Status of Scintillator Development at Fermilab

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Fermilab

Sept 25, 2023

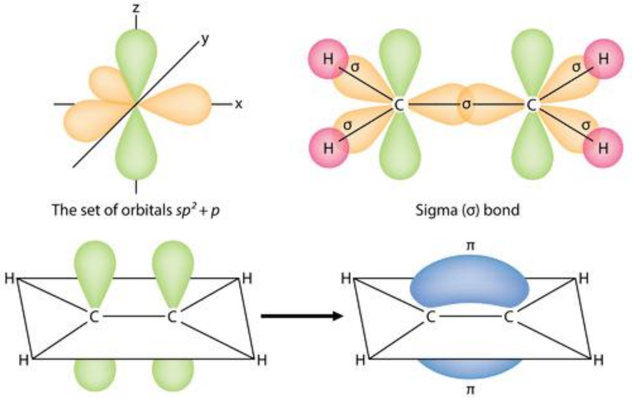
Outline

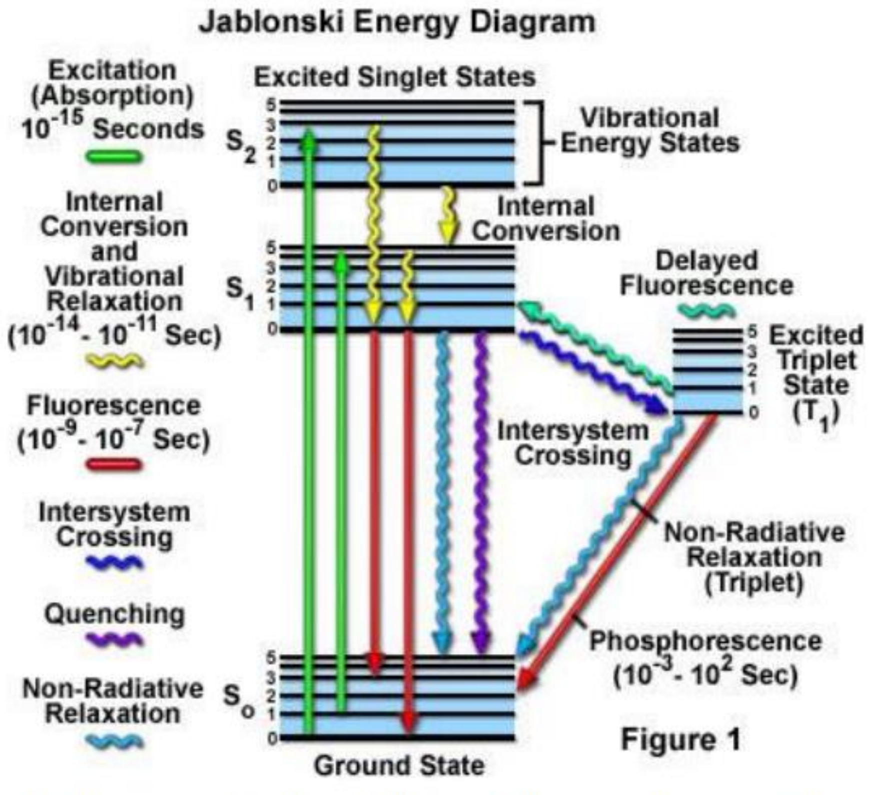
- Organic Scintillator
- FNAL Scintillator Extrusion and Injection Molding
- Applications
  - Archeology
  - Geology
  - Biology
  - Astroparticle
  - HEP
- R&D and future projects

Benzene, Sigma, Pi Orbitals, radiative, vibrational decays

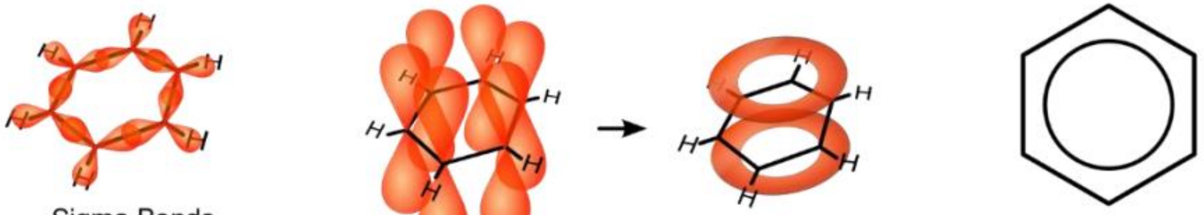
All scintillators made at FNAL use benzene rings as the fundamental scintillator. Polystyrene, polycarbonate

Carbon 1s2;2s2;2p2





http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html



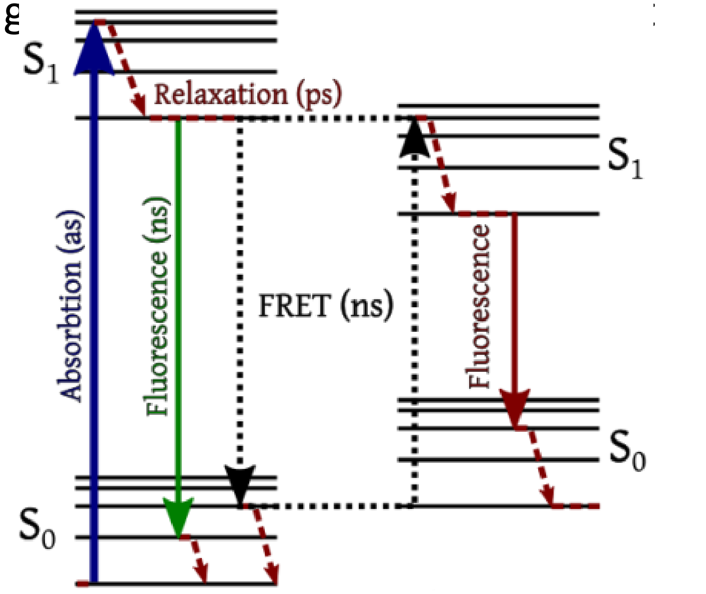
Sigma Bonds
sp^2 Hybridized orbitals

6 p_z orbitals

delocalized pi system

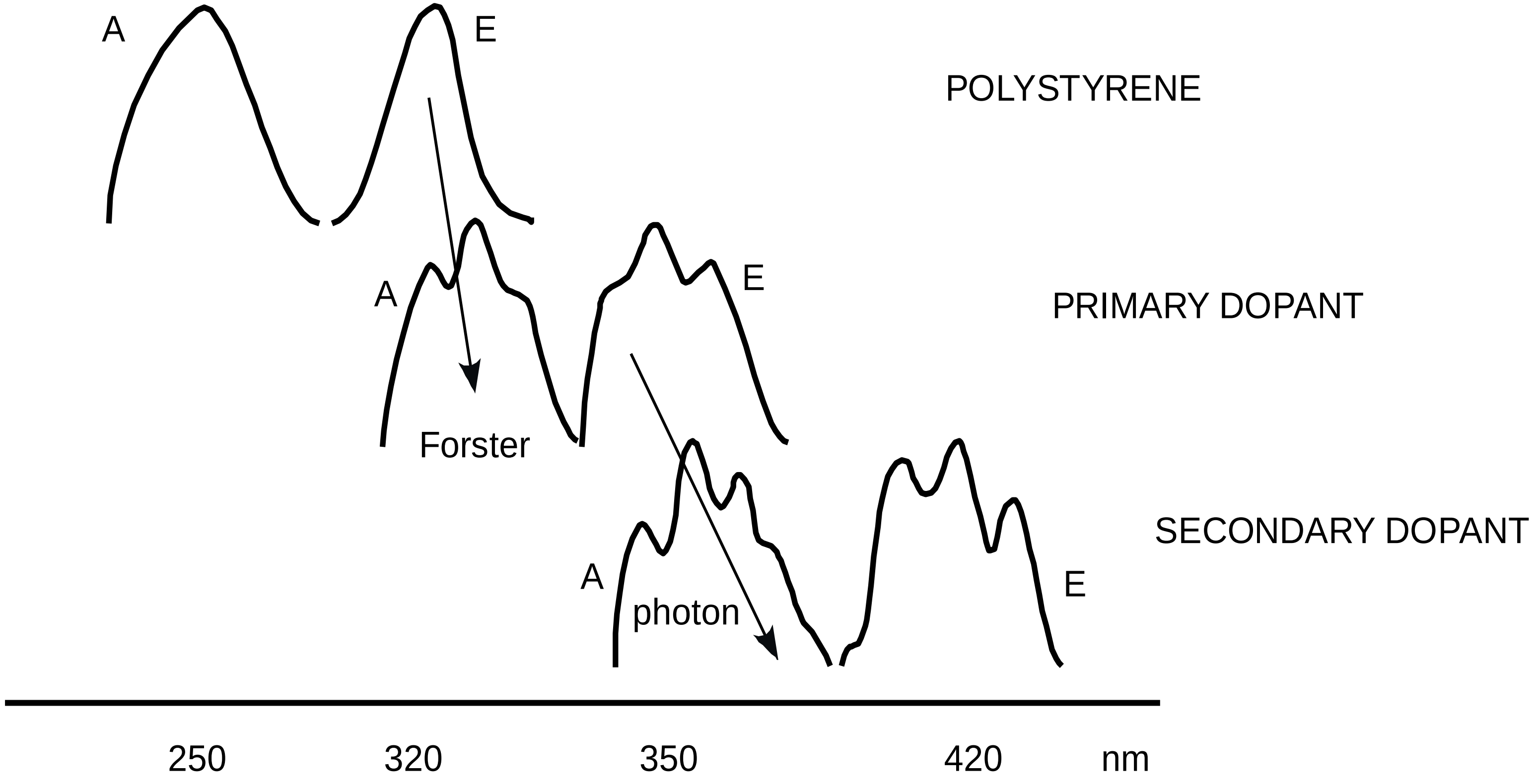
Benzene ring
Simplified depiction

Radiative deexcitation of polystyrene slow and low probability. 95% are vibrational decays. Add primary dopant in high concentration (1%) to allow for direct energy transfer from benzene to primary. ~100% probability. Photonic decay



