# Ultimate Low Light-Level Sensor Development

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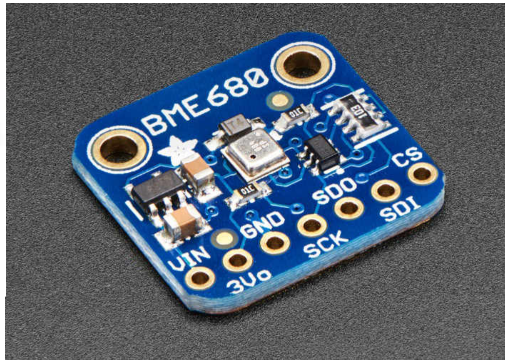
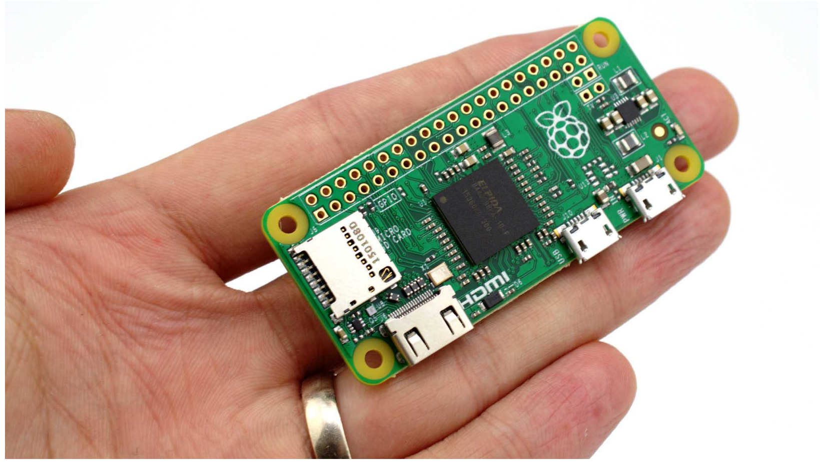
This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 713171

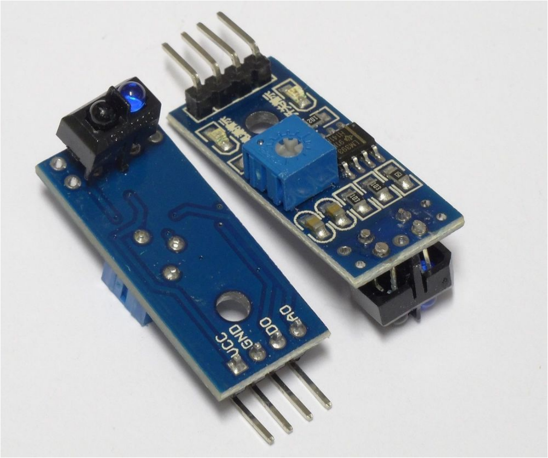
# Sensors – essential for science, but can be fun to play with



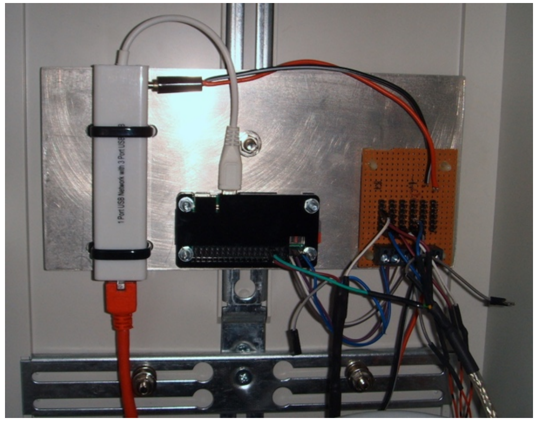




- Cheap equipment available
- Lots of software examples online
- Educates how to work with signals and data



# Sensors – at (my) home



Raspberry Pi

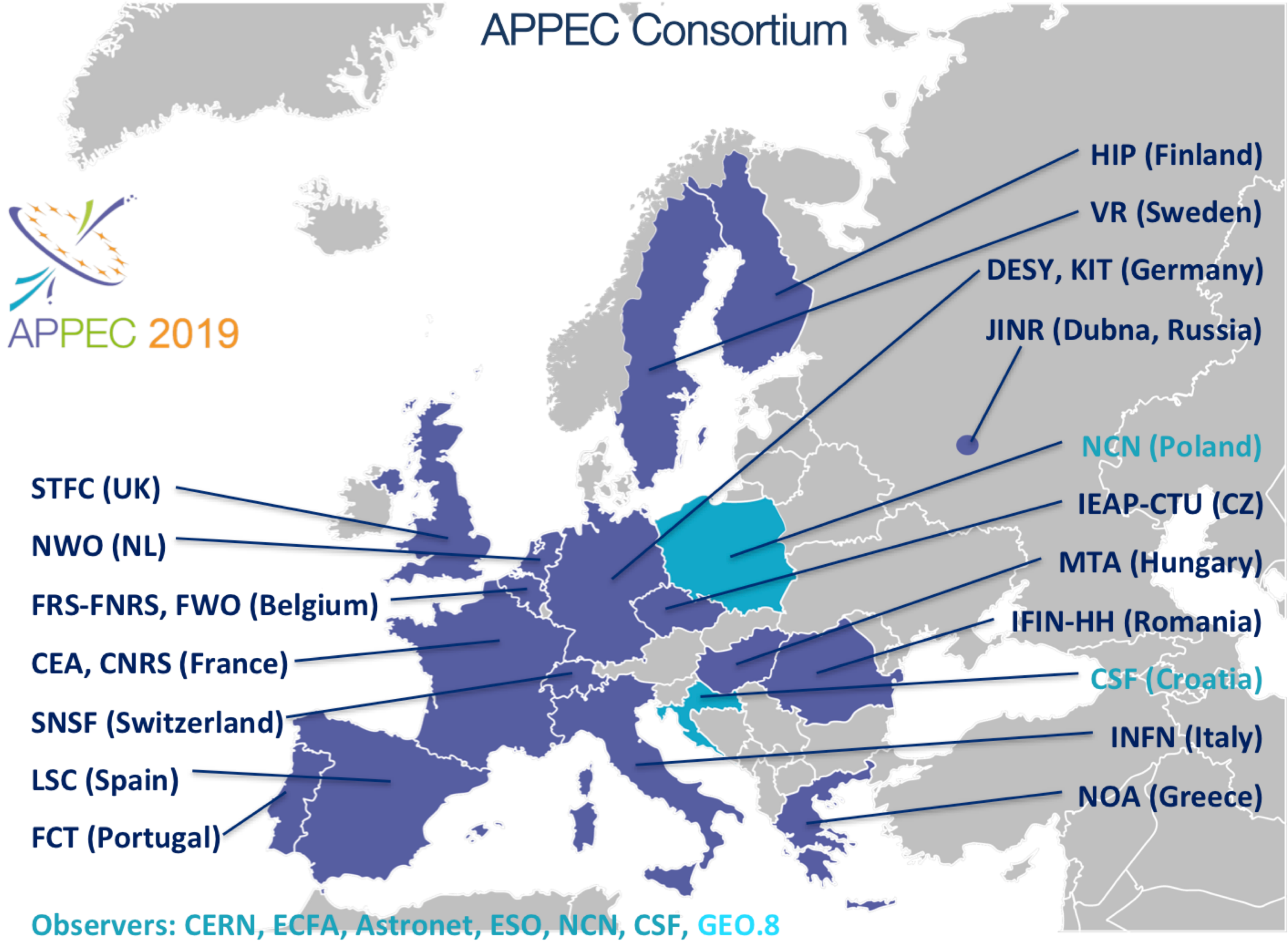
IR barrier to read out electricity meter


Ultrasonic distance measuring sensor to measure the filling level of rainwater tanks

# Outline

- Short intro to the AstroParticle Physics European Consortium (APPEC)
- Overview of the SENSE project
- Intro to low light-level sensors (will be followed up in detail by Thomas)
- Achievements of SENSE
- SENSE Detector School

# Astroparticle Physics European Consortium




Observers: CERN, ECFA, Astronet, ESO, NCN, CSF, GEO.8

# Astroparticle Physics European Consortium

The APPEC Consortium is based on an informal MoU between funding agencies and organisations (started in 2001) .
6 domains: **high-energy cosmic messengers** and **gravitational waves, dark matter** and **energy**, **proton decay**, and the properties of **neutrinos**.

APPEC is the outcome of the preparatory work provided by the EU funded ERANETs ASPERA and ASPERA-2 (2006-2012)

APPEC organisation is based on :

The **General Assembly** : strategic, decision making and supervisory body (Chair: TM (UniGeneva), Deputy Chair C. Stegmann (DESY), General Secretary (J. De Kleuver)

Teresa Montaruli

The **Scientific Advisory Committee** (L. Baudis Chair, vice-Chair: J. Monroe)

The **Joint Secretariat** (Chair: J. De Kleuver) running the **functional centres**

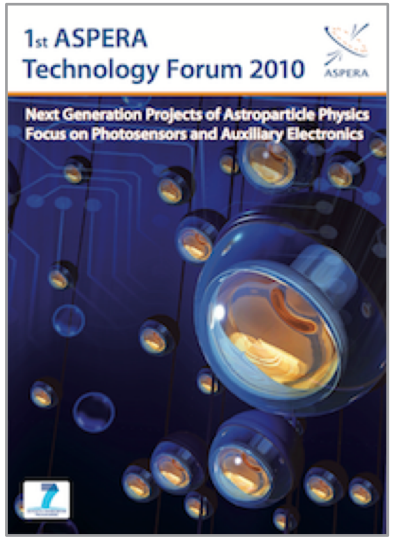

APPEC General Assembly 2016

# ASPERA/APPEC Technology Fora

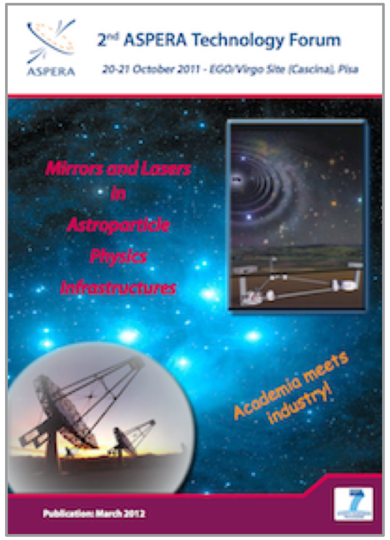
- Focus on technological challenges in astroparticle physics and neighboring fields
- Developers from academia and companies and interested young scientists are invited
- Talks, open discussions and interdisciplinary exchange

