

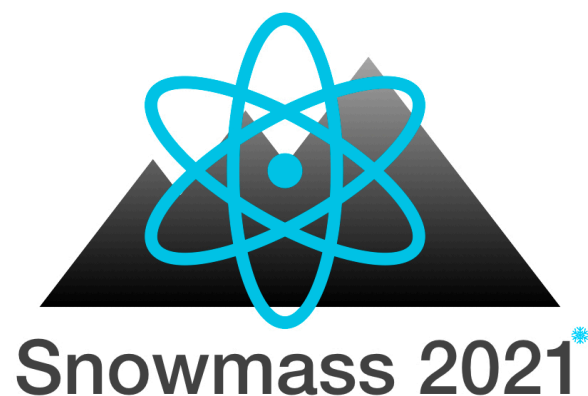
Key points from IF06 - Calorimetry

Andy White¹, Minfang Yeh², Rachel Yohay³

¹UT Arlington, ²BNL, ³FSU

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White papers

- From 65 letters of interest, the following themes (\leftrightarrow white papers) emerged
 - Particle flow calorimetry for future colliders
 - Dual readout calorimetry for future colliders
 - Precision timing for collider experiment based calorimetry
 - Materials for future calorimeters

Key messages

- **Differently to the past**, future calorimetry at fixed target and colliding beam experiments should be **fundamentally multidimensional**, providing shower position, time, energy, and a detailed look at shower constituents through the exploitation of an application-specific **combination of particle flow techniques, materials with intrinsically good time or energy resolution, and/or dual readout techniques**. This is required to achieve the physics goals related to the study of electroweak symmetry breaking, flavor symmetries, CP violation and neutrino properties, and what lies beyond the Standard Model.

Key messages

- With **timing information and excellent timing resolution, challenging physics studies** such as $h \rightarrow s\bar{s}$ can be made. This timing will also allow for long-lived particle searches either in combination with tracking, or in the calorimeter alone.

Key messages

- Sustained R&D is needed to move multidimensional calorimetry **from prototype to realistic detector**.
Scaling to hundreds of thousands or tens of millions of channels while maintaining the required quality is a huge challenge—it's an entirely new scale for academia, but often too small for industry.

Key messages

- Electronics must be developed to allow new features such as fast timing **without significantly adding to the power budget or cooling load**. This may only be achieved by monitoring and working closely with industry as new electronics options emerge. It will also be necessary to have HEP personnel trained in the new technologies.

Key messages

- Effective partnerships with chemists, materials scientists, industry, and radiation facilities must be continued and strengthened to **explore the landscape of materials** that enable precision calorimetry.

Backup

Particle flow

Table 6-1. Overview of the characteristics of several particle flow calorimeter concepts and technologies.
Reprinted from Ref. [4].

name	purpose	project	active material	channel size	readout	# of layers (depth)
CALICE SiW ECAL	ECAL	ILC ^a	silicon	$5 \times 5 \text{ mm}^2$	analog	30 ($24X_0$)
SiD ECAL	ECAL	ILC	silicon	13 mm^2	analog	30 ($26X_0$)
HGCAL Si	ECAL ^b	HL-LHC	silicon	$52\text{-}118 \text{ mm}^2$	analog	28 ($25X_0$)
FoCal	ECAL	HL-LHC	silicon	$30 \times 30 \mu\text{m}^2$	digital	28 ($25X_0$)
CALICE Sci-ECAL	ECAL	ILC ^c	SiPM-on-tile	$5 \times 5 \text{ mm}^2$ ^d	analog	30 ($24X_0$)
RADiCAL	ECAL	FCC-hh	crystal + WLS ^e	$4 \times 4 \text{ mm}^2$ ^f	analog	29 ($25X_0$)
CALICE AHCAL	HCAL	ILC ^g	SiPM-on-tile	$3 \times 3 \text{ cm}^2$	analog	40 ($4\lambda_I$)
HGCAL Scint	HCAL	HL-LHC	SiPM-on-tile	$6\text{-}30 \text{ cm}^2$	analog	22 ($7.8\lambda_I$) ^h
CALICE DHCAL	HCAL	ILC	RPC	$1 \times 1 \text{ cm}^2$	digital	40 ($4\lambda_I$)
CALICE SDHCAL	HCAL	ILC	RPC	$1 \times 1 \text{ cm}^2$	semi-digital	40 ($4\lambda_I$)

