The development of radiation-resistant SiPM at IHEP and SPD with SiPM

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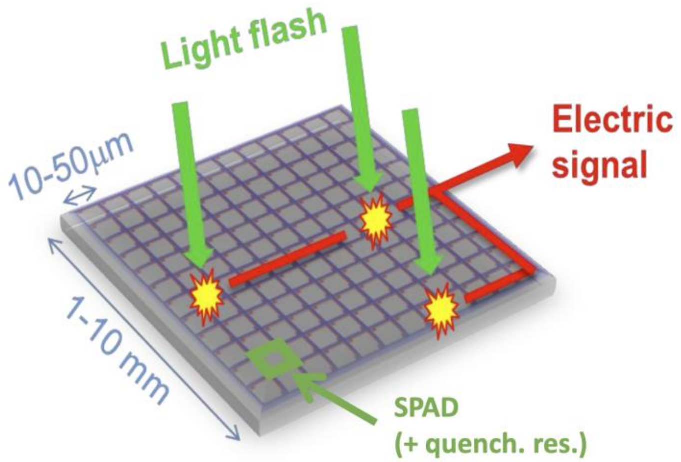
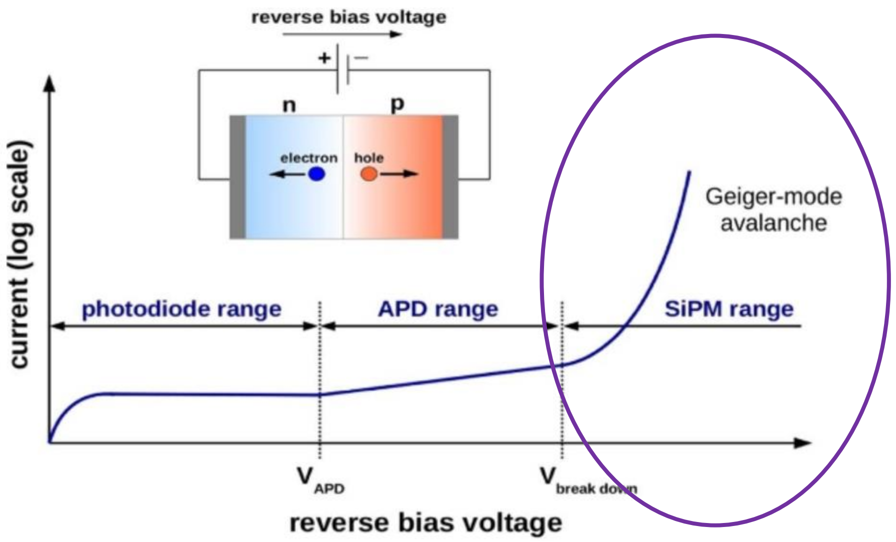
Outline

- **Background of SiPM**
- **Applications of SiPM**
- **SiPM samples and weak light tests**
- **SiPM simulation and design**
- **SiPM neutron irradiation experiment**
- **SPD with SiPM**
- **Summary**

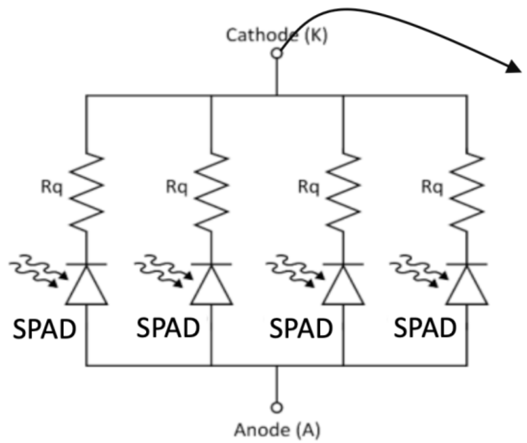
SiPM(Silicon Photomultiplier)

- Composed of a single photon avalanche diode (SPAD) array in parallel
- Working above avalanche break voltage, with avalanche quenching mechanism
- Excellent photon number resolution and high single photon detection sensitivity

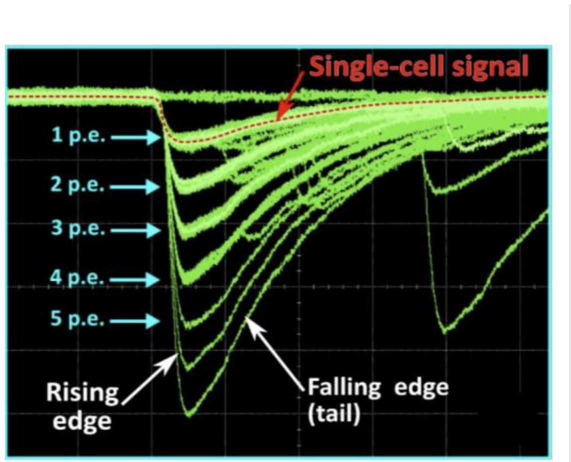




Operating Voltage of SiPM



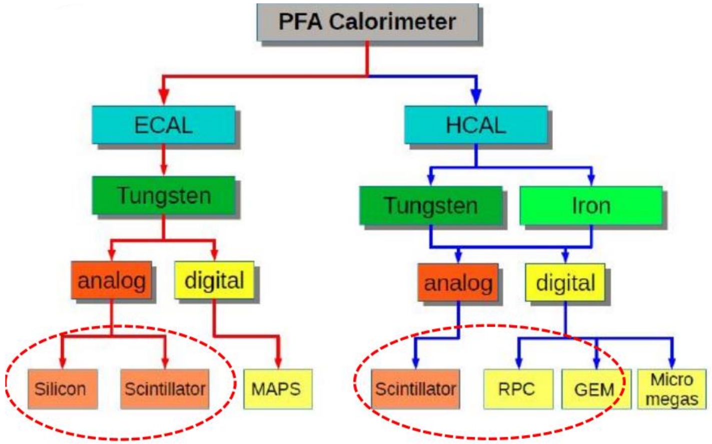
Equivalent circuit of SiPM



Typical waveform of SiPM

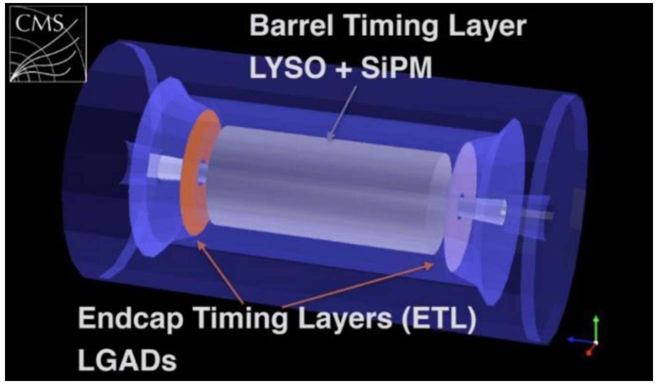
The application of radiation resistant SiPM

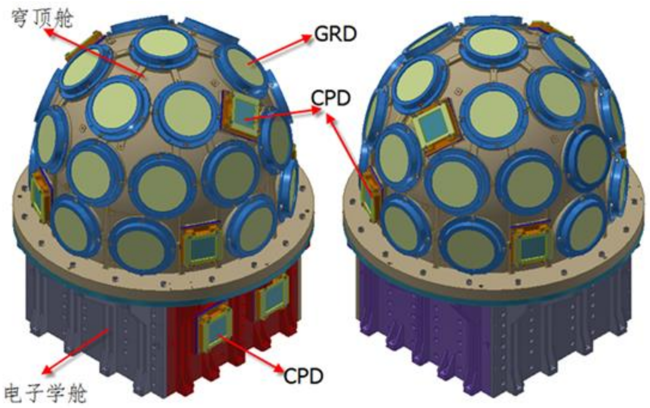
CEPC calorimeter, Space station scientific experiment (Herd …)



