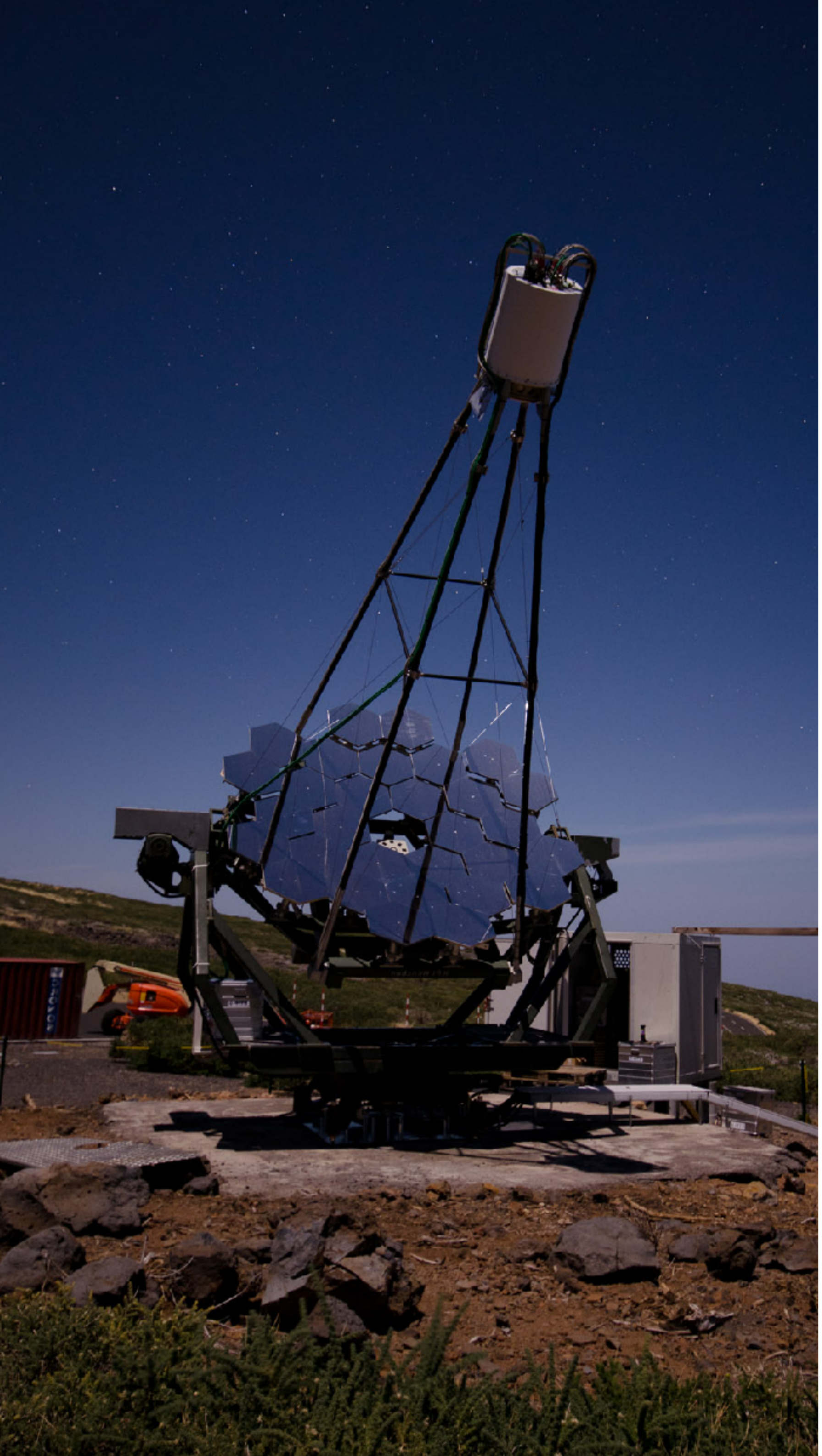


# FACT
# The G-APD revolution in Cherenkov astronomy
(or: conclusions from FACT)


Thomas Bretz
(ETH Zurich)



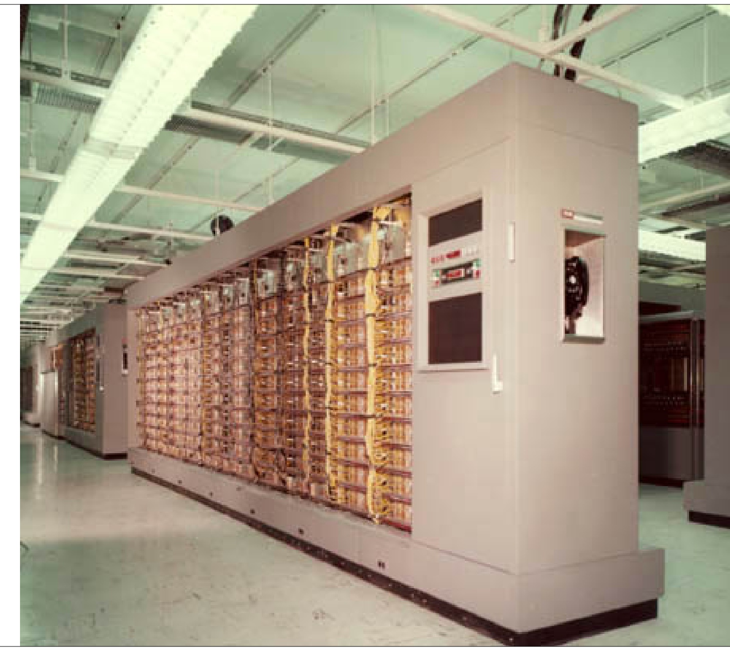
**[arXiv:1304.1710]**

# Outline

- Technical motivation
- Physics motivation
- Cherenkov astronomy
- Construction
- G-APDs
- Feedback
- First results
- Conclusions

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

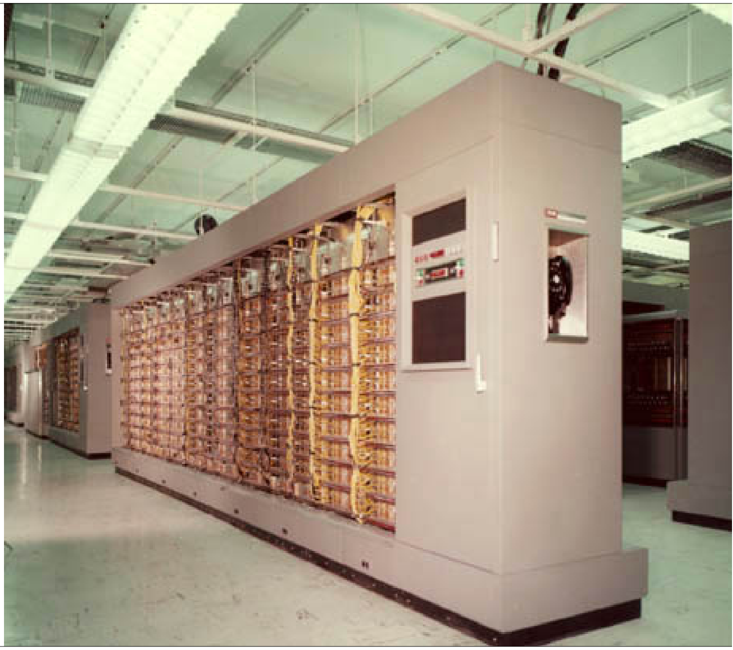
tubes →

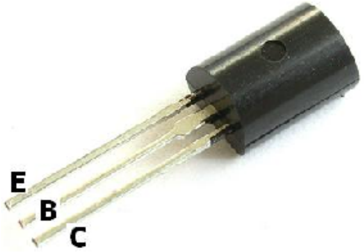


# FACT

# **F**irst G-**A**PD **C**herenkov **T**elescope

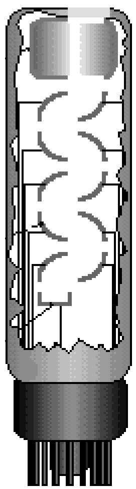
tubes →



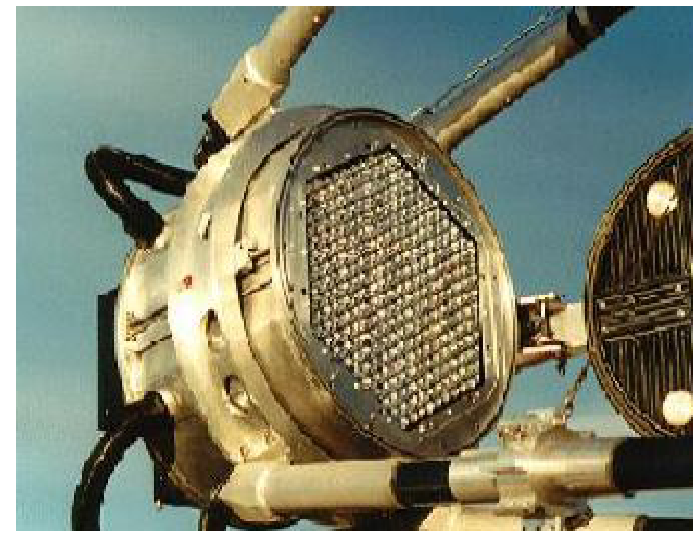



silicon → devices

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope



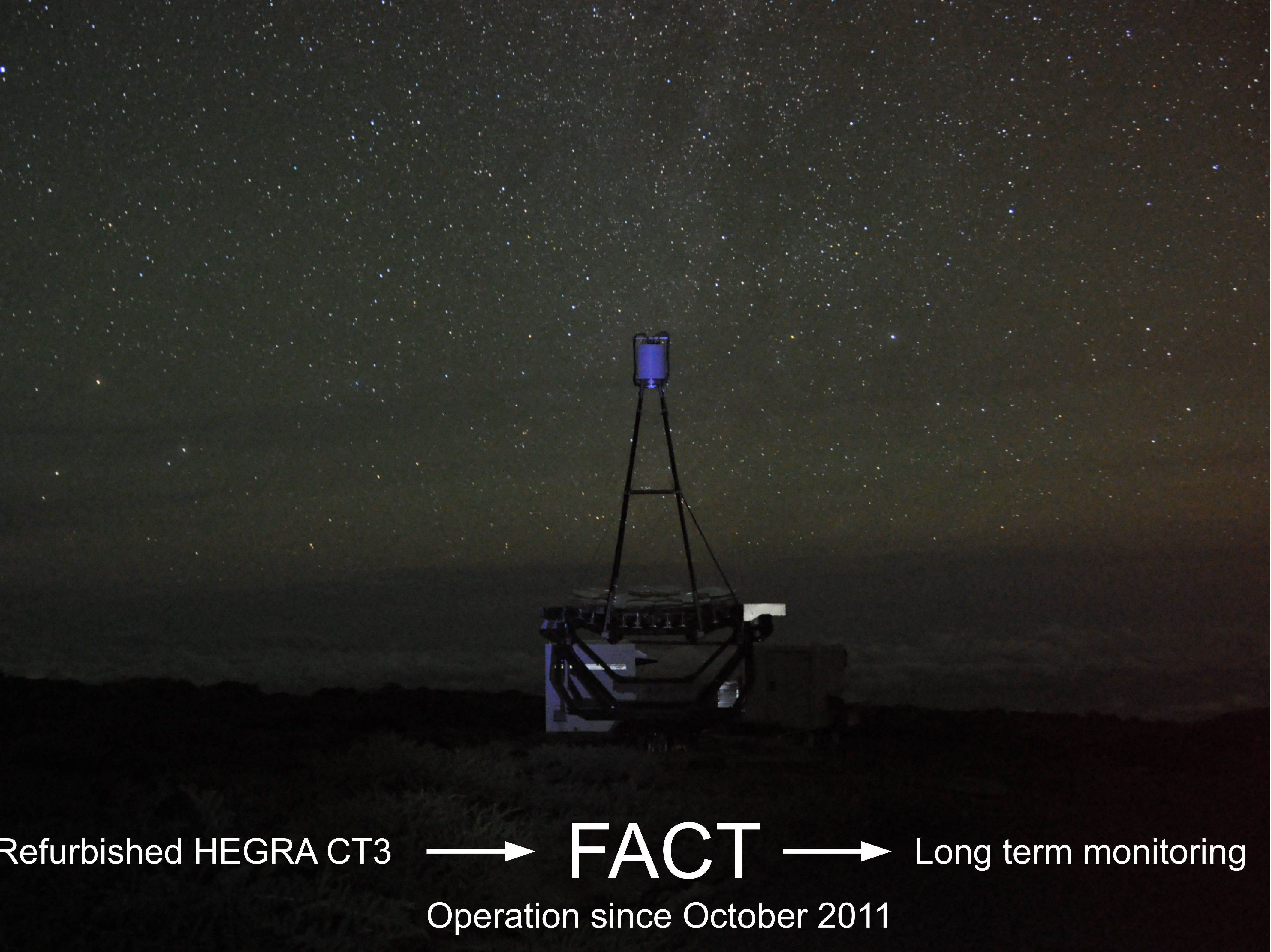
tubes →



silicon devices →

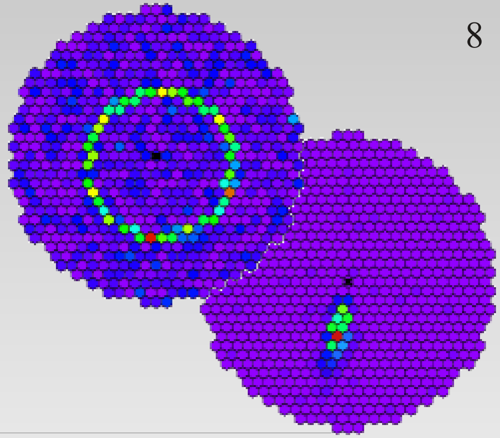
?

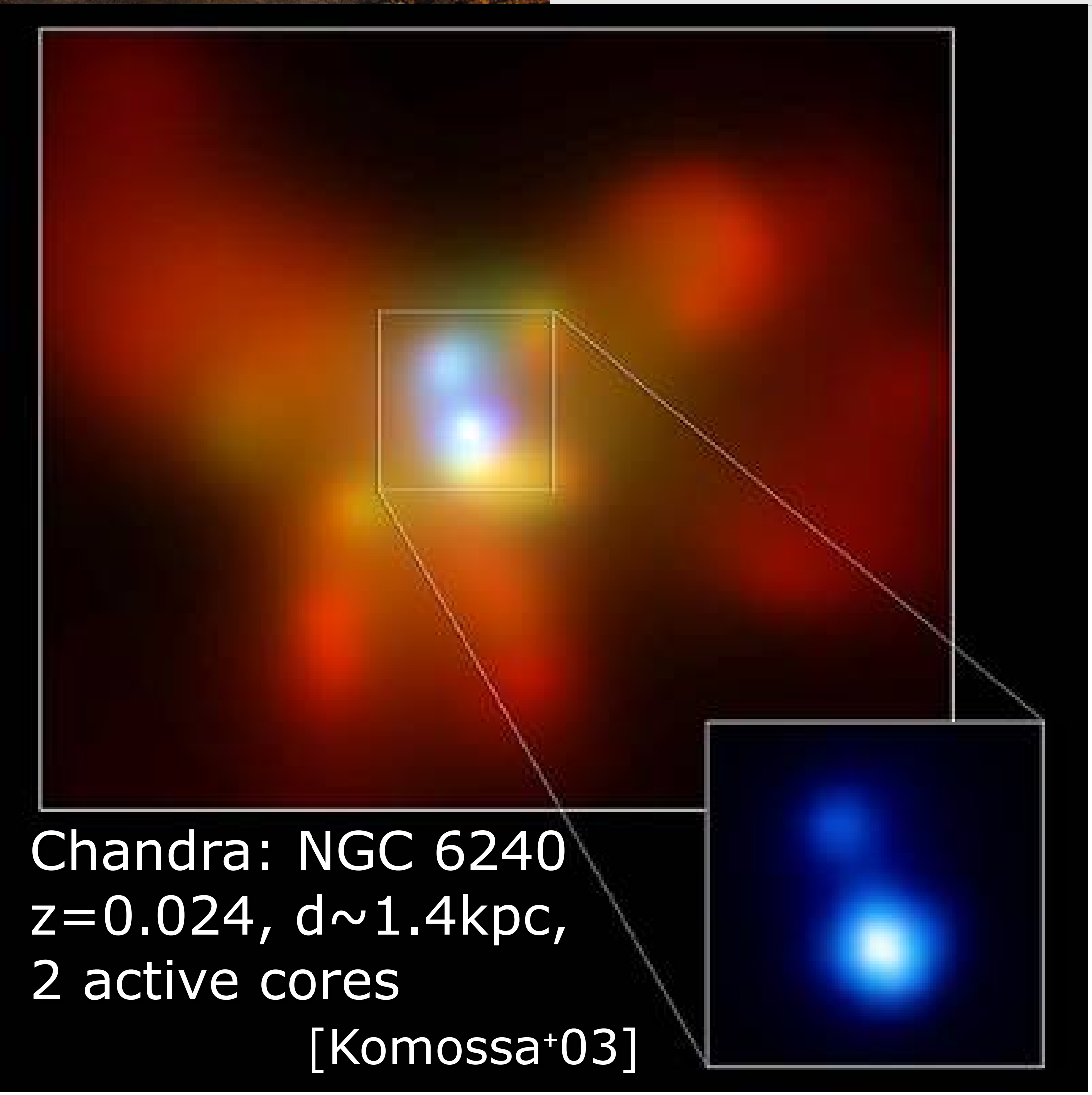
only about
10 active FTE
working on the
commissioning
and analysis


Refurbished HEGRA CT3
FACT
Long term monitoring
Operation since October 2011

# Motivation

Active galactic nuclei

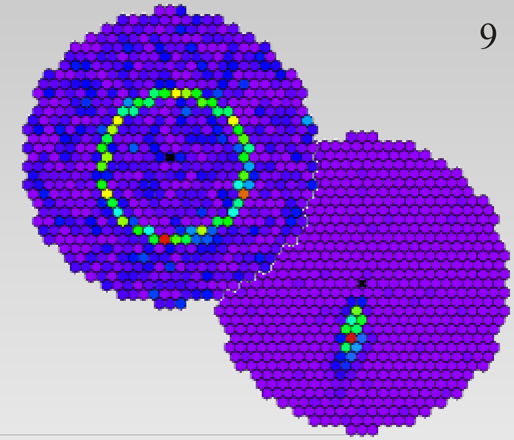


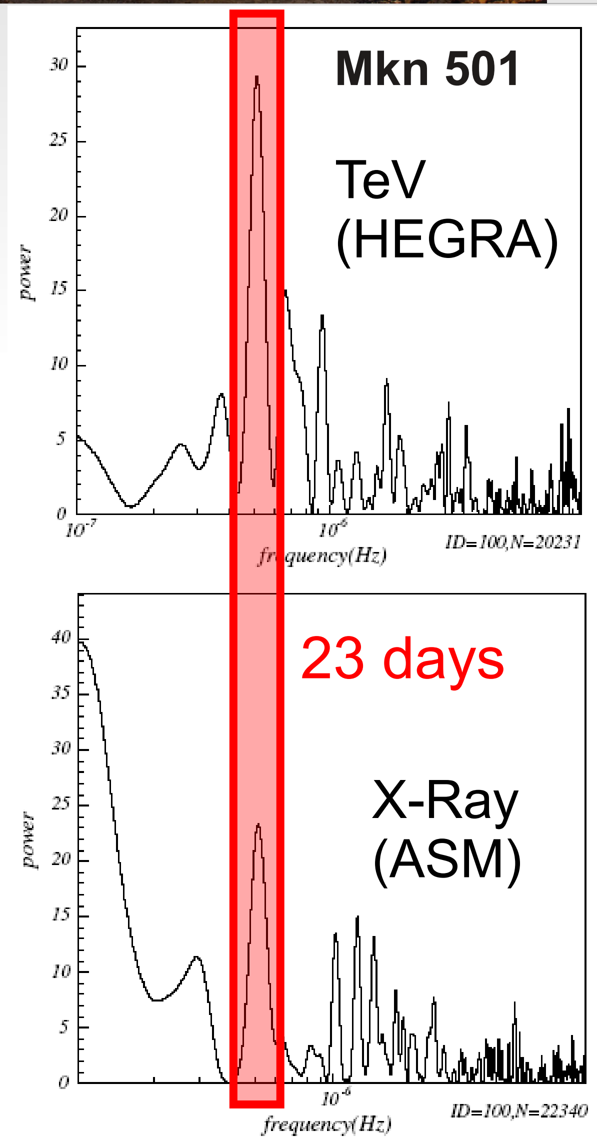



- Understand extreme blazar variability on time scales from minutes to years
- Jet modulation due to binary black holes (months to years), expected naturally in hierarchical galaxy formation
- Jet formation at light cylinder
- Fundamental modes of central engine
- Radiation mechanism

# Motivation

Active galactic nucleii

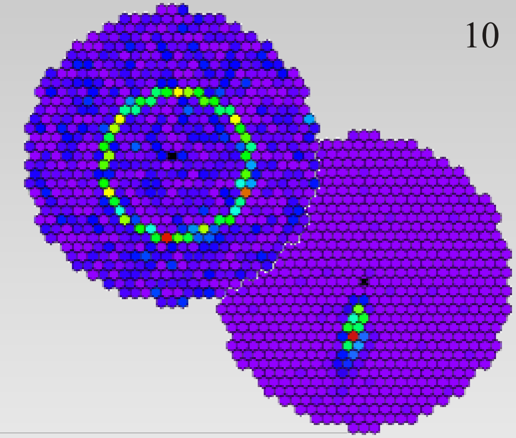


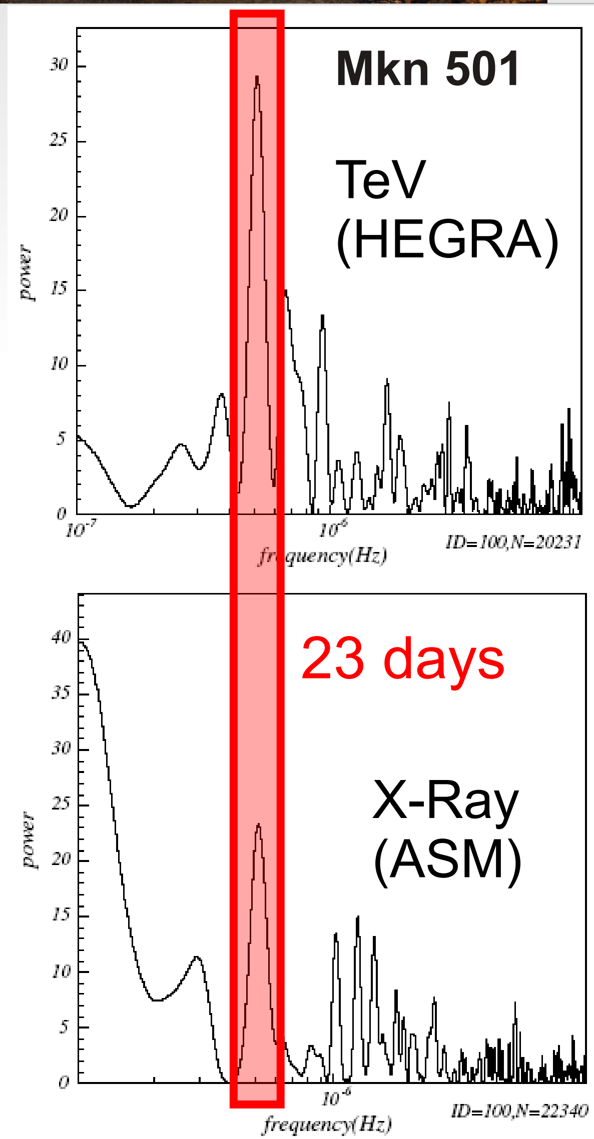



- Understand extreme blazar variability on time scales from minutes to years
- Jet modulation due to binary black holes (months to years), expected naturally in hierarchical galaxy formation
- Jet formation at light cylinder
- Fundamental modes of central engine
- Radiation mechanism

# Motivation

Active galactic nucleii



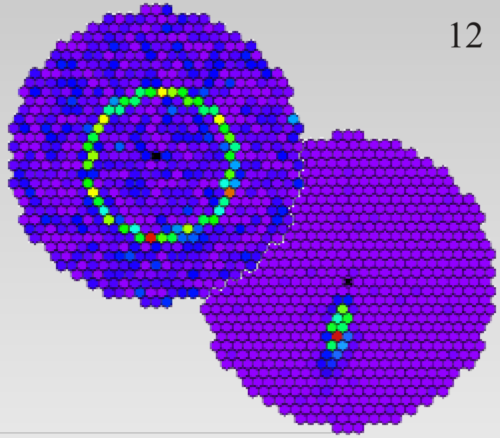



- Understand extreme blazar variability on time scales from minutes to years
- Jet modulation due to binary black holes (months to years), expected naturally in hierarchical galaxy formation
- Jet formation at light cylinder
- Fundamental modes of central engine
- Radiation mechanism

**Long-term observations mandatory! O(>=months)**

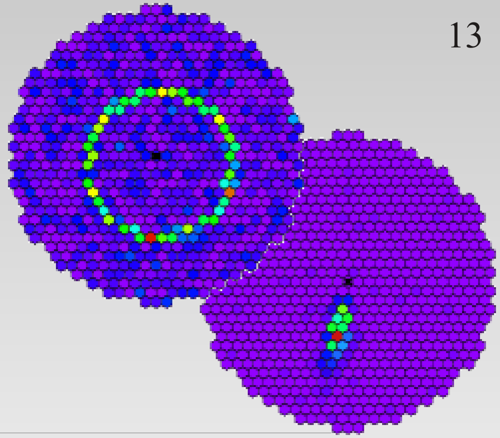
# Existing instruments

Overview



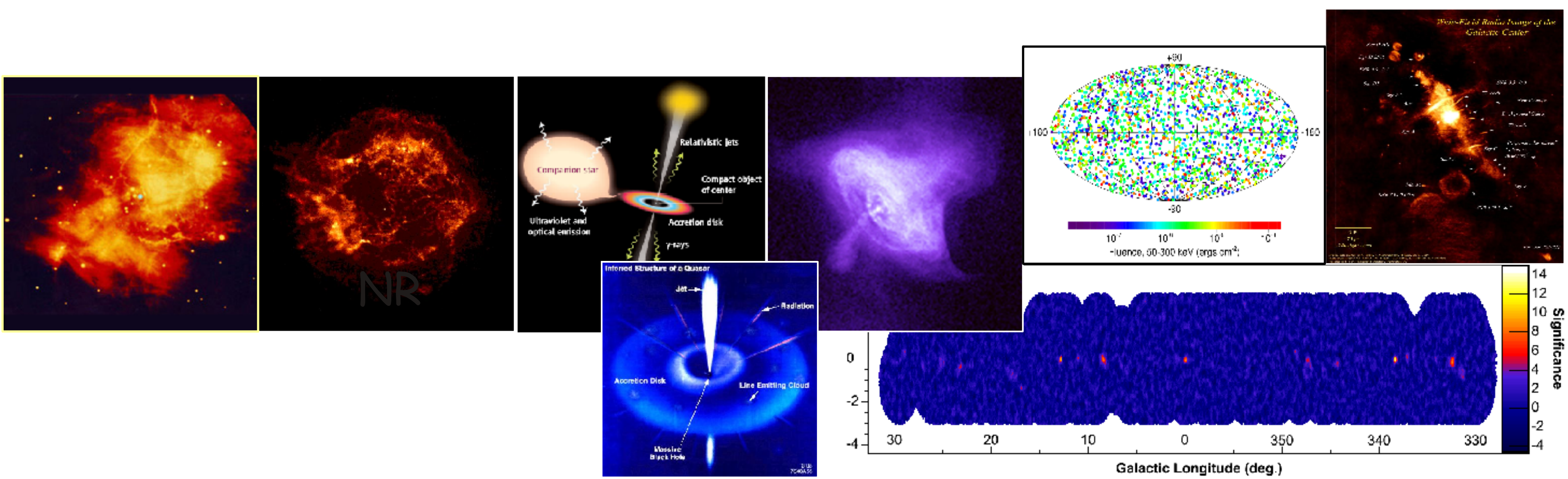
# Existing instruments

Overview



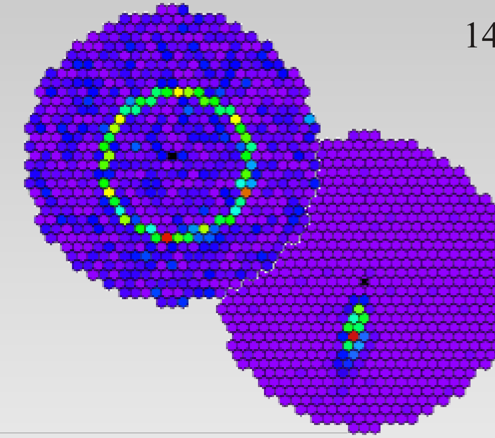
## High sensitivity and low energy threshold

