The R&D Progress of the GSHCAL

闪烁玻璃合作组
Glass Scintillator Collaboration

Sen QIAN

qians@ihep.ac.cn;   On Behalf of the GS R&D Group

Institute of High Energy Physics, CAS

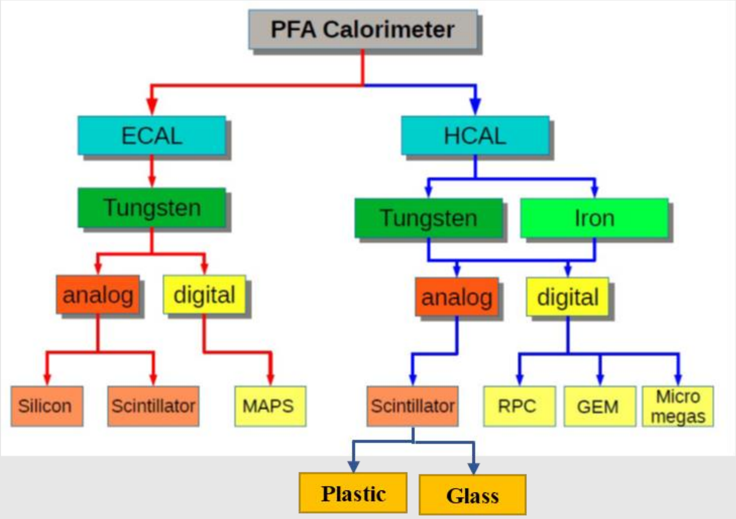
2024. May 20th-24th,   **The 20th International Conference on Calorimetry in Particle Physics (Tsukuba, Japan)**

Outline

- **1. The new Design of the GSHCAL;**
- 2. PFA performance of the GSHCAL;
- 3. The Progress of the GS Production;
- 4. Summary and Next Plan;

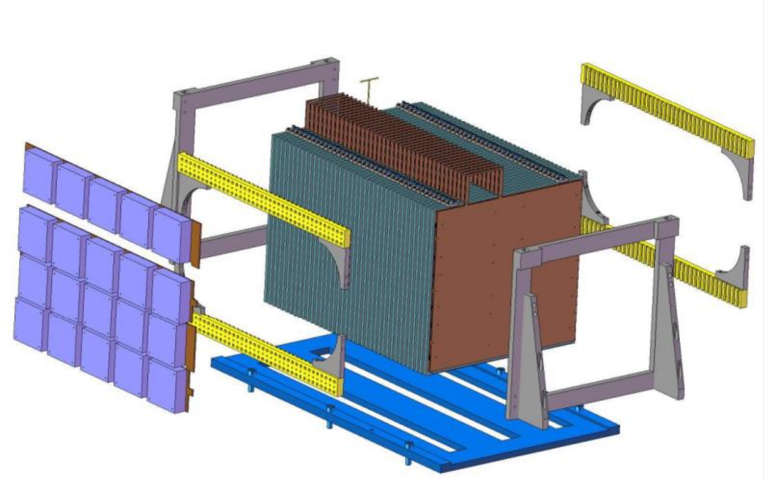
1.0 HCAL Design Options

- **Several HCAL design options have been proposed**
  - Based on **Gaseous Detector**
    - e.g. CALICE SDHCAL doi:10.1088/1748-0221/11/04/P04001
  - Based on **Liquid Argon**
    - e.g. ATLAS LAr Endcap HCAL doi:10.1016/j.nuclphysbps.2011.03.150
  - AHCAL: **Plastic Scintillator** & SiPM readout
    - e.g. CEPC AHCAL doi:10.1088/1748-0221/17/11/P11034



➢ CALICE SDHCAL Prototype

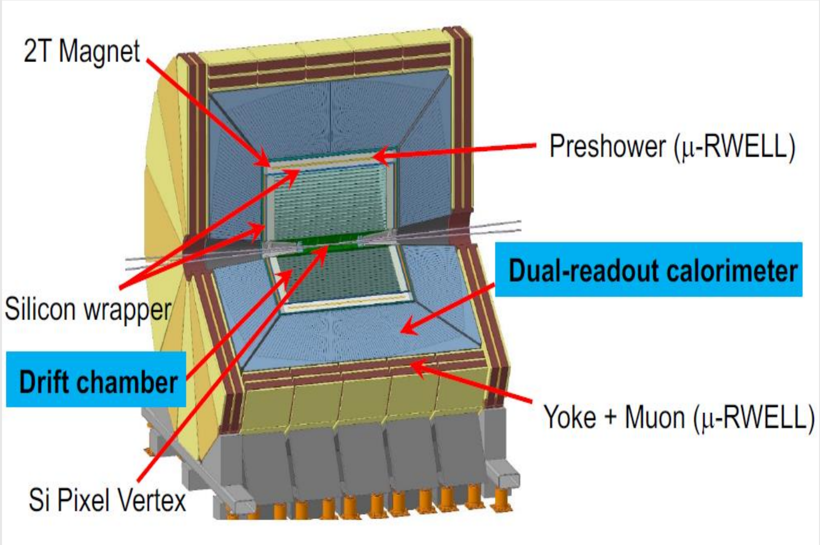
➢ ATLAS LAr Endcap HCAL



➢ CEPC AHCAL Prototype

1.1 CEPC Conceptual Detector Design

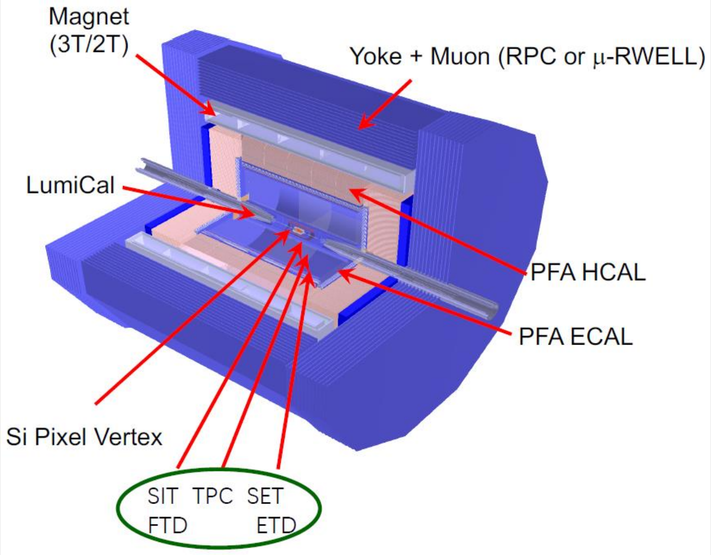
1st IDEA Concept
(also proposed for FCC-ee)



- **Dual-readout calorimeter (Cerenkov-Fiber & Scint-Fiber)**

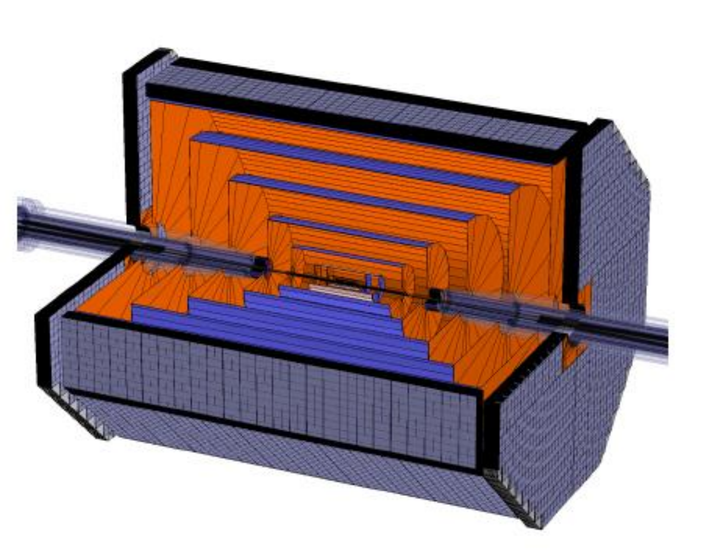
both for EM and Hadronic Shower

2nd CDR Baseline Design
(Particle Flow Approach)