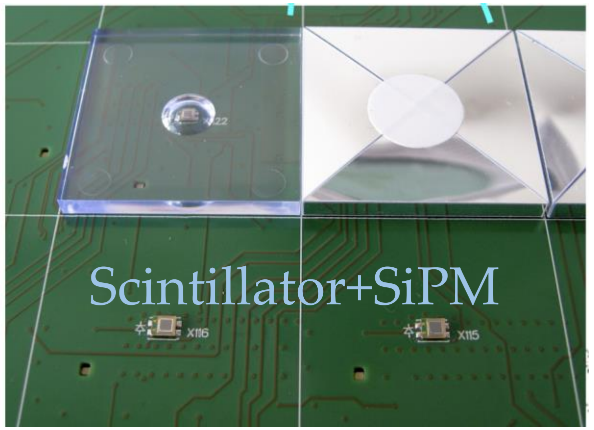
CEPC PFA

CMS Barrel Timing Detector

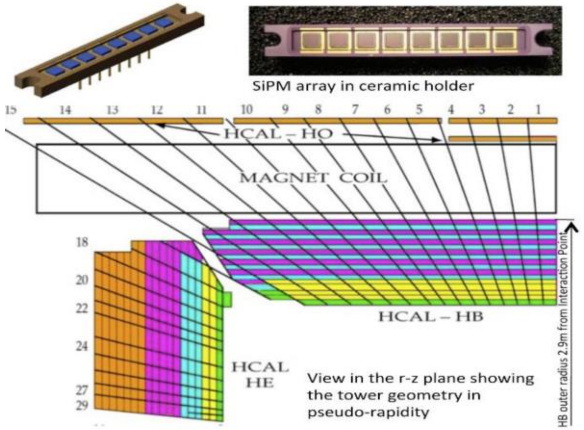




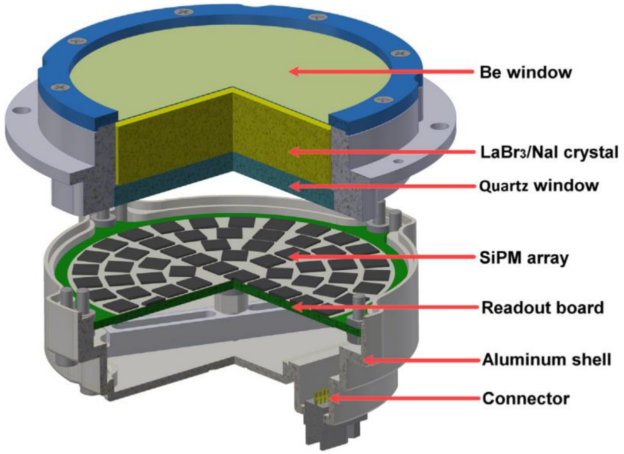
AHCAL prototype



CMS-HCAL upgrade

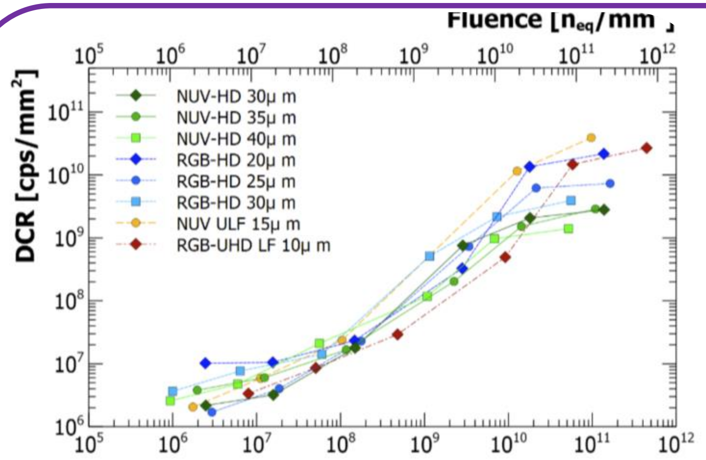


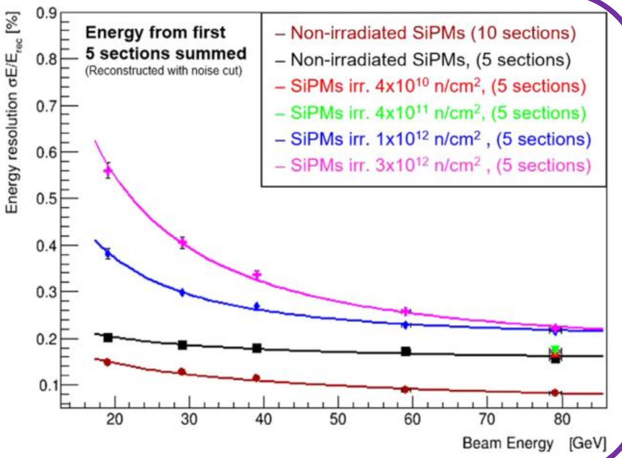
GECAM



The requirements for radiation resistant SiPM

After 10^{10} n_{eq}/cm^2 or 10Krad dose
- Signal gain decrease
- Energy resolution decrease
- Dark count increase



