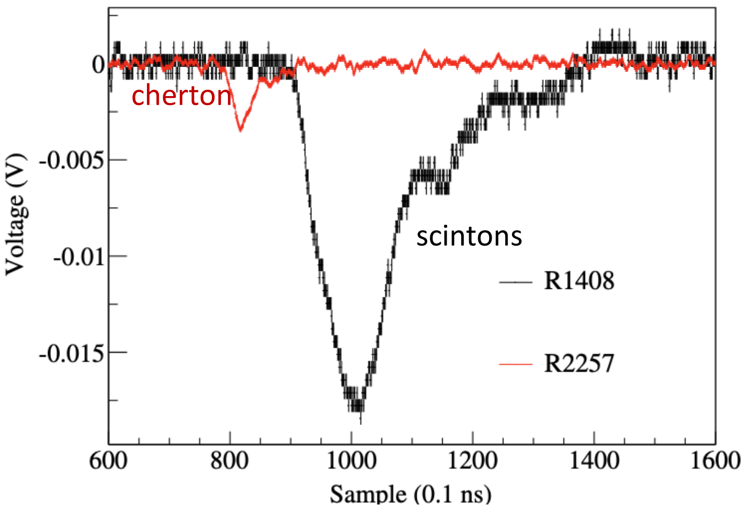


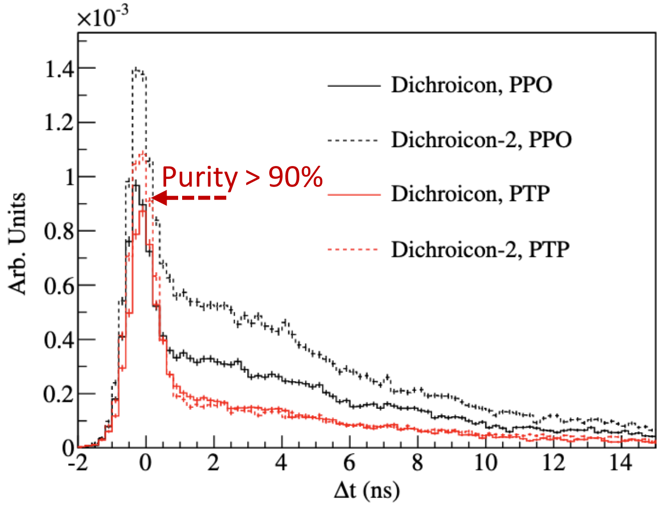






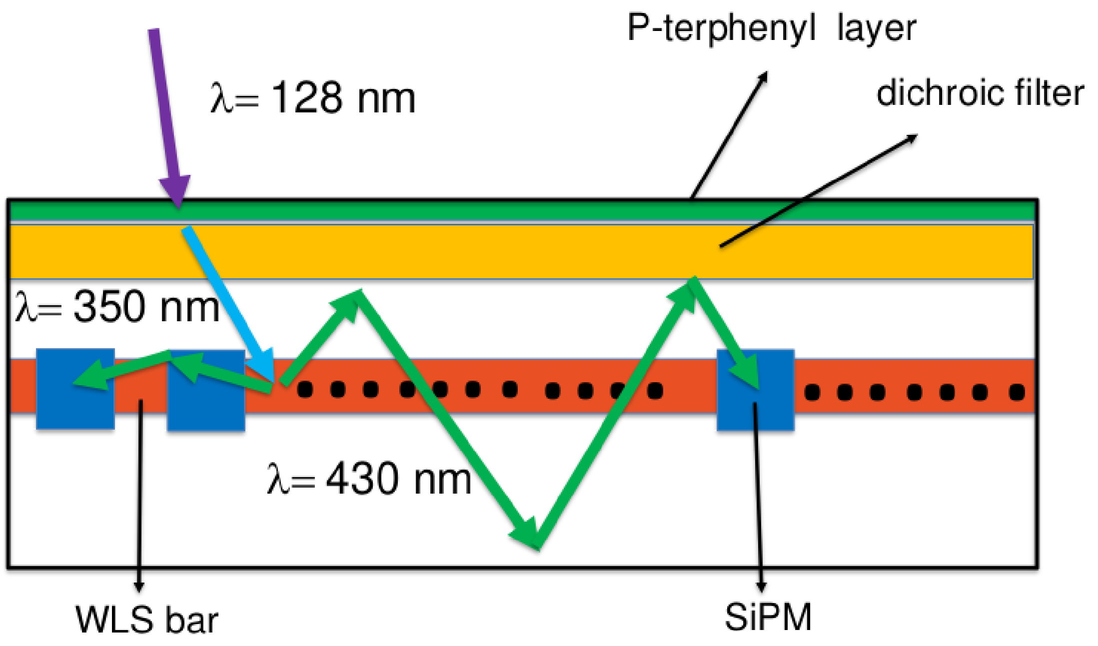


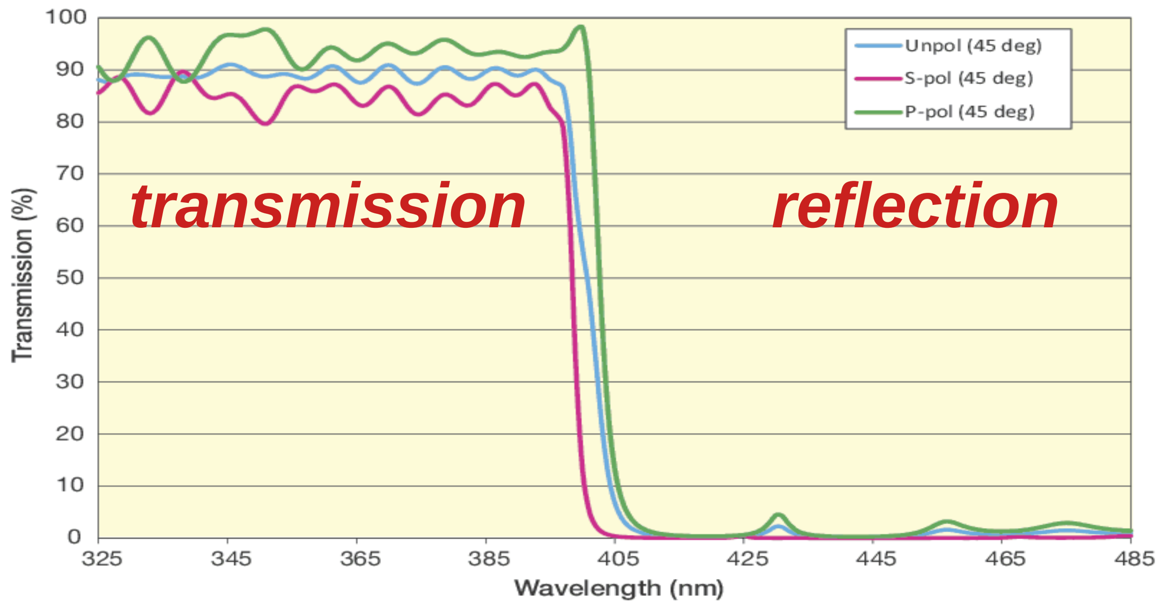




Phys. Rev. D 101, 072002

DUNE PD System: X-ARAPUCA

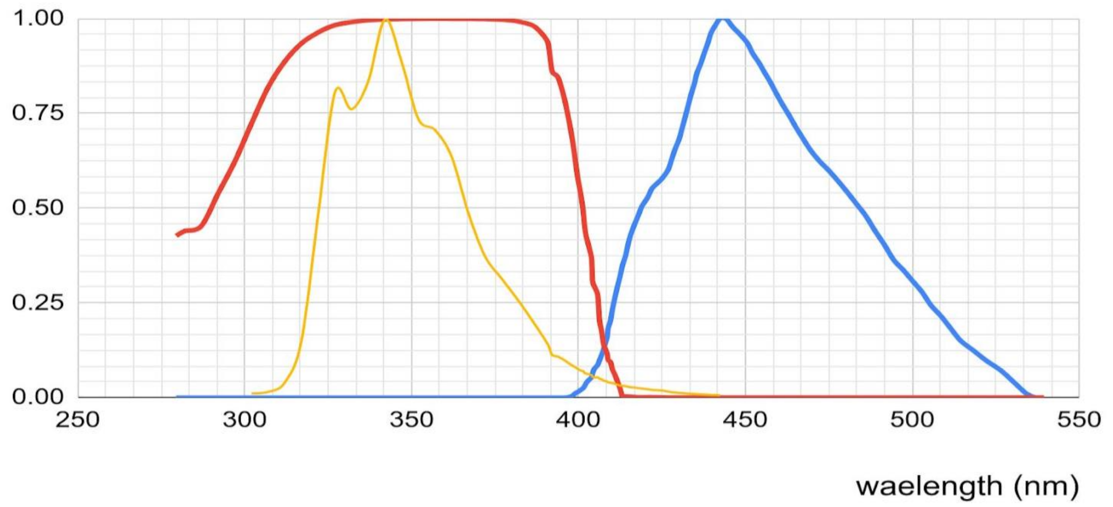




Large area photon collector coupled to an array of SiPMs

Photon trapping through:

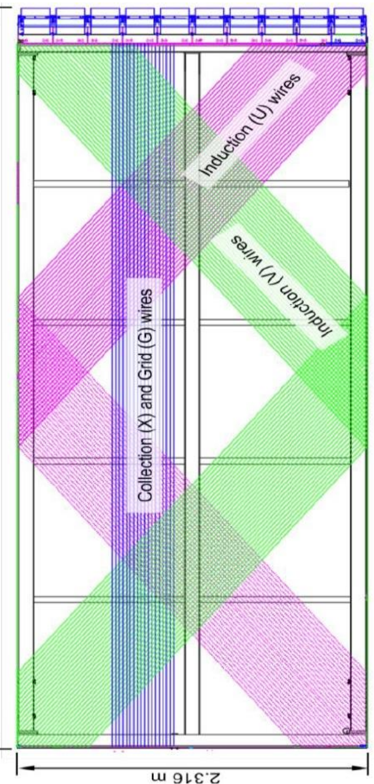
- ✓ ***Total internal reflection in the WLS***
- ✓ ***Trapping through dichroic filter***

