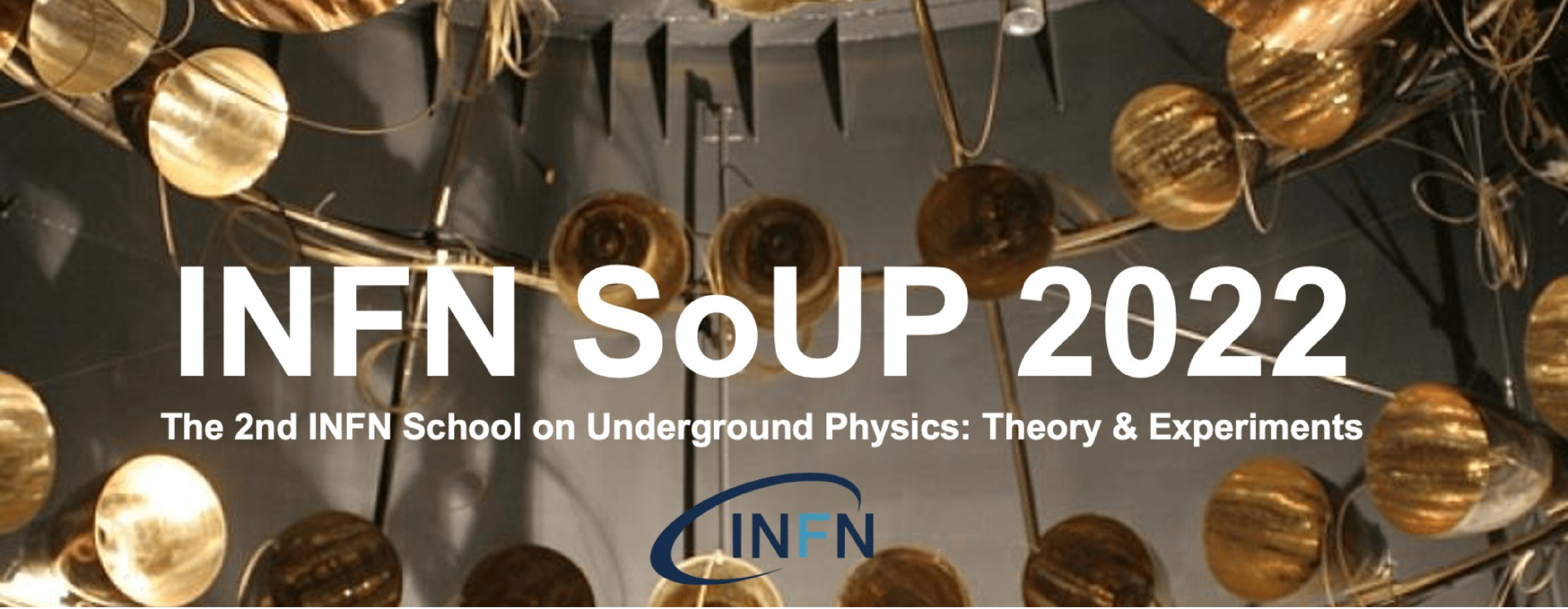

New Photodetectors

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FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

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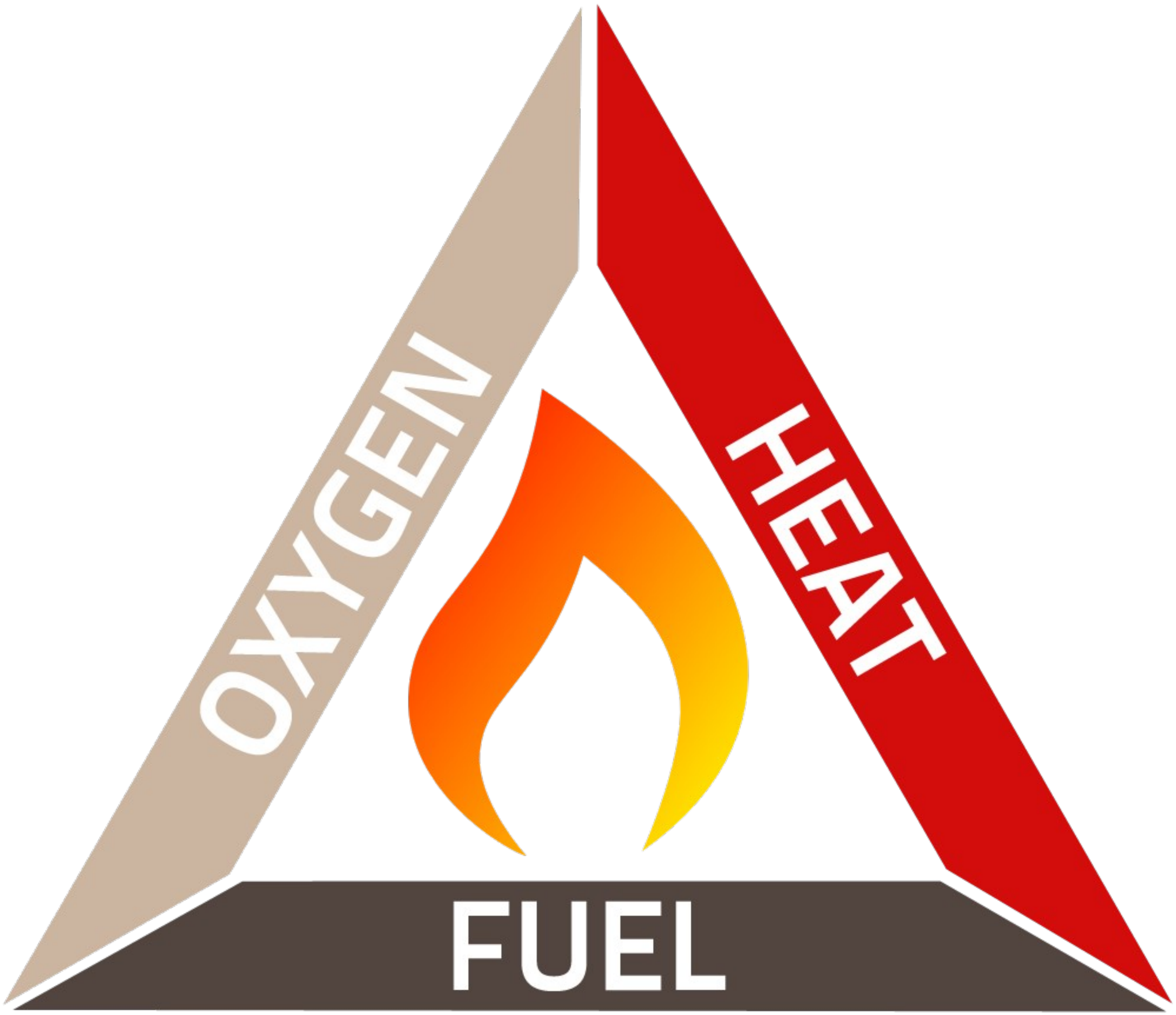
Outline

- Introduction
- Vacuum Photosensor
  - ✓ *PMTs, MaPMTs, LAPPD, ...*
- Solid State detectors
  - ✓ *APD, SiPM*
- Hybrid Photosensors
- Estimating the Light Yield of a detector

Light detection in particle physics

- **Light detection** played a *central role in particle physics in the last century*
- 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

Triangle of fire



Triangle of light

Triangle of light

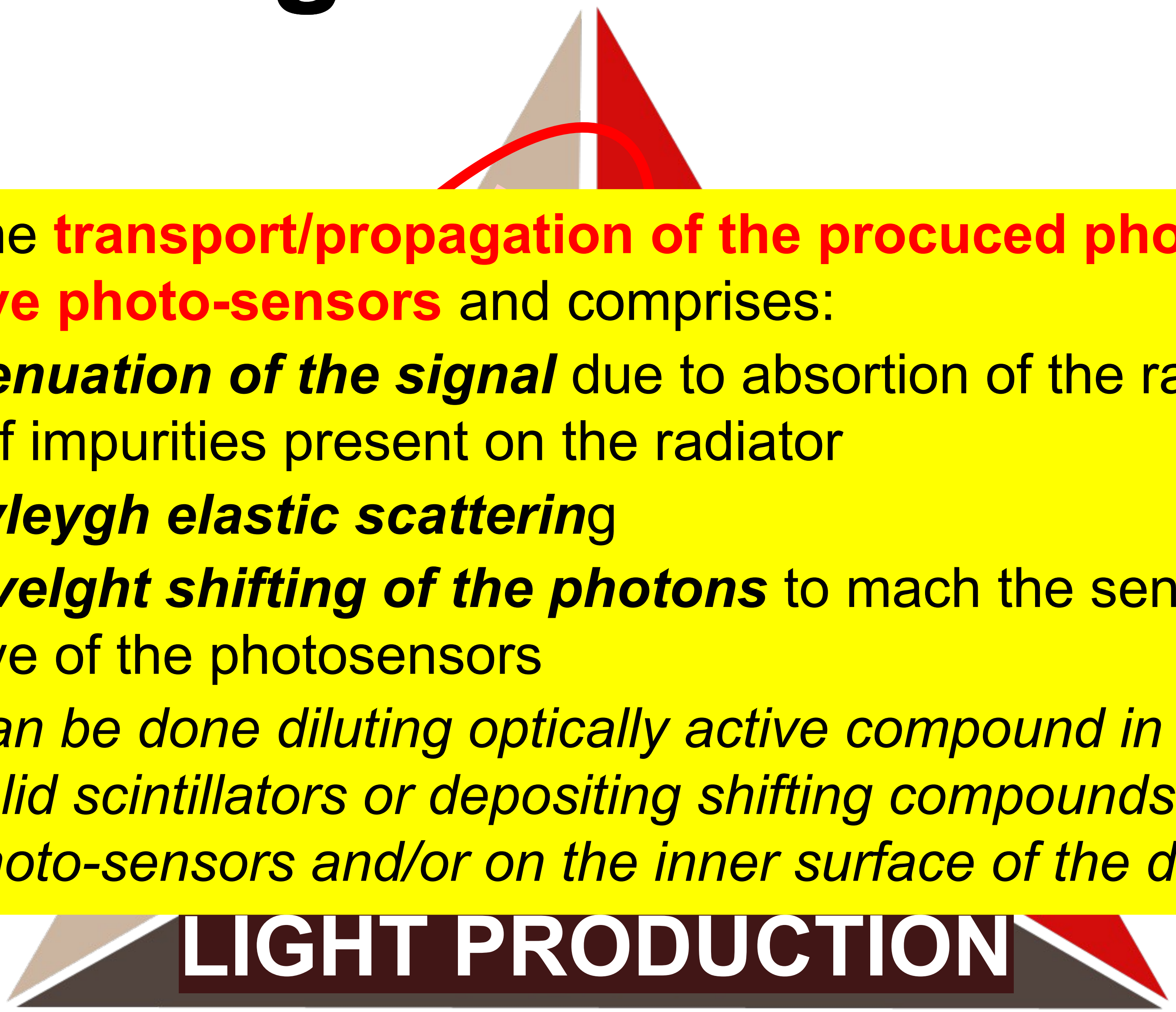
Triangle of light

Determined by the characteristics of the incoming particle:

- **Depostied energy** (or better LET – linear energy transfer): the **number of emitted photons is usually proportional to the energy deposted in the medium** (unless quenching process are in act)
- **Particle type**: in many scintillators the emission of light happens throught the *transition of an excited molecule from the first excited state to ground state*. Depending on the total spin of the excited state (triplet or singlet) *the de-excitation can be fast or slow*. **The abundance of fast and slow components in the light signals depends on the particle type**
- **Direction**: Especially in **Cherenkov detectors** ==> The shape of the Cherenkov rings give the direction of the particle

Triangle of light

Triangle of light

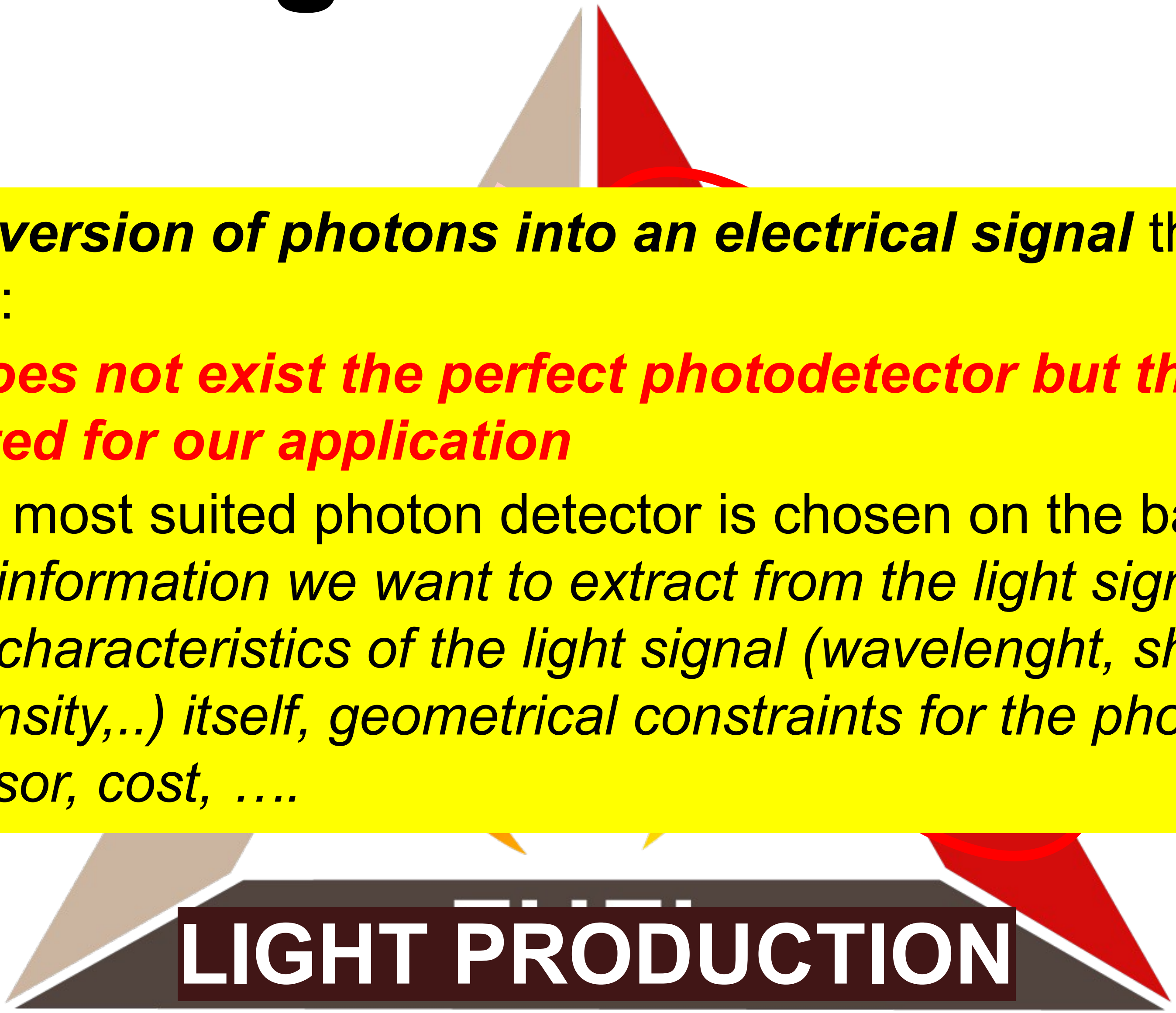


This is the **transport/propagation of the procuced photons to the active photo-sensors** and comprises:

- ***Attenuation of the signal*** due to absortion of the radiator or of impurities present on the radiator
- ***Rayleygh elastic scatterin***g
- ***Wavelght shifting of the photons*** to mach the sensitivity curve of the photosensors
  - *Can be done diluting optically active compound in liquid or solid scintillators or depositing shifting compounds on the photo-sensors and/or on the inner surface of the detector*

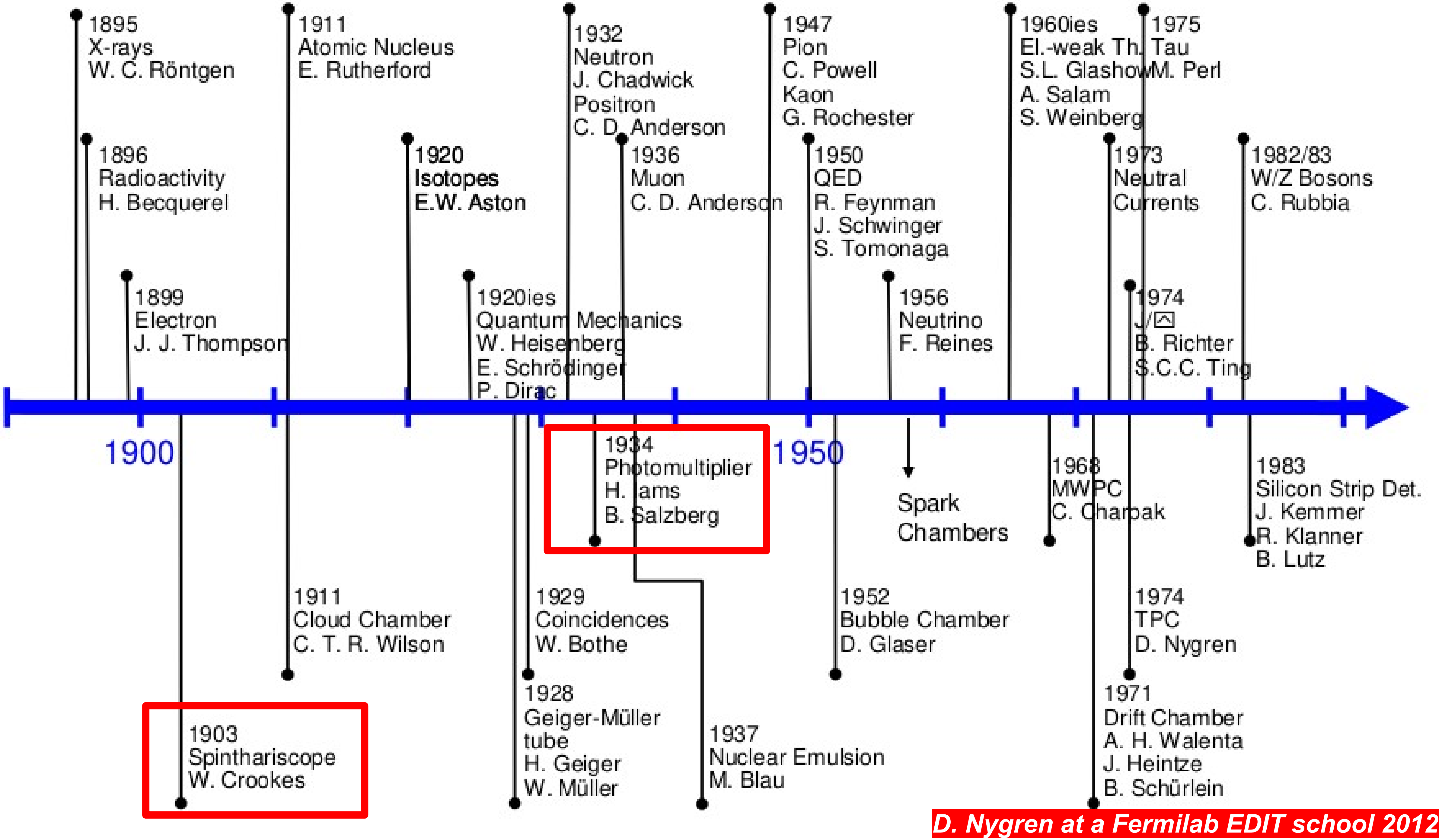
Triangle of light

Triangle of light



The conversion of photons into an electrical signal that we measure:

- It ***does not exist the perfect photodetector but the most suited for our application***
- The most suited photon detector is chosen on the basis of the *information we want to extract from the light signal, from the characteristics of the light signal (wavelenght, shape, intensity,..) itself, geometrical constraints for the photo-sensor, cost, ….*


1895
X-rays
W. C. Röntgen
1896
Radioactivity
H. Becquerel
1899
Electron
J. J. Thompson
1911
Atomic Nucleus
E. Rutherford
1920
Isotopes
E.W. Aston
1920ies
Quantum Mechanics
W. Heisenberg
E. Schrödinger
P. Dirac
1932
Neutron
J. Chadwick
Positron
C. D. Anderson
1936
Muon
C. D. Anderson
1947
Pion
C. Powell
Kaon
G. Rochester
1950
QED
R. Feynman
J. Schwinger
S. Tomonaga
1956
Neutrino
F. Reines
1960ies
El.-weak Th.
S.L. Glashow
A. Salam
S. Weinberg
1975
Tau
M. Perl
1973
Neutral
Currents
1974
J/
B. Richter
S.C.C. Ting
1982/83
W/Z Bosons
C. Rubbia
1900
1950
1903
Spinthariscope
W. Crookes
1911
Cloud Chamber
C. T. R. Wilson
1928
Geiger-Müller
tube
H. Geiger
W. Müller
1929
Coincidences
W. Bothe
1934
Photomultiplier
H. Iams
B. Salzberg
1937
Nuclear Emulsion
M. Blau
1952
Bubble Chamber
D. Glaser
Spark
Chambers
1968
MWPC
C. Charpak
1971
Drift Chamber
A. H. Walenta
J. Heintze
B. Schürlein
1974
TPC
D. Nygren
1983
Silicon Strip Det.
J. Kemmer
R. Klanner
B. Lutz
D. Nygren at a Fermilab EDIT school 2012

Spinthariscope

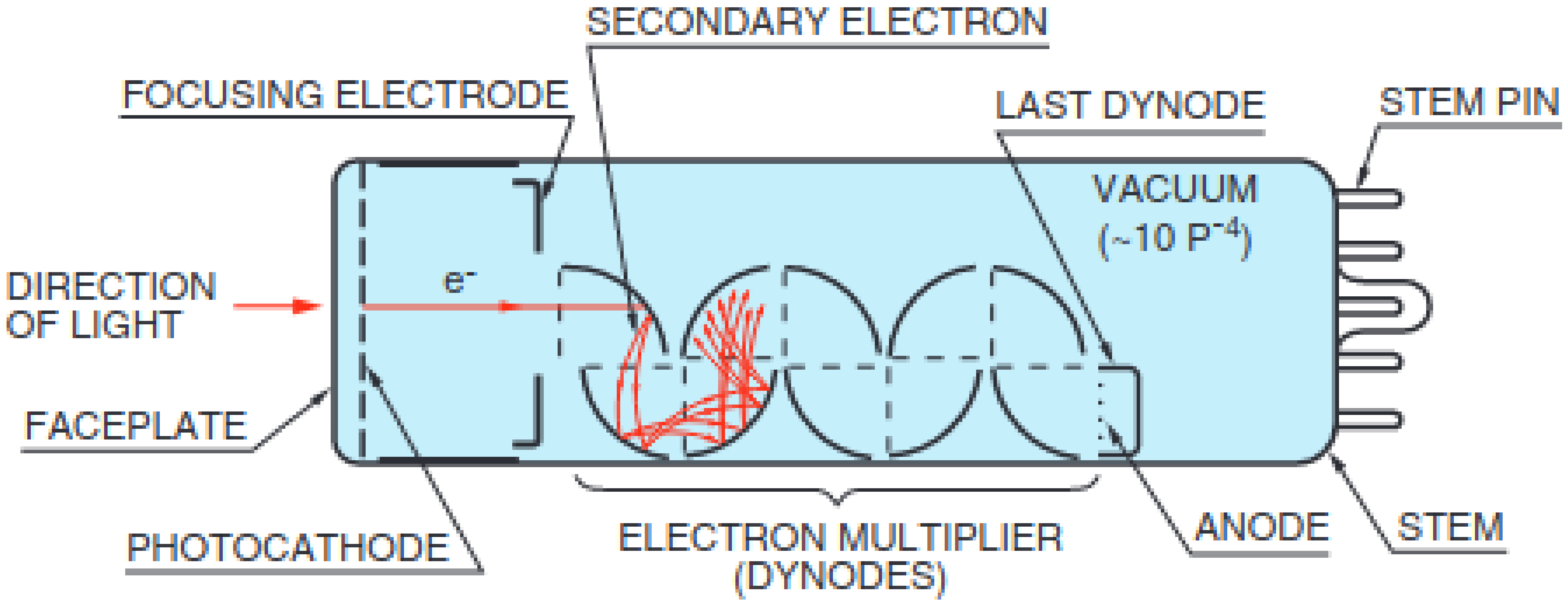
- Invented by *William Crookes in 1903!*
- Allows to observe the scintillation light emitted from a thin foil of zinc sulfide with a lens in a dark little box
- Crookes named his device from Ancient Greek: ***σπινθήρ (spinthḗr) "spark"***
- Photon detector is human eye...

Beautiful story of this device on wikipedia: https://en.wikipedia.org/wiki/Spinthariscope

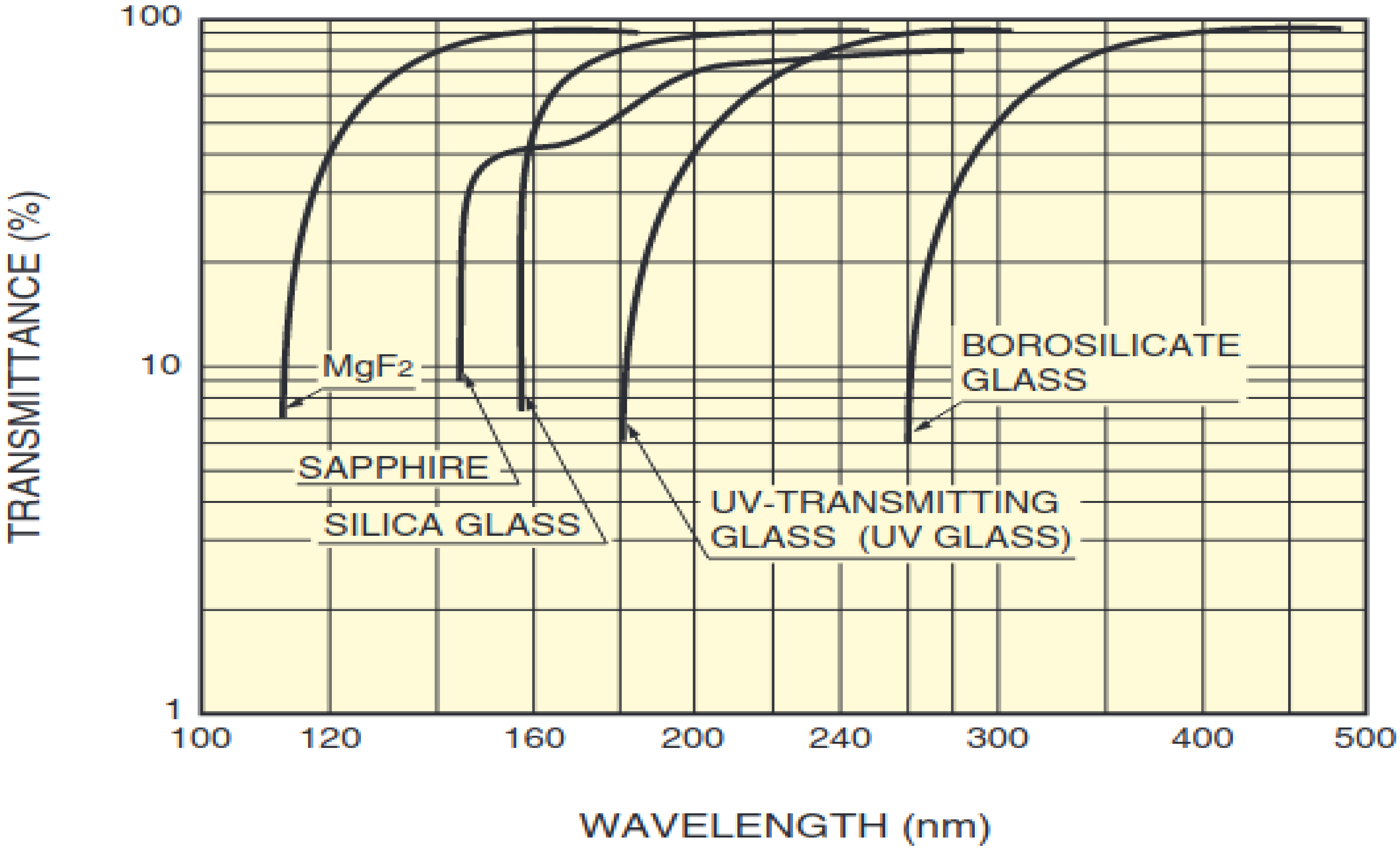
Photomultipliers tube

- The ***first demonstration of a photomultiplier*** (PMT) dates back to 1934. The floor for the invention of PMTs 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 were a **sort of spin-off** of the technology developed to build the ***first practical television cameras*** *(iconoscope, orthicon…)*
- H. Iams and B. Salzberg realized ***the first prototype of PMT integrating a photocathode and a single stage of multiplication***. The tube had a gain of **8 and operated at frequencies above 10 kHz!**

PMT scheme


SECONDARY ELECTRON
FOCUSING ELECTRODE
LAST DYNODE
STEM PIN
VACUUM
(~10 P-4)
e-
DIRECTION
OF LIGHT
FACEPLATE
PHOTOCATHODE
ELECTRON MULTIPLIER
(DYNODES)
ANODE
STEM

PMT basic principles: window

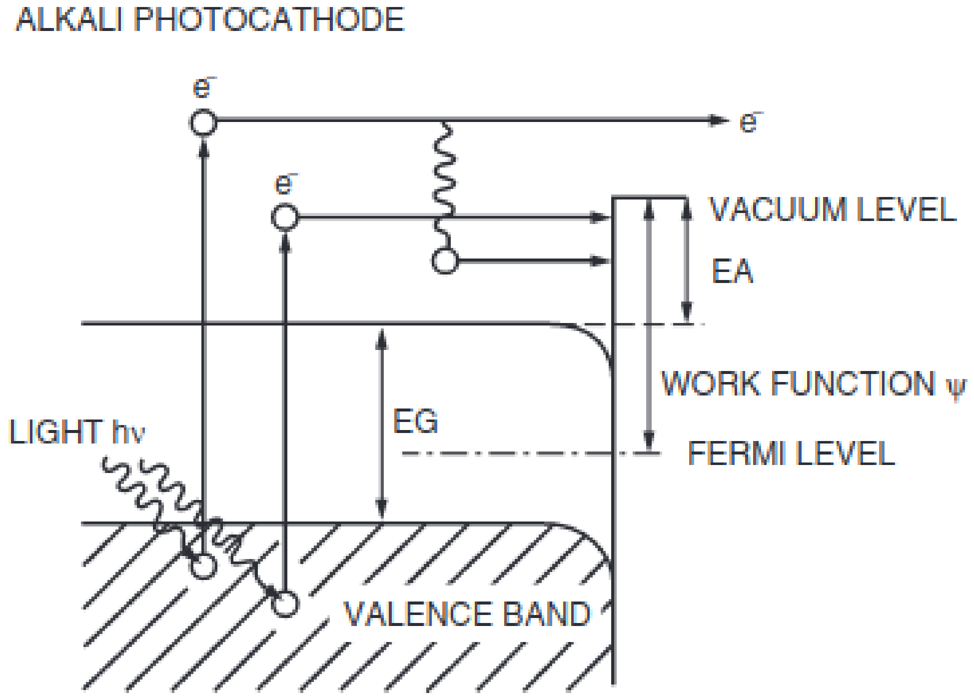


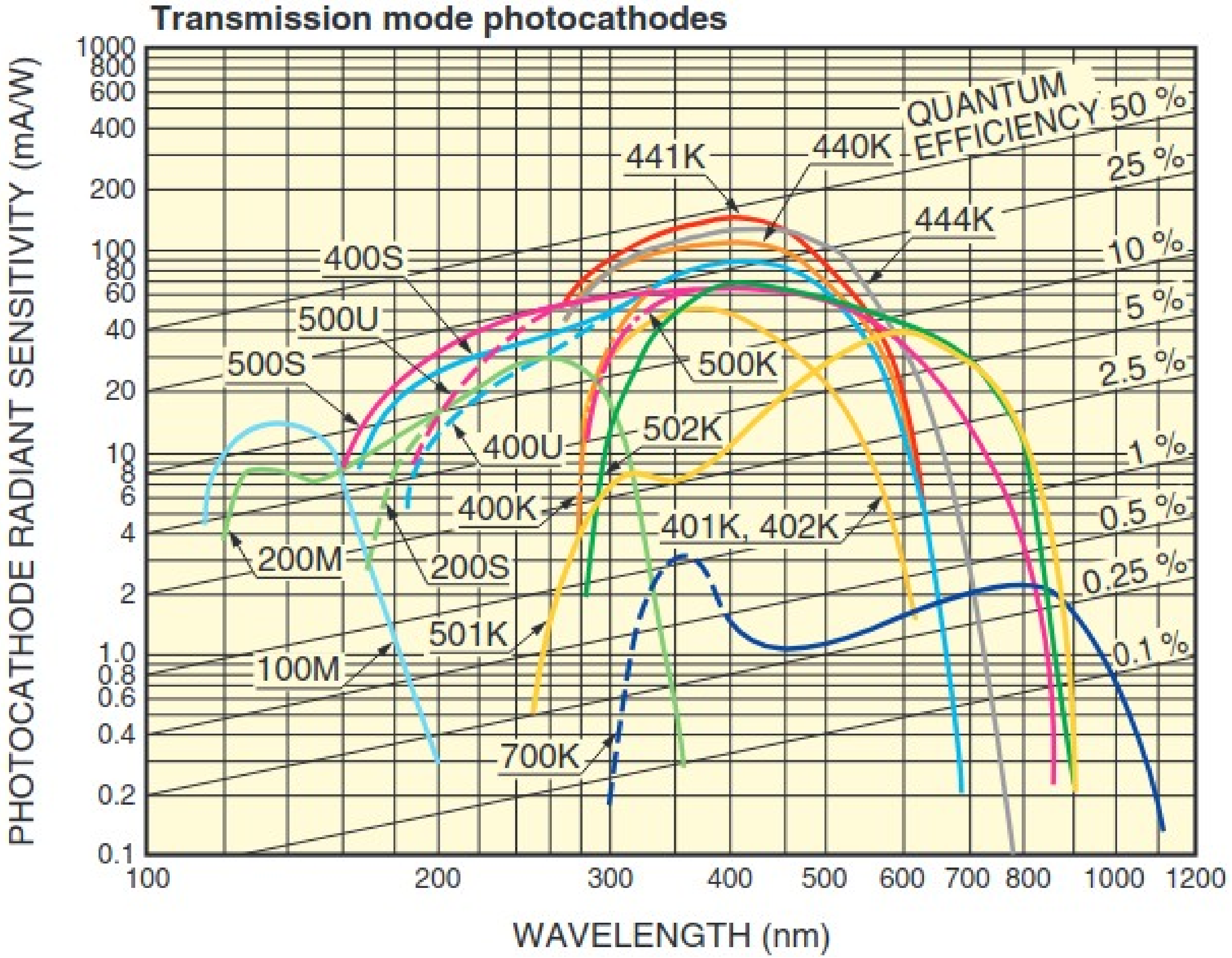
PMT basic principles: photocatode

Photoelectric emission and cathode

Quantum efficiency

$$QE(\lambda)=(1-R)P_V\frac{1}{1+\lambda_a/\lambda_e}P_{escape}$$





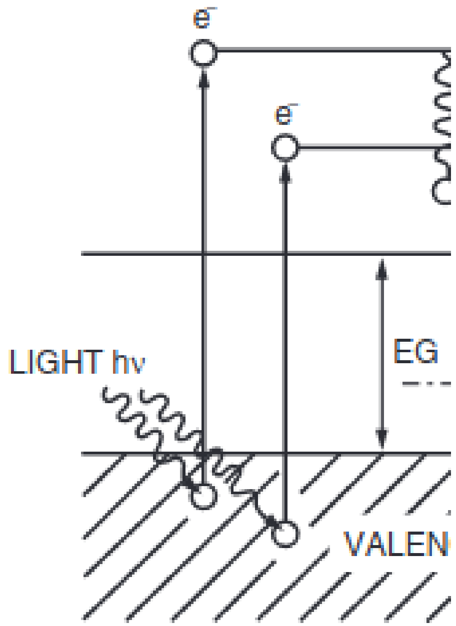
PMT ba … ocatode

Photoelectric emissi

Quantum efficiency

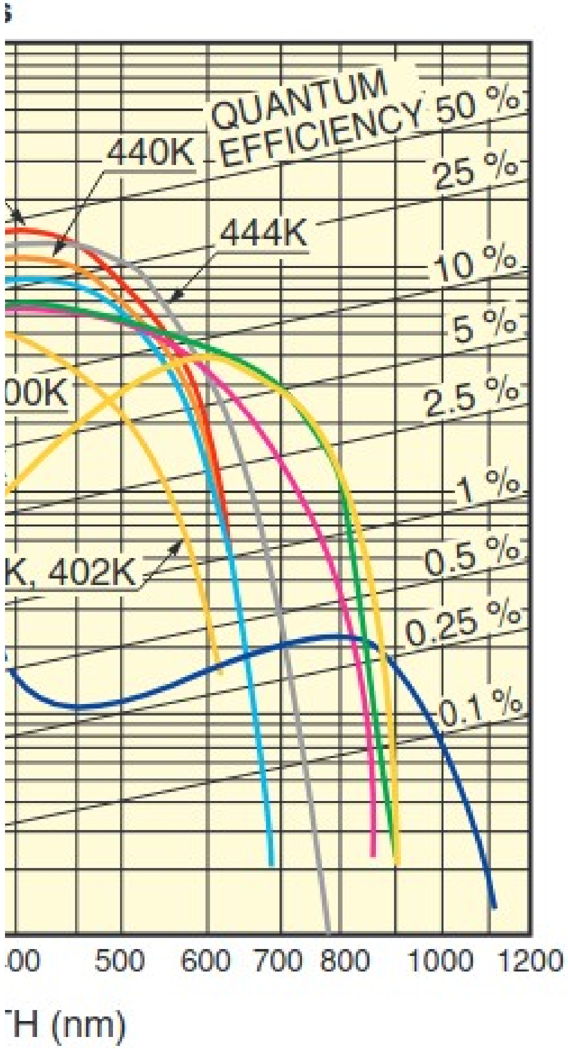
$$QE(\lambda)=(1-R)\,P$$

ALKALI PHOTOCATHODE

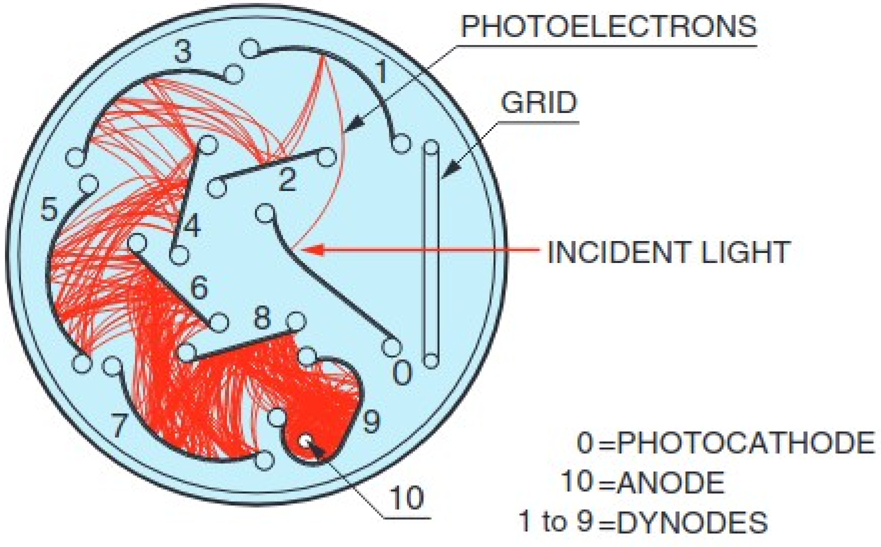


Transmission mode photocathodes

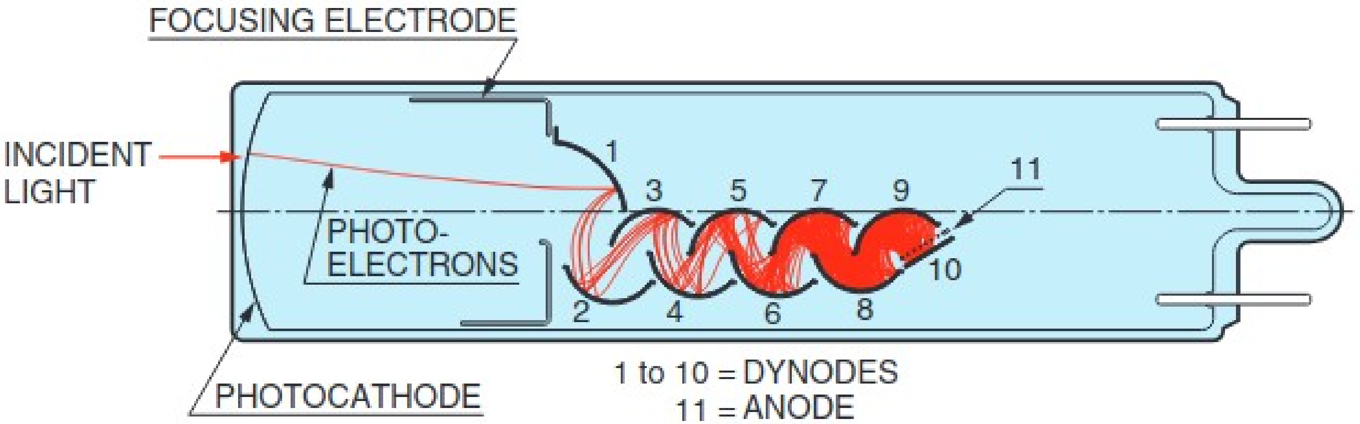
Curve code	Photocathode material	Window material	Luminous sensitivity (Typ.) (µA/lm)	Spectral response: Spectral range (nm)	Peak wavelength: Radiant sensitivity (mA/W)	Radiant sensitivity (nm)	Quantum efficiency (%)	Quantum efficiency (nm)
100M	Cs-I	MgF_2	—	115 to 200	14	140	13	130
200S	Cs-Te	Silica	—	160 to 320	29	240	16	210
200M	Cs-Te	MgF_2	—	115 to 320	29	240	17	200
201S	Cs-Te	Silica	—	160 to 320	31	240	17	210
400K	Bialkali	Borosilicate	95	300 to 650	88	420	27	390
400U	Bialkali	UV	95	185 to 650	88	420	27	390
400S	Bialkali	Silica	95	160 to 650	88	420	27	390
401K	High temp. bialkali	Borosilicate	40	300 to 650	51	375	17	375
402K	Low noise bialkali	Borosilicate	40	300 to 650	54	375	18	375
500K	Multialkali	Borosilicate	150	300 to 850	64	420	20	375
500U	Multialkali	UV	150	185 to 850	64	420	25	280
500S	Multialkali	Silica	150	160 to 850	64	420	25	280
501K	Extended red multialkali	Borosilicate	200	300 to 900	40	600	8	580
502K	Multialkali	Borosilicate (prism)	230	300 to 900	69	420	20	390
600K	GaAsP(Cs)	Borosilicate	700	280 to 720	180	550 to 650	40	480 to 530
601K	Extended red GaAsP(Cs)	Borosilicate	750	280 to 820	160	550 to 650	36	480 to 530
602K	GaAs(Cs)	Borosilicate	700	370 to 920	85	750 to 850	12	600 to 750
700K	Ag-O-Cs	Borosilicate	20	400 to 1200	2.2	800	0.36	740
900S	InP/InGaAsP(Cs)	Silica	—	950 to 1200	18	1100	2	1000 to 1100
901S	InP/InGaAs(Cs)	Silica	—	950 to 1700	24	1500	2	1000 to 1550
440K	Super bialkali	Borosilicate	105	300 to 650	110	400	35	350
441K	Ultra bialkali	Borosilicate	135	300 to 650	130	400	43	350
442K	Super bialkali	Borosilicate	105	230 to 700	110	400	35	350
443K	Ultra bialkali	Borosilicate	135	230 to 700	130	400	43	350
444K	Extended green bialkali	Borosilicate	160	300 to 700	127	420	40	380

