Cost-Effective Inorganic Scintillators for CalVision

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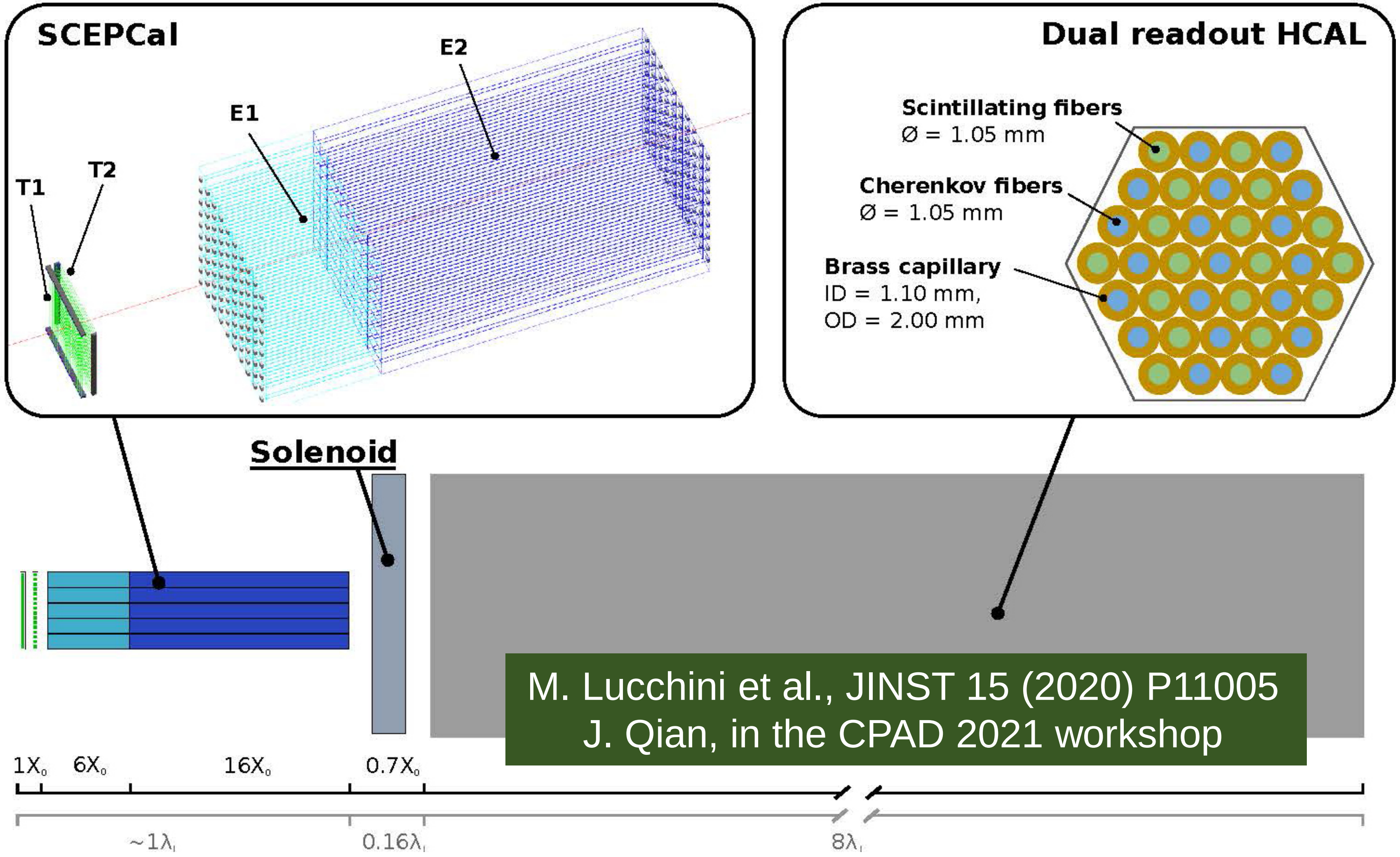
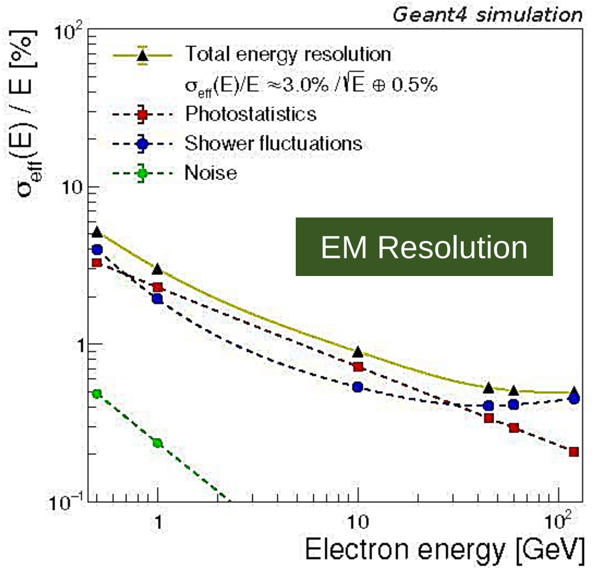
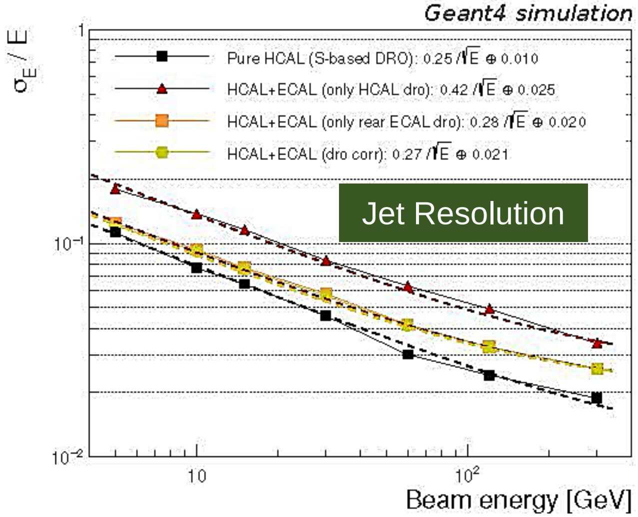
CalVision: A Dual Readout Crystal ECAL