Brochures available from https://www.appec.de/doku.php?id=technology

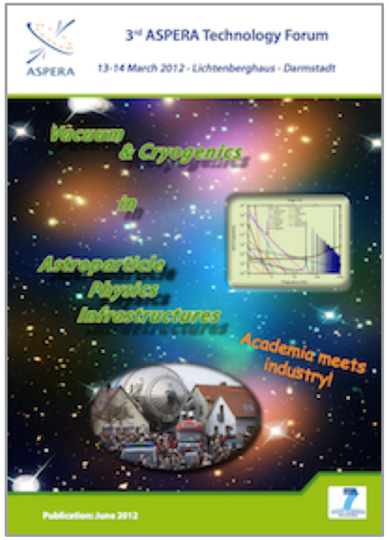
2010



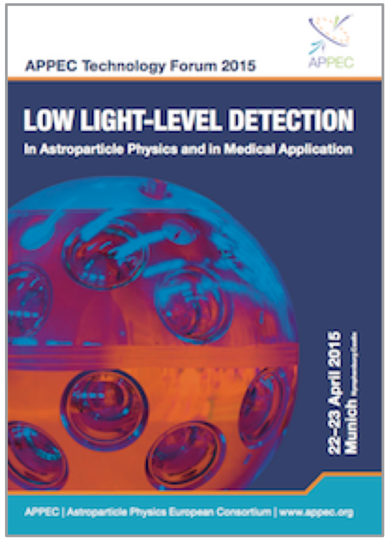

2011



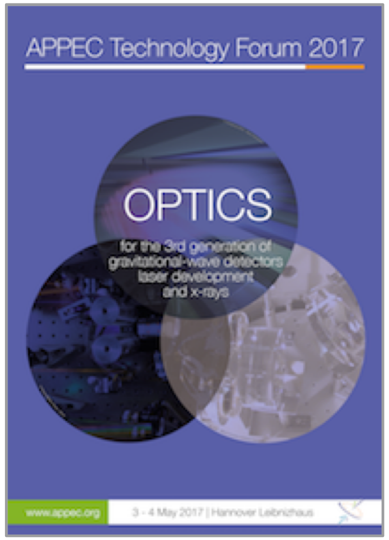

2012




2015




2017




2018

# APPEC Satellites (both EU funded)

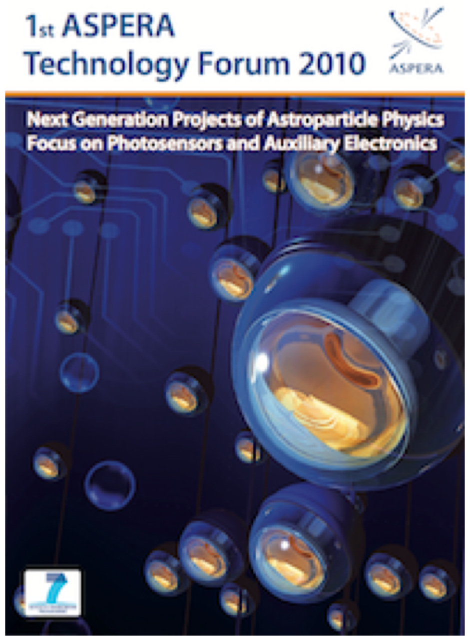
Support physics institutes
In their efforts to improve
on gender balance
(Sept. 2015 – Aug. 2018)
www.genera-project.com

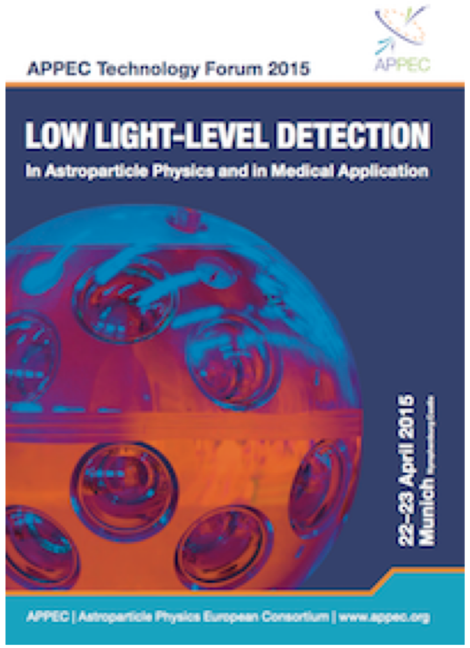
APPEC

Coordinate efforts
in R&D towards
ideal photosensors
(started Sept. 2016)
https://www.sense-pro.org/

# SENSE – Background

- SENSE is a Coordination and Support Action funded by EU in Horizon 2020 aiming to coordinate research and development efforts in academia and industry in low light-level sensoring
- Started in September 2016 for three years
- Evolved from ASPERA and APPEC technology fora in 2005 and 2010 and the LIGHT workshop series at Ringberg Castle



# SENSE – Why?

- For most astroparticle physics experiments signals consist of
  - individual photons
  - mostly with high timing resolution (nsec)
- Defines a need for low light-level sensors
- Coming experiments (e.g. CTA, KM3NeT) need several 100000 photosensors
- Substantial fraction (about 30-40%) of investment cost for astroparticle program is for photosensors

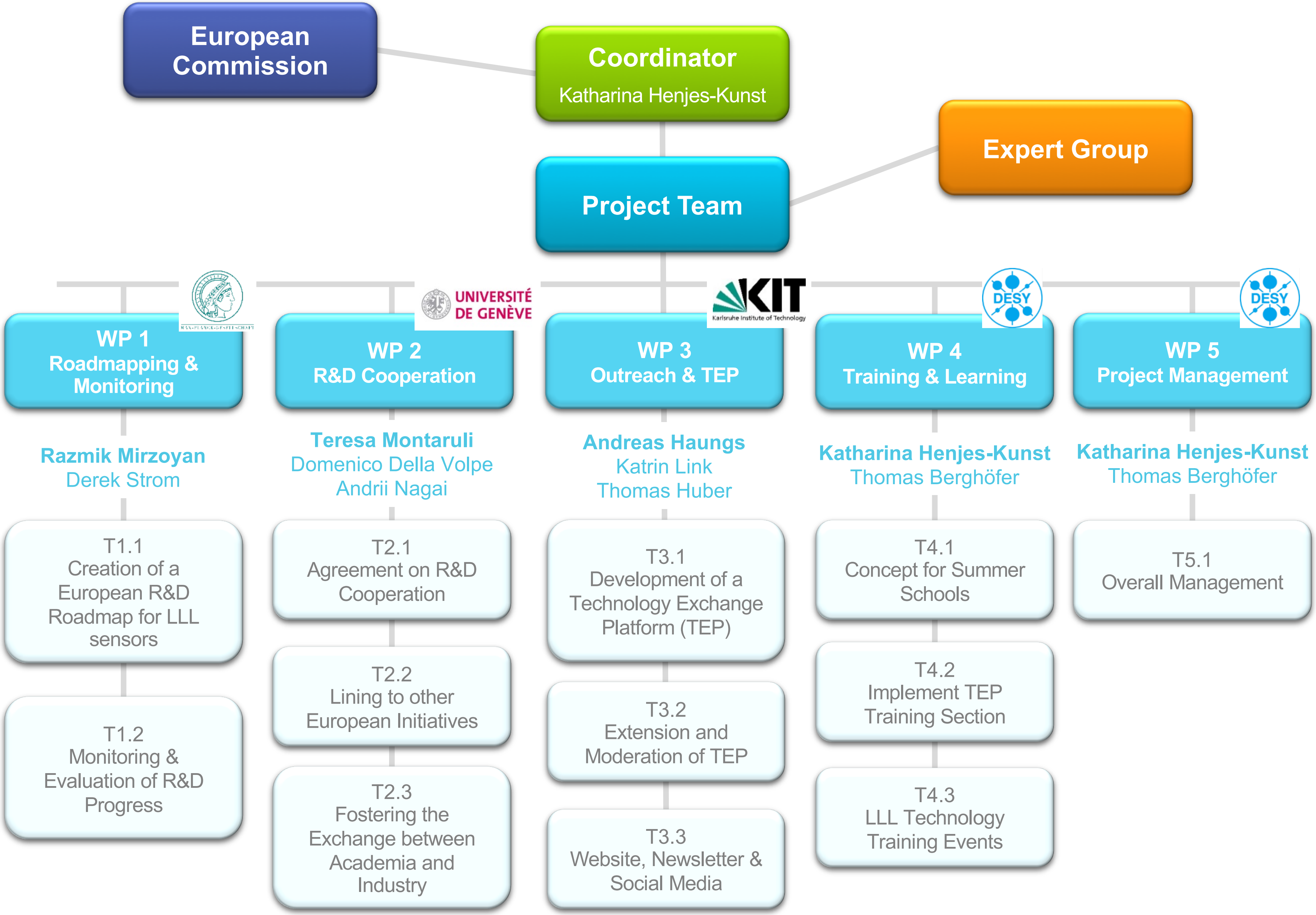
# SENSE – Why?

- Medical diagnostic instrumentation is the mass market for low light-level sensors (about 600000 PMTs/year)
- Demand of reaching lower and lower levels of in light detection efficiency in astroparticle, particle and nuclear physics in the main R&D driver
- Interesting synergies e.g. with medical applications, geosciences
- Any improvement in PMT technology evolving from science projects allows medical diagnostics industry to immediately come up with advanced products
- But, sensor improvements happened by chance

=> Can‘t we define the necessary R&D efforts in a roadmap?