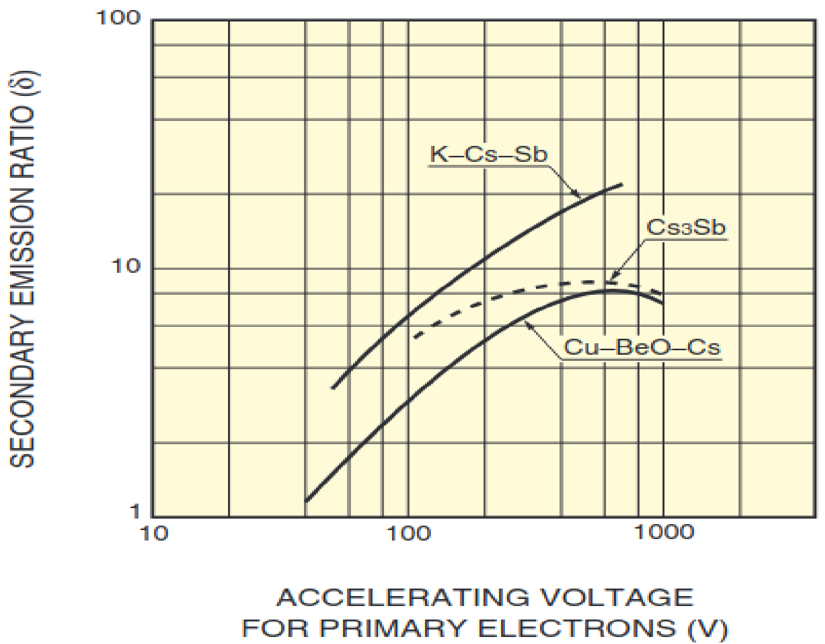


PMT basic principles: dynodes

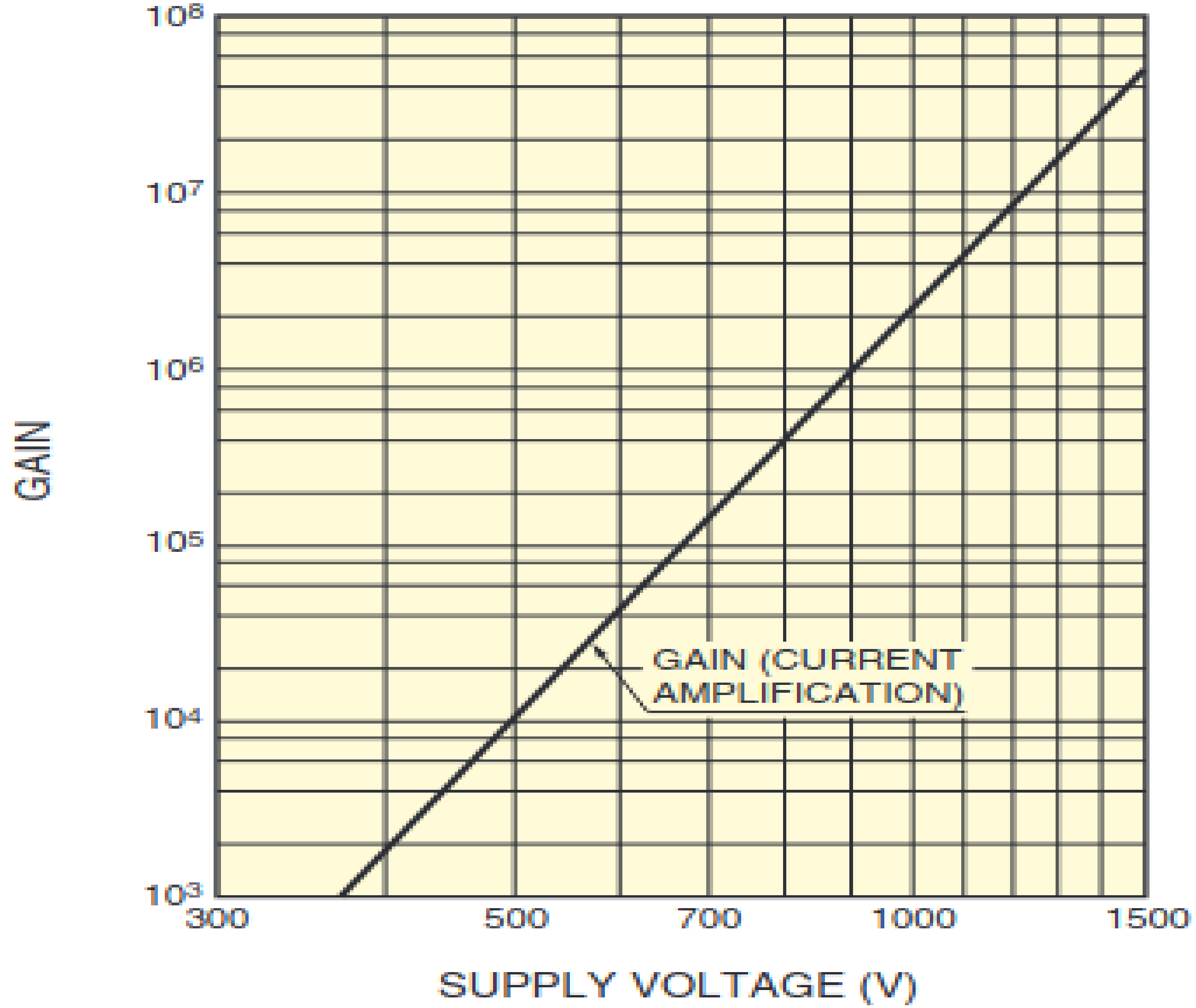


- *Photoelectrons from the cathode* are focused on the **first multiplication stage (dynode)**
- If multiplication factor of one dynode is δ => overall gain is δ^n , where n is the number of dynodes
- **δ ~ aE^k**





PMT basic principles: gain

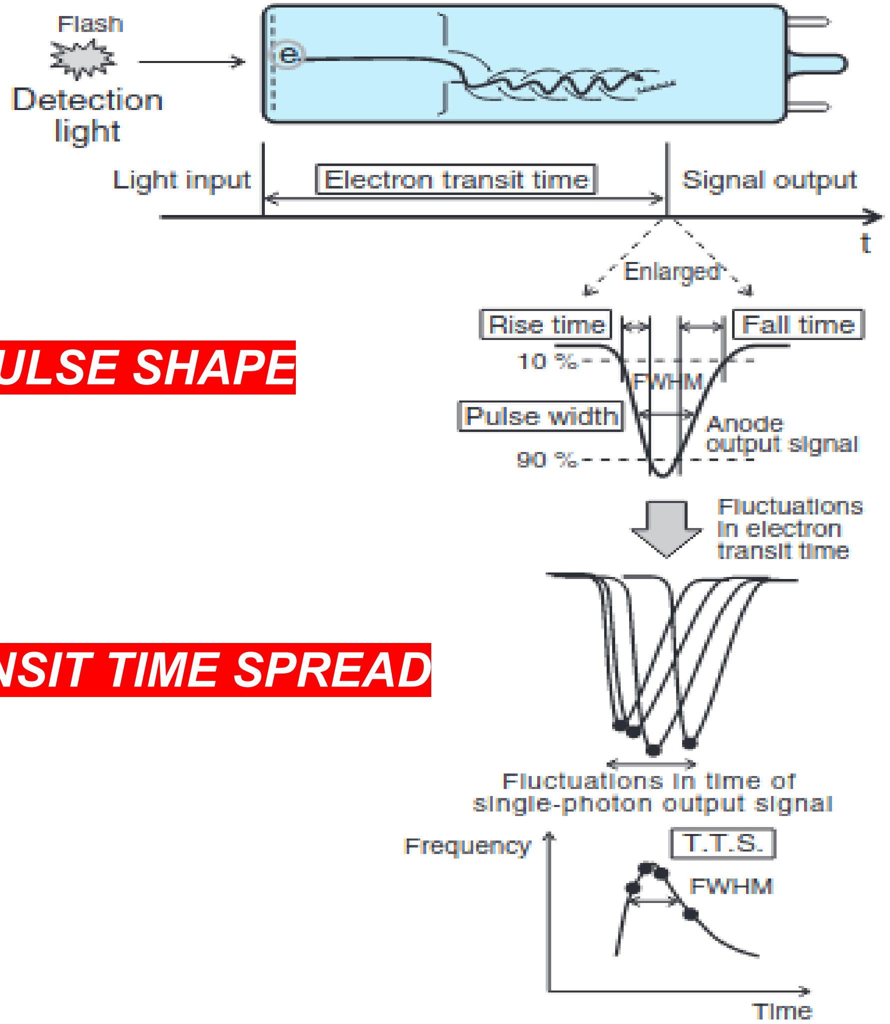


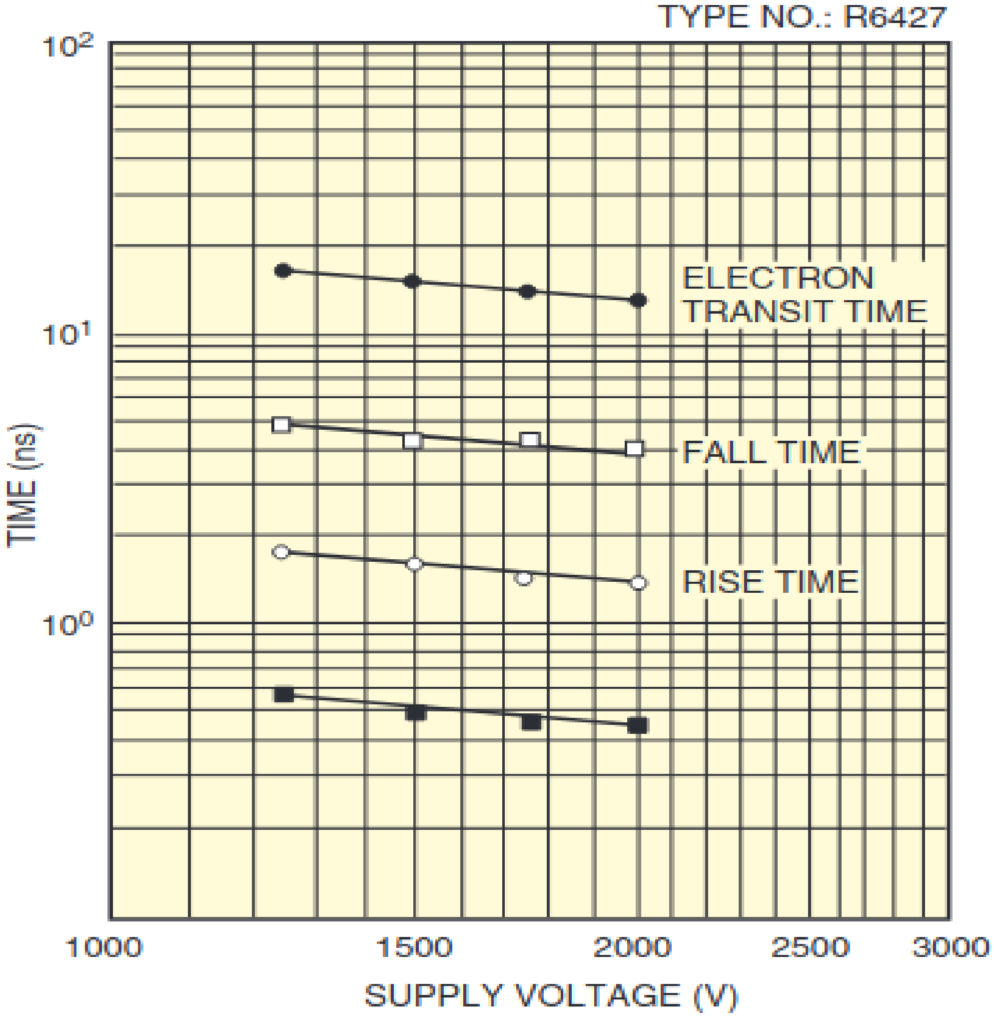
- $G = \delta^n = (aE^k)^n$

PMT basic principles: timing

PULSE SHAPE

TRANSIT TIME SPREAD





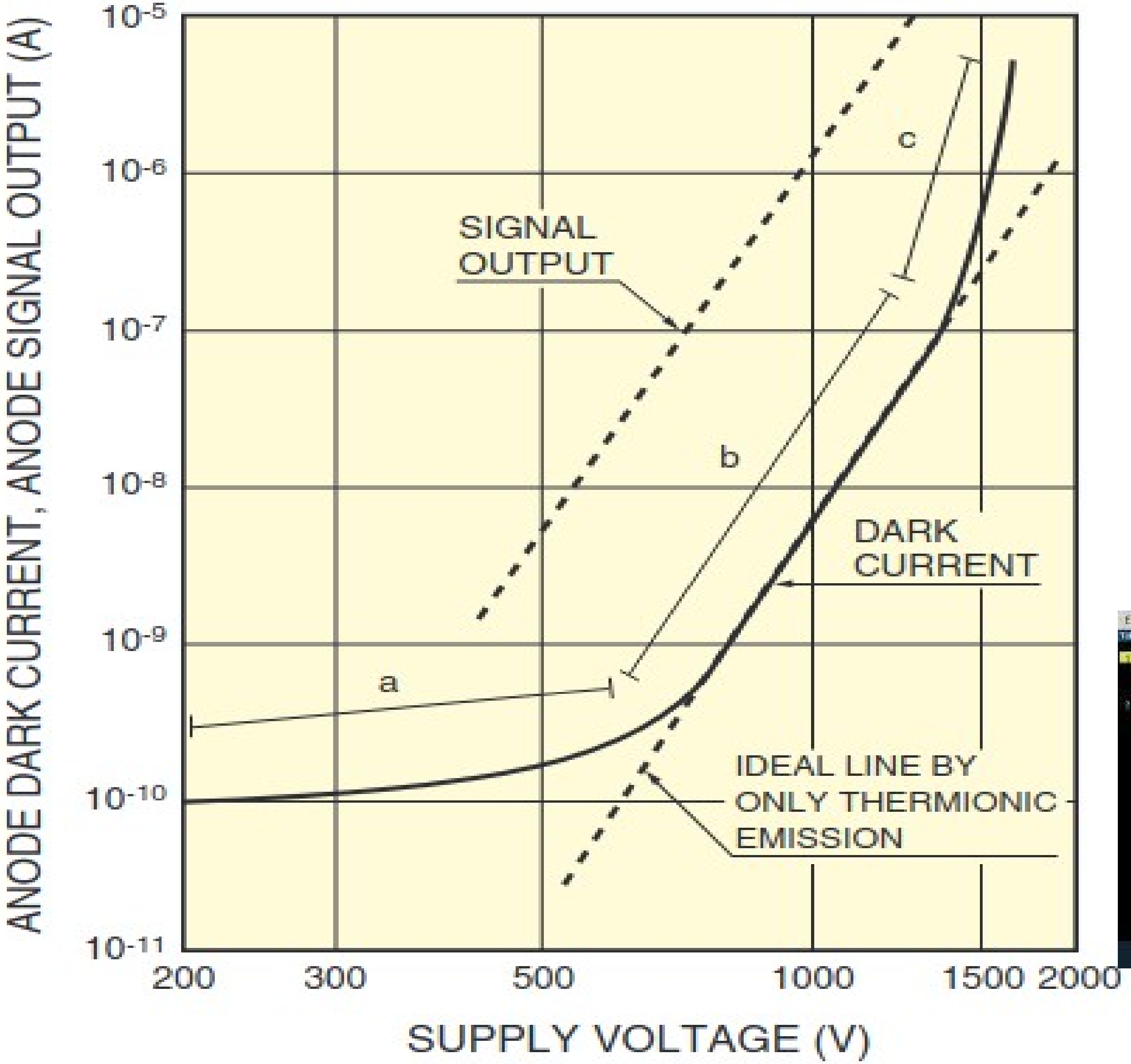
PMT basic principles: timing

Unit: ns

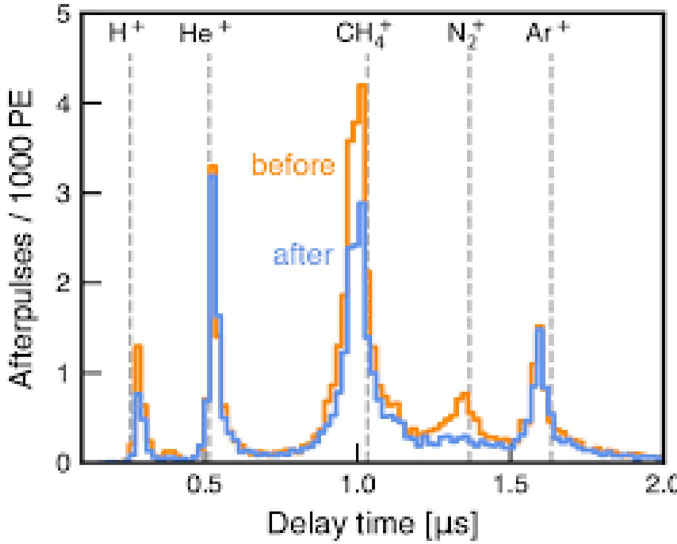
Dynode type	Rise time	Fall time	Pulse width (FWHM)	Electron transit time	T.T.S.
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	Less than 10
Venetian blind	to 7	25	25	60	Less than 10
Mesh	2.5 to 2.7	4 to 6	5	15	Less than 0.45
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8	0.4

T.T.S.: Transit Time Spread

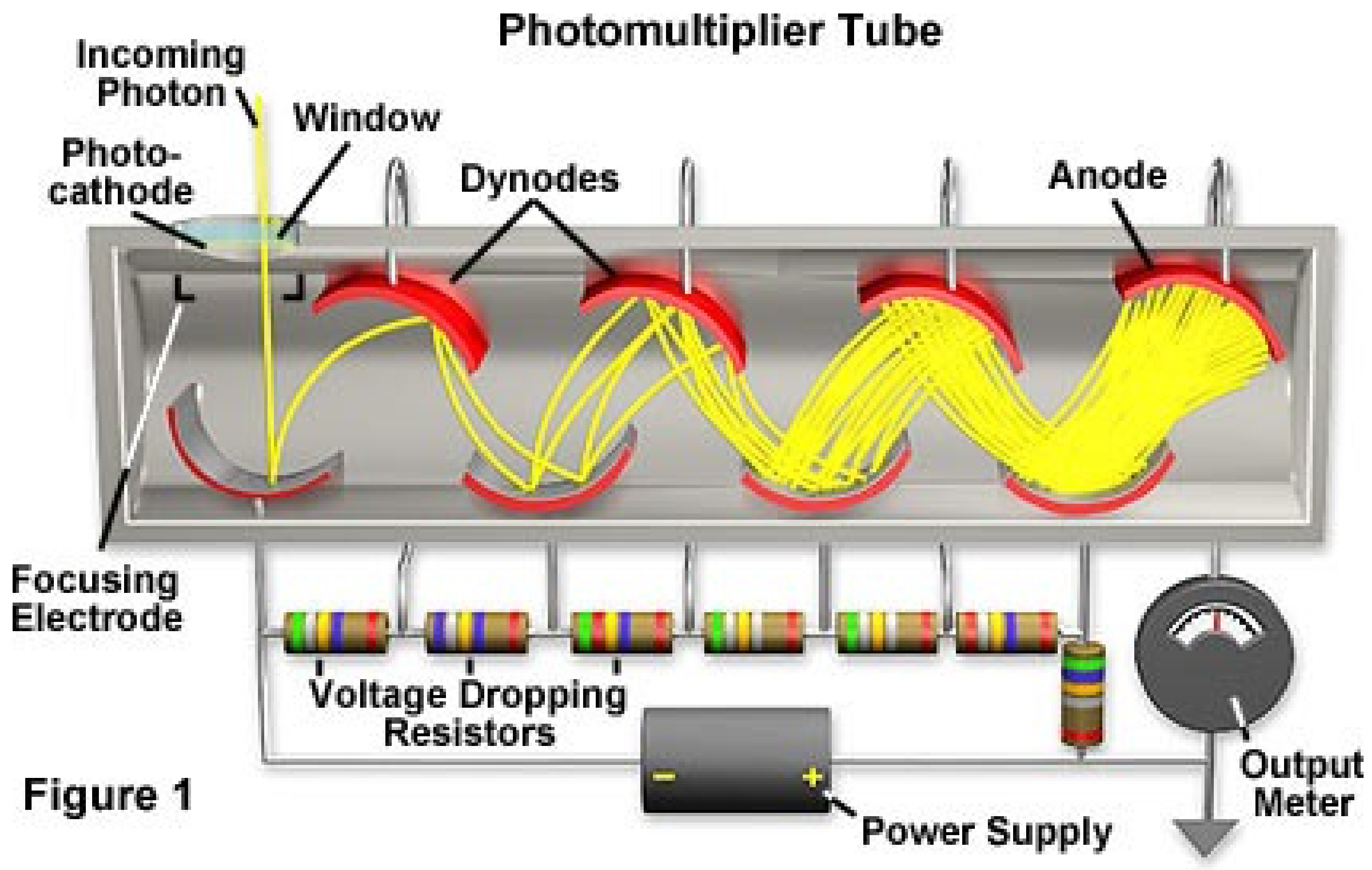
PMT dark current and afterpulses



- ***Region a*** dominated by *leakage current*
- ***Region b*** dominated by *thermoionic emisison from the cathode*
- ***Region c*** dominated by *field emission and scintillation of the materials*
- **Region b in general offers the best S/N**
- **Afterpulsing is a correlated noise,** which manifests itself as **delayed pulses**
- Produced by the ionization of the residual gas



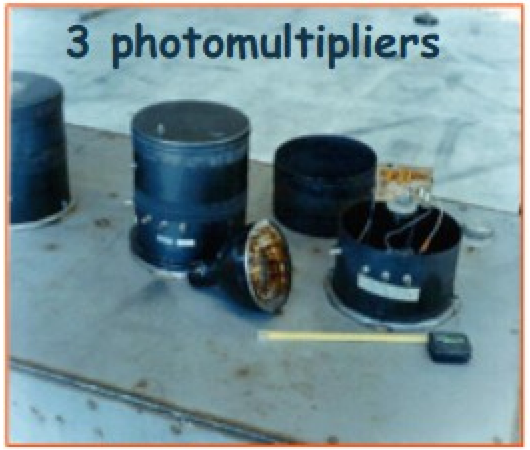
Photomultipliers: pros and cons



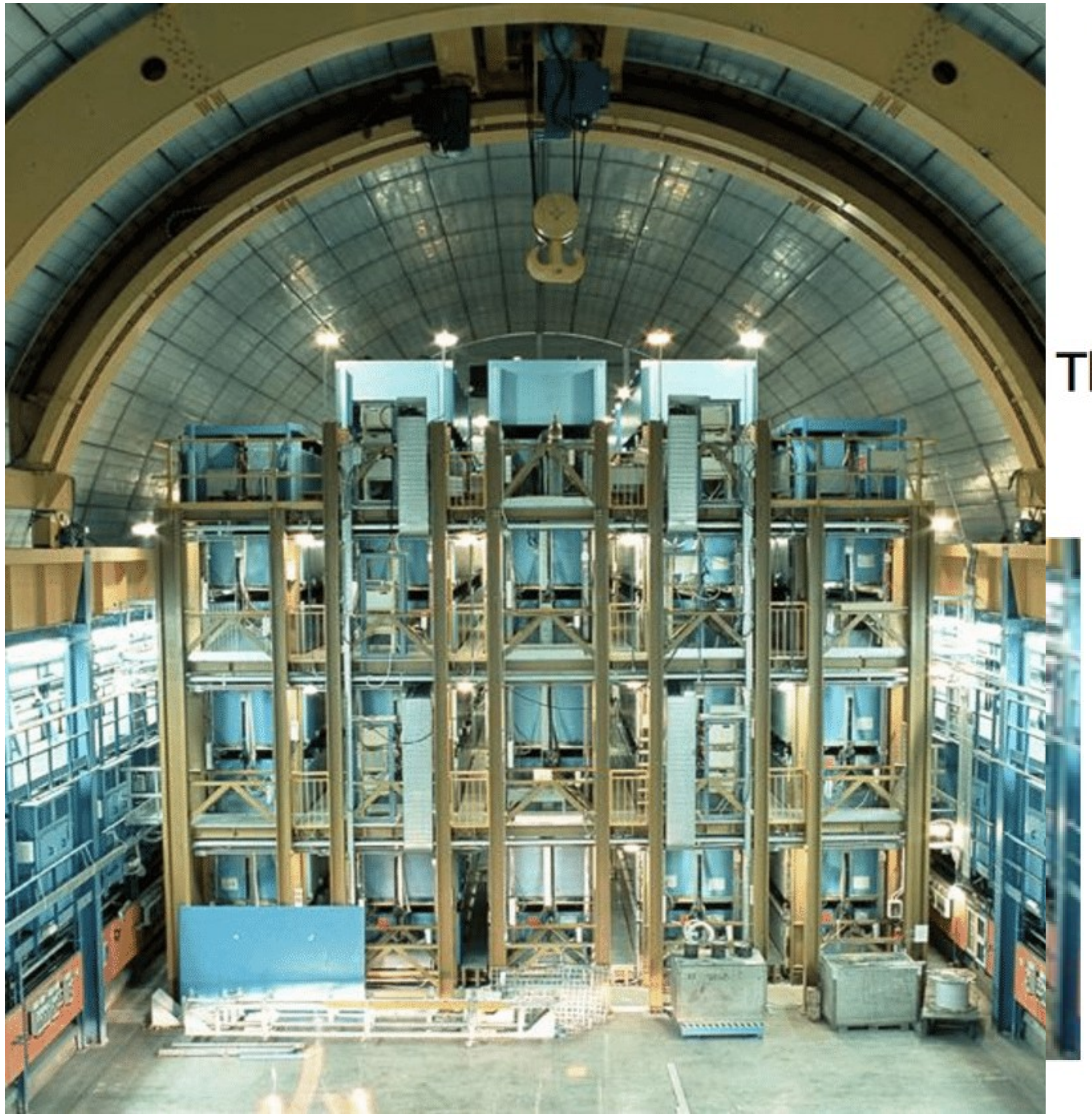
- Well known and mastered technology
- Good detection efficiency (10 – 30%)
- Needs high voltage (1000 – 3000 Volt)
- Typically large devices which occupies a big volume
- Not so easy to make them radiopure

PMTs in Astroparticle: LVD

- ***Observaotry for Supernova neutrino Burst operating since 1992***
- ***840 scintillator counters*** of 1,5 m^3 *in three independent towers*
- Each counter viewed by ***three 15 cm PMTS*** => *FEU49b or FEU125*
- Detects (anti) neutrino through **inverse beta decay** => two correlated signals: a prompt one from *emission and annihilation of the positron* and a *delayed neutron absorption*



PMTs in Astroparticle: LVD



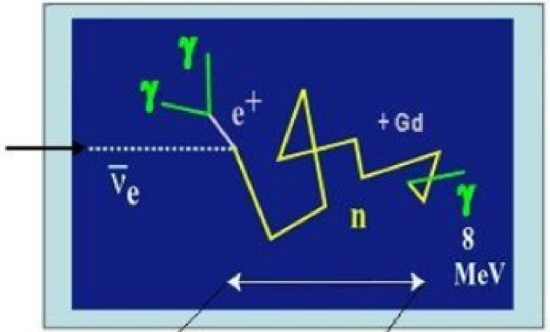
the Inverse Beta Decay:

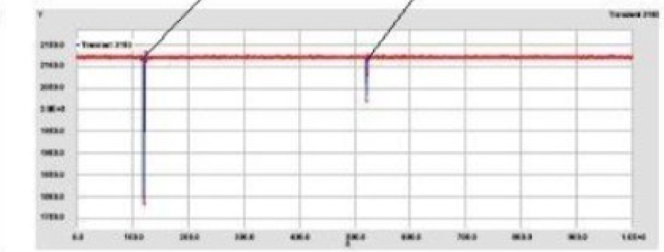
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$e^+ + e^- \rightarrow \gamma$$

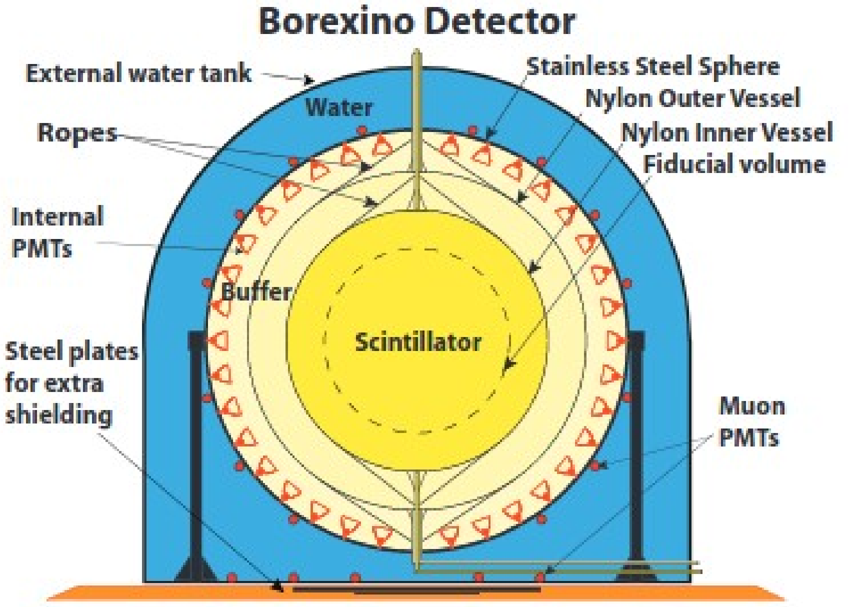
The visible energy for this interaction:

$$E_{vis} = E_{\bar{\nu}_e} - 0.789 MeV$$





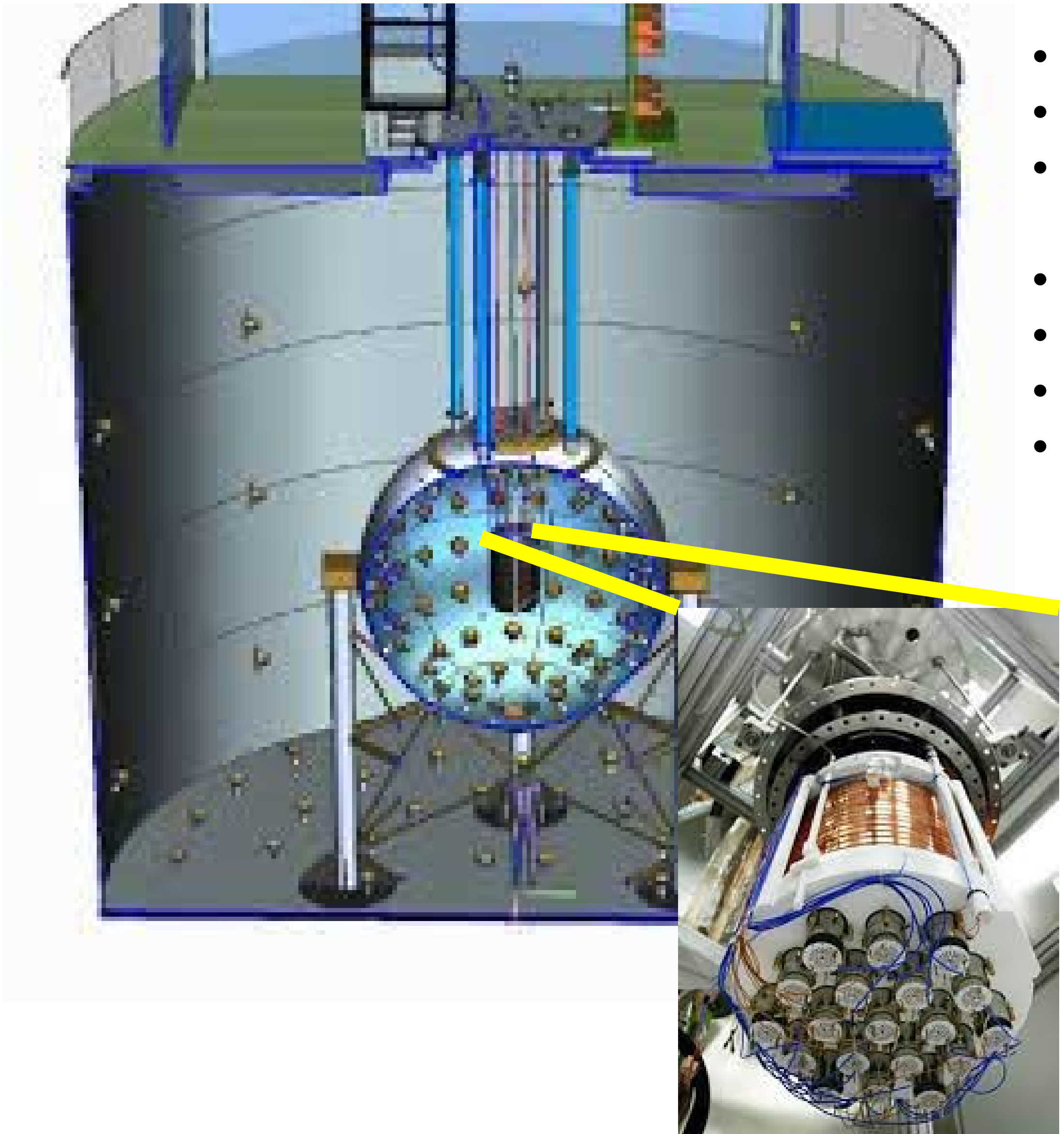
PMTs in Astroparticle: Borexino



- Detects ***solar neutrinos*** through elastic neutrino scattering on electrons.
- ***Graded shielding*** form outside to inside
- **Inner scintillator** mass (pseudocumene+PPO) is ~**300t**

2200 ETL9351 => 8" PMTs
High gain => 10^7
Short TTS=> 1 ns

PMTs in Astroparticle: DarkSide50



- Experiment for the ***direct detection of Dark Matter***
- **Dual phase depleted Ar (from ^{39}AR) TPC**
- **38 PMTs in the inner LAr detecto**r=> *Hamamatsu 3” R11065 crygenic*
- **High quantum efficiency > 35%**
- **Very low radioactive background**
- *110 Hamamatsu R5912 (8”) in the liquid scintillator of the veto*
- 80 ETL 9351 8” PMTs in the water Cherenkov muon veto.

