# *SiPM在WFCTA上的应用研究*

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LHAASO合作组会议

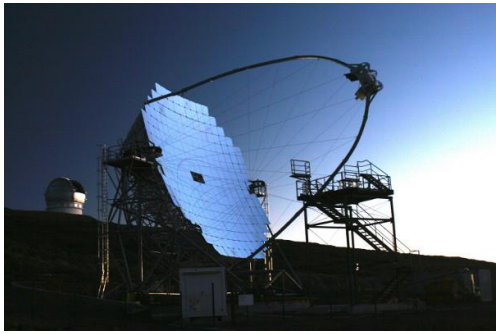
在云南大学2017.1.17-20

# Outline

- *Introduction*
- *LHAASO-WFCTA SiPM camera R&D*
- Conclusion and discussion

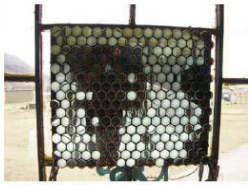
# Motivation

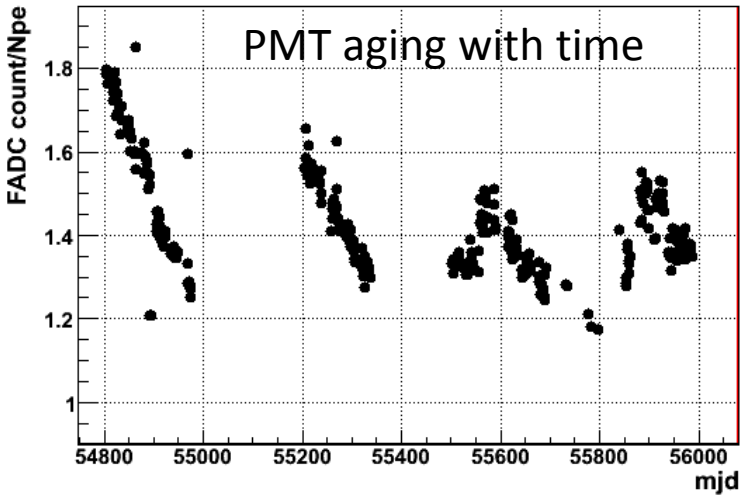
- 基于光电倍增管（PMT）的大气成像切伦科夫光和荧光望远镜技术：
  - •大气成像契伦科夫望远镜实验： VERITAS，HESS，MAGIC …
  - • 荧光探测器实验：HIRES，TA，AUGER …
  - • 运行在晴朗无月夜
  - • PMT老化：随着曝光光强增加，增益逐渐降低，
  - • 有效观测时间10%



- **此研究领域对长有效观测时间的望远镜有强烈的需求。**

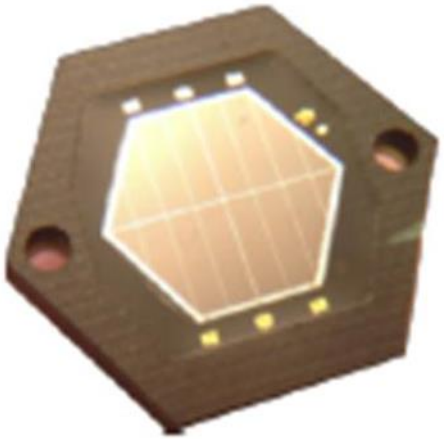
**LHAASO-WFCTA 样机**

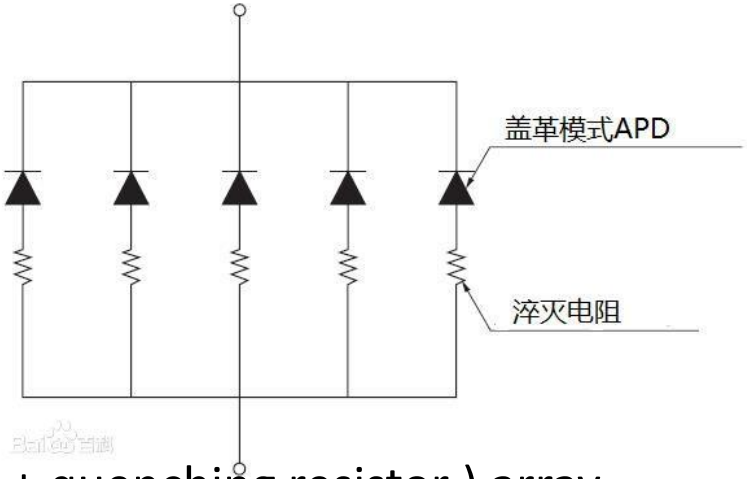


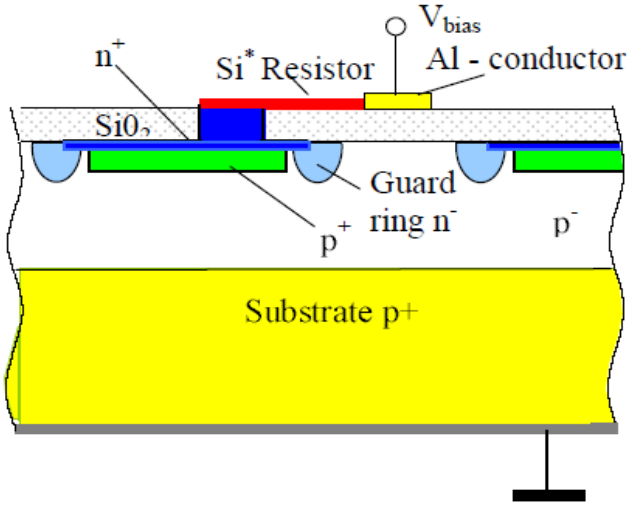


# SiPM技术

- 优点：**强曝光不老化**、高光探测效率（25% - 50%）、低偏置电压（几十伏）和对磁场不敏感等；
- 基于SiPM技术的大气成像切伦科夫望远镜，可以**月光下观测**，**有效观测时间增加到30%**。
- SiPM：由工作在盖革模式的雪崩二极管阵列组成；
- 发明于二十世纪九十年代末，被核医学和高能物理领域寄予厚望，有望取代PMT，是未来极微弱光探测器的发展方向；



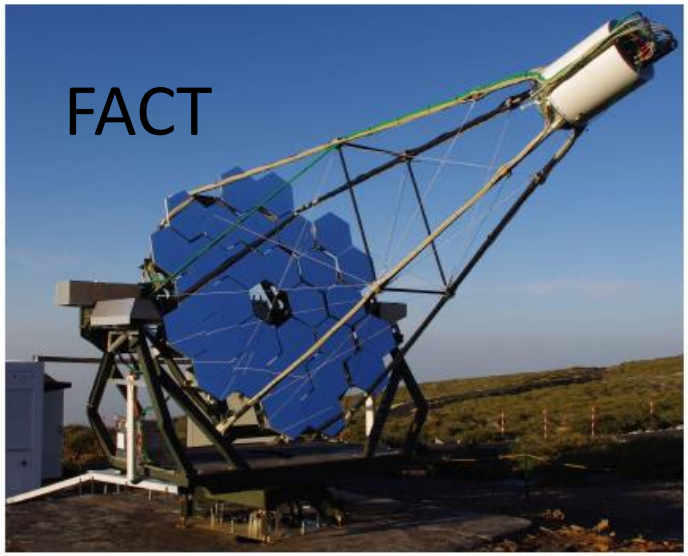


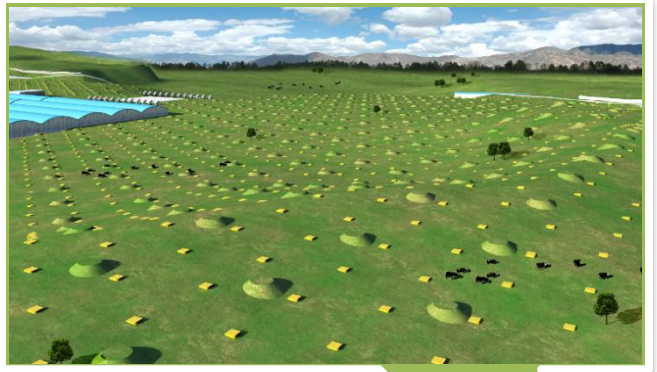

- Is made of an (APD + quenching resistor ) array
- APD: operates in Geiger mode, the output signal is 0 and 1 analog signal
- APD size: 15 μm – 100 μm
- 1600 APDs/mm² （25μm）

# 应用例子

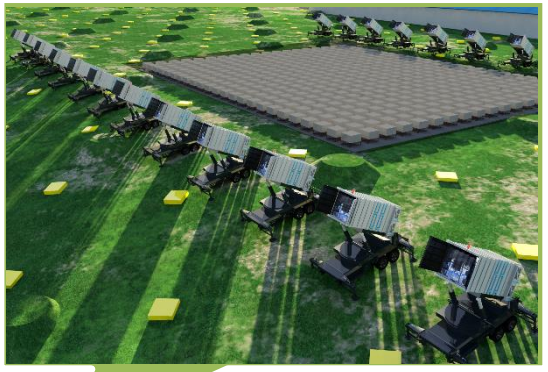
- The first G-APD Cherenkov telescope （FAST）： La Palma, Canary Islands, Spain，2011年运行
  - FOV ： 4.5°， 1440 pixels，9.5㎡的反射镜， pixel size：0.11°
- CTA：小型望远镜 （ 5 TeV – 300 TeV），Schwarzschild-Couder telescope



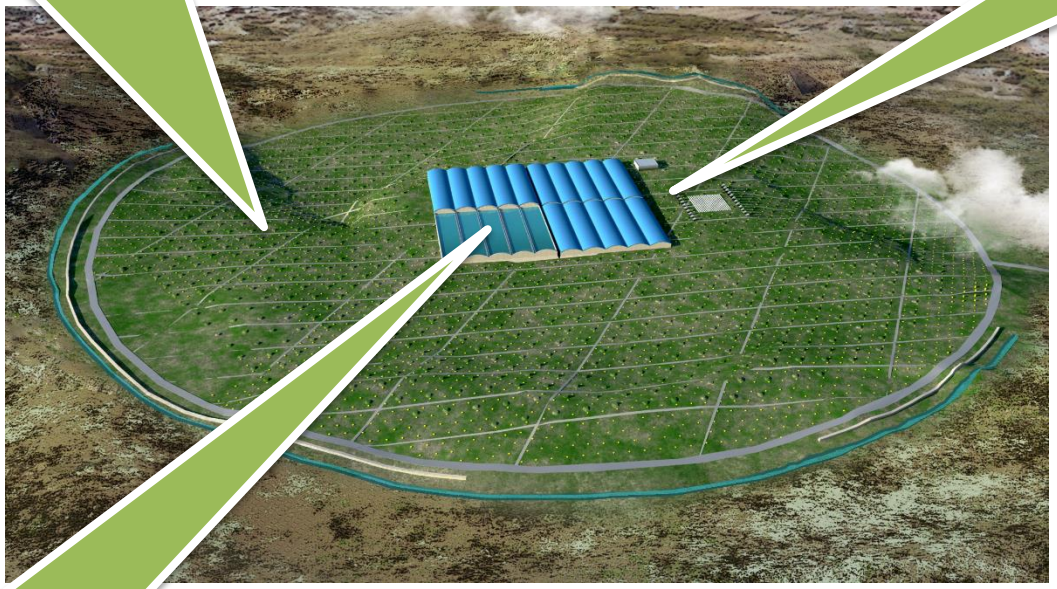

CTA：SiPM成像探头样机



# LHAASO

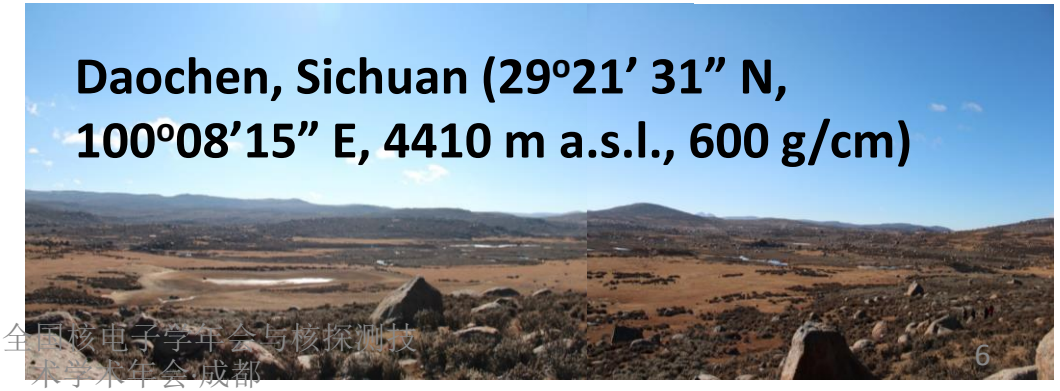


**KM2A:**
5195 EDs
1171 MDs



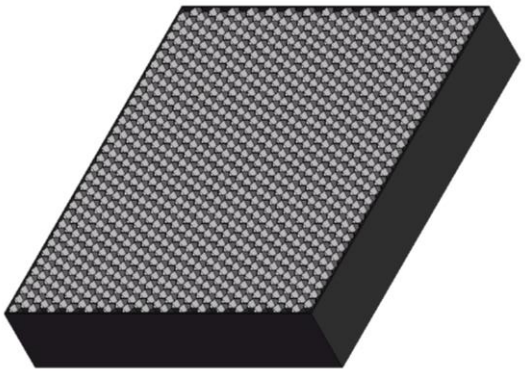
**WFCTA:**
18 Cherenkov telescopes (1024 pixels/telescope)

**WCDA:**
3000 cells
(25m$^2$/cell)



# Wide Field of View Cherenkov Telescope (WFCTA)

- **5m$^2$ spherical mirror;**
- **32×32 SiPMs array**
- **Pixel size 0.5° ;**
- **FOV: 14° × 16° .**