# SENSE – What?

- Set up an expert group and facilitate the development of a European R&D roadmap towards the ultimate low light-level (LLL) sensors,
- Monitor and evaluate the progress of the developments with respect to the roadmap,
- Coordinate the R&D efforts of research groups and industry in advancing LLL sensors,
- Develop a database of light sensor specifications and lab equipment, test stands and expertise available in the different institutions,
- Liaise with strategically important European initiatives and research groups and companies world-wide,
- Create the Technology Exchange Platform to enable an efficient exchange between researchers and developers being involved in SENSE,
- Prepare training events and teaching material especially towards young researchers,
- to frame up a technology training session that can be implemented in any existing summer/winter school.


European Commission
Coordinator
Katharina Henjes-Kunst
Expert Group
Project Team
WP 1
Roadmapping & Monitoring
Razmik Mirzoyan
Derek Strom
T1.1
Creation of a European R&D Roadmap for LLL sensors
T1.2
Monitoring & Evaluation of R&D Progress
UNIVERSITÉ DE GENÈVE
WP 2
R&D Cooperation
Teresa Montaruli
Domenico Della Volpe
Andrii Nagai
T2.1
Agreement on R&D Cooperation
T2.2
Lining to other European Initiatives
T2.3
Fostering the Exchange between Academia and Industry
KIT
Karlsruhe Institute of Technology
WP 3
Outreach & TEP
Andreas Haungs
Katrin Link
Thomas Huber
T3.1
Development of a Technology Exchange Platform (TEP)
T3.2
Extension and Moderation of TEP
T3.3
Website, Newsletter & Social Media
DESY
WP 4
Training & Learning
Katharina Henjes-Kunst
Thomas Berghöfer
T4.1
Concept for Summer Schools
T4.2
Implement TEP Training Section
T4.3
LLL Technology Training Events
DESY
WP 5
Project Management
Katharina Henjes-Kunst
Thomas Berghöfer
T5.1
Overall Management

SENSE

Razmik Mirzoyan
Max-Planck-Gesellschaft, Munich, Germany

# SENSE – Expert Group

Experts board

Sergey Vinogradov
Lebedev Physical Institute, Moskow, Russia

Elena Popova
MEPHI, Moscow, Russia

Klaus Attenkofer
Brookhaven National Laboratory, Upton, US

Bayarto Lubsandorzhiev
INR of the Russian Academy of Sciences, Moskow, Russia

Samo Korpar
Jožef Stefan Institute, Ljubljana, Slovenia

Osvaldo Catalano
IASF-Palermo/INAF, Palermo, Italy

Claudio Piemonte
Fondazione Bruno Kessler, Trento, Italy

John Smedley
Brookhaven National Laboratory, Upton, US

Stefan Schönert
Technische Universität München, Munich, Germany

Eric Delagnes
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Peter Krizan
Jožef Stefan Institute, Ljubljana, Slovenia

Nicoleta Dinu-Jaeger
CNRS ARTEMIS, Nice, France

Giovanni Bonanno
INAF - Osservatorio Astrofisico di Catania, Catania, Italy

David Gascon
Institut de Ciències del Cosmos (ICCUB), Barcelona, Spain

Wei Shen
KIP, Heidelberg University, Heidelberg, Germany

Hiro Tajima
ISEE, Nagoya University, Nagoya, Japan

Andrey Formozov
INFN/ Sezione di Milano, Milan, Italy

SENSE

Acts as advisory panel

# Low Light-Level Sensors

Here two basic principles of low light-level (LLL) sensors:

- Photomultiplier Tubes (PMT)
- Silicon Photomultiplier (SiPM)

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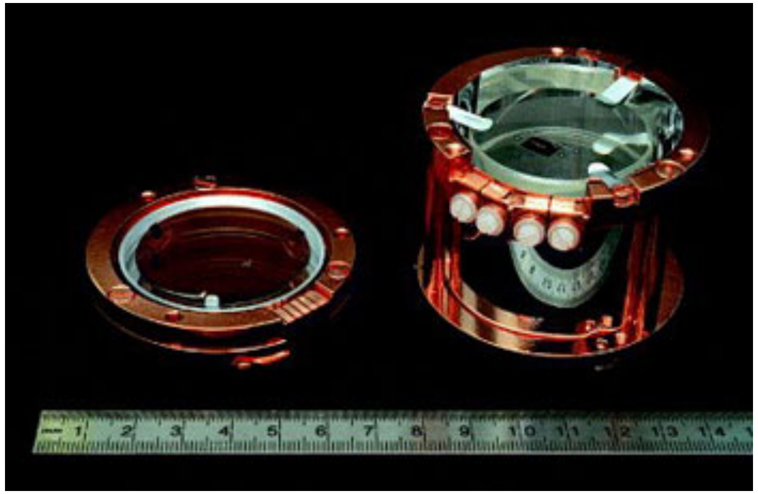
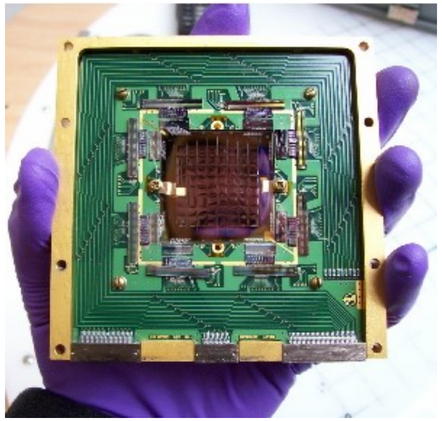
Others (see SENSE brochure):

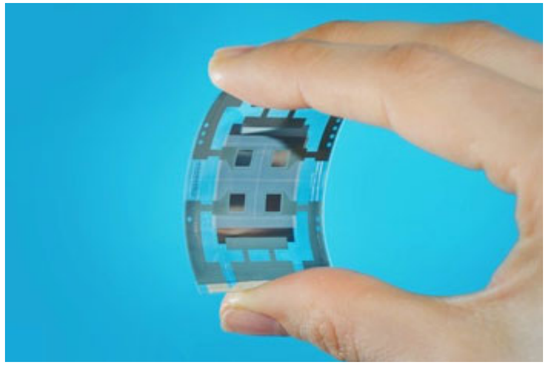
Abalone concept

Neganov-Luke sensor





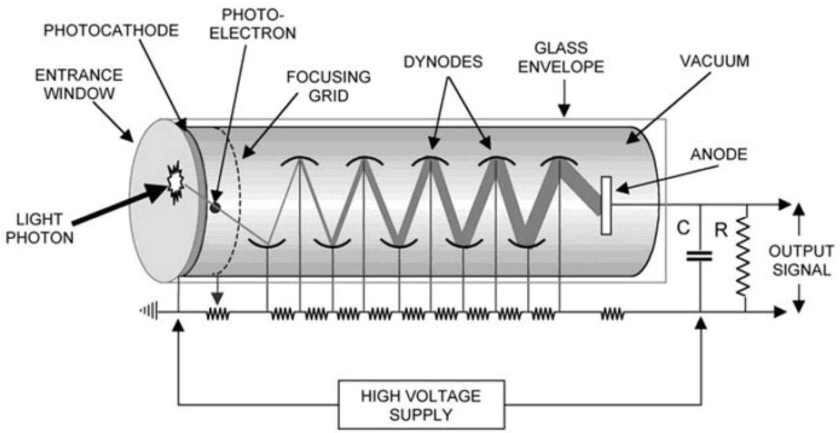
Transition Edge Sensor

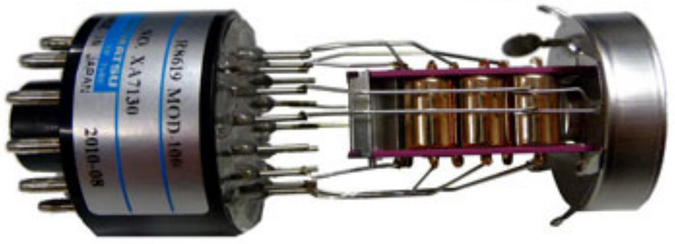


Organic sensors

# The classical PMT: one of the best known light sensors

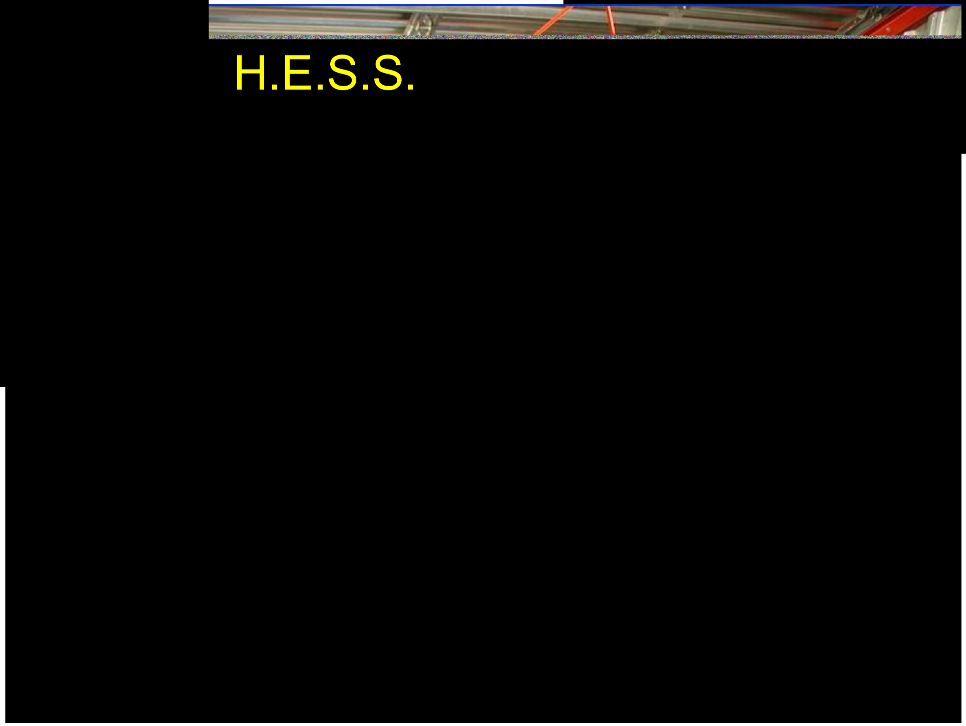
- The impinging photons kick out $e^-$ from the thin photo cathode (~25nm)
- $e^-$ are accelerated in a static electric field (~100V) and hit dynodes arranged in a sequential topology
- Every dynode enhances the number of $e^-$ by a factor 4-5
- The net gain of a PMT could reach $10^5 – 10^7$
- That allows measuring single photons