Many science goals – many different targets



# Existing instruments

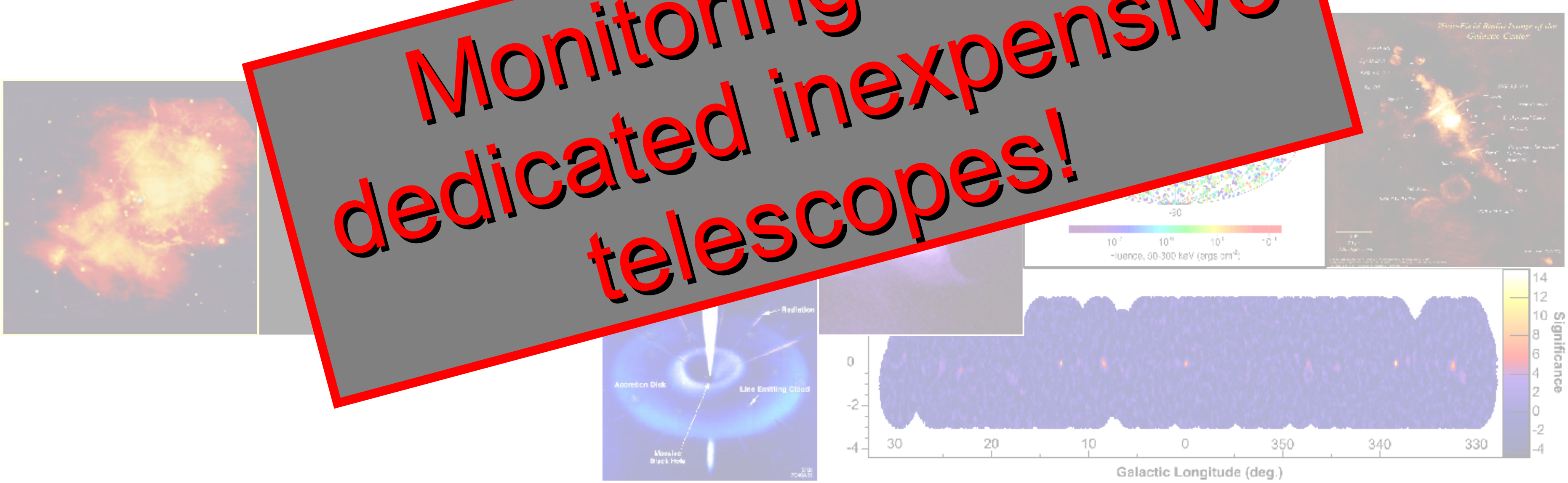
Overview



## High sensitivity and low energy threshold

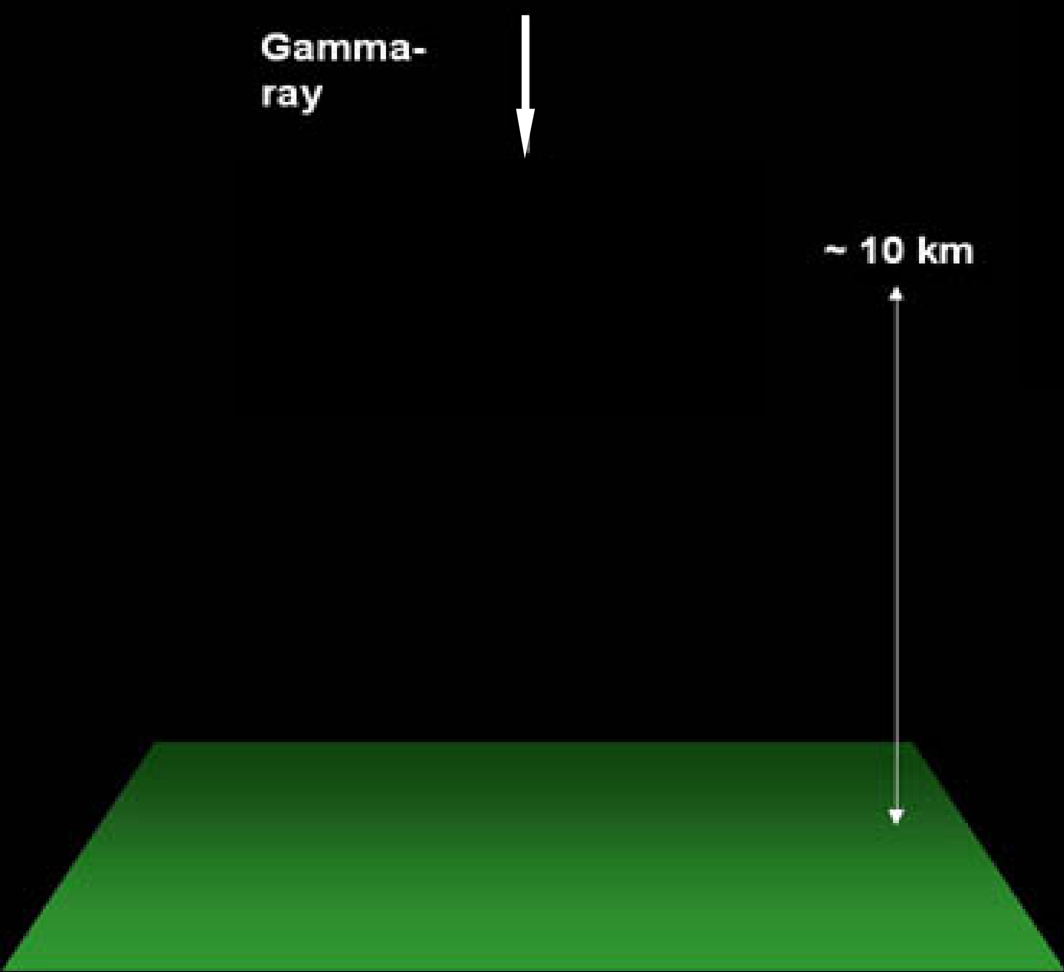
Many science goals – many diff…

**Monitoring needs dedicated inexpensive telescopes!**



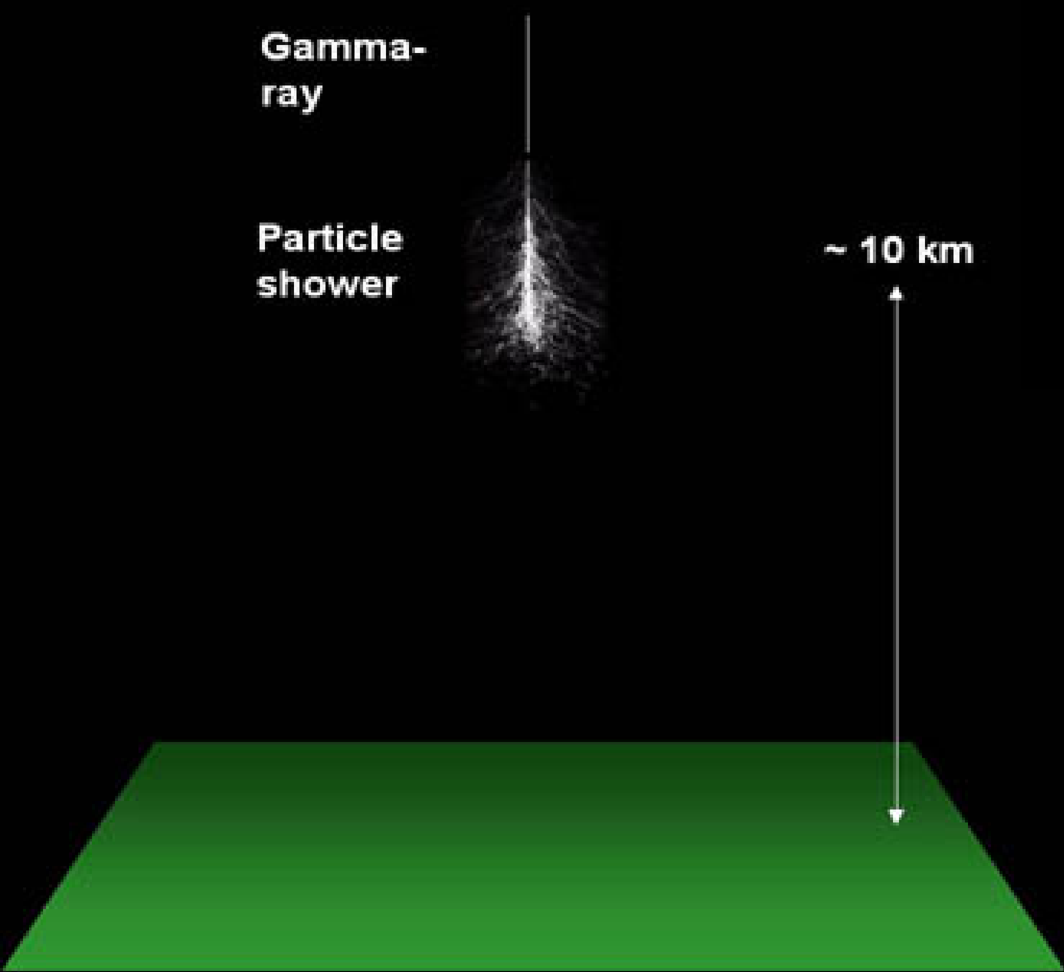
# Detection principle

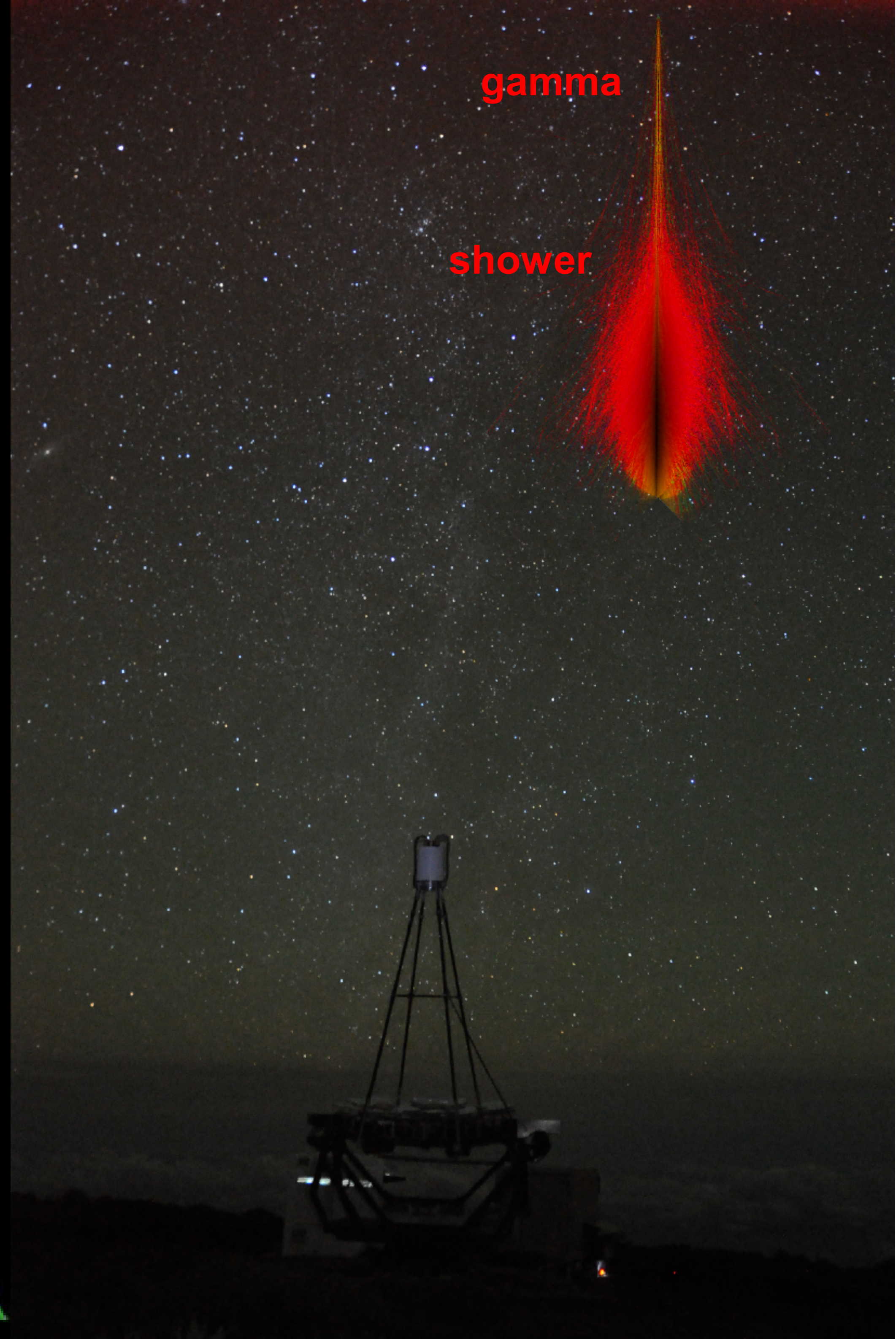
- Pair production from primary gammas in the atmosphere
  - ➜ electromagnetic shower




# Detection principle

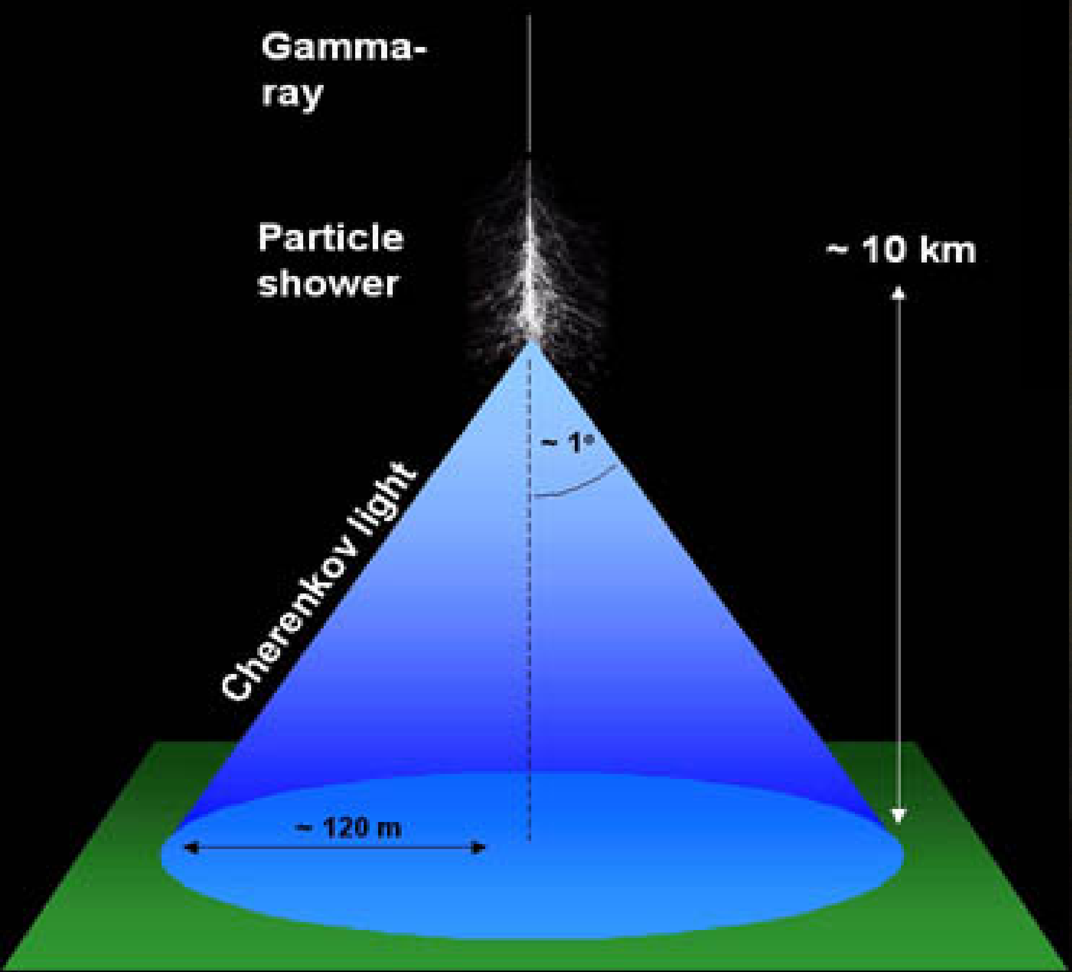
- Pair production from primary gammas in the atmosphere
  - ➔ electromagnetic shower

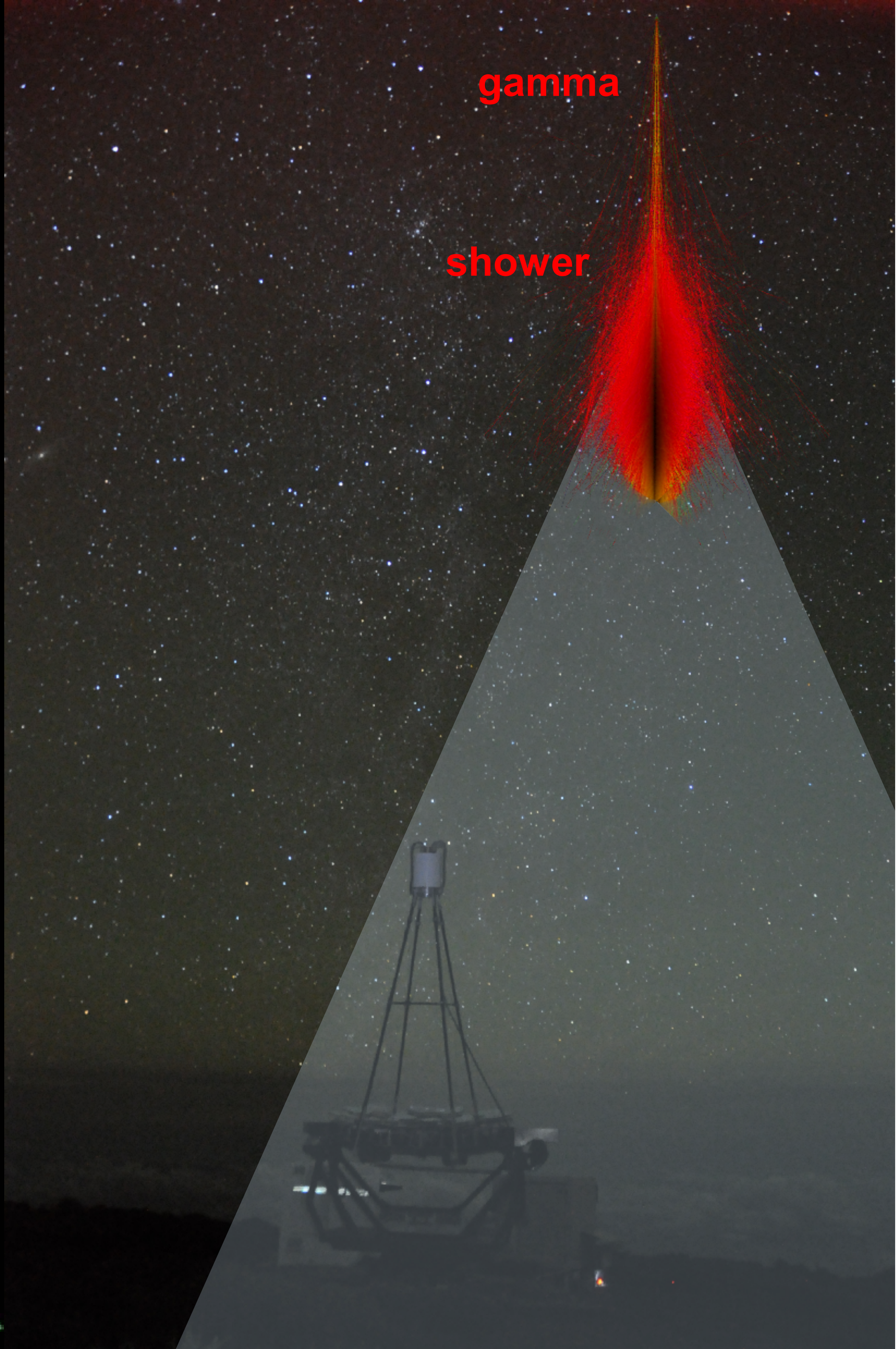


# Detection principle

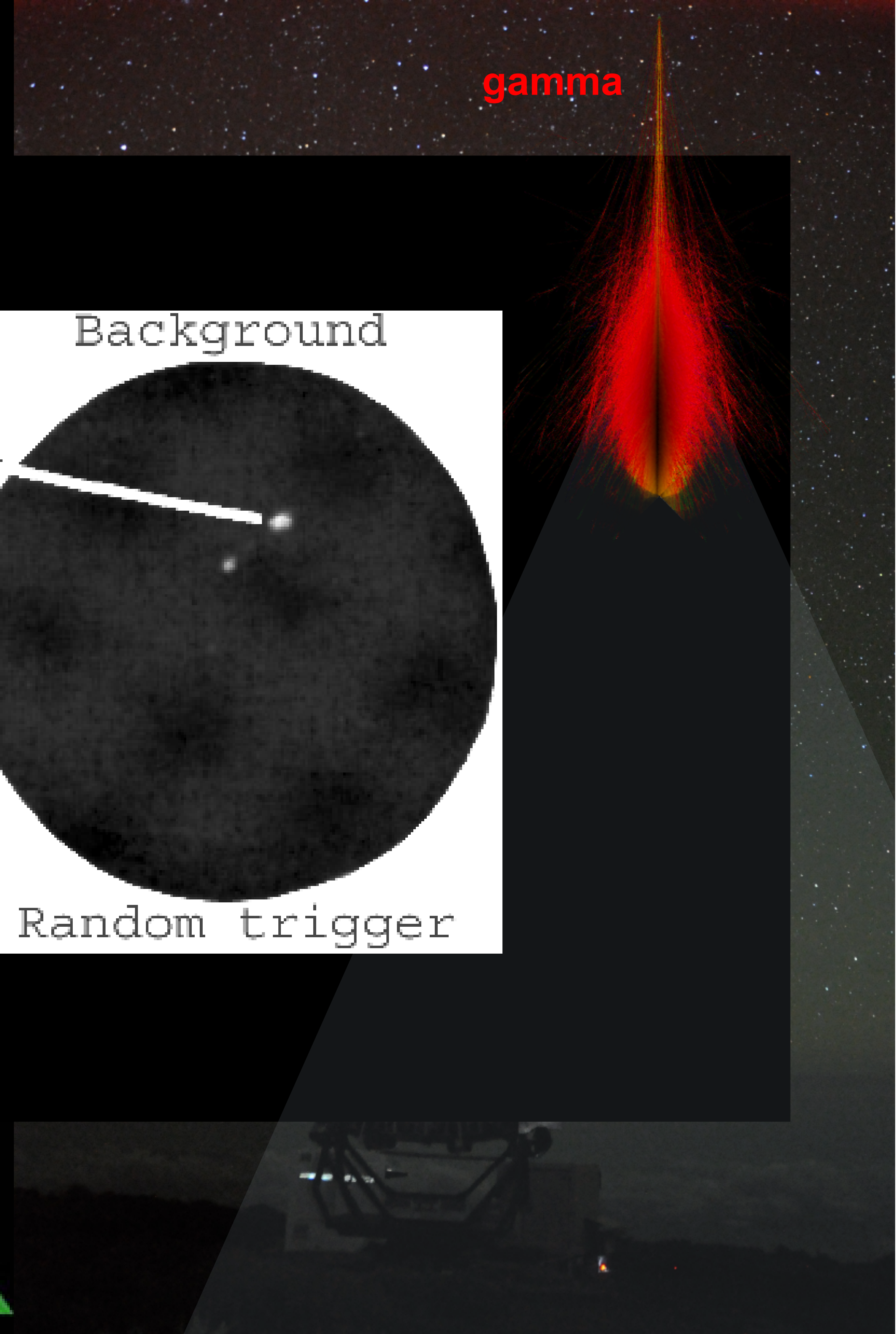
- Pair production from primary gammas in the atmosphere
  - ➔ electromagnetic shower
  - ➔ Cherenkov light

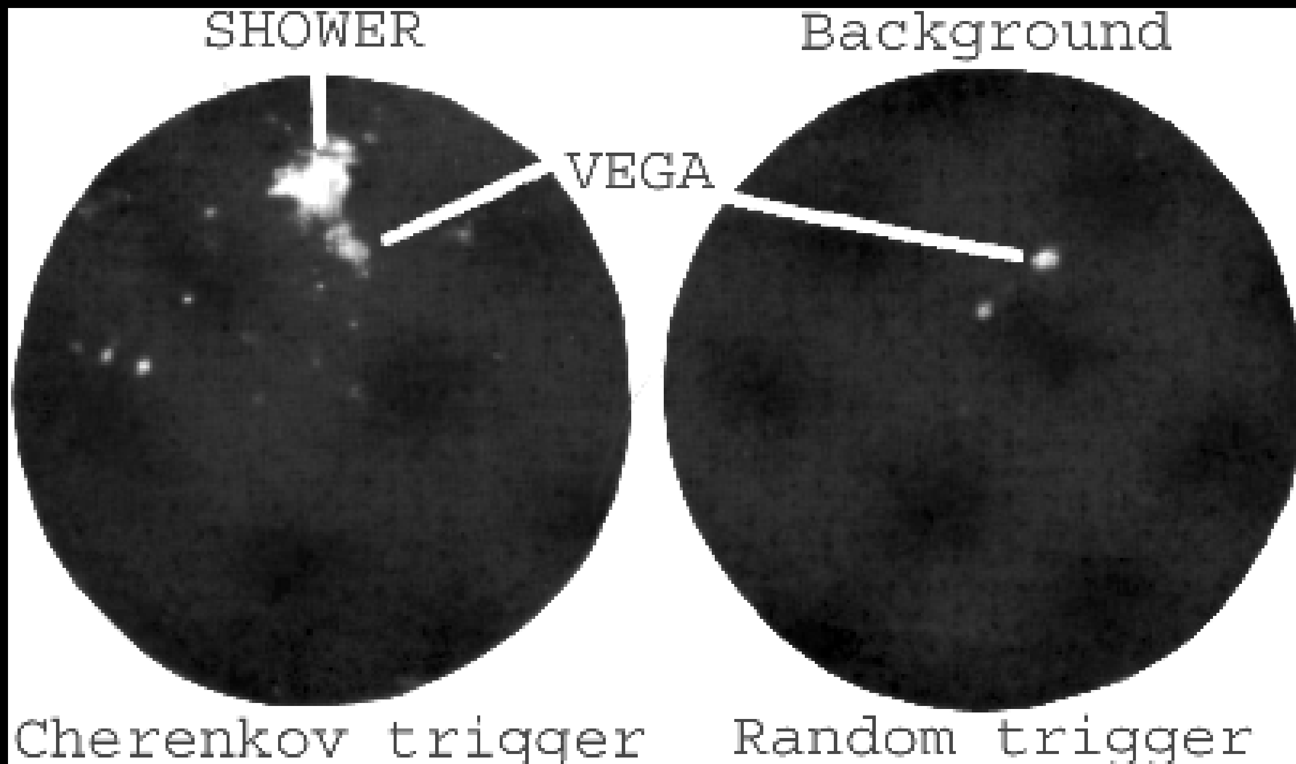


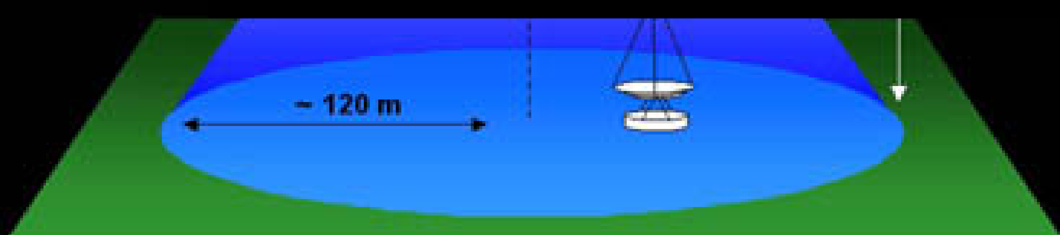



# Detection principle

- First attempts to detect air-showers in the 60's with standard photo plates

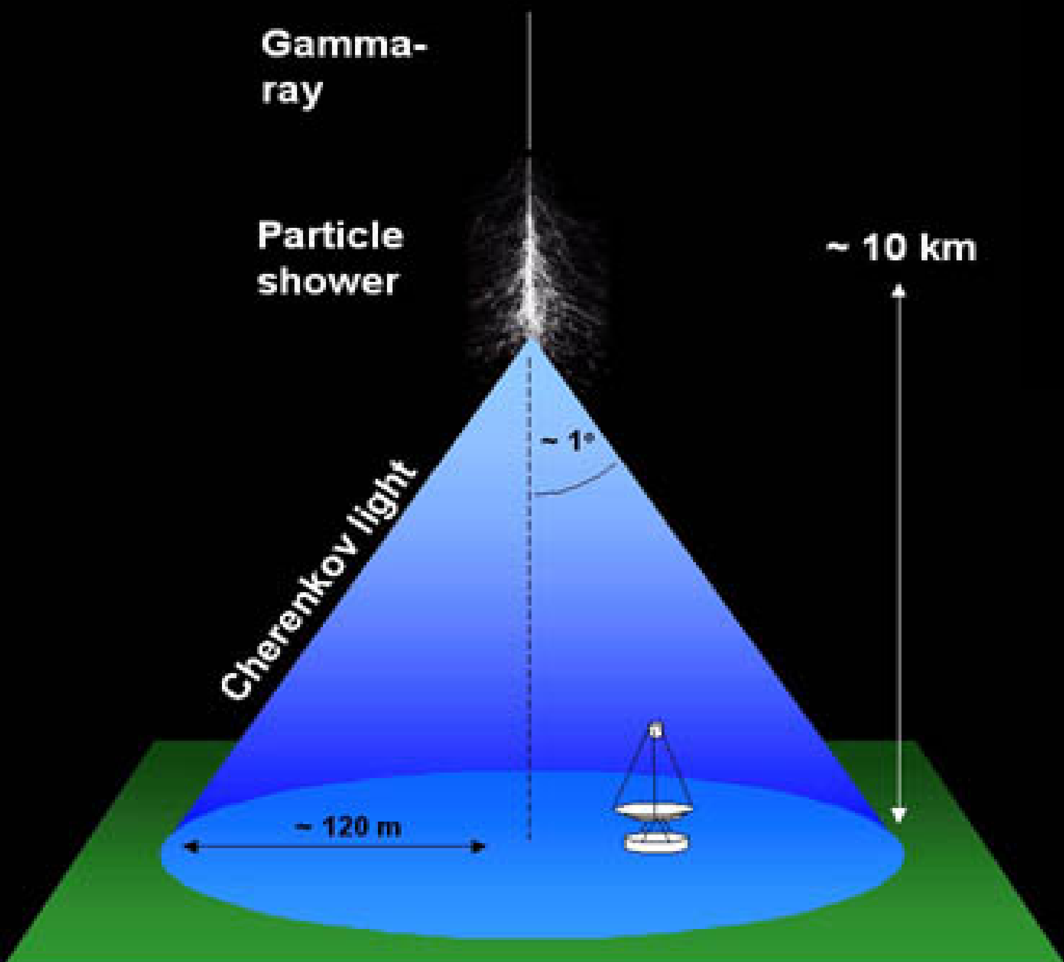


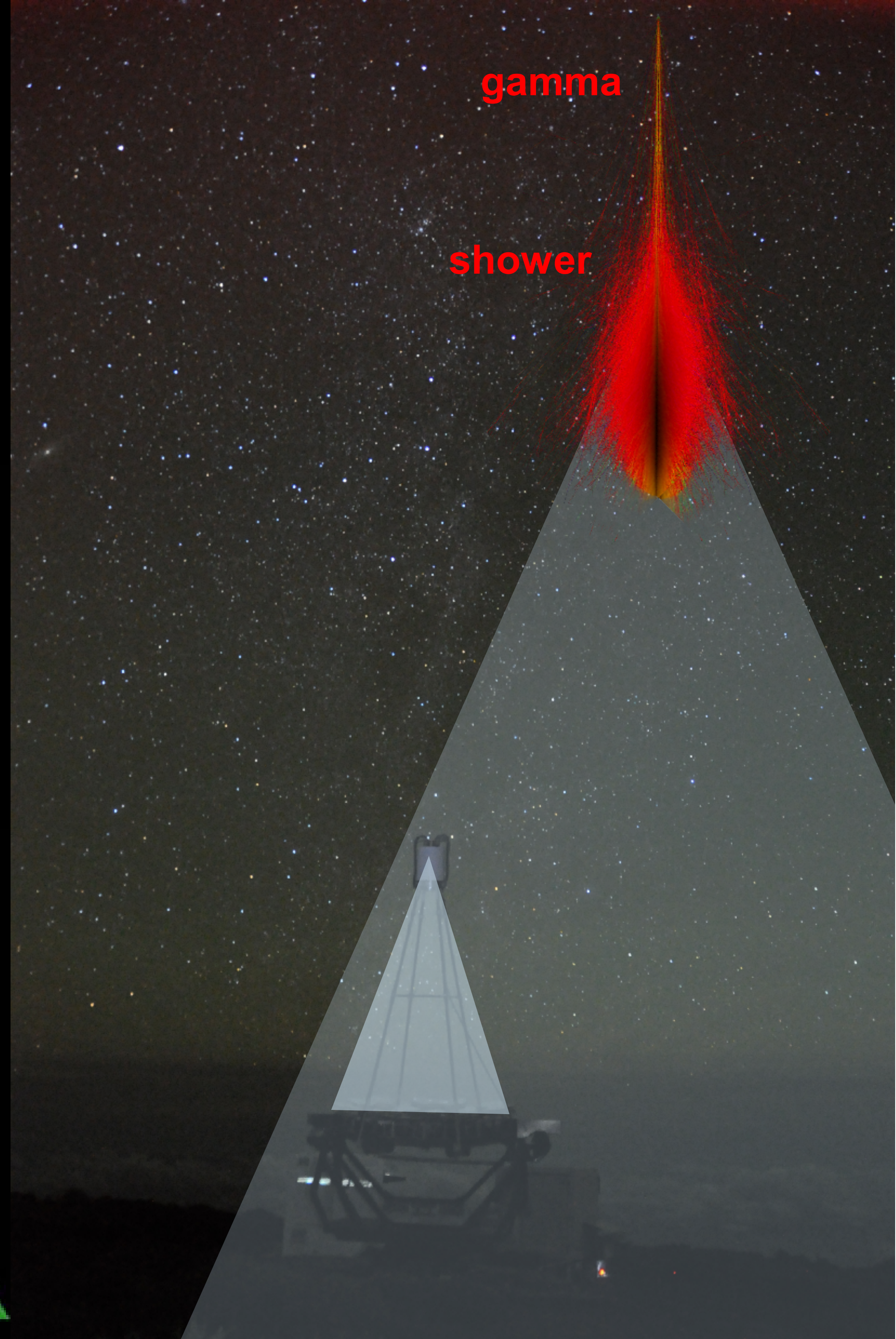



# Detection principle

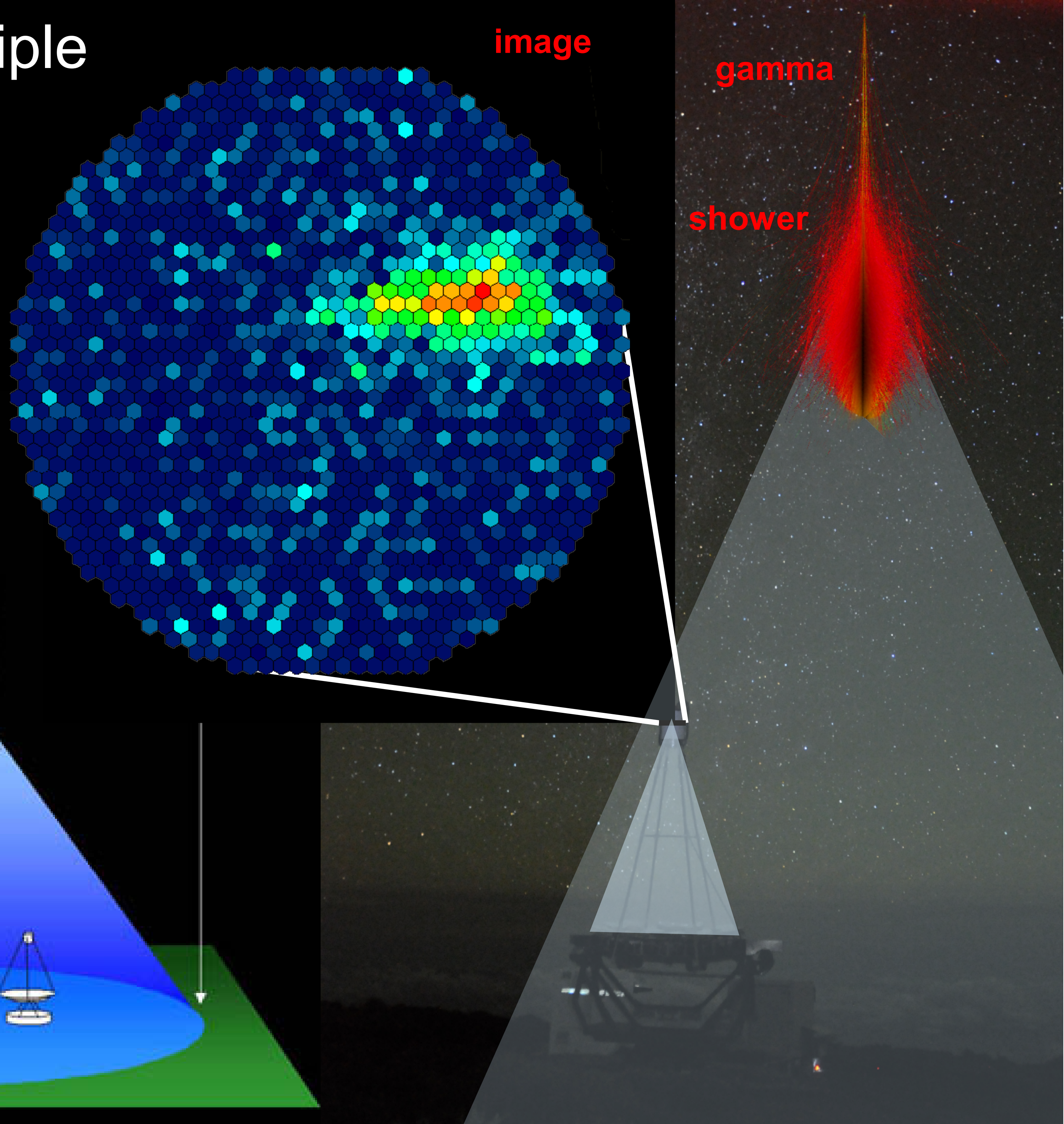
- Detection today:
  - Collect and focus light
    with mirror