SiPM camera

instead of


A prototype of WFCTA

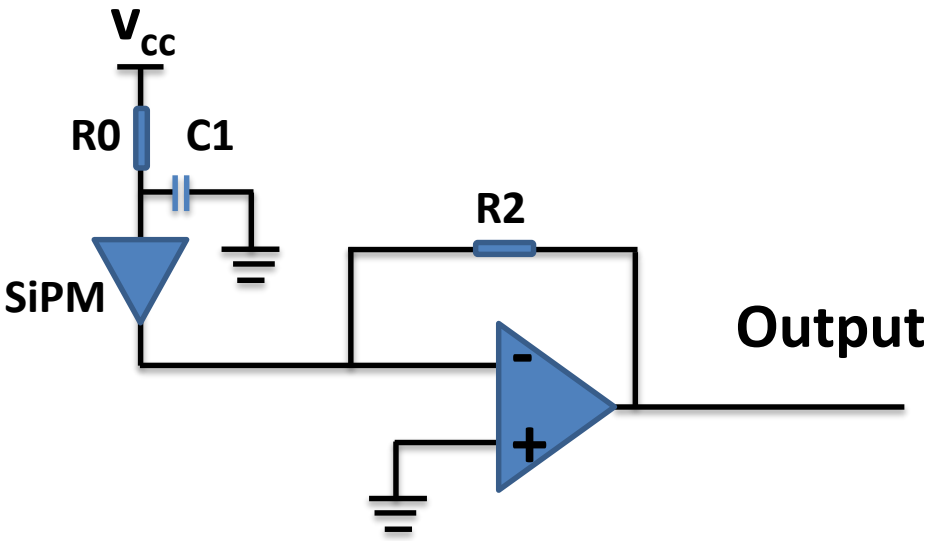
# SiPM 应用的关键点

- 动态范围
- 长光脉冲响应
- 增益–温度补偿回路
- 信噪比

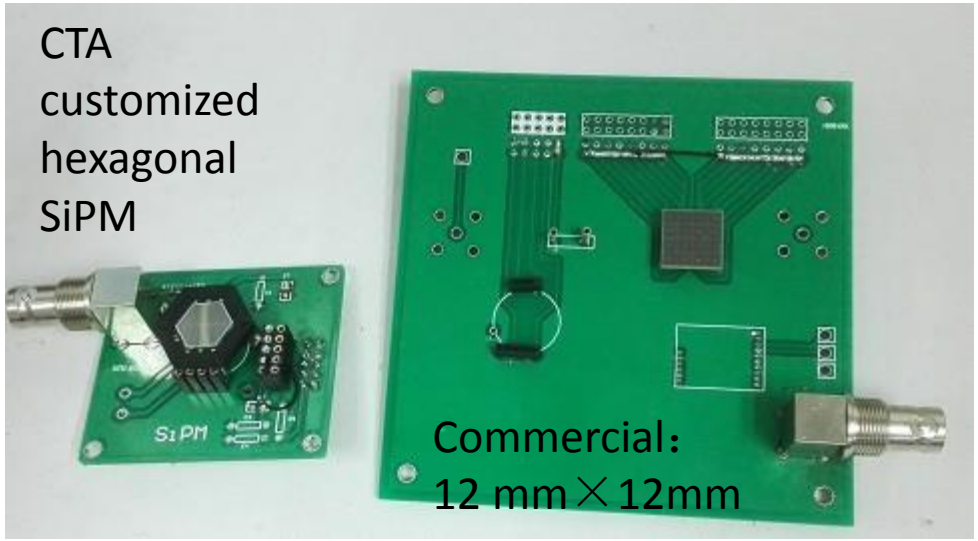
# FBK vs. Hamamatsu

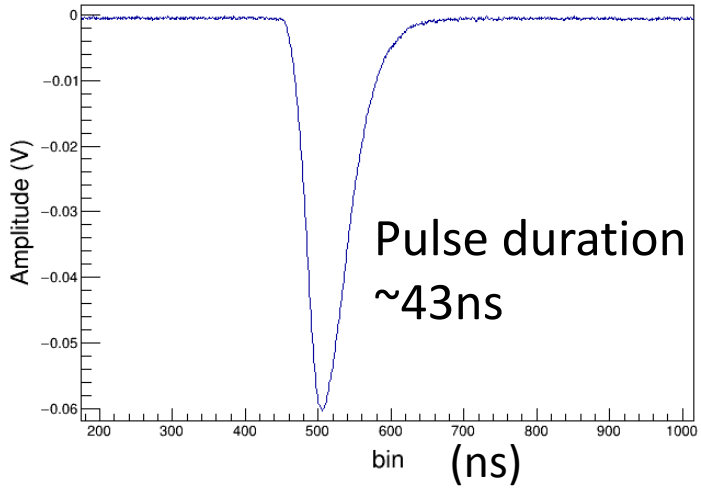
| | FBK (25 μm) | Hamamatsu （25 μm） |
|---|---|---|
| **PDE** | **40%@400 nm** | **23%@400 nm** |
| **Fill factor** | **72%** | **47%** |
| **Dark count rate** | **~80kHz/mm$^2$** | **~50k/mm$^2$** |
| Optical cross talk | ~15% | ~1% |
| Gain | ~2×10$^6$ | ~0.7×10$^6$ |
| Break down voltage | ~26.5V | ~53V |
| Gain vs. temperature | ~1.5%/℃ | ~1.5%/℃ |
| Break down voltage vs. temperature | ~26 mv/℃ | ~54 mv/℃ |