^aalso for CLIC & FCC-ee

^bsilicon also used in HCAL part

^calso for CEPC

^deffective size, strips have $5 \times 45 \text{ mm}^2$

^ewavelength-shifting fiber

^feffective size at shower max; module cross-section is $14 \times 14 \text{ mm}^2$

^galso for CEPC, CLIC & FCC-ee

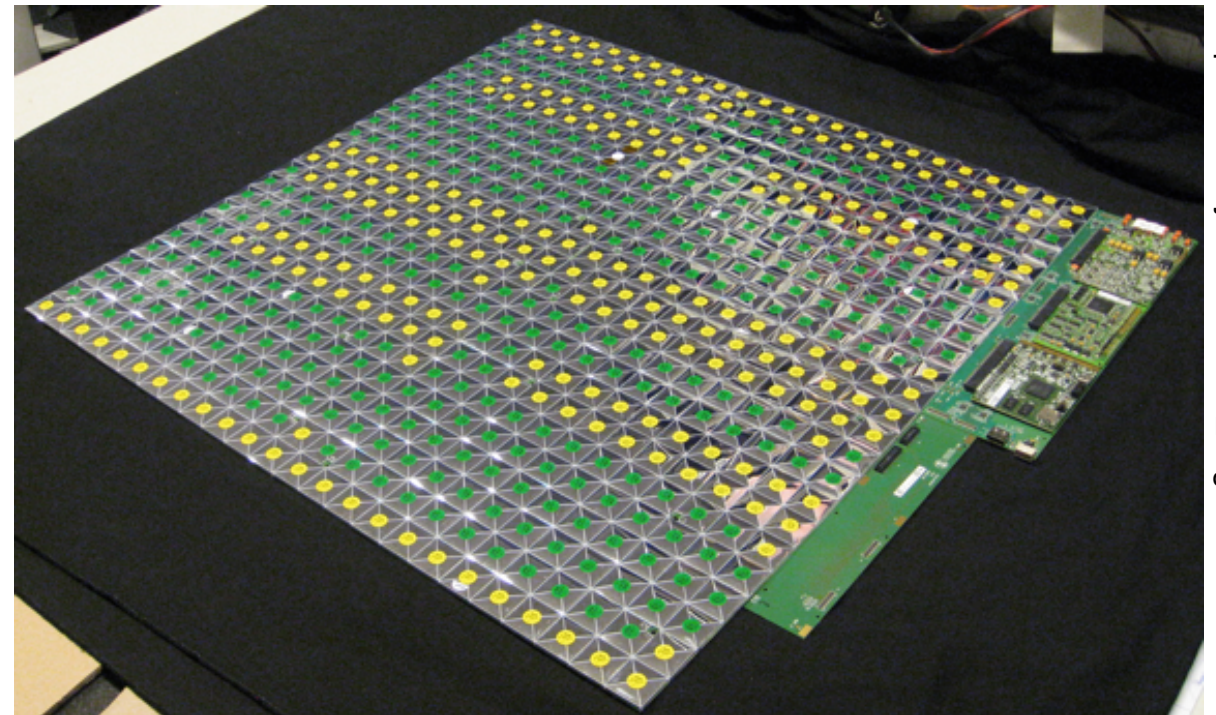
^hcontains also pure silicon and mixed layers

Extensive interest from e⁺e⁻ community,
which has driven much R&D

First realization in HL-LHC, motivated by
radiation hardness and pileup

Particle flow

- R&D continues to advance along many fronts
- Challenges remain:
 - Scaling to 10-100M channels at reasonable cost
 - Thermal and power management of front end ASICs
 - Compact design (minimizing gaps between sampling layers)