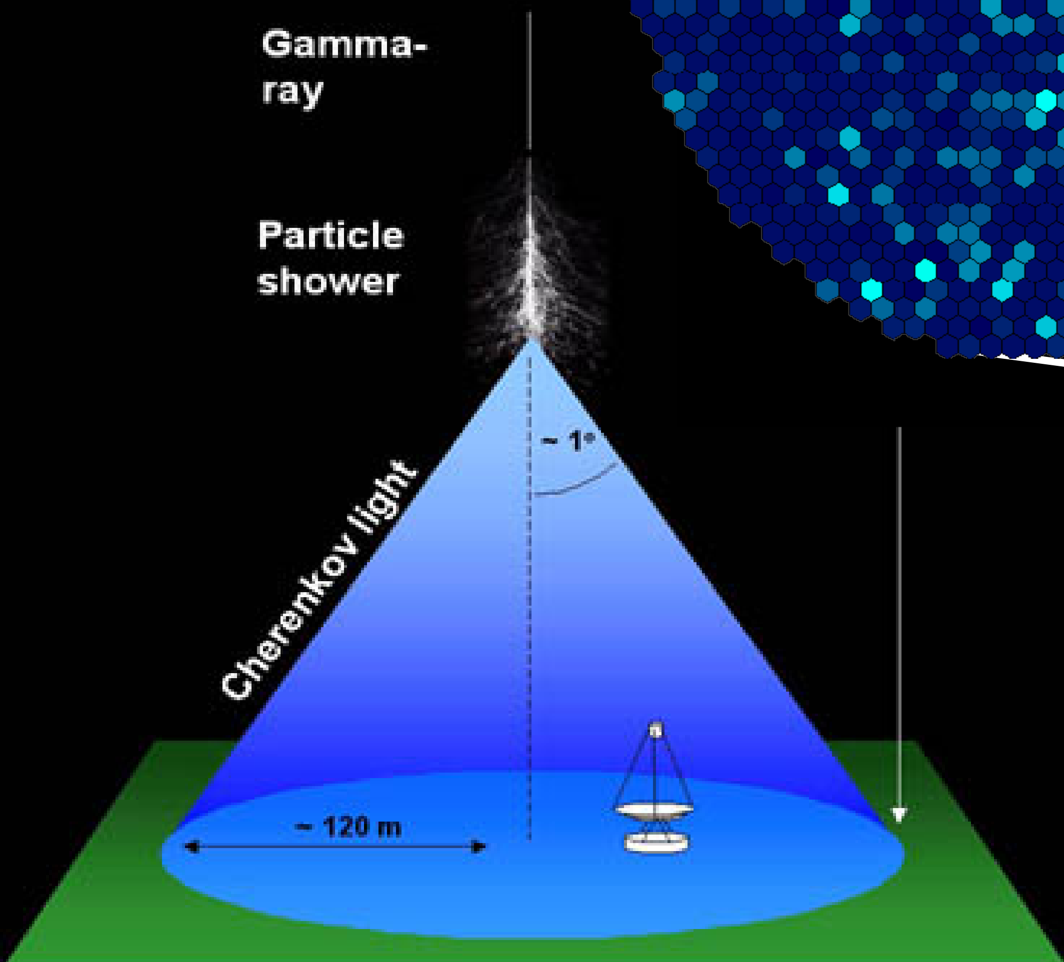


# Detection principle

- Detection today:
  - Collect and focus light with mirror
  - Use of high sensitive photon detectors



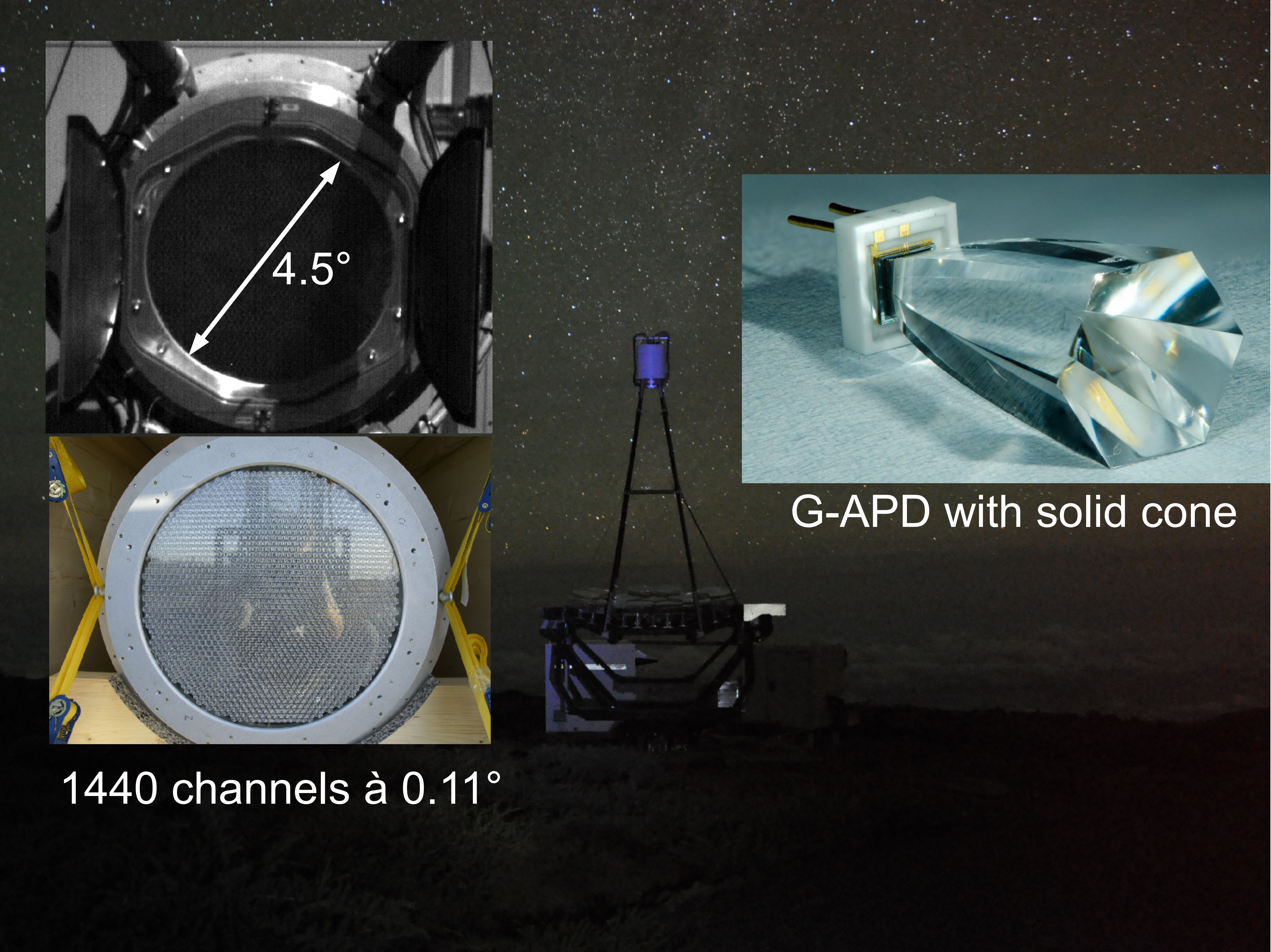



Refurbished HEGRA CT3
Reflective area 9.5m²

→ FACT → Long term monitoring

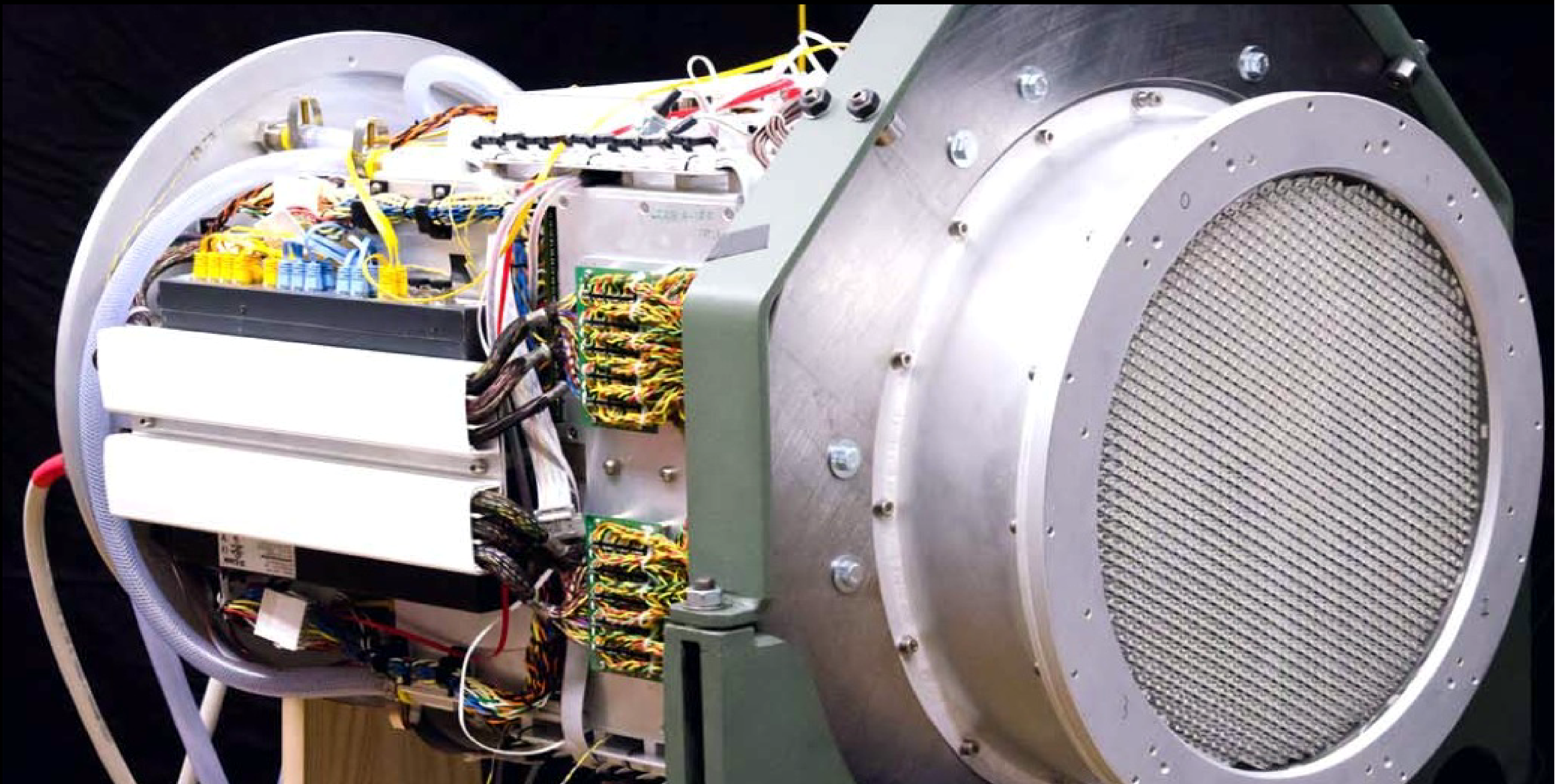
Operation since October 2011


4.5°
1440 channels à 0.11°


4.5°
G-APD with solid cone
1440 channels à 0.11°

Integrated electronics
DRS4 readout

320 bias voltage channels
(1 per 4/5 G-APDs)

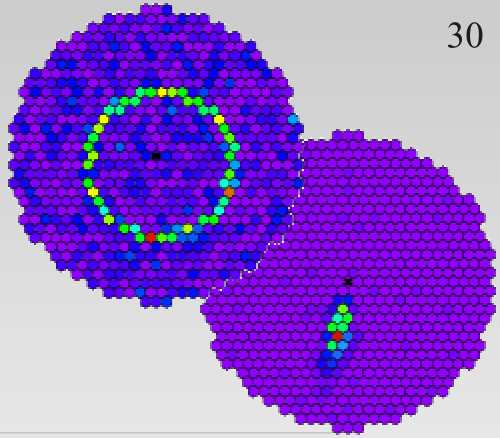


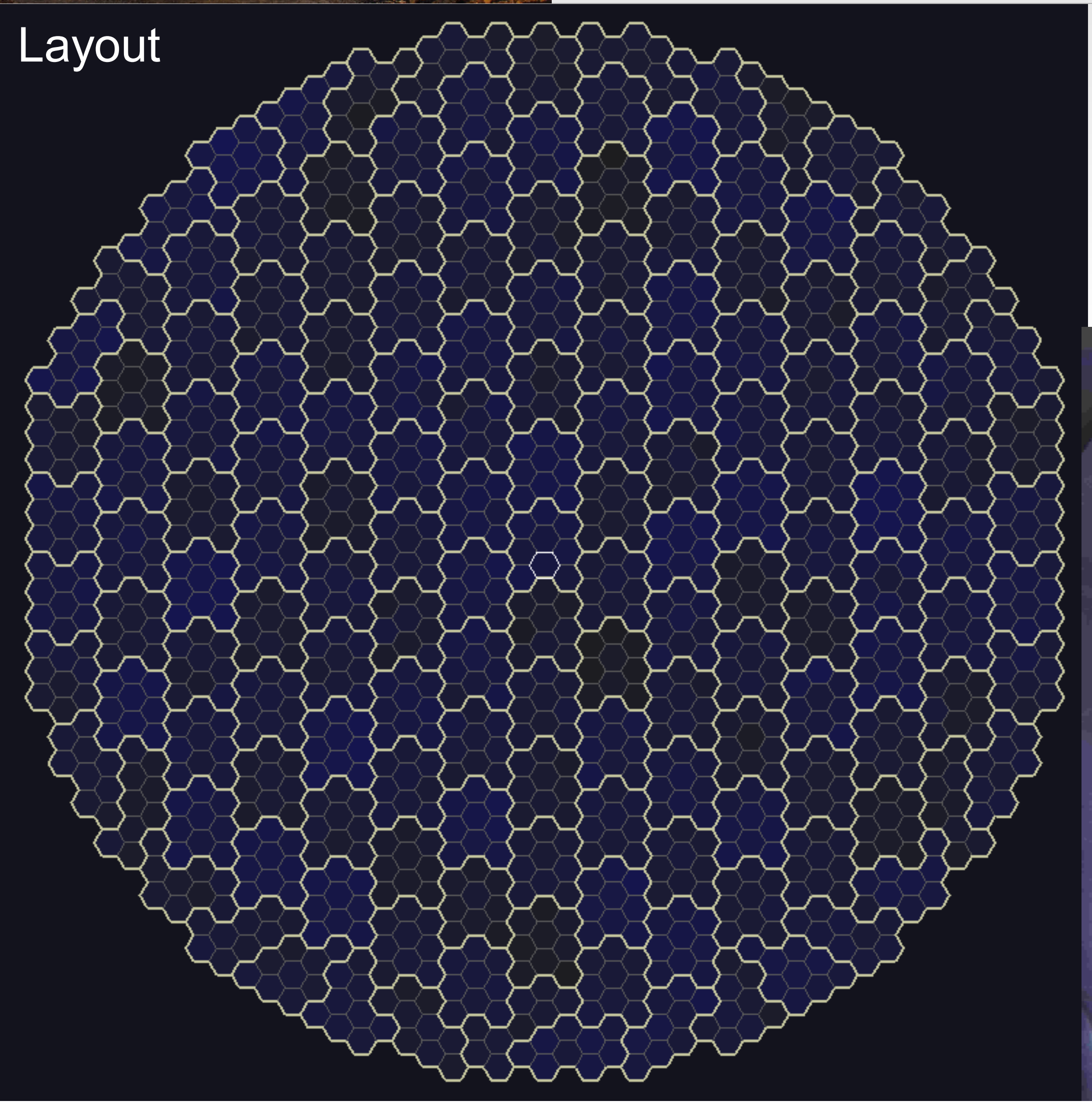
Power consumption ≤500W
(passive water cooling)

Readout via Ethernet

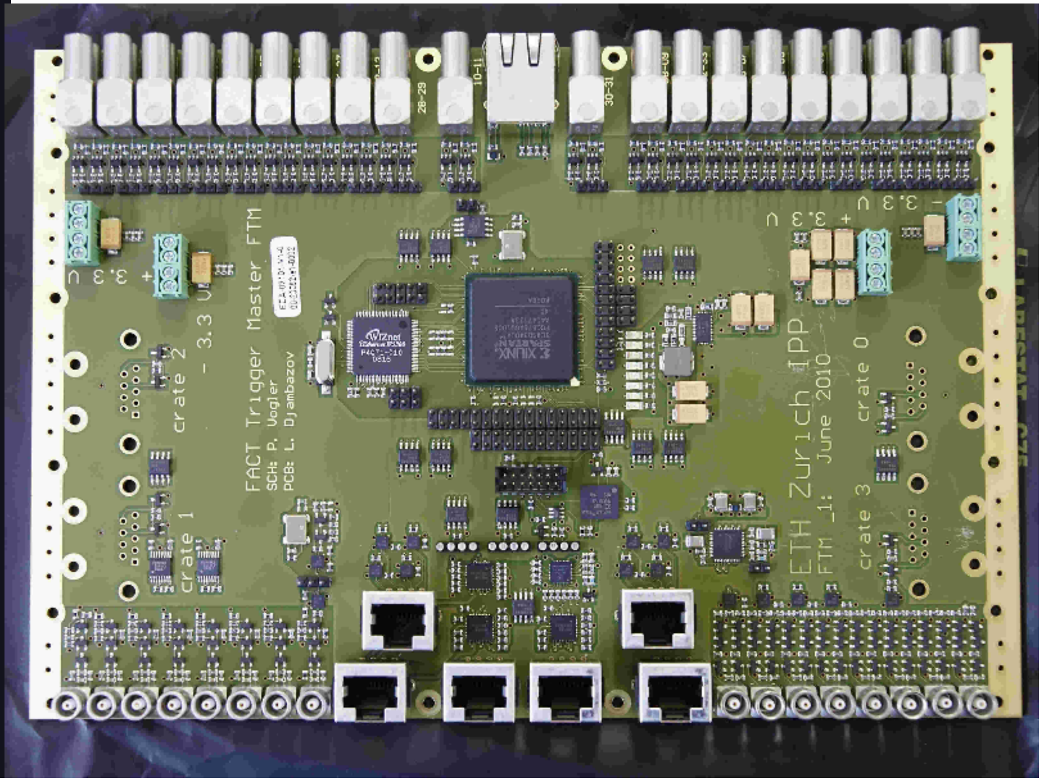
160 trigger patches
(sum of 9 channels)

# The Trigger

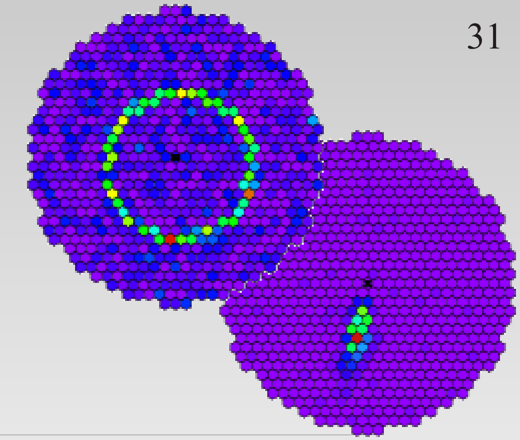


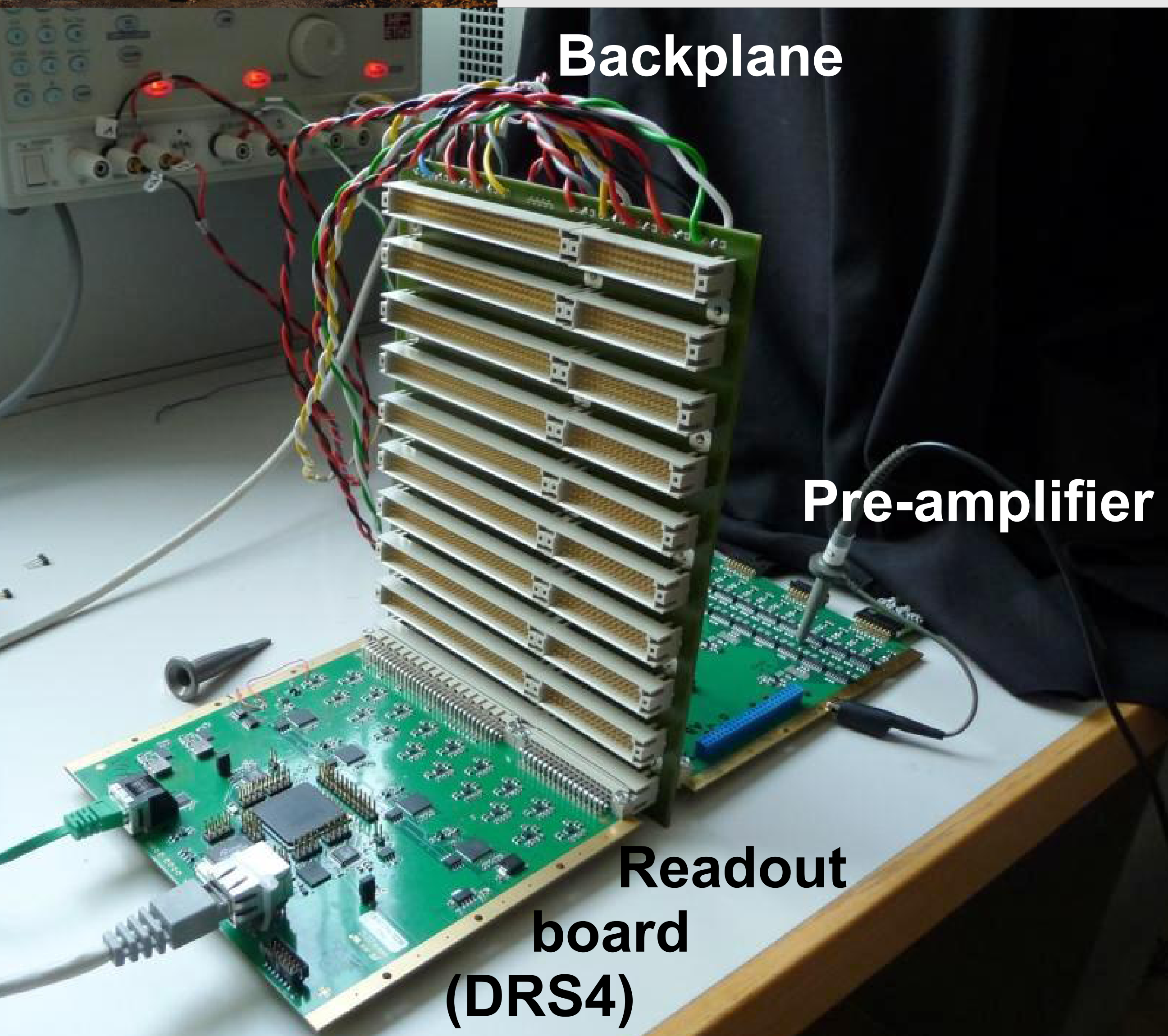



- Sum-trigger patches of nine pixels (close to *ideal*)
- Layout optimized by Monte Carlo

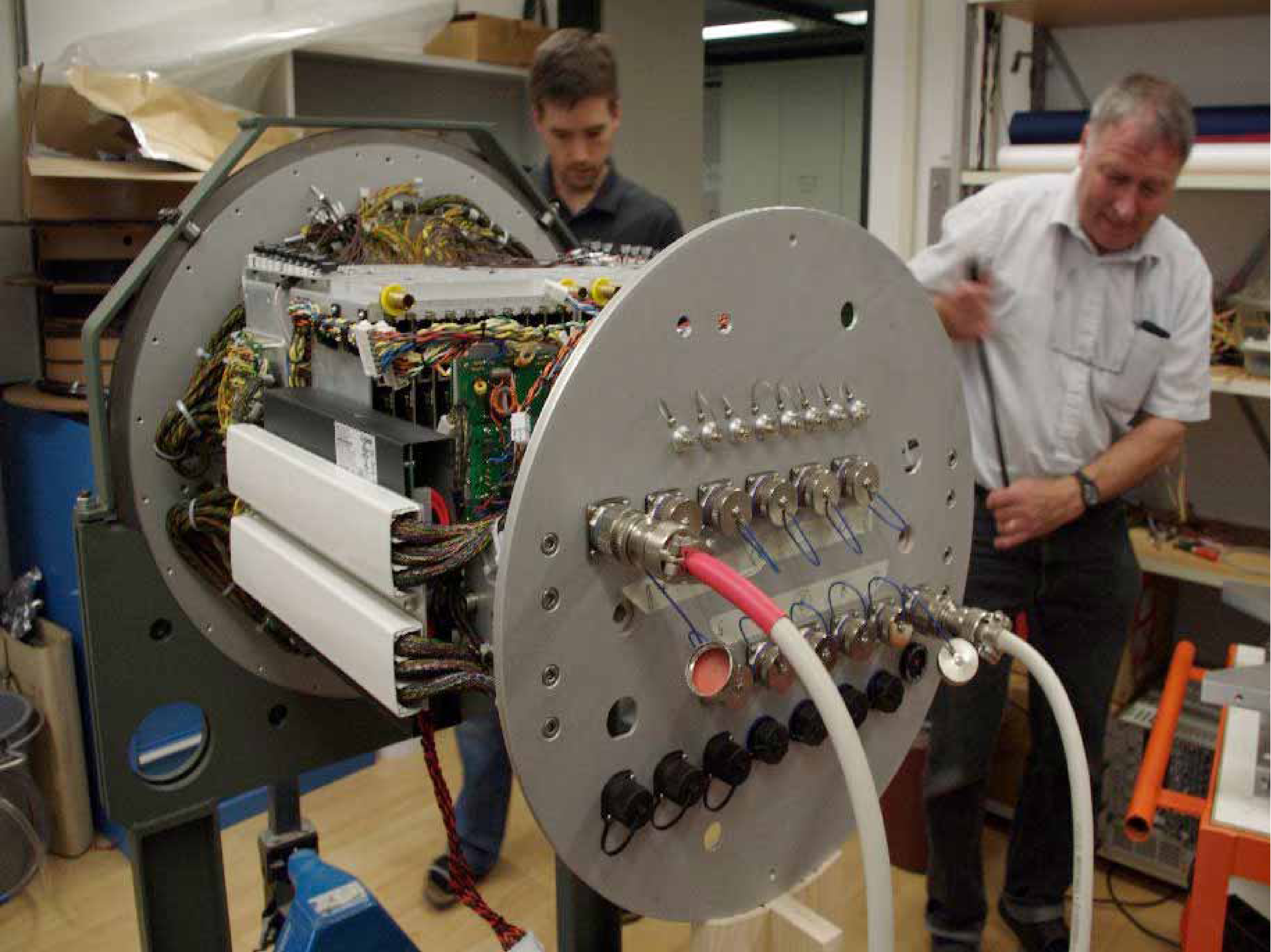


# Crate with pre-amp and readout



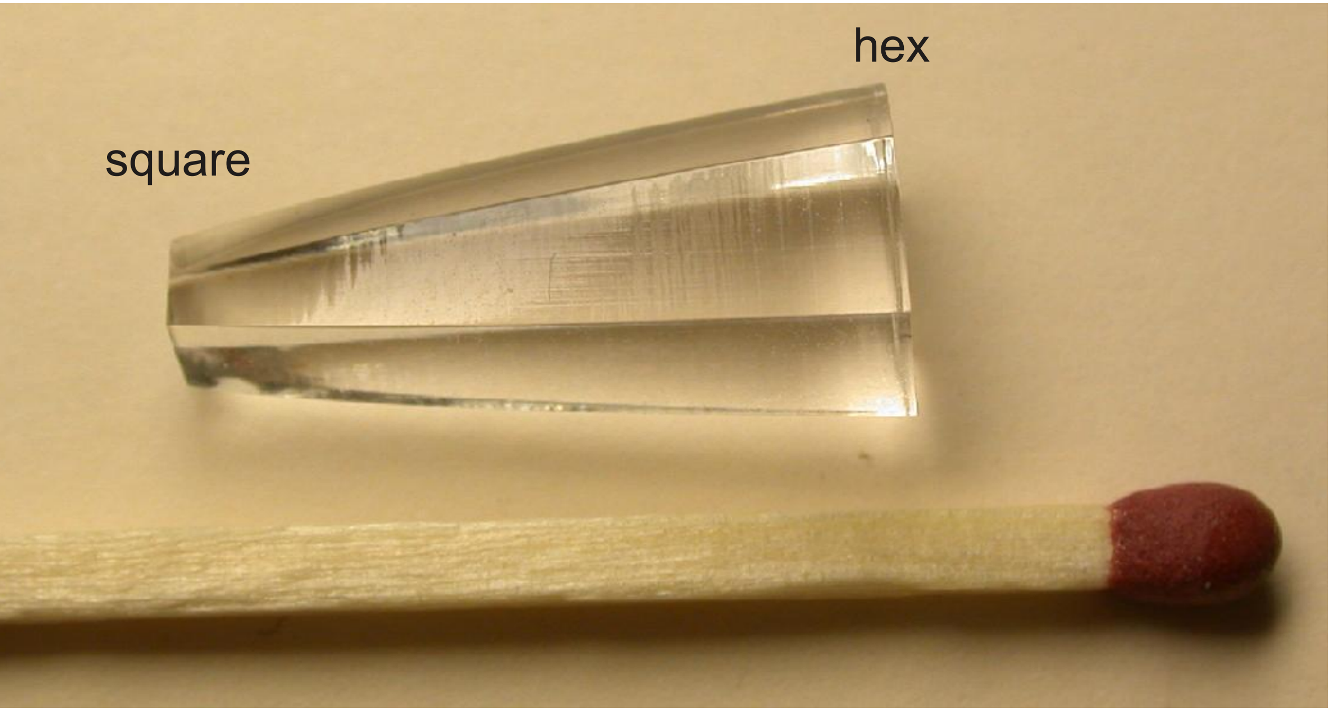



- The pre-amplifier board does
  - amplify the signals
  - sum nine as trigger input
- The backplane is the connection to the readout electronics
  - DRS4
  - ~11 bit effective resolution
- Ethernet readout (One connection to each of the 40 board)
  - fast enough to readout 50ns @ 1GHz with >1.3kHz