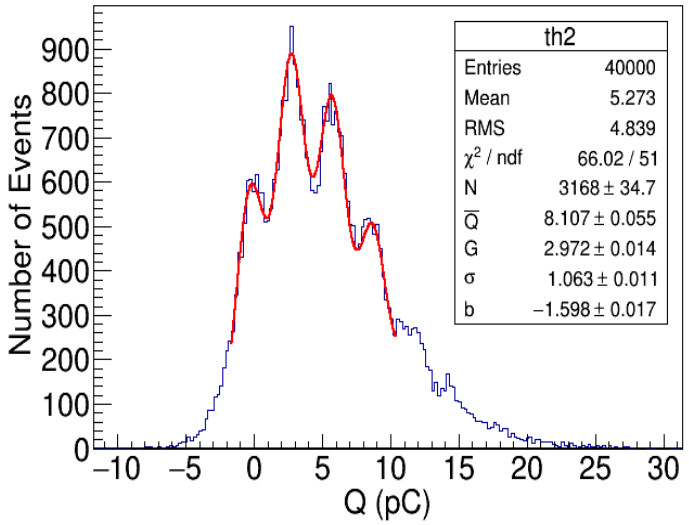
# HAMAMASTU



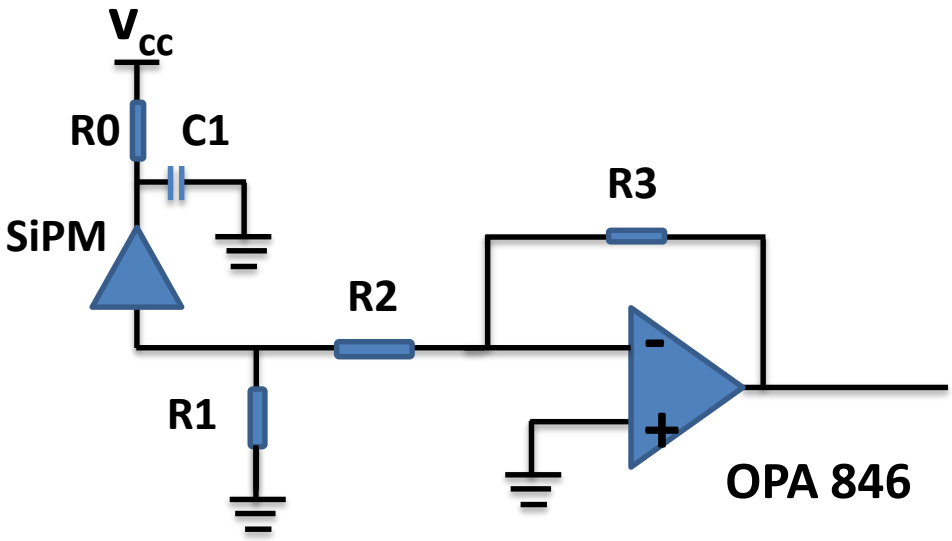

SiPM testing board

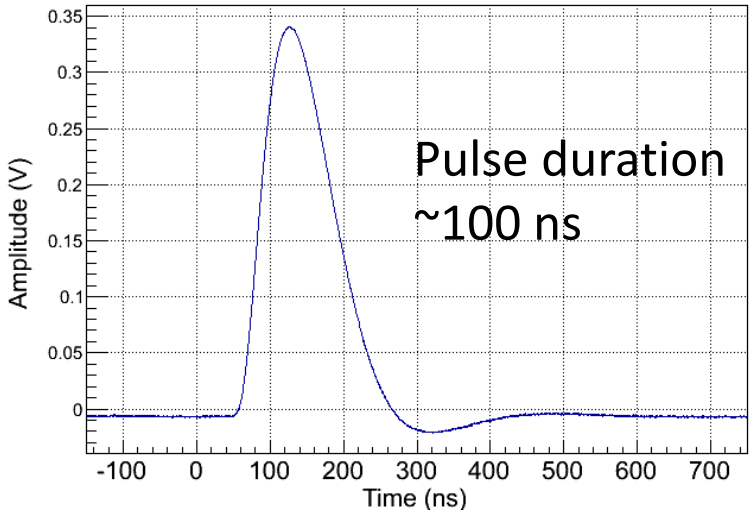


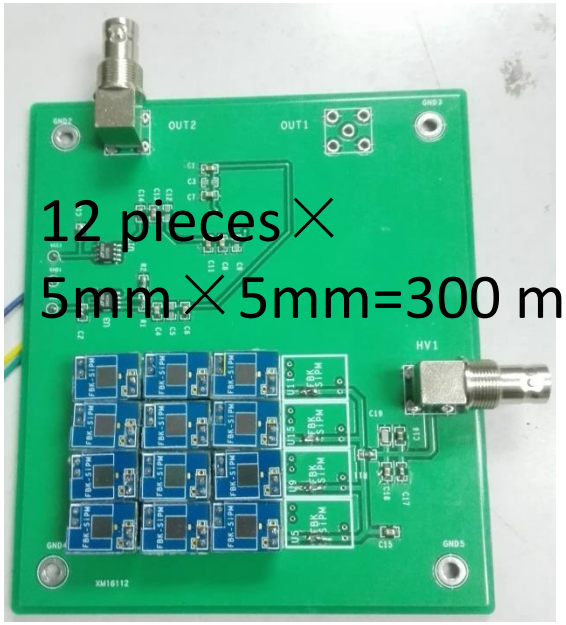



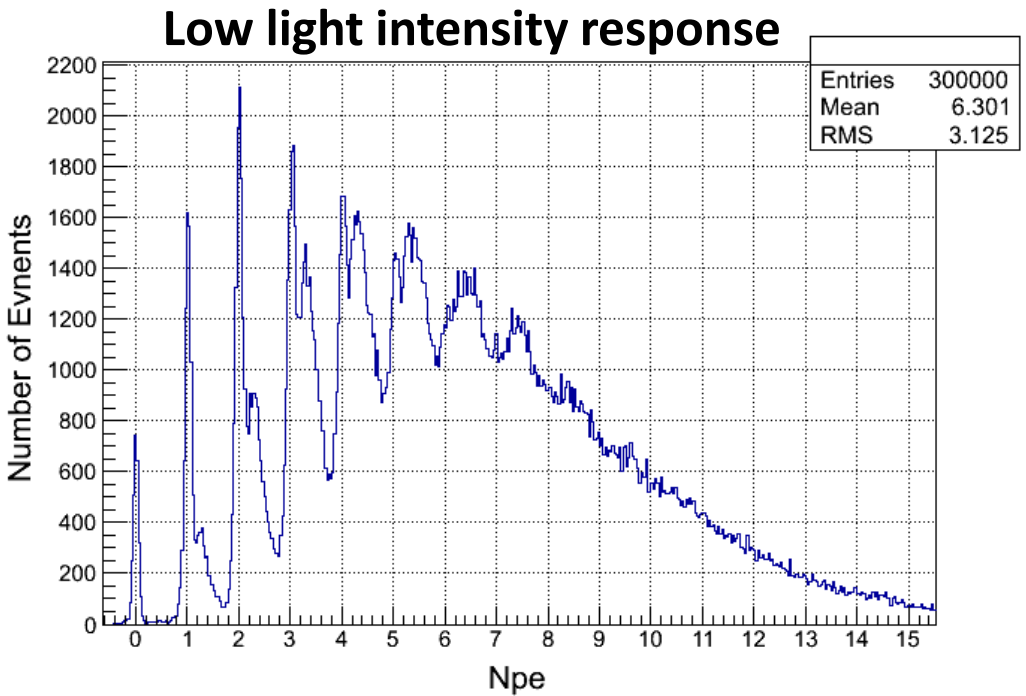

**Low light intensity response**



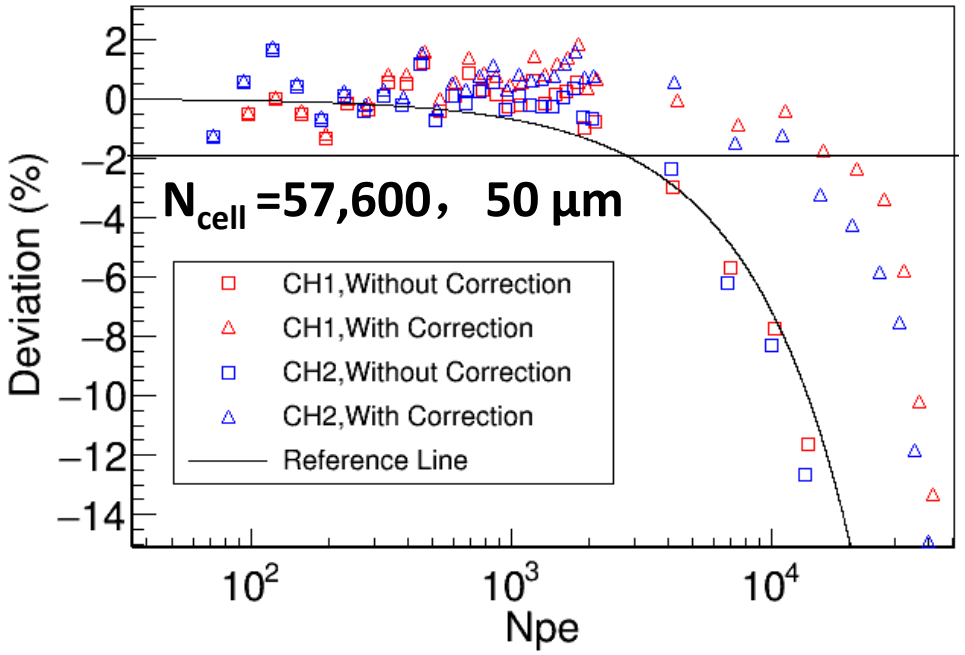



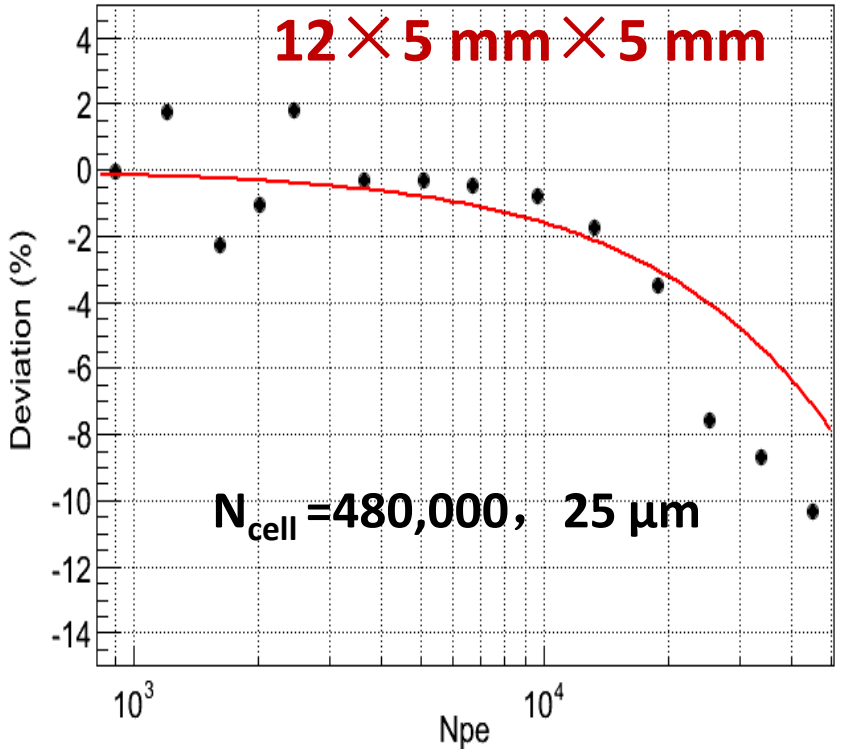

SiPM & pre-amplifier board



## HAMAMASTU: 12 mm ×12 mm




## FBK: 25mu
## 12×5 mm×5 mm

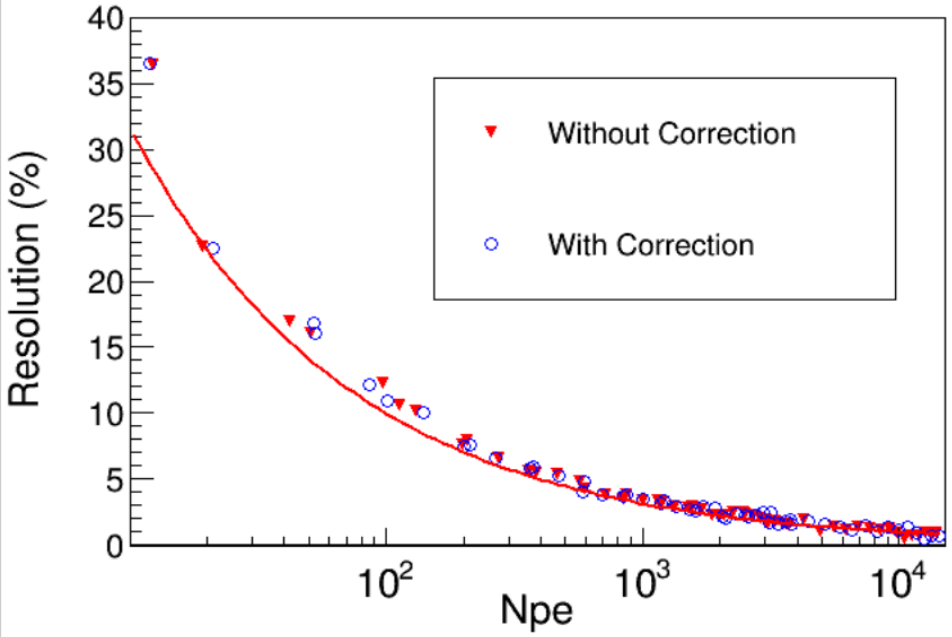


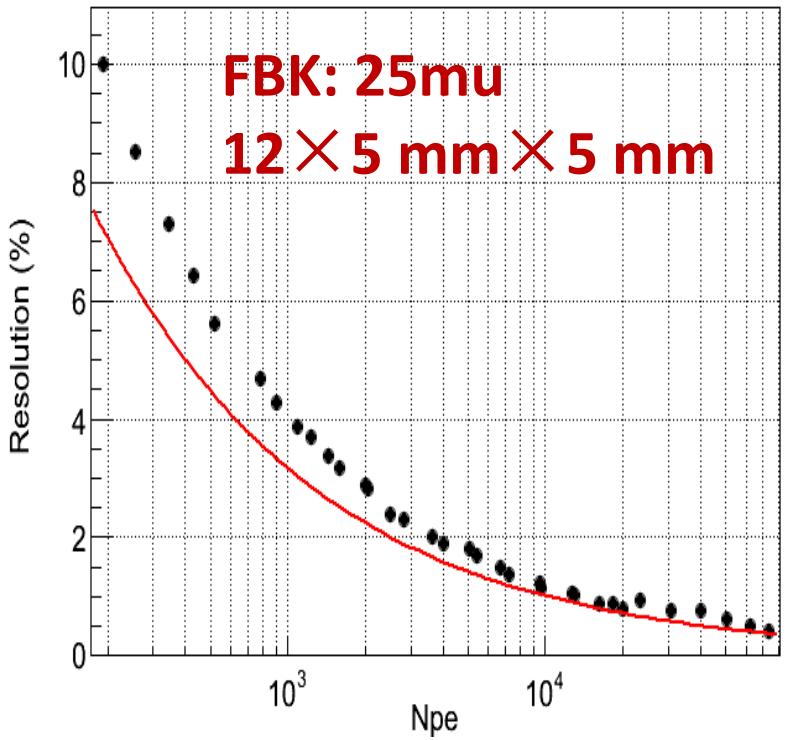

- The dynamic range of the SiPM is proportional to the total number of cells.
  - At least 200,000 cells is required for 32,000 pe.
  - Larger area SiPM has a bigger DCR.
  - The small cell pitch: will produce small fill factor and then small PDE.

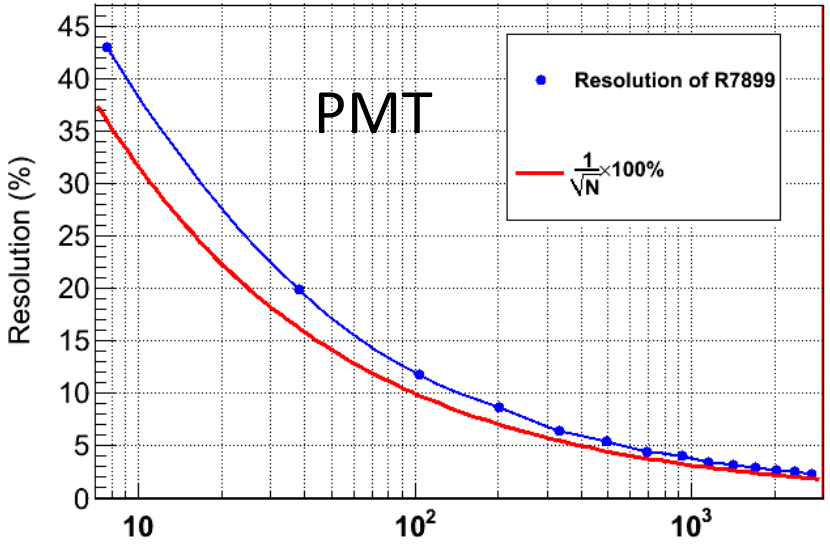
$$N_{pe}^{m} = N_{cell}(1-e^{-N_{pe}^{\exp}/N_{cell}}) \quad N_{\text{cell}}\ ? \quad N_{pe}^{\exp} \Rightarrow N_{pe}^{m}\ ; \quad N_{pe}^{\exp}$$

$$Deviation = \frac{N_{pe}^{m} - N_{pe}^{\exp}}{N_{pe}^{\exp}}$$

## HAMAMASTU: 12 mm ×12 mm

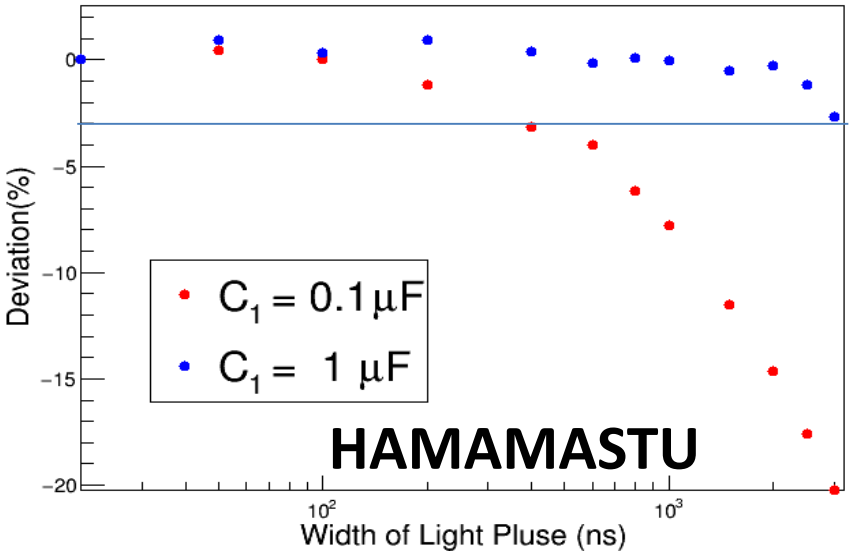


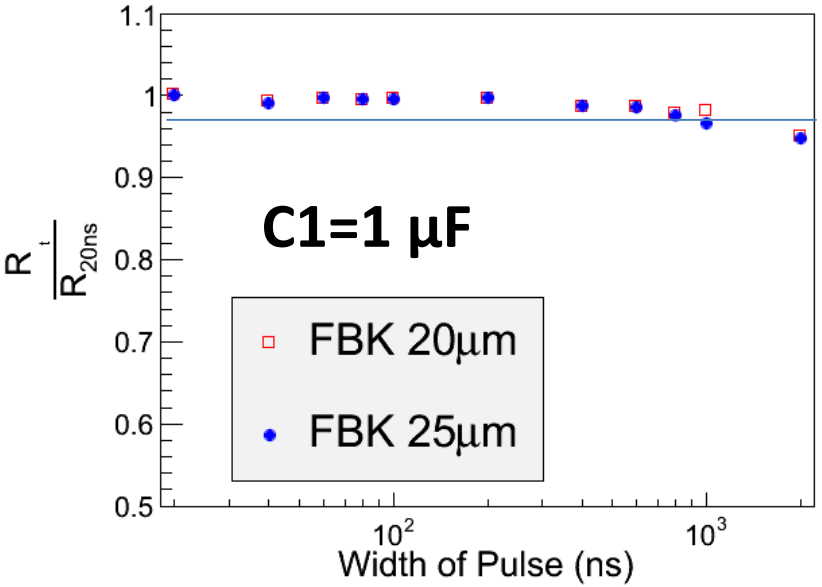



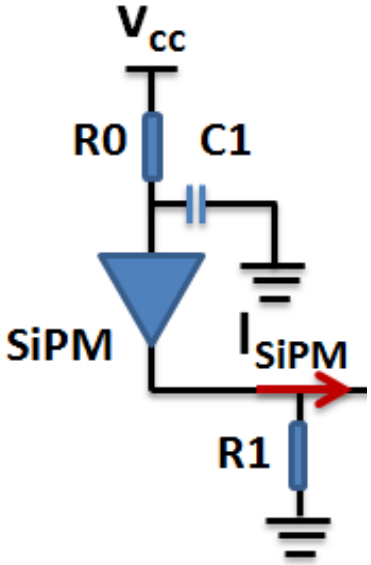



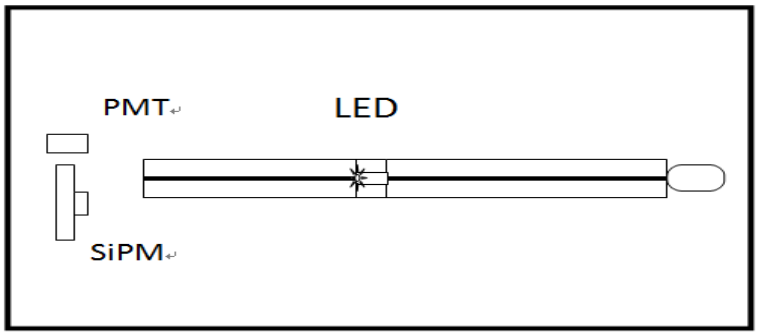

- Charge resolution:
  - SiPM: 12-13%@100pe, 4%@1000pe
  - PMT: 12%@100pe, 4%@1000pe