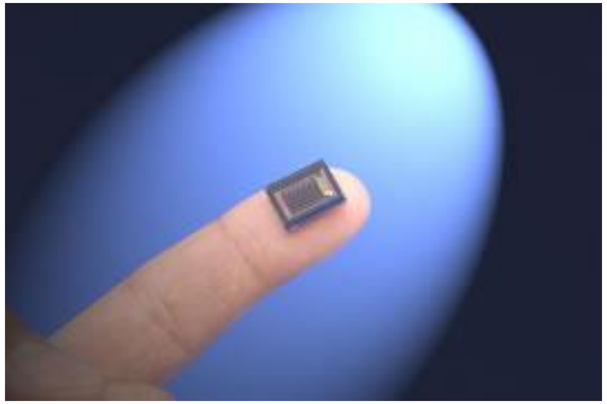



# Photos of imaging cameras of leading IACTs





# Low Light-Level Sensors: PMTs



<u>Advantages</u>

Quantum efficiency: 36 – 43%

Gain: $10^5 - 10^7$

Single photon resolution

Low dark current

<u>Disadvantages</u>

Mechanically fragile

Need HV (~few kV) power supply

Sensitive to magnetic fields

Afterpulsing

# HAMAMATSU
PHOTON IS OUR BUSINESS

# PHOTOMULTIPLIER TUBE R12992-100

## FEATURES
- High sensitivity
- Low noise

## APPLICATIONS
- High energy physics

## SPECIFICATIONS

### GENERAL

| Parameter | | Description / Value | Unit |
|---|---|---|---|
| Spectral response | | 300 to 650 | nm |
| Wavelength of maximum response | | 400 | nm |
| Window material | | Borosilicate glass | — |
| Photocathode | Material | Super bialkali | — |
| | Minimum effective area | $\phi$30 | mm |
| Dynode | Structure | Linear-focused | — |
| | Number of stages | 7 | — |
| Base | | JEDEC No. B12-43 | — |
| Operating ambient temperature | | -30 to +50 | °C |
| Storage temperature | | -80 to +50 | °C |
| Suitable socket | | E678-12A (Supplied) | — |

### MAXIMUM RATINGS (Absolute maximum values)

| Parameter | | Value | Unit |
|---|---|---|---|
| Supply voltage | Between anode and cathode | 1700 | V |
| | Between anode and last dynode | 250 | V |
| Average anode current | | 0.1 | mA |

### CHARACTERISTICS (at 25 °C)

| Parameter | | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|
| Cathode sensitivity | Luminous (2856 K) | 90 | 120 | — | μA/lm |
| | Radiant at 400 nm | — | 110 | — | mA/W |
| | Blue sensitivity index (CS 5-58) | 12.5 | 14.0 | — | — |
| | Quantum efficiency at 350 nm | 32 | 40 | — | % |
| Anode sensitivity | Luminous (2856 K) | — | 4.8 | — | A/lm |
| | Radiant at 400 nm | — | $4.4 \times 10^3$ | — | A/W |
| Gain | | — | $4.0 \times 10^4$ | — | — |
| Anode dark current (After 30 minute storage in darkness) | | — | 5 | 20 | nA |
| Time response | Anode pulse rise time | — | 2.3 | — | ns |
| | Electron transit time | — | 20 | — | ns |

**NOTE:** Anode characteristics are measured with a voltage distribution ratio and supply voltage shown below.

### VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

| Electrodes | K | Dy1 | Dy2 | Dy3 | Dy4 | Dy5 | Dy6 | Dy7 | P |
|---|---|---|---|---|---|---|---|---|---|
| Ratio | 350 V (ZD) | 1 | 2 | 1 | 1 | 1 | 2 | 1 | |

Supply voltage: 1000 V, K: Cathode, Dy: Dynode, P: Anode, ZD: Zener diode



## PHOTOMULTIPLIER TUBE R12992-100

Figure 1: Typical spectral response

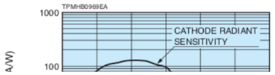



Figure 2: Typical gain

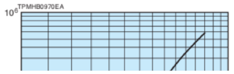
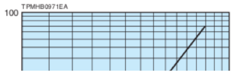


Figure 3: Typical dark current



# Some Terminology

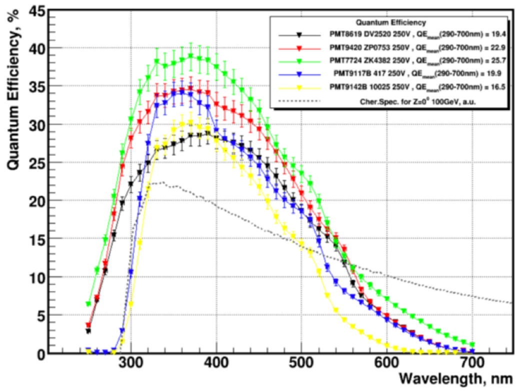
**Quantum Efficiency** : QE(λ)
ratio of generated photoelectrons to impinging photon flux

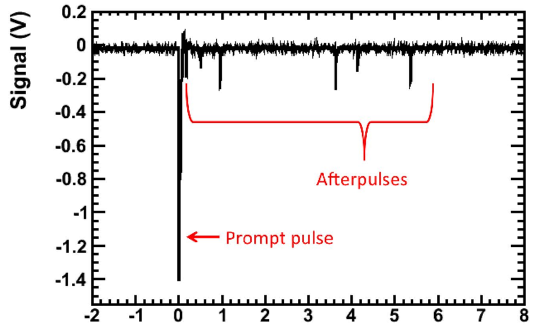
**Photoelectron Collection Efficiency** : ph.e.CE(λ)
fraction of generated photoelectrons that are collected by the 1st dynode

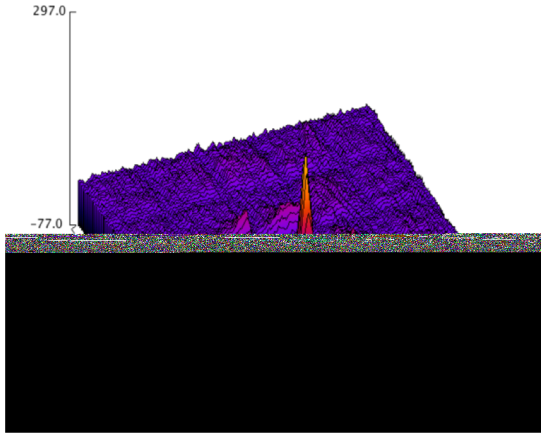
**Photon Detection Efficiency** : PDE(λ) = QE(λ) x ph.e.CE(λ)

**Afterpulses** – delayed pulses generated by non-photo-generated carriers (e.g. trapped carriers).

**Cross-Talk** – photon emission propagating to and triggering neighboring cells



# Quantum Efficiency

Quantum efficiency (QE) of a sensor is defined as

$$QE = N(\text{photon electrons}) / N(\text{photons})$$

Conversion of a photon into photon electrons is a purely binomial process (and not poisson!)

Assume N photons are impinging onto a photocathode and every photon has the same probability P to kick out a photon electron.

