# Photo-Detectors in Astroparticle Physics Experiments

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# Outline

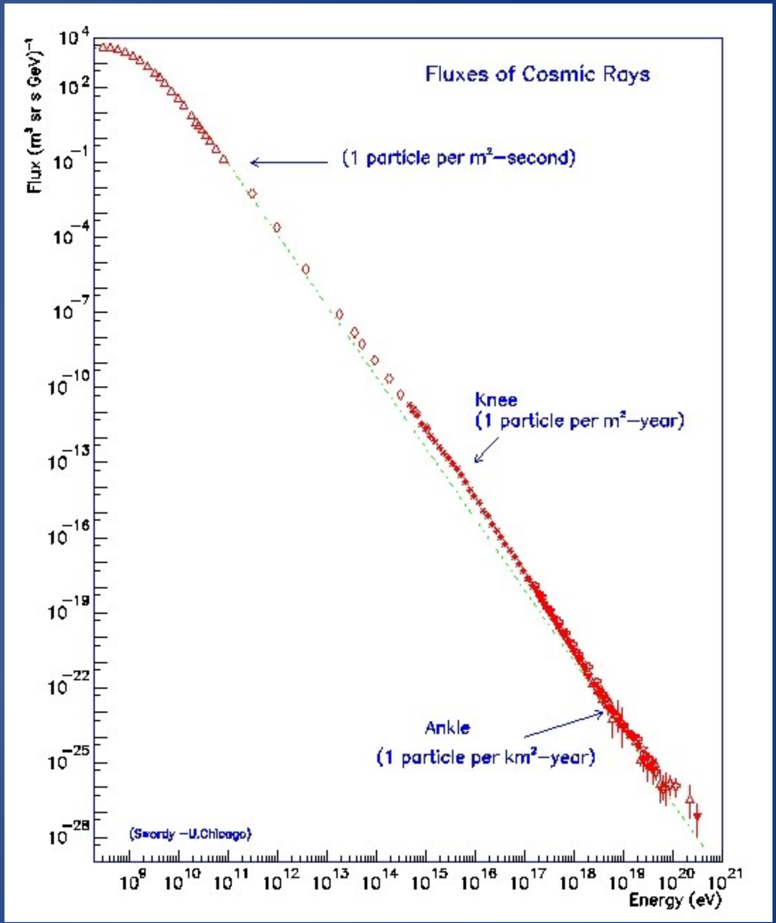
- Astroparticle physics
  - Cosmic rays, VHE gamma-rays, neutrinos
- Detection of cosmic rays
- Detection of gamma rays from ground
- G-APDs for  Cherenkov telescopes
- Two slides about large hemispherical PMTs

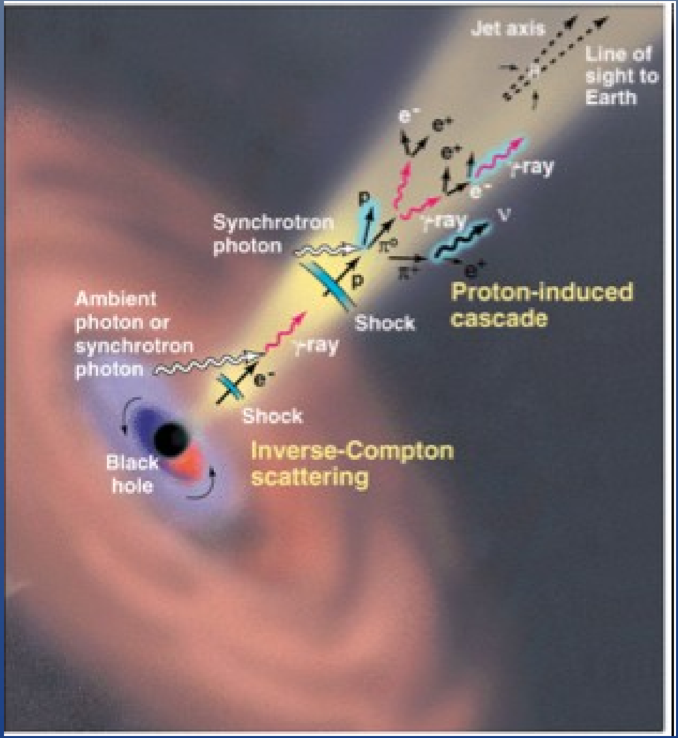
# Particle Astrophysics

What are the cosmic accelerators?

Use:

- Cosmic Rays
- Gamma Rays
- Neutrinos




Often one deals with very low fluxes

Need large detector areas/volumes

-> Atmosphere / ice / water

# Air Showers

**Use measured air shower characteristics for:**

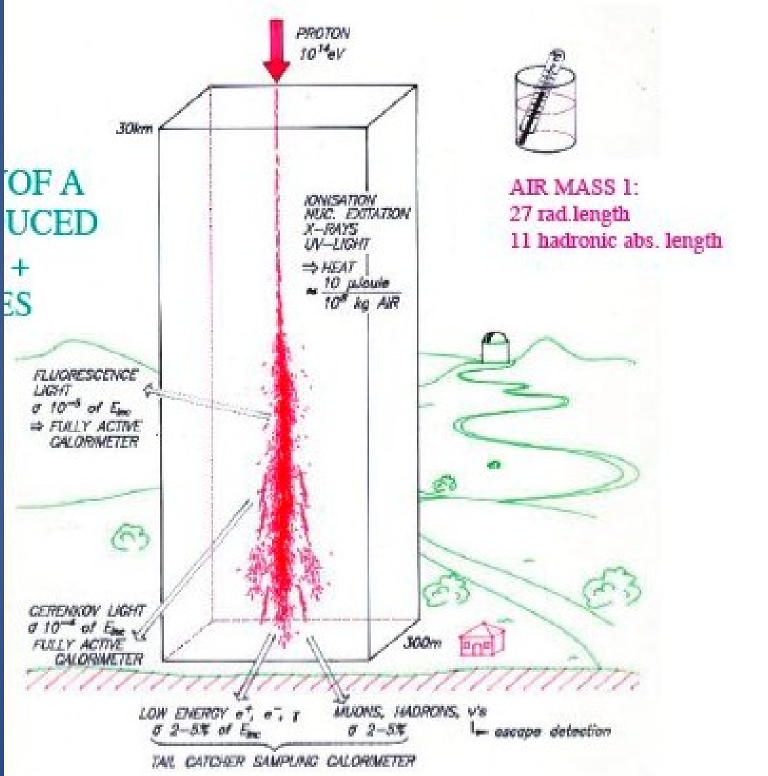
**- calorimetry**

**- particle ID**

**- tracking**

Readout:

- Fluorescence light
- Cherenkov light
- Particles
- Radio

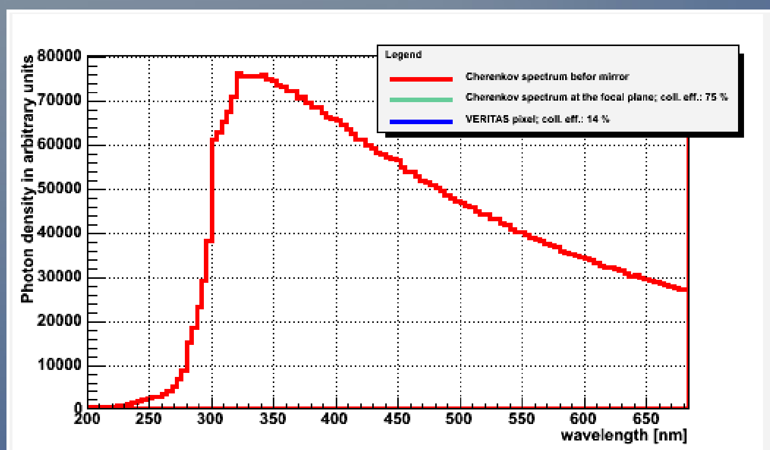



E. Lorenz

- Not like in a laboratory
  - Remote places
  - Weather
  - Inhomogenous detector medium
  - Background ( light from the sky )

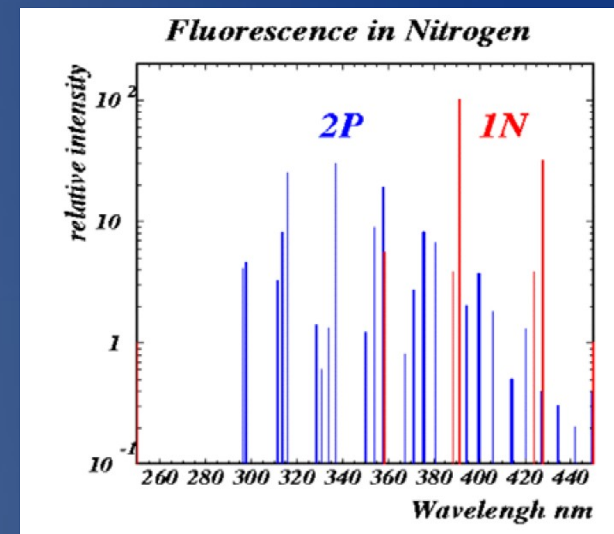
# Light from Air Showers

## Cherenkov Light



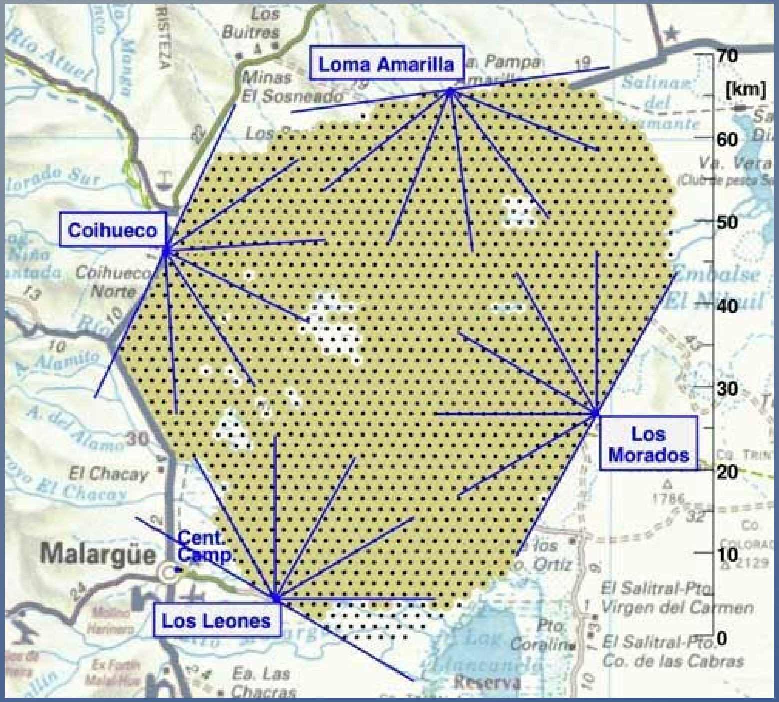

- Emitted by shower particles
- Continuum emission
- Typically $10^{-3}$ of the energy of the primary
- Directed forward in narrow cone
    * ~1deg opening angle
    * Illuminates 100,000 $m^2$ area on ground
- Used to detect cosmic rays and gamma rays with energies above $E > 10^{10}$ eV

## Fluorescence Emission




- Deexcitation of atmospheric nitrogen molecules
- Line spectrum
- Typically $10^{-5}$ of the energy of the primary
- Isotropic emission
    → can be viewed from large distances
- Used to detect particles with energies above $E > 10^{16}$ eV

# Pierre Auger Observatory




Detection of cosmic rays above $10^{16}$ eV

Surface array:
1600 stations
1.5 km spacing

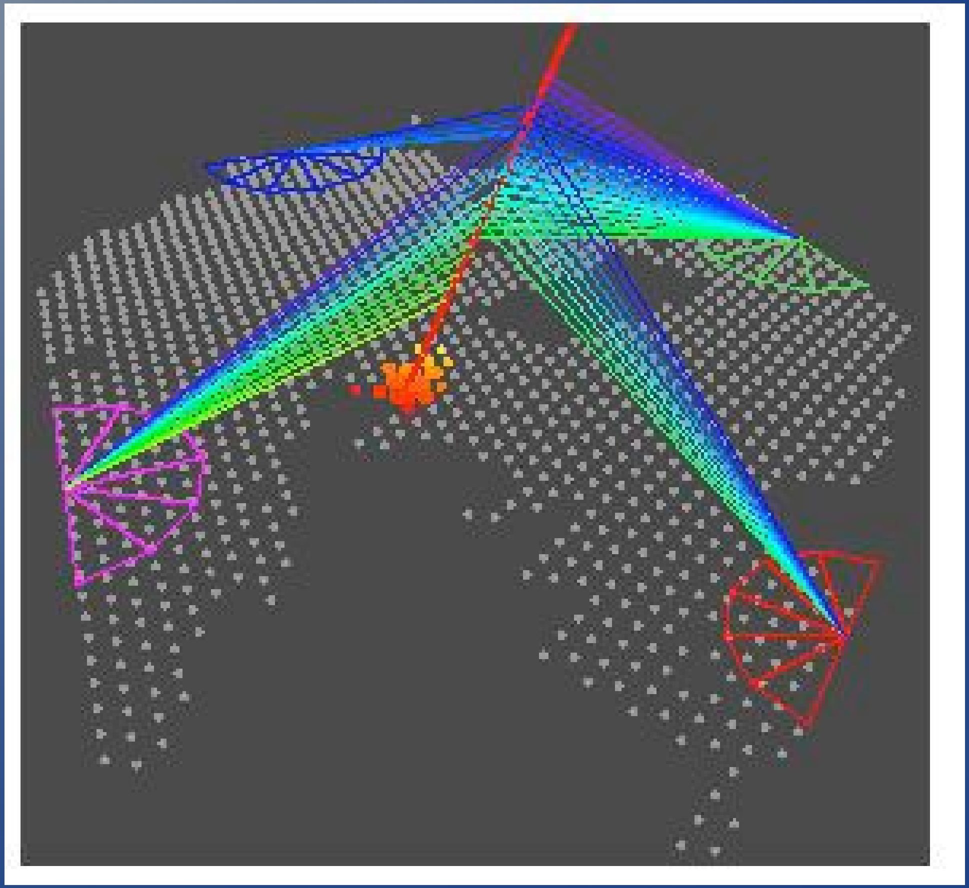

Detects shower particles coming to ground

Fluorescence detectors:

