PHOTO-TRAP

a low cost solution for a large-area, low-noise SiPM pixel

Daniel Guberman

INFN Pisa and Università di Siena

daniel.guberman@pi.infn.it

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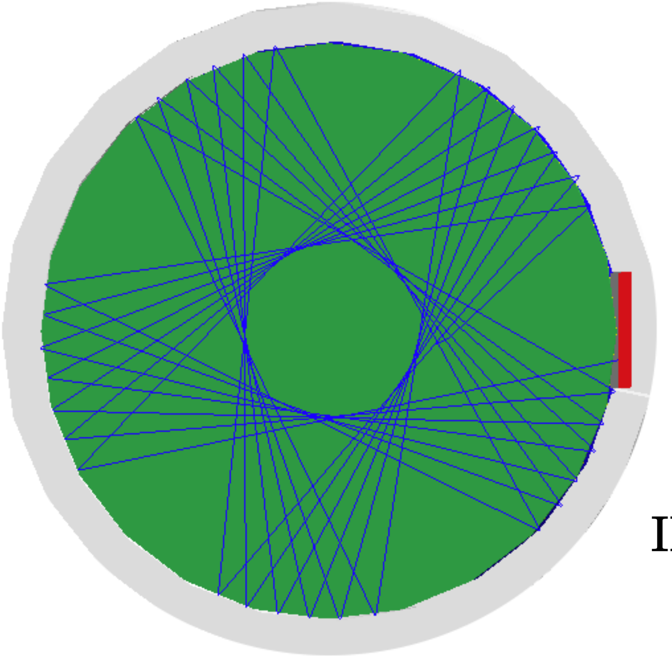


INFN Pisa Seminar

31th March 2021

Outline

1. Introduction: Large-area SiPM pixels

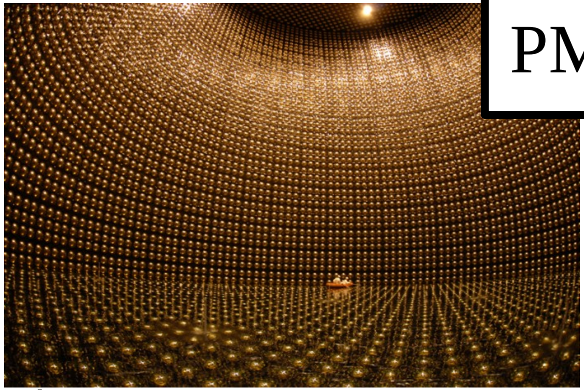
2. The Photo-Trap Project

3. Possible applications

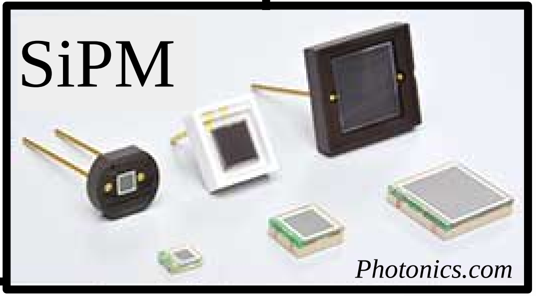
4. Notes on the expected performance

Like Photomultiplier tubes, **SiPMs** are **fast photosensors**, sensitive to **low light levels**

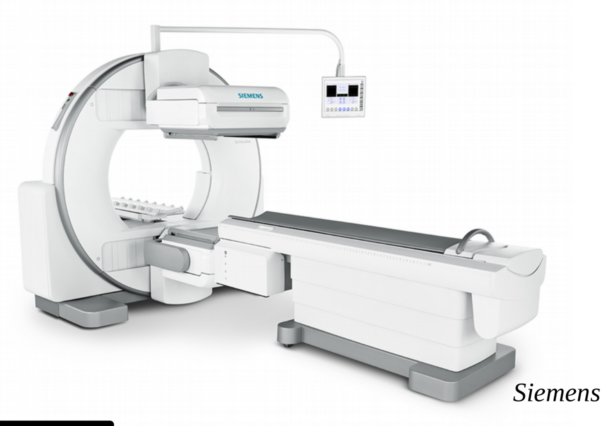

A. Gonzalez

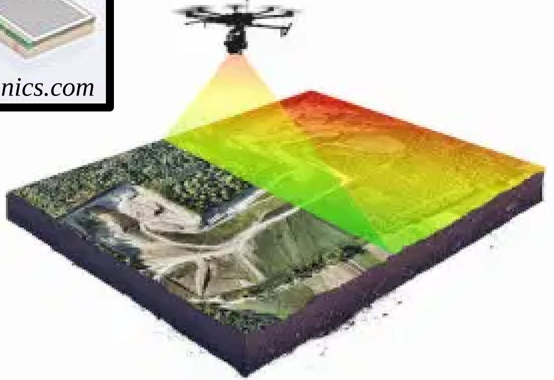

t2k-experiment.org

Hamamatsu



Photonics.com


Siemens


computationalarchaeology.wordpress.com

SiPMs vs PMTs

Compared to **photomultiplier tubes (PMTs), SiPMs** offer several **advantages**:

- High photodetection efficiency (PDE)
- Better timing performance
- Single photoelectron resolution

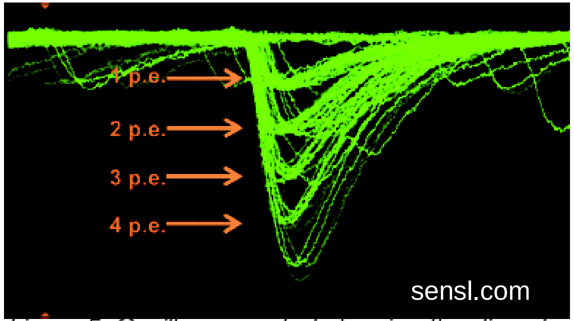


Figure 5 Oscilloscope shot showing the discrete nature of the SPM output when illuminated by brief pulses of low-level light.

Hamamatsu

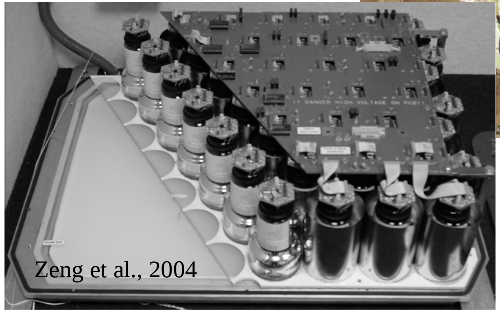
- Low voltage operation
- Insensitivity to magnetic fields
- Robustness
- Compactness…

Main drawback: pixel size

- SiPMs are typically available in **sizes ≤ 6x6 mm^2**
- **Capacitance** and **dark count rate (DCR)** increase with size
- This a **severe limitation** for building **large cameras/experiments**:

flickr/the_parabola/

www-sk.icrr.u-tokyo.ac.jp

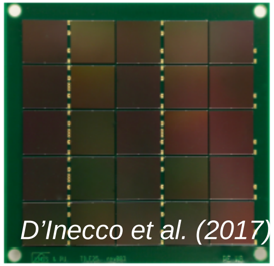


Zeng et al., 2004

- More pixels needed to fill a camera
- More readout channels
- Cost and complexity of the readout increases

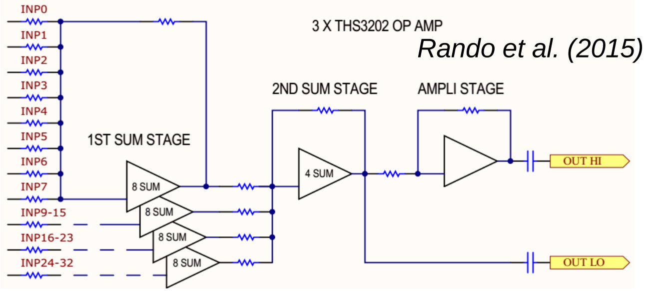
Some attempts to build Large pixels based on SiPMs

Dark Side → 24 cm^2 area SiPM detector


D'Inecco et al. (2017)

Works at 80K (Dark counts and electronic noise are reduced by orders of magnitude)

Analog sum of SiPMs



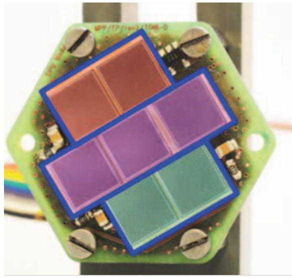
Rando et al. (2015)

The individual currents of ~10 SiPMs are summed into a single output

Several prototypes in VHE astrophysics. **Largest one sums 14 SiPMs of 6x6 mm^2 (~ 5 cm^2 area)** *[Mallamaci et al. (2019)]*

- Scalability in size is limited:

- ✗ Noise severely harms single photoelectron resolution
- ✗ DCR still increase linearly with the area.
- ✗ Pixel cost scales with pixel area

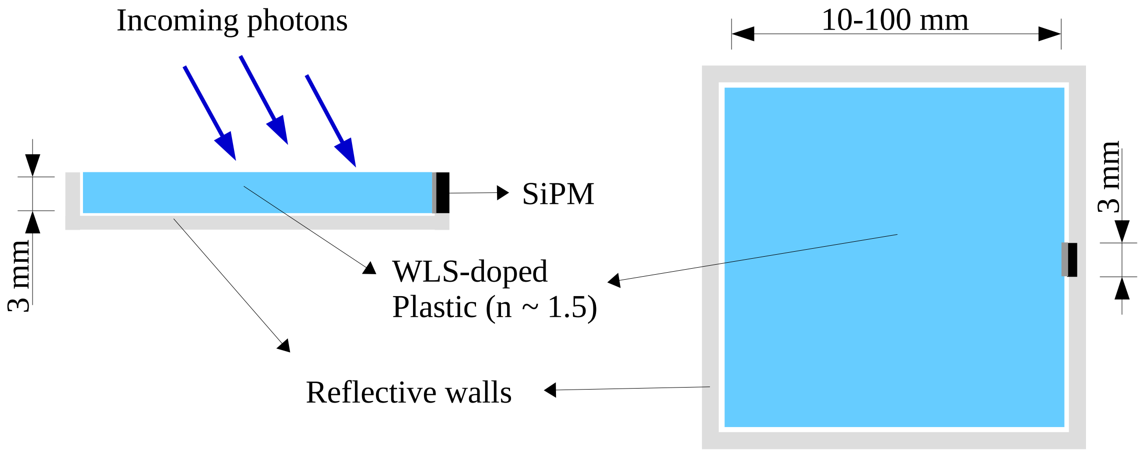

Fink et al., (2016)

The Light-Trap

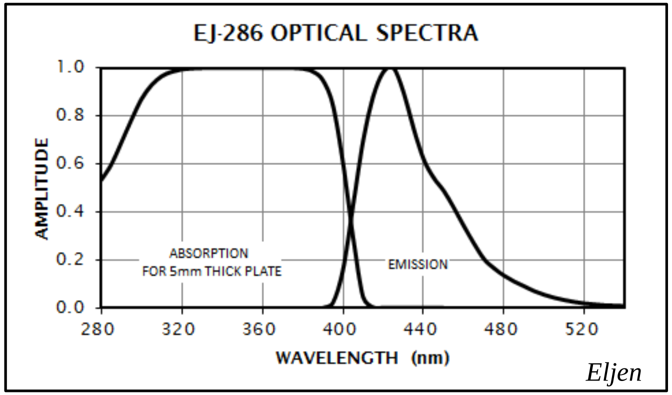
A **Light-Trap pixel** consists of a **plastic piece**, **doped** with some **wavelength shifter (WLS)**, coupled to a **SiPM.**