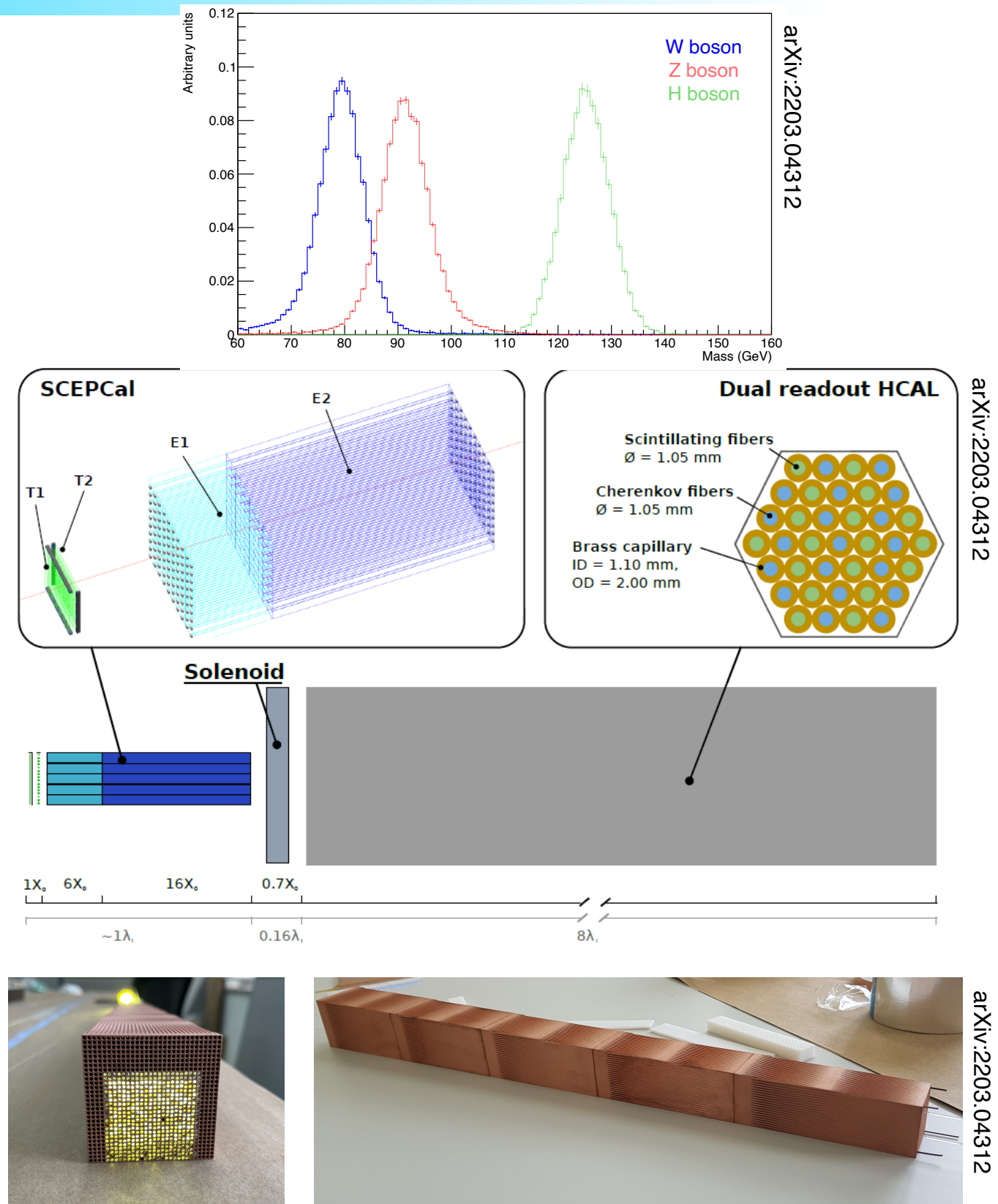
https://flic.desy.de/hcal/index_eng.html