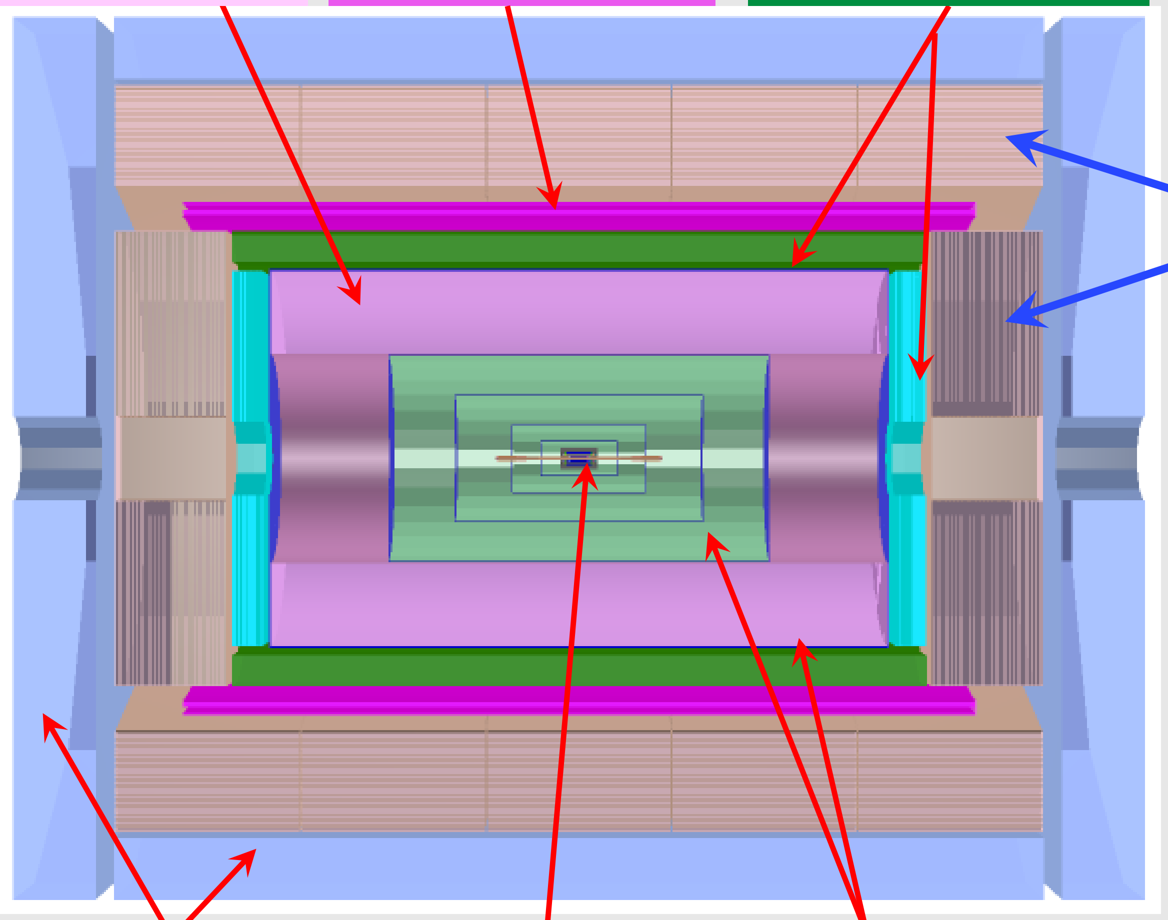
- **AHCAL (PS/Steel) or SDHCAL (Gas/Steel)**
- Si/W ECAL or PS/W ECAL

3rd FST concept
(Full Silicon Tracker)



- **AHCAL (PS/Steel) or SDHCAL (Gas/Steel)**
- Si/W ECAL or PS/W ECAL

1.2 The 4th Conceptual Detector Design

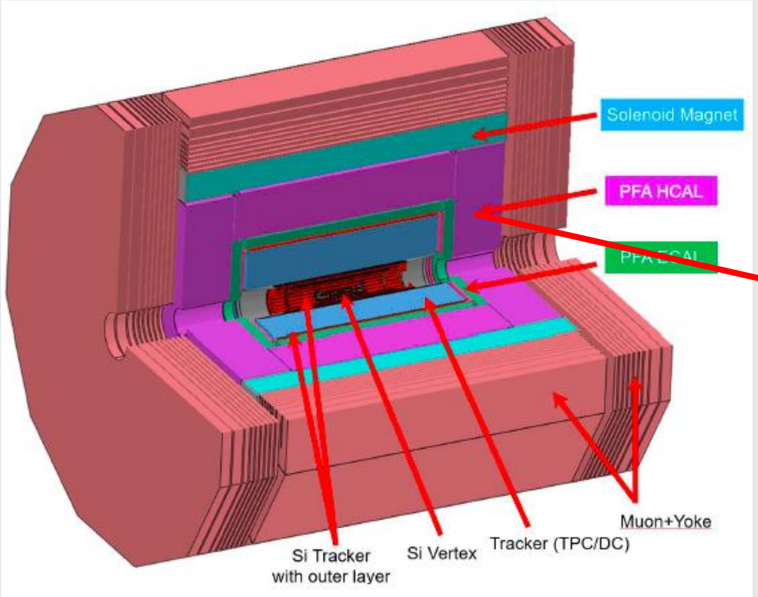


- Further performance goal: BMR 3.8% -> 3%
- Dominant factors on **BMR**: charged hadron fragments & **HCAL resolution**

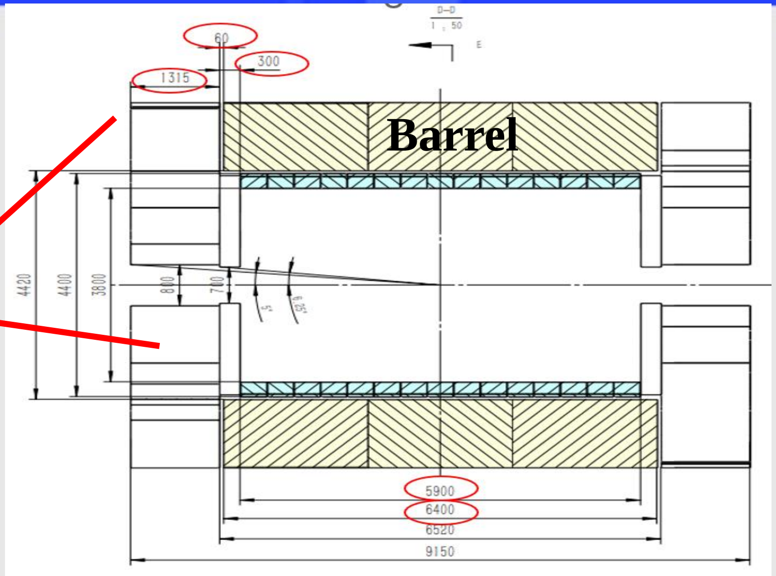
Glass Scintillator HCAL (GSHCAL)

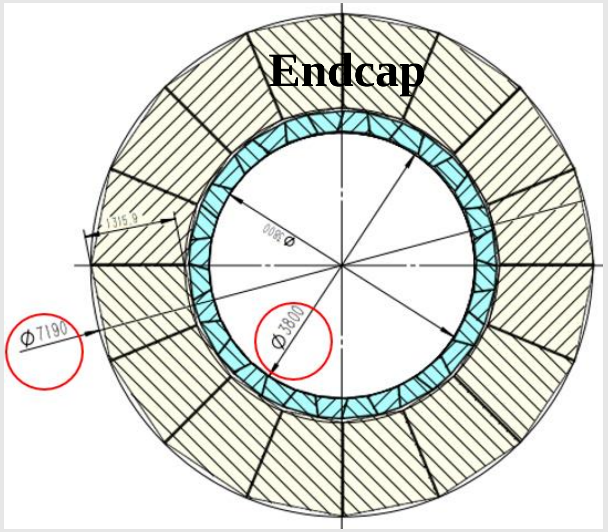
- Glass Scintillator:
  - low cost & feasible for ~ 10 cm^3 size
  - high density -> better ER/BMR & more compact
  - moderate light yield
  - short decay time
  - long absorption length
- Readout with SiPMs:
  - low cost & compact structure
  - immune to magnetic field
- To do: Simulation & offline calibration

1.3 GSHCAL Overall Structure



GSHCAL
Barrel+EndCap





- The overall structure of the GSHCAL consists of two parts: the Barrel (16, Hexagon), Endcap
  - Thickness of the Barrel: 6 λ
  - **Number of Layers: 48**
  - **GS/Steel Volume: 28.37 m³ (GS) 177.33 m³ (Steel)**
  - **Number of SiPM readout Channels: ~10⁶**