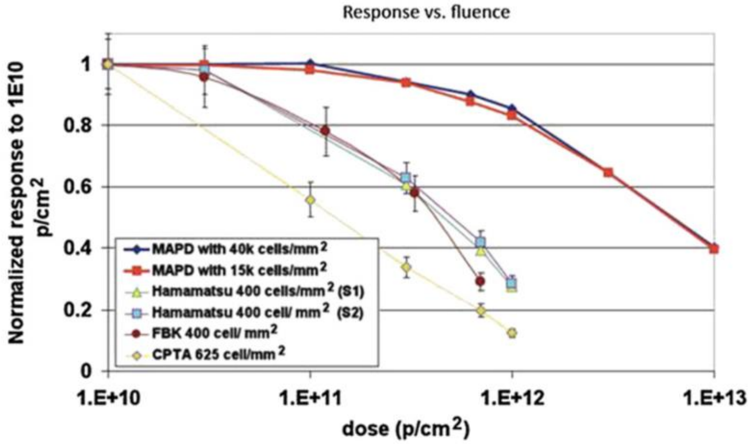


Energy resolution after irradiation

Urgent requirement 1: excellent radiation resistance

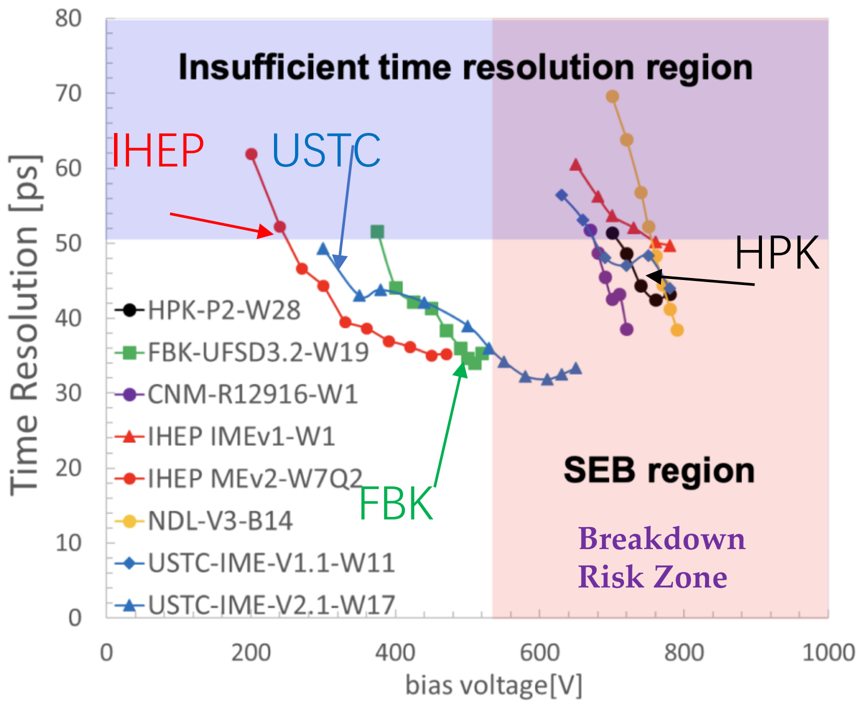
Urgent requirement 2: Low dark count

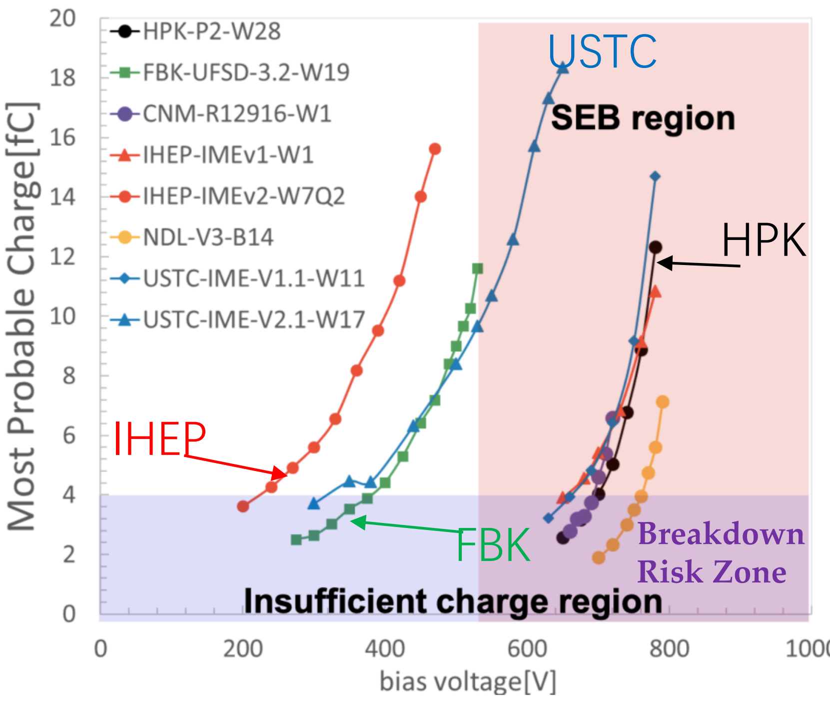
SiPM Signal VS Fluence

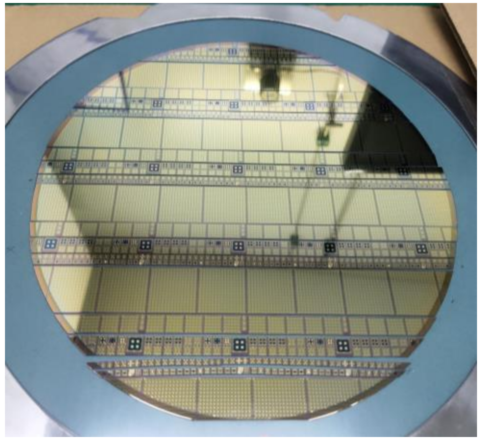


	Long term Satellite or Space station application	CEPC requirement
TID does	100 krad	>100 krad
Fluence	$\sim10^{10}$ n_{eq}/cm^2	$>10^{13}$ n_{eq}/cm^2

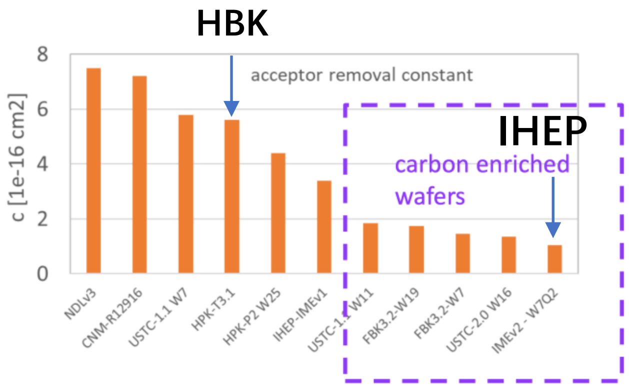
SiPM R&D Foundation







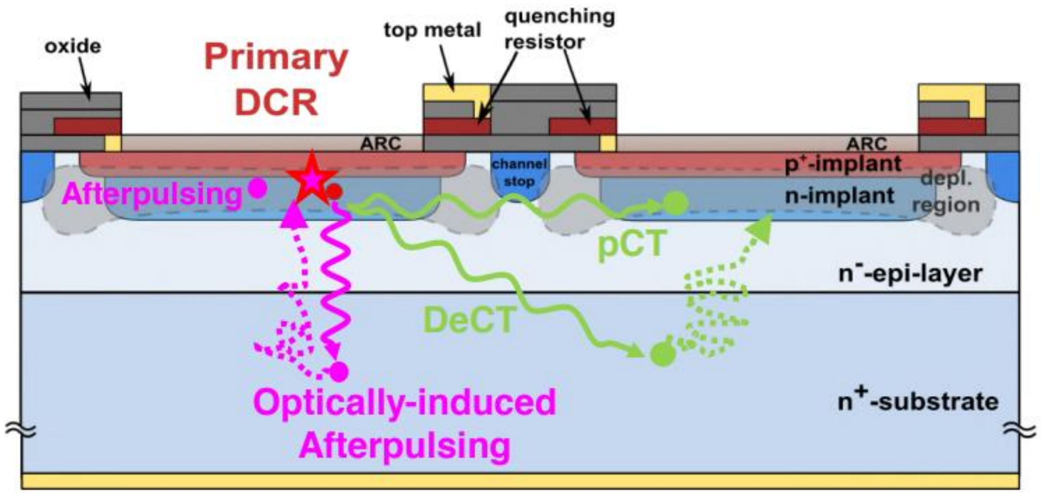
Acceptor removal rate c

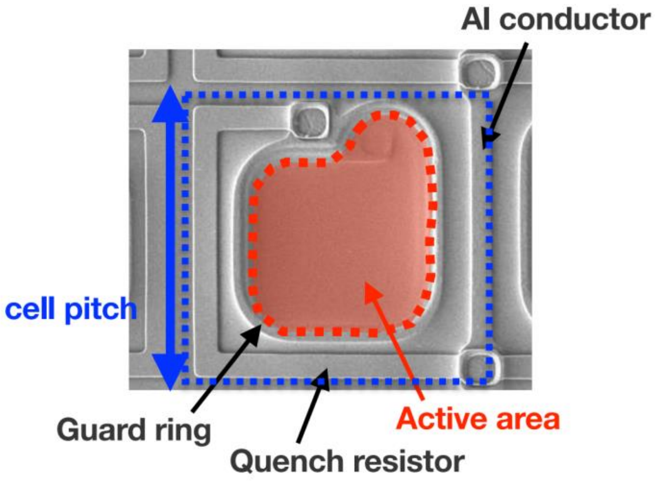


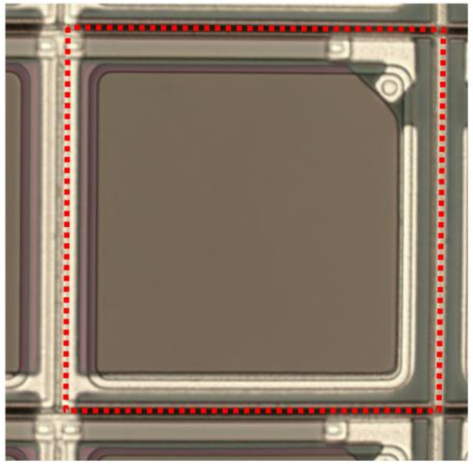
IHEP-IME LGAD

- The acceptor removal rate c is the smallest in the world. ($1.1\times10^{-16}cm^2$)
- 350V operating voltage at 4fC, the lowest in the world, to avoid single-particle burnout.
- Irradiation resistance exceeds HPK, is comparable to FBK and exceeds FBK in some parameters