Excellent EM and jet resolutions with IDEA DR HCAL for Higgs Factory

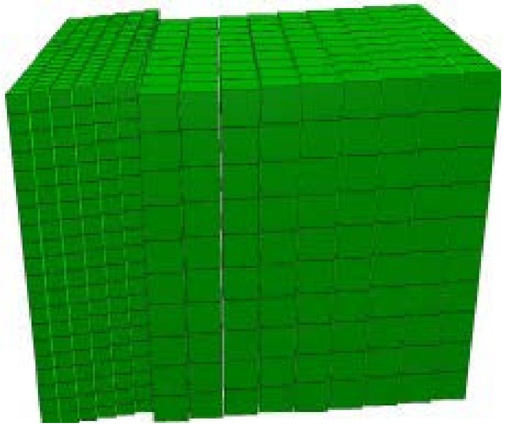


M. Lucchini et al., JINST 15 (2020) P11005
J. Qian, in the CPAD 2021 workshop





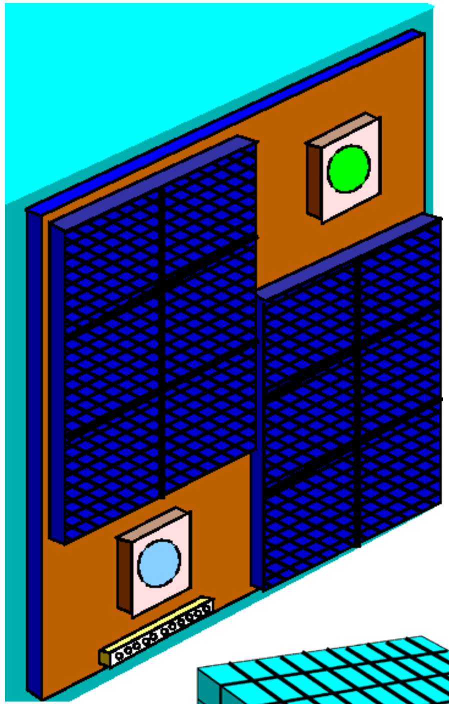
HHCAL : A Total Absorption Hadron Calorimeter



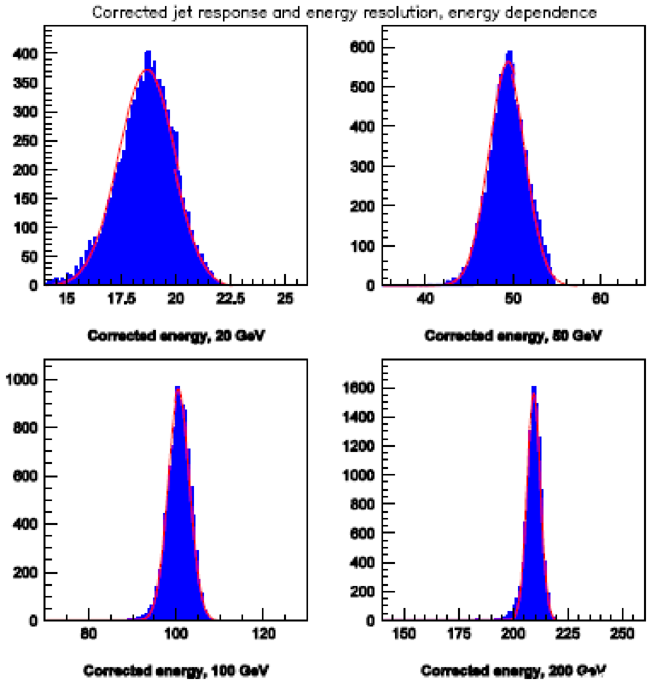
A. Para, H. Wenzel, and S. McGill in Callor2012 Proceedings;
A. Benaglia *et al.*, IEEE TNS **63** (2016) 574:

Jet energy resolution of <20%/√E is achievable by HHCAL with dual readout of S/C or dual gate

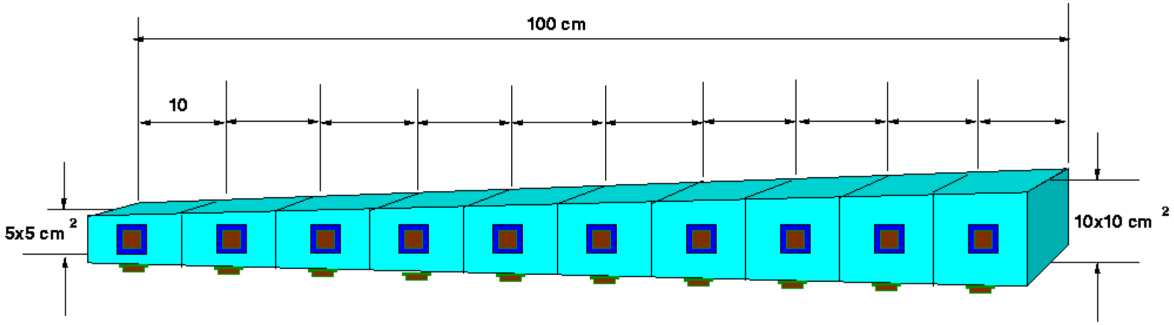
M. Demarteau and H. Wenzel in the CPAD 2021 Workshop

