The Progress of HCAL

2024-12-11

Qian Sen, on behalf of the HCAL Group

qians@ihep.ac.cn

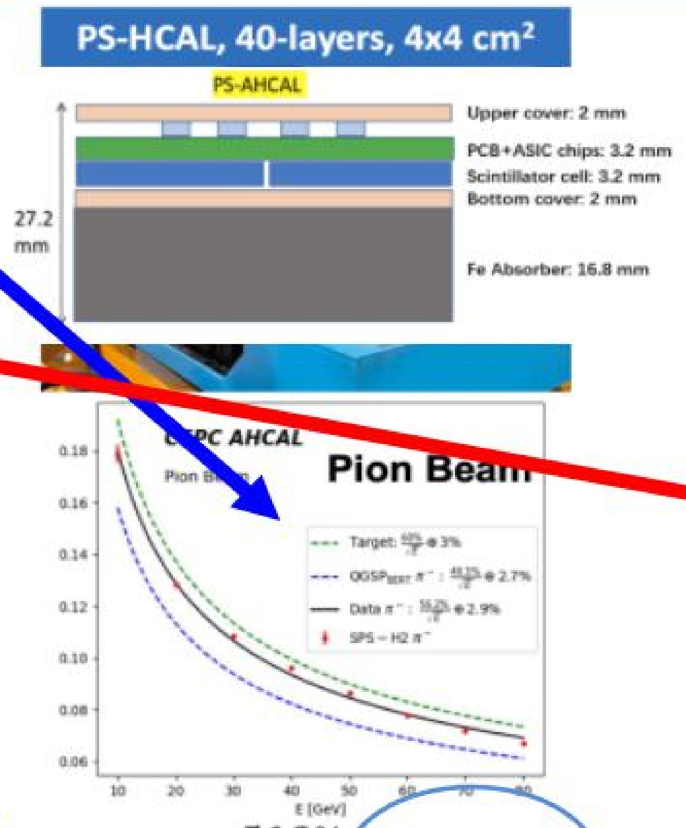
Outline

- **1. The Design of the HCAL ;**
  - 1.1. The HCAL Constant Term;
  - 1.2. The Glass simulation: Birks effect;
  - 1.3. The Attenuation Length of GS;
  - 1.4. The 4SiPM+1GS Cell design;
- **2. The Mechanics of the HCAL ;**
- **3. The Progress of GS;**

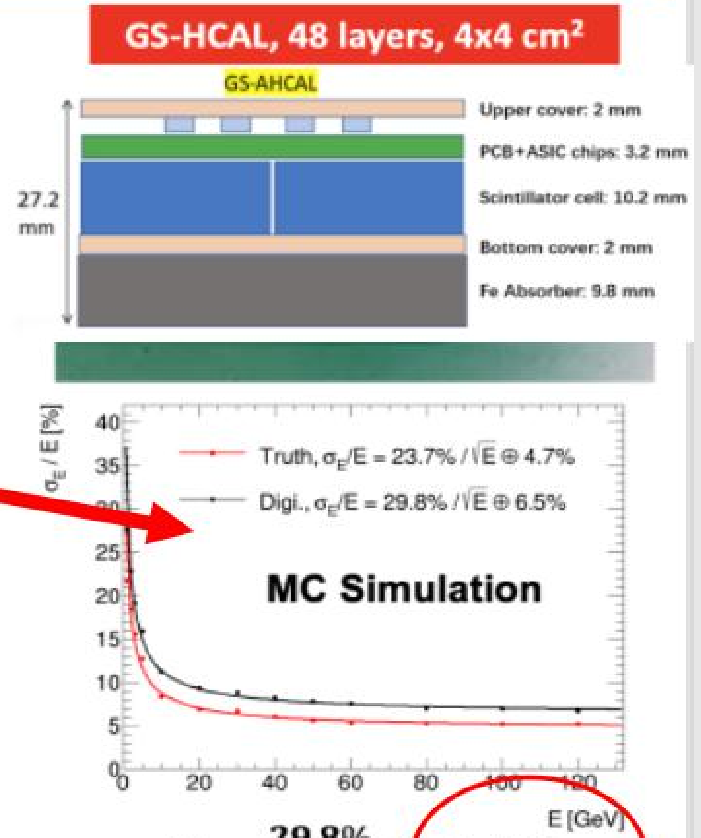
1.1 The HCAL Constant Term

Understanding the "big" HCAL constant term

- What is the story about?
  - PS-HCAL beam test shows good (~3%) constant term,
  - But GS-HCAL simulation looks "abnormally big" (4.7% truth, 6.5% after digi).
- Similar Cell-level geometry: we DO NOT expect this level of big difference in the constant term.
- The "issue" is now understood to be NOT an issue in the GS-HCAL design. It is simply a small overlook in drawing the plot, the longitudinal leakage events were not removed.



$$\sigma_E/E = \frac{56.2\%}{\sqrt{E}} \oplus 2.9\%$$

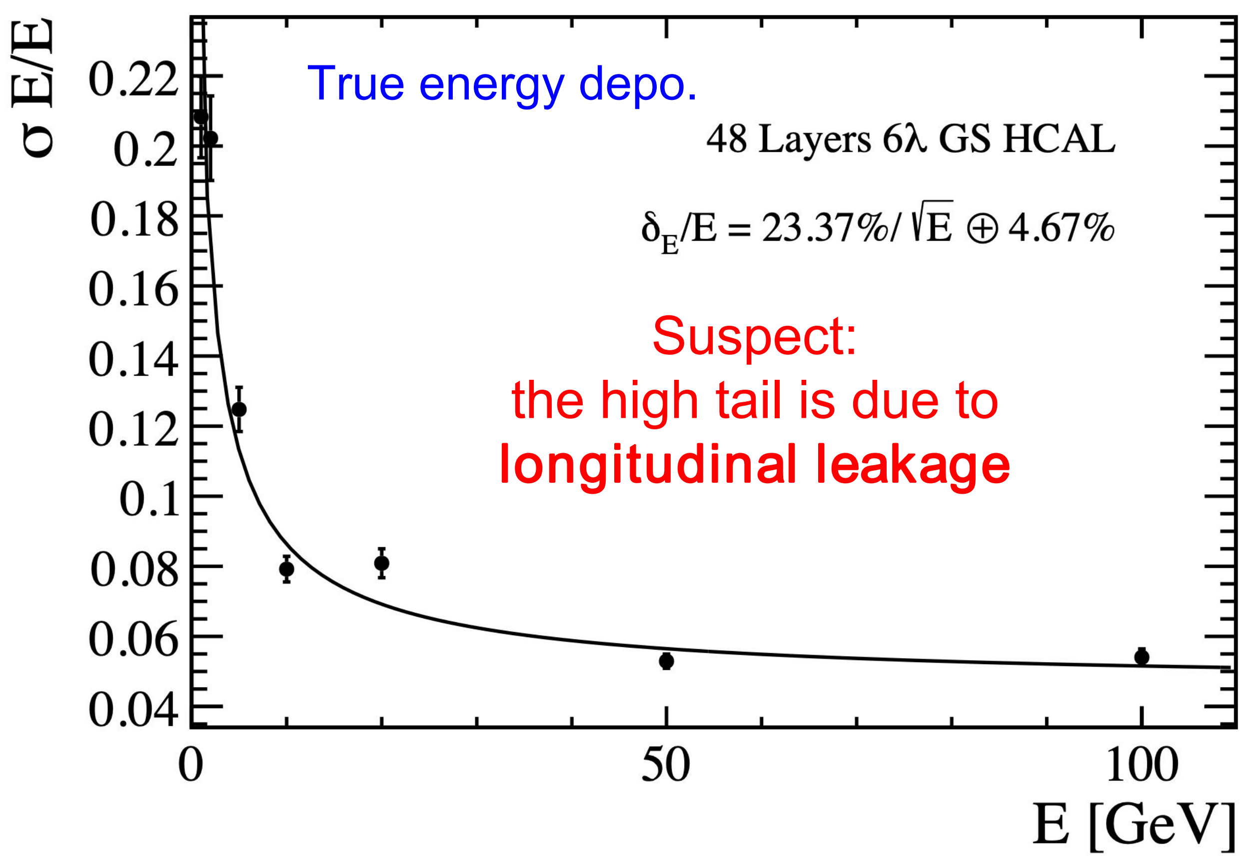


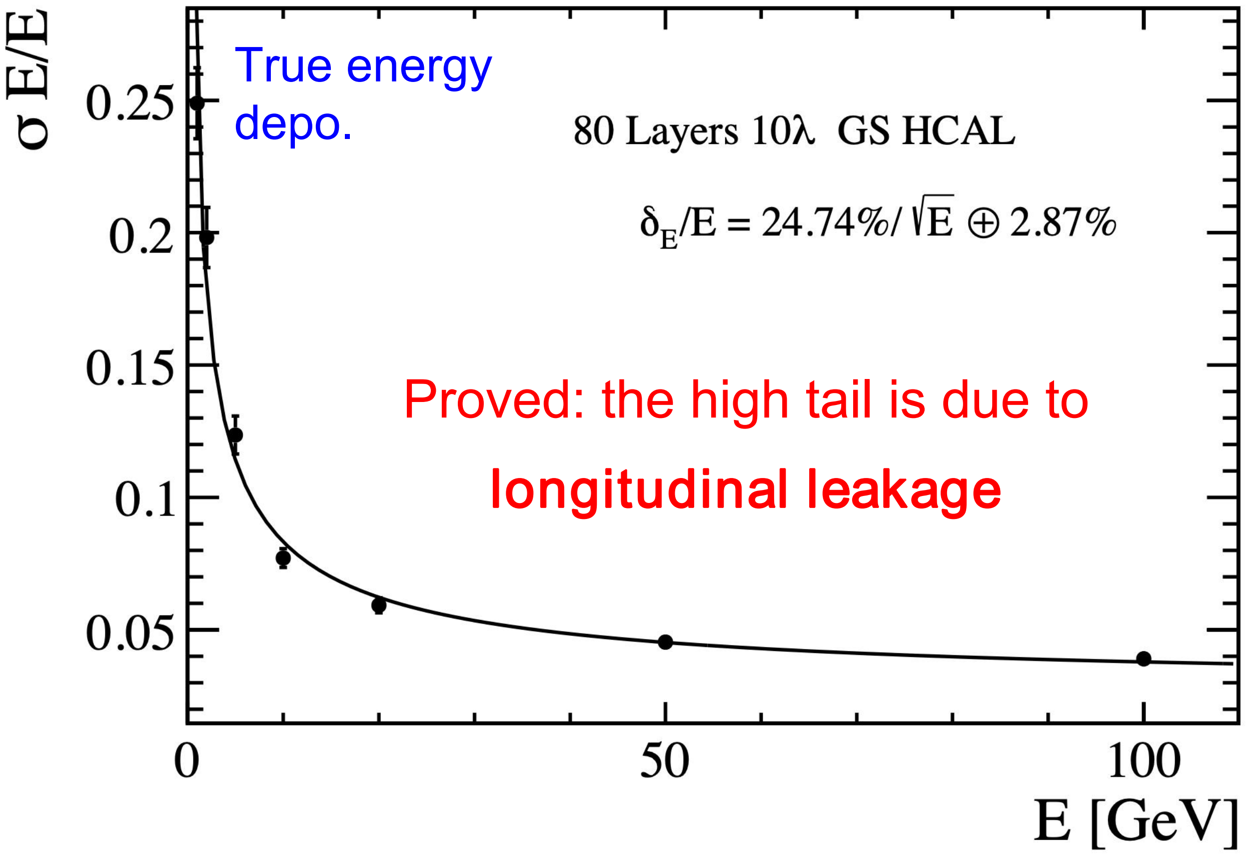
$$\sigma_E/E = \frac{29.8\%}{\sqrt{E}} \oplus 6.5\%$$

Understanding the "big" HCAL constant term

Step 1: Verify the observation: Indeed, constant term is ~4.7% for 48 layers 6 lambda using pions up to 100GeV.

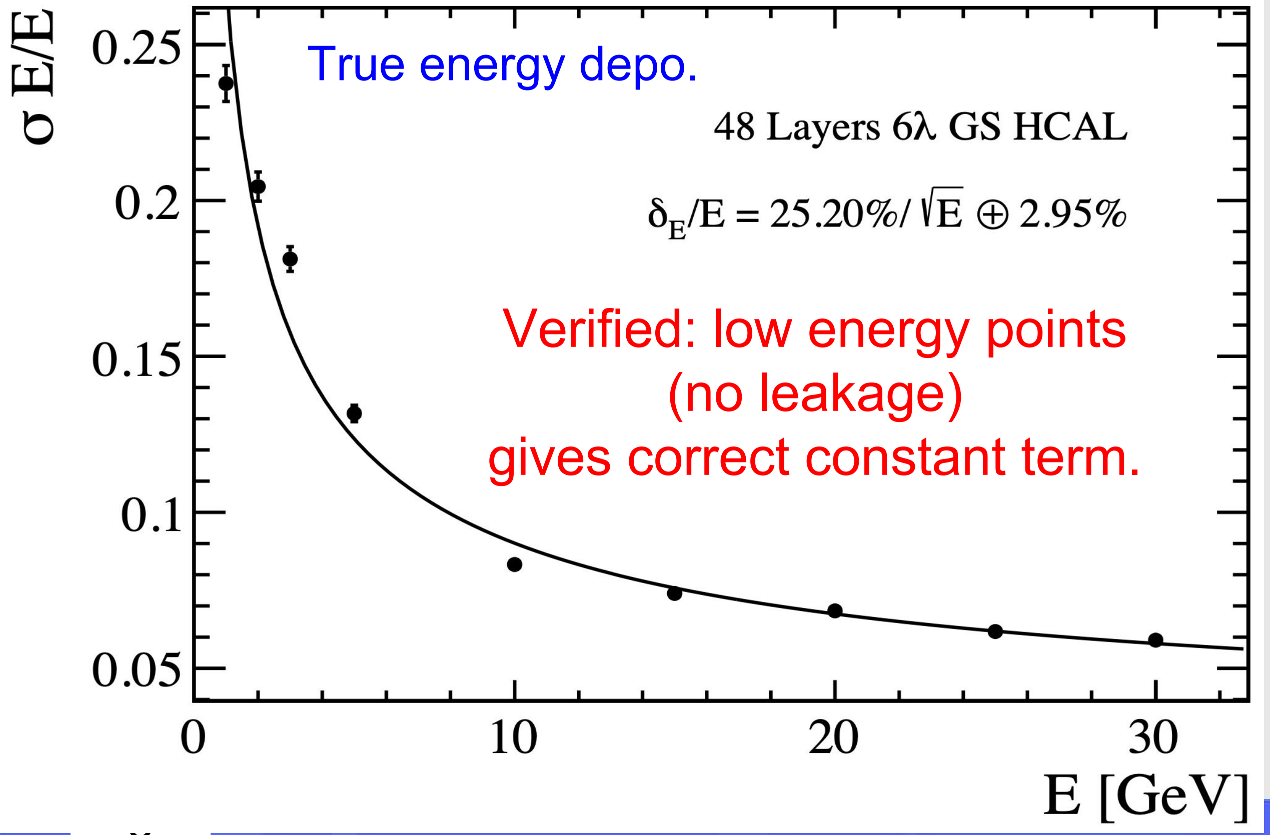
Step 2: Confirm the suspicion, when using 80 layers 10 lambda (thick enough), the resolution at100 GeV greatly lowered down, constant term reduced to 2.9%.