Side view

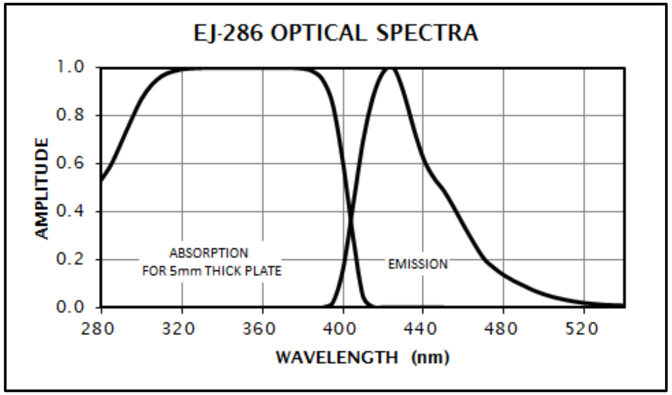
Top view

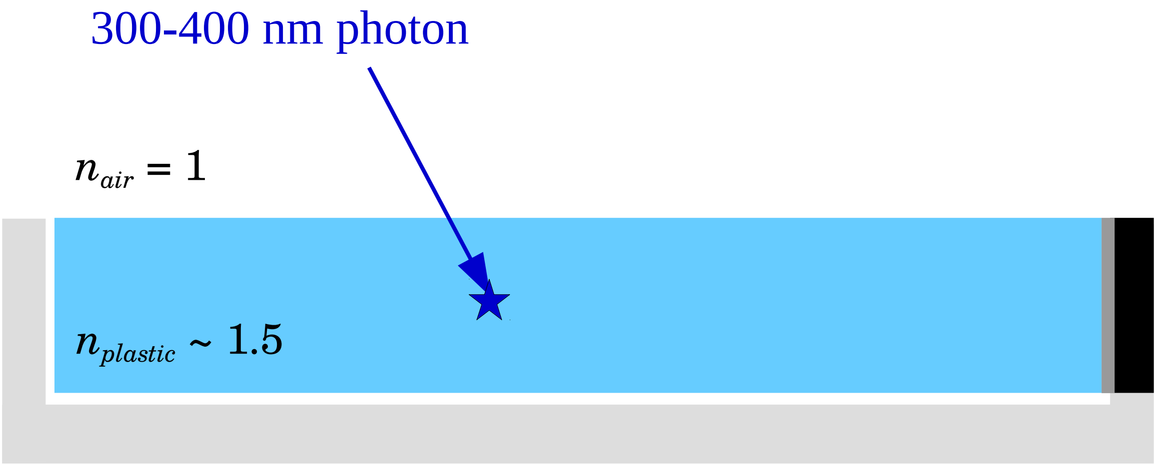


WLS absorption/emission

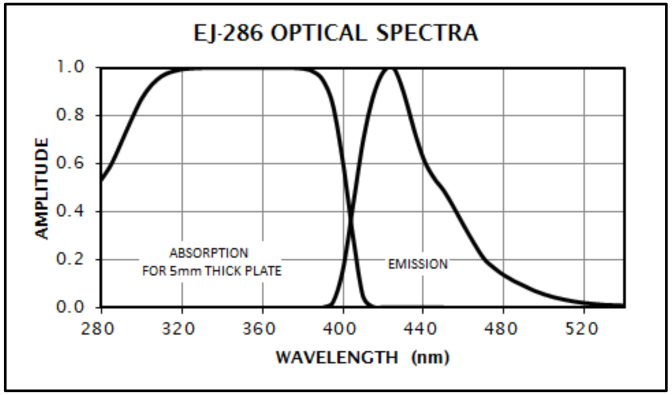


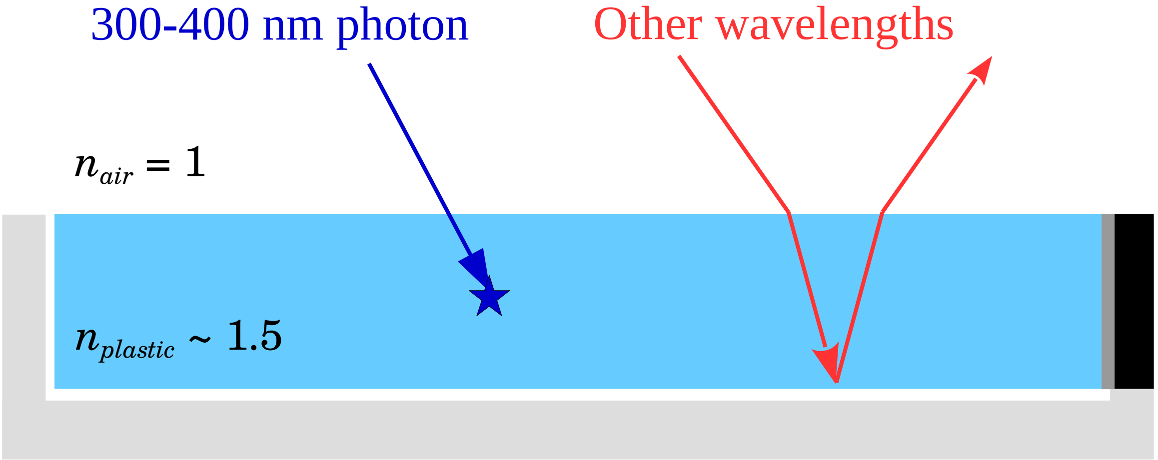
The Light-Trap concept



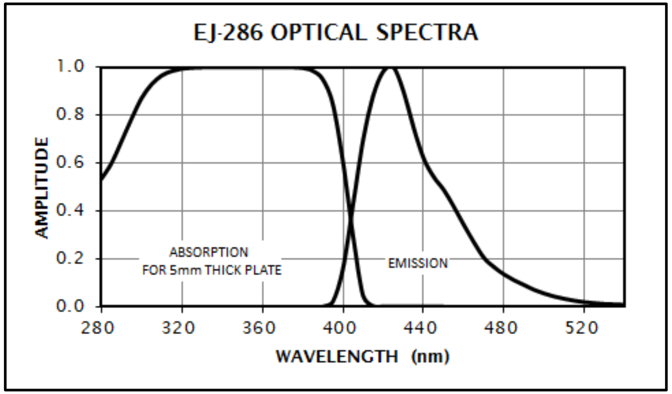


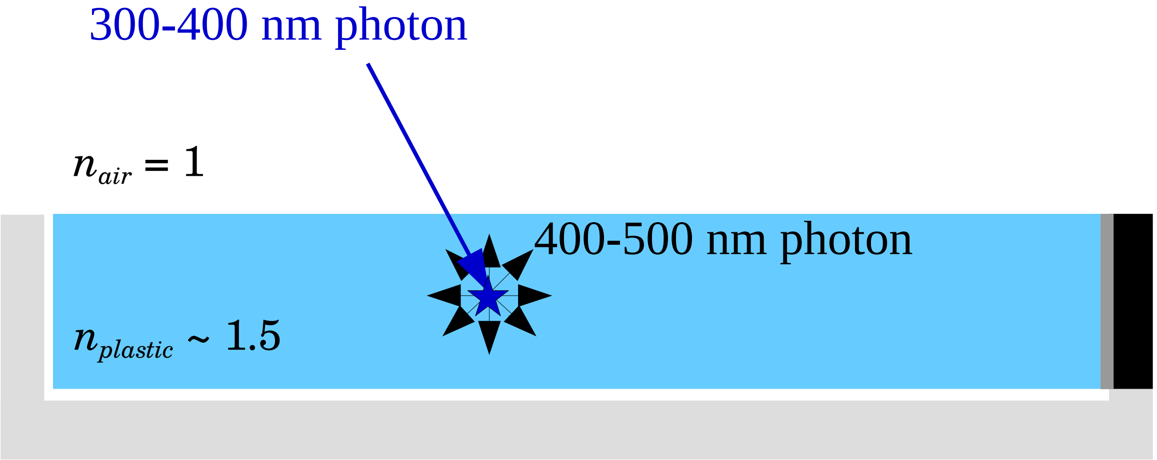
The Light-Trap concept



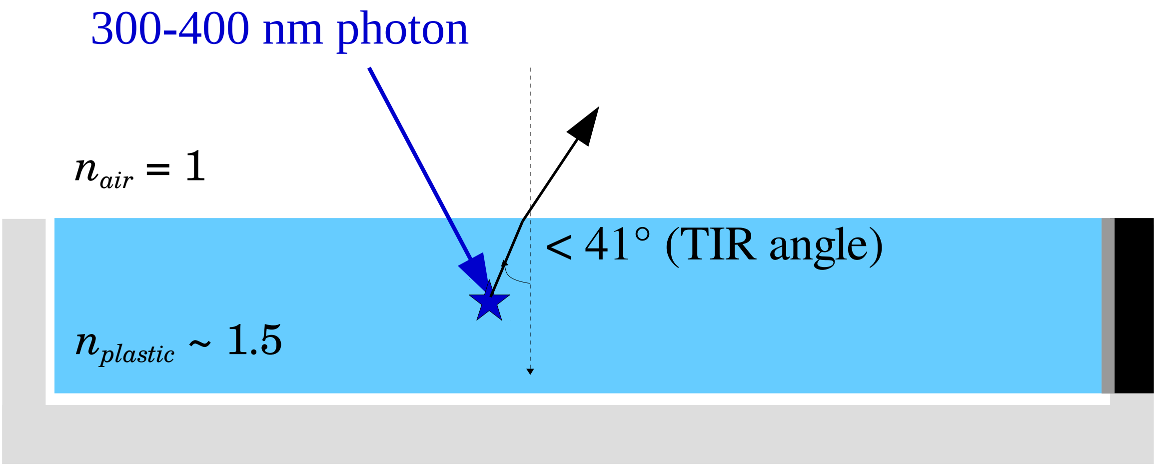


The Light-Trap concept

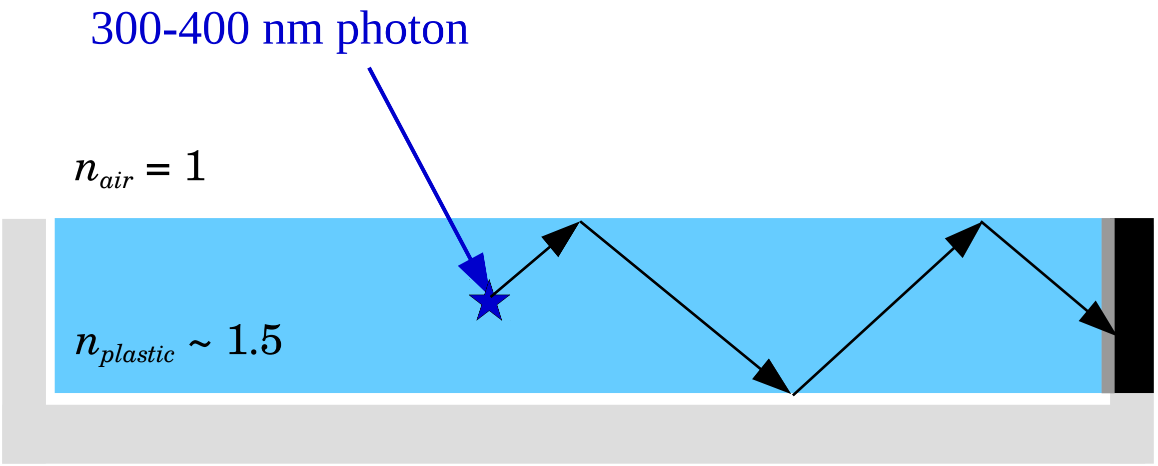




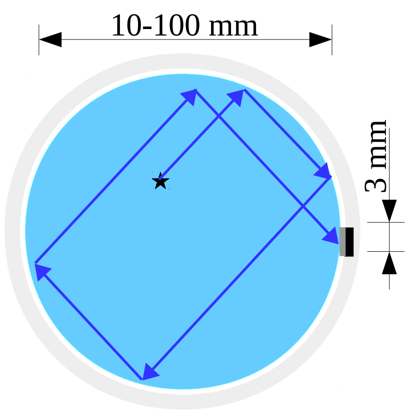
The Light-Trap concept

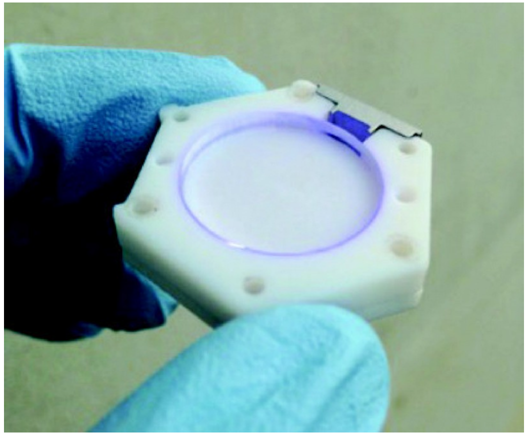


The Light-Trap concept



The Light-Trap idea





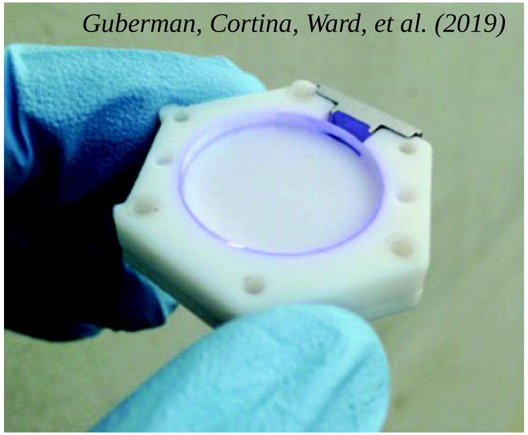
Proof-of-concept Light-Trap pixel developed at IFAE, Spain: 15 mm diameter.

- Pixel area **~10-100 times area of a single SiPM**.
- Pixel noise = **noise of a single SiPM**
- Pixel cost ~ **cost of a single SiPM** (if the cost of the plastic is low)

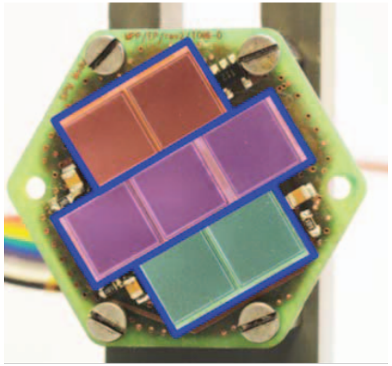
***D. Guberman** et al. (2019), The Light-Trap: A novel concept for a large SiPM-based pixel for Very High Energy gamma-ray astronomy and beyond, NIM-A, 923, 19*

Light-Trap vs Analog sum of SiPMs

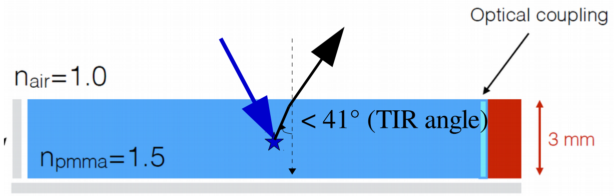
Guberman, Cortina, Ward, et al. (2019)



- ✓ **Very good single photoelectron** resolution over a **large area**
- ✓ **Low DCR** and **capacitance** (even at room temperature)
- ✓ Cheap
- ✓ In principle easily **scalable** to larger sizes and **adaptable** to **different wavelengths**.