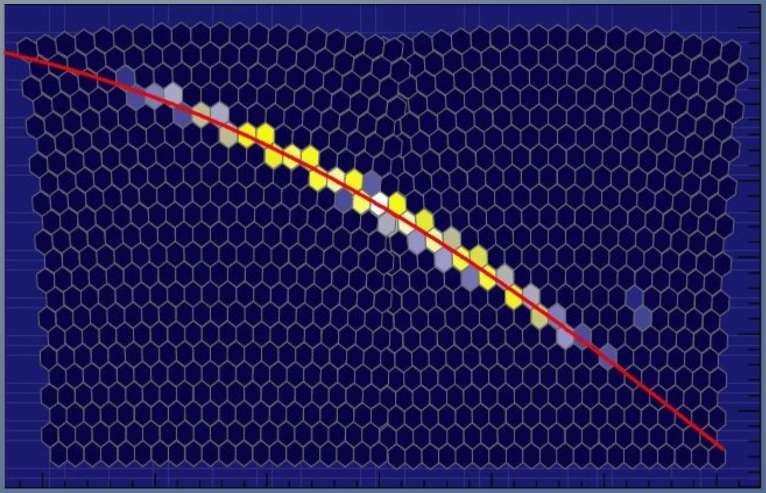
4 telescope enclosures
6 telescopes per enclosure
24 telescopes in total

# One 4-fold Event

E~$10^{19}$ eV

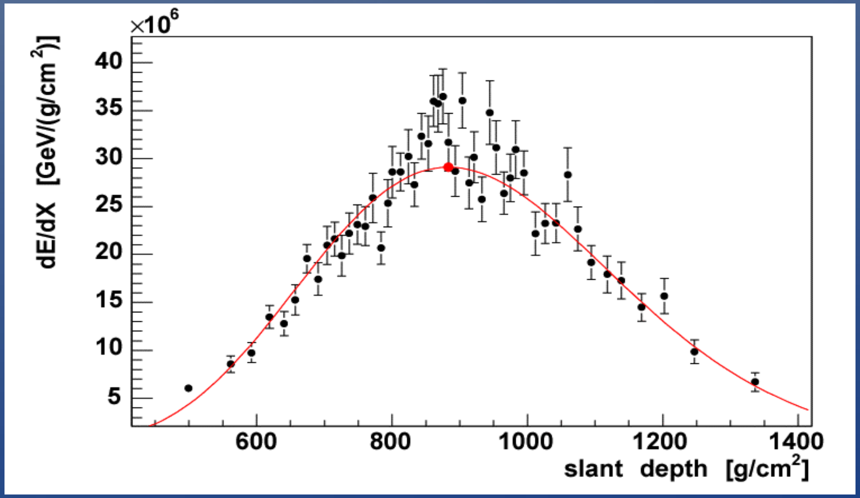


# Fluorescence Detectors





One AUGER fluorescence telescope

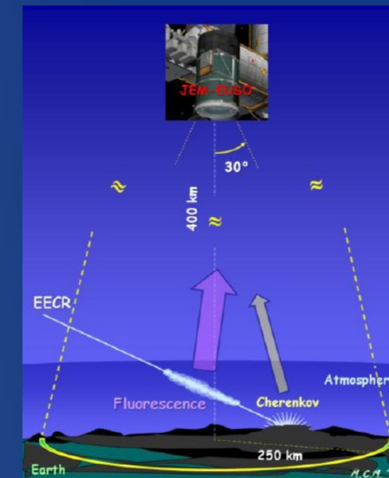



- Shower observed from 20-30 km distance
- Shower development takes several 100 μs

Reconstruct:

- Energy from the light yield
- Particle ID from shower maximum
- arrival direction with stereoscopy and Information from surface array

# Observation of Cosmic Rays from Space




**shower parameter:**

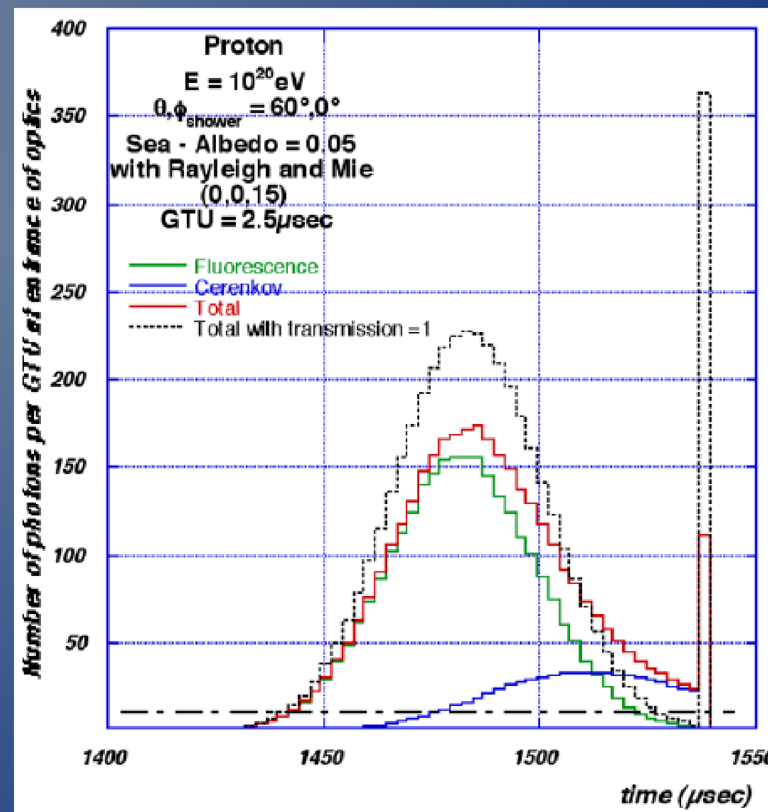
**angular size:**
a few degree up to several ten degree
(≈5° for 1^20eV zenith angle < 75°)

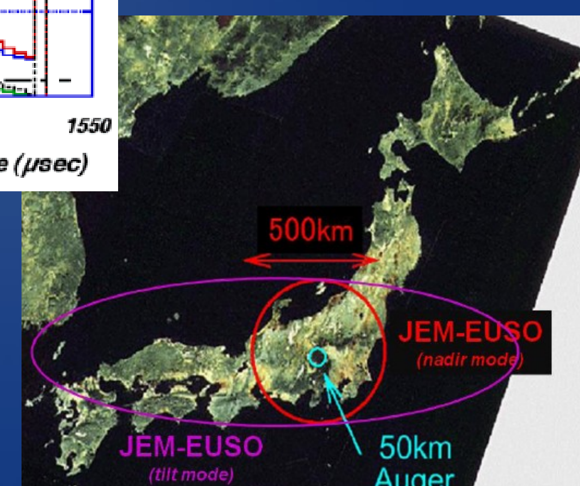
**photons arriving at EUSO:**
≈550 ph/m² ($10^{20}$eV zenith angle 45° in half of FOV of EUSO optics)

**shower duration:** ≈100µs…≥300µs

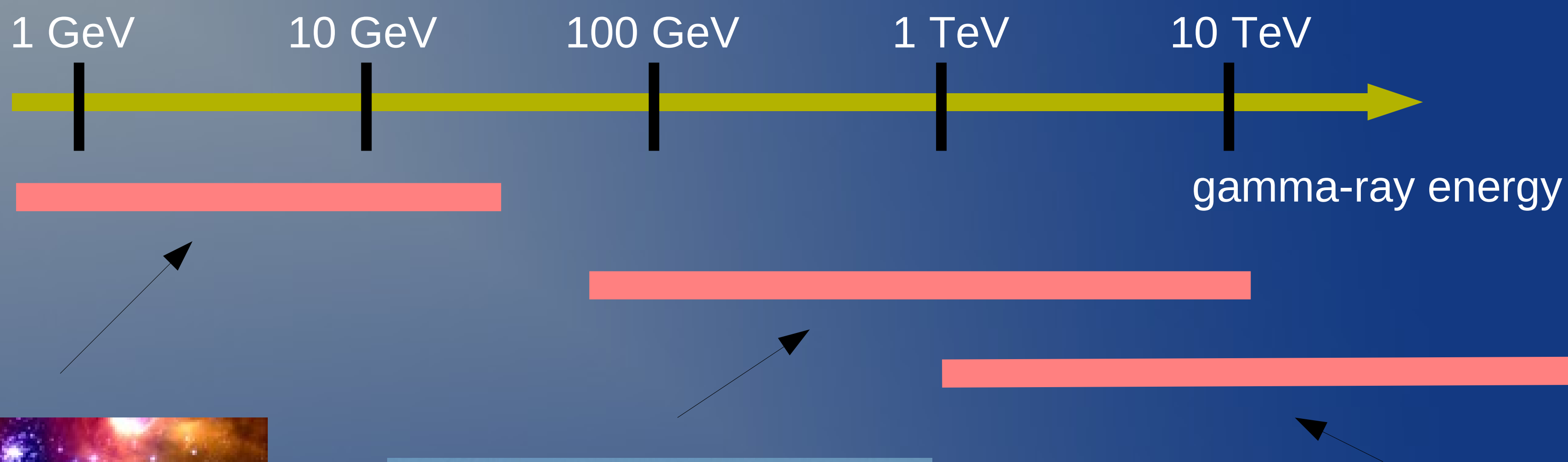
**wavelength range:** 330nm…400nm

**Cherenkov light:**
opening angle: ≈1° -> 1km diam. for shower in 10km at 60° zenith angle
photons arriving at EUSO: ≈ 500 ph for albedo of 5%



# Gamma-Ray Instruments

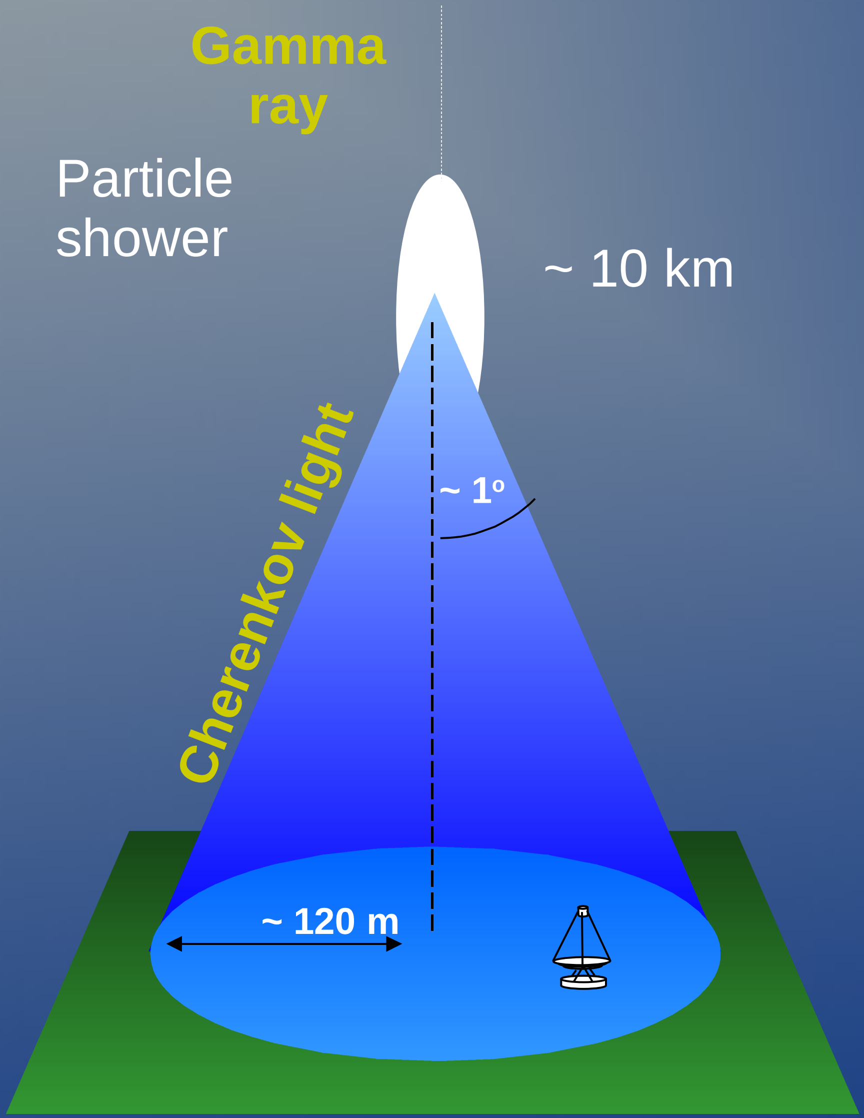



satellites

Cherenkov telescopes

water Cherenkov detectors
and particle detectors

# Imaging Air Cherenkov Technique




Cherenkov light from an air shower illuminates ~100,000 $m^2$ area

faint and fast bluish flash of light

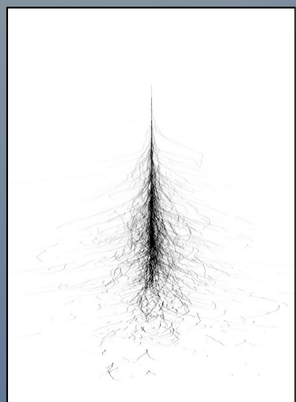
2 photons per $m^2$ for a 50 GeV gamma ray

2-3 ns spread in photon arrival time

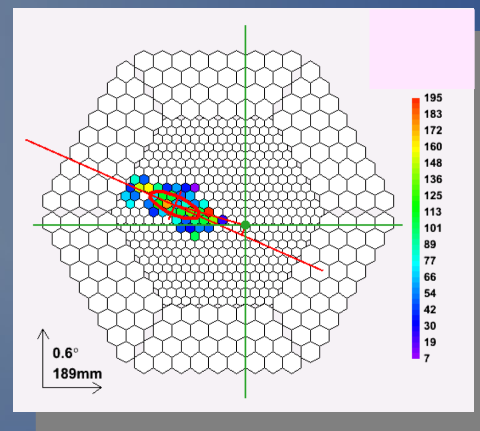
Energy threshold limited by:

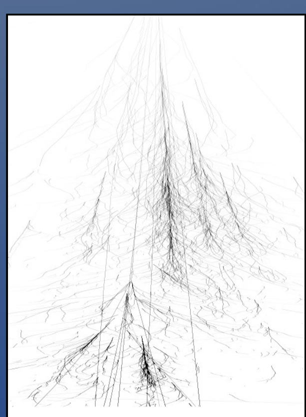
1. The number of collected Cherenkov photons
   - large mirror surfaces (~200 $m^2$ )
   - high efficiency photon detectors
2. Separation of shower signals from fluctuations in the night sky background

# Imaging Technique

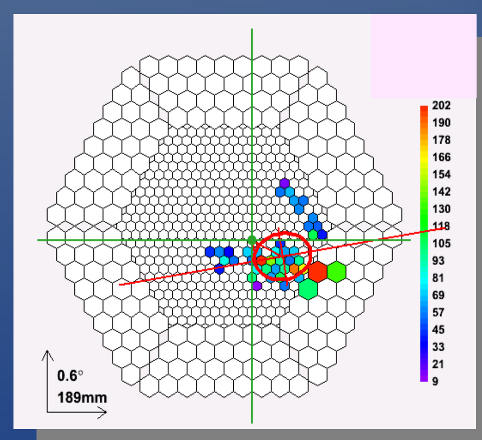


Gamma ray



Proton




MAGIC I camera

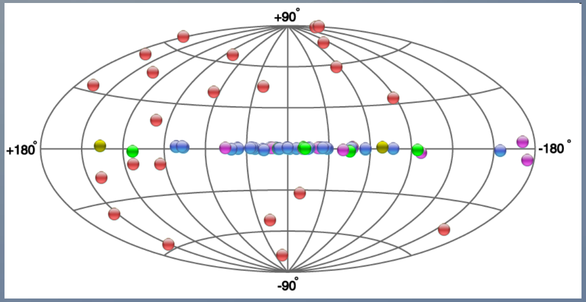
Background:

- Charged cosmic rays (hadrons)
- $10^3 \ldots 10^4$ times more abundant

Background rejection:

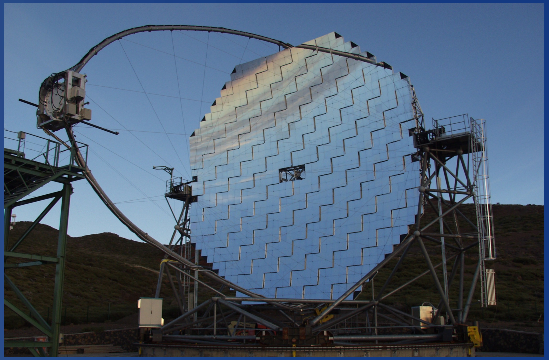
- Based on shower shape
- Orientation of the image

# Observation of Gamma-Rays from Ground




80+ sources detected in the last 20 years

VERITAS in Arizona



MAGIC in the Canaries

Energy Range: ~100 GeV - ~10 TeV

Energy Resolution: ~15%

Angular Resolution: 0.05°- 0.1°

Sensitivity: 1Crab in < 30 sec

Field of View: ~4°

H.E.S.S. In Namibia

**Now in planning: arrays of ~50 telescopes**

# Use of Photomultiplier in IACTs

Cherenkov telescopes f/D >= 1
-> large plate scale
-> large photon sensors 1” diameter

MAGIC I camera

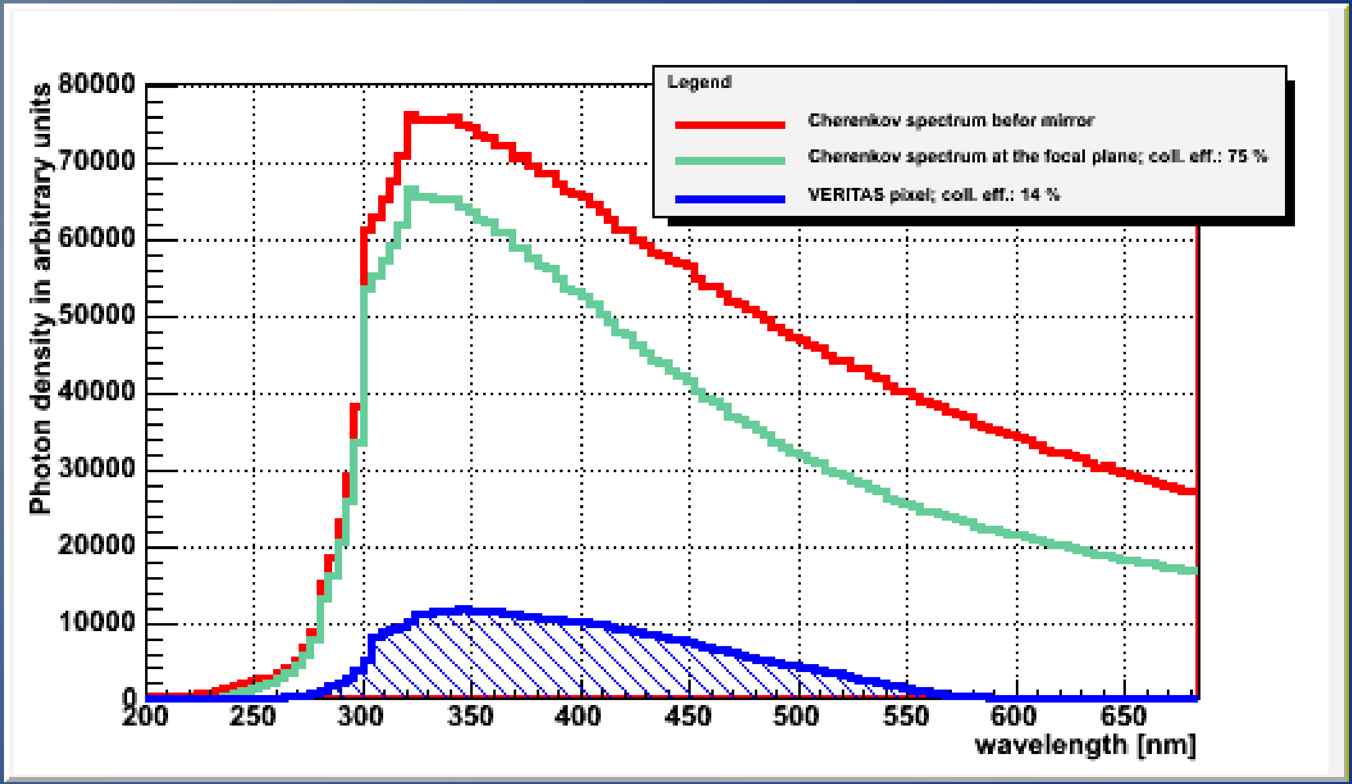
**PMT advantages/disadvantages**

Large areas
Large gain
Single photoelectron resolution
Well established technology

Sensitive to magnetic fields
Damaged in daylight/sunlight
Afterpulsing
Use of high voltage
Bulky and fragile
Aging
Costly
Average QE <20%

# Cherenkov Light Detection Efficiency

Cherenkov telescopes
have an optical
throughput of about 10%
The detection efficiency of the
photomultipliers is the bottleneck




**Higher throughput means:**

- lower threshold
- better energy resolution
- better angular resolution
- better background suppression

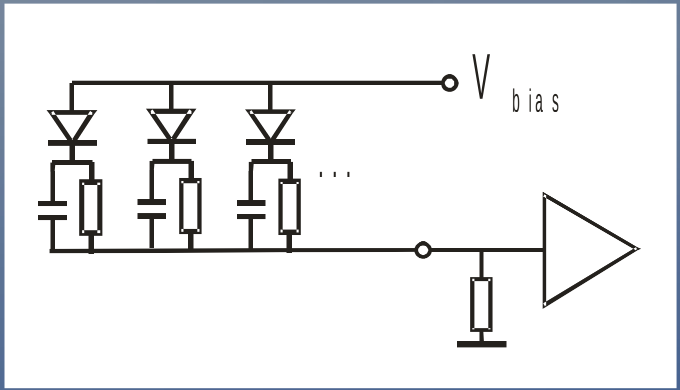
**With immediate impact on the science:**

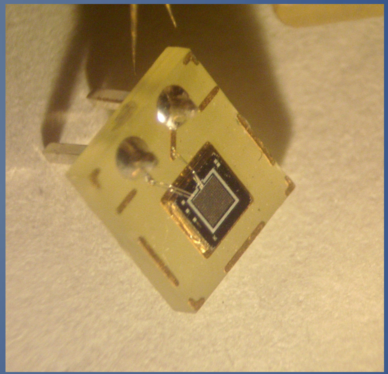
- deeper into the universe
- many sources have intrinsic cutoffs below 100 GeV
- morphology studies:
  - pulsar wind nebula
  - shell type supernova remnants
  - pair halos around AGN

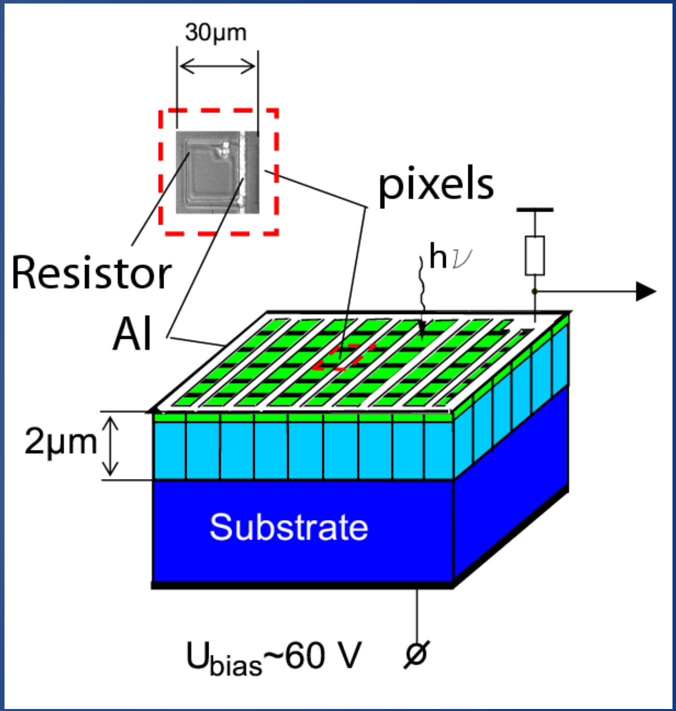
**High efficiency sensors → better physics**

# The G-APD

a promising photon detector concept invented in Russia in the 80's
available now in large quantities and from many producers






*P. Buzhan et al.*
*http://www.slac-stanford.edu/pubs/icfa/fall01.html*

**Major advantages:**

- High intrinsic QE of a semiconductor
- Geiger mode operation → sensitive to single photons
- Bias voltage < 100 V
- High intrinsic gain
- Is not damaged in daylight
- Mechanical and electrical robust

# Factors limiting the Photon Detection Efficiency

- Geometrical occupancy of the Geiger diodes (aimed at 70%)
- Reflection losses on the SiPM surface (<10% possible)
  - Can be tuned by coating
- $\lambda_{min}$ determined by thickness of surface implantation
- $\lambda_{max}$ determined by thickness of active volume
- Classical Quantum efficiency (~100%)
- Breakdown Initiation Probability (~90%)
  - Function of the electric field in the avalanche region

Currently achieved 20-40%

# The short List of Requirements

- **Price:** G-APD are presently 5-10 times more expensive than PMT
  want to be cheaper than PMTs
  (not a matter of production costs)

- **PDE 300nm-600nm:** 100% is the limit but we would even be happy with 60% in the blue
  seems possible in the future **Biggest challenges**

- **Size:** 5x5 $mm^2$ to 10x10 $mm^2$

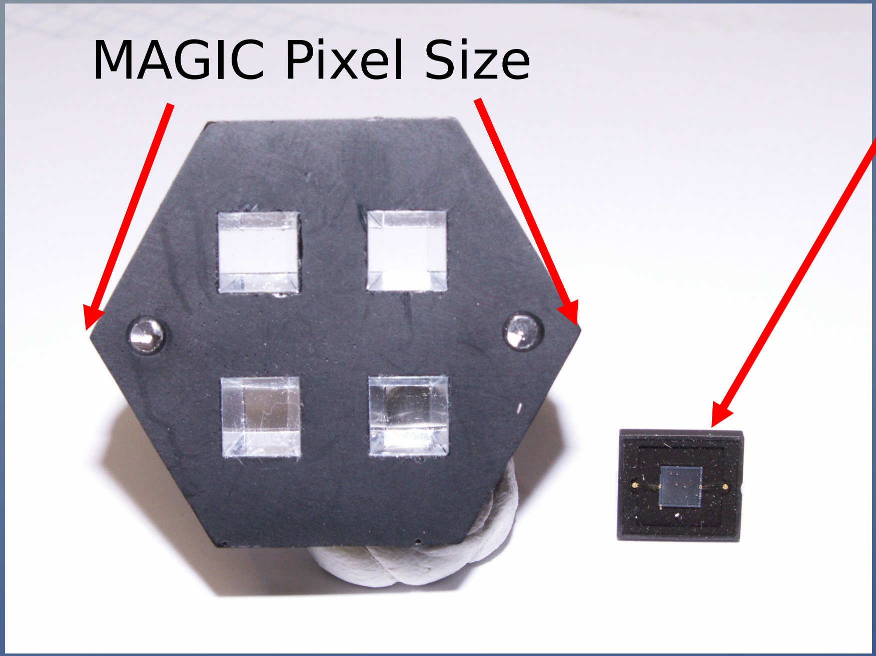
- **Dark count rate:** < 100 kHz/$mm^2$ needed
  Thermal generated Charge carriers, afterpulsing, optical crosstalk
  achieved by some devices at room temperature otherwise
  moderate cooling necessary

- **Temperature Dependence of Gain:** varies between ~5%/K and 0.3%/K; 0.3%/K is ok
  Requires large breakdown voltages, small cell capacitances, high overvoltages

- **Optical Crosstalk:** can be several 10% needed are less than a few %
  Trenches between cells → now pursued by most producers