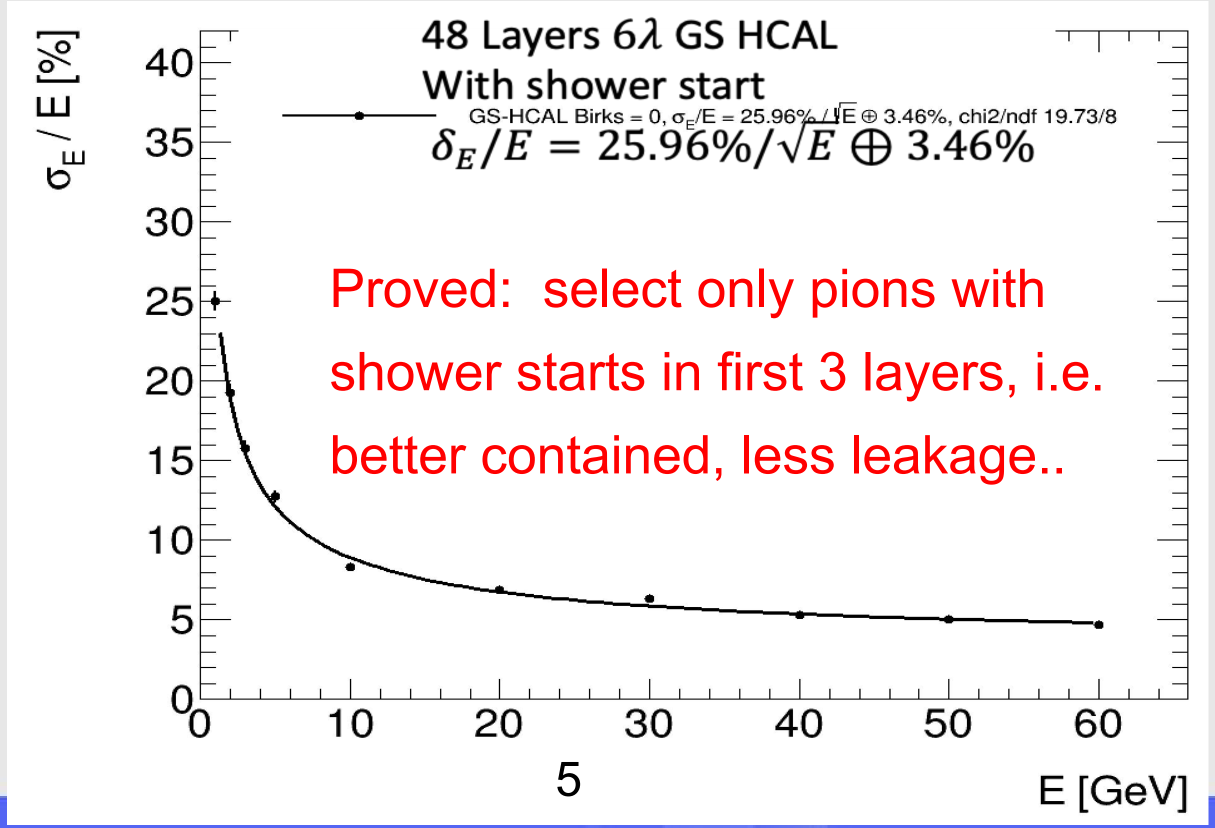


Understanding the “big” HCAL constant term

Step 3 (a): Verify the understanding: constant term reduced to ~2.9% for 48 layers 6 lambda if ONLY using pions w/o Leakage (below 30 GeV).



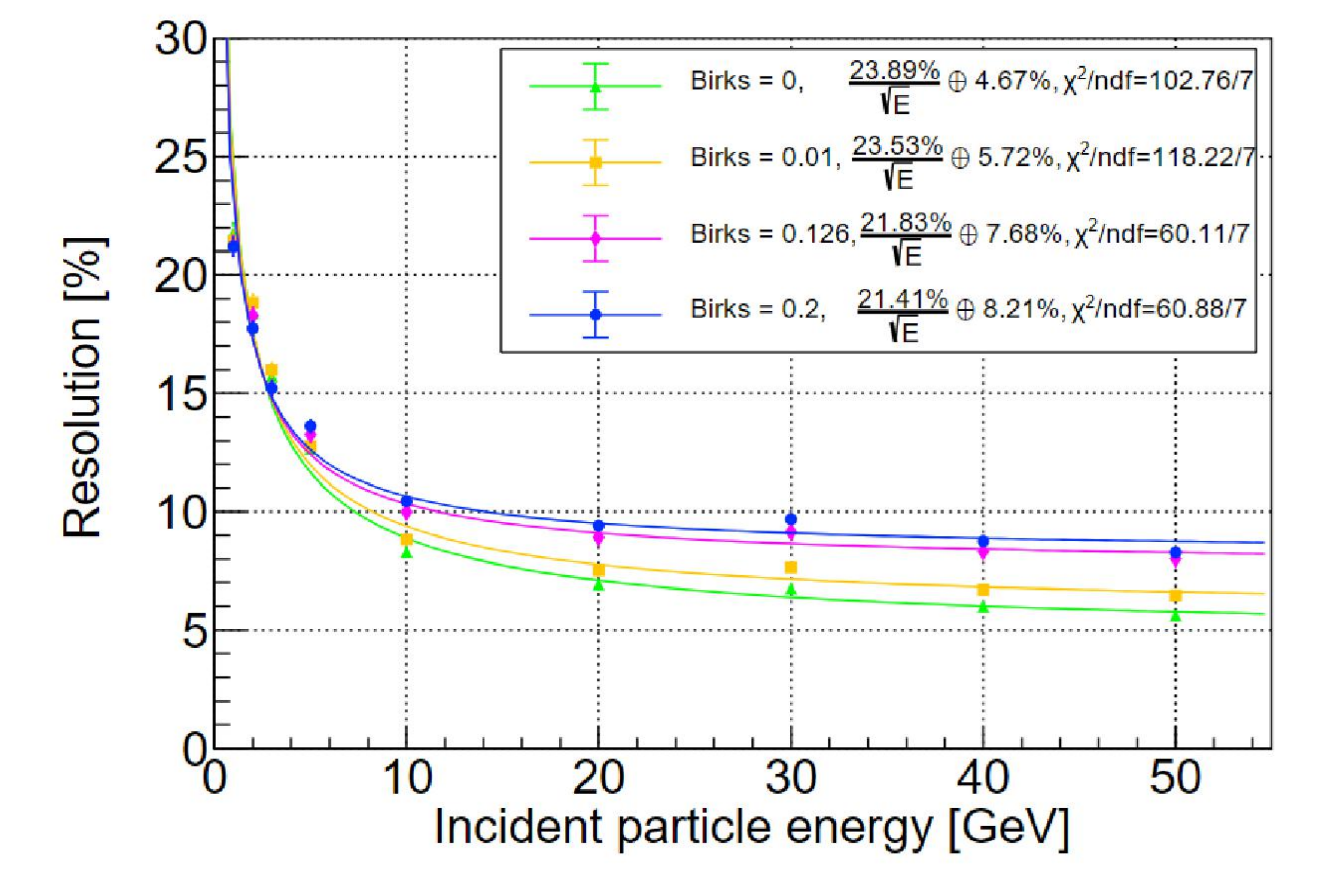
Step 3 (b): Verify the understanding: constant term reduced to ~3.4% for 48 layers 6 lambda when selecting events with shower starts in first 3 layers, i.e. events with less leakage.



- Constant term of GS-HCAL and PS-HCAL: longitudinal leakage from high energy hadrons (>60 GeV)
  - PS-HCAL prototype:5λ, $\frac{\sigma_E}{E} = \frac{56.2\%}{\sqrt{E}} \oplus 2.9\%$, with shower start and end selection (require shower start at first 5 layers).
  - GS-HCAL in full sim+digi: 6λ, $\frac{\sigma_E}{E} = \frac{29.8\%}{\sqrt{E}} \oplus 6.5\%$, all events in HCAL barrel.
    - In a large HCAL (80 layers, 10λ): $\frac{\sigma_E}{E} = \frac{24.7\%}{\sqrt{E}} \oplus 2.9\%$ (truth level, same for below)
    - Select events with shower start at first 3 layers: $\frac{\sigma_E}{E} = \frac{25.9\%}{\sqrt{E}} \oplus 3.5\%$
    - Only consider low energy beam ($E_{\pi-}$ from 0 to 30 GeV): $\frac{25.2\%}{\sqrt{E}} \oplus 2.9\%$

1.2 The Glass simulation: Birks effect

- Birks effect: scintillator non-linearity in light output caused by quenching.



- The Birks date will impact to the energy resolution: constant term.
- Truth energy in simulation, No digitization, no threshold.
- For BGO: Birks ~ 0.008;
- Lack of the GS measurement result;
- Just Suppose ~ 0.01;
- How to measurement?

Birks constant in different materials

$$\frac{d\mathcal{L}}{dx} = \mathcal{L}_0 \frac{dE/dx}{1 + kB \times dE/dx}$$

kB —Birks constant,

quantify the relationship between excitation molecular density and non-radiative relaxation in scintillation materials

dE/dx —Energy deposition of particles per unit length in a material

$\mathcal{L}$ —The light yield of a material under ionized particles

$\mathcal{L}_0$—Light yield of a material at low ionization density

	Material	Density (g/ml; g/cm^3)	kB ($\times 10^{-3}$gMeV^{-1}cm^{-2})
Organic Scintillator	C_8H_8	1.06	9
	PXE ($C_{16}H_{16}$)	0.7734	6.8
	C_9H_{12}	0.857	9.4
			42 (Proton)
Scintillation Crystal	$CdWO_4$	7.9	5.3
			5.1(F^- ions)
	CaF_2(Eu)	3.18	10.5
	$ZnWO_4$	7.41	9.0
	$CaWO_4$	**6.062**	**6.2**
			8(O^{2-} ions)
			9.8(Partial electron)
	CsI(TI)	4.53	3.2(Cs^+, I^-)
			2.3(α particle)
	CsI(Na)	4.51	5.5
	NaI(TI)	3.67	3.8(Initial value)
			6.5(Low energy)
			1.25(α particle)
	CeF_3	**6.16**	**11.1**
	BGO	7.13	8 (CEPC Setup)

How to test the Birks constant of GS

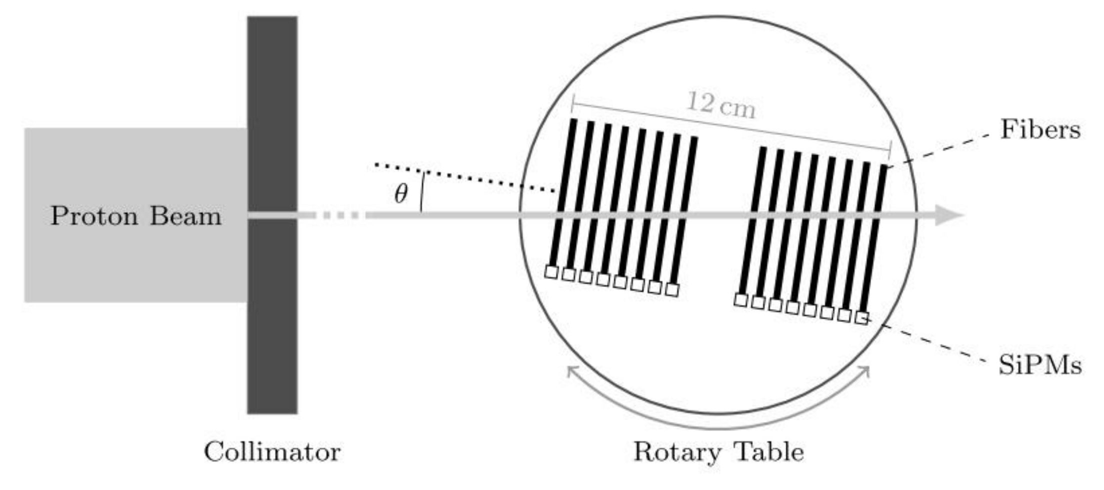
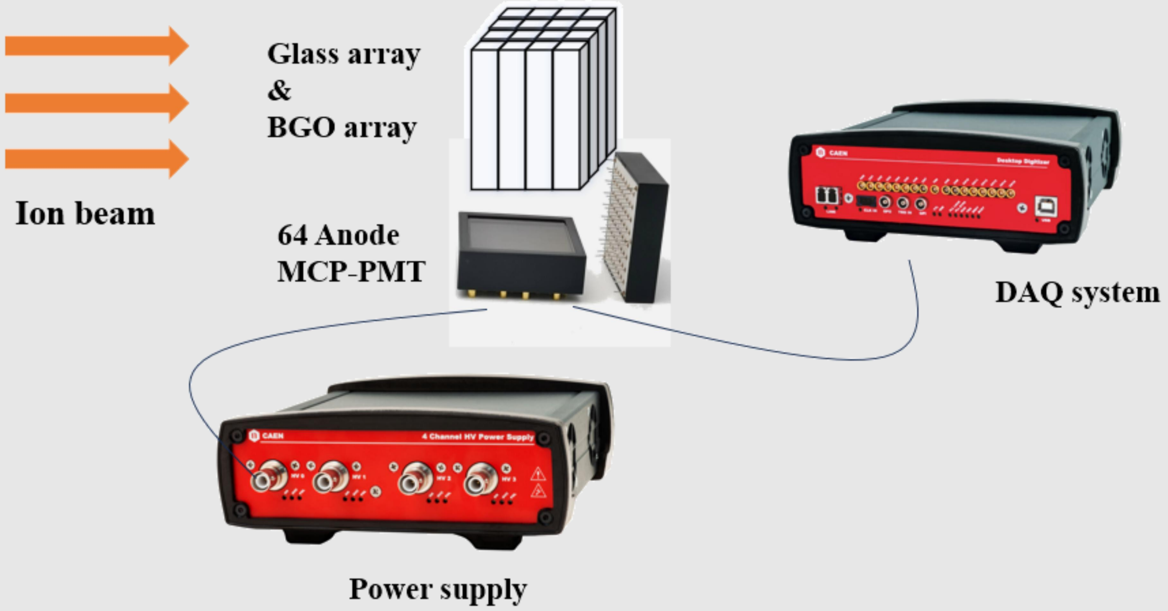


Fig. 1. Schematic of the experimental setup.



Experimental design

- Birks effect: scintillator non-linearity in light output caused by quenching.
- Birks constant of GS has a significant effect on the energy resolution of HCAL.
- The GS and BGO arrays will be prepared, tested under the **ion beam**, just like tested the data of LS in Lanzhou, and their Birks constants will be calculated (the work of one Doctor Student in 2025).

1.3 The Attenuation Length of GS

- **For theoretical light attenuation length:** $LAL = l/ln\frac{T(1-T_S)^2}{\sqrt{4T_S^4+T^2\left(1-T_S^2\right)^2}-2T_S^2}$

***LAL*—Theoretical light attenuation length**; l—Thickness of material

T—Actual transmittance; T_S—Theoretical maximum transmittance (related to refractive index)

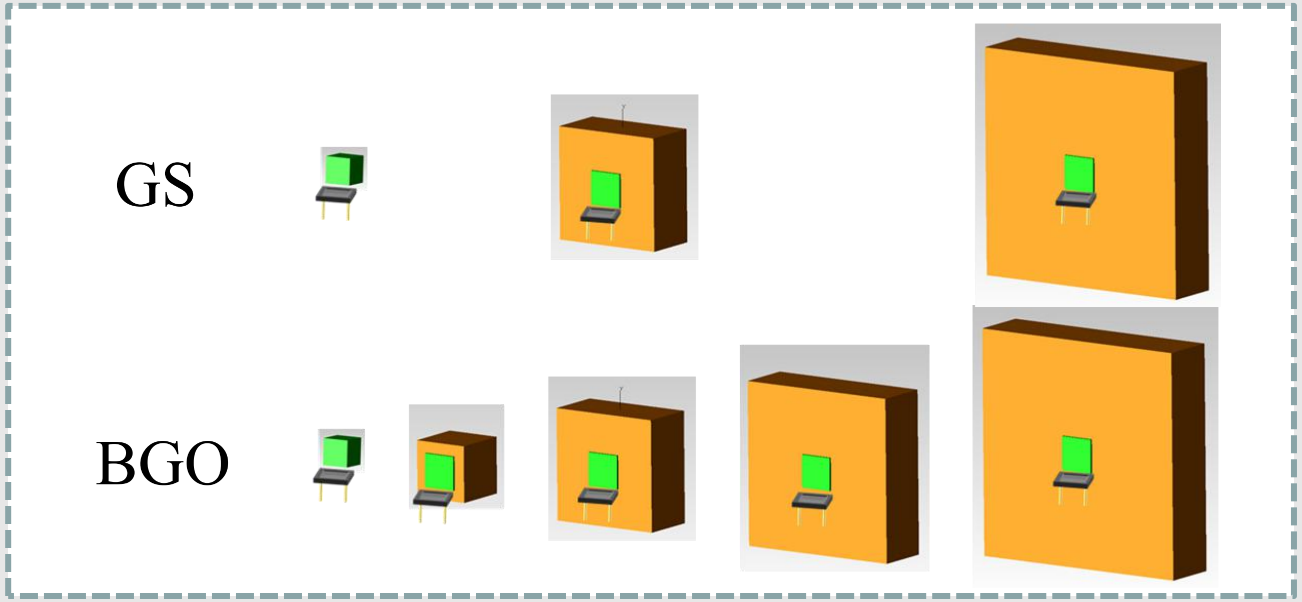
		300 nm	400 nm	500 nm	600 nm
LAL (cm)	BGO	1.5	222.4	270.2	304.8
	Glass (T)	0.16 (0.2%)	3.8 (66%)	21.9 (83%)	23.0 (83%)
	Glass (T_S)		14.2 (80%)	299.7 (86%)	5614 (86.4%)