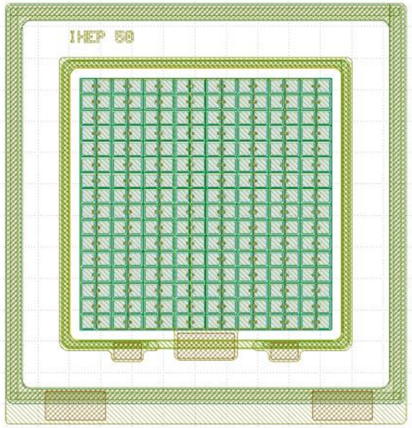
IHEP SiPM-V0

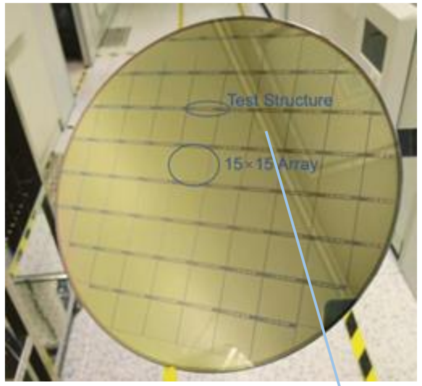


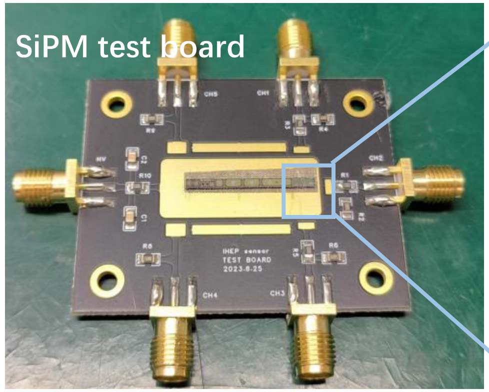


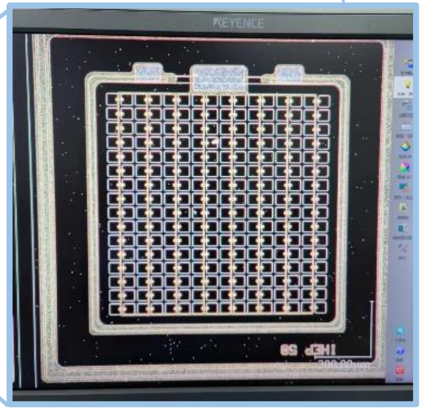


Fraction of active area, typically 50-70%





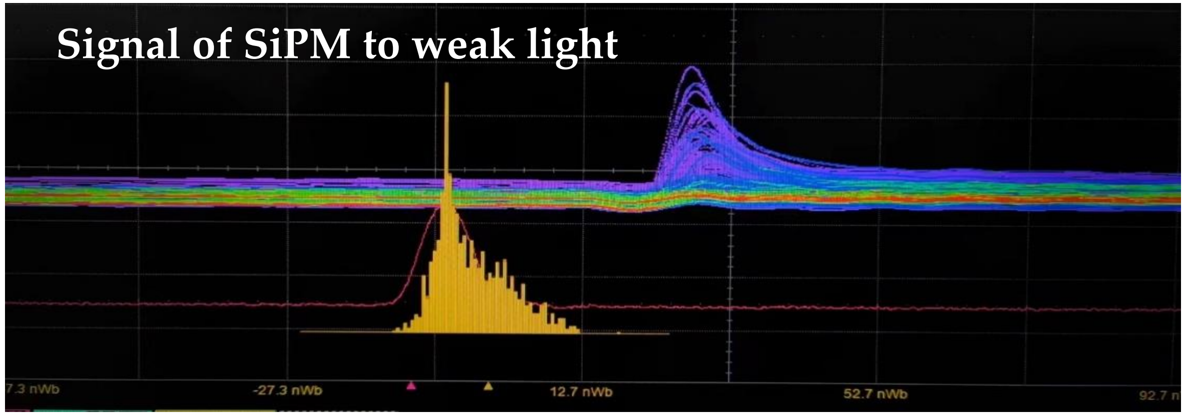


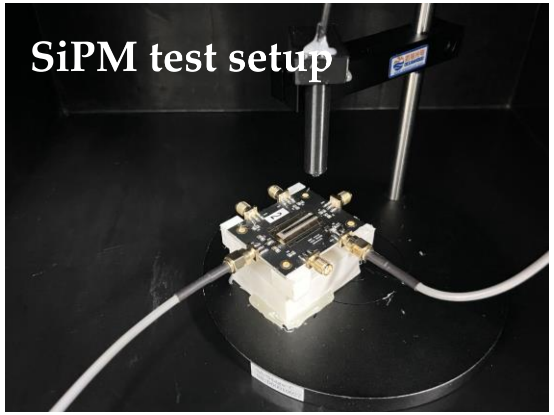


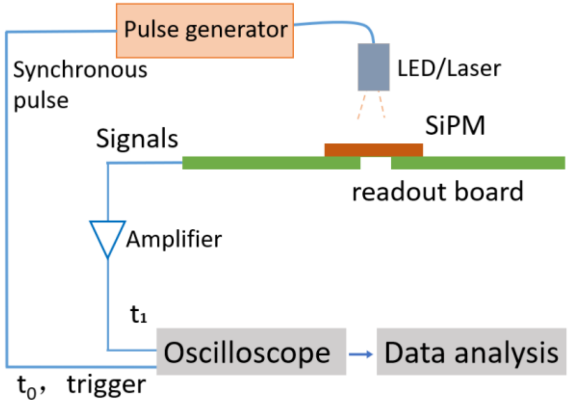
SiPM sample produced along with LGAD pre-production

- Pixel size： 50μm
- 16 x 16 pixels

Weak light experiment

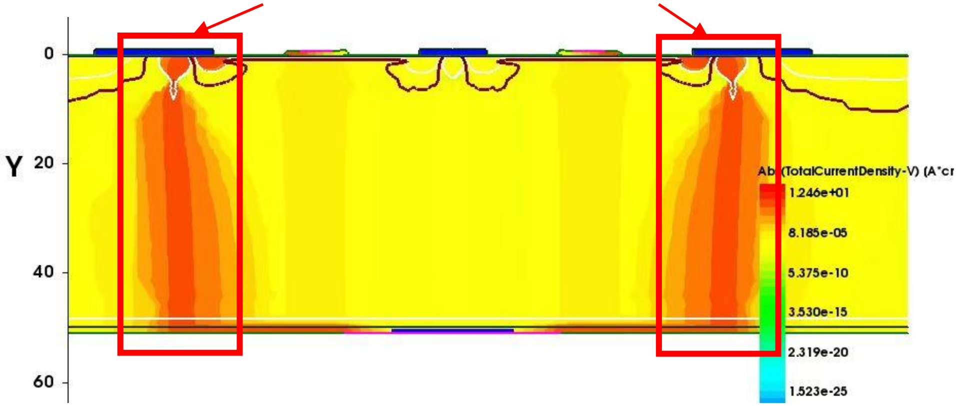


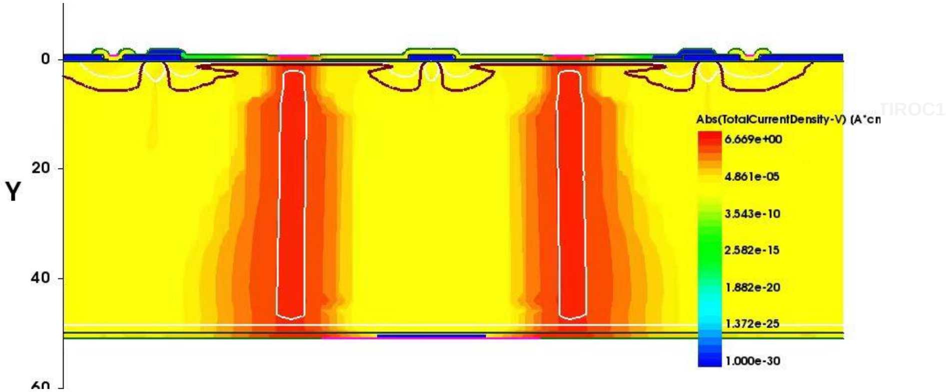




- The structural design and some processes of SiPM have been validated.
- Energy resolution needs to be optimized.

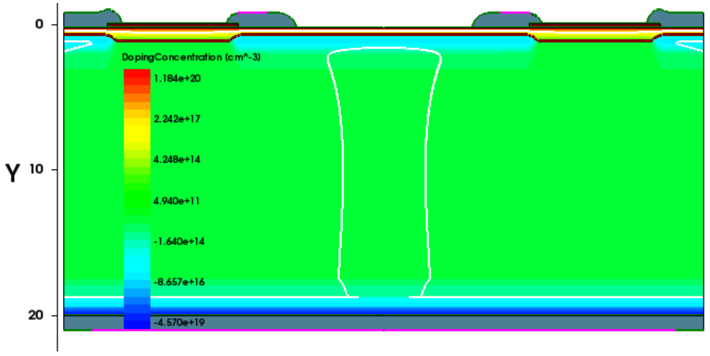
Large edge leakage current



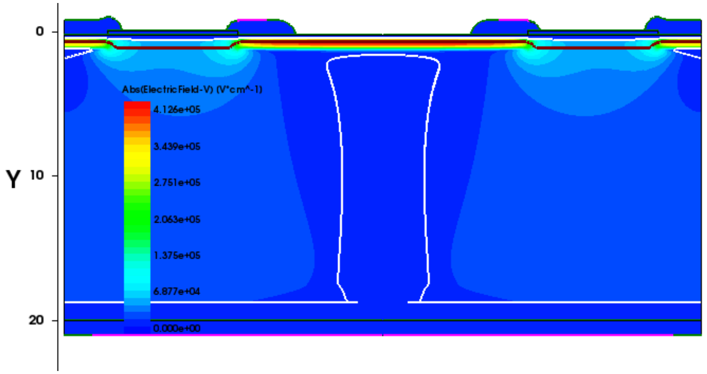


Optimize the Pstop and GR structures through simulation to reduce the leakage current of the edge Pstop;