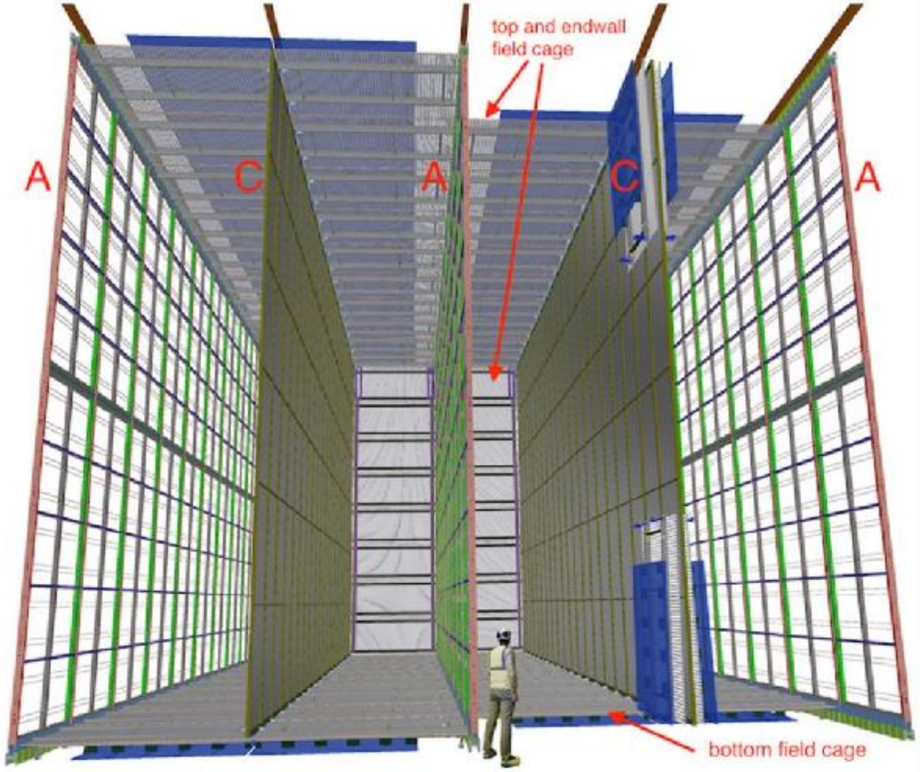


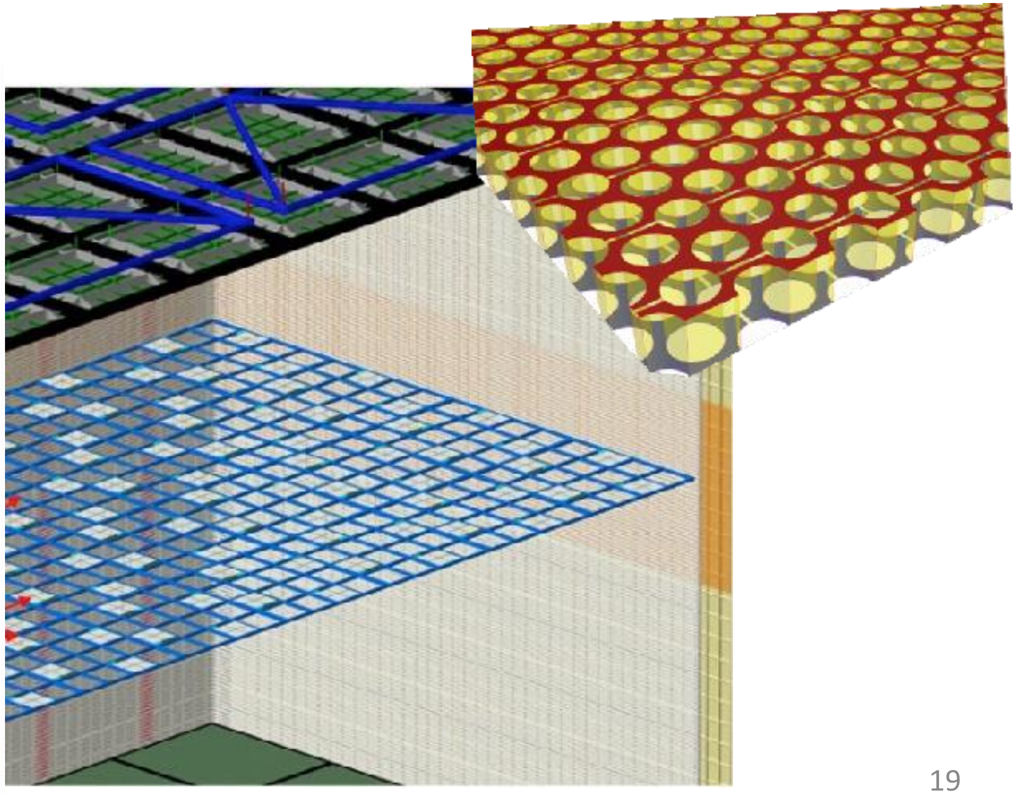
LAr Read-out Technologies of DUNE far detectors

Horizontal Drift
-3.6 m horizontal drift
-vertical anode wire planes
-vertical resistive cathode
photon detectors → ***XARAPUCAs***

Vertical Drift
-6.5 m vertical drift
-horizontal PCB anode readout (CRP)
-horizontal grid cathode
photon detectors → ***XARAPUCAs***





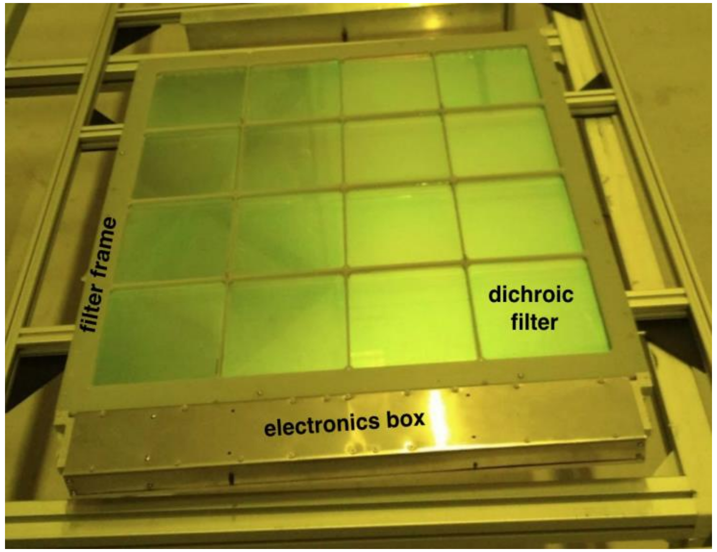


X-ARAPUCAs in DUNE

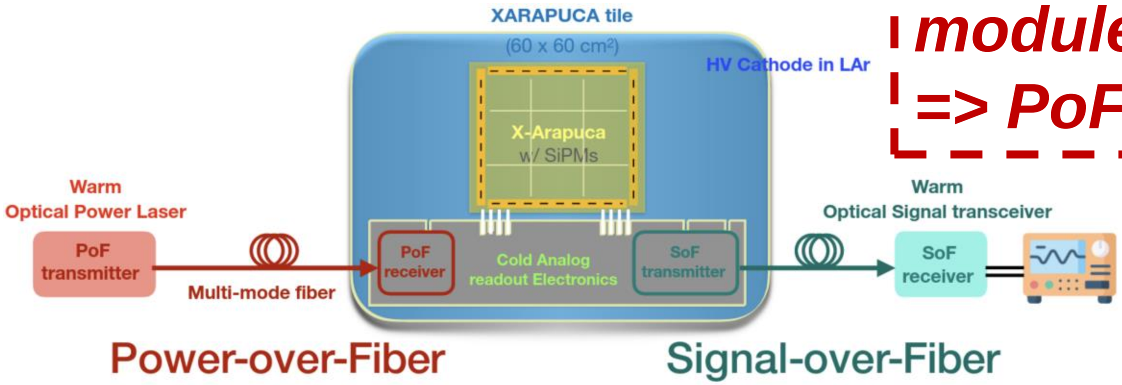
- ✓ Bar shaped modules
- ✓ 200 x 10 cm^2
- ✓ 4 independent read-out channels
- ✓ 4 x 48 SiPMs ganged together

- ✓ Square modules
- ✓ 60 x 60 cm^2
- ✓ 2 independent read-out channels
- ✓ 2 x 80 SiPMs ganged together