Then the mean number of photon electrons is $N \times P$

and the Variance is equal to $N \times P \times (1 - P)$

and the signal to noise ratio is $\sqrt{[N \times P/(1 - P)]}$

# Signal-to-Noise Ratio

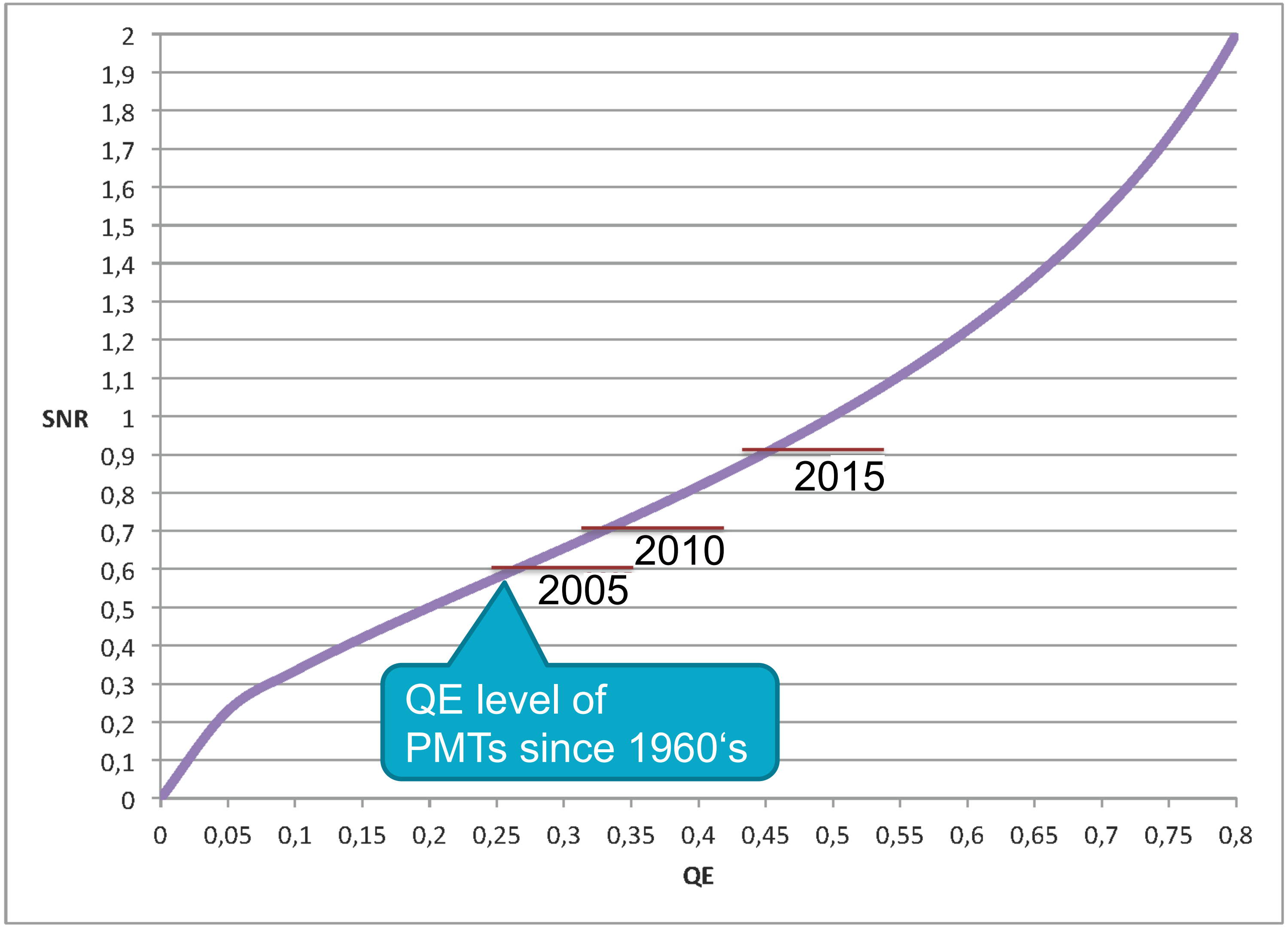
QE level of
PMTs since 1960's

For example,

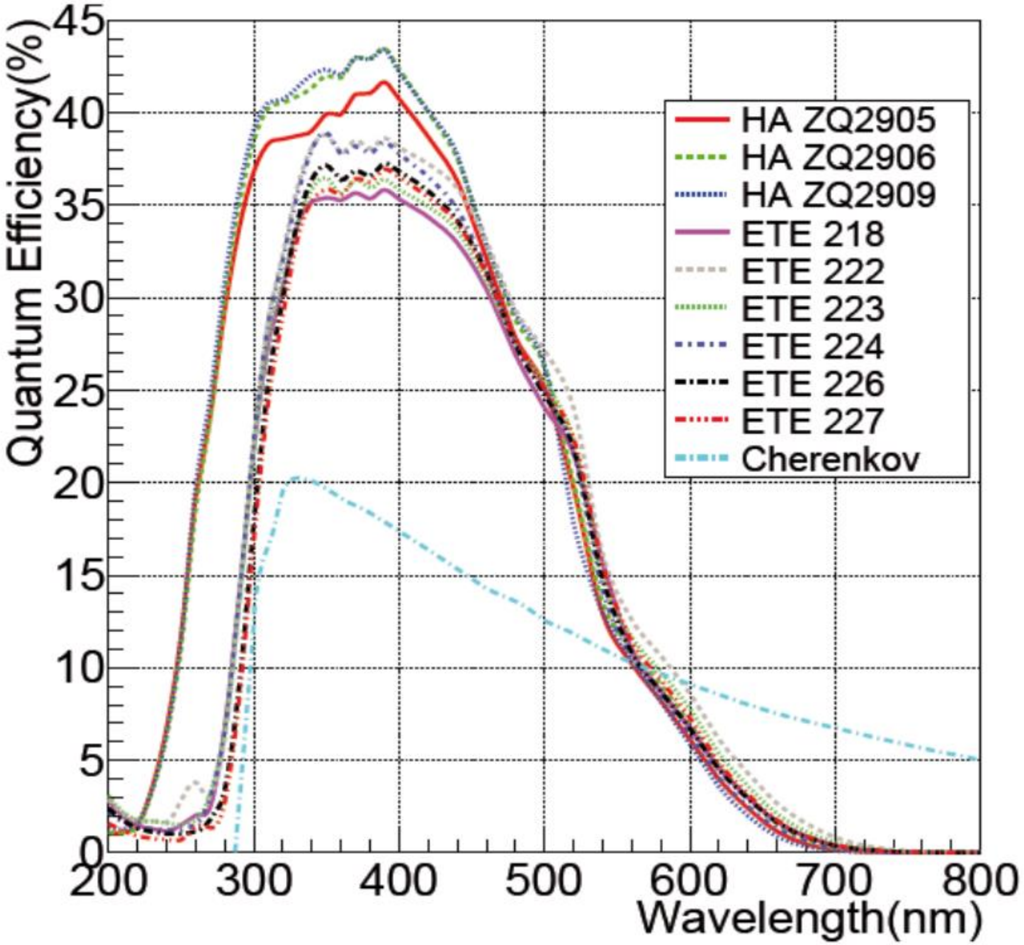
for N = 1

(single impinging photon):

Result of two PDE improvement programs with manufacturers Hamamatsu (Japan), Photonis (France) and Electron Tubes Enterprises (England).



# Quantum Efficiency of modern PMTs




Mirzoyan 2015

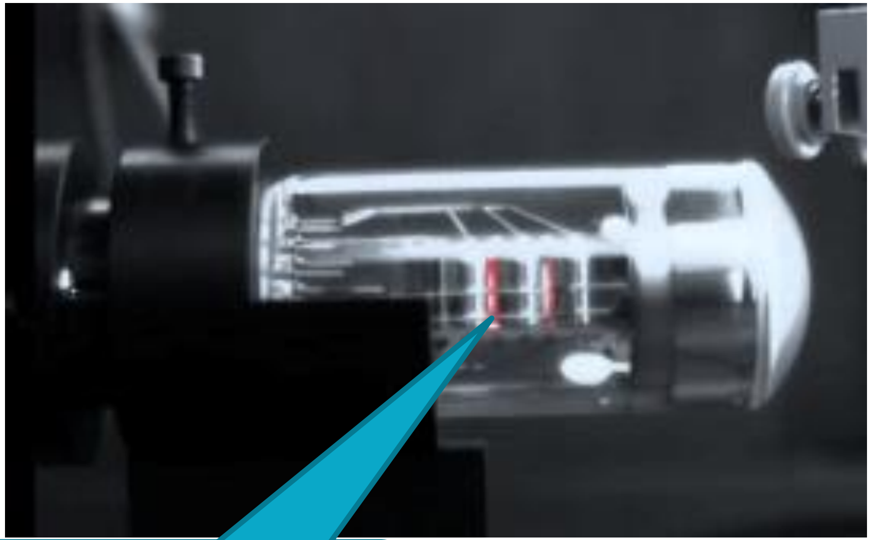
# How to improve the QE of PMTs

- Improve the material purity
- Improve “crystallinity”
- Reduce defects
- Move towards smooth surface structure
- Reduce electron affinity – further optimize surface treatment
- Build a preferential electrical field within the cathode
- Optimize the wavelength response
- In the real PMT design one can incorporate reflectors for re-utilizing the transmitted, not interacted light

# Light-induced afterpulsing

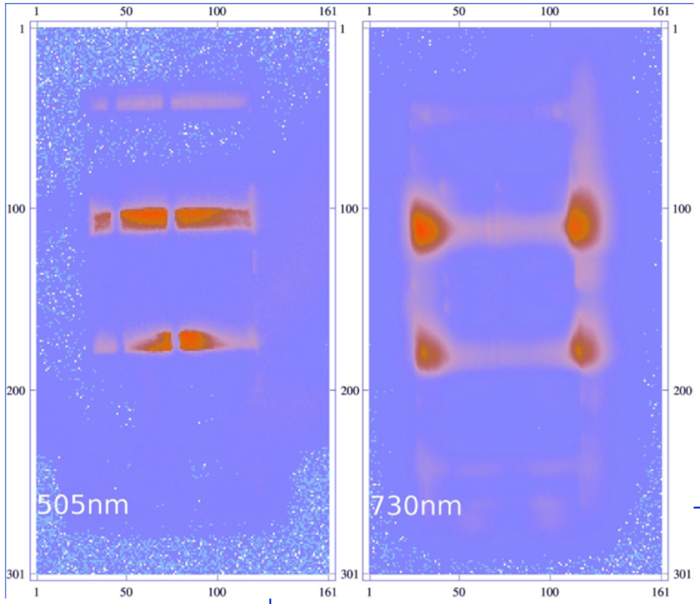
In a huge number of processes and phenomenae light is emitted

- Also true for light sensors
- The majority of known light sensors not only detect light, but also emit light
- This can be used for diagnostic purposes
- One can still improve the performance of existing sensors by reducing the impact of the emitted light

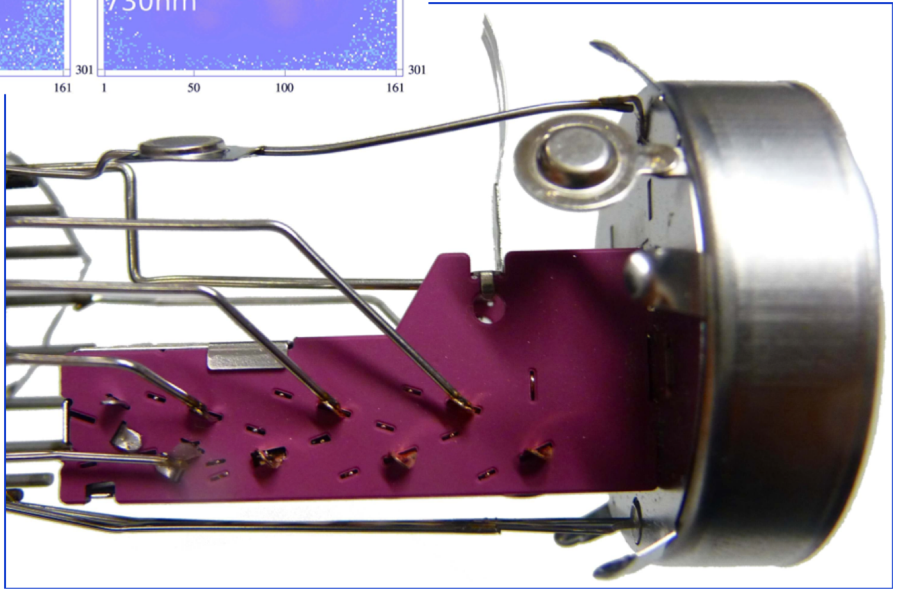


Light emission

# Light-induced afterpulsing




Not only the dynodes of a PMT, bombarded by $e^-$, are glowing, but also its holding structure. The material of the isolating holding structure could be largely identified as corundum chromium (ruby)



