Use of SiPMs in Astro-Particle Physics and Space

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What makes SiPM so attractive for using in astro-particle physics and in space

- Due to mass-production of semiconductor sensors the produced batches will have practically identical parameters.
- Under applied voltage they can be exposed to intense (ambient) light
- For operation they need a low applied voltage 25-100 V
- Light-weight, very compact and rugged, can tolerate fast acceleration
- Remarkable amplitude resolution; even at pre-set light intensity producing ~100 ph.e. in a 5x5 mm² SiPM, individual peaks are clearly resolved
- The dynamic range of several thousands or more is sufficient for most applications; very low power consumption

What is not so good:

- The size is limited to ≤ 10mm. This is dictated by the speed but also by the desire to limit the gain, which is proportional to the capacitance of the µ-cell (which is proportional to its surface area). The net capacitance of the SiPM chip is limiting the signal speed but this one can overcome with a proper split-design and multiple readouts, like is done for CCDs
- There is a potential to produce almost ideal SiPMs with a cross-talk below 1% level. One may argue if one needs this. But still there exist tasks, which ask for no-cross talk. To achieve this, more sophisticated treatment of the SiPM chip is necessary like, for example, covering its bottom surface with strongly absorbing materials (our earlier studies showed that even when a 4-fold cross-talk suppression technology there remained a 2-3 % cross-talk)

1st Mention of Using SiPM in Astro-Particle Physics and Space Applications

- In the 1st time the SiPM was suggested to be used in Astro-Particle Physics and Space
  - for the MAGIC Telescope Project and
  - space project EUSO

by the author at the General Meeting of the EUSO Collaboration in Munich, Germany, on 17-20 November 2003

1st Mention of Using SiPM in Astro-Particle Physics and Space Applications

SiPM: towards the ideal light sensor

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Munich, Germany

18 November 2003
MPI Munich

EUSO meeting: R. Mirzoyan

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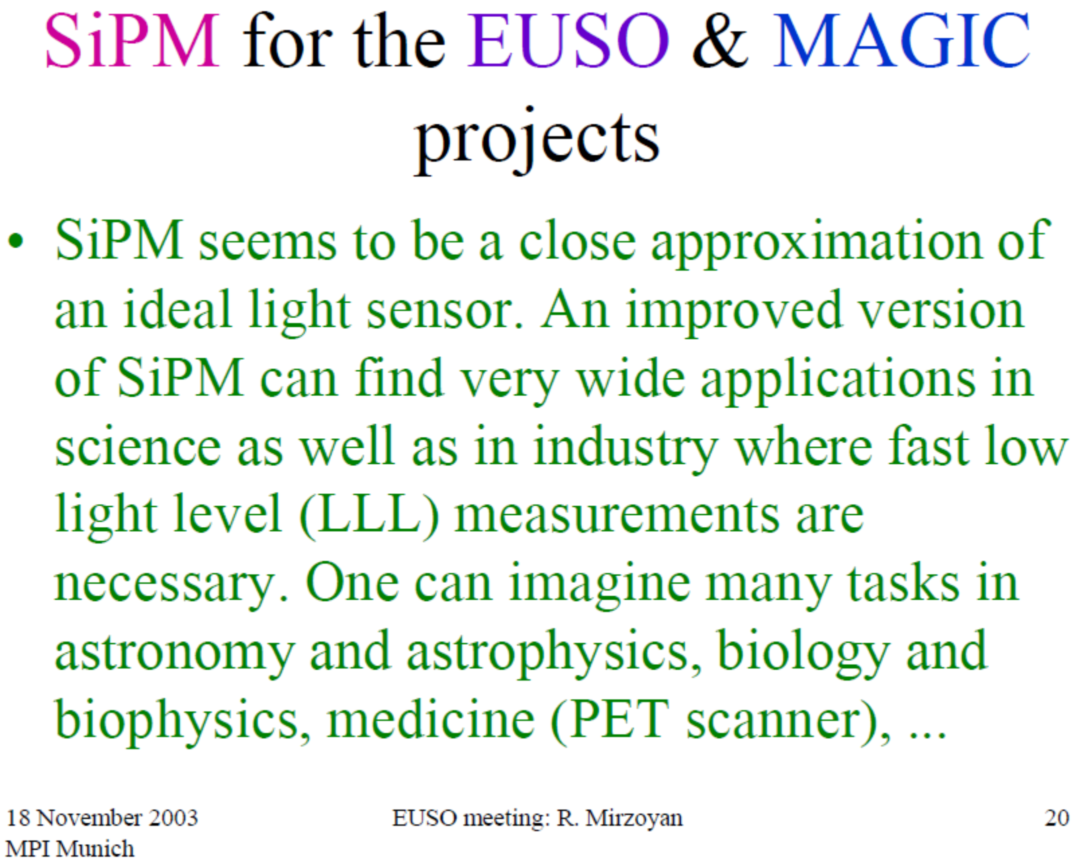
1st Mention of Using SiPM in Astro-Particle Physics and Space Applications



SiPM for the EUSO & MAGIC projects

- SiPM seems to be a close approximation of an ideal light sensor. An improved version of SiPM can find very wide applications in science as well as in industry where fast low light level (LLL) measurements are necessary. One can imagine many tasks in astronomy and astrophysics, biology and biophysics, medicine (PET scanner), ...

18 November 2003
MPI Munich

EUSO meeting: R. Mirzoyan

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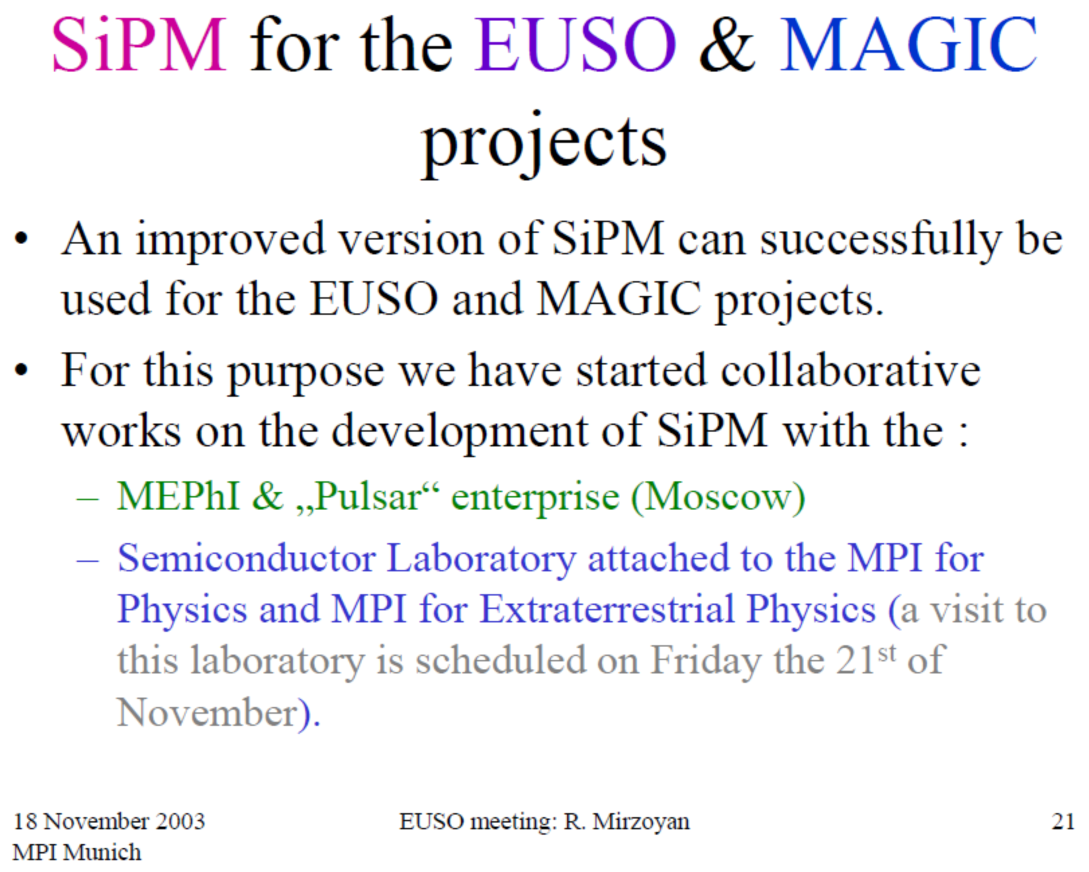
1st Mention of Using SiPM in Astro-Particle Physics and Space Applications



SiPM for the EUSO & MAGIC projects

- An improved version of SiPM can successfully be used for the EUSO and MAGIC projects.
- For this purpose we have started collaborative works on the development of SiPM with the :
  - MEPhI & „Pulsar“ enterprise (Moscow)
  - Semiconductor Laboratory attached to the MPI for Physics and MPI for Extraterrestrial Physics (a visit to this laboratory is scheduled on Friday the 21st of November).

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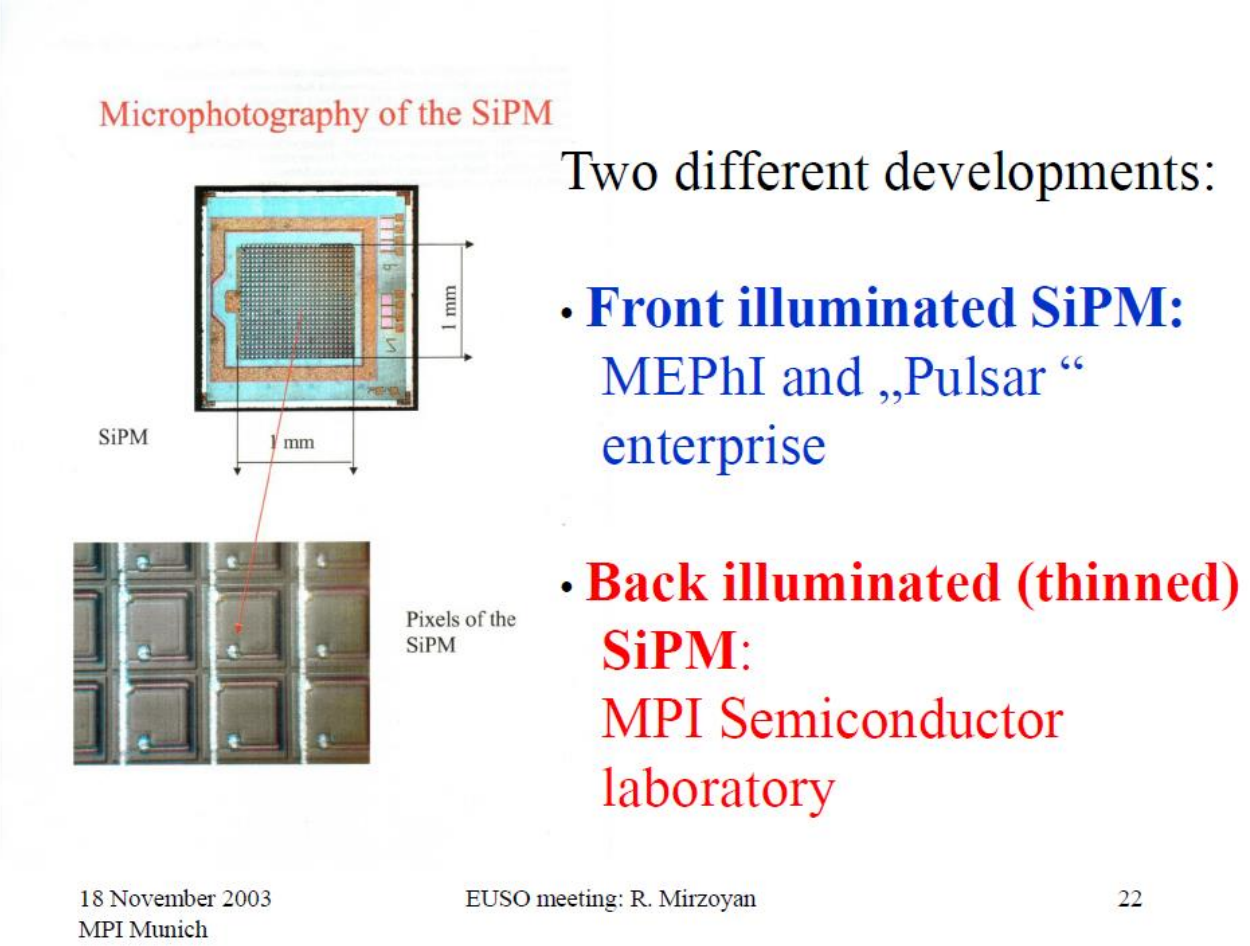
1st Mention of Using SiPM in Astro-Particle Physics and Space Applications



Microphotography of the SiPM

Two different developments:

- **Front illuminated SiPM:** MEPhI and „Pulsar “ enterprise
- **Back illuminated (thinned) SiPM:** MPI Semiconductor laboratory

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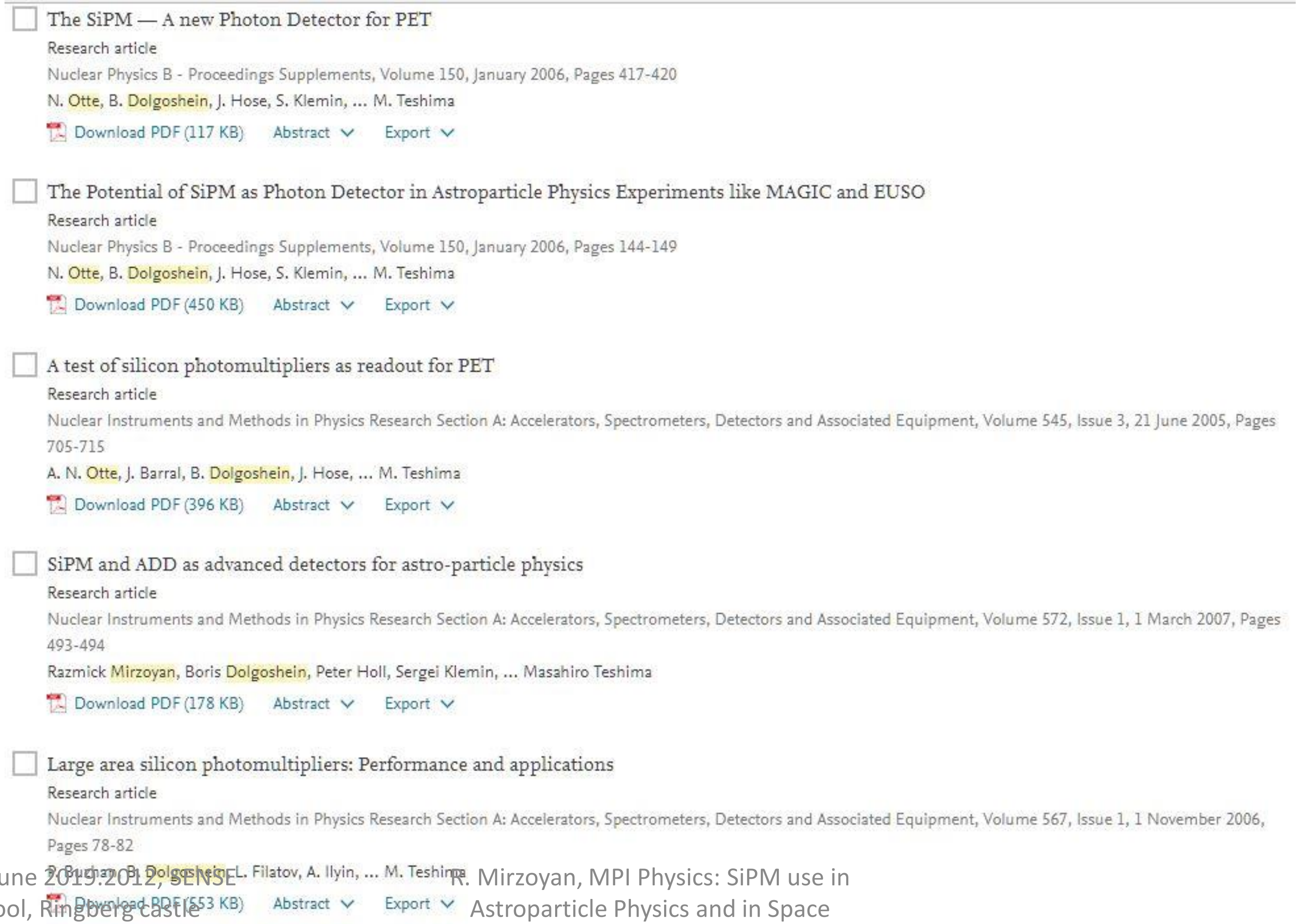
First publications on SiPM Use for Astro-Particle Physics, EUSO and for PET with my colleagues



☐ The SiPM — A new Photon Detector for PET

Research article

Nuclear Physics B - Proceedings Supplements, Volume 150, January 2006, Pages 417-420

N. Otte, B. Dolgoshein, J. Hose, S. Klemin, ... M. Teshima

Download PDF (117 KB) Abstract ⌄ Export ⌄

☐ The Potential of SiPM as Photon Detector in Astroparticle Physics Experiments like MAGIC and EUSO

Research article

Nuclear Physics B - Proceedings Supplements, Volume 150, January 2006, Pages 144-149

N. Otte, B. Dolgoshein, J. Hose, S. Klemin, ... M. Teshima

Download PDF (450 KB) Abstract ⌄ Export ⌄

☐ A test of silicon photomultipliers as readout for PET

Research article

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 545, Issue 3, 21 June 2005, Pages 705-715

A. N. Otte, J. Barral, B. Dolgoshein, J. Hose, ... M. Teshima

Download PDF (396 KB) Abstract ⌄ Export ⌄

☐ SiPM and ADD as advanced detectors for astro-particle physics

Research article

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 572, Issue 1, 1 March 2007, Pages 493-494

Razmick Mirzoyan, Boris Dolgoshein, Peter Holl, Sergei Klemin, ... Masahiro Teshima

Download PDF (178 KB) Abstract ⌄ Export ⌄

☐ Large area silicon photomultipliers: Performance and applications

Research article

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 567, Issue 1, 1 November 2006, Pages 78-82

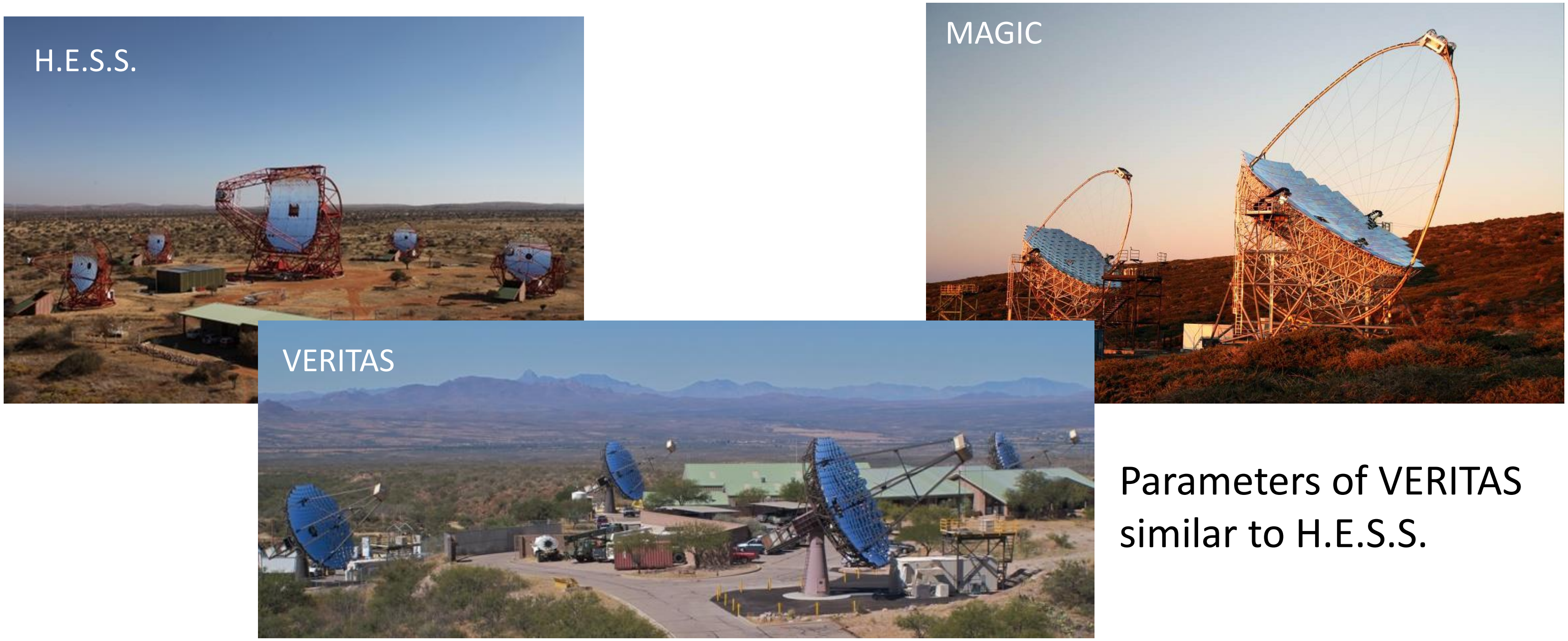
P. Buzhan, B. Dolgoshein, L. Filatov, A. Ilyin, ... M. Teshima

Download PDF (553 KB) Abstract ⌄ Export ⌄

17m Ø MAGIC Imaging Atmospheric Cherenkov Telescopes for 50GeV-50TeV γ astrophysics

Location: Roque de los Muchachos
Observatory, Canary islands,
La Palma, 2200m a.s.l.