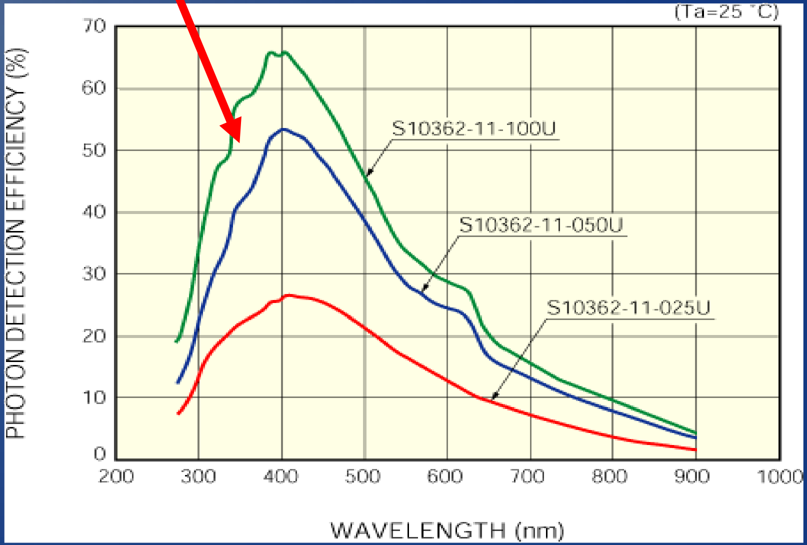
**Suitable G-APD become available now**

# Test on La Palma with MAGIC




MPPC-33-050C from Hamamatsu:

sensor size: 3x3mm²
single APD size: 50x50µm²
nominal bias: 70.4V
dark rate at nominal bias: ~2MHz
gain at nominal bias: $7.5 \cdot 10^5$
crosstalk at nominal bias: 10%




Array of 4 MPPCs:
Light catchers with factor 4 concentration; 6x6mm² to 3x3mm²

One bias for all MPPCs

A big promise

Array mounted next to the MAGIC camera for 3 nights for fine tuning and tests

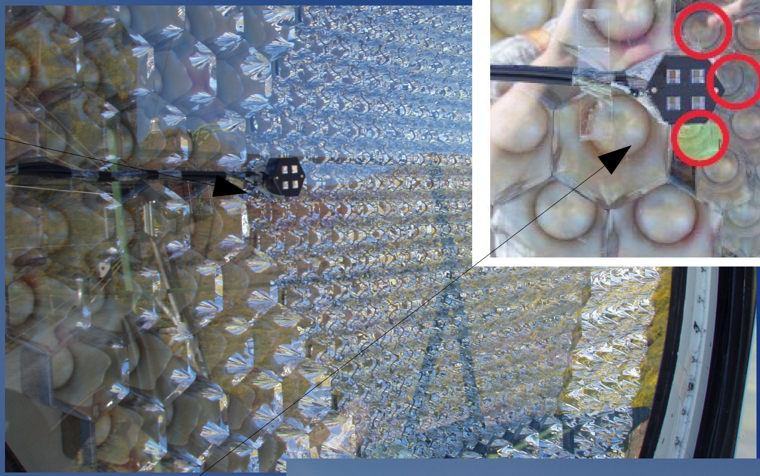
G-APDs signals recorded by the MAGIC DAQ for each trigger

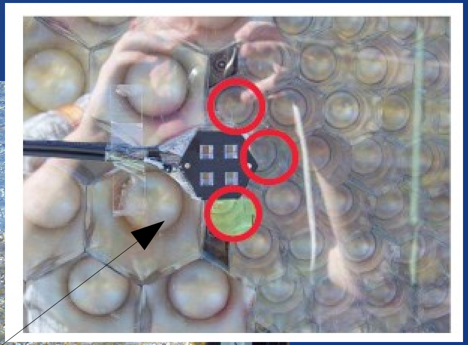
- Array not removed or protected during day
- It was raining for one day; no problem!

Dark rate at night ~ 20 MHz

10 times higher than intrinsic dark rate of MPPC

# Recording Photons from Air Showers with G-APD

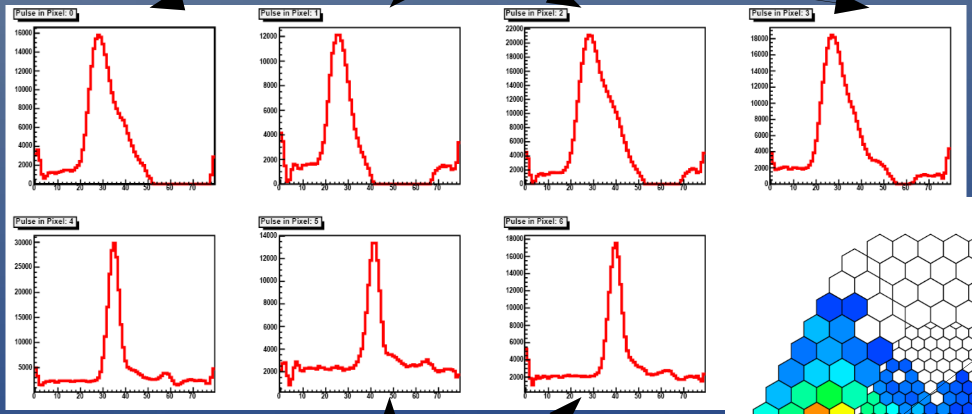




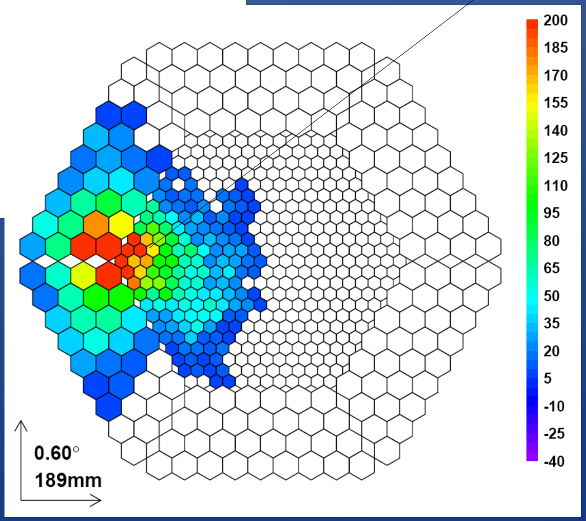
4 G-APDs in the focal plane of MAGIC

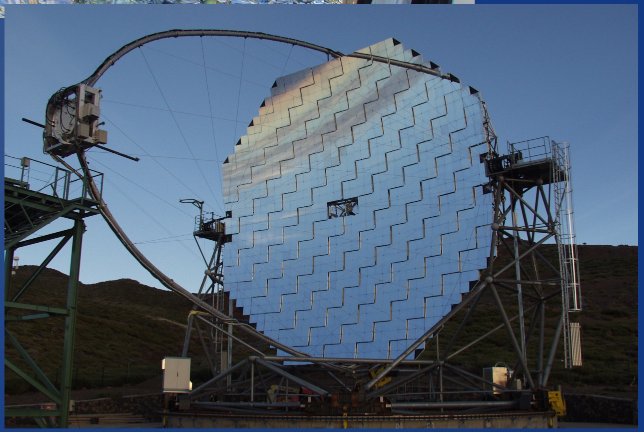
**One recorded event:**

G-APD signals



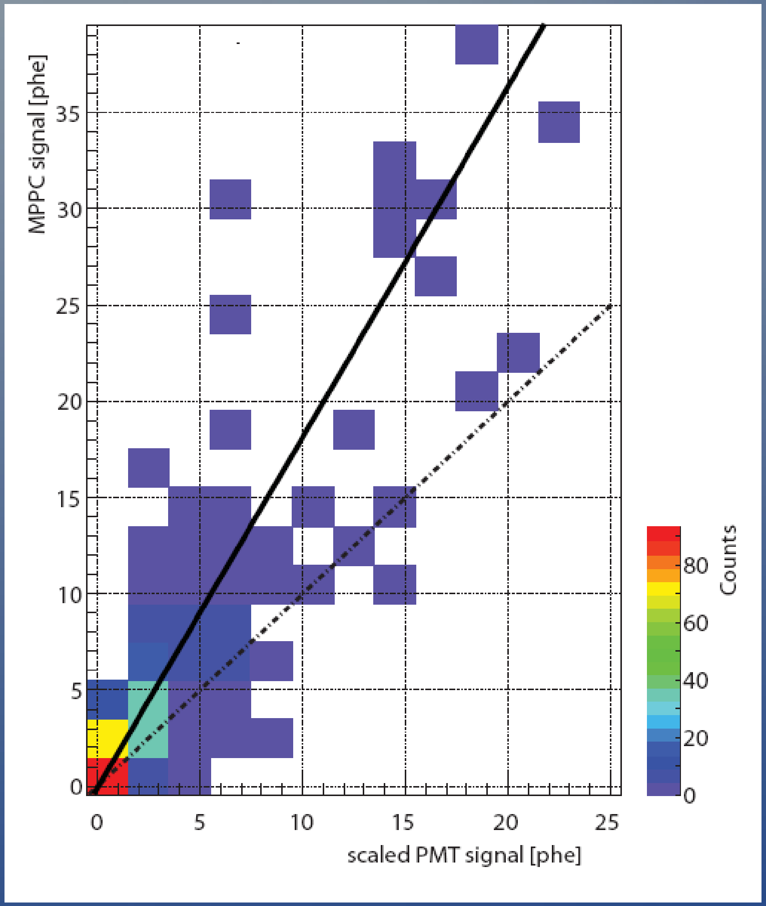
Signals of surrounding PMTs



MAGIC

# Shower Signals: MPPC vs PMT




event selection:
two PMTs next to MPPCs with more than 15 photoelectrons in each tube

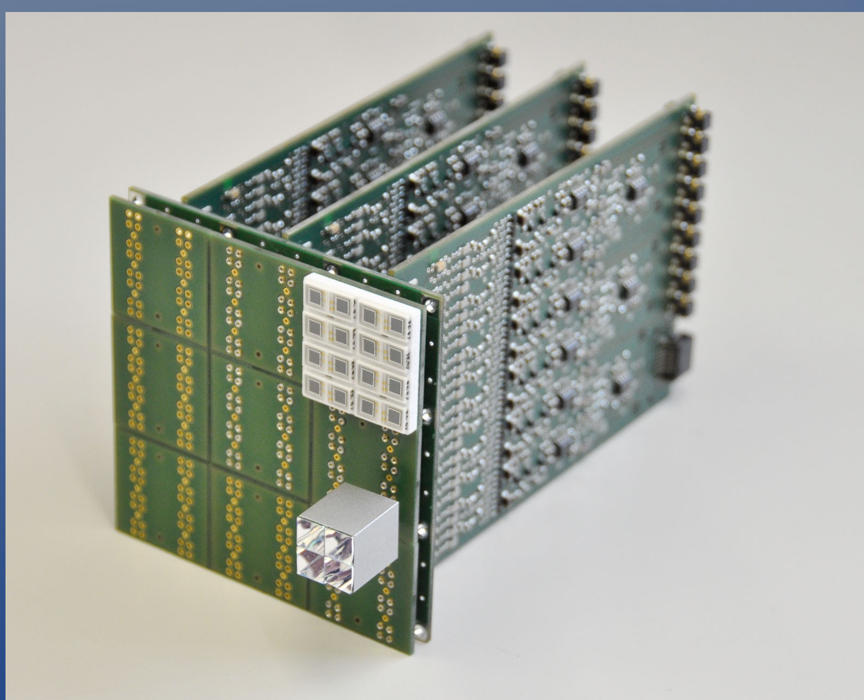
~300 events from ~30 min data

**On average the MPPC records 1.6 times more photons**

# A Prototype G-APD Camera

Reactivation of the
CT3 telescope of HEGRA

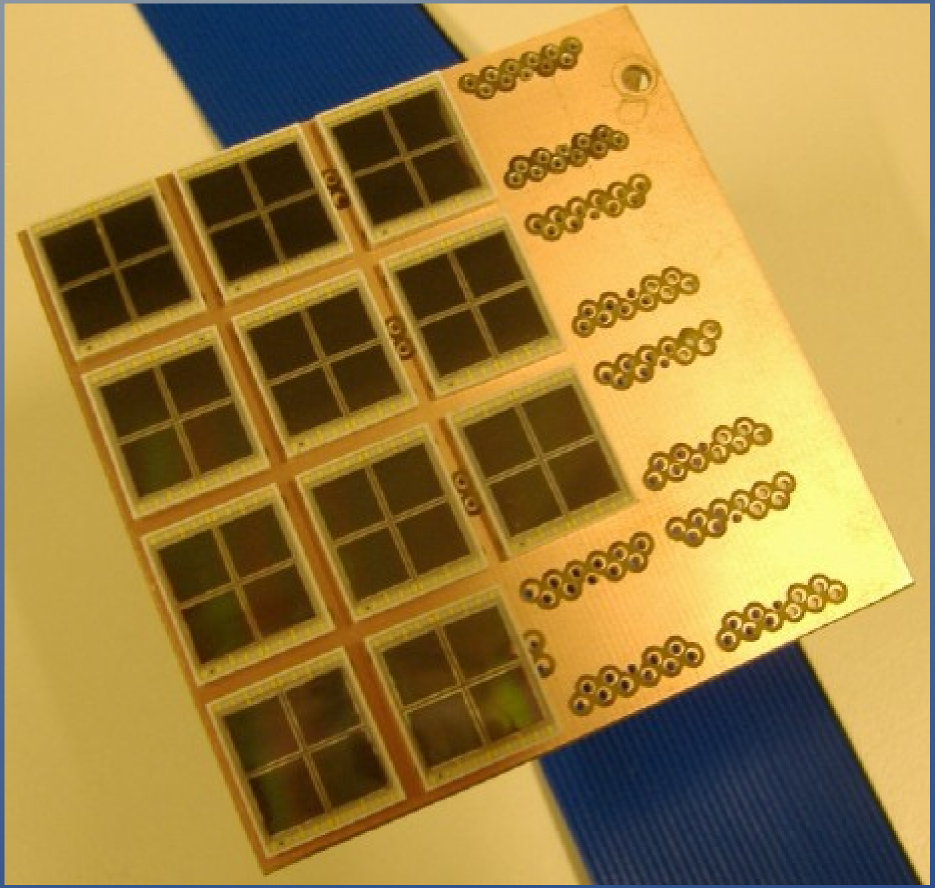
Tests planned with one of the former
HEGRA telscopes (CT3) this summer