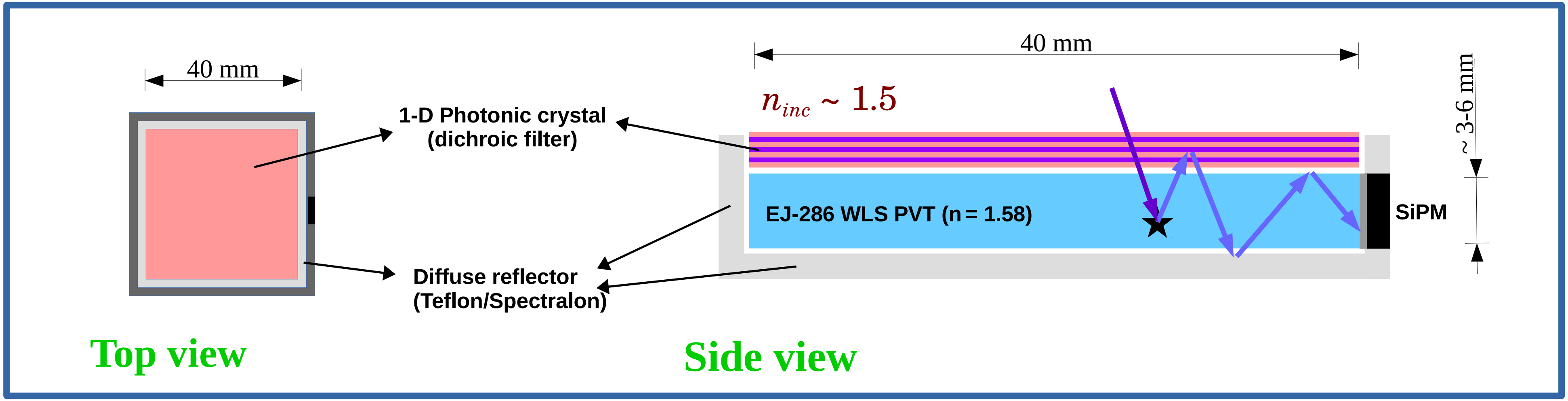
Fink, Hahn, Guberman, et al., (2016)



- ✗ **Low efficiency**
- ✗ Only works if light arrives from a **medium with *n*≈1**

The Photo-Trap Project

Photo-Trap attacks the two limitations of the Light-Trap by **introducing a 1-D Photonic Crystal filter** on top.

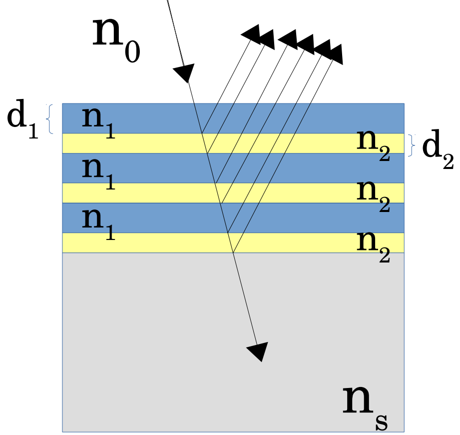


Proof-of-concept: We will build a **pixel of ~4×4 cm^2** sensitive to **near-UV light (300-400 nm**, where Cherenkov light peaks) incident from a medium with **n ~ 1.5** (typical of plastics and glasses).

1-D Photonic crystals *(a.k.a. dichroic/interference filter)*

- **Alternating thin** (~50-100 nm) **layers** of **high** and **low refractive index** materials are deposited on a substrate to build a **filter**.

- By properly choosing the refractive index (n_1, n_2), the thickness of each layer (d_1, d_2) and the number of layers we can achieve **high reflectivity in a certain wavelength range**

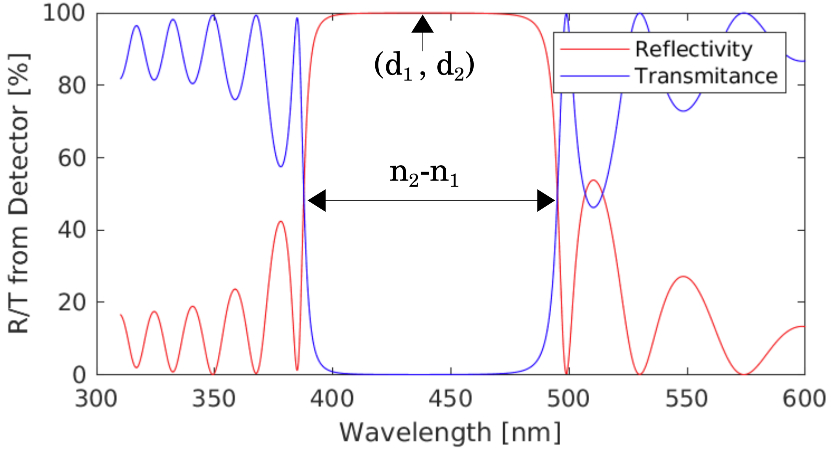


Rule of thumb:

(d_1, d_2) → "Band-gap" center

↑ (n_2-n_1) → ↑ "Band-gap" width

↑ Nr of layers → ↑Reflectivity



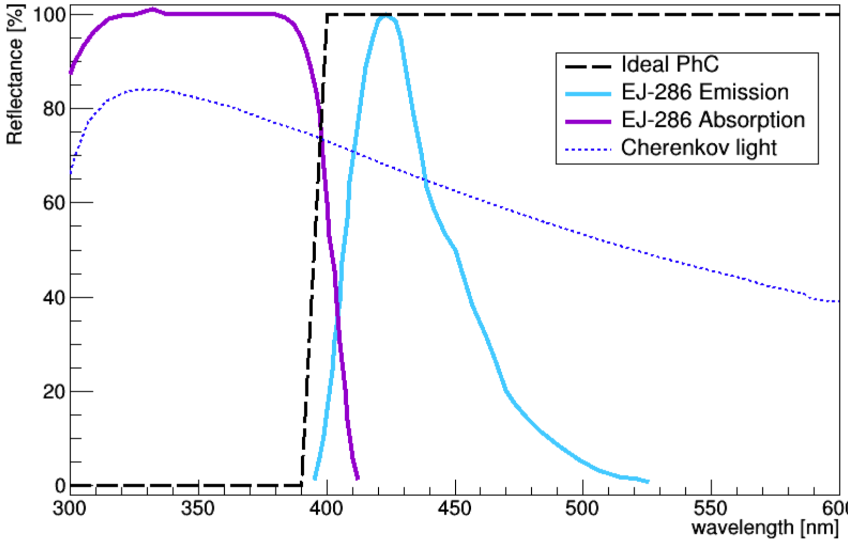
A Photonic crystal for Photo-Trap

In Photo-Trap we will

1. Design a Photonic Crystal (code by A. Paghi, UNIPI)

2. Build a Photonic crystal

3. Integrate it into a proof-of-concept Photo-Trap pixel

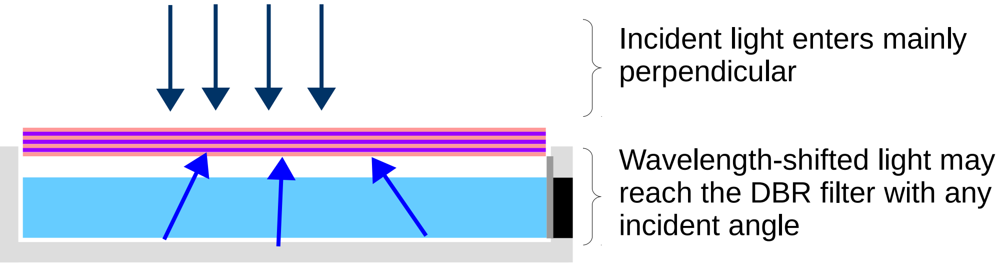


CHALLENGE: The Photonic Crystal should have

1. High Transmission at 300-390 nm

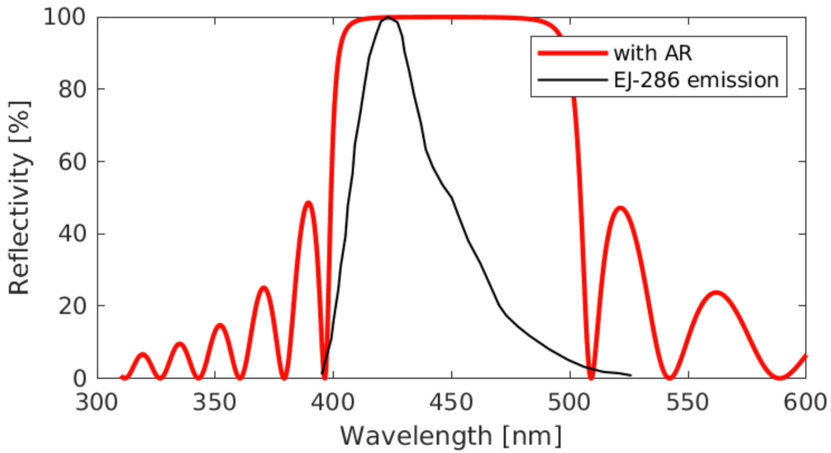
2. High Reflectivity at 400-500 nm

3. Low dependence on the incident angle

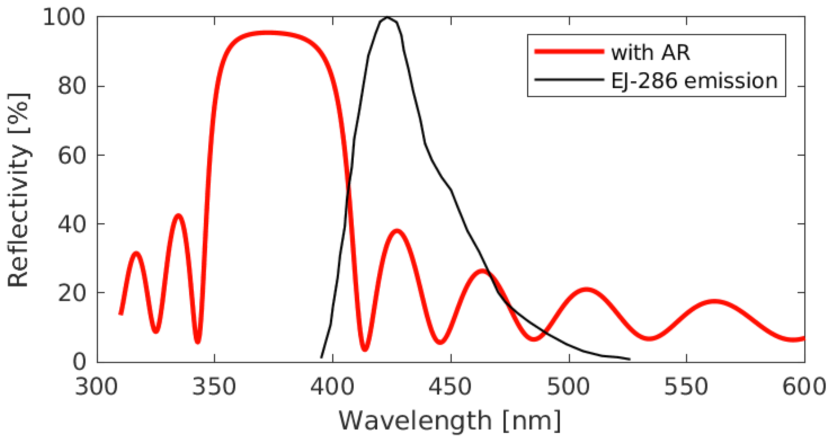


Filter response depends on the incident angle...

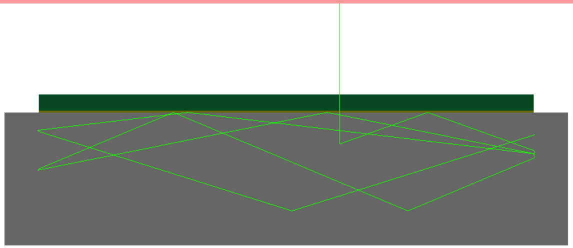
Normal incidence



40 deg incidence (p-polarized)



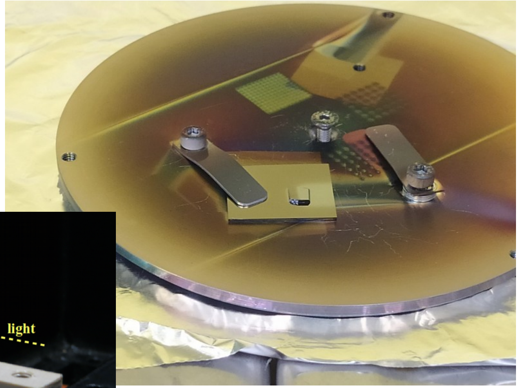
Project Roadmap

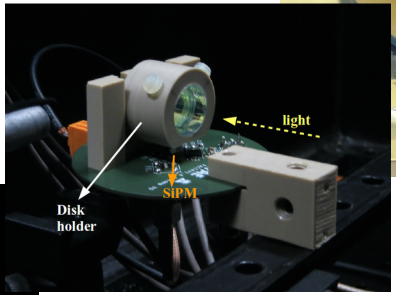


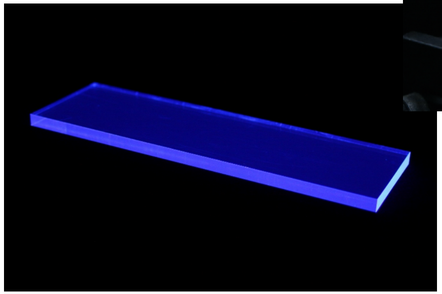
Within two years we plan to

- Optimize the pixel geometry through Geant4 simulations
- Design and build the photonic crystal
- Build prototype pixels
- Characterize those prototypes in the lab
- Perform a field test

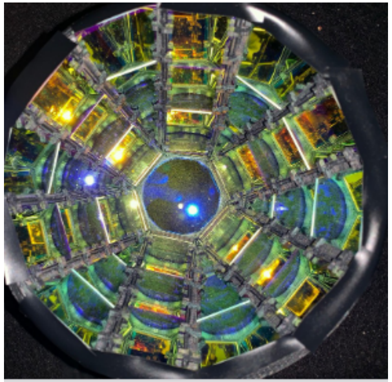
We are here!