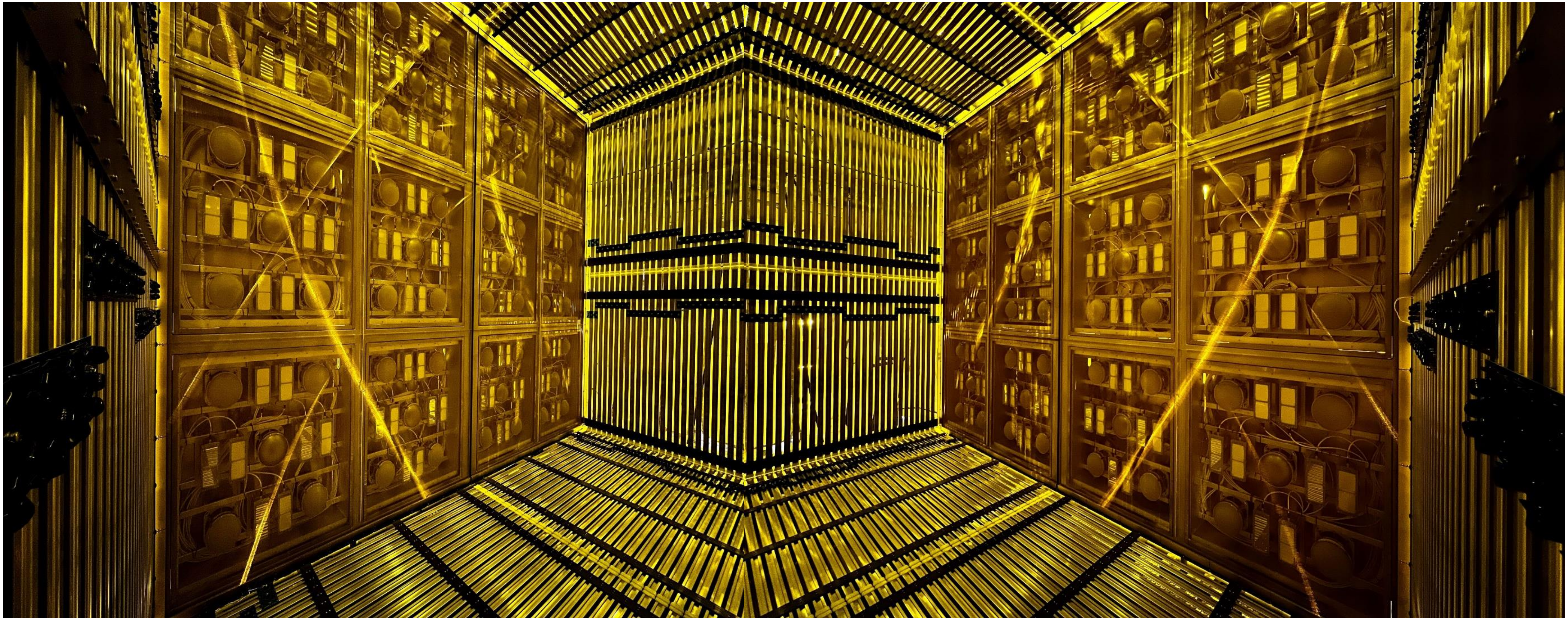
Efficiencies around 2% - 4%



Half of the modules at 300 kV => PoF and SoF

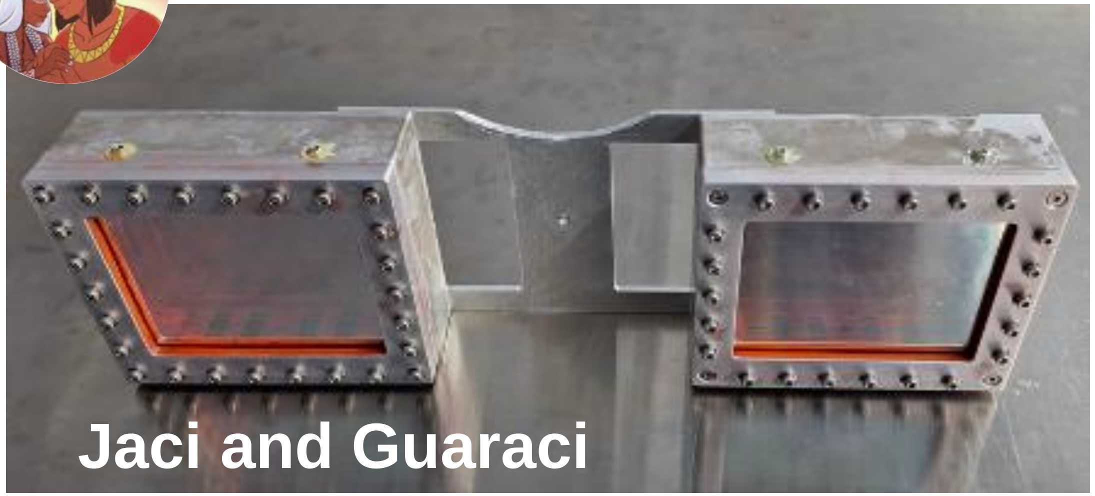


X-ARAPUCAs in SBND



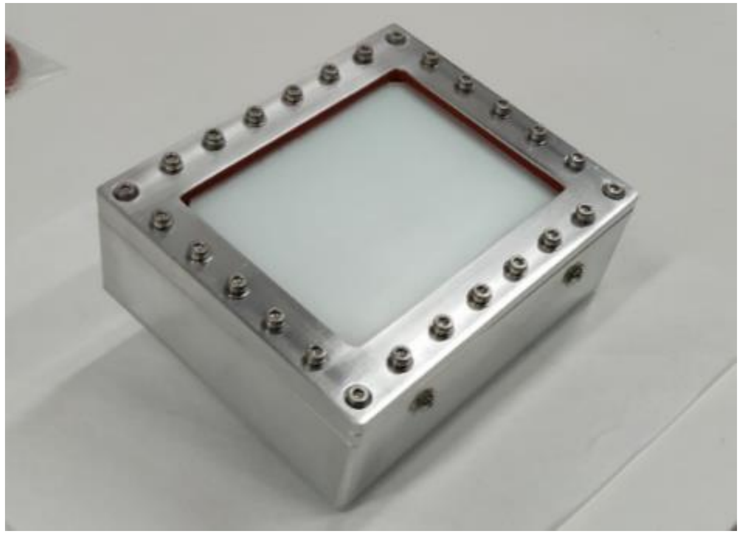
196 small X-ARAPUCAs installed in the SBND detector at Fermilab

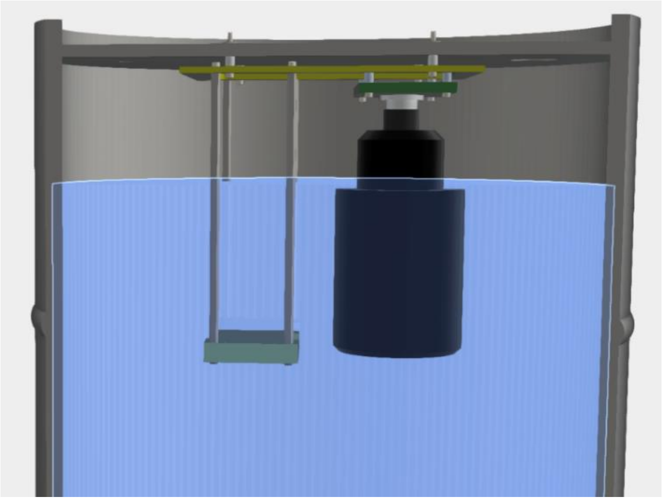
C-ARAPUCA

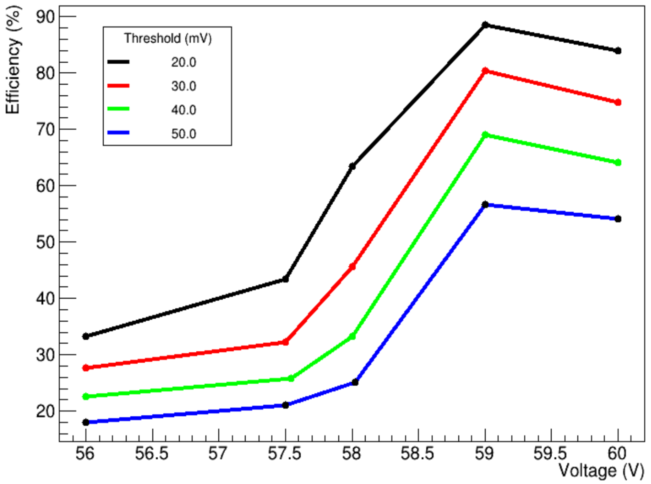


Spin-off of the ARAPUCA program for the detection of Cerenkov light in water

Dichroic filter and light guide tuned for the Cerenkov spectrum in water

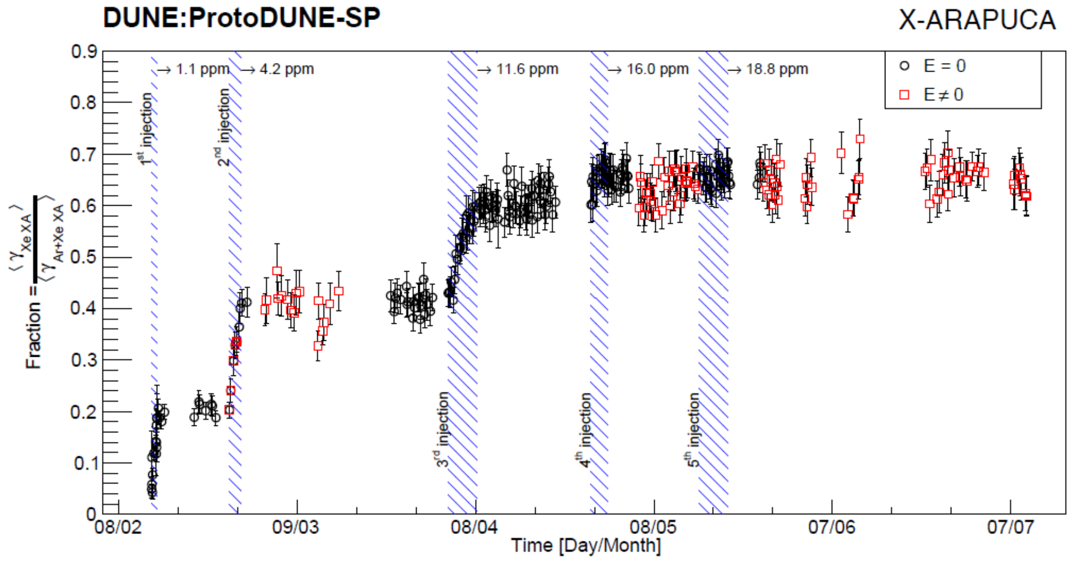


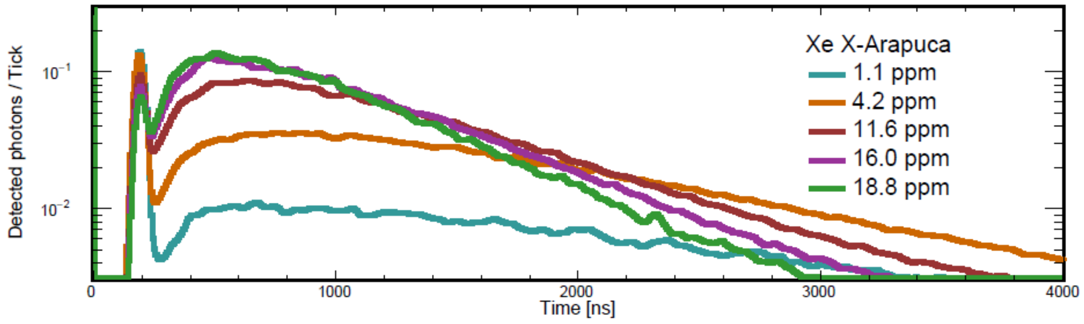




Xenon doping of liquid Argon

Diluting small quantities of Xe @ 10 ppm level into LAr shifts the slow component of scintillation light (70% of the total for a m.i.p.) from 128 nm to 175 nm and shortens the pulse