# The long light pulse response

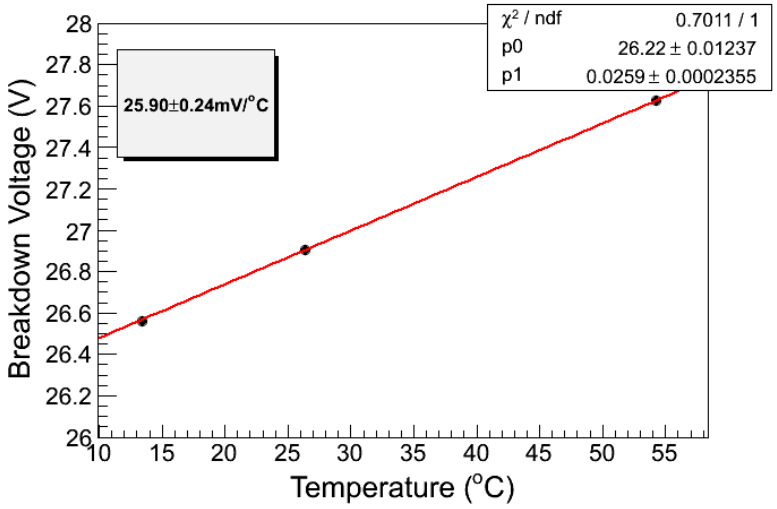


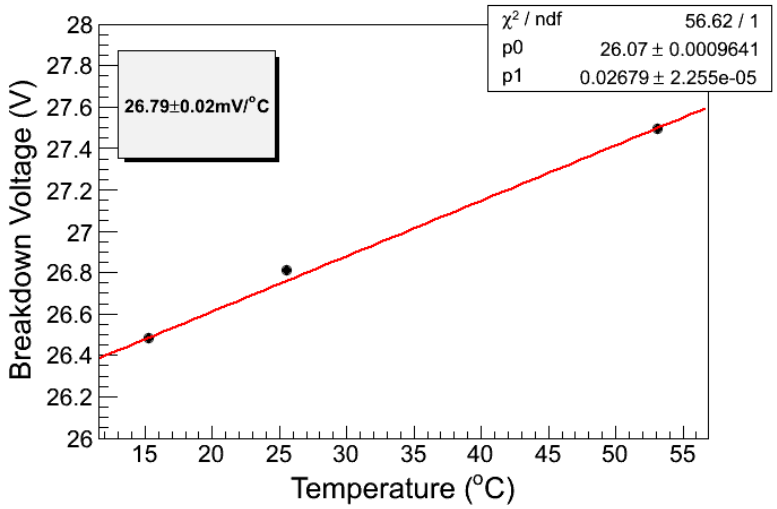



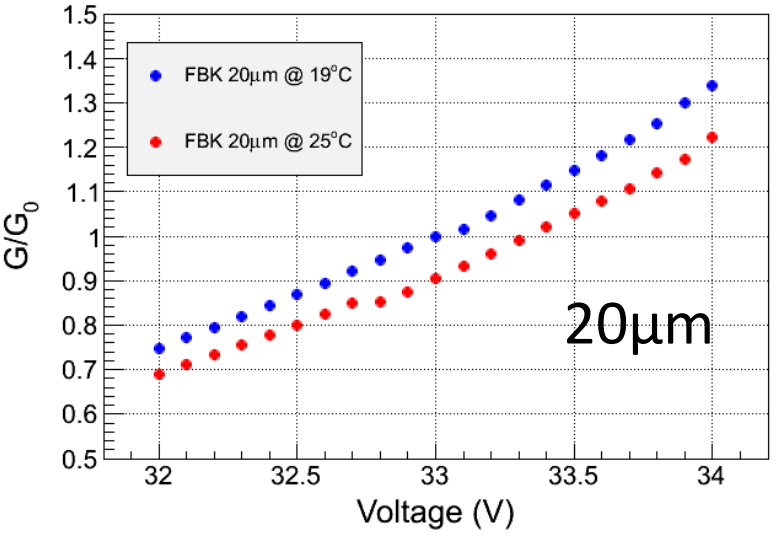



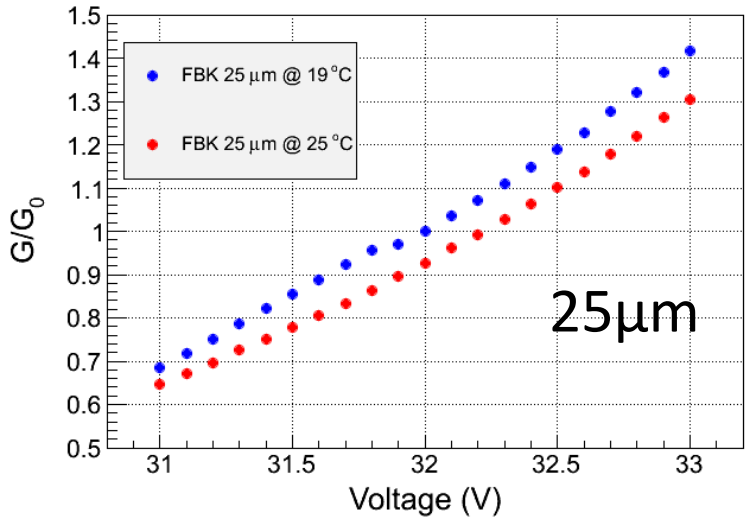




➢ The relative deviation is less than 3% with C1=1 μF.



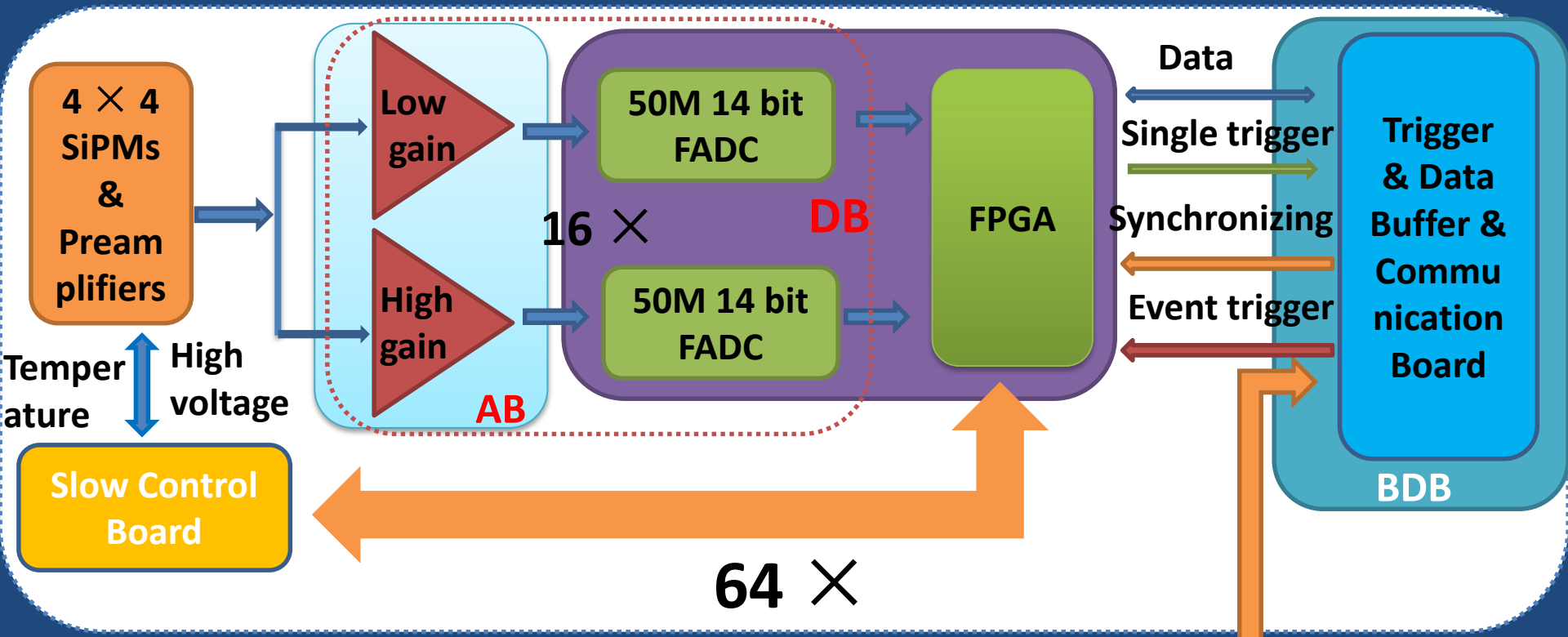




**Breakdown voltage vs. temperature: ~26 mv/℃**

**Gain vs. temperature： ~1.5%/ ℃**




The architecture of SiPM camera readout electronics

Low voltage power supply

TCP/IP

Switch

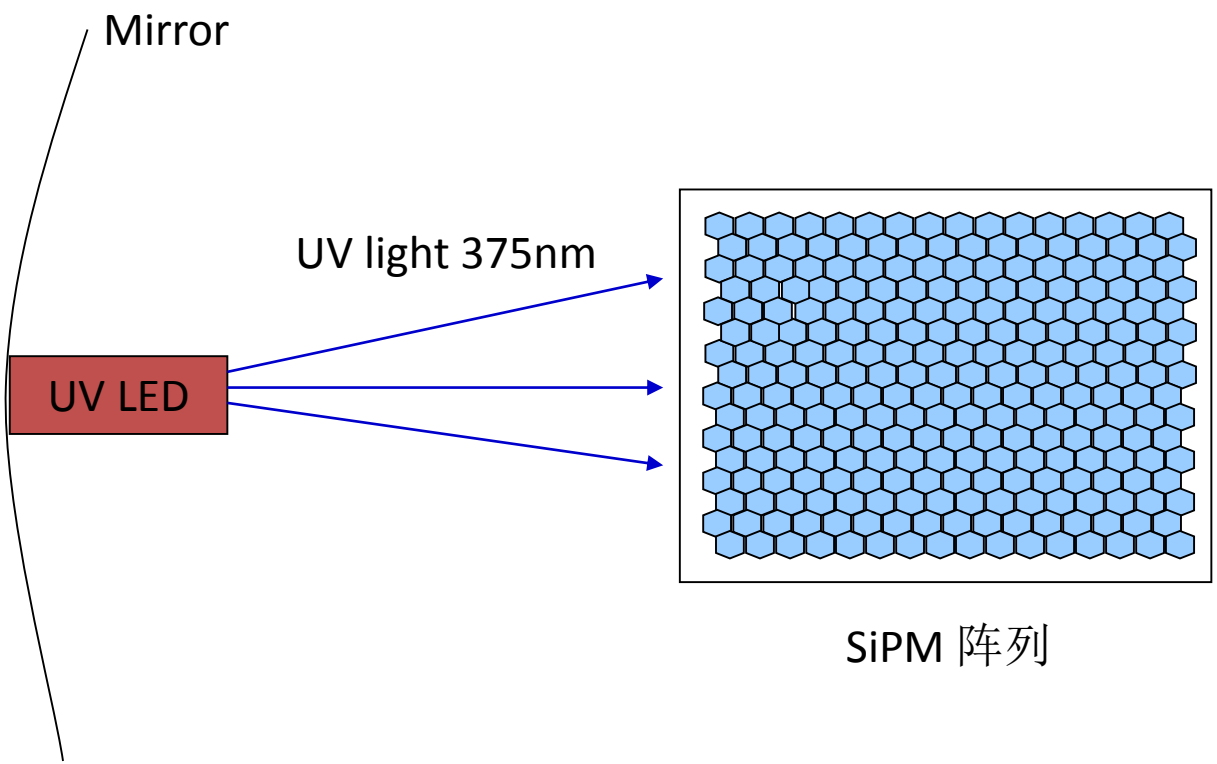
TCP/IP

Service

Slow Control Board: temperature & high voltage compensation loop.

SiPM pulse duration： 20 ns – 50 ns

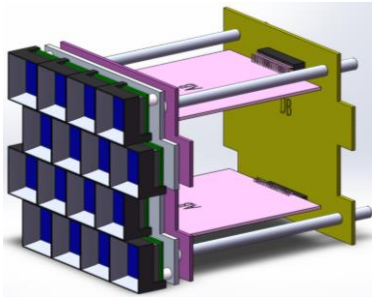
# SiPM阵列增益监测



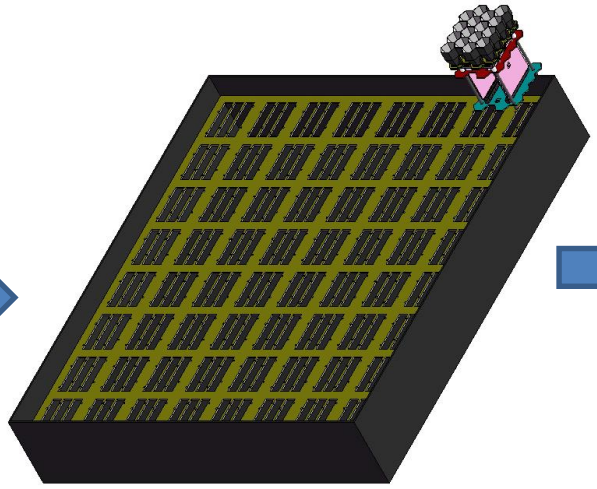

- SiPM增益监测：LED安装在反射镜前，频率1Hz，光强~1000pe
  - 无月亮的晴朗晚上，夜空背景光的典型强度：~50MHz
  - Resolution: $\sigma/1000/\sqrt{N}=\sqrt{\sigma_b^2+\sigma_e^2+\sigma_{SiPM}^2}/1000/\sqrt{N}$
  - 检测精度：<1%@1 minute @ 1000×typical sky background