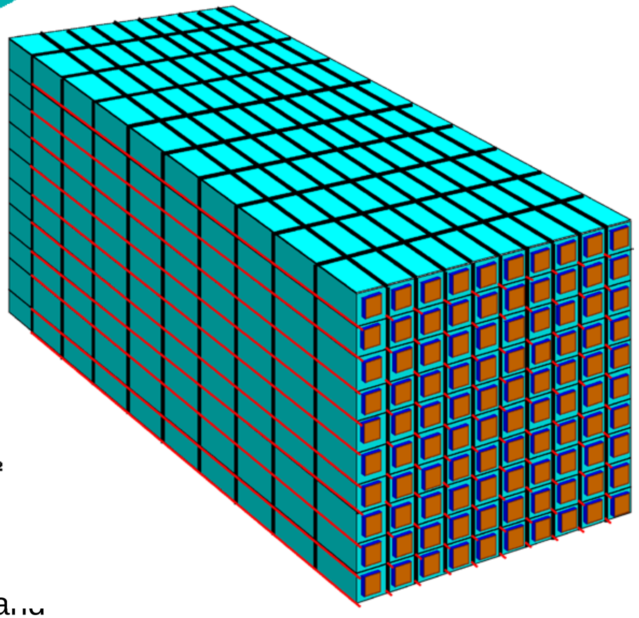


Readout with two SiPMs monitoring with two LEDs



Can we afford?





BGO Crystals at Fermilab

ID	Dimension (mm^3)	Polishing
BGO SIC2015-C1 to C16	50x50x50	Six faces
BGO SIC2015-R1 to R16	25x25x50	Six faces

Experiments

- Properties measured at room temperature: Photo-Luminescence (PL), Longitudinal Transmittance (LT), Emission Weighted LT (EWLT), Pulse Height Spectra (PHS), Light Output (LO) & Decay Kinetics
- Light output measured with a small face coupled to a Hamamatsu R1306 PMT with Grease coupling, two layers Tyvek paper wrapping, Na-22 source and coincidence trigger

Aiming at testing dual readout with crystals, 32 BGO crystals were procured from SIC with a DOE CDRD award: 16 each of 5 x 5 x 5 cm^3 and 2.5 x 2.5 x 2.5 cm^3.

They may be used for a 10 x 10 x 25 cm^3 matrix of 4.5 R_M x 4.5 R_M x 22.3 X_0 (1.1 λ_I).

HHCAL Workshops a Decade ago

5/9/2010, Beijing: http://indico.ihep.ac.cn/conferenceTimeTable.py?confId=1470
10/31/2010, Knoxville: http://www.nss-mic.org/2010/program/ListProgram.asp?session=HC1,2,3,4

1) HHCAL and General Requirement:

Gene Fisk, FNAL: "Fermilab's History in the Development of Crystals, Glasses and Si Detector Readout for Calorimetry"
Adam Para, FNAL: "Scintillating Materials for Homogeneous Hadron Calorimetry"
Steve Derenzo, LBL: "Search for Scintillating Glasses and Crystals for Hadron Calorimetry"
Paul Lecoq, CERN: "A CERN Contribution to the Dual Readout Calorimeter Concept"

2) Materials for HHCAL (I) :

Alex Gektin, SCI: "Crystal Development for HHCAL: Physics and Technological Limits"
Liyuan Zhang, Caltech: "Search for Scintillation in Doped Lead Fluoride for the HHCAL Detector Concept"
Guohao Ren, SIC: "Development of Halide Scintillation Crystals for the HHCAL Detector Concept "
Hui Yuan, SIC: "BSO Crystals Development with the Modified Multi-crucible Bridgman Method for the HHCAL Detector Concept"

3) Materials for the HHCAL (II) followed by discussions

Mingrong Zhang, BGRI: "R&D on Scintillation Crystals and Special Glasses at BGRI"
Tiachi Zhao, U Washington/IHEP and Ningbo University: " Study of Dense Scintillating Glass Samples"
Jing Tai Zhao, SIC: "Status of Scintillating Ceramics and Glasses at SIC and Their Potential Applications for the HHCAL Detector Concept"
Richard, Wigmans, Texas Tech University: "Some thoughts about homogeneous dual-readout calorimeters"

1. A. Para, Prospects for High Resolution Hadron Calorimetry
2. G. Mavromanolakis , Studies on Dual Readout Calorimetry with Meta-Crystals
3. D. Groom, Degradation of resolution in a homogeneous dual readout hadronic calorimeter
4. S. Derenzo, High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters
5. M. Poulain, Fluoride Glasses: State of Art and Prospects
6. I. Dafinei, High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry
7. P. Hobson, Prospects for Dense Glass Scintillators for Homogeneous Calorimeters
8. G. Dosovitski, Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry
9. Tianchi Zhao, Study on Dense Scintillating Glasses
10. Jin-tai Zhao, BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter
11. Guohao Ren, Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL
12, N. Cherepy, Transparent Ceramic Scintillators for Hadron Calorimetry
13. J. Dong, Experimental Study of Large Area GEM
14. H. Frisch, The Development of Large-Area Flat-Panel Photodetectors with Correlated Space and Time Resolution

Low-Cost Inorganic Scintillators

Scintillating glasses will be investigated after crystals

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	DSB:Ce Glass[1]	DSB:Ce,Gd Glass[2,3]	HFG Glass[4]
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	3.8	4.7 - 5.4	5.95
Melting point (℃)	1050	1030	1123	824	608	2040	980[5]	1420[6]	1420[6]	570
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	3.36	2.14	1.74
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.89	3.52	2.56	2.45
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	32.8	24.2	23.2
Z_{eff} value	72.9	75.3	74.5	77.4	75.8	11.2	42.8	44.4	48.7	56.9
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	5.56	7.68	8.24
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	440 460	440 460	325
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	\	\	\	1.50
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	3,150	2,500	150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	180 30	120, 400 50	25 8
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	-0.04	-0.04	-0.37
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6?	?	2.0	2.0?	?