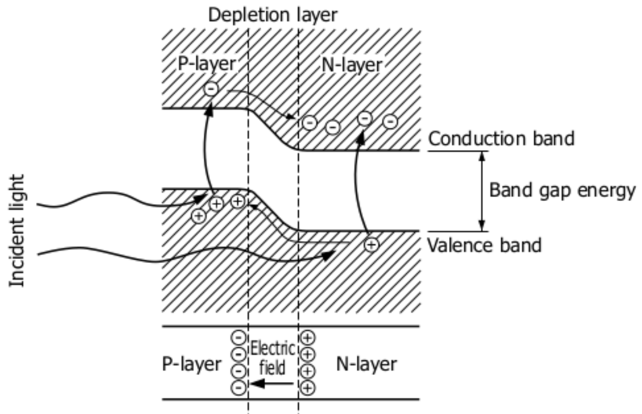


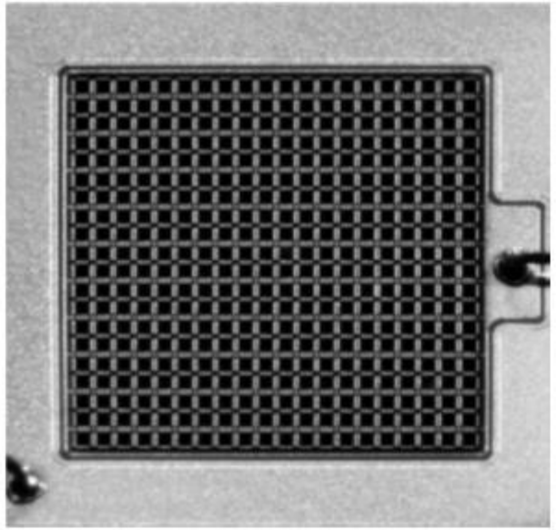
- ✓ Rayleigh scattering length 6 times larger at 175 nm
- ✓ Better uniformity in light collection
- ✓ 175 nm photons more easily detected
- ✓ Potential recovery from N_2 contaminations

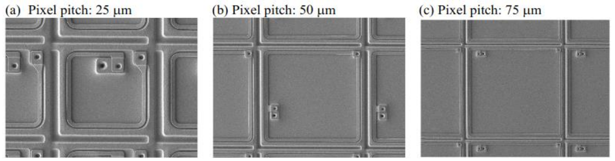
✓ *Fast component seems to be partially absorbed. Impact on trigger.*

Tested in protoDUNEs runs at CERN

SiPMs

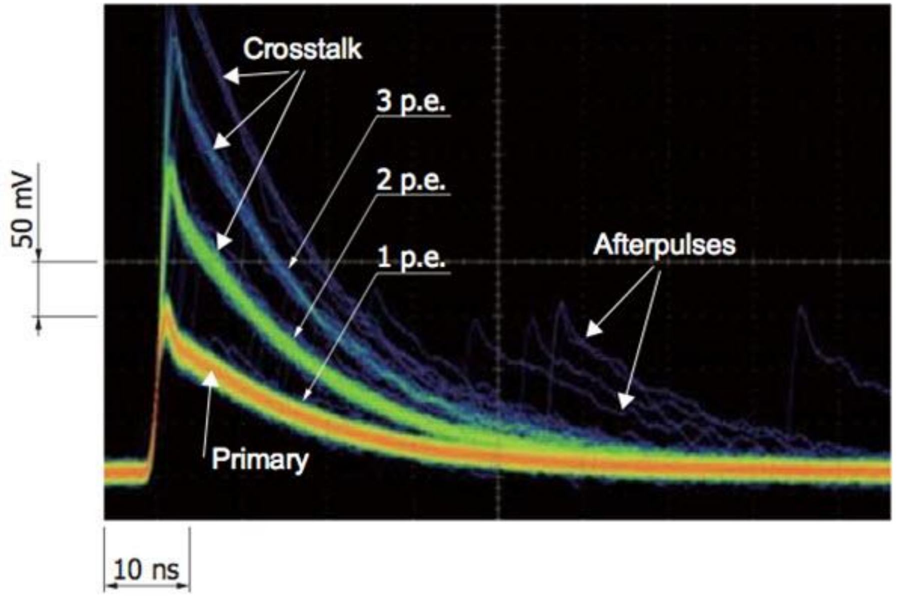


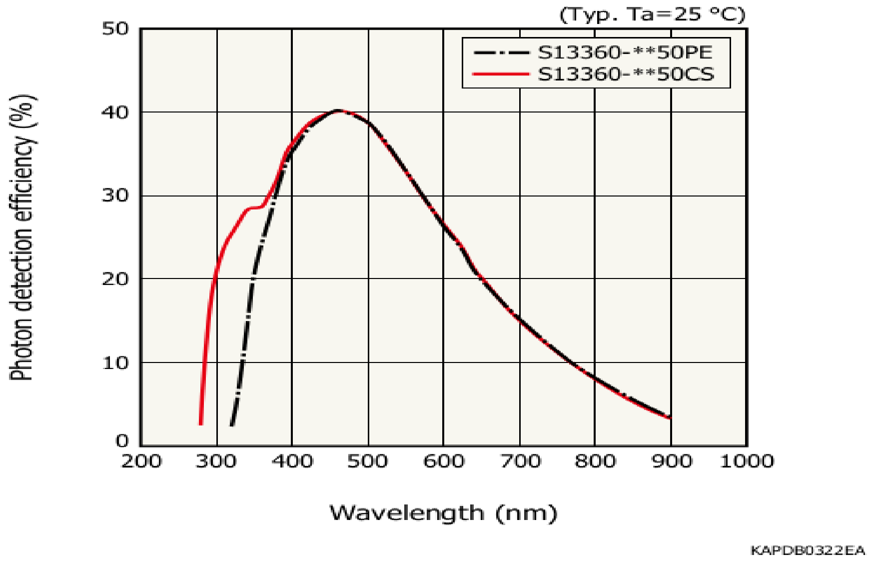


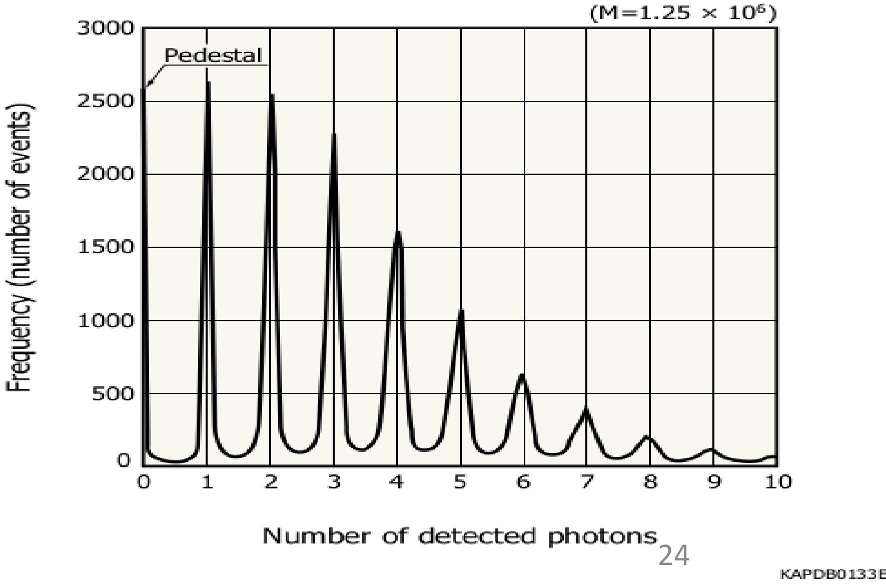


Becoming very popular in particle physics

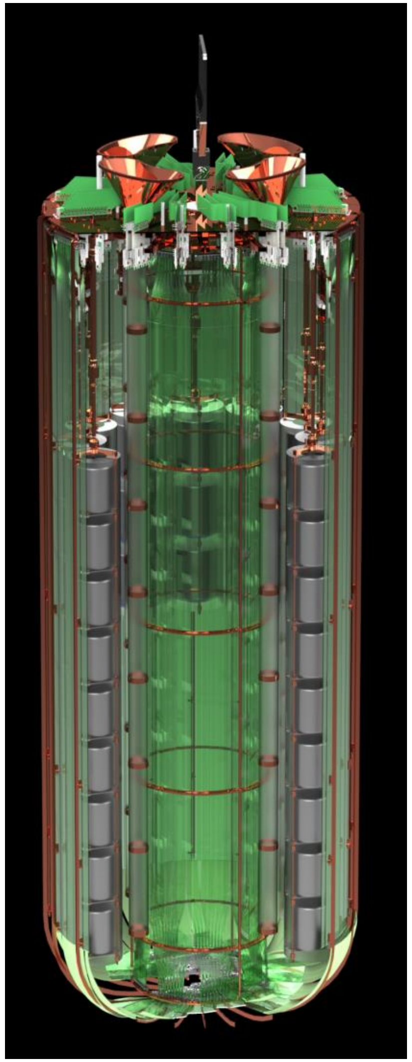
- ✓ ***Low bias voltage (< 100 V)***
- ✓ ***High gain and High QE (~50%)***
- ✓ ***Fast devices***
- ✓ ***Low dark counts at cryogenic temperature***
- ✓ ***High Single Photon resolution***
- ✓ ***Low background***