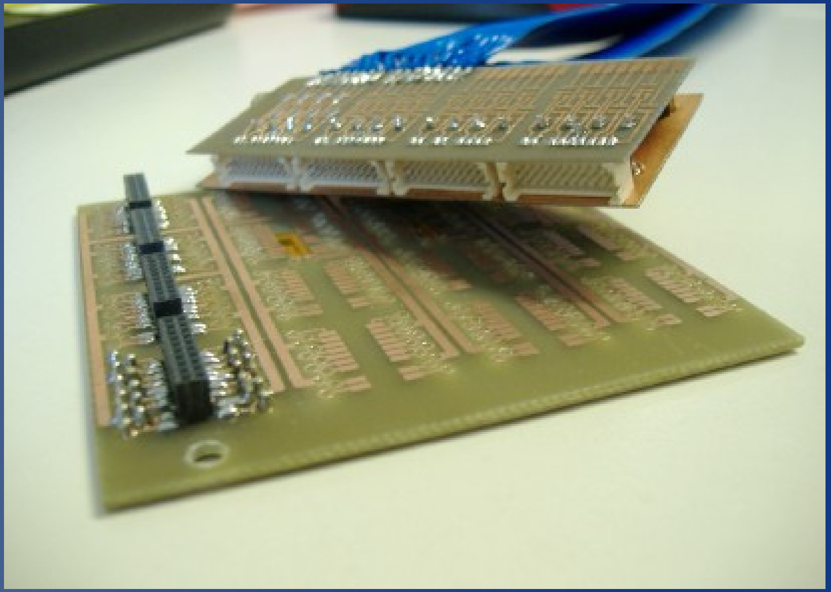


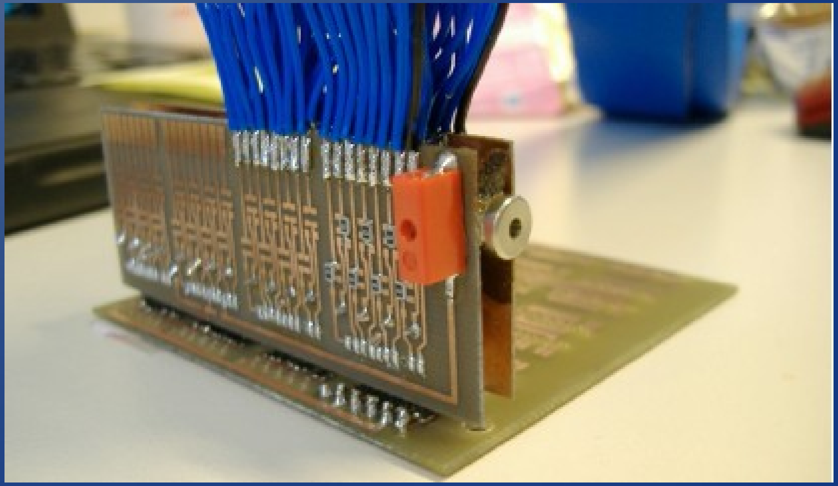
A test module of a  G-APD camera
built at ETH

Thanks to I. Braun (ETH) for providing
picture and info about DWARF/FACT

# More Camera Developments





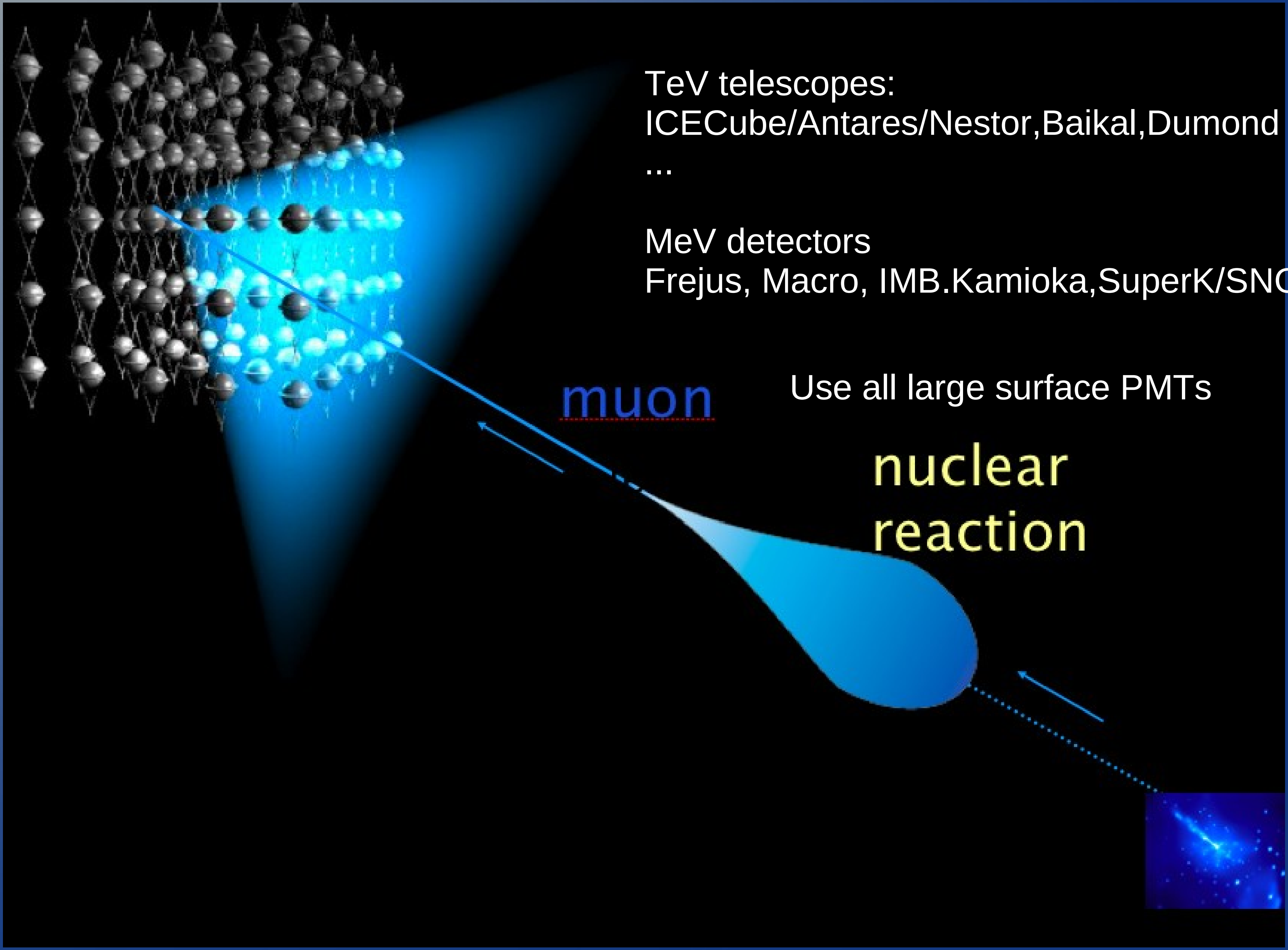


For EUSO and Cherenkov telescopes

Hiroko Miyamoto

MPI for Physics, Munich

# Neutrino Detectors




TeV telescopes:
ICECube/Antares/Nestor,Baikal,Dumond
...

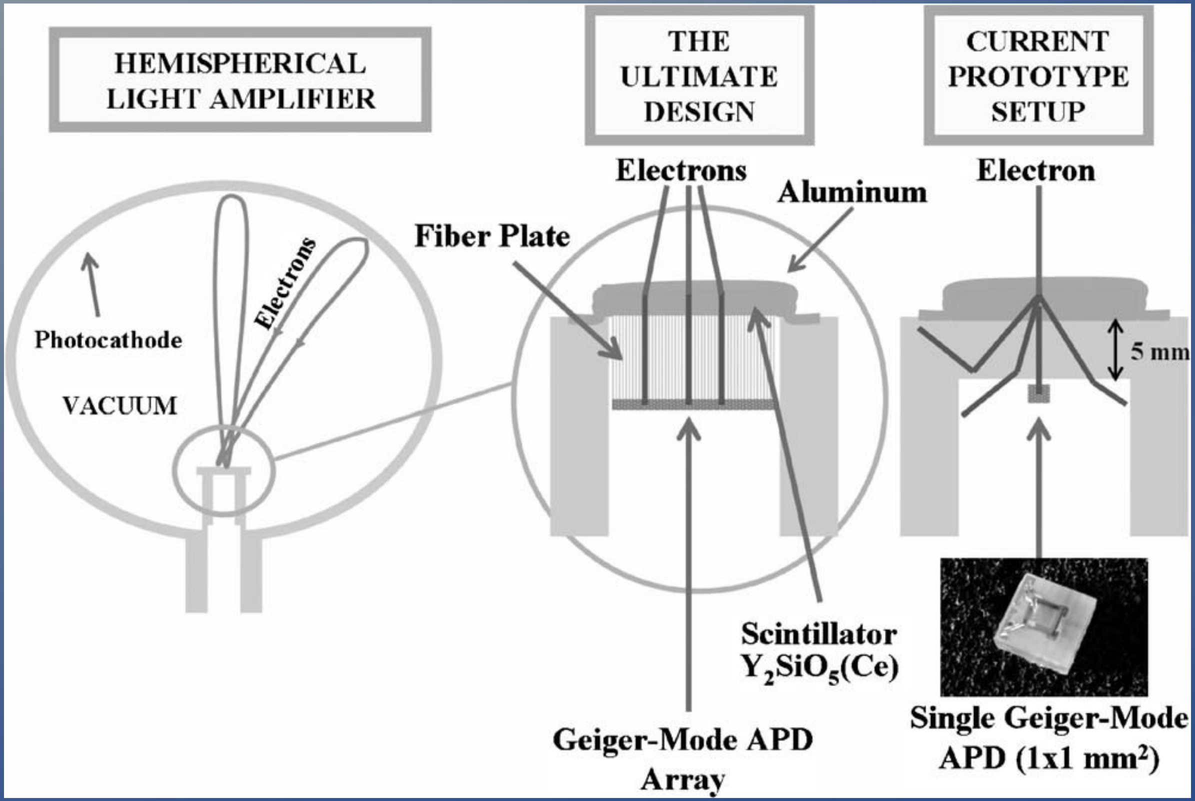
MeV detectors
Frejus, Macro, IMB.Kamioka,SuperK/SNO ....

Use all large surface PMTs

# Large Spherical PMT

Used in:
- Surface Cherenkov detectors:
  Auger SD, ICE top
- Neutrino detectors:
  ICEcube, ANTARES,
  Baikal, ...

# Hemispherical Light Amplifier




- Bombard fast scintillation crystal with photoelectron
- Readout scintillation light with G-APD

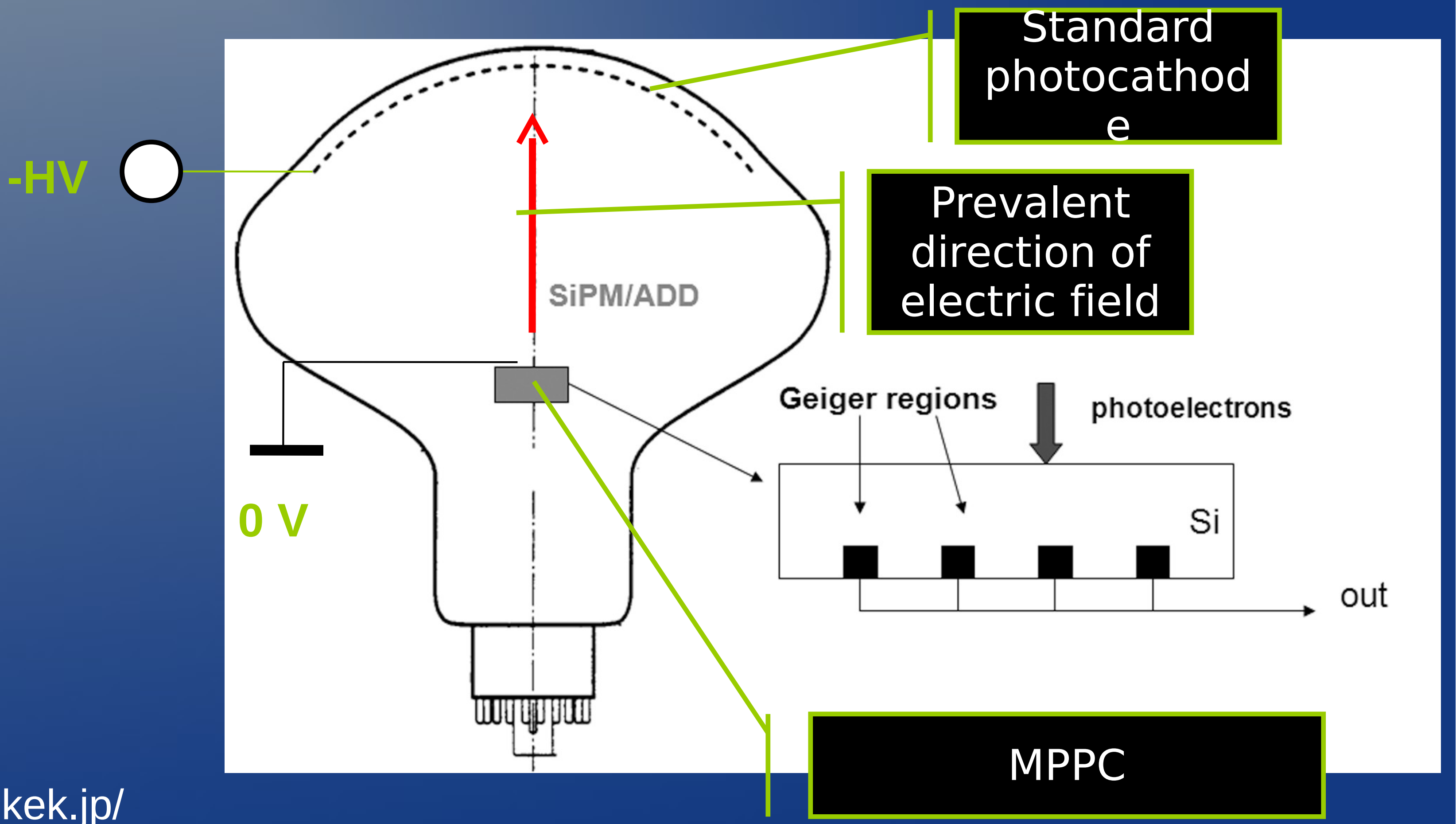
Daniel Ferenc et al. NIM-A 567 (2006)