The Big 3: H.E.S.S., VERITAS & MAGIC

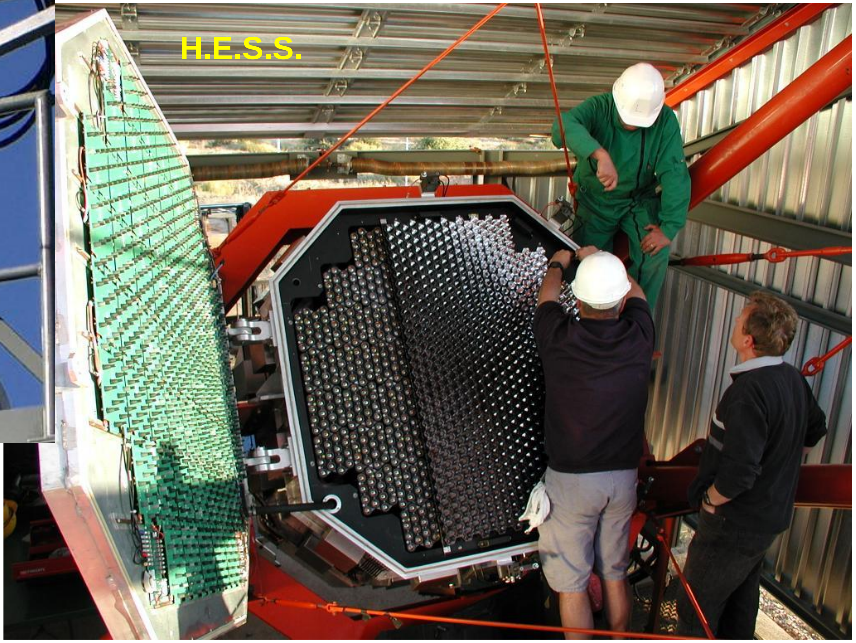


Parameters of VERITAS similar to H.E.S.S.

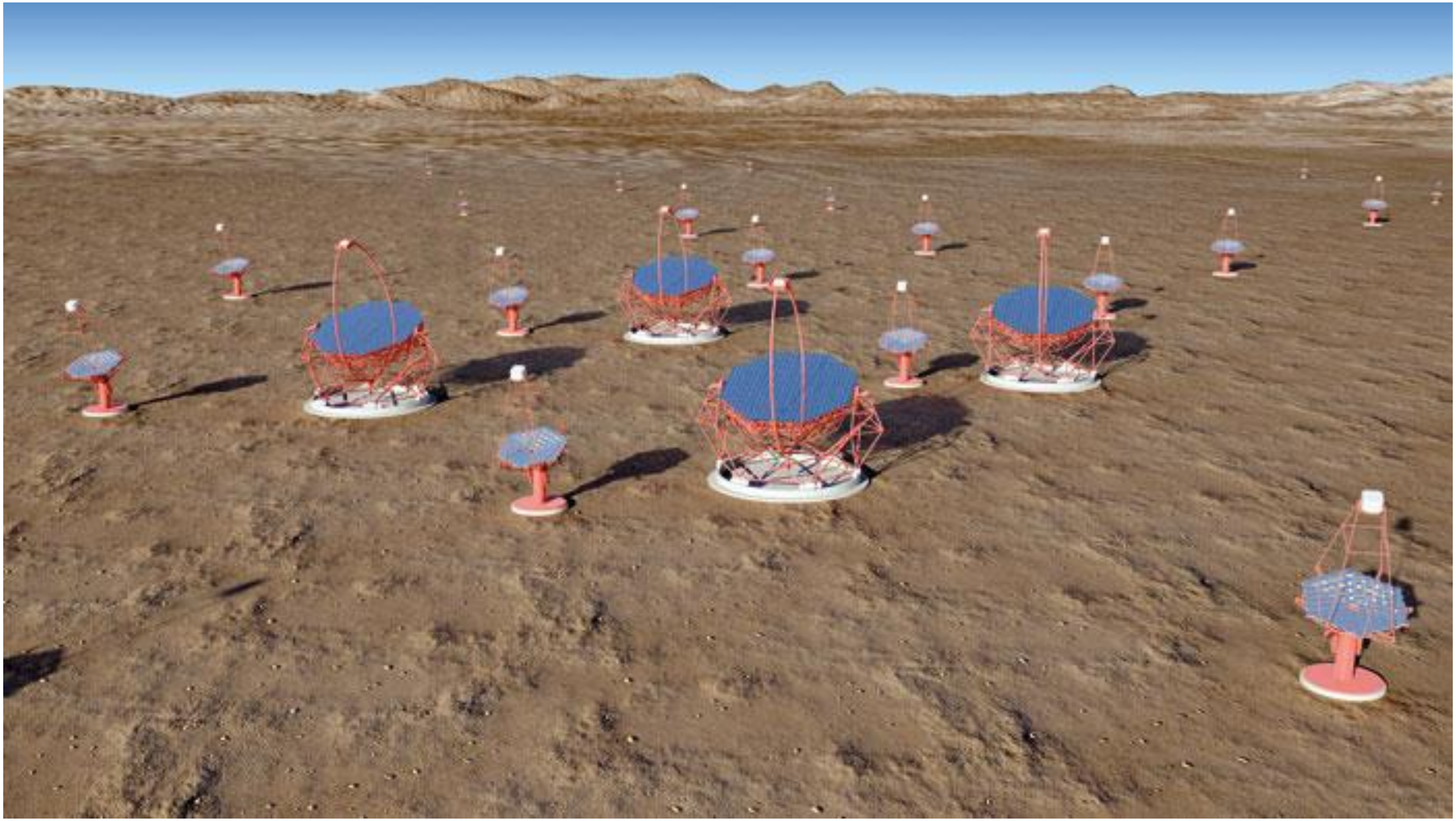
	H.E.S.S.	MAGIC
# telescopes	4 + 1	2
Field of view	5°	3.5°
Reflector diameter	12 m + 28m	17 m
Energy threshold	160 GeV	50 GeV (25 GeV – special trigger)
Sensitivity:	1 % Crab (25 h)	0.6 % Crab (50 h, E ≥ 260 GeV)

The imaging cameras of the three leading IACTs

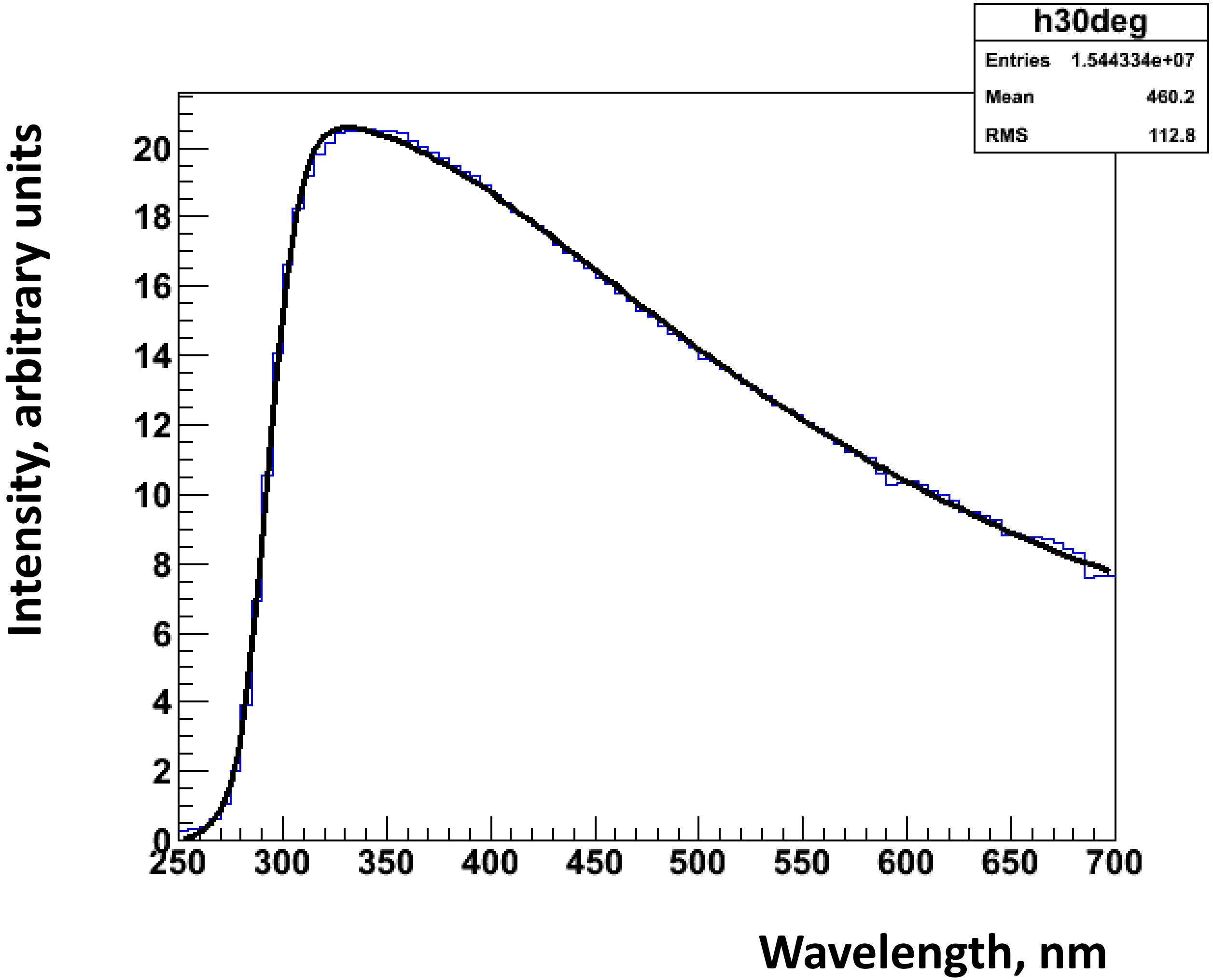
1039-pixel imaging camera of MAGIC-I. Superbialkali PMTs each covering 0.10° in the sky.



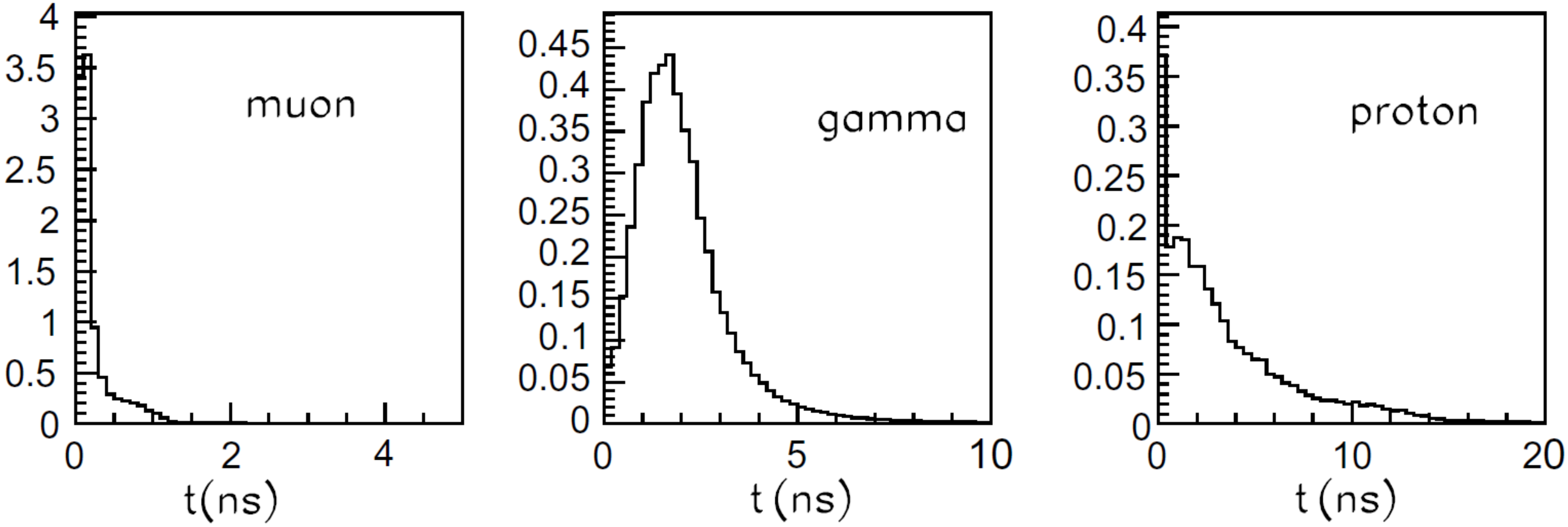
Cherenkov Telescope Array: > 100 telescopes in South and North, of 23m, 12m and 4m class (+ SCT)



Cherenkov light emission spectrum from a 100 GeV air shower, arriving to a telescope at a height of ~ 2km a.s.l.; shower zenith angle = 30°



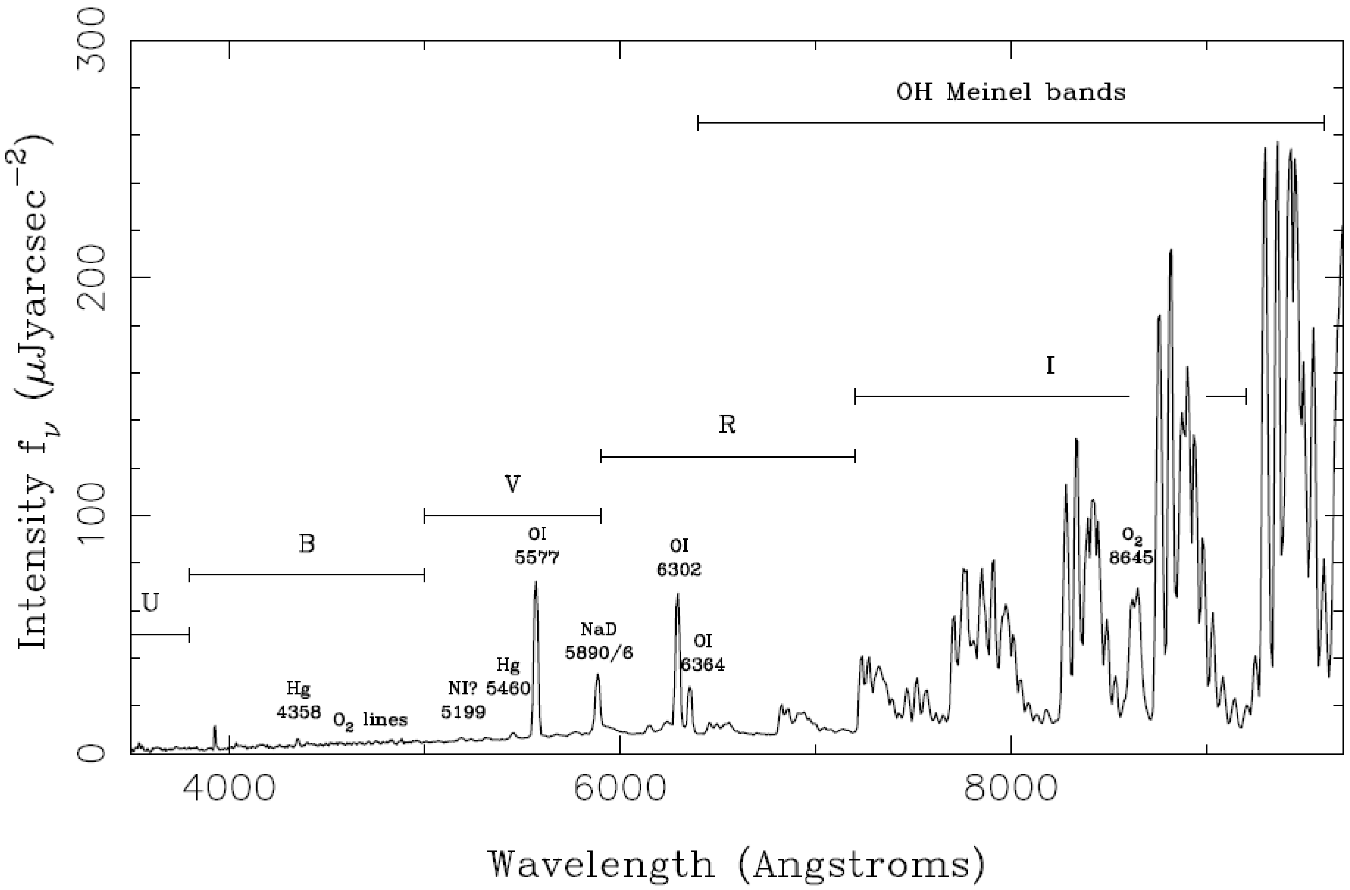
Time structure of gamma (useful signal, ~2 ns), muon and proton events (background) measured by an imaging atmospheric Cherenkov telescope



The key features and parameters:

- Cherenkov Light from air showers measured at ground level:
  - Spectrum range: 290 – 700 nm
  - Peaking at ~ 330 nm for small zenith angles (after passing through atmosphere)
  - Duration of a flash: 3-5 ns
- LoNS (main sources are the air glow- long-time fluorescense induced by the sun, and the unresolved starlight):
  - Spectrum starting from ~300 nm, stretching > 1000 nm
  - When going from short wavelengths towards longer ones, the 1st strong peak is at 557,7 nm, 2nd at 589 nm,…, strong increase > 600nm, + more peaks, very strong > 680 nm
  - It is a strong, quasi-DC background that is considered as noise for Cherenkov measurements; ➔ high sensitivity in infrared is a disadvantage