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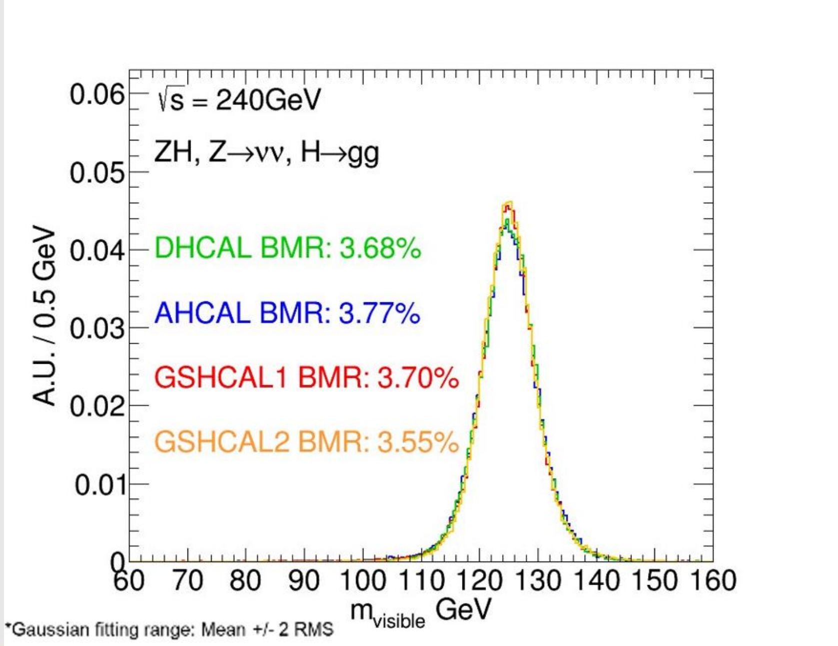
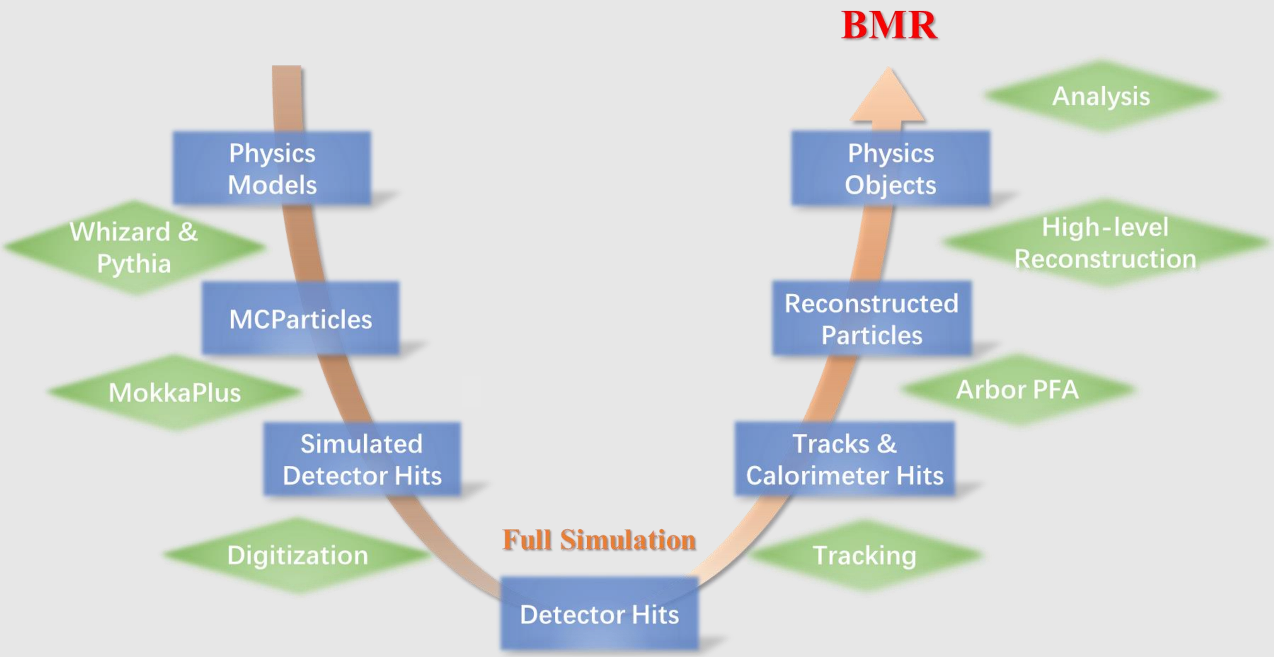
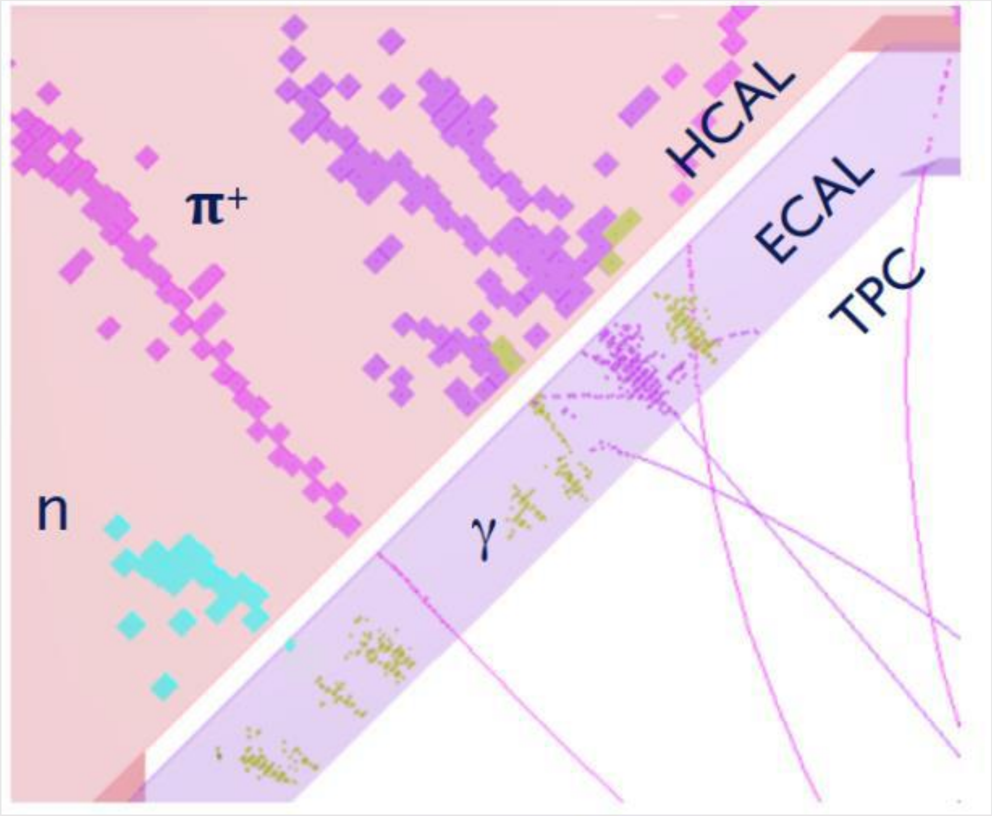


2.1 Simulation Studies of GSHCAL Performance

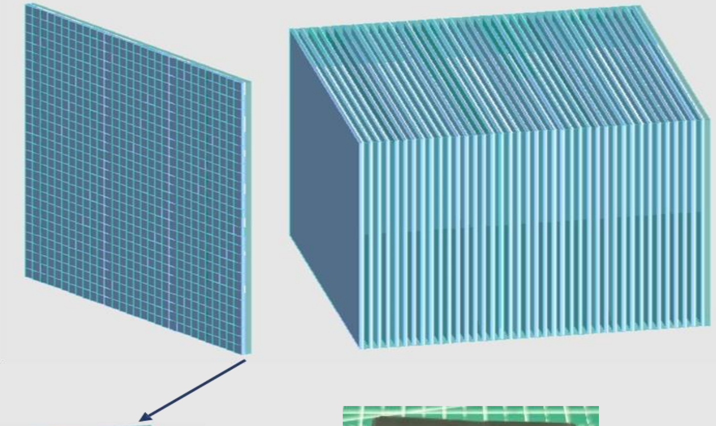
- **Standalone module simulation -> Hadronic energy resolution -> Input for fast simulation**
- **Full simulation -> PFA performance (BMR) based on the GSHCAL**
- **The focus of this part is the PFA performance (BMR) obtained from the Full simulation**



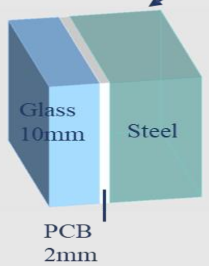


2.2 Full Simulation Setup

- Current full simulation is based on **CDR baseline design**, except for replacing the AHCAL with GS/steel HCAL
- Primary input: 240 GeV e+e- -> nu_nu H (H -> gg)
- Glass components : Gd-B-Si-Ge-Ce^{3+}



GSHCAL Standalone Module



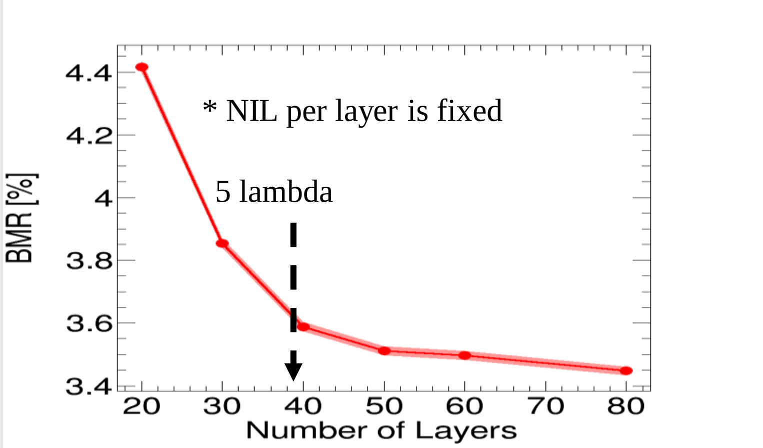
4x4x1 cm^2 GS readout with the SiPM

* Nominal setup for the GSHCAL in full simulation:

	GSHCAL Structure (+ECAL option)	No. layer	Cell Size	Thickness	Glass Density	Readout Threshold
Currently (at CDR)	Octagon GSHCAL (+Si/W ECAL)	**40**	**40x40x10 mm^3**	**5 λ**	**6 g/cm^3**	**0.1 MIP**
To do (for TDR)	Hexadecagon GSHCAL (+BGO Crystal ECAL)	**48**	**40x40x10 mm^3**	**6 λ**	**6 g/cm^3**	**0.1 MIP**

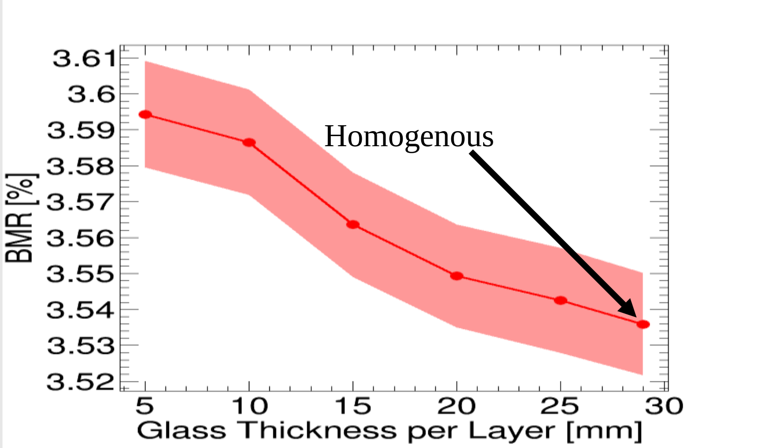
2.3 Impact of Some Key Parameters

Number of Layers



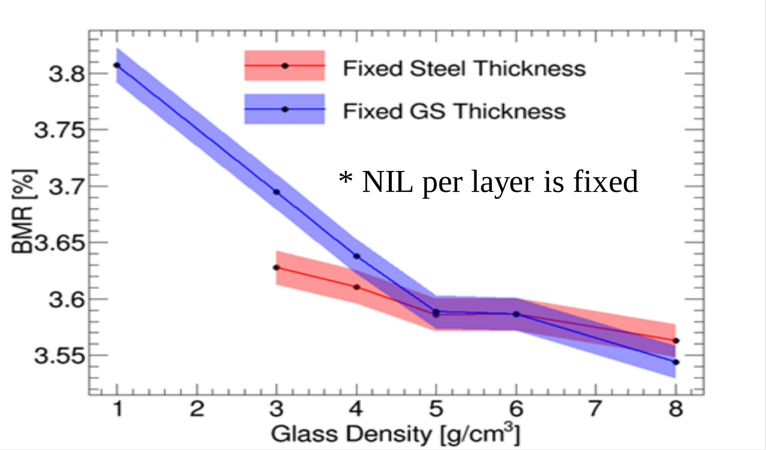
- More layers ->better BMR (pros)
- More layers -> thicker GSHCAL & more readout channels (cons)
- **Preliminary results show > 5 λ is necessary to suppress shower leakage;**

Glass Thickness per Layer



- Thicker glass -> better BMR (pros)
- Thicker glass -> thicker GSHCAL & worse optical performance (cons)
- **Preliminary results show that BMR is weakly dependent on the glass thickness**

Glass Density

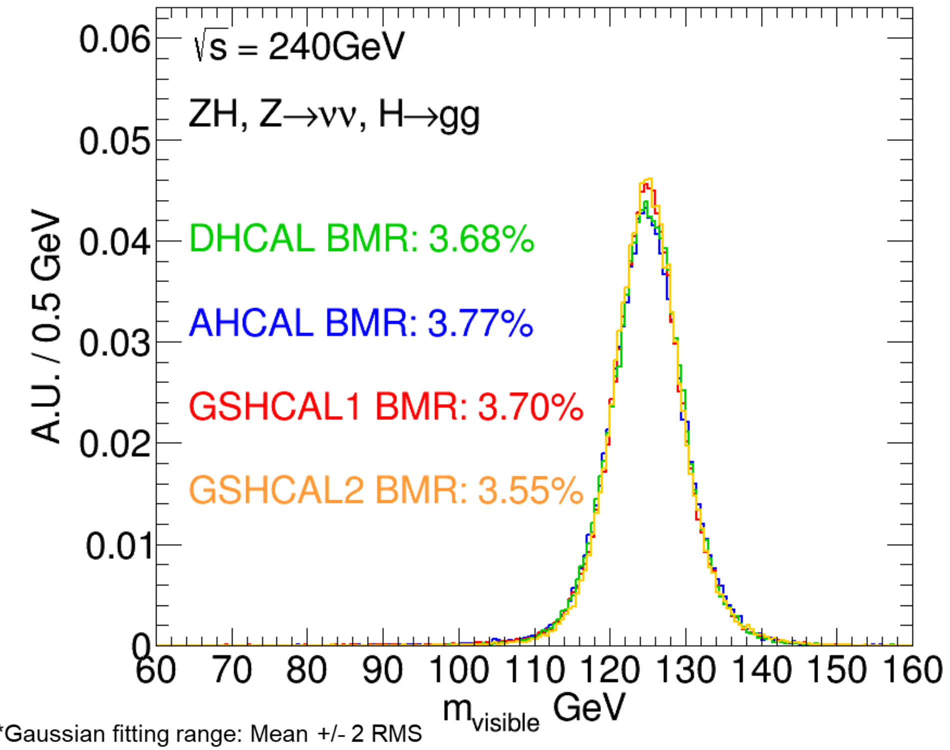


- Higher glass density -> compact & better BMR (pros)
- Higher glass density -> higher cost (cons)
- **Preliminary results show > 5 g/cm3 can fully exploit the advantage of high density**

⇨ **Further studies are still needed to balance the BMR and the cost**

2.4 Different GSHCAL Designs

Status	CDR	CDR	CDR	Pre-TDR
Design Option	DHCAL	AHCAL	GSHCAL1	GSHCAL2
Material	RPC	PS	GS	GS
BMR	3.68%	3.77%	3.70%	3.55%
No. layers	40	40	40	48
Layer thickness （0.125 lambda）	3mm RPC+ 20mm Steel	3mm PS+ 20mm Steel	3mm GS+ 18.75mm Steel	3mm GS+ 18.75mm Steel
Inter. Length	4.8 lambda	5 lambda	5 lambda	6 lambda
Trans. Cell Size	10x10 mm^2	40x40 mm^2	40x40 mm^2	40x40 mm^2
Mat. Density	< 10^{-3} g/cm^3	1 g/cm^3	6 g/cm^3	6 g/cm^3
HCAL Thick.	931 mm	931 mm	873 mm	1059 mm
HCAL Volume	14 m^3(RPC) 91 m^3(Steel)	14 m^3(PS) 91 m^3(Steel)	13 m^3(GS) 81 m^3(Steel)	17.4 m^3(GS) 126 m^3(Steel)
No. Cells	4.5×10^7	2.8×10^6	2.7×10^6	3.62×10^6



*Gaussian fitting range: Mean +/- 2 RMS

- By using a similar setup with the AHCAL in the CDR, the GSHCAL can achieve a **more compact structure and less readout channels**, as well as a slightly better PFA performance
- Design optimization of GSHCAL for the TDR is still ongoing： Thicker GS

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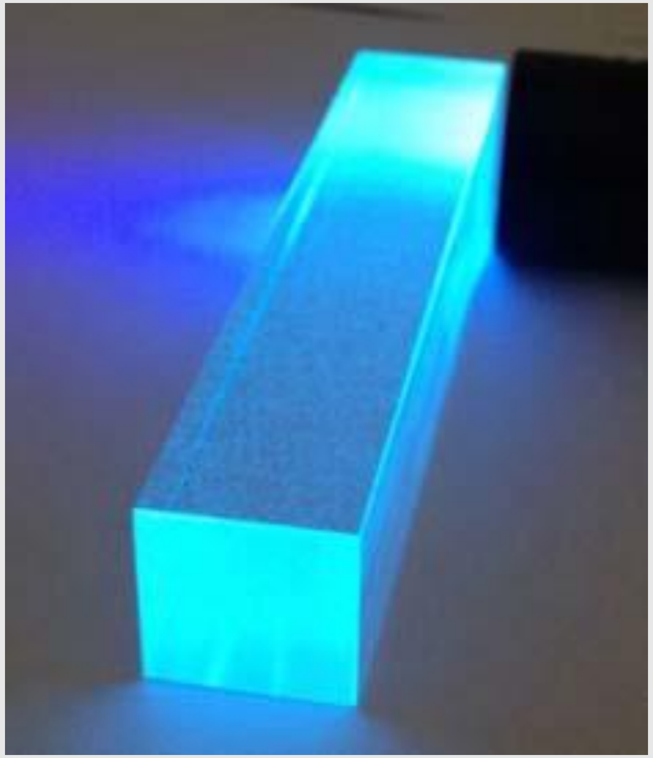
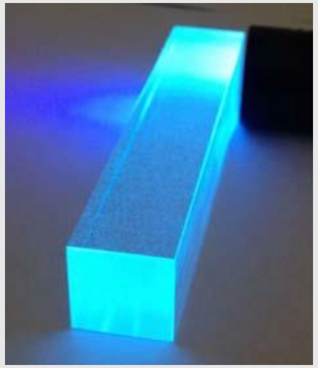


