PHOTO-TRAP

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

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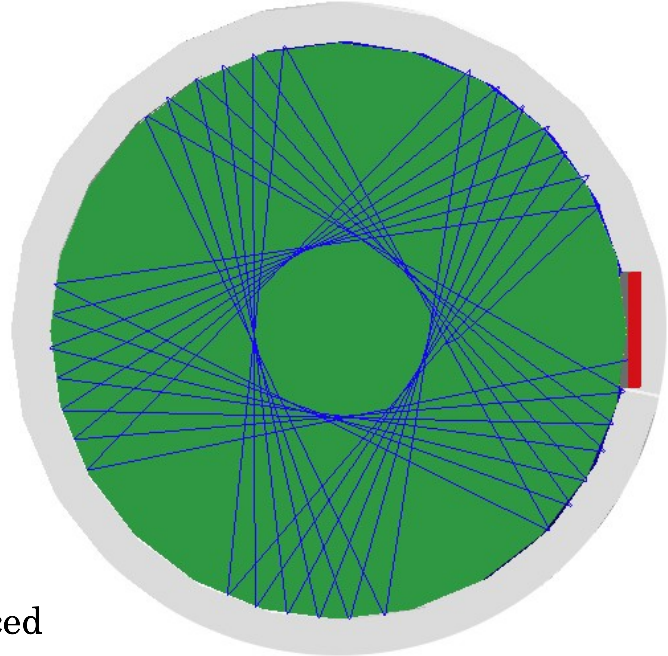
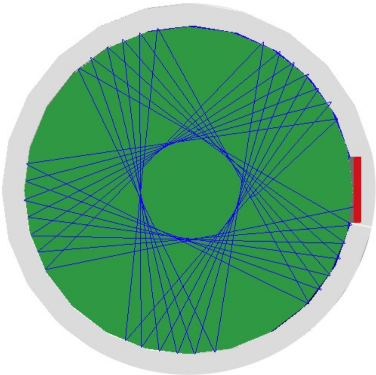


INFN ICCUB

15th Pisa Meeting on Advanced Detectors
23th May 2022

Outline

1. The Photo-Trap concept
2. Photo-Trap protoypes
3. Performance
4. Applications and future prospects



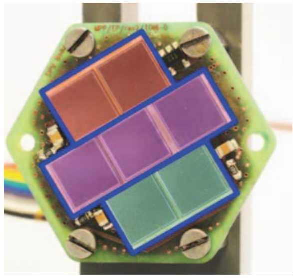
The need of Large Area SiPMs

flickr/the_parabola/

Probably one of the main **drawbacks** of **SiPMs** is the **lack of large-area pixels**:

- SiPMs are typically available in **sizes $\leq$ 6x6 mm²**
- **Capacitance**, **dark count rate (DCR)** and **cost** increase with size
- Larger pixels (a few cm²) can be achieved by **summing SiPMs**, but:

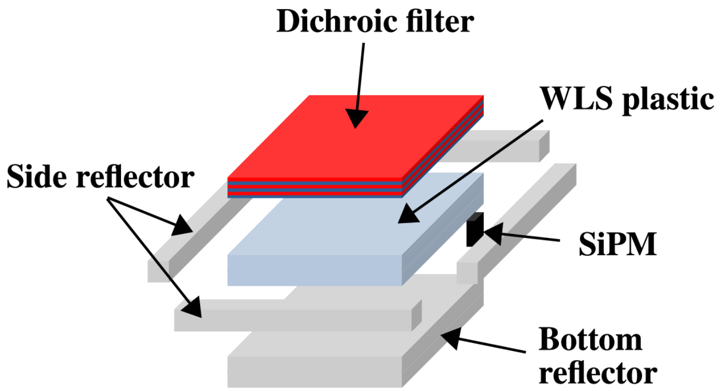
  - SNR degrades (single-phe resolution is often lost)
  - DCR still increases linearly with size...
  - ...and also cost



Fink et al., (2016)

Photo-Trap

A **low-cost**, **low-noise**, **large-area SiPM** pixel



- A **SiPM** is coupled to a **Wavelength shifter (WLS) plastic**
  → WLS area >> SiPM area

- A **dichroic filter** is placed at the **front**.
  → High T in the absorption band of the WLS
  → High R in its re-emission band

- **Reflectors** are placed at the **back** and **sides** of the WLS plastic

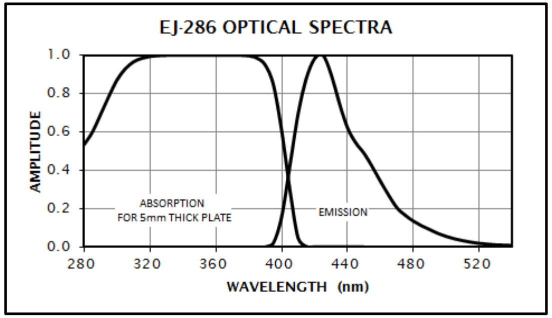
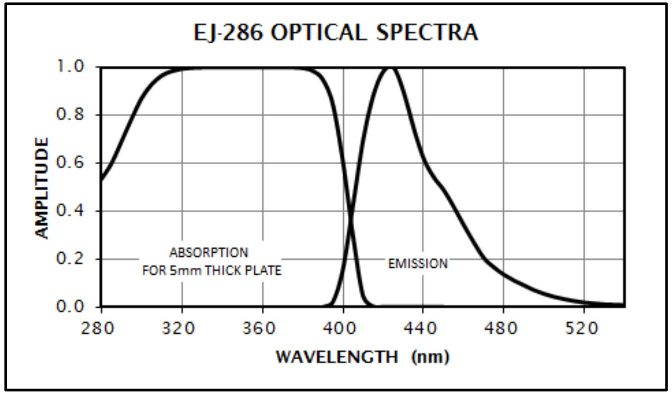
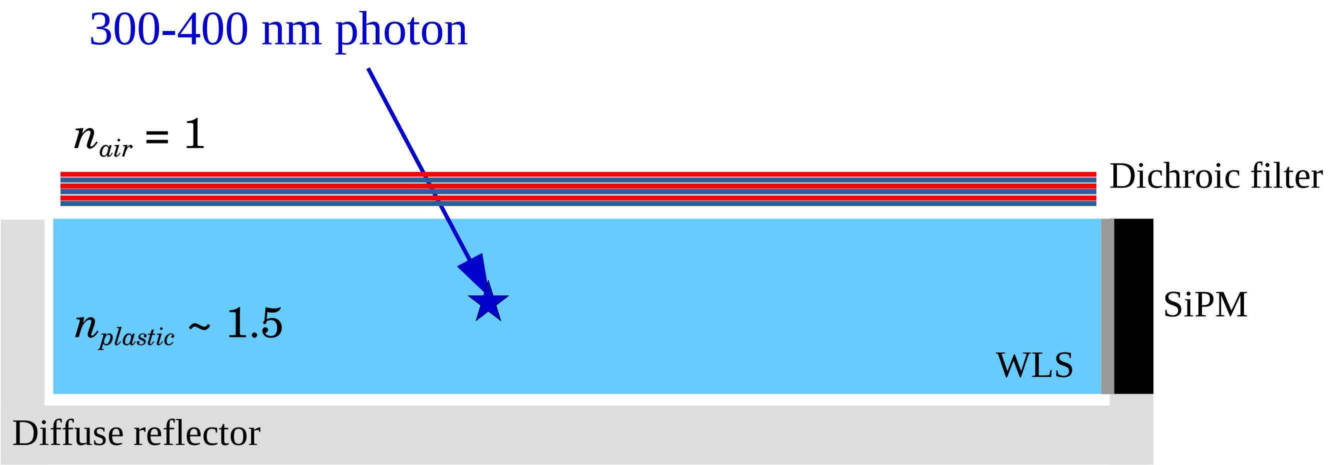


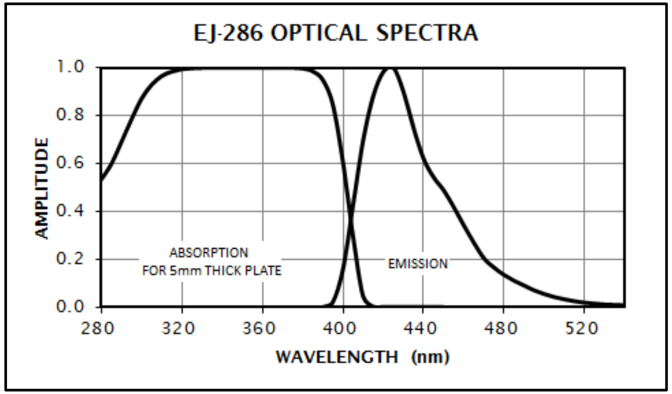
Photo-Trap is an upgrade of the former EU project "Light-Trap" [D. Guberman** et al. (2019)**,** NIM-A, 923, 19]*