- **For actual light attenuation length:** $q = q_0 \cdot e^{-\frac{L}{L_0}}$

q_0—Photon number at the starting position of scintillators; q—Photon number after propagating a certain distance;

L—Distance of light propagation; **L_0—Actual light attenuation length**

The phenomenon of the Size Effect on Light Output



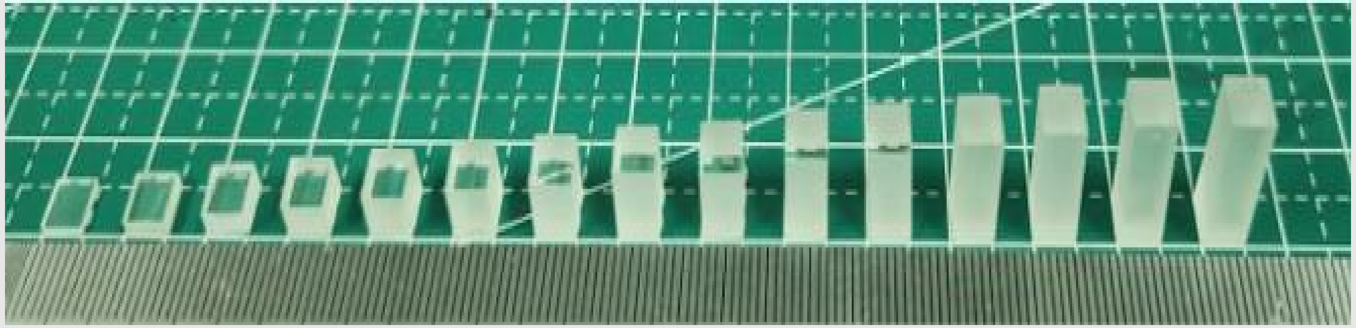
GS	T (%) @400 nm	LO (ph/MeV)	Norm.
5*5*5	74	1029	1
20*20*10	73	193	18.8%
40*40*10	66	180	17.5%

BGO	T (%) @400 nm	LO (ph/MeV)	Norm.
5*5*5	74	6970	1
10*10*10	75	3238	46.4%
20*20*10	76	2609	37.4%
30*30*10	76	1398	20%
40*40*10	75	1101	15.8%

- GS and BGO samples of different sizes were coupled with the same SiPM to study the size effect on light output (LO);
- Light output is nearly steady when GS cell size is larger than 20 mm, while a significant decrease for BGO was observed;
- More GS samples of different sizes are needed to test to understand the result; Why is 2cm?

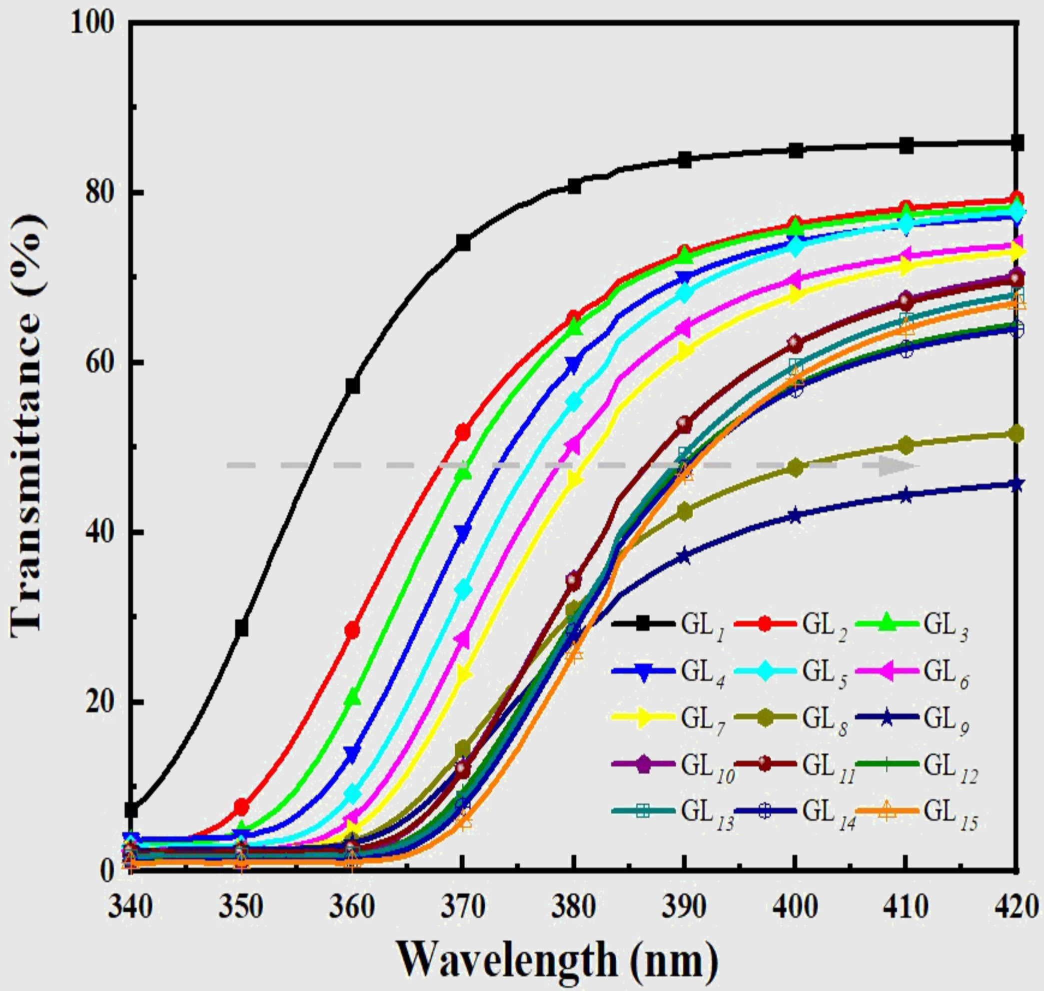
---the answer is the Attenuation Length of GS!

Theoretical Attenuation length of GS

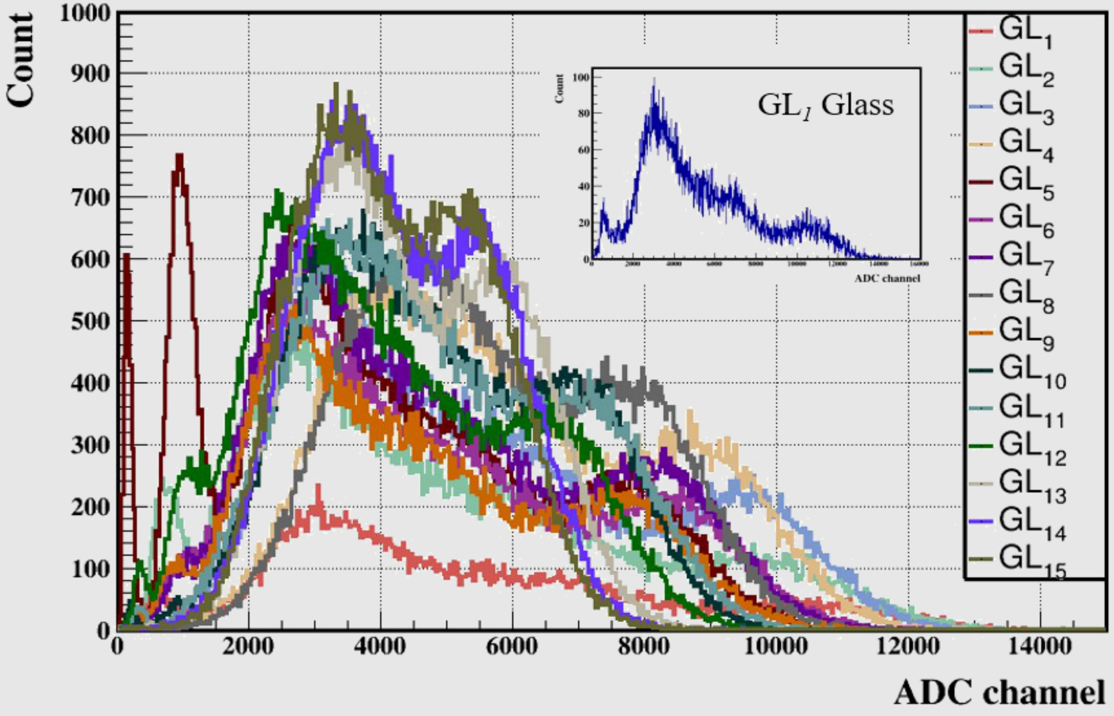


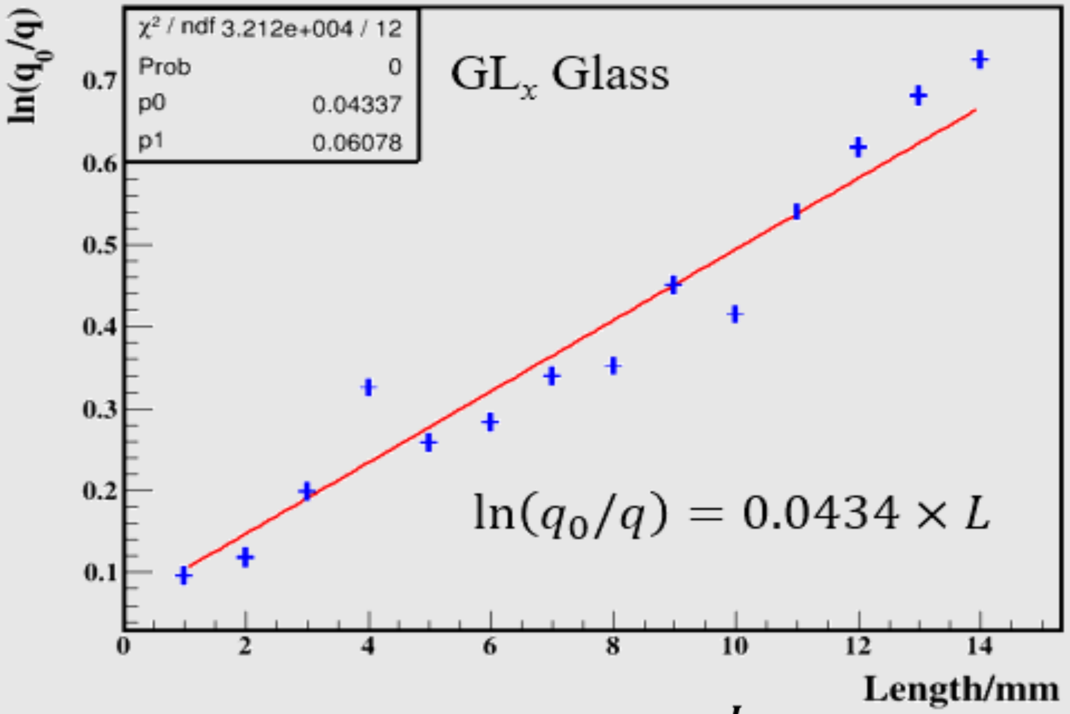
From BGRI

- $LAL = l/ln\frac{T(1-T_S)^2}{\sqrt{4T_S^4+T^2(1-T_S^2)^2}-2T_S^2}$
- **LAL=3.01cm@390nm； 4.57cm@400nm； 6.46cm@410nm**



Actual attenuation length Test





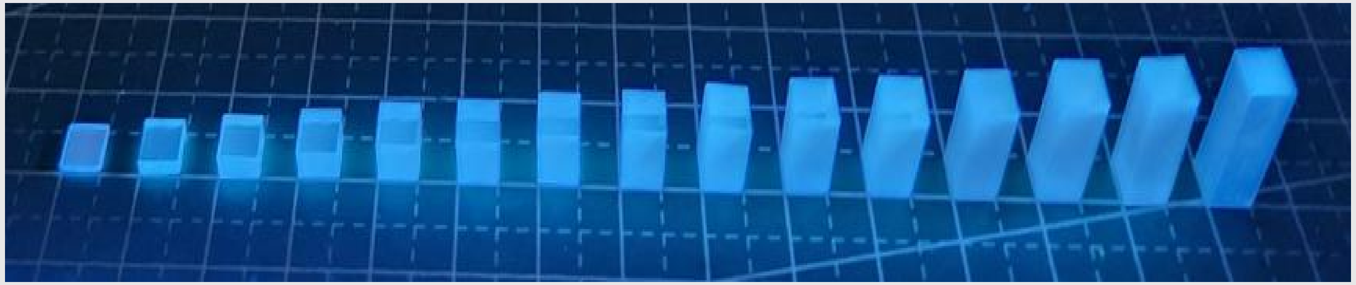
$$q = q_0 \cdot e^{-\frac{L}{L_0}}$$

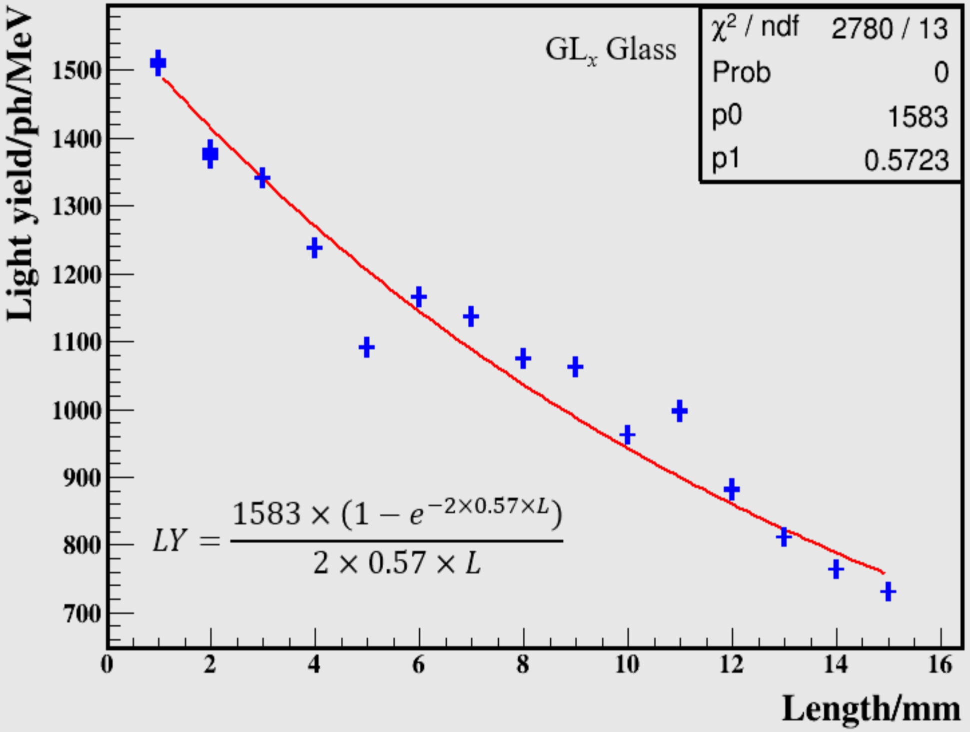
- GS of 1000 ph/MeV grade:
- **actual attenuation length→2.30 cm （around emission peak）<<3.01-6.46 cm**
- Defects and self-absorption in glass → lower light attenuation length

$L_0 = A \times LAL; \; A = 0.36\sim0.76$

Attenuation length --> The Intrinsic Light Yield

	Light yield(ph/MeV)
GL_1 glass	1504±7
GL_2 glass	1367±9
GL_3 glass	1337±3
GL_4 glass	1233±3
GL_5 glass	1087±4
GL_6 glass	1162±3
GL_7 glass	1133±3
GL_8 glass	1071±3
GL_9 glass	1058±4
GL_{10} glass	959±3
GL_{11} glass	993±4
GL_{12} glass	877±4
GL_{13} glass	810±2
GL_{14} glass	761±2
GL_{15} glass	728±2





$$LY = LY_0 \frac{1 - e^{-2\mu h}}{2\mu h}$$

LY_0—Intrinsic light yield

μ—Light loss coefficient (cm^{-1})