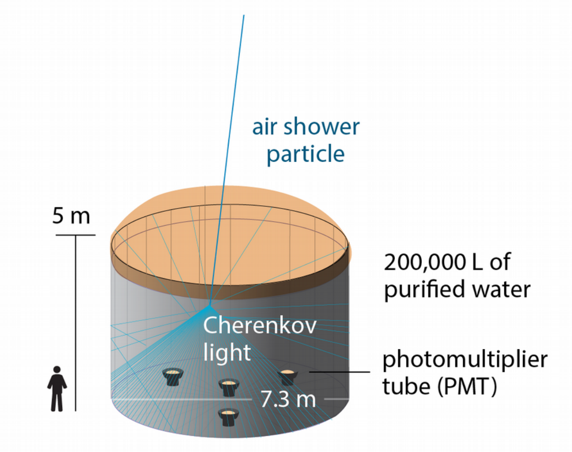






Some possible applications





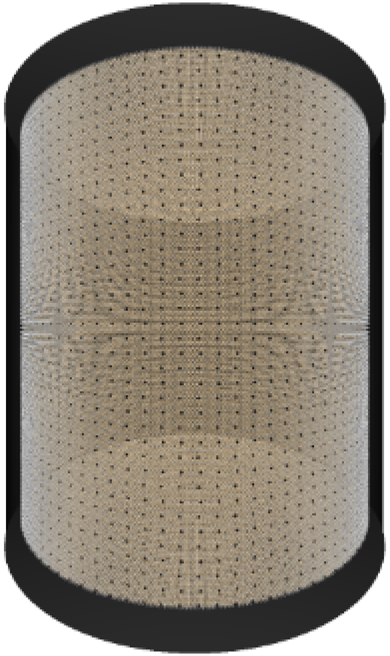
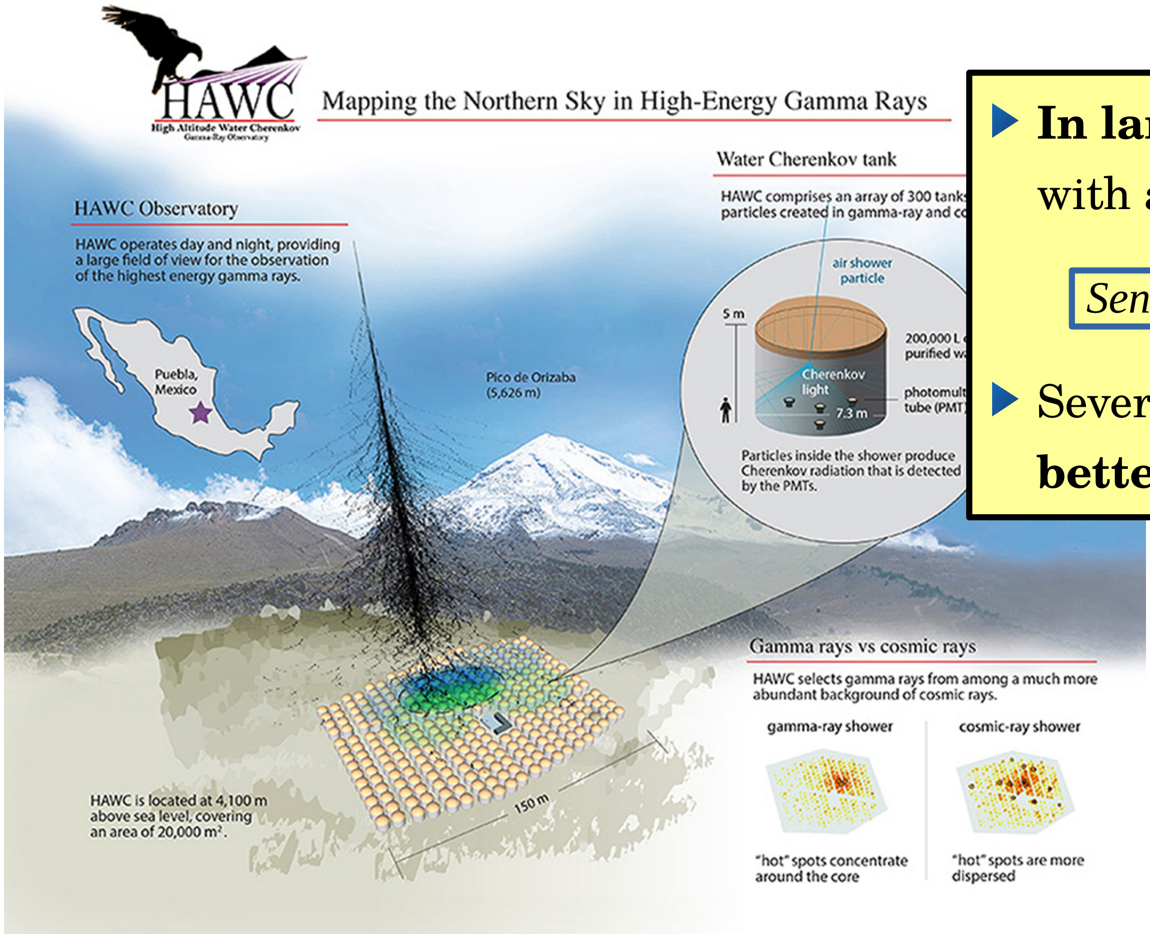


Image credits: HAWC/WIPAC, Kaptanoglu, Saint-Gobain, Askins et al.

1. Water Cherenkov Detectors



- **In large volumes efficiency** can be increased with a **larger collection area**

$$Sensitivity = Detection\ Efficiency \cdot Collection\ Area$$

- Several **cheap pixels** can be distributed for **better sampling the shower**.

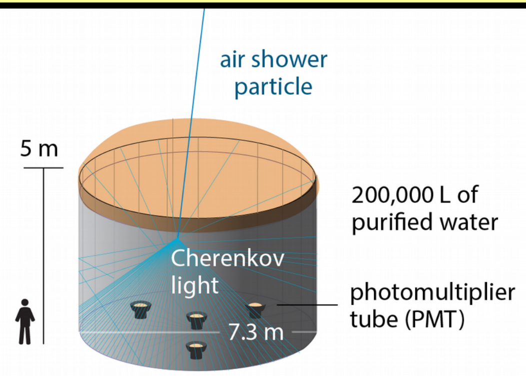
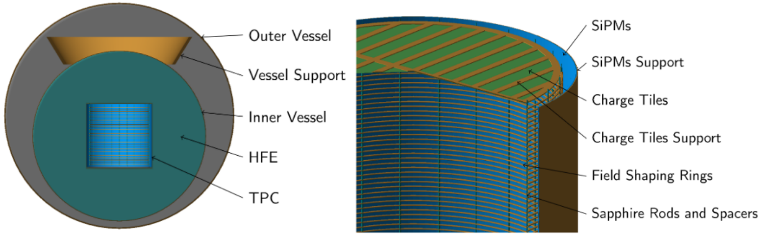


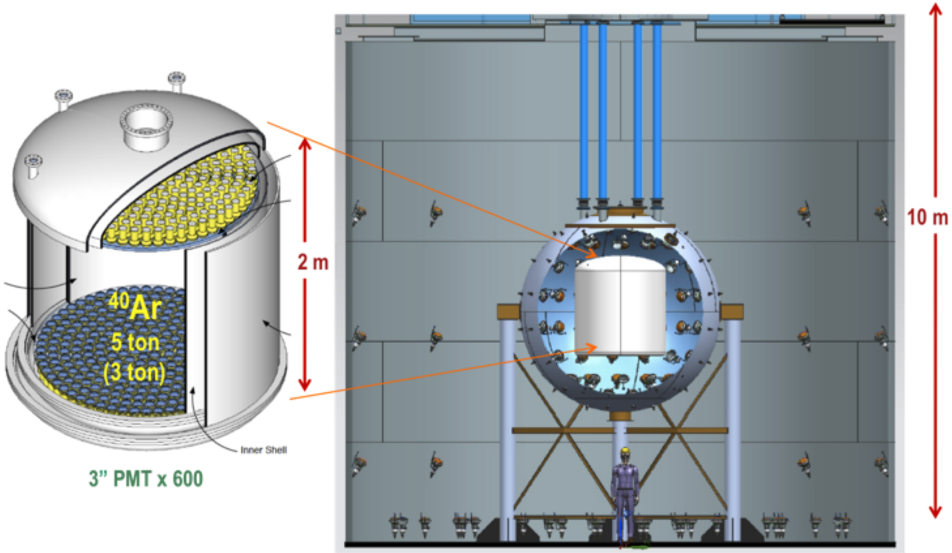
Image credits: HAWC/WIPAC

2. Dark Matter and Neutrino experiments



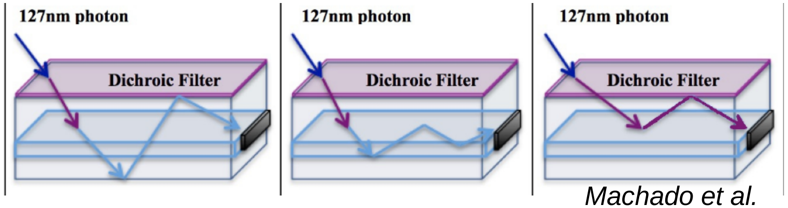
nEXO Coll.

- **Detection efficiency** in LXe/LAr is (already) **increased** by using **WLS**.
- There is also a tendency to go for **larger volumes**



UCLA (DarkSide)

ARAPUCA (DUNE)

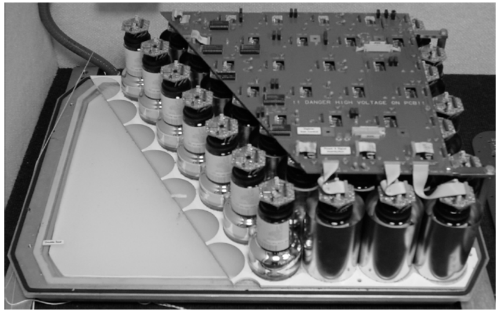


Machado et al.

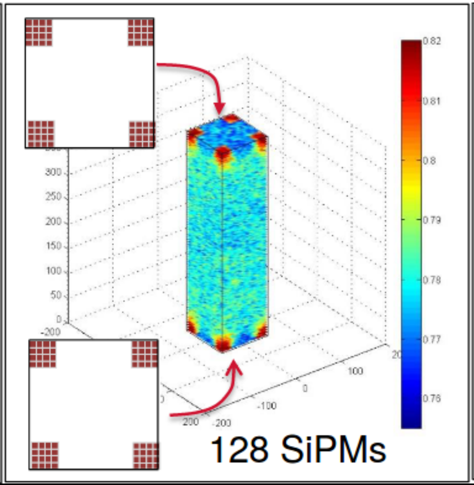
3. Large scintillators

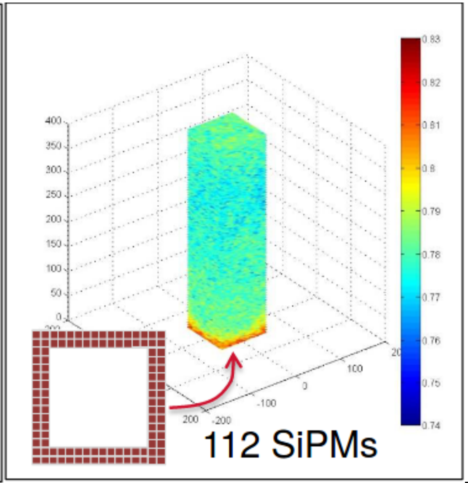
- **SiPM** readout for **scintillators** offers **compactness** and **flexibility**.
- Covering large areas is difficult:
  - **- High Cost**
  - **- Dark counts** degrade energy resolution

SPECT



Zeng et al., 2004





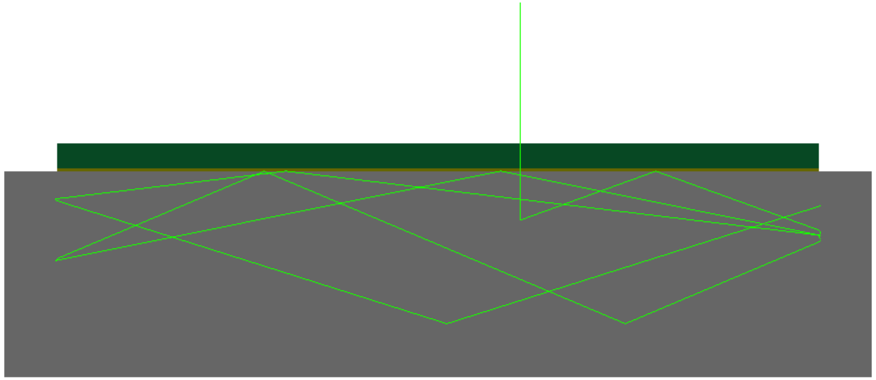
Menge et al. (Saint-Gobain), 2018

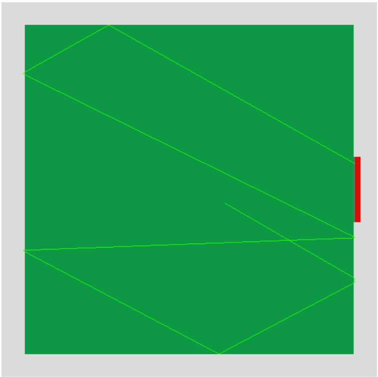
In general, Photo-Trap could be useful…

- When **efficiency loss** can be **compensated** with a **larger detection area**
- When **wavelength shifting** can **increase** the detection **efficiency**
- When **low noise** at **room temperature** is required
- When a **sensitivity** in a **specific wavelength** band is desired
- When **cost** is a limitation…