Mirzoyan 2019

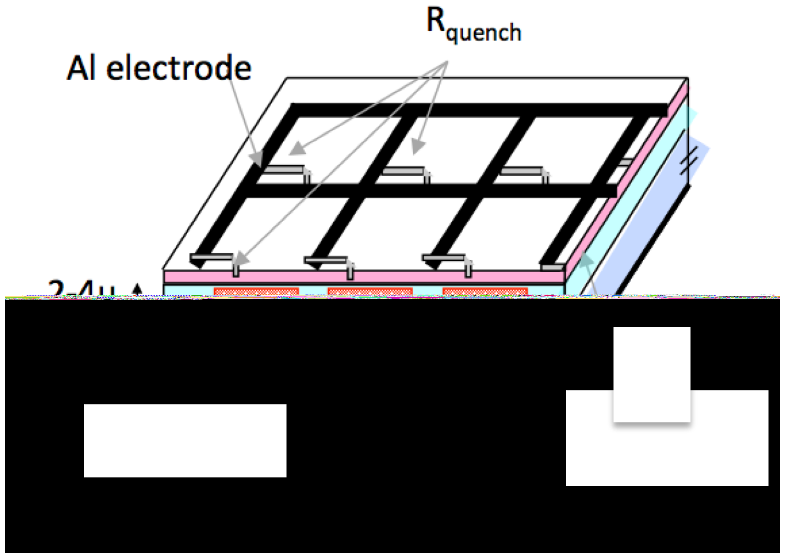
# Low Light-Level Sensors: SiPMs

## Silicon Photomultiplier

Invented by Boris Dolgoshein (MEPhI)

Single photon avalanche diode (SPAD)
p-n junction under reverse bias*

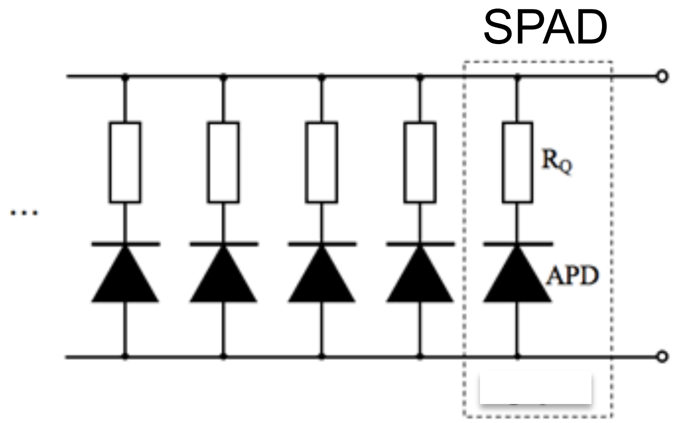
SiPM device is an array of SPADs



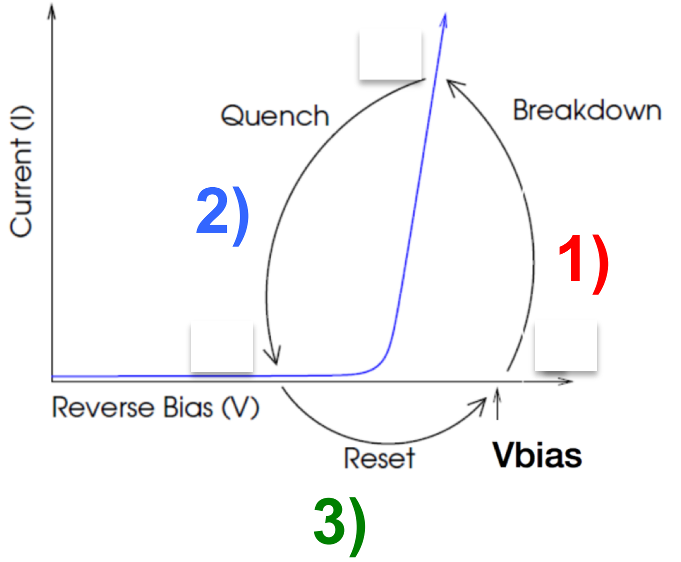

Geiger-mode : voltage of cathode is positive with respect to anode.

# Low Light-Level Sensors: SiPMs

## Silicon Photomultiplier



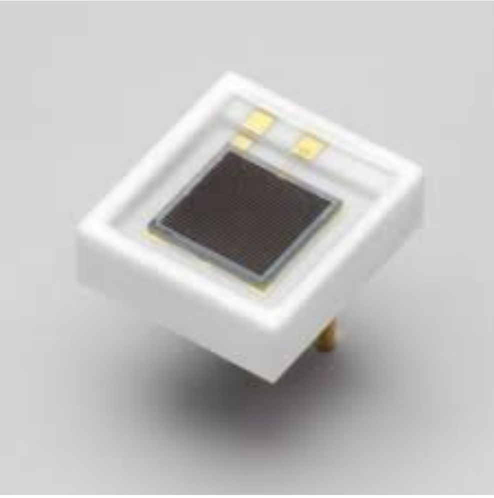

Geiger mode

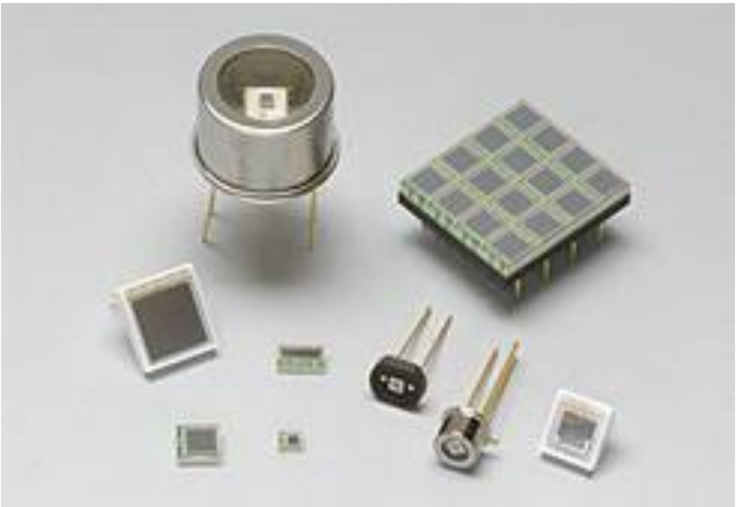


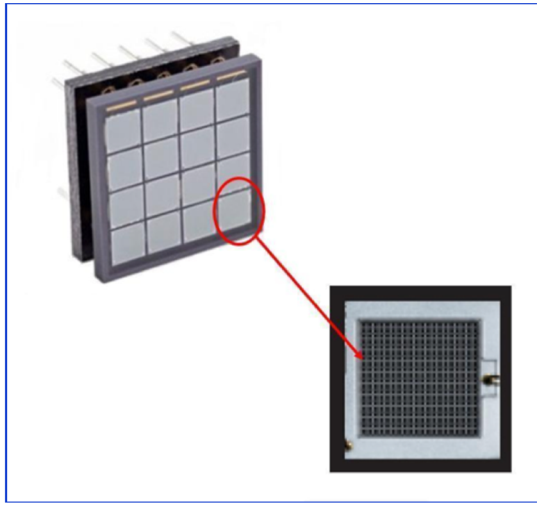

1) Trigger
2) Quenching
3) Reset

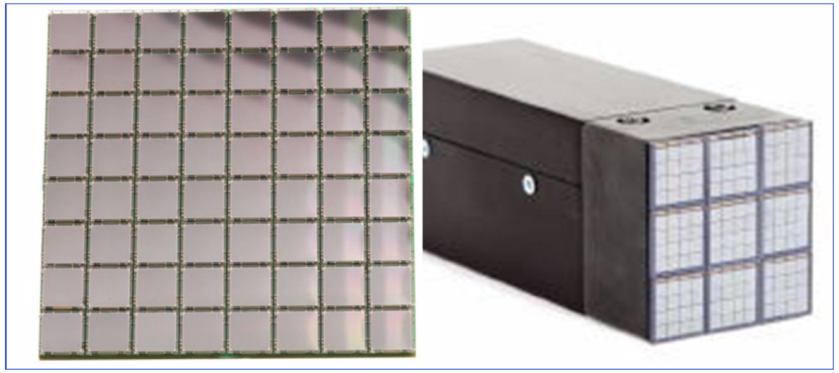
Quenching resistor $R_Q$ and diode in series
Output is sum of all SPADs