3.0 What is the Glass Scintillator?

Plastic Scintillator



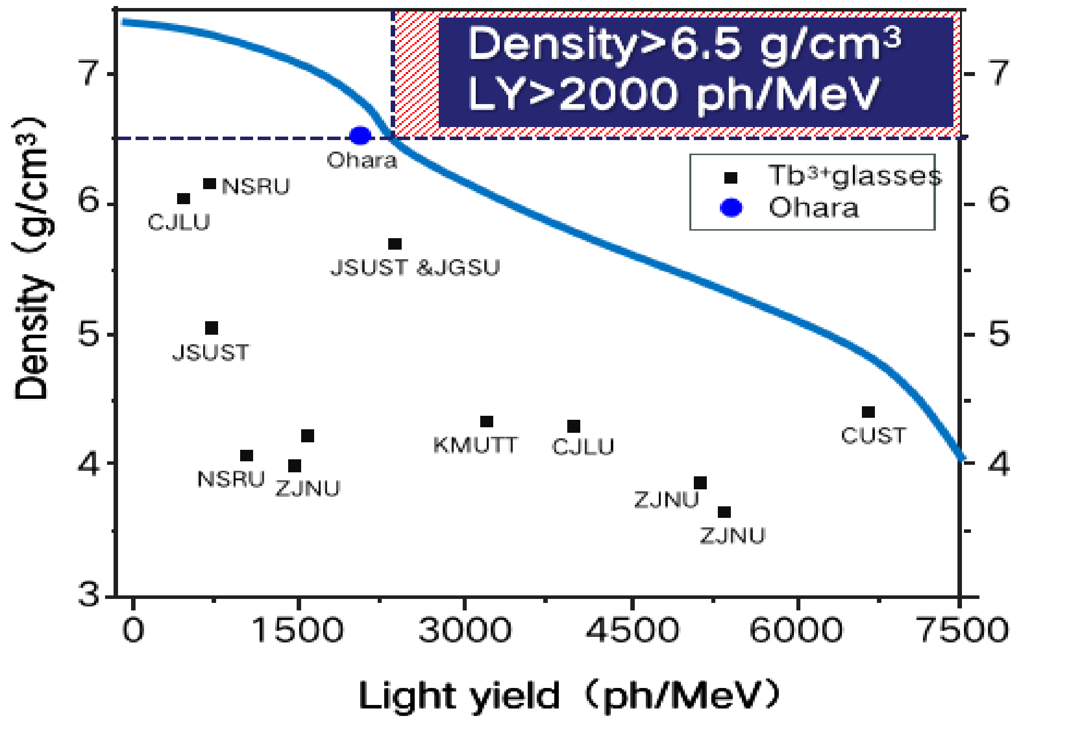
Glass Scintillator

Crystal Scintillator

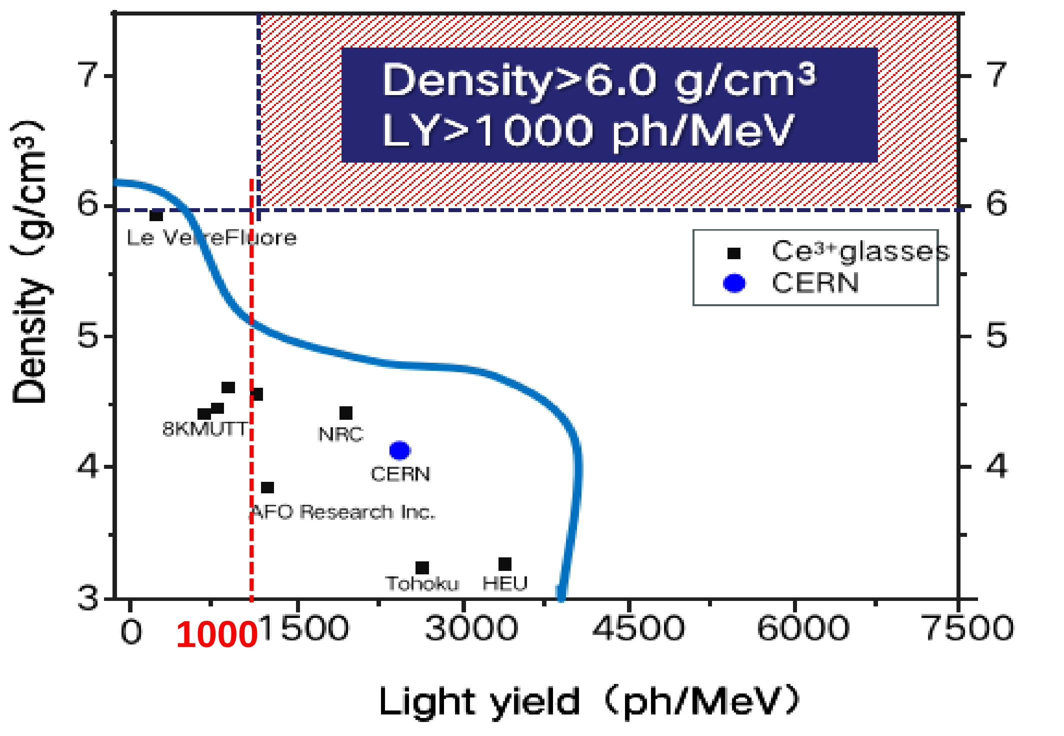
	Plastic Scintillator	Glass Scintillator	Crystal Scintillator
High light yield	★★★	★	★★★
High Density	★	★★	★★★
Low cost	★★★	★★★	★
Large size	★★★	★★	★
Fast decay	★★★	★	★★
Energy resolution	★★	★	★★★

3.1 Current Research Status of the GS

- Before 2000, the high-density GS is mainly based on Pb (plumbum) or Bi (bismuth), with poor scintillation light;
- After 2000, GS with rare-earth elements （Tb,Terbium; Ce,**Cerium**） attract more attention for improved LY
- However, **it's a great challenge to realize a high density and high light yield at the same time**

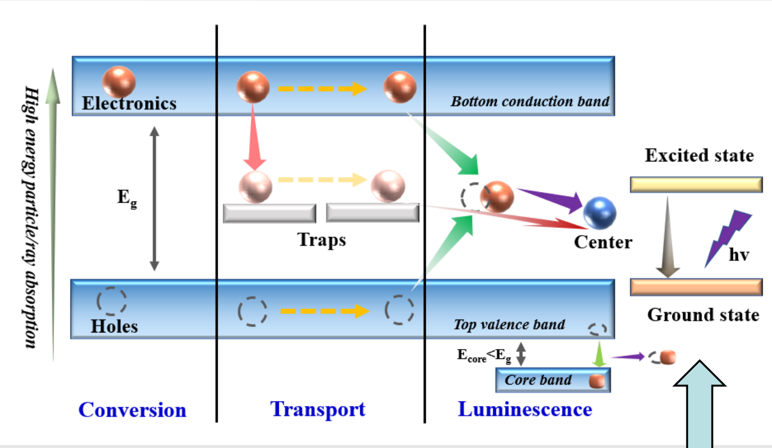


Tb^{3+} doped glass with high light yield



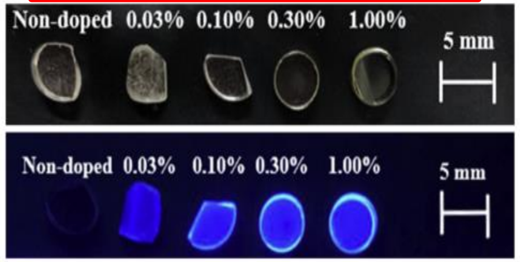
Ce^{3+} doped glass with short decay time

3.2 The Design of the GS



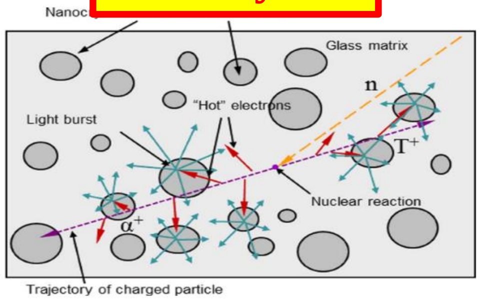
- **Scintillation mechanism---- Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



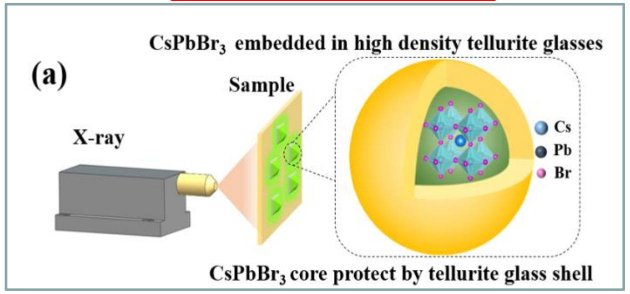
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