Notes on the expected performance

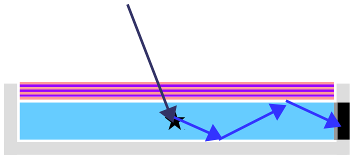
(from Geant4 simulations)



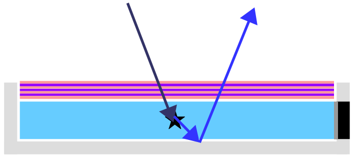


Trapping Efficiency (TE)

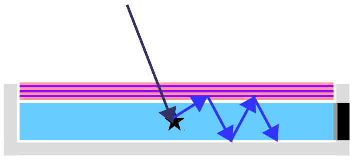
$$TE = \frac{Nr\ of\ photons\ that\ hit\ the\ SiPM}{Nr\ of\ incident\ photons}$$



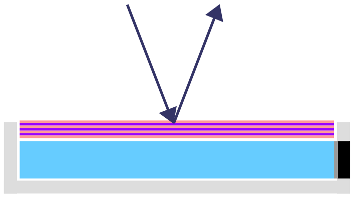
Photon **hits** the SiPM



Photon escapes



Photon absorbed by reflector



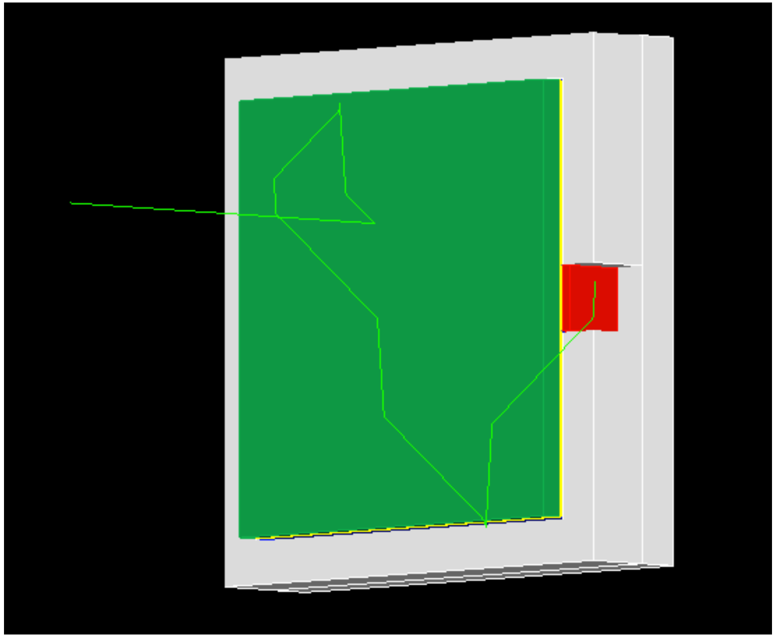
Photon reflected before entering the detector

Note that

$$PDE(Photo-Trap) \simeq TE \cdot PDE(SiPM)$$

TE in Geant4 Simulations

- 340 nm photons are fired from a medium with *n~1.5*, perpendicular to the detector, all over the detector surface.
- Photons are tracked until they are absorbed, escape hit the SiPM.
- All relevant physics and material properties are simulated.

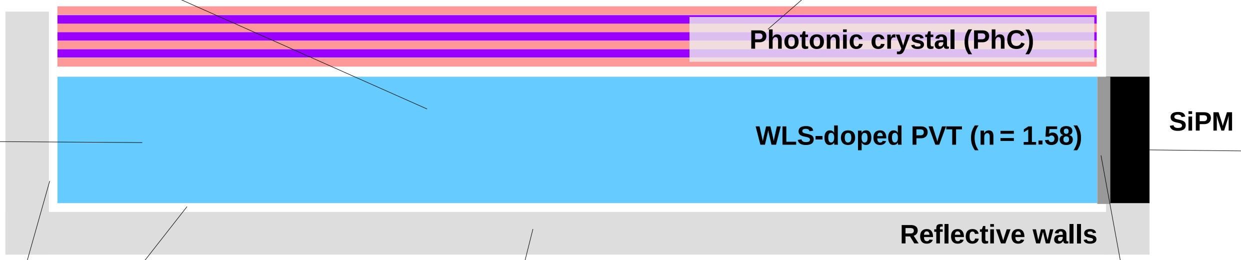


Trapping Efficiency = Nr of photons that hit the SiPM / Nr of simulated photons

Factors affecting the TE

PVT dimensions and geometry

T/R properties of the Photonic Crystal



QE of the WLS

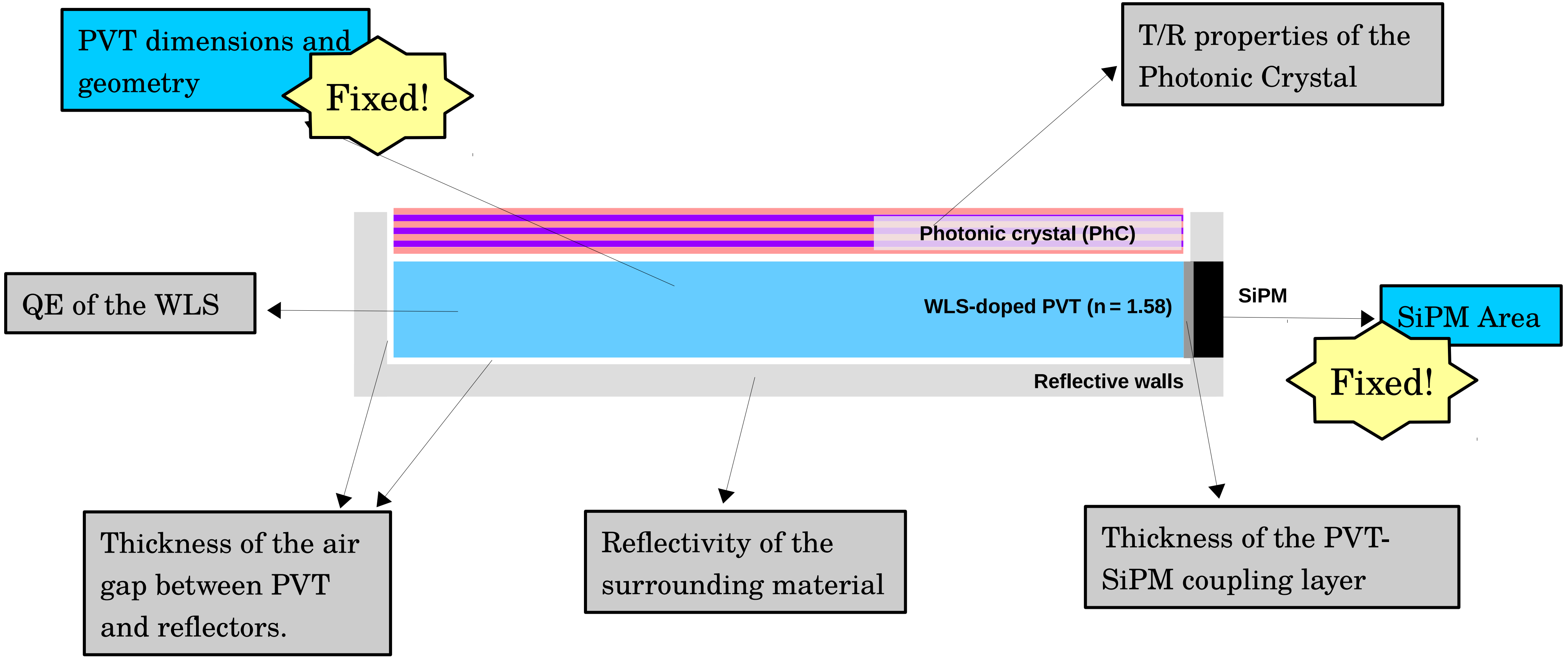
SiPM Area

Thickness of the air gap between PVT and reflectors.

Reflectivity of the surrounding material

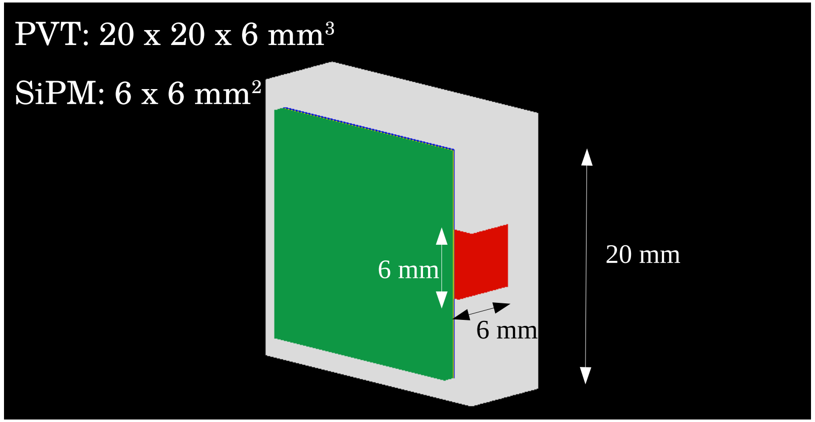
Thickness of the PVT-SiPM coupling layer

For fixed goemetry and SiPM area...



Pixel Geometry and SiPM area

Photo-Trap Area ~ 11 x SiPM Area



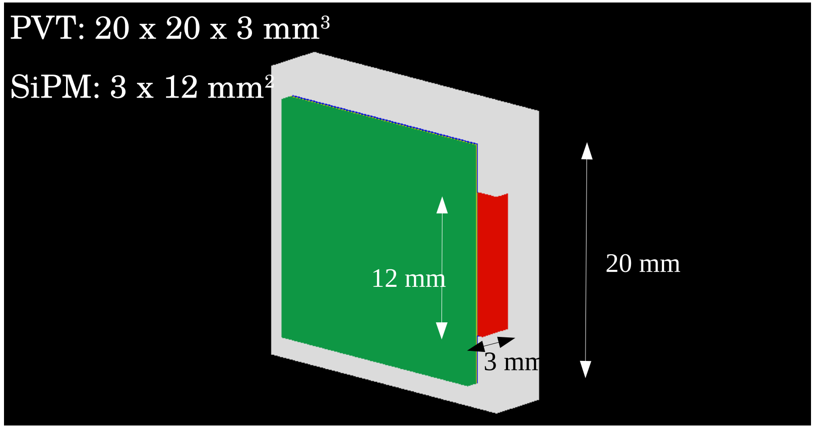
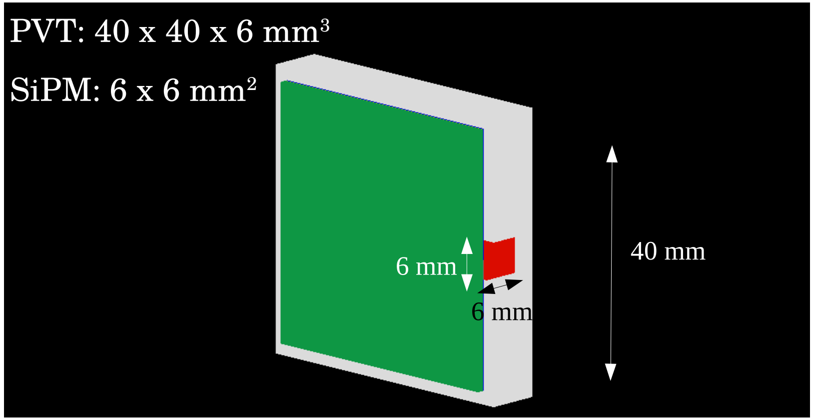
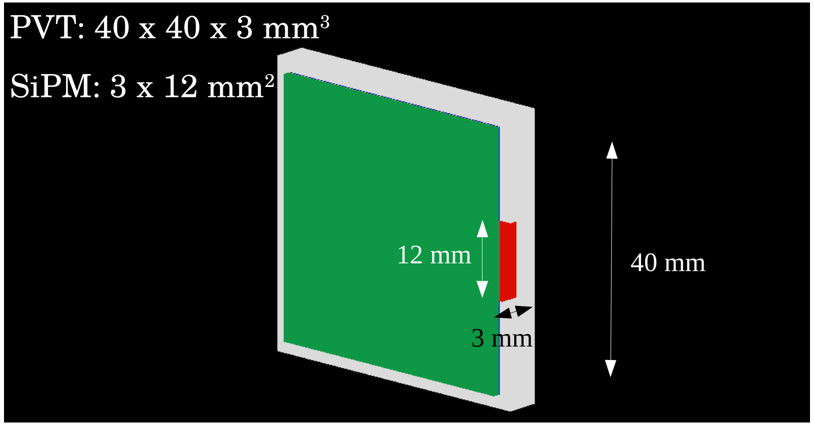


Photo-Trap Area ~ 44 x SiPM Area





The Ideal Photo-Trap

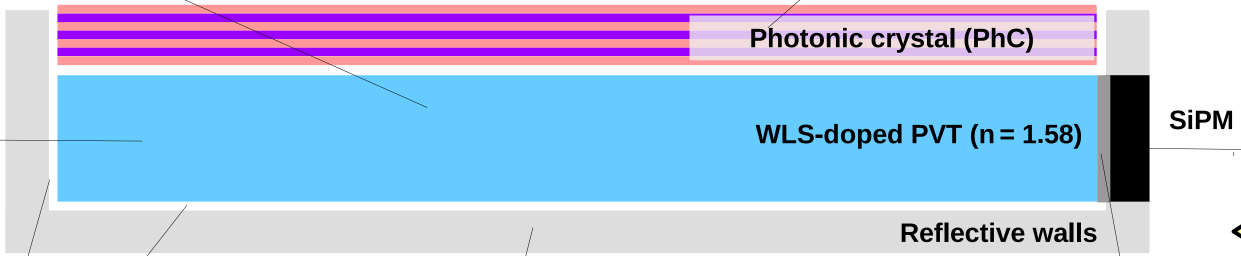
PVT dimensions and geometry — Fixed!