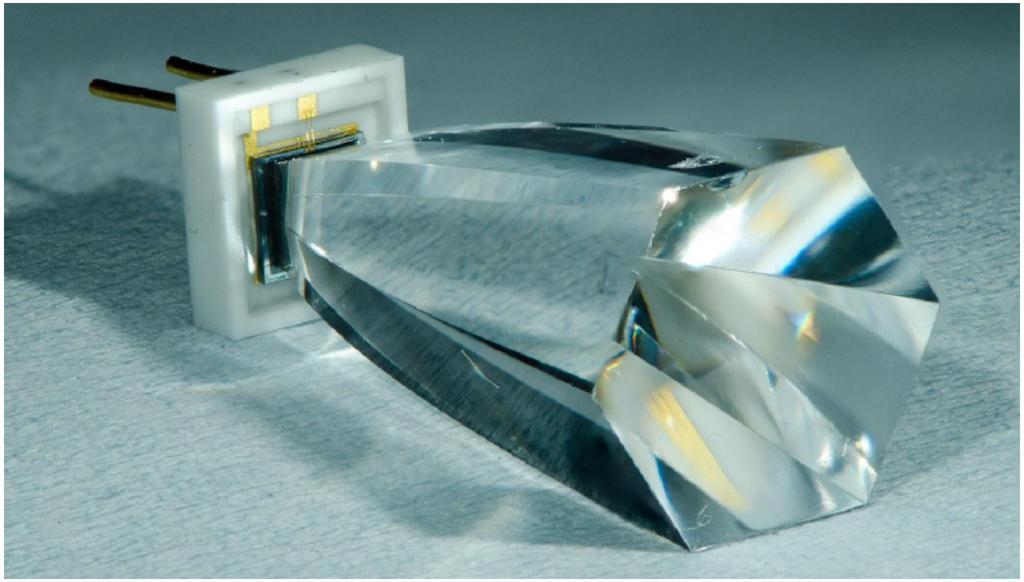
# Empty camera housing

# Solid light guides




- inexpensive casting (UV transparent PMMA), O(Eur/piece)
- Complicated shapes possible
  **→ (FACT: square → hexagon)**

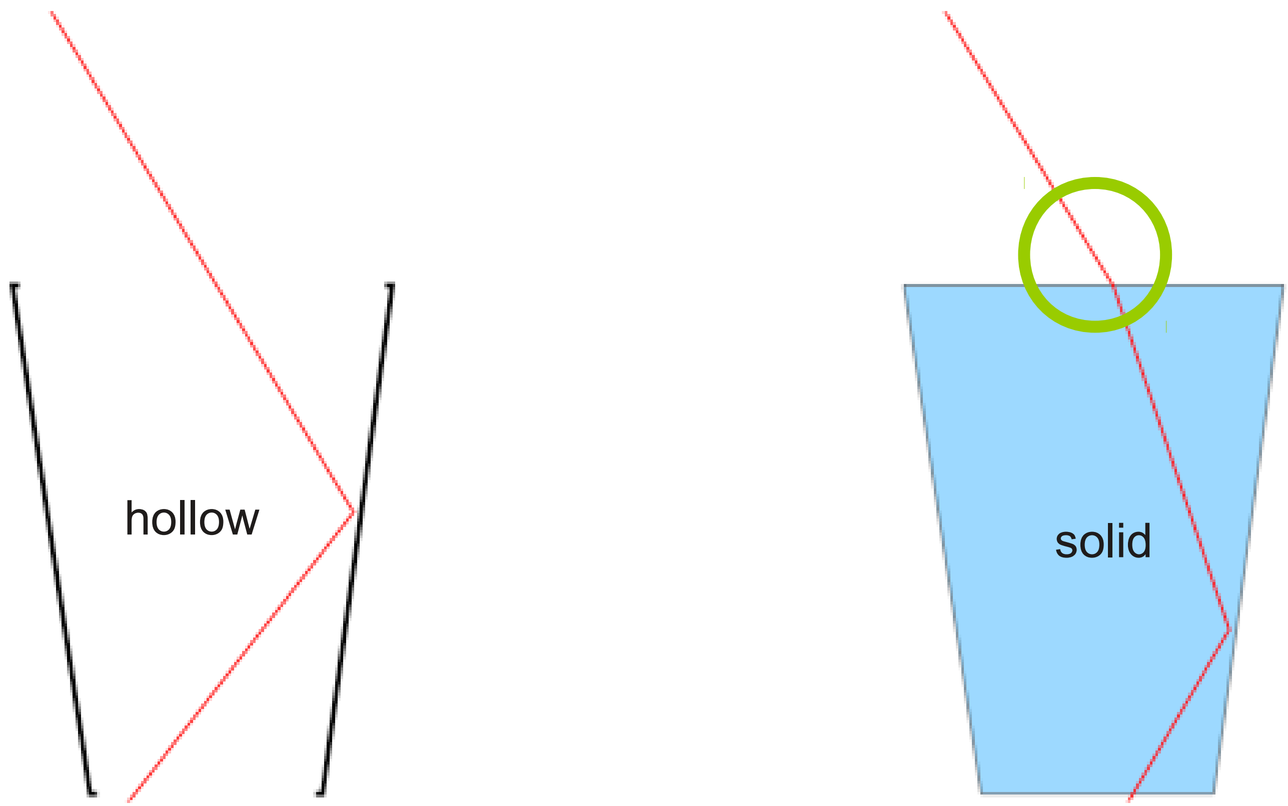
# Solid light guides



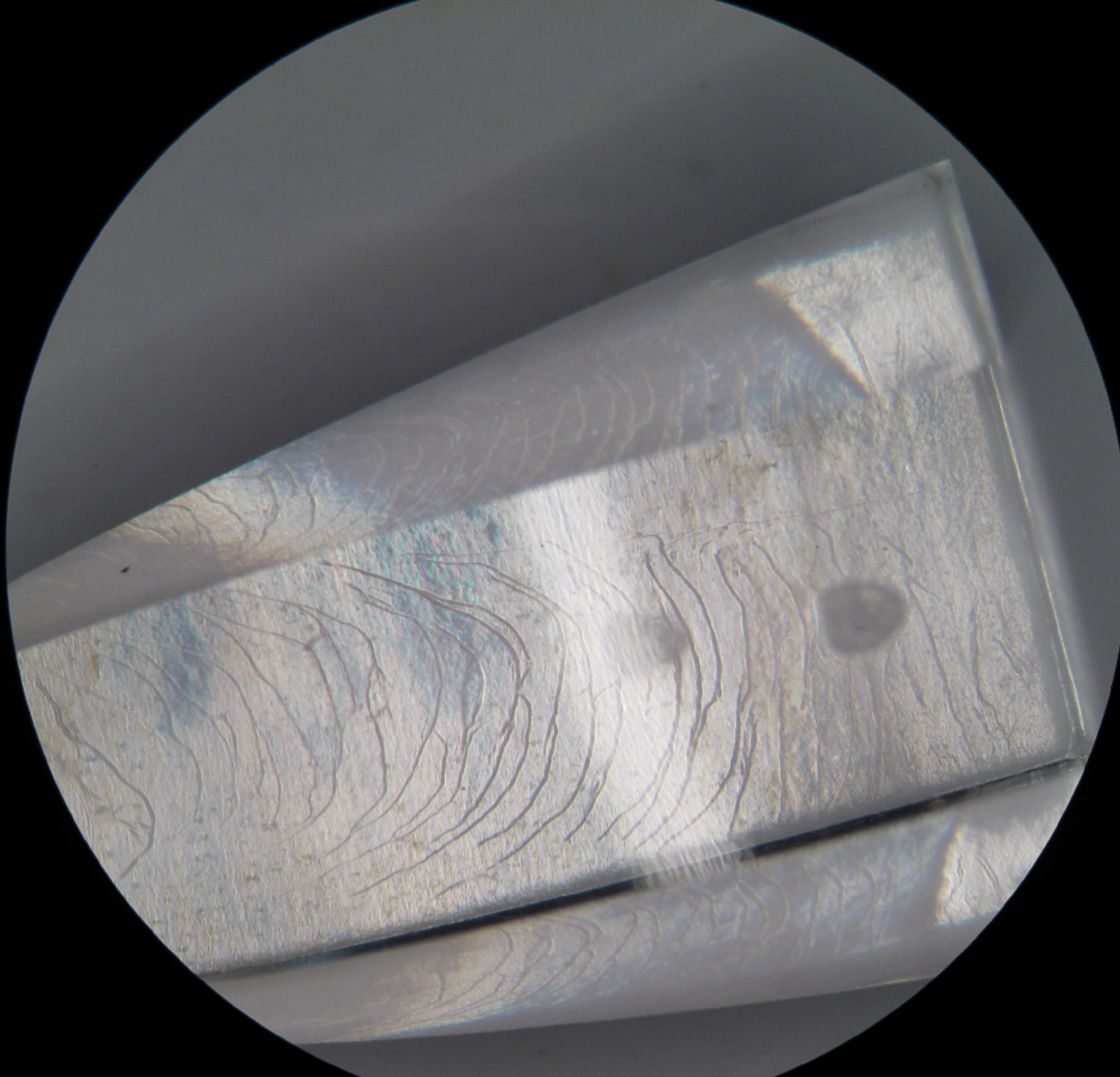
→ not the price per detector area is important,
but the price per sensitive area in the camera!

*Design constraints on Cherenkov telescopes with Davies-Cotton reflectors*
**Bretz, Ribordy, Astropart. Phys.** (*in press*) **[arXiv:1301.6556]**

# Solid light guides




→ **higher concentration than hollow cones**
**due to change of refractive index,** O(12-17)

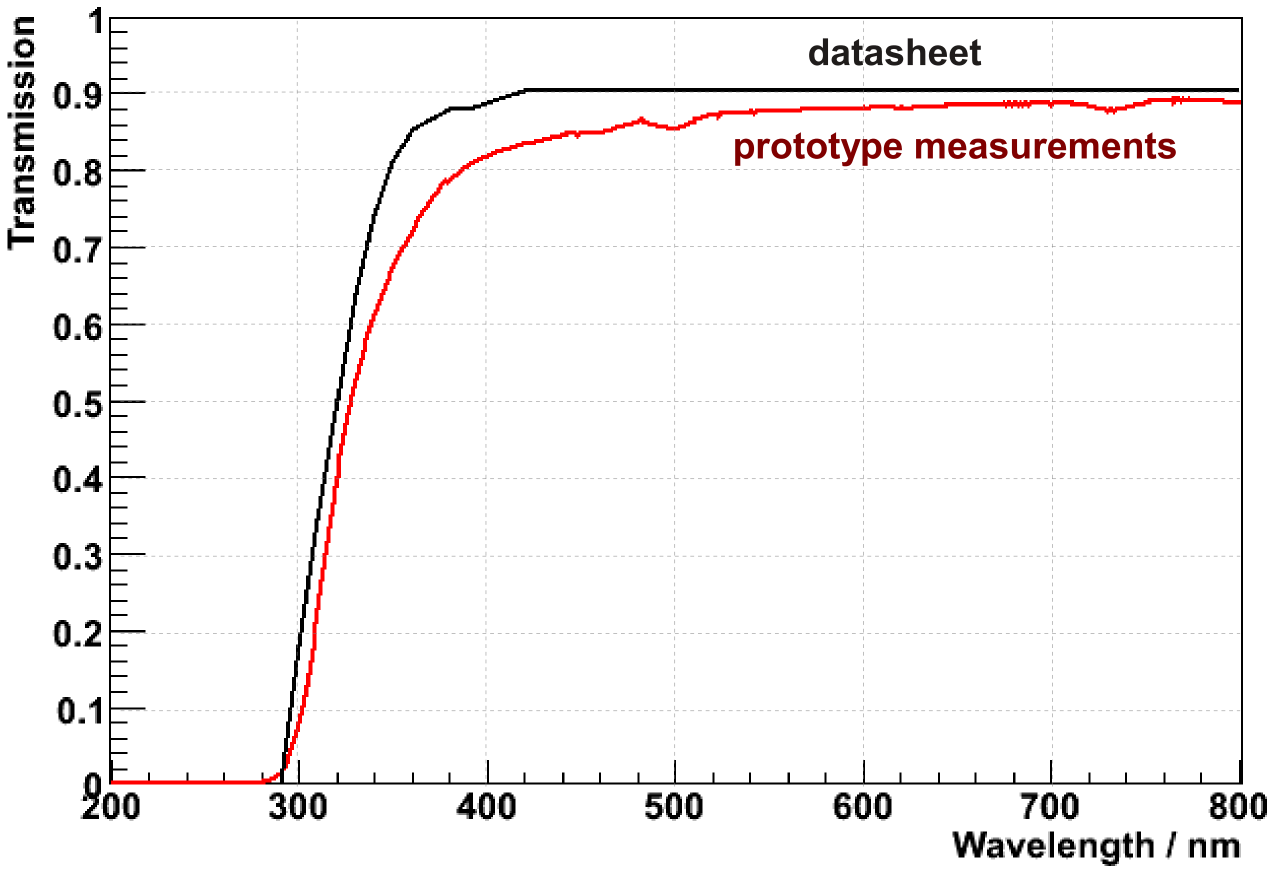


Some iterations were necessary to optimize the production for good transmission

→ finally we got >1440 good ones

minor PMMA impurities destroy UV transmission

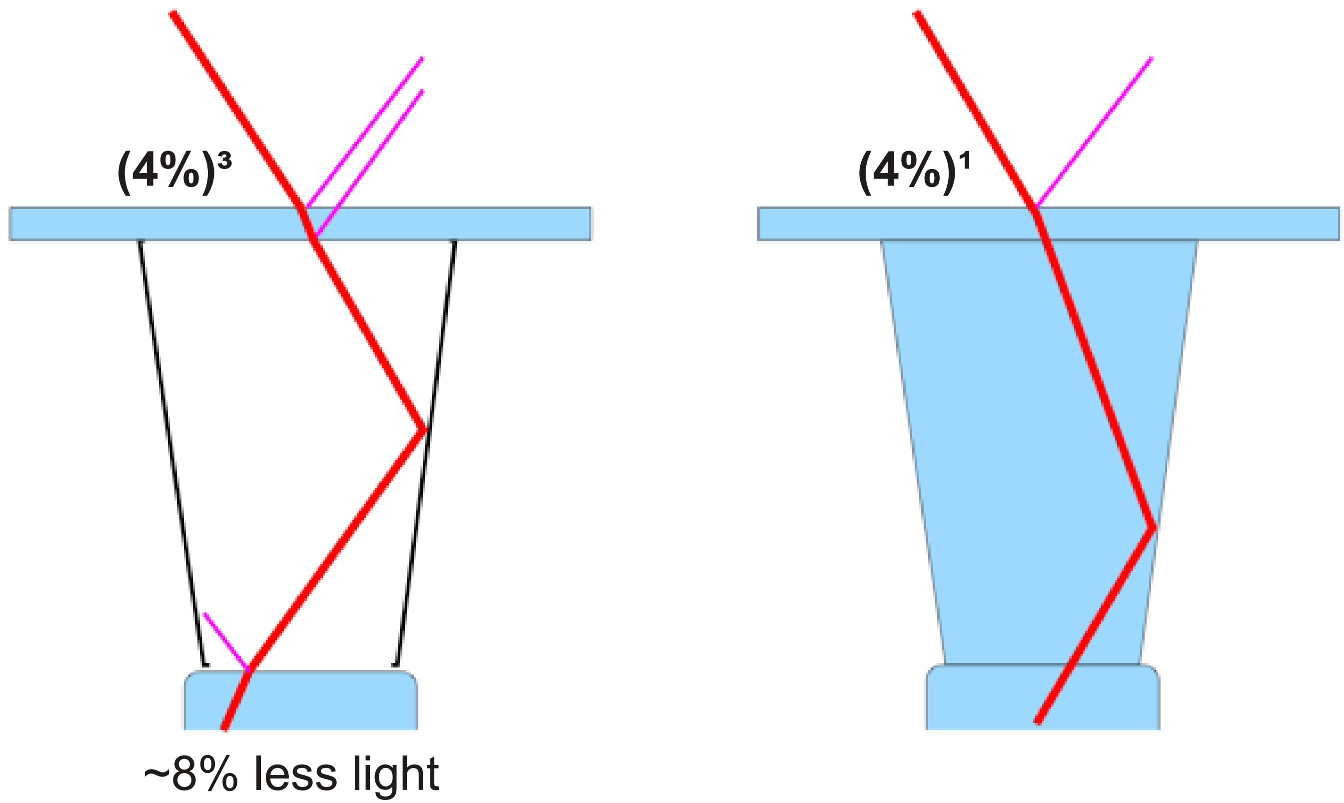
# Solid light guides




→ **total reflection** (reflectivity O(100%))
→ **transmission losses very small (short enough)**

→ needs high optical quality

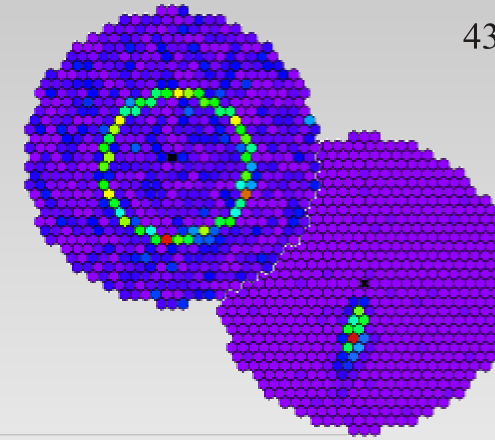
# Solid light guides



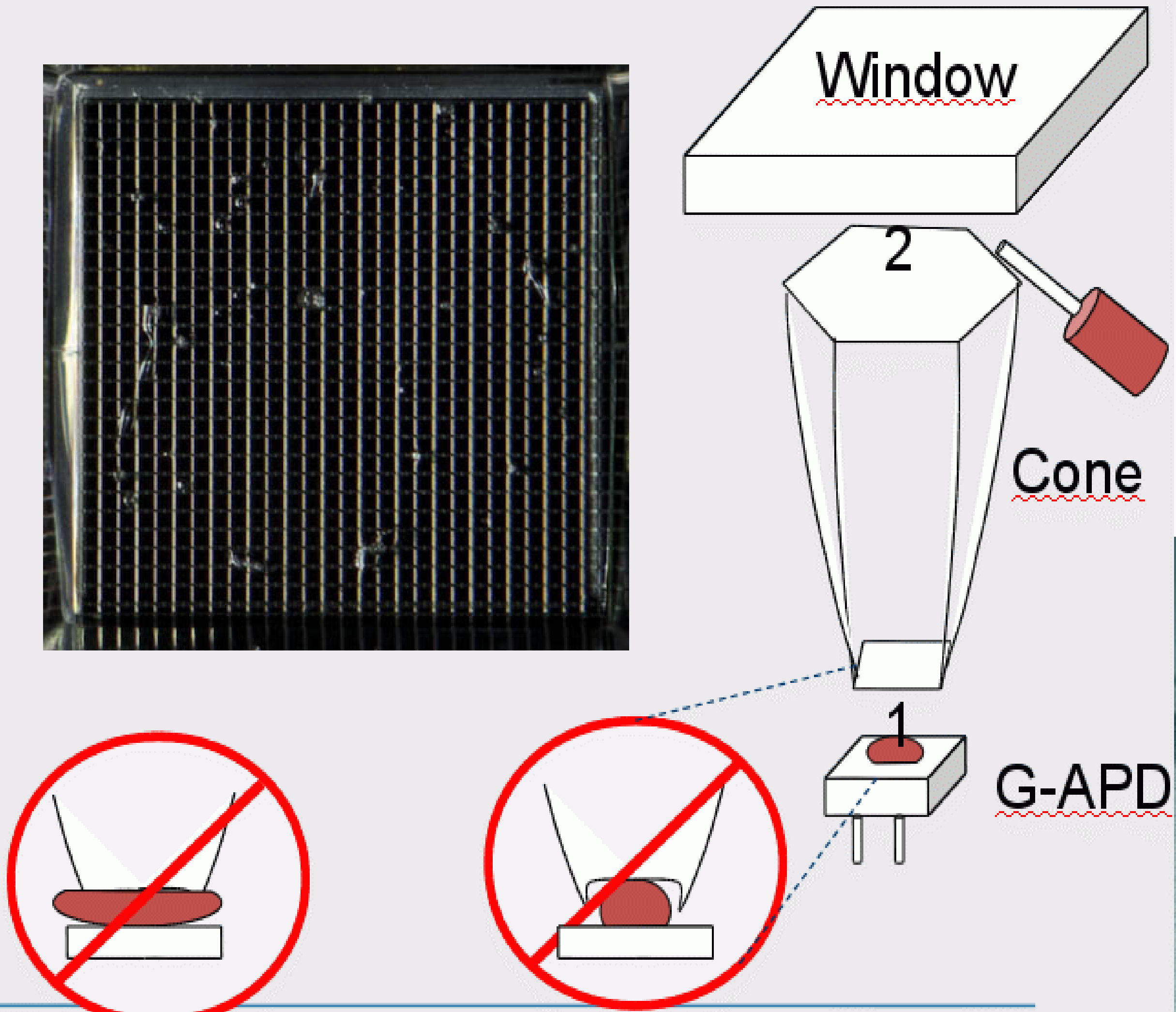

**→ two Fresnel reflections less, ~8% gain**

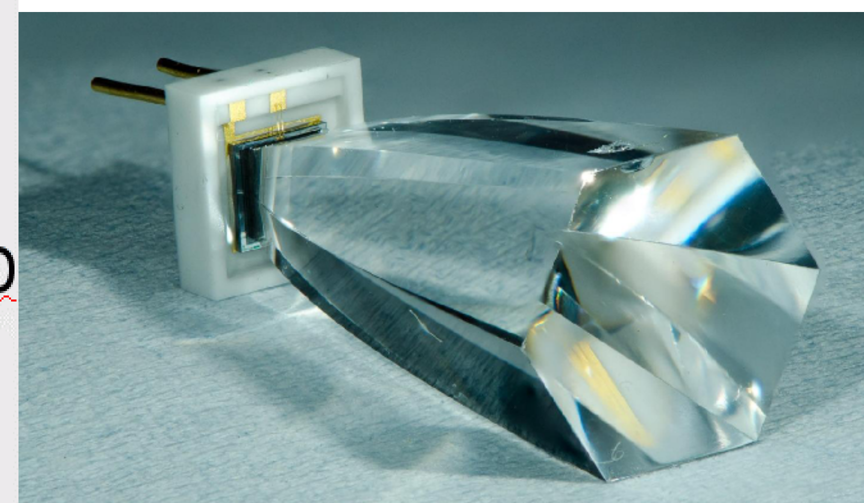
→ needs *good* optical coupling, i.e. good glueing