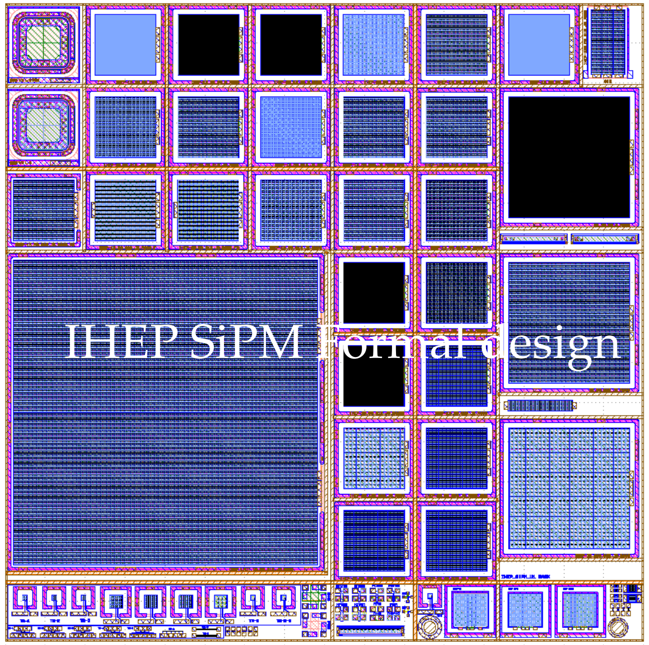
TCAD simulation of radiation hard SiPM



Doping profile



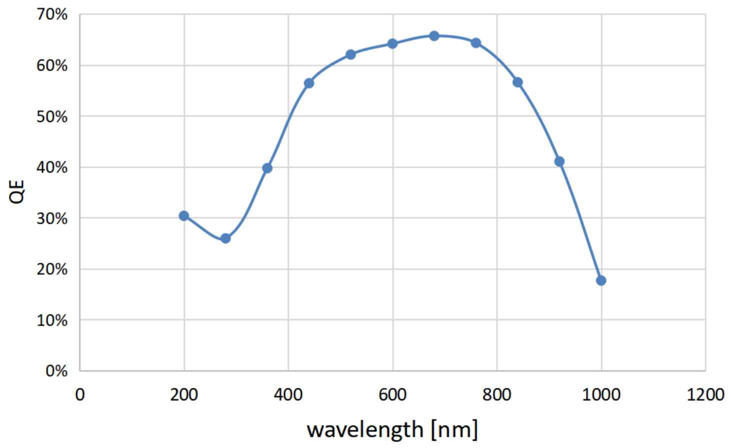
Electric field distribution



SiPM size:

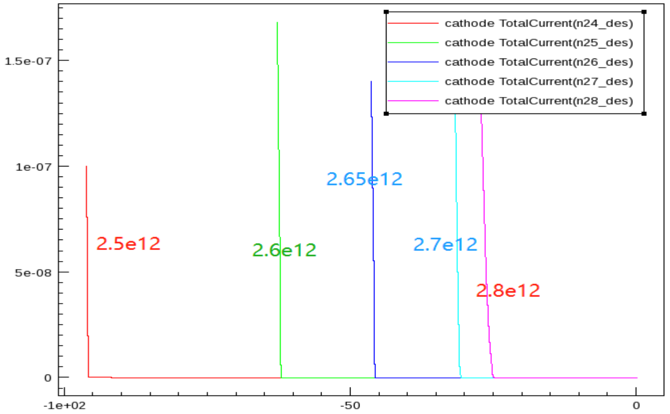
- 7.6mm×7.6mm
- 3.0mm×3.0mm
- 1.5mm×1.5mm

Pixel size：
100μm、50μm、20μm、10μm



QE vs. Wavelength

Quantum Efficiency > 50% @ 420nm



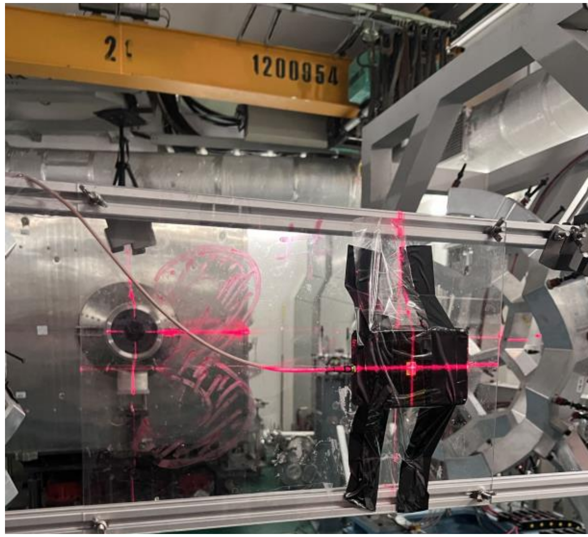
I-V

Break Voltage 30V-100V

Formal tape-out plan:

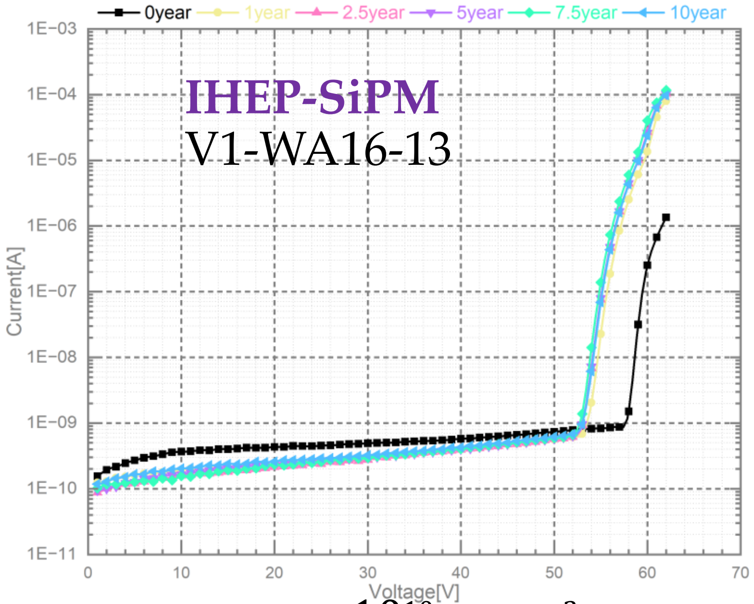
- Submit the official design layout at the end of July
- All 9 layers of mask boards have been produced so far
- Complete the first version of tape-out by the end of this year

Neutron irradiation of SiPM in CSNS

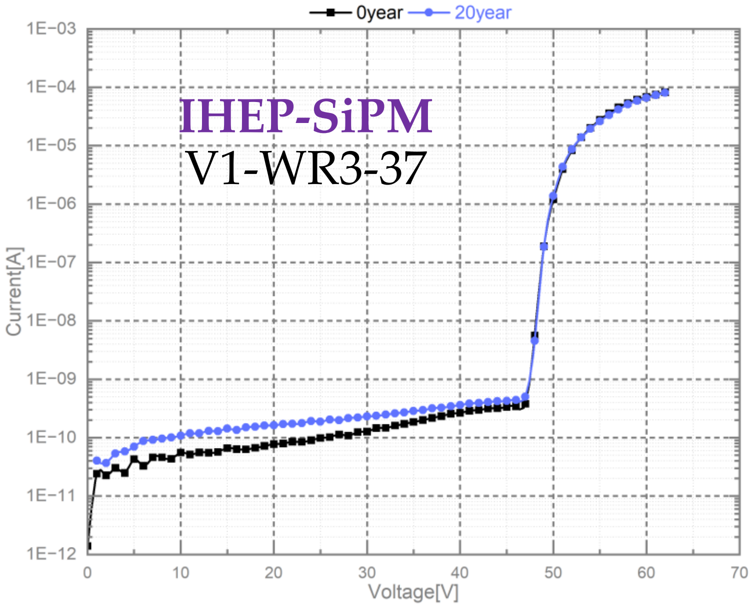


Under the same irradiation conditions, SiPM is compared to the Hamamatsu S13360 series. At operating voltage, the leakage current of S13360 is $0.2778\mu A/cm^2$, the leakage current of SiPM is $0.1094\mu A/cm^2$.