# Schematic diagram of SiPM camera assembly

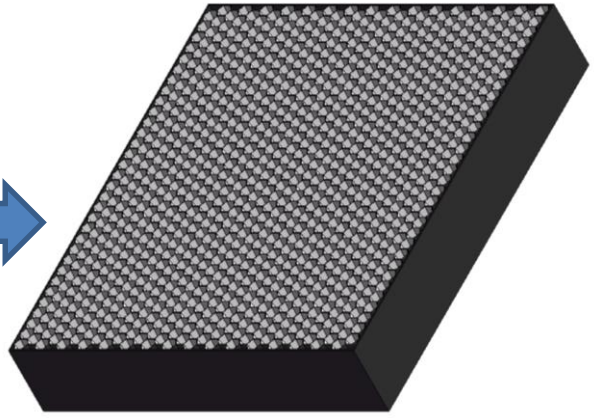
64 ×



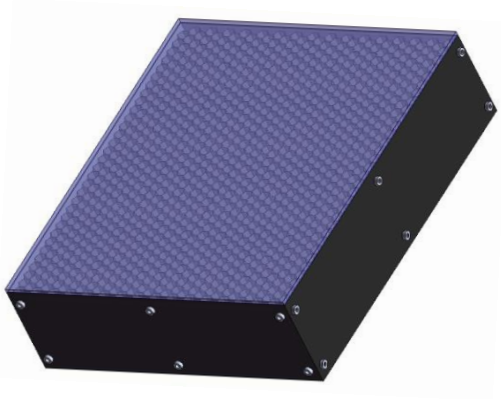
**A module has 4×4 SiPMs.**



SiPM camera box

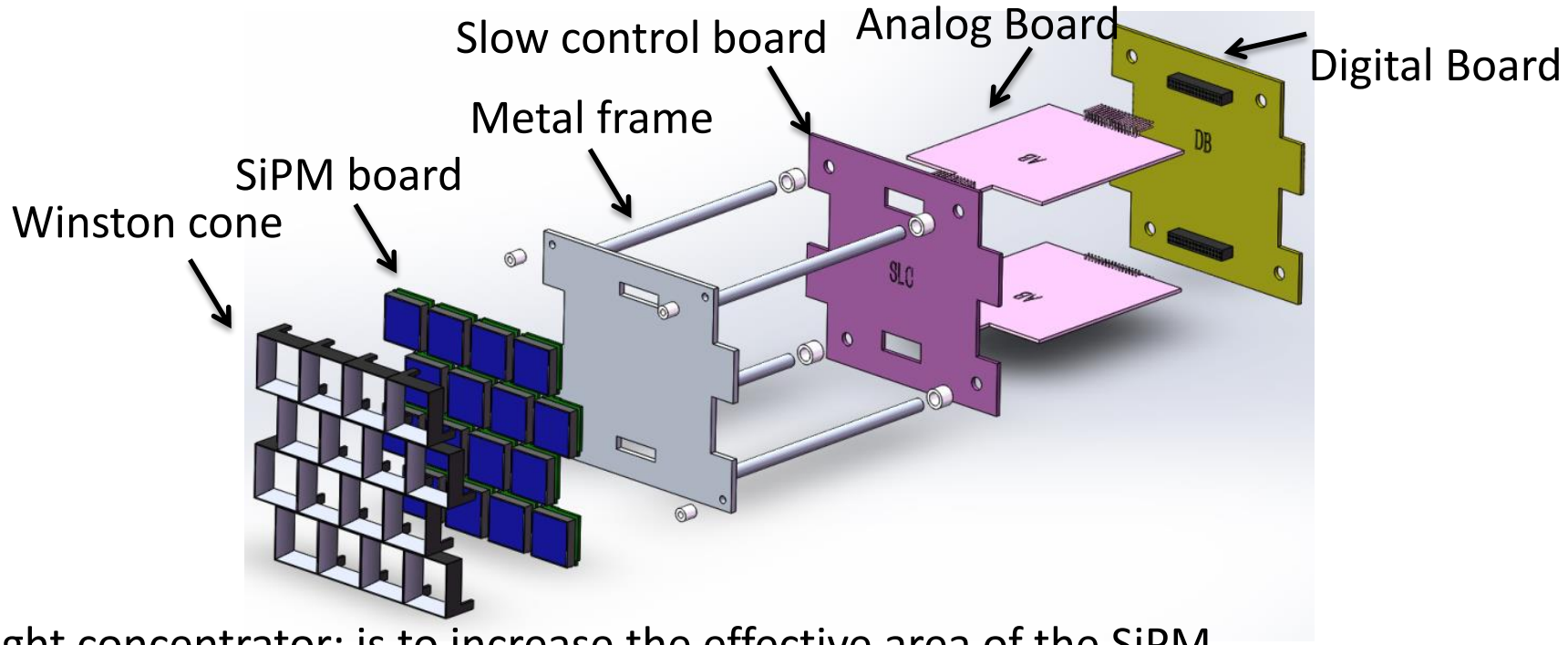


SiPM camera：
32×32 SiPMs

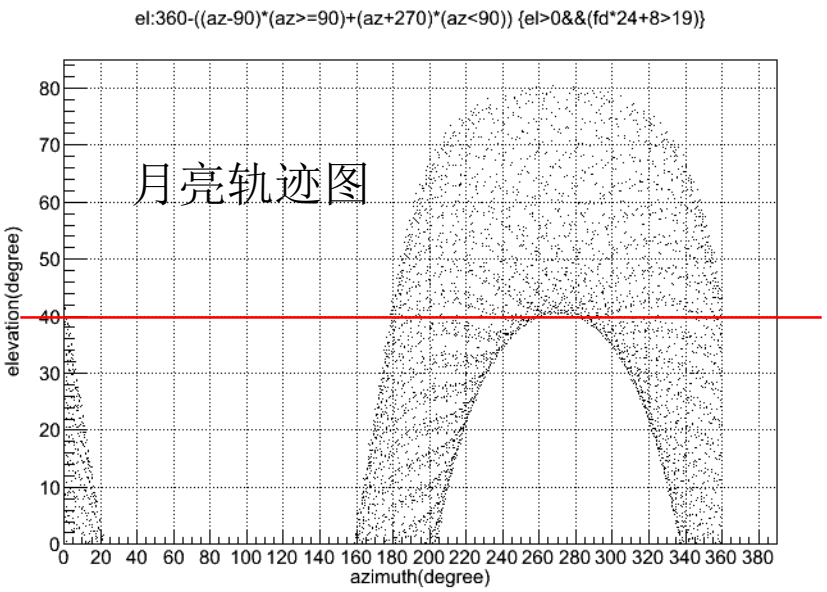


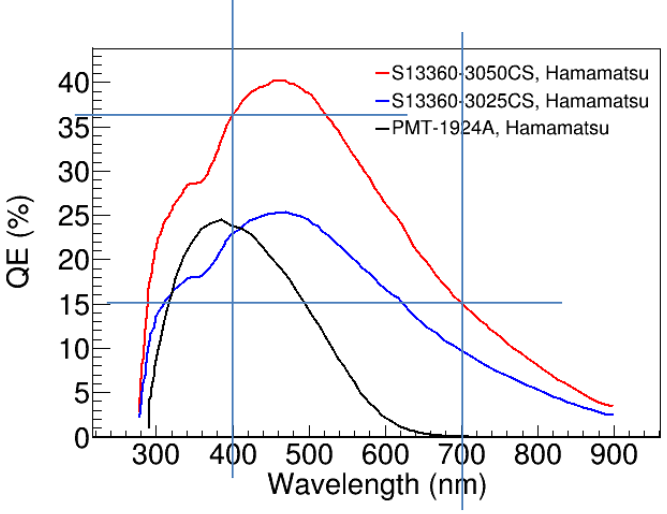
Optical filter

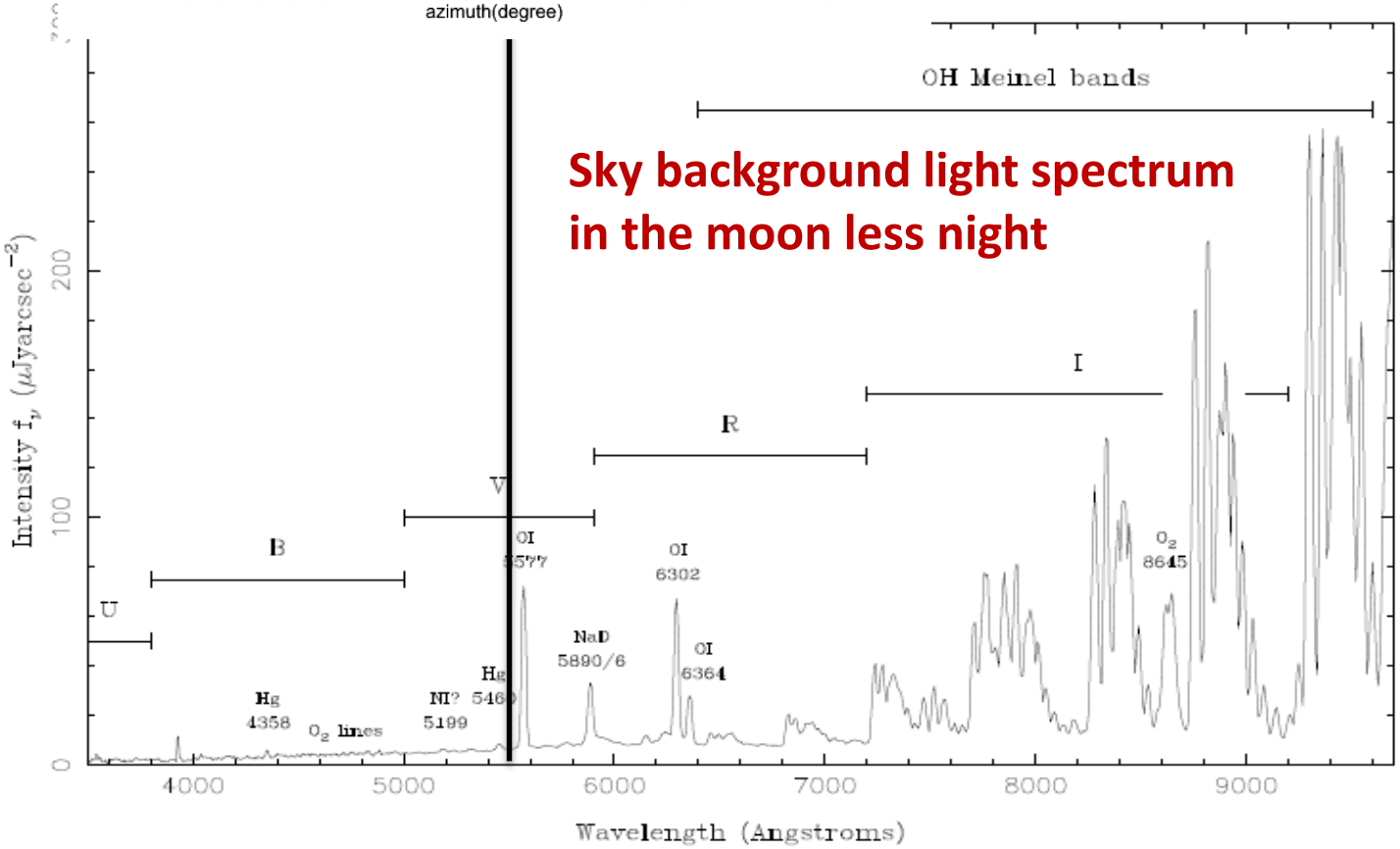
# Square SiPM array： 20 mm×20mm



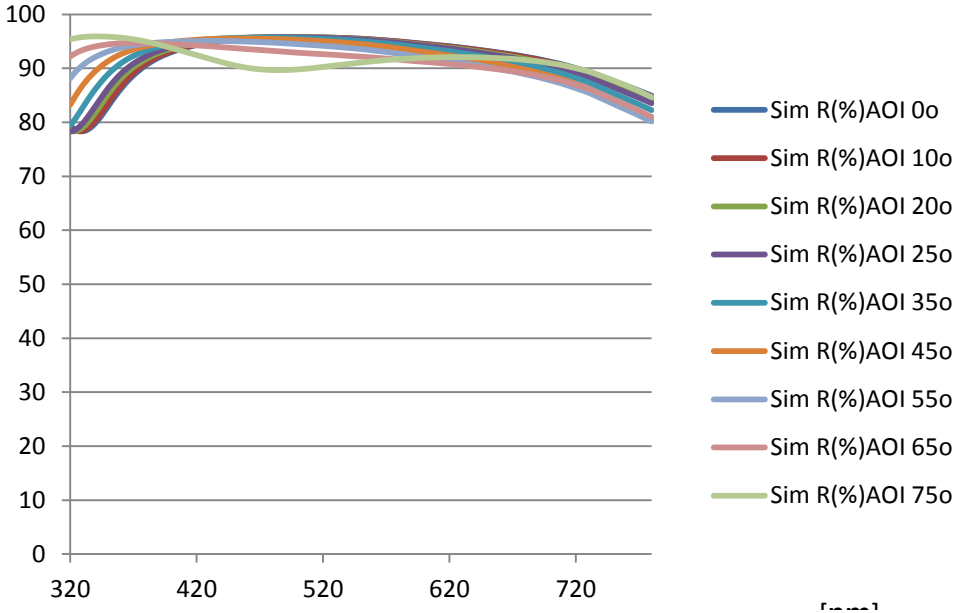

- Light concentrator: is to increase the effective area of the SiPM
- SiPM base board: 16 SiPMs, 16 temperature sensors (embedded in the SiPM chip ), and 16 pre-amplifiers
- Slow control board:
  - 16 temperature and high voltage compensation loops;
  - 16 channels of high voltage power supply.
- Analogue board: 16 channels of amplifier (high gain and low gain) and shaping circuit
- Digital board: 50 MHz FADC and FPGA

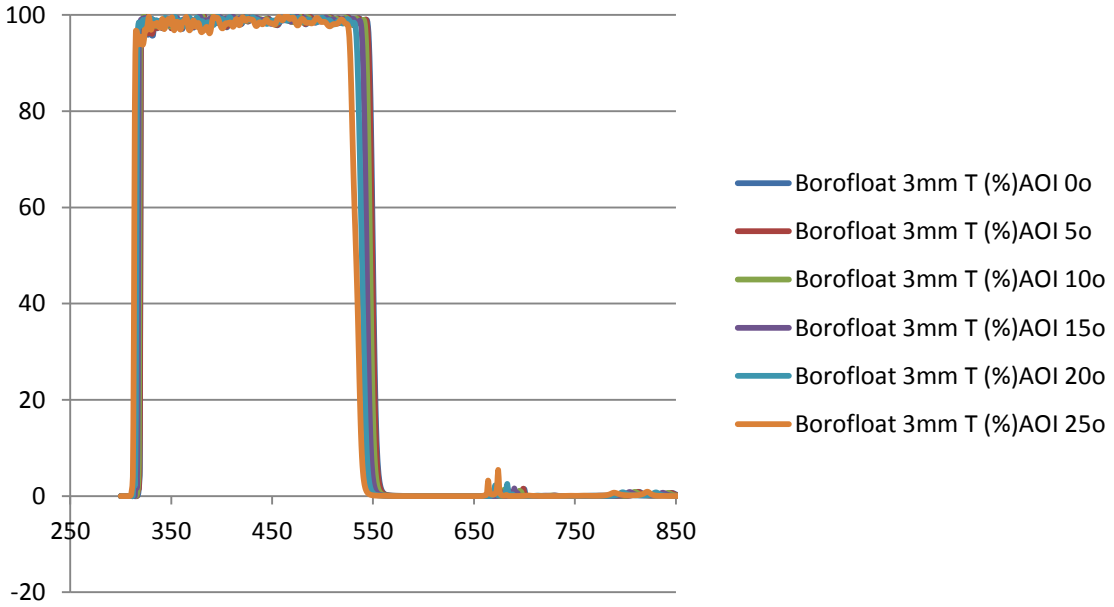

el:360-((az-90)*(az>=90)+(az+270)*(az<90)) {el>0&&(fd*24+8>19)}
月亮轨迹图
elevation(degree)
azimuth(degree)


S13360-3050CS, Hamamatsu
S13360-3025CS, Hamamatsu
PMT-1924A, Hamamatsu
QE (%)
Wavelength (nm)

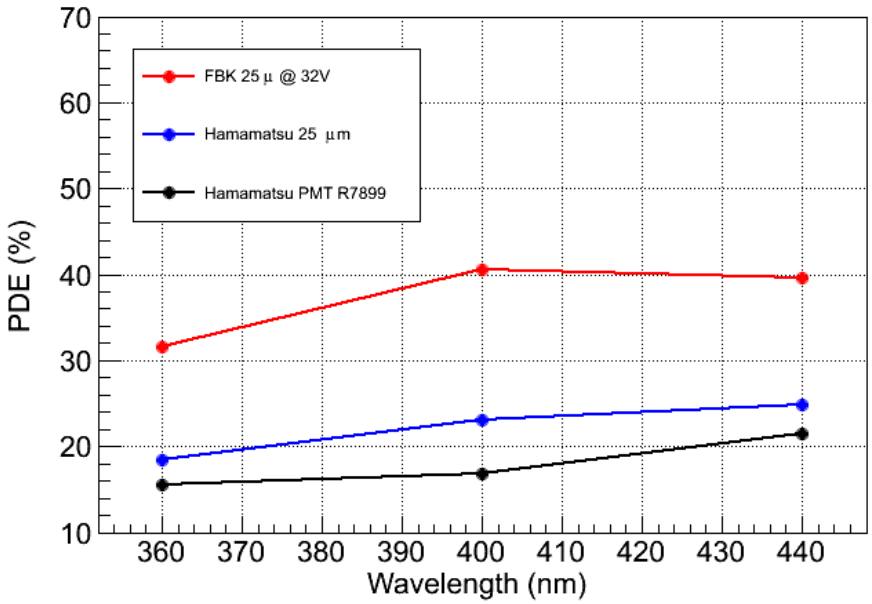

Sky background light spectrum
in the moon less night
OH Meinel bands
U
B
V
R
I
Hg 4358
O2 lines
NI? 5199
Hg 5461
OI 5577
NaD 5890/6
OI 6302
OI 6364
O2 8645
Intensity fν (μJyarcsec−2)
Wavelength (Angstroms)

Data from Geneva University group



# Relative PDE




$$\frac{Signal}{Noise} = \frac{N_s^{ph} \bullet PDE}{\sqrt{N_{BG}^{ph} \bullet PDE + N_{DCR}^{pe}}}$$

$$\frac{S/N(20\times 20)}{S/N(Hexagonal)} = 1.18$$

$$\frac{S/N(20\times 20)}{S/N(PMT)} = 1.35$$

| | FBK: 20×20 mm² | Hamamatsu: Hexagonal | PMT |
|---|---|---|---|
| Relative PDE | 40%@400 nm | 23%@400 nm | 16%@400 nm |
| Dark count rate | 32 MHz | 7MHz | ~kHz |
| Sky background noise | ~50 MHz | ~30 MHz | ~20 MHz |