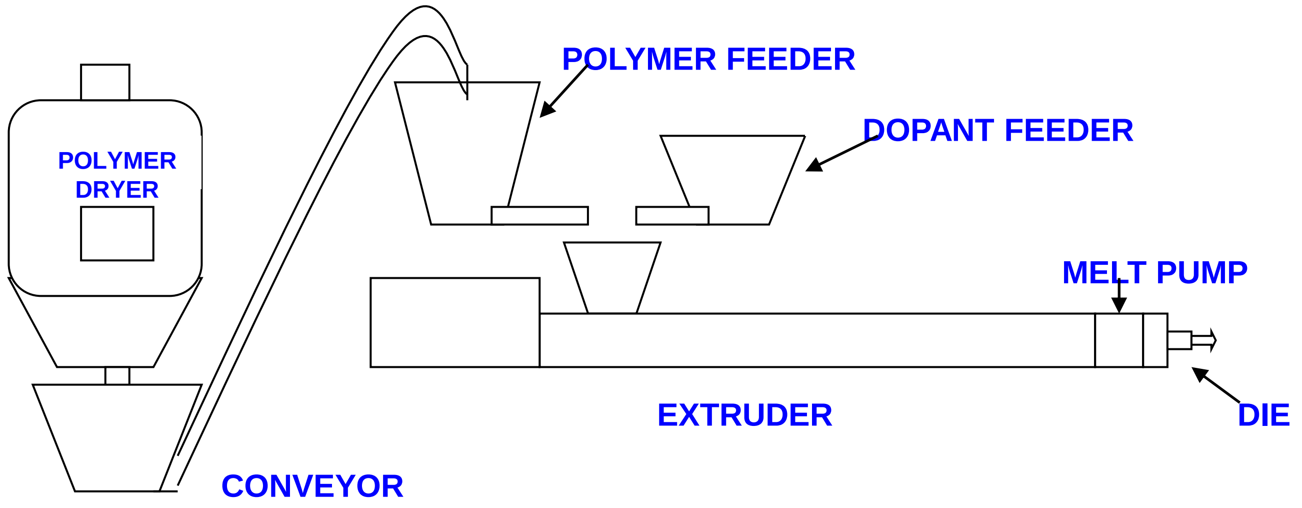
Benzene primary dopant

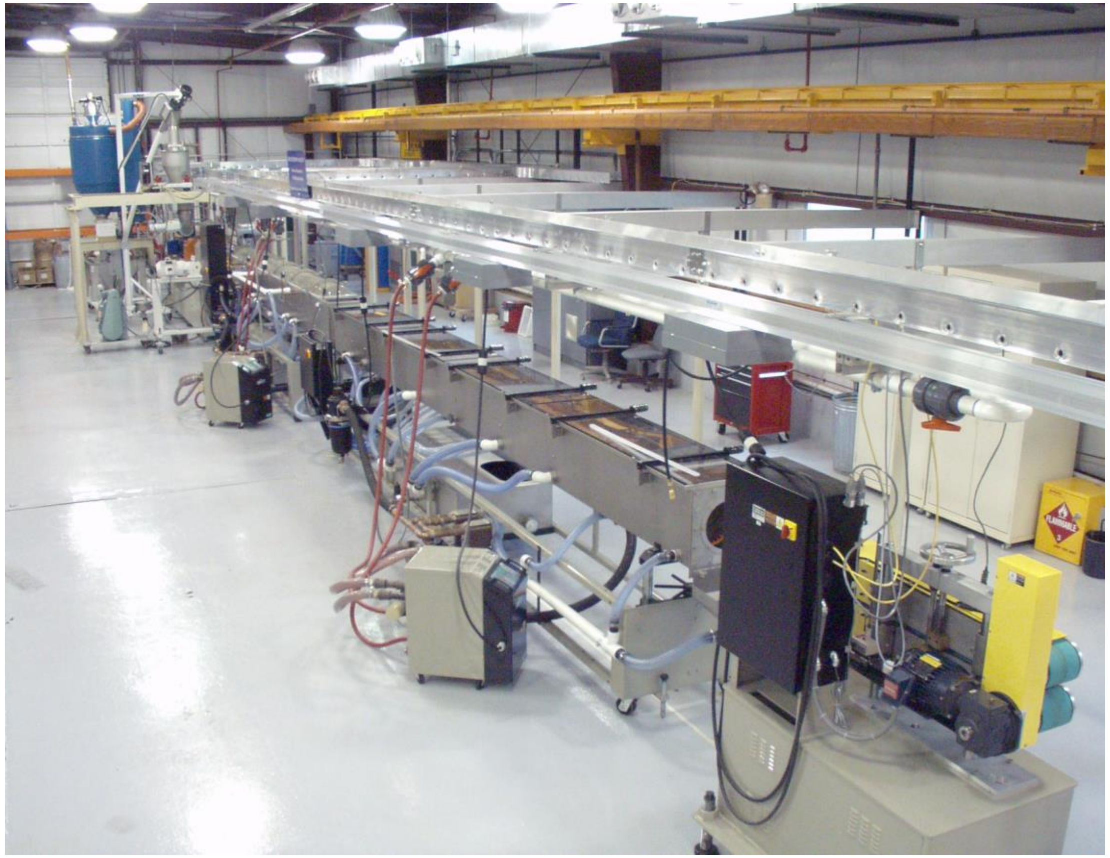
Primary scintillation light and dopants



Primary and secondary dopants absorb and re-emit the light at longer wavelengths until useable.
Primary PT, PPO
Secondary bis-MSB, POPOP

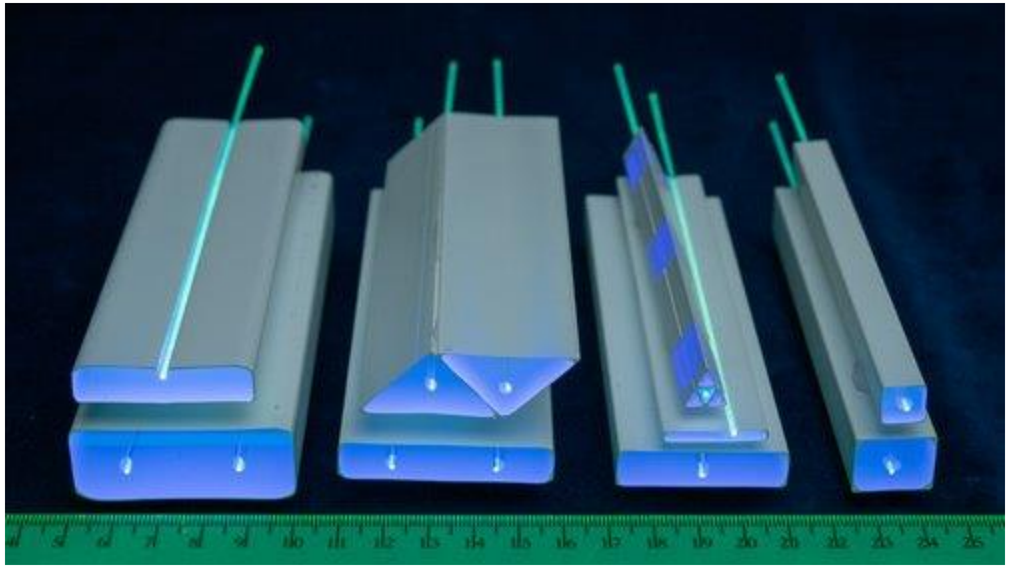
Fermilab Scintillator Extruder System





System ~50m long.
Can make ~75kg scintillator per hour, limited by cooling.
100 tons/year. One of largest scintillator producers in the world

Extrusion Profiles for various experiments



Hole(s) for fibers and white (TiO_2) cladding coextruded. Each new shape usually needs new die.

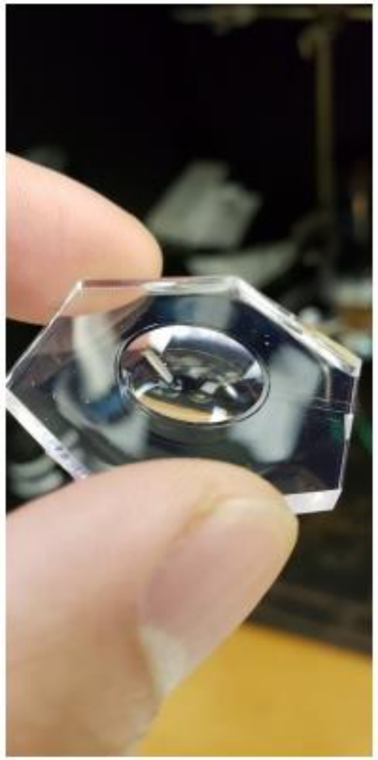
Factory Floor. Largest part so far: 4x4cmxL

Injection Molding at Fermilab. Example Hexagon tile

3 injection molding machines, 20 ton, 100 ton, 165 ton presses
Can make parts from 0.1 gram to 200 grams

100 ton Injection Molding Machine Lab 5


HEX mold in place



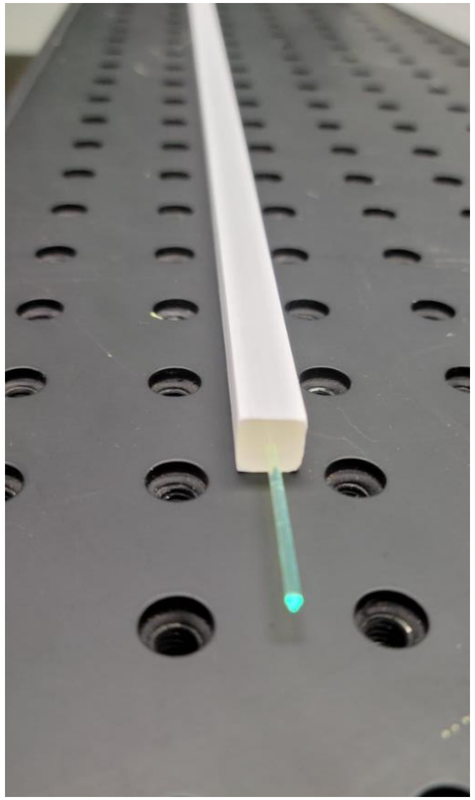
Fermilab Scintillator Extrusion and Injection Molding past/planned projects

- FNAL experiments:
  - MINOS (supervision & QC)
  - MINERvA
  - Mu2e CRV
  - TMS – DUNE
  - Mu2e II
- Large projects:
  - K2K (Supervision & QC)
  - T2K: P0D, ECal, INGRID
  - DoubleCHOOZ
  - Pierre Auger: CNEA, KIT
  - ICECUBE
  - IDEON – Canada
  - LDMX
  - MATHUSLA
- DOE complex:
  - ANL: STAR
  - JLAB: CLAS, CDet
  - LANL