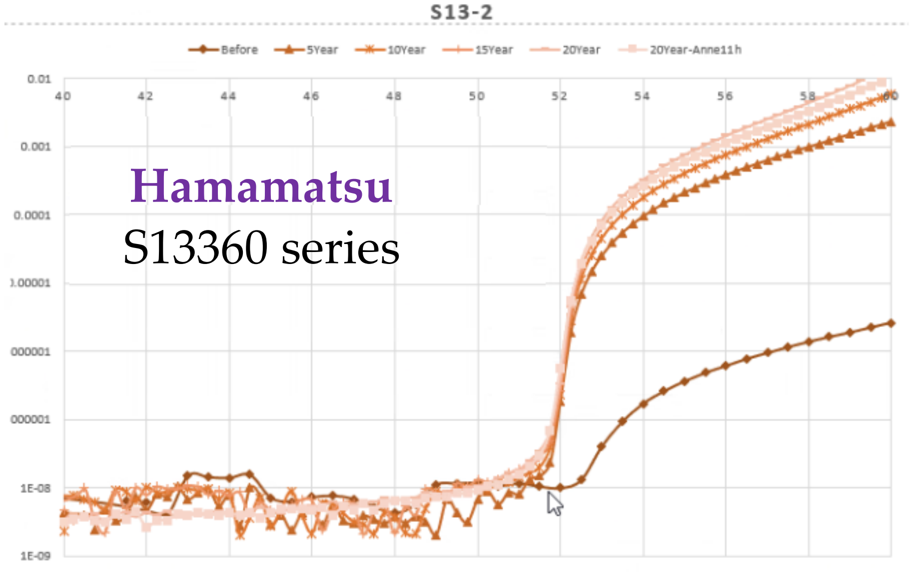
- When the irradiation dose reaches $2.17 \times 10^{10} n_{eq}/cm^2$, the break voltage of SiPM maintains, and the leakage current remains basically unchanged(0.1nA);
- When the irradiation dose reaches $1.09 \times 10^{10} n_{eq}/cm^2$, the break voltage of SiPM decreases by 5V and the leakage current remains basically unchanged(0.2nA).



Dose: $1.09 \times 10^{10} n_{eq}/cm^2$



Dose: $2.17 \times 10^{10} n_{eq}/cm^2$



Dose: $2.17 \times 10^{10} n_{eq}/cm^2$

SiPM Test Plan

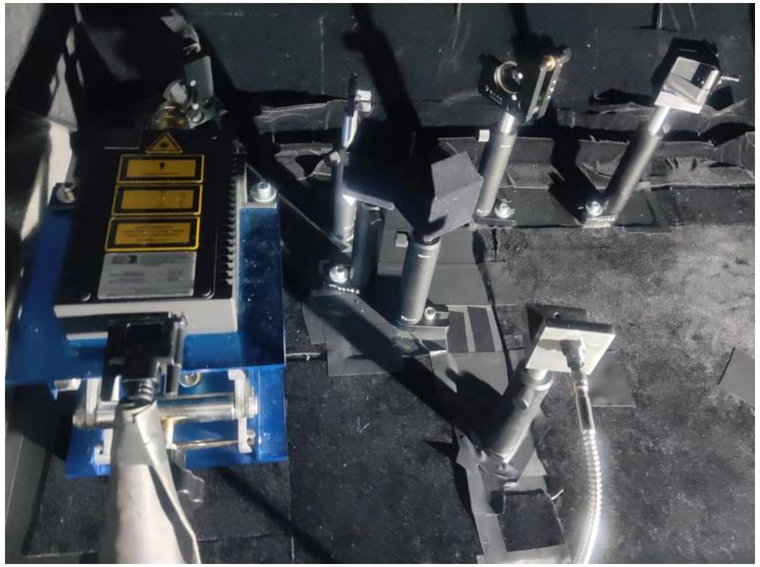
- Performance test plan:

Existing single photon testing platforms and low-temperature testing platforms

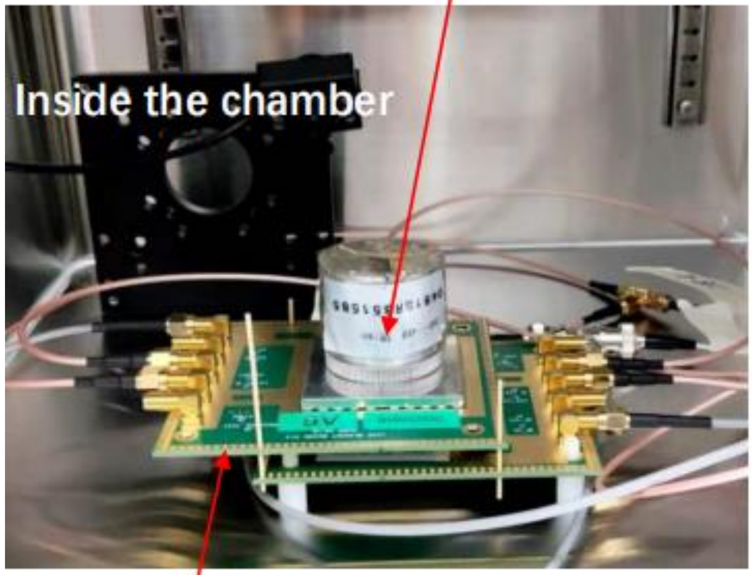
- Irradiation test plan:

Plan to collaborate with the Dongguan spallation team to conduct proton irradiation of SiPM

Single photon testing platform
(based on picosecond lasers)



Beta Source

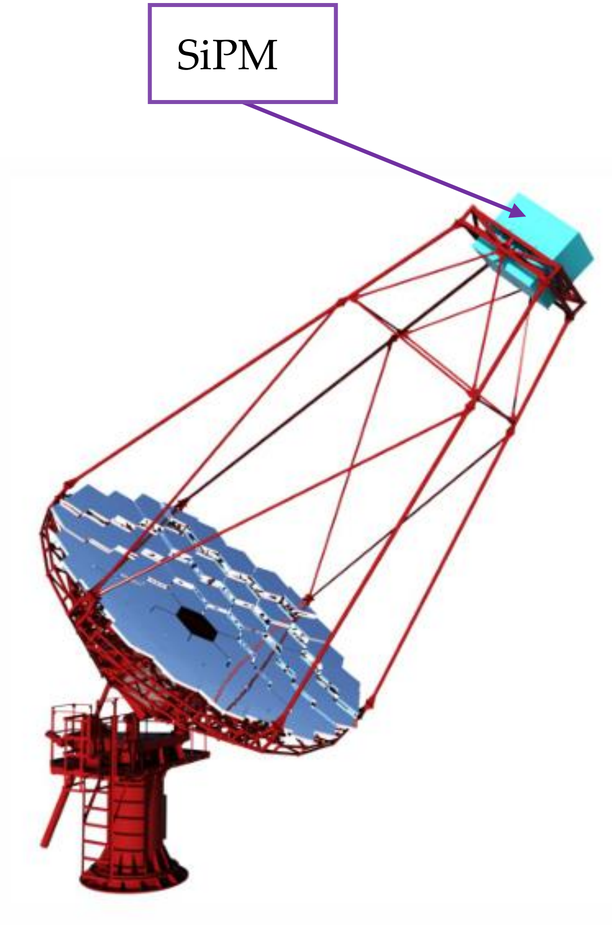


Readout

CSNS proton irradiation site

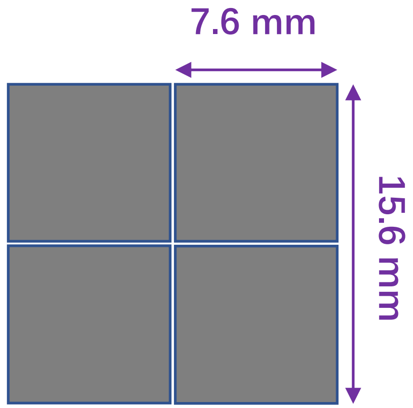
Single photon detection with SiPM

Large Array of imaging atmospheric Cherenkov Telescopes (LACT)
- ➢ aims to locate the position of ultra-high-energy gamma-ray radiation and determine the celestial sources of ultra-high-energy gamma rays, etc.