# Vacuum Silicon Photomultiplier

Group in Naples Italy

Direct detection of 10kV photoelectron
With MPPC

NIM-A, Volume 594, September 11, 2008




See http://tipp09.kek.jp/

# Summary

- There is big need for high efficiency photo-detectors in astroparticle experiments
- All diameters between a few mm to several 10 cm
- All application have in common
  - Low photon intensities in mostly large backgrounds
  - Blue sensitivity 300-400 (600) nm
  - Single pe resolution
- Currently used by all experiments: the classical PMT
- The G-APD is a promissing photo detector
  - Some applicable G-APDs exist
  - We want more
    - Lower prices
    - Higher photon detection efficiencies

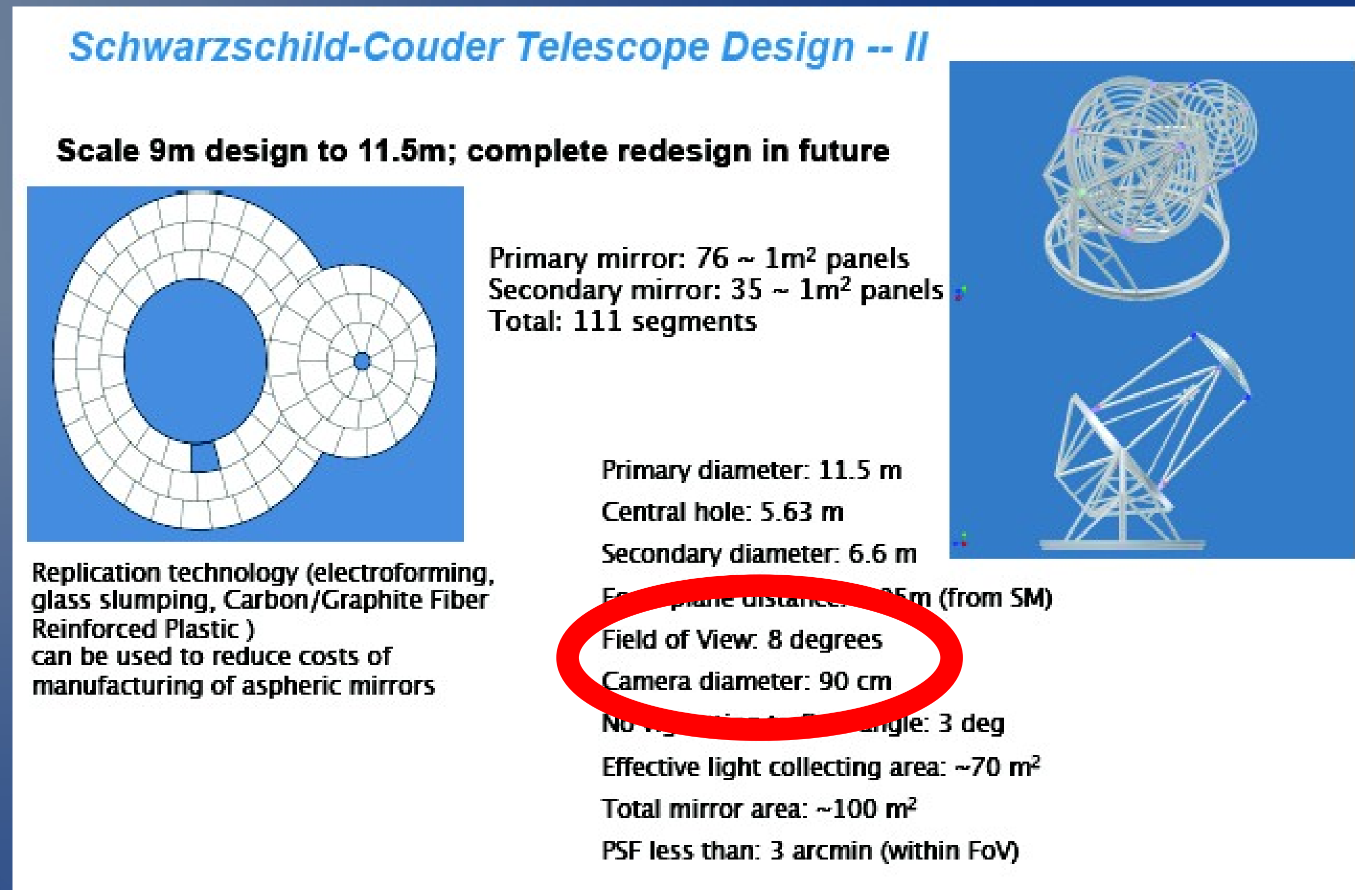
# Backup

# Schwarzschild-Couder Telescope

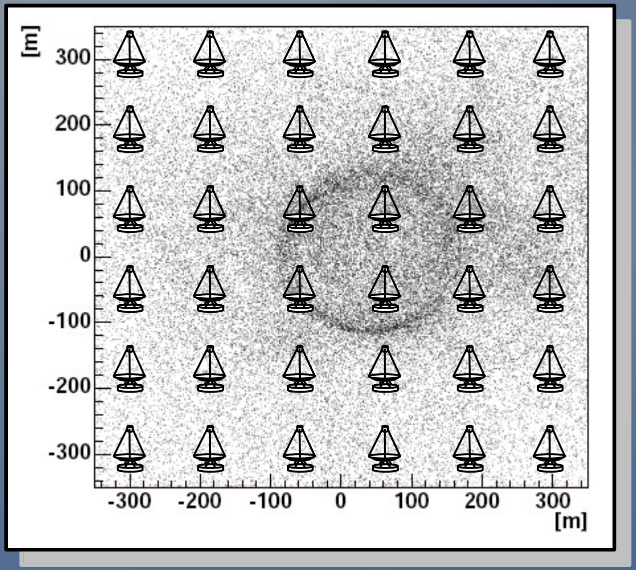
Present AGIS base line

Advantage:
  Small plate scale
  0.05 deg → 5mm

  No need for large photon detectors



# Future Plans




Cherenkov photon density on ground for a 50 GeV gamma ray

J. Buckleys view of AGIS

Large arrays of Cherenkov telescopes (~50)
Extending energy range to lower and higher energies

Two ongoing initiatives:
AGIS in the US
CTA in Europe

AGIS:

- $ 120 million project
- Array of ~ 50 telescopes
- Schwarzschild Couder telescopes
  - 8° FoV
  - Camera with 15 000 pixel
  - Pixel size: 3x3 – 5x5 mm$^2$

# Blue and Green sensitive Devices

Astroparticle experiments need Blue sensitive devices

Blue light is absorbed within the first few 100 nm

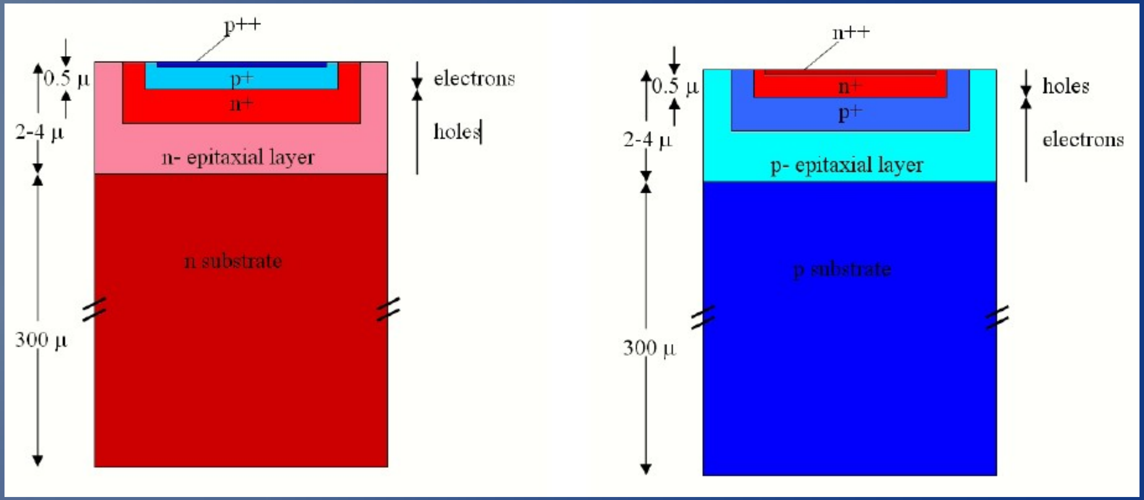
→ thin entrance windows

Electrons have a higher probability of starting an avalanche

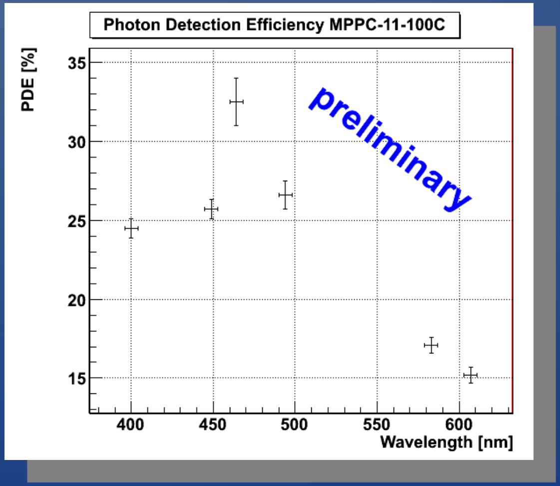
→ Need p-on-n structure
for blue sensitivity

Or new concepts
e.g. back side illumination

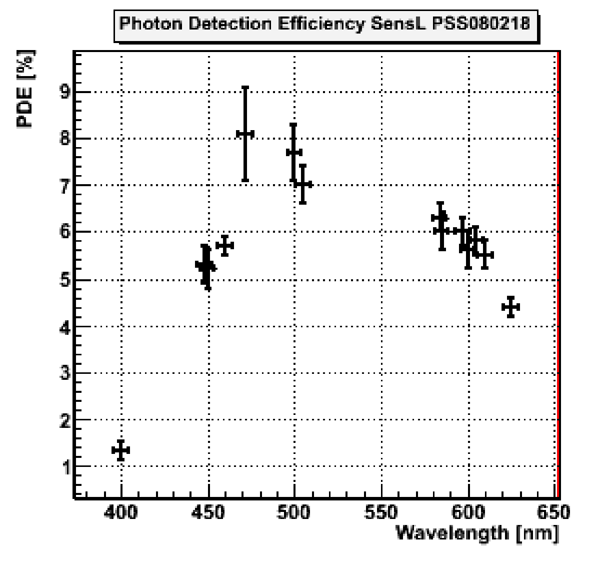
Pursued by the HLL/MPI for Physics




D. Renker, E. Lorenz, JINST 4 )2009)



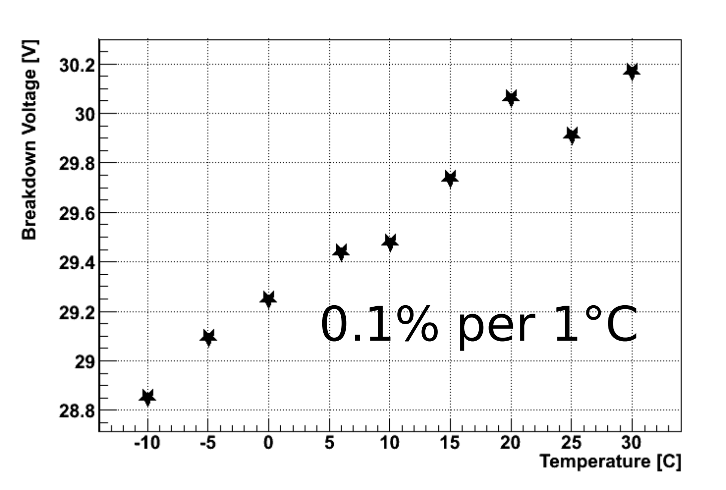

Nepomuk Otte



# Temperature Dependence

Temperature dependence of parameters increases systematic uncertainties

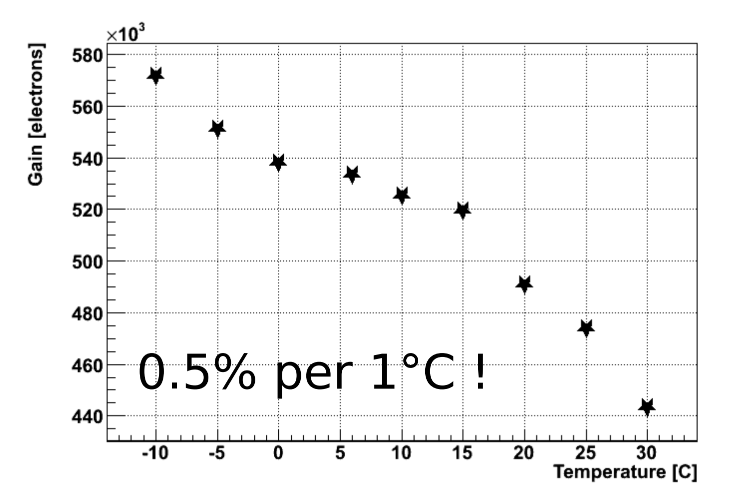
- energy estimation
- flux measurements




Solutions:

- Compensate with external thermistor
- Thermal control ( ~1 degree)
- Do a good job producing devices
    * Low breakdown voltages
    * Low cell capacitances
    * High overvoltage

DG= Tempcoef*BrkdwnVoltage/DOvervoltage




A good device

# Dark Counts

Needs to be below the photon background from the night sky

G-APD are noisy devices:

100 kHz – 1 MHz per $mm^2$

Rate depends on many parameters

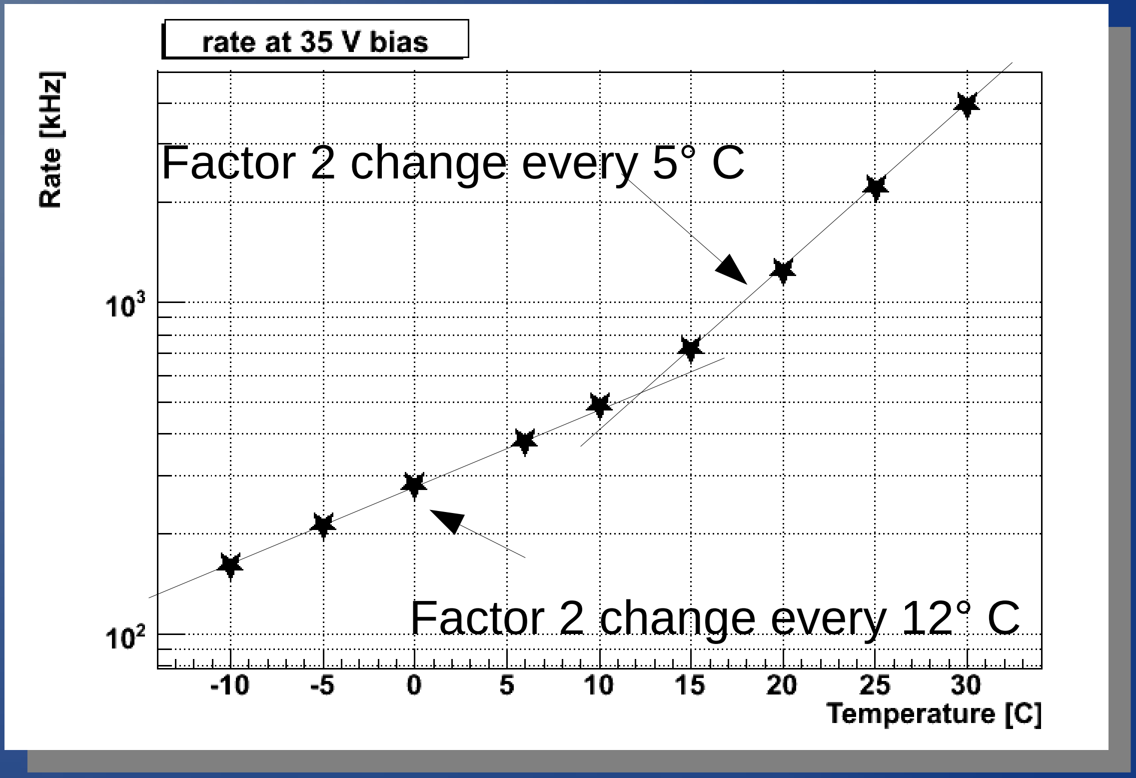
Mostly thermal generated e/h-pairs

Additional effects:
- Afterpulsing
- Tunneling

In astroparticle physics: needs to be lower than photon background rate

Rates of 100 kHz/$mm^2$ should do

1$mm^2$ G-APD from ST Microelectronics

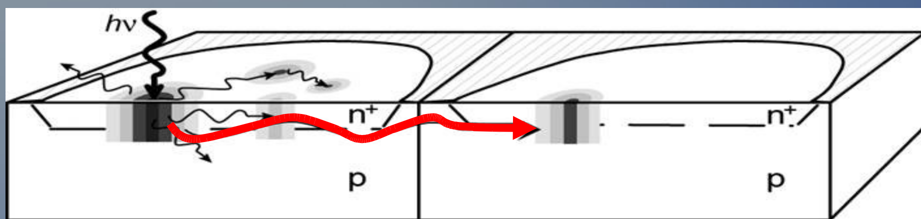


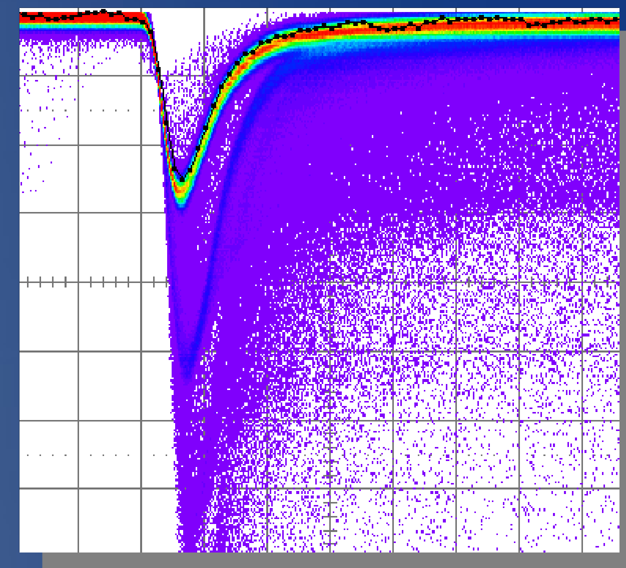

Affects lower energies

Trigger: increase in accidental triggers

Analysis: noise in shower images

# Optical Crosstalk



Avalanches emit photons

~1 photon per $10^5$ e/h-pairs

Causes additional cells to fire -> pile up

Non-negligible probability that 5 or more cells fire

Increase of accidental triggers in IACT
-> higher energy threshold

Probability needs to be ~1% not to
be dominating the rate of accidental triggers

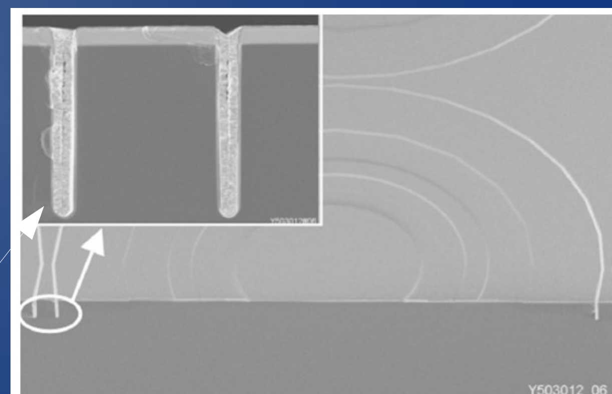



Fig. 5. Scanning electron microscope top view of a pixel of an array with trench techonology. In the inset is shown a vertical enlarged section where it is possible to view the trench details. Trenches are 10 $\mu$m deep and 0.8 $\mu$m large.

IEEE PTL, VOL. 18, NO. 15, 2006

Most promising solution: trenches between cells

Example from ST Microelectronics

# Future Plans in VHE Astrophysics

Goals:

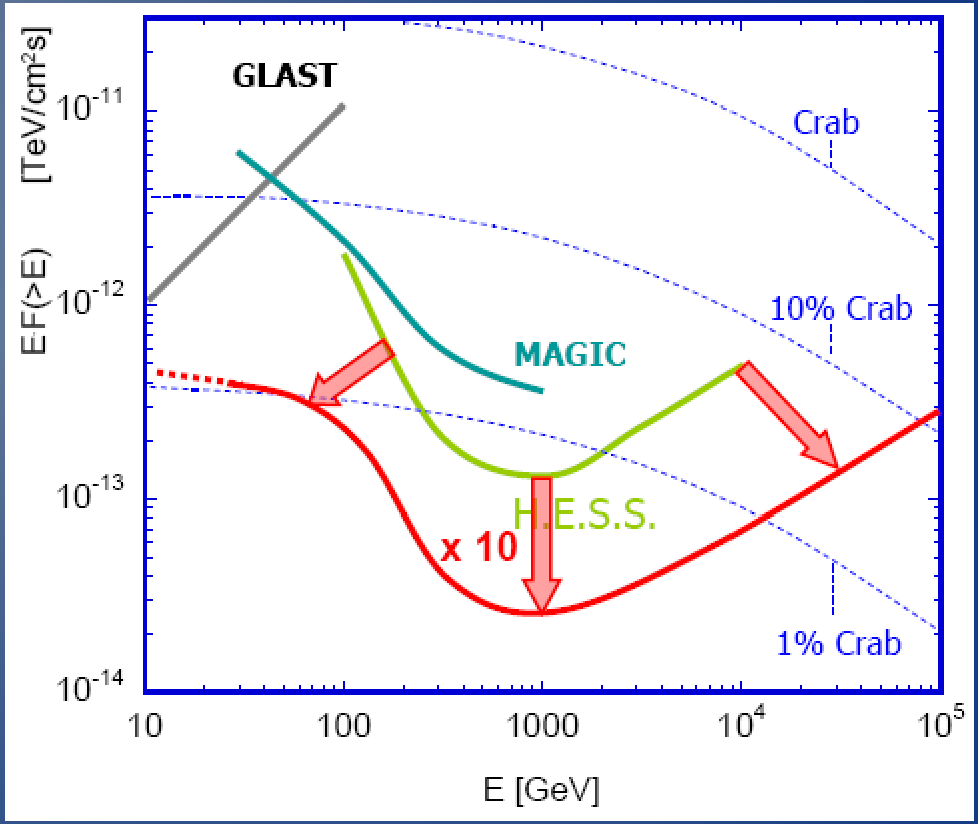
- 10x improved sensitivity
- Extended energy range

Require:

- Large arrays of Cherenkov Tel.
- Telescopes with larger FoV
- Novel trigger concepts
- Higher detection efficiency for Cherenkov light

European initiative:
CTA

US initiative:
AGIS



# SiPM requirements (Dynamic Range)

## γ – Characteristics

**arrival time window:** 1ns…3ns

**angular size:** 0.1°…~1°

**photon yield:** ≈100 ph/m² (1TeV γ)

**wavelength range:** 300nm…600nm

→ necessary dynamic range per camera pixel <$10^4$ phe

→ SiPM cell sizes of 100µm x 100µm are just at the limit

# SiPM requirements (dark rate)

Night Sky Background (photons) per MAGIC Camera Pixel:
$10^9$ Hz

$2 \cdot 10^6$ Hz NSB per mm² in the camera pixel

$10^5$ Hz/mm² intrinsic dark rate is the baseline

50% PDE
and
Intrinsic Dark rate = 10% NSB

$10^5$ Hz dark rate is possible at room temperature with available prototype SiPMs

# SiPM requirements (optical crosstalk)

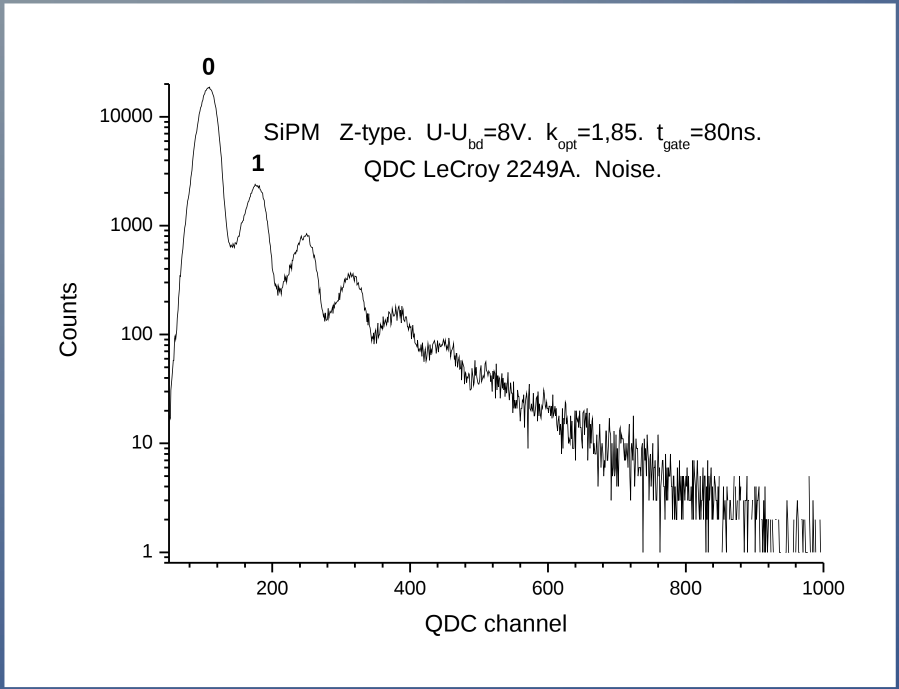
In avalanche produced photons cause inter SiPM pixel crosstalk
→Overestimation of the signal
→Influences signal shape studies for g/h separation

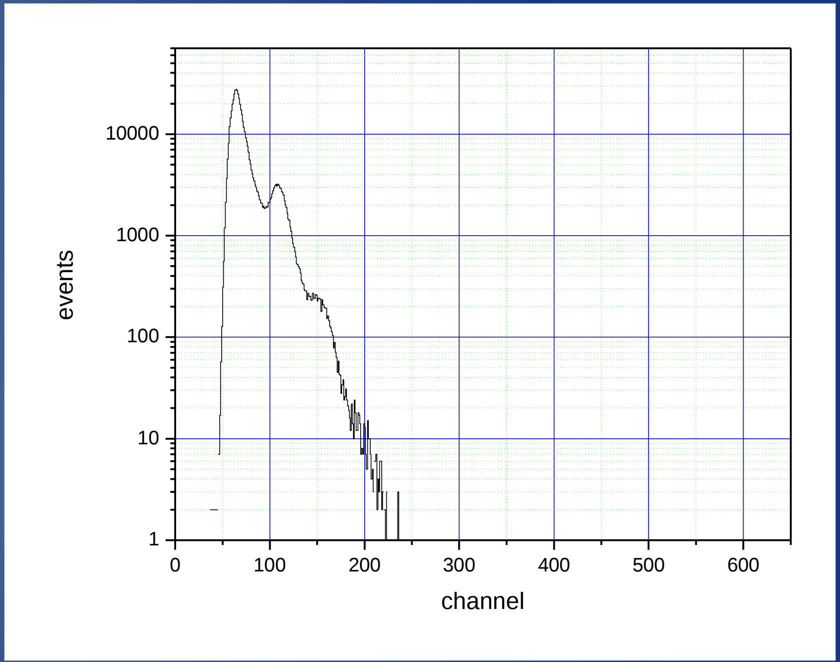
Crosstalk is proportional to charge generated in breakdown

Solutions:

- Trenches between SiPM pixels
- lower Gain
  → lower electric field → lower breakdown probability → lower PDE
- Modelling
  →simulations can fit crosstalk measurements over a wide range of parameters (Temperature of hot electrons; photon emission efficiency)
  A crosstalk probability of a few percent can be corrected for by simulations