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C).

1. E. Auffray, et al., J. Phys. Conf. Ser. 587, 2015
2. R. W. Novotny, et al., J. Phys. Conf. Ser. 928, 2017
3. V. Dormenev , et al., the ATTRACT Final Conference
4. E. Auffray, et al., NIMA 380 (1996), 524-536
5. R. A. McCauley et al., Trans. Br. Ceram. Soc., 67. 1968
6. I. G. Oehlschlegel, Glastech. Ber. 44, 1971

Low density crystals/glasses

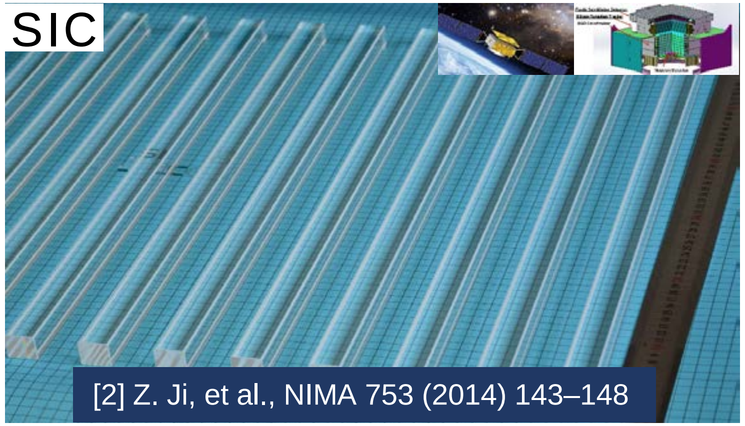
Crystal Cost for CEPC (Mar 2019)

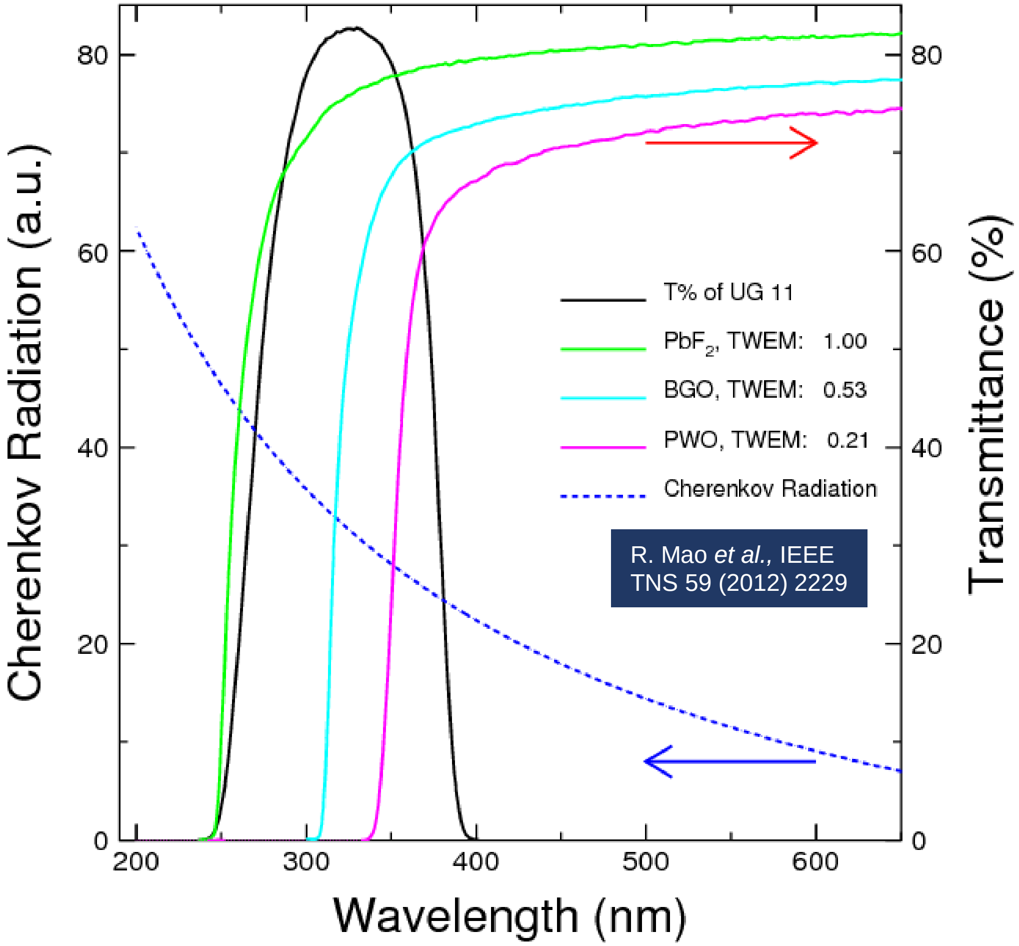
Cost-effectiveness scaled with X_0: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

Item	Size (R_MxR_Mx25 X_0)	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09

BGO Improvement

As the main vendor of BGO crystals for GE's PET scanner, SIC produces 4 m^3 BGO crystals yearly
SIC also provides 40 and 60 cm long BGO crystals for CEPC [1] and DAMPE [2] respectively
Select doping or BGSO may be tried to improve UV cut-off, decay time and radiation hardness