# 总结和讨论

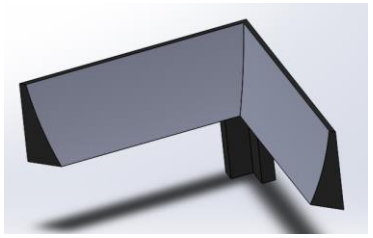
- SiPM的性能能够满足LHAASO-WFCTA的要求
  - 有效观测时间增加到30%（PMT：10%）；
  - SiPM还具有高光探测效率（25% - 50%）、光子计数、低偏置电压（几十伏）和对磁场不敏感等优点；
  - 低成本：价格约是PMT价格的一半；
  - 在常温下（~20°）：信噪比、电荷分辨率等和PMT方案相当。
- SiPM技术是下一代大气成像契伦科夫望远镜和荧光探测器的发展方向之一。
- 下一步工作计划：4月底之前完成WFCTA-SiPM成像探头定型。

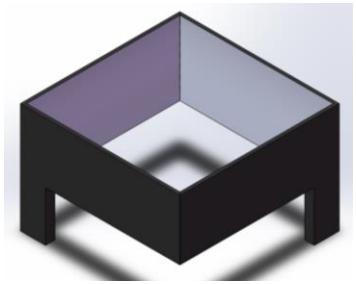
*Thank you for your attention!*

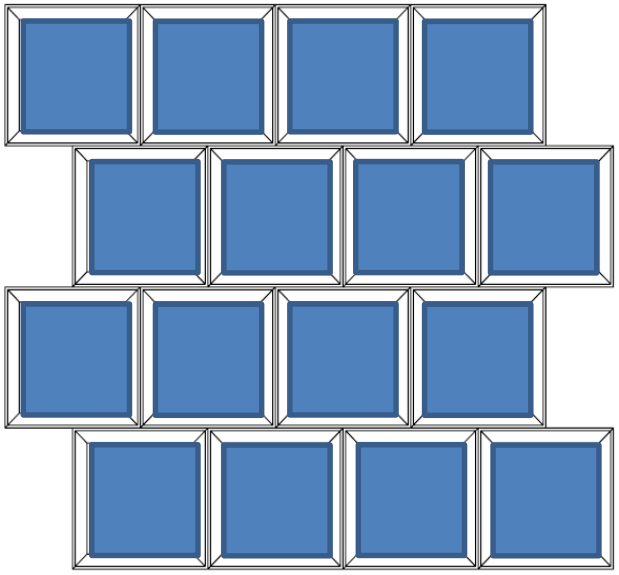
# Three proposals of SiPM array

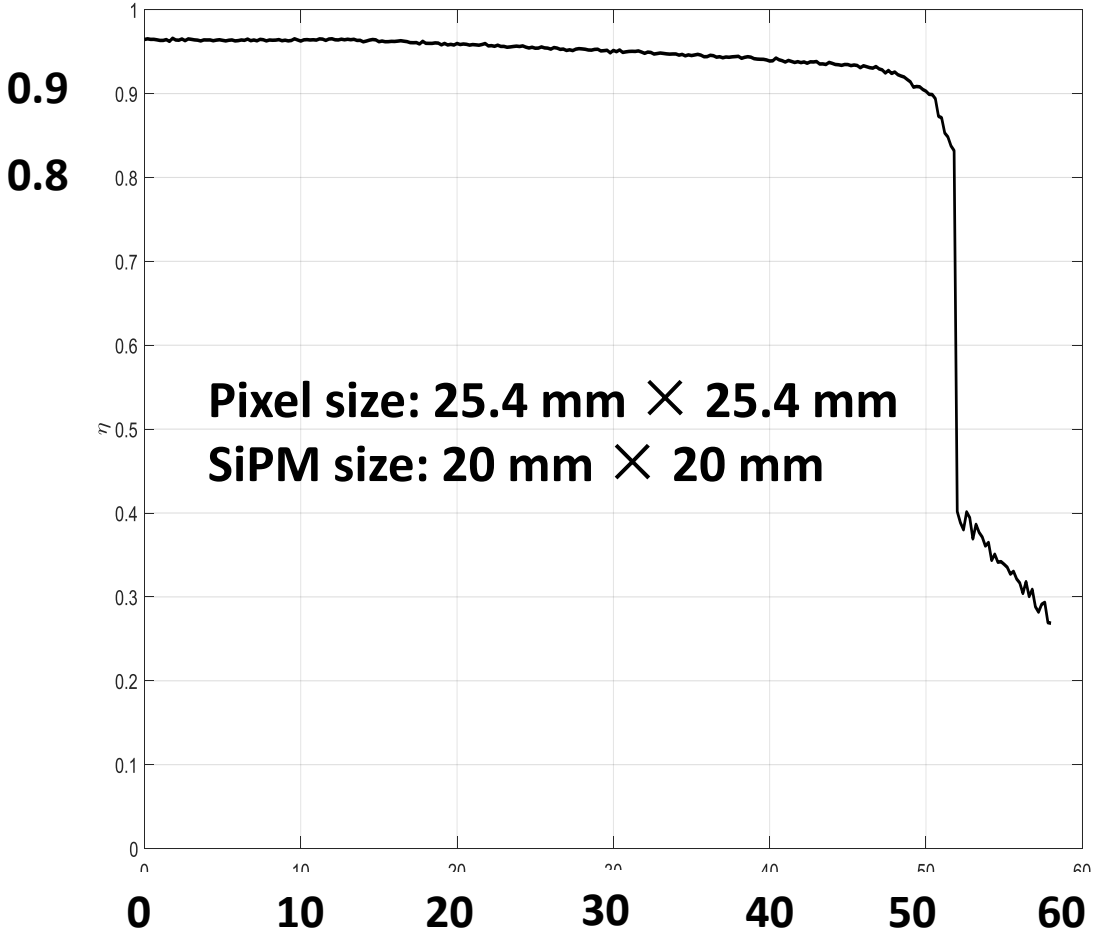
| | Square SiPM 20mm×20mm | Hexagonal（side length=7.2mm） | Square SiPM 12mm×12mm |
|---|---|---|---|
| **SiPM** | **Collaboration with INFN (FBK)** | **Hamamatsu（customized）** | **Hamamatsu（commercial）** |
| **PDE** | **40%@400 nm** | **23%@400 nm** | **23%@400 nm** |
| **Fill factor** | **72%** | **47%** | **47%** |
| **Inlet to outlet ratio of Winston cone** | **1.49** | **4.42** | **4.13** |
| Cell size | 25μm | 25μm | 25μm |
| SiPM area | 400 $mm^2$ | 134.7 $mm^2$ | 144 $mm^2$ |
| Relative deviation | 4%@32000pe | 4%@32000pe | 5%@32000pe |
| Charge resolution | 13%@100pe | 12%@100pe | 12%@100pe |
| **Dark count rate** | **32 MHz** | **7MHz** | **7.2MHz** |
| Sky background noise | **~50 MHz** | **~30 MHz** | **~30 MHz** |

# Square SiPM array： 20 mm×20mm







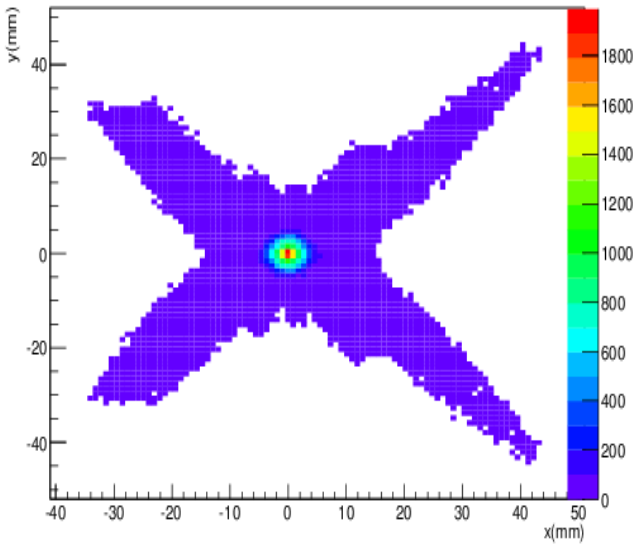



EXIT： 20mm×20mm

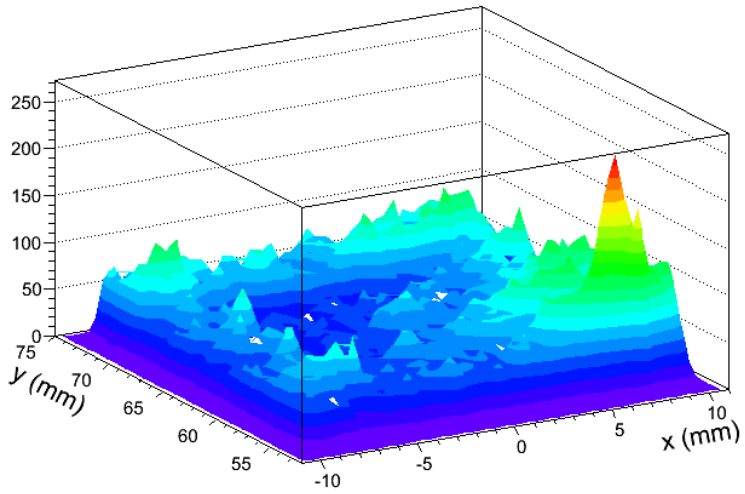
ENTRANCE:24.4mm×24.4mm

HEIGHT:9.6mm

Light spot from the reflective mirror

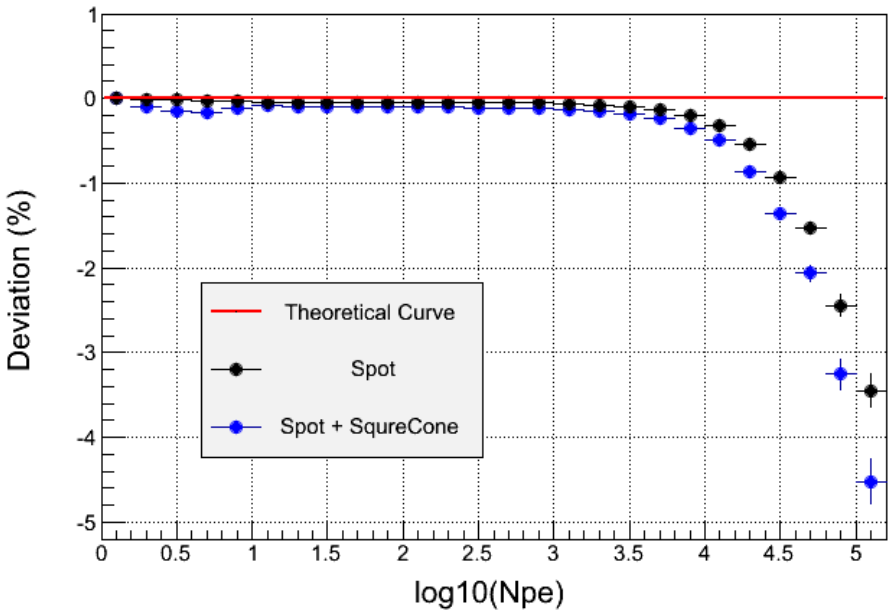



Light distribution output from the cone




➢ Estimate the non-linearity from the nonuniform light distribution cause by the light spot and the light concentrators

$$N_{pe}^{m} = N_{cell}(1-e^{-N_{pe}^{\exp}/N_{cell}})$$

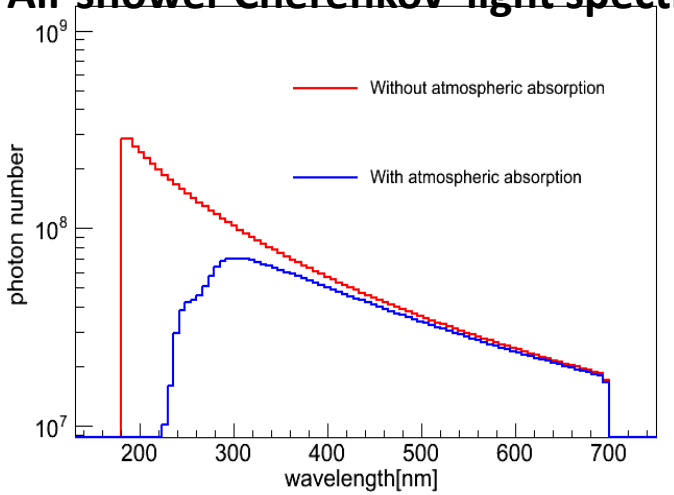


| | SiPM | PMT |
|---|---|---|
| Dynamic range | Proportional to total number of APD cells | Dependent on PMT type, HV distribution and readout method |
| Photon counting | Yes | No |
| Charge resolution | 12-13%@100pe，4%@1000pe | 12%@100pe, 4%@1000pe |
| Pulse duration | 20 - 50 ns | ~6 ns |
| Dark count rate | 80 kHz/1 $mm^2$ @ thrd=0.5 pe | <1kHz @ thrd=0.5 pe |
| Aging | No aging | Aging |
| Magnetic fields | No sensitive | Sensitive |
| Gain | $1\times10^6$ @ several tens volts | $1\times10^6$ @ >1000 V |
| Temperature | ~1.5%/℃ | ~0.2%/℃ |
| Optical cross talk | 3% - 15% | No |

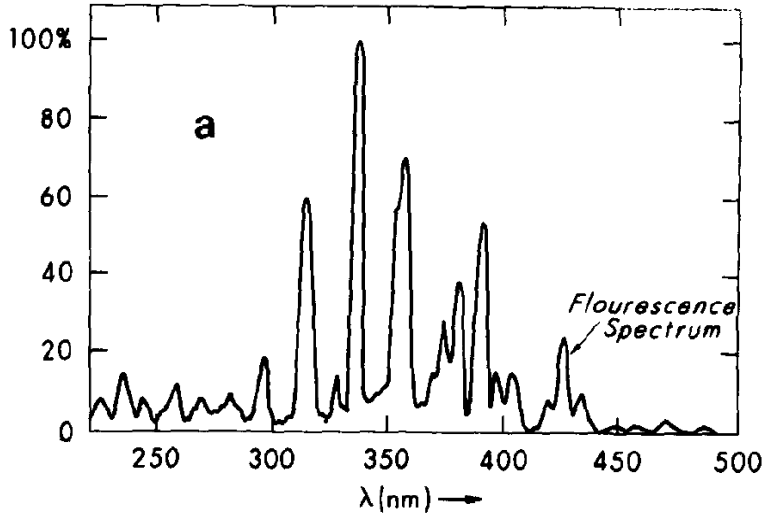
# LHAASO-WFCTA vs. CTA

| | CTA-SSTs | LHAASO-WFCTA |
|---|---|---|
| Energy range | 5 TeV – 300 TeV | 30 TeV – 1 EeV (Cherenkov mode: 30TeV – 10 PeV, 10PeV-100PeV; Fluorescence mode: > 100PeV) |
| Diameter of mirror | ~ 4 m | ~ 2.3 m |
| Pixel size | ~ 0.25 | ~ 0.5 |
| FoV | 9° ×9° | 16° ×16° |
| Dynamic range | 1 pe - 2000 pe | 10 pe – 32000 pe |
| Light pulse duration | 6 ns - 50 ns | 6 ns - 3 μs |
| Observation mode | Cherenkov light | Cherenkov and Fluorescence light |