T = 100 % if λ<400 nm

T = 0 if λ>400 nm

For all incident angles

QE = 100 %



SiPM Area — Fixed!

Air gap ~ 1 um

R = 100 %

Thickness ~ 1 um

The Ideal Photo-Trap

PVT dimensions and geometry

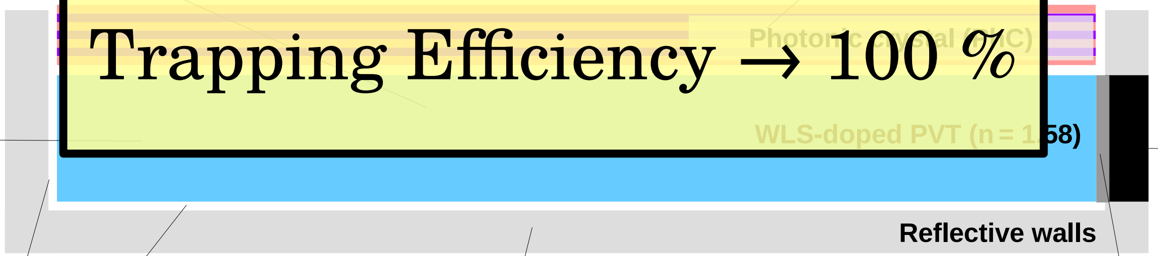
Fixed!

T = 100 % if λ<400 nm

T = 0 if λ>400 nm

For all incident angles

Trapping Efficiency → 100 %



QE = 100 %

SiPM Area

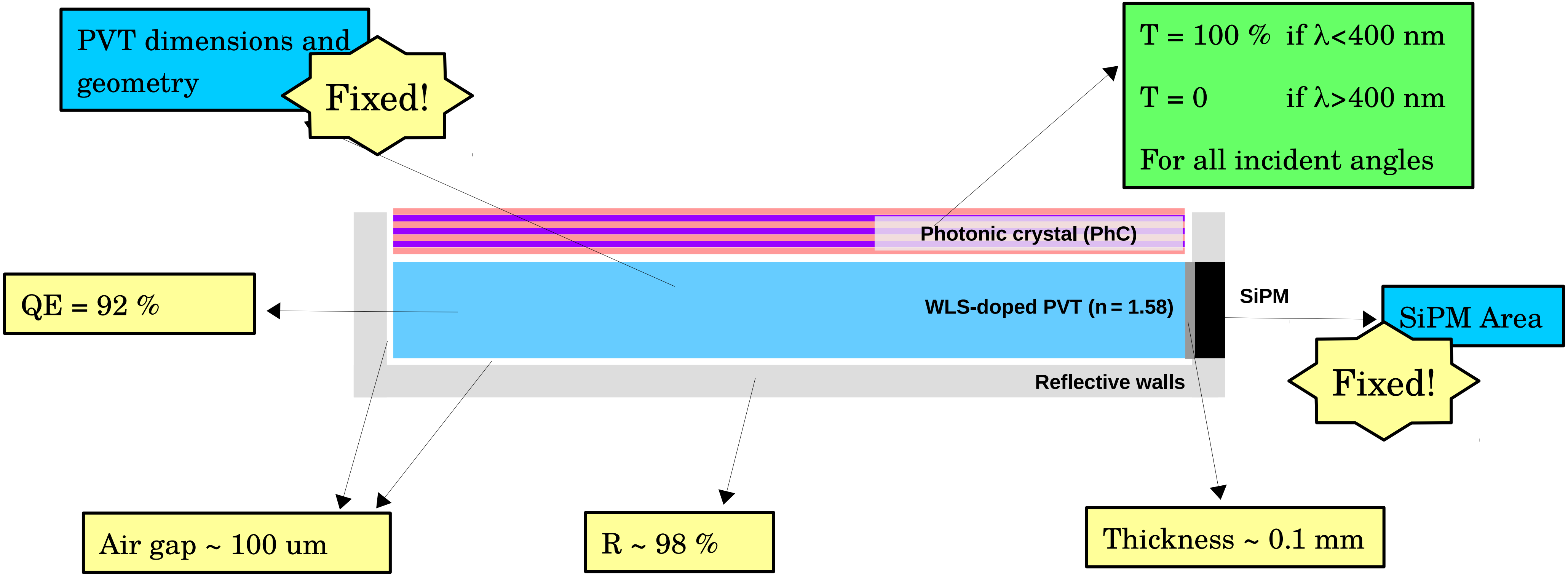
Fixed!

Air gap ~ 1 um

R = 100 %

Thickness ~ 1 um

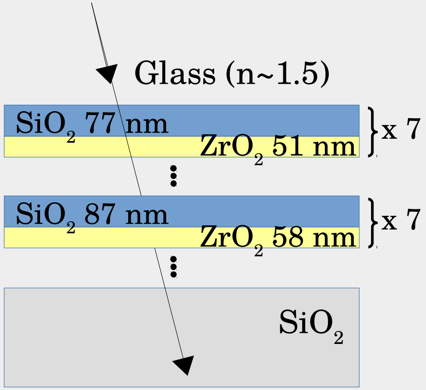
A more realistic Photo-Trap with ideal PhC



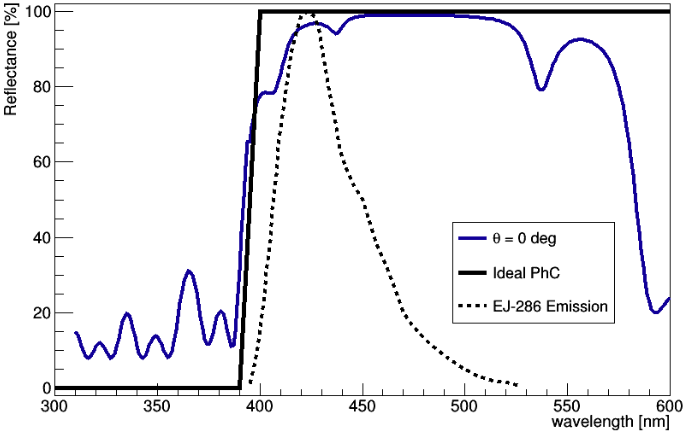
A more realistic PhC

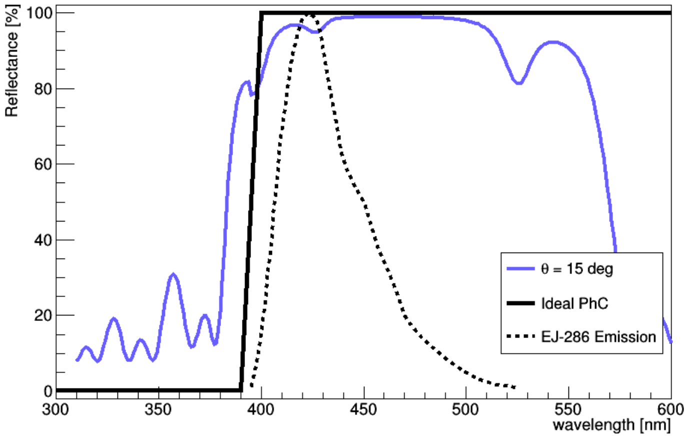
Prototype PhC:

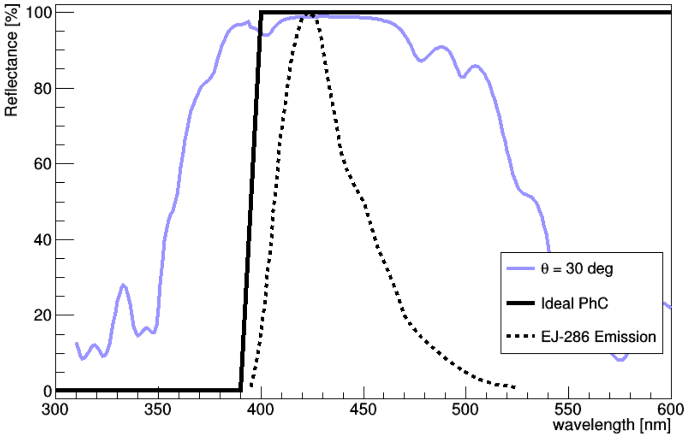
28 layers of SiO_2 (n~1.5) and ZrO_2 (n~2.15-2.4) on a substrate of SiO_2

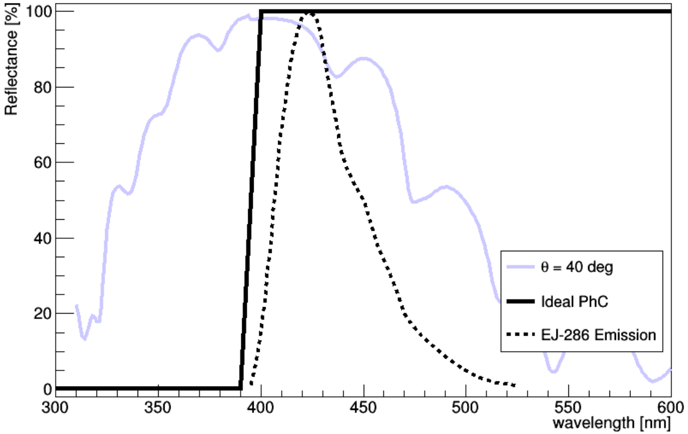


*A constant absorption coefficient k = 1e-3 was assumed both for SiO_2 and ZrO_2

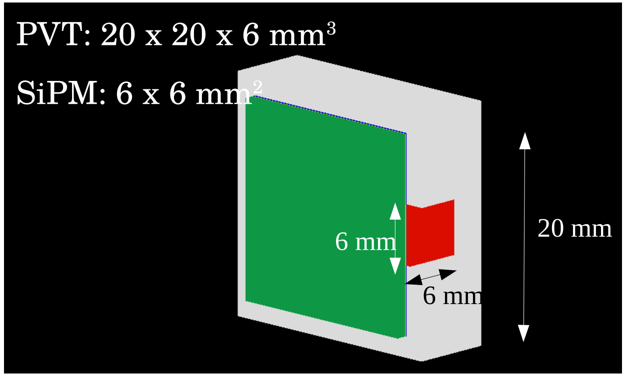








Expected TE: 20 x 20 mm^2 pixel



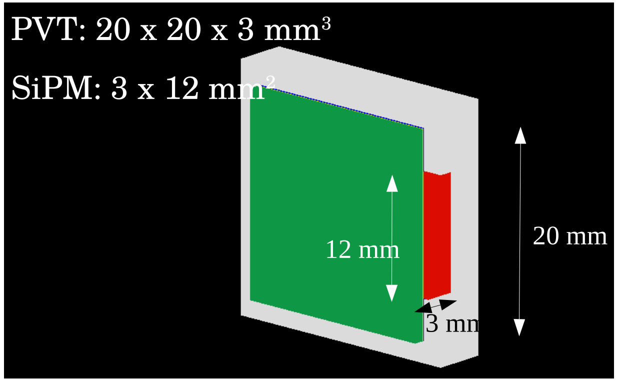


Photo-Trap Area ~ 11 x SiPM Area

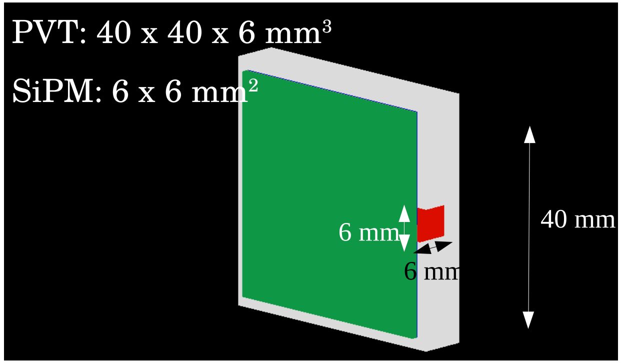
Pixel sensitive area: 4 cm^2

SiPM area: 0.36 cm^2

Pixel size [mm³]	SiPM area [mm²]	TE @ 340 nm	
		Ideal PhC	Prototype PhC
20 x 20 x 6	6 x 6	**52%**	**44%**
20 x 20 x 3	3 x 12	**56%**	**48%**

Calculated *trapping efficiency*. A diffuse reflector (R~98% was considered) with 100 um gap between the WLS-doped plastic and the reflectors. 92% Quantum Efficiency for the WLS was considered. Optical coupling thickness: 100 um.