PMTs in Astroparticle: XenonNT

- ***Dual phase Xe*** experiment ***for direct Dark Matter detection***
- XenonNT ***uses 8 ton of Lxe readoout by 494 PMTs***
- **Hamamatsu 3" R11410-21**
- **Cryogenic**
- **High QE ~ 35% -UV sensitive**
- **Ultra low background**

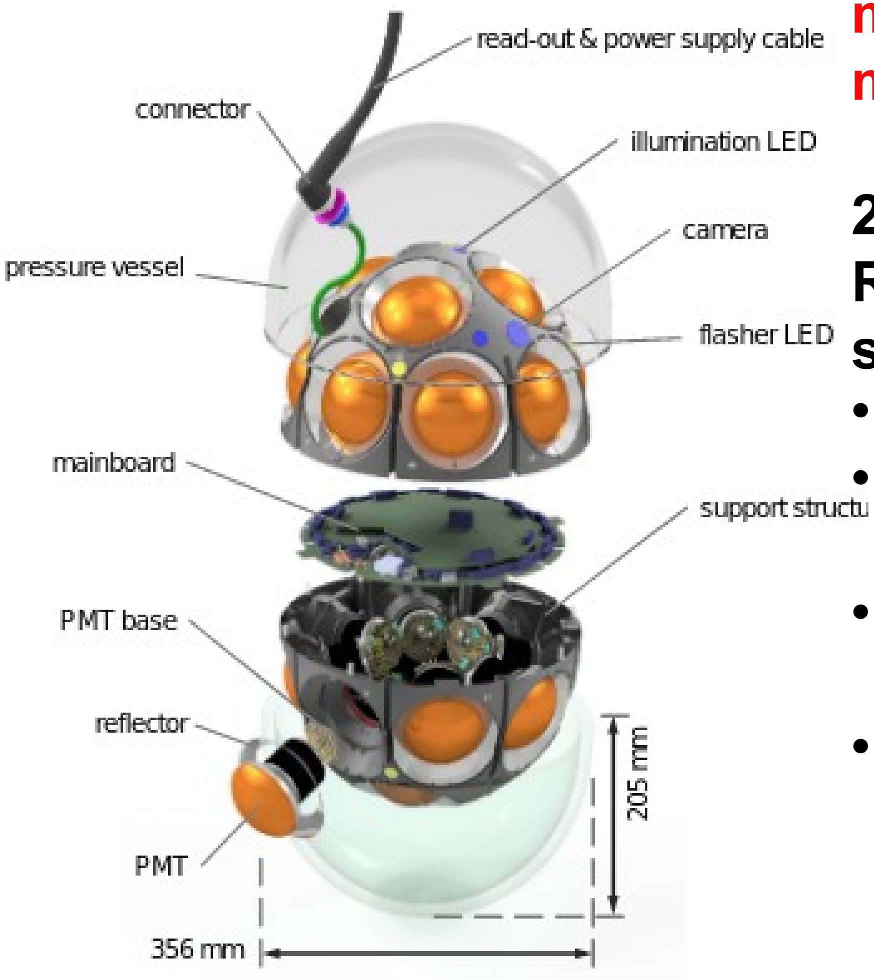
KM3NeT multi-PMT optical module

Undrsea experiment for atmospheric and high energy neutrinos: two sites in the Mediterranean Sea

Optical module is made of a **glass sphere containing 31 3" PMTs, *calibration and and readout electronics***

- A ***Photocathode area of about 1300 cm^2*** three times the area of a single 10" PMT,
- **Uniform angular coverage**
  - *Sensitivity to the incoming direction of detected photons*
- Good photon counting performance;
- Possibility to define **local triggers** (implemented onshore) **based on the pattern of PMT signals** => *background soppression*

ICECUBE mDOM



The ***ICECUBE upgrade*** foresee the installation of ~**400 new multiMpmt digital optical modules**

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

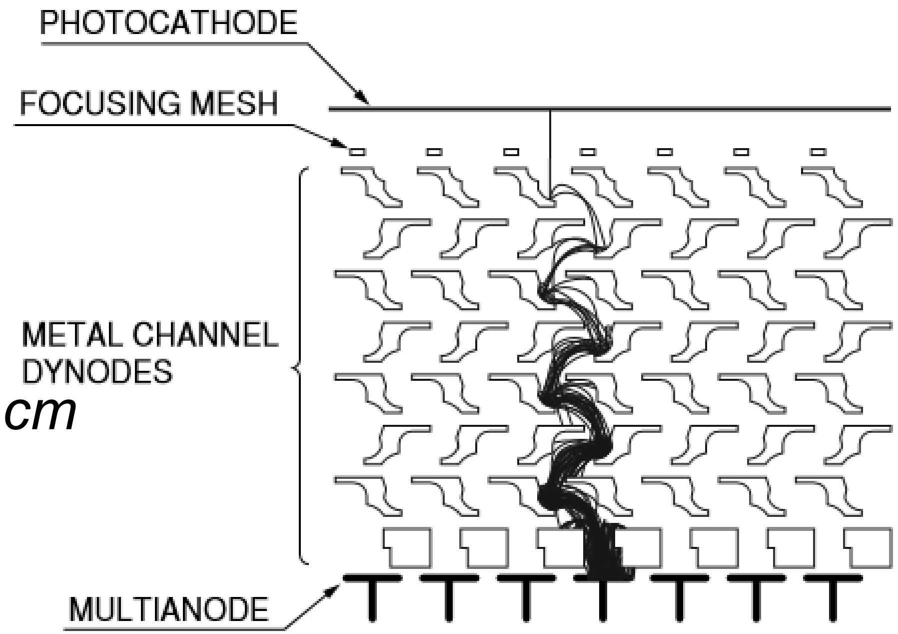
- Large optical comerage
- Homogeneus solid angle coverge
- Allows to access directional information
- Implement multiplicity triggern inside oone module

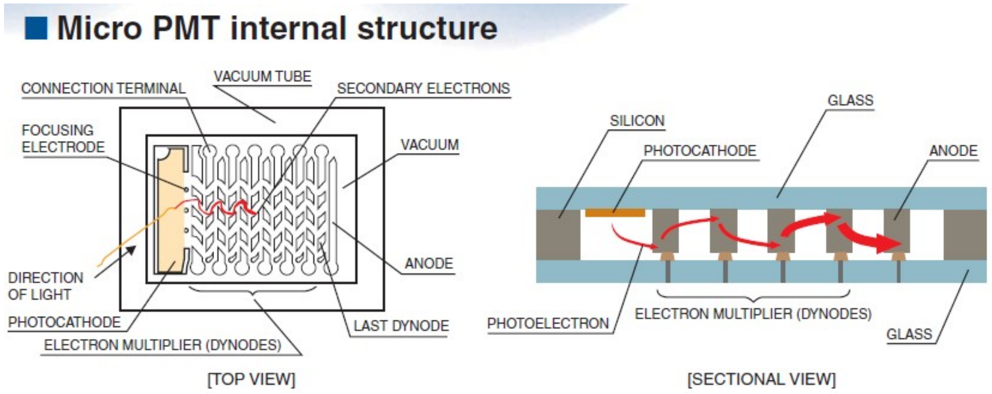
Multi Anode PMT

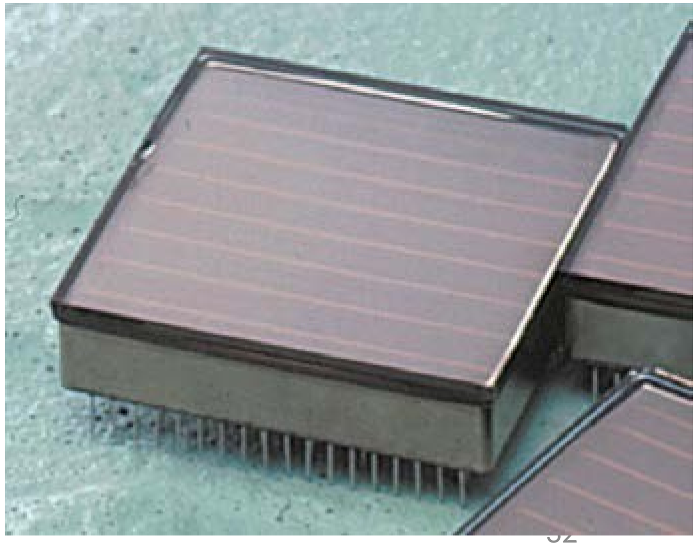
- ***Electron multiplication in narrow, independet channel***
  - The read-out is performed with a **segmented anode**
  - *Position sensitive*
  - *Tolerance to modest B field*

- *Exist in many anode segmentation. Dimensions ~5 cm x 5 cm*
- **High gain, high QE**
- Limited cross talk <2%

- ***MicroPMT***: very small, flat single channel devices

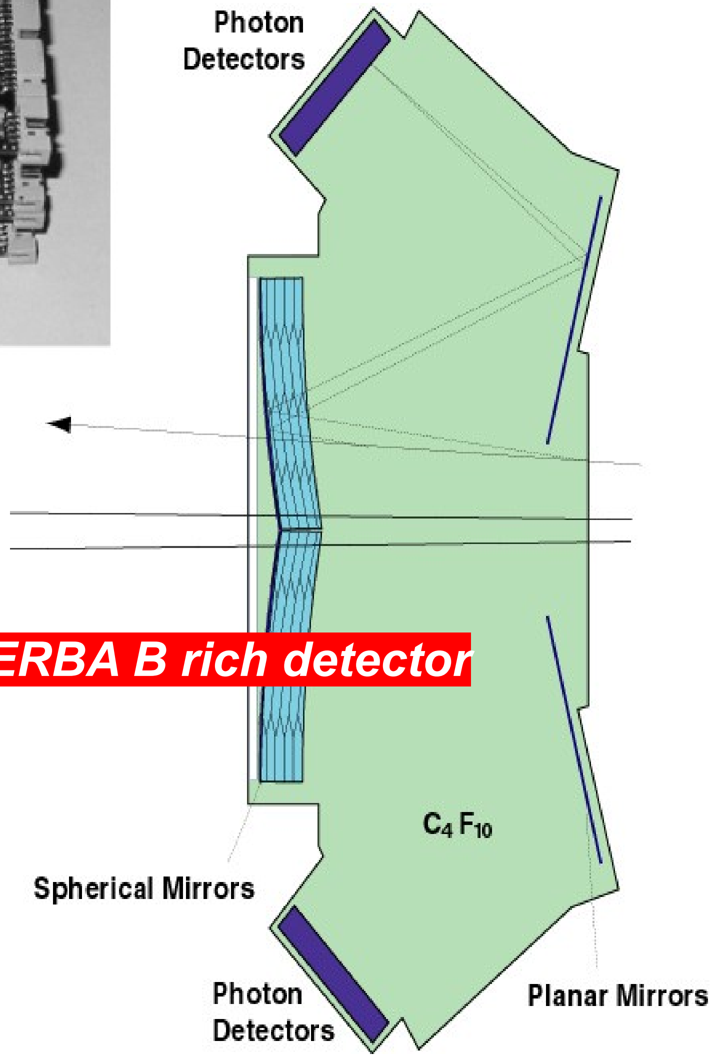


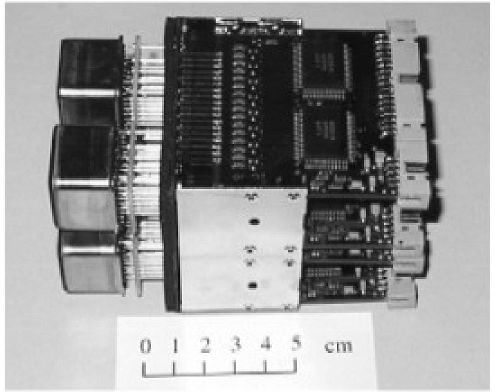




Multi Anode PMTs: Applications

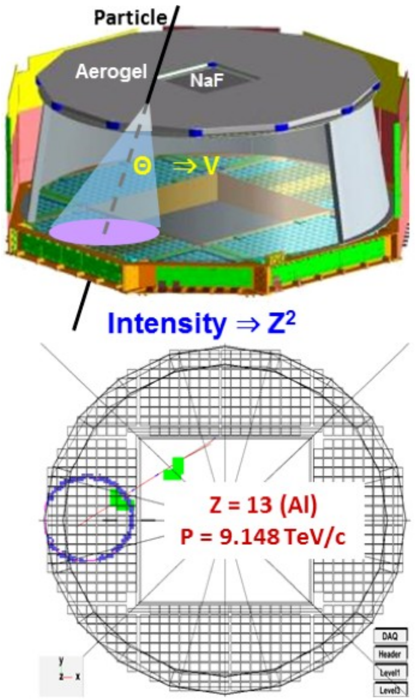
- ***RICH detectors*** (HERA-B first with MaPMTS)
- ***Positron Emission Tomography***

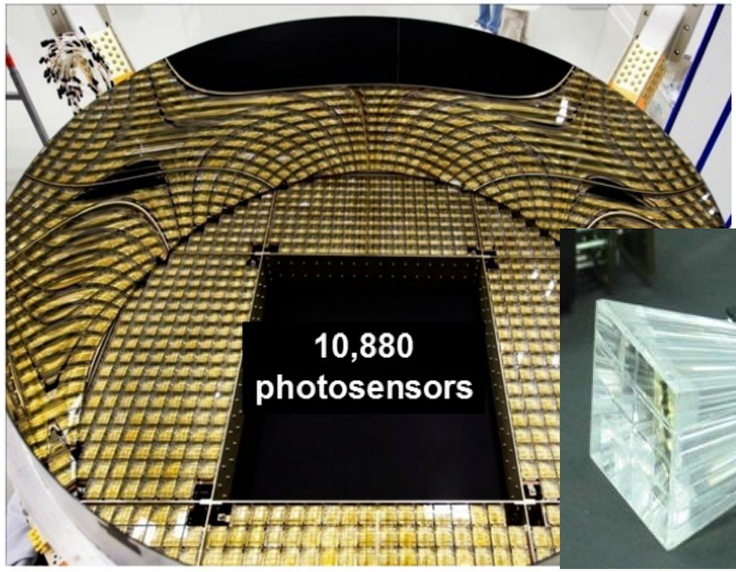


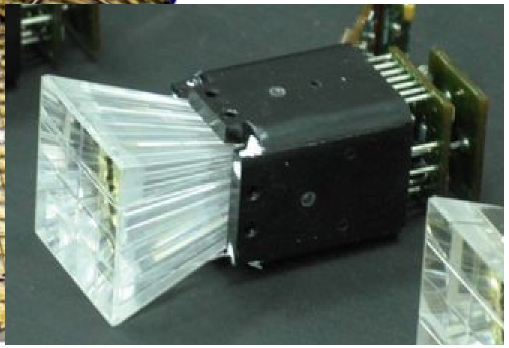


HERBA B rich detector

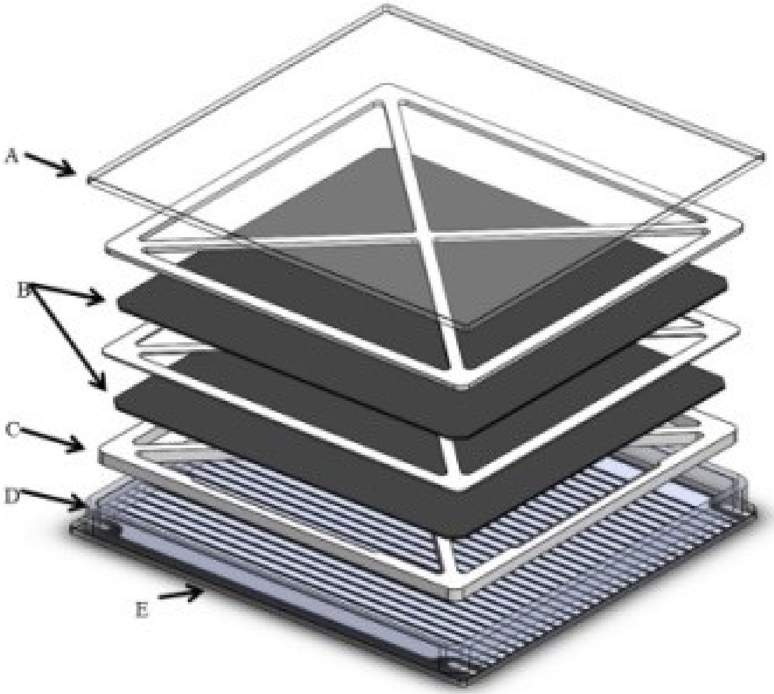
AMS Rich detector

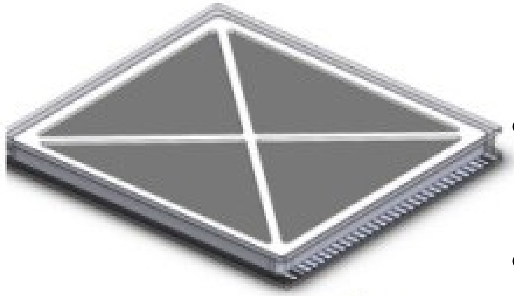




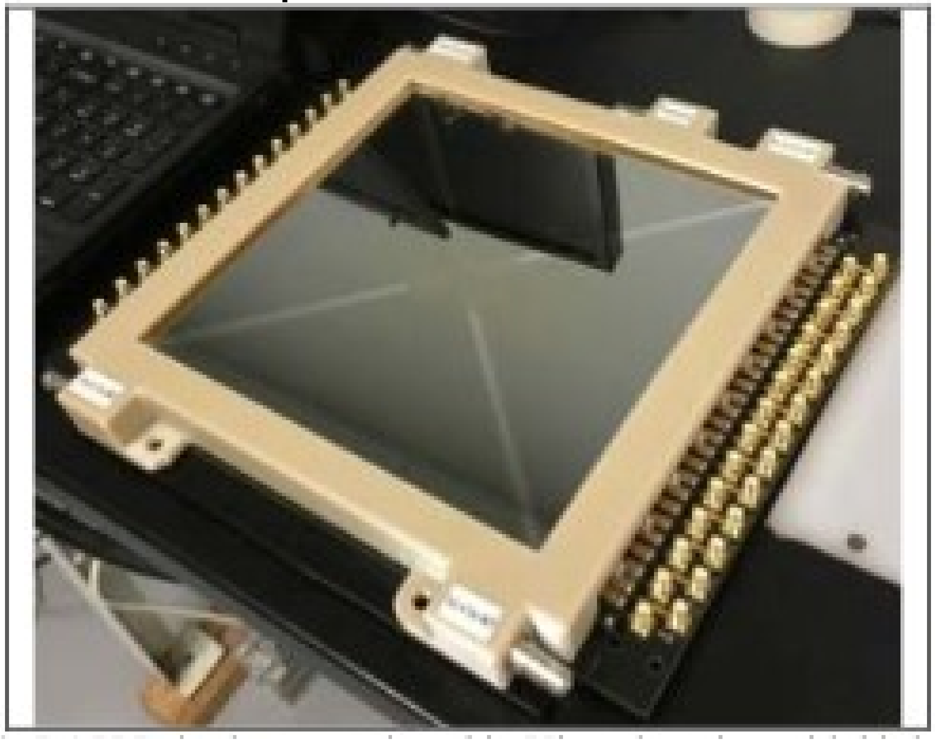


LAPPD Large Area Picosecond Photodetector





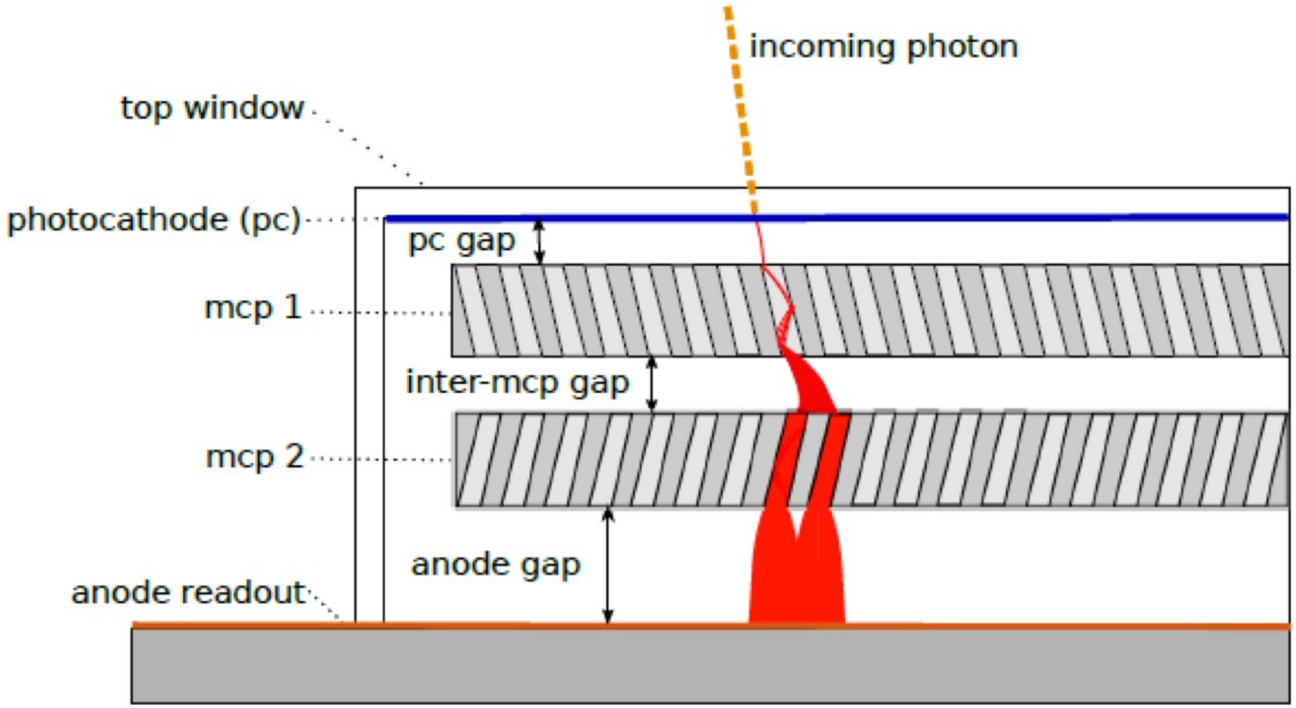
- **Large area** (20 cm X 20 cm) ***vacuum device***
- *Fused silica window with MultiAlkali photochatode on the inside*
- Two strage of electron multiplication through ***microchannel plates***
- **Strip anode** =>spatial reconstruction of the hit



- **QE ~20%**
- ***Time resolution < 100 ps for single photon events***
- **Space resolution < 1 mm** in both directions
- *Gain 10^7 @ 1 kV*
- *Dark noise ~20 Cts/s/cm^2*

LAPPD Large Area Picosecond Photodetector

Micro Plates Channel



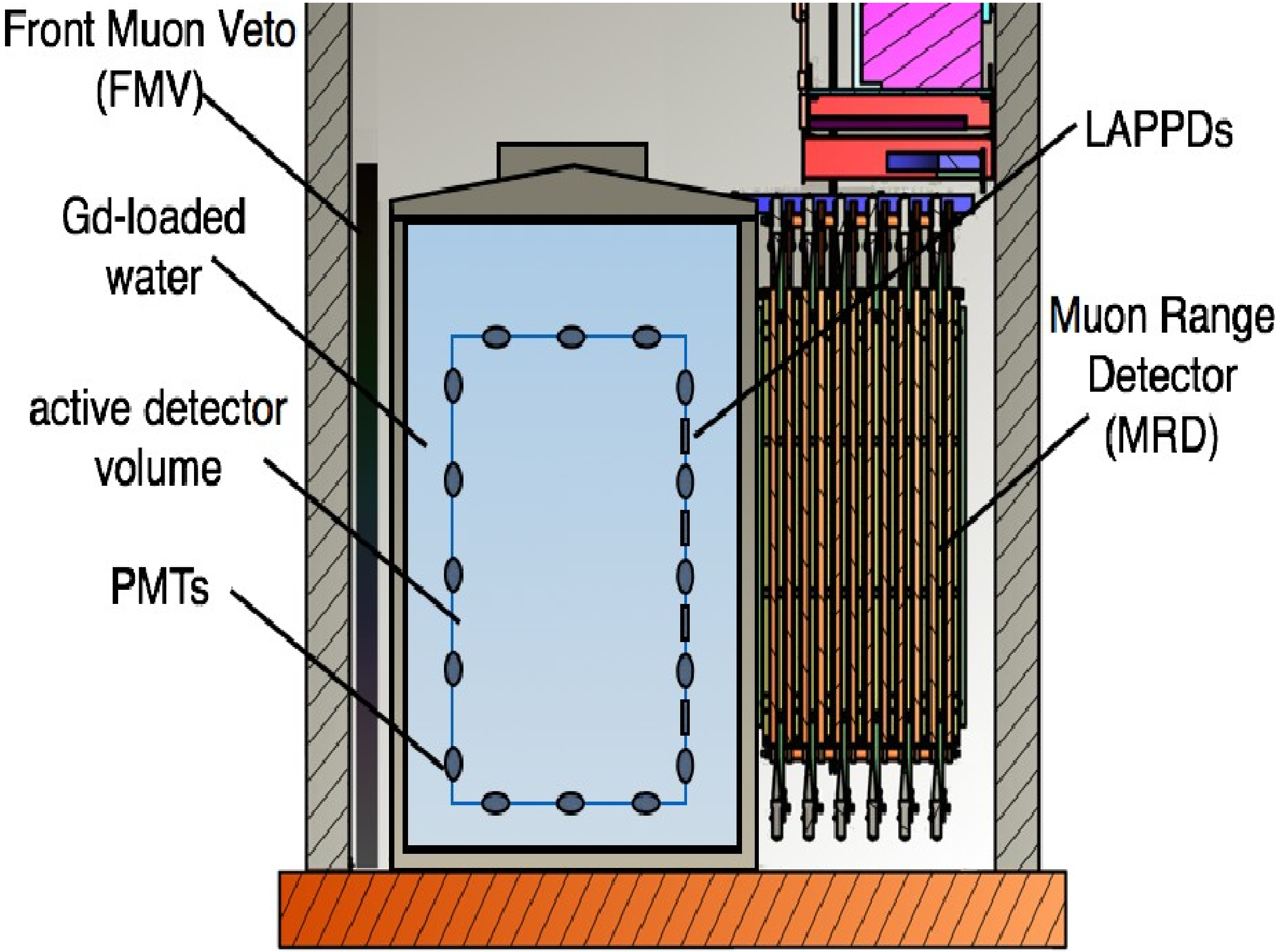
New generation large-area high performance MCPs - enabled by two technological breakthroughs

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

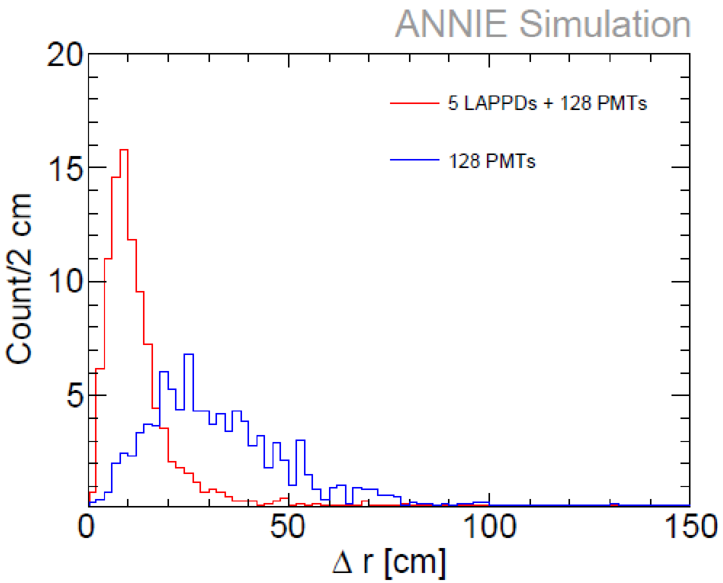
- **Accelerator Neutrino Neutron Interaction Experiment**
- ***26-ton Gd-doped water Cherenkov*** detector installed in the *BNB at Fermilab*
- **Study the neutron multiplicity** in *CC neutrino-nucleus interaction in water*
- **Demonstrate the use of LAPPD**

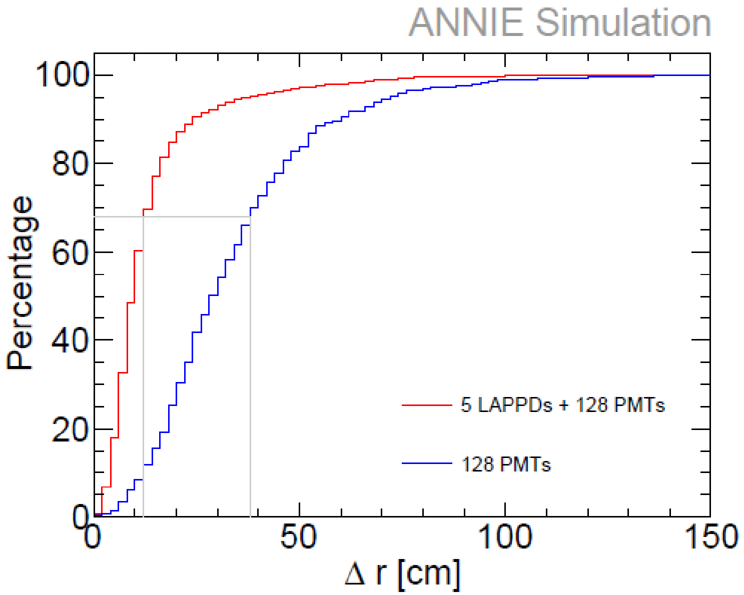


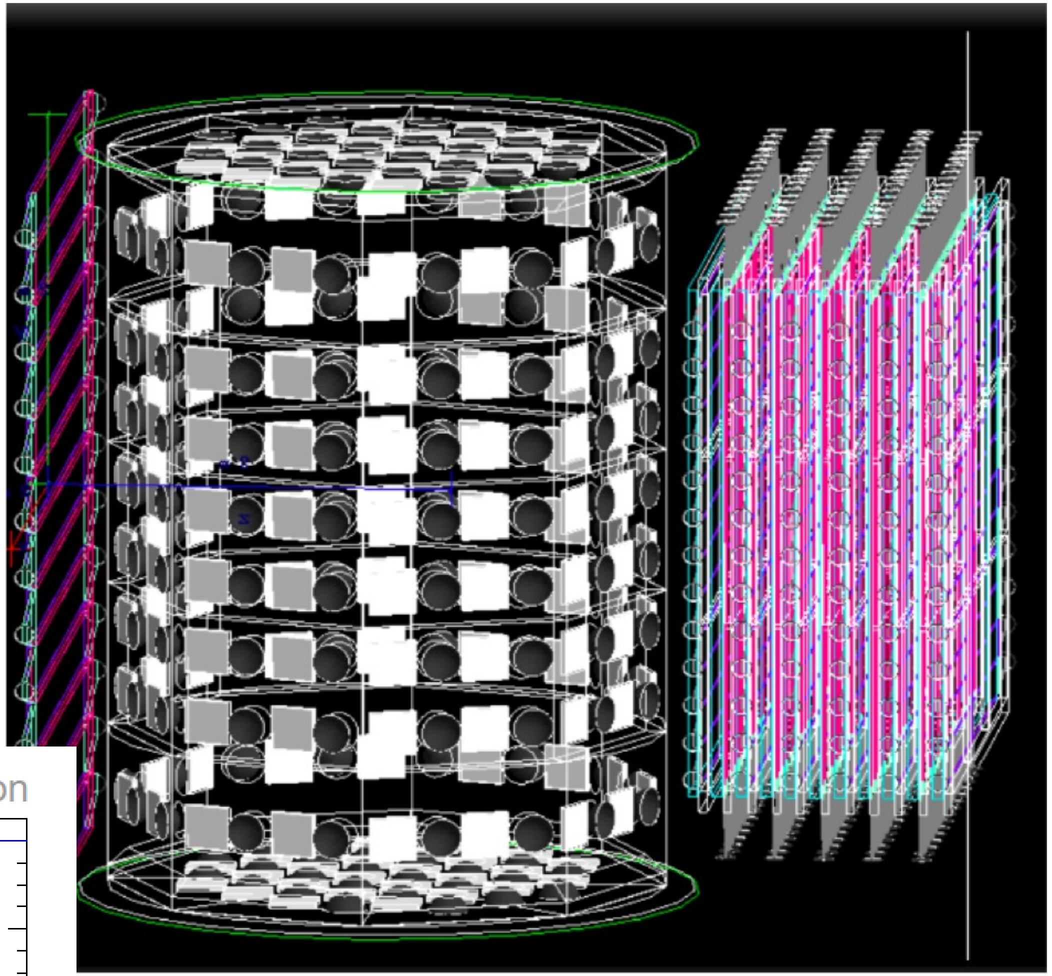
I*dentifying and counting final state neutrons is important to understand and reduce the systematic uncertainties of the neutrino energy reconstruction in oscillation experiments*

LAPPD: ANNIE detector

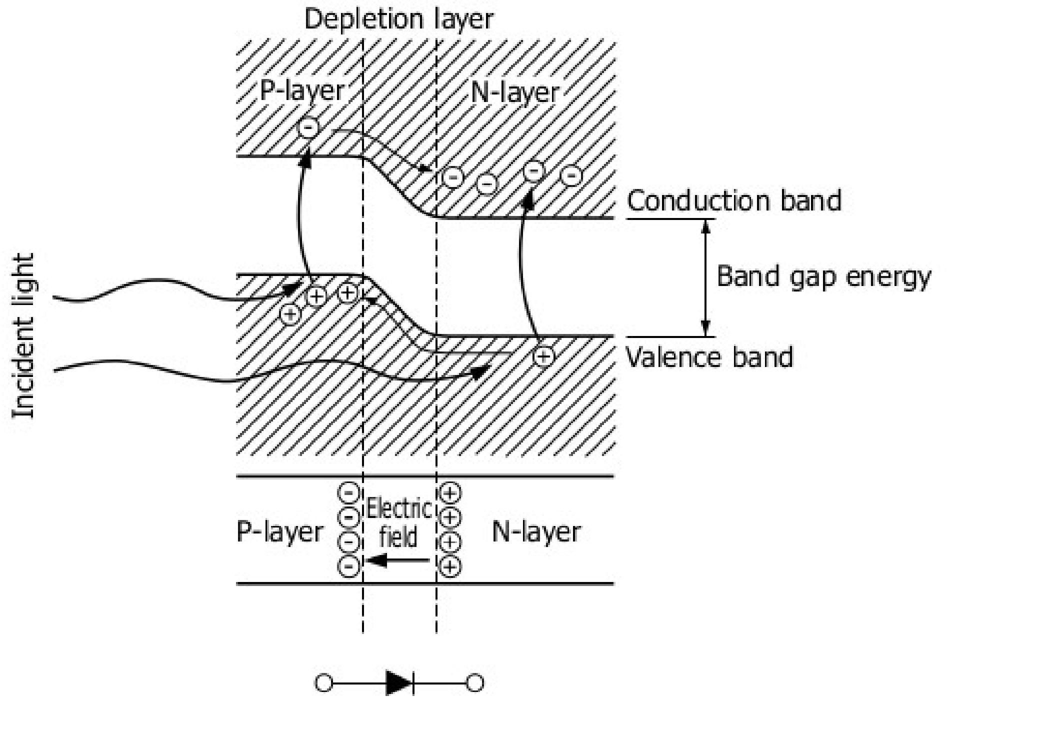
- ***Fundamental measuring with precision the interaction vertex*** of the neutino to **fiducialize the active volume** => *maximize the capture prob. of neutron by Gd after thermalization*
- Using just **a small coverage of LAPPD,** complementing standard PMT (5 over 128) ***significantly improves the localization of the vertex*** (factor 3)



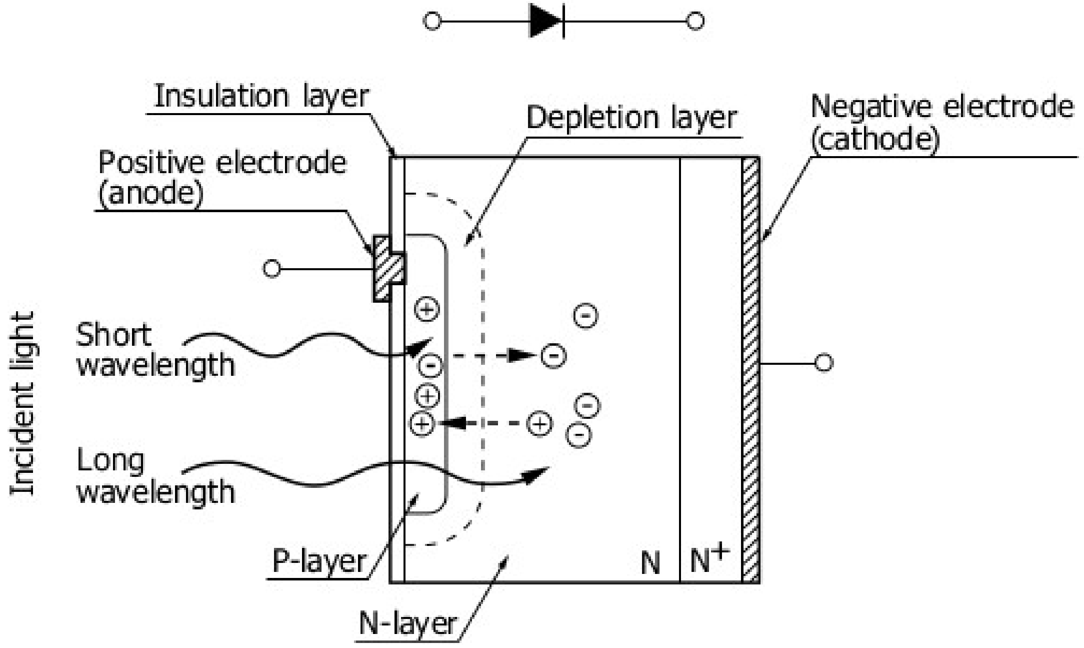




Silicon devices: PN junction



KAPDC0071EB

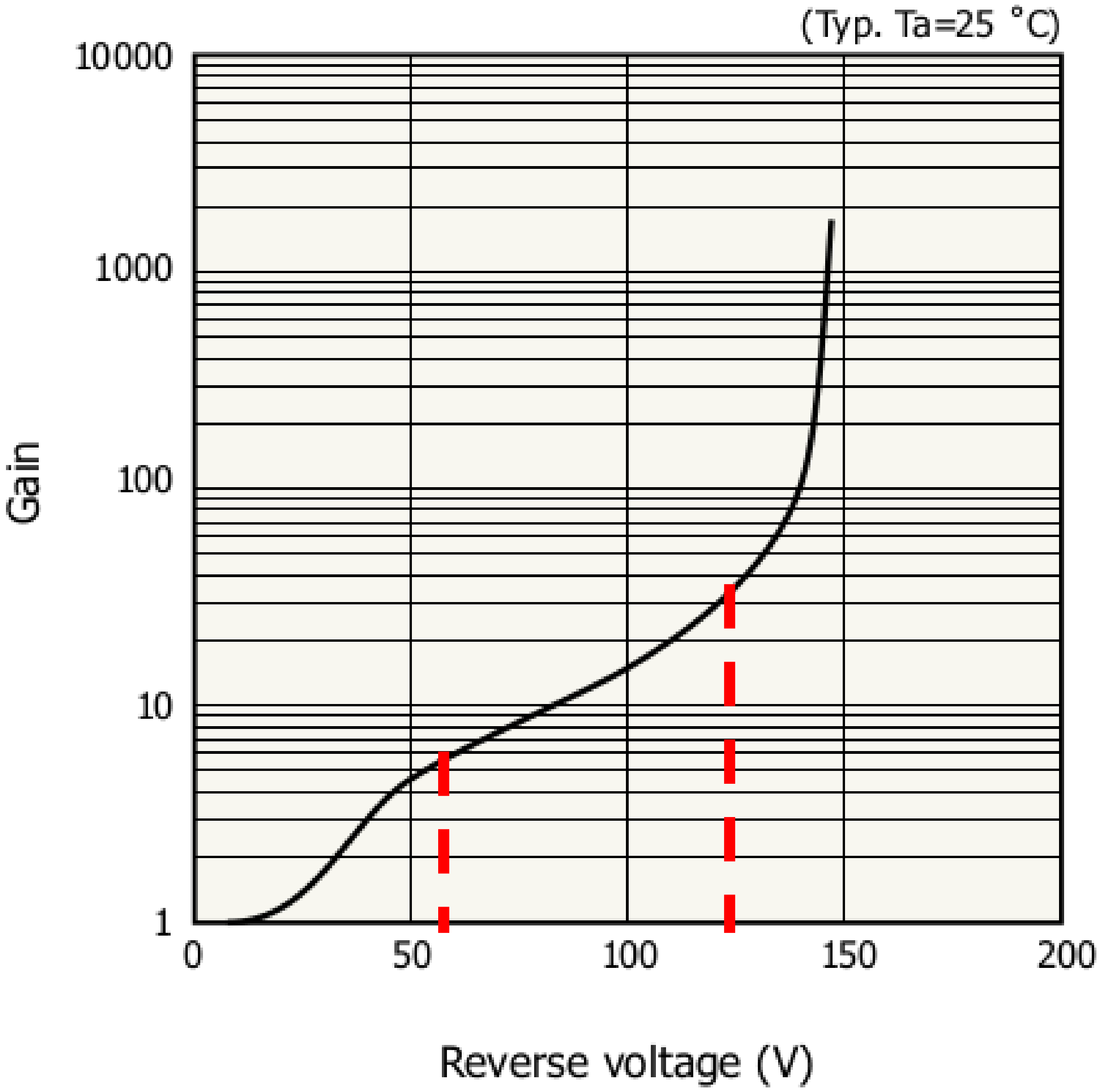


KPDC0002EA

Members of a larger family with PIN diode and APD (Avalanche Photo Diode). They differ for the amplification mechanism

Hamamatsu handbook: https://www.hamamatsu.com/resources/pdf/ssd/mppc_kapd9005e.pdf