# Trenches to suppress crosstalk



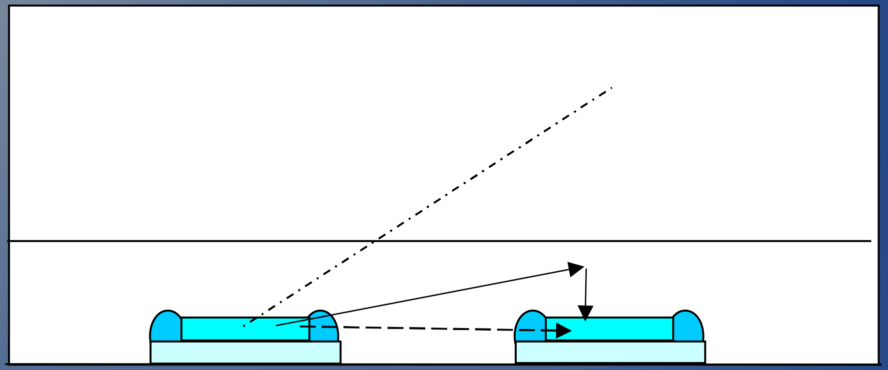




without trenches (Gain 3*10$^6$)

with trenches (Gain 3*10$^7$)

done by MEPhI

# Fast and slow Crosstalk Component



1: picoseconds (conversion and immediate breakdown)
2: ~ 1nsec (conversion, phe drift and breakdown)
3: ~10-100nsec (conversion; diffusion; drift and breakdown)

Component three contributes to afterpulsing (dark rate) in addition to trapped electrons in the avalanche region

# Application of SiPMs in IACTs

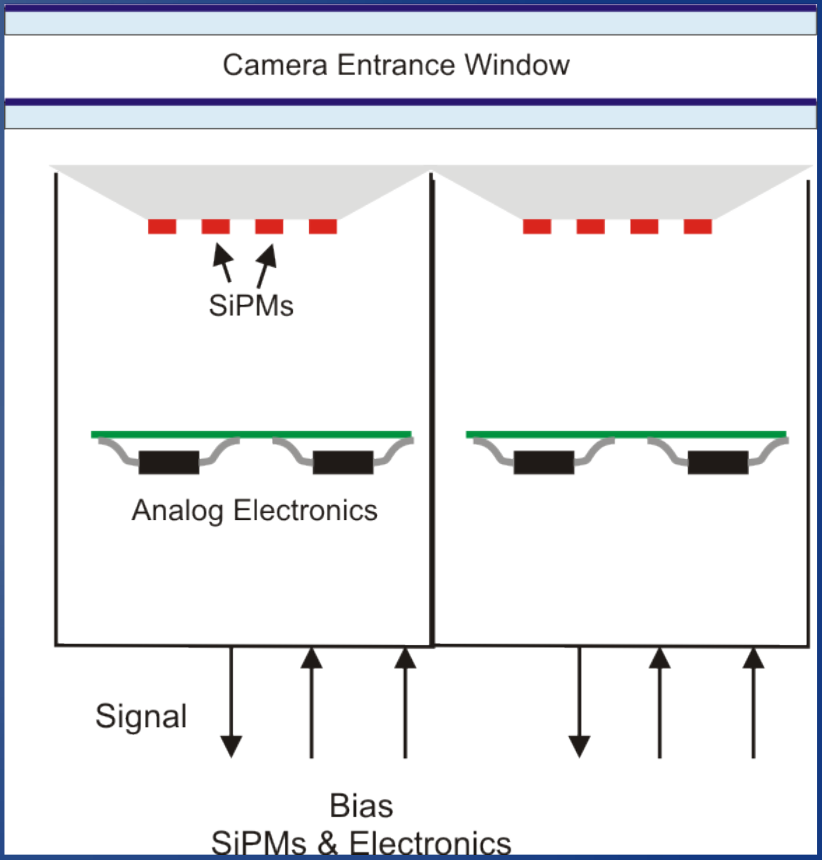
SiPM sizes of 5x5 mm² require interconnection of several SiPM to one camera pixel with one common signal readout

R&D necessary on:

Photon concentrators:
to overcome dead space between SiPMs

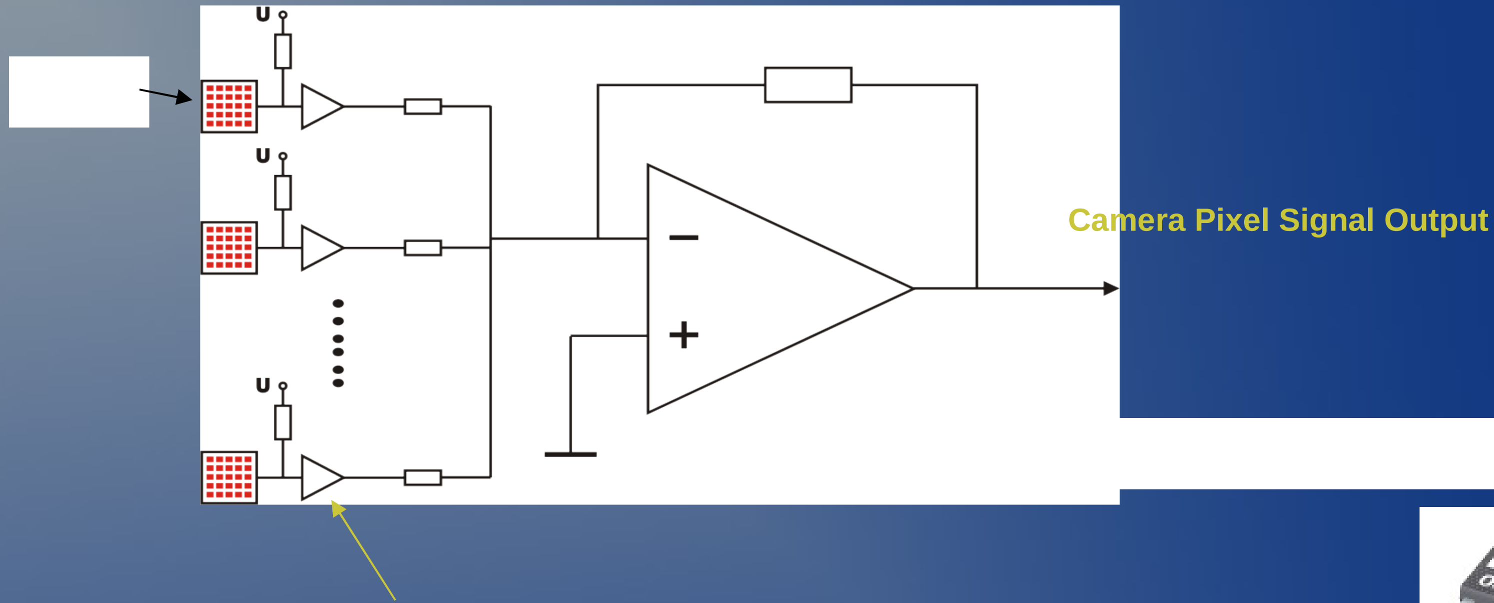
Electronic readout:
low power consumption
ultra high bandwidth
summing amplifier

Cooling:
thermal isolation




Two camera pixel

# Signal Readout



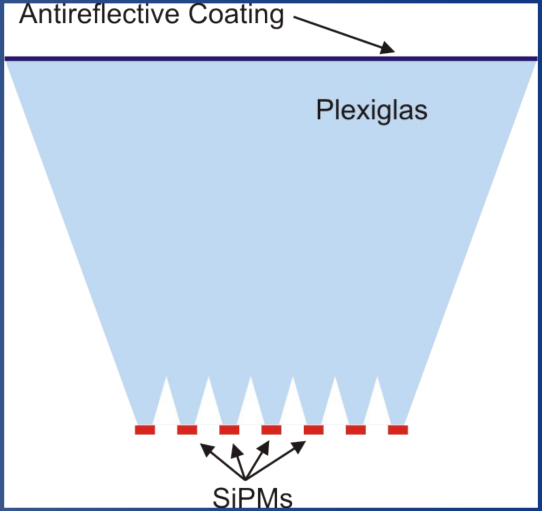


Fast transimpedance amplifier → currently developed at MPI

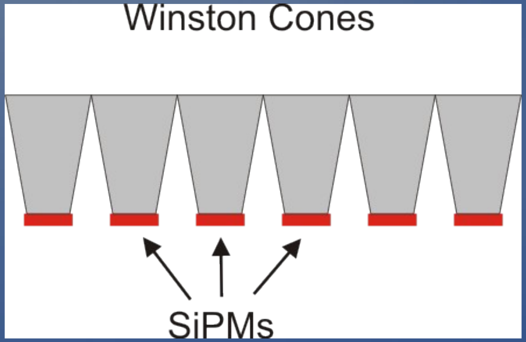
- 1 GHz broadband buffer/preamplifier after each SiPM
- all SiPMs (4) of one camera pixel connected to summing amplifier
- good HF layout mandatory
- ASIC is not fast enough

# Photon Concentrators

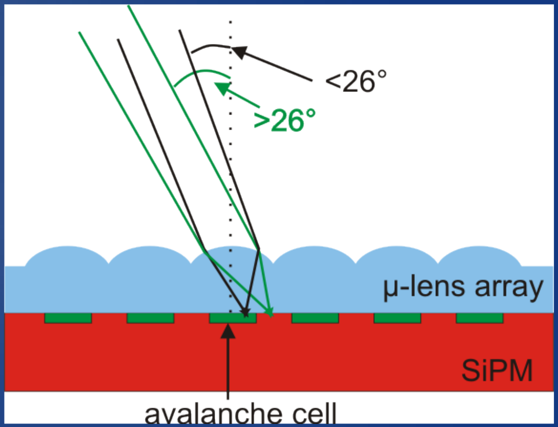
1. Lightguide made out of Plexiglas




2. Winston Cones



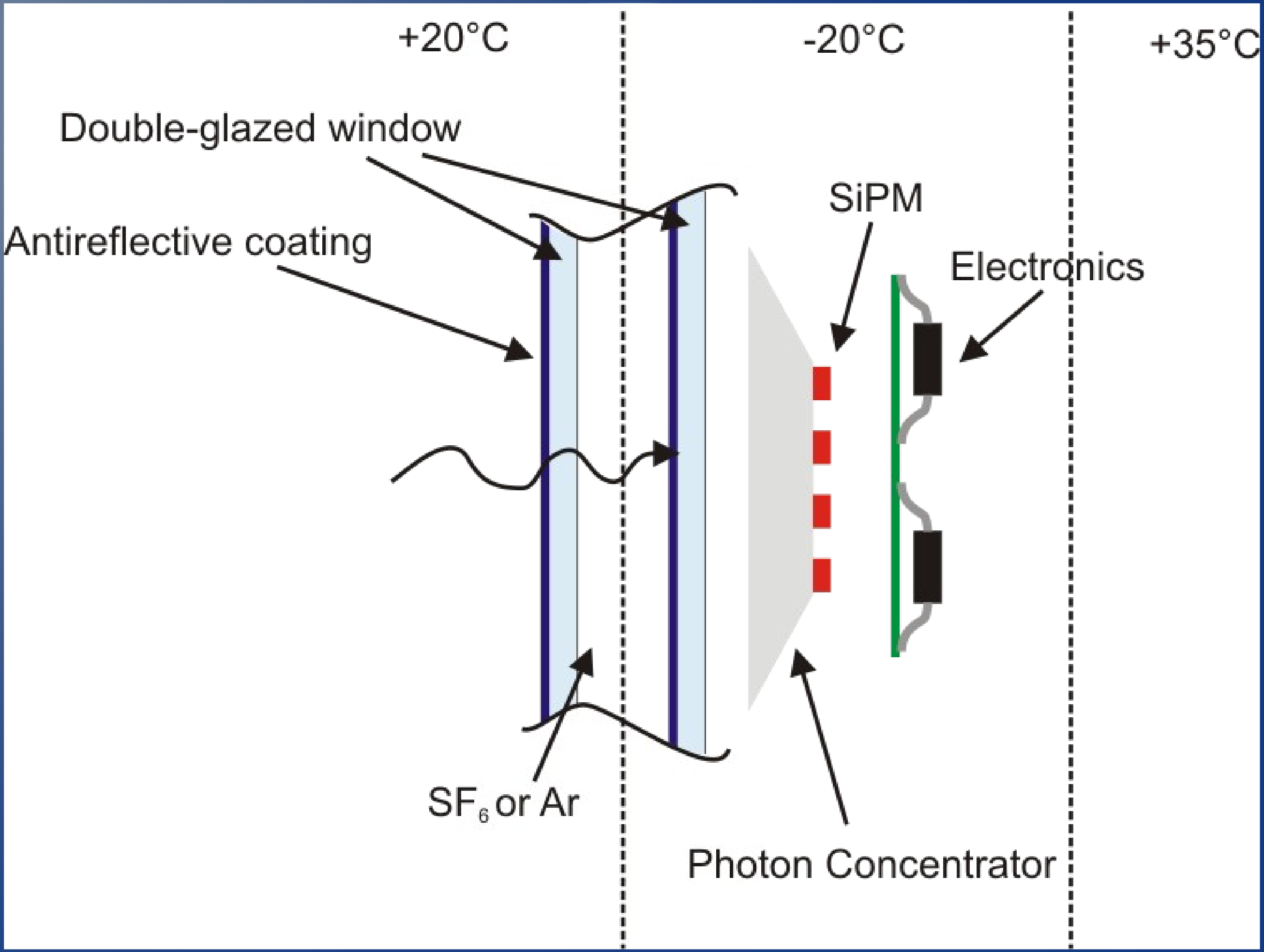

+ Additional µ-lens array on top of each SiPM




Light concentrators needed to reduce dead area between SiPMs

# Cooling

- Moderate Cooling (-20 °C) needed to reduce dark noise rate below NSB
- Might not be necessary with new SiPMs
- double glazed Camera entrance window
  - Gas with low thermal conductivity $SF_6$ or Ar



# Comparison G-APD / PMT

| PMTs | G-APD |
| --- | --- |
| Large areas | Small |
| Large gain | Large gain ~$10^5$- ~$10^6$ |
| Single photoelectron resolution | Single photoelectron resolution |
| Well established technology | Early stage of commercialization |
| Fast signals (~ns) | Signals ~ns to several 10 ns |
| | |
| Sensitive to magnetic fields | Not sensitive to magnetic fields |
| Damaged in daylight/sunlight | Not Damaged in daylight/sunlight |
| Afterpulsing | No Afterpulsing but optical crosstalk |
| Use of high voltage | Bias < 100 V |
| Bulky and fragile | Electrical and mechanical robust / light weight |
| Average QE <20% | Average QE <20%, possible > 50% |
| Temperature stability <0.5%/C | Temperature stability <3%/C |
| | Low power consumption 40µW per mm² |

# PDE dependence on the Bias Voltage