Expected TE: 40 x 40 mm² pixel



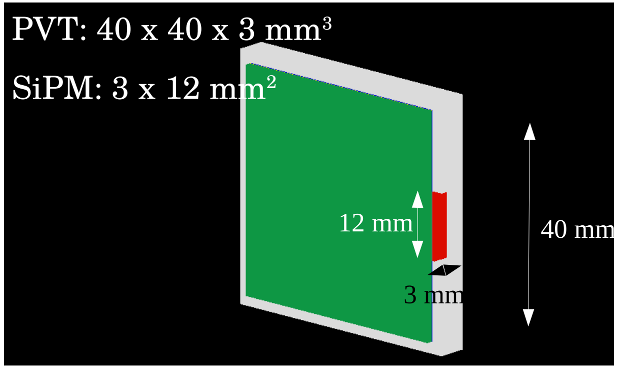


Photo-Trap Area ~ 44 x SiPM Area

Pixel sensitive area: 16 cm²

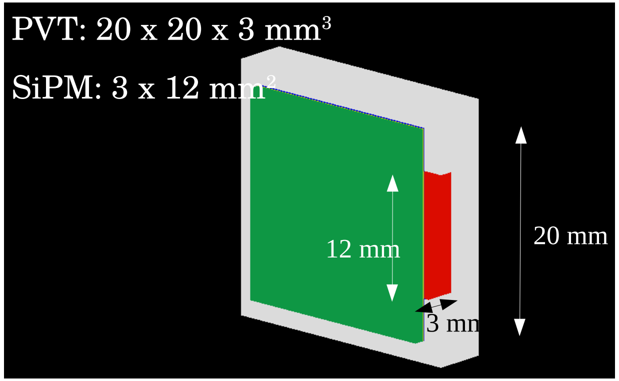
SiPM area: 0.36 cm²

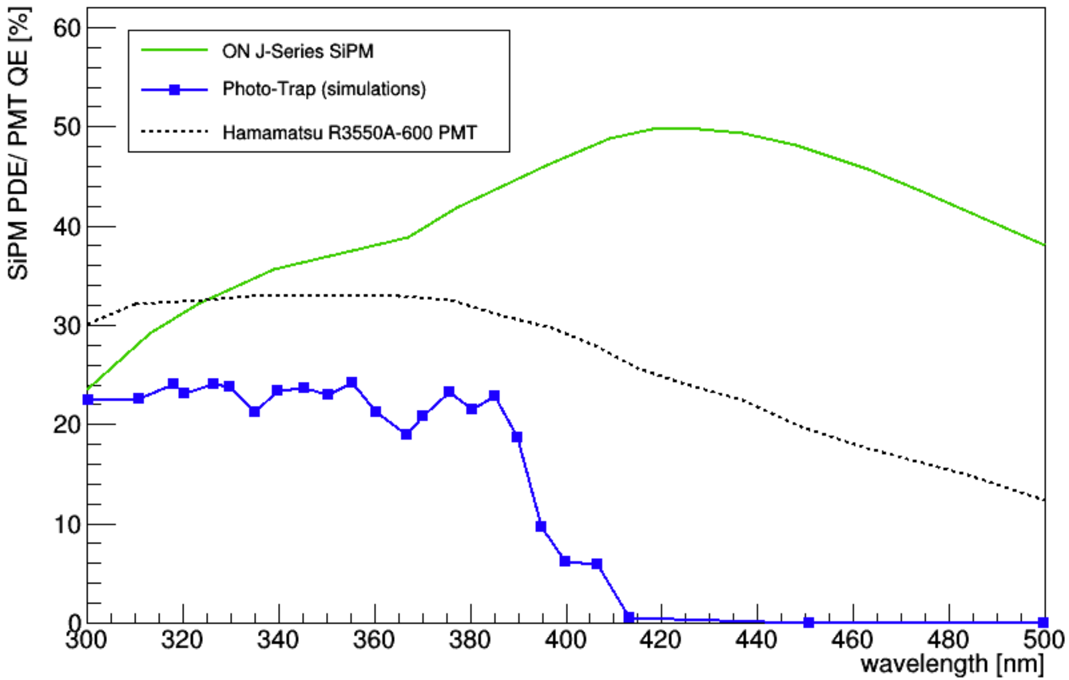
Pixel size [mm³]	SiPM area [mm²]	TE @ 340 nm	
		Ideal PhC	Prototype PhC
40 x 40 x 6	6 x 6	**44%**	**39%**
40 x 40 x 3	3 x 12	**46%**	**36%**

Calculated *trapping efficiency*. A diffuse reflector (R~98% was considered) with 100 um gap between the WLS-doped plastic and the reflectors. 92% Quantum Efficiency for the WLS was considered. Optical coupling thickness: 100 um.

Simulated PDE

For a **20 x 20 x 3 mm³** pixel with the **prototype PhC**, using a **3 x 12 mm² ON J-Series SiPM**

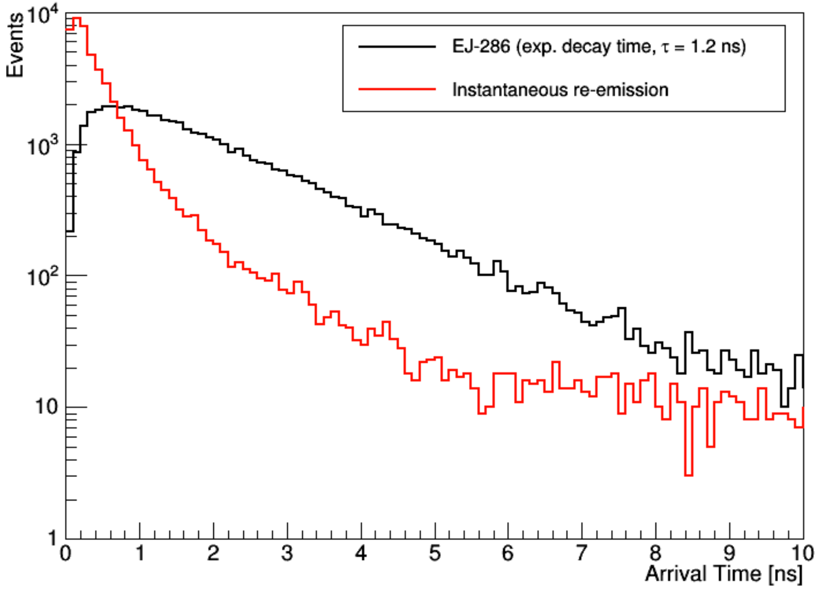


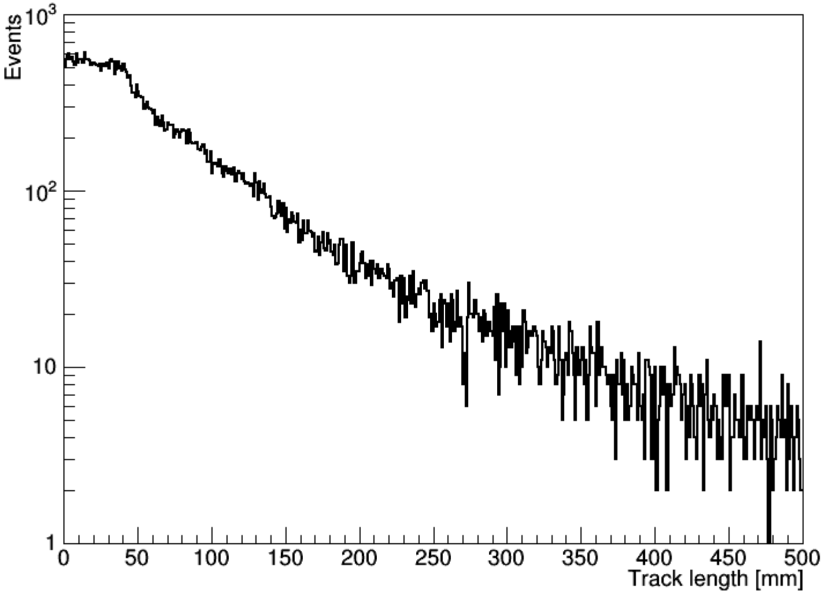


Timing properties: 20 x 20 mm^2 pixel

Time resolution is dominated by:

- Re-emission time of the WLS
- Distance traveled by photons before reaching the SiPM (track length)



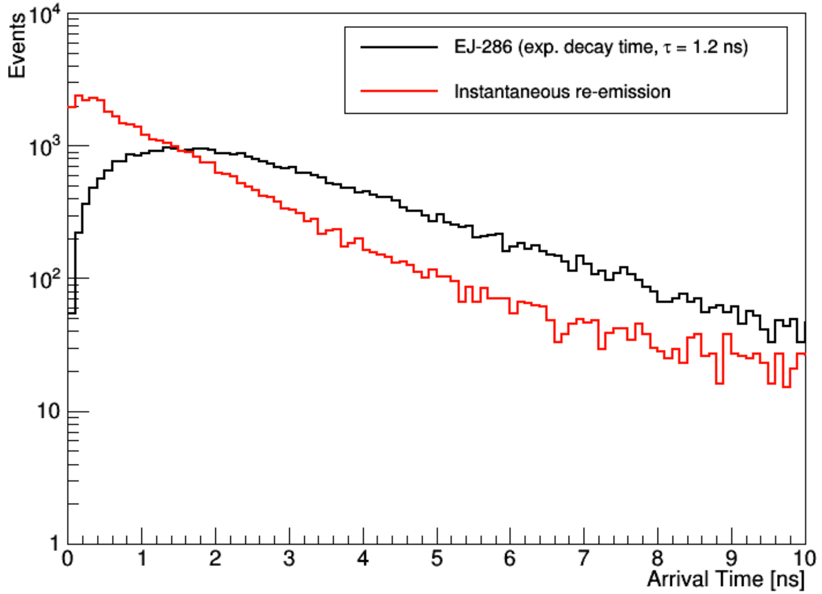


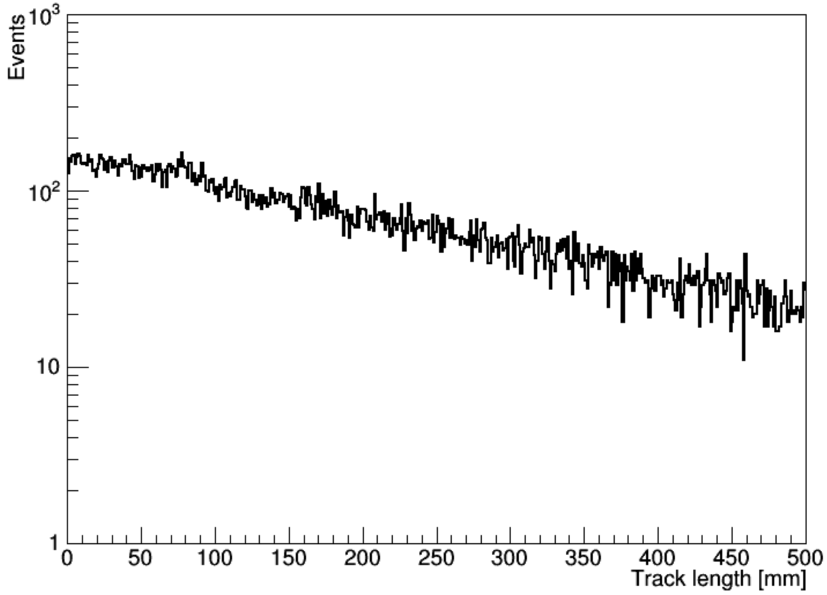
*Here “Arrival Time” is defined as the time it takes to the photons to reach the SiPM (i.e., they do not include the SiPM time resolution)

Timing properties: 40 x 40 mm^2 pixel

Time resolution is dominated by:

- Re-emission time of the WLS
- Distance traveled by photons before reaching the SiPM (track length)





*Here “Arrival Time” is defined as the time it takes to the photons to reach the SiPM (i.e., they do not include the SiPM time resolution)

Final Remarks

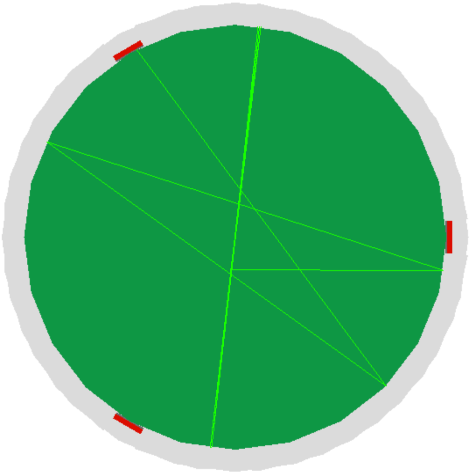
- **Trapping Efficiency** can be **increased** if using **more SiPMs per pixel** (cost also increases).

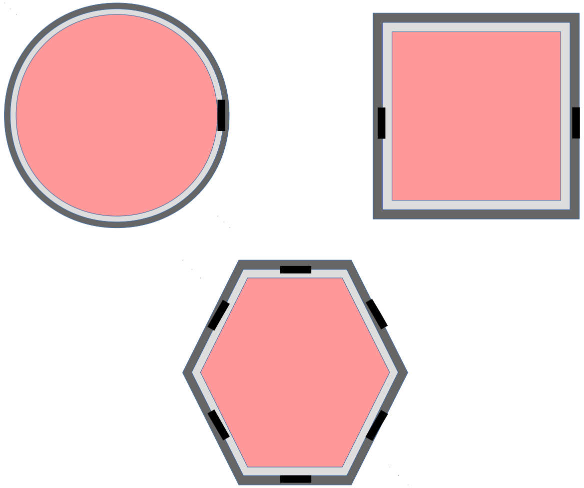
- The pixel can be **adapted** to achieve a **sensitivity** in the **wavelength band of interest.** Photonic crystal and WLS must be selected accordingly.