Particle flow

- Synergies with other areas of HEP instrumentation
 - Silicon detectors, SiPMs, fast scintillators, and gas ionization detectors are all good candidate active media, depending on the use case
 - Smart, low-power, radiation-tolerant front end electronics are needed to realize compact designs
 - PF reconstruction provides a benchmark for optimizing novel computational methods, like the use of machine learning in triggering or particle reconstruction, and in turn requires performance advances that can speed up detector simulation or improve jet energy resolution

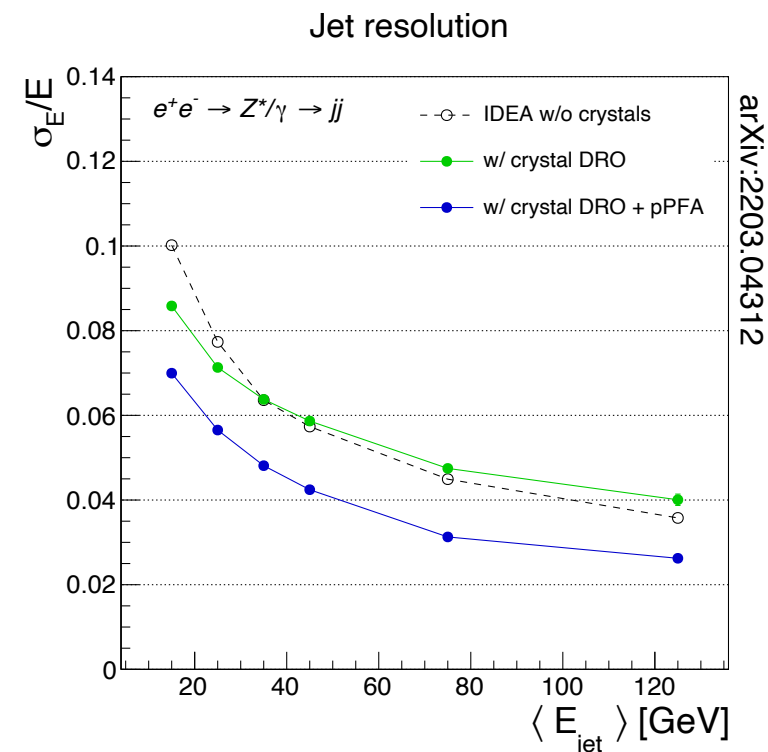
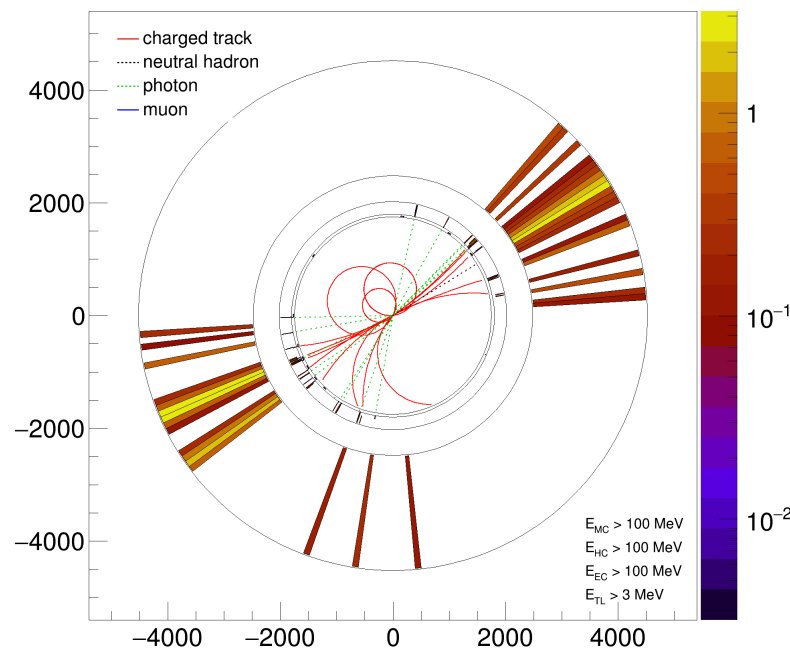
Dual readout