- Smaller Projects
  - MURAVES – INFN Napoli
  - CANFRANC – Spain
  - SNOLAB -- Canada
  - INFN: Bologna, Brescia, Gran Sasso, Padova
  - Inst. Phys. Globe, France -- Volcano tomography Guadeloupe Soufrière
  - NYU – Abu Dhabi
  - Tel Aviv University – Erez City of David tomography
  - UIS – Colombia
  - Univ. Liverpool
  - LDMX Veto Prototype – Lund University
  - INO – mini ICAL Cosmic Veto
  - CMS
  - Naval Research Facility
  - MATHUSLA – U. Toronto
  - LHCB
  - INFN Catania
- Injection Molding (New capability as of this year)
  - CMS HGCAL
  - ePIC LFHCal – ORNL, BNL
  - Shashlik – HIKE calorimeter

Archeology

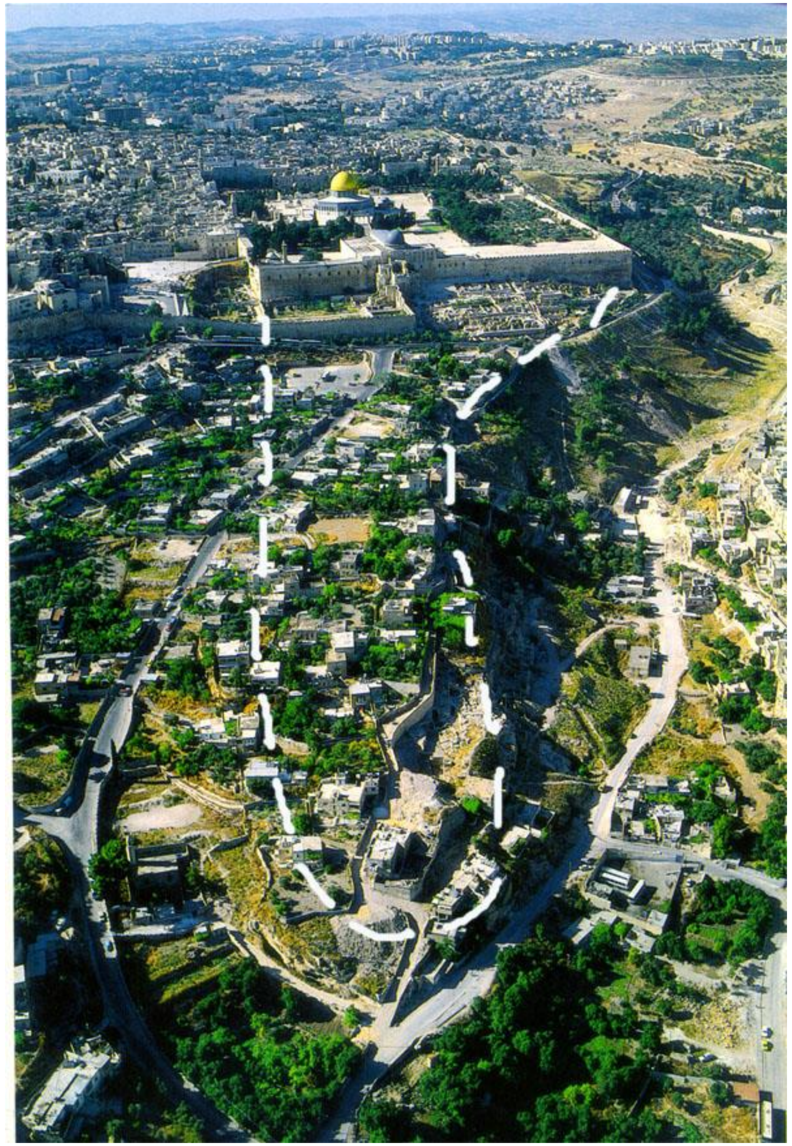
ScanPyramid



Extrusion Profile
1cmx1cmx120cm
co-extruded hole
and cladding

ScanPyramid Consortium uses 3 muon hodoscope technologies: scintillator (from FNAL), micromegas, emulsion. 2 layers, 1.2x1.2m

City of David, Jerusaleum
Archeology Muon Tomography

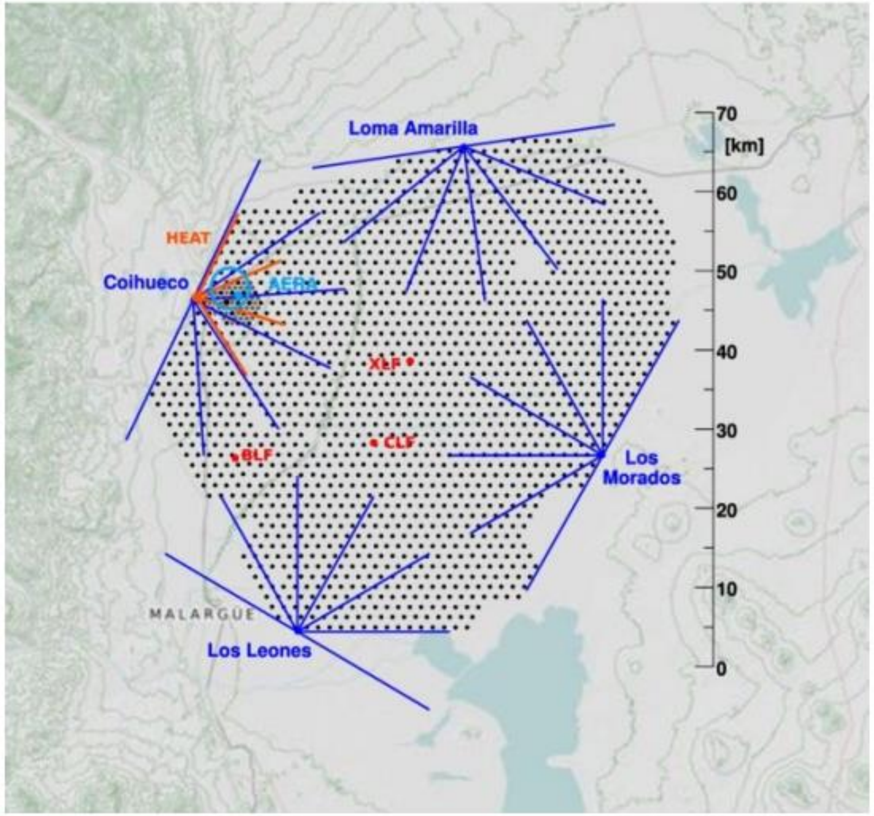


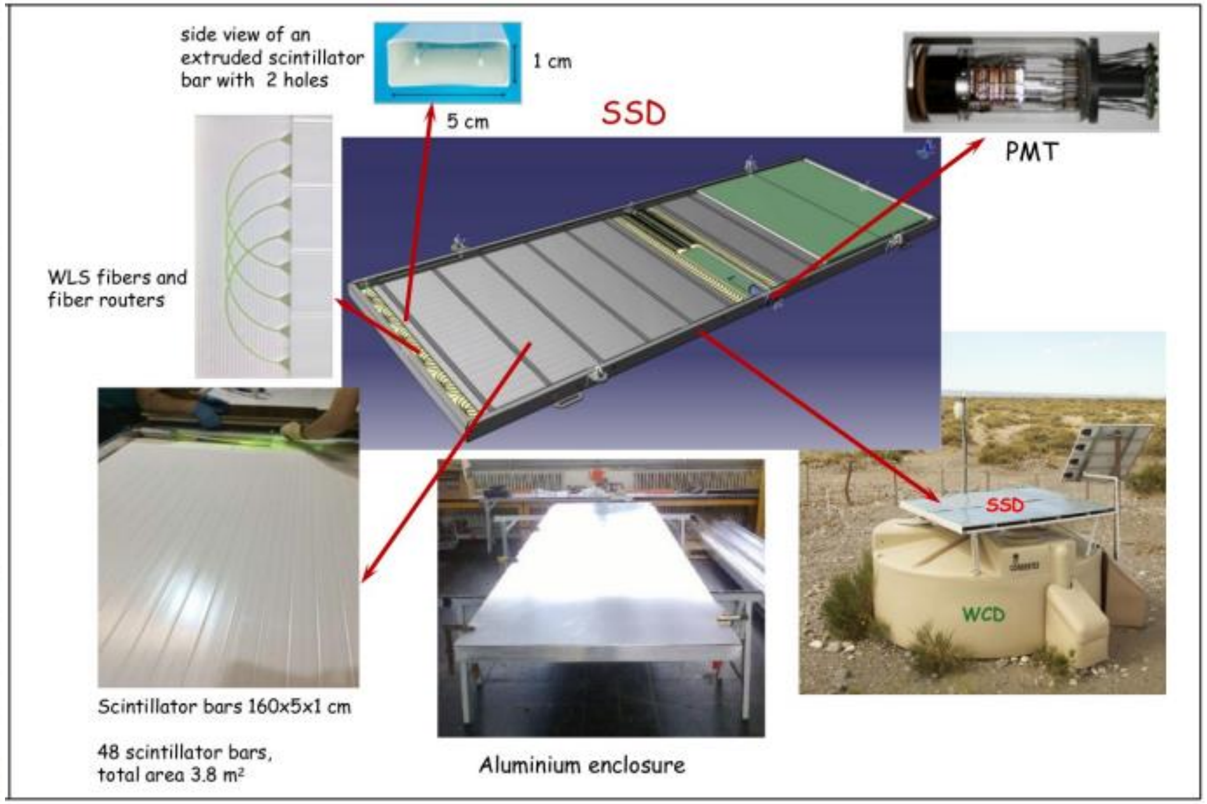
Group led by Erez Etzion in early phase of density mapping City of David (adjacent to Temple Mount) using muon detectors installed in water spring caverns under the site. Site dates from 4500 BC. Difficulties: access, high humidity.