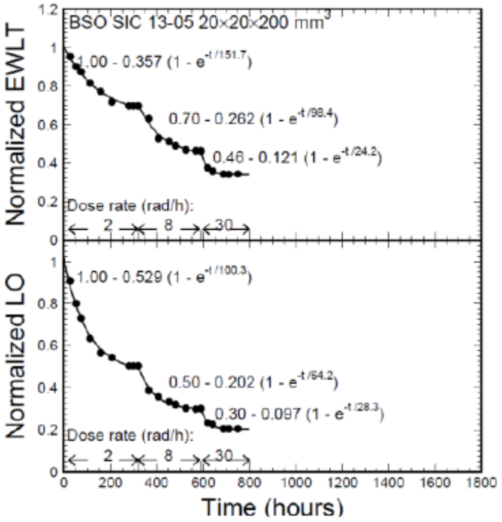


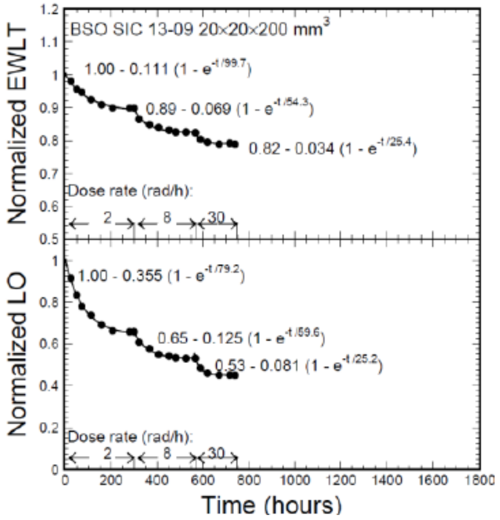


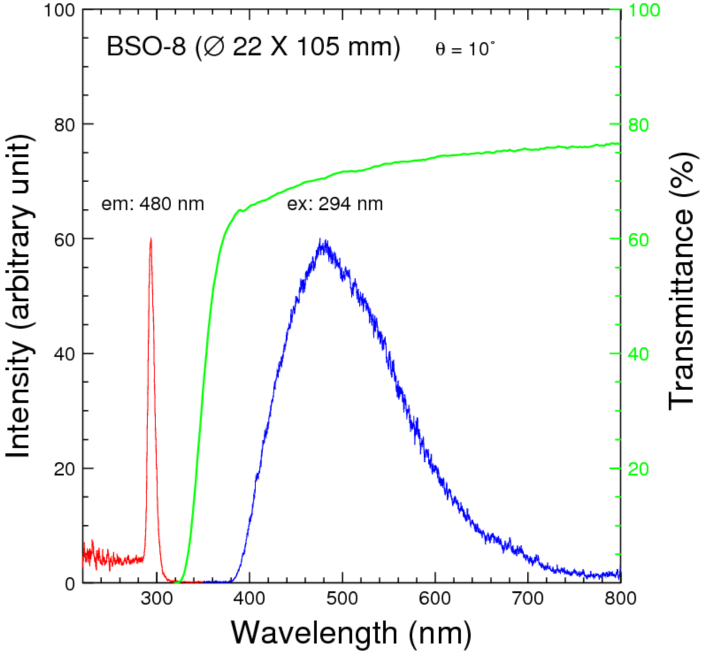
BSO Crystals at Caltech

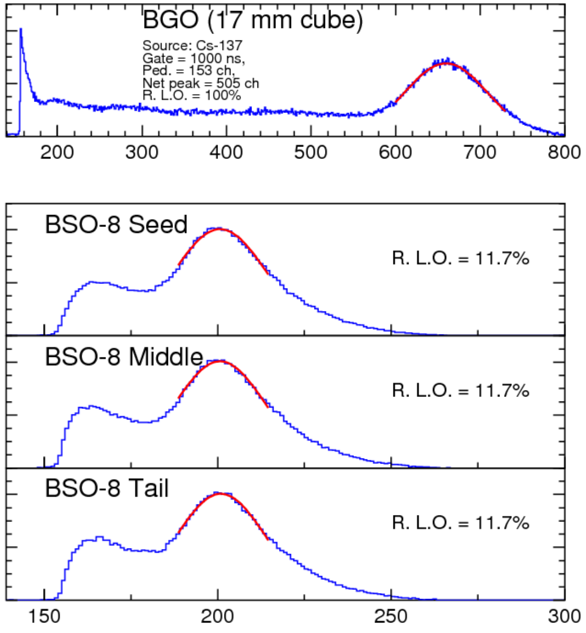
Lower light output (12%), faster decay time (100 vs. 300 ns), poorer optical property and radiation hardness then BGO.

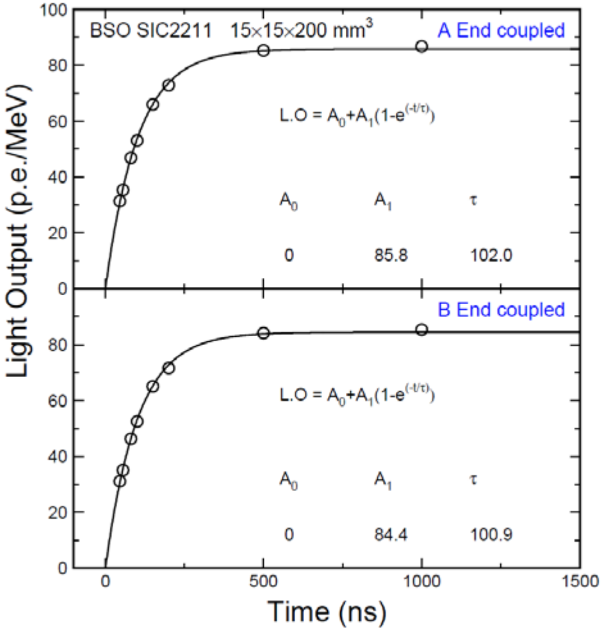
F. Yang et al., Journal of Physics: Conference Series 587 (2015) 012064