APD

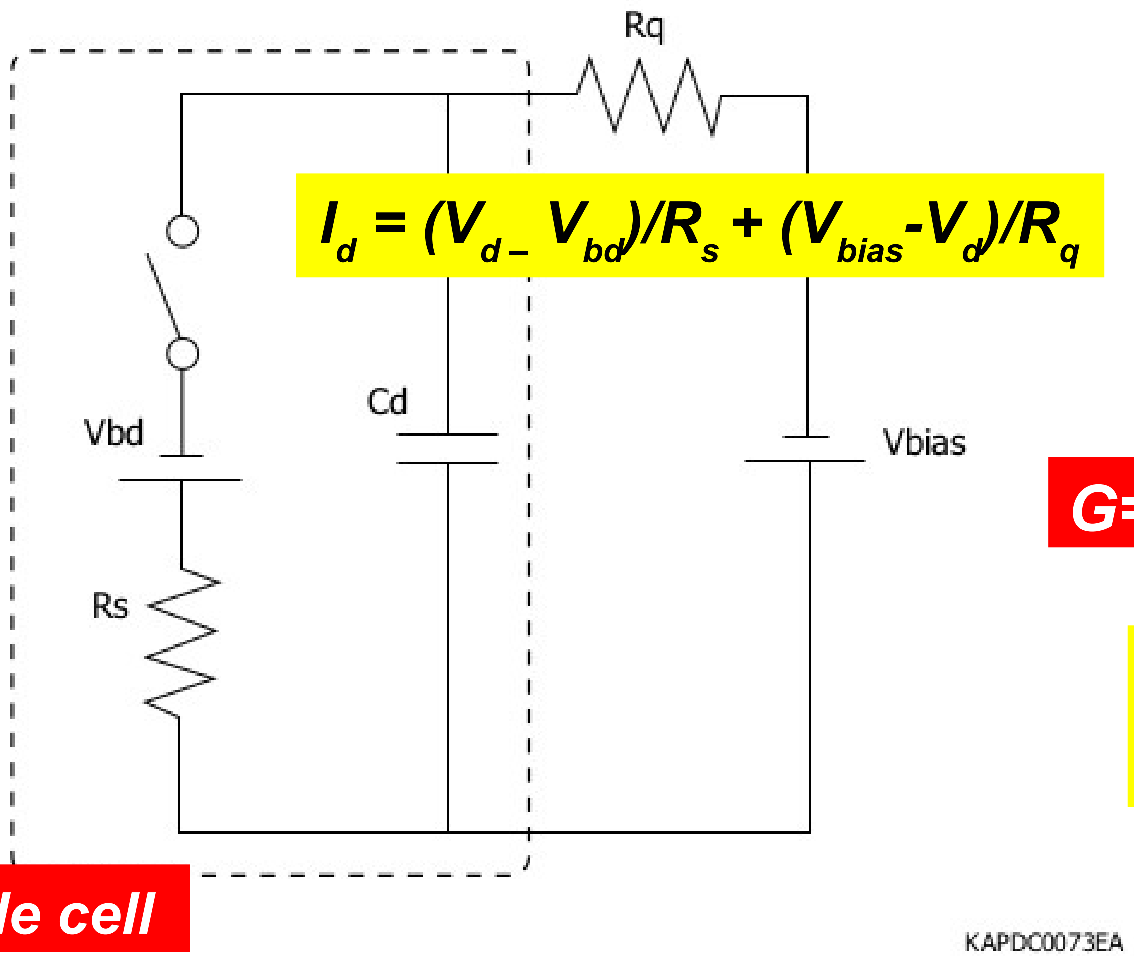


- ***Depletion layer can be deepened*** biasing the PN junction ***in reverse***
- Increases the electric force on charge carriers => *more kinetic energy between collisions*
- If E is high enough => mean energy of carriers can exceed the silicon band gap energy between collisions => ionize lattice atoms upon impact and ***release at least another electron-hole pair into conduction and valence bands per impact***

$$G = 2 + 2P^2 + 2P^3 + \ldots = \sum P^i = \frac{1}{1-P}$$

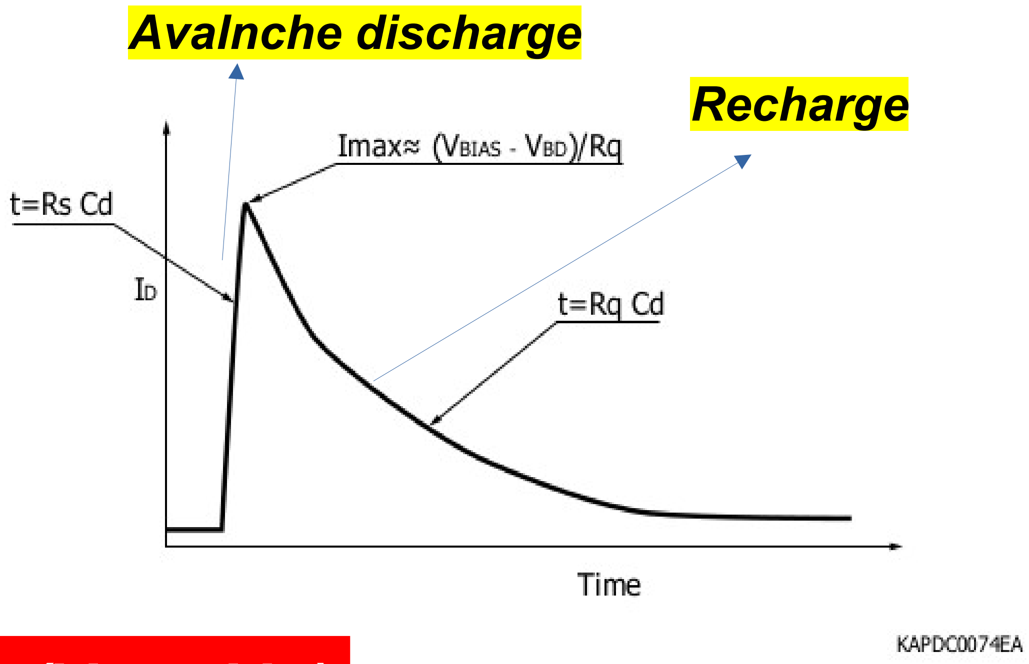
Geiger Mode APD (GAPD)

APD working in Geiger mode → digital device



$$I_d = (V_d - V_{bd})/R_s + (V_{bias} - V_d)/R_q$$

single cell

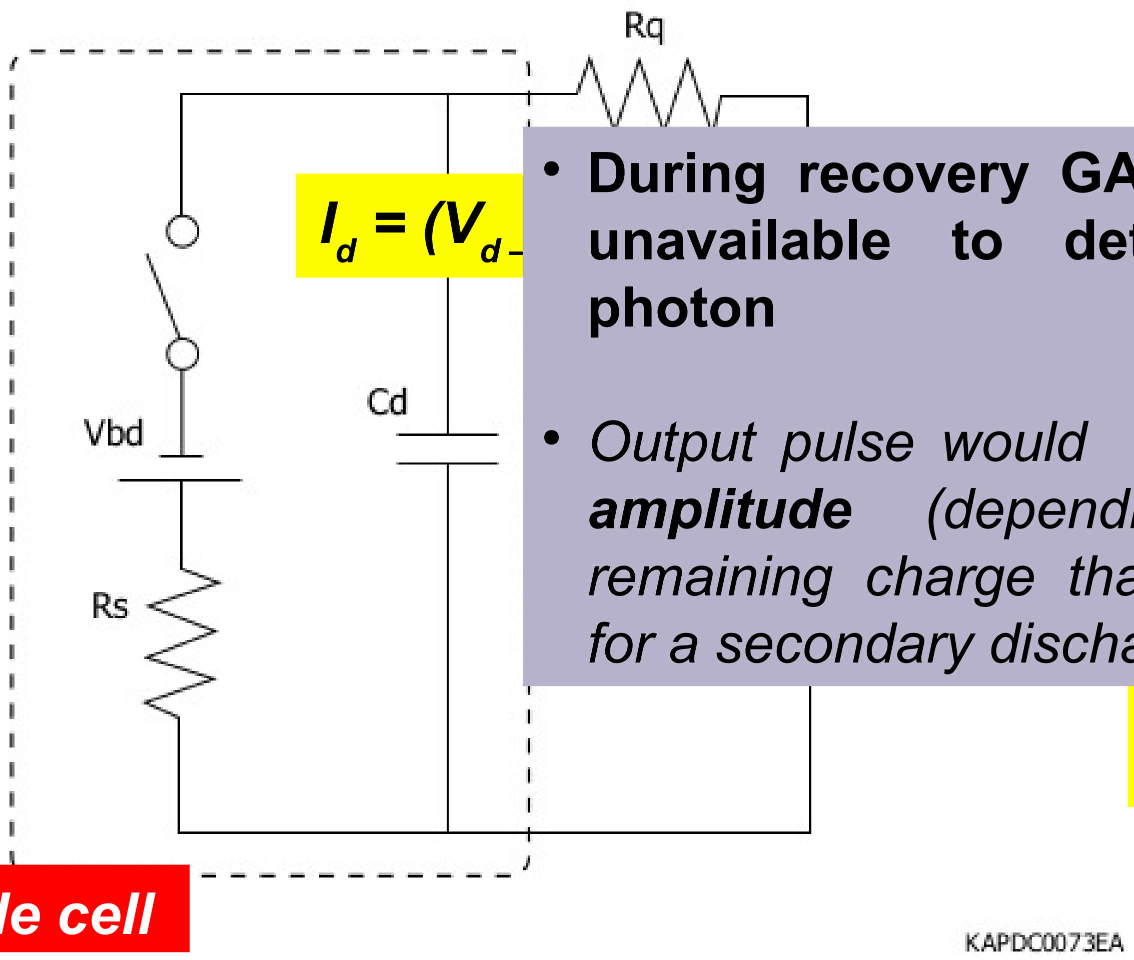


$$G = C_d\,(V_{bias} - V_{bd})$$

Rise time is fast ~ ns (good for timing)
Decay time slower ~hundreds of ns

Silicon Photomultipliers equivalent circuit

APD working in Geiger mode → digital device

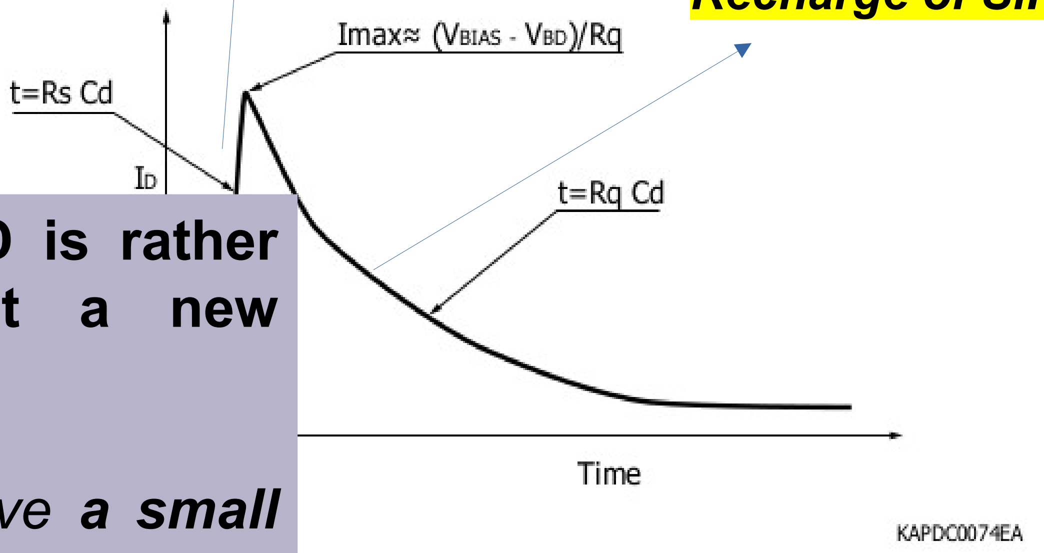


$I_d = (V_d -$

- **During recovery GAPD is rather unavailable to detect a new photon**
- *Output pulse would have **a small amplitude** (depending on the remaining charge that is available for a secondary discharge)*

Avalnche discharge

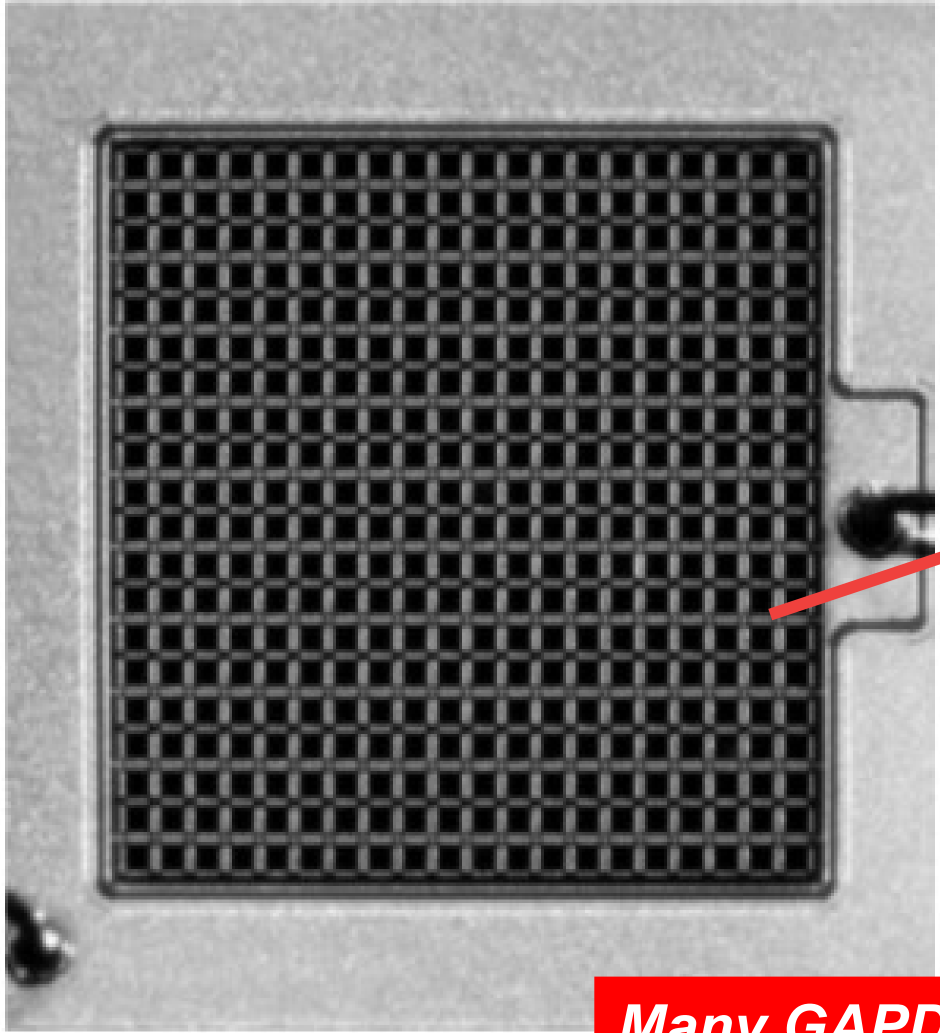
Recharge of SiPM

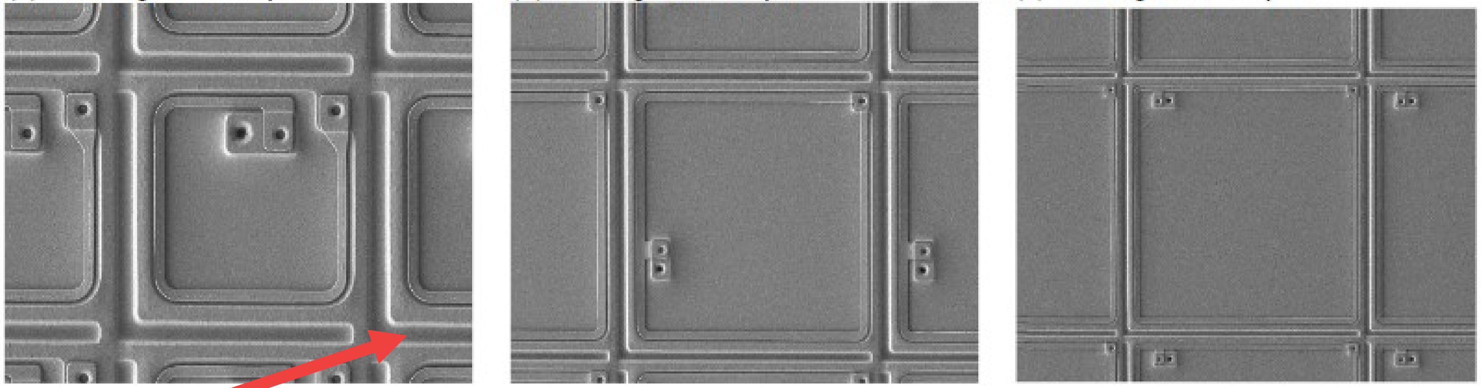


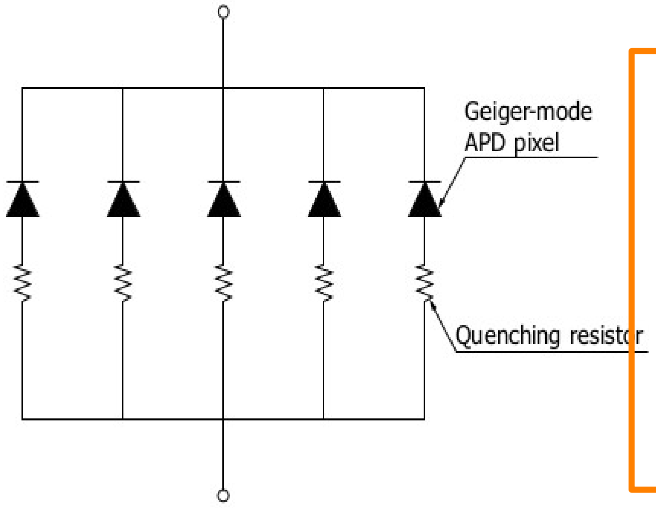
Rise time is fast ~ ns (good for timing)
Decay time slower ~hundreds of ns

single cell

Silicon Photomultipliers (SiPM)







KAPDC0029EA

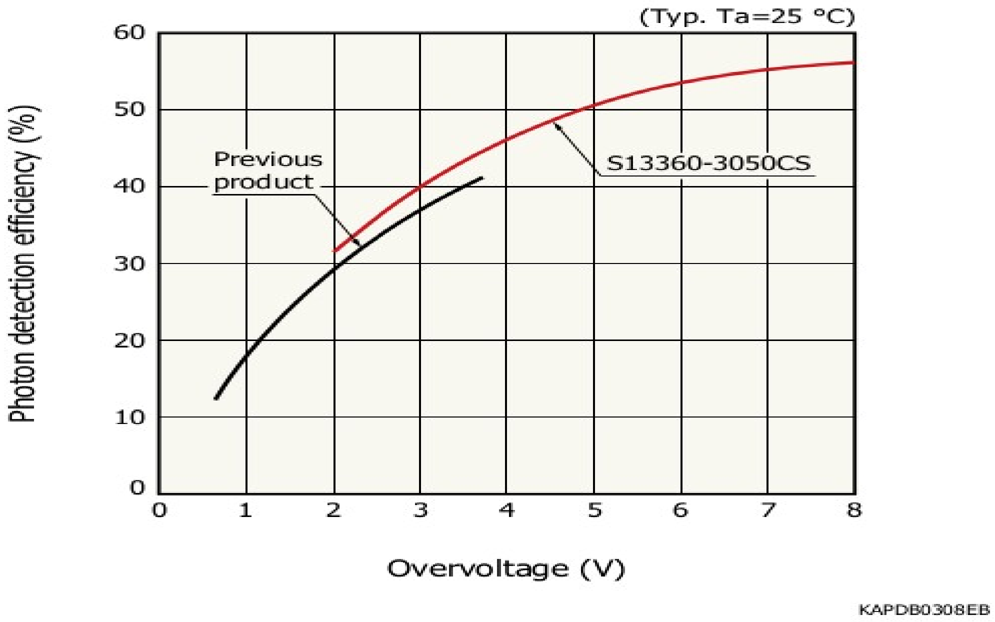
PDE = QE X F X P_a

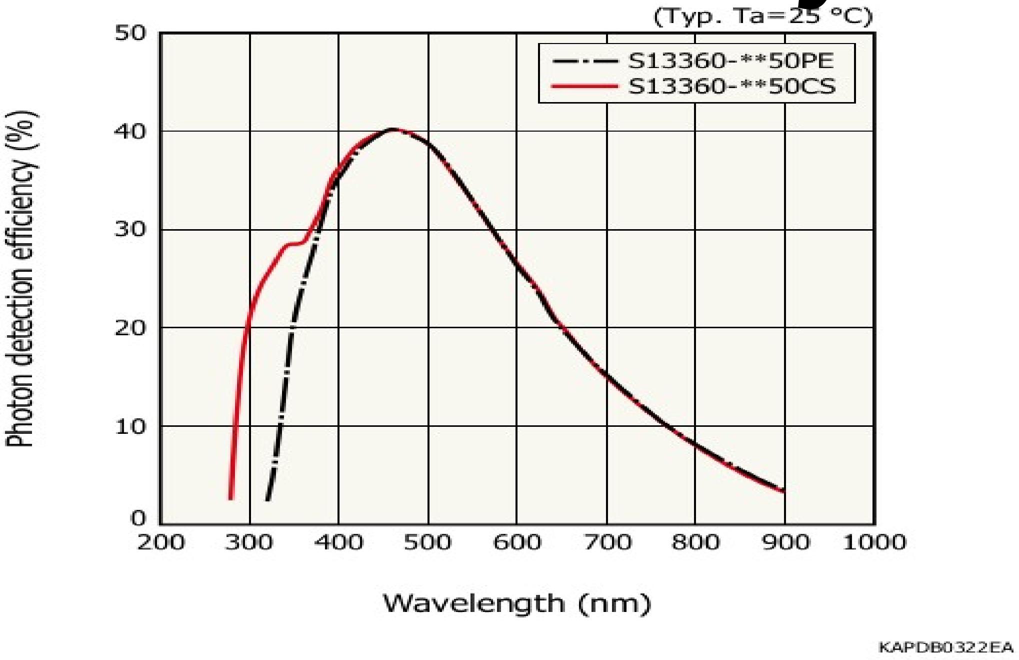
QE quantum efficiency
F fill factor
P_a probability of triggering an avalnche

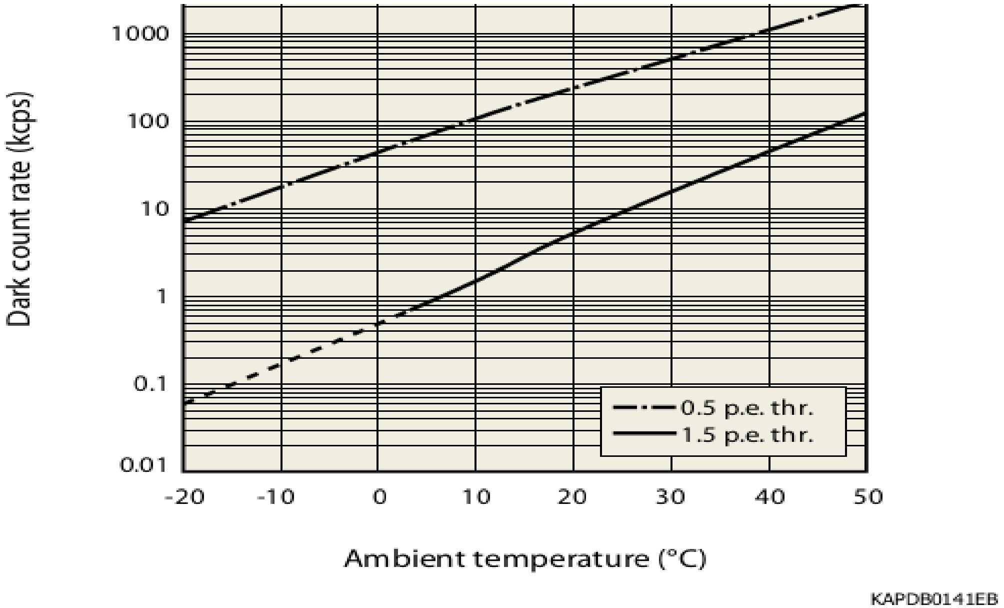
Many GAPD in parallel

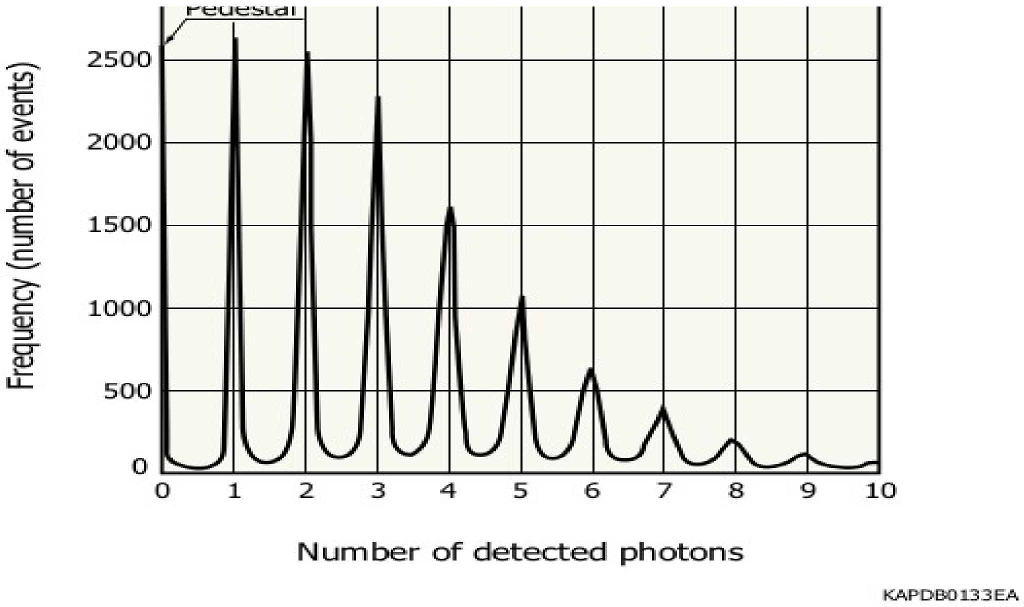
KAPDC0049EA

Gain and Photon Detection Efficiency



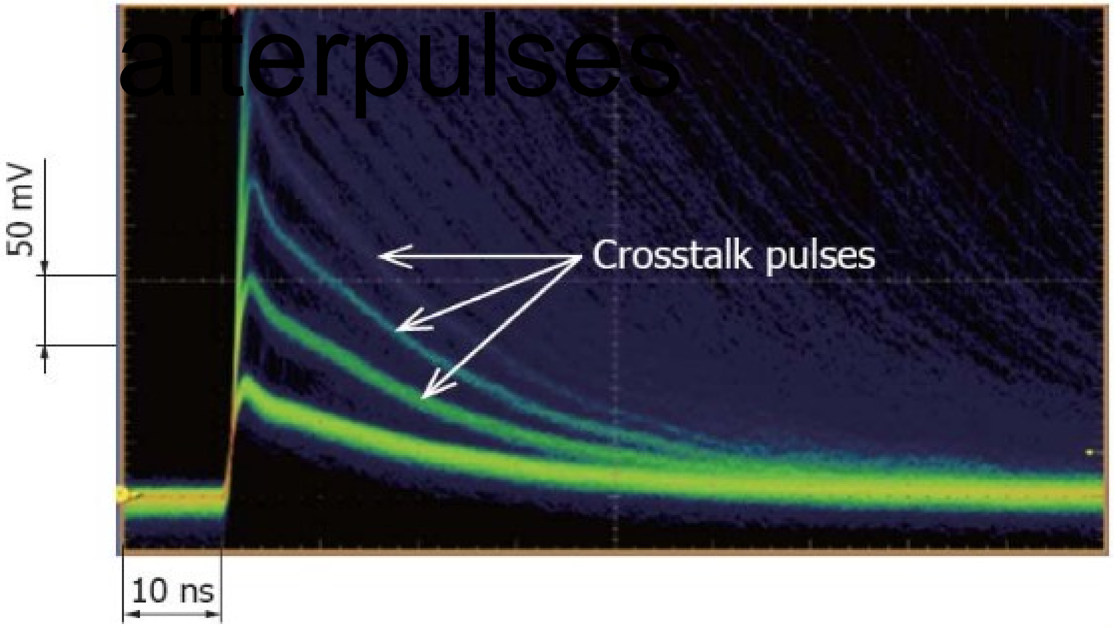






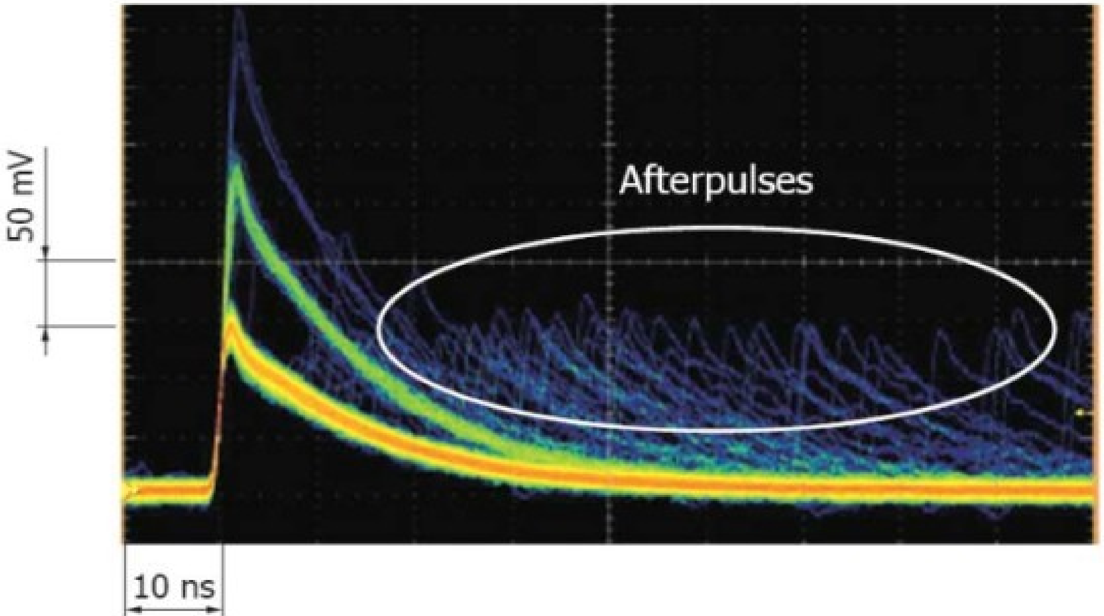
Cross talk and afterpulses

afterpulses



- During avalanche process, kinetic energy of avalanching carriers can be lost ***through photon ewmission***

- Photons ***can travel to the neighboring pixels and initiate avalanches***

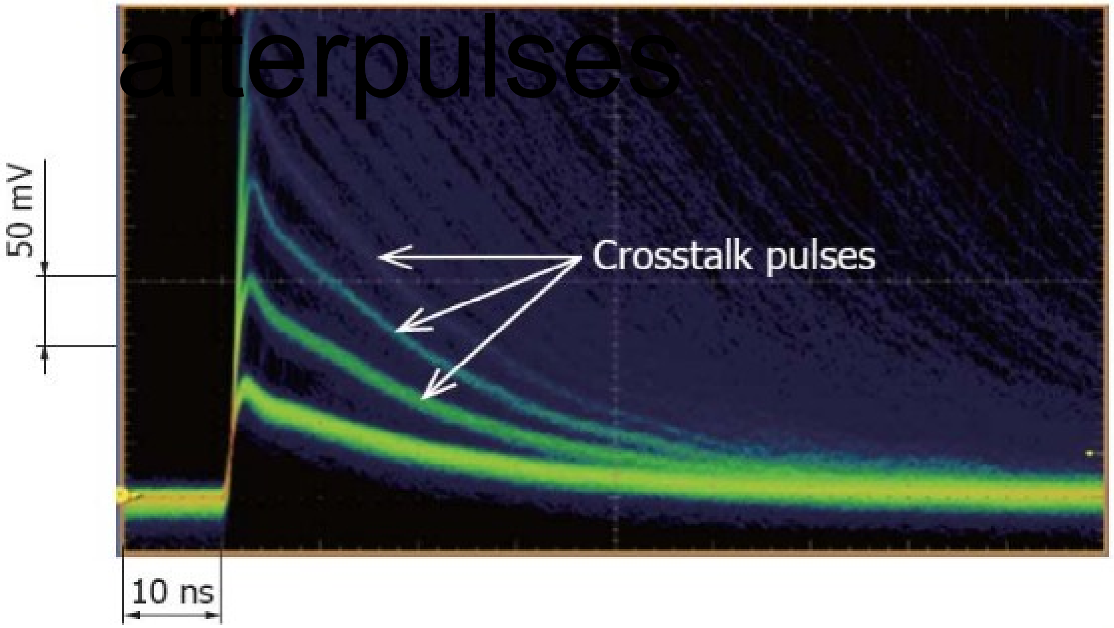


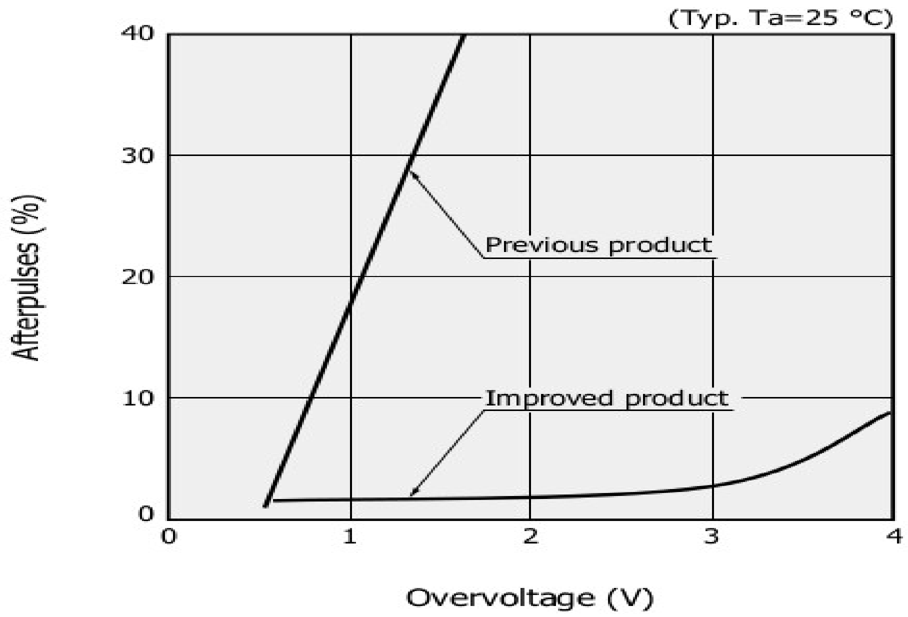
- During avalanche process a small fraction of avalanching carriers can be ***trapped in impurityenergy levels***

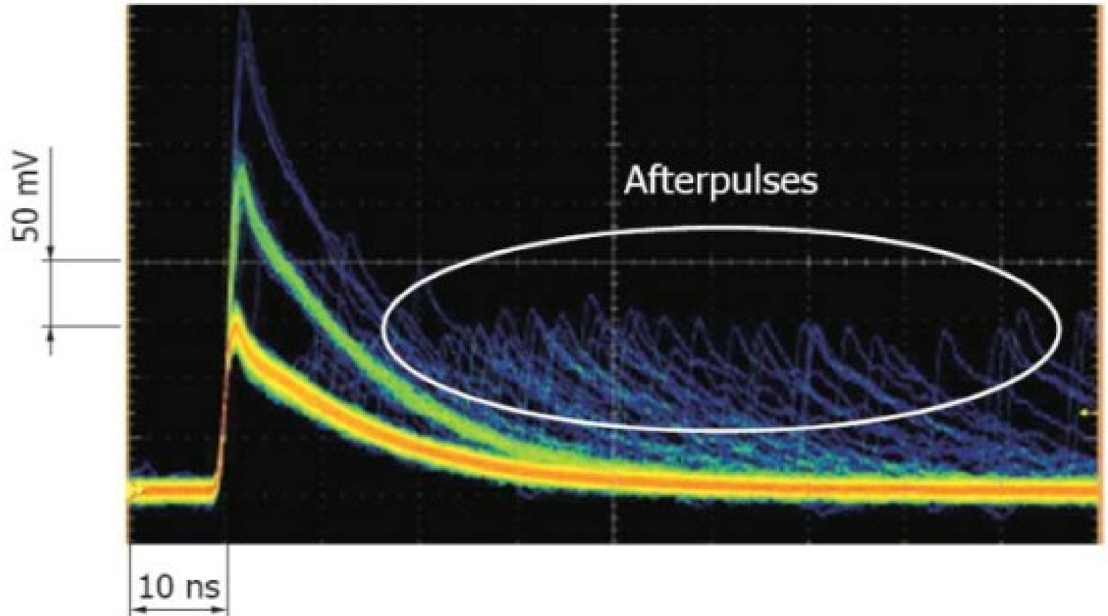
- **Released after short delays**

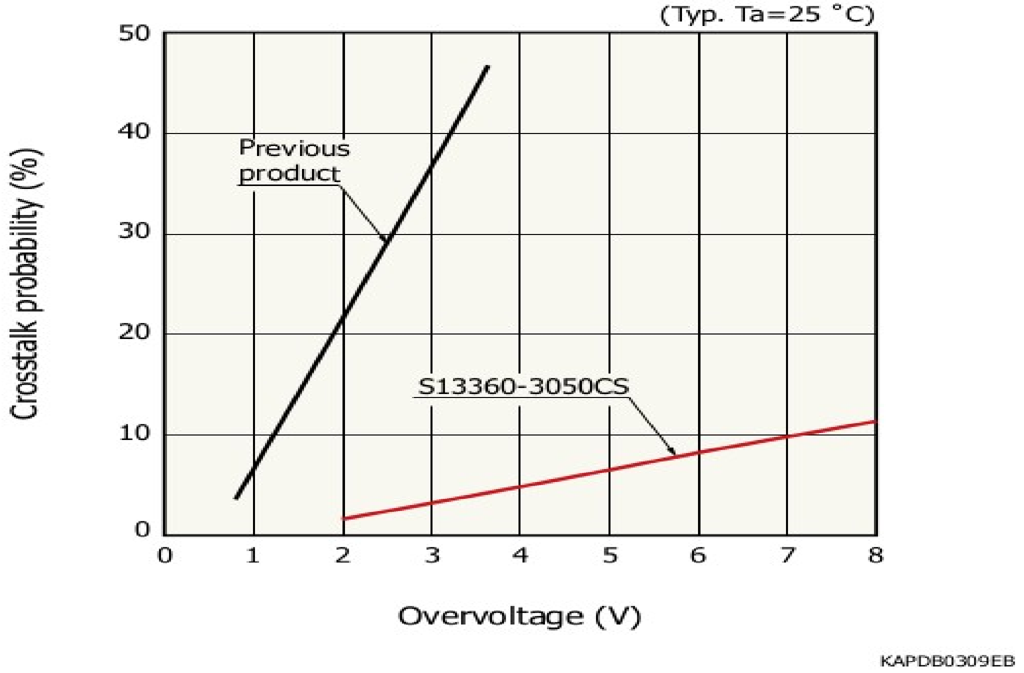
Cross talk and afterpulses

afterpulses





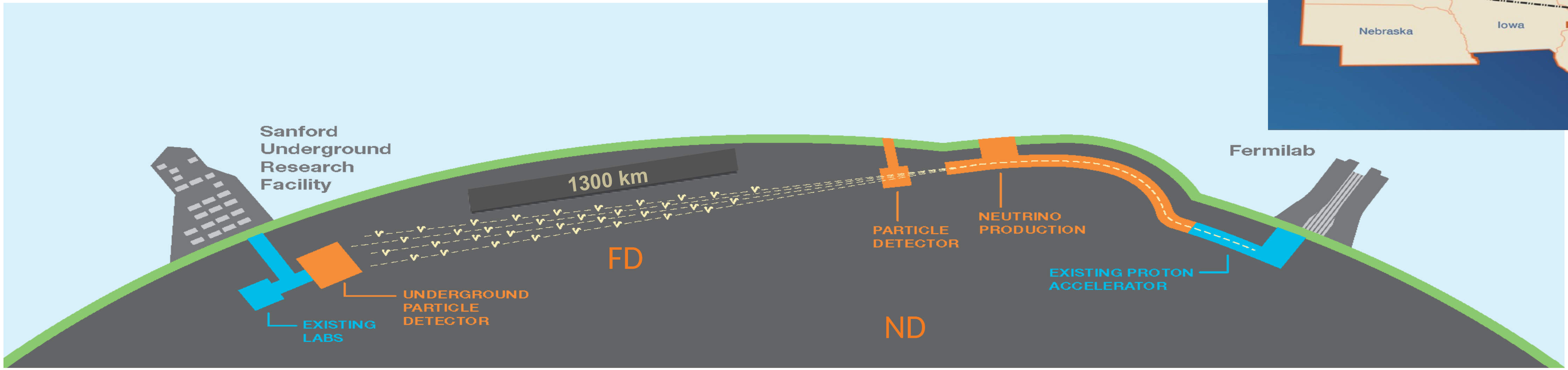




Silicon Photomultipliers – pros and cons

- *Low bias voltage O(50 Volt)*
- *Digital detectors*
- *High gain → Single Photo electron reconstruction capability*
- *Small amount of material => Good for low background experiments*
- *But small active area O(1 cm^2) each*
- *High Dark count rate at room temperature*
- *Need of ganging schemes to reach the coverage of a standard PMT*
- *and/or coupling with passive photon collectors*

Example: DUNE photon detection system

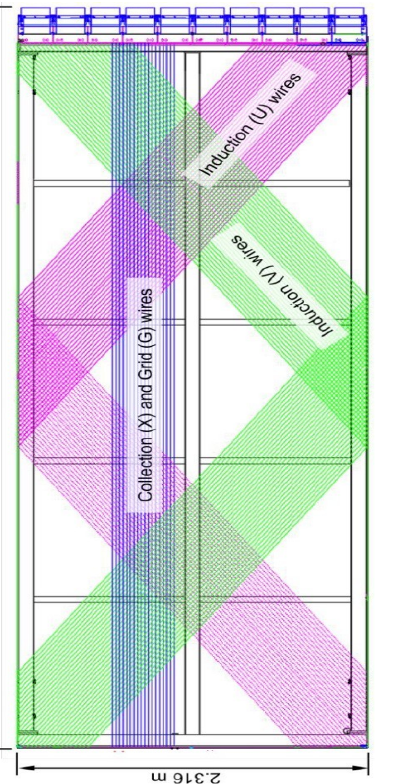


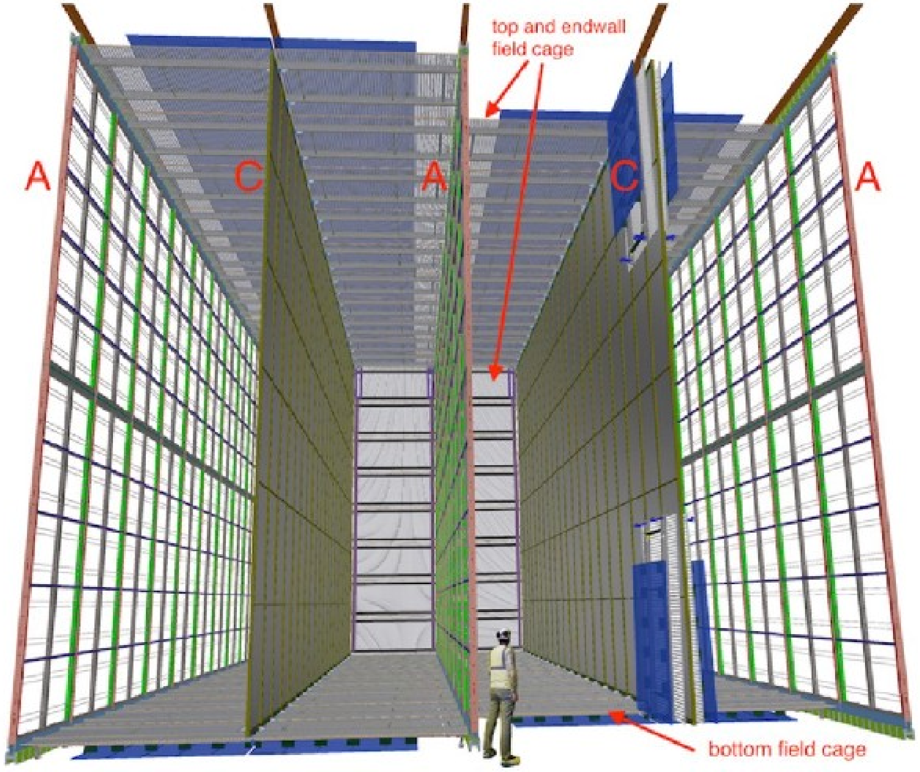
1. A high-power, wide-band neutrino beam (~ GeV energy range).
2. A ≈ 40 kt liquid-argon Far Detector in South Dakota, located 1478 m underground in a former gold mine.
3. A Near Detector located approximately 575 m from the neutrino source at Fermilab close to Chicago.