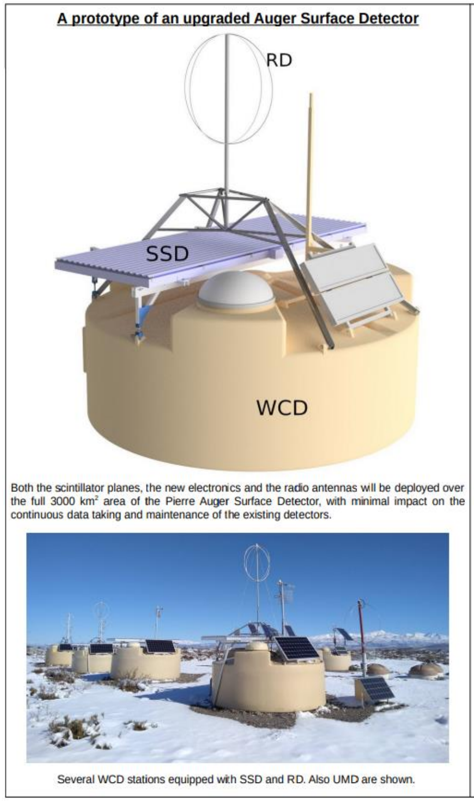
[Muon detector for underground tomography 2205.03722] [physics.ins-det]

Astroparticle

Pierre Auger Cosmic Ray Observatory







Pierre Auger Observatory: 3000 km^2 detector in Malargue, Argentina. Goal to measure highest energy cosmic rays. Cosmics are detected through multiple methods to give rich information about the event. Scintillation, Cerenkov, radio, and fluorescence detection telescopes. FNAL produced ~80,000 bars, 100 tons of extrusion for the SSD Surface Scintillator Detector. SSD used to provide muon aspect of cosmic shower.

(figures from Nataliia Borodai, TIPP 2021 May 24-28, 2021)

IceCube

Ice Cube adding scintillator array on surface to study PeV cosmic rays and provide for partial veto of downward cosmics. Scintillator is cheap and can survive the harsh conditions.

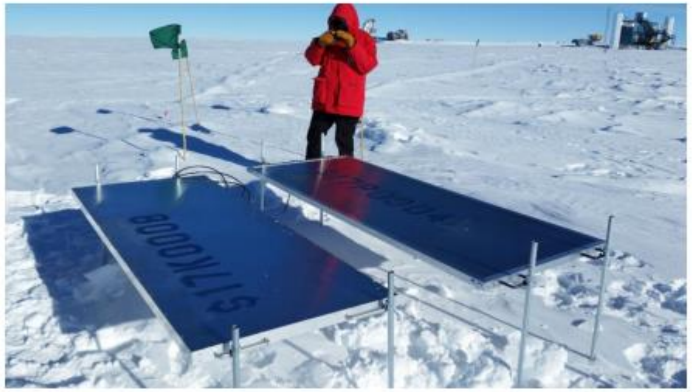


Figure 1. Installation of the first prototype scintillation detectors at the South Pole in January 2018.

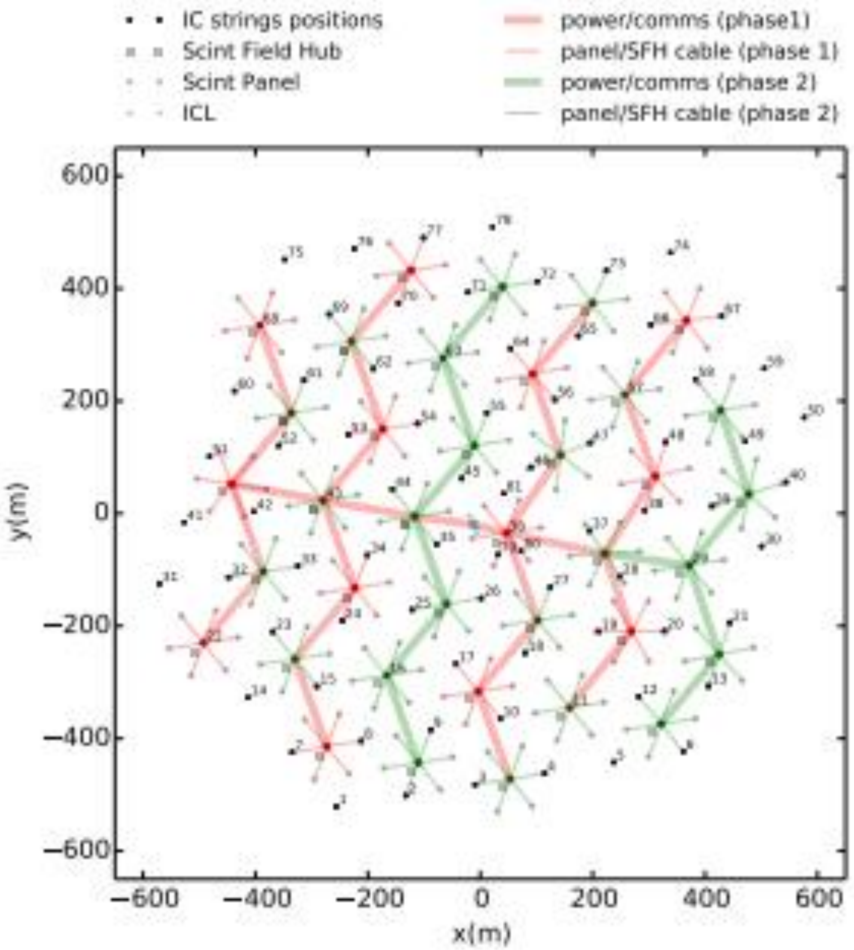
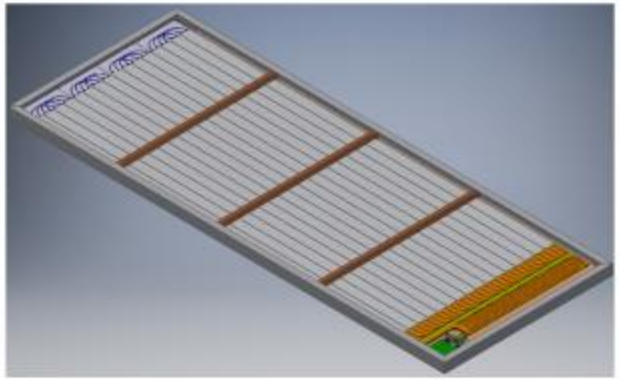


Figure 1: Map of the scintillator array as designed for the IceTop upgrade, in IceCube coordinates. Each number denotes the location of an existing IceTop station.

Each panel has 16 extrusions, 2m x 1cm x 5cm, readout Y-11 fiber and SIPM

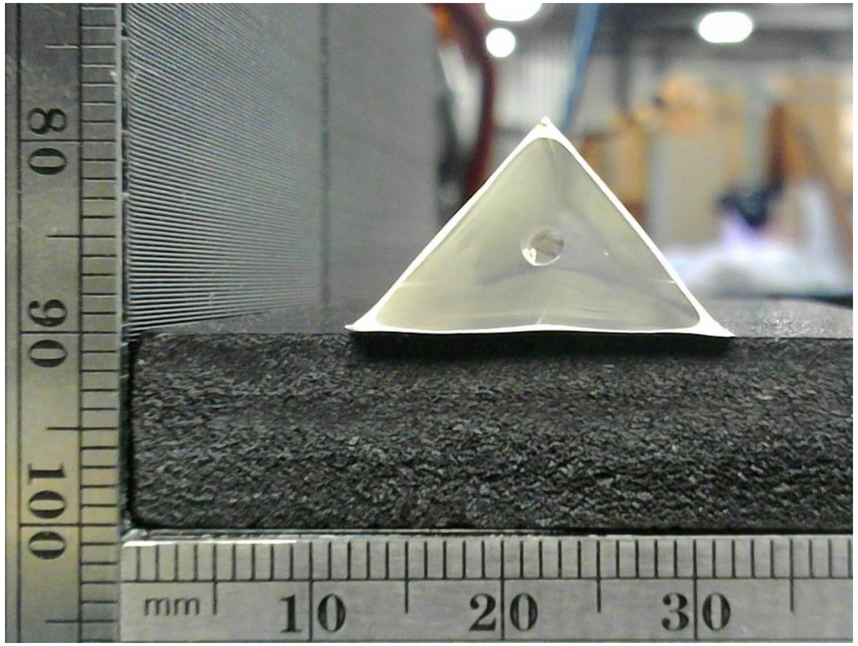


7 panels per hub. 37 hubs in array roughly 1km x 1km

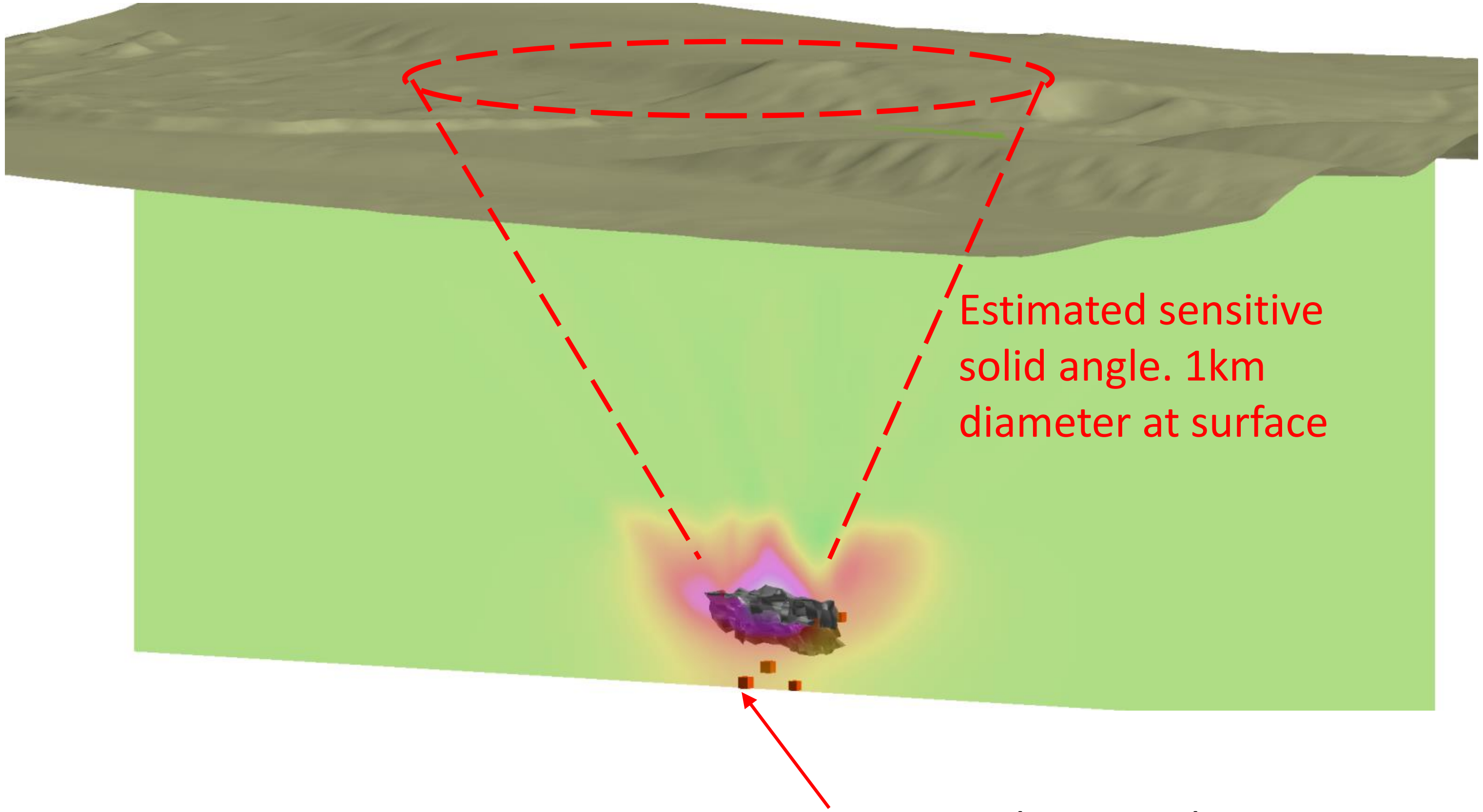
https://pos.sissa.it/301/401/pdf

Geology

IDEON geological exploration for mining. Example McArthur River Uranium Deposit, Canada