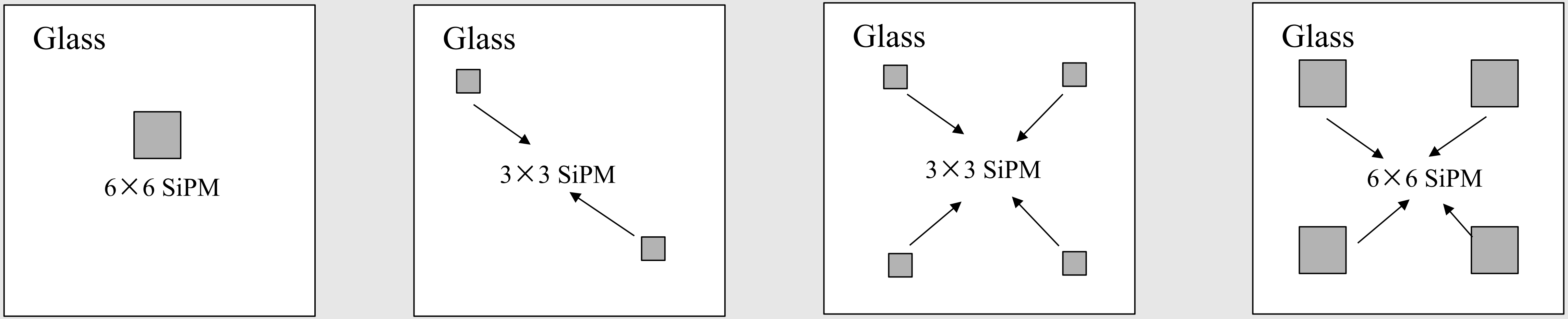
h—Thickness

- **GS of 1000 ph/MeV grade:**

LY_0=1583 ph/MeV; μ=0.57 cm^{-1}

1.4 The 4SiPM+1GS Cell design

Design of SiPM coupled glass



SiPM coupled glass	P.E. Number		
	TiO_2	Teflon	ESR
Single 3×3 mm	28		
Single 6×6 mm	**40**	**57**	**36**
Double 3×3 mm	36	61	32
Double 6×6 mm	71		
Four 3×3 mm	**83**	**96**	**58**
Four 6×6 mm	119	168	100

PCE：

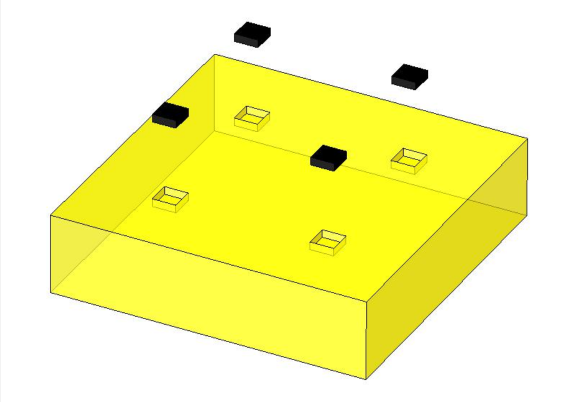
- Four 3*3 mm^2 SiPM >> Single 6*6 mm^2 SiPM ≈ Double 3×3 mm^2 SiPM
- Teflon >> TiO_2 > ESR

Plan

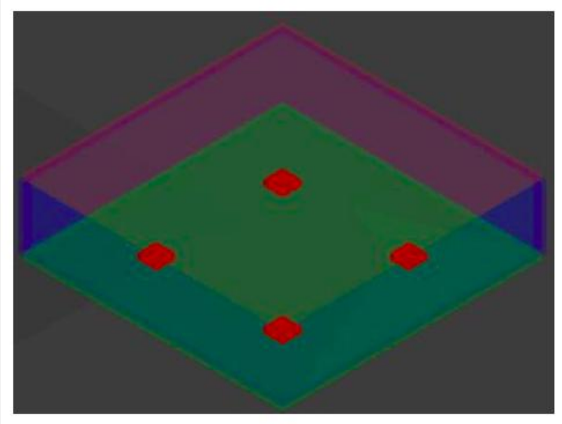
Calibrate each channel and SiPM

Try Al and Ag reflectors

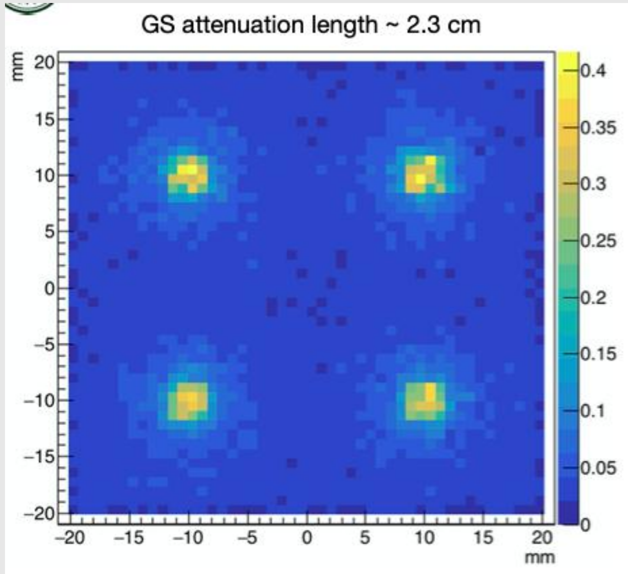
The simulation of 4SiPM result for ER

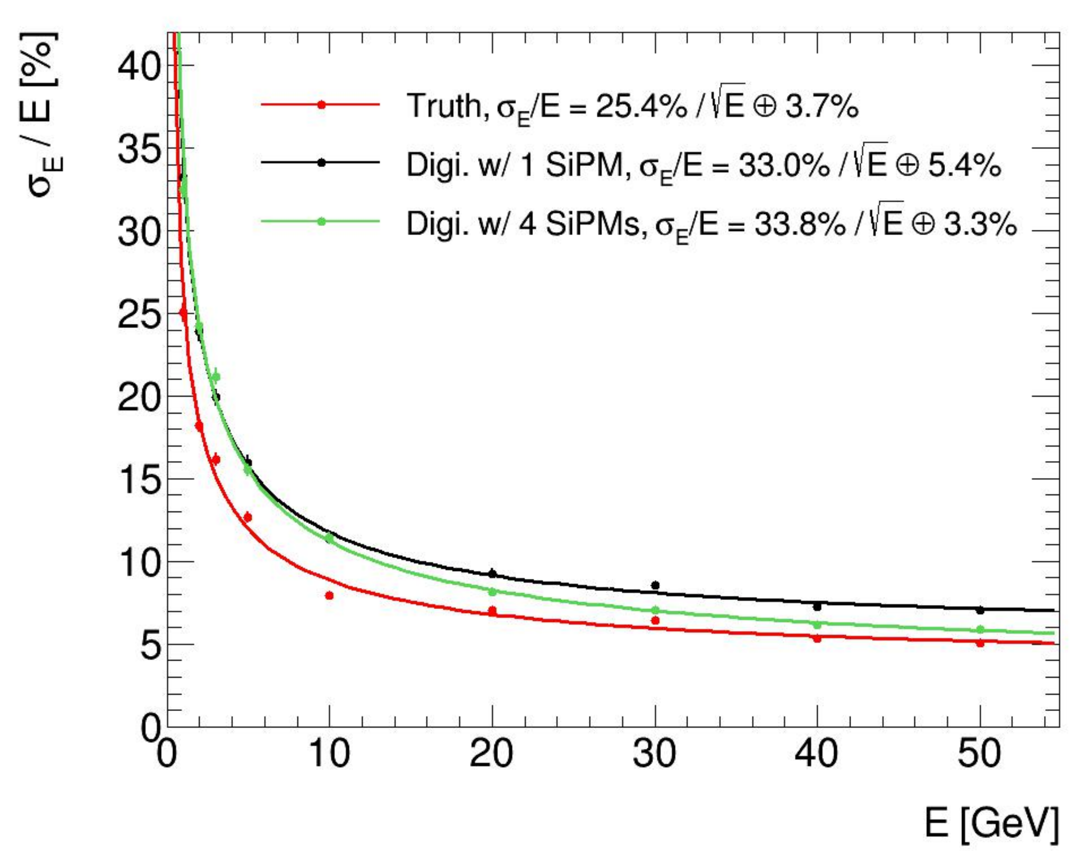


Mechanics



Design

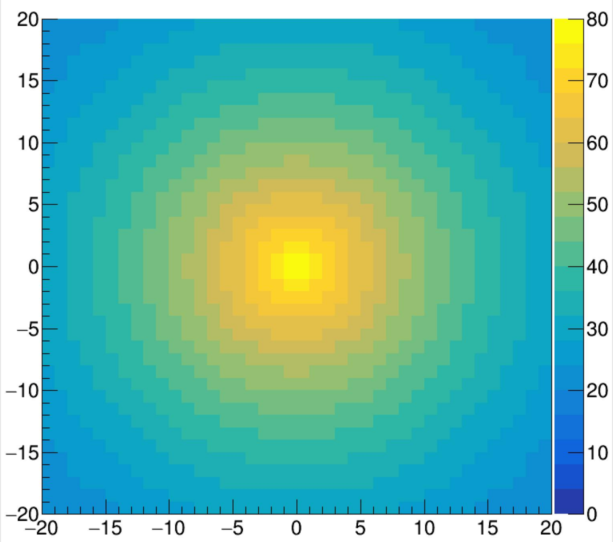




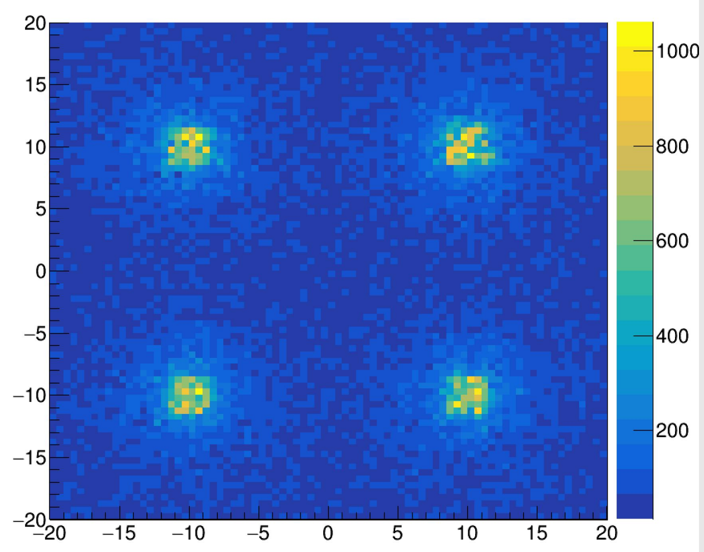
- **Energy resolution:**
  - π^- single p, θ~90°, ϕ~0°, Birks constant 0.
  - Shower start at first 12 cm (4 layers)
  - 4 SiPMs can improve the tile uniformity and reduce the constant term.

Glass simulation: attenuation length + 4SiPM Cell

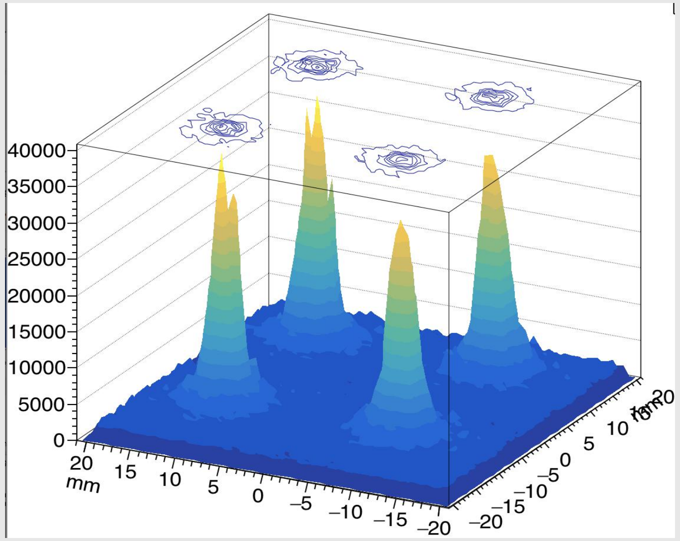
- **Impacts in a 40×40×10 mm tile: tile non-uniformity**
  - A combined effect from reflect + transportation + attenuation + ..., can only be modeled with optical simulation.
    - For 1 $6\times6\,mm^2$ SiPM readout at central: a Level-0 toy model $E_{det} = \Sigma_i E_{dep}^i \times e^{-L_i/L_{att}}$.
    - For 4 $3\times3\,mm^2$ SiPMs readout: optical simulation with muon.
  - A (very rough) cross check: tile non-uniformity scan with beam test.