# Solid light guides



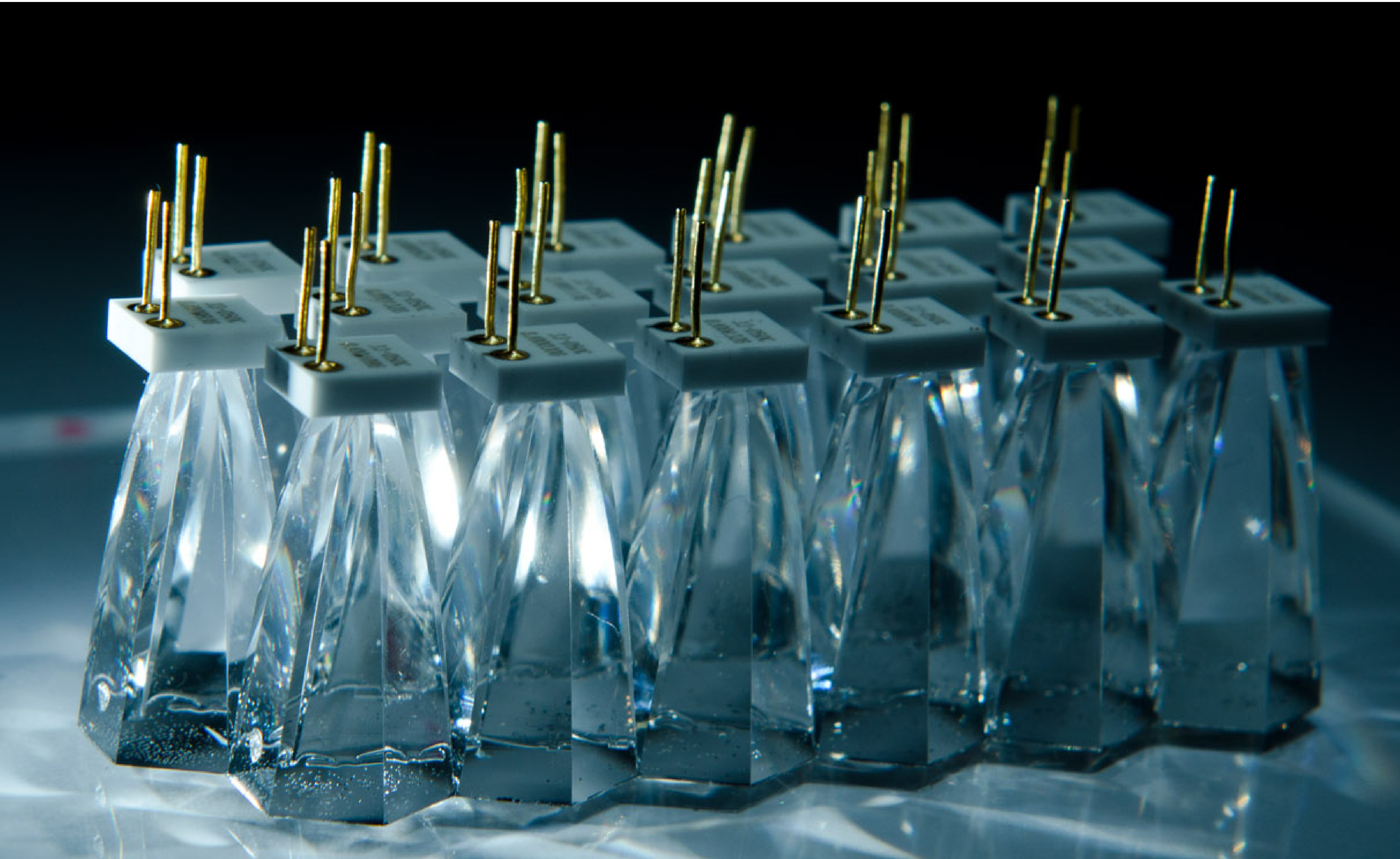
Tedious and time consuming glueing



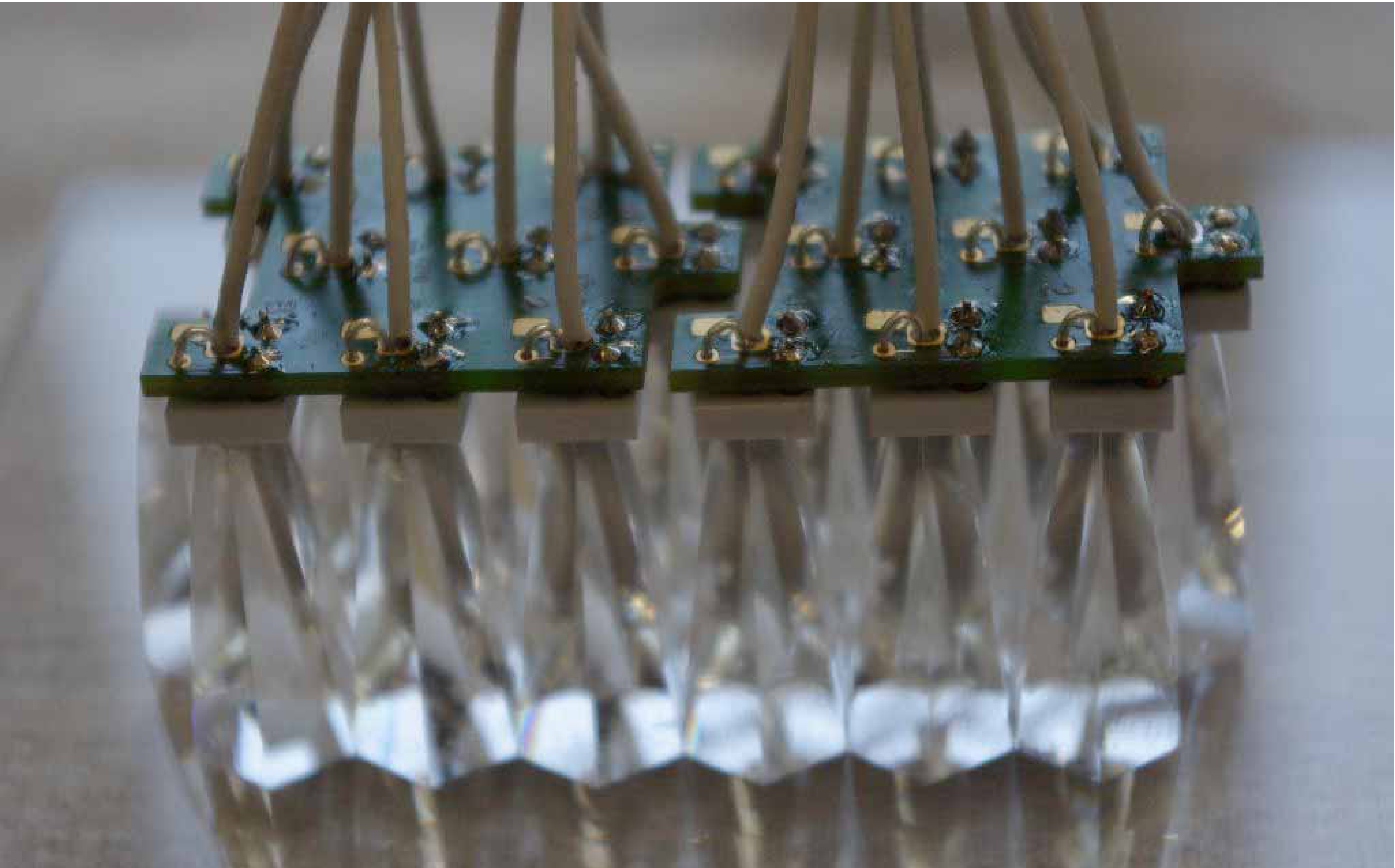



# Cones glued on G-APDs

...glued to front window

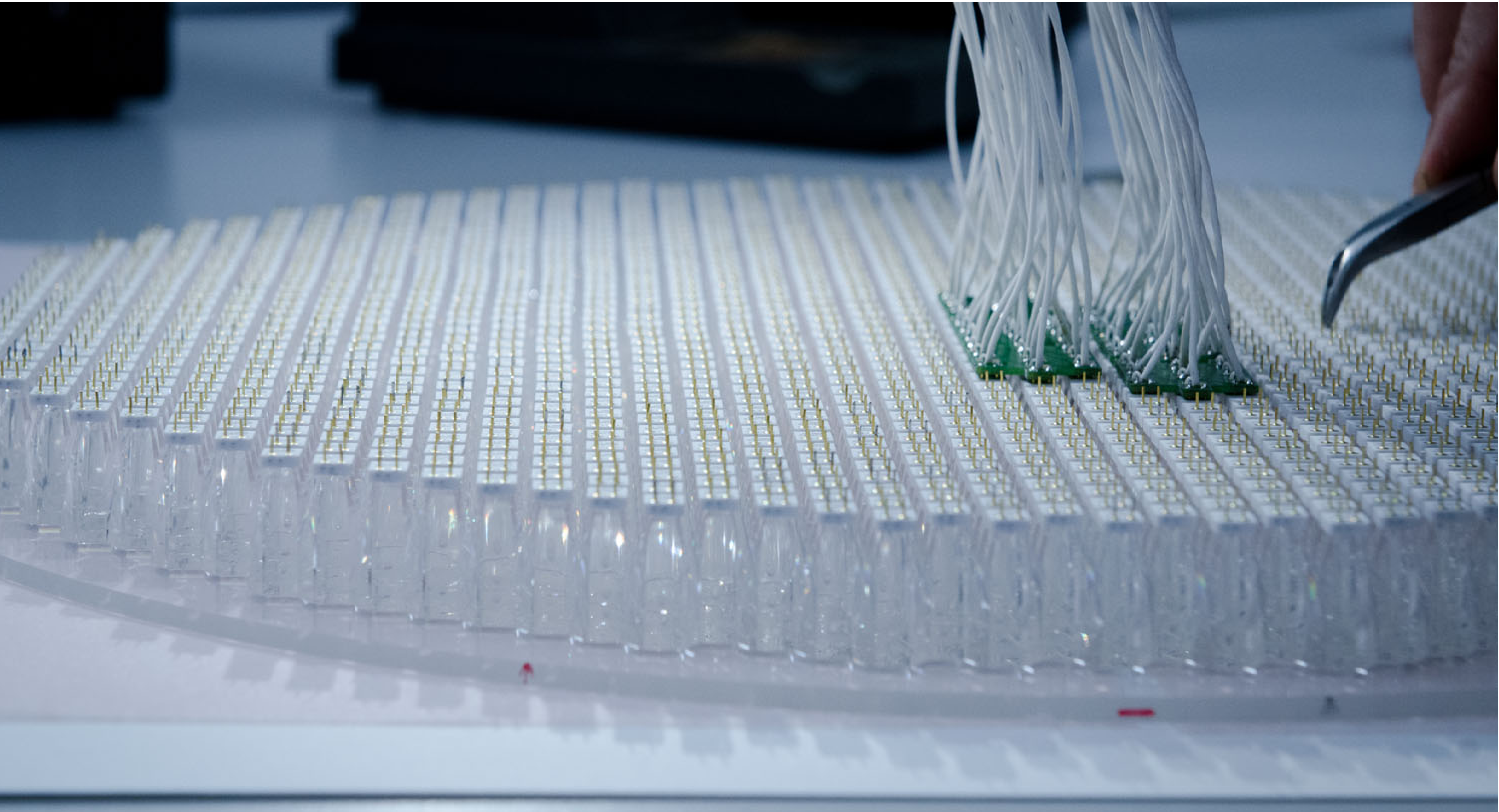


...equipped with PCB



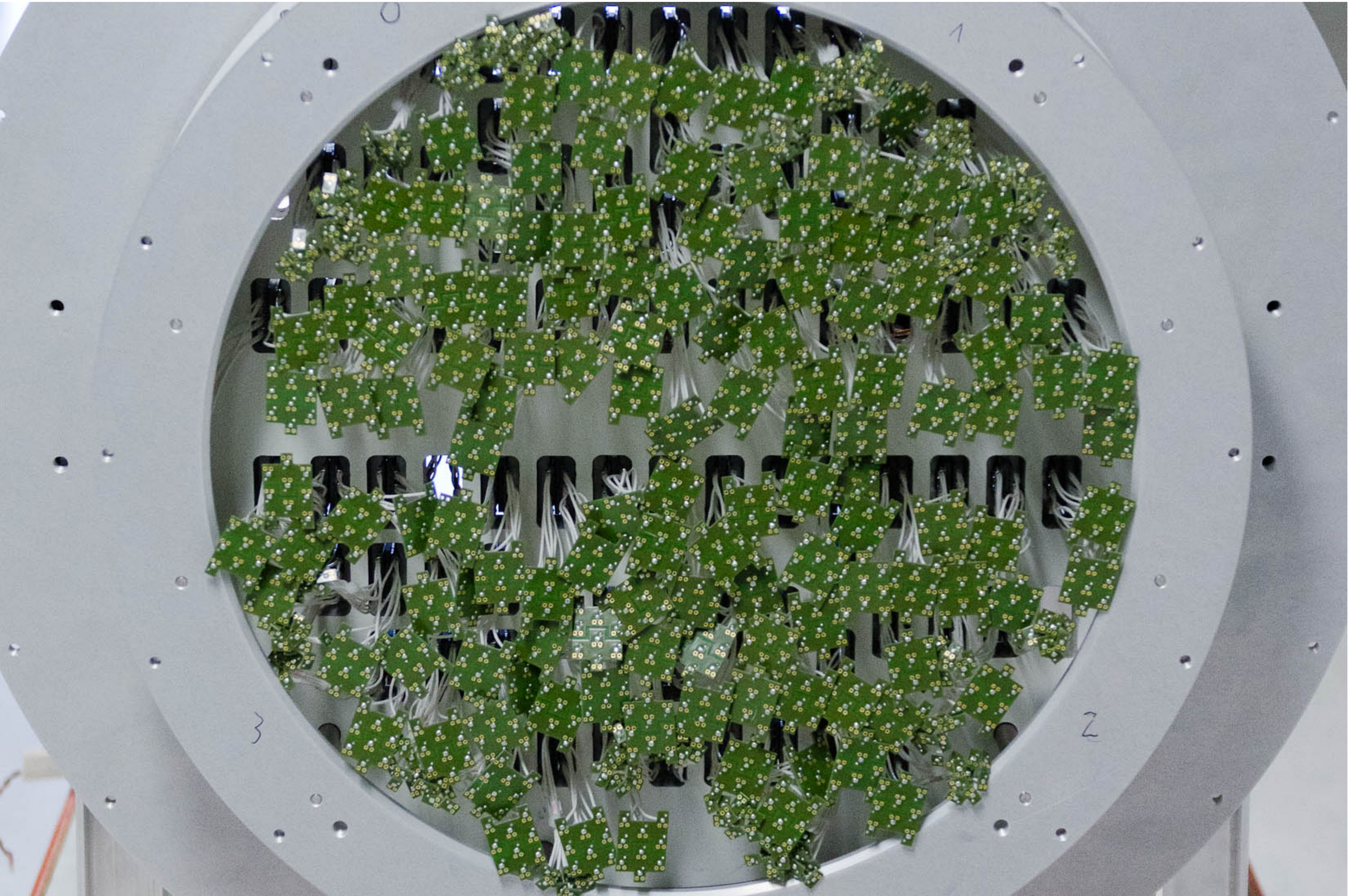

Cones with G-APDs
glued on the window

# First PCBs soldered

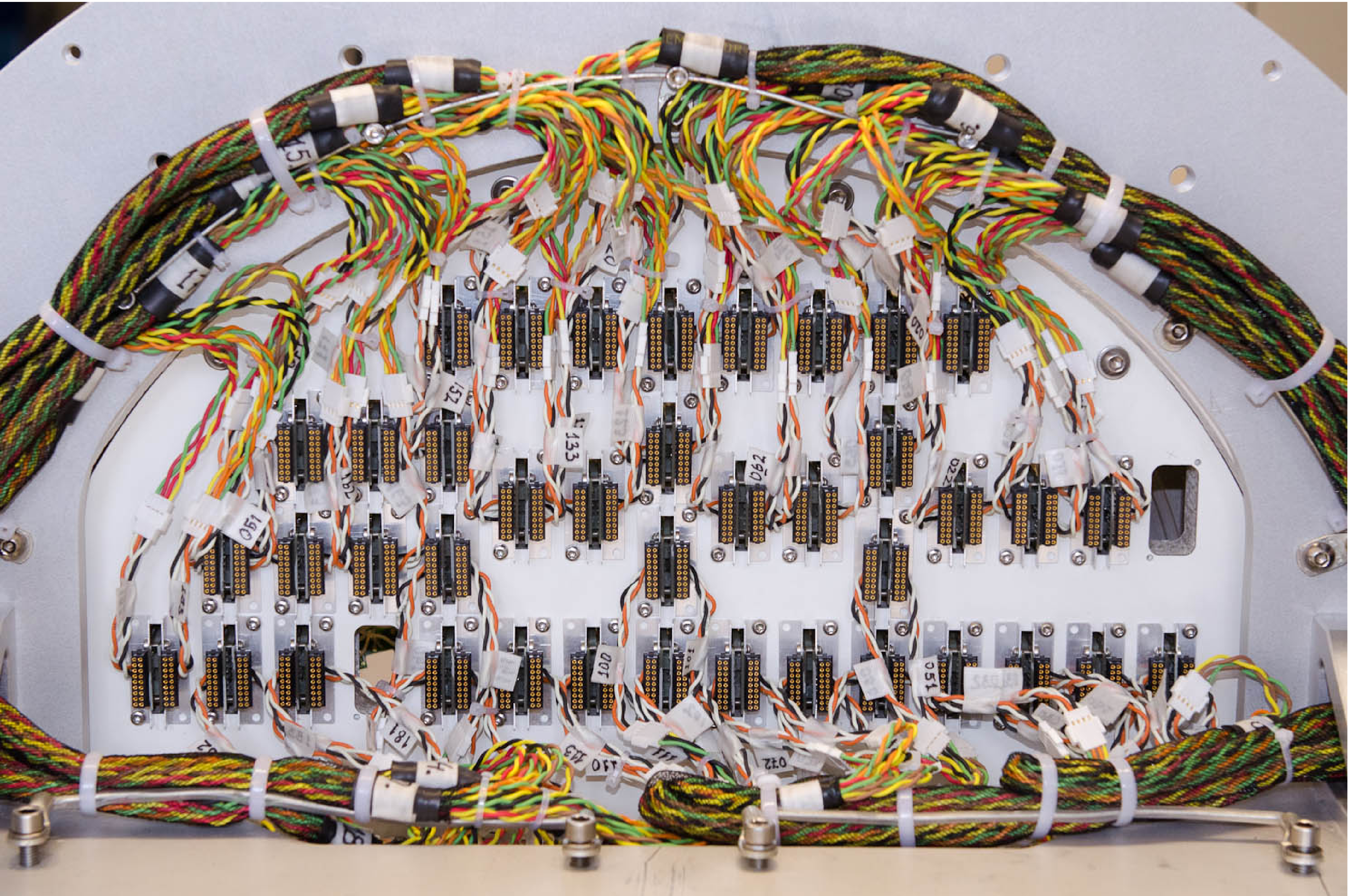


# Empty camera housing

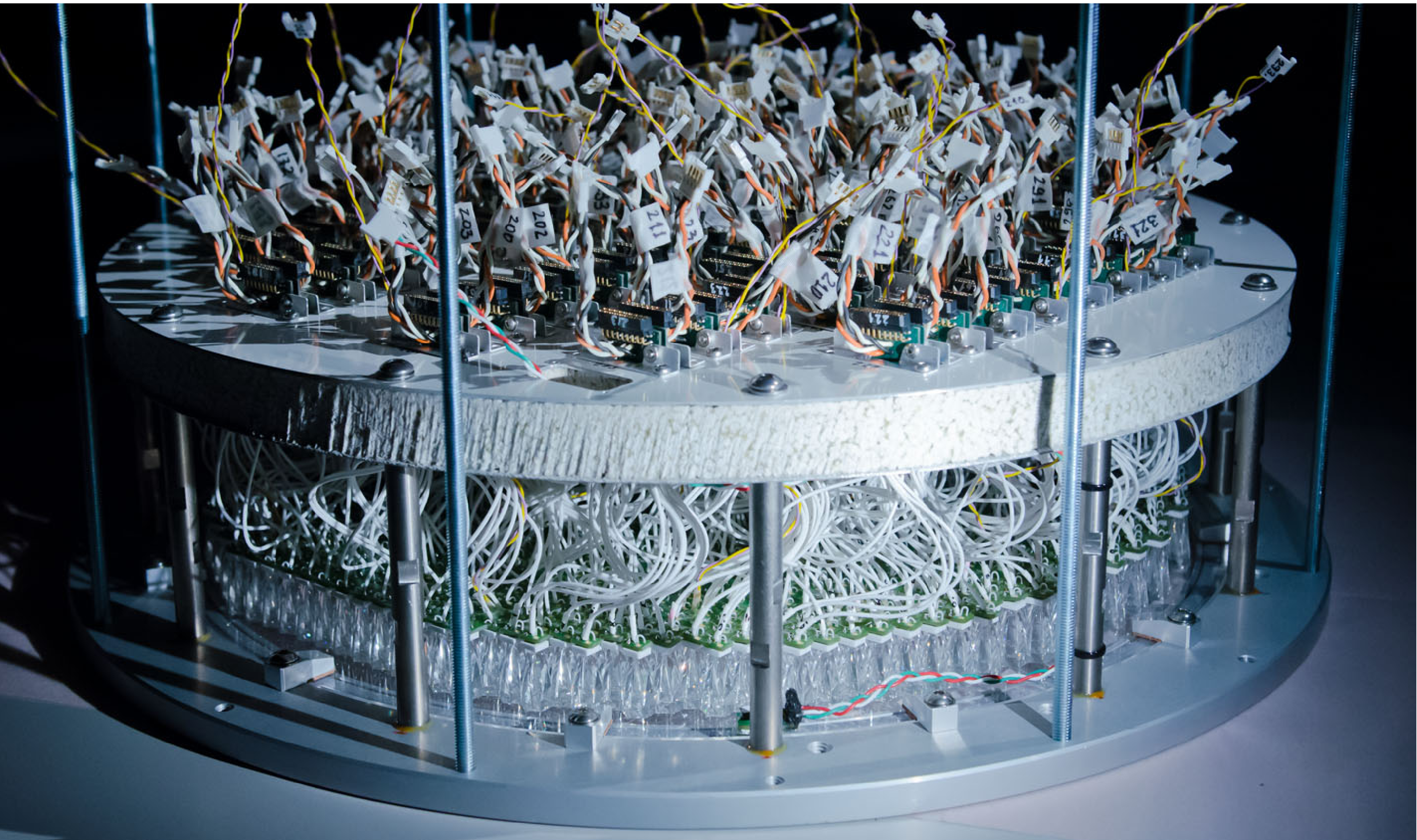
# Front view of the sensor compartment



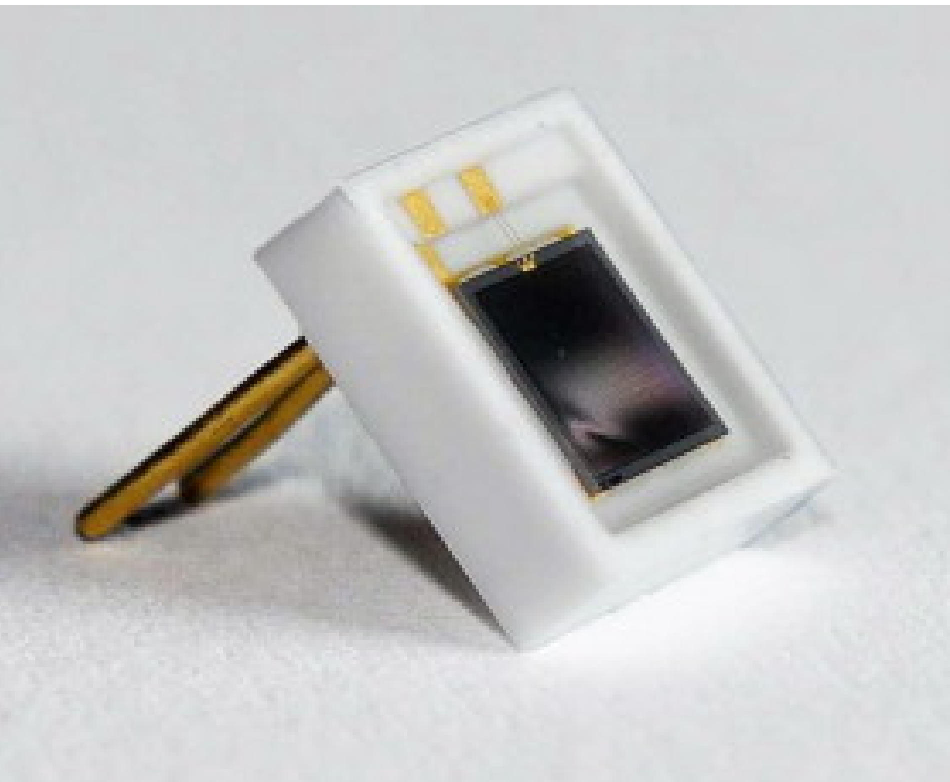
# Back view of the sensor compartment



Side view of the sensor compartment
with all channels connected



# G-APDs

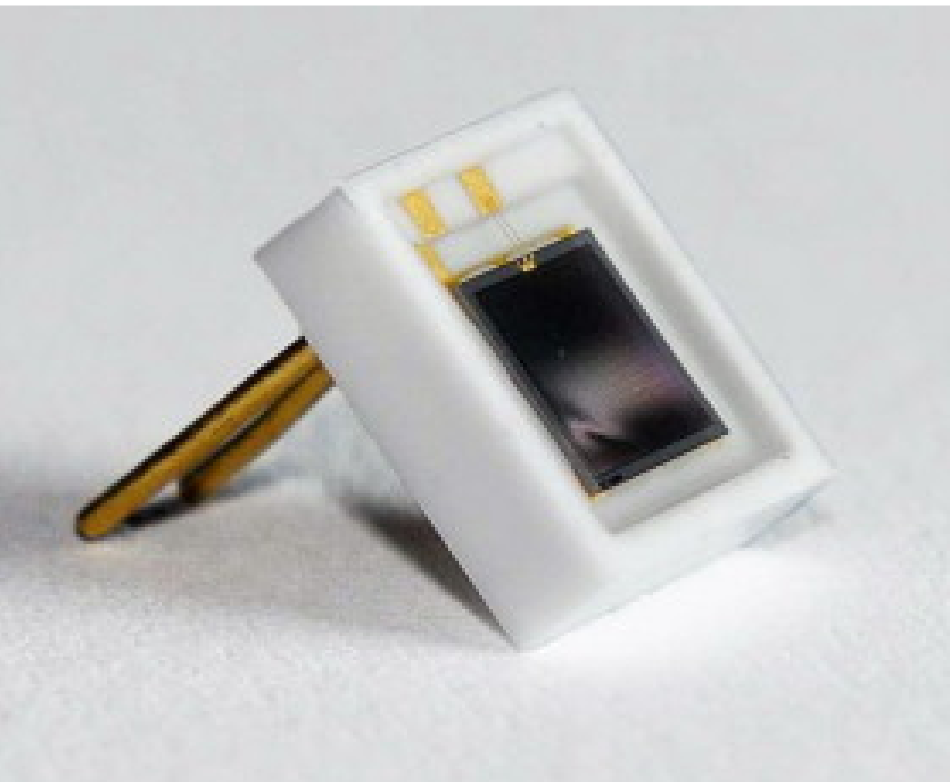


- Performance comparable to best available PMTs
- Cheaper than PMTs
- Future potential (PDE~70%)
- Very good timing
- Very easy to handle (U<100V)

- Afterpulses, crosstalk and darkcounts are **no problem** for Cherenkov telescopes

- Gain depends on
  - temperature
  - applied voltage

# G-APDs



- Performance comparable to best available PMTs
- Cheaper than PMTs
- Future potential (PDE~70%)
- Very good timing
- Very easy to handle (U<100V)

- Afterpulses, crosstalk and darkcounts are **no problem** for Cherenkov telescopes

- Gain depends on
  - temperature
  - applied voltage

# G-APDs

- Dark counts
- Afterpulses
- Crosstalk

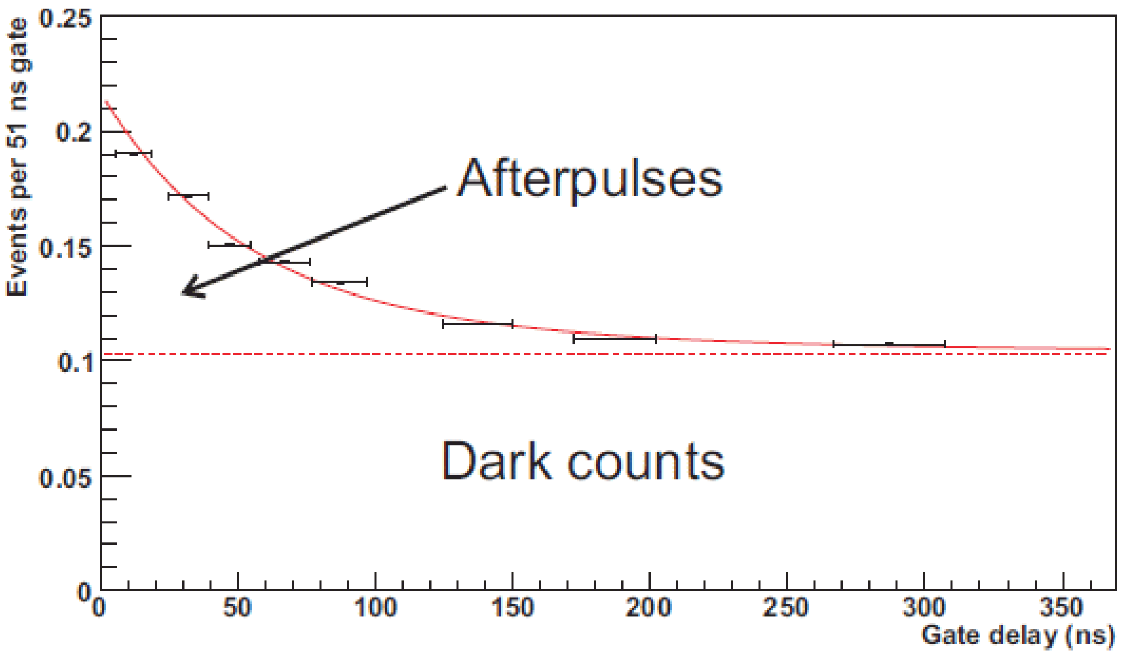
# G-APDs

- Dark counts (in our case O(5MHz) per G-APD)
  → **NSB rate O(50MHz)**
- Afterpulses
- Crosstalk

# G-APDs

- ~~Dark counts~~
- Afterpulses (gain-dep. prob. 5%-20%)
  **→ incoherent (prolongate signal, but no fake triggers)**
- Crosstalk

**Exponentially decr. prob. after breakdown**



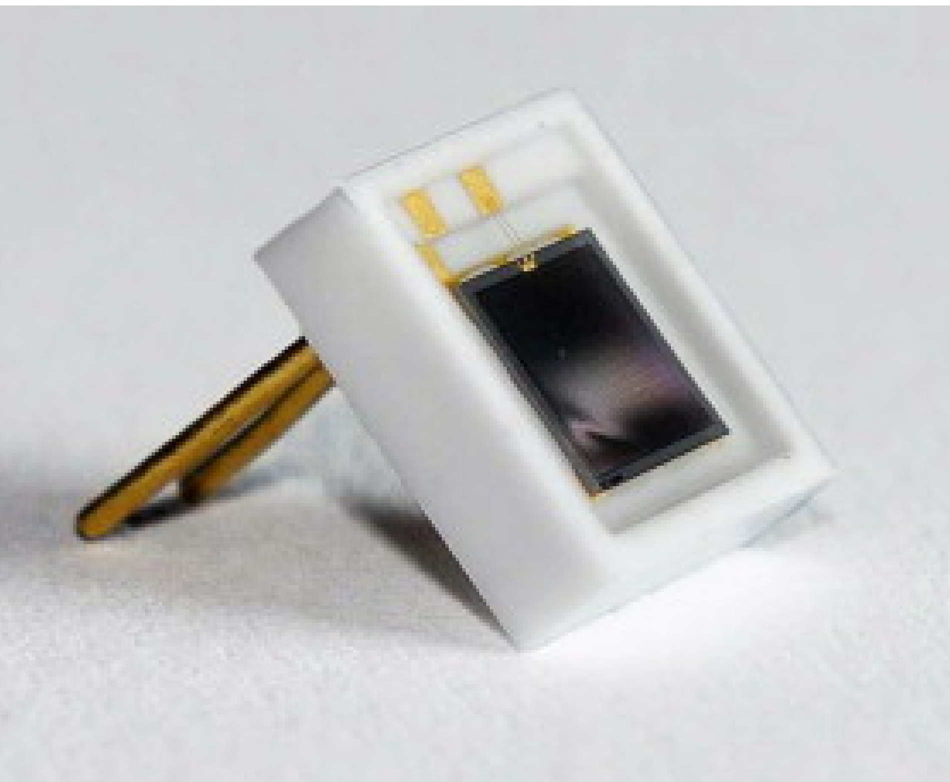
# G-APDs

- ~~Dark counts~~

- ~~Afterpulses~~

- Crosstalk (gain-dep. prob. 5%-20%)
  → **Important for single pe counting, but not for CTs**
  → **just increases the average signal height and slightly its fluctuations**

# G-APDs

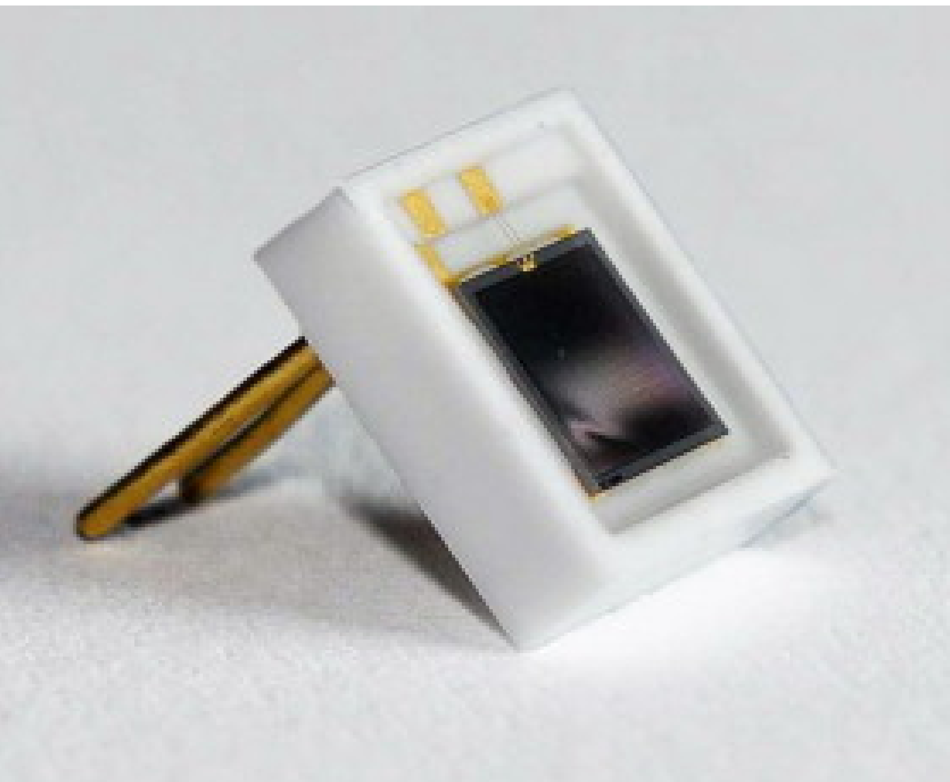


- Performance comparable to best available PMTs
- Cheaper than PMTs
- Future potential (PDE~70%)
- Very good timing
- Very easy to handle (U<100V)

- Afterpulses, crosstalk and darkcounts are **no problem** for Cherenkov telescopes

- Gain depends on
  - temperature
  - applied voltage

# G-APDs



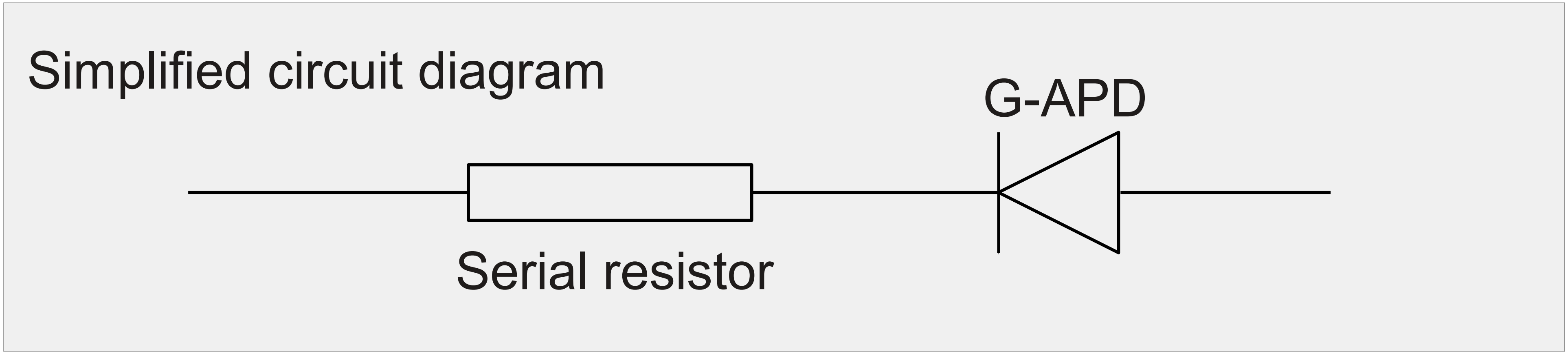
- Performance comparable to best available PMTs
- Cheaper than PMTs
- Future potential (PDE~70%)
- Very good timing
- Very easy to handle (U<100V)

- Afterpulses, crosstalk and darkcounts are **no problem** for Cherenkov telescopes