- Hadronic and electromagnetic calorimetry
 - Spaghetti calorimeter with clear (Čerenkov) and scintillating fibers installed in a tower of passive material
- Electromagnetic section only (of an ECAL+HCAL system)
- Homogeneous scintillating crystals with two filter-SiPM readout assemblies, sensitive to either Čerenkov or scintillation light
- Challenges remain:
 - Mechanics, integration, and costing of a realistic spaghetti calorimeter
 - Red-sensitive SiPMs and novel optical materials to boost the Čerenkov signal/noise in homogeneous crystal setups



Two great tastes that taste great together?

- ADRIANO2 for proposed η factory
 - Highly granular particle flow-like sampling calorimeter, but alternating lead glass absorber/scintillator (sensitive to Čerenkov) and plastic scintillator
 - Discrimination between photons, neutrons, and π^0 s
- Spaghetti calorimeter with individual SiPM readout of each fiber
- SCEPCal for CEPC or FCC-ee
 - Coarser longitudinal segmentation than CALICE-style particle flow
 - Tuned particle flow reconstruction algorithm + dual readout information yields better results than dual readout alone
- Both concepts being considered for a muon collider detector



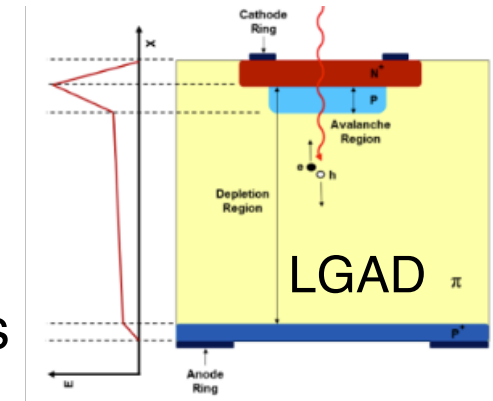
Precision timing

- An extra dimension to calorimeter systems: $O(10,1,0.1)$ ps depending on application and technology
- Volume timing—timing for all active cells in calorimeter
 - Benefits for pattern recognition, shower reconstruction/separation, energy measurement
 - Potentially high cost
- Timing layers—small number of dedicated timing layers, e.g. before and after ECAL
 - Likely cheaper (amount of material) for better resolution (splurge on better materials)
 - Need good association between MIP and shower

Precision timing

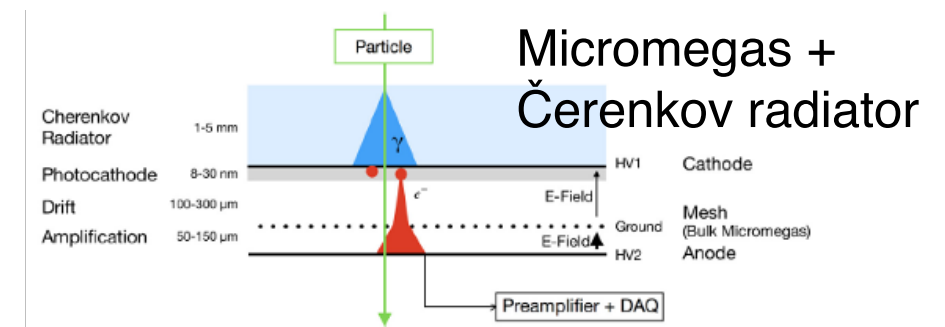
- Timing layers

- Low-Gain Avalanche Detectors (LGADs) $\sim 30\text{ps}$ and 1mm spatial resolution
- Ultra-fast silicon monolithic sensors with integrated readout (CMOS) 10-20ps
- Micro-channel plate (MCP) detectors detection of single ionizing particles $\sim \text{few ps}$
- 2-stage Micromegas detector + Cherenkov radiator equipped with a photocathode $< 100\text{ps}$
- LYSO crystals + SiPM few $\times 10\text{ ps}$
- Deep diffused avalanche photodiodes $\sim 40\text{ps}$
- Askaryan effect $\sim 0.3 - 3\text{ps}$