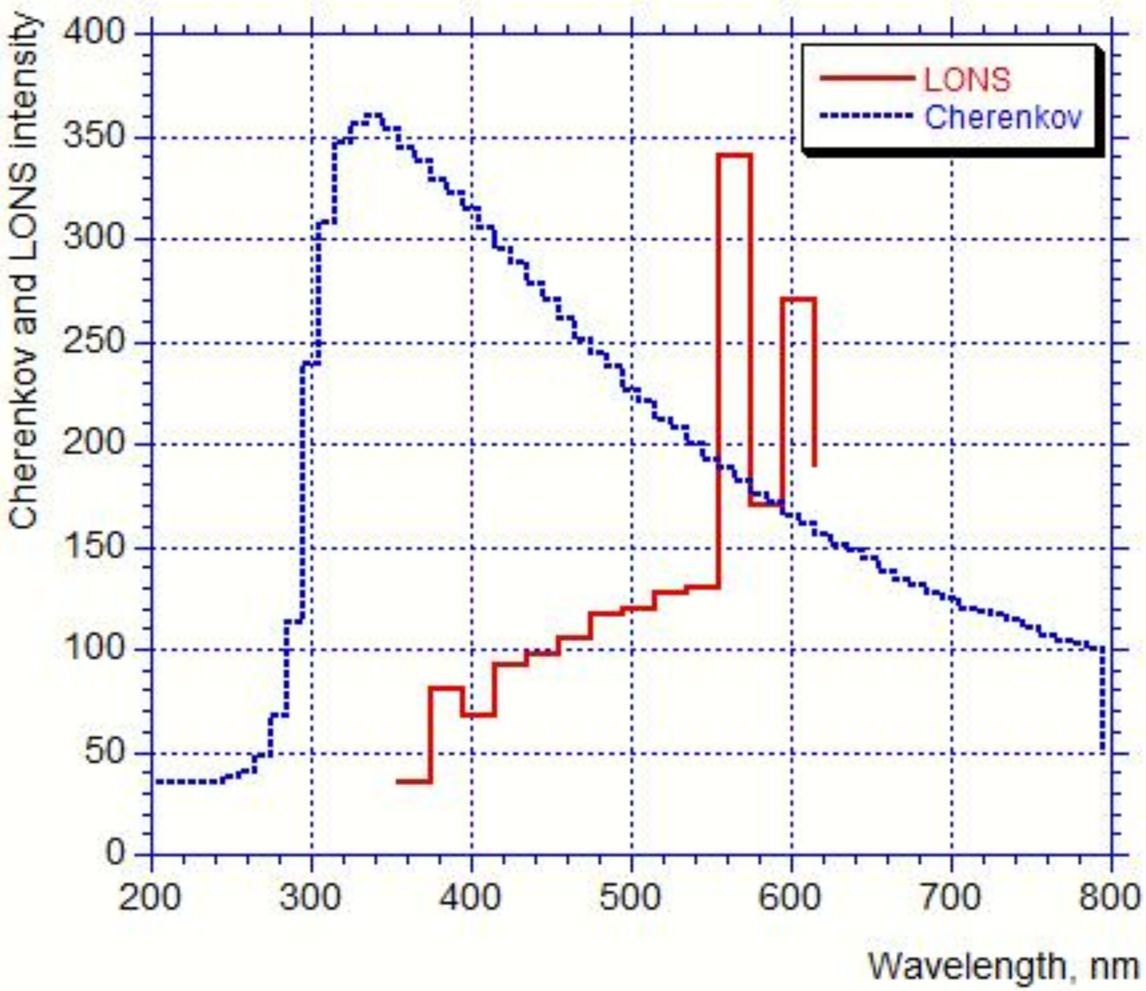
Light of Night Sky spectrum; LoNS is a strong background for IACTs; minimize this noise by integrating only for few ns



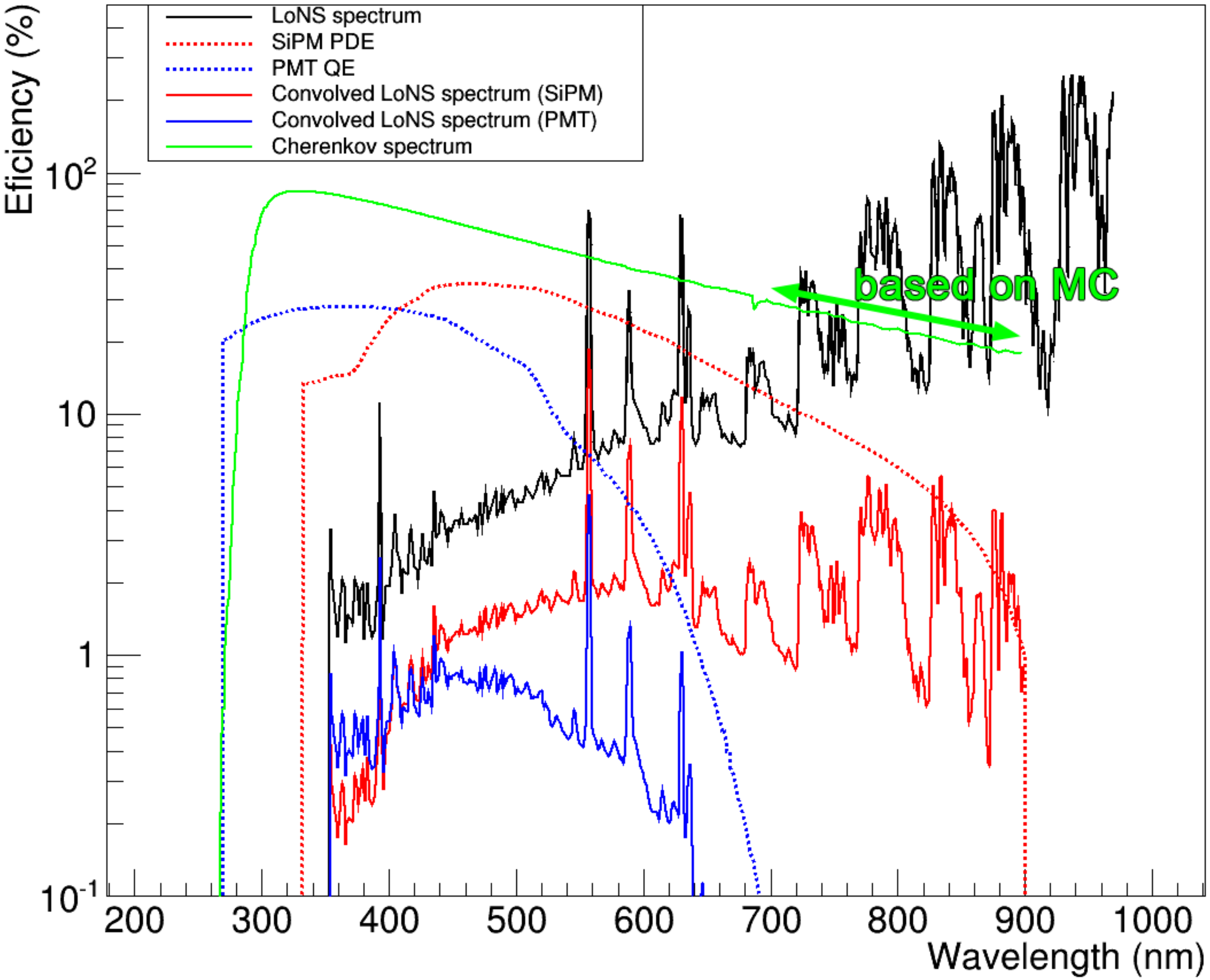
Cherenkov Light integration window

10 Angstroms = 1nm

The spectra of Cherenkov light and of LoNS



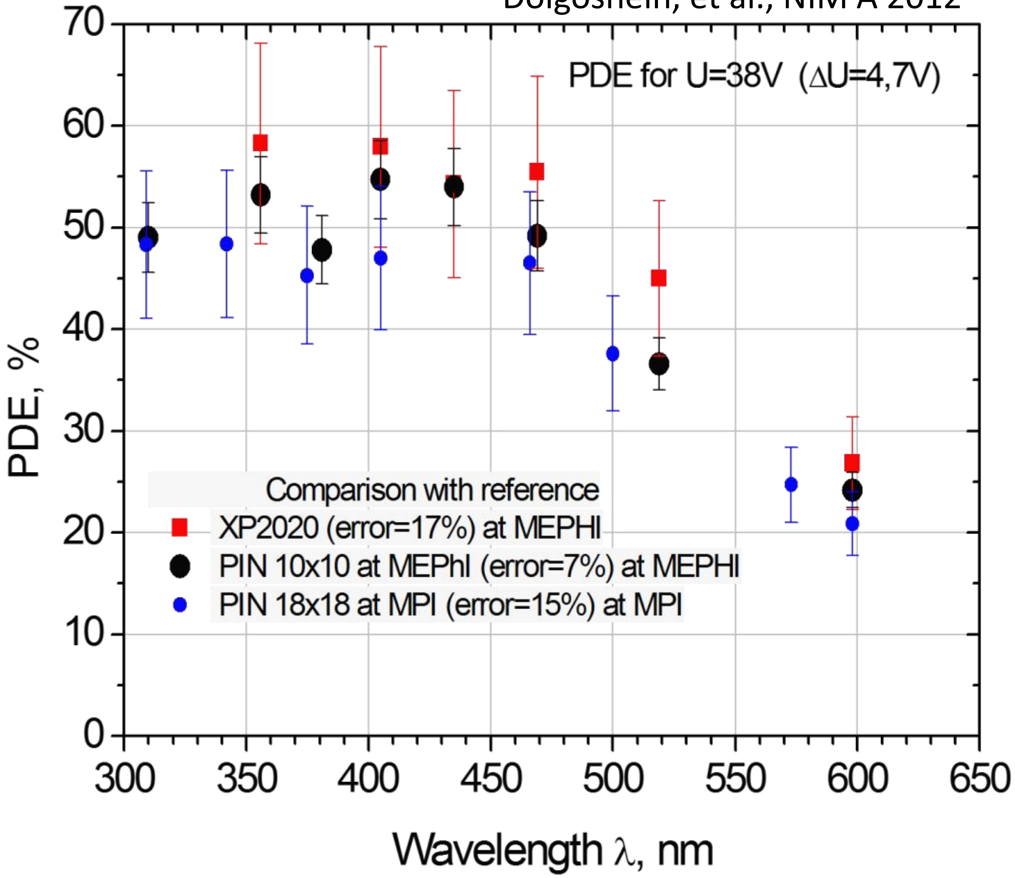
PMT QE & SiPM PDE fold with LoNS



In 2011 we came quite close to ideal light sensor
Today‘s sensors are comparable or better

- PDE for 1mm² type 100B experimental SiPM produced by MEPhI-Excelitas in 2011.
- PDE shape is closely matching the desire shape for IACTs
- What is needed:
  a) ≥ 50 % PDE for the most range,
  b) a few x 100kHz/mm² dark noise
     at ~20° C
  c) X-talk ≤ 3-5 %
  d) low afterpulsing

Dolgoshein, et al., NIM A 2012



4+ Fold X-talk suppression pursued by MEPhI – MPP researchers

- Ways to suppress the X-talk:
  - Isolating trenches, total internal reflection: reduction 8-9 times;

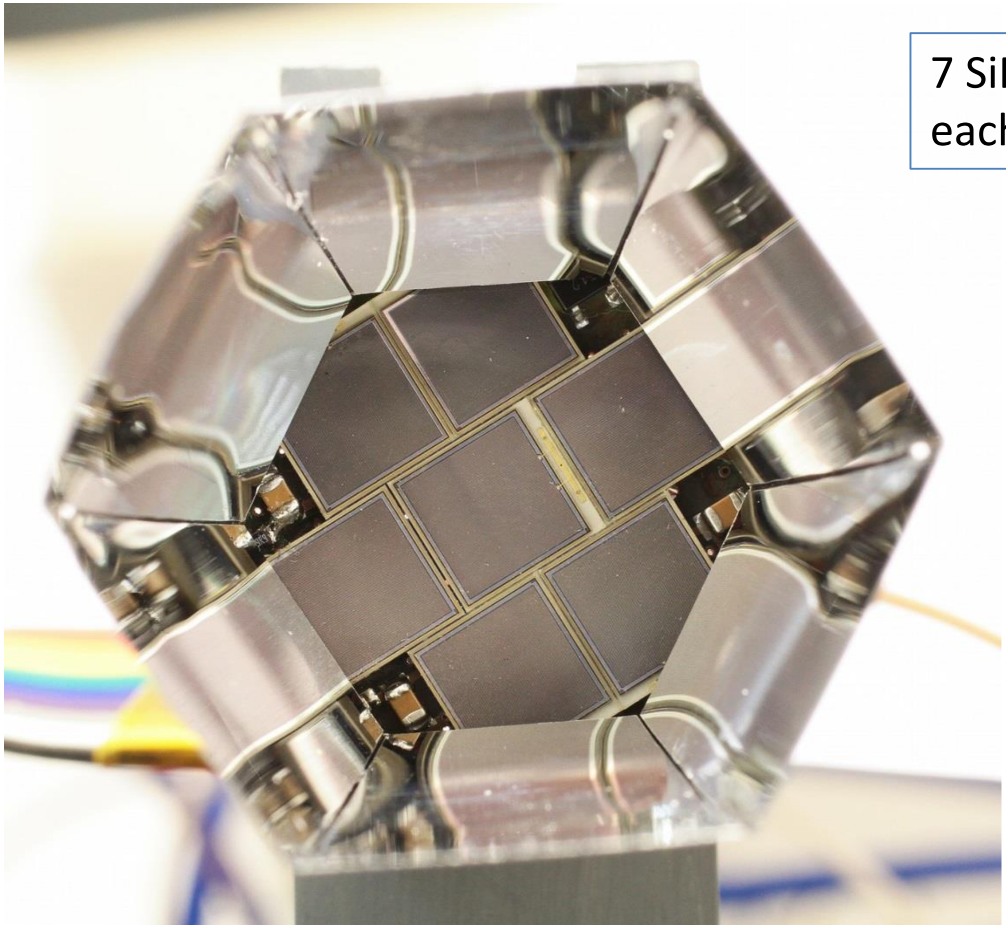
    (intelectual property)
  - 2nd p-n junction for isolating the bulk from the active region: reduction 4-5 times;

    (intelectual property)
  - High-energy ion implantation: reduction ≥ 2-times

    (Intelectual property)
  - Special absorbing coating of the chip: ≥ 2-times

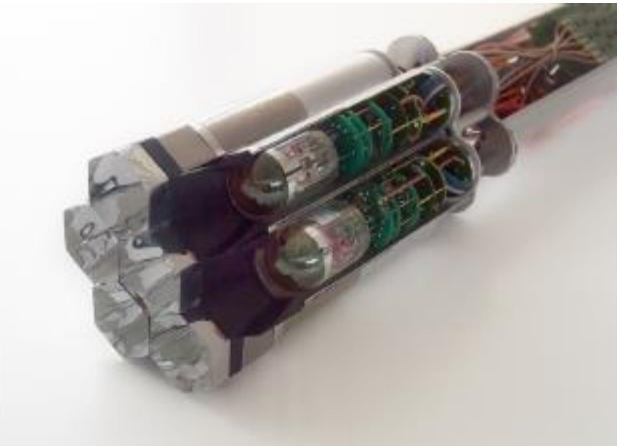
    (Intelectual property)
  - Ultra-thin SiPM: expected reduction should be a large number

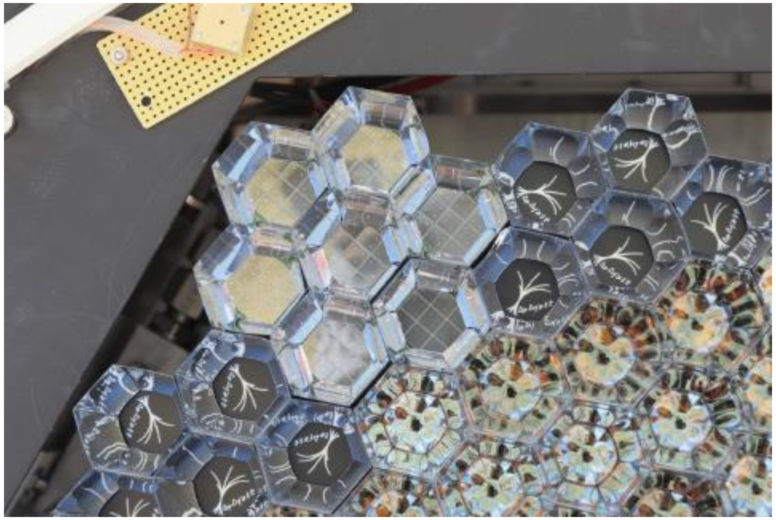
SiPM-based pixel for MAGIC



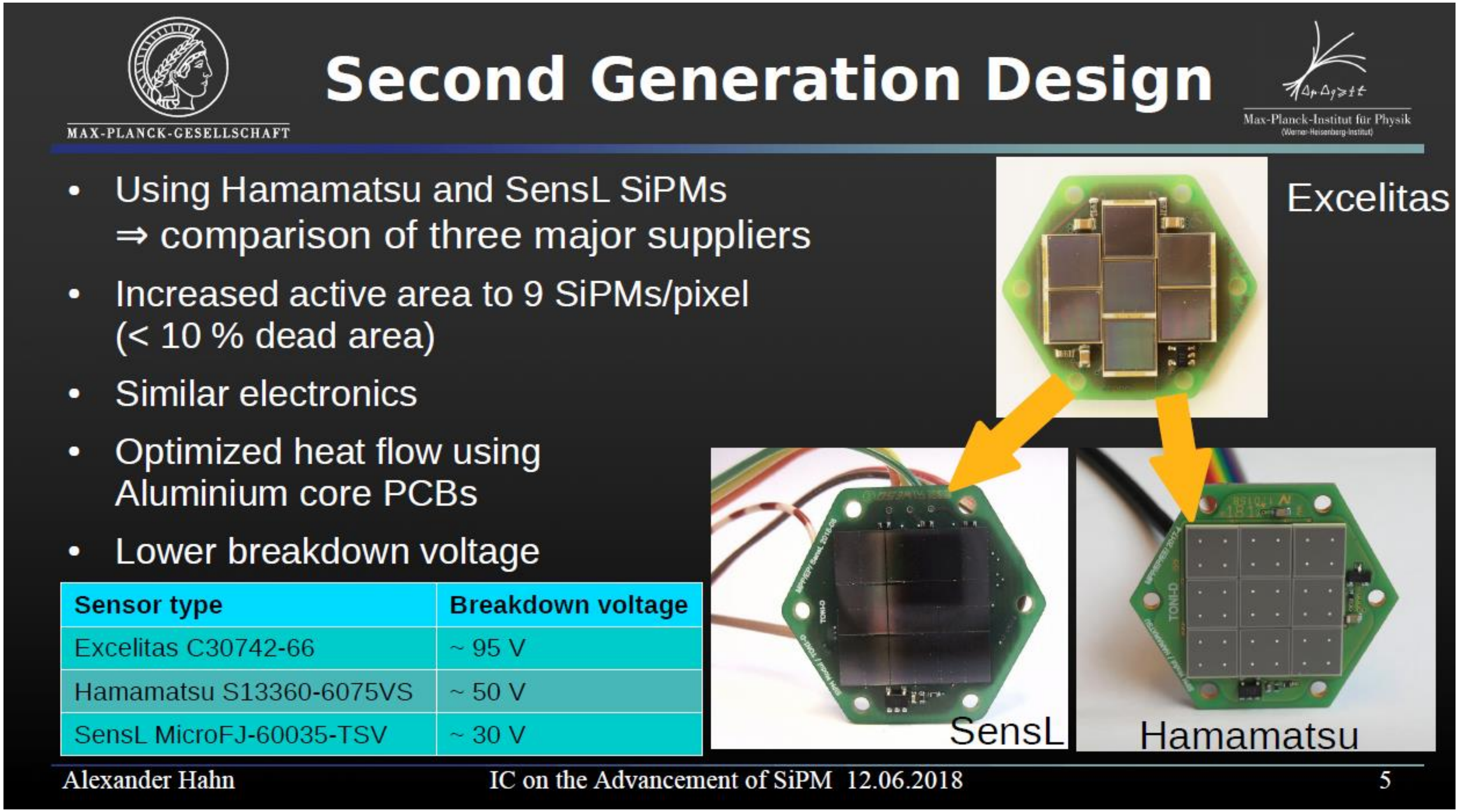
7 SiPMs from EXCELITAS, each 6mm x 6mm

SiPM cluster test in MAGIC imaging camera





Clusters based on SiPM from EXCELITAS, SensL and Hamamatsu are simultaneously under test