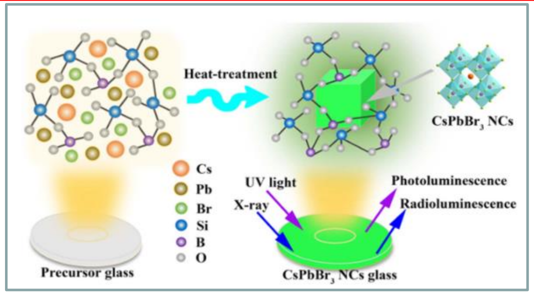
IEEE TNS 60 (2) 2013

Quantum Dots



Optics Letters 46(14) 3448-3451 (2021)

Lanthanide + Quantum Dots



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- **High Light Yield (> 2000 ph/MeV): Lanthanide for the Luminescence Center: Cerium (Ce);**
- **High Density (> 6 g/cm^3) and Low radioactivity background: Gadolinium (Gd); ~~lutetium（Lu）~~**

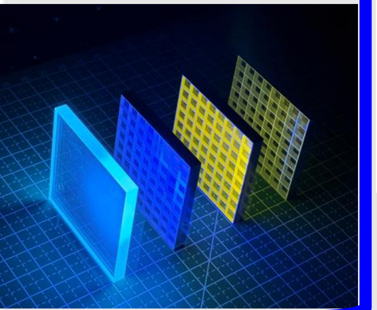
3.3 Large Area Glass Scintillator Collaboration

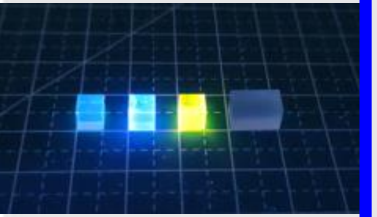
Spokesperson：Sen QIAN

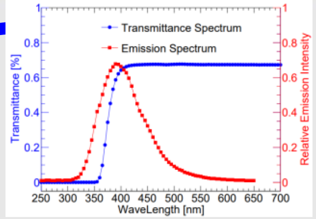
-- The Glass Scintillator Collaboration Group established in Oct.2021；

-- There are 3 Institutes of CAS, 5 Universities, 3 companies joined us for the R&D of GS;

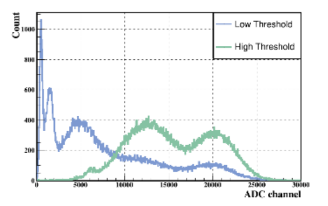
3.4 Scintillator Test Facilities for GS



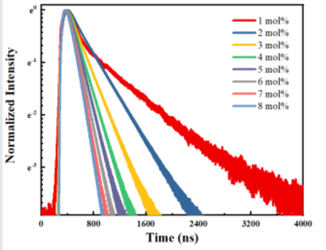




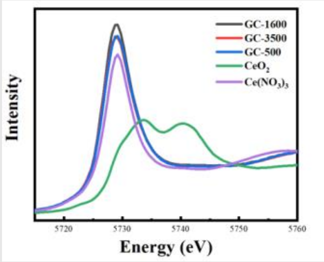
- Transmittance
- Absorbance
- Refractive index
- Emission peak



- Light yield
- Energy resolution
- MIP response
- Neutron discrimination



- Rise time
- Fall time
- Decay time
- Afterglow
- Coincidence time



- Valence state
- Coordination
- Elemental analysis
- Structural analysis

Others

……

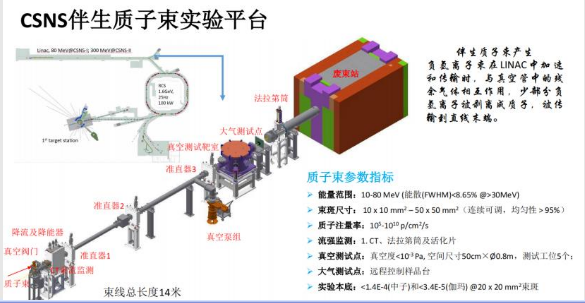
- Faraday effect
- Radiation resistance
- Homogeneity

- IHEP--PMT Lab for Scintillator Test

- IHEP--Radioactive Test

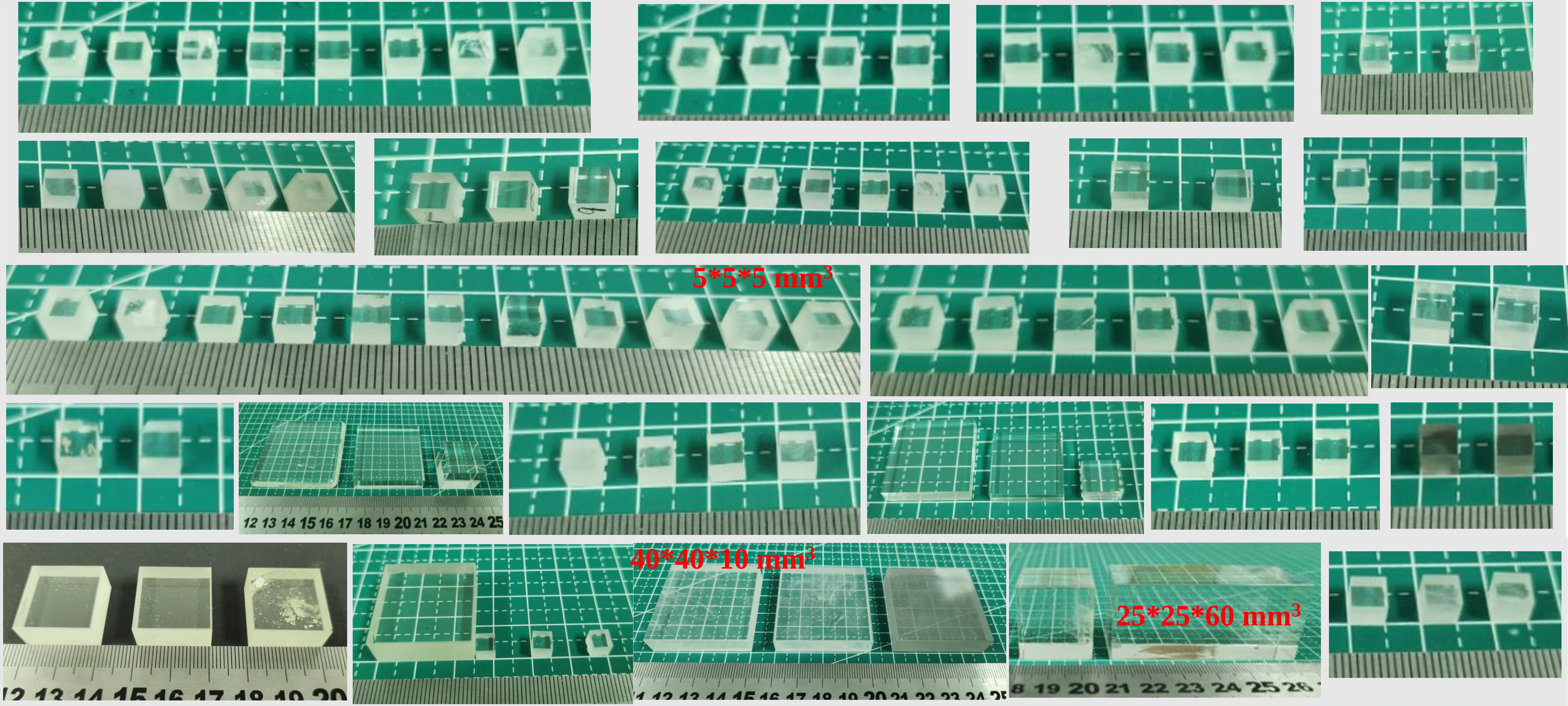
- IHEP--XAFS

- IHEP-CSN-- P Beam



- CERN-MUON Beam

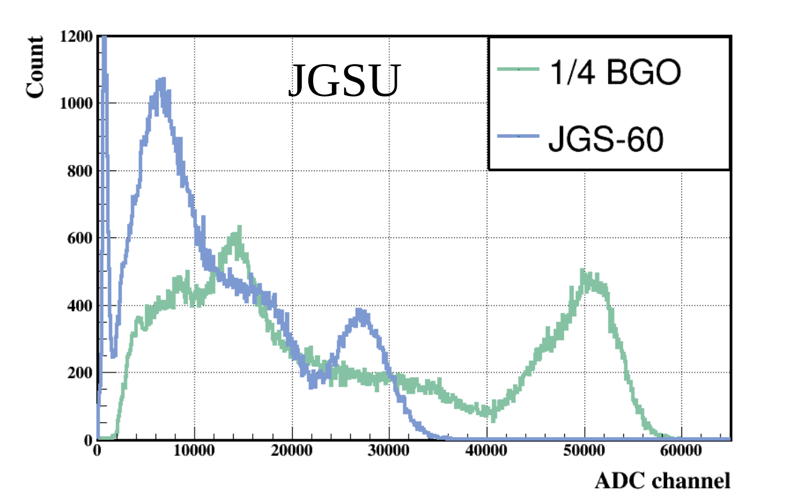
3.5 GS Samples produced （>700)