- Gain depends on
  - **temperature**
  - applied voltage

**can be corrected by adapting the voltage (50mV/K)**

# Voltage correction

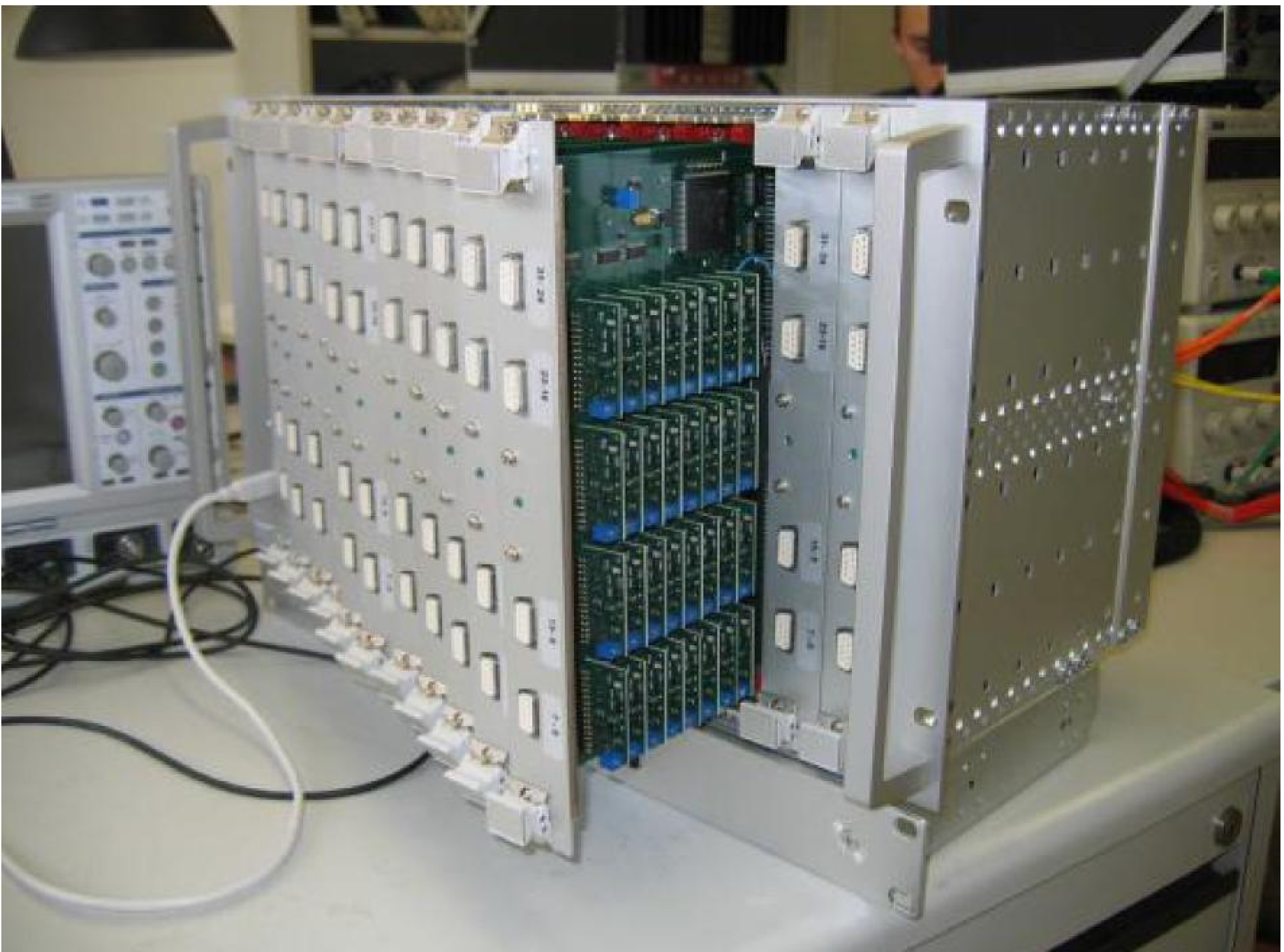



- Night-sky background induces continuous current

  → voltage drop at the resistor

  → to correct for that the current is measured and the voltage adapted accordingly

# Bias power supply



320 bias voltage channels

Voltage setting
Current readout

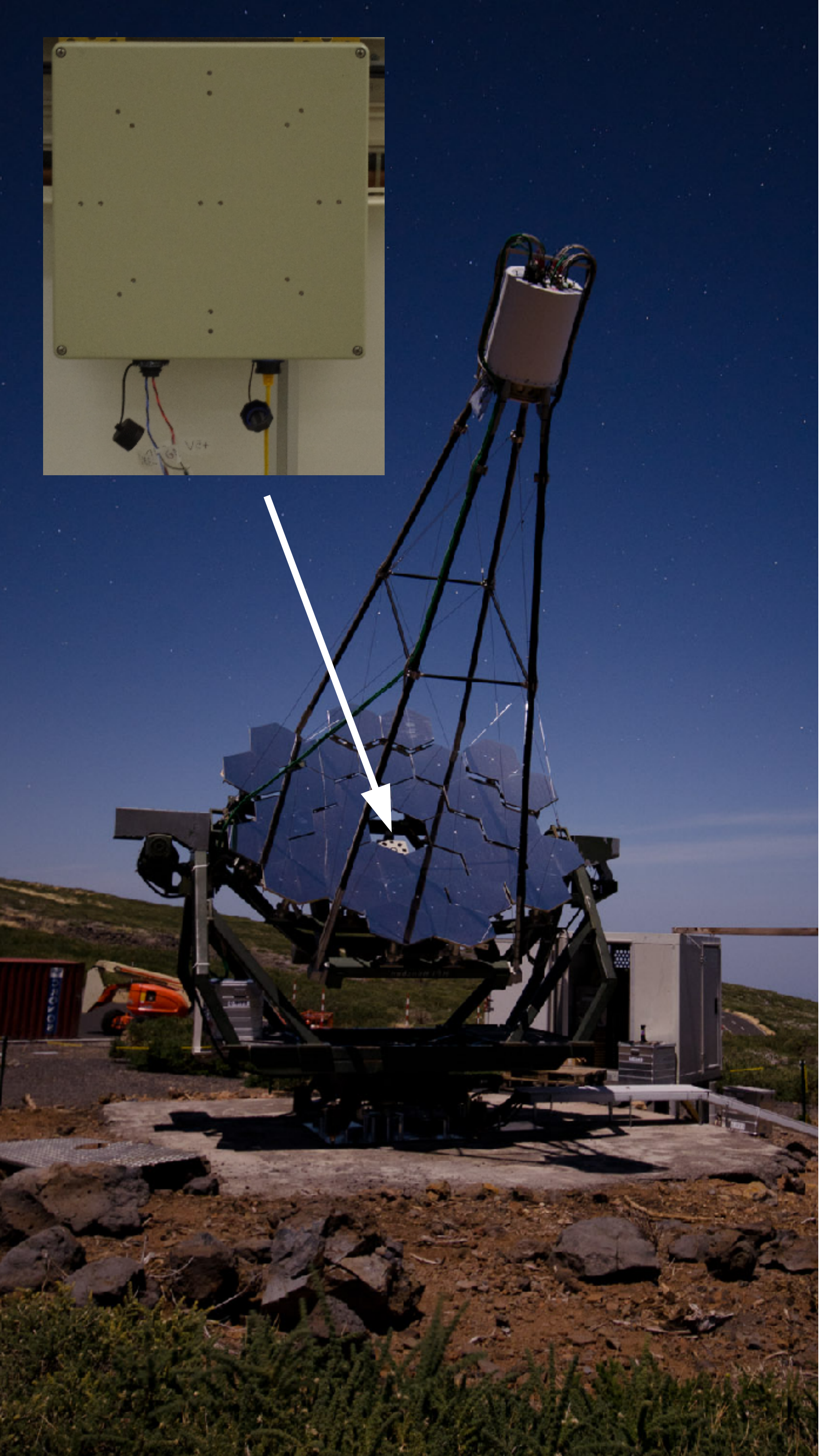
Maximum per channel:
U = 90V
I = 4mA

Resolution
U ~ 22mV
I ~ 1.2µA

Typical during operation:
U = 72V
I < 1mA (per ch, crate)
I < 500µA (per ch, camera)
I < 100µA (per G-APD)

# Three methods to check for gain stability

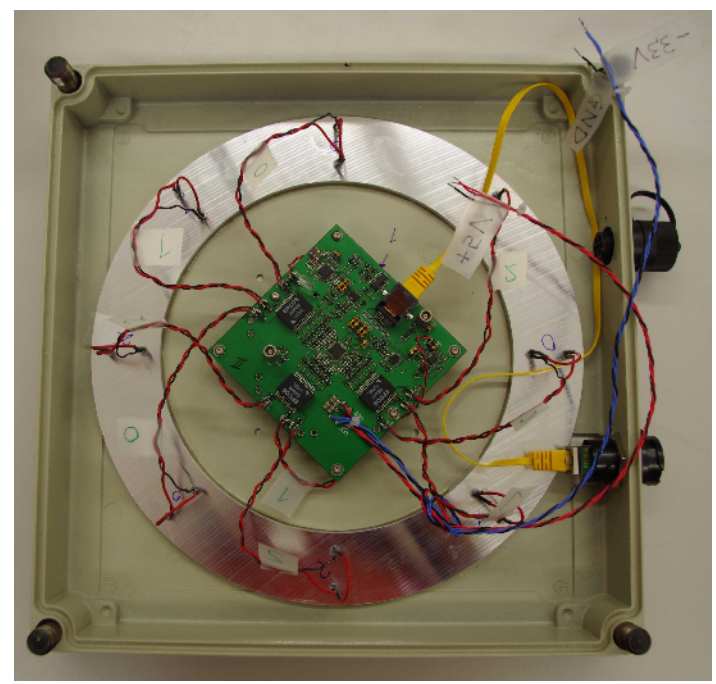
- Measure the amplitude of an external light source
- Measure the gain directly (dark count spectrum)
- Measure the response of the system
  on a changing trigger threshold



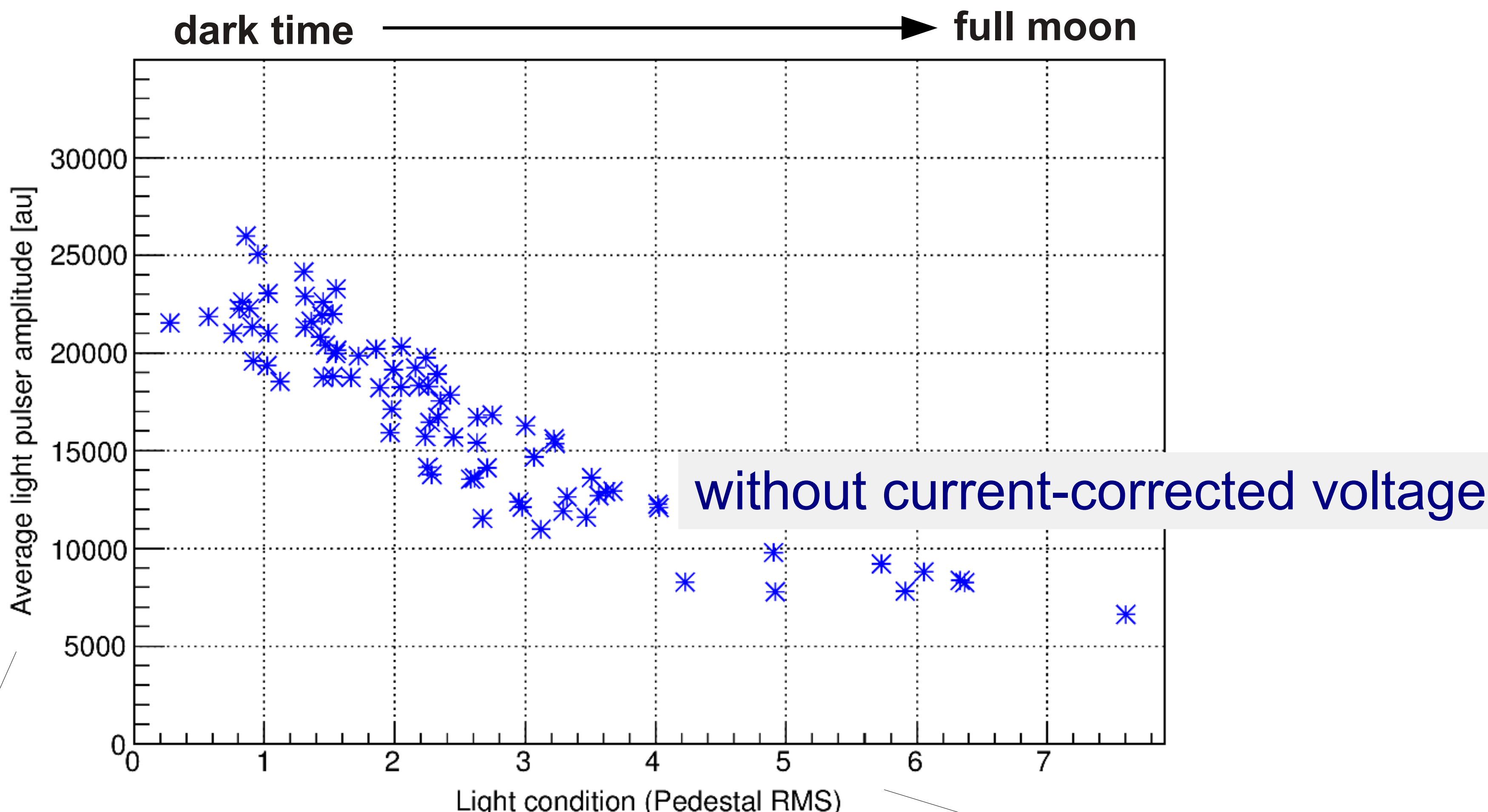
# Light pulser

- ~100ns pulse
- temperature stabilized
- average charge constant

→ gain measurement



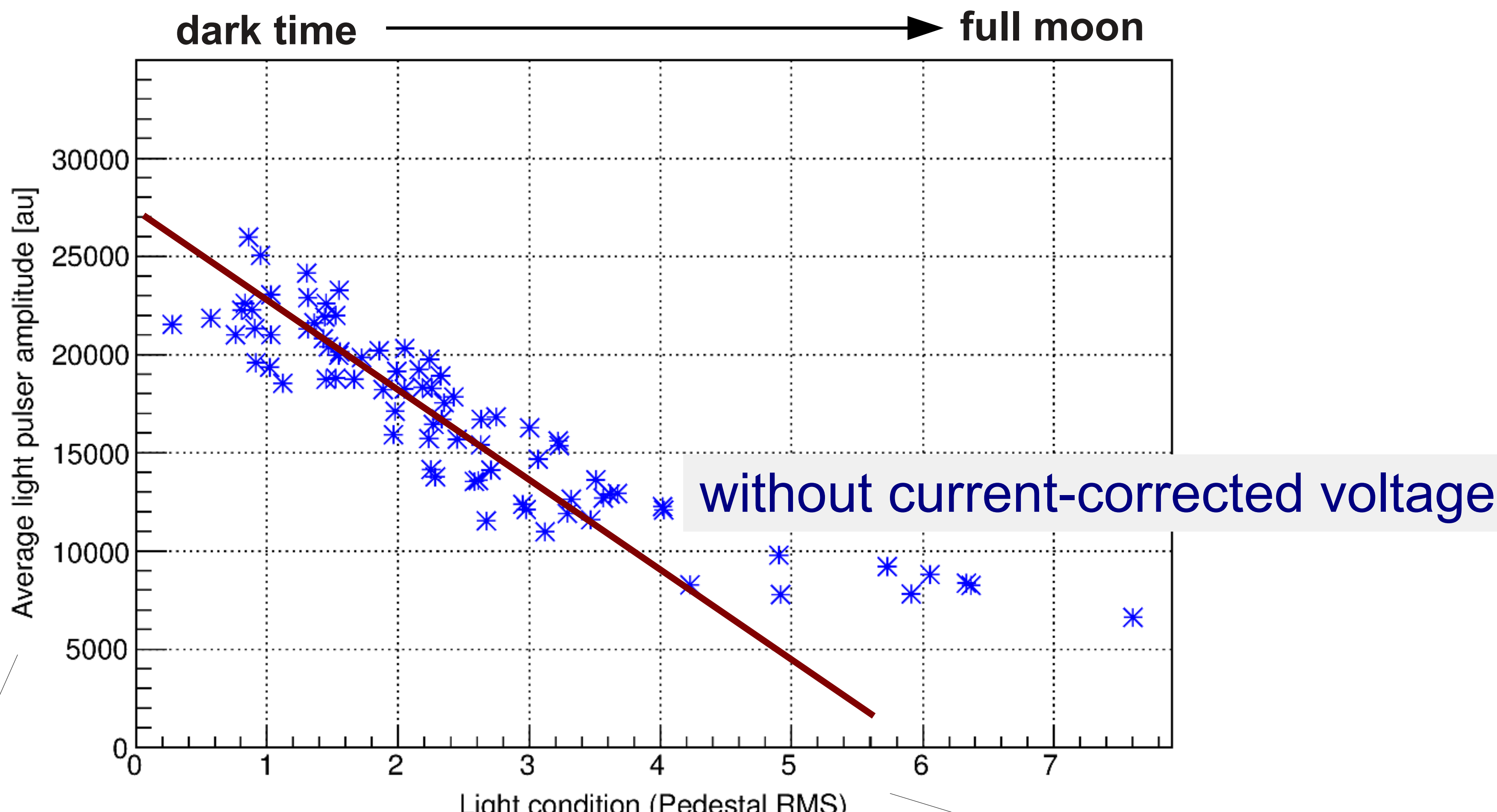
# Light-pulser amplitude vs. light condition




Indirect measurement of the gain

The noise of the data is a measure for the brightness

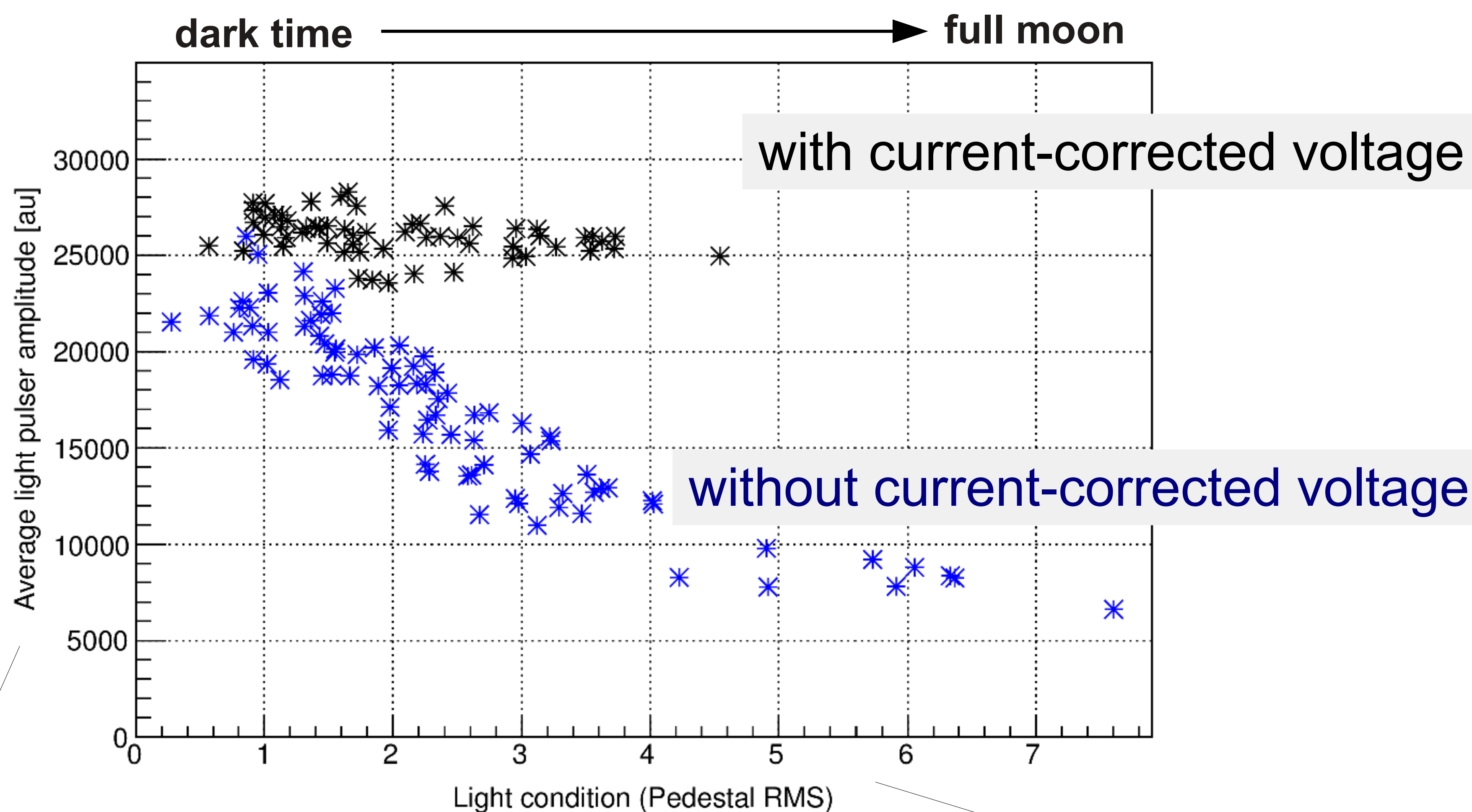
# Light-pulser amplitude vs. light condition




Indirect measurement of the gain

The noise of the data is a measure for the brightness

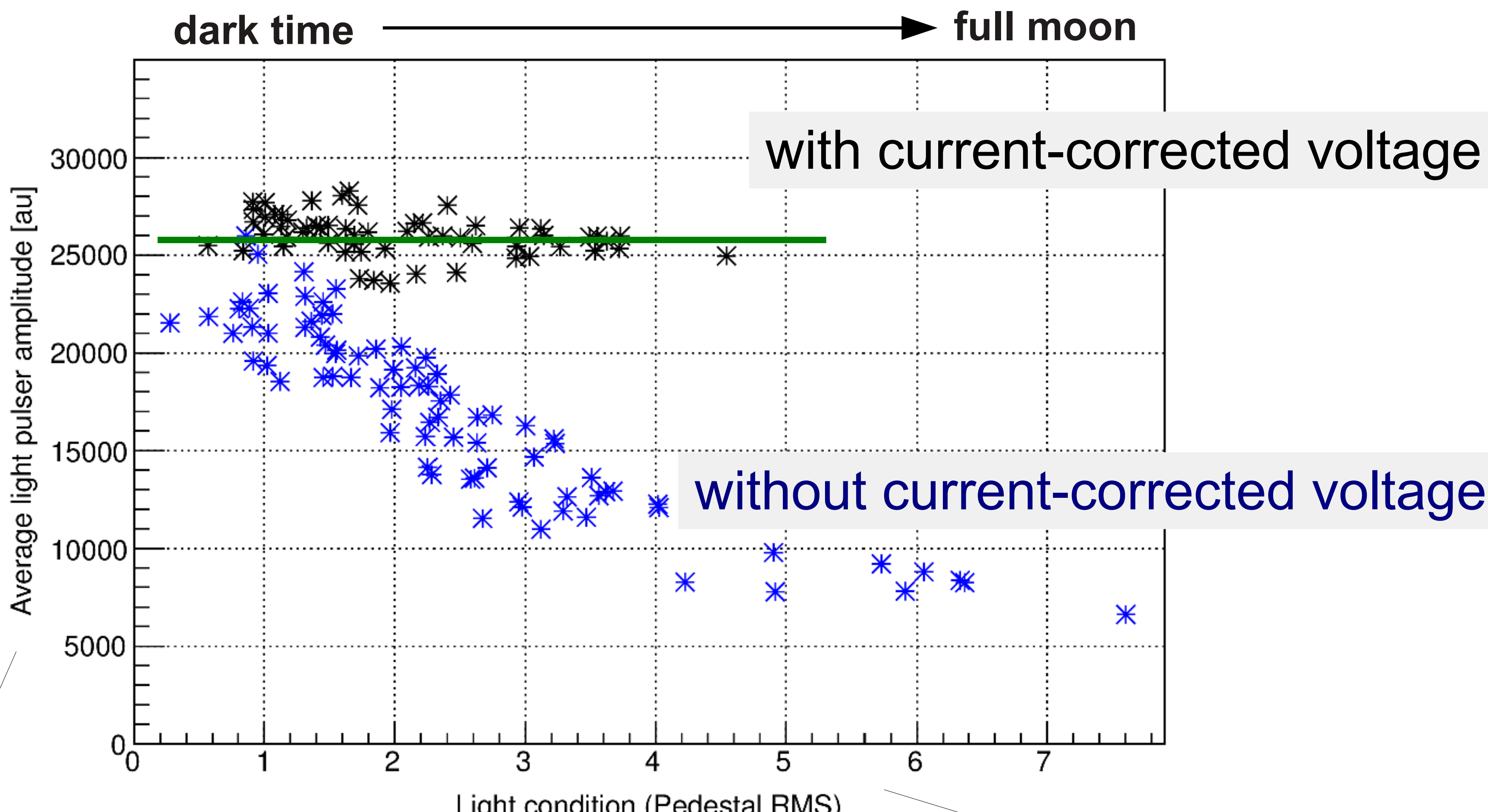
# Light-pulser amplitude vs. light condition




Indirect measurement of the gain

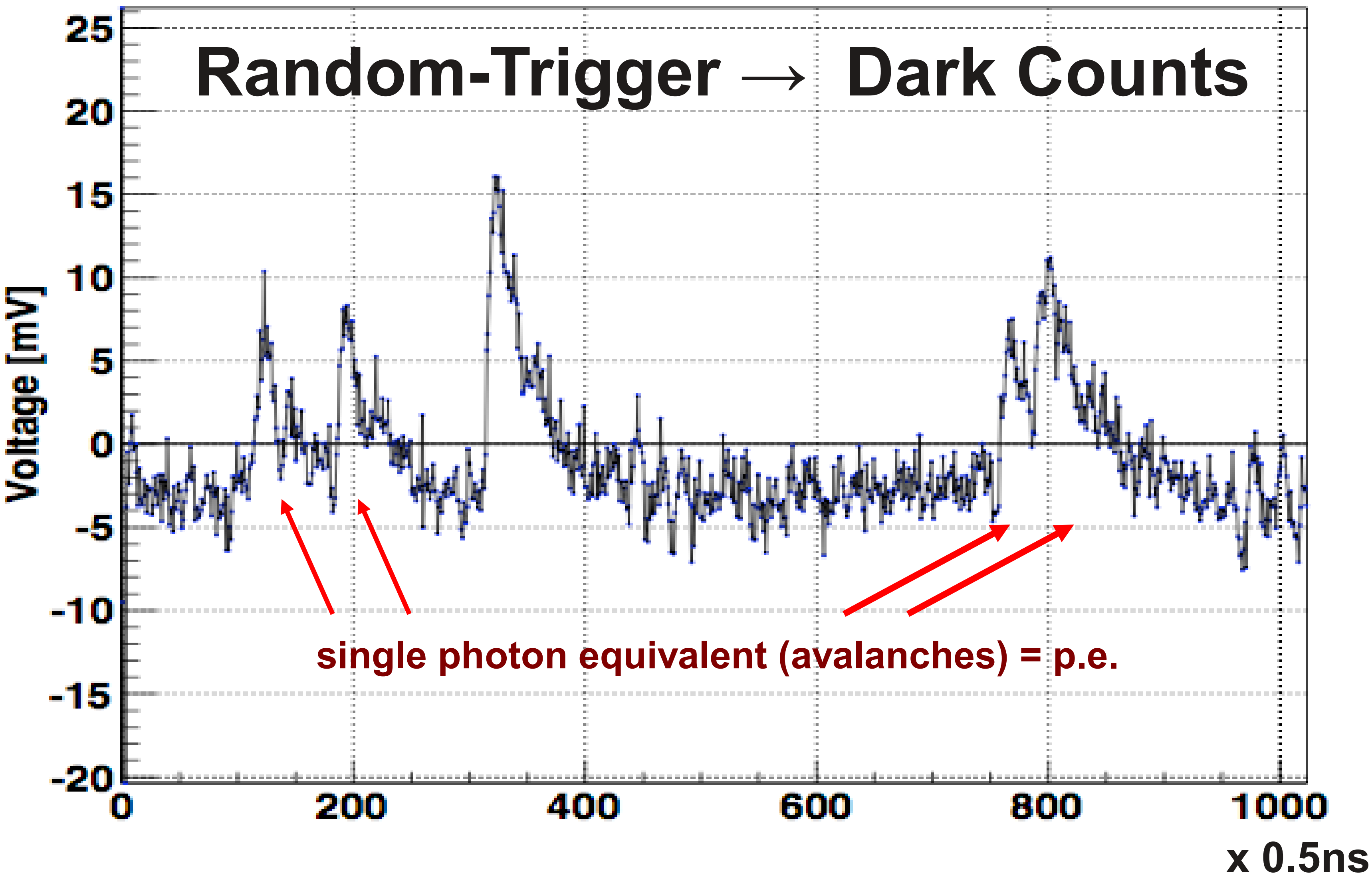
The noise of the data is a measure for the brightness

# Light-pulser amplitude vs. light condition

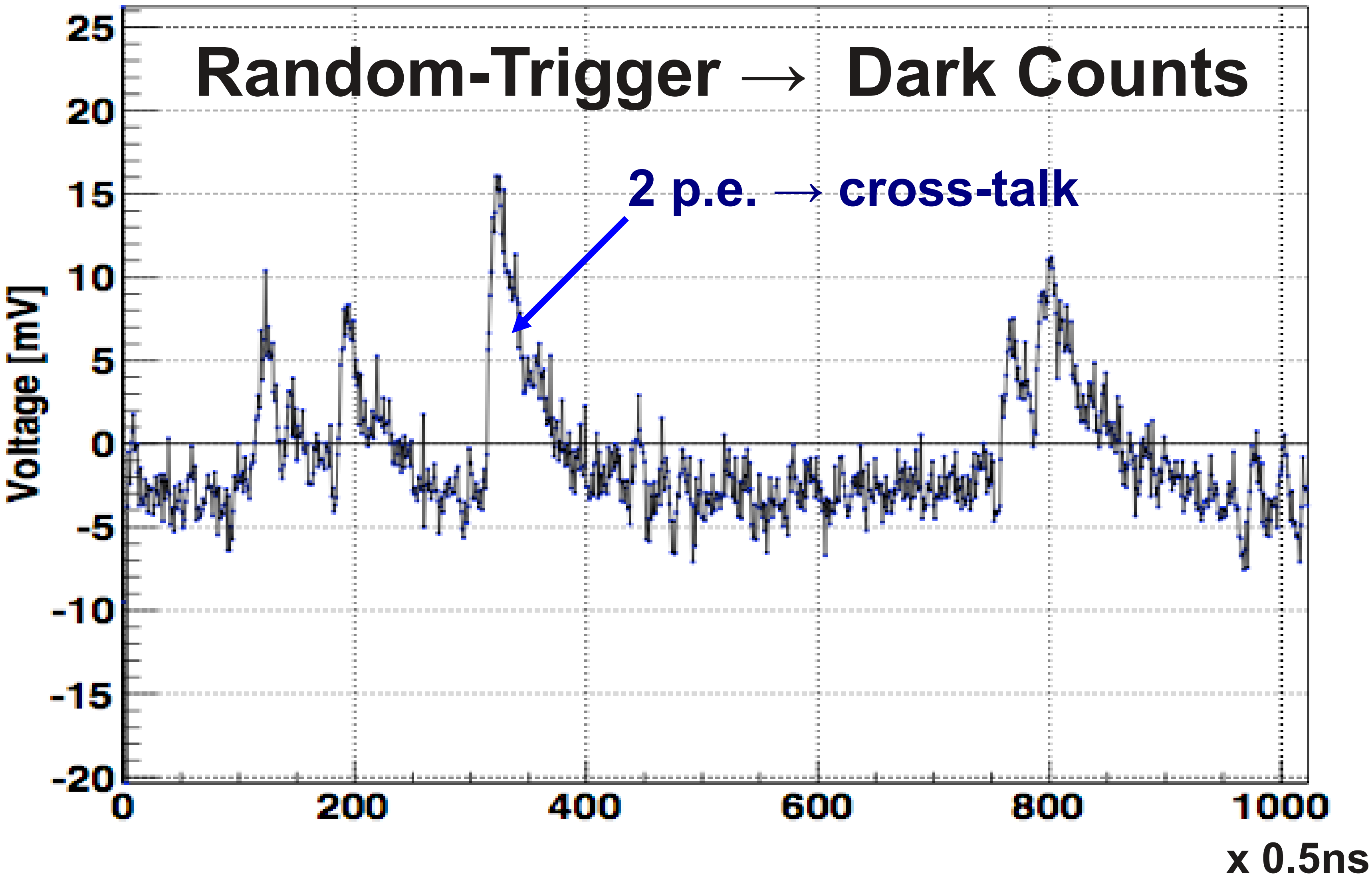



Indirect measurement of the gain

The noise of the data is a measure for the brightness

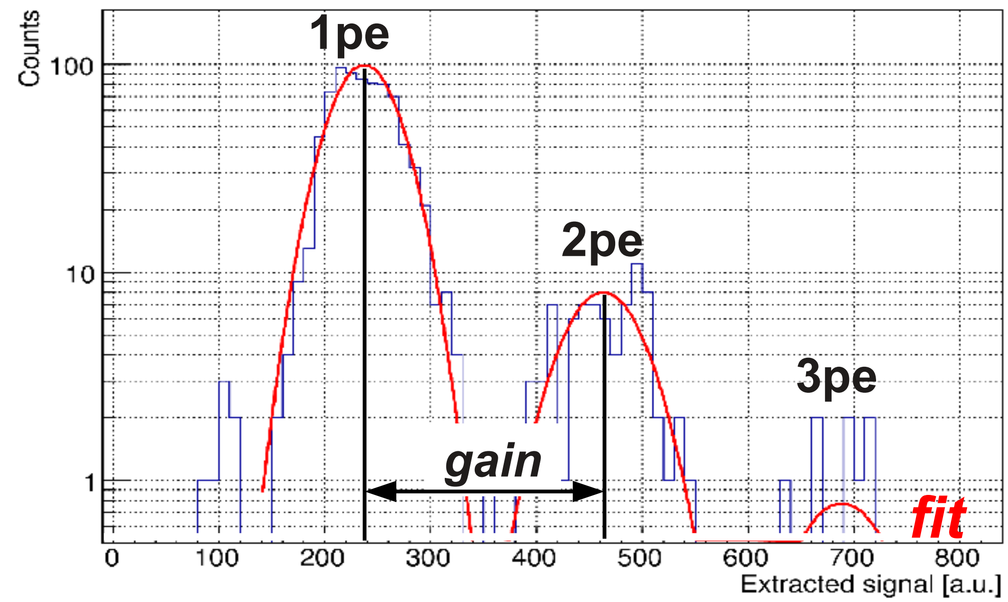


Random-Trigger → Dark Counts
Voltage [mV]
25
20
15
10
5
0
-5
-10
-15
-20
0
200
400
600
800
1000
x 0.5ns
single photon equivalent (avalanches) = p.e.