**Air shower Cherenkov light spectrum**

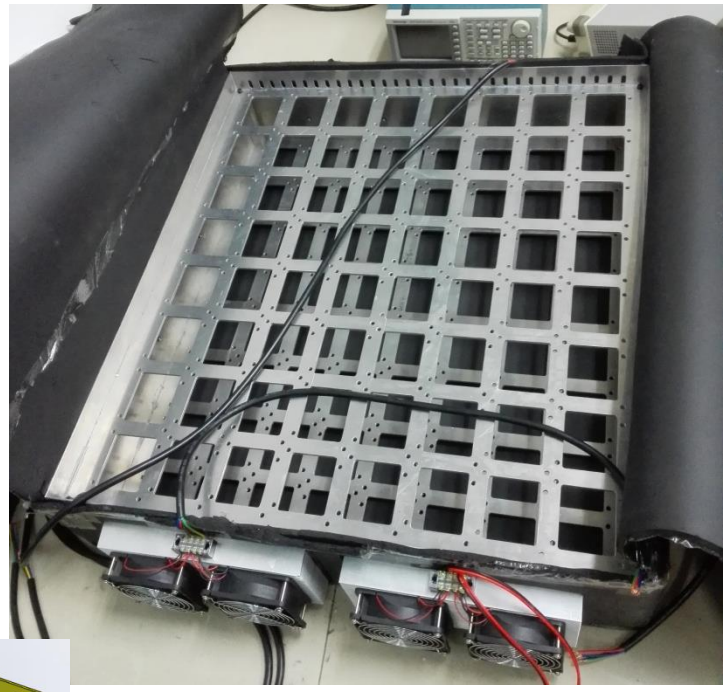



**Fluorescence light spectrum**

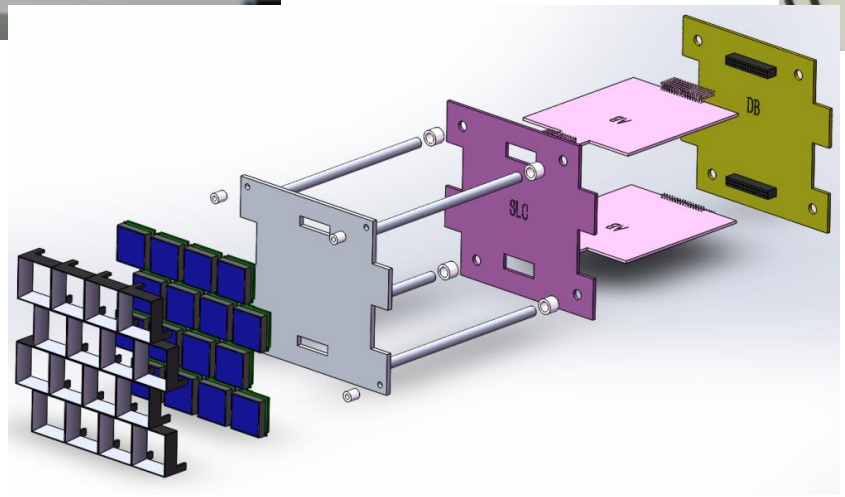


# Cooling System

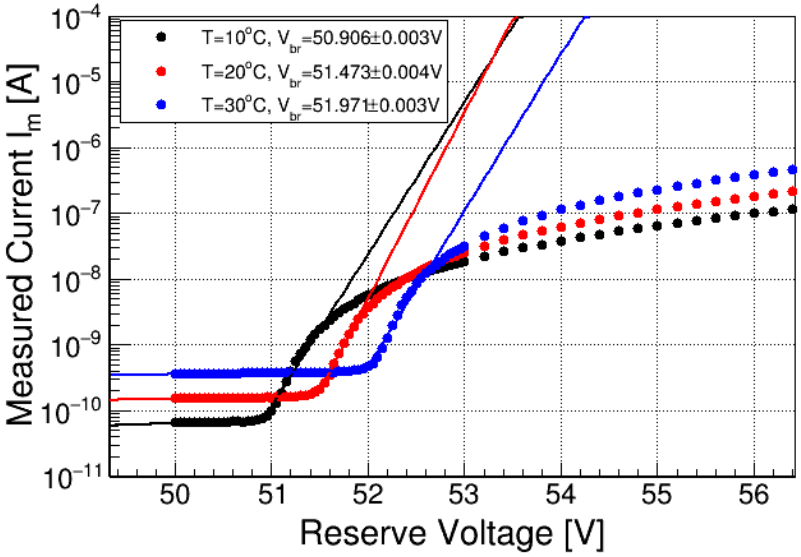
Aluminum alloy framework

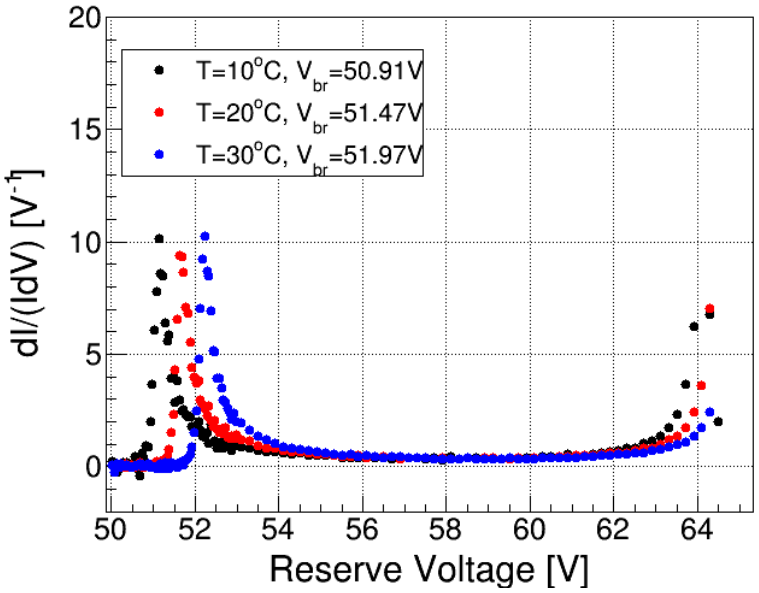


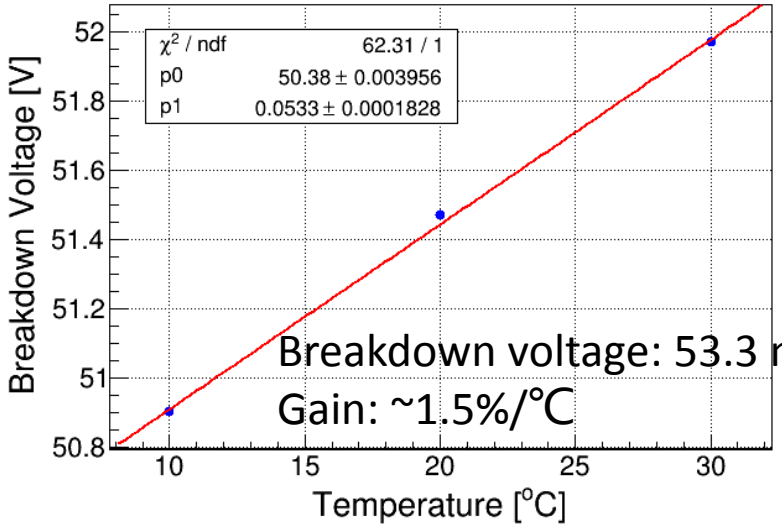
Refrigeration semi-conductor



# I-V curve for breakdown voltage and quenching resistor

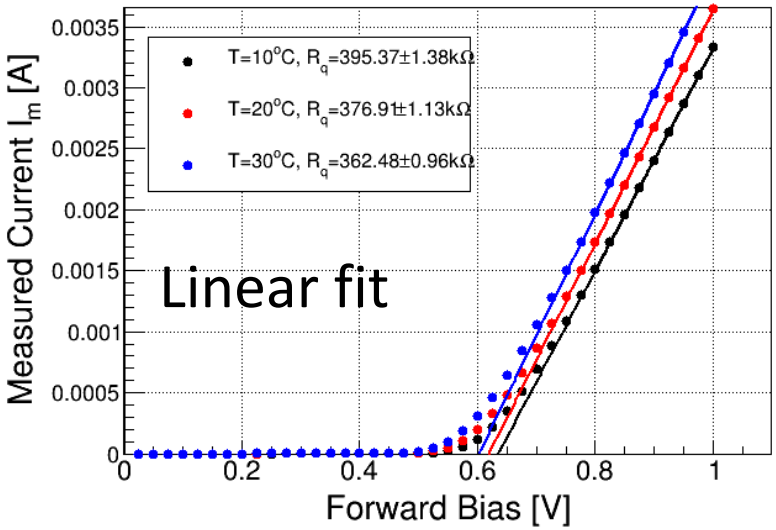


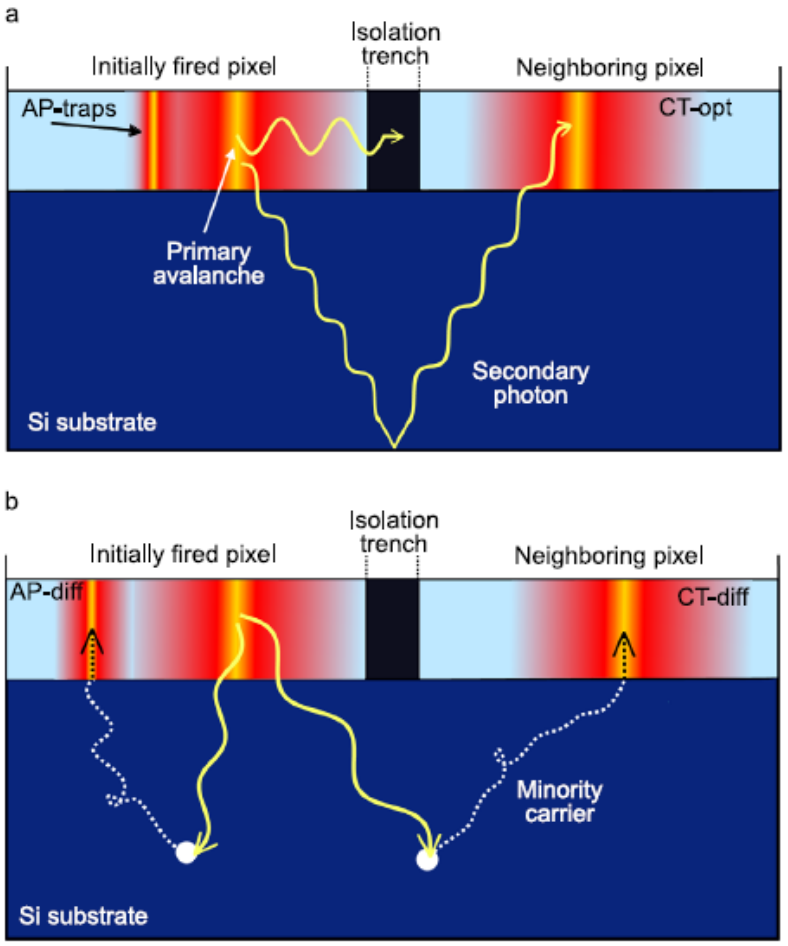




Breakdown voltage: 53.3 mv/℃

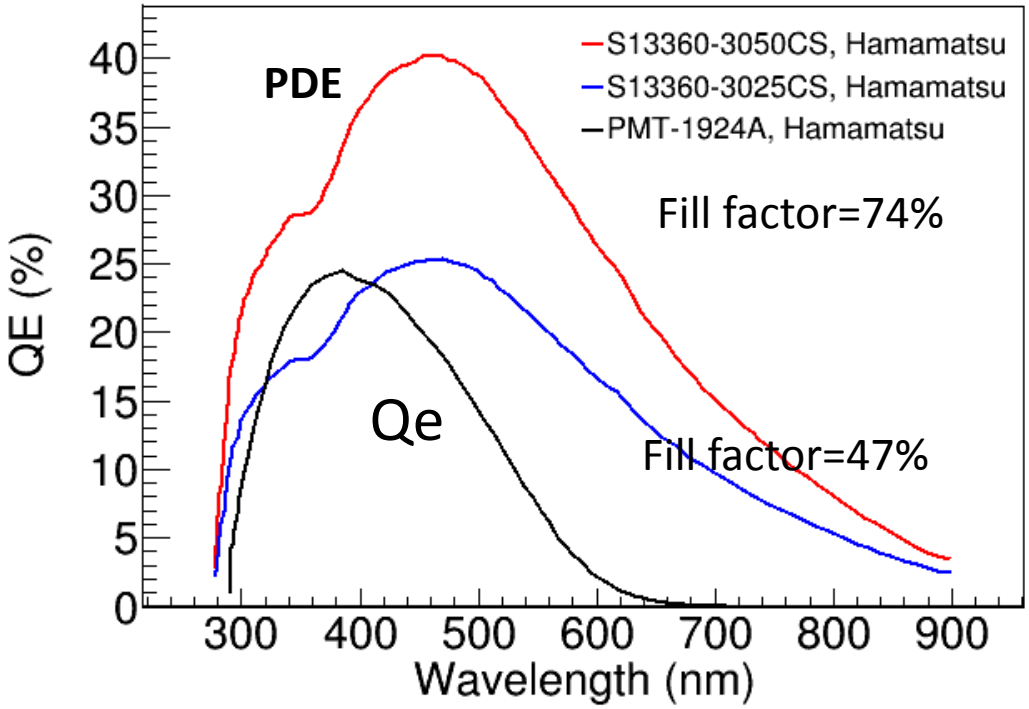
Gain: ~1.5%/℃



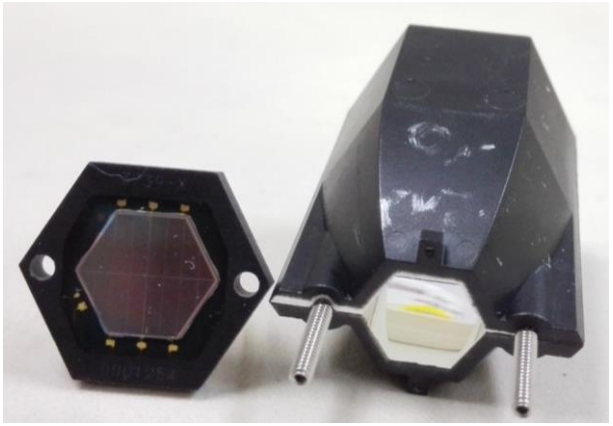
# Optical Cross talk & After pulse

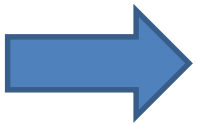


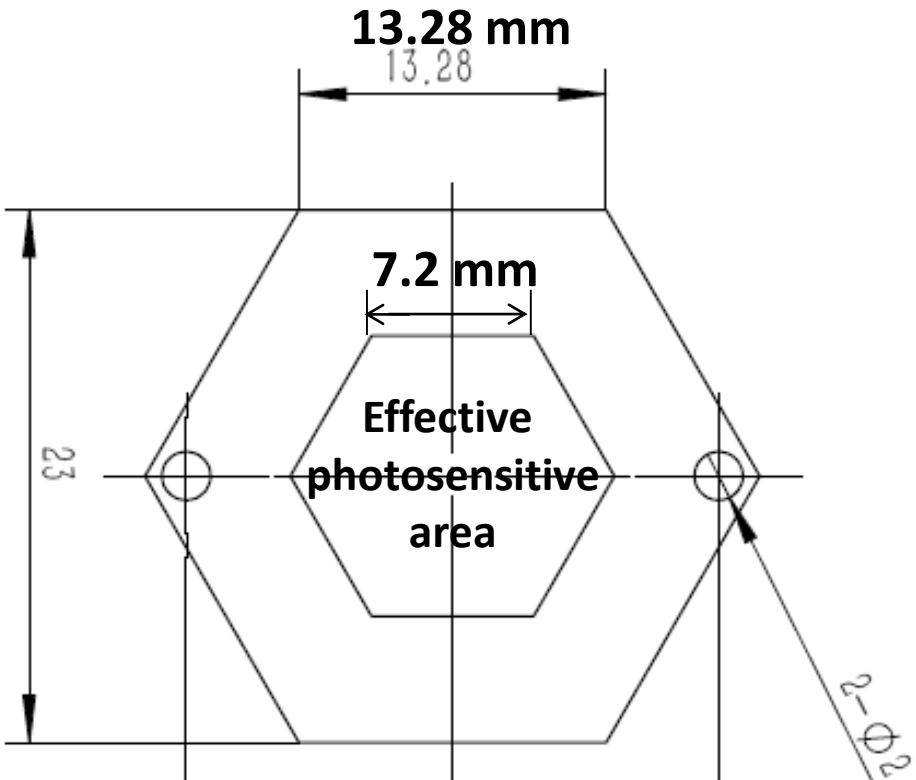

PDE=Qe(APD) × fill factor



# Hexagonal SiPM array

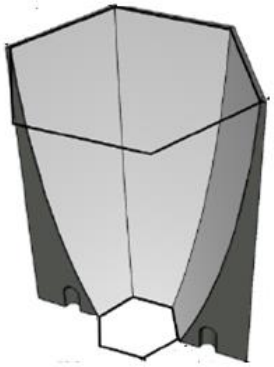




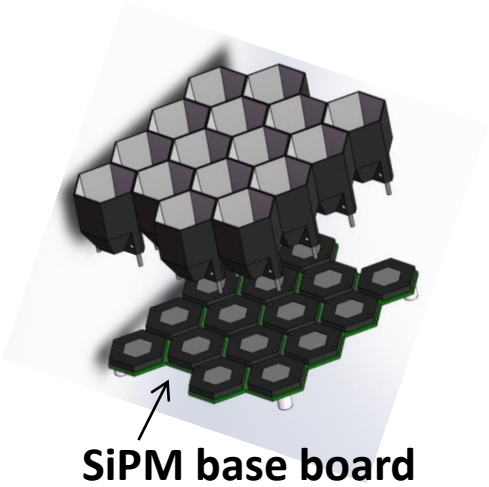


# Schematic diagram of SiPM camera assembly

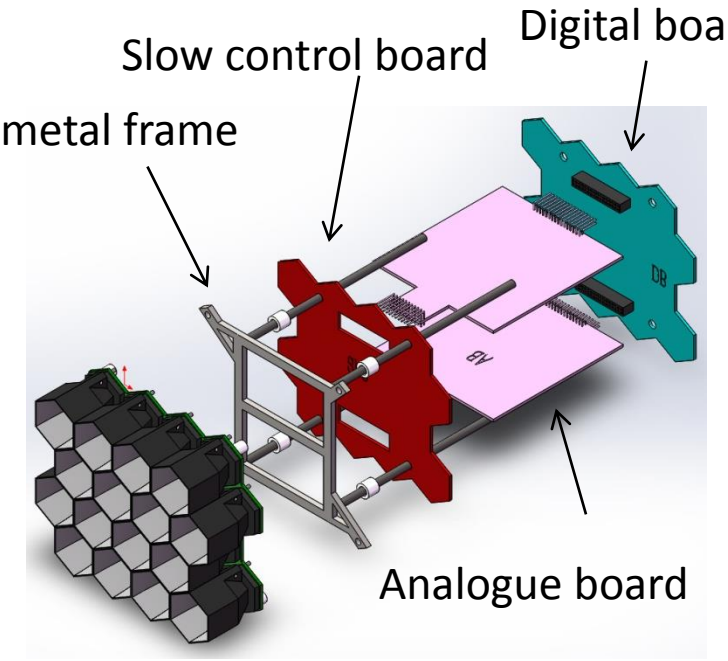
Entrance window: Side to side length is 25.4 mm
Exit window: Side to side length is 12.12 mm



**light concentrators**

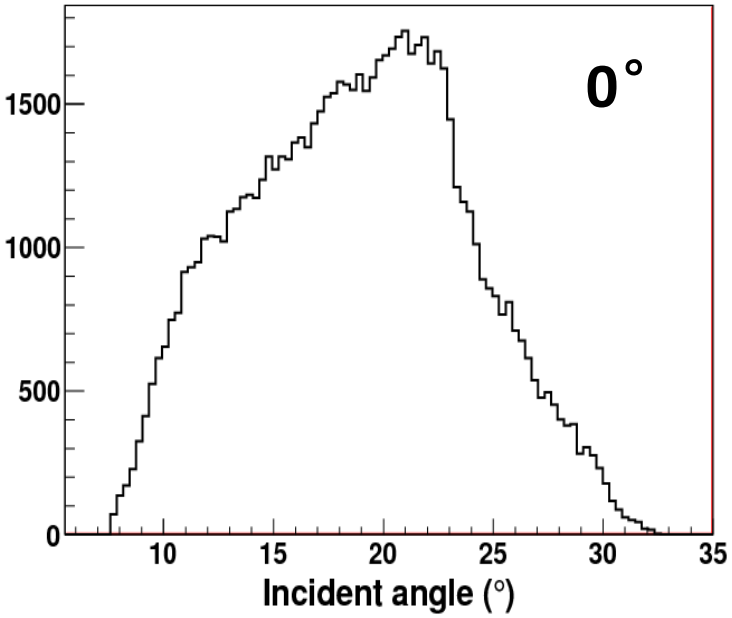


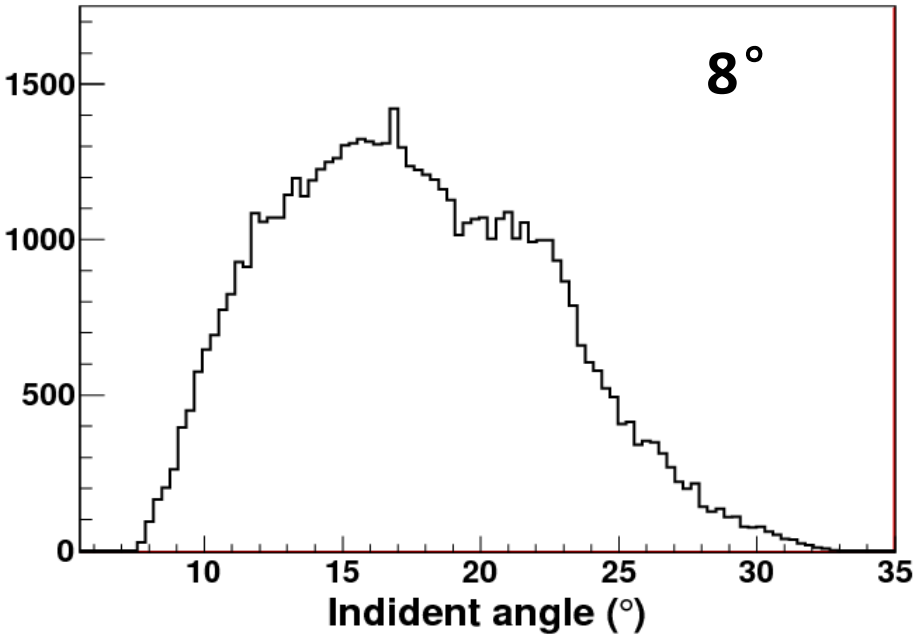
**SiPM base board**

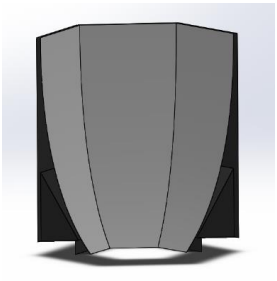