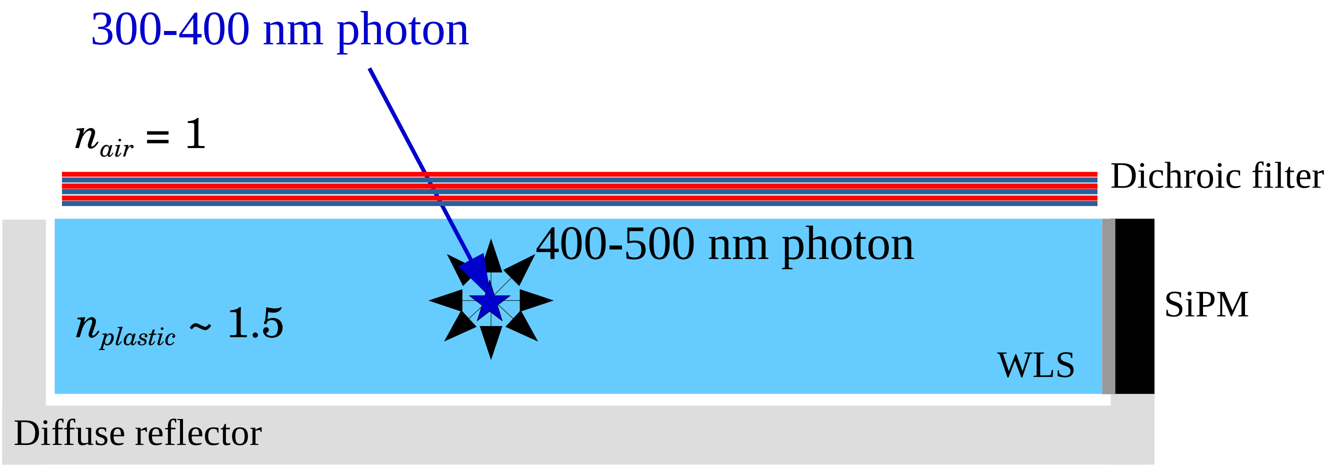
The Photo-Trap concept



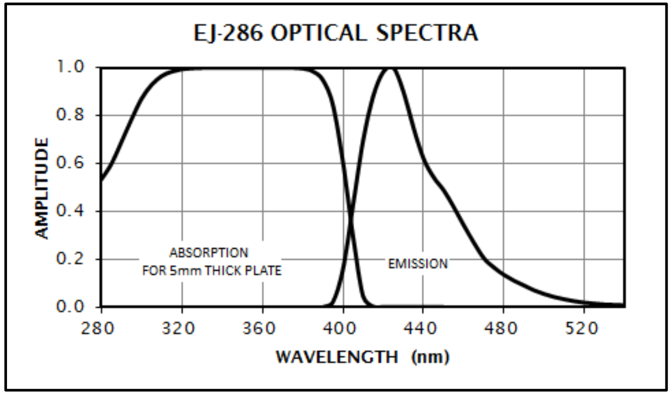


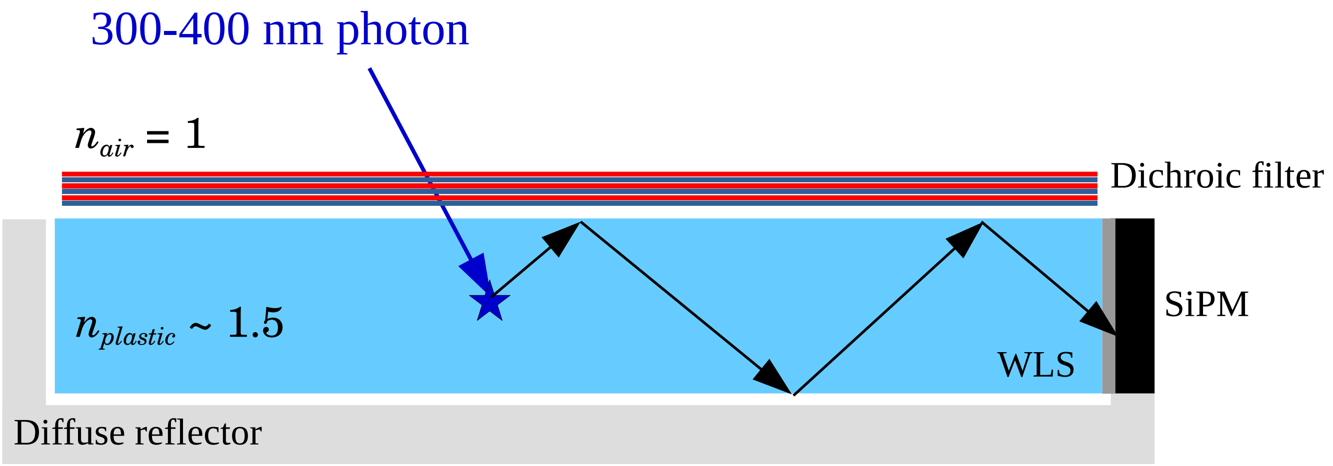
The Photo-Trap concept





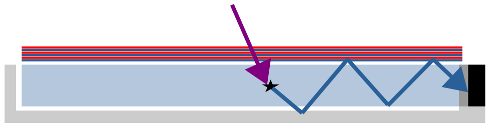
The Photo-Trap concept



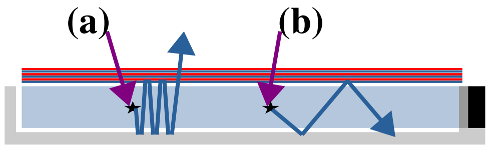


Operation principle

(i) Incident photons with the *proper* λ go through the filter, are absorbed by the WLS, re-emitted and remain **trapped** inside the pixel until they **reach the SiPM.**



(ii) Some of the absorbed photons may **escape** or be **re-absorbed** and will not reach the SiPM



(iii) Photons at **other wavelengths** are **rejected**

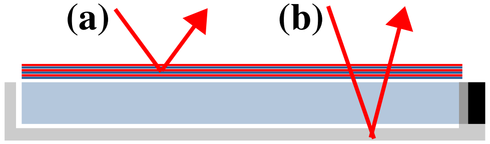
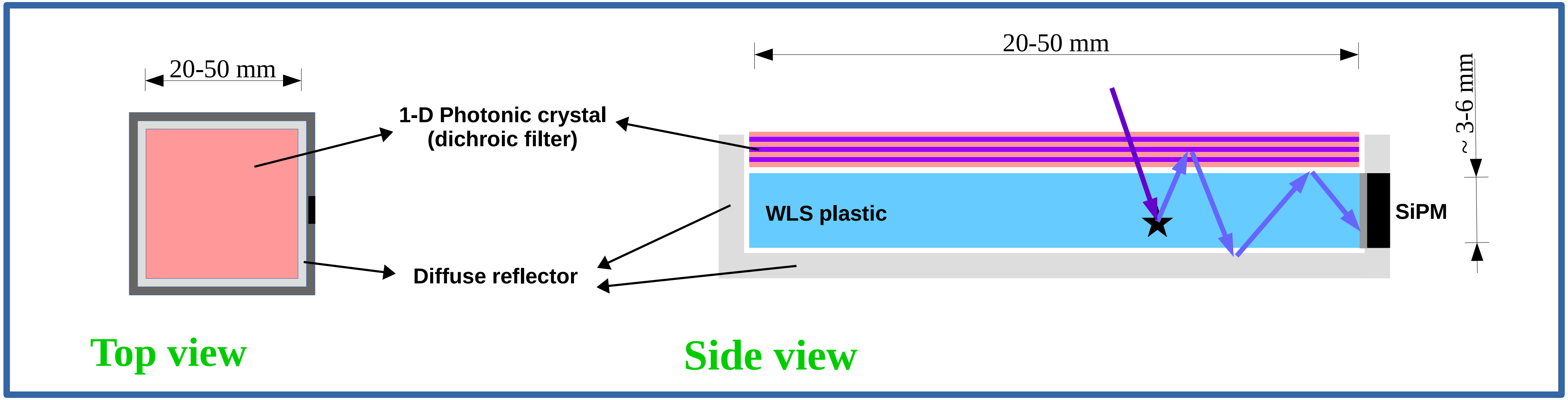
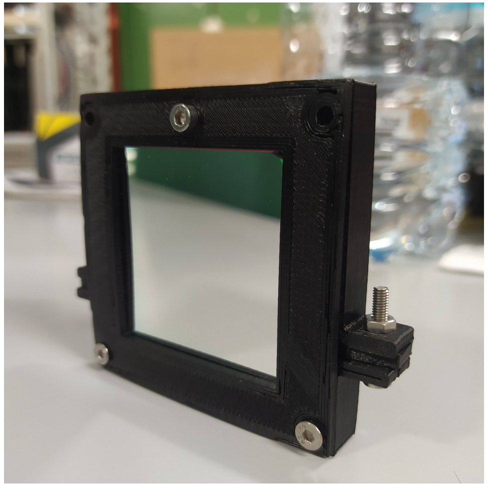


Photo-Trap



- 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 and filter are low)

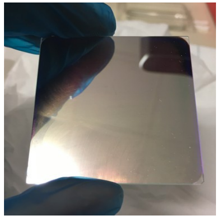
Prototypes

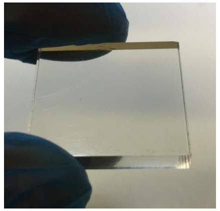


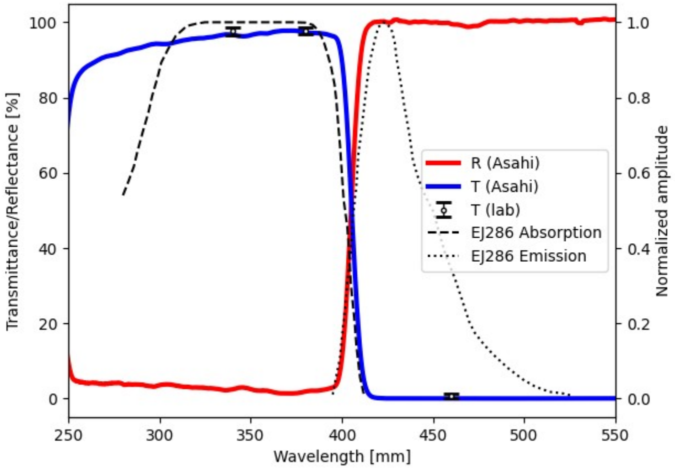
Proof-of-concept prototypes

Main components of our prototype pixels:

- 3 mm thick EJ-286 **WLS** from Eljen
  - Sensitive at ~ 320 - 390 nm
  - Peak Emission ~ 420 nm
  - Decay time ~ 1.2 ns
  - Light Yield ~ 92%

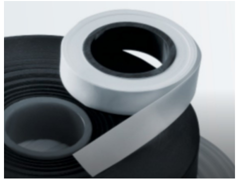


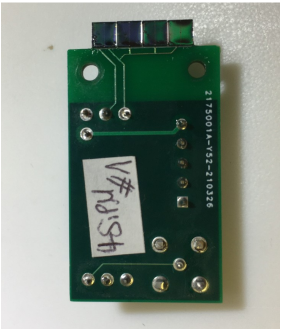




- Asahi ZUV0400 **UV-pass filter**
  - T (0º AOI) > 95% @320-395 nm
  - R (0º AOI) > 98% @400-700 nm

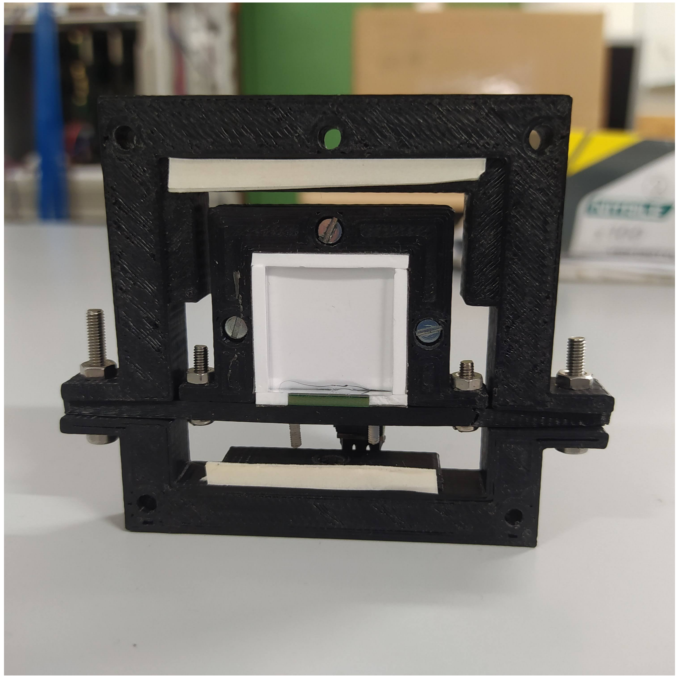
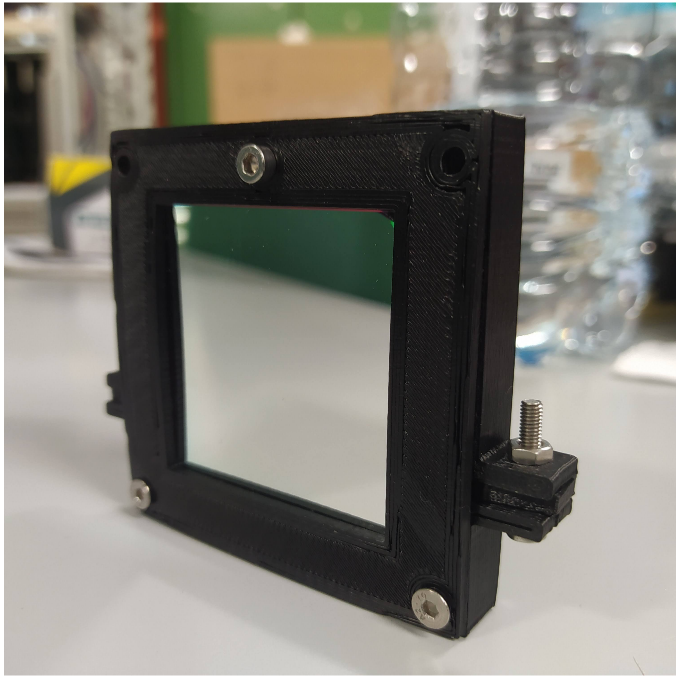
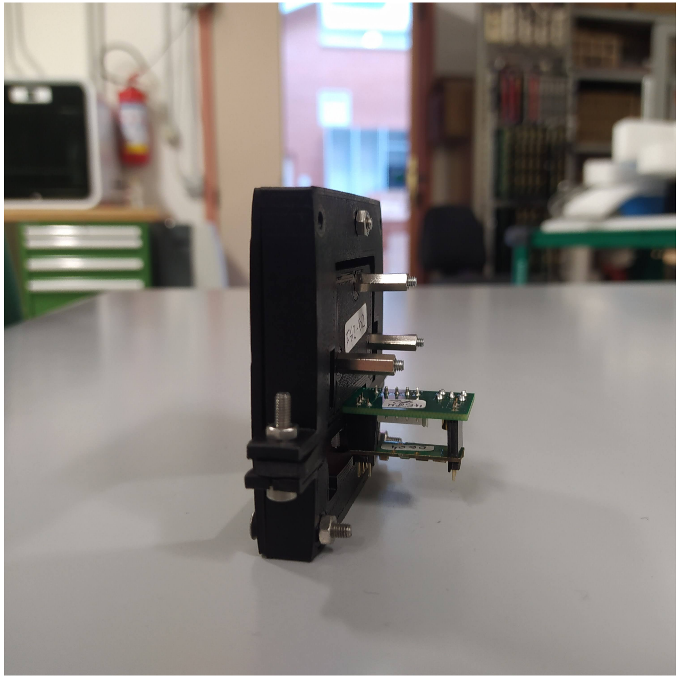
- ON MicroFJ–30035 **SiPMs** (3x3 mm²)
  - Custom-made PCB to read a single SiPM or 4 in parallel (same area than a 6 x 6 mm²)





- Berghof Optopolymer **reflective film**
  - R~98% > 400 nm

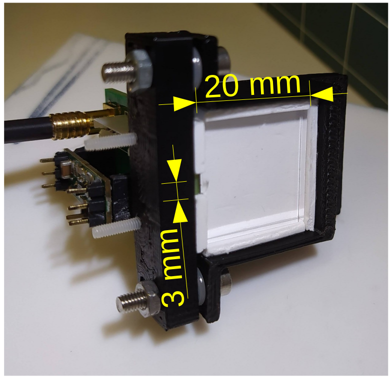
Proof-of-concept prototypes

Prototype configurations

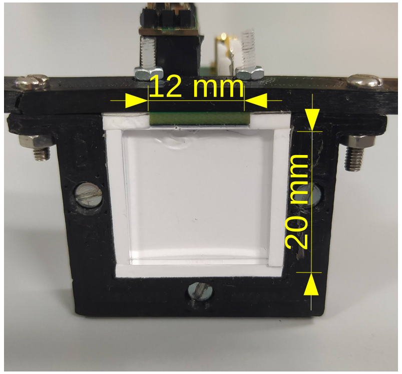
Prototype I

- WLS Area ~ 20 x 20 mm^2
- SiPM Area ~ 3 x 3 mm^2
- **Area ratio ~ 42**



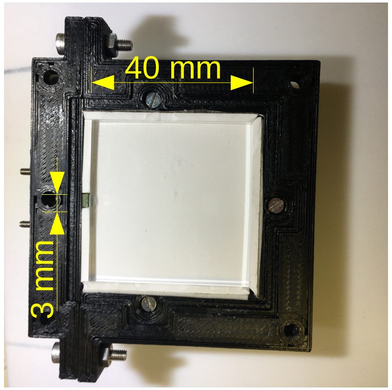
Prototype II

- WLS Area ~ 20 x 20 mm^2
- SiPM Area ~ 3 x 12 mm^2
- **Area ratio ~ 10**



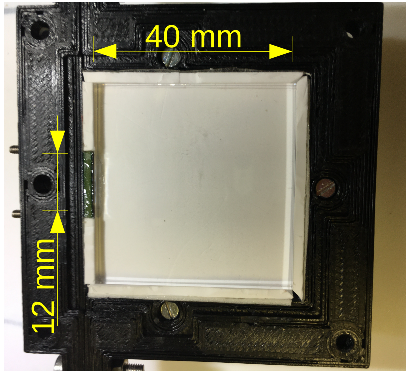
Prototype IV

- WLS Area ~ 40 x 40 mm^2
- SiPM Area ~ 3 x 3 mm^2
- **Area ratio ~ 170**

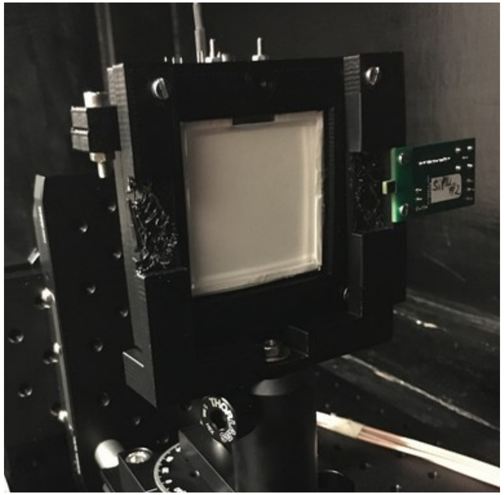


Prototype IV

- WLS Area ~ 40 x 40 mm^2
- SiPM Area ~ 3 x 12 mm^2
- **Area ratio ~ 42**

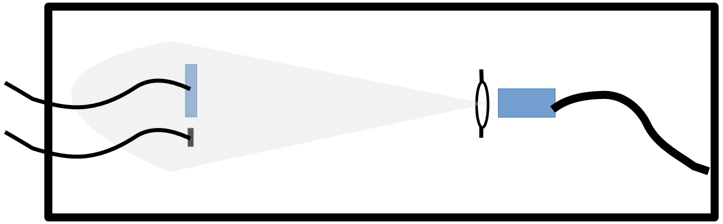


Performance evaluation

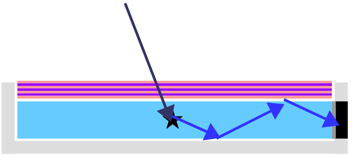


Optical Gain (G) / Trapping Efficiency (TE)