# Low Light-Level Sensors: SiPMs





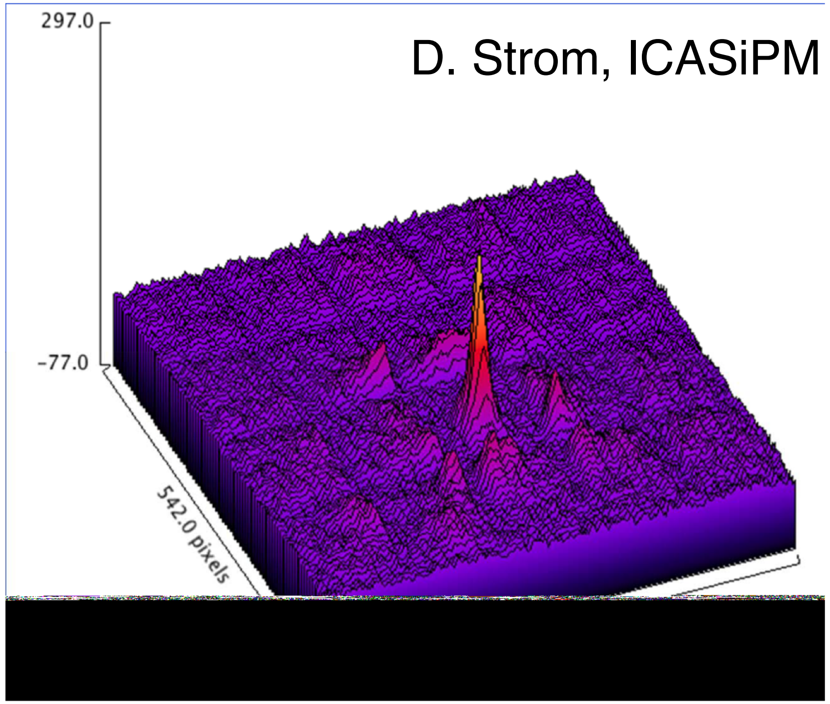


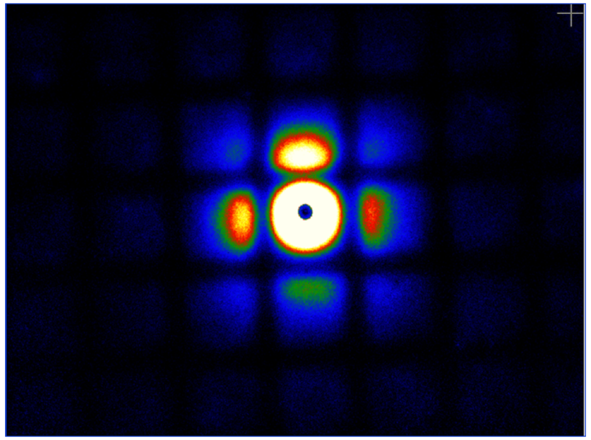


Advantages
Quantum efficiency: up to 80%
Gain: $10^5 - 10^7$
Single photon resolution
Few ns time resolution
Mechanically robust
Low voltage (20 – 100V)
Not sensitive to magnetic fields
Large dynamic range

Disadvantages
High dark current
Afterpulsing and cross-talk
Radiation damage
Temperature dependence
Small effective area

# Cross-Talk in SiPMs



Light emission from Si avalanches is important

- Discovered in 1955 (Newman)
- Cross-talk in SiPMs spoils the amplitude resolution
- The light emission is proportional to the number of $e^-$ in the avalanche.
- Limits the maximum gain under which SiPMs can be operated
- If no measures are taken against the cross-talk, then the filling factor is worse than in classical PMTs
- As a consequence one encounters major problems in selftrigger schemes when measuring very low light-level signals

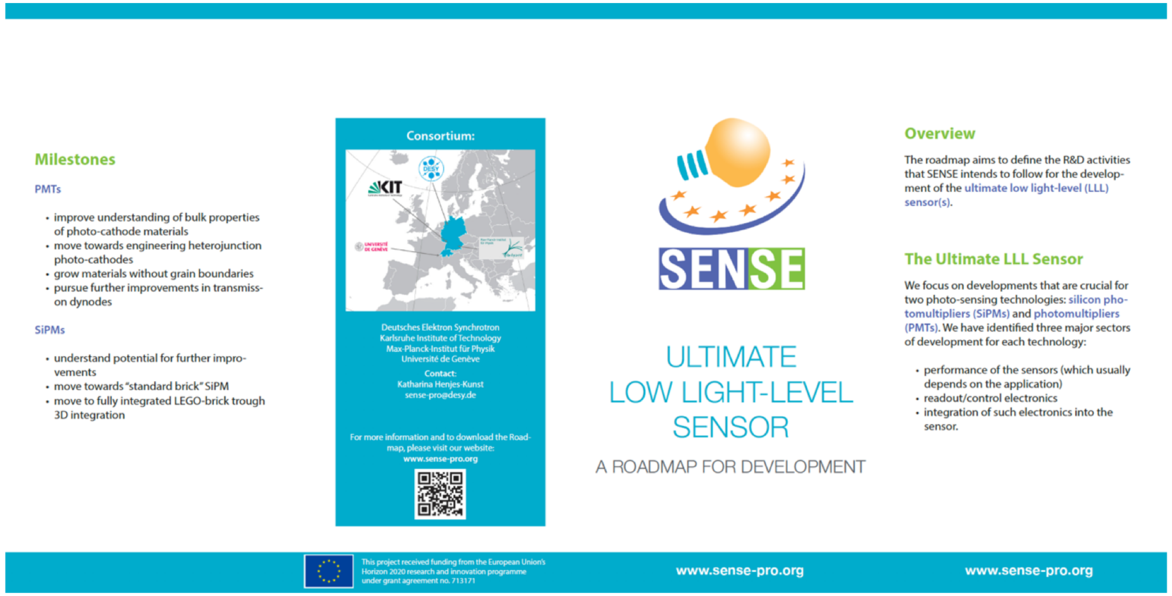
# How to improve SiPMs

- Understand the potential for further improvements to the major parameters of SiPMs as sensors and outline the possible developments and interactions with possible industrial partners
- Give contours to a " standard brick" of the SiPM-based sensor of one or two-inch size
- Move towards the SiPM "standard brick" with a "universal" fast readout scheme. This would be a first step towards the LEGO-brick principle for assembling imaging cameras of arbitrary size;
- Progress from semi-integrated standard brick to fully integrated LEGO-brick through the implementation of 3D integration.

# Achievements of SENSE – Roadmap

- Prepared by the SENSE Experts Group
- Describes all R&D activities necessary for the development of (the) ultimate LLL sensor(s)
- first version of roadmap is online since October 2018, final version in preparation

https://www.sense-pro.org/documents/roadmap



Milestones

PMTs

- improve understanding of bulk properties of photo-cathode materials
- move towards engineering heterojunction photo-cathodes
- grow materials without grain boundaries
- pursue further improvements in transmission dynodes

SiPMs

- understand potential for further improvements
- move towards "standard brick" SiPM
- move to fully integrated LEGO-brick trough 3D integration

Consortium:

Deutsches Elektron Synchrotron
Karlsruhe Institute of Technology
Max-Planck-Institut für Physik
Université de Genève

Contact:
Katharina Henjes-Kunst
sense-pro@desy.de

For more information and to download the Roadmap, please visit our website:
www.sense-pro.org

SENSE

ULTIMATE
LOW LIGHT-LEVEL
SENSOR

A ROADMAP FOR DEVELOPMENT

Overview

The roadmap aims to define the R&D activities that SENSE intends to follow for the development of the ultimate low light-level (LLL) sensor(s).

The Ultimate LLL Sensor

We focus on developments that are crucial for two photo-sensing technologies: silicon photomultipliers (SiPMs) and photomultipliers (PMTs). We have identified three major sectors of development for each technology:

- performance of the sensors (which usually depends on the application)
- readout/control electronics
- integration of such electronics into the sensor.

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 713171

www.sense-pro.org

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# Achievements of SENSE – R&D Cooperation

**By now:**

- The experimental setup was build & calibrated: DCR(ΔV, VThr.), PXT(ΔV), PDE(ΔV, λ);
- Cooperation agreement between 5 institutes was established:
- DESY; UNIGE; KIT; Nagoya University – ISEE, MPI for Physics, INAF –OAC
- SiPM devices were distributed among institutes
- Receiving newest devices from producers (Hamamatsu, SensL, AdvansID, Ketek, Ndl Sipm)

**Future:**

- Evaluate systematic errors for each experimental setup;
- Establish measurements and analysis procedures;
- Applying for European money to further develop SiPMs
- Foundation of a database for analyses and calibrations for different applications

# Achievements of SENSE – Outreach

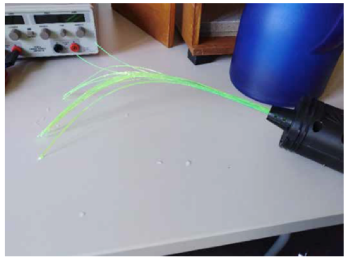
- Website (https://www.sense-pro.org) and newsletter online/ active
- SENSE @ several upcoming workshops/ conferences: NSSMIC 2018, VCI 2019 ...,

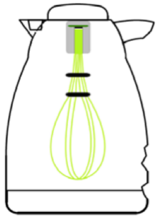
  several other workshops already done, first two SENSE publications
- Calendar with LLL-related events and workshops online
- Forum: place for technical discussions with experts, after signing up

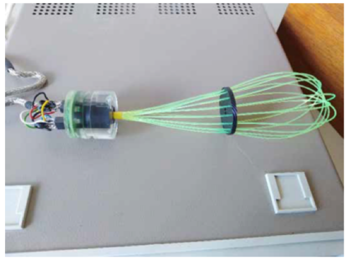
# Achievements of SENSE – Show case experiment

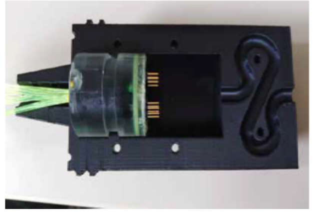
Measurement of cosmic muons with thermos flask used as water cherenkov detector

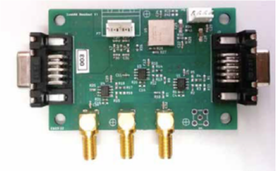
Optical fibers in water → Frontend-board with SiPM → Readout-Board → DAQ/ Picoscope → Software