MAX-PLANCK-GESELLSCHAFT

Second Generation Design

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

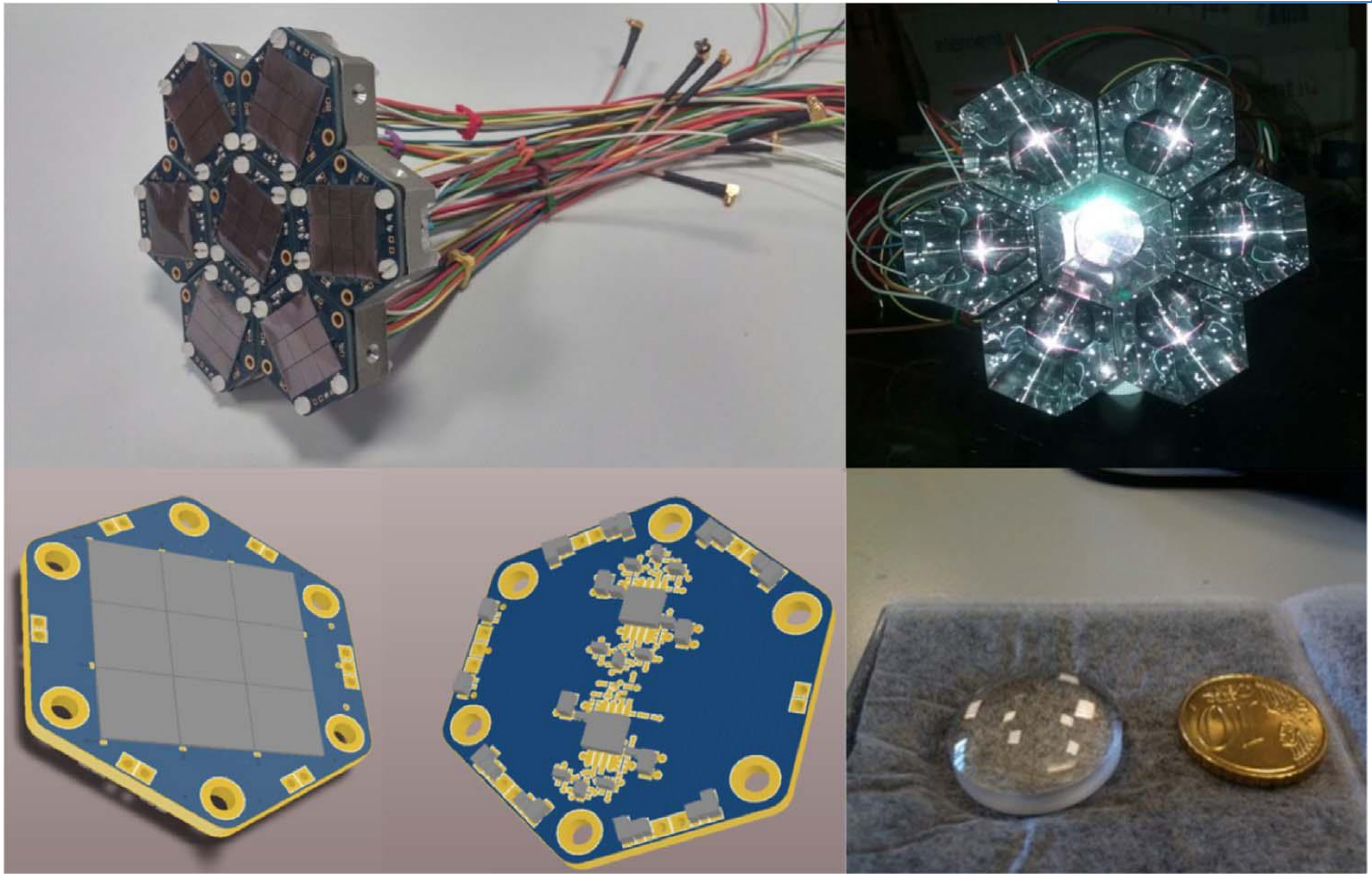
- Using Hamamatsu and SensL SiPMs
  ⇒ comparison of three major suppliers
- Increased active area to 9 SiPMs/pixel
  (< 10 % dead area)
- Similar electronics
- Optimized heat flow using Aluminium core PCBs
- Lower breakdown voltage

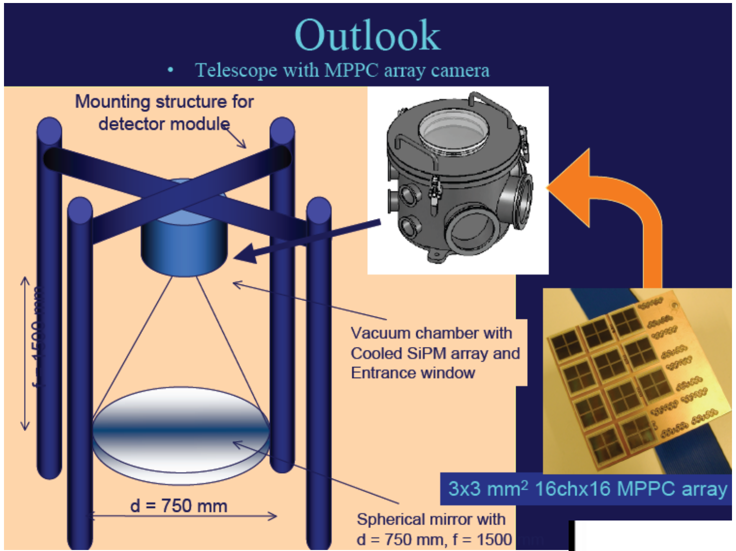
Sensor type	Breakdown voltage
Excelitas C30742-66	~ 95 V
Hamamatsu S13360-6075VS	~ 50 V
SensL MicroFJ-60035-TSV	~ 30 V

Alexander Hahn IC on the Advancement of SiPM 12.06.2018 5

Also our MAGIC colleagues from Italy have prepared their own SiPM cluster

Arcaro, et al, NIM A





Outlook

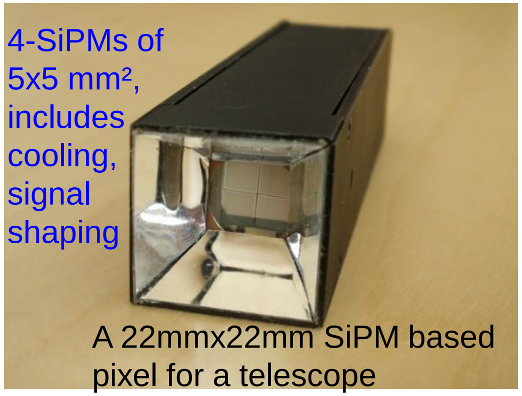
- Telescope with MPPC array camera

Mounting structure for detector module

Vacuum chamber with Cooled SiPM array and Entrance window

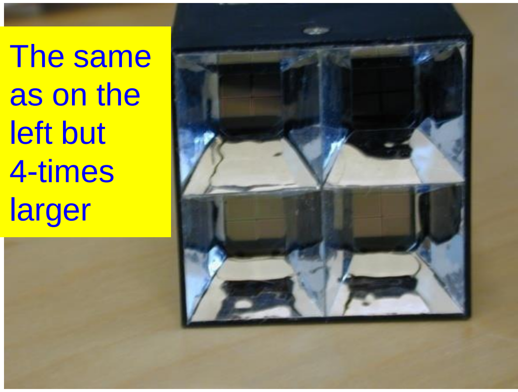
3x3 mm² 16chx16 MPPC array

Spherical mirror with d = 750 mm, f = 1500

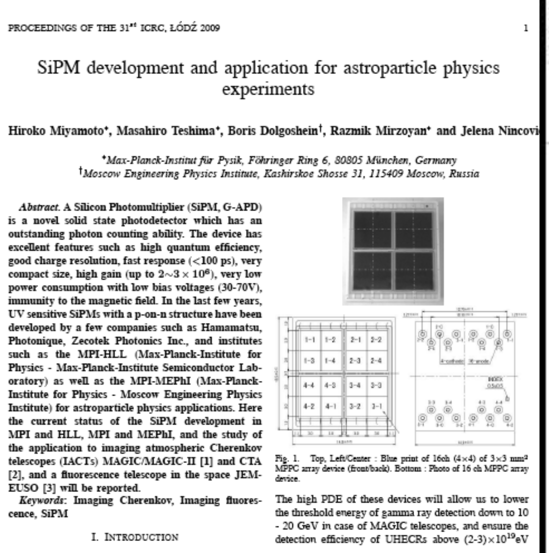


4-SiPMs of 5x5 mm², includes cooling, signal shaping

A 22mmx22mm SiPM based pixel for a telescope



The same as on the left but 4-times larger



PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009 1

SiPM development and application for astroparticle physics experiments

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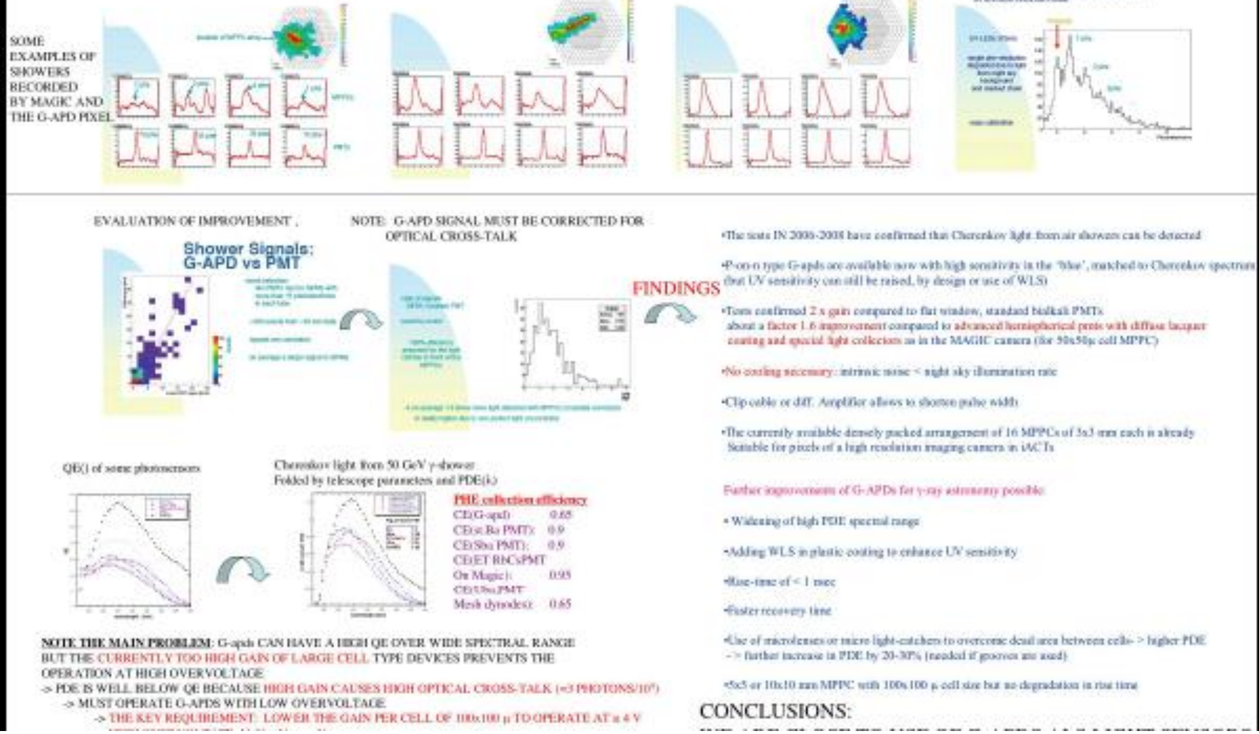
Abstract. A Silicon Photomultiplier (SiPM, G-APD) is a novel solid state photodetector which has an outstanding photon counting ability. The device has excellent features such as high quantum efficiency, good charge resolution, fast response (<100 ps), very compact size, high gain (up to $2{\sim}3\times10^6$), very low power consumption with low bias voltages (30-70V), immunity to the magnetic field. In the last few years, UV sensitive SiPMs with a p-on-n structure have been developed by a few companies such as Hamamatsu, Photonique, Zecotek Photonics Inc., and institutes such as the MPI-HLL (Max-Planck-Institute for Physics - Max-Planck-Institute Semiconductor Laboratory) as well as the MPI-MEPhI (Max-Planck-Institute for Physics - Moscow Engineering Physics Institute) for astroparticle physics applications. Here the current status of the SiPM development in MPI and HLL, MPI and MEPhI, and the study of the application to imaging atmospheric Cherenkov telescopes (IACTs) MAGIC/MAGIC-II [1] and CTA [2], and a fluorescence telescope in the space JEM-EUSO [3] will be reported.

Keywords: Imaging Cherenkov, Imaging fluorescence, SiPM

I. Introduction

Fig. 1. Top, Left/Center : Blue print of 16ch (4×4) of 3×3 mm² MPPC array device (front/back). Bottom : Photo of 16 ch MPPC array device.

The high PDE of these devices will allow us to lower the threshold energy of gamma ray detection down to 10 - 20 GeV in case of MAGIC telescopes, and ensure the detection efficiency of UHECRs above $(2\text{-}3)\times10^{19}$eV



SOME EXAMPLES OF SHOWERS RECORDED BY MAGIC AND THE G-APD PIXEL

EVALUATION OF IMPROVEMENT :

NOTE: G-APD SIGNAL MUST BE CORRECTED FOR OPTICAL CROSS-TALK

Shower Signals: G-APD vs PMT

QE(λ) of some photosensors

Cherenkov light from 50 GeV γ-shower
Folded by telescope parameters and PDE(λ)

PHE collection efficiency
CE(G-apd) 0.65
CE(st.Ba PMT): 0.9
CE(Sba PMT): 0.9
CE(ET RbCsPMT
On Magic): 0.95
CE(UBa PMT
Mesh dynodes): 0.65

FINDINGS

- The tests IN 2006-2008 have confirmed that Cherenkov light from air showers can be detected
- P-on-n type G-apds are available now with high sensitivity in the 'blue', matched to Cherenkov spectrum (but UV sensitivity can still be raised, by design or use of WLS)
- Tests confirmed 2 x gain compared to flat window, standard bialkali PMTs about a factor 1.6 improvement compared to advanced hemispherical pmts with diffuse lacquer coating and special light collectors as in the MAGIC camera (for 50x50μ cell MPPC)
- No cooling necessary: intrinsic noise < night sky illumination rate
- Clip cable or diff. Amplifier allows to shorten pulse width
- The currently available densely packed arrangement of 16 MPPCs of 3x3 mm each is already Suitable for pixels of a high resolution imaging camera in IACTs

Further improvements of G-APDs for γ-ray astronomy possible:

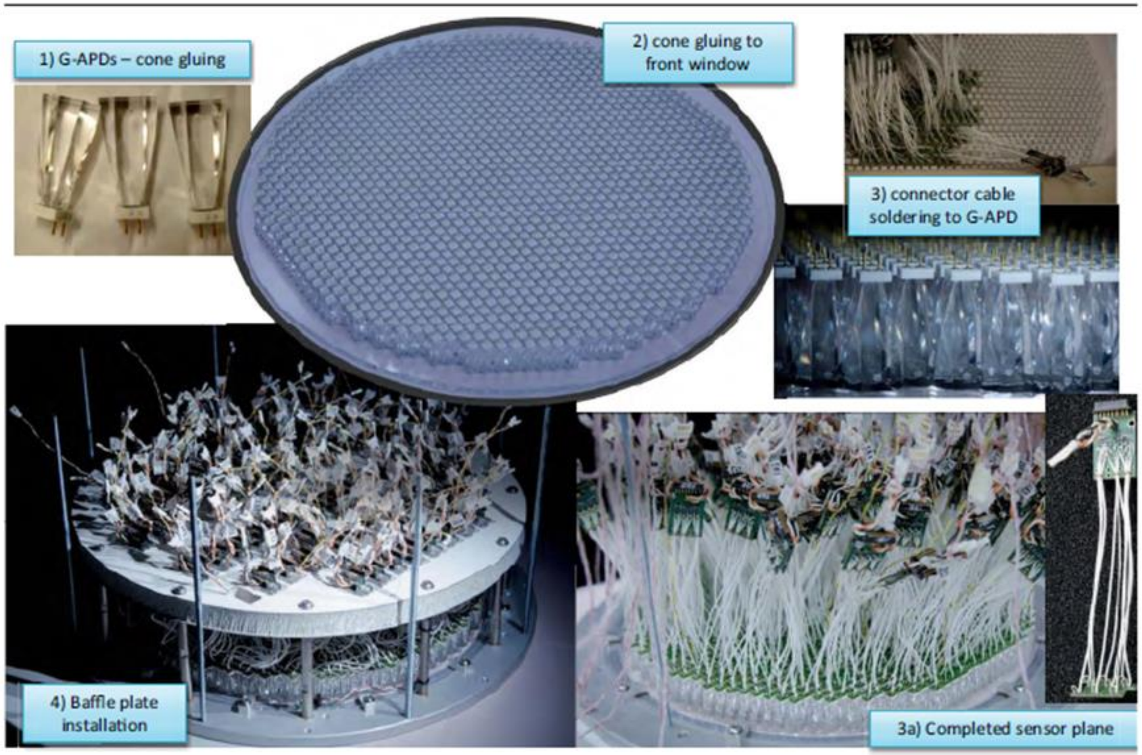
- Widening of high PDE spectral range
- Adding WLS in plastic coating to enhance UV sensitivity
- Rise-time of < 1 nsec
- Faster recovery time
- Use of microlenses or micro light-catchers to overcome dead area between cells -> higher PDE -> further increase in PDE by 20-30% (needed if grooves are used)
- 5x5 or 10x10 mm MPPC with 100x100 μ cell size but no degradation in rise time

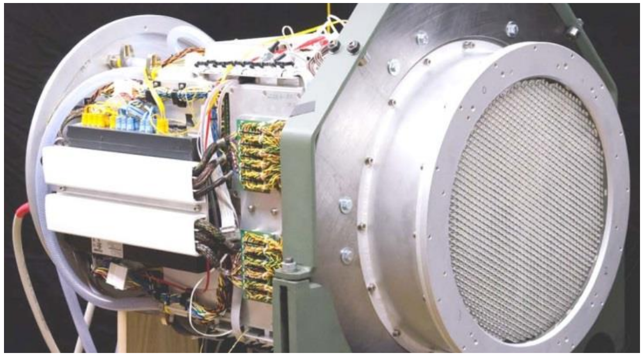
NOTE THE MAIN PROBLEM: G-apds CAN HAVE A HIGH QE OVER WIDE SPECTRAL RANGE BUT THE CURRENTLY TOO HIGH GAIN OF LARGE CELL TYPE DEVICES PREVENTS THE OPERATION AT HIGH OVERVOLTAGE
-> PDE IS WELL BELOW QE BECAUSE HIGH GAIN CAUSES HIGH OPTICAL CROSS-TALK (≈3 PHOTONS/10⁷)
-> MUST OPERATE G-APDS WITH LOW OVERVOLTAGE
-> THE KEY REQUIREMENT: LOWER THE GAIN PER CELL OF 100x100 μ TO OPERATE AT ≥ 4 V

CONCLUSIONS:

The FACT telescope, operating the 1st full-scale SiPM camera

FACT camera



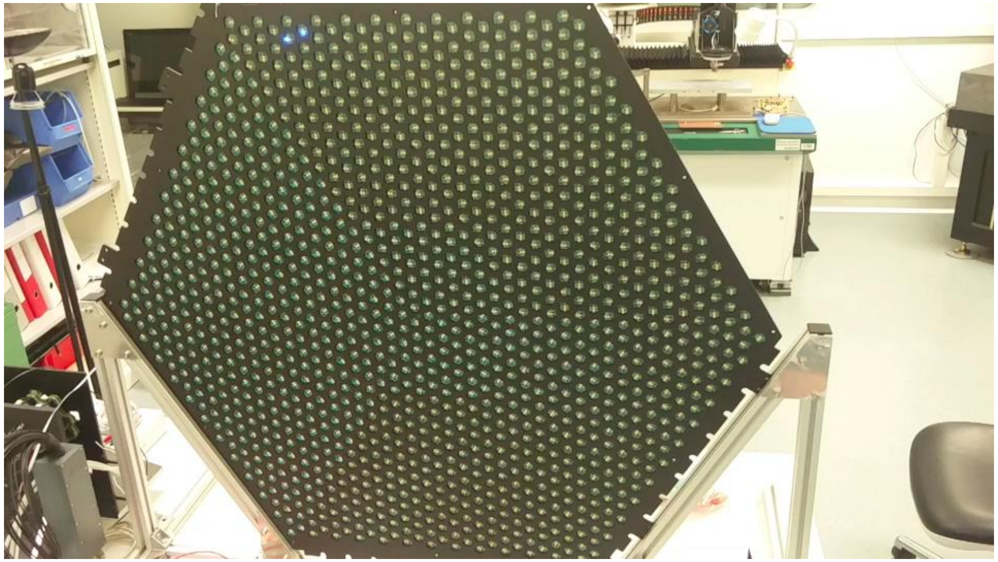


1440 pixels
4.5 degree FOV
Photo sensors: G-APDs
Solid light guides

Location: 2200 m a.s.l.,
MAGIC site, ORM, La Palma,
Mirror area: 9.5 m²
Energy domain: TeV