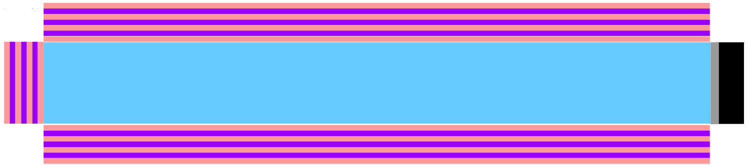
- After **two years** we will have developed a **proof-of-concept prototype**. There will be plenty of space for **further developments...**

Playroom for new developments (I)

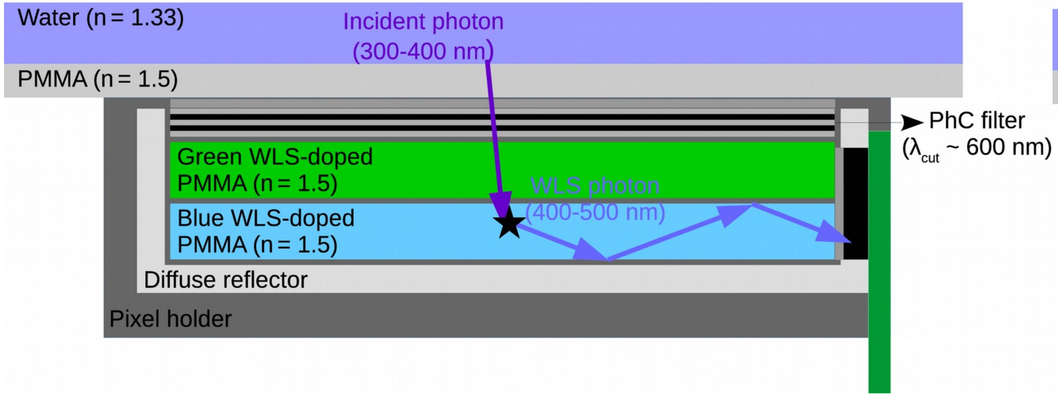
- Number of SiPMs per pixel (position sensitive?)
- Pixel Geometry
- Direct deposition of the PhC filter in the WLS plastic

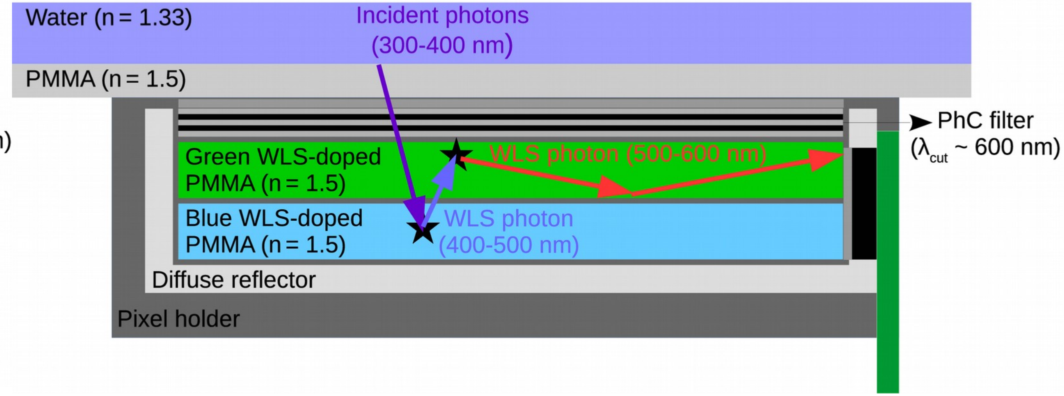






Playroom for new developments (II)





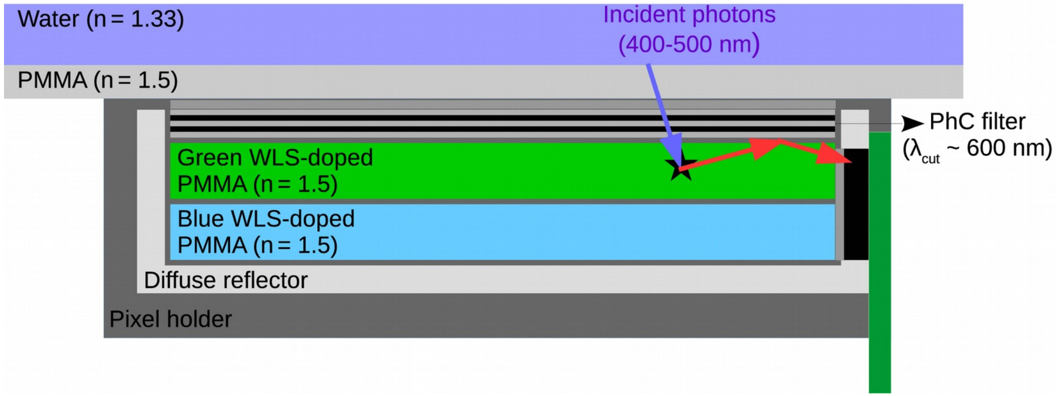


Photo-Trap team

INFN Pisa

- Andrea Rugliancich
- Carolin Wunderlich
- Ricardo Paoletti
- Daniel Guberman (PI)

INFN Padova

- Cornelia Arcaro (RL)
- Mosè Mariotti
- Alessandro de Angelis

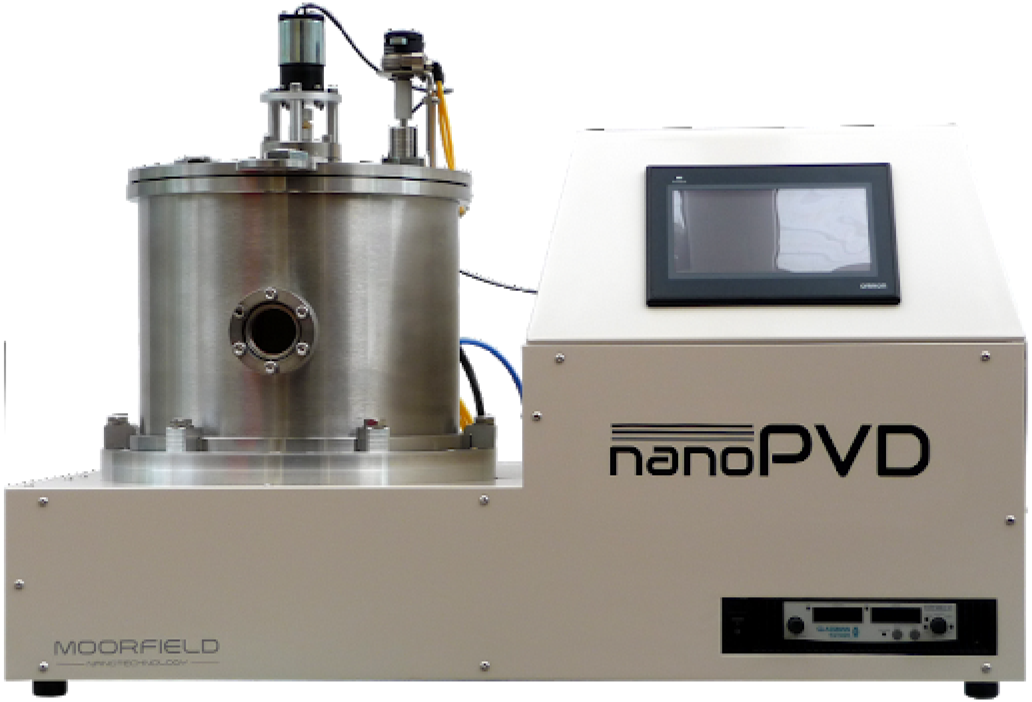
Dipartimento di Ingegneria dell'Informazione (DII), Università di Pisa

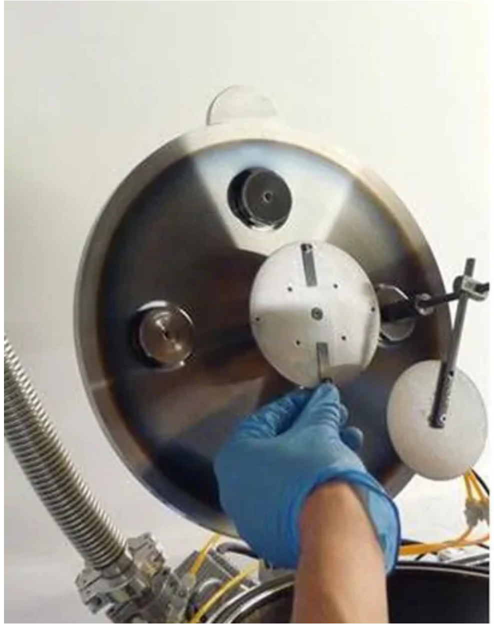
- Alessandro Paghi
- Giuseppe Barillaro

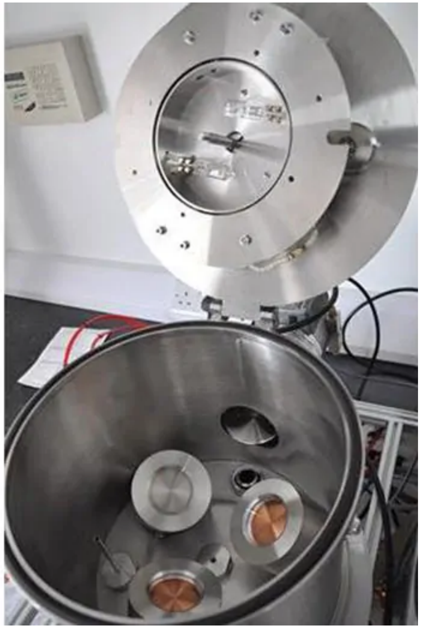
Special thanks to J. Cortina (CIEMAT), the 'father' of this project and to all who participated in the developments of the Light-Trap: D. Estrada, J.L. García, A. Mihi (ICMAB), J. E. Ward, E. Do Souto, O. Blanch (IFAE)

Backup

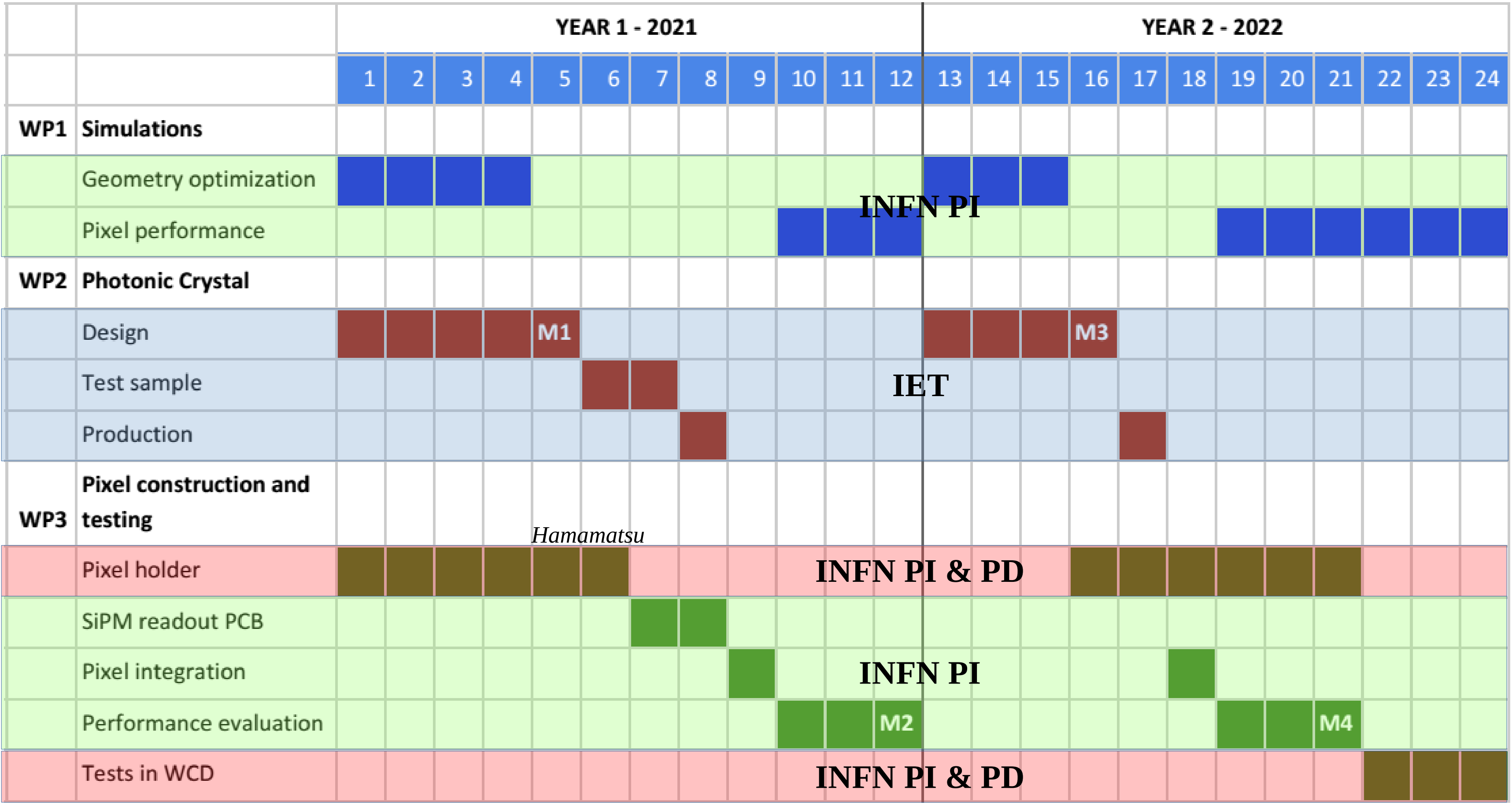
Sputtering







Schedule



M1: Final PhC design (pIa, pIb)

M2: Performance of pIa and pIb

M3: Final PhC design (pII/pIc)

M4: Performance of pII/pIc