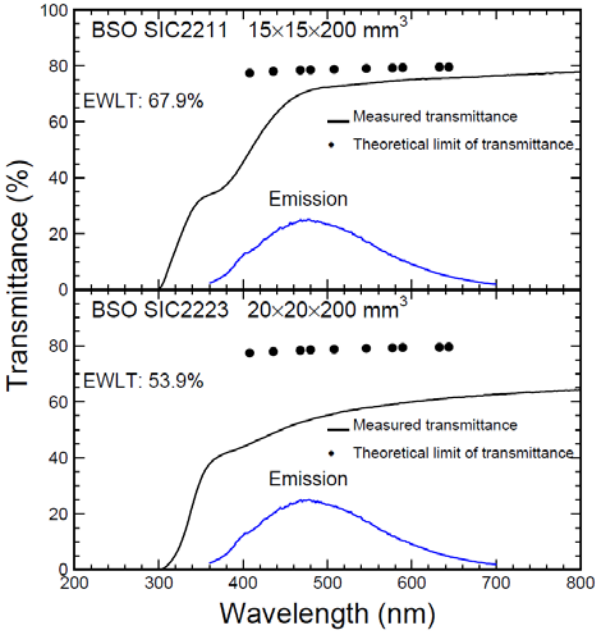






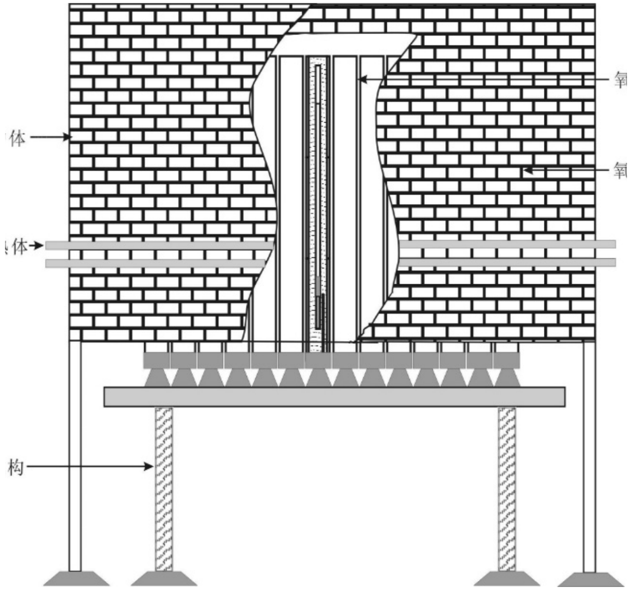


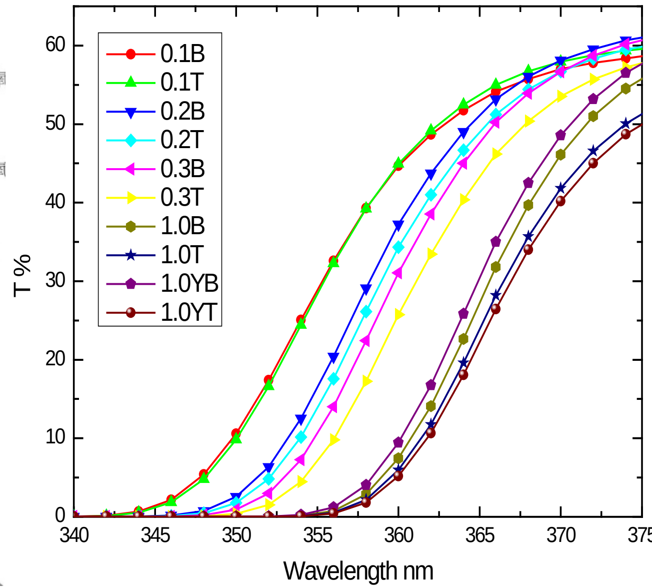


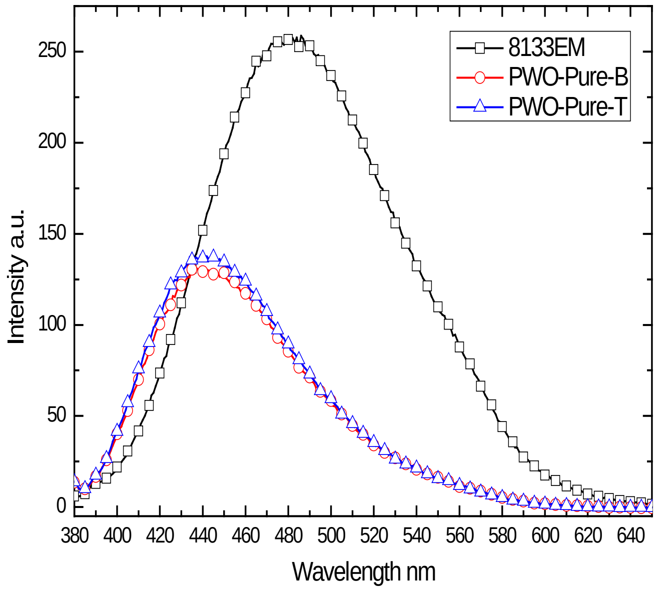


PWO Improvement

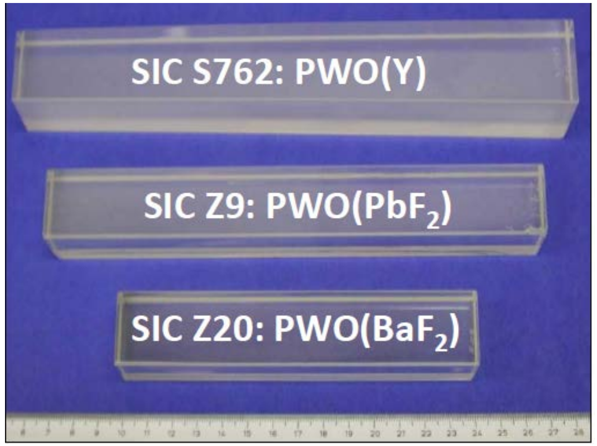
Optical quality of Bridgman PWO is not as good as Czochralski PWO

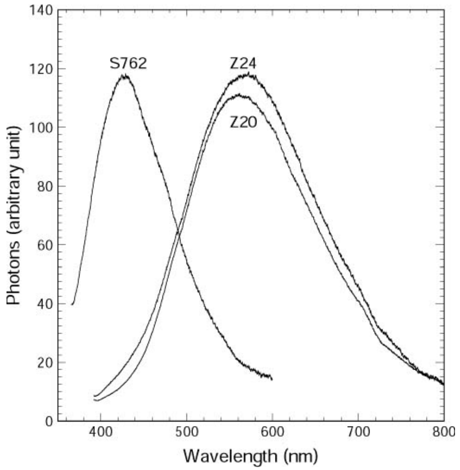


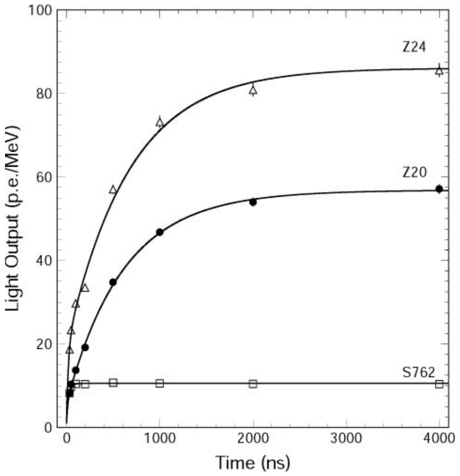


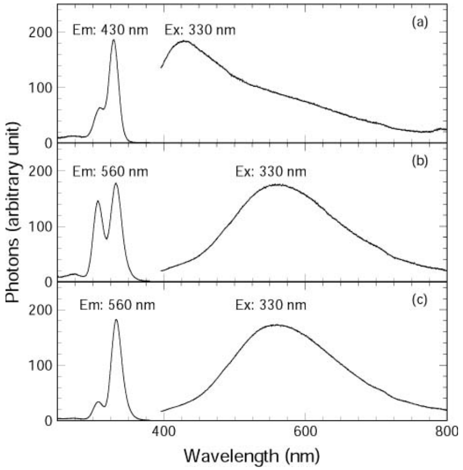


As the densest crystal, it appears worthwhile to improve PWO optical property by selective doping to tune UV cut-off and emission, so enhancing Cerenkov and help discrimination against scintillation.