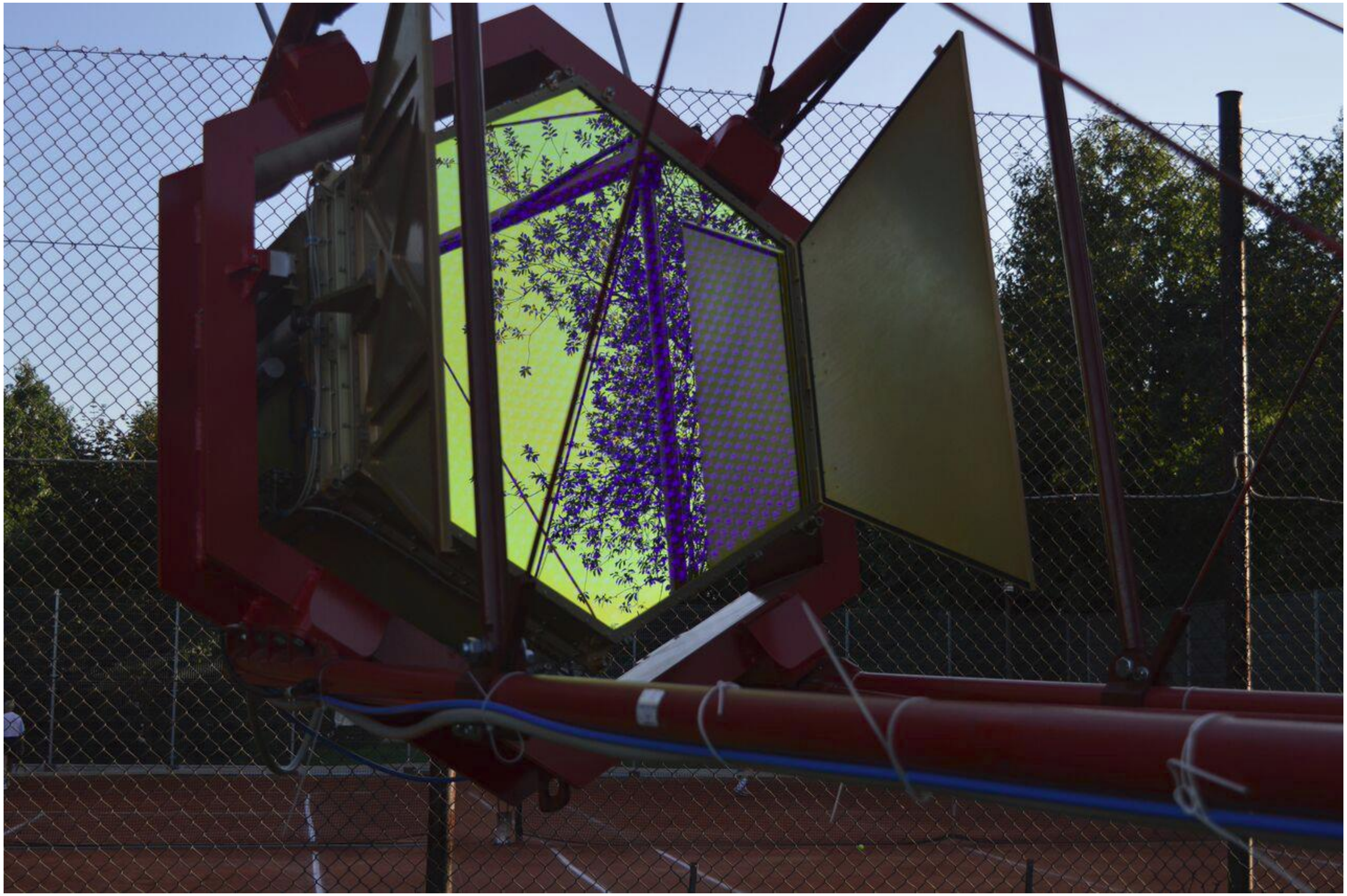
SST-1M IACT

SST-1M

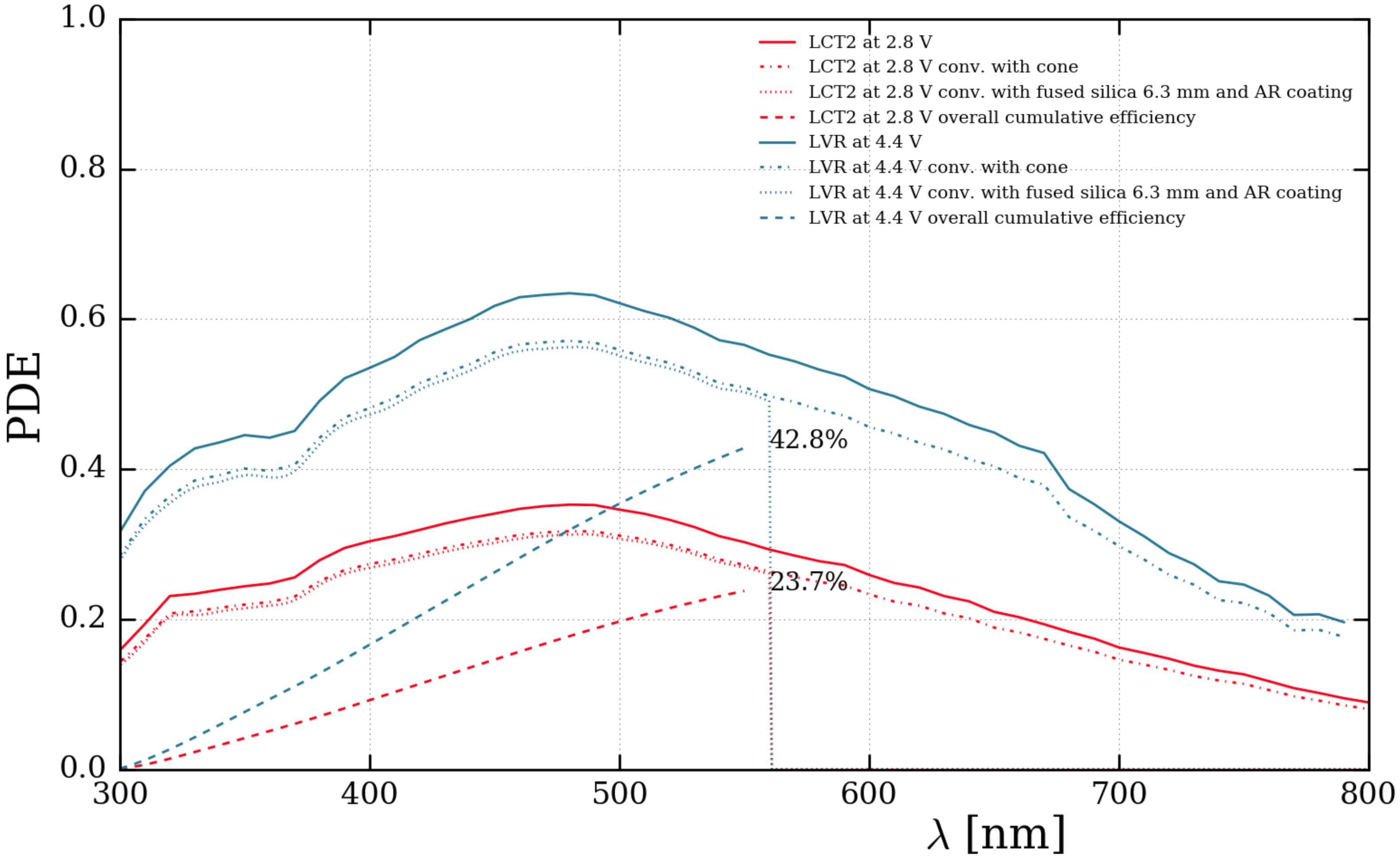


4 m diameter
6.5 m2 eff. dish area
5.6 m focal length
78 cm mirror facets face to face
Active mirror alignment
9° field of view
1296 x 0.24o pixels
Camera Ø over 90 cm
First data with 1.2 GHz/pixel NSB

SST-1M camera lid open

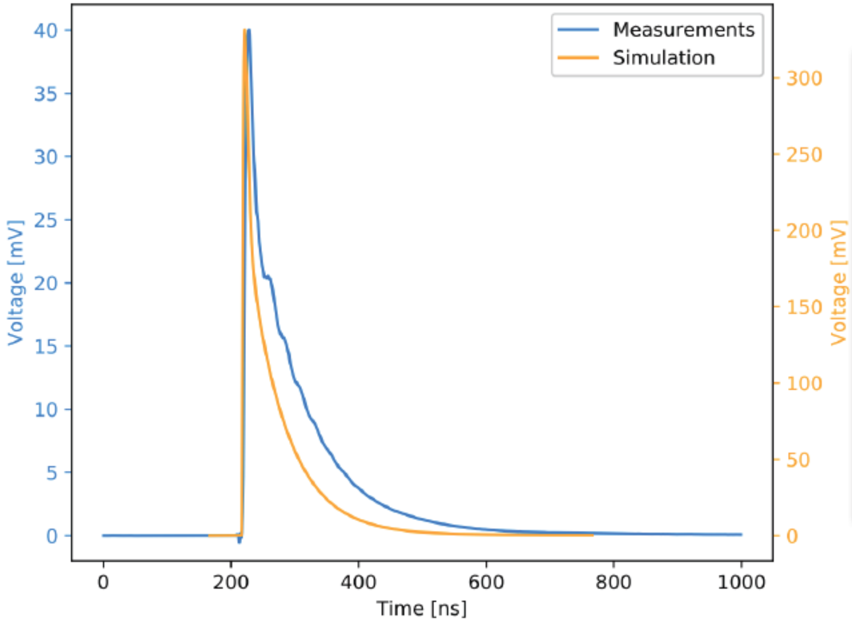


Special filter for SST-1M for suppressing LoNS



Using LVR with SST-1M front end

- Simulation and measurements ongoing with LVR3 6x6 mm² (50 um cells)



- pSpide Model of OPA846 to be tuned for better agreement
- Higher diode capacitance leads to higher gain and longer pulse as expected
- Non-negligible effort to go from LCT2 to LVR3

M. Heller | SST-1M camera update | Paris , 14-18 May 2018 16

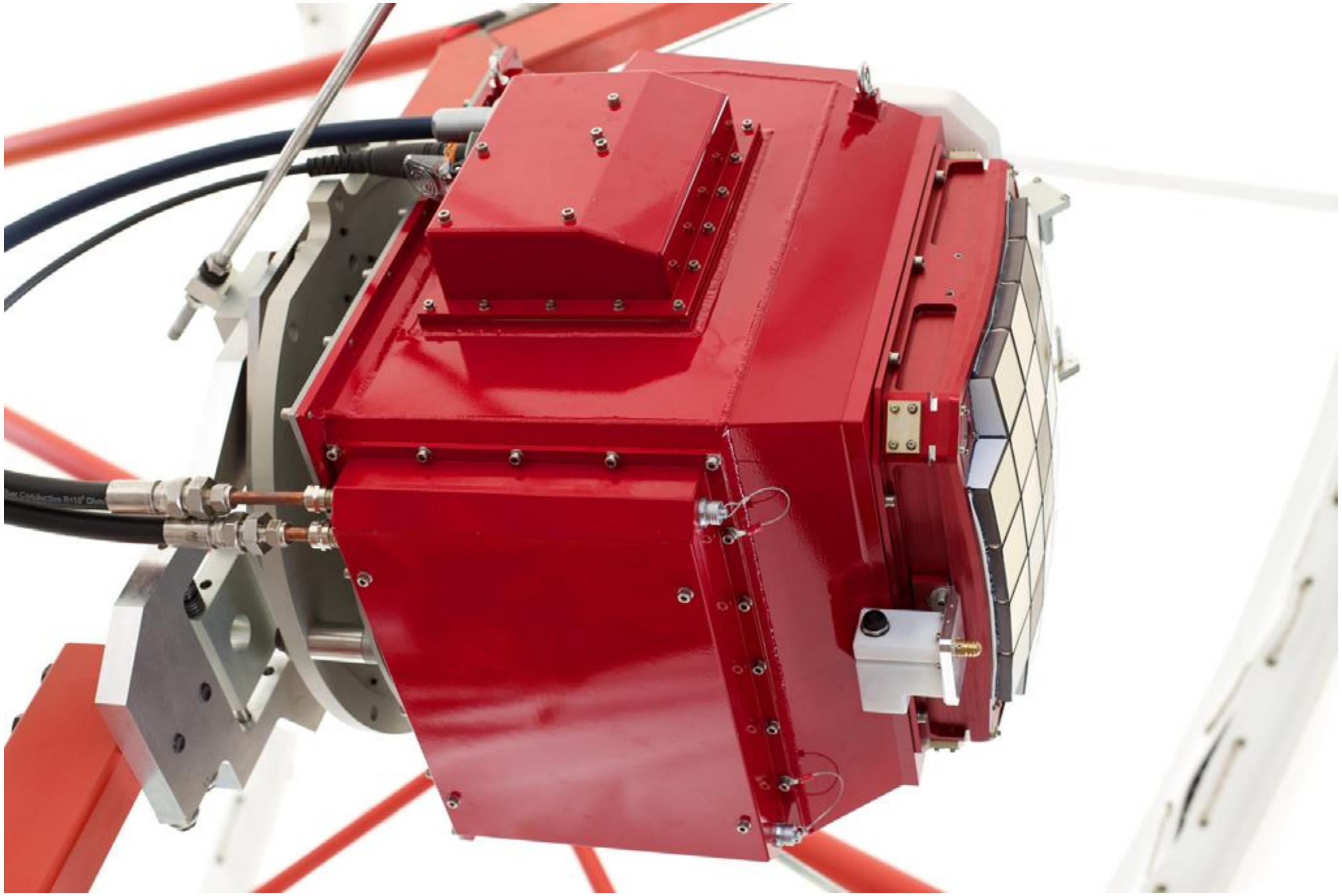
SST GCT

SST-2M GCT Structure
Project overview

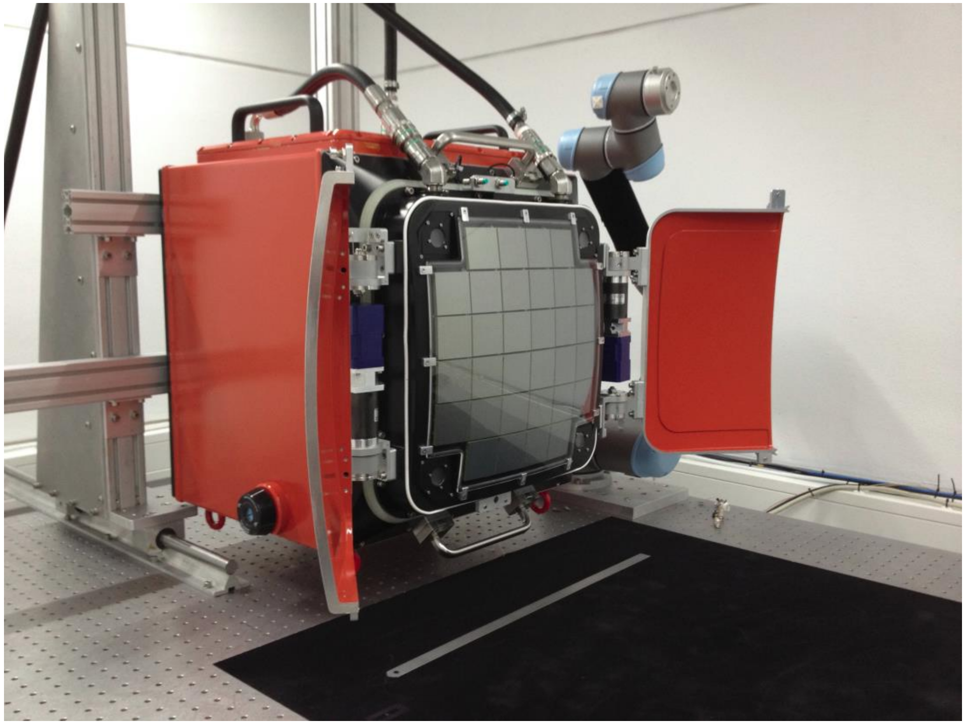
SST session, Orsay
May 14th 2018,
Oriane Le Blanc

GCT seen from side

The GCT-MAPM camera on the telescope in November 2015



CHEC-S camera for GCT

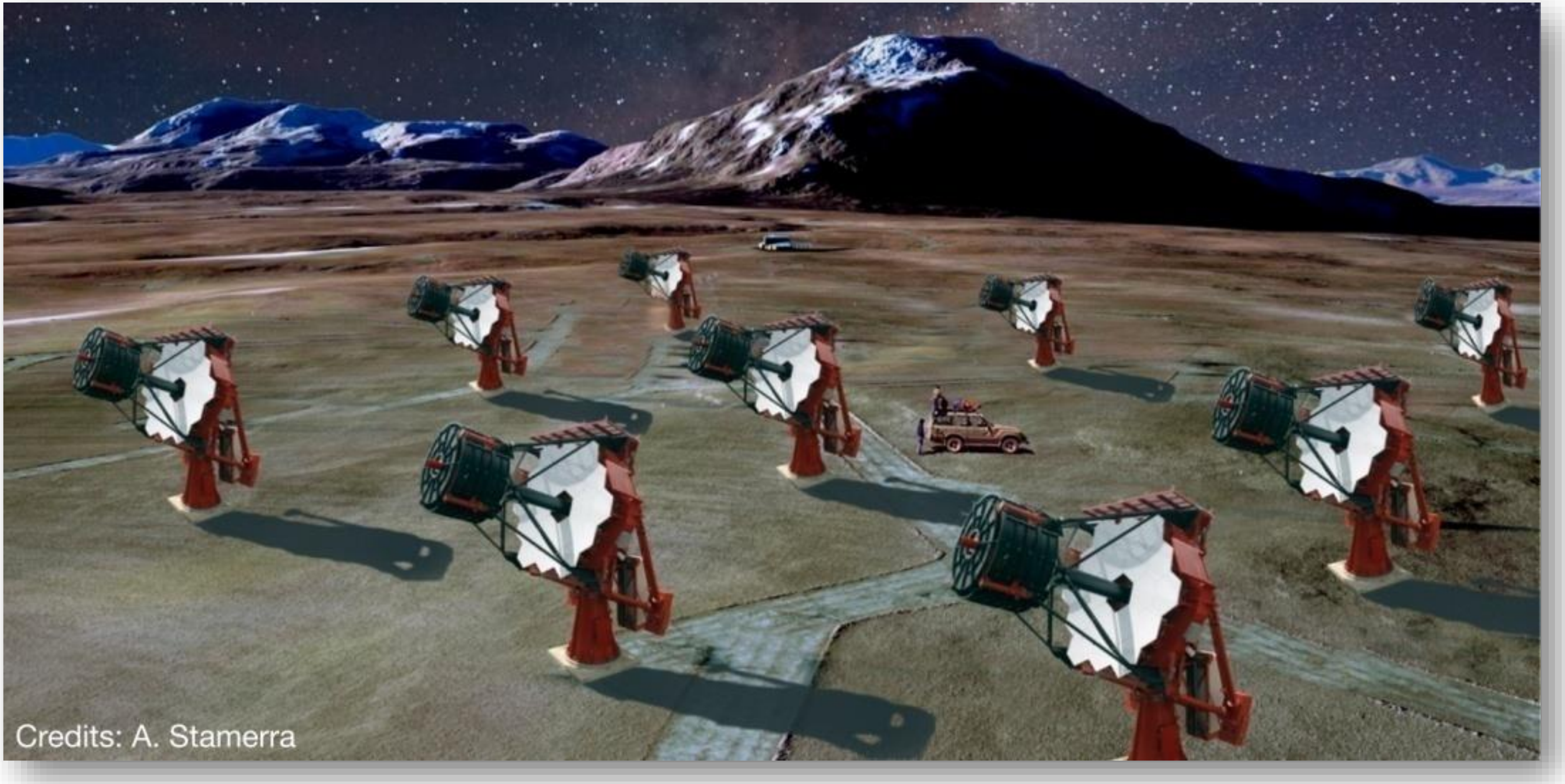


The CHEC-S design represents the latest Generation of GCT camera prototypes. The camera size is 50×52×56 cm3, weighs 44 kg, power consumption of ~600 W. The curved focal plane is tiled with 32 camera modules each with a SiPM tile comprising a 16×16 array of 3×3 mm2 pixels electrically organised as 8×8 6×6 mm^2 pixels by summing 2×2 channels: a camera total of 2048 pixels imaging a field of view of 8°