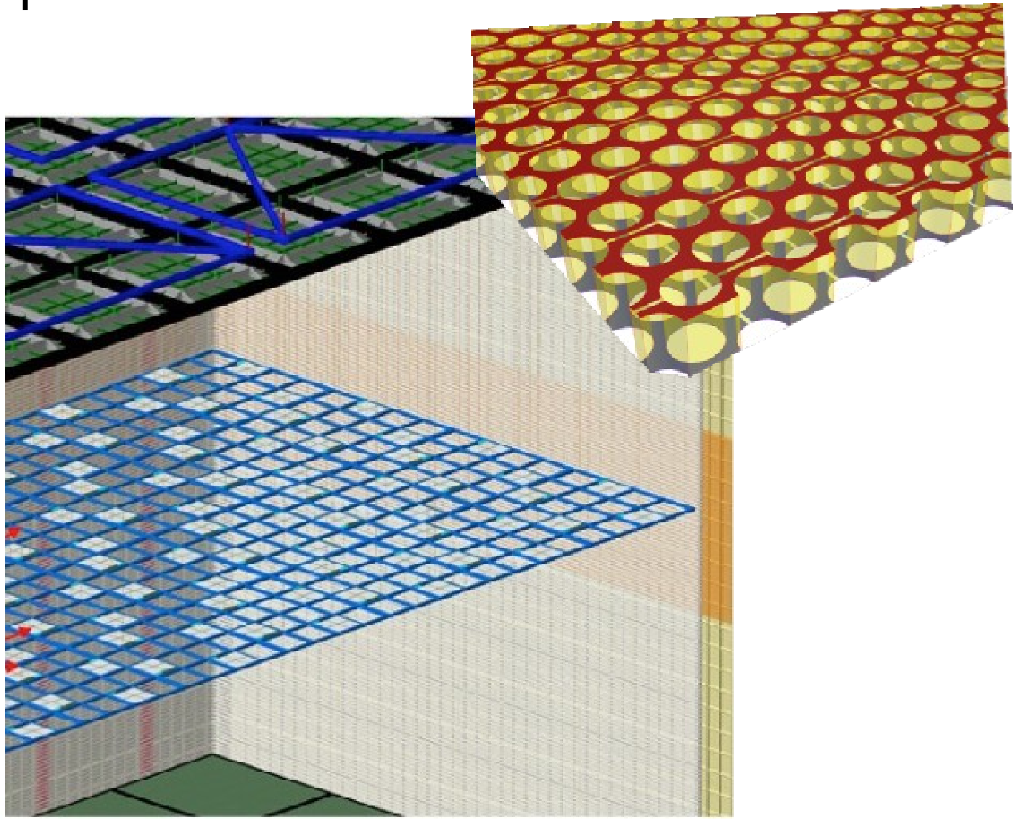
LAr read-out technologies

Module #1
-3.6 m horizontal drift
-vertical anode wire planes
-vertical resistive cathode
photon detectors → ***XARAPUCAs***

Module #2
-6.5 m vertical drift
-horizontal PCB anode readout (CRP)
-horizontal grid cathode
photon detectors → ***XARAPUCAs***





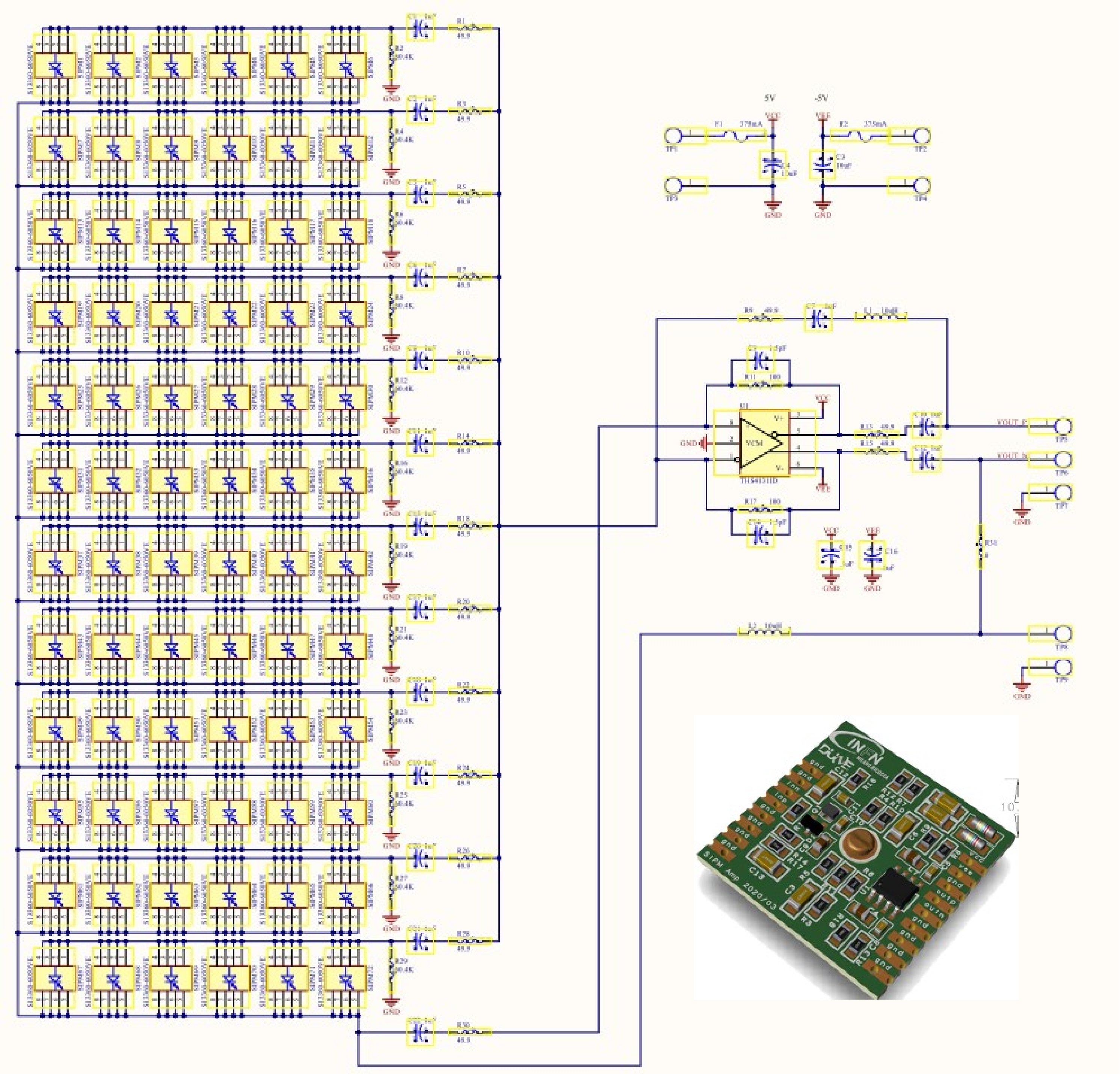


48 6x6 mm² ganged together in a single electronic channel

Ganging scheme:

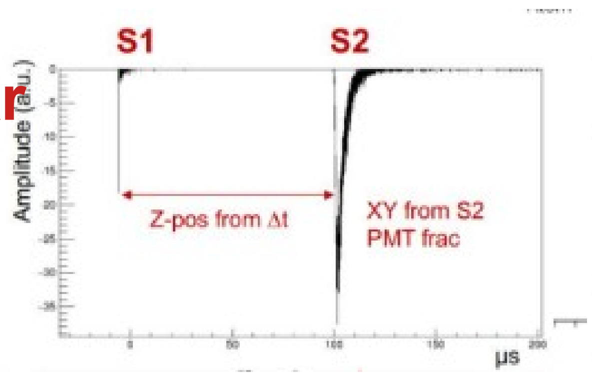
- SiPM **passively ganged in parallel in groups of 6**
- 8 groups of 6 SiPMs ***ganged actively together throug an OpAmp***
- *Passive ganging of SiPM reduces the amplitude of single photon signals given the increased overall capacitance*
- Active ganging ***does not affect the amplitude*** but adds electronic noise

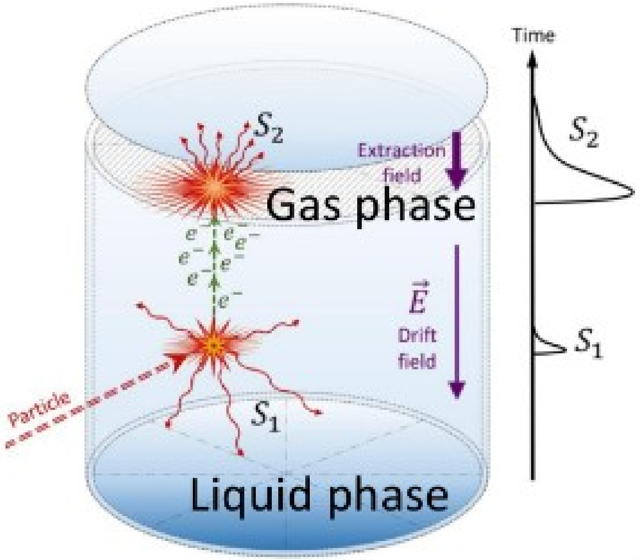
Total number of SiPM ~ 300,000

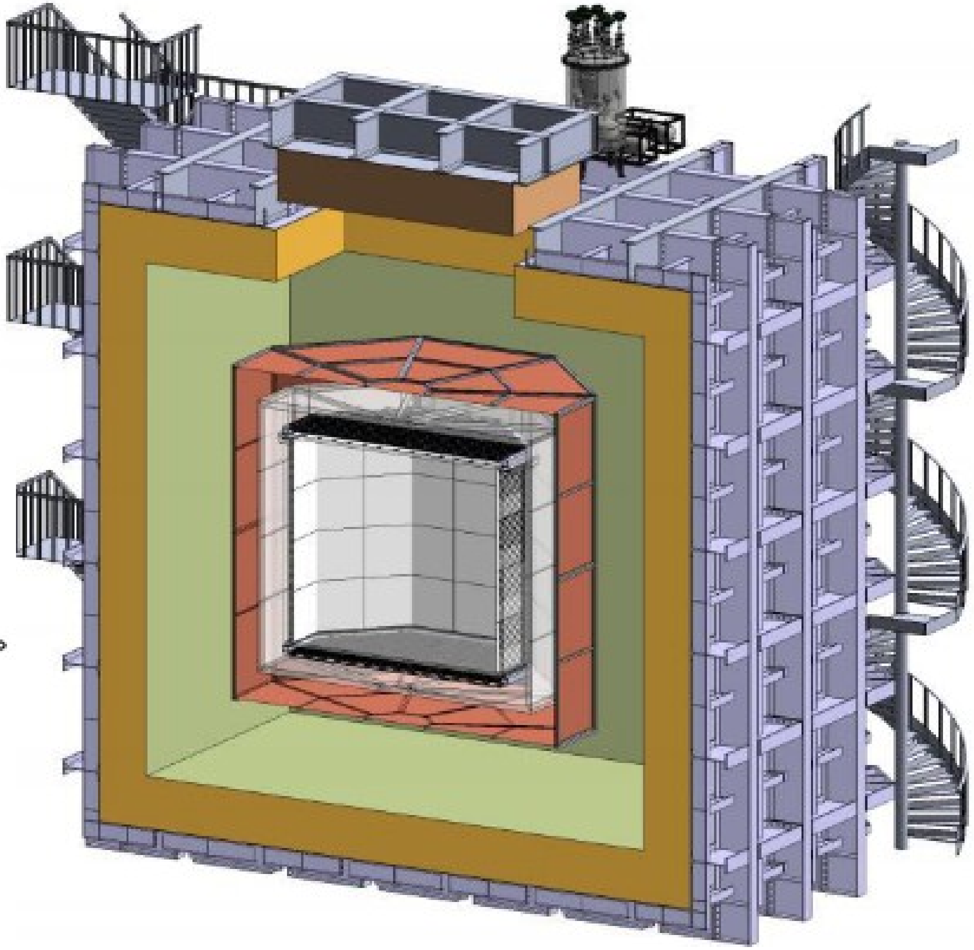


Example: DarkSide 20k

- **50t of Ultrapure depleted Ar**
- Primary (S1) and secndary (S2) scintillation and electroluminescence signals detected by ***two planes of SiPM arrays***
- SiPM allow for a **denser coverage** of the surfaces, **higher PDE** and **improved radiopurity**

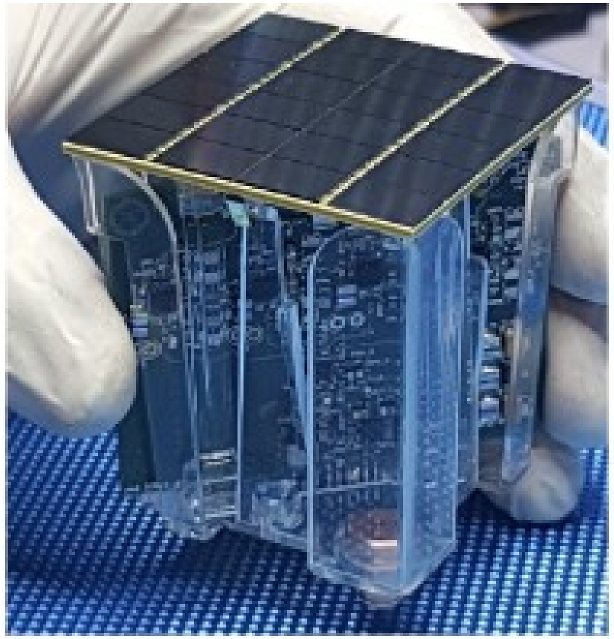


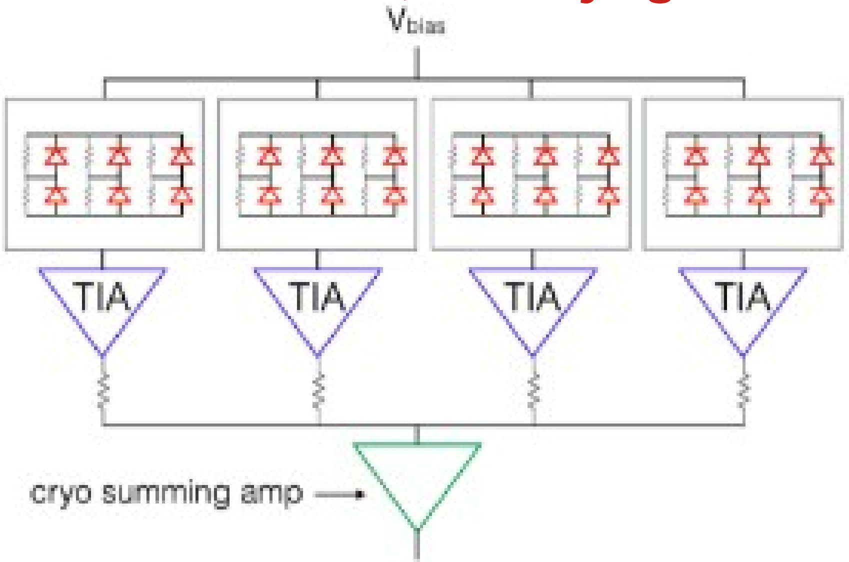


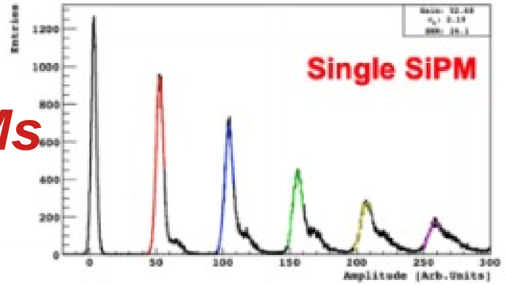


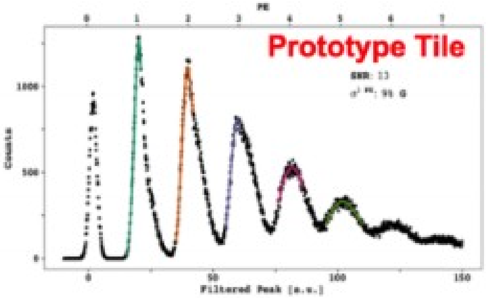
Example: DarkSide 20k

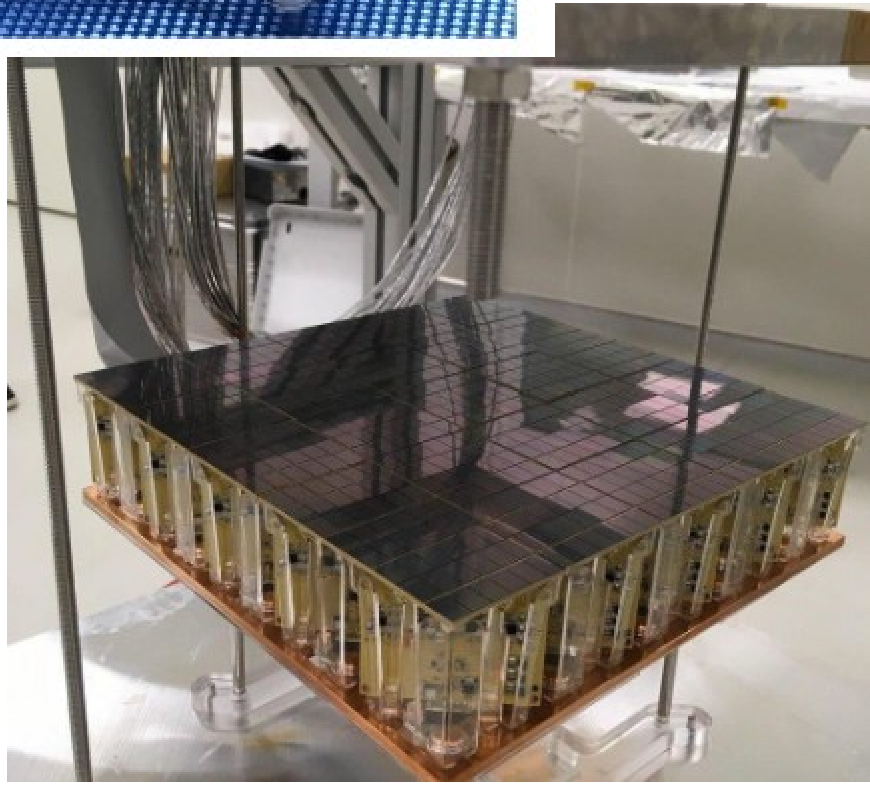
- Basic photo-detection module is an array of ***24 SiPM => PDM***
- SiPM *passively ganged in groups of 6 – mixed series/parallel* and *actively ganged in 4 groups of 6*
- ***25 PDMs arrangend in a Motherboard***
- ***8,200 PDMs => 196,800 cryogenic SiPMs***







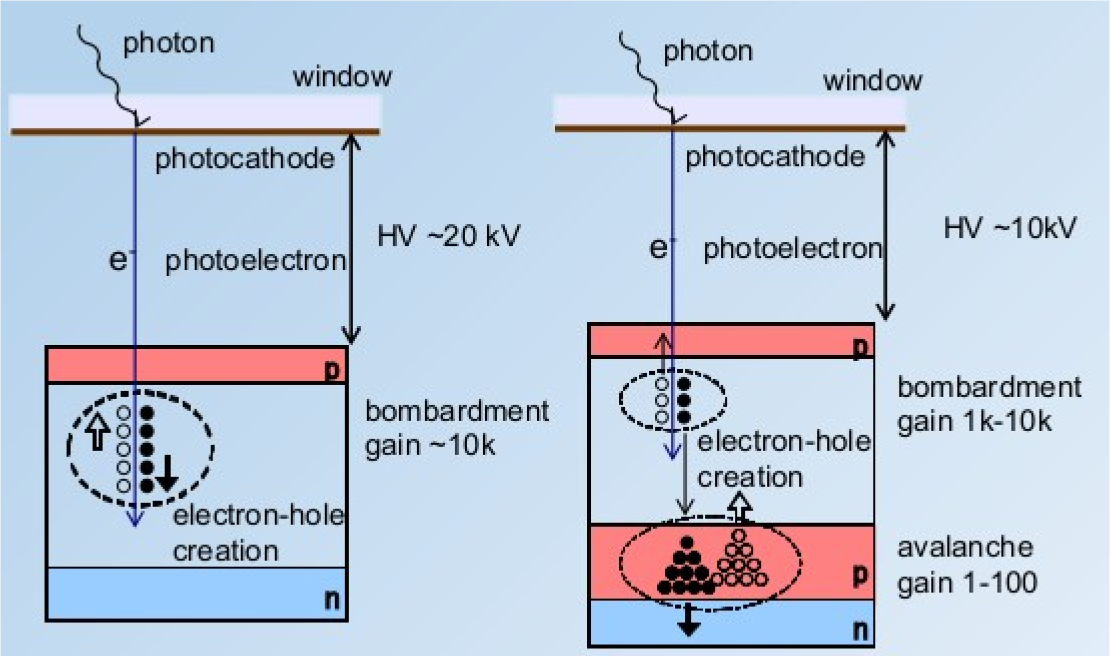




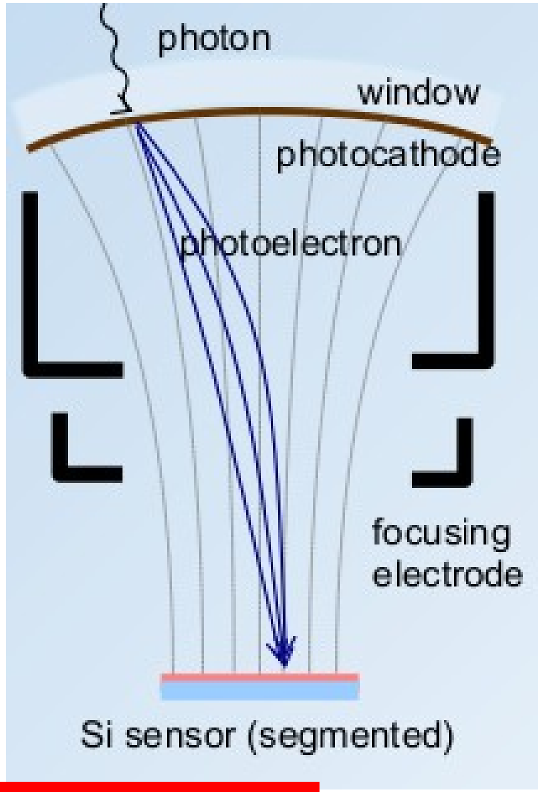
Hybrids: HPD, HAPD, QUPID, VSIPM, ABALONE

- Hybrid detectors are **cobinations of vacuum and silicon devices**
- They have ***large photocathode*** which ensure a large photoelectron conversion area
- Photolectrons are accelerated by a strong high field (10-20 kV) and fo***cused on a silicon device***
- Photoelectrons loose energy ***prodcuing a number of electron-hole pairs proportional to the electron kinetic energy***, eventually multiplied by the intrinsic gain of the silicon device
- **$G = e\, G_{Si}(\Delta V - V_{th})/W_{si}$ W_{Si} = 3.6 eV for silicon**
- Very low fluctuation in the Gain => Fano factor of Si ~0.12 $\sigma = \sqrt{FG}$

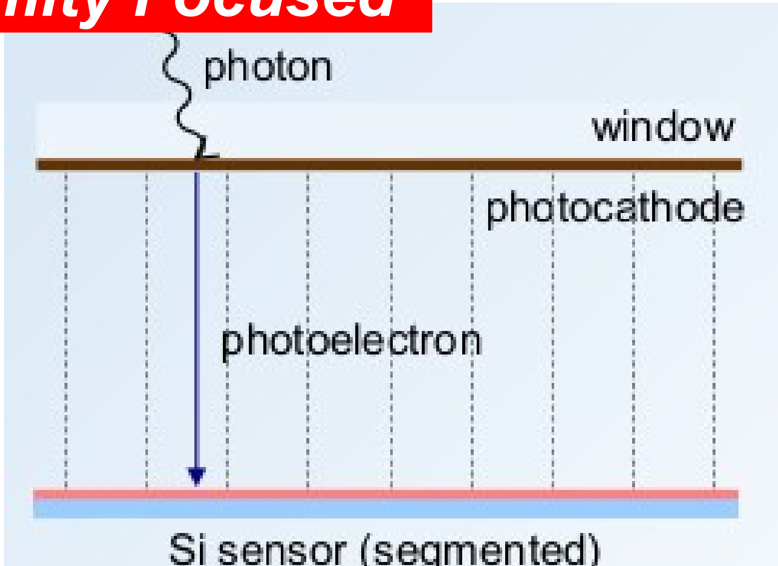
Hybrids: HPD



Cross Focused

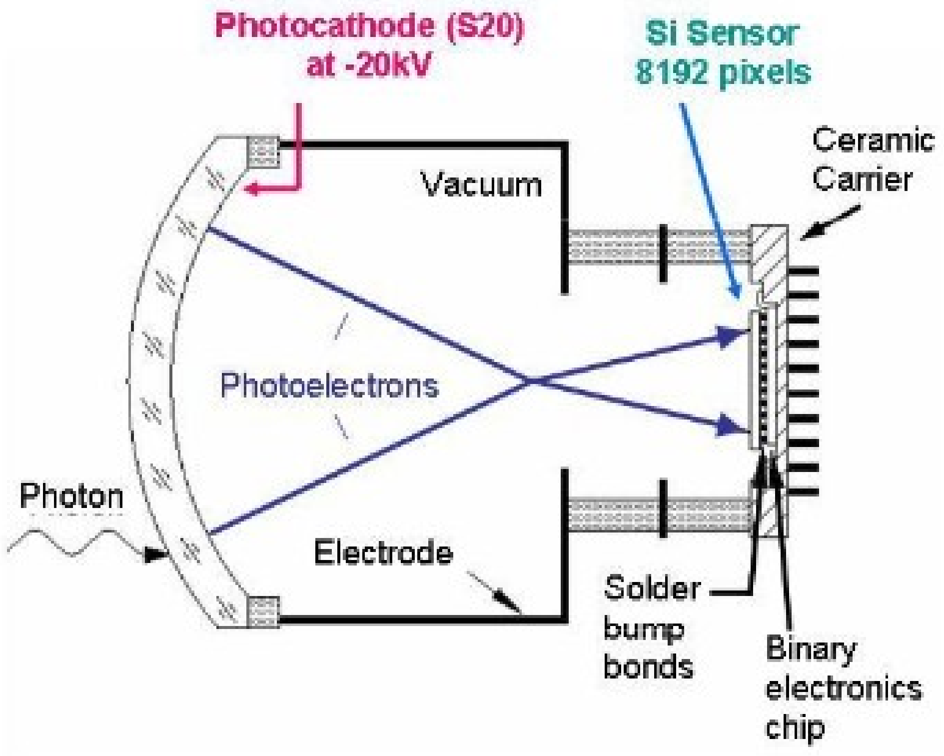


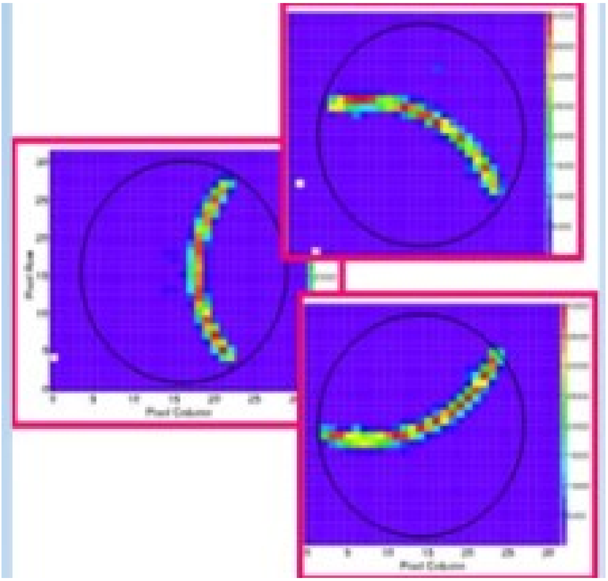
Proximity Focused



LHCb HPD

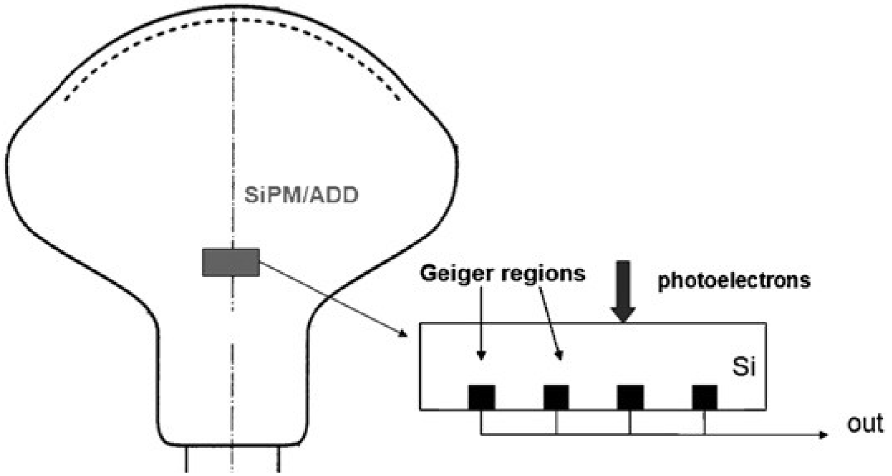
- Used in the **RICH detector of LHCb**
- *Cross focused HPD – HV = 20kV, G = 5,000*
- **8192 pixels of size 500μm x 62.5μm**
- **QE ~30%** @ 350nm
- Vacuum degradation causes ion feedback and aging of the device



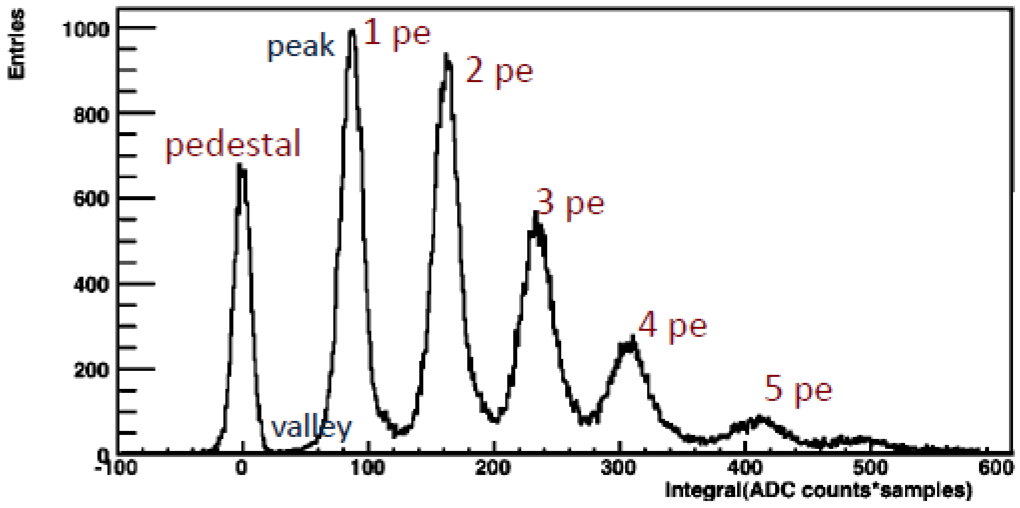


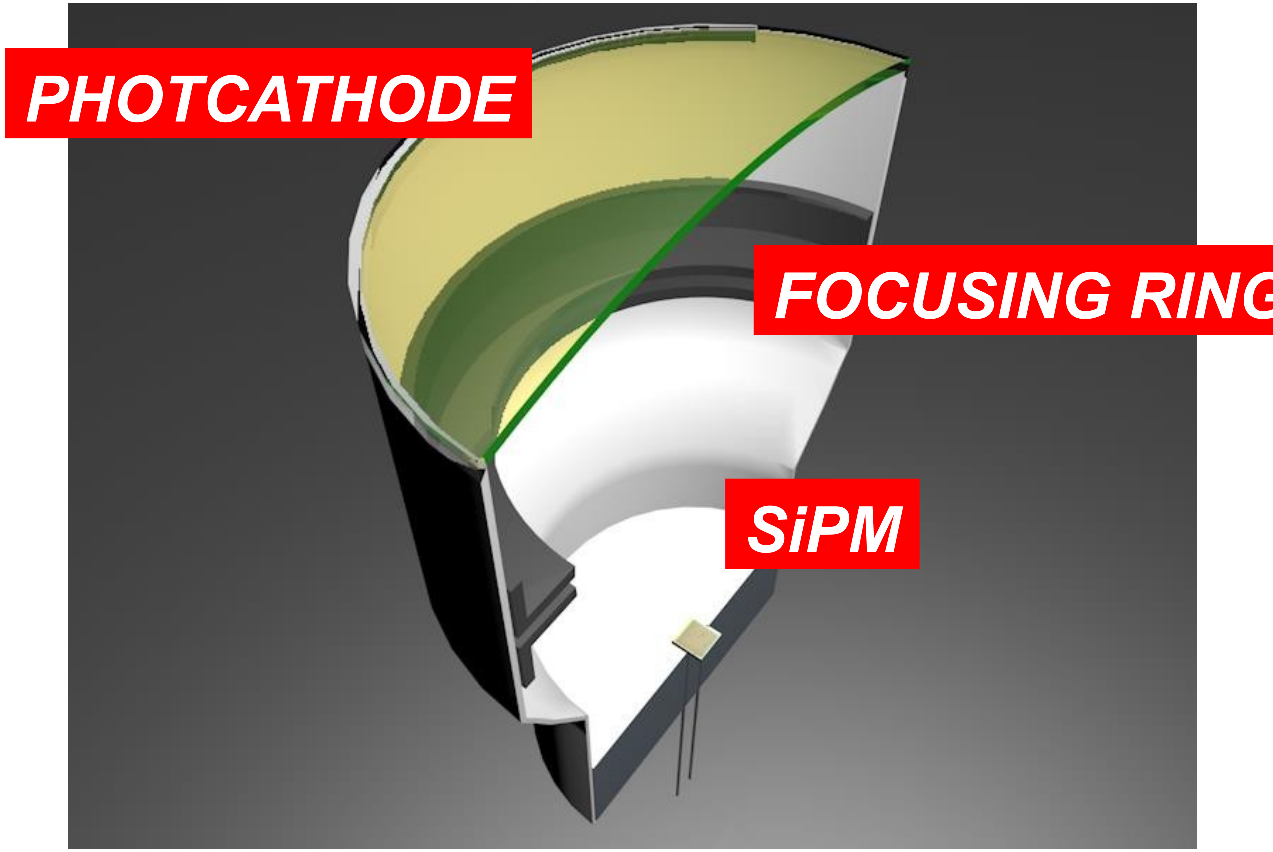
Hybrids: Vacuum SiPM - VSiPM

- Vacuum device coupled to a Silicon Photomultiplier
- Good photo detection efficiency
- Gain ~$10^5 - 10^6$
- Good Spe resolution



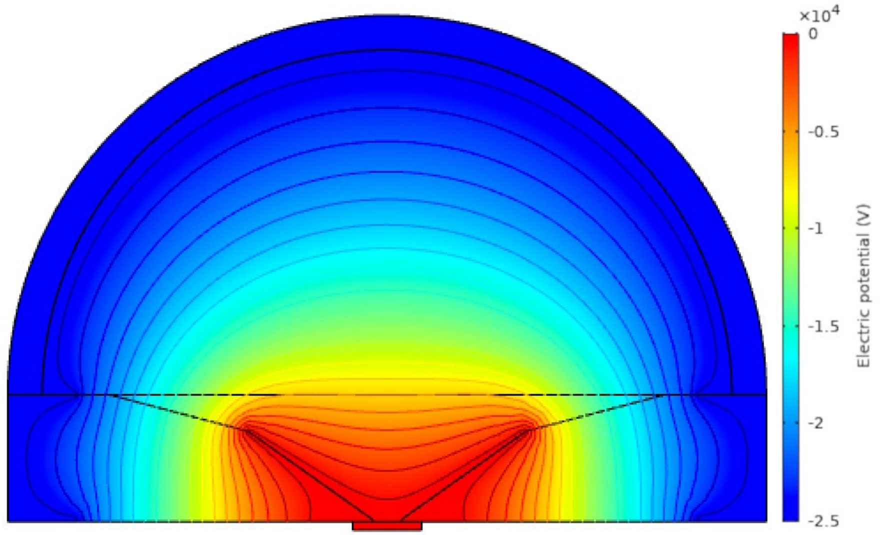
G. Barbarino et al. NIM-A594(2008)326





Hybrids: ABALONE

- ***Ultra high vacuum device***
- Photocathide coupled to a **scintillator read-out by a SiPM**
- ***Great optical aperture ~2π***
- QE determined by the photocatode
- **Excellent gain ~10^8**
- Proposed as photosensor for the ***future dark matter experiment DARWIN***