Array of triangles read out with WLS, designed to fit into Bore Hole. FNAL provided 30,000 extrusions.



3 Detectors ~600m underground.
Solid dark is ore deposit as understood by core samples. Colored is density slice from IDEON muon data, in agreement.

MURAVES - Vesuvius

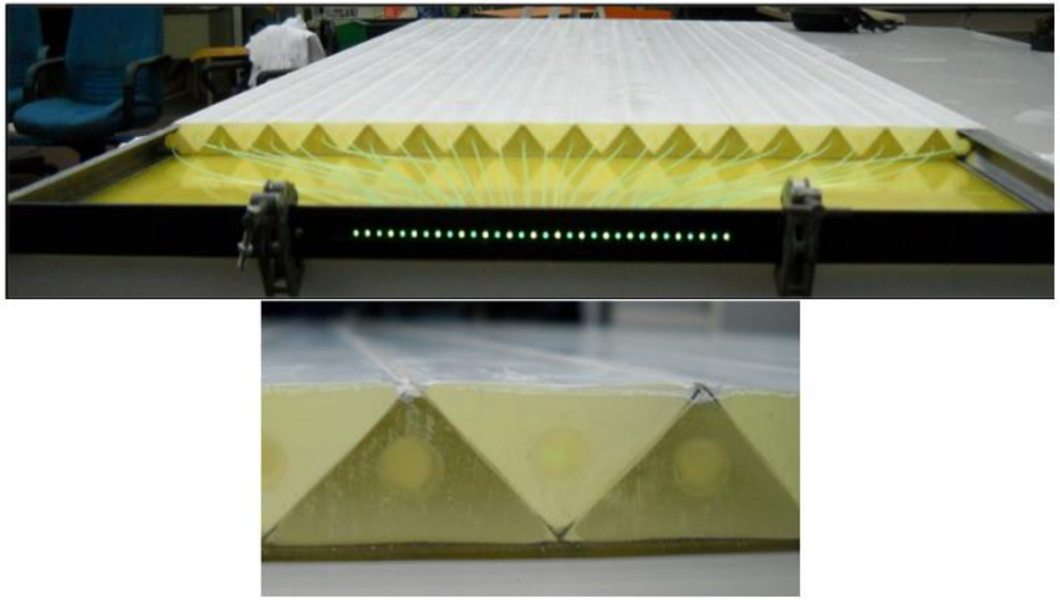
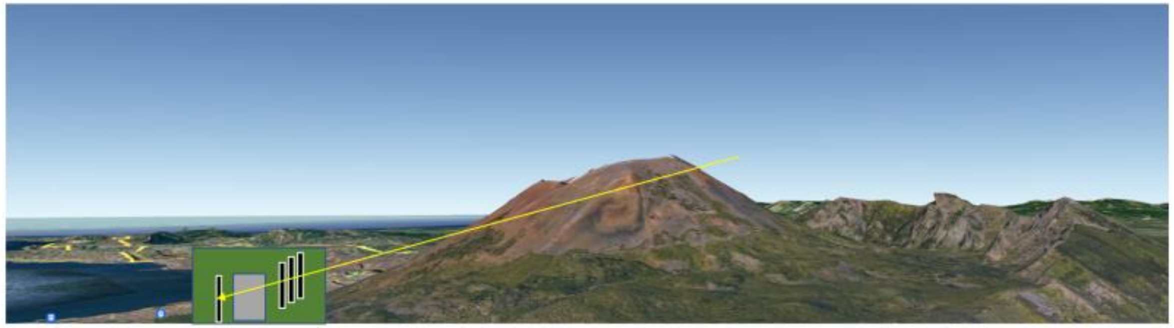


Figure 2: Top: The 32 scintillator bars and WLS fibers assembled in a half of a planar array. Bottom: triangular section of the scintillator bars.

arXiv:2202.12000v1
M. D’errico et al.



3 Stations of x-y planes of scintillator, Pb hardener, final station

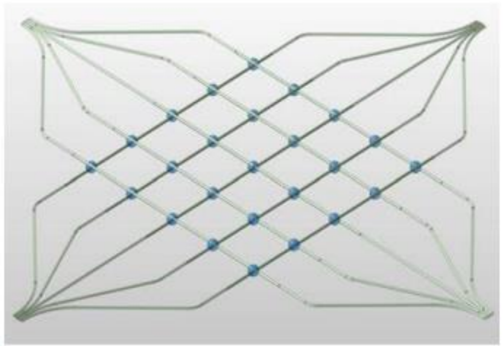
Agriculture/Biology

Development of a Plastic Scintillation-based Detector for Real-Time Radioisotope Imaging of ^{32}P Uptake in Plant Root Systems

B. Kross[a], S.J. Lee[a], A. Llodra[b], J. McKisson[a], J.E. McKisson[a],
A. Pla-Dalmau[c], A.G. Weisenberger[a], W. Xi[a], C. Zorn[a]*
[a]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
[b]Illinois Institute of Technology, Chicago, Illinois 60616
[c]Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Recent years have seen the development of radioisotope tracking or imaging systems based on detection of light from scintillators for agricultural studies [1,2]. The goal is to track the phosphorus movement between the roots of a plant and the beneficial fungi that are known to grow near the roots and have a beneficial role with the plant.

(a)



(b)

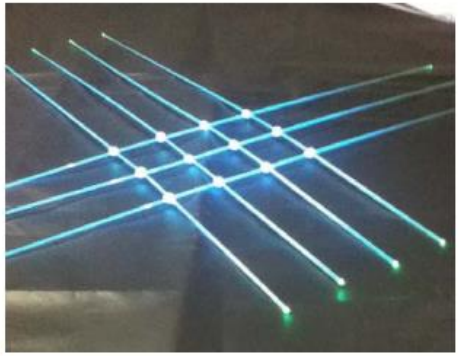
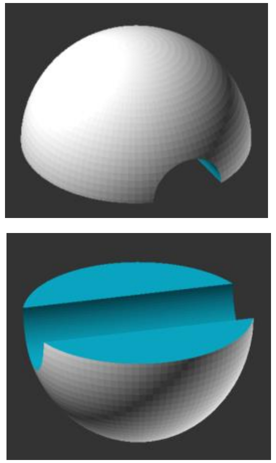
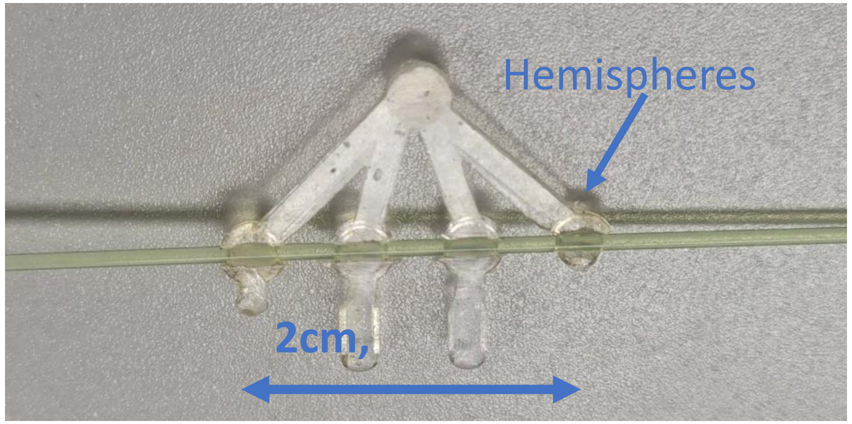


Figure 1: (a) Sketch of the basic element of the detector showing a crossed array of wavelength shifting (WLS) fibers that carry the converted light from the array of plastic scintillating beads formed at the intersections of the fibers. (b) Photograph of present prototype under initial characterization tests. Note the blue glow from the scintillating beads and converted green light from the WLS fibers. The beads will provide a large localized source of light from a nearby beta source that is converted to green light in the WLS fiber. At the same time, the WLS fibers provide a very low background signal from any radiation source, allowing the scintillation beads to act as the position locators of the beta source.