Random-Trigger → Dark Counts
2 p.e. → cross-talk
Voltage [mV]
x 0.5ns

# Normalized dark count spectrum

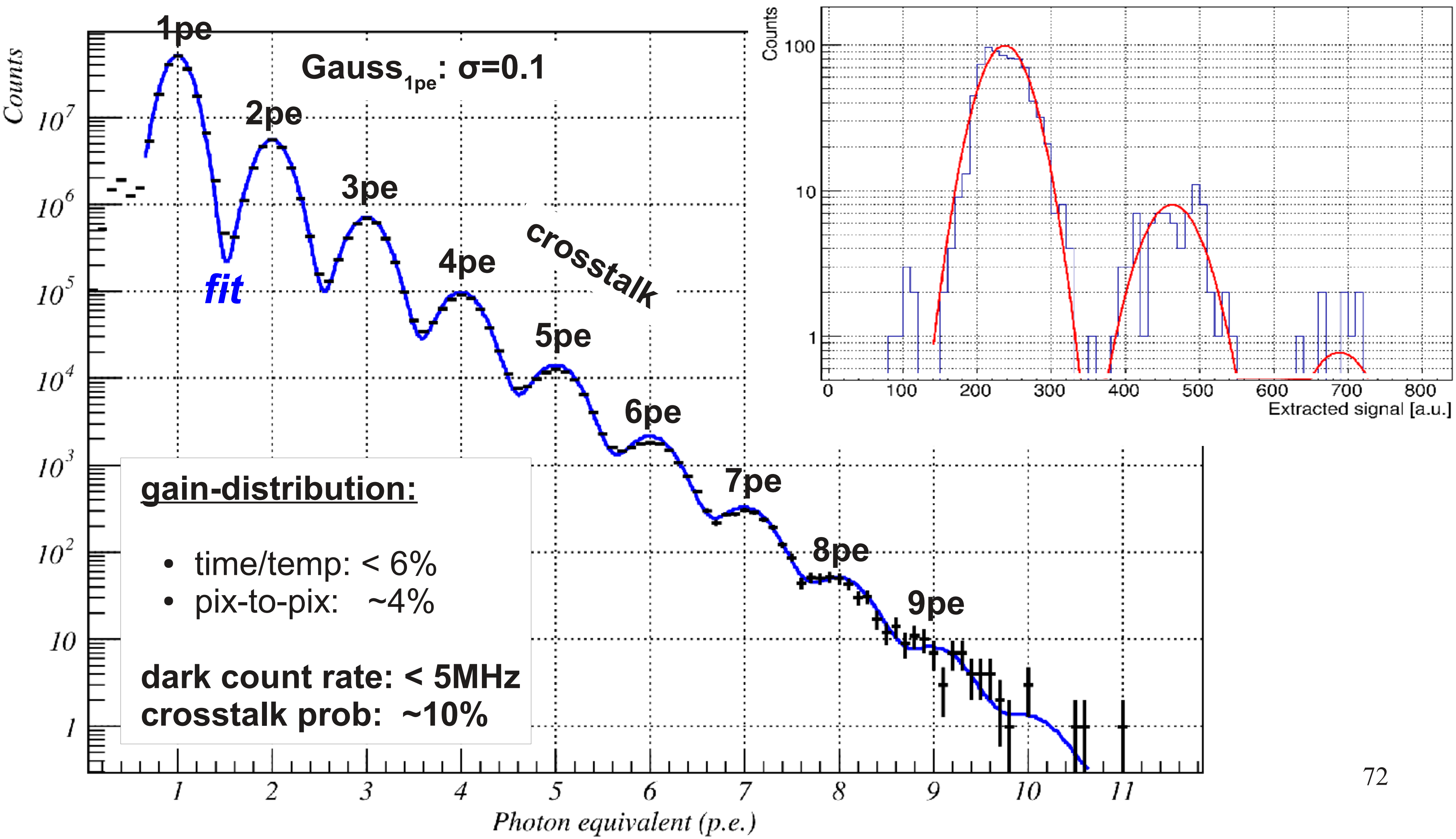
(~1440 pixel x 100 runs x 3000 evts x ~130ns; Temp: ~0°C – 25°C; closed lid)



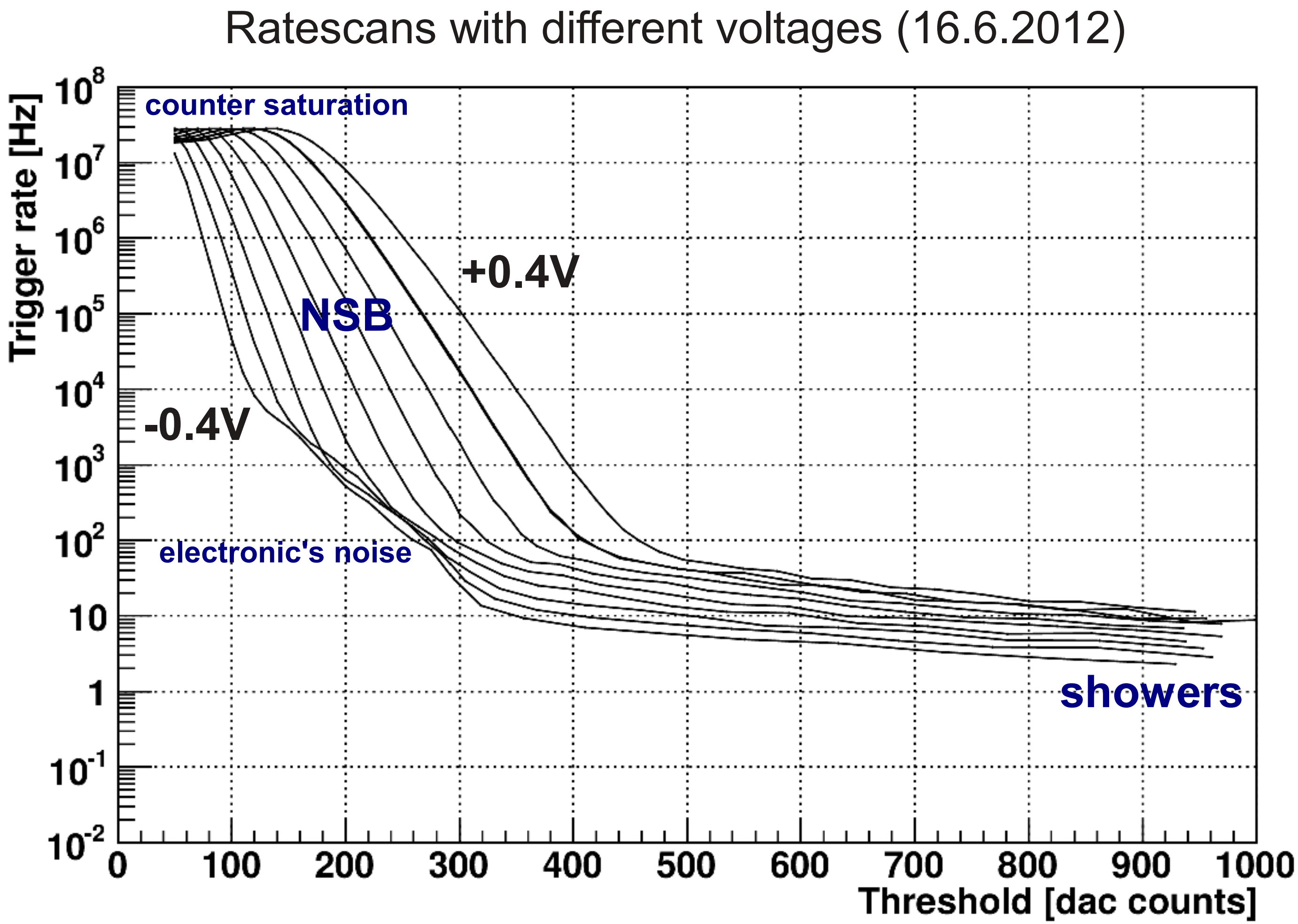

*single pixel / single run*

# Normalized dark count spectrum

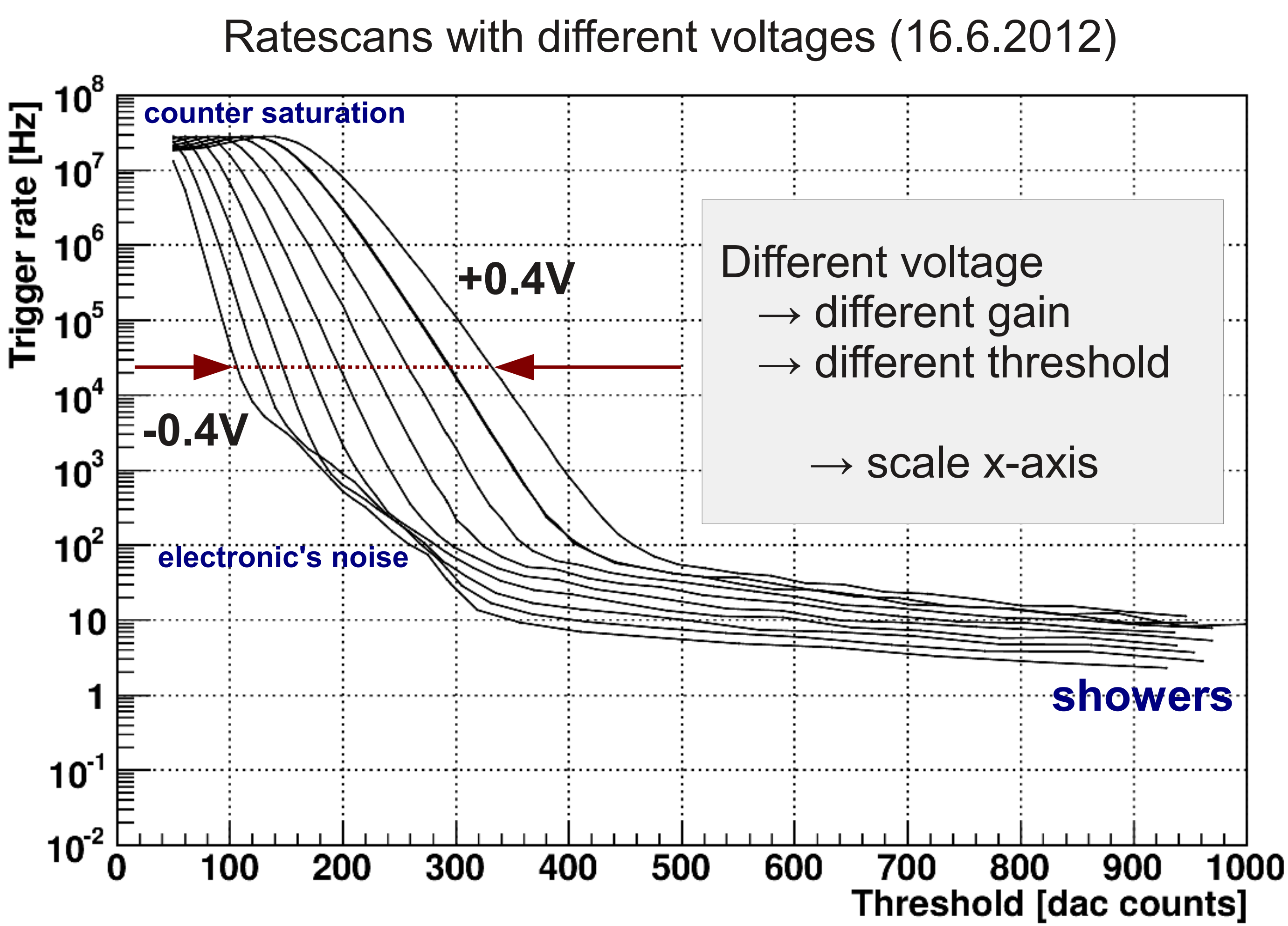
(~1440 pixel x 100 runs x 3000 evts x ~130ns; Temp: ~0°C – 25°C; closed lid)



# Ratescans with changing applied voltage (gain)

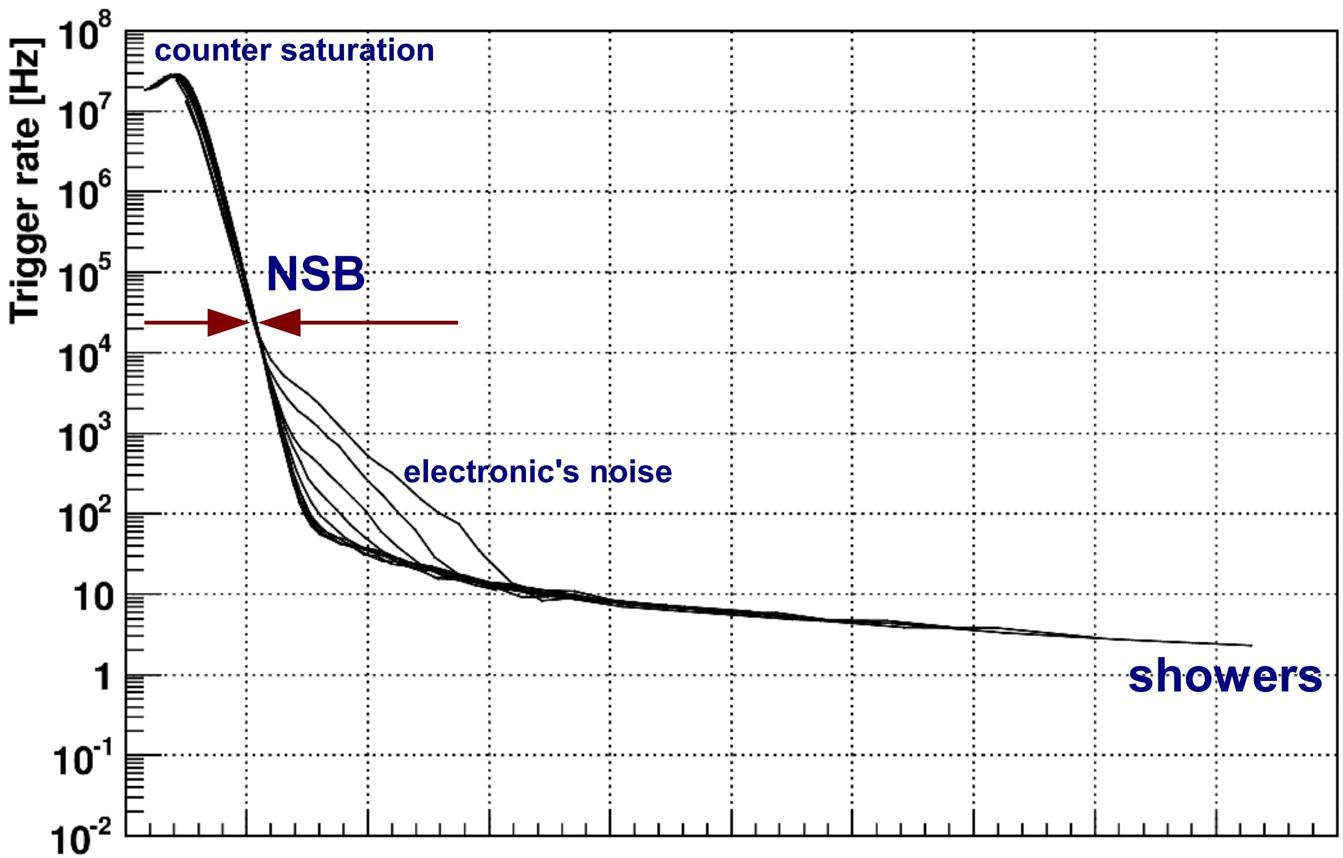


# Ratescans with changing applied voltage (gain)



# Ratescans with changing applied voltage (gain)

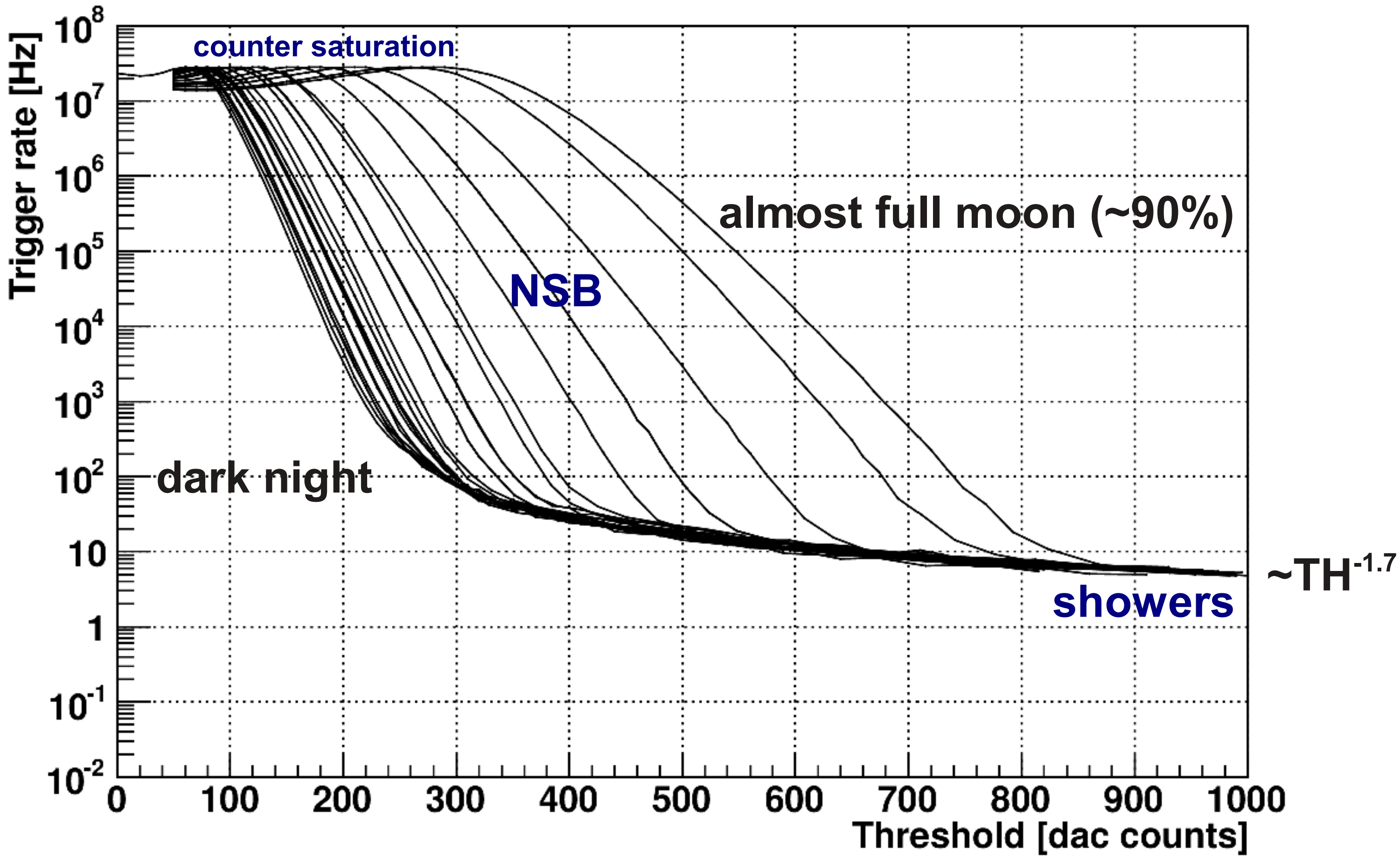
Ratescans with different voltages (16.6.2012)




→ If the gain is stable only the NSB-shoulder should shift with changing light conditions

# Ratescans with changing light conditions

26 ratescans with different light conditions (March – July)

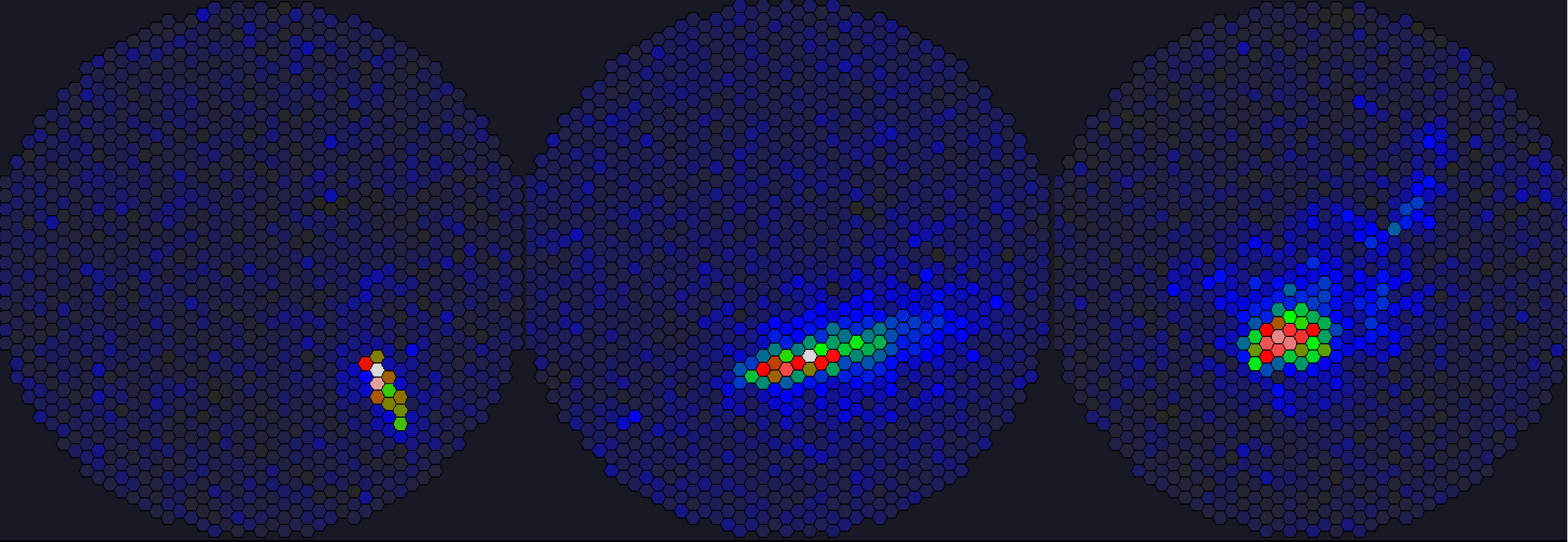



→ Gain independent of light conditions

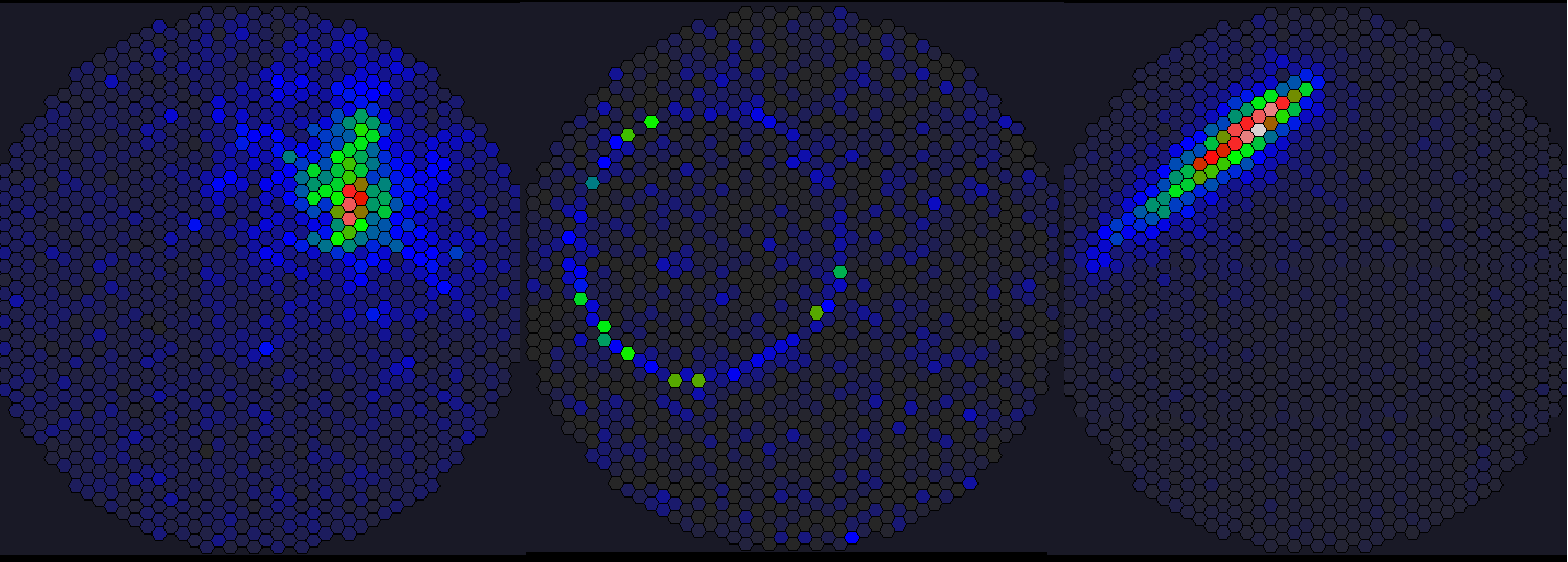
→ Observations at full moon possible (large gain in observation time)

# Data analysis

- **Data selection:**
  - Only dark-night data and data with zenith distance < 25°
- **Analysis:**
  - $\theta^2$ analysis
    (Disp coefficients taken from MAGIC I Monte Carlo!)
  - Very simple dynamical cuts
- **Note:**
  - Systems are still in commissioning (e.g. ratecontrol, bias feedback)

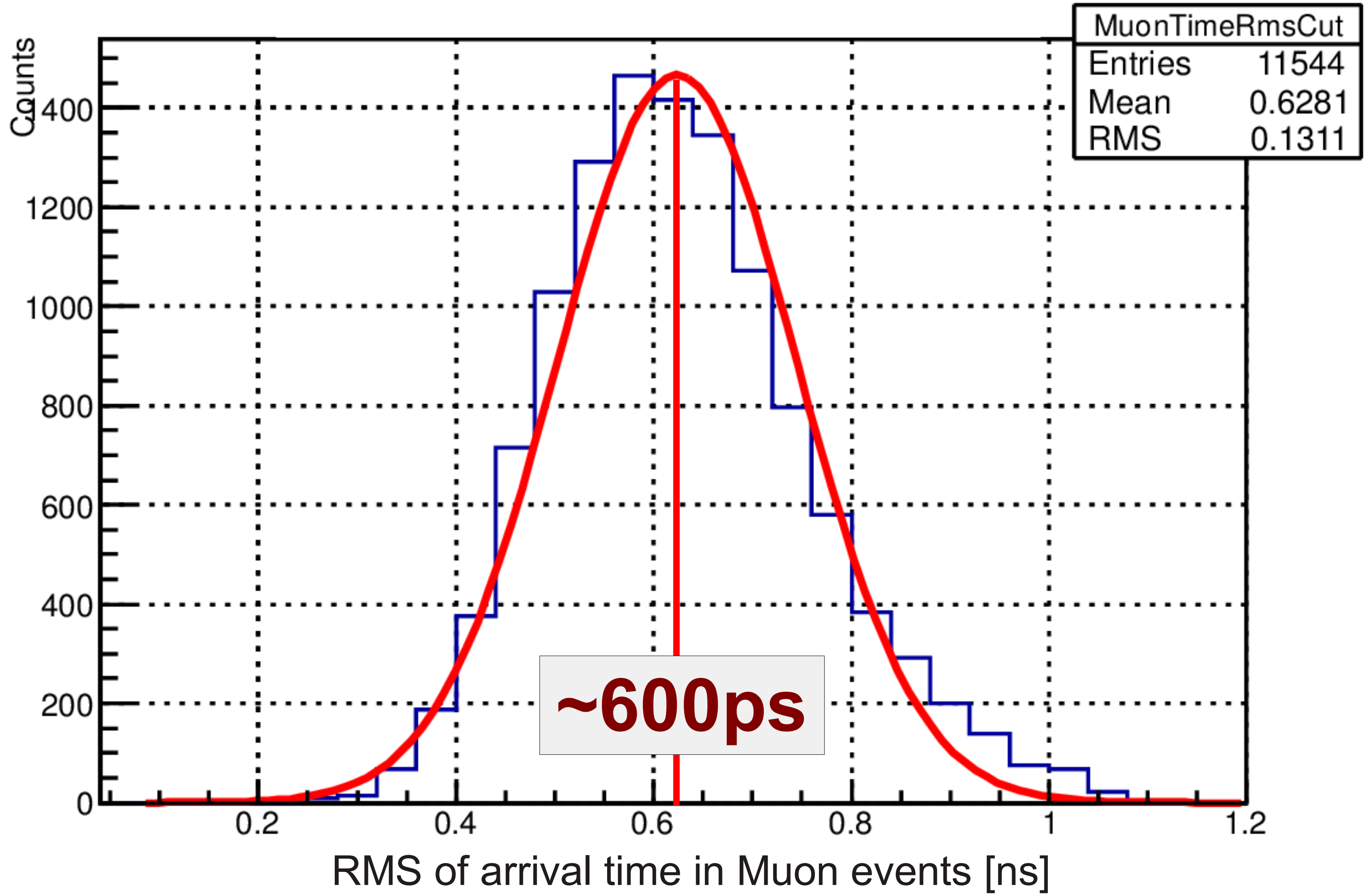


FACT – Selected events of the first nights of data-taking (October 2011)