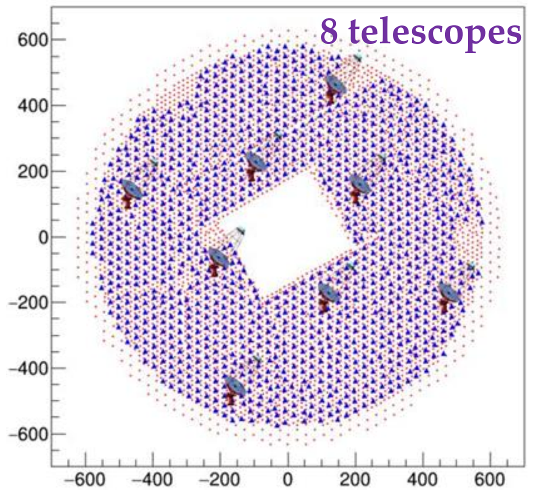


- ➢ A few photons -> photon sensitive
- ➢ Not aging under strong light irradiation -> radiation resistant
- ➢ Narrow output pulse width -> good energy resolution

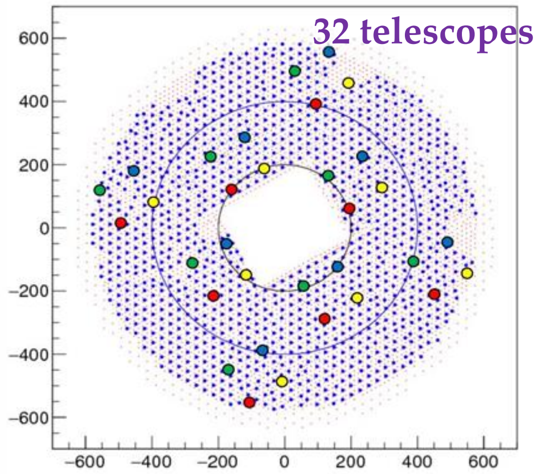
Requirements of LACT for SiPM:
- ➢ Detection wavelength: ~300nm
- ➢ Module area: 15.6 mm × 15.6 mm (Module composed of 4 pieces of 7.6 mm x 7.6 mm)
- ➢ Pixel size: 50 μm
- ➢ Total required number of pieces: ~288768 pieces * 7.6 mm x 7.6 mm (~16.7 m2)



LACT SiPM module



2026 science operation

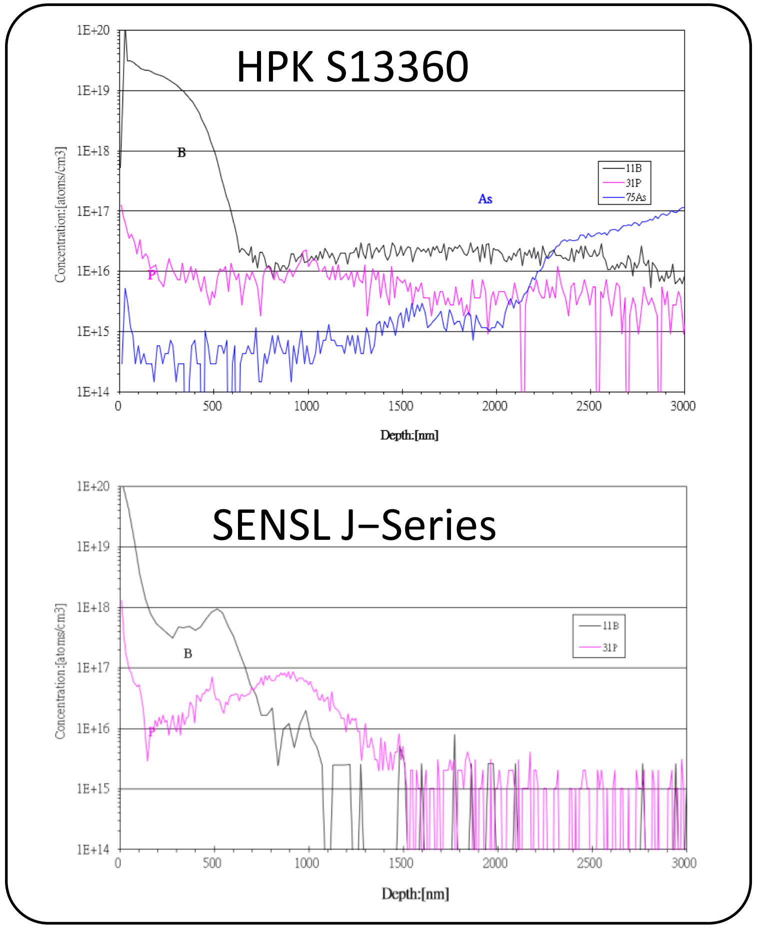


2029 science operation

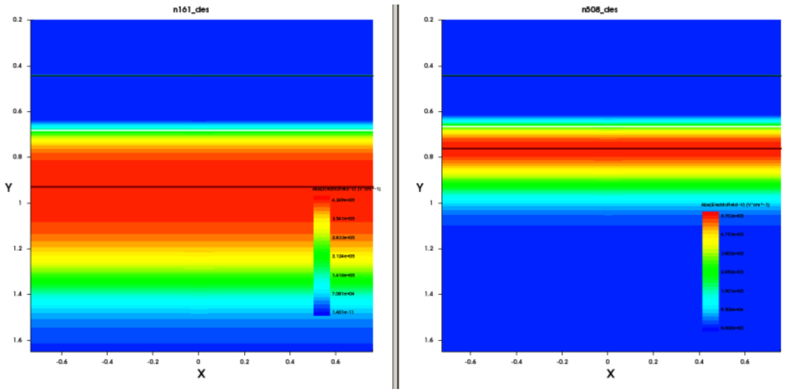
Single photon detection with SiPM

Improved Cherenkov light detection sensitivity

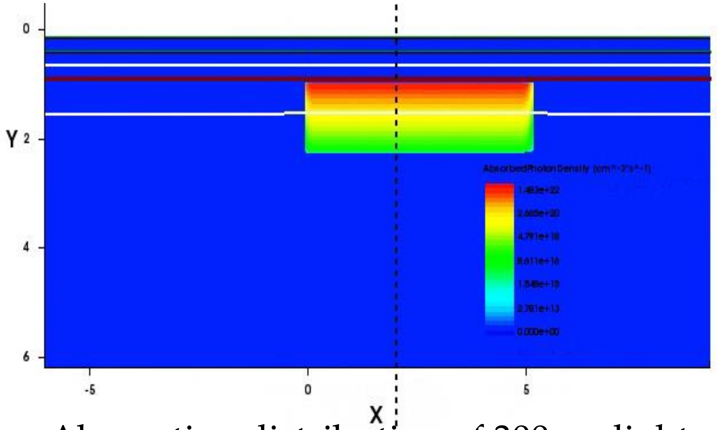
Adjustment of the injection energy of the P+ layer to obtain a shallower gain layer and improve detection sensitivity



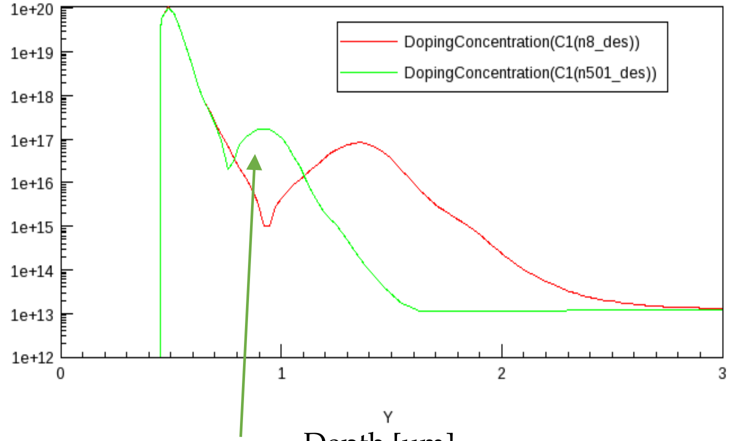
SIMS testing of HPK with SENSL SiPM



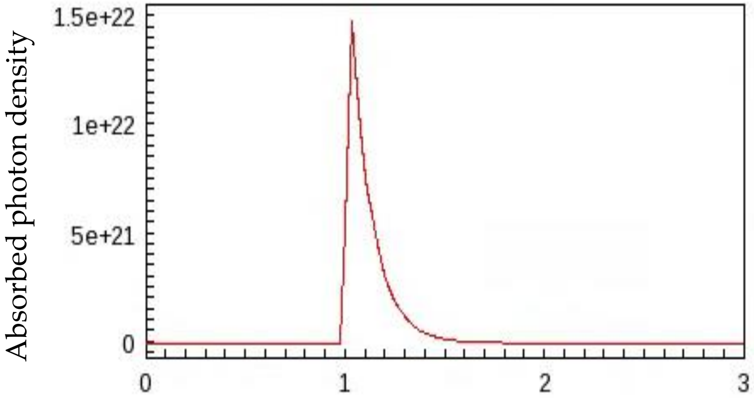
Gain layer field strength distribution before and after optimization