A factor of ten intensity of slow (μs) green light (560 nm) was observed in doped PWO.

R. Mao et al., NIMA 486 (2002) 196, and Frascati Physics Series Vol. XXI (2000) 709-720

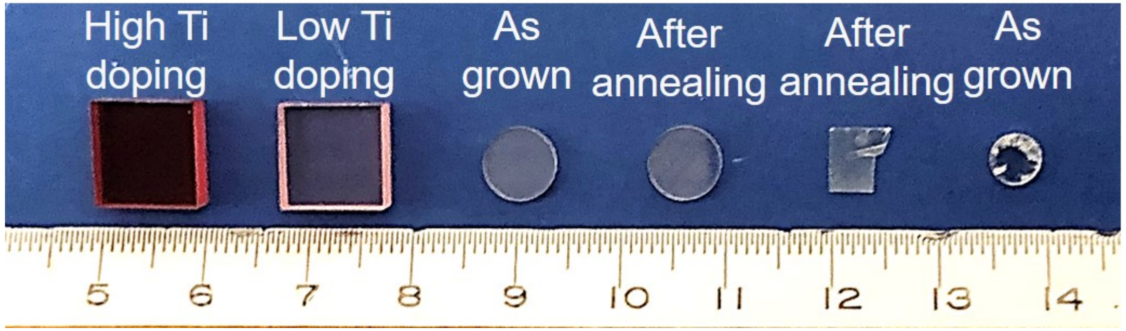
Cost-Effective Sapphire Crystals for HHCAL

Large sapphire crystal of 400-450 kg

Prof. Xu Jun of Tongji University: Sapphire crystals by Kyropoulos (KY) technology A producer can grow 1,000 tons ingots annually with 400 to 450 kg/ingot Cost of mass-produced Sapphire crystals including processing: less than $1/cc

	Weight (kg)	Size (cm)	Unit Price	Comment
ingot boule	400	Φ50×55	US$12000/pc	for undoped
cutting/polishing	4	1×1×1	**~US$0.6/cc**	for undoped