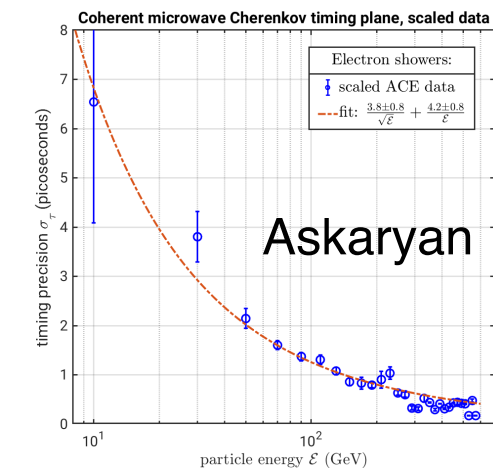


- Volume timing

- Silicon tiles e.g. LGADs few $\times 10\text{ ps}$
- Plastic scintillator tiles or strips with SiPM readout sub-ns \rightarrow few $\times 10\text{ps}$
- Multi-gap RPCs sub-100ps
- Highly granular crystal-based detectors, using a highly segmented readout



- *R&D needed on electronics* to support timing resolution satisfying the constraints on power consumption associated with highly integrated systems with extreme channel counts



- (Issues) stringent challenges to calorimeter materials in radiation tolerance, energy resolution, time response and project cost
 - Enhance calorimetry energy resolution for precision electroweak mass and missing energy measurements.
 - Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments.
 - Develop ultrafast media to improve background rejection in calorimeters and improve particle identification.
- WP summarized materials in the form of inorganic, liquid (oil- and water-based), and plastic scintillators from LOIs and consortiums
 - $\text{BaF}_2\text{:Y}$ \rightarrow feasible to TOF system; Mu2e-II, (also by RADICAL)
 - LYSO:Ce or LuAG:Ce \rightarrow best fit to radiation hardness; HL-LHC, FCC-hh (RADICAL)
 - BGO, PWO, Glass \rightarrow good EM and jet resolutions; Higgs-Factory, ILC and FCC-ee (CalVision and HHCAL)
 - Liquid (oil- and water-based) and plastics scintillators (from neutrino and other particle physics experiments)
- Inorganic scintillator crystals dominate the calorimetry applications
 - New glass materials (OGS) are promising
 - Organics scintillators are less selected, but could have usages in future large volume (cost) calorimeters

high density, good optical quality, high light-yield, fast decay time, good radiation hardness and low cost

- Materials for Future Calorimeters : arXiv:2203.07154 (material performance described)

Materials (noble gas not included)	LY (ph/MeV)	Cost ⁺ (per kg)	Decay Time (ns)	Comments
Inorganic Scintillators	140 – 63,000	\$1k-\$5k	Sub to 1,000s	High density, easy deployment, low optical, scale-up challenge for large volume application, e.g. HHCAL; RADiCAL uses WLS*
Organic Scintillator Plastics	1,000s	\$10s	1s	Medium density, easy deployment, m-optical, scale-up challenge (3D-print?), WLS*
(High Z-doped, 1s%) Organic Liquid Scintillator	9,000-14,000	\$1s	Sub	~10m-optical, low density (mitigated by high-Z?) , large volume; WLS-doped
(High Z-doped, 10s%) Water-based Liquid Scintillator	1,000s	<\$1s	Sub	~10m-optical, low density (mitigated by high-Z?) , environmentally-friendly, large volume, WLS-doped

- WLS (fibers) bridging emission to photosensor are required for plastics; direct coupling (no WLS) used by crystal calorimetry
- + See slide 27 of http://www.hep.caltech.edu/~zhu/talks/ryz_210316_EIC_Crystal_CAL.pdf, for mass-produced crystal cost per cc.