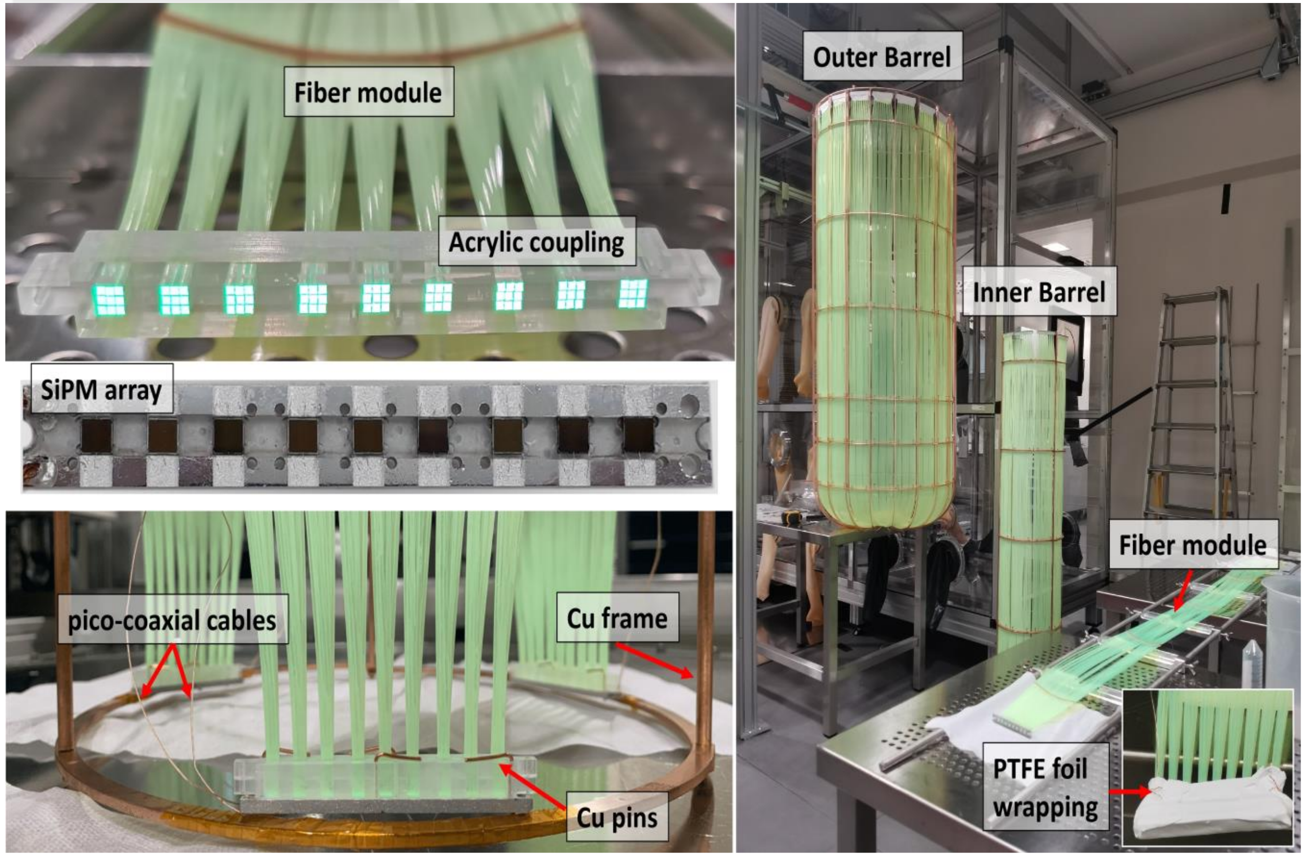






SiPMs: Legend





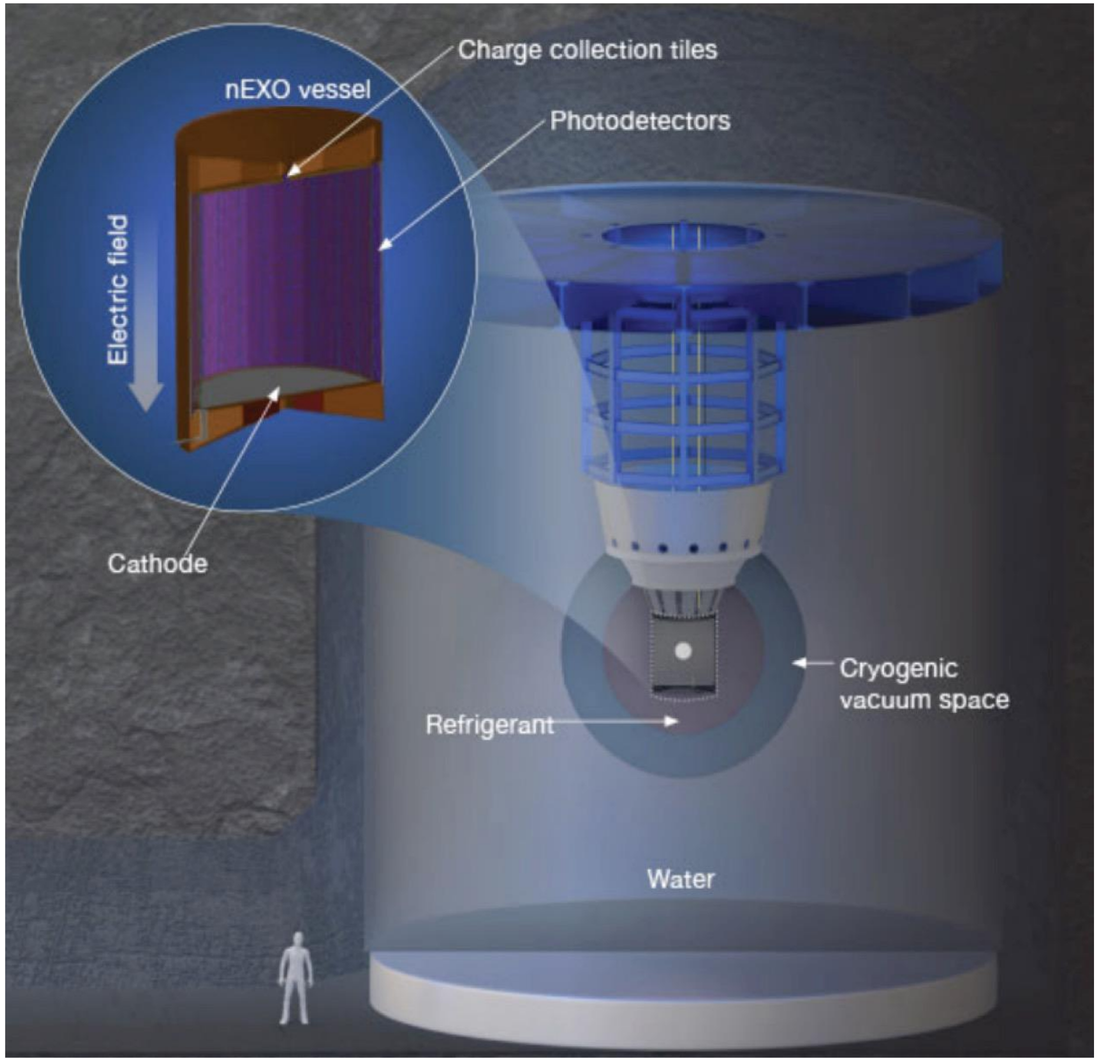
Array of SiPMs to read-out the liquid argon veto of the Ge detectors

SiPM read-out of LAr active veto
SiPM coupled to WLS fibers coated with TPB. Double shift of the VUV LAr scintillation photons.

Excellent background rejection with Particle ID

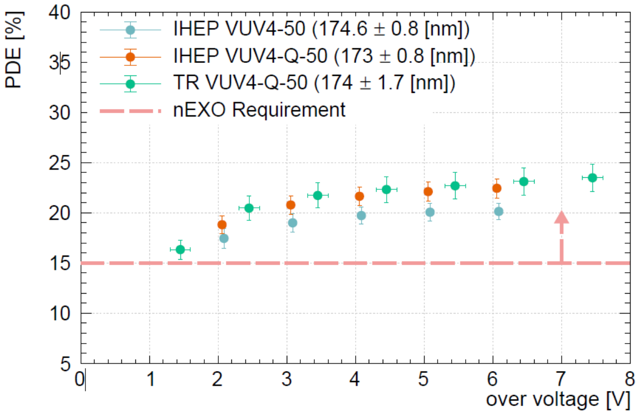
Nina Burlac

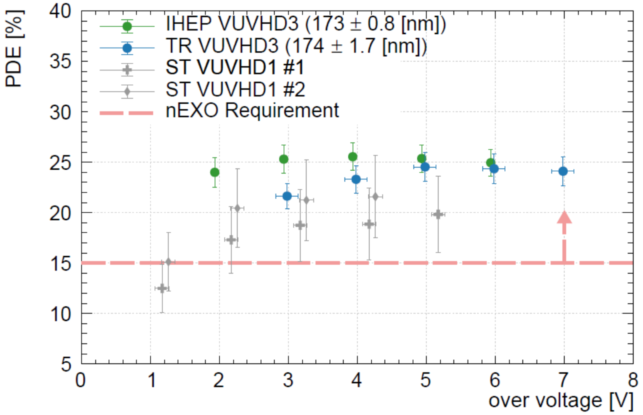
SiPMs: nEXO



Large array covering an overall area of 4.5 m^2

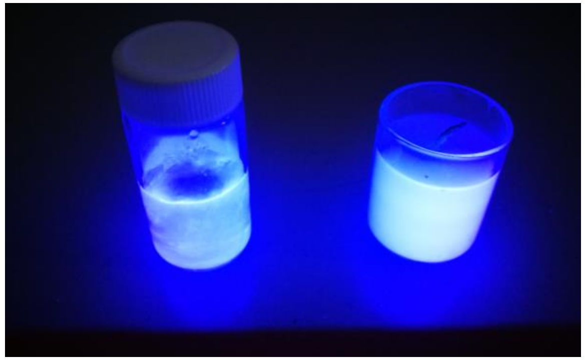
Cryogenic (operating @ 165 K) and VUV sensitive SiPMs (175 nm)