Absorption distribution of 300nm light



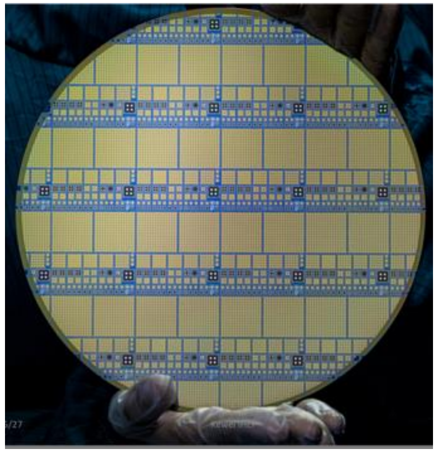
Depth of gain layer after optimization



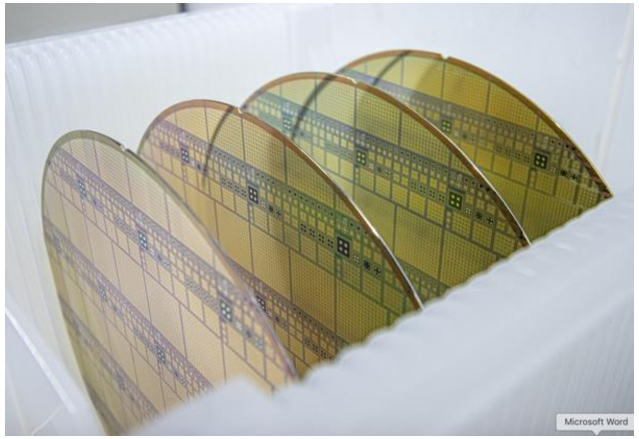
Absorption of 300nm light in devices

Time line for radiation hard SiPM

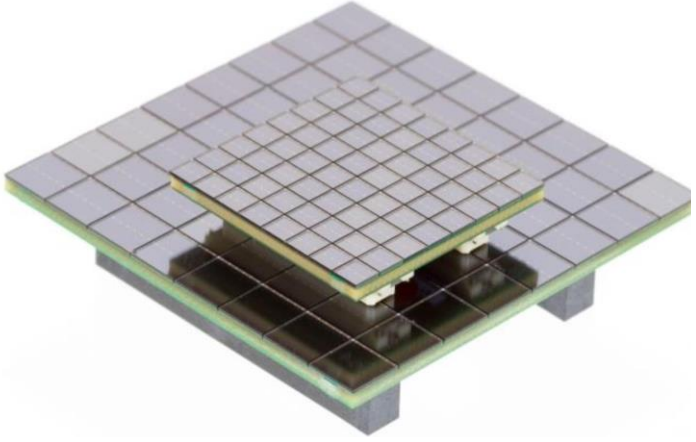
- 2023 1st half: SiPM irradiation hard design validated in LGAD engineering run
- 2024 1st half: 1st Dedicated SiPM engineering run submission
- 2025: 1~2 more dedicated SiPM engineering run
- 2026: Further optimization for specific projects



Simulation and exploration of various process parameters



SiPM multiple flow sheets to determine process parameters



2023 **2024** **2025**

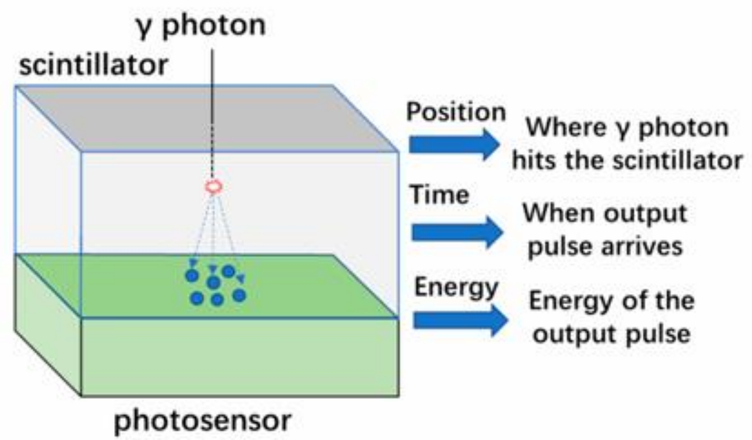
Summary

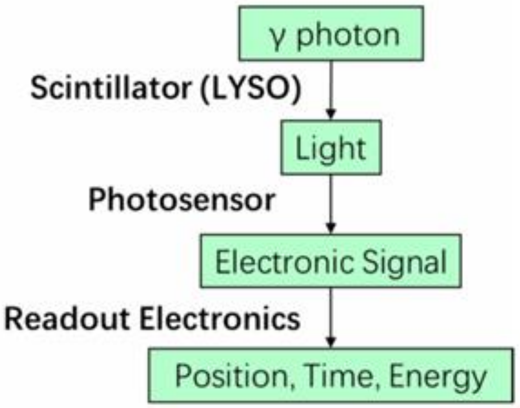
- **Development for radiation hard SiPM**
  - Aim for CEPC and Astrophysics application.
- **Key technology has been validated in ATLAS HGTD detector project**
  - Radiation hard LGAD sensor developed by IHEP team;
  - At operating voltage, SiPM has a smaller leakage current compared to the Hamamatsu S13360 series under the same irradiation conditions.
- **Radiation SiPM R & D project**
  - Formal tape-out plan was submitted at the end of July;
  - All 9 layers of mask boards have been produced so far;
  - Complete the first version of tape-out by the end of this year.

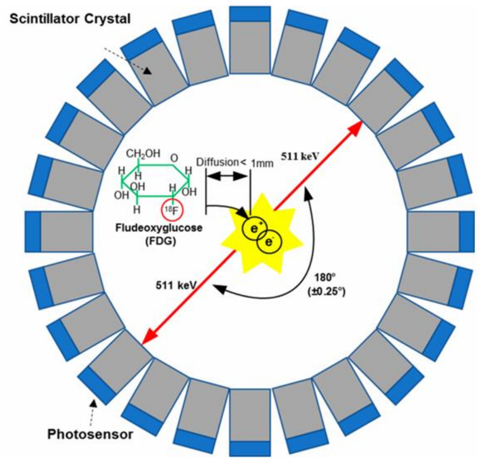
Thanks for Your Attention

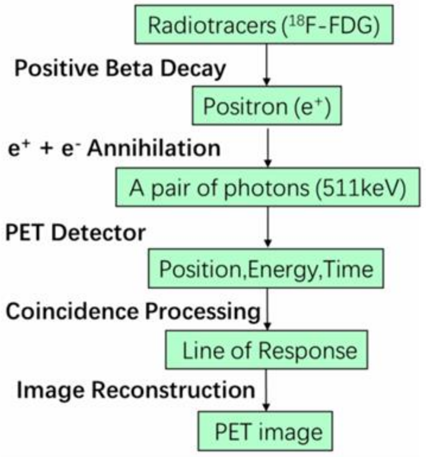
The application of SiPM

➢ PET: Scintillator crystals + photosensor (PMT/APD/SiPM)









Jiang, W. (2019). Sensors for Positron Emission Tomography Applications. Sensors, 19(7), 1587.

The application of SiPM: SPD with SiPM

Performance of several common photoelectric converters

	PMT	APD	SiPM
Gain	10^4~10^9	30~10^3	10^5~10^7
Quantum effciency	25~40	60~80	80
Wave Length	400nm~700nm	400nm~700nm	800nm~1100nm
Operating Voltage	1000V~3000V	100V~500V	20V~80V
Rise time	Fast	Slow	Fast
Magnetic Field Compatibity	No	Yes	Yes
Compactness	Low	Medium	High
Single-photon detection	Y	N	Y
Temperature	Low	High	Low
price	Medium	Low	Low