3.6 Best Performance Achieved up to now

Small-Size

- **Size=5*5*5 mm^3**
- Density~5.9 g/cm^3
- LY~1070 ph/MeV
- ER=24.4%
- LO in 1μs=899 ph/MeV
- Decay=92 (8%), 473 ns



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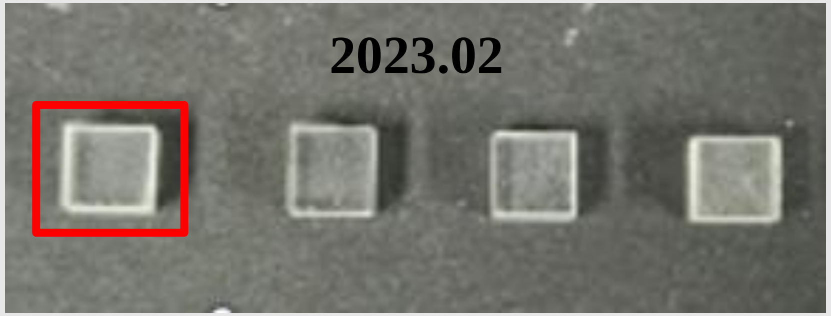
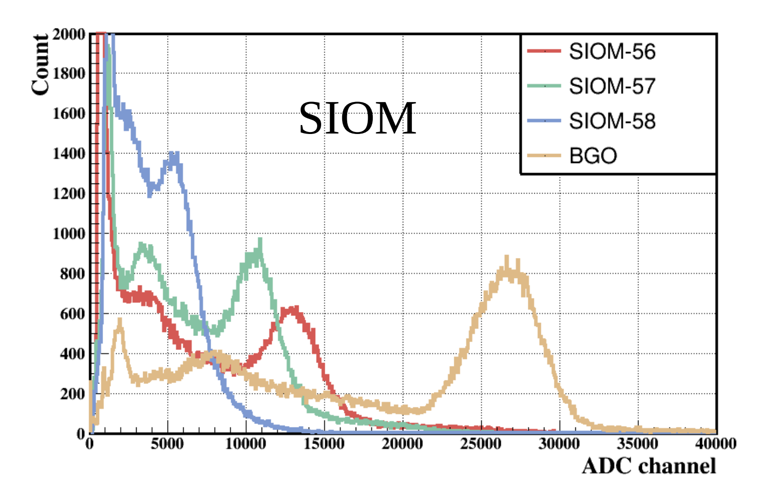


Large-Size

- **Size=40*40*10 mm^3**
- Density=6.0 g/cm^3
- LY ~1200 ph/MeV
- ER=33.0%
- LO in 1μs=607 (51%)
- Decay=117 (3%), 1368 ns



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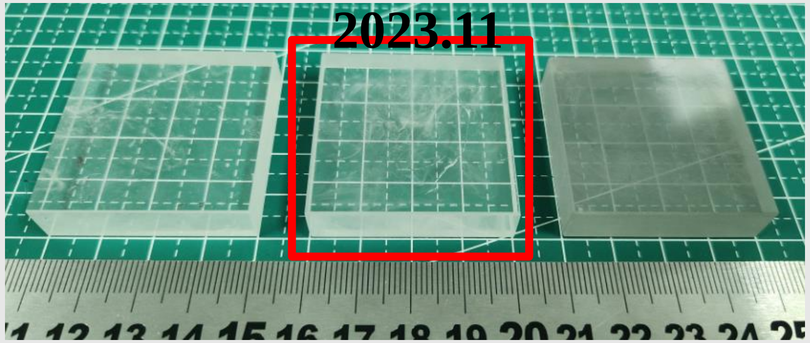
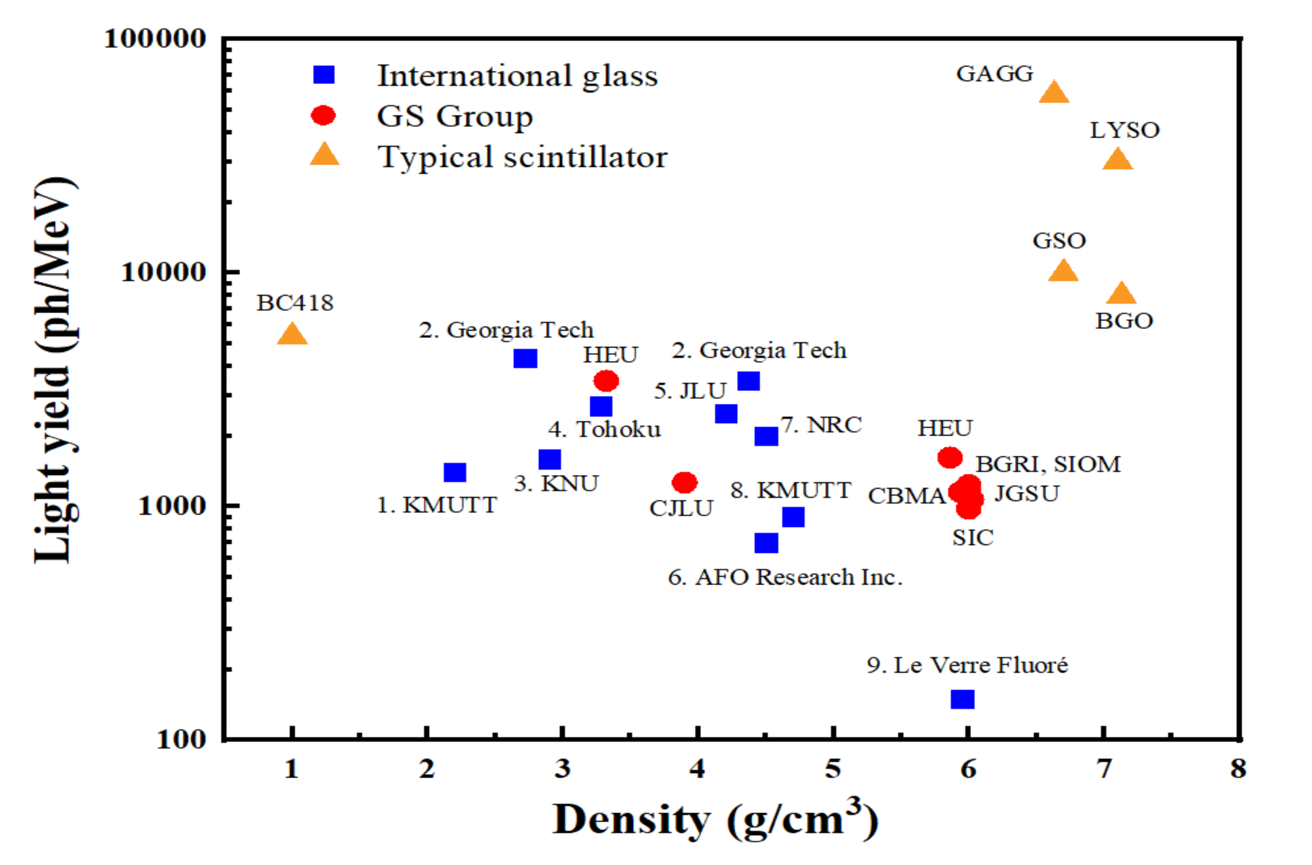
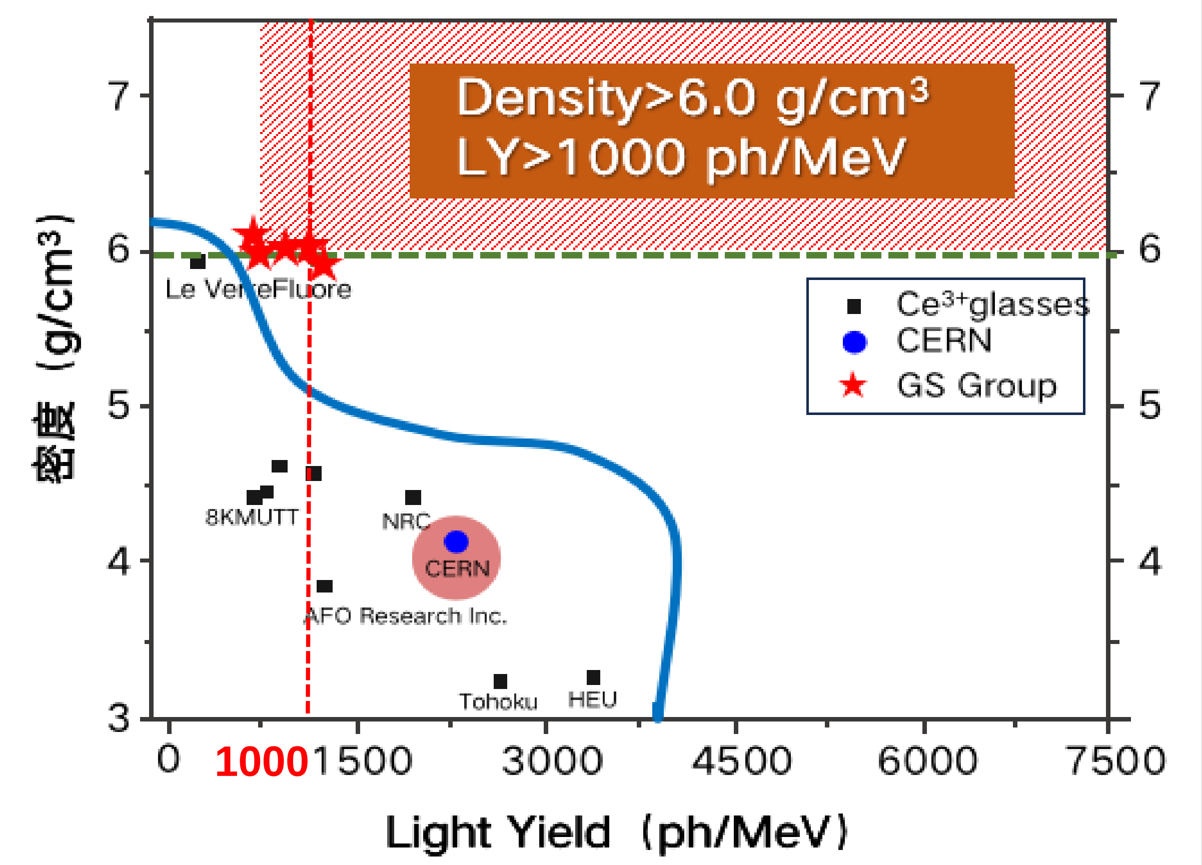