ASTRI

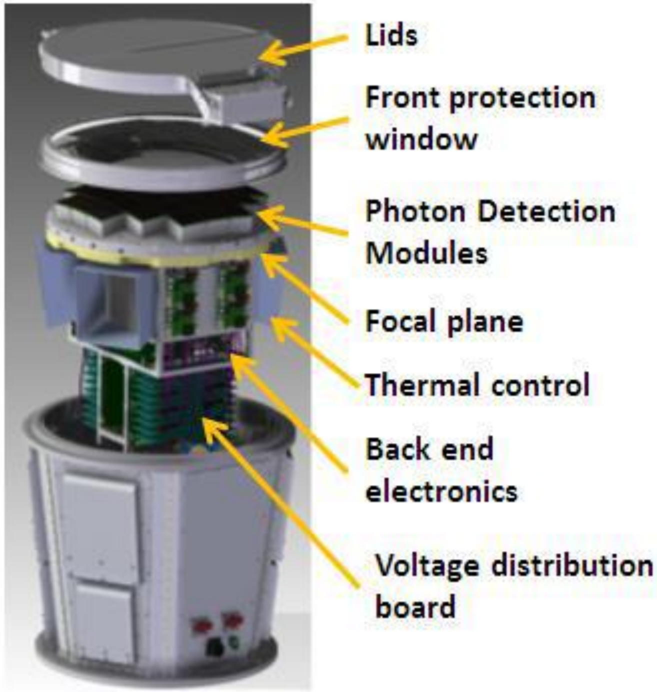
Volcano Ethna is active

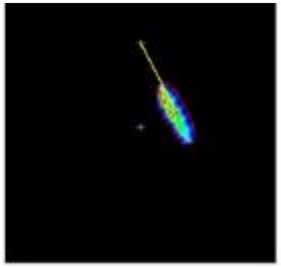
Artists impression: mini-array of 9 ASTRI SST-2M

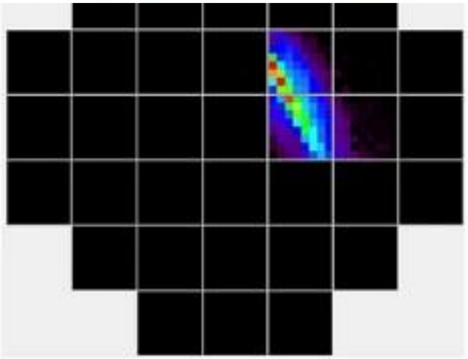


Credits: A. Stamerra

ASTRI telescope and camera

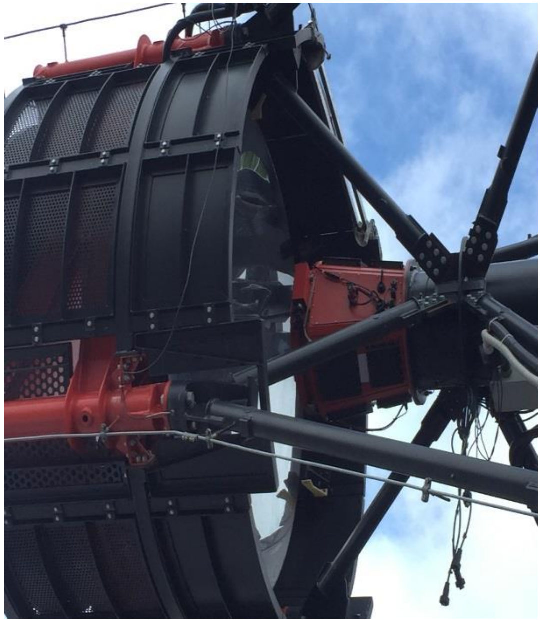


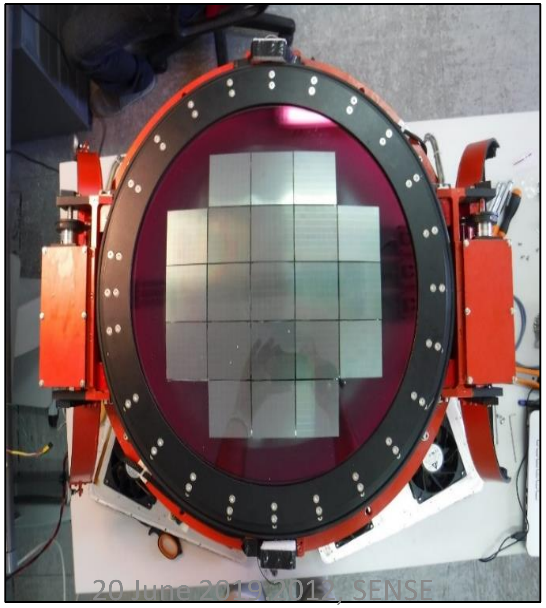




1st Cherenkov light observed in May 2017

ASTRI imaging camera

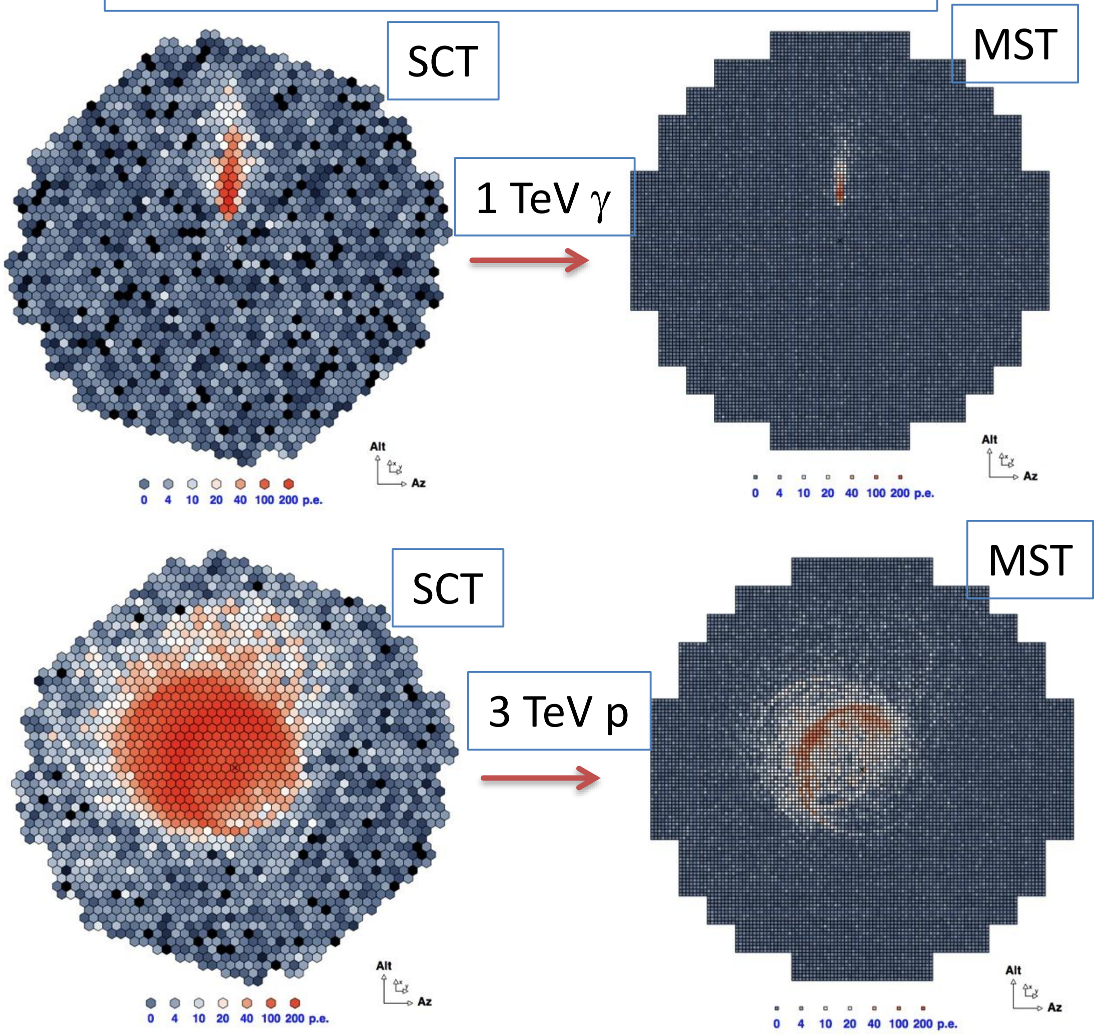




Cherenkov Camera	
Camera opening Angle	70°
Sensors	SiPM
Number of Pixels	2368 (1344 protoype)
Pixel size	7x7 mm
Pixel rate	600 Hz
Dynamical range	1 – 2000 pe$^-$/pixel
Photon Detection Efficiency	> 35% @ 400nm
FoV	10.5° (7.8° prototype)
Weight	73 kg
Dimensions	0.52m x 0.66m x 0.56m
Power consumption	0.65 kW

Schwarzschild-Couder Telescope (SCT)

B. Humensky, J. Vandenbroucke, CTA GM Paris, 2018



SCT

MST

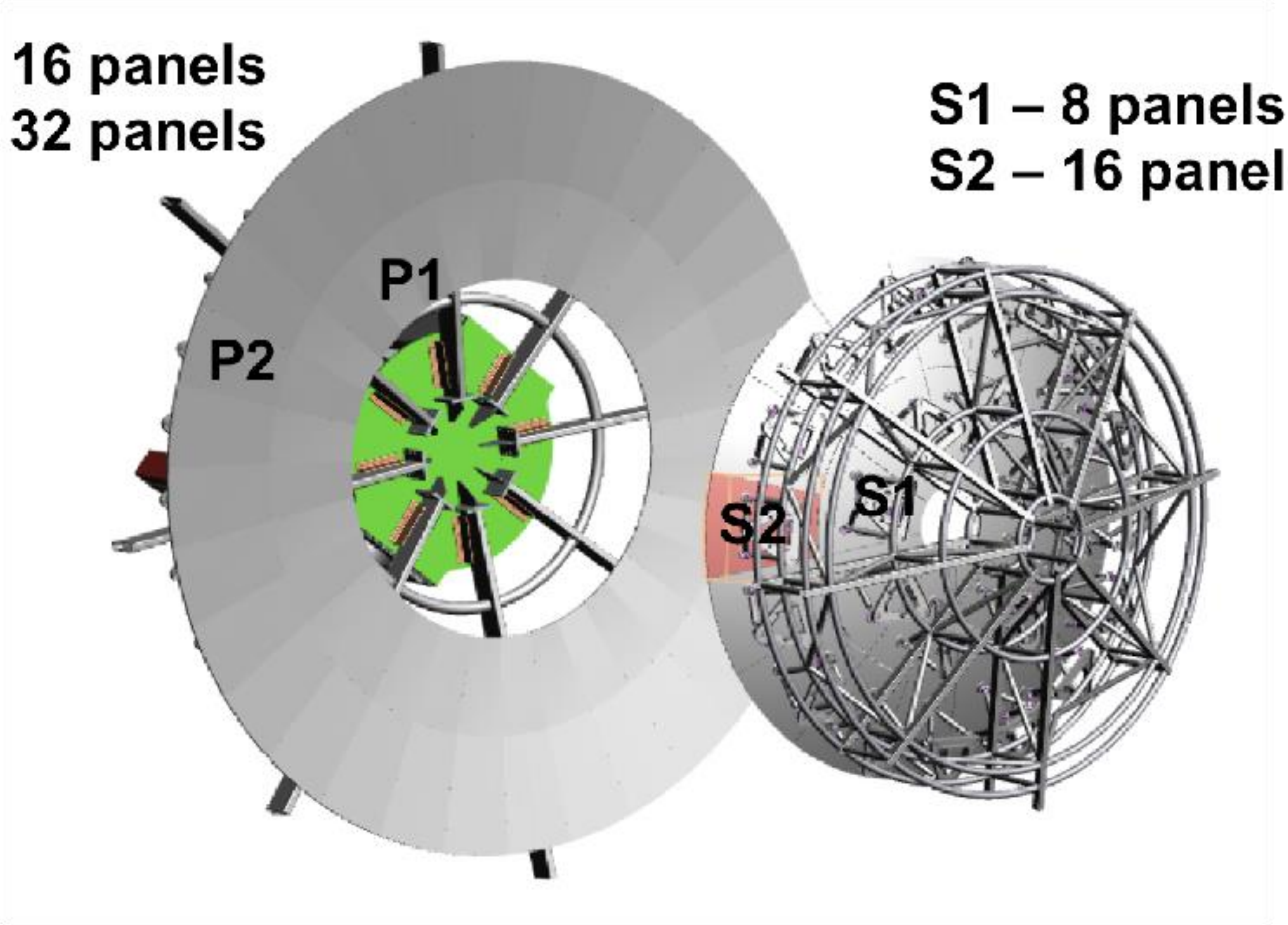
1 TeV γ

SCT

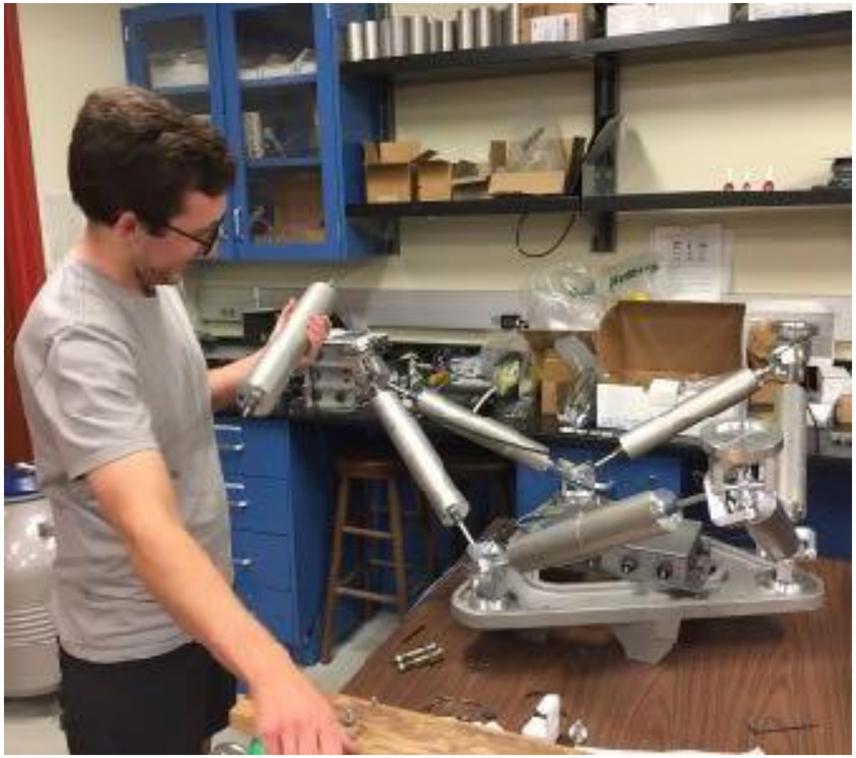
MST

3 TeV p

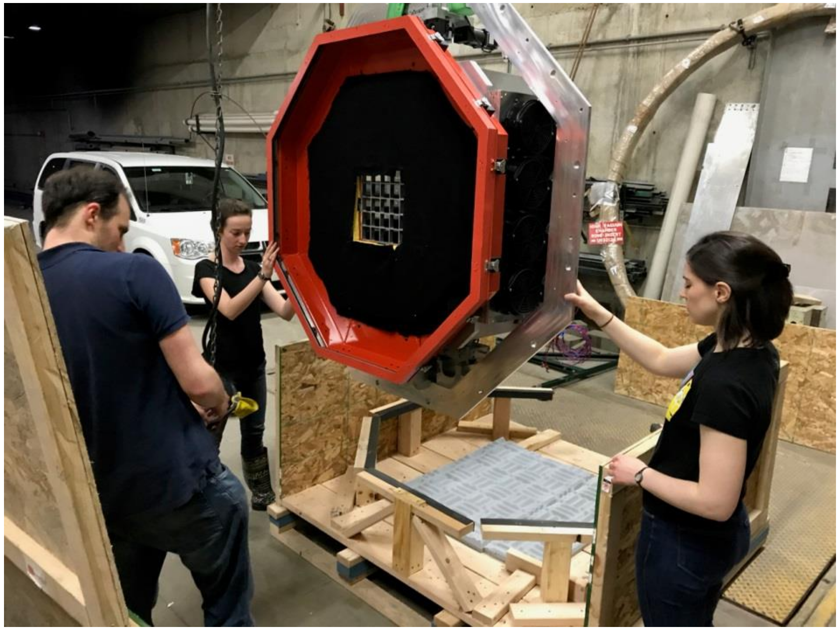
Optical design of SCT



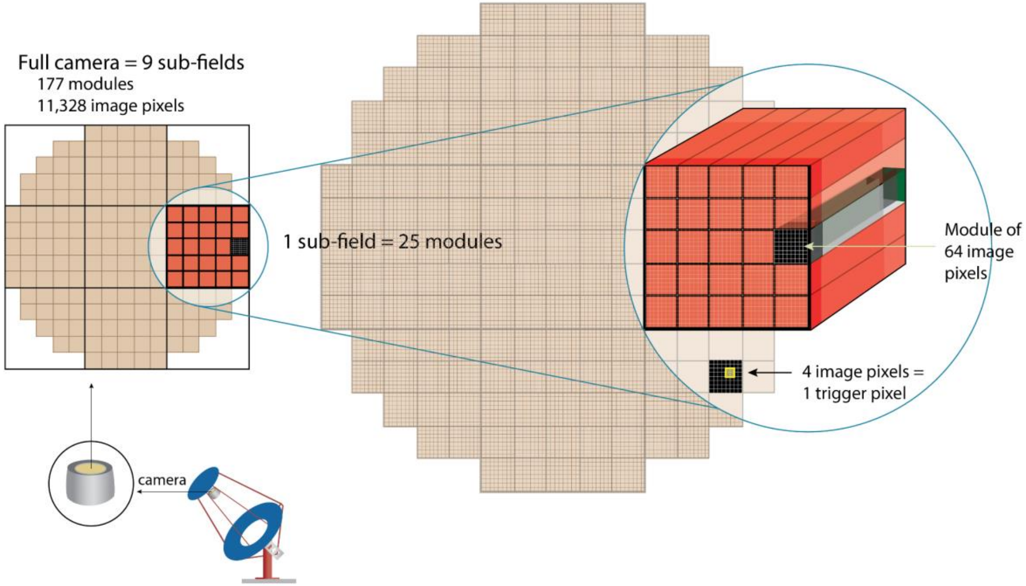
SCT: Complex motion of mirror segments on the primary requests 6 degrees of freedom

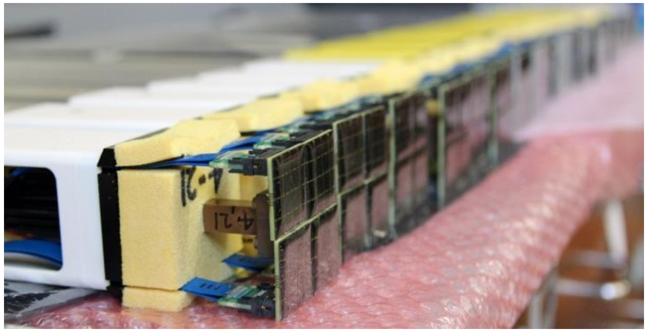


SCT side view and the mini-camera



SCT camera design





- modular design based on using 11328 SiPMs;
- waveform sampling using TARGET chips
- 8° field of view, 0.8 m focal plane
- each pixel 0.067°(6 mm) square

1st Use of SiPM in Space

- In the 1st time the SiPM was launched to space already in April 2005 in the "LAZIO-Sirad" Russian-Italian experiment onboard of the ISS.

29th International Cosmic Ray Conference Pune (2005) 00,

101–106

Preliminary results from the LAZIO-Sirad experiment on board of the International Space Station

F. Altamura, R. Bencardino, V. Bidoli, M. Casolino, M.P. De Pascale, M. Minori, P. Picozza, et al.,

1st Use of SiPM in Space

Page 2

…The silicon modules are based on the AMS tracker module design [6]. Each detector has an active area of 16 * 7 *cm*2. The system was triggered by three scintillators (S1-S2-S3) placed on top and bottom of the tower. ***In addition, between the scintillators and the silicon, there were two planes (T1-T2) each composed of 8 Silicon-Photomultipliers (SiPM) tiles.*** The order of planes is thus: S1, T1, Sil1-4, S2, T2 S3…

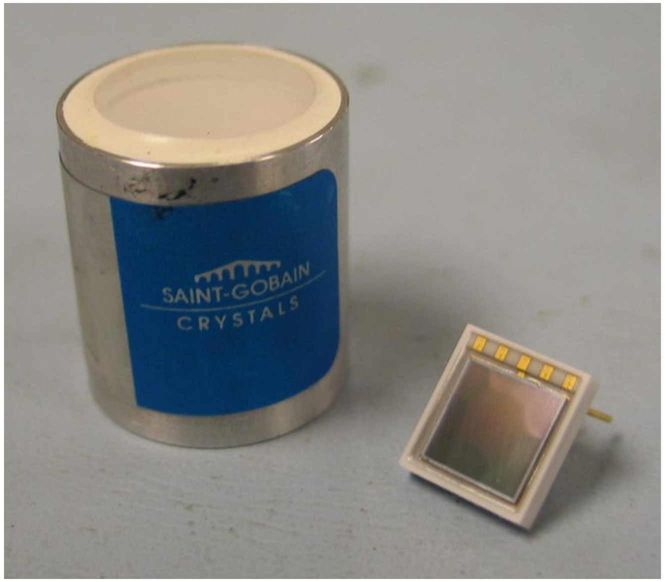
These were SiPM provided by B. Dolgoshein and his colleagues

Use of scintillators in space flights as radiation detectors

- The use of scintillators in space flight applications as radiation detectors are constrained by the volume, mass, power, and robustness of the associated readout device for the scintillation light. Traditional PMTs are large, fragile vacuum tubes that require high voltage and extensive mechanical support; their size can easily exceed that of the detector they are reading out. Still, PMTs have important advantages as the very high gain (10**6) and very fast response time. To fully realize the potential of new scintillator materials it is desirable to find a new light sensor that matches the QE, gain, and speed of PMTs in a compact, rugged, low-power package. The SiPMs offer the promise of just such a device.