Toy model: tile response for $L_{att} = 20mm$, 1 SiPM

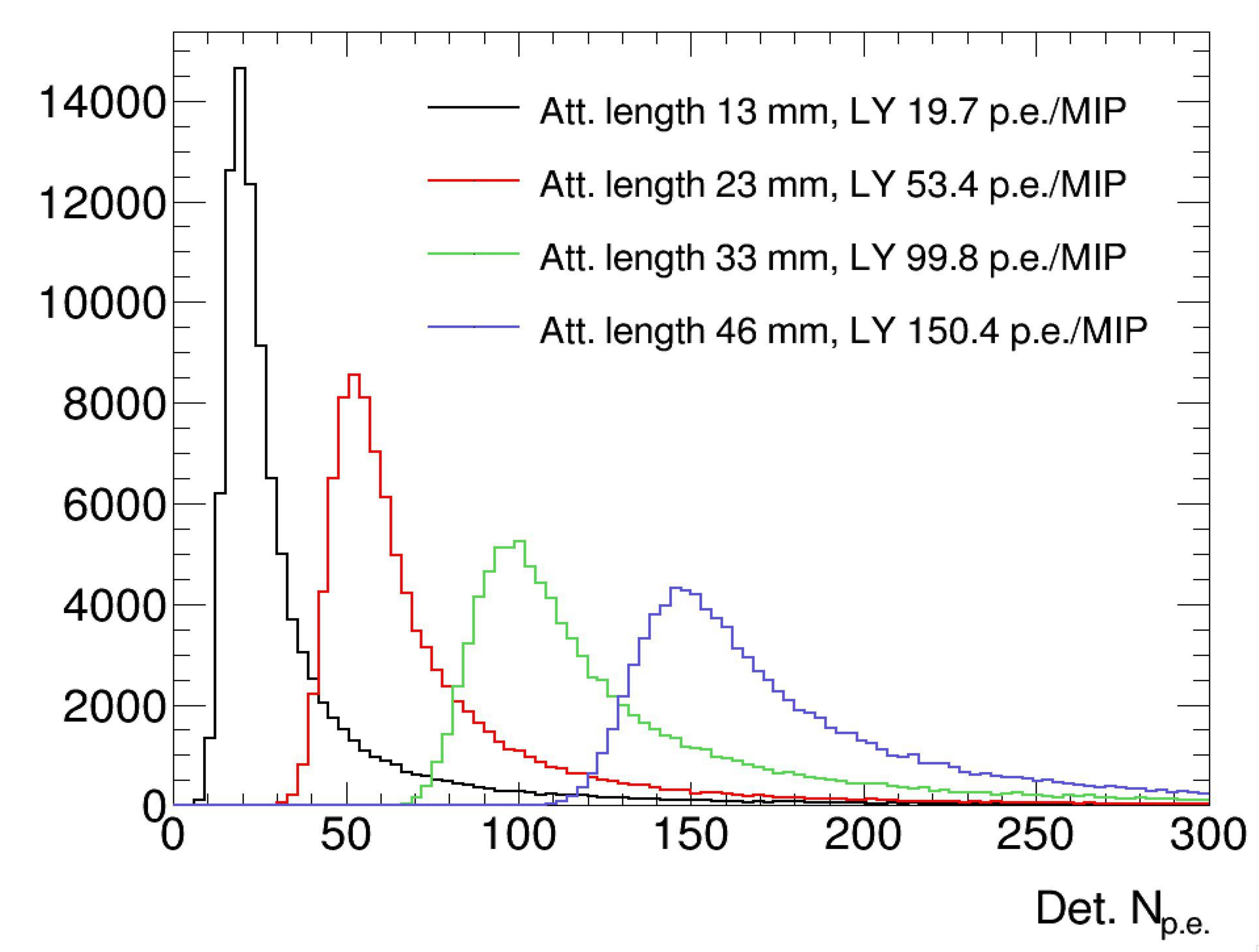


Optical simulation for $L_{att} = 23\,mm$, 4 SiPMs

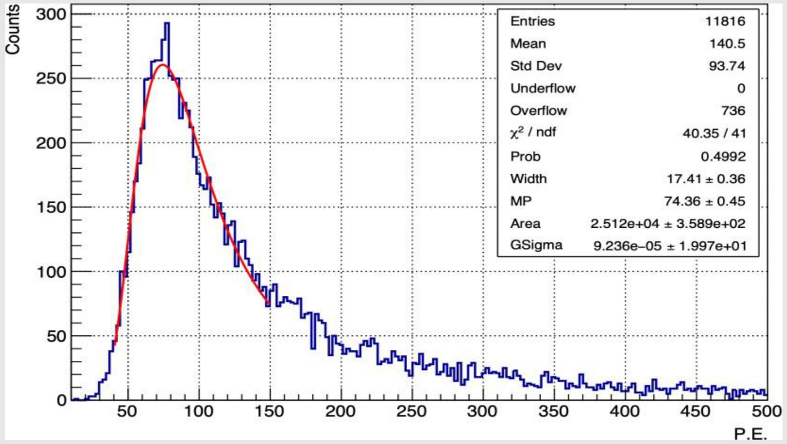


the average received P.E by SiPM

(1) Attenuation length simulation VS LY



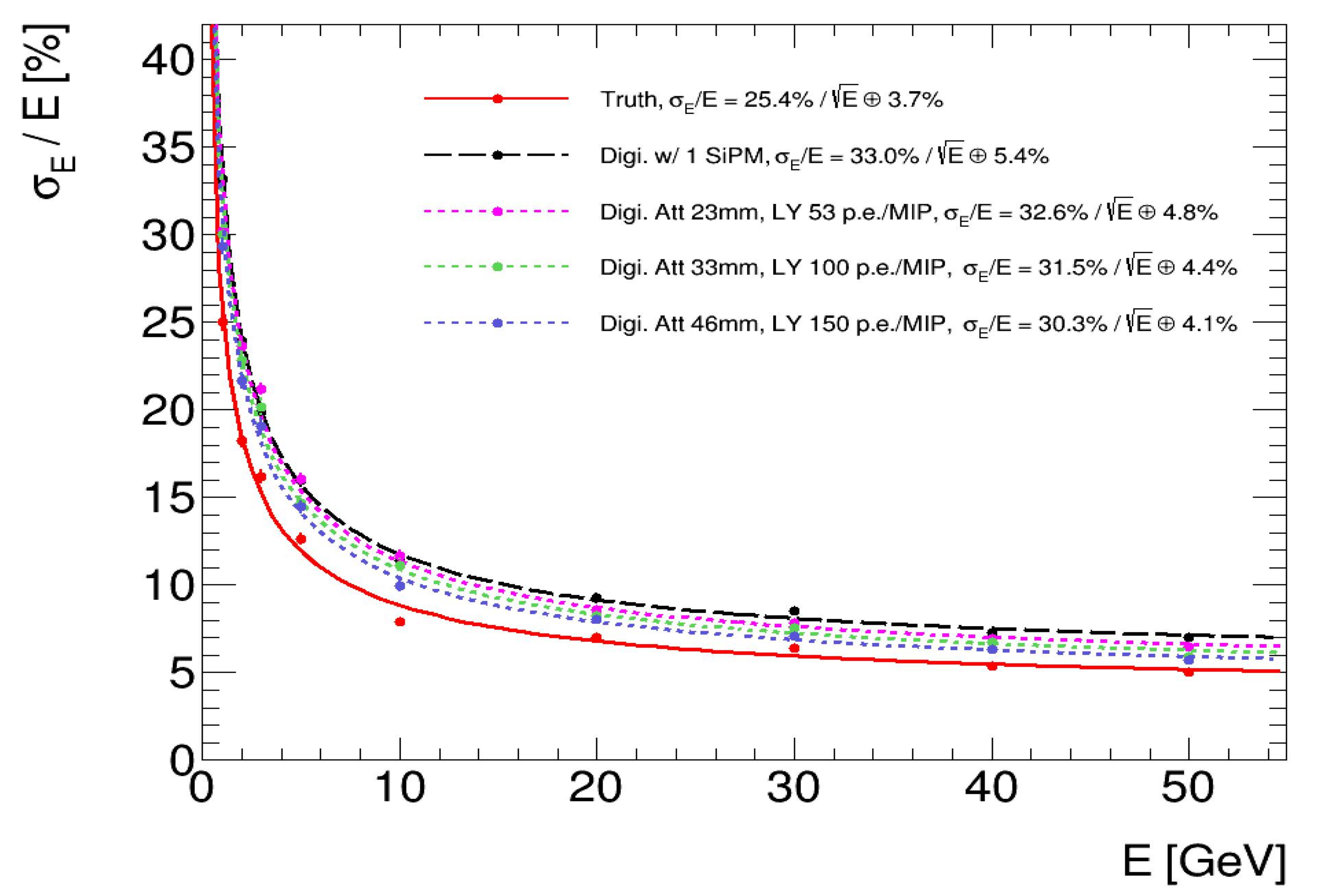
Increasing the attenuation length can improve the energy resolution of HCAL When the light yield of GS unchanged and the attenuation length of GS is doubled (4.6cm), the average received P.E. increases by almost three times



MIP signal in beam test (2023, CERN)

- **Typical Light Yield:** 500 – 600 ph/MeV
- **Typical MIP response:** 60 – 70 p.e./MIP

(2) Glass simulation vs attenuation length

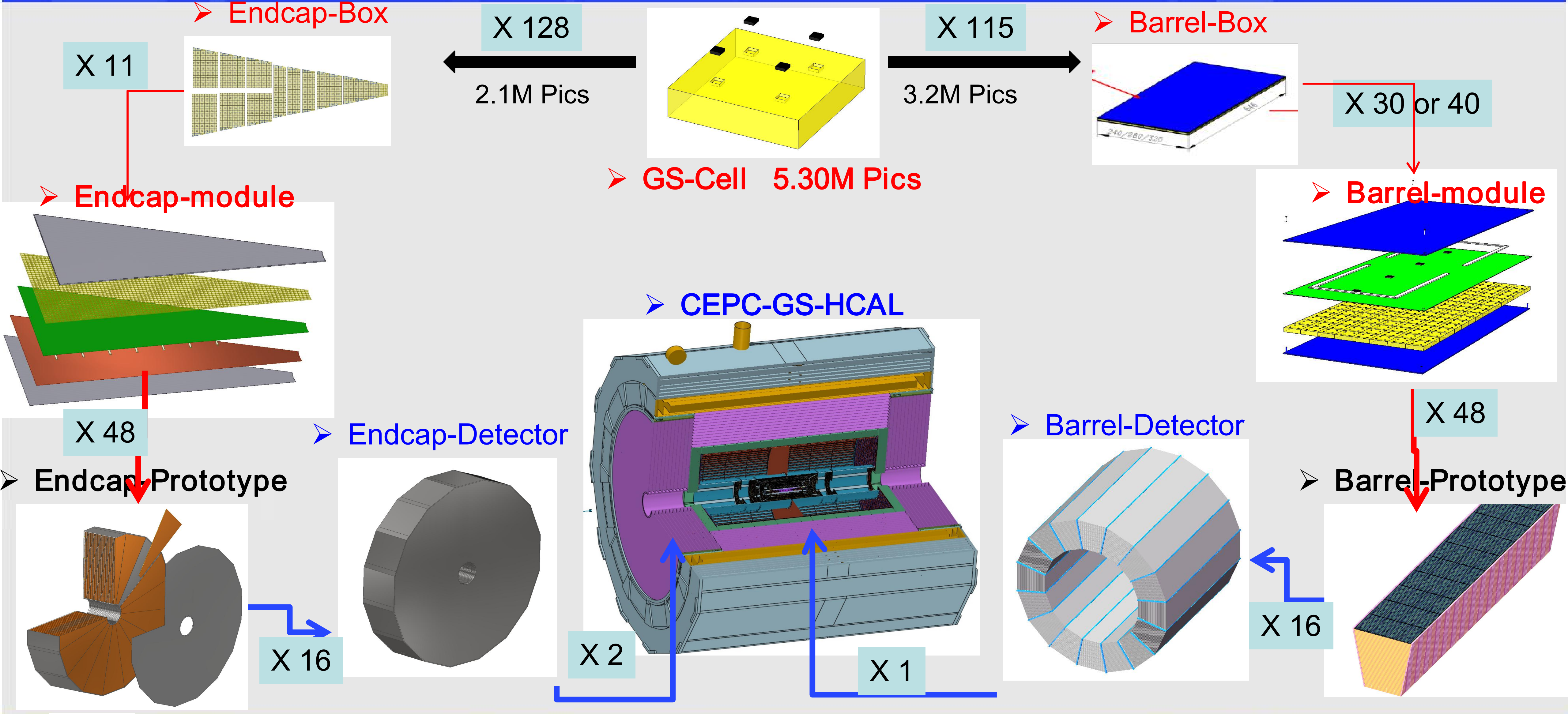


- Energy resolution vs attenuation length
- Implement the light yield map into HCAL digitization in CEPCSW
- Birks constant 0,
- threshold 0.1 mip,
- no SiPM/electronics digitization.

Outline

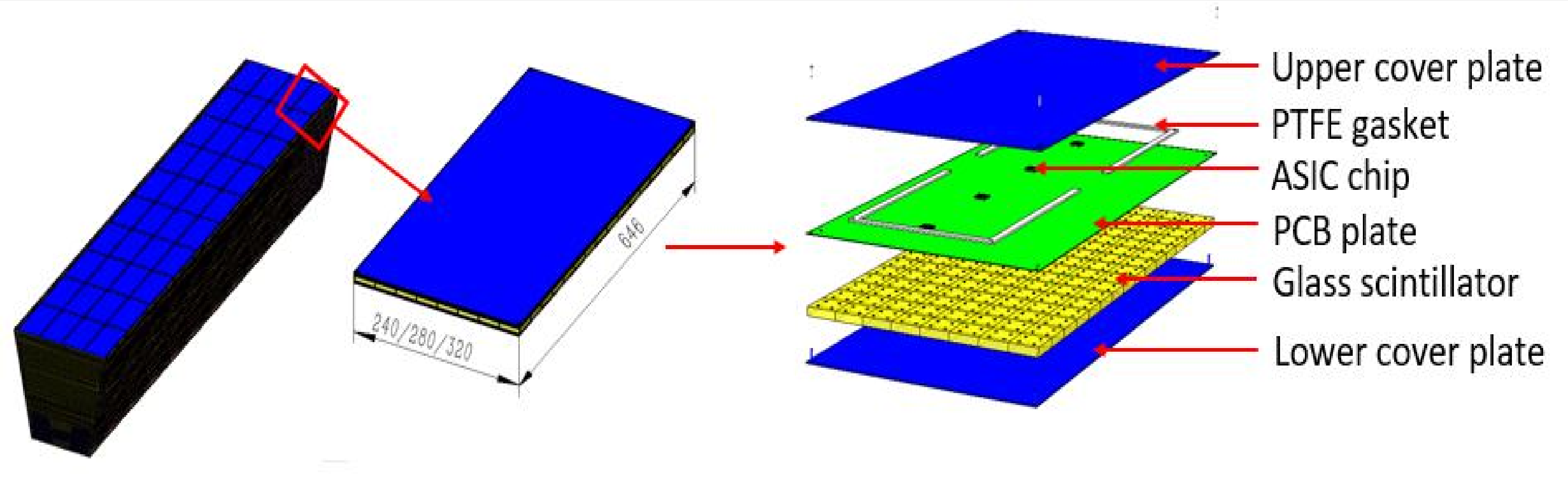
- **1. The Design of the HCAL ;**
  - 1.1. The HCAL Constant Term;
  - 1.2. The Glass simulation: Birks effect;
  - 1.3. The Attenuation Length of GS;
  - 1.4. The 4SiPM+1GS Cell design;
- **2. The Mechanics of the HCAL ;**
- **3. The Progress of GS;**

2.1 the Conceptual Detector Design of GS-HCAL



The Box Design for the **GS** in the Prototype

- The bias voltage for the SiPMs in GS-AHCAL is applied as a uniform base bias through a PCB-Box.
- All the SiPM in the same Box will using the same power supply!



Glass Cell: 5.3M

SiPM: 5.3X4 ?

Box: 34K

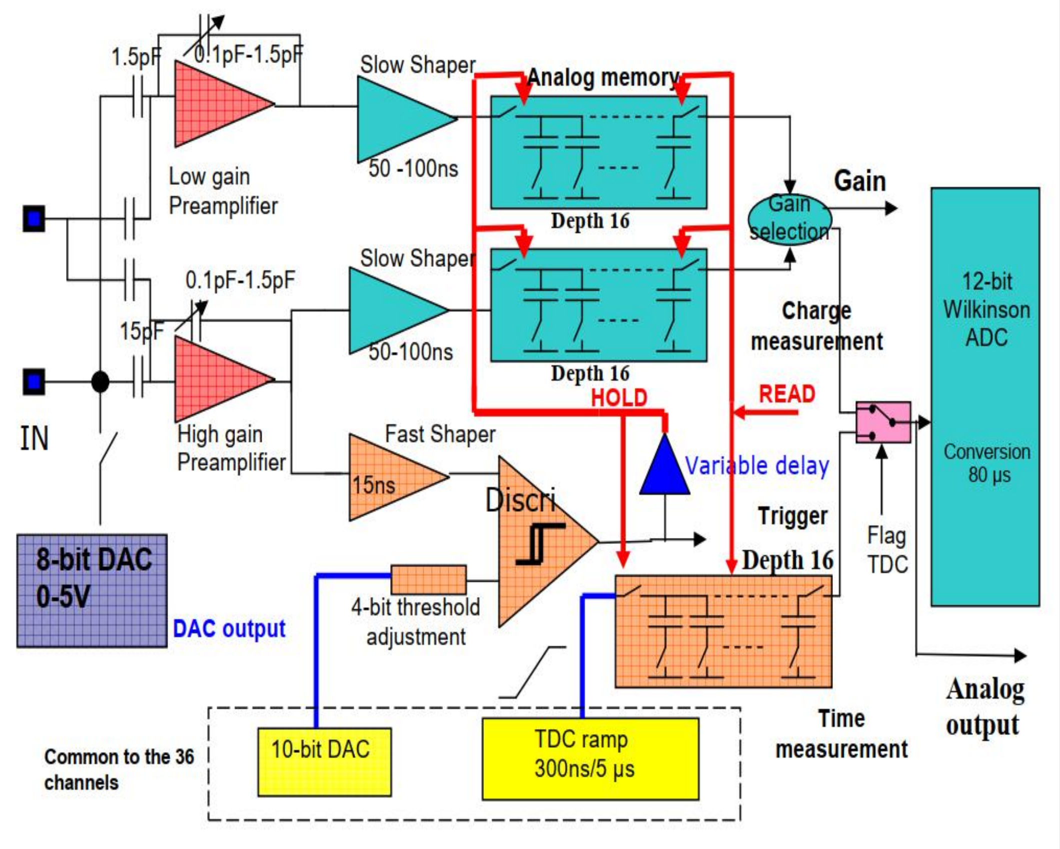
Power supply： 34K

- Endcap Part:There are 6144 boxes in total, 2230272 glass scintillator ，
- Barrel Part: There are 27840 boxes in total, 3,212,800 glass scintillator