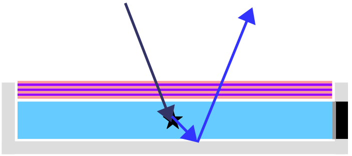
$$G = \frac{Nr\ of\ photons\ detected\ by\ Photo-Trap}{Nr\ of\ photons\ detcted\ by\ a\ 'naked'\ SiPM}$$



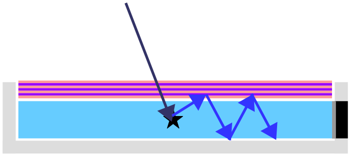
$$TE = \frac{Nr\ of\ photons\ that\ hit\ the\ SiPM}{Nr\ of\ incident\ photons}$$



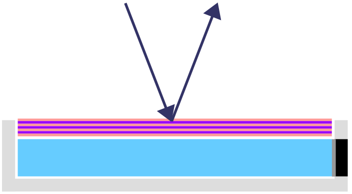
Photon **hits** the SiPM



Photon escapes



Photon absorbed by reflector



Photon reflected before entering the detector

Note that

$$G = \frac{S_{WLS}}{S_{SiPM}} \cdot TE$$

Note that

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

Optical gain/ Trapping efficiency

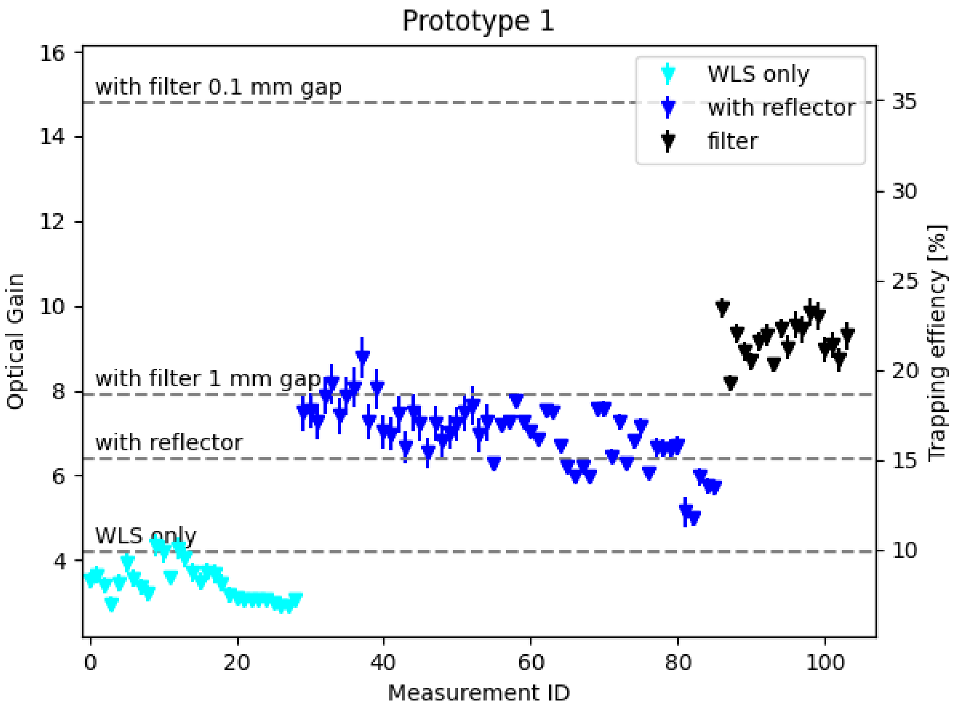
- Filter allows to increase the efficiency by > 25%

- With **simulations** we could identify some critical factors affecting the trapping efficiency:

    - **Thickness** of the **gaps** between WLS and filter/reflectors

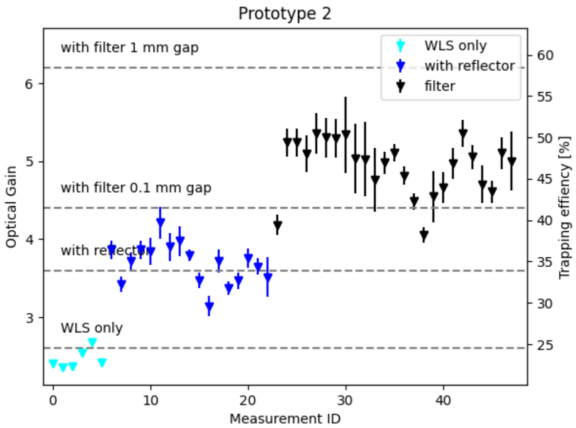
    - **Walls reflectivity** and **filter** properties

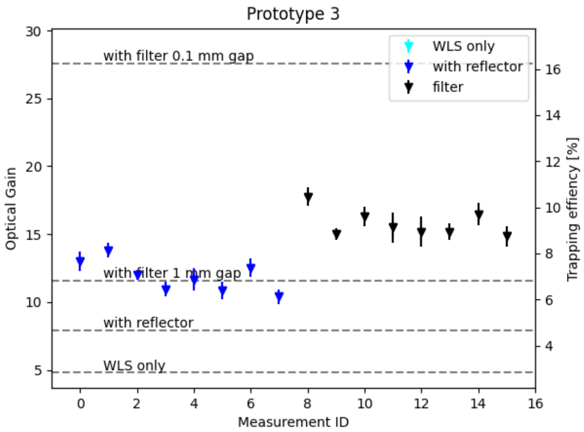
    - **Surface roughness**…

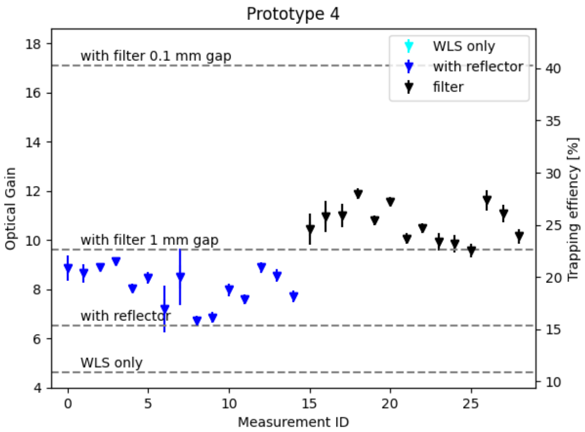


Plot by C. Wunderlich

Optical Gain/Trapping efficiency



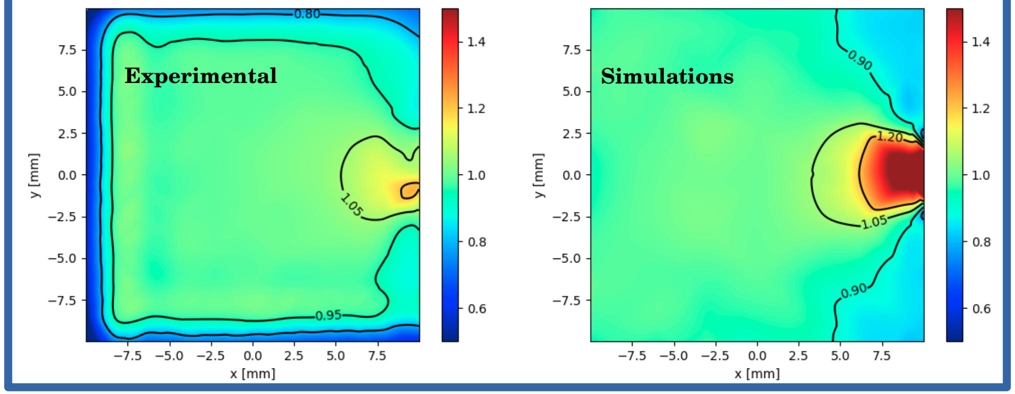




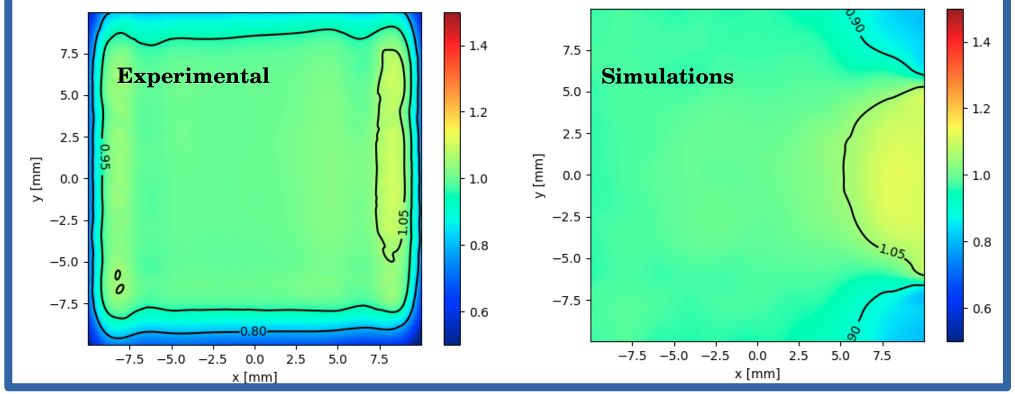
Nr.	S_{WLS} [mm^2]	S_{SiPM} [mm^2]	$\frac{S_{WLS}}{S_{SiPM}}$	Optical Gain	Trapping efficiency
I	20 × 20	3 × 3	∼42	∼10	∼24%
II	20 × 20	3 × 12	∼10	∼5	∼50%
III	40 × 40	3 × 3	∼170	∼15	∼10%
IV	40 × 40	3 × 12	∼42	∼12	∼26%