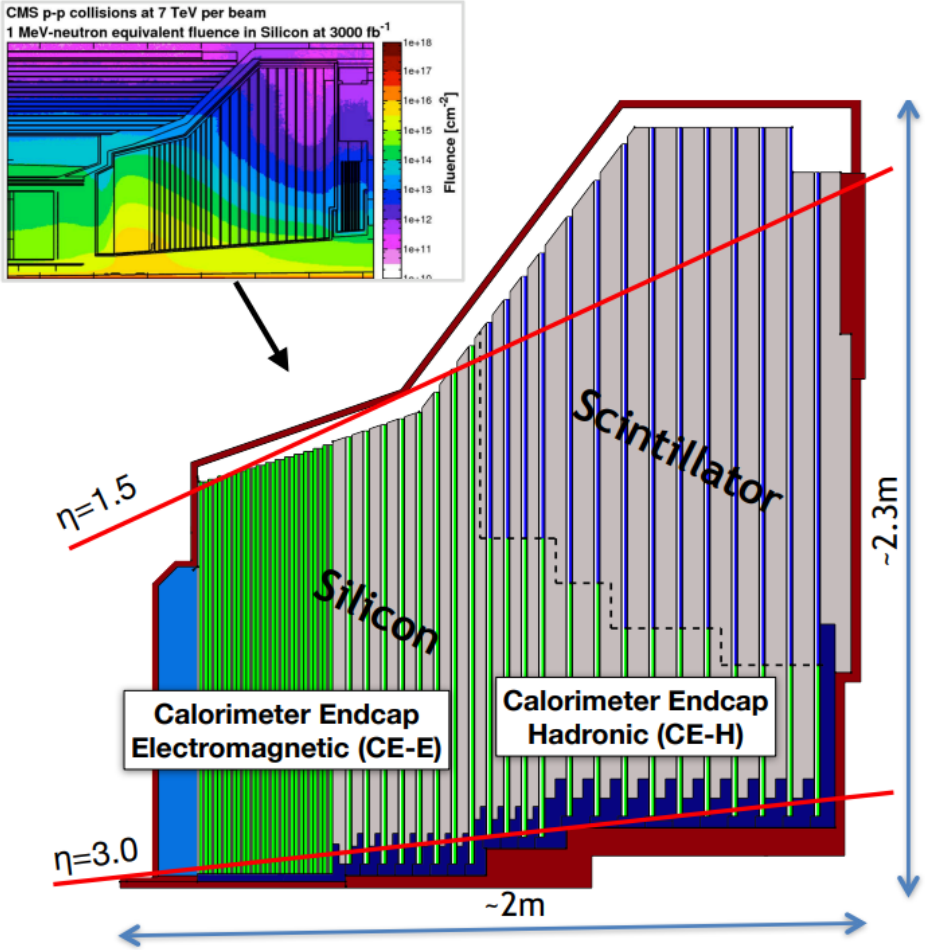


Top and bottom hemispheres glued to orthogonal fibers.
4mm diameter sphere.
Glue seals optical interface from dirt, water



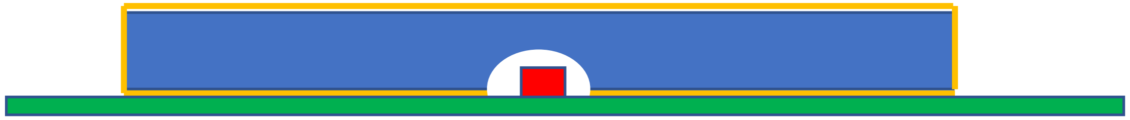
HEP

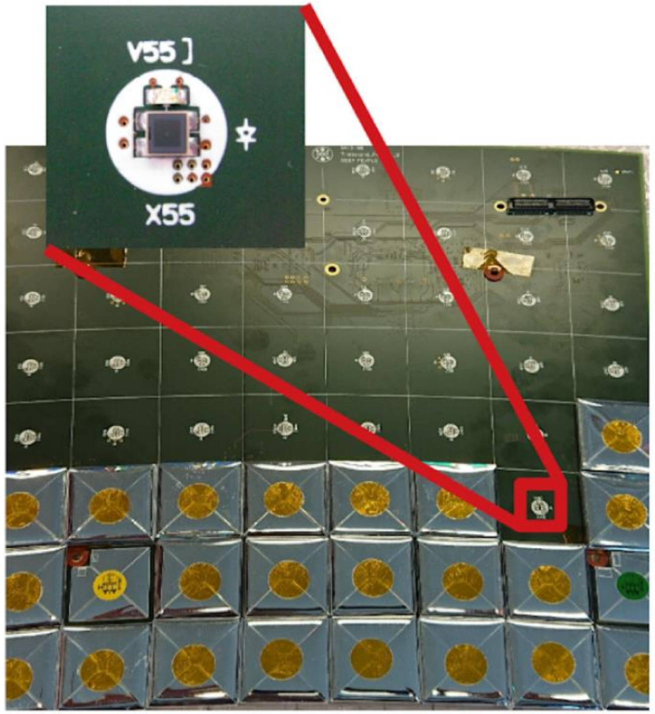
CMS – SIPM-on-tile for HL-LHC endcap calorimeter upgrade



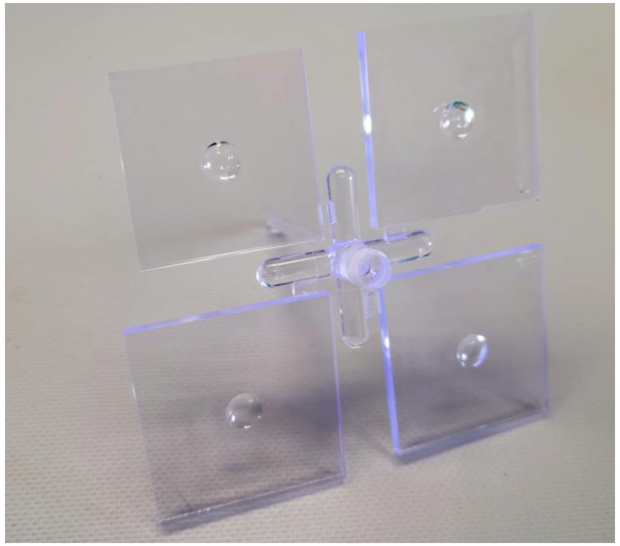
HL-LHC upgrade. A 5-D calorimeter designed for particle-flow pattern recognition. Silicon for ECAL and high radiation prgions of HCAL. Scintillator for the rest. 240K channels of SIPM-on-tile.

SIPM-on-tile: Green PCB Red SIPM Yellow ESR wrapper Blue Scintillator





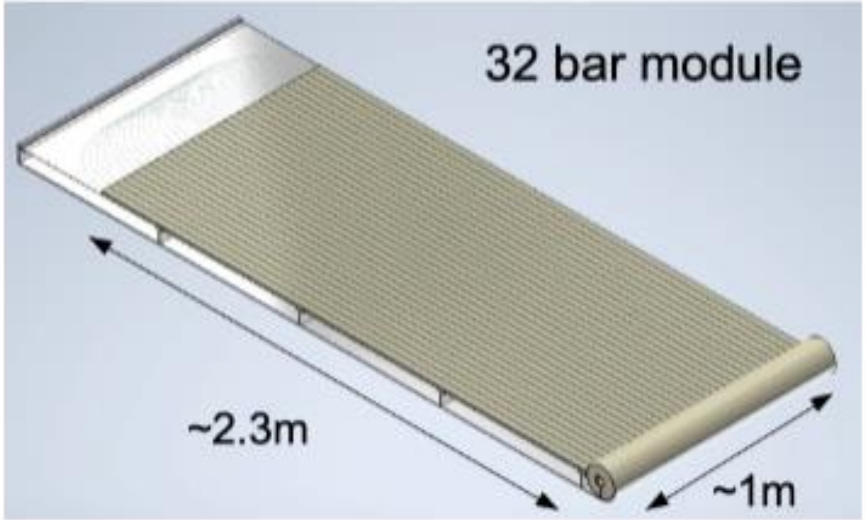
Tileboard with SIPMs, wrapped tiles



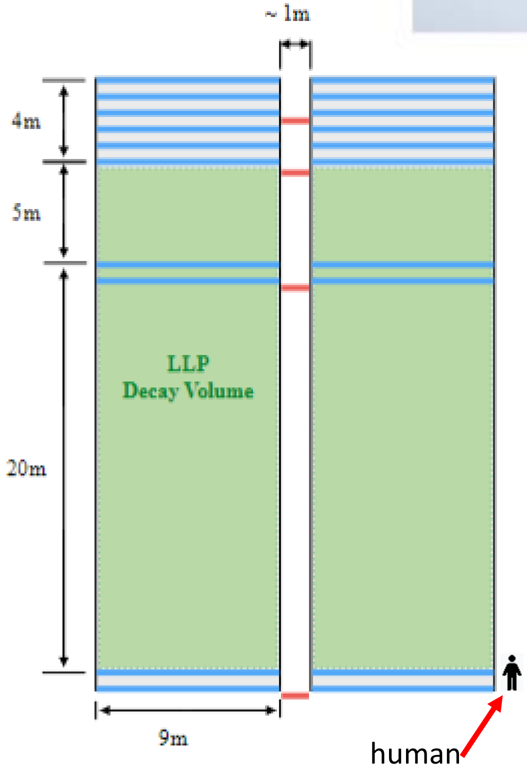
Tiles injection-molded at FNAL

MATHUSLA

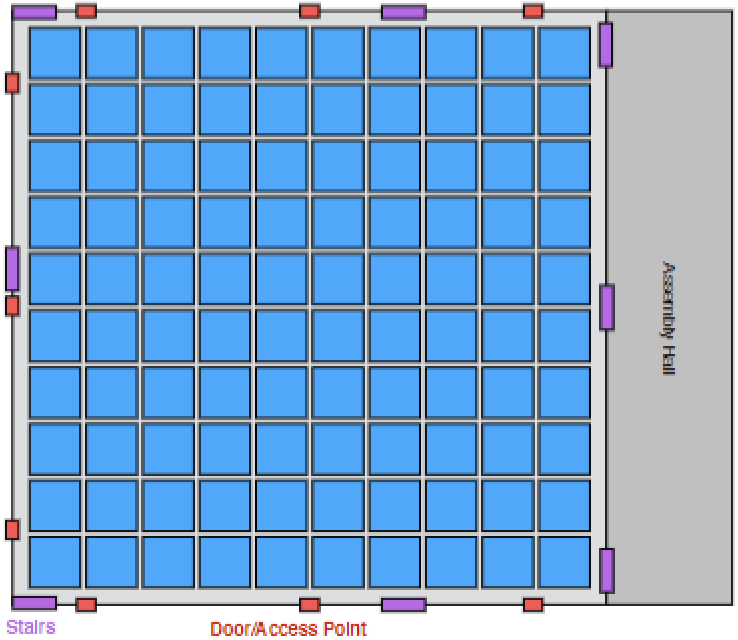
MATHUSLA is a very large experiment being proposed to be built on the surface of LHC point 5 by the CMS experiment. It will search for long-lived particles produced by proton-proton collisions at the CMS interaction point. The experimental volume is quite large (100mX100mX30m), to allow for the LLPs to decay in the volume.
Extruded scintillator layers are installed to allow for tracking of the decay products. 1000 tons of scintillator required.