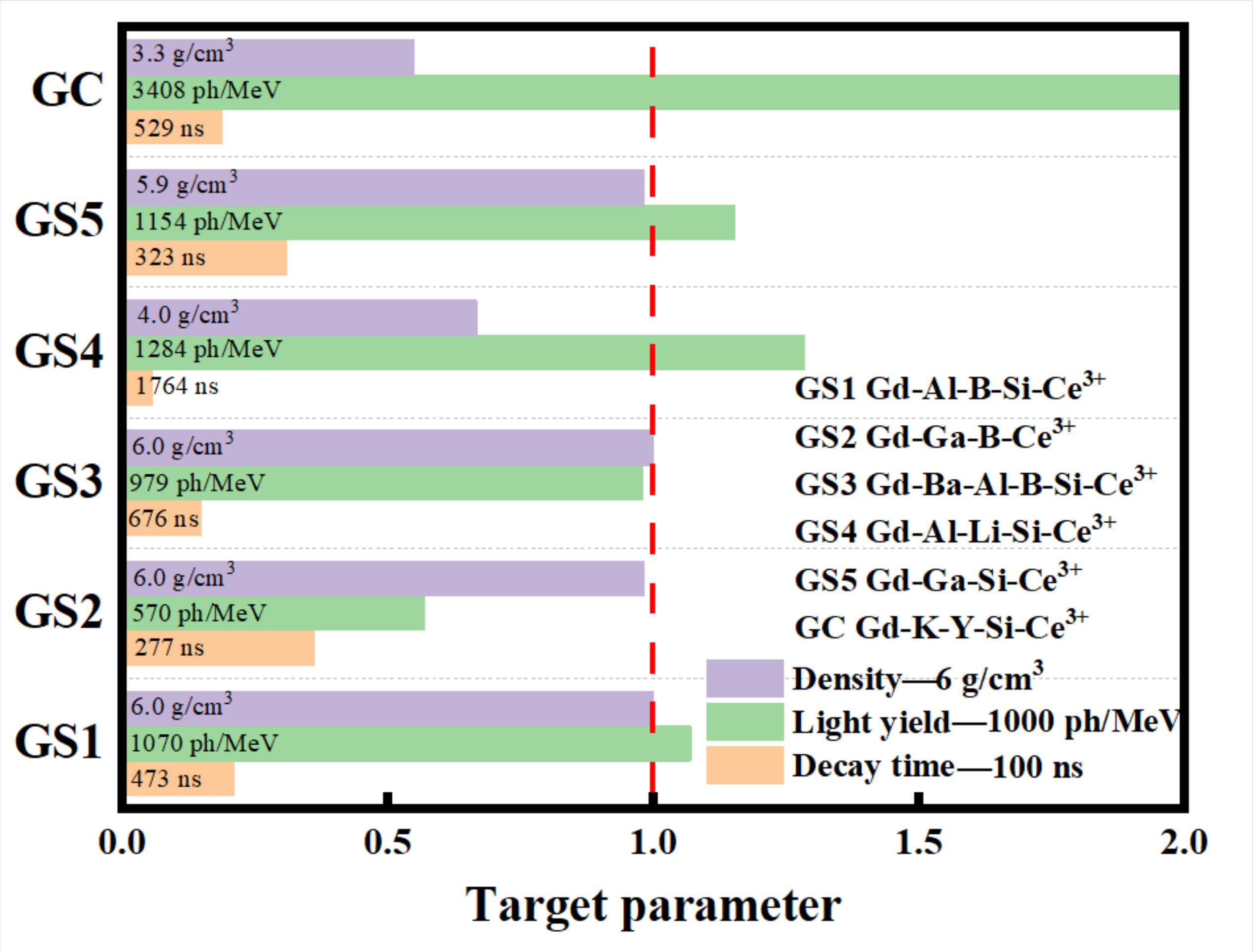
3.7 GS Group Samples vs International Samples





- 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.

3.8 Performance of Small-size Samples



* The sample size is 5x5x5 mm^3, except for **GC** (5x5x2 mm^3)

Glass scintillator of high density and high light yield

◆ **GS1: Gd-Al-B-Si-Ce^{3+} glasses：(Borosilicate Glass)**

6.0 g/cm^3 & 1235 ph/MeV with 24.0%@662keV & 588 ns

◆ **GS5: Gd-Ga-Si-Ce^{3+} glasses：(Silicate glass)**

5.9 g/cm^3 & 1154 ph/MeV with 25.4%@662keV & 323 ns

Other Highlights:

- Ultra-high density **Tellurite Glass**—6.6 g/cm^3
- High light yield **Glass Ceramic**—3500 ph/MeV
- Fast Decay Time **Pr^{3+}-doped Glass**—100 ns
- Large size Glass—51mm*51mm*10mm

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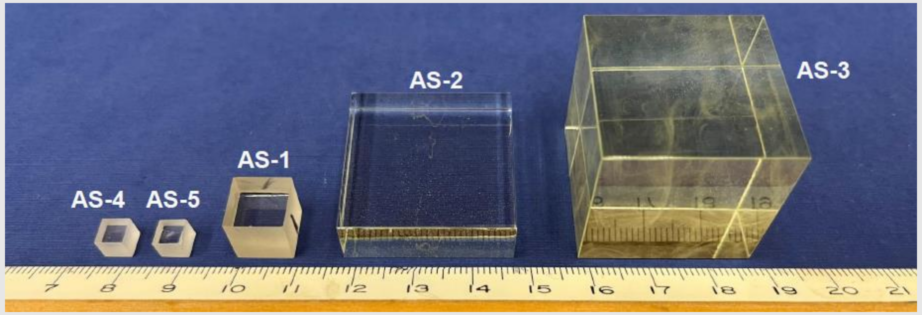
4.1 Summary of GS R&D

Parameters	Unit	BGO	LYSO	GAGG	GS1	GS5	Goals
Cost		~8 $/cc	~30 $/cc		N/A	N/A	**<< 1$/cc**
Density	g/cm^3	7.13	7.5	6.6	6.0	5.9	6
Hygroscopicity	--	No	No	No	No	No	No
Radiation Length, X_0	cm	1.12	1.14	1.63	1.59	1.61	1.6
Transmittance	%	82	83	80	80	80	80
Refractive Index	--	2.1	1.82	1.91	1.74	1.75	1.75
Emission peak	nm	480	420	520	390	390	~400
Light yield, LY	ph/MeV	8000	3000	54000	1347	1154	>1000
Energy resolution, ER	%	9.5	7.5	5.0	25.3	25.4	<25
Decay time	ns	60, 300	40	100	80, 600	90, 300	<100



□We are not far from our goals

4.2 Summary of GSHCAH R&D and Next Plan

- Performance of the GSHCAL for BMR seems adequate by simulation.
- R&D of GS started, good progresses, not very far from our goals
- Test beam results are promising

Next Plan

- Optimize the GSHCAL design, together with ECAL
- Implement the digitization using real data in the simulation
- More and larger samples, and the medium scale production
- A prototype module for testbeam

See the unseen
change the unchanged

The Innovation

THANKS