Position-dependent sensitivity

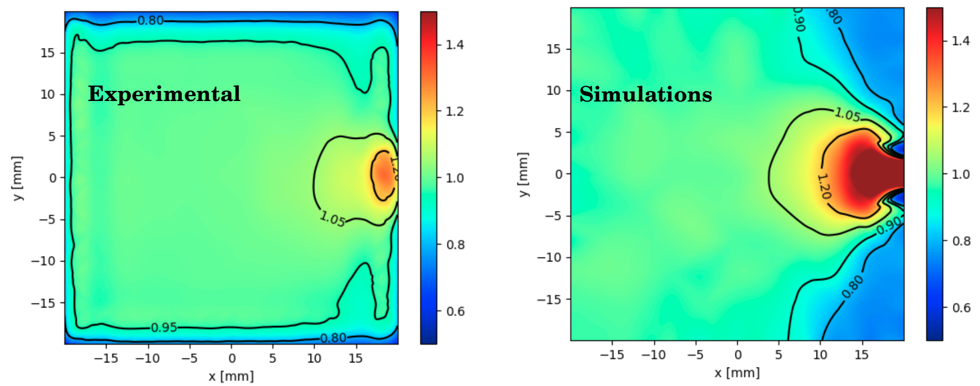
3x3 mm² SiPM – 2x2 cm² WLS



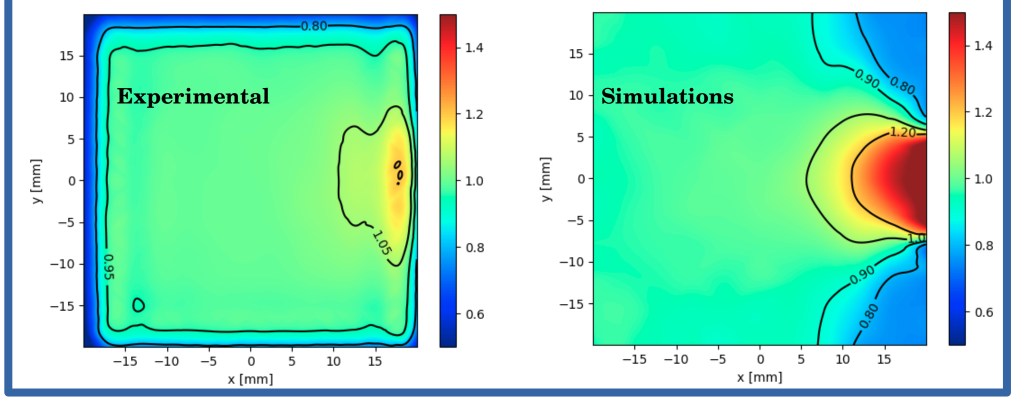
3x12 mm² SiPM – 2x2 cm² WLS



3x3 mm² SiPM – 4x4 cm² WLS

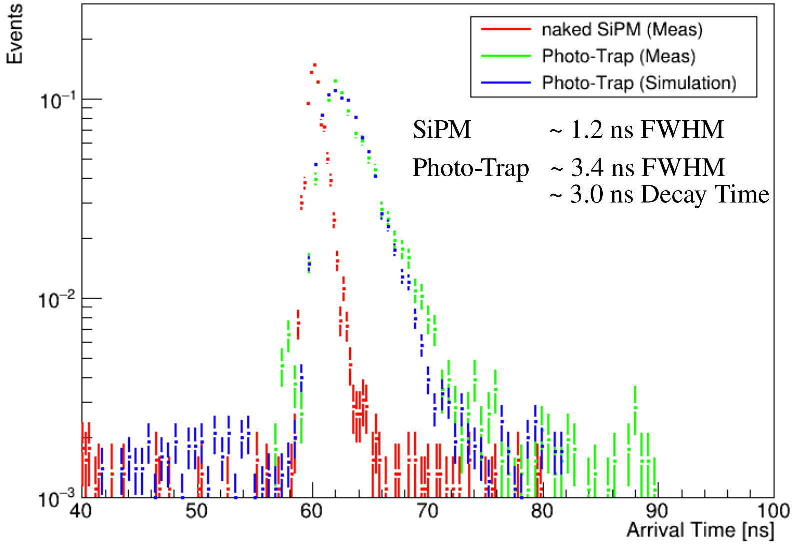


3x12 mm² SiPM – 4x4 cm² WLS



Timing performance

Prototype III: 3x3 mm² SiPM – 4x4 cm² WLS



Arrival time distribution for 1 phe events

- Timing measurements performed using Advatech AMP-0611 preamp (~0.7 ns rise time) and pulsed LED
- Photo-Trap induces a **degradation of the timing** performance (*w.r.t.* the *naked* SiPM) which is due to:
  - **Re-emission time profile** of the WLS
  - Distribution of the **total path traveled by photons** before reaching the SiPM
    - → **Timing** is **better** in pixels with **lower S_{WLS} / S_{SiPM}**
    - → **Distributing SiPMs** in the WLS **improves** the **timing**
- For all the 4 prototypes, the **additional degradation** of the time resolution is of **~2-3 ns**

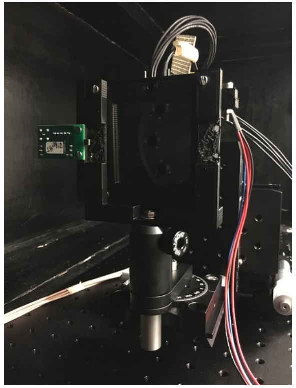
Performance summary

	PMT	SiPM	Photo-Trap
PDE*	~35%	~50%	~5-25 %
Time resolution [ns]	~1	~0.1	~2-3
High-Voltage	Yes	No	No
Compactness	No	Yes	Yes
Ambient light exposure	No	Yes	Yes
Sensitive to Magnetic field	Yes	No	No
Largest Area [cm²]	$\sim 10^2$	$\sim 10^{-1}$	$\sim 10^1$
DCR* [kHz/mm²]	-	~50	~0.2-5
Capacitance/mm²	Low	High	Low
Cost/mm²	Low-Medium	High	Low

* "Educated" rough values at room temperature and ~375 nm

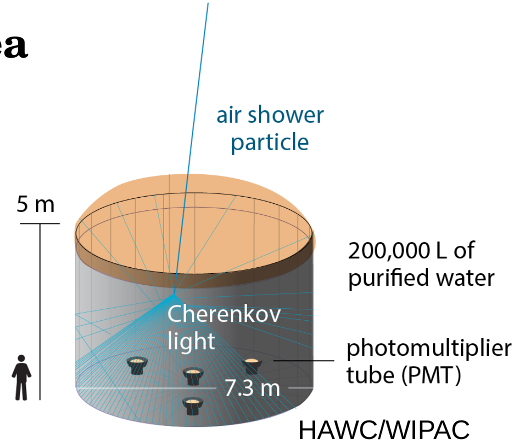
- WLS and filter should be **optimized** depending on the **application** (e.g.: background rejection)
- A **wider sensitivity spectrum** can be achieved by **combining** different **WLS**
- **Distributing SiPMs** in different positions of the WLS will **improve sensitivity** and **timing** (but also **cost** and readout **complexity**).
- Performance can probably be improved with a non "home-made" production

Applications and further developments

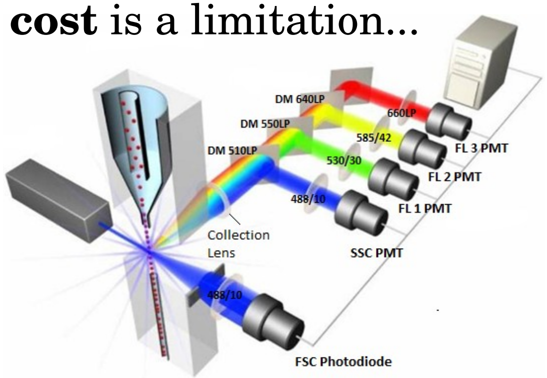


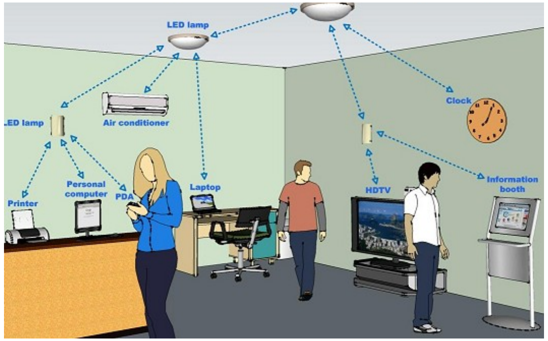
In general, Photo-Trap could be useful…

- 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…

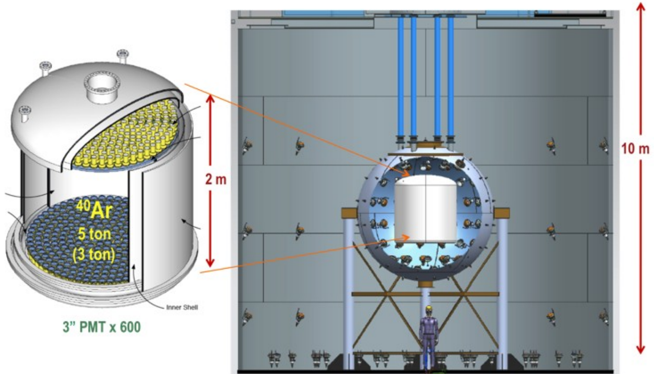


HAWC/WIPAC



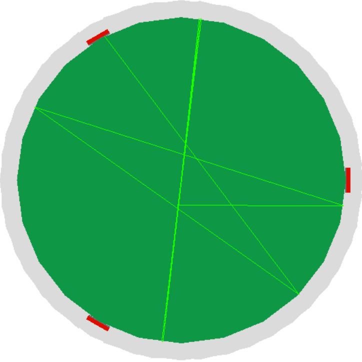


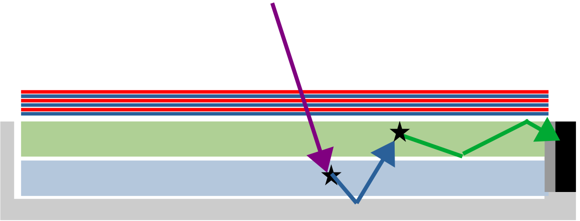
Amanor et al. (2018)