The Box Design for the **SiPM** in the Prototype

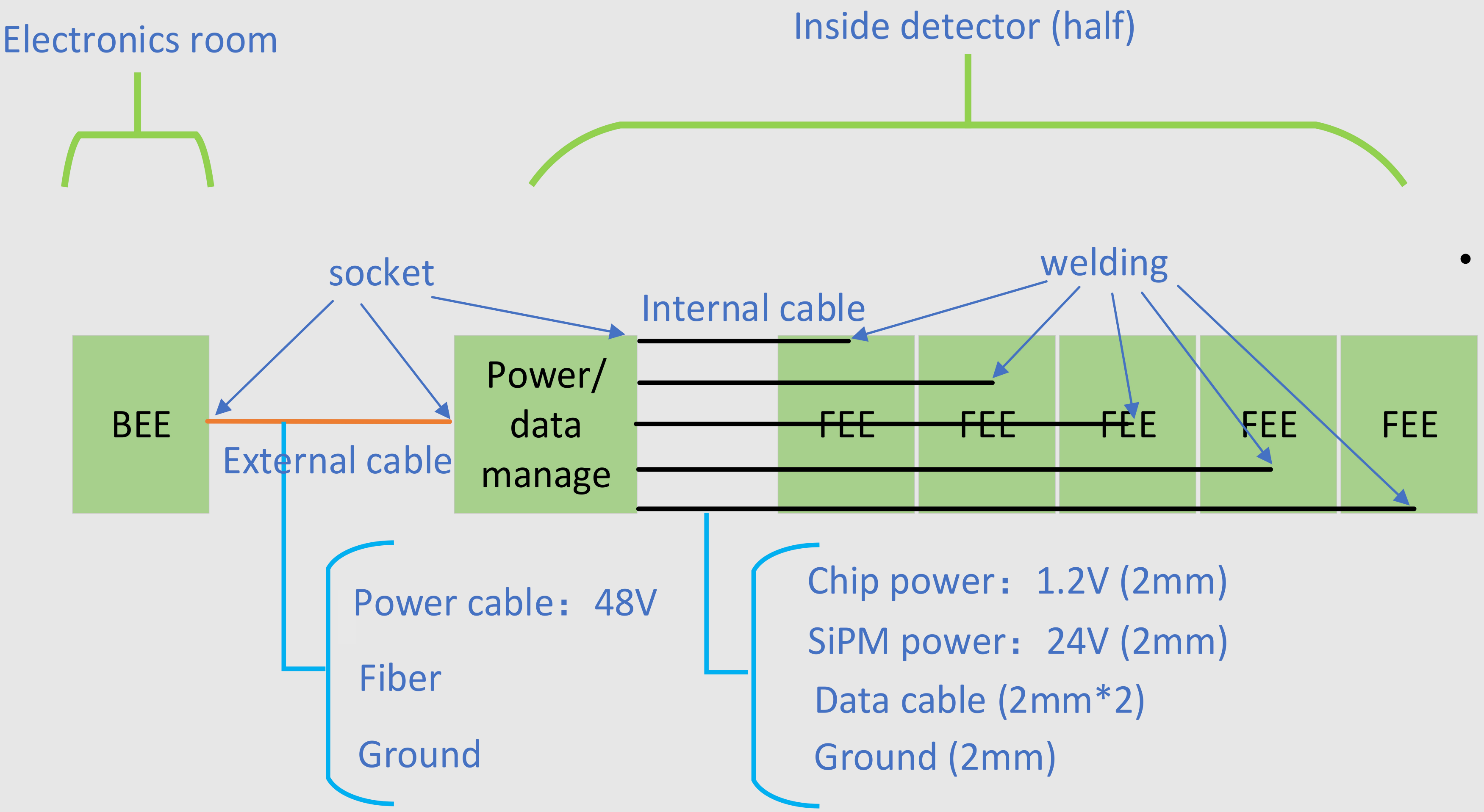
SiPM bias voltage control

- The ASIC chip has a regulation capability of ±0.5V for the bias voltage, which is less than the 5V regulation capability of SPIROC2E.
- This limitation is due to the ASIC chip being powered at 1.2V. However, experimental tests have shown that using ±0.5V regulation for the SiPMs is feasible.
- In the utilization of SiPMs, they will also be categorized, with those having similar bias voltages being grouped together in one Box.



SPIROC2E-ASIC
bias voltage module

The Box Design for the Cables in the Prototype



- AWG18
  - Diameter : 1.02mm,
  - Current : 3.2A/3.7A,
  - Resistor : 21.4Ohm/km

  AWG12
  - Diameter : 2.05mm,
  - Current : 13.1A/14.9A,
  - Resistor : 3.3Ohm/km ）

- Basis for power consumption
  - Chomin 15mW/Ch, Chitu 0.75W, Kinwu 0.25W, DCDC efficiency : 85%
- FEE power： 1.92W （ 1.2V*1.6A）
- Single external power cable power： 12.5W （48V*0.26A）

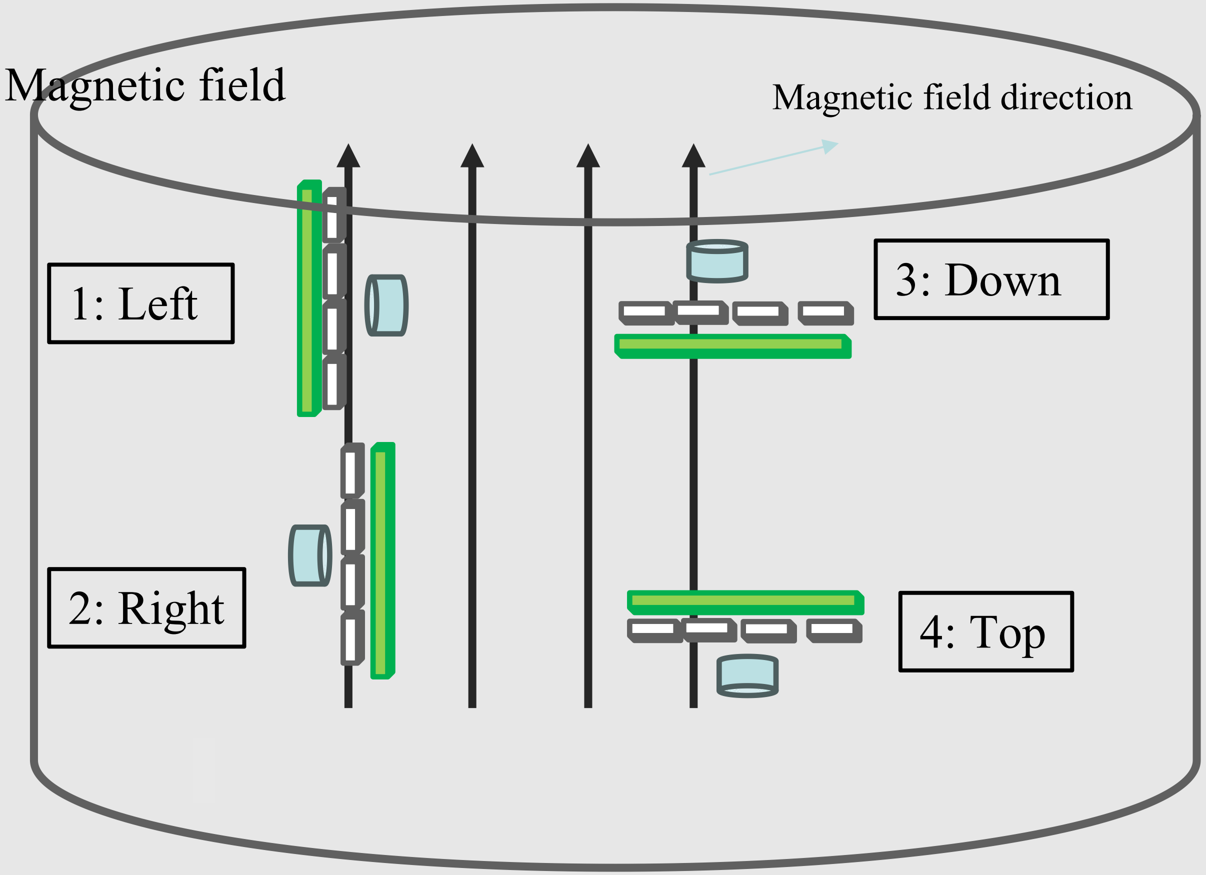
- Internal cable length : 3m (Max) ,
  Cable loss power : 0.16W,
  percentage of power supply : 1.3%（AWG18）
- External cable length : 100m (estimated)
  - Cable loss power : 0.145W, percentage of power supply : 1% （if AWG18）
  - Cable loss power : 0.022W, percentage of power supply : 0.18% （if AWG12）

- AWG18
  - Diameter : 1.02mm,
  - Current : 3.2A/3.7A,
  - Resistor : 21.4Ohm/km
- AWG12
  - Diameter : 2.05mm,
  - Current : 13.1A/14.9A,
  - Resistor : 3.3Ohm/km ）

Outline

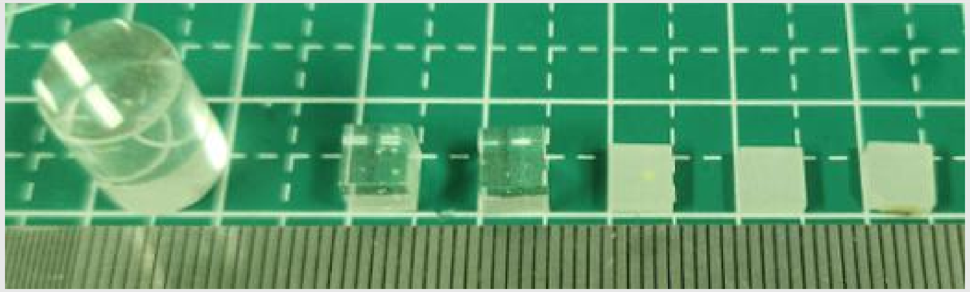
- 1. The Design of the HCAL ;
- 2. The Mechanics of the HCAL ;
- 3. The Progress of GS;

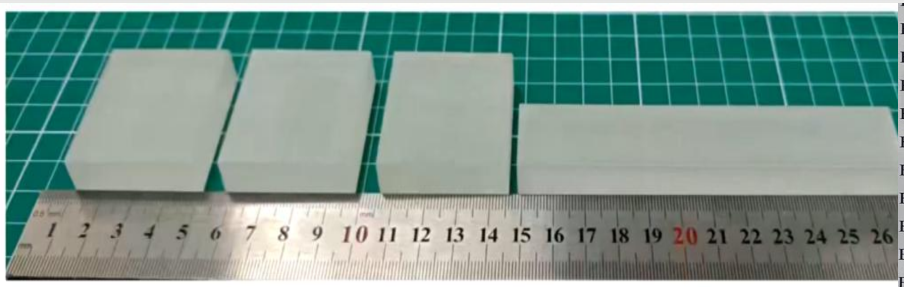
3.1 Scintillation properties under magnetic field



- The scintillation properties of GS were tested under magnetic field and different directions.

3.2 Mechanical property test



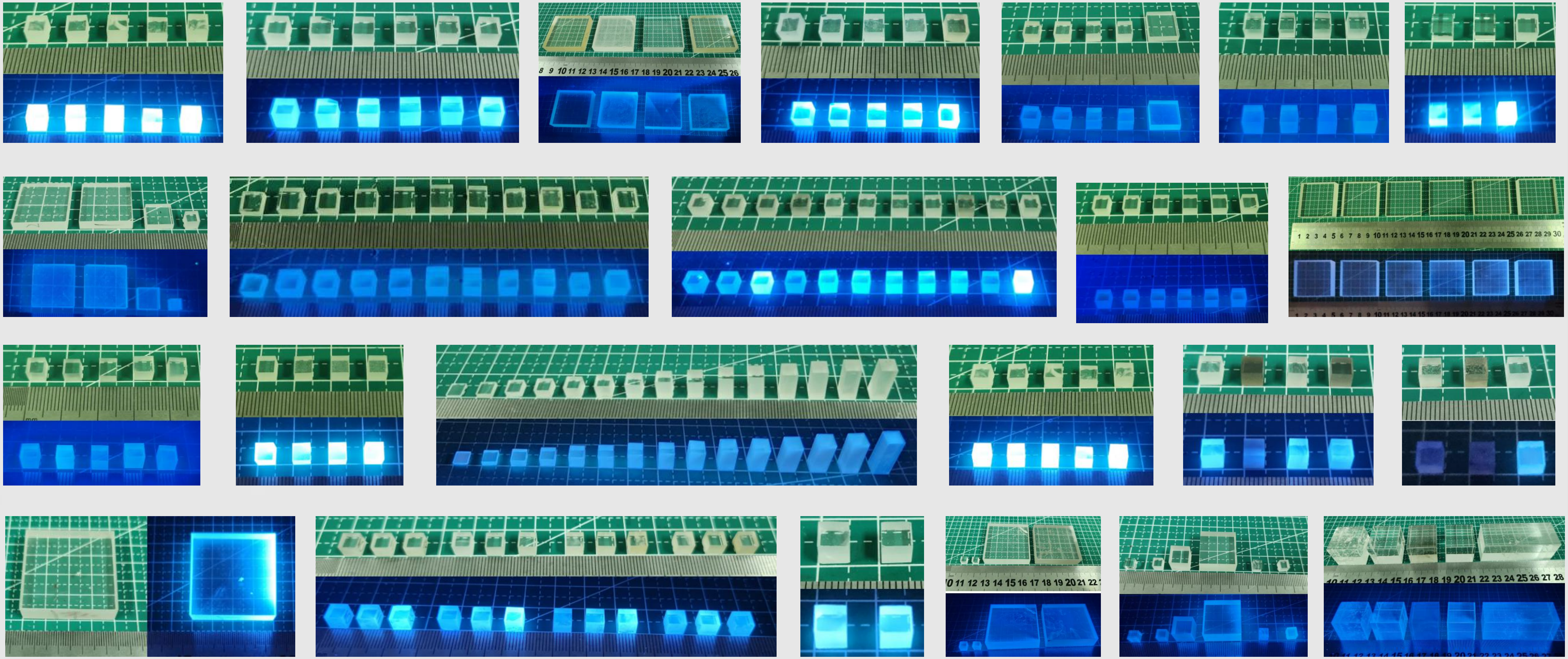


Test item	Result
Vickers-hardness (kgf/mm^2)	750
Young's modulus (Gpa)	132.71
Shear modulus of elasticity (Gpa)	51.35
Bulk modulus (Gpa)	106.49
Poisson's ratio	0.29
Fracture toughness (Mpa·m$^{1/2}$)	0.84
Coefficient of thermal expansion (1/K)	$7*10^{-6}$

Item to be tested	Dimension requirement (mm)
Compress	40*40*10
Stretch	Φ10*12.5
Bending strength	120*20*10
Coefficient of thermal expansion	5*5*2
Thermal conductivity	40*40*10

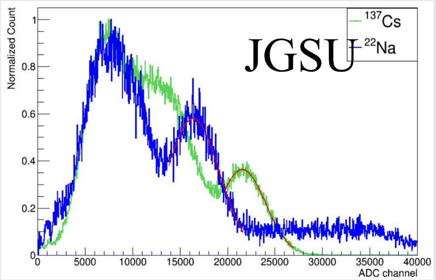
- **The three company have already produced different size of the GS for the mechanical property test.**

3.3 The GS Samples produced （>1000）

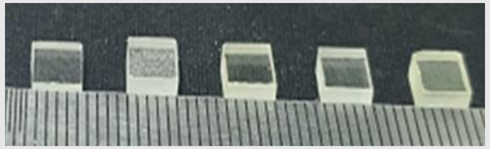


3.4.1 The GS1 (5mm³)

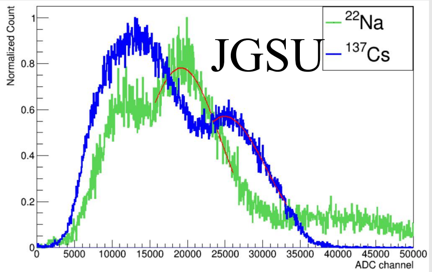
- Density~4.5 g/cm³
- LY=802 ph/MeV
- ER=26.8%
- Decay=262 (18%)
  1235 ns



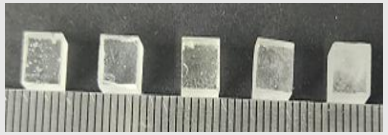
2021.11



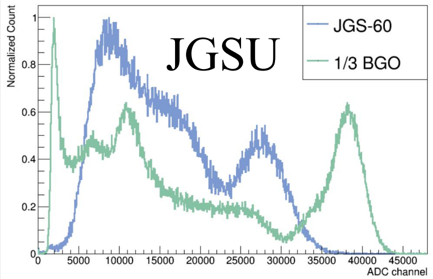
- Density~6.0 g/cm³
- LY>1000 ph/MeV
- ER=49.6%
- Decay=847 ns



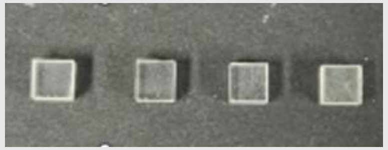
2022.11



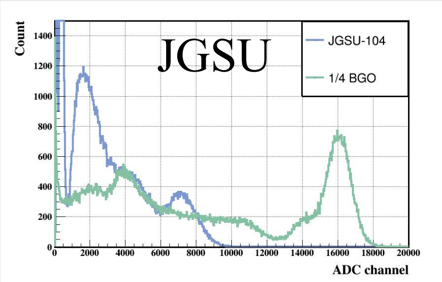
- Density~6.0 g/cm³
- LY~1100 ph/MeV
- ER=24.4%
- LO in 1μs=899 (84%)
- Decay=92 (8%)
  473 ns