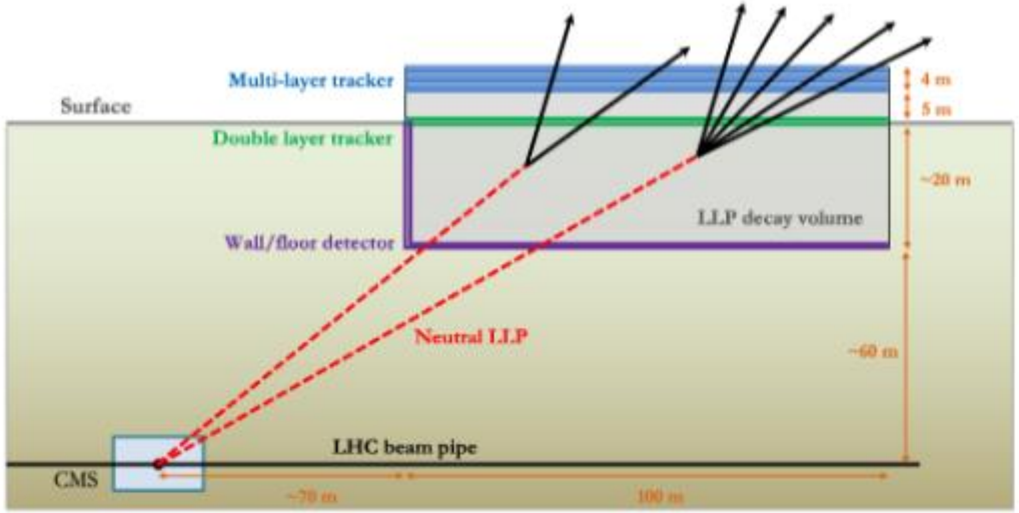


100 9mx9mx30m modules. 10 planes of scintillator

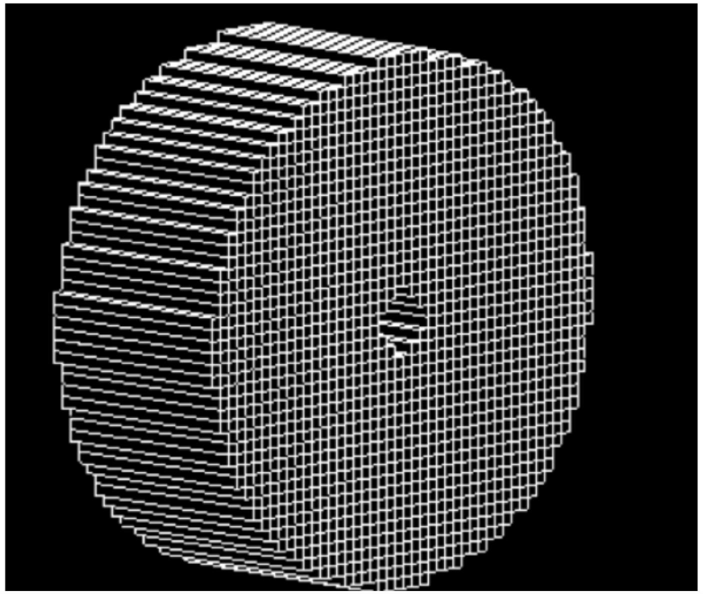


10x10 array of 9x9x30m modules



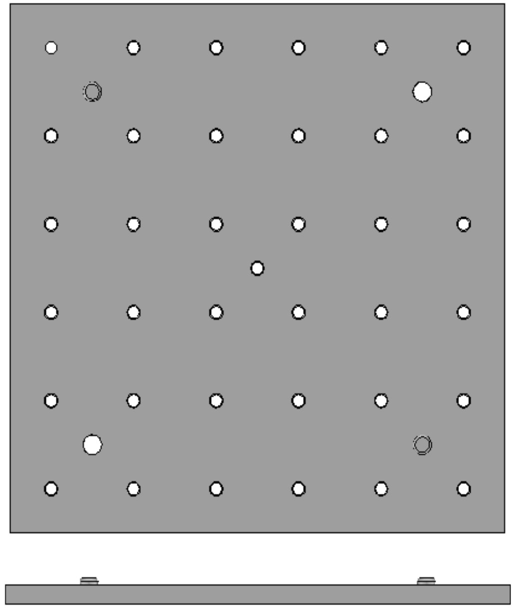


HIKE, High Intensity Kaon Experiments at the CERN SPS

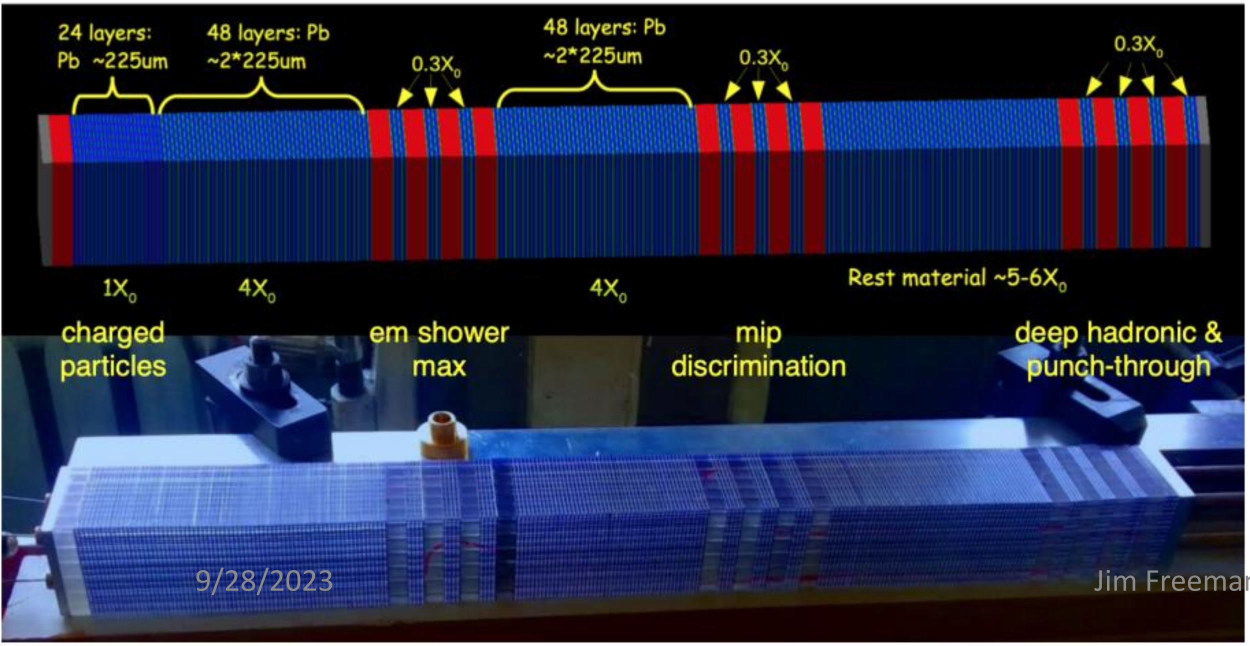


Main Electron Calorimeter based on Shashlik concept. 1M tiles. Stack of Pb foils and scintillators

https://arxiv.org/abs/2211.16586

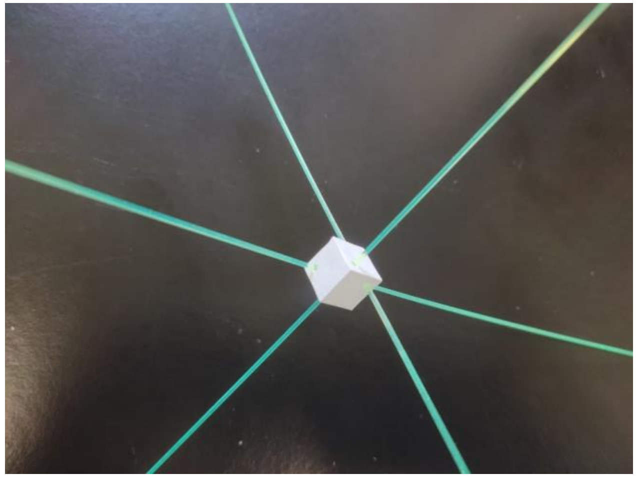


5.5x5.5x0.3cm

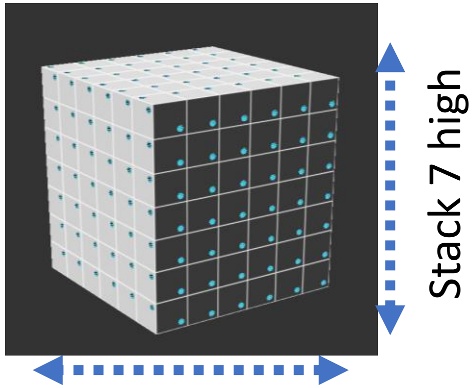


FNAL preparing to prototype molding the tiles

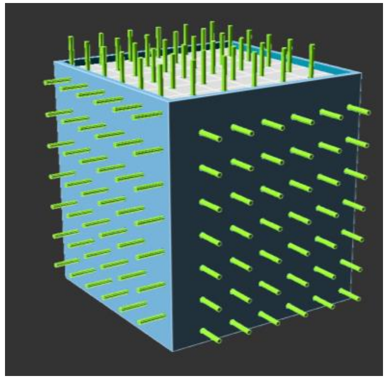
"VOXEL" – Volume pixels for scintillator trackers. Proposed 10M voxels for Dune Near Detector



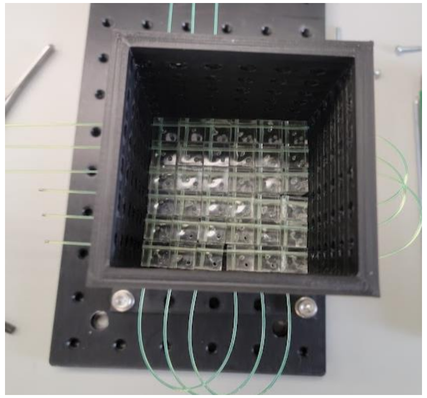
3 orthogonal holes for WLS fibers



Small scale prototype: 6x6 array per layer, 7 layers high



Voxels in frame



Voxel prototype with 1 layer of un-coated voxels and fibers

R&D

New Wavelength Shifting Fibers

Setup	Fiber	Decay Time Constant (ns)	Comment
1	405nm Laser	0.31	Apparent laser decay time
	Y-11	7.193 (0.16)	Fiber Decay Time
	BCF-91A	7.036 (0.083)	
	BCF92	1.893 (0.025)	
	BCF9929A	1.882 (0.032)	
	YS-1	2.89 (0.03)	
	YS-2	3.53 (0.05)	
	YS-4	1.577 (0.011)	
	YS-6	1.298 (0.011)	

Look at new WLS fibers from Saint Gobain and Kuraray: BCF9929A, YS-1, YS-2, YS-4, YS-6
Excite with laser. Count arrival time of single photoelectrons with SIPM. Measure fiber decay time

Table 4. Measured light yields for WLS fibers.