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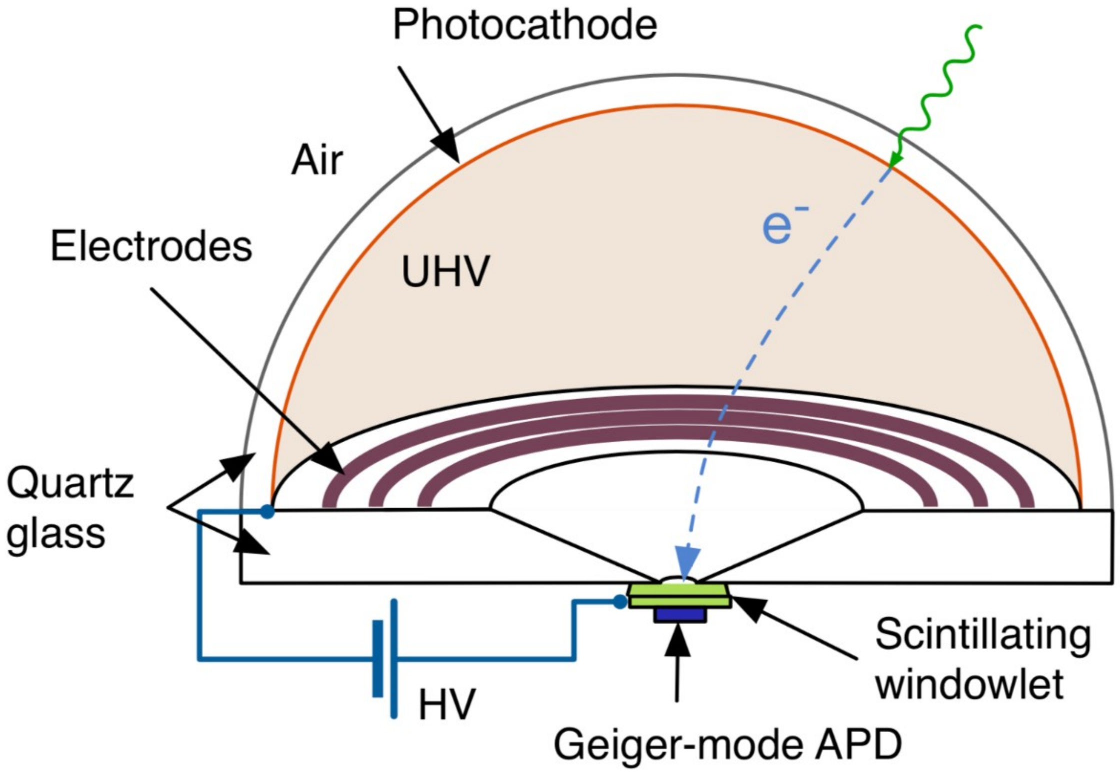
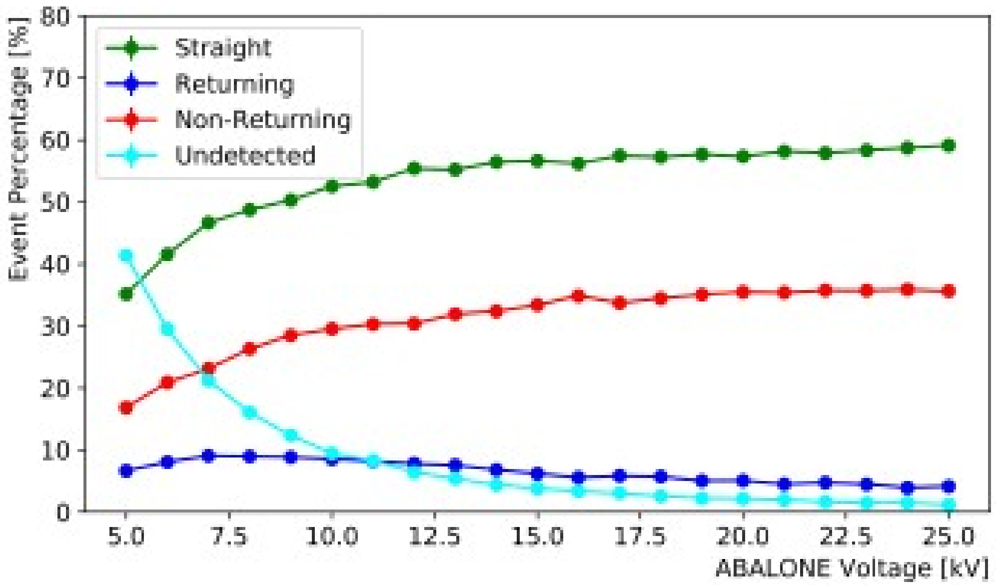
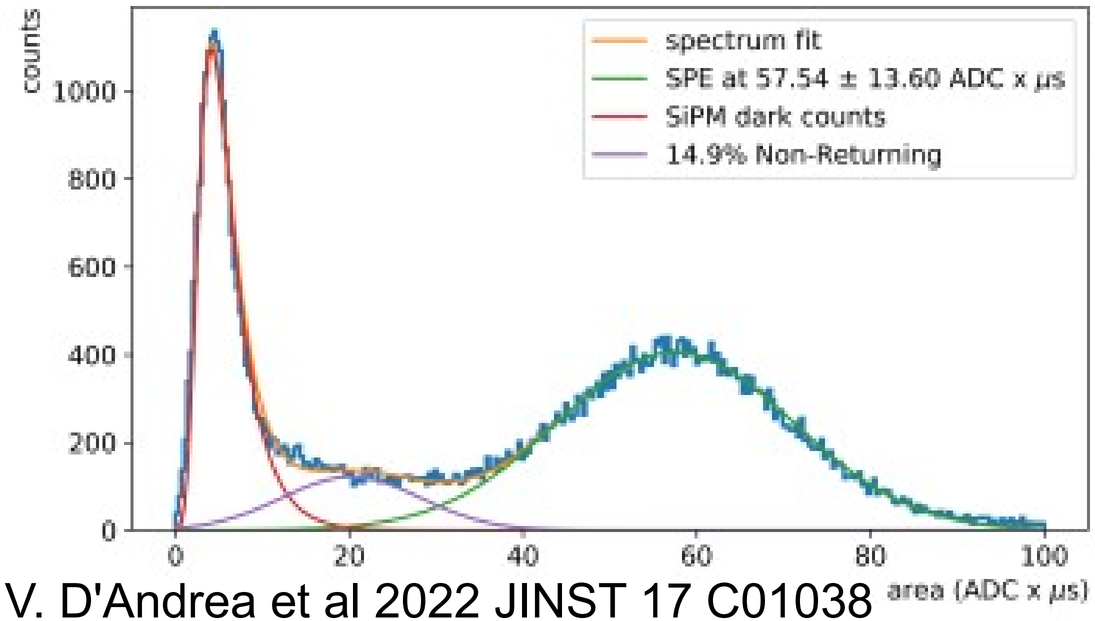
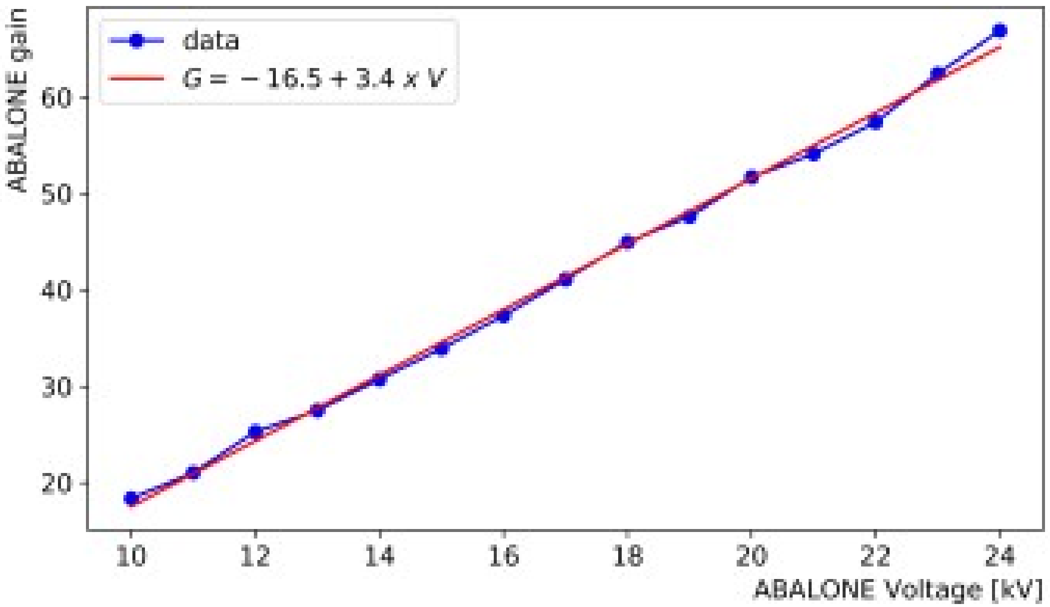


Hybrids: ABALONE

- Operated ***at 25 kV***
- *LYSO scintillator*
- Gain of the Scintillator ~100
- **Overall gain ~10^8**
- Non negligible fraction of electrons ***escapes from the crystal and does not deposit entire energy*** (non-returning)
- *A dedicated R&D program to minimize this effect*







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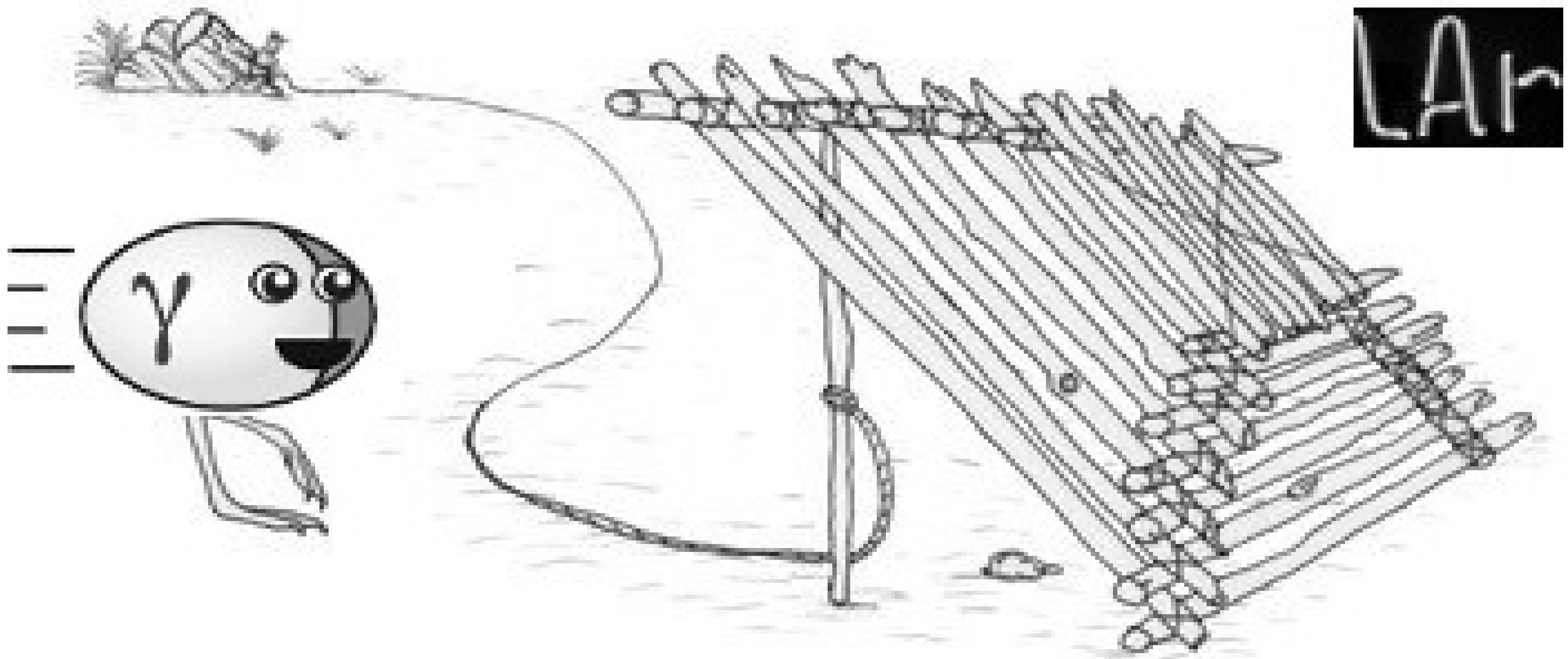
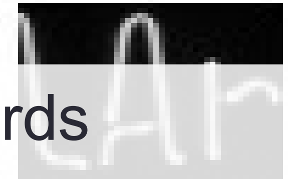
ARAPUCA concept



ARAPUCA concept

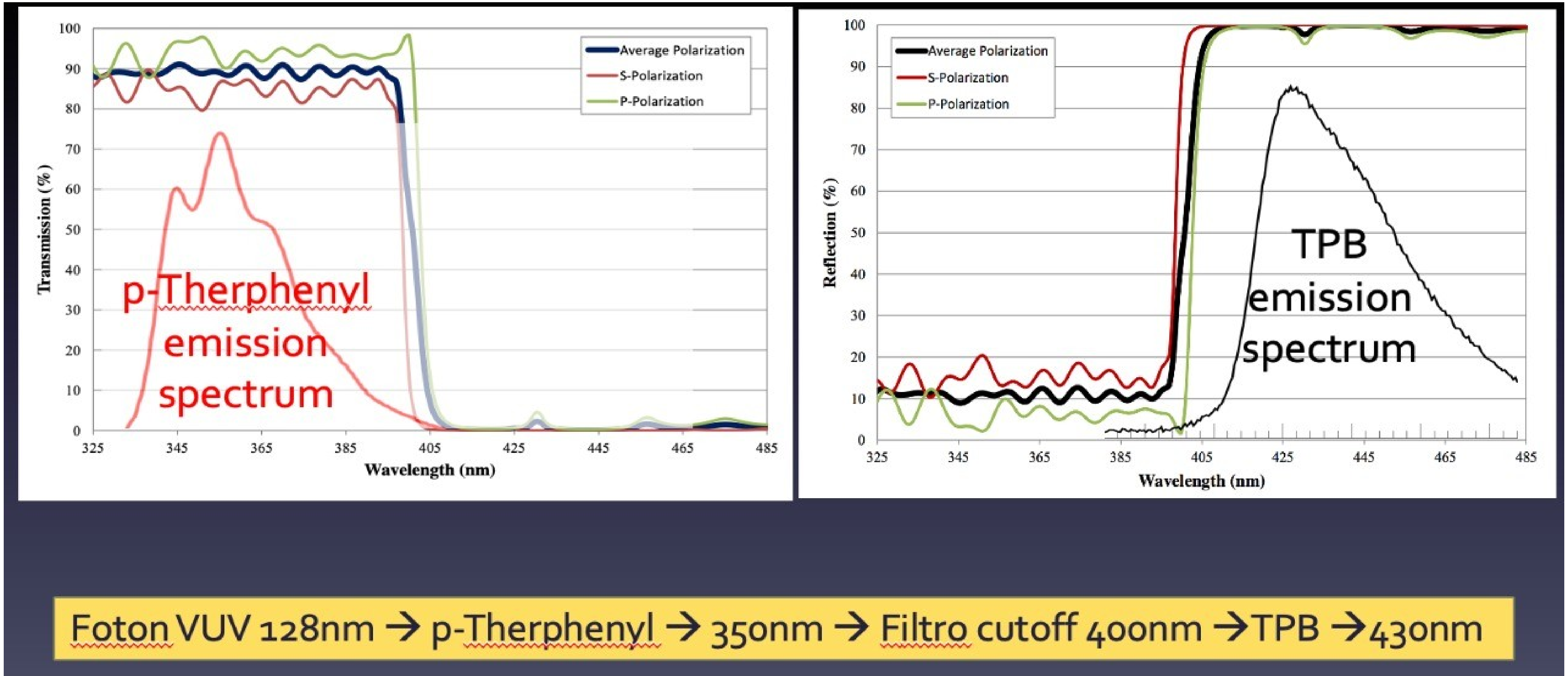


- **ARAPUCA** in the language of *native Brazilian* means ***trap*** for birds
- **Trap photons** inside a **box with highly reflective internal surfaces =>** Increase detection efficiency even with a limited active coverage of its internal surface
- Detection efficiency can be ***tuned by varying the number of SiPMs (ratio between acceptance window and SiPM areas)..***
- **Baseline DUNE design of Photon Detection System of 2 far detector modules**

Dichroic filter

- The core of the device is a **dichroic filter**. It is a dielectric interference **film** deposited on a fused silica substrate.

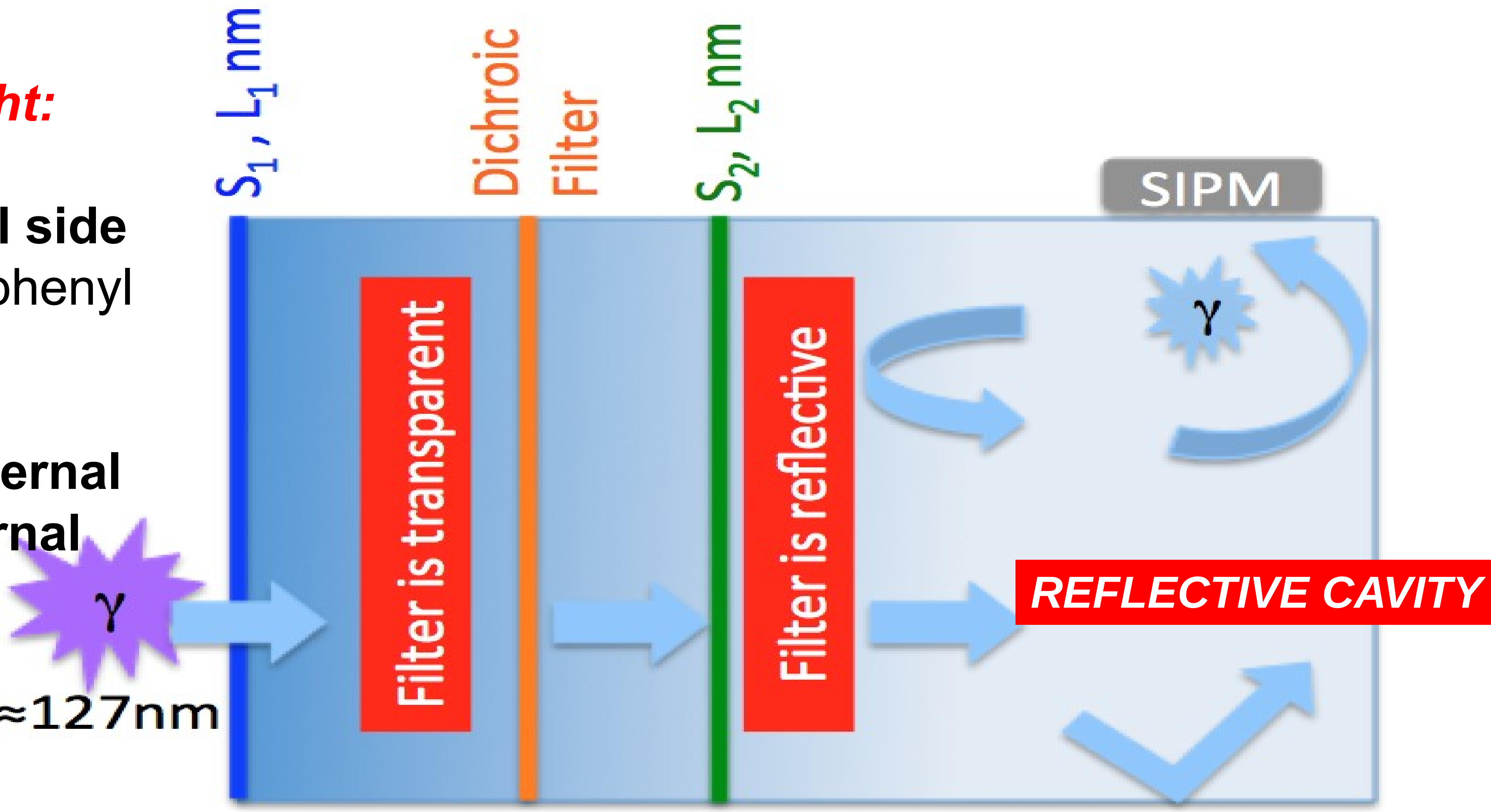
- It has the property of being **highly transparent** for wavelength **below a cutoff** and **highly reflective above it**.



ARAPUCA Operating Principle

Two shifts of the light:

- One on the **external side of filter** (Para-Therphenyl **127nm => 350nm**)
- The other on the **internal side or on the internal walls** (Tetraphenyl-Butadiene **350nm=>430nm**)



ARAPUCA for neutrinos!

symmetry
dimensions of particle physics

https://www.symmetrymagazine.org/article/arapuca-let-there-be-light-traps?language=pt-br

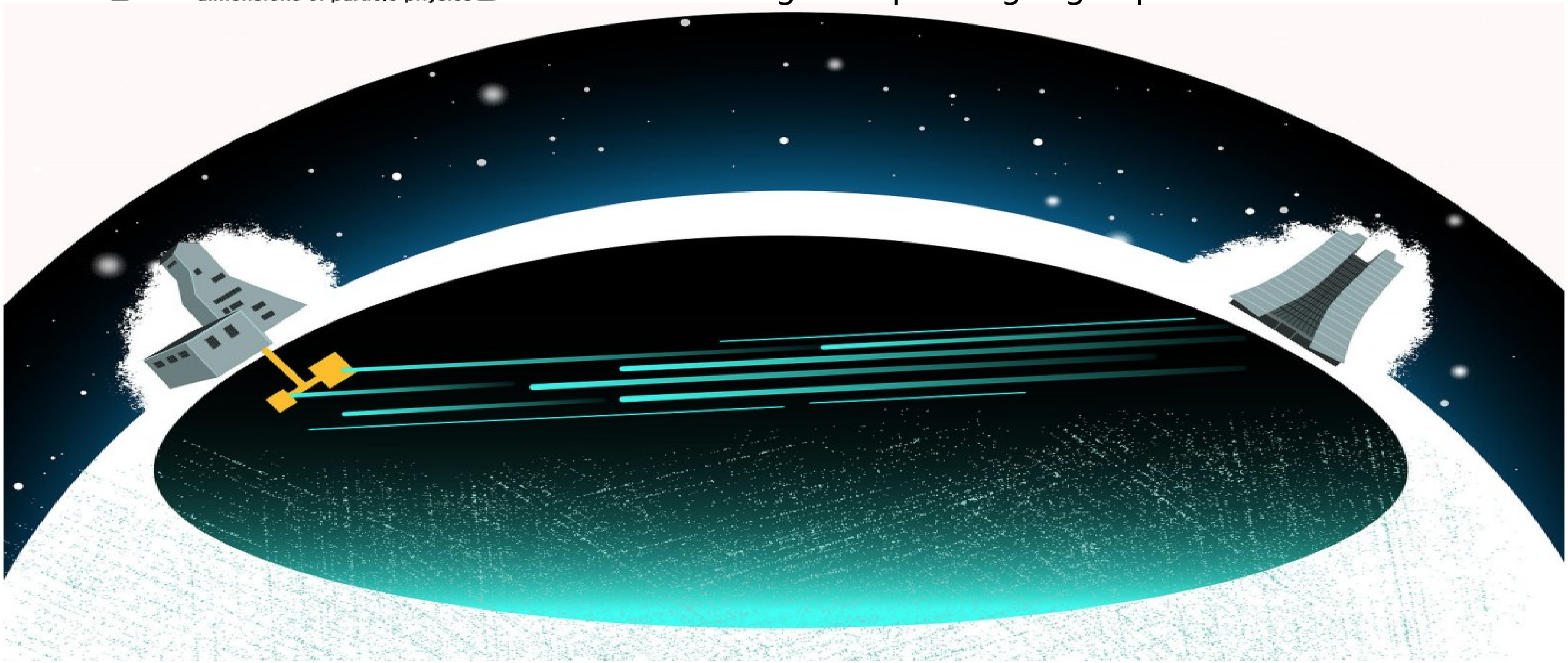


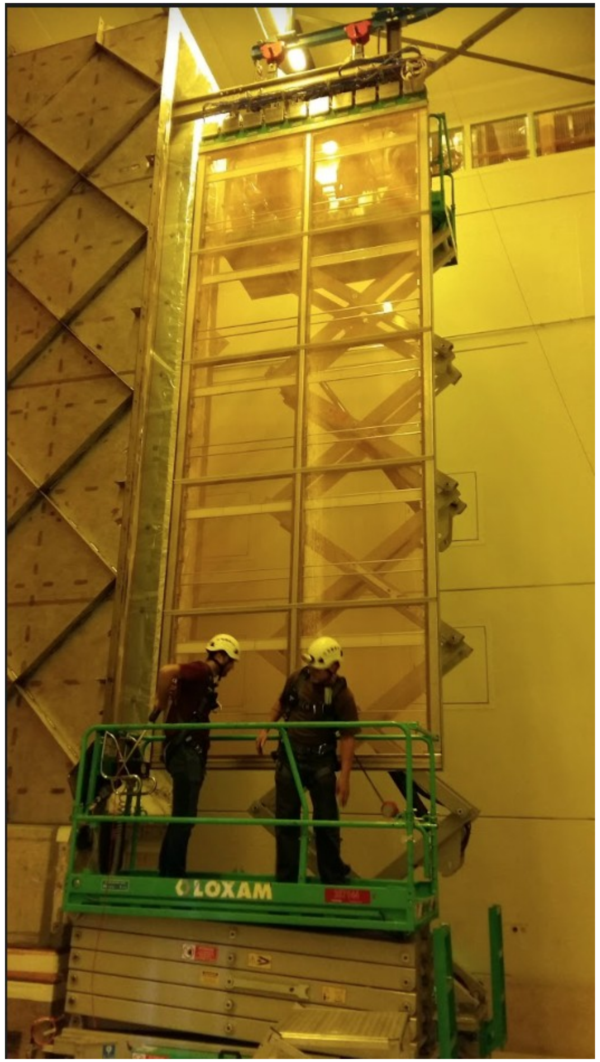
Illustration by Sandbox Studio, Chicago with Pedro Rivas

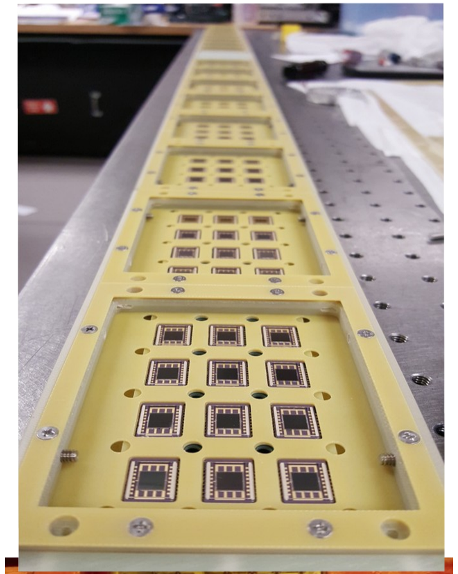
ARAPUCA: Façam-se armadilhas para a luz

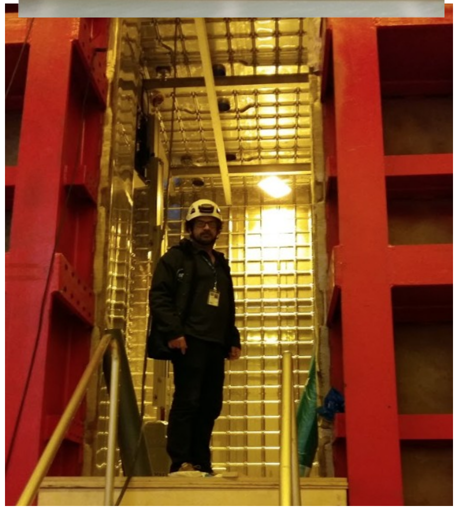
10/24/19 | By Lauren Biron

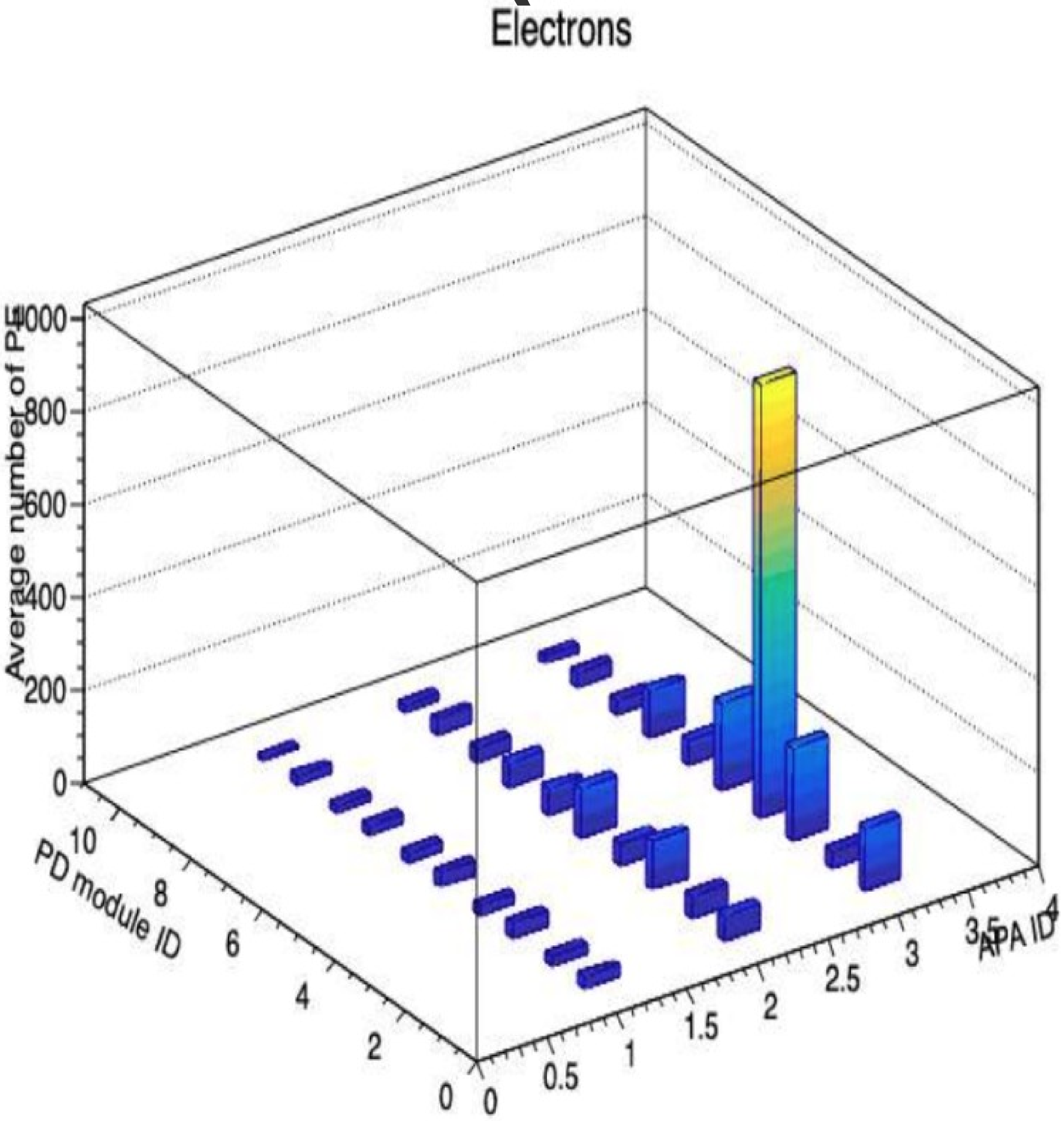
As instituições latino-americanas são imprescindíveis para a criação dos detetores de fotões usados na Experiência de Neutrinos em Grande Profundidade.

ARAPUCA in protoDUNE Run I (2018-2020)

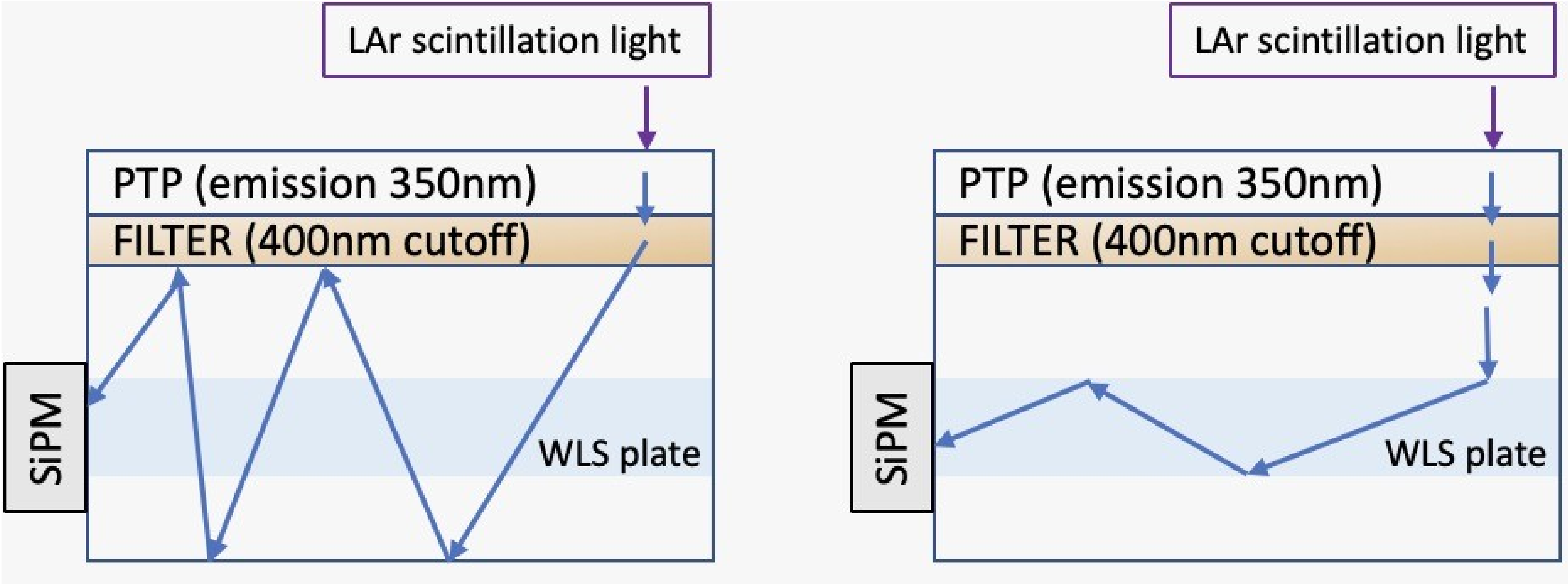




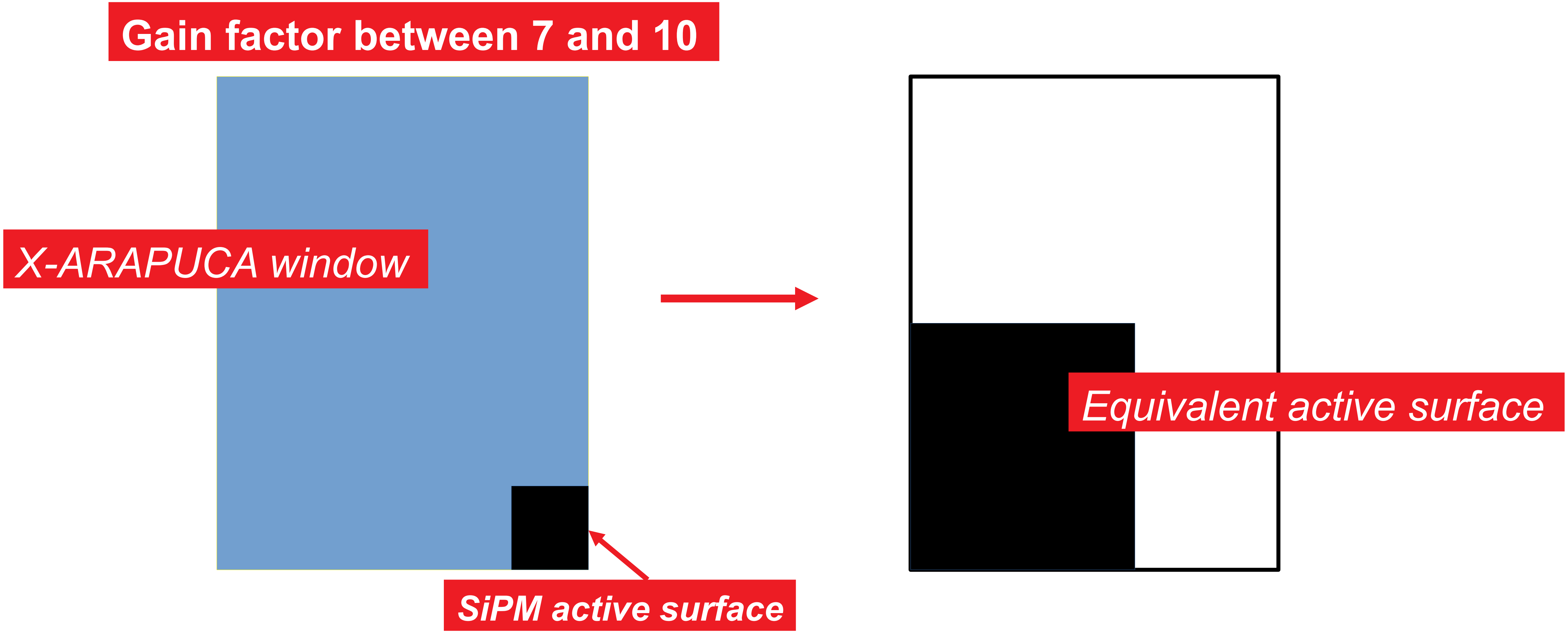




X-ARAPUCA


LAr scintillation light
PTP (emission 350nm)
FILTER (400nm cutoff)
SiPM
WLS plate
LAr scintillation light
PTP (emission 350nm)
FILTER (400nm cutoff)
SiPM
WLS plate

X-ARAPUCA detection efficiency

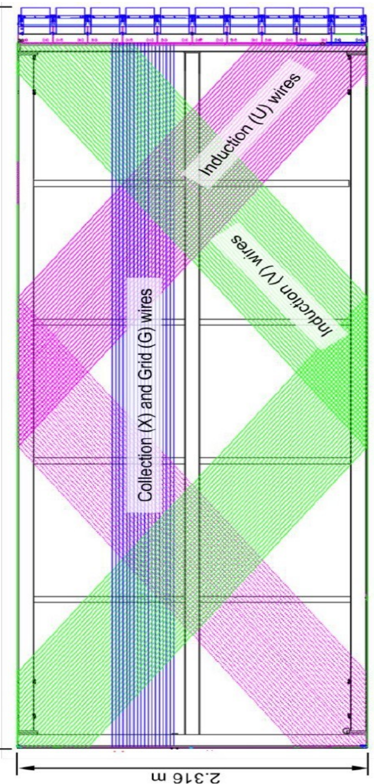


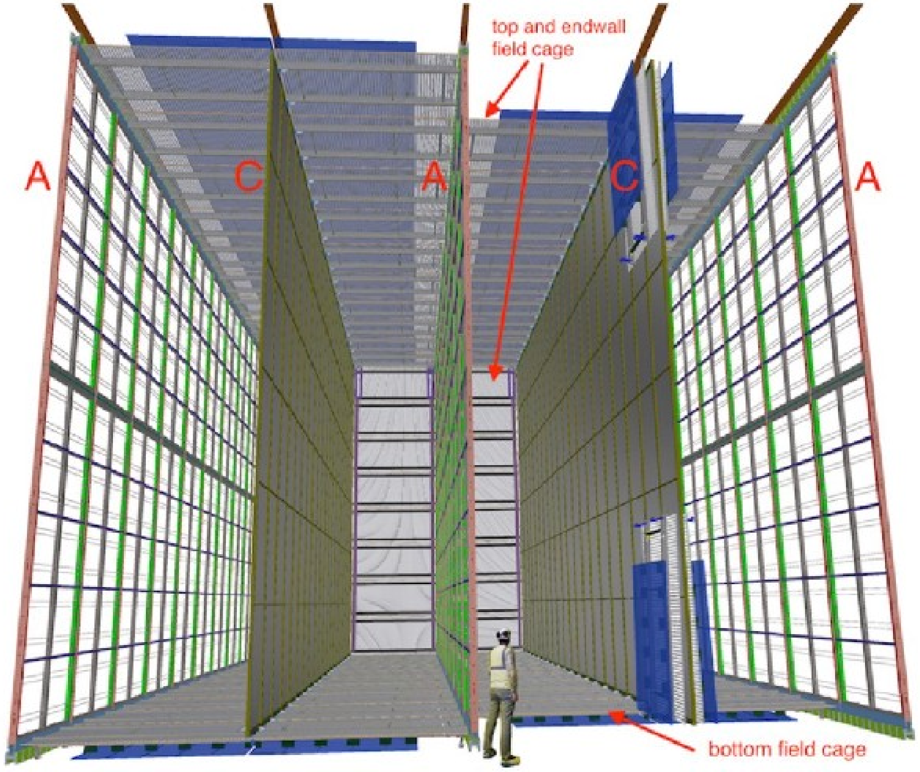
In units of 8” PMT: 1 ***X-ARAPUCA bar*** is equivalent to ***2.5 8” PMTs***

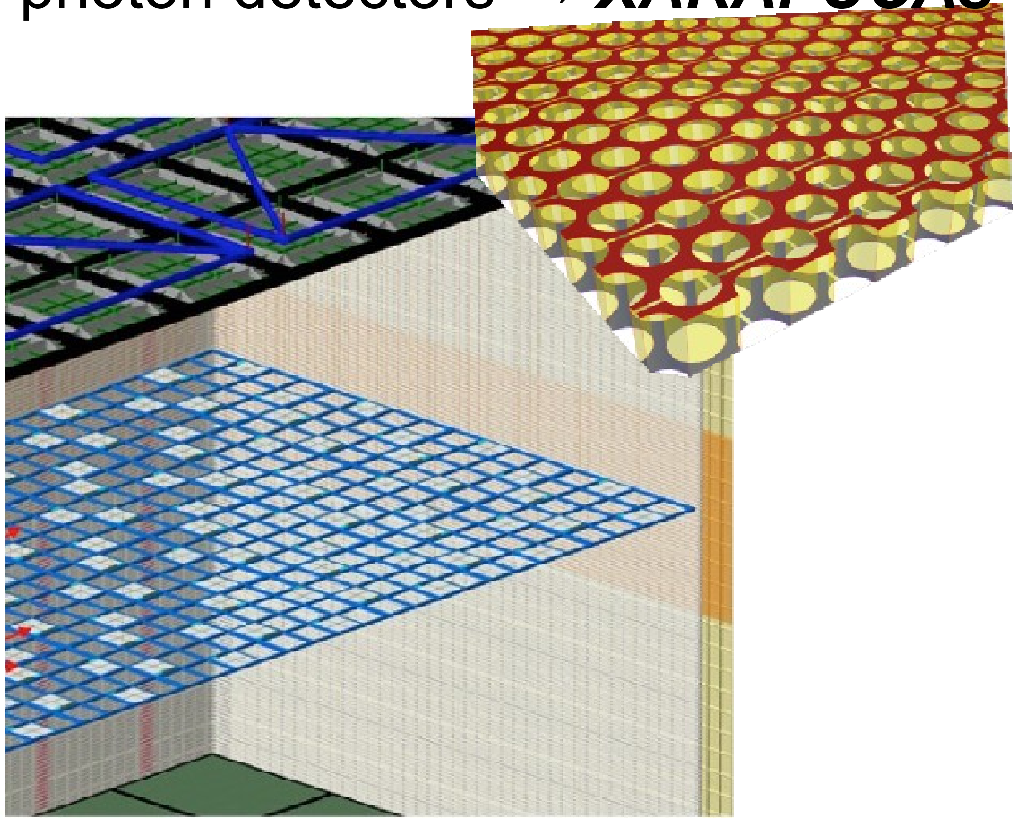
LAr Read-out Technologies of DUNE far detectors