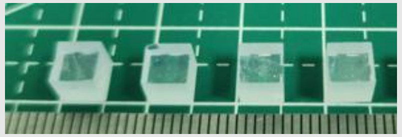
2023.02



- **Density~6.0 g/cm³**
- **LY=985 ph/MeV**
- **ER=30.3%**
- **LO in 1μs=982 (99%)**
- **Decay=36 (8%)**
  105 ns



2024.04

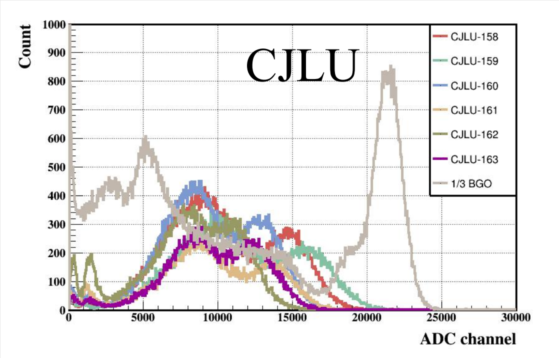


(2022.05)Opt. Mater. 2022(130): 112585

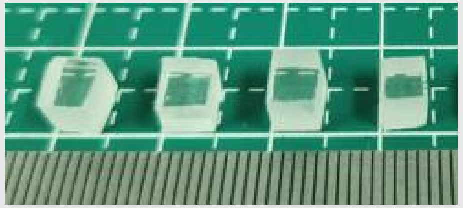
(2024.06) J. Mater. Chem. C, 2024, 12, 11149–11156

3.4.2 The GS1+ ($5mm^3$)： LY>2000 ph/MeV

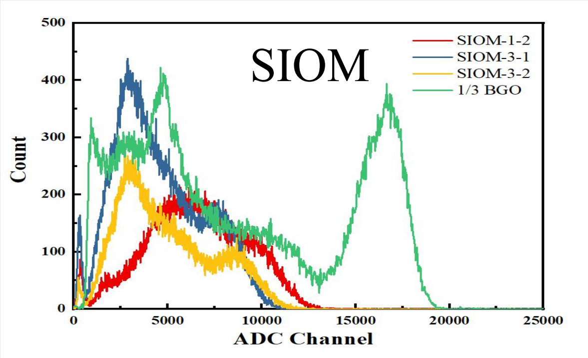
- Density~5.6 g/cm^3
- LY=2202 ph/MeV
- ER=27.7%
- Decay=129 (6%), 2466 ns



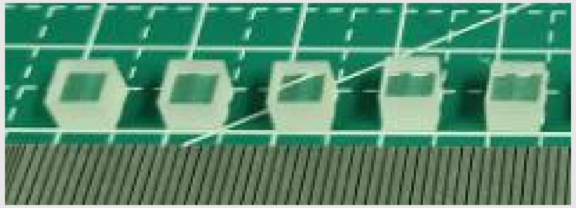
2024.04



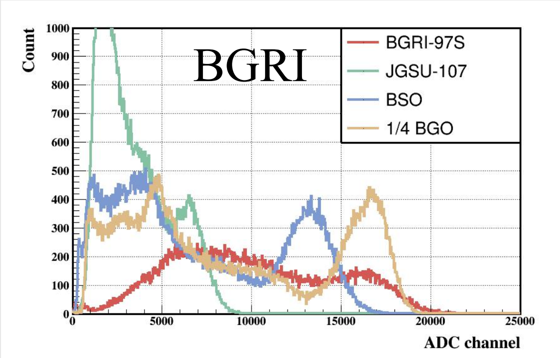
- Density~6.0 g/cm^3
- LY=2005 ph/MeV
- ER=37.6%
- Decay=111 (5%), 1063 ns



2024.06

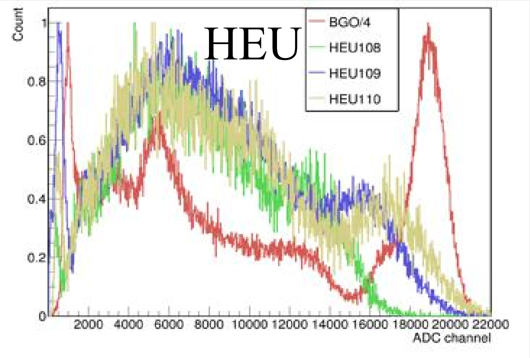


- **Density~6.0 g/cm^3**
- **LY=2455 ph/MeV**
- **ER=25.8%**
- **Decay=101 (2%), 1456 ns**

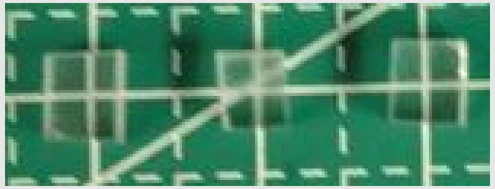


2024.06

- Density~5.1 g/cm^3
- LY=2066 ph/MeV
- ER=30.2%
- Decay=125 (4%), 1782 ns

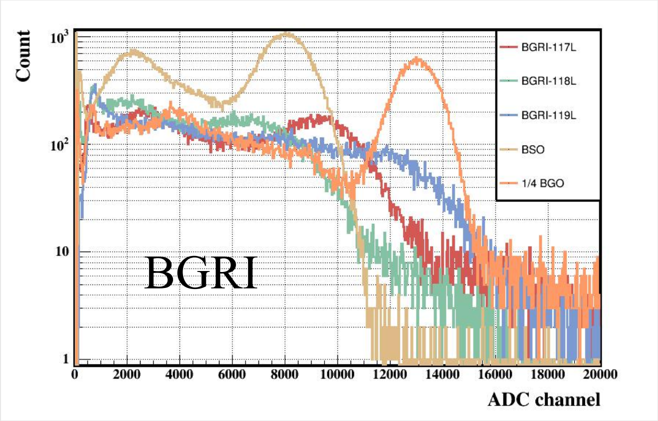


2024.08

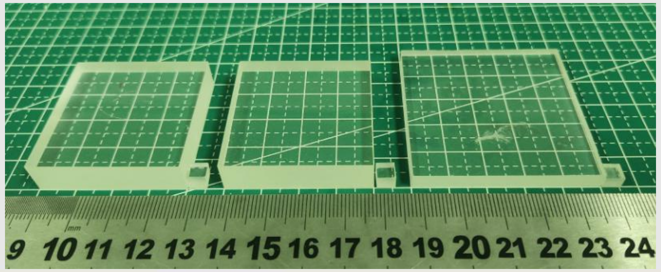


3.4.3 The GS1 (4cmX4cmX1cm)

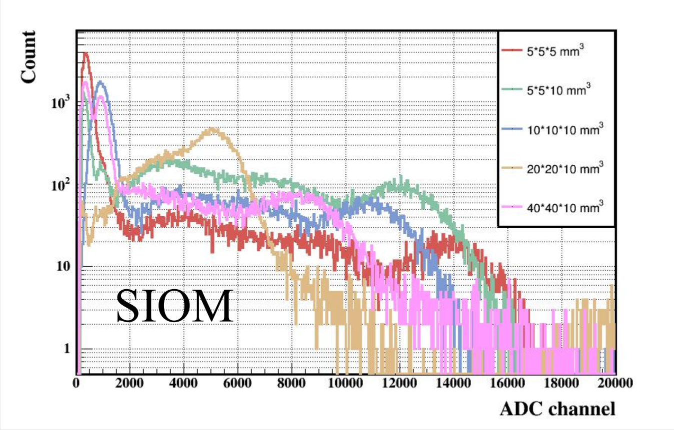
- Size=40*40*10 mm^3
- Density=6.0 g/cm^3
- LY=1025 ph/MeV
- ER=40.9%
- LO in 1μs=863 (84%)
- Decay=81 (7%), 520 ns



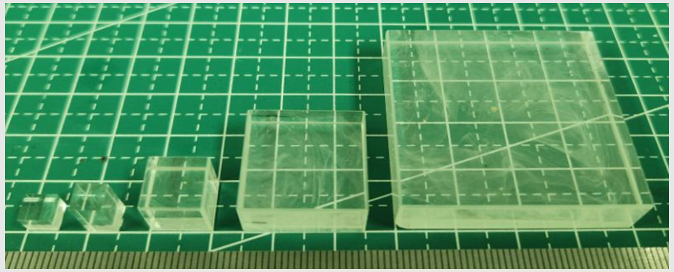
2024.12



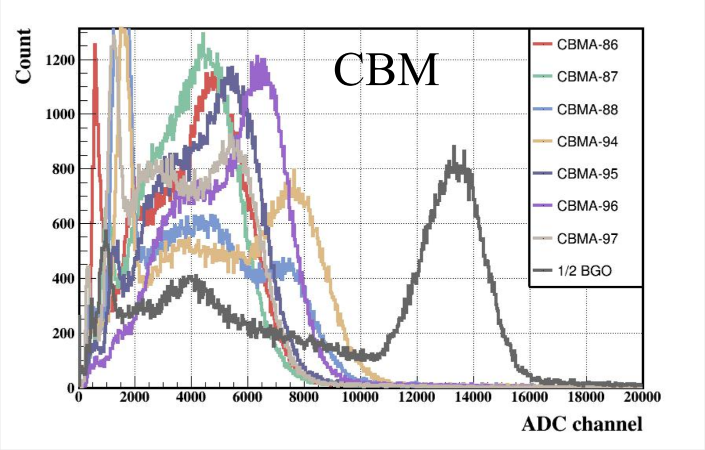
- Size=40*40*10 mm^3
- Density=6.0 g/cm^3
- LY=861 ph/MeV
- ER=41.7%
- Decay=114 (11%), 516 ns



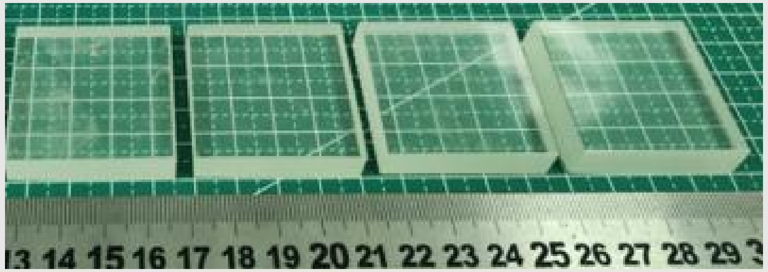
2024.10



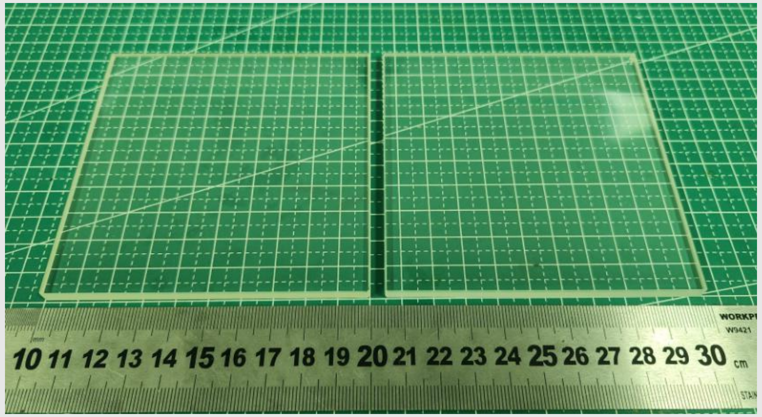
- Density~5.9 g/cm^3
- LY=602 ph/MeV
- ER=37.3%
- LO in 1μs=275 (46%)
- Decay=110 (5%), 1328 ns