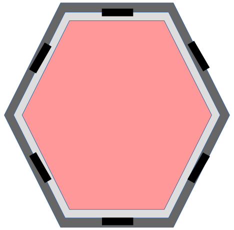


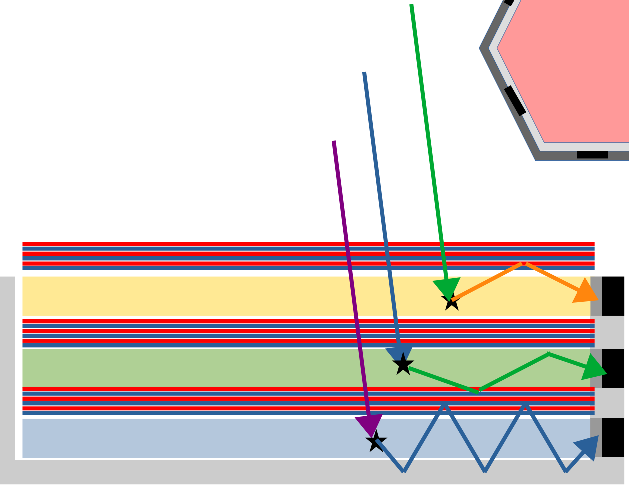
UCLA (DarkSide)

Further developments...









Avantama

The Photo-Trap team

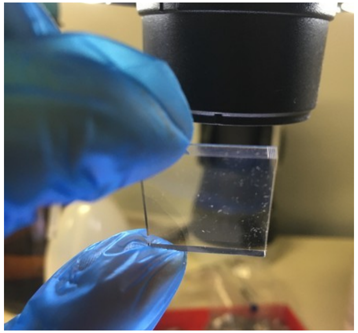
Photo-Trap was funded by a INFN CSN5 call for young researchers (22260/2020). Special thanks to J. Cortina (CIEMAT), the ‘father’ of this project and to all who participated in the developments of the Light-Trap: D. Estrada, J.L. García, A. Mihi (ICMAB), J. E. Ward, E. Do Souto, O. Blanch (IFAE).

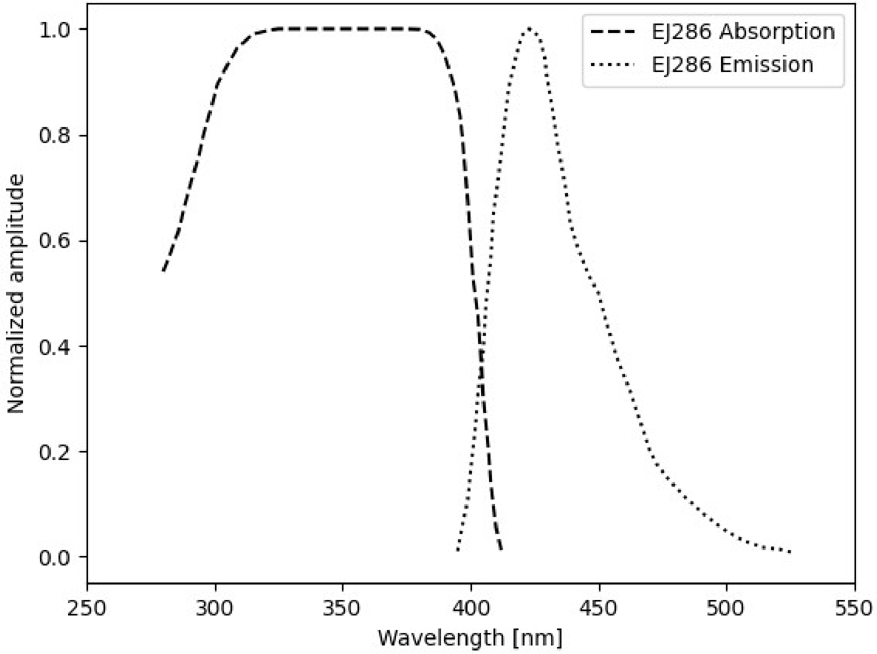
Bakcup

Wavelength shifter

Eljen EJ-286 WLS plastic

- Sensitivity at ~ 320 - 390 nm
- Peak Emission ~ 420 nm
- Thickness [mm]: 3
- Area [mm^2]: 20 x 20 / 40 x 40
- Substrate material: PVT/PS
- Decay time [ns] ~ 1.2
- Light Yield ~ 92%

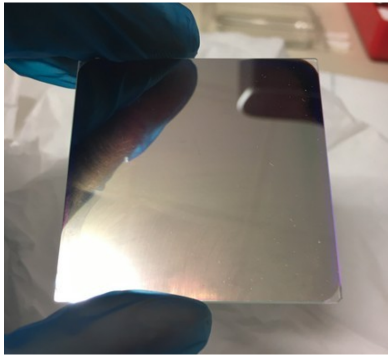


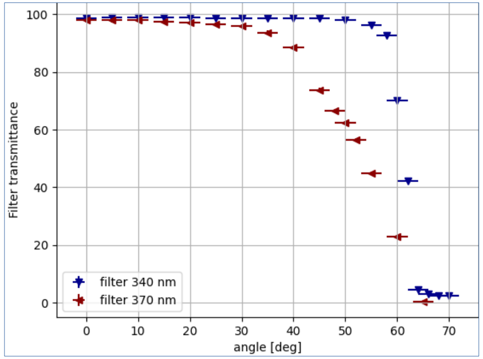


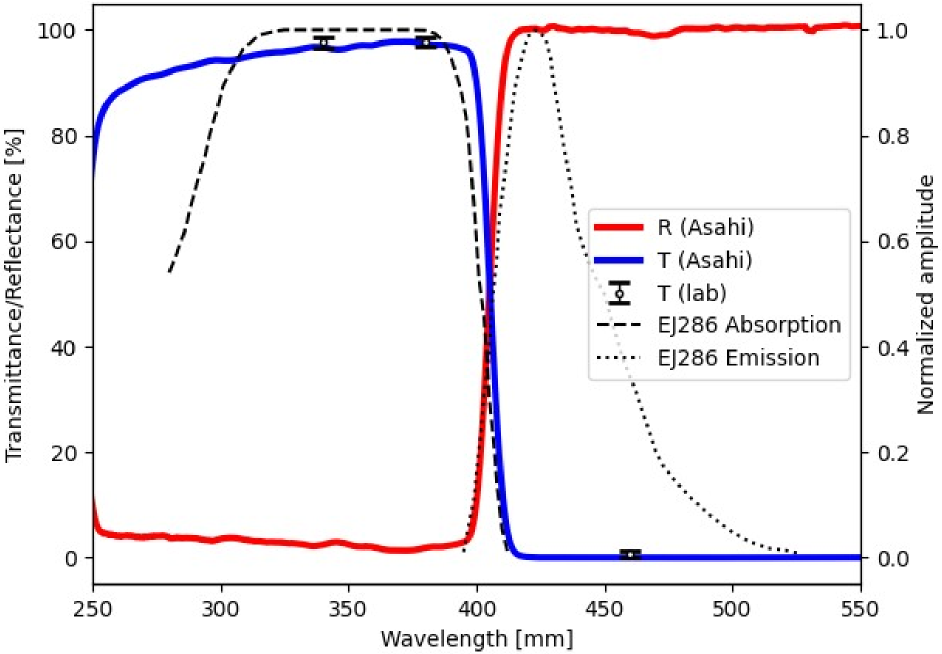
Filter

Asahi ZUV0400 UV-pass filter

- Size: 50x50x1 mm^3 (CA: 46x46 mm^2)
- Wavelength cut ~ 400 nm
- T (0º AOI) > 95% @320-395 nm
- R (0º AOI) > 98% @400-700 nm