Module #1
-3.6 m horizontal drift
-vertical anode wire planes
-vertical resistive cathode
photon detectors → ***XARAPUCAs***

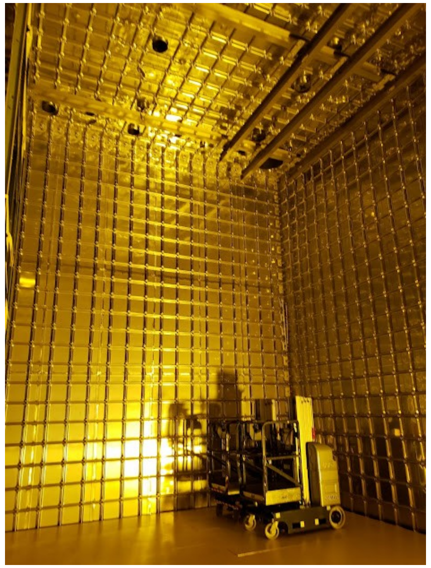
Module #2
-6.5 m vertical drift
-horizontal PCB anode readout (CRP)
-horizontal grid cathode
photon detectors → ***XARAPUCAs***



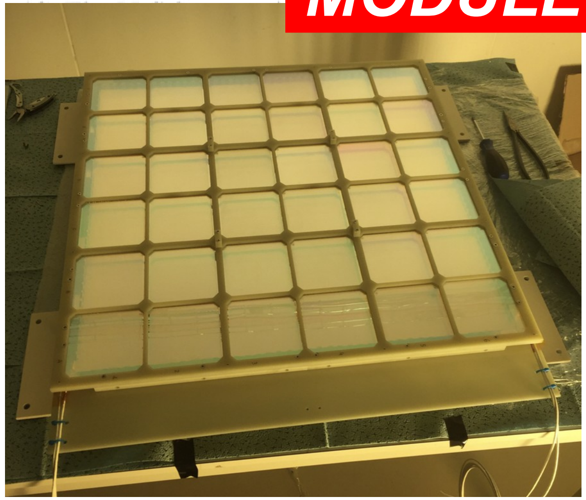




X-ARAPUCA in ProtoDUNE Run II (2022-2023)

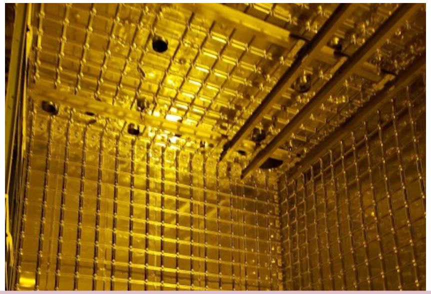
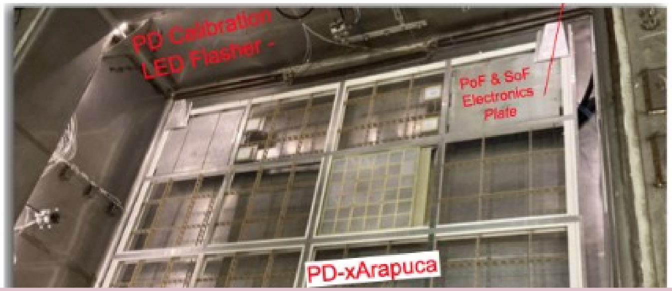


MODULE 1



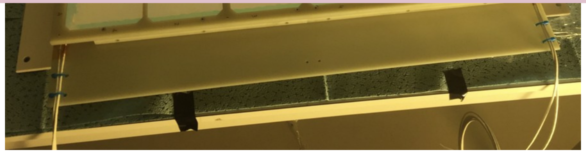
MODULE 2

X-ARAPUCA in ProtoDUNE Run II (2022-2023)

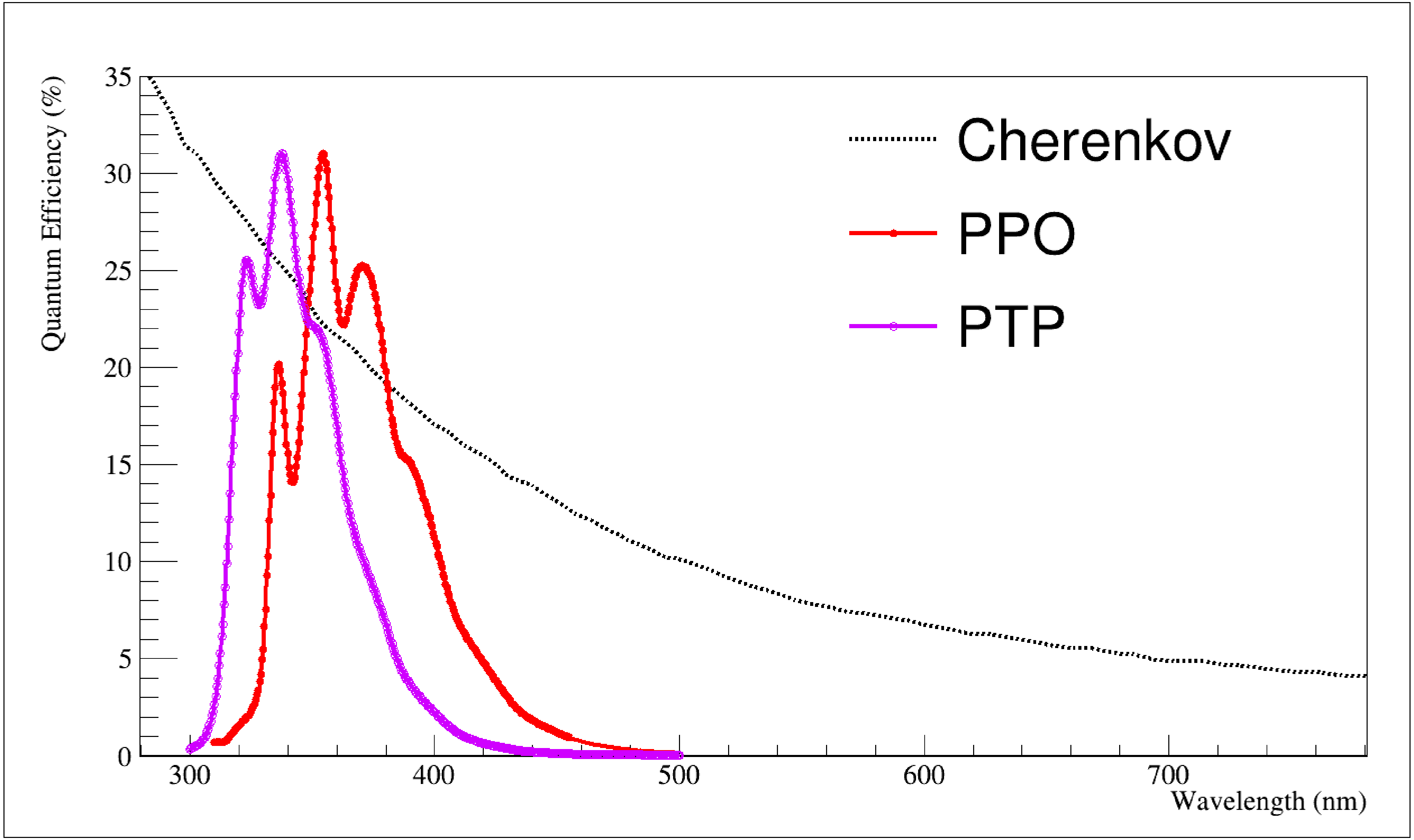




- ***X-ARAPUCA is the baseline design for the two DUNE far detector modules***
- ***Design and construction managed by a Consortium of more than 50 Institutions in 3 continents***
- ***1,500 bar shaped modules in module 1 (Horizontal Drift) => 300,000 SiPMs ~10 m^2 area***
- ***640 square X-ARAPUCA modules for module 2 (Vertical Drift) => 100,000 siPMs 3 m^2 area***





Dichroicon: sorting photons

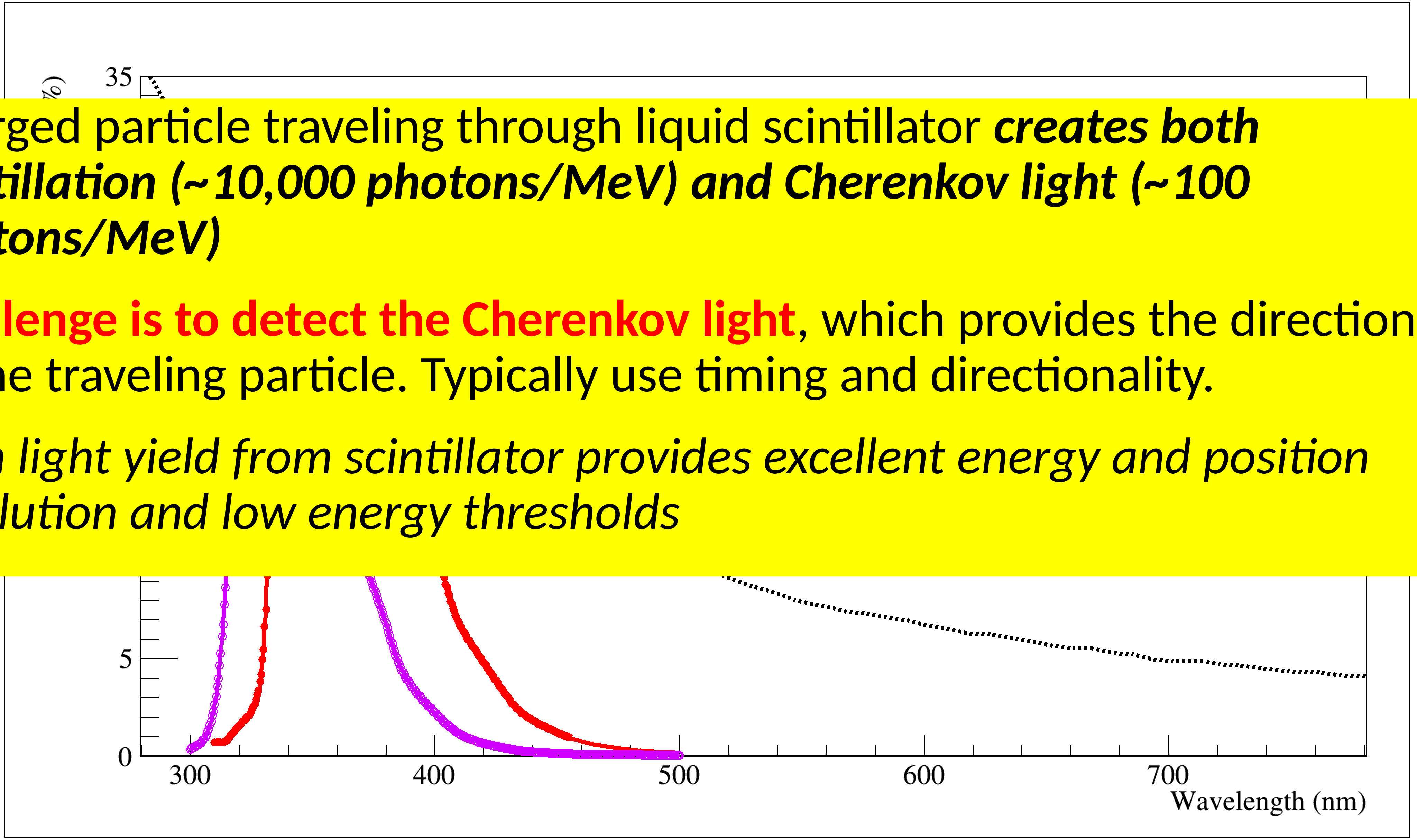


Dichroicon: sorting photons

- Charged particle traveling through liquid scintillator ***creates both scintillation (~10,000 photons/MeV) and Cherenkov light (~100 photons/MeV)***

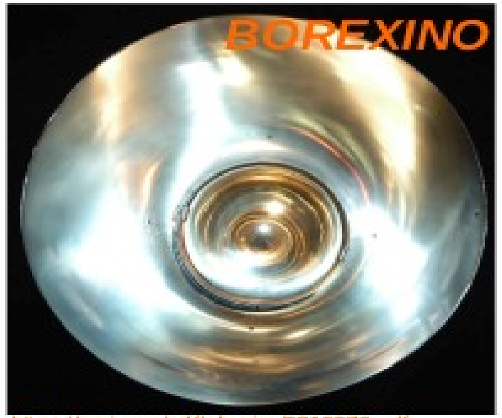
- **Challenge is to detect the Cherenkov light**, which provides the direction of the traveling particle. Typically use timing and directionality.

- *High light yield from scintillator provides excellent energy and position resolution and low energy thresholds*

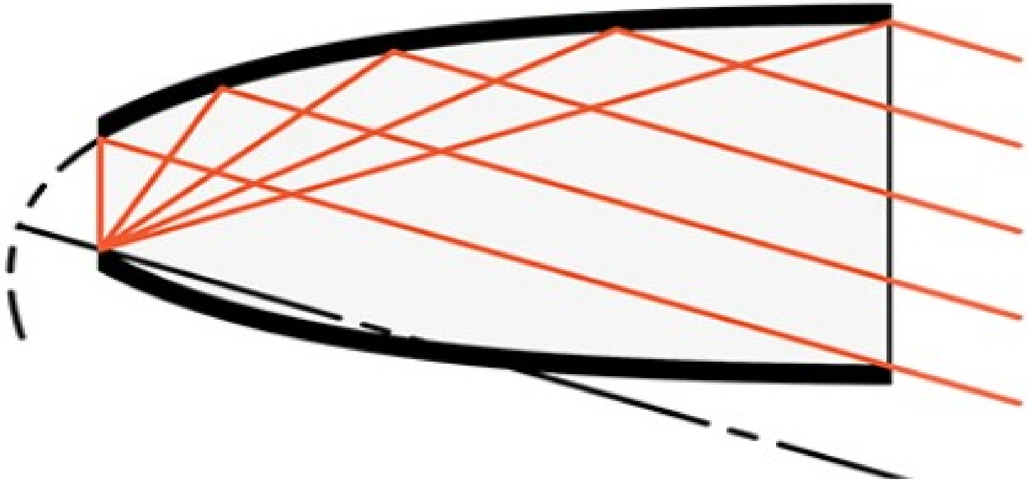


Dichroicon: combining two technologies

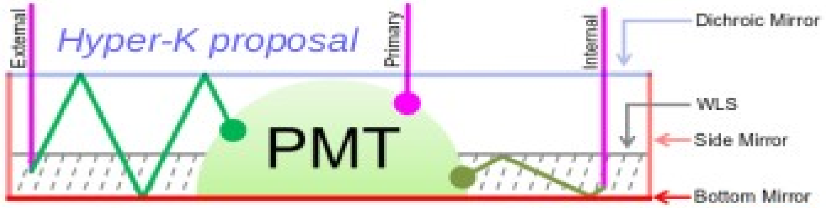
Winston Cones



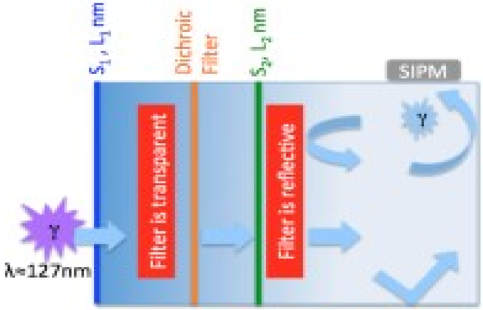
https://arxiv.org/pdf/physics/0310076.pdf



Dichroic Filters

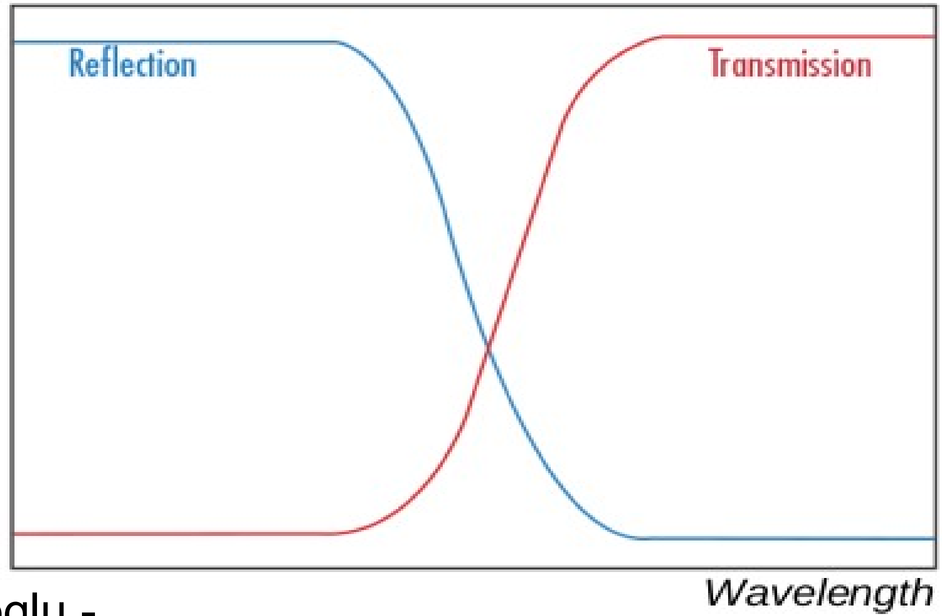


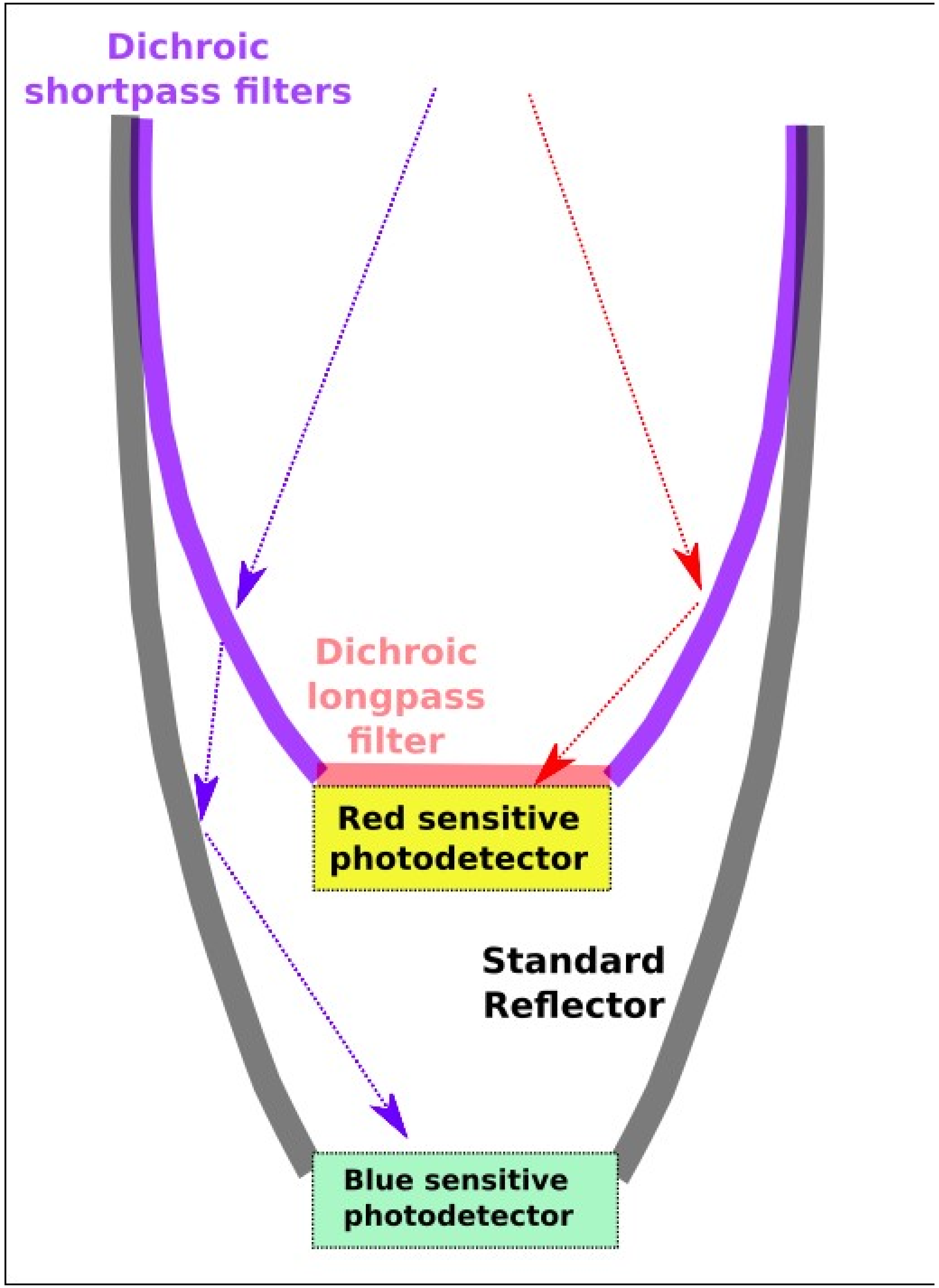
C. Rott et al. JINST 12 (2017)

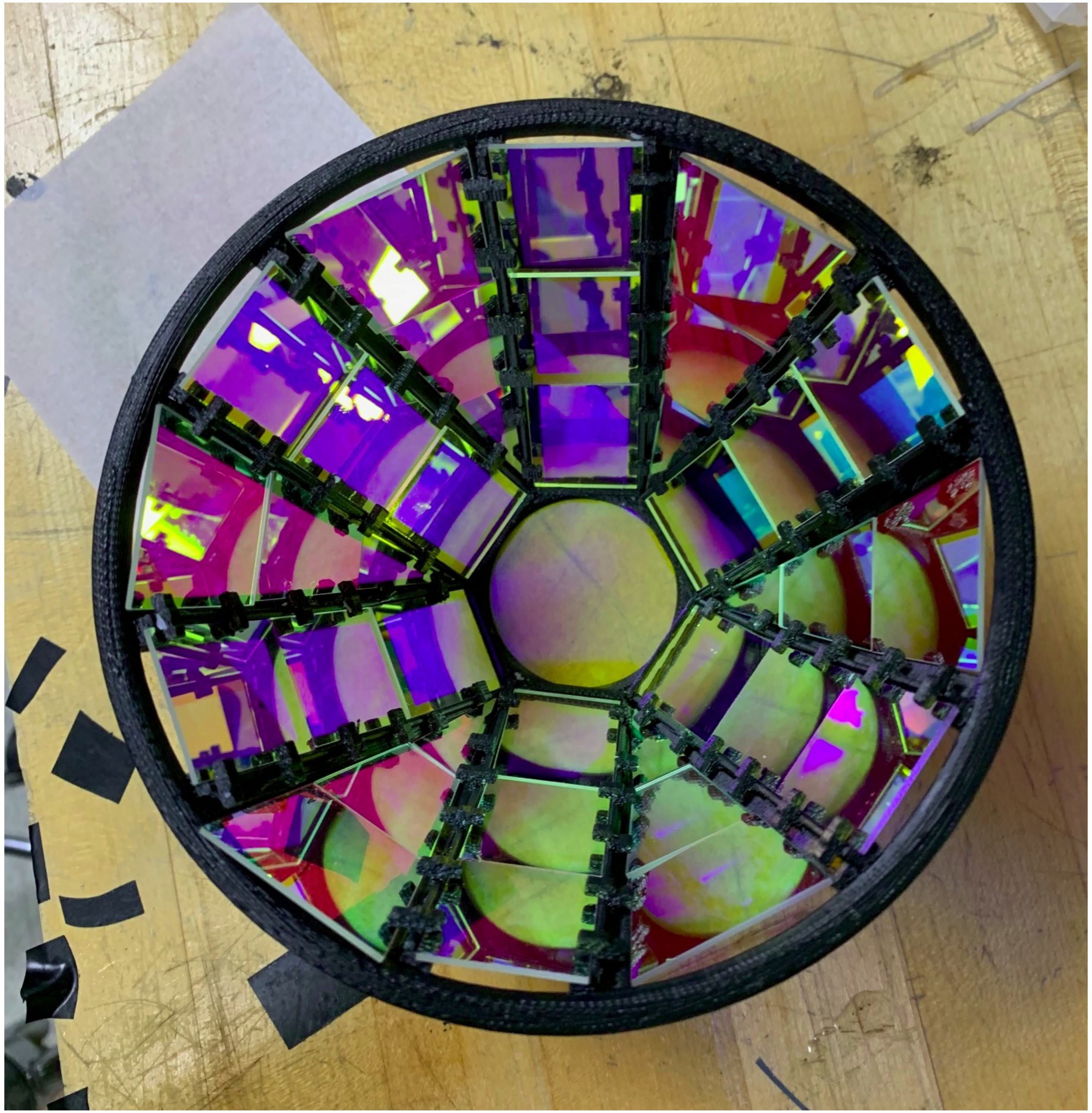


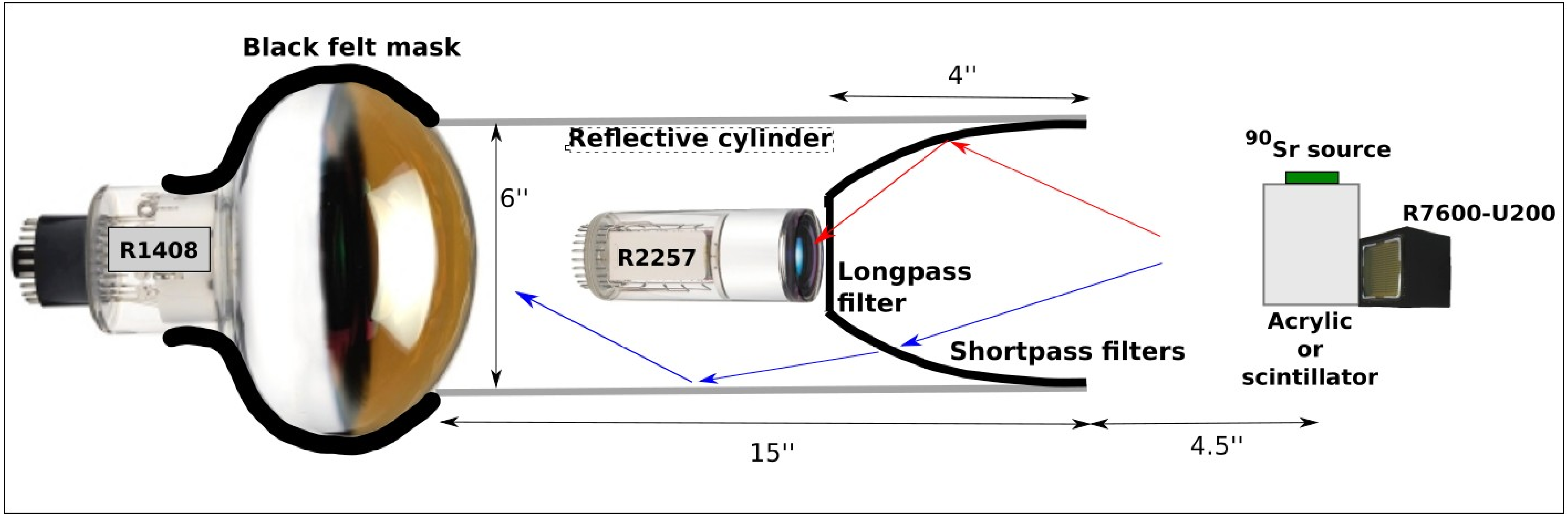
ARAPUCA for DUNE

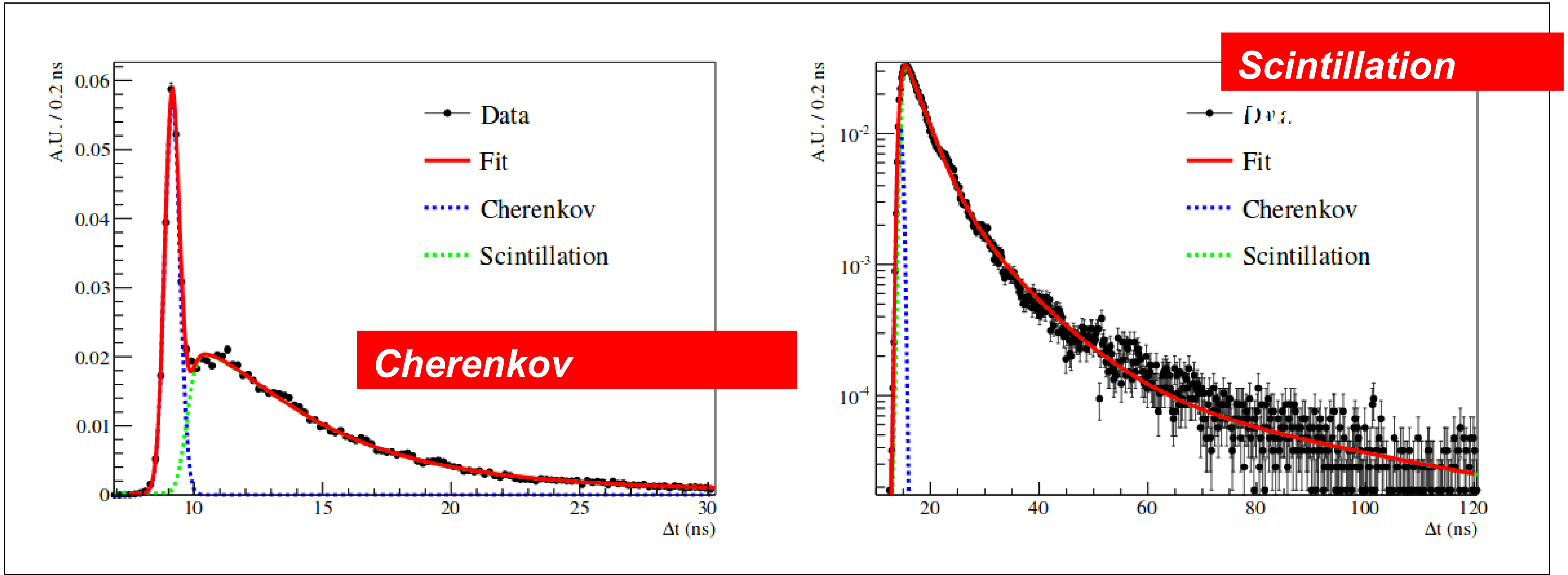
E. Segreto et al., JINST 13 (2018)



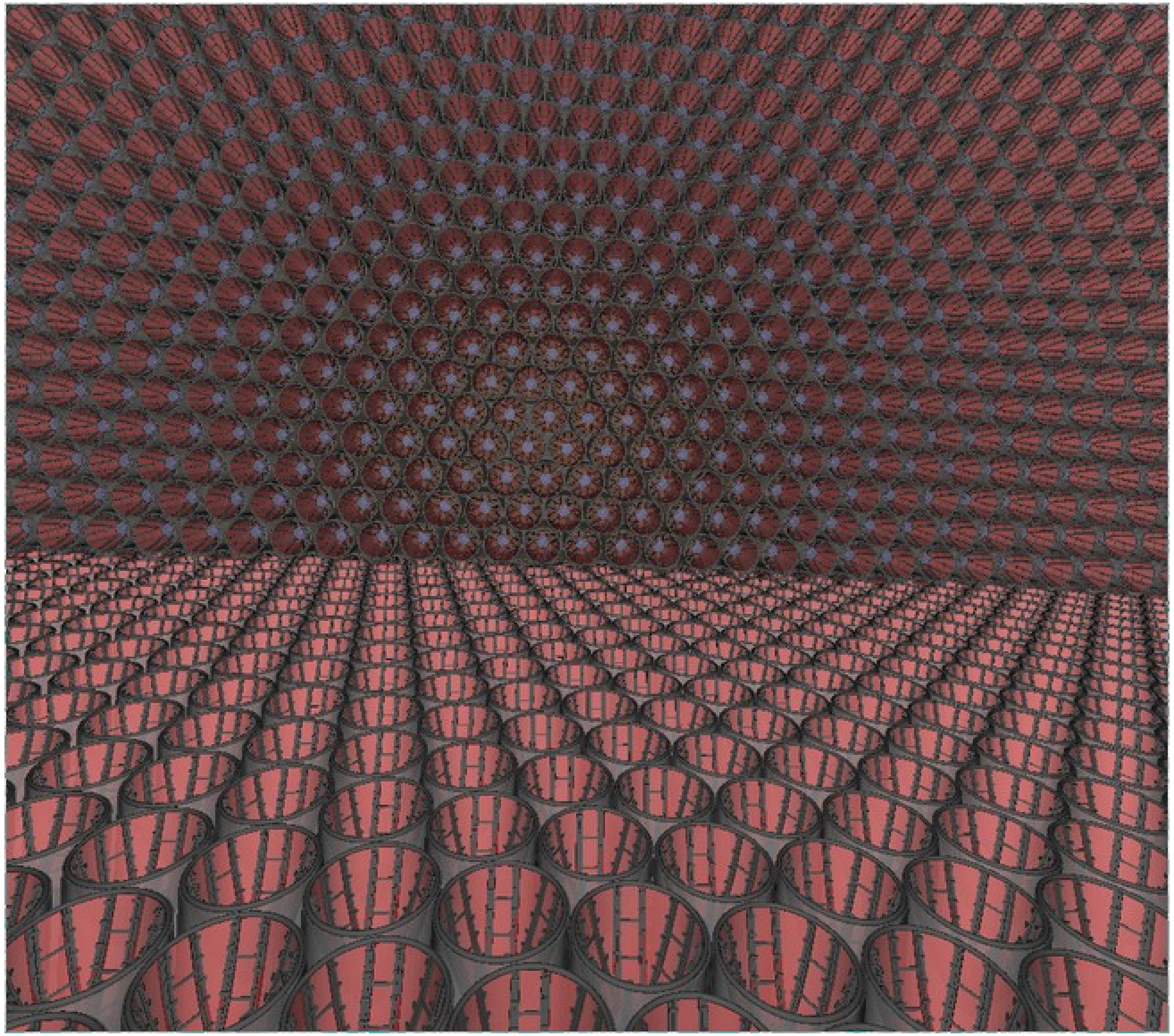

Dichroic
shortpass filters
Dichroic
longpass
filter
Red sensitive
photodetector
Standard
Reflector
Blue sensitive
photodetector




Black felt mask
Reflective cylinder
4''
6''
R1408
R2257
Longpass
filter
Shortpass filters
^{90}Sr source
R7600-U200
Acrylic
or
scintillator
15''
4.5''


A.U. / 0.2 ns
0.06
0.05
0.04
0.03
0.02
0.01
0
10
15
20
25
30
Δt (ns)
Data
Fit
Cherenkov
Scintillation
Cherenkov
A.U. / 0.2 ns
10^{-2}
10^{-3}
10^{-4}
20
40
60
80
100
120
Δt (ns)
Scintillation
Fit
Cherenkov
Scintillation

THEIA Experiment (proposed)



- **Water based Liquid Scintillator**
- Read-out system possibly based on **LAPPD, PMTs and Dichroicon**
- Large-scale detector that can ***discriminate between Cherenkov and scintillation signals.***
- Reconstruct ***particle direction and species using Cherenkov light*** while having ***excellent energy resolution and low threshold of a scintillator detector***
  - *low- and high-energy solar neutrinos*
  - *Neutrino mass ordering*
  - *measurement of the neutrino CP-violating phase*
  - *observations of diffuse supernova neutrinos and neutrinos from a supernova burst*
  - *nucleon decay*

Light Yield of a scintillation detector

LY can be factorized as:

$$LY = N_\gamma \, \varepsilon_{PSD} \, \varepsilon_{OPT}$$

Where:

- ✓ **N_γ** is the photon yield of the scintillator => *number of photons produced per unit of deposited energy by a certain radiation*
- ✓ **ε_{PSD}** is the *conversion efficiency of the PSDs* => *the efficiency of the PSD system in converting photons into signal (photo-electrons)*
- ✓ **ε_{opt}** is the *optical efficiency* => *the fraction of the originally produced photons that manages to cross the windows of the PSDs*

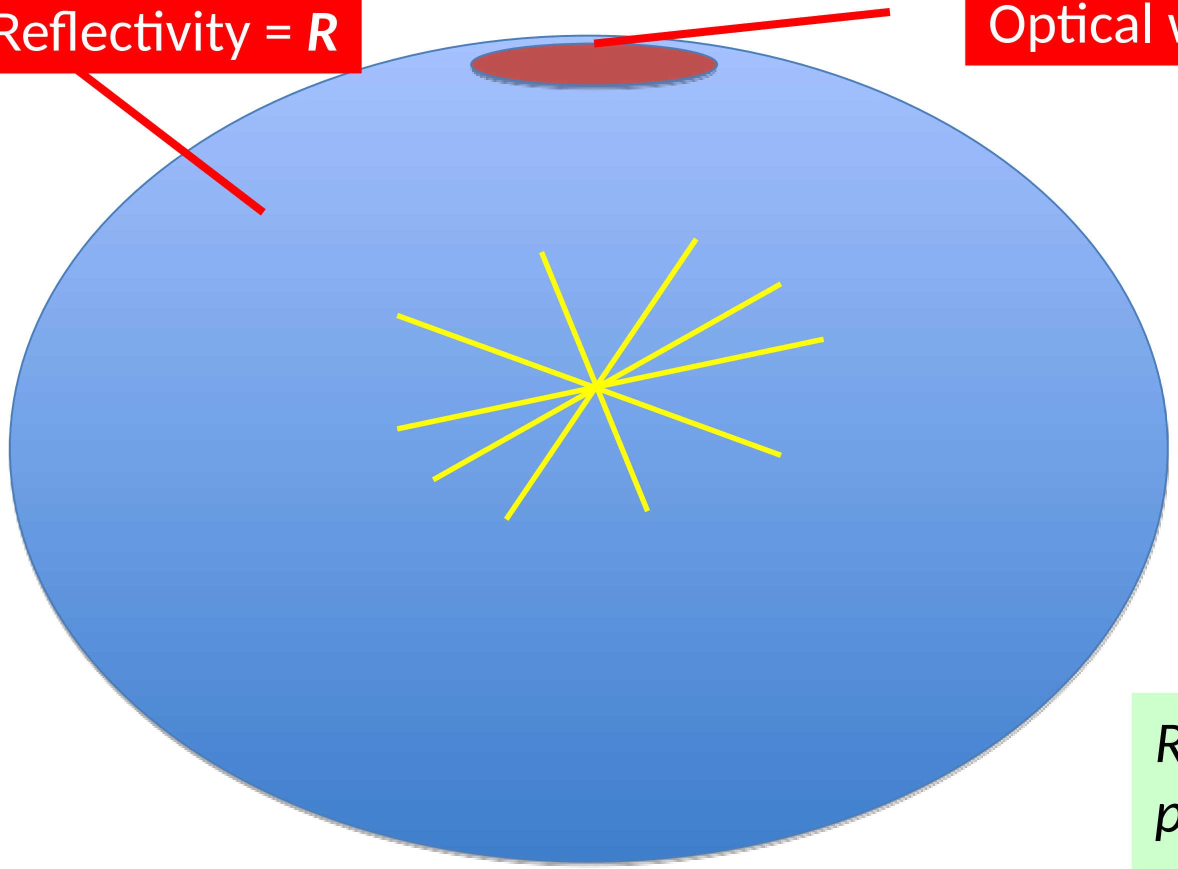
N_γ *and* ε_{PSD} *in the majority of the cases are precisely known*. On the other side **ε_{opt} is typically unknown and needs to be estimated.**

Recursivity of light propagation (think to a sphere...)

The propagation of photons inside a scintillation detector is an *intrinsically recursive process*.