Typical example of a small-size detector for possible application in space

P.F. Bloser, et al., NIM A, 2014



The 6mm x 6 mm Hamamatsu S10985-050C MPPC, together with a 0.5″ x 0.5″ packaged LaBr3 crystal from Saint-Gobain

The hermetically sealed LaBr3/SiPM Detector fabricated by Saint-Gobain, consisting of the S10985-050C and a 6mm x 6mm 10mm scintillator crystal Packaged in an aluminum housing

Balloon flight test of a Compton telescope based on scintillators with SiPM readouts

NIM A, P.F. Bloser, et al., Space Science Center, Univ. New Hampshire, Durham, NH03824, USA

The first high-altitude balloon flight test of a concept for an advanced Compton telescope making use of modern scintillator materials with silicon photomultiplier(SiPM)readouts. There is a need in the fields of high-energy astronomy and solar physics for new medium-energy gamma-ray (0.4-10MeV) detectors capable of making sensitive observations of both line and continuum sources over a wide dynamic range. A fast scintillator-based Compton telescope with SiPM readouts is a promising solution to this instrumentation challenge, since the fast response of the scintillators permits both the rejection of background via time-of-flight (ToF) discrimination and the ability to operate at high count rates.

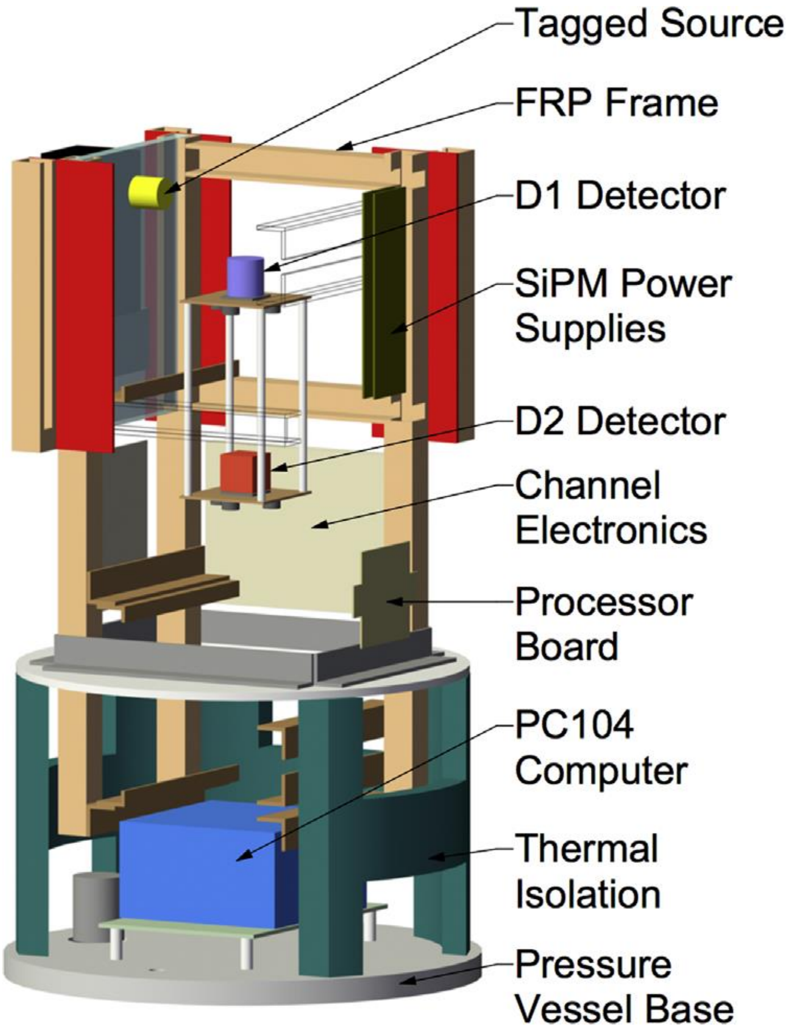
Balloon flight test of a Compton telescope based on scintillators with SiPM readouts

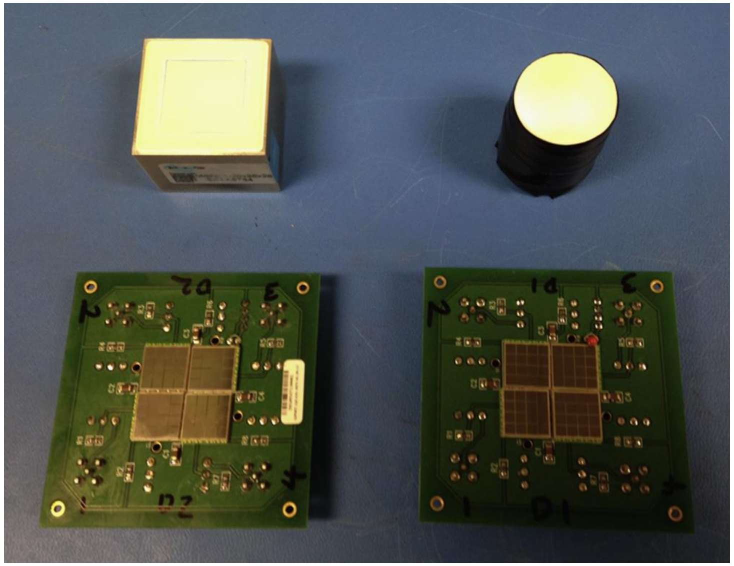
NIM A, P.F. Bloser, et al., Space Science Center, Univ. New Hampshire, Durham, NH03824, USA

- The Solar Compton Telescope (SolCompT) prototype presented here was designed to demonstrate stable performance of this technology under balloon-flight conditions. The SolCompT instrument was a simple two element Compton telescope, consisting of an approximately one-inch cylindrical stilbene crystal for a scattering detector and a one-inch cubic LaBr3:Ce crystal for a calorimeter detector. Both scintillator detectors were readout by 22 arrays of Hamamatsu S11828- 3344 MPPC devices.
- The SolCompT balloon payload was launched on 24 August 2014 from Fort Sumner, NM, and spent 3.75 h at a float altitude of 123,000ft

Balloon flight test of a Compton telescope based on scintillators with SiPM readouts

NIM A, P.F. Bloser, et al., Space Science Center, Univ. New Hampshire, Durham, NH03824, USA

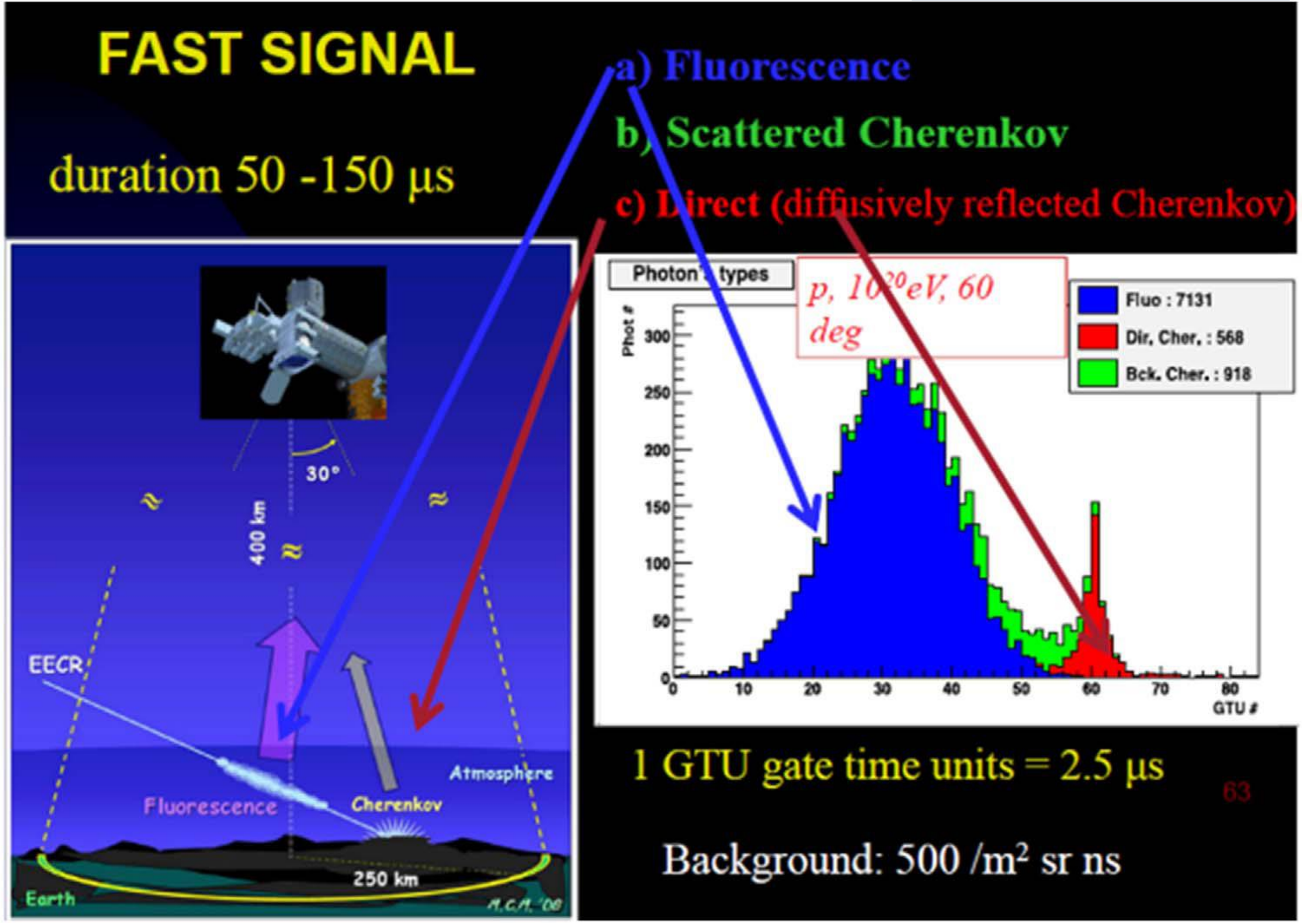




SolComp TD1 stilbene crystal(right), D2LaBr3 crystal (left), and Hamamatsu S11828-3344 SiPM readout arrays

EUSO

Fuglesang, NIM A, 2017



FAST SIGNAL

duration 50 -150 µs

a) Fluorescence

b) Scattered Cherenkov

c) Direct (diffusively reflected Cherenkov)

p, 10^{20} eV, 60 deg

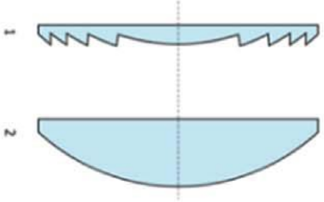
1 GTU gate time units = 2.5 µs

Background: 500 /m² sr ns

Two different options for EUSO

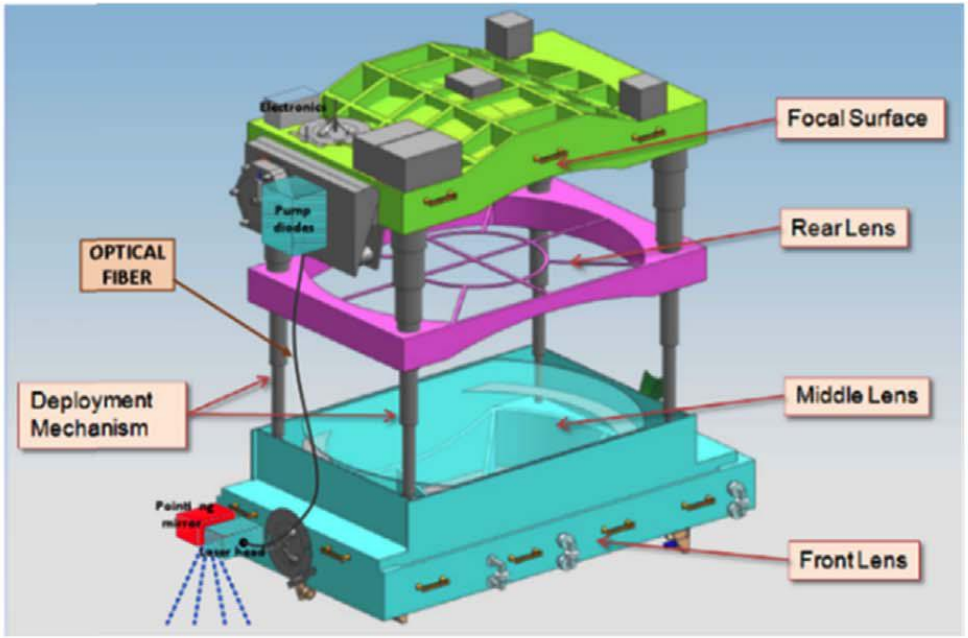
Fuglesang, NIM A, 2017

Fresnel lens
(JEM-EUSO)

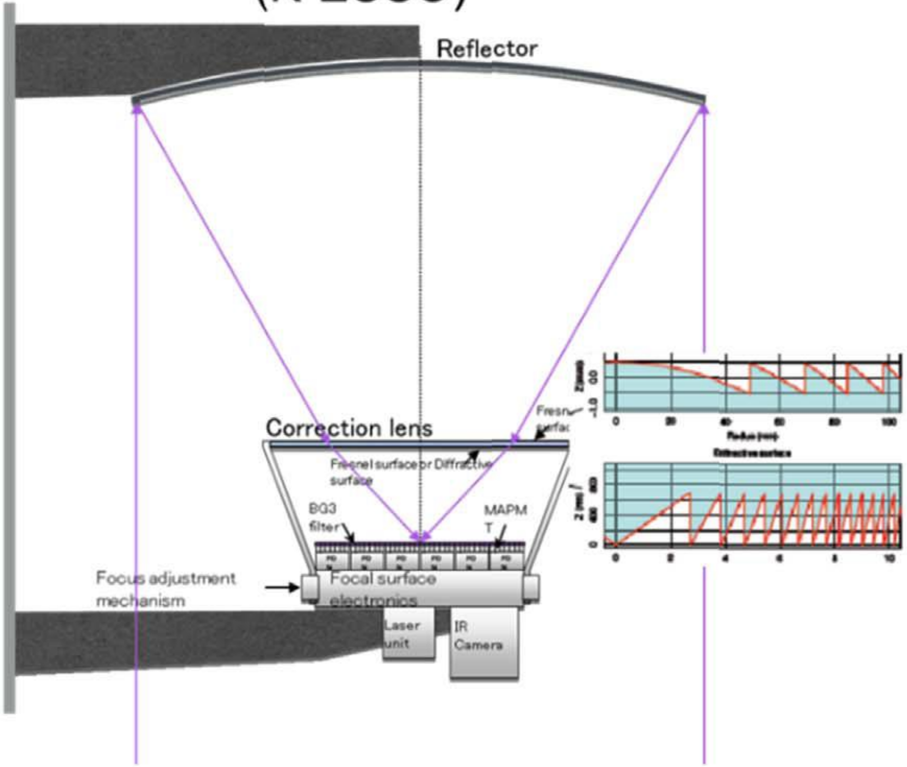


vs

Mirror
(K-EUSO)



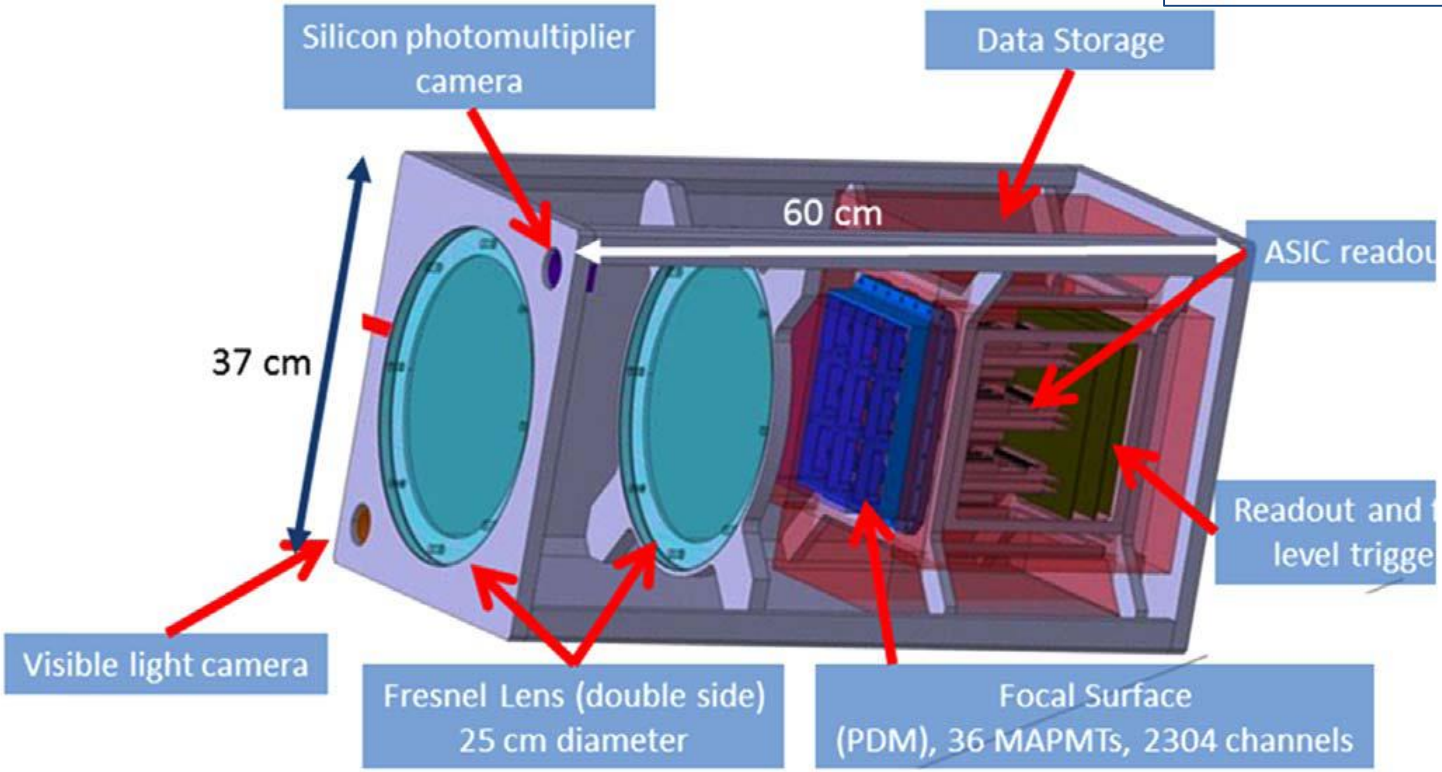
FOV : ± 30°



FOV : ± 14°

Sketch of mini EUSO, to be launched on ISS

Fuglesang, NIM A, 2017



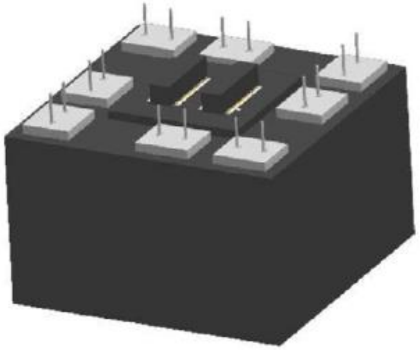
Currently the light is detected with 64-pixels multi-anode Photo-multiplier tubes (MAPMT). In the future silicone based photo sensors (SiPMs) are expected to be space-qualified and used