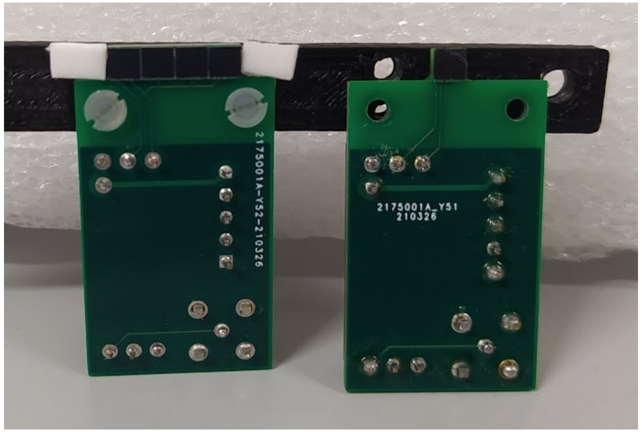


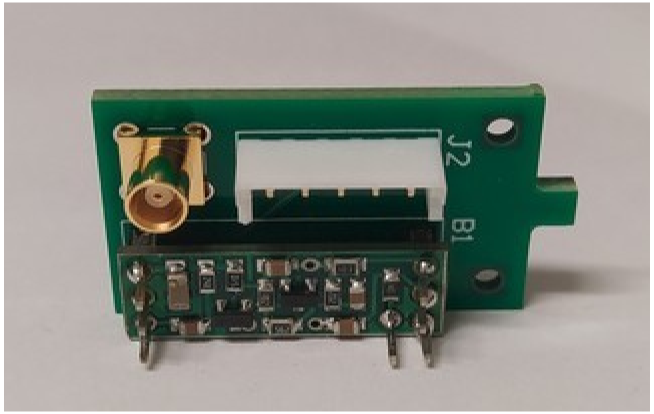




SiPM and Electronics

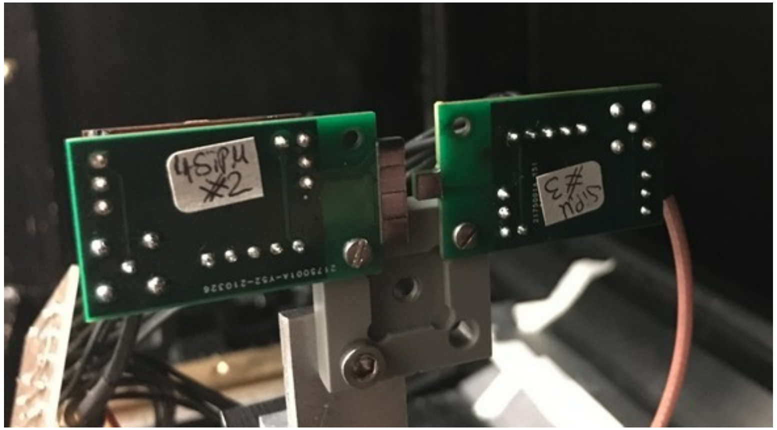
ON MicroFJ–30035 SiPMs
Active area: 3.07 x 3.07 mm^2
Nominal chip size: 3.16 x 3.16 mm^2



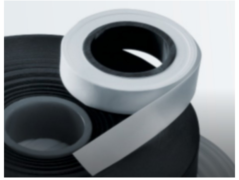


PreAmp home-made Boards
V1 for one SiPM
V2 connects 4 in parallel

Allows to switch between 2 Advatech preAmps:
AMP-0604 (x20 - x60 gain, ~5 ns rise time)
AMP-0611 (x10 - x20 gain, ~0.7 ns rise time)

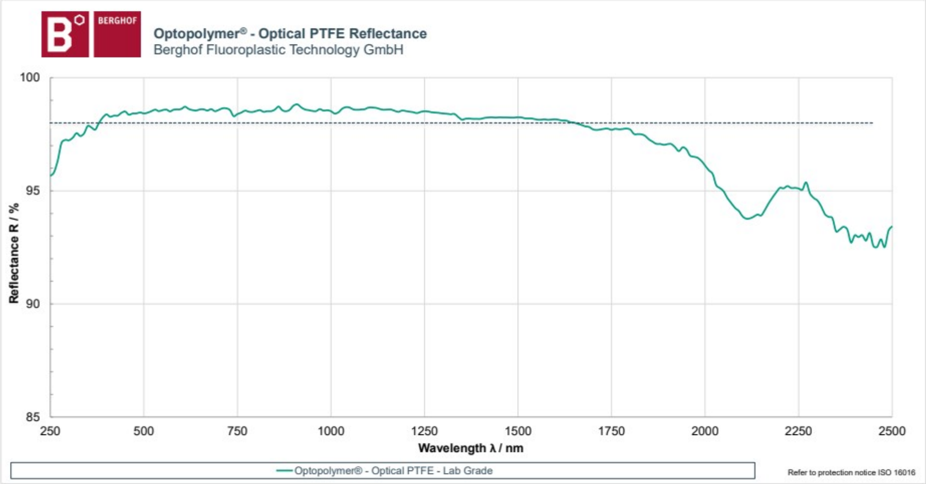


Mechanics



Berghof Optopolymer reflective film

2 mm thick film
Diffuse reflection (R~98% > 400 nm)



SS-998 Optical Grease

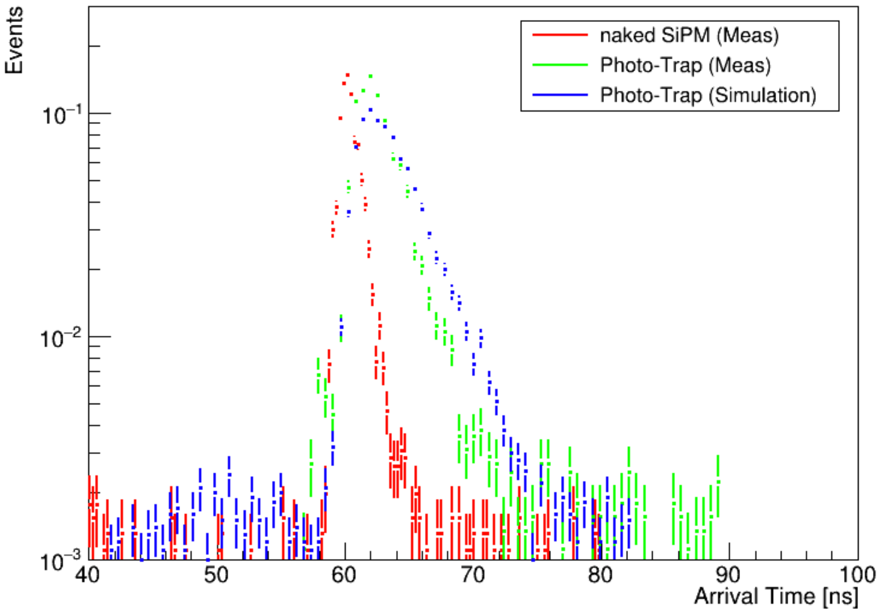
For SiPM-WLS plastic coupling
Refractive index ~ 1.47
T~99.99% above 400 nm

Pixel Holder

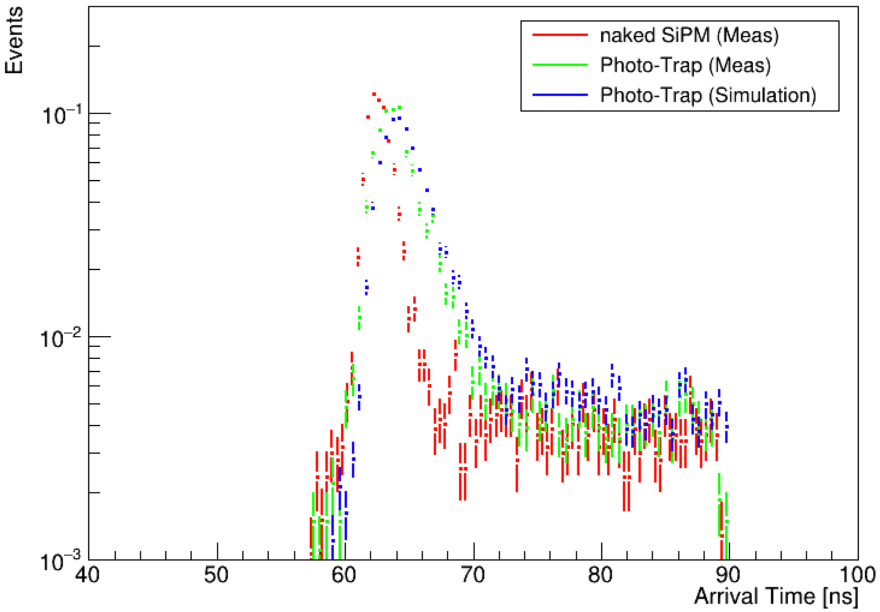
Fast 3D-printed prototype that holds all components
Designed to apply pressure from SiPM to WLS-plastic