Reflectivity = ***R***

Optical window – photcatodic coverage = ***f***



A photon produced in a **random point inside the sphere** with a random direction when reaches the boundary surface has an *average probability* ***f*** *to be detected*

And a probability ***R(1-f)*** to be sent back into the chamber

Reflected photons has again a detection probability equal to ***f*** *and a probability to be reflected equal to* ***R(1 – f)*** *when hit the boundary surface for the second time*

The same situation will repeat again ***identical to itself after any reflection.***

...let's generalize a little bit (I)

- Consider a ***general scintillation detector*** and assume that the ***process is recursive***
- It can be divided into a *series of subsequent and indistinguishable steps* and *it is possible to define two quantities:*
  - ✓ ***α*** *is the average probability per step that a photon is detected*
  - ✓ ***β*** *is the average probability per step that a photon is regenerated, that is the probability that it is not lost (detected or absorbed) and that some physical process randomizes again its direction (reflection for instance)*
  - ✓ *α and β are constant for all the steps (recursivity of the process)*
  - ✓ $\alpha \leq 1$ and $\beta < 1$
- **Detection and regeneration probabilities after n steps are easily calculated:**

	detection probability	regeneration probability
step 0	α	β
step 1	$\alpha\beta$	β^2
step 2	$\alpha\beta^2$	β^3
...	...	...
step n	$\alpha\beta^n$	β^n

…let's generalize a little bit (II)

$$\varepsilon_{opt} = \sum \alpha\beta^n = \frac{\alpha}{1-\beta}$$

For the *spherical scintillator* (and one can safely extend ***to scintillators of regular shapes***) this means that:

$$\varepsilon_{opt} = \frac{f}{1-R(1-f)}$$

$\alpha = f$

$\beta = R(1\text{-}f)$

If the optical window has *transmissivity* $\boldsymbol{T_w}$ and *reflectivity* $\boldsymbol{R_w}$:

$$\varepsilon_{opt} = \frac{T_w f}{1-R(1-f)-R_w f}$$

$\alpha = T_w\, f$

$\beta = R(1\text{-}f) + R_w f$

Including Rayleigh scattering and absorption

Define:

$$\frac{1}{\tilde{\lambda}} = \frac{1}{\lambda_R} + \frac{1}{\lambda_A}$$

λ_R -> Rayleigh scattering length

λ_A -> absorption length

and: U_{RA}

probability that a photon reaches the end of the step, as defined in absence of scattering/absorption, without interactions

It is possible to define:

$$\alpha = U_{RA}\alpha_0$$

$$\beta = U_{RA}\beta_0 + (1-U_{RA})\frac{\tilde{\lambda}}{\lambda_R}$$

Photon regenerated by reflections

Photon regenerated by scattering

with α_0 and β_0 detection and regeneration probabilities in absence of scattering and absorption

Including Rayleigh scattering and absorption (II)

After little algebra one finds:

$$\varepsilon_{opt} = \frac{\alpha_0}{Q - \beta_0}$$

α_0 and β_0 detection and regeneration probability in absence of scattering and absorption

With:

$$Q = \frac{1 - (1 - U_{RA})\frac{\tilde{\lambda}}{\lambda_R}}{U_{RA}}$$

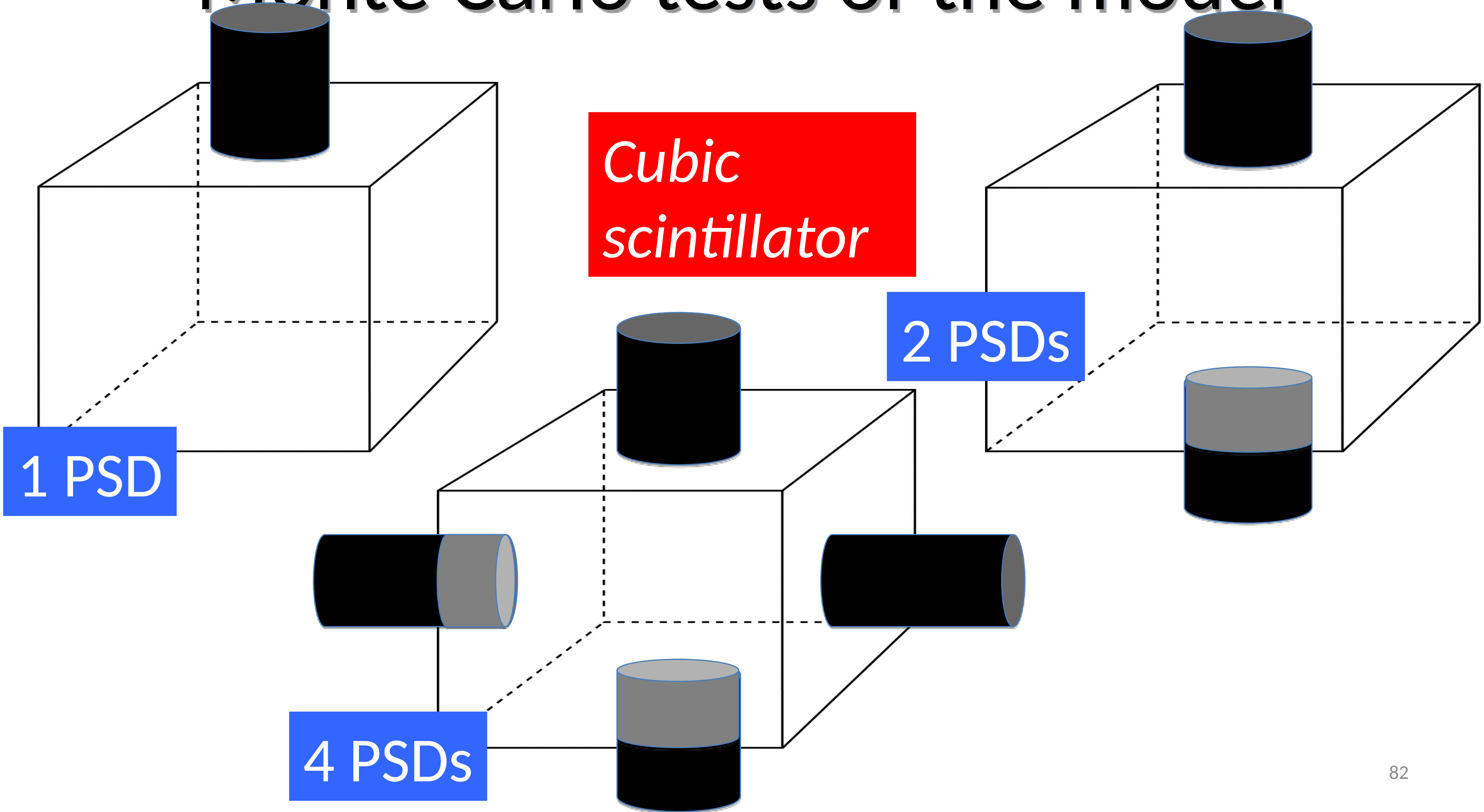
This factor takes into account all the effects of scattering and absorption

For our simple detector, under reasonable hypotheses, one obtains:

$$U_{RA} = \frac{\tilde{\lambda}}{\tilde{L}}(1 - e^{-\tilde{L}/\tilde{\lambda}})$$ with: $$\tilde{L} = 6\frac{V}{S}$$

It is the characteristic linear dimension of the detector

Monte Carlo tests of the model

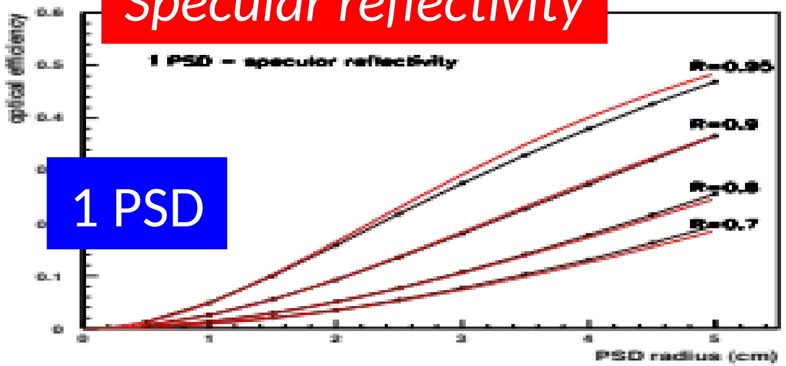


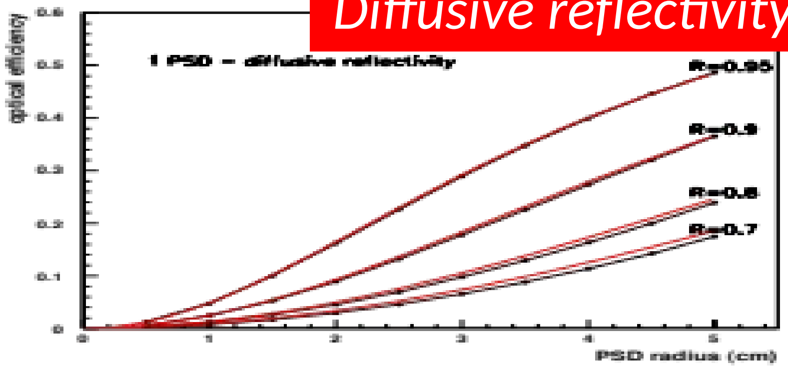
Monte Carlo tests of the model (II)

Specular reflectivity

Diffusive reflectivity

1 PSD

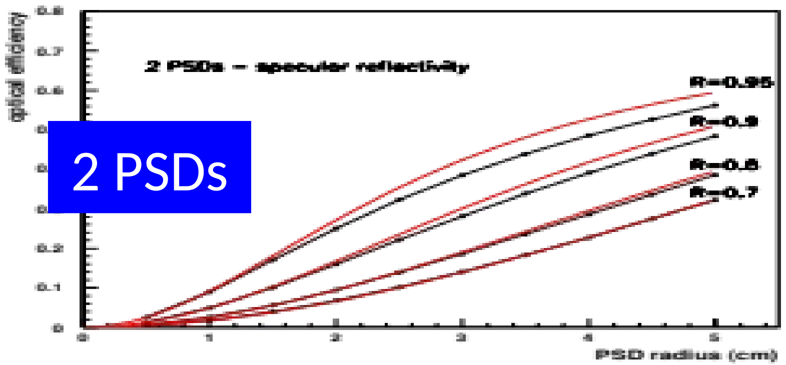


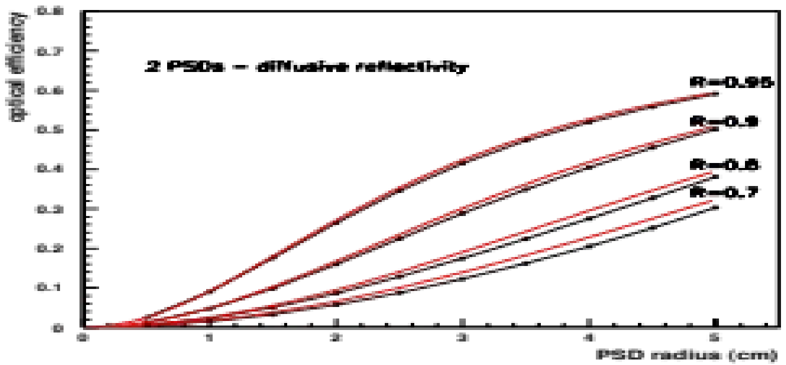


RED LINES :

$$\varepsilon_{opt} = \frac{T_w f}{1 - R(1-f) - R_w f}$$

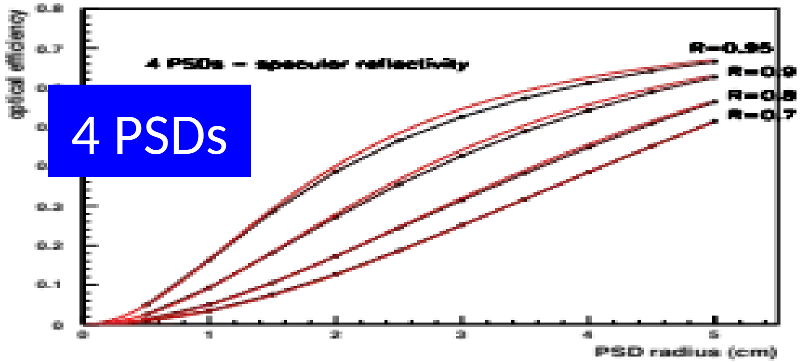
2 PSDs

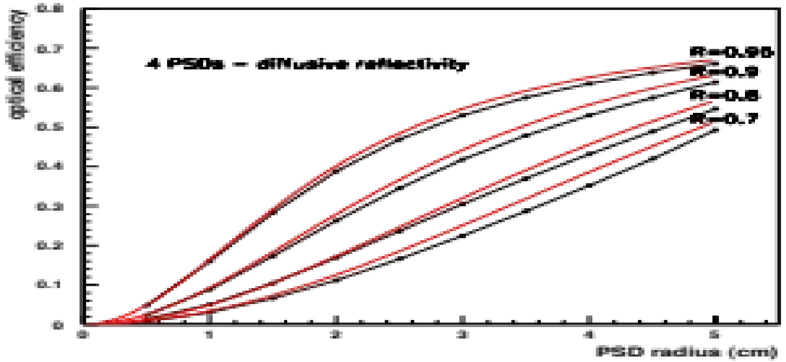




In the case of 2 (4) PSDs the formula is calculated with respect to one PSD. R is the average reflectivity of inactive surfaces and other PSDs' windows. The total efficiency is 2 (4) times the single PSD efficiency

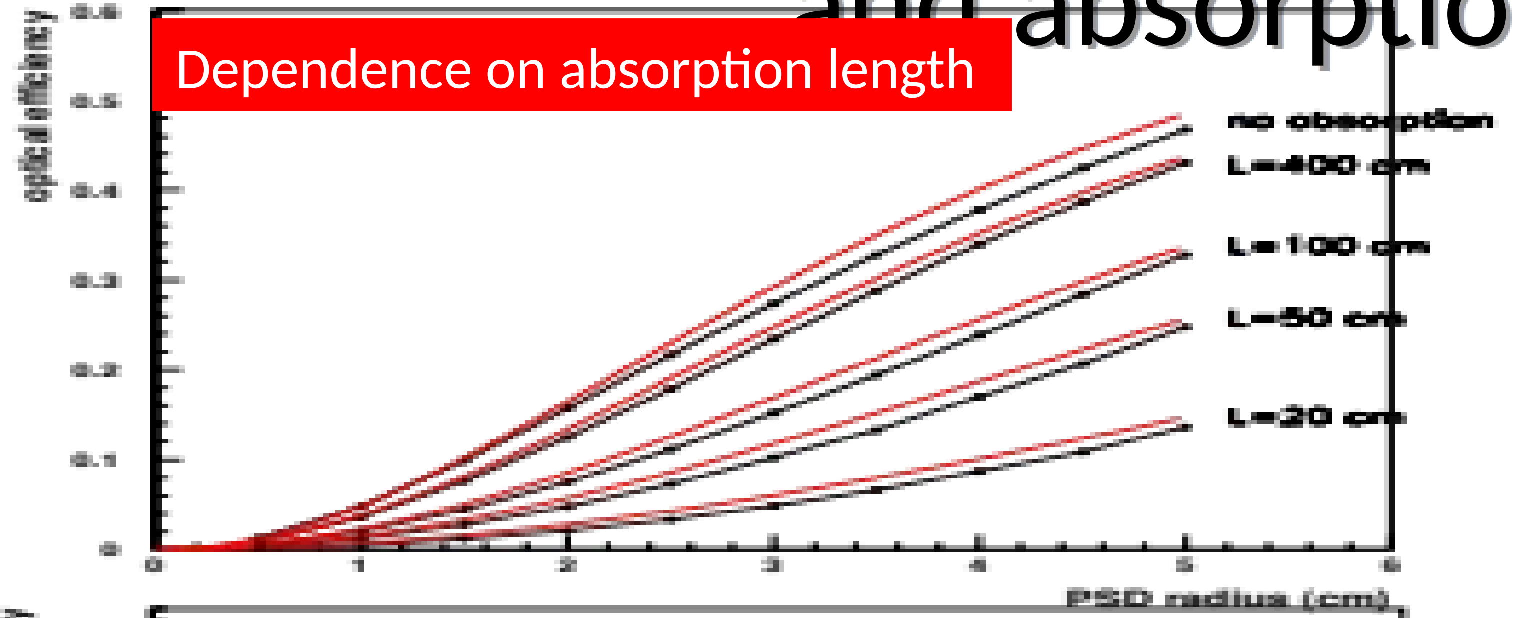
4 PSDs



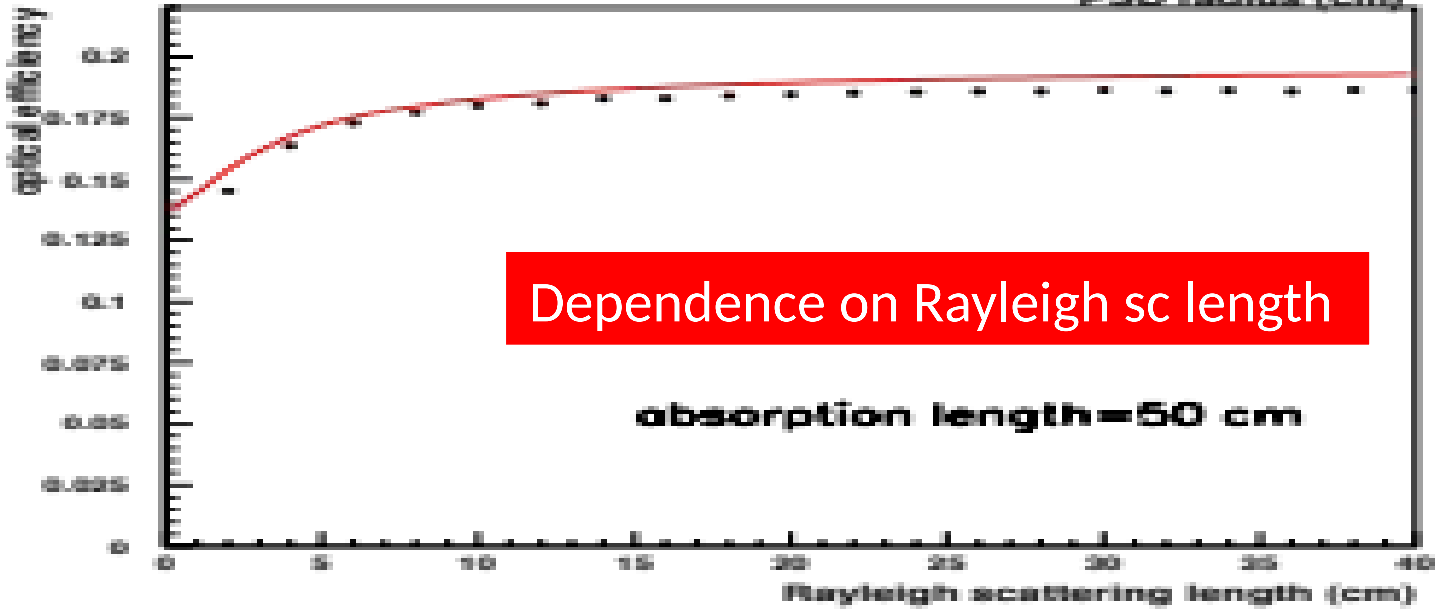


Monte Carlo tests of the model (scattering and absorption)

Dependence on absorption length



Dependence on Rayleigh sc length

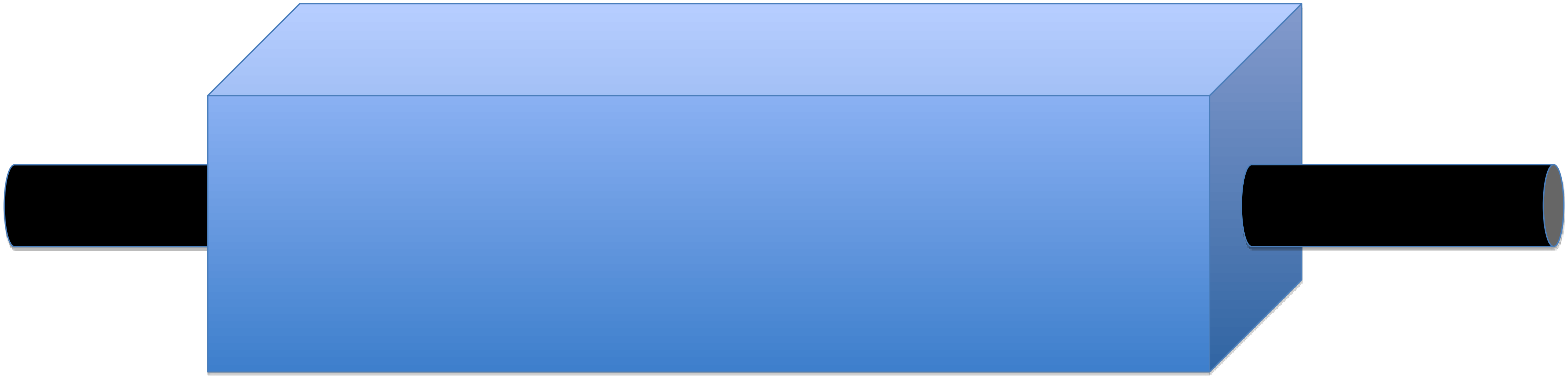


1 PSD
Specular reflectivity
R = 0.95
Rayleigh scattering = 10 cm

1 PSD
PSD radius = 4 cm
Specular reflectivity
R = 0.95
Absorption length = 50 cm

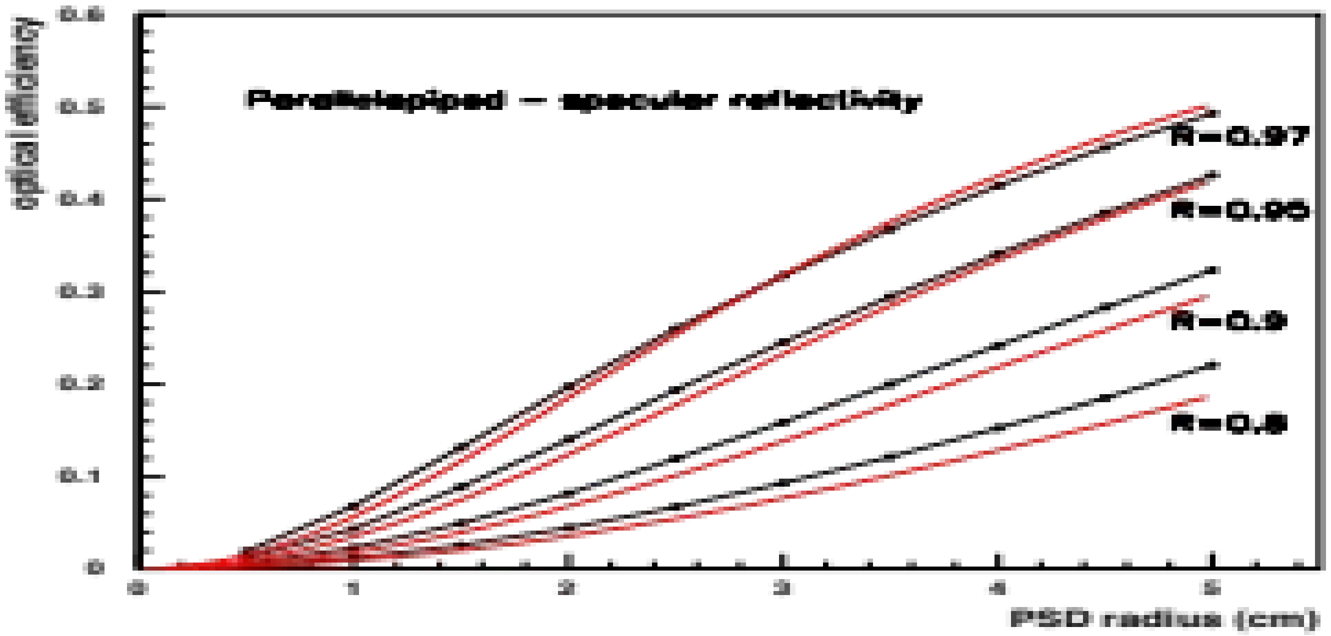
$$U_{RA} = \frac{\bar{\lambda}}{\bar{L}}\left(1 - e^{-\bar{L}/\bar{\lambda}}\right)$$

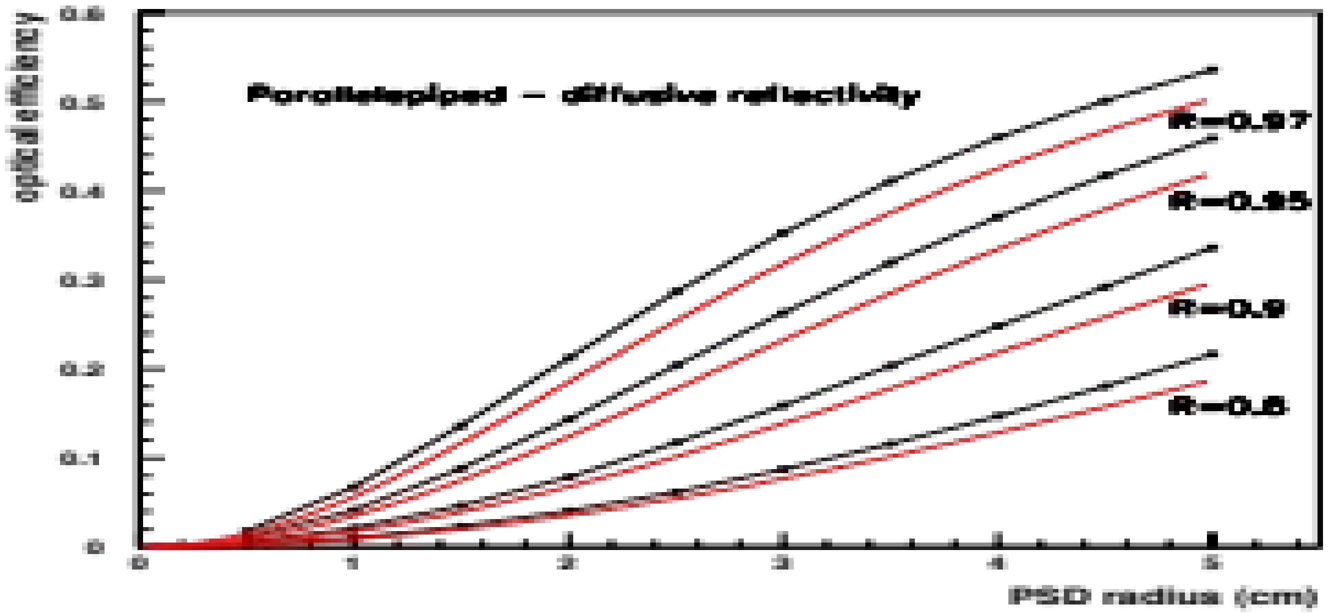
Monte Carlo tests of the model: Parallelepiped



- ✓ Parallelepiped 10 cm × 10 cm × 30 cm (l × w × h).
- ✓ 2 PSDs on the opposite faces
- ✓ Windows' reflectivity is set at 0.3 and transmissivity at 0.5 (as for the cubic scintillator)

Parallelepiped (cont.)





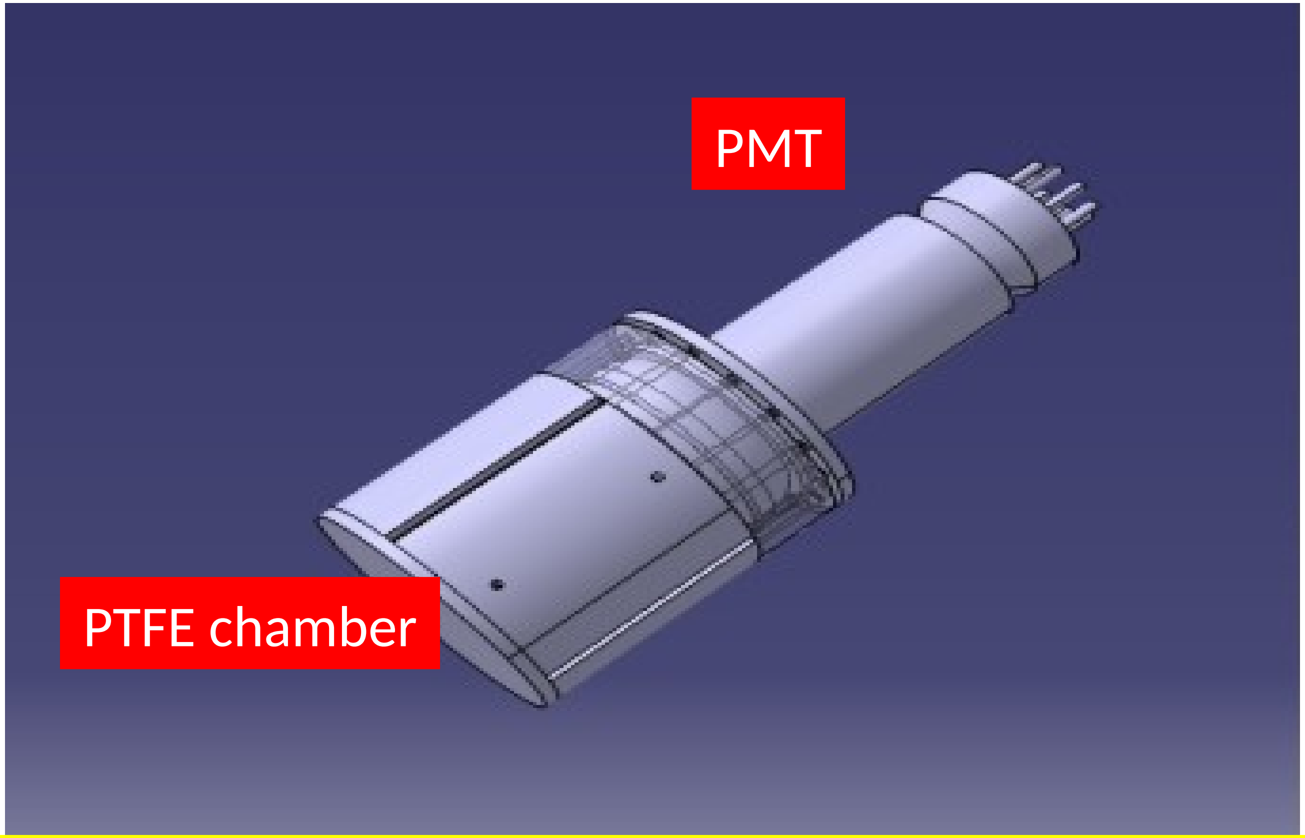
RED LINES :

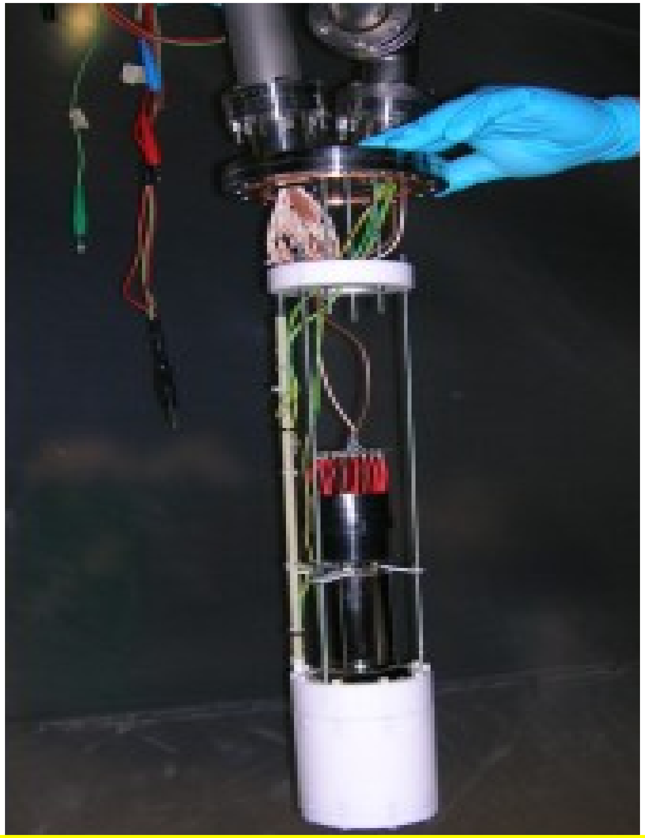
$$\varepsilon_{opt} = \frac{T_w f}{1 - R(1-f) - R_w f}$$

Extremely asymmetric detector

- ✓ Surprisingly good agreement between MC simulation and model outcomes
- ✓ For specular reflectivity, above 0.9, discrepancies at the level of few percent are found
- ✓ In all other cases they are of the order of 10%.

LY estimation of a real detector





LAr scintillation chamber - PTFE cell (h = 9.0 cm and φ = 8.4 cm) - observed by a single 3” photomultiplier (Hamamatsu R11065)
Internal surface of the cell completely covered with a reflective foil deposited with Tetra Phenyl Butadiene.

WARP Collaboration, *Demonstration and comparison of photomultiplier tubes at liquid Argon temperature*, 2012 JINST 7 P01016 [arXiv:1108.5584].

LY estimation of a real detector (I)

Parameters used for LY estimation

photon yield	$N_\gamma = 40$ photons/keV [11]
photocathodic coverage	$f = 13\%$
transmissivity of PMT window	$T_w = 0.94$ [12]
reflectivity of PMT window	$R_w = 0$
conversion efficiency of PMT	$\varepsilon_{PSD} = 28\%$
no absorption of VUV photons	$Q_{VUV} = 1$
no absorption of visible photons	$Q_{vis} = 1$
conversion efficiency of passive surface	$\varepsilon_{WLS} = 1$ [13]
conversion efficiency of PMT window	
(no shifter)	$\varepsilon_{wls} = 0.$
reflectivity of passive surface (reflector+TPB)	$R = 0.95$ [14]

LAr is assumed to be pure => no absorption (Q = 1)

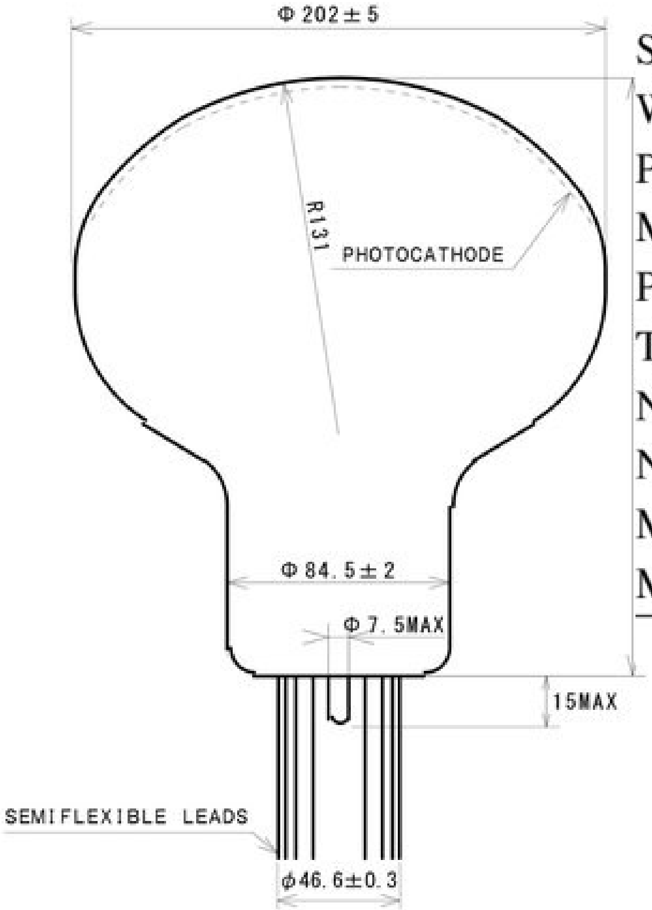
Photons converted on the walls

$$LY_{estimated} = N_\gamma \varepsilon_{PSD} \varepsilon_{WLS} (1-f) \frac{T_w f}{1 - R(1-f)} = 6.9 \frac{phel}{keV}$$

$$LY_{measured} = 7 \frac{phel}{keV} \pm 5\%$$

BACK-UP

Hamamatsu R5912



Spectral Response	300 ÷ 650 nm
Window Material	Borosilicate glass (sand blasted)
Photocathode	Bialkali with Pt under-layer
Max supply voltage (anode-cathode)	2000 V
Photocathode Q.E. at 420 nm	≥ 16%
Typical Gain	1×10^7 at 1500 V
Nominal anode pulse rise time*	≤ 4 ns
Nominal P/V ratio*	2.5
Max. dark count rate*	$5000\ s^{-1}$
Max. transit time variation	2.5 ns (center-border)

* Values for $G = 1 \times 10^7$

Journal of Instrumentation 13(10):P10030-P10030 ICARUS Collaboration

Hamamatsu R11065

HAMAMATSU

TENTATIVE DATA SHEET
Mar. 2009

PHOTOMULTIPLIER TUBE

R11065

For Low Temperature Operation down to -186 deg. C
Special Bialkali Photocathode (Bialkali LT), Low Radioactivity
76 mm (3 Inch) Diameter, 12-stage, Head-on Type, Synthetic Silica

General

Parameter		Description / Value	Unit
Spectral response		160 to 650	nm
Wavelength of Maximum Response		420	nm
Window material		Synthetic silica	-
Photocathode	Material	Bialkali	-
	Minimum Effective Area	64	mm dia.
Dynode	Structure	Box & Linear-focused	-
	Number of Stages	12	-
Operating Ambient Temperature		-186 to +50	deg. C
Storage Temperature		-186 to +50	deg. C

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)
  - The active ganging board is installed on the X-ARAPUCA module and *operates at LAr temperature*

- *Two active ganging circuits developed by the Consortium*. With different degrees of maturity at this moment. Both **demonstrated LAr operat**

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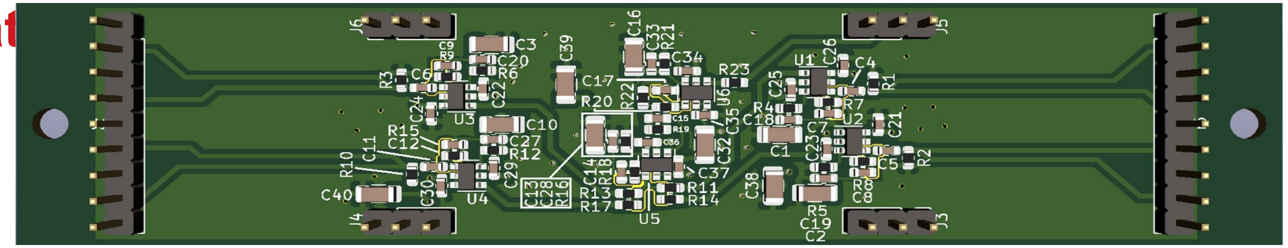

X-ARAPUCA concept

- 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.

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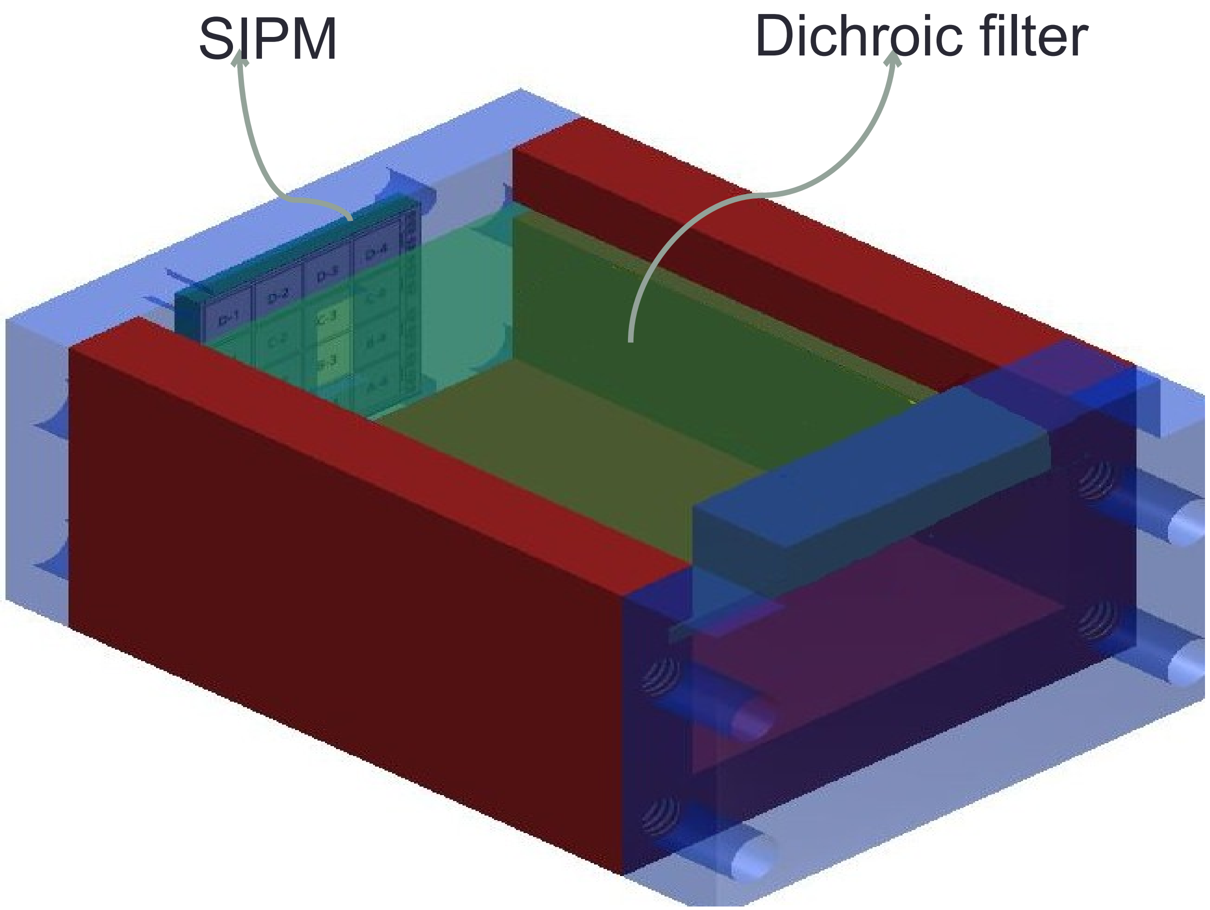
Operating principle



- 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**