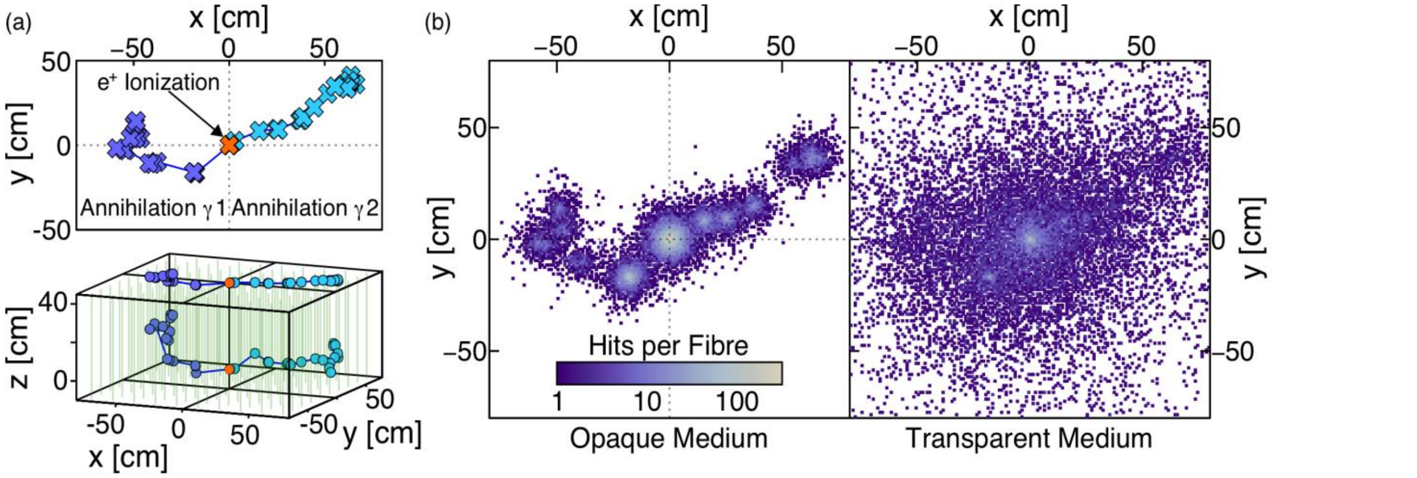


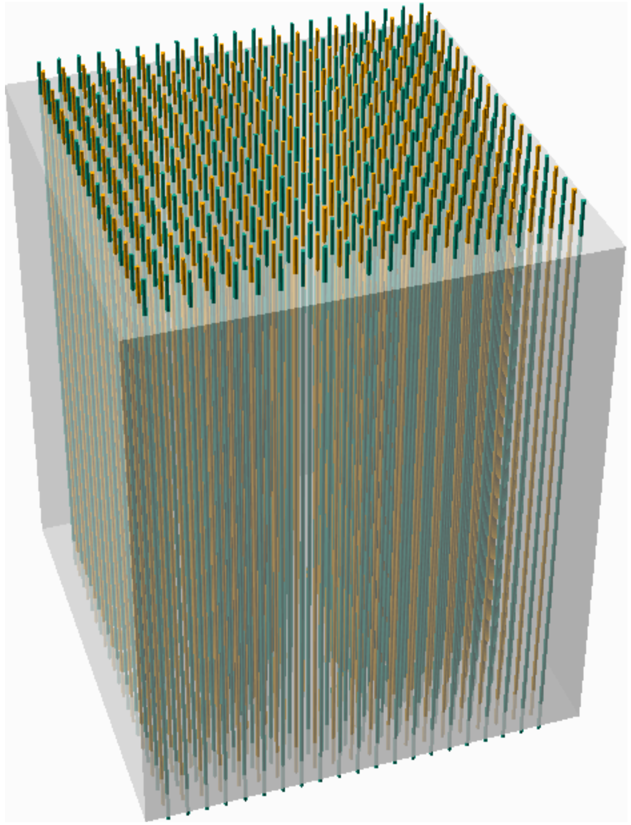


LiquidO

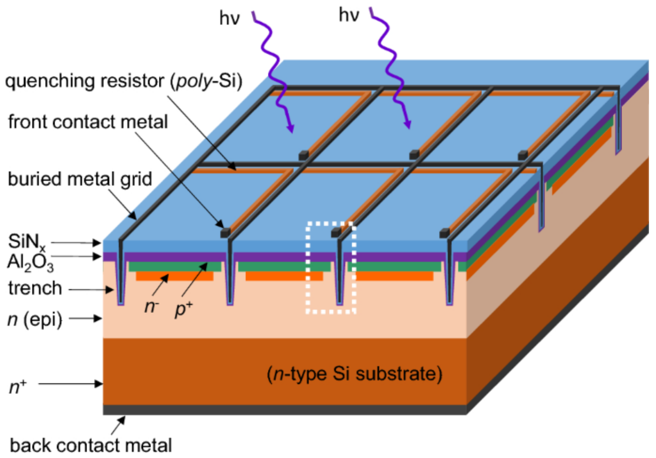
- ✓ *Scintillation in an opaque medium*
- ✓ *Scattering cross section >> absorption cross section*
- ✓ *Light confined through Raileigh or Mie scattering*
- ✓ *Dense array of wls fibers to collect scintillation light coupled to SiPM*
- ✓ *Fiber position gives 2-D projection of the event (mm resolution)*
- ✓ *Third dimension given by time difference in the arrival time of light at the wls extremities (~cm resolution)*

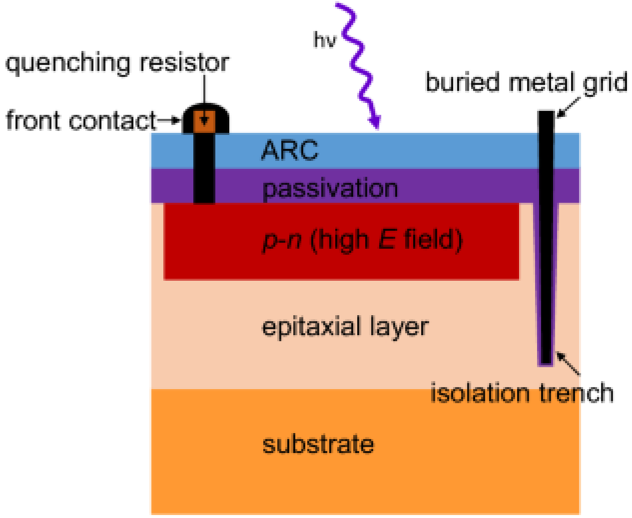


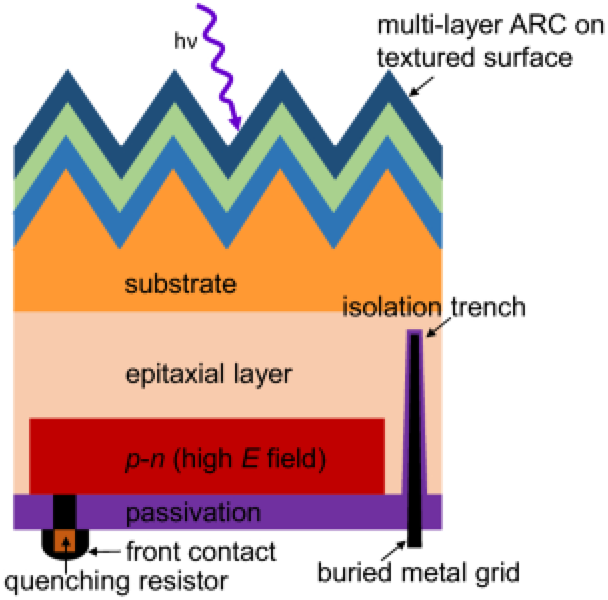




SiPMs: back illuminated

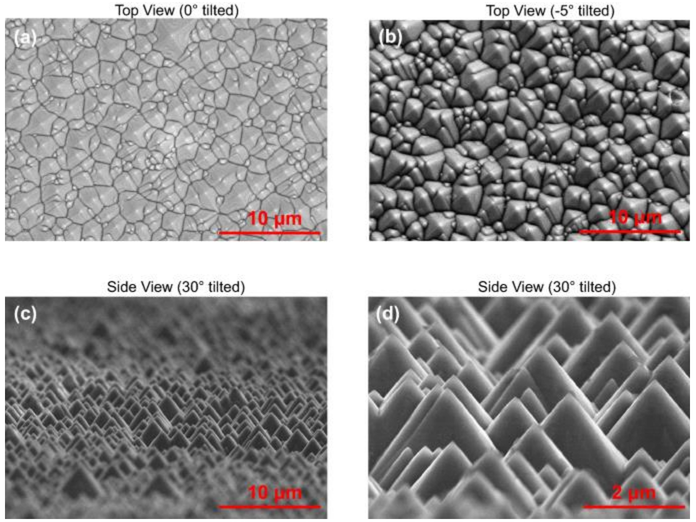






SiPM detection efficiency (PDE) limited by:

- ✓ ***Fill factor of the pixelated area***
- ✓ ***Reflections***

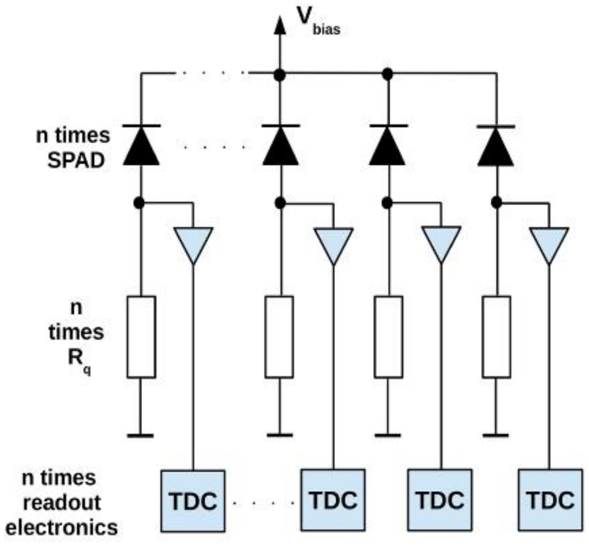


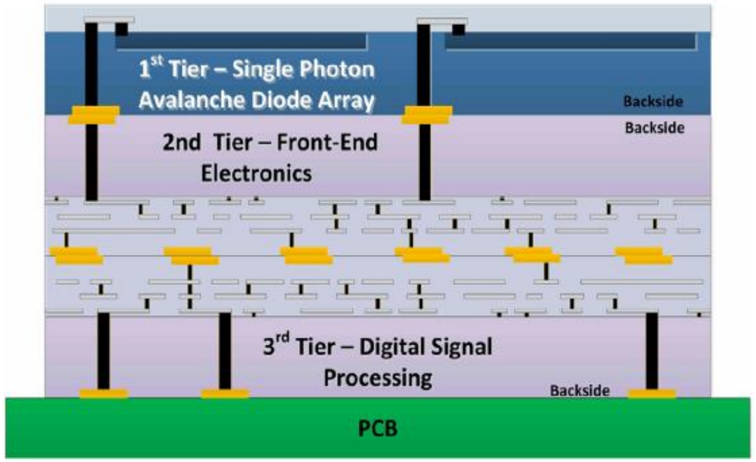
BI design minimizes dead areas and combination with Anti Reflective coatings and textured surface reduces reflections significantly