Timing performance

3x3 mm² SiPM – 2x2 cm² WLS

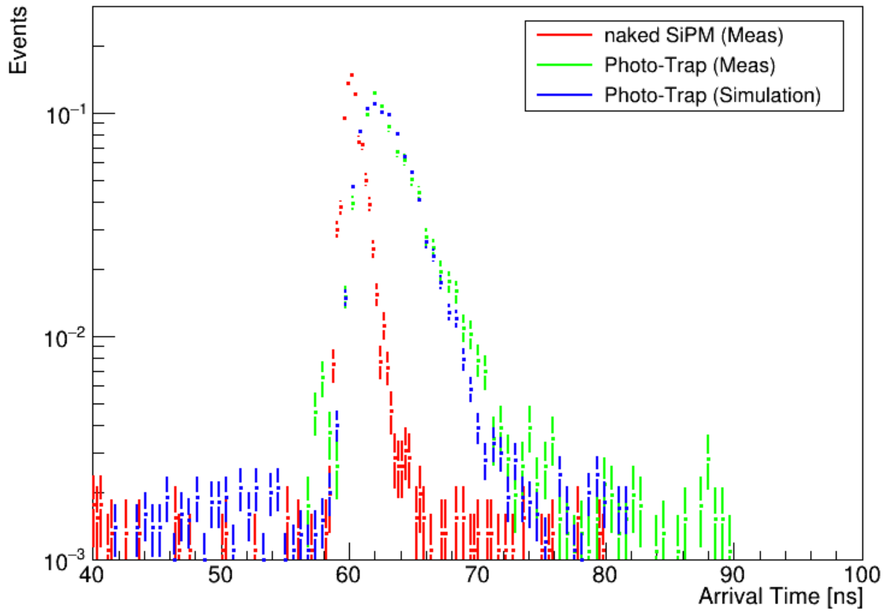


3x12 mm² SiPM – 2x2 cm² WLS

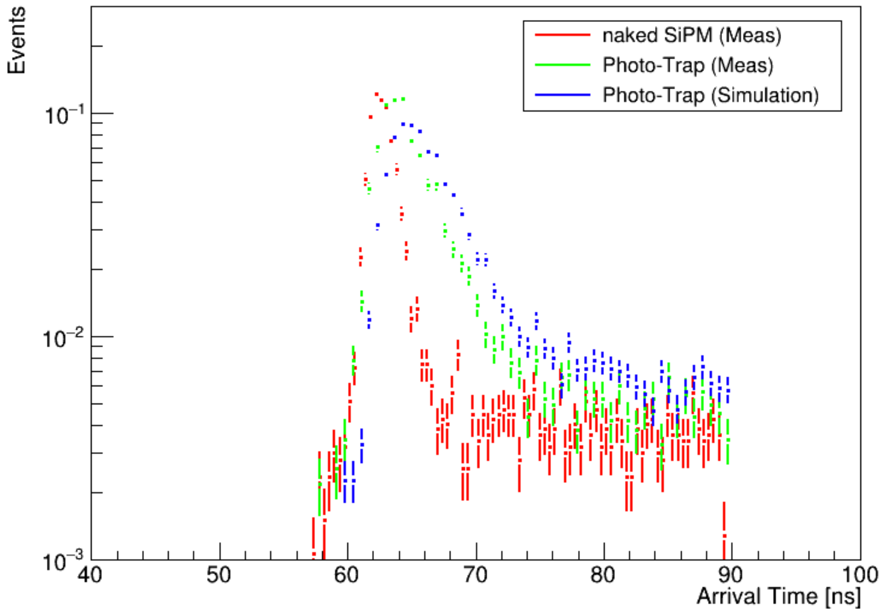


Preliminary results: timing

3x3 mm² SiPM – 4x4 cm² WLS

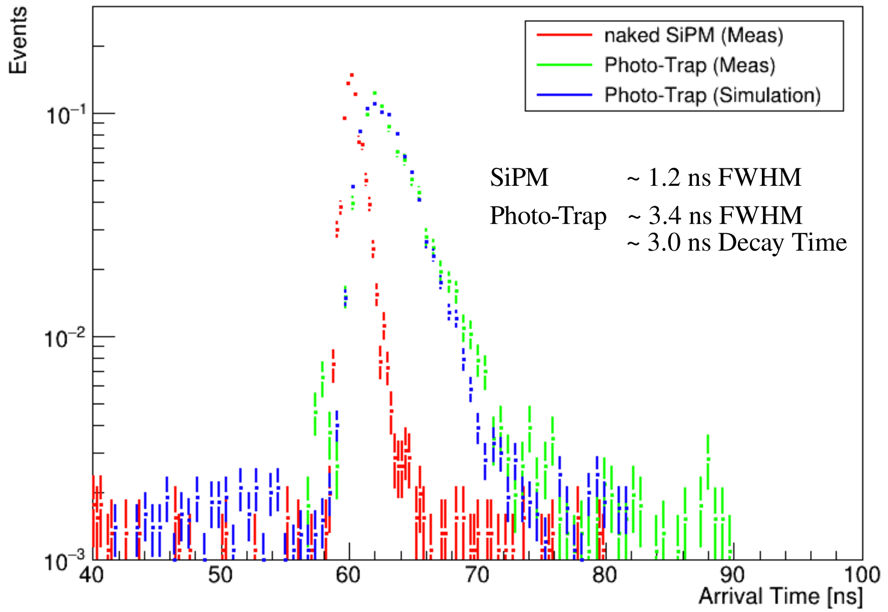


3x12 mm² SiPM – 4x4 cm² WLS

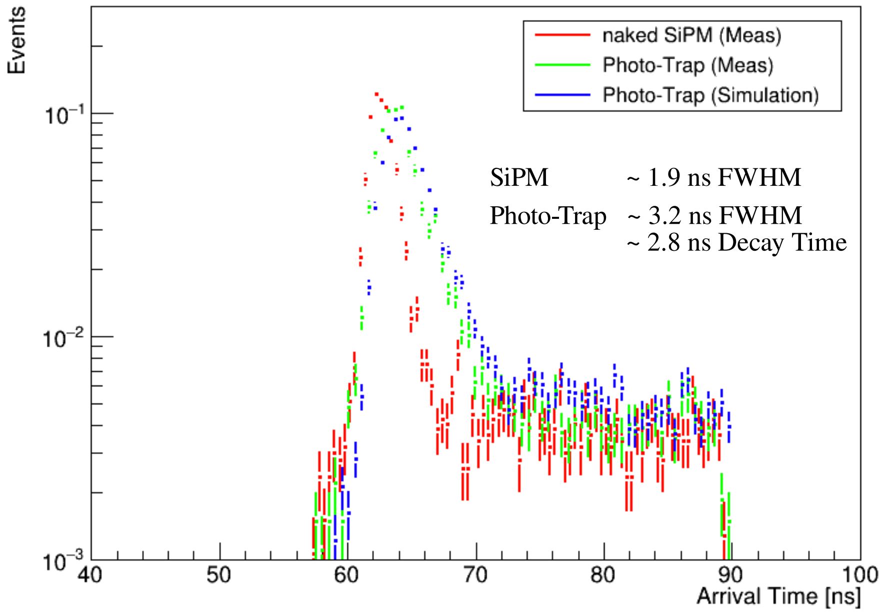


Timing performance

3x3 mm² SiPM – 4x4 cm² WLS



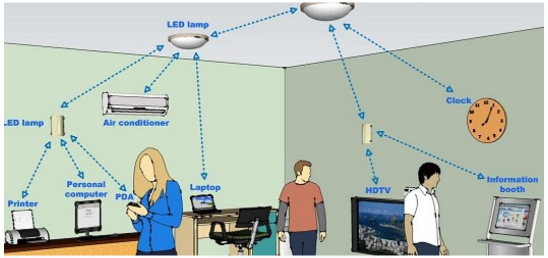
3x12 mm² SiPM – 2x2 cm² WLS

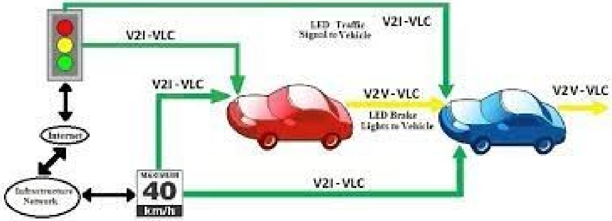


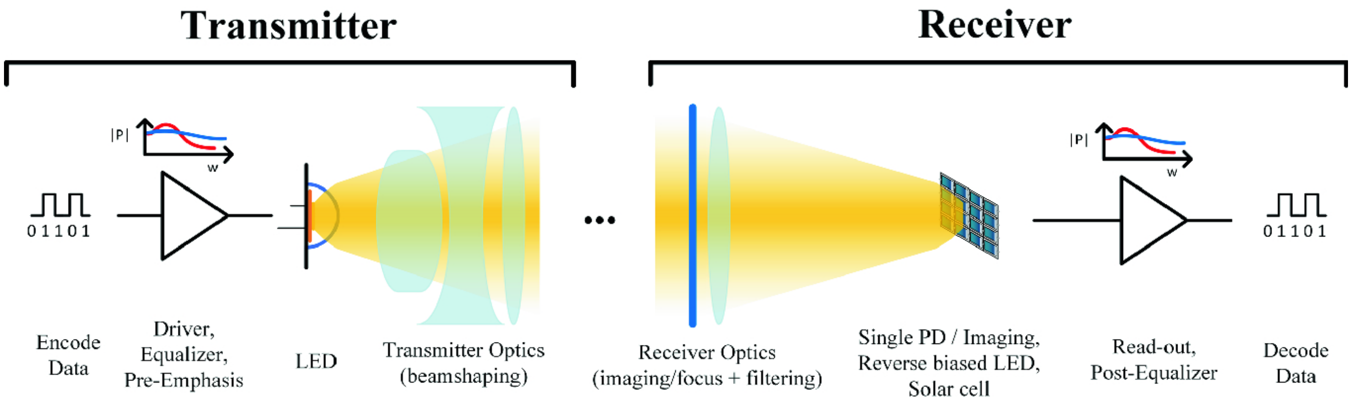
Optical Wireless Communication (OWC)

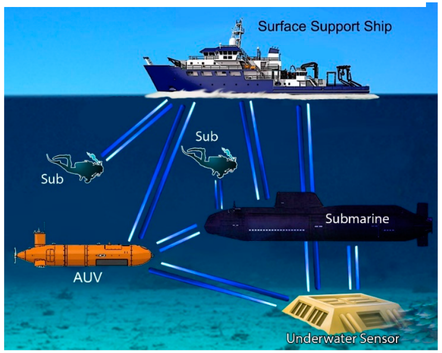
Alternative to RF for wireless communication offering some advantages:

- “Unlicensed” band
- High data rate (potentially >Gbps)
- Directional (secure communication channel)
- LEDs are everywhere!









Turan et al., 2019, https://doi.org/10.1007/978-3-030-24892-5_8

Why Photo-Trap in OWC?

- LEDs have a large emitting angle → Large area and FOV is desired
- High Gain → Single-photon sensitivity → Allows for dimmer sources / Longer links
- Still has the advantages of traditional Pin diodes (compactness, robustness, low voltage operation…)
- Low cost per mm^2
- Use of SiPMs in OWC has been explored. Also use of WLS. Never both of them together
- Low PDE ~ 20% (prototype @320-380 nm), but can be compensated with larger area
- Time resolution ~ 2-3 ns. Still good, but may limit maximum data rate
- Low Dark count rate ~2-10 kHz/mm^2 at ~20 C
- Large sensitive area ~400-1600 mm^2
- High background rejection (can be optimized with the proper filter/WLS)