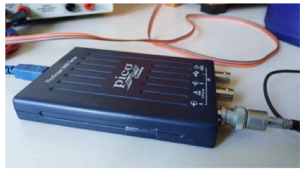


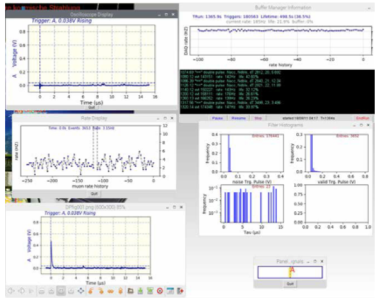




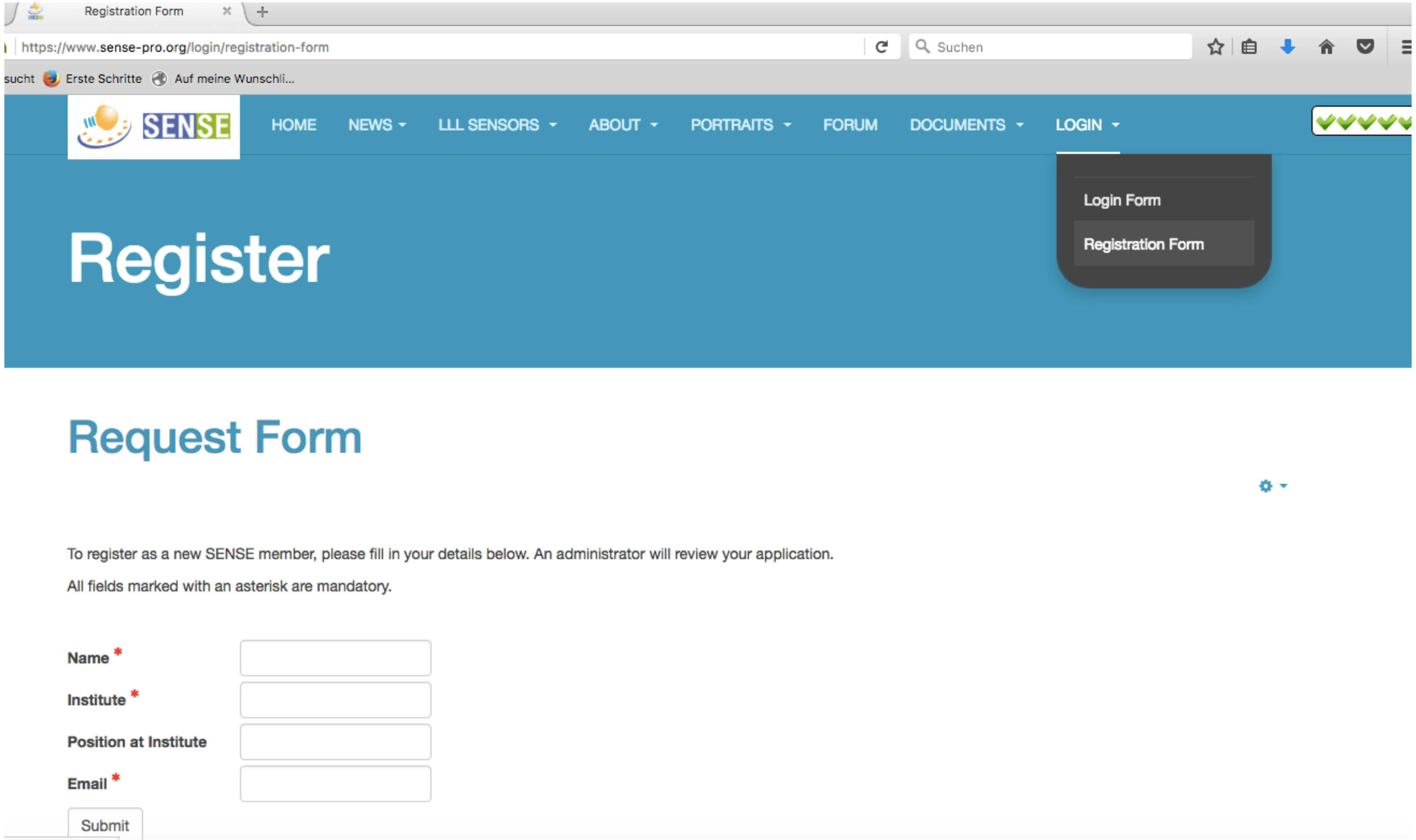








# SENSE – come and join!



Photoelektrischer Effekt – Phys | SENSE Detector School | Search Result | Hamamatsu Ph | SENSE Detector School (19-22

https://www.sense-pro.org/news/events/87-sense-detector-school

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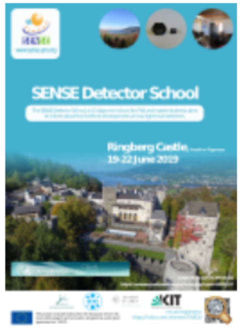
# SENSE Detector School

Events 28 March 2019




We are happy to announce the SENSE Detector School at the Ringberg Castle in Kreuth am Tegernsee in Bavaria, Germany, from 19 - 22 June 2019. The 2.5 days mini-school for PhD and master students aims to inform about the forefront developments on low light-level detectors.
The speciality of the school is the small group of students with a continuous possibility to discuss with the teachers

The participation of 25 students is sponsored by SENSE. You can apply for the school until 3 May 2019 with a letter of motivation. The nomination of participants will be announced on 10 May 2019. We aim to achieve a balanced mix of working topics as well as gender and nationalities.If required, childcare can also be organised.

As soon as the timetable has been finalised, a decision will be made on a possible contribution from the students.

More information and registration: https://indico.cern.ch/event/791832/

Next

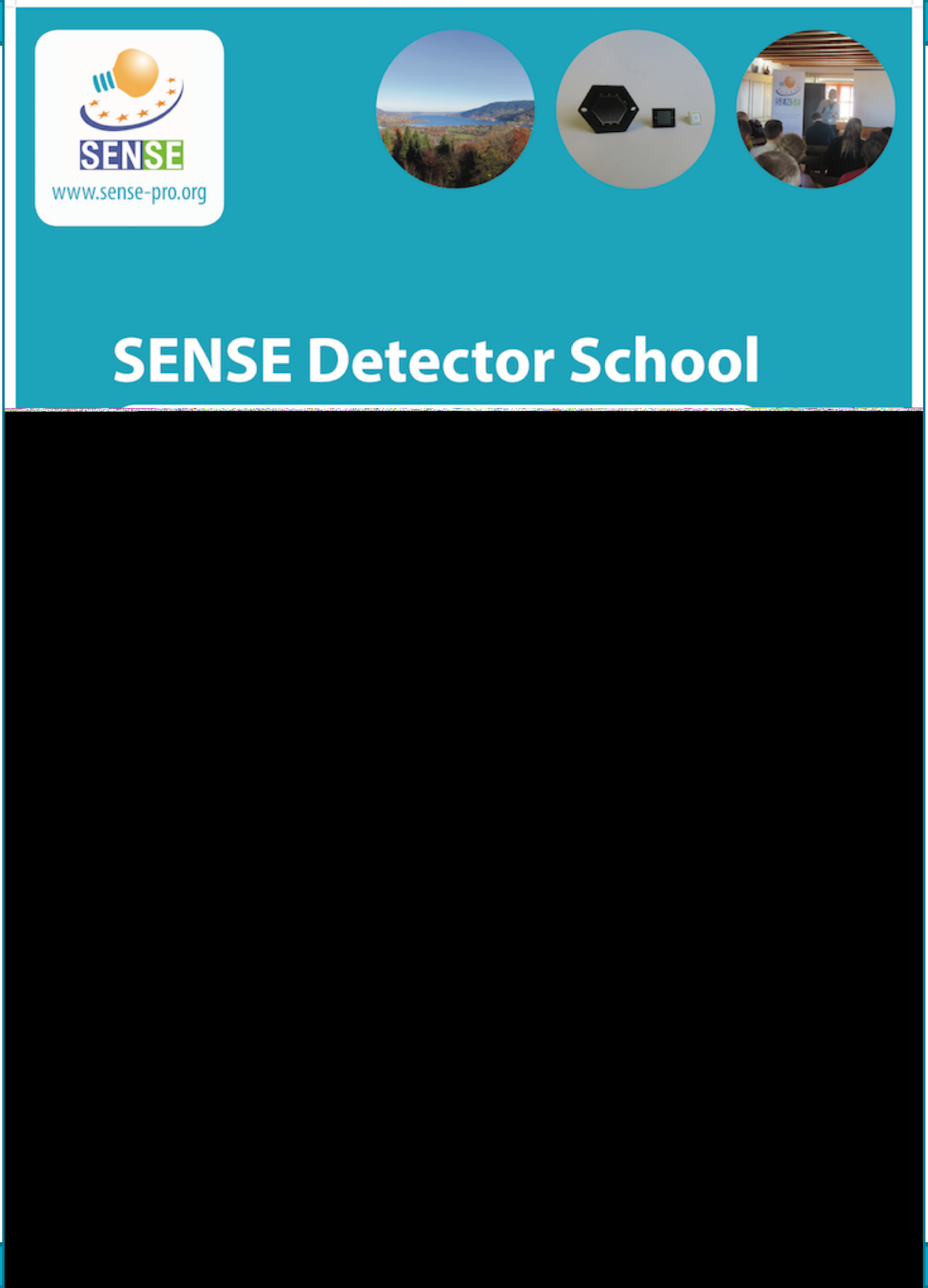
IN BRIEF SEE ALSO

SENSE Detector School
2019-03-28
We are happy to announce the SENSE Detector School at the Ringberg Castle in Kreuth am Tegernsee...

International Cosmic Day
2018-11-09
The 7th International Cosmic Day will be on 29th of November 2018. The International Cosmic Day...

SENSE-booth at the Spring Meeting of DPG
2018-02-09
The Spring Meeting of the German Physical Society (DPG Frühjahrstagung) of the Matter and Cosmos...

TechForum 21-22 June
2017-12-22
SENSE is organizing a Technology


SENSE
www.sense-pro.org
SENSE Detector School

# SENSE

Would you like to join SENSE

- as new SENSE expert?
- with your experiment?
- in the discussions on the forum?

Please visit *sense-pro.org* for the latest news and the SENSE Forum for latest discussions and stay in contact with us

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or
sensepro@desy.de