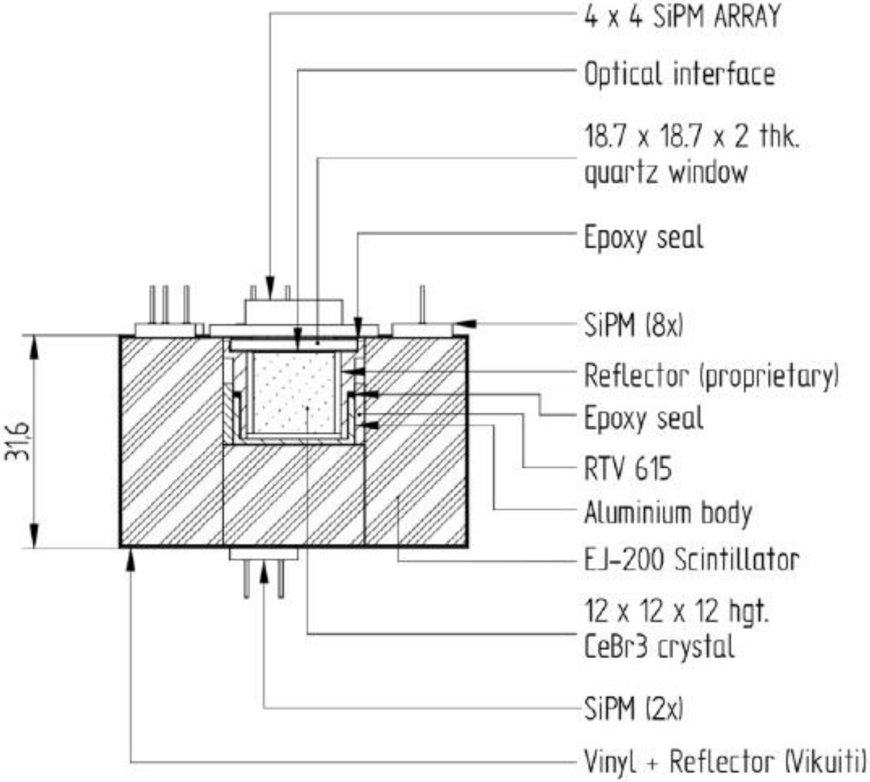
IGOSat - A 3U Cubesat for measuring the radiative/electrons content in low Earth orbit and ionosphere

Phan el al, NIM A, 2018

- The IGOSat (Ionospheric Gamma-ray Observations Satellite) satellite aims at measuring the spectrum of gamma radiations (20 keV to 2 MeV) and electrons (1 MeV to 20 MeV) in the polar zones and in the South Atlantic Anomaly, as well as the total electronic content of the ionosphere.
- The scintillator payload is composed of plastic (organic) and crystal (CeBr3, inorganic) scintillators read by a 4x4 matrix and 10 SiPMs
- The IGOSat project had completed its phase C in September 2017.
- The satellite is scheduled for launch in 2019 and is designed for one year of operation in space.

IGOSat





The electrons and gamma-rays measurements performed by the scintillation payload will allow completing existing measurements on Low Earth orbit and might also be useful for Space Weather applications.
This payload is also a technological demonstration as the CeBr3 Crystal and SiPM arrays have never been used on a satellite for gamma-ray detection.

SiPM @ Cryogenic T

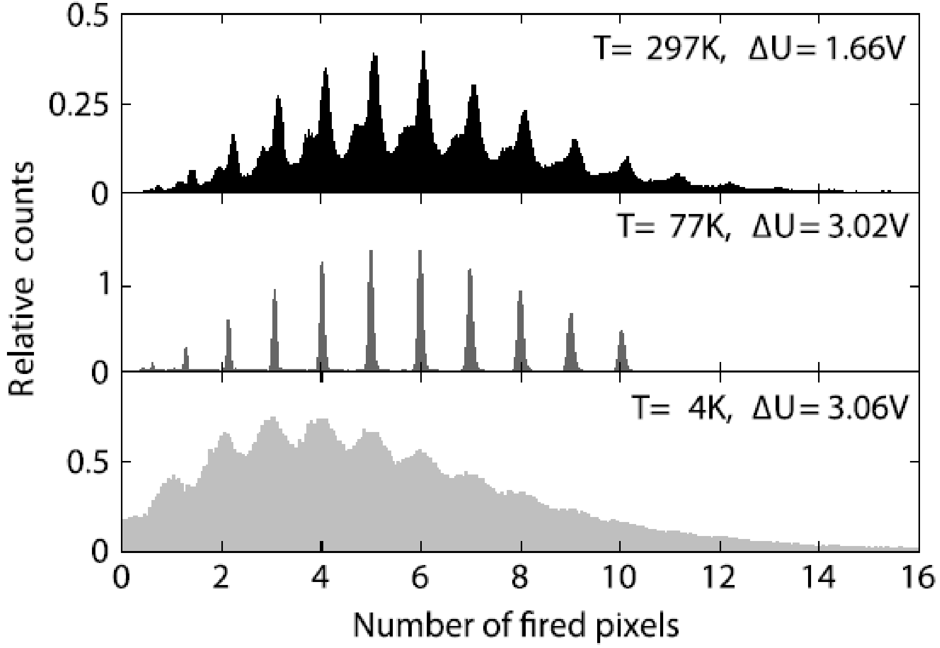
- The development of detectors based on liquefied noble gas (LAr, LXe) is performed for experiments studying physics beyond the Standard Model. For this purpose, it is fundamental to detect the Vacuum Ultra Violet (VUV) scintillation light, produced after the passage of ionizing particles inside the detector sensitive volume, to be used for trigger, timing and calorimetric purposes. Besides the tradi- tional cryogenic Photo Multiplier Tubes (PMTs), one possibility is to adopt SiliconPhoto-Multipliers (SiPMs).
- Direct detection of vacuum ultraviolet (VUV) light is required by liquid xenon (LXe) based experiments (λ scintillation ≈ 178 nm), while in liquid argon (LAr, λ scintillation ≈ 125 nm) a wavelength shifter is usually needed

SiPM @ cryogenic T

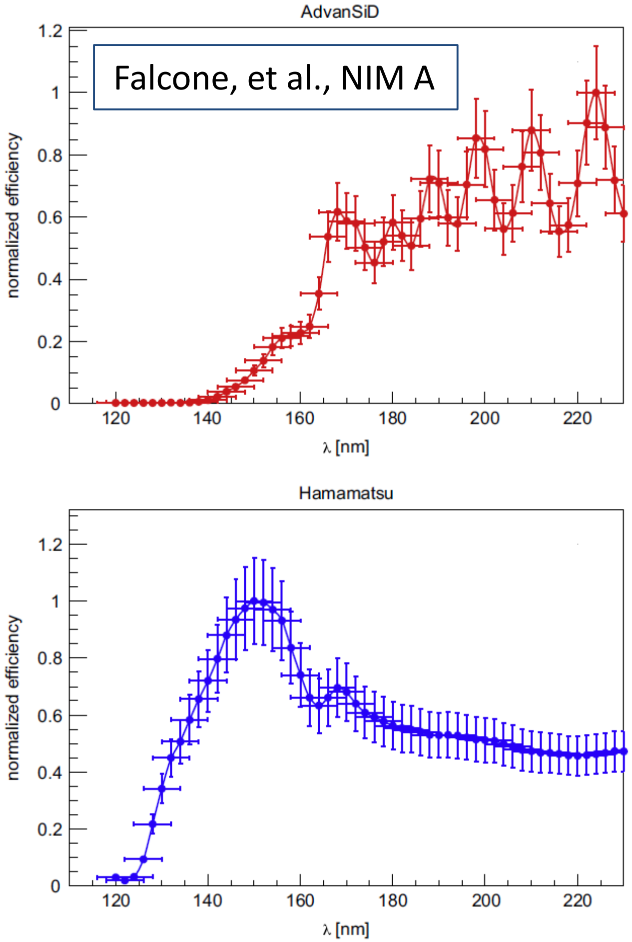
- A number of detectors dedicated to neutrino physics and DM searches use liquid noble gases as target medium. The aim is to detect the Vacuum Ultra-Violet (VUV) scintillation light produced after the passage of a charged particle in those media. Future liquid noble gases detectors dedicated to the search for sterile neutrino states and CP violation in the leptonic sector need strong magnetic fields, ~1 T or more, to distinguish better neutrino from anti-neutrino charged-current (CC) interactions. SiPM-based photo-detectors are mostly insensitive to magnetic field, thus being suitable to be deployed in these detectors. Their main drawback, however, is their non-sensitivity in the VUV light region, where emission spectrum of the noble gases scintillation is peaked.

Some characteristics of SiPM at cryogenic T

Achenbach, et al., NIM A



Charge spectra of SensL Series-C devices at T = 297°, 77° and 4° K



Falcone, et al., NIM A

AdvanSiD (top) and Hamamatsu (bottom) SiPMs response to the VUV light

VUV4-MPPC for cryogenic applications

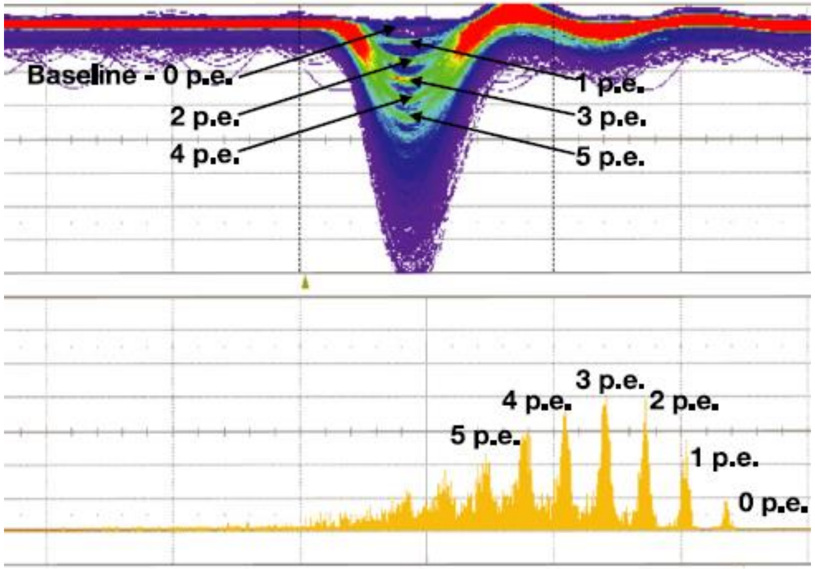
Arneodo, et al., NIM A

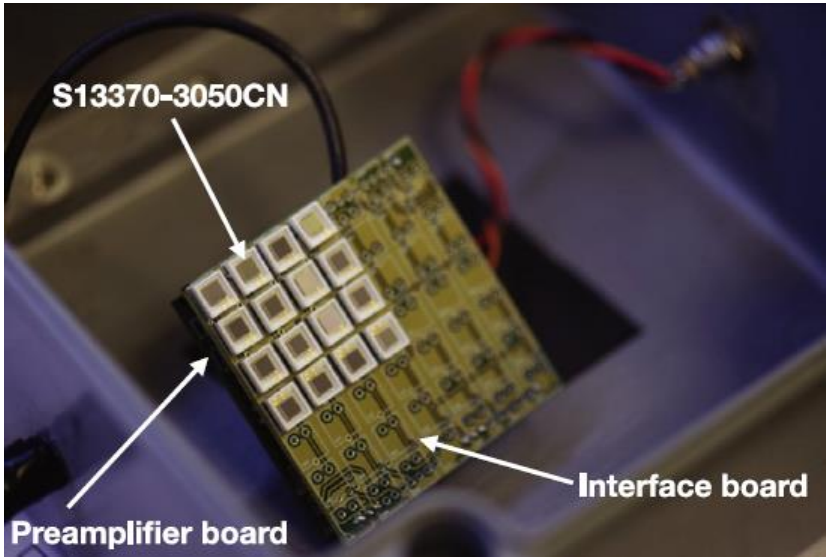
- The fourth generation of vacuum ultraviolet (VUV) multi-pixel photon counters (VUV4-MPPC) manufactured by Hamamatsu: the 3 × 3 mm^2 S13370-3050CN
- The most interesting features of a VUV4 MPPC are listed below:

1. can be used in cryogenic environment,
2. single photon counting capability,
3. PDE close to 25% at 178 nm,
4. can be operated at gains larger than 2×10^6

Test of a single photon detection capability; operating 16 VUV4 MMPC array

Arneodo, et al., NIM A





(Top) Waveforms taken in persistence mode at 175 K, $VOV = 3\ V$, by illuminating the detector with a LED pulser. The spacing between signal families is after summing up the 16 individual MPPCs

Example of a cryogenic experiment: XMASS

XMASS is a project aimed at detecting dark matter, pp and ^{7}Be solar neutrinos and neutrino-less double beta decay using a ton-scale ultra-pure liquid xenon

This project searches for nuclear recoils in liquid xenon caused by WIMPs. The advantages of using liquid xenon as the target material are, first, liquid xenon yields a large amount of scintillation light, comparable to the yield of a NaI(Tl) scintillator. Second, xenon has a high atomic number Z=54, and liquid xenon has a high density (∼2.9 g/cm^{3}). Thus, the target volume can be small, and external background (BG) gamma rays can be absorbed within a short distance from the detector wall.

Example of a cryogenic experiment: XMASS

- The XMASS detector is located at the Kamioka Observatory of the Institute for Cosmic Ray Research, the University of Tokyo, Japan.
- The detector has two components, the inner and outer detectors (ID and OD, respectively).
- The ID is equipped with 642 inward-facing photomultiplier tubes (PMTs) in an approximate spherical shape in a copper vessel filled with pure liquid xenon.
- The amount of liquid xenon in the sensitive region is 835 kg.
- The ID is installed at the centre of the OD, which is a cylindrical water tank with seventy two 20-inch PMTs
- PMTs are chosen to be from low-radioactivity glass

SENSE Project: Endeavour for a EU Roadmap for best, fast photo sensors, SiPM & PMT: what to do next

- SiPM
- To pursue large-size matrixes of SiPM for covering with sensor possibly large areas
- To further improve the SiPM parameters

Large size (composite) SiPM ?

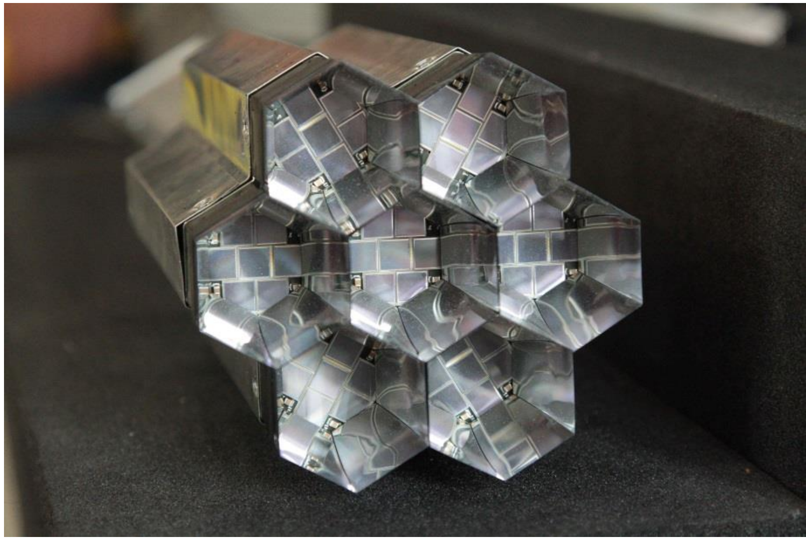
- Required fast timing limits the size of largest SiPM to several mm
- With increasing size of a SiPM cell its *C* and the gain ↑

  → also the X-talk is ↑ with size
- → good for “slow” applications, but need strong suppression of X-talk
- → R_{input} x C ↑

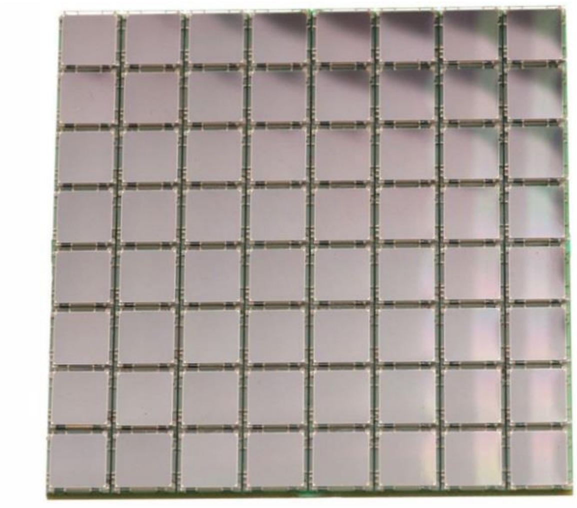
  → pulse becomes slow:

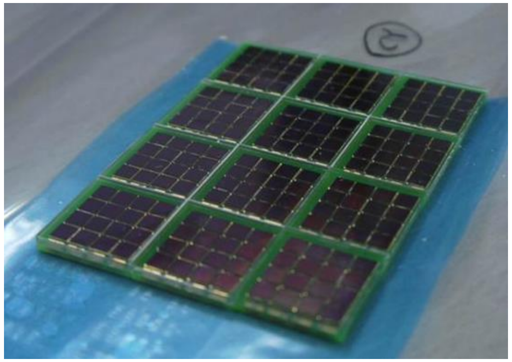
But one can still apply intelligent methods for overcoming these

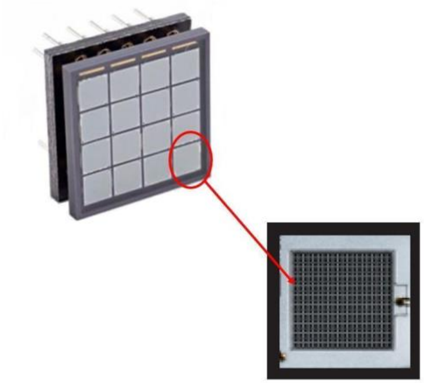
SiPM-based sensor cluster for MAGIC

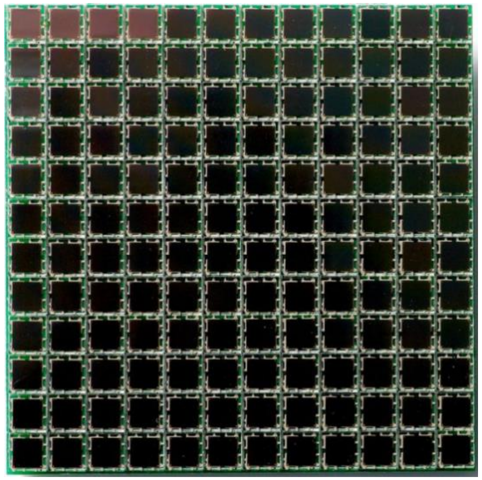


SiPM matrixes









SENSE Project: EU Roadmap for best fast photo sensors, SiPM: what to do in the next

- Move towards scalable, **scalable in size solution for building SiPM-based imaging cameras**
- Pursue special electronic solutions for using 1’ or 2’ size SiPM matrixes, where one can select the number of SiPM chips either to work individually or as a sum-of-a-group-of-N, providing trigger and a full readout; all controlled by software
- This could be, for example, a further development of the **MUSIC** chip (D. Gascon, et al).
- It can provide essentially full functionality of a (universal) camera of an arbitrary size
- This can find very wide applications not only in physics experiments, but also in medicine and industry

SENSE Roadmap, SiPM: what to do next

- We could try to further improve the performance of the SiPM
- We think we rather concrete, good ideas for
  - suppressing the cross-talk to well below < 1 % level for the cell size < 50µm
  - For providing the fast component of the signal, just due to the proper, alternative design of a SiPM

For making this real we will need to interact with industrial partners and we need non-negligible financial support; we are hoping that sometime soon in future we can arrive at this possibility

Conclusions

- SiPMs are used practically everywhere: in astro-particle physics and high-energy experiments, in space experiments and missions, in medical applications, in LIDAR, soon probably in many industrial applications, including the automotive one
- Their parameters have almost saturated, but still there is some space for important improvements
- Some diversity of commercial SiPMs in near future will probably be tailored to meet the needs of different applications: very large size or ultra-fast time resolution or a very high photo detection efficiency or a very high spatial resolution,…