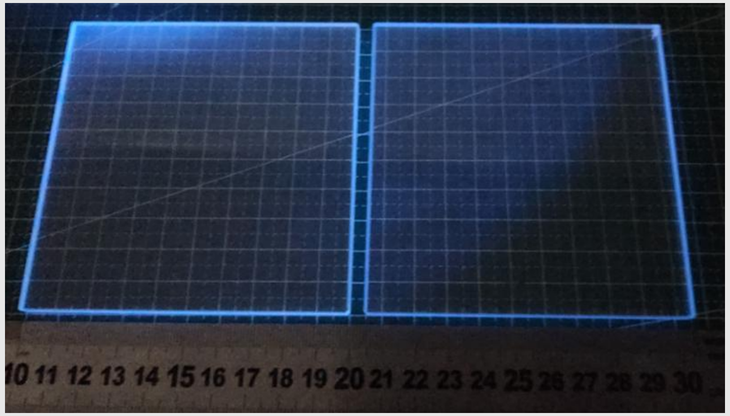


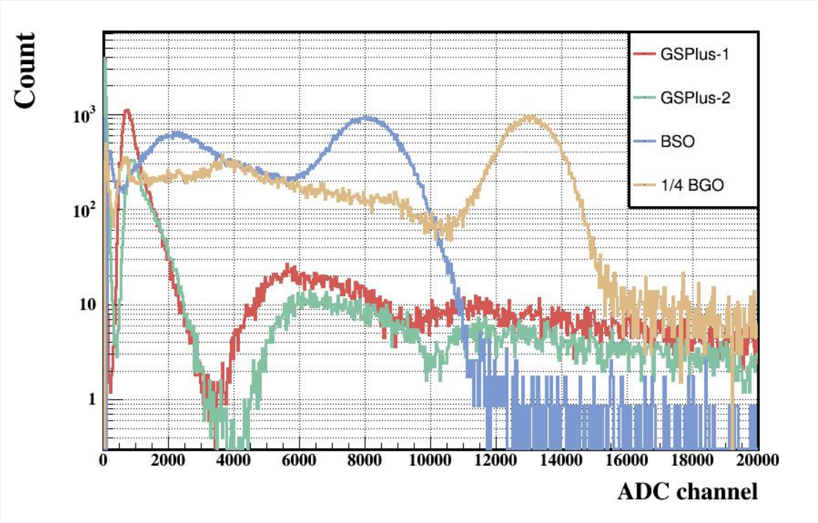
2024.02

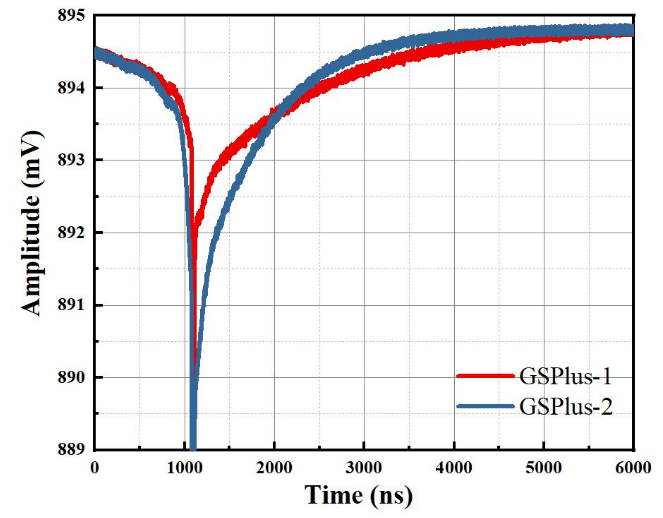


3.5 Ultra-Large size glass （1）（10cm X 10cm）





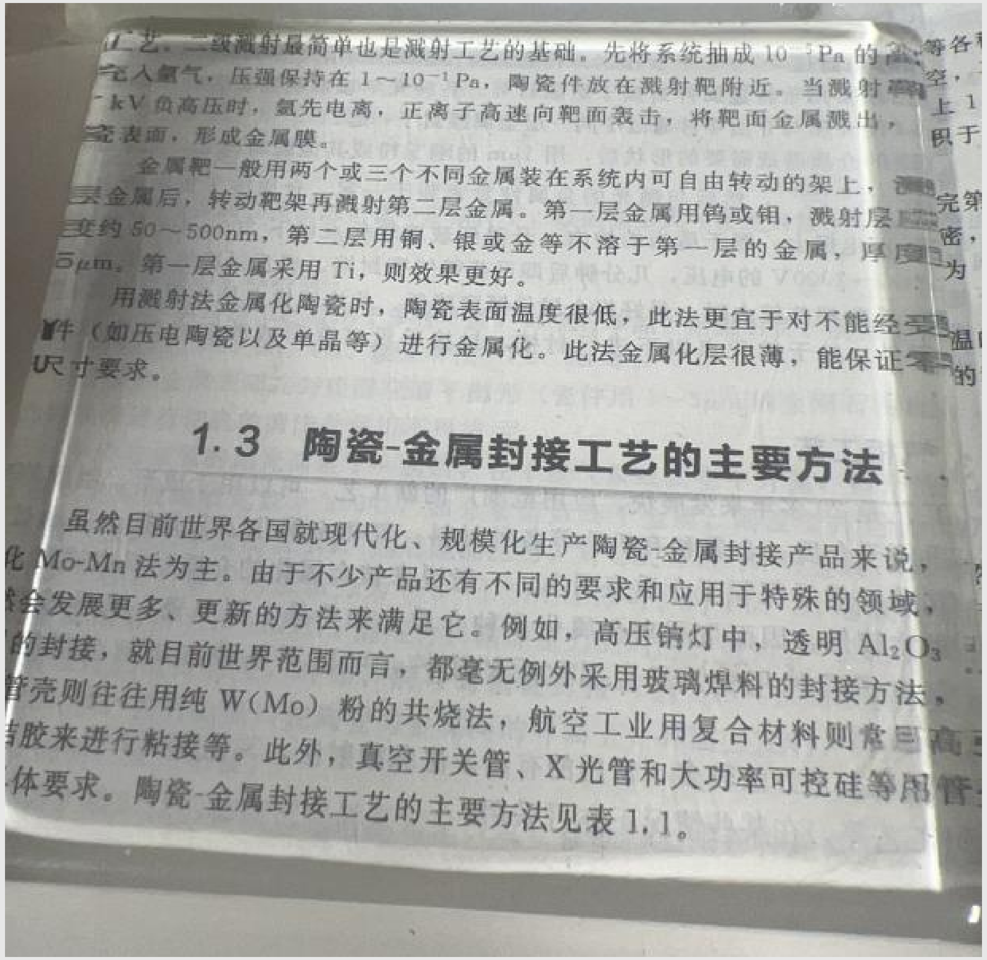


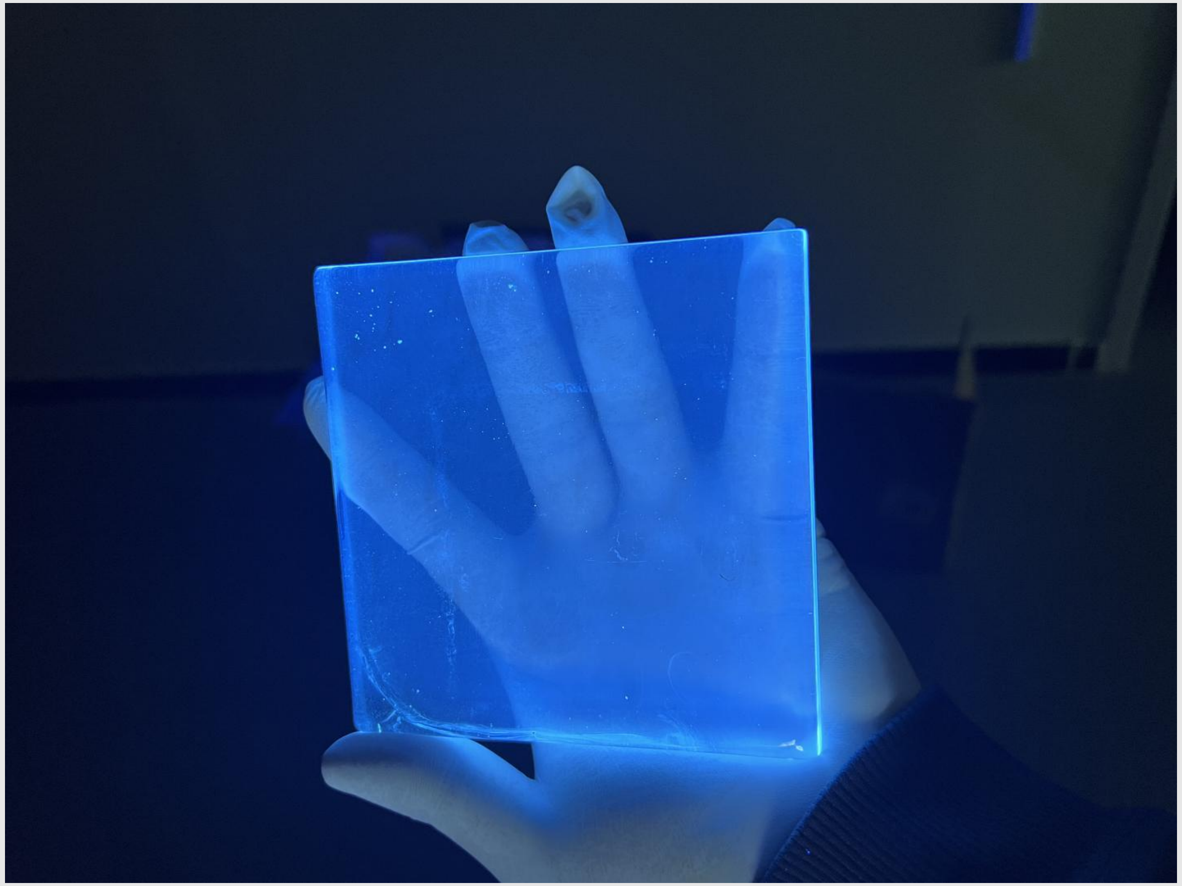


	LY (ph/MeV)	Decay time (ns)
GSPlus-1	732	101.9 (1.0%), 1456.5
GSPlus-2	795	72.1 (3.3%), 783.0

	5*5*5 mm^3	5*5*10 mm^3	10*10*10 mm^3	20*20*10 mm^3	40*40*10 mm^3
LY from PMT (ph/MeV)	1464	1273	1155	941	861

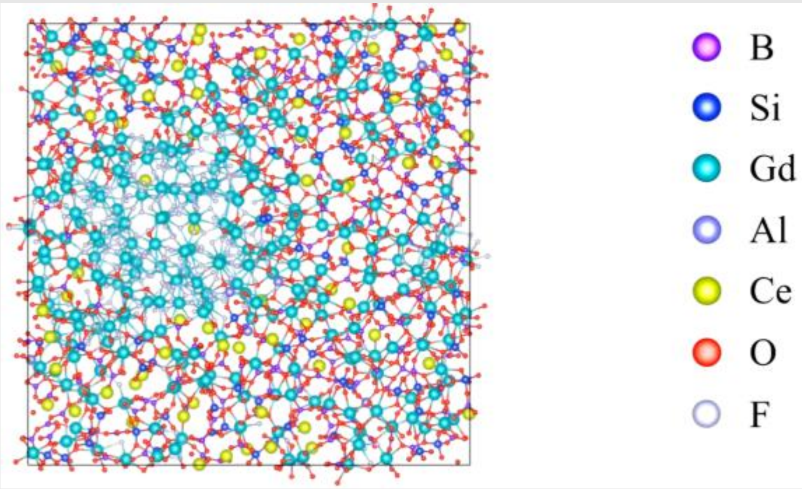
3.5 Ultra-Large size glass （2） （12.5cm X 122cm）





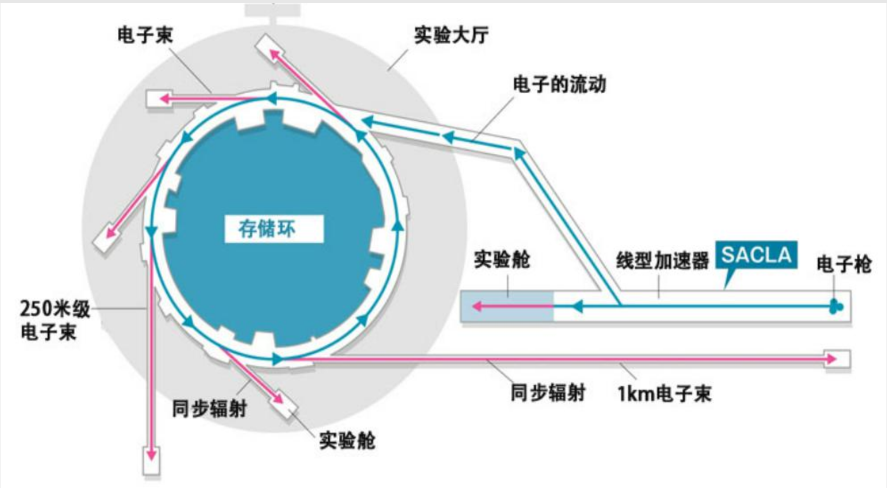
3.6 New study and appliaction

- Simulation and calculation of GS



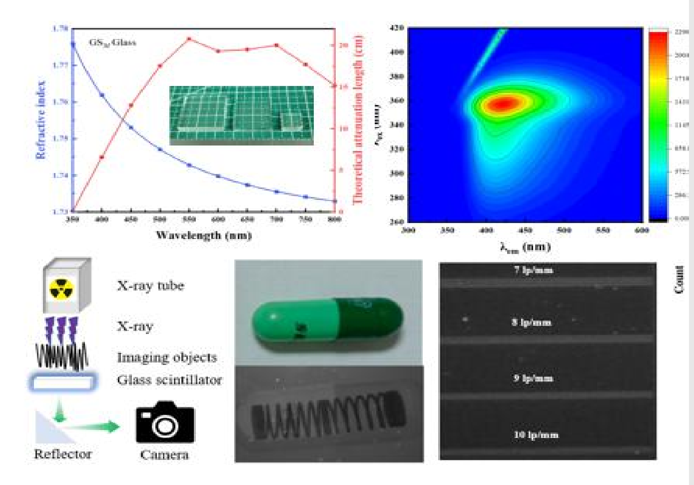
The optimum glass composition will be obtained by calculating the coordination structure

- Synchrotron radiation characterization



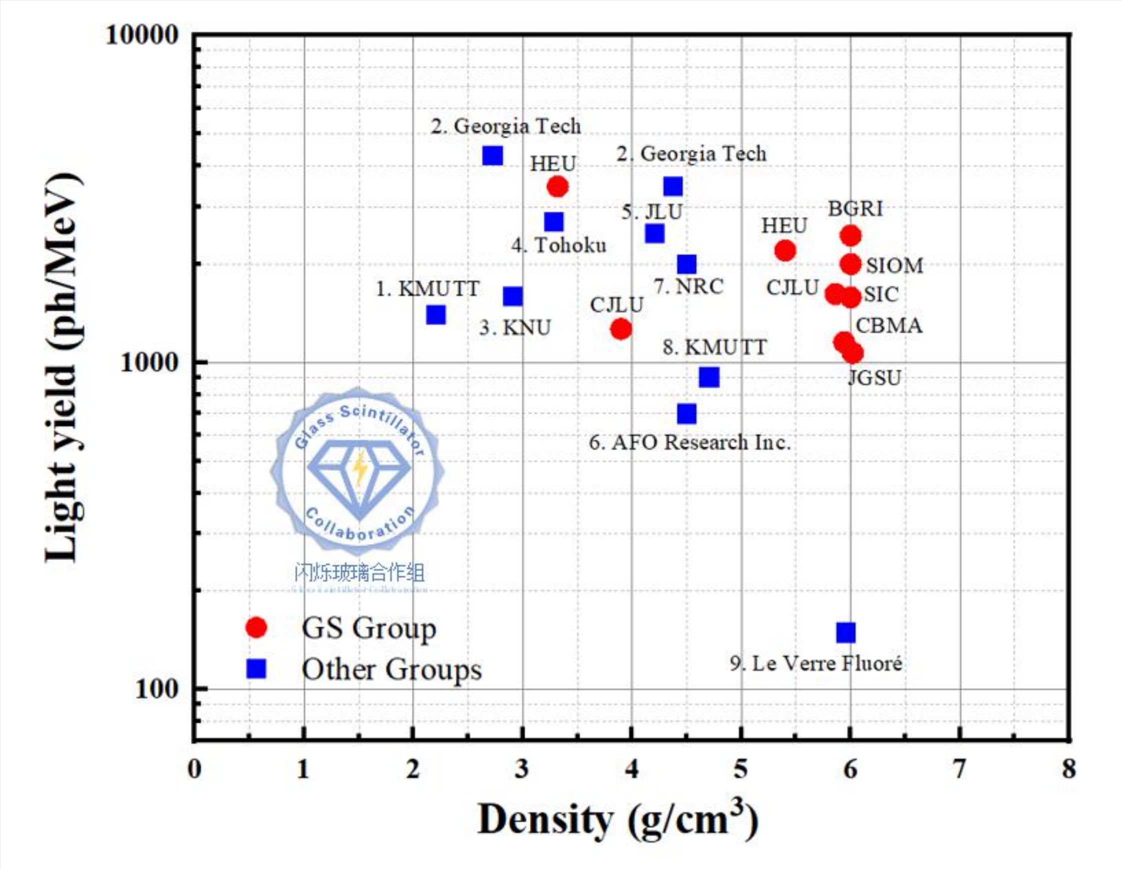
- Service condition simulation: Explore the relationship between glass structure and performance under different service conditions

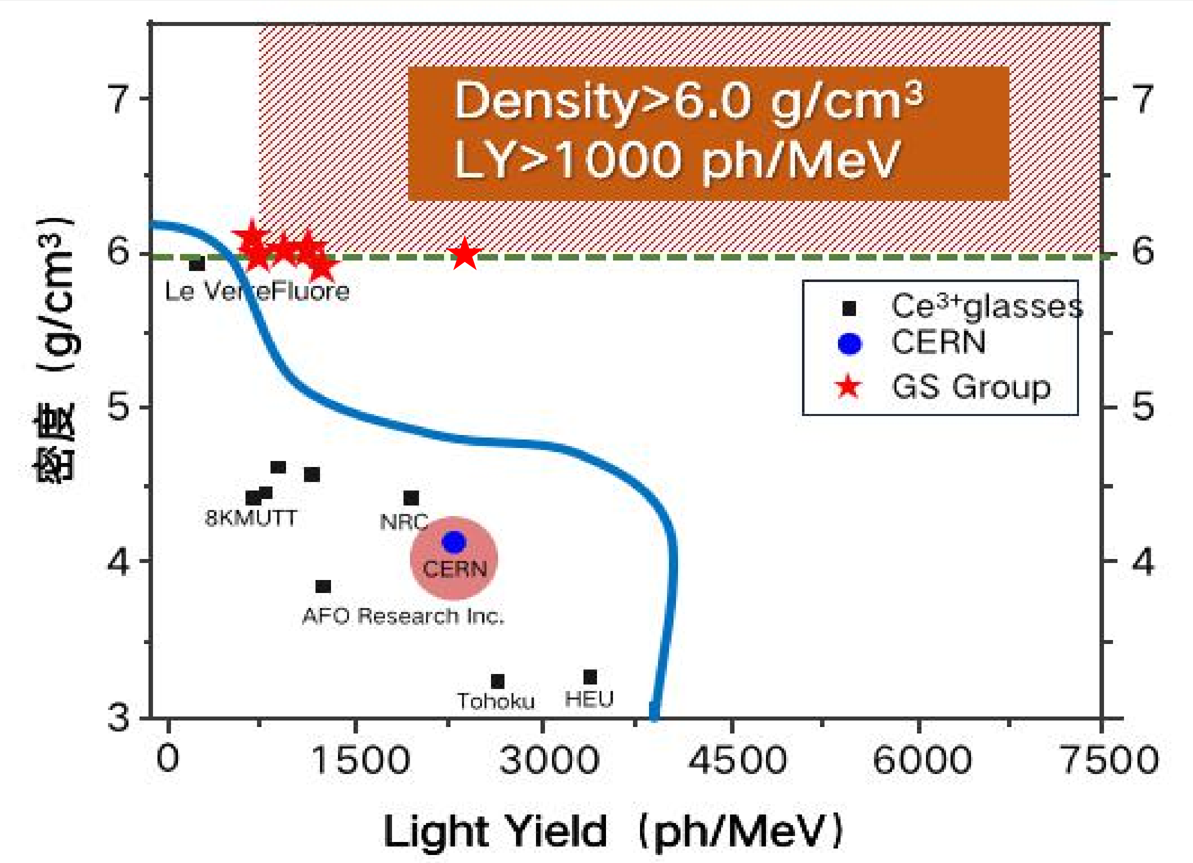
- X-ray imaging with GS



Develop a new paradigm of high-density scintillation glass research and seize the commanding heights of science and technology in the field of X-ray imaging.

3.7 GS Group Samples vs International Samples





- The GS group has carried out a comprehensive and complete study;
- For high density glass scintillator, the light yield of GS group samples is in the absolute lead.