SiPMs: digital

Possibly the perfect photodetector :

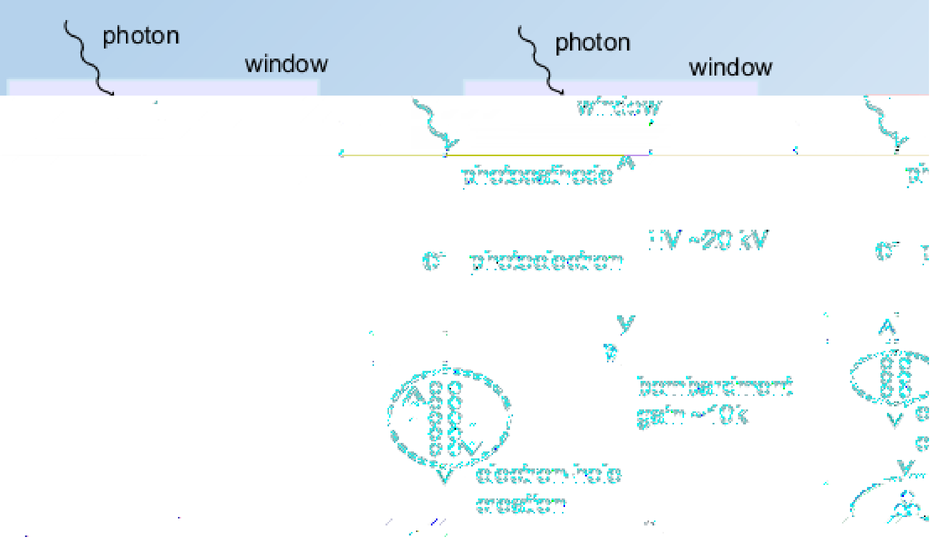
- ✓ Each pixel connected to its own readout electronics => time-stamp
- ✓ First commercial dSiPM introduced by Philips around 2010 → one time-stamp per scintillation event (PET application and Cerenkov light detection)
- ✓ Latest developments → 3D assembly → 1) pixels 2) quenching circuits 3) signal processing and readout

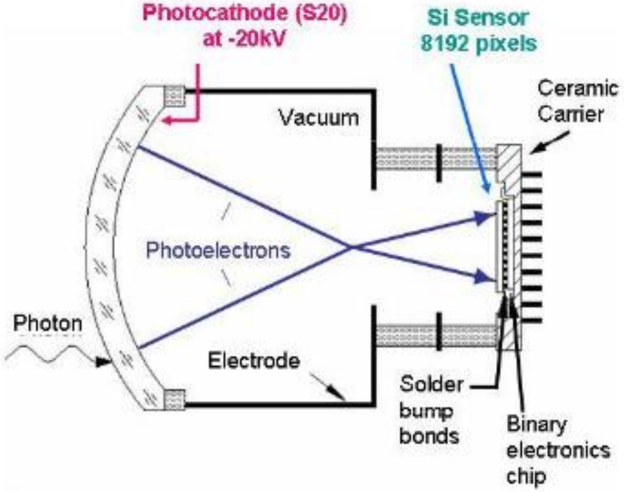




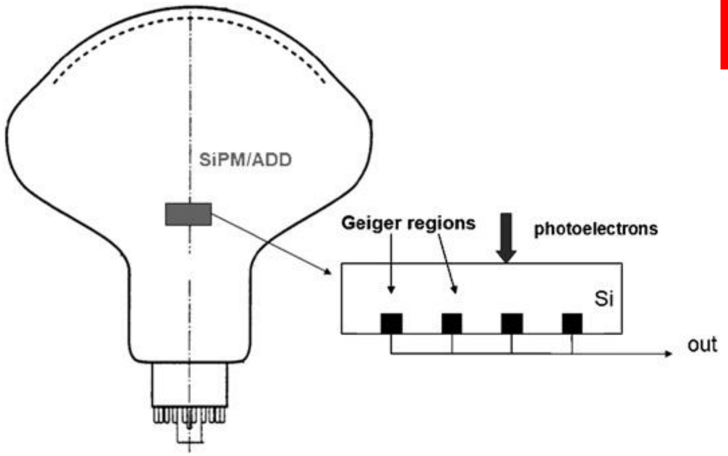
Hybrids: HPD, HAPD, QUPID, VSIPM, ABALONE

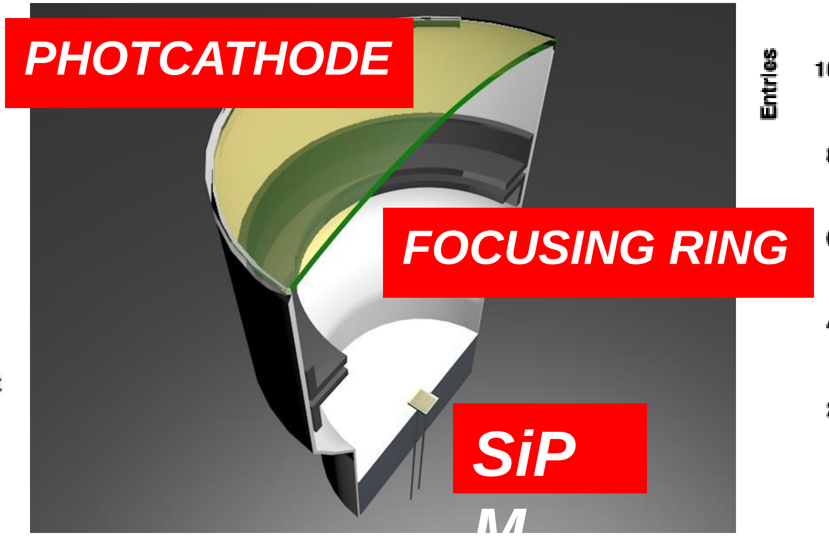
- ✓ Hybrid detectors are **combinations of vacuum and silicon devices**
- ✓ They have ***large photocathodes*** which ensure a large photoelectron conversion area
- ✓ Photoelectrons are accelerated by a strong high field (10-20 kV) and ***focused on a silicon device***
- ✓ Photoelectrons loose energy ***producing a number of electron-hole pairs proportional to the electron kinetic energy***, eventually multiplied by the intrinsic gain of the silicon device
- ✓ Very low fluctuation in the Gain → Fano factor of Si ~0.12