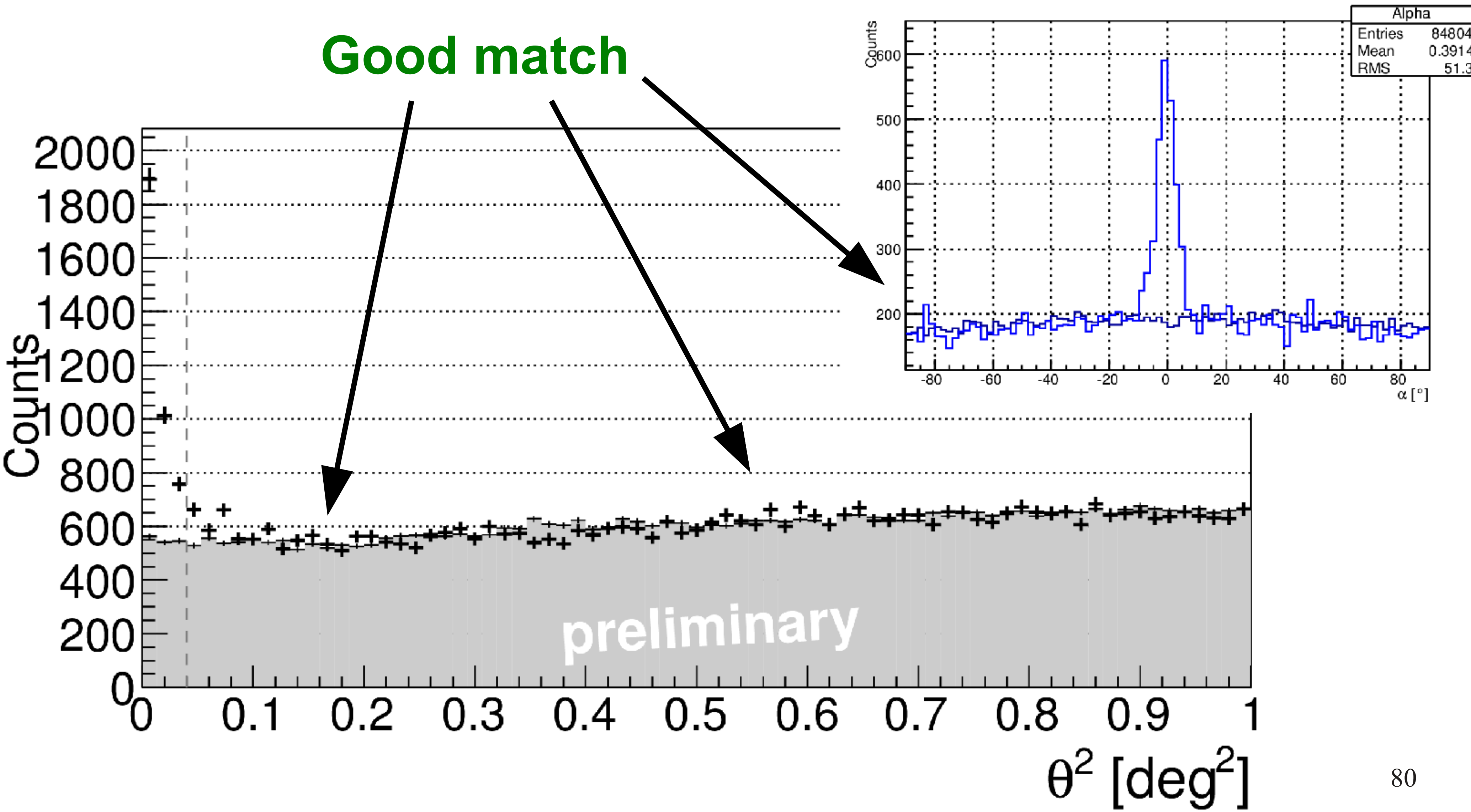


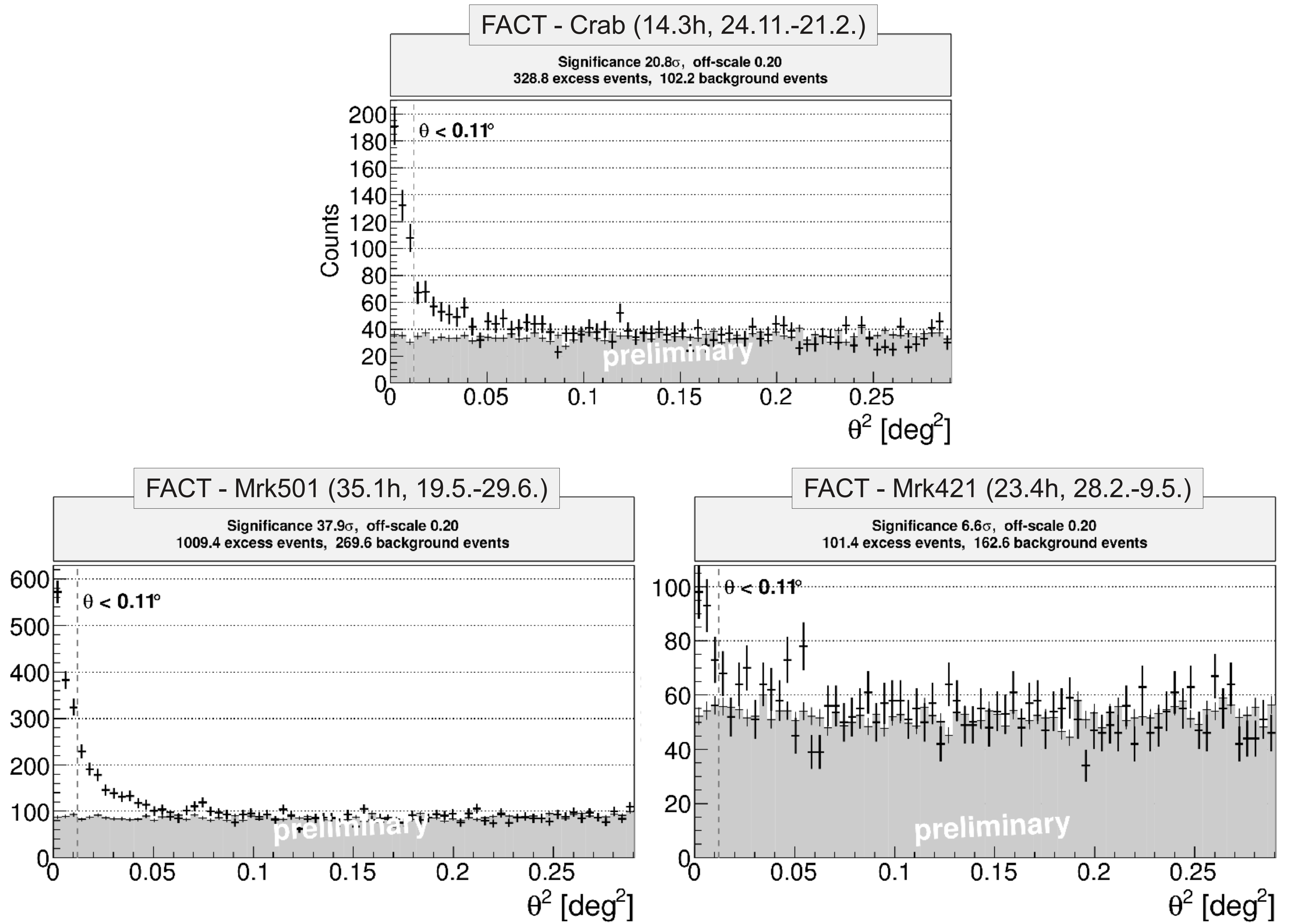
# Time resolution

→ Time resolution of the **whole system better than 600ps** (typical signal per pixel in muon rings in FACT: **<10pe**)



# Background match





FACT - Crab (14.3h, 24.11.-21.2.)
Significance 20.8σ, off-scale 0.20
328.8 excess events, 102.2 background events
θ < 0.11°
Counts
θ² [deg²]
preliminary
FACT - Mrk501 (35.1h, 19.5.-29.6.)
Significance 37.9σ, off-scale 0.20
1009.4 excess events, 269.6 background events
θ < 0.11°
θ² [deg²]
preliminary
FACT - Mrk421 (23.4h, 28.2.-9.5.)
Significance 6.6σ, off-scale 0.20
101.4 excess events, 162.6 background events
θ < 0.11°
θ² [deg²]
preliminary

# Energy threshold

- ***<u>Very simple analysis:</u>***
  - Sensitivity cuts (optimized for best integral sensitivity):
    **(very similar excess rate than CT1)**
    → **~700 GeV**
  - Open cuts
    **(excess rate extrapolated with Crab spectrum)**
    → **~400 GeV**

# Sensitivity (Crab in 50h)

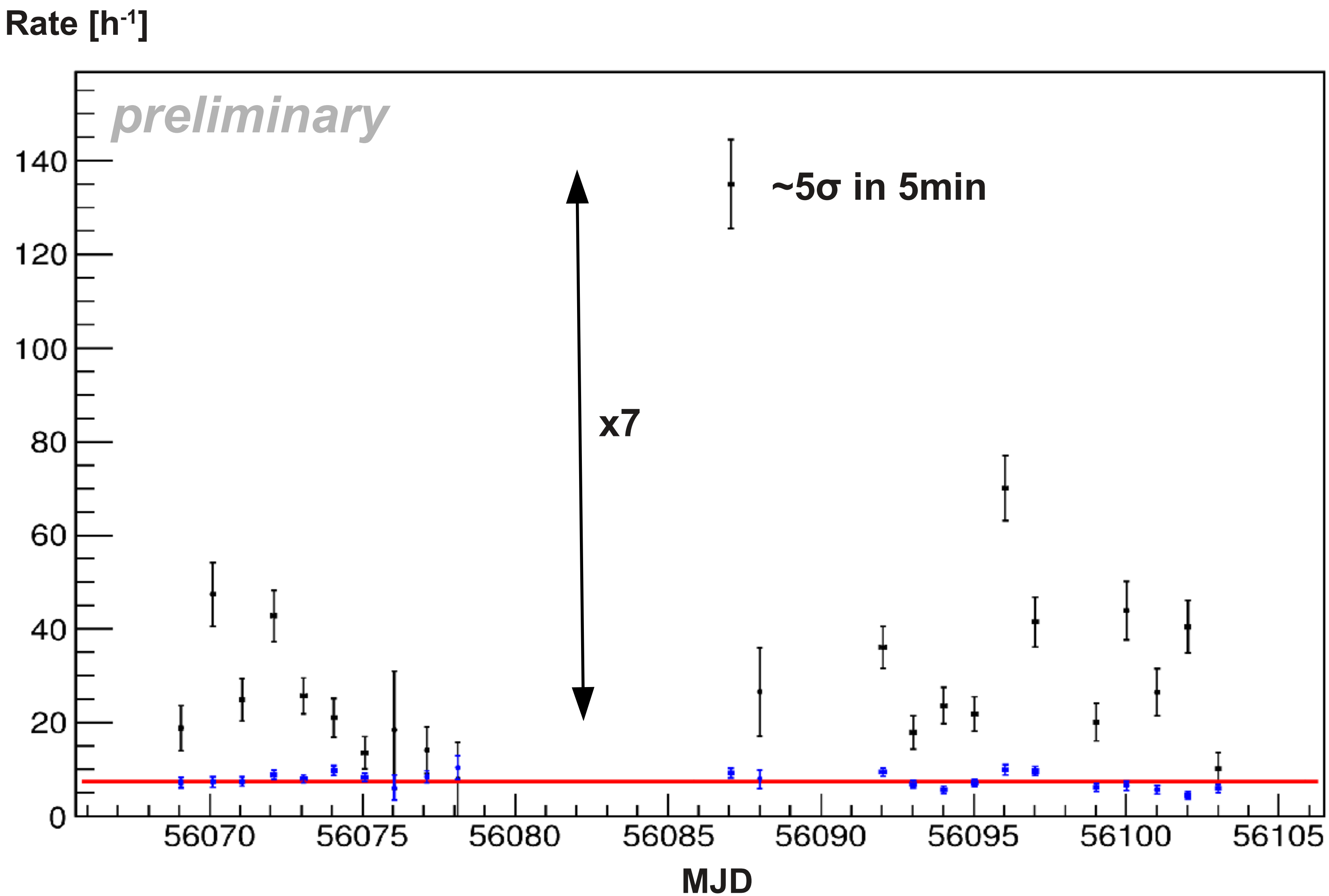
- ***Very simple analysis:*** $$5 \cdot \sqrt{\frac{T_{obs}}{50\mathrm{h}}} \cdot \frac{\sqrt{background}}{excess}$$

  - HEGRA CT1 (Eckart Lorenz, priv. com.) ~15%
    ( 3.7 σ / √h )

  - HEGRA System (astro-ph/9901094) ~10%
  - HEGRA System (astro-ph/0306123) ~6%

  - **FACT: ~8%**
    **( 5.5 σ / √h )**

# Mrk501 “light curve”



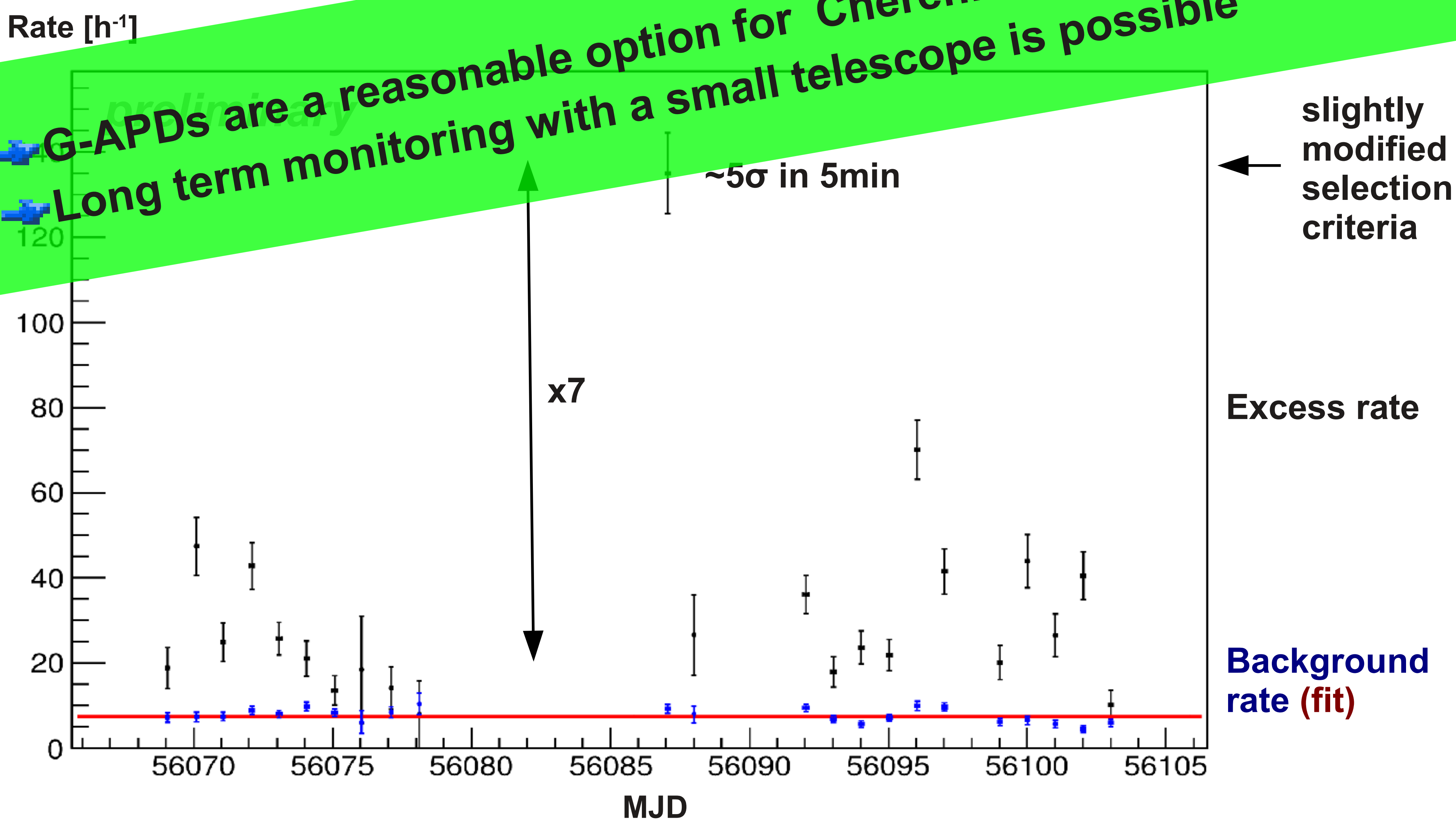

slightly modified selection criteria

Excess rate

Background rate (fit)

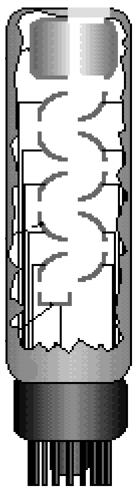
# Conclusion

- G-APDs are a reasonable option for Cherenkov telescope
- Long term monitoring with a small telescope is possible



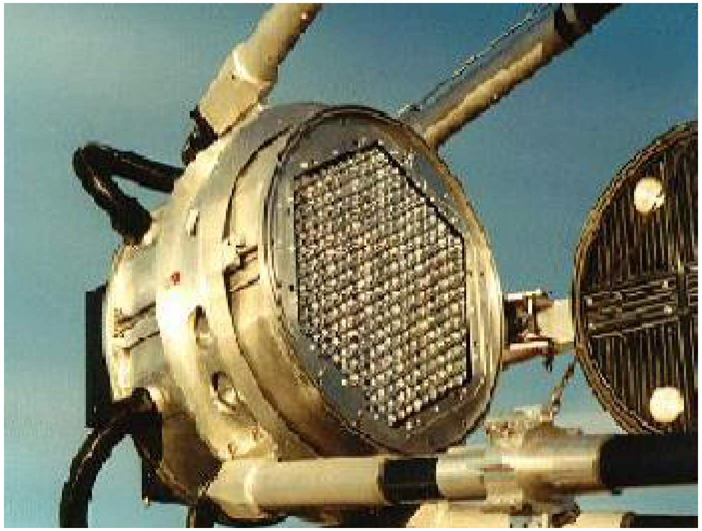
# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

1930's



tubes →

1990's



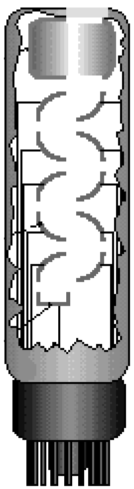
<2009

silicon devices →

?

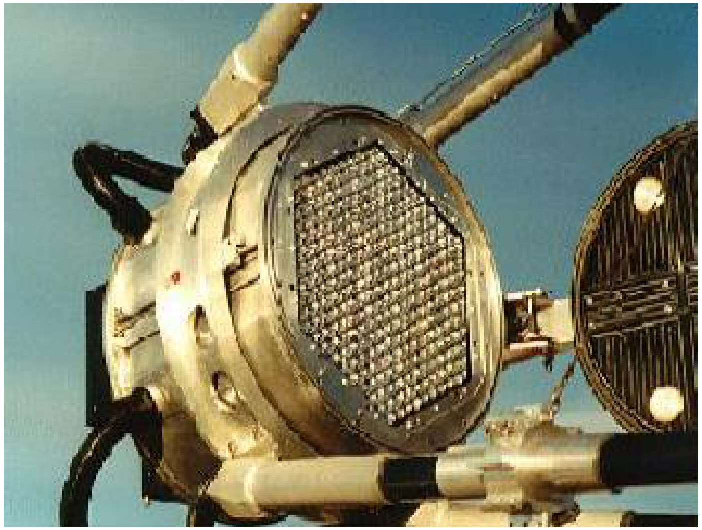
# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

1930's



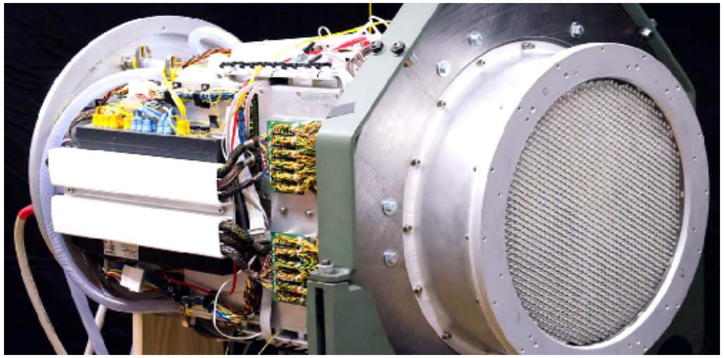
tubes →

1990's



<2009

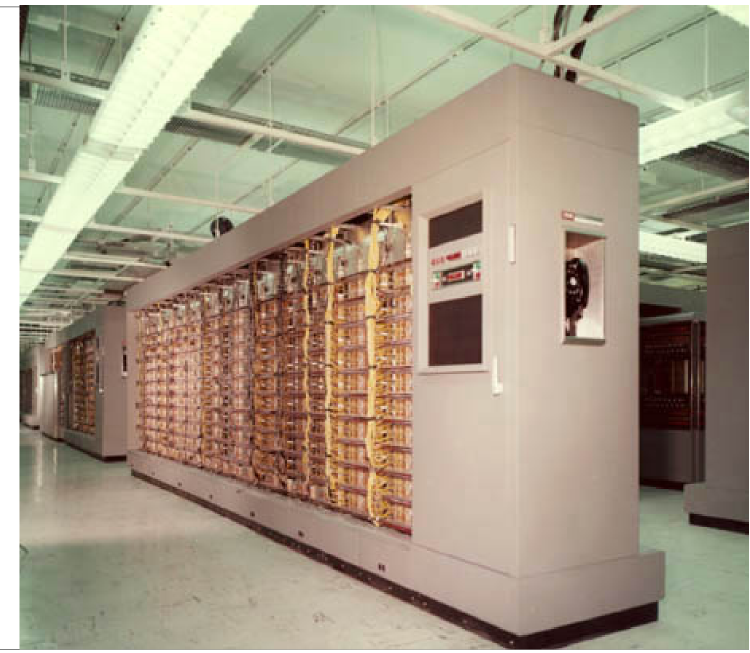
silicon devices →

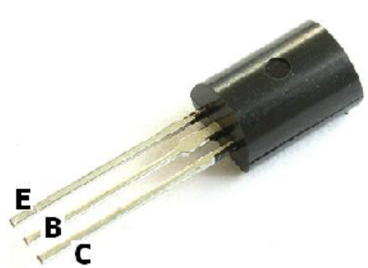


>2011

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

tubes →





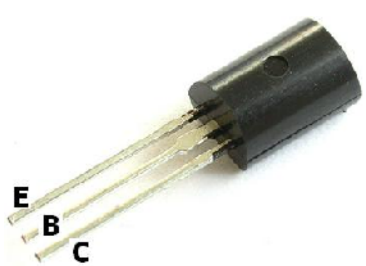

silicon devices →

where are we today?

?

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

tubes →


silicon devices →

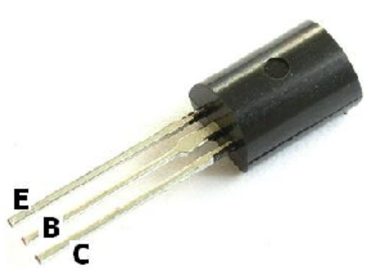
where are we today?

?

not yet the smartphone, but...

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

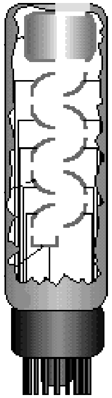
tubes →




silicon devices →

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

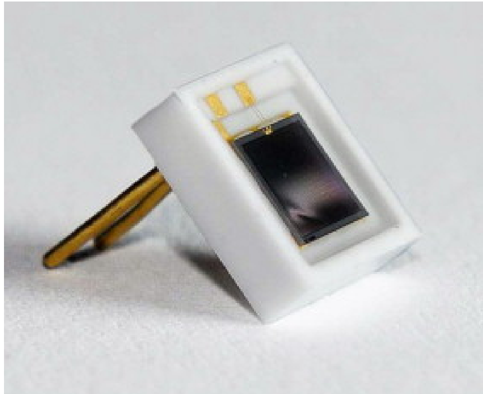
technology of 1930's



still hand made → large spread

**FACT** →

technology of 2009



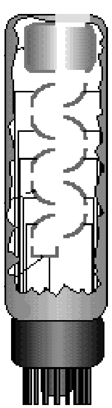
high precision mass production

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

## The FACT prove:

- **G-APDs work very well in Cherenkov astronomy**
  (not a single problem related to the G-APDs so far)
- **G-APDs can give a perfomance improvement**
- **G-APDs give a big stability improvement**

technology of 1930's



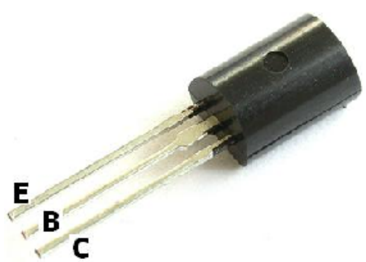
still hand made → large spread


technology of 2009

high precision mass production

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

past




today

<2009

?

future

# FACT
# **F**irst G-**A**PD **C**herenkov **T**elescope

- Afterpulses (factor ~8, *e.g. Hamamatsu, Excelitas*)
- Optical crosstalk (factor 6-10, *e.g. Hamamatsu, KETEK, Excelitas*)
- Dark count rate (factor 6, *e.g. Hamamatsu*)
- Active area (*e.g. Hamamatsu*)
- Temperature stability (*e.g. Hamamatsu*)
- Pulse Width (*e.g. SensL*)

  → **Eventually 100µm cells yielding a total PDE of up to 70%**
  **(50µm with PDE of 40% – 50% expected by end of 2013,** *KETEK***)**

- **Price already a factor of 10 lower than when we bought our G-APDs**

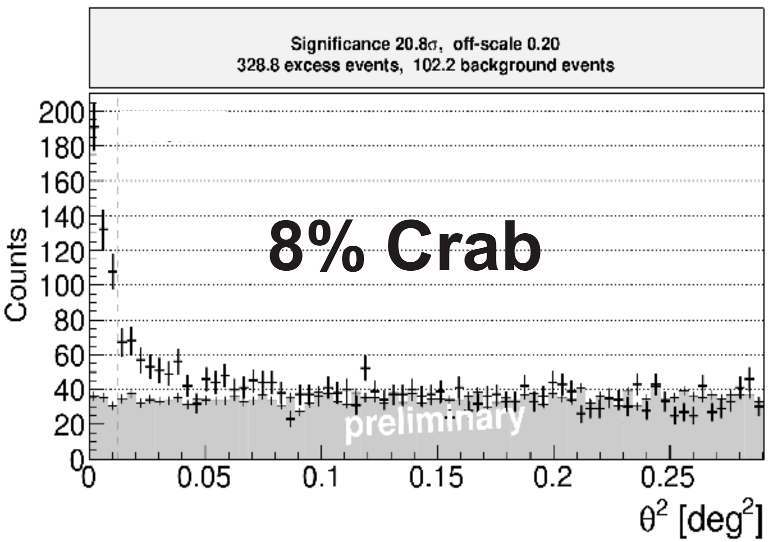
<2009

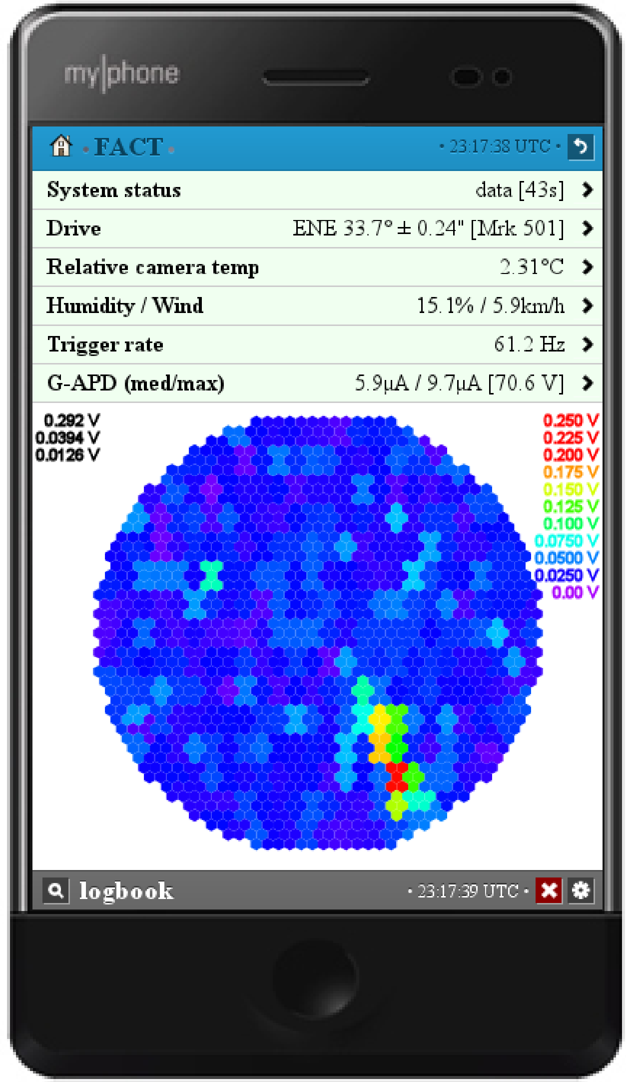
→ ?

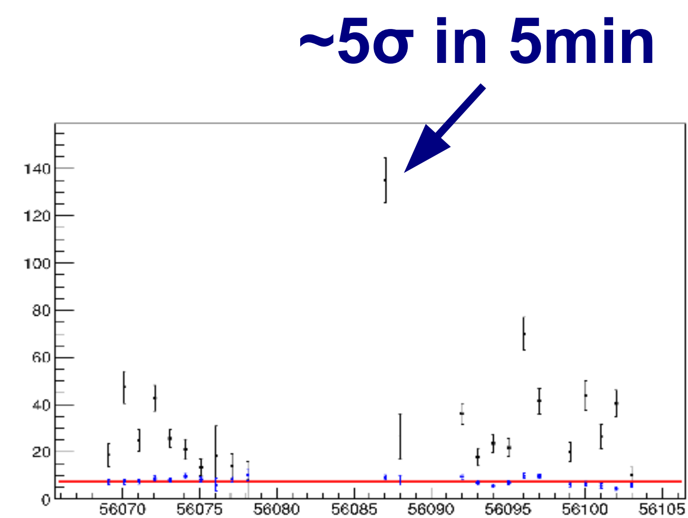
future

# www.fact-project.org/smartfact

The First G-APD Cherenkov Telescope




[arXiv:1304.1710]

**You are invited to join us during monitoring!**