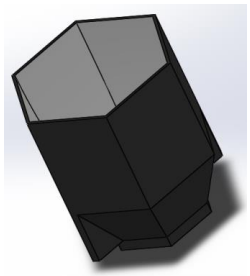

**A module has 4×4 SiPMs.**

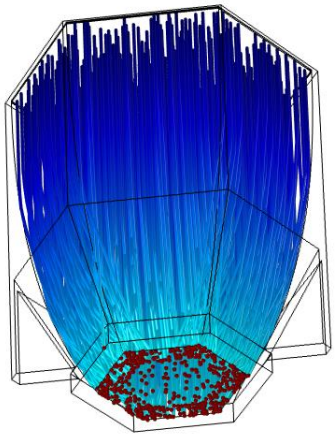
- Light concentrator: is to increase the effective area of the SiPM
- SiPM base board: 16 SiPMs, **16 temperature sensors (embedded in the SiPM chip ),** and 16 pre-amplifiers
- Slow control board:
  - 16 temperature and high voltage compensation loops;
  - 16 channels of high voltage power supply.
- Analogue board: 16 channels of amplifier (high gain and low gain) and shaping circuit
- Digital board: 50 MHz FADC and FPGA

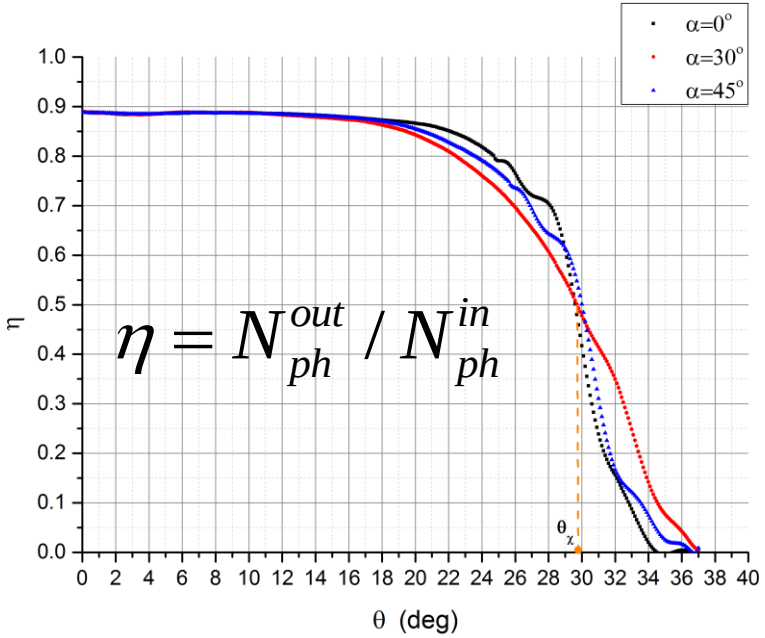

0°
1500
1000
500
0
10
15
20
25
30
35
Incident angle (°)


8°
1500
1000
500
0
10
15
20
25
30
35
Indident angle (°)

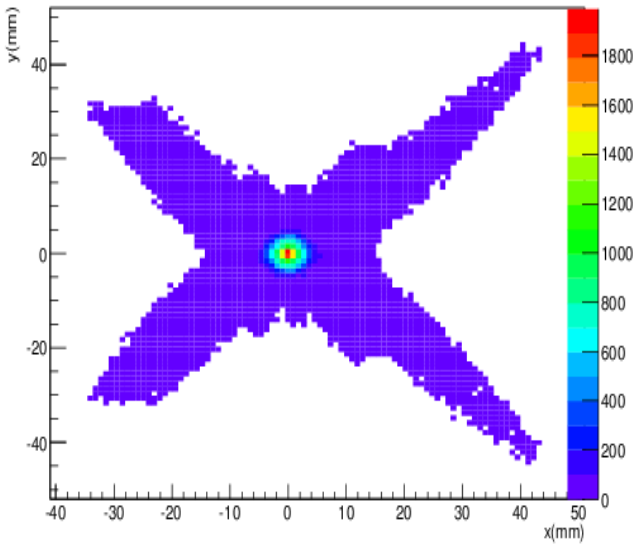




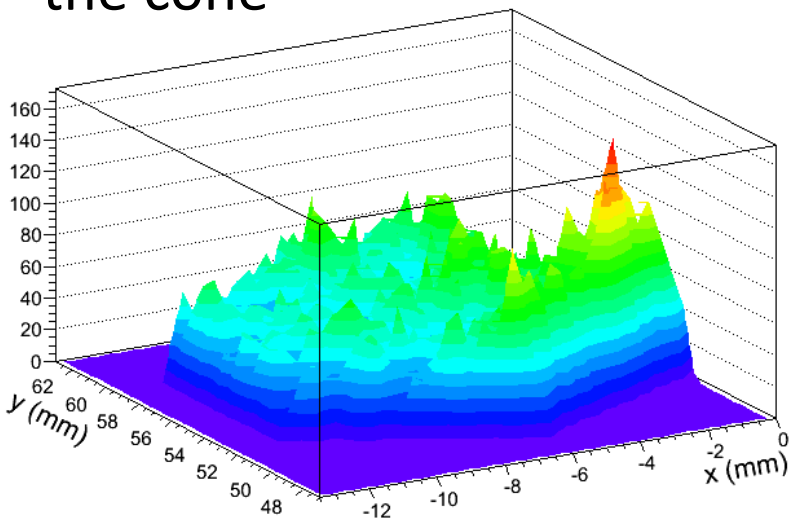



α=0°
α=30°
α=45°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
η
$\eta = N_{ph}^{out} / N_{ph}^{in}$
θχ
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
θ (deg)

Light spot from the reflective mirror




Light distribution output from the cone




➢ Estimate the non-linearity from the nonuniform light distribution cause by the light spot and the light concentrators

$$N_{pe}^{m} = N_{cell}\left(1 - e^{-N_{pe}^{\exp} / N_{cell}}\right)$$