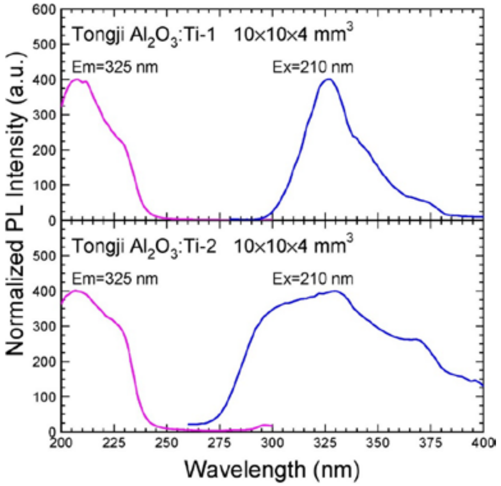
Sapphire:Ti Emission & Transmittance



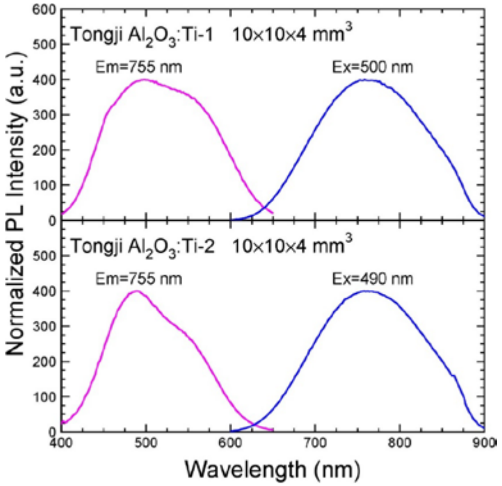
ID	Dimension (mm^3)	#	Polishing
Tongji Al_2O_3:Ti-1,2	**10×10×4**	**2**	**Two faces**
Tongji Al_2O_3:C-1,2	Φ7×1	2	Two faces
Tongji Lu_2O_3:Yb	6.4×4.8×0.4	1	Two faces
Tongji $LuScO_3$:Yb	Φ4.8×1.3	1	Two faces

A weak emission at 325 nm with 150 ns decay time
A strong emission at 755 nm with 3 μs decay time

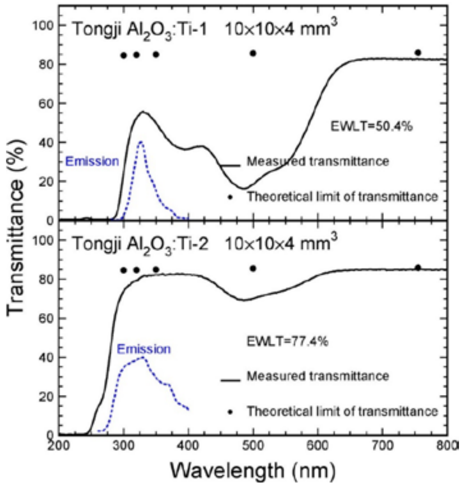
Fast @325 nm



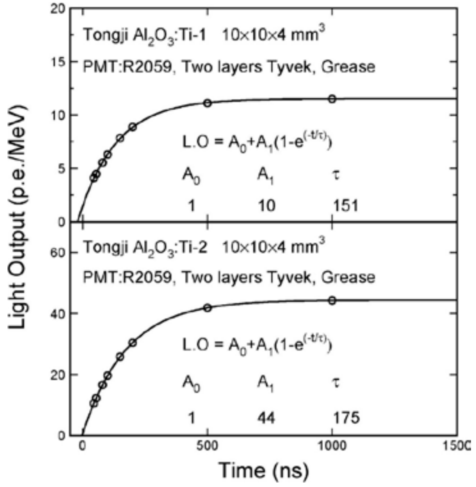
Slow @755 nm



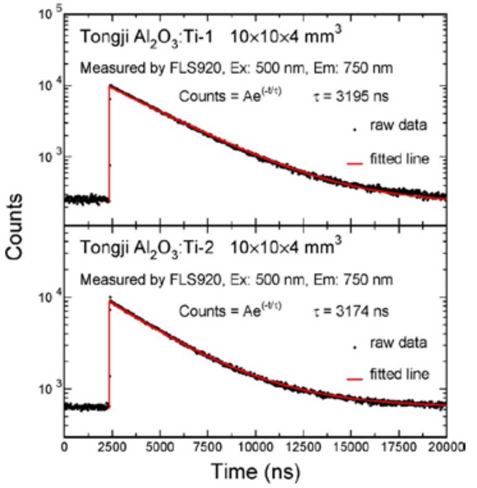
EWLT for Fast & Slow



Fast = 162 ns



Slow = 3.2 μs



Summary

The **CalVision** mission is to build a longitudinally segmented crystal ECAL for the Higgs factory by using heavy crystals, such as BGO or PWO. Their optical property may be improved, particularly the Bridgman PWO.

The **HHCAL concept** promises the best jet mass resolution with a challenge in the cost of inorganic scintillators. Following crystal investigation heavy scintillating glasses are to be investigated.

Novel cost-effective inorganic scintillators will play important role

Acknowledgements: DOE HEP Award DE-SC0011925

Raw Material Cost for Glasses

Weight ratio (%)	DSB Glass	DSB:Gd Glass	HFG Glass	Price/kg*
BaO	56.1	44.9	\	5
B_2O_3	\	\	\	3.4
SiO_2	43.9	35.1	\	0.57
Al_2O_3	\	\	\	1.5
Lu_2O_3	\	\	\	500
Gd_2O_3	\	20	\	10
BaF_2	\	\	28	0.95
AlF_3	\	\	2	0.8
YF_3	\	\	2	3
NaF	\	\	12	1
HfF_4	\	\	56	160
CeF_3	Unknown	Unknown	Unknown	10
Price/CC	0.01	0.02	0.54	

Use low-cost raw materials, such as Gd_2O_3 and BaF_2, would help

* https://www.alibaba.com/