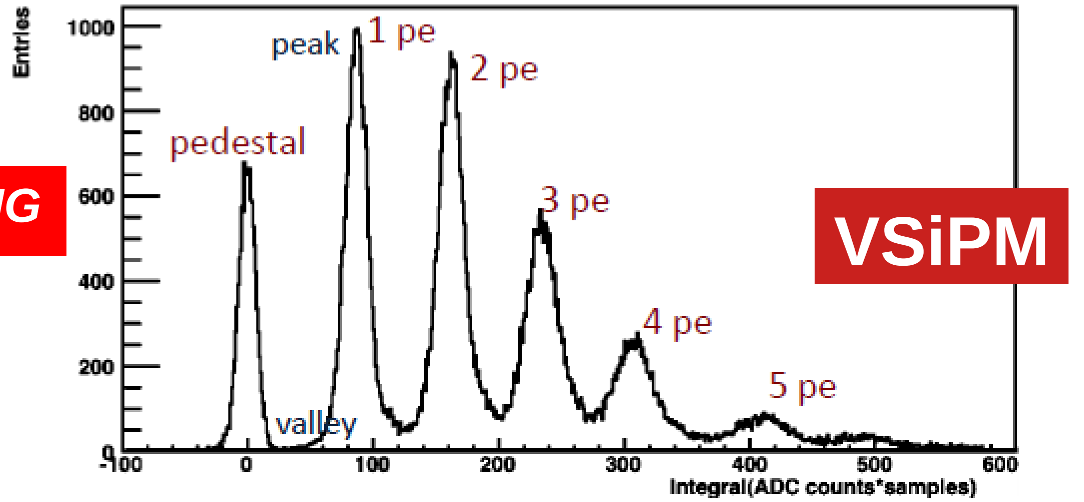




Large area Photocathode coupled to an APD in vacuum



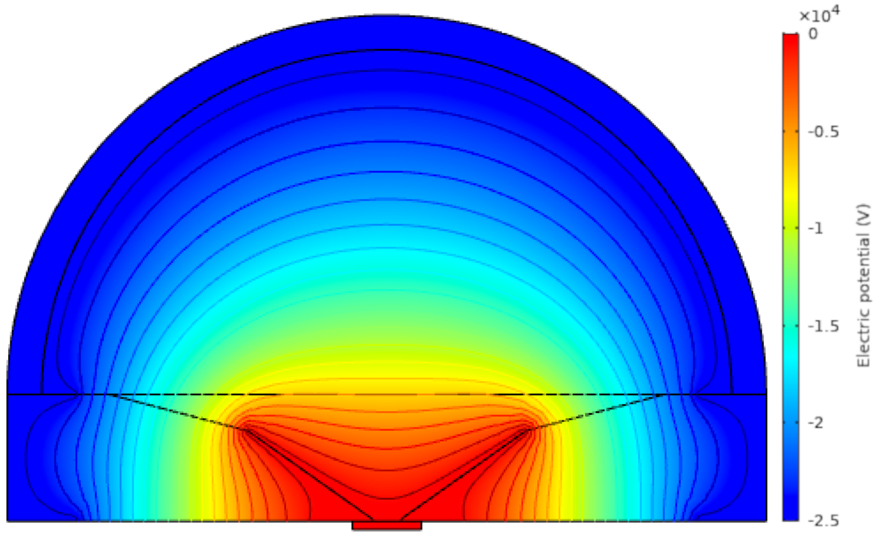


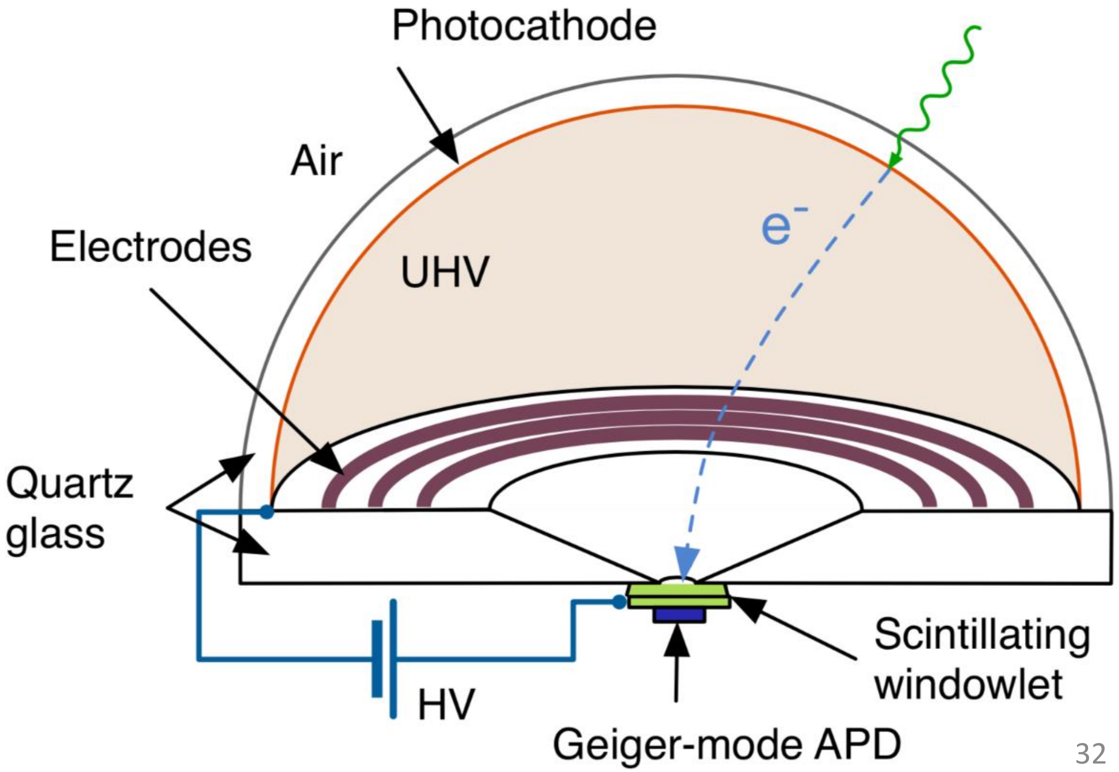


Large area Photocathode coupled to a SiPM in vacuum

Hybrids: ABALONE

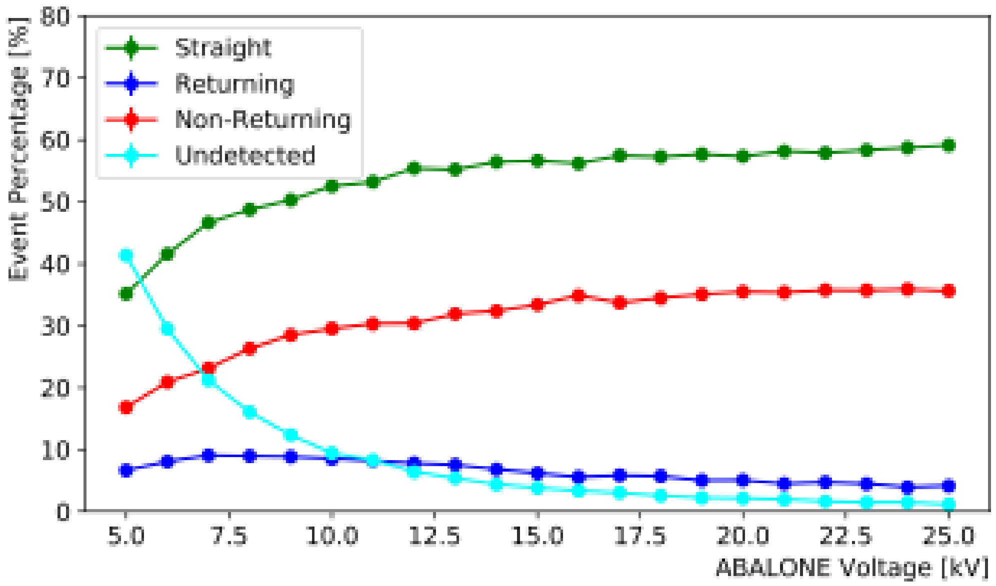
- ***Ultra high vacuum device***
- Photocathode coupled to a **scintillator read-out by a SiPM**
- ***Great optical aperture ~2π***
- QE determined by the photocathode
- **Excellent gain ~10^8**

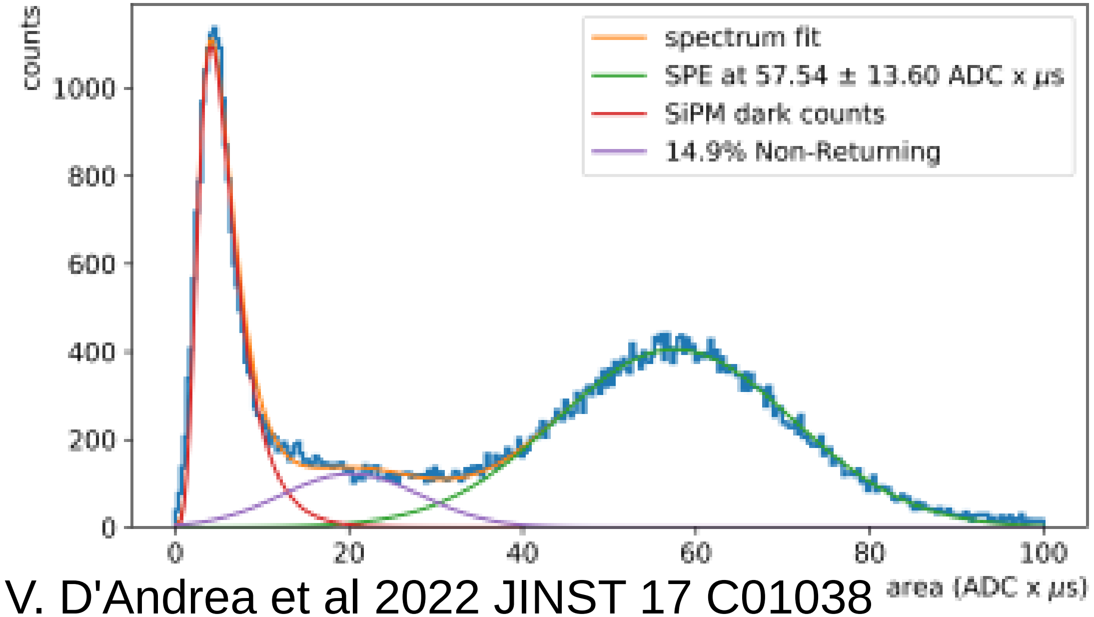




Hybrids: ABALONE

- ✓ Operated ***at 25 kV***
- ✓ *LYSO scintillator (~30 ph/keV)*
- ✓ Gain of the Scintillator ~100
- ✓ **Overall gain ~10^8**
- ✓ A fraction of electrons ***escapes from the crystal and does not deposit entire energy*** (non-returning)





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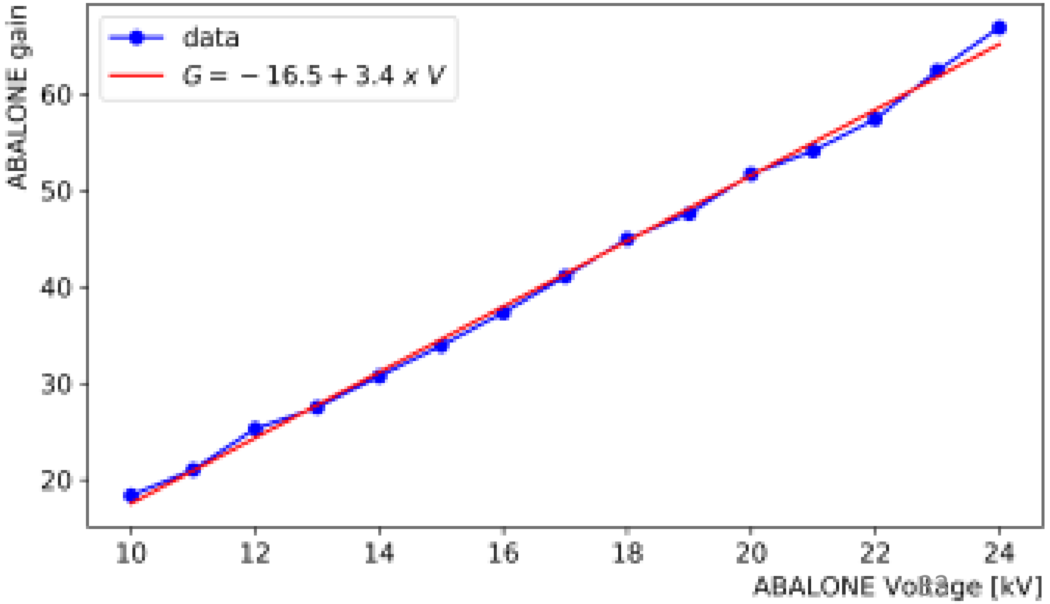

Conclusions

- ✓ ***Light detection plays a central role in neutrino physics***
- ✓ ***PMT still widely used by the community***
- ✓ ***New technologies are emerging and are being considered/used by some of the next generation experiments***
- ✓ ***New developments and new ideas need to be pursued and encouraged***
- ✓ ***New sensors and detection technique will enable the discoveries that are in front of us***

THANK YOU!!!