Fiber	Diameter (mm)	Avg. Light Yield (sum of both ends)
YS-1 MJ	1.0	32.2
YS-2 MJ	1.0	61.0
YS-4 MJ	1.0	50.6
YS-6 MJ	1.0	21.2
Y-11 MJ	1.0	64.9

BCF9929A light yield somewhat less than YS-4

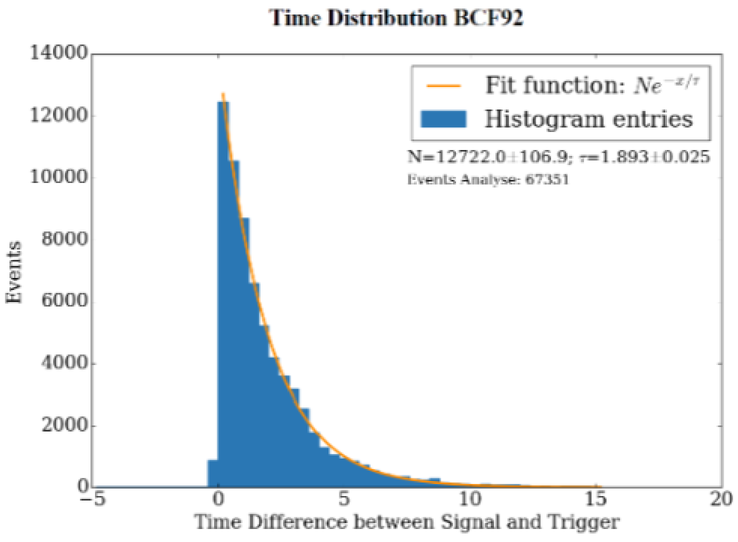
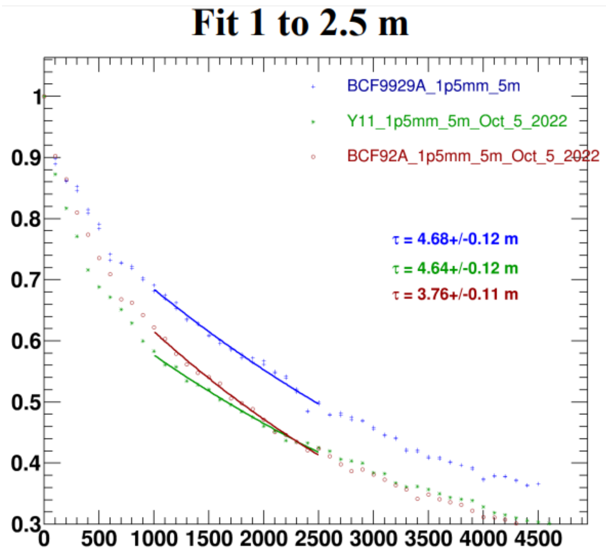


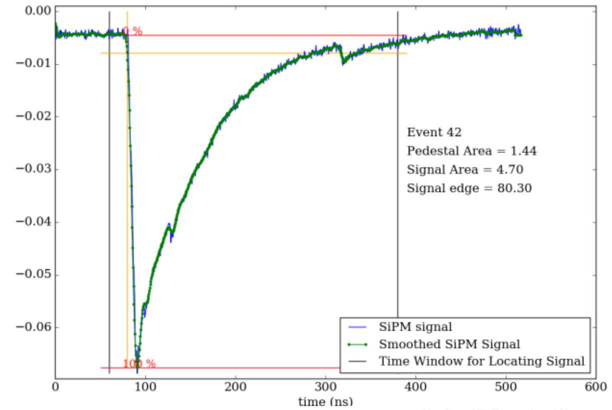
Figure 9. Decay time measured for San Gobain BCF92 fiber.

Attenuation lengths of 5m long fibers, measured in region 1 to 2.5m

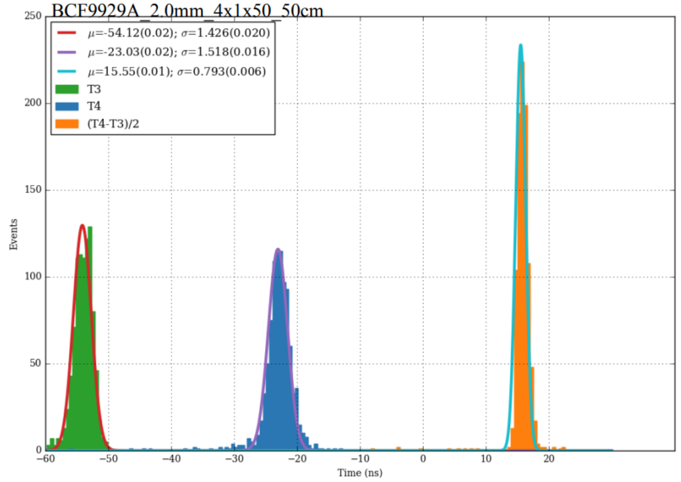


Improve timing for extrusion/WLS fiber system

Improving timing along length of extrusion gives better coordinate measurement in that direction. (Other direction coordinate determined by which bar is hit.) Measure time difference between ends to find hit location.
Cosmic runs that create different light yields. **Timing resolution function of sqrt(τ/N_{pe})**
System with most light and fastest WLS has best timing resolution.



Cosmics timing:
Cut on single photoelectron



Position resolution (T4-T3)/2

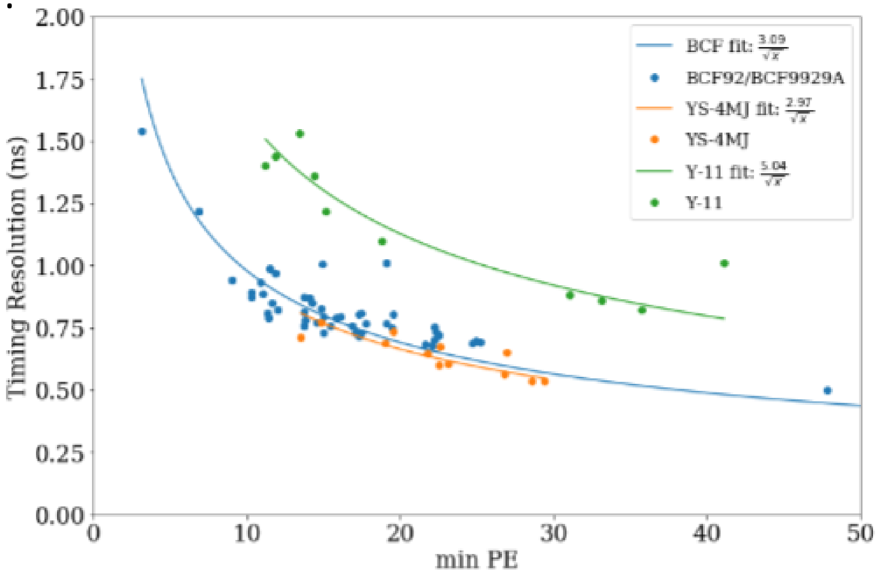


Figure 22. The timing resolution vs. the minimum light yield for BCF92 or BCF9929A, Y-11, and YS4-MJ fibers. Each point is a separate cosmic ray measurement.

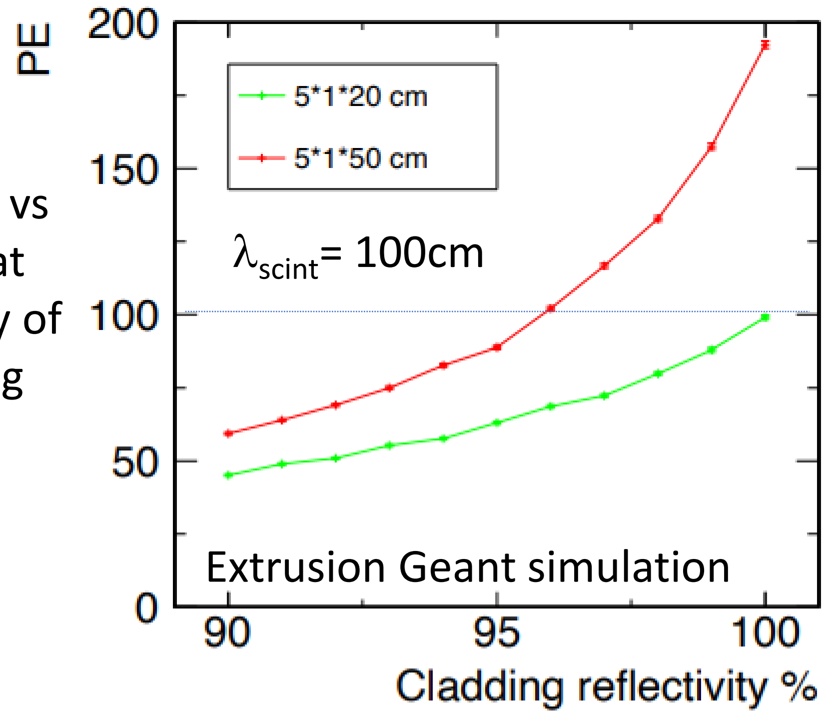
Table 2. Light Yield and Timing For Different Excitation points, 1.5mm diameter, 5.0m or 5.6m fiber, 1x4 cm extrusion profile.

Fiber Type	position along fiber	Avg. LY (SiPM 1)	Avg. LY (SiPM 2)	Timing res. (ns)
BCF9929A	250 / 500	22.2	22.5	0.70
BCF9929A	50 / 500	37.9	13.7	0.81
YS-4	50 / 560	31.1	14.8	0.79
YS-4	260 / 560	29.4	31.7	0.54

Improve reflectivity of cladding around extrusion to improve light yield.

Geant sim to see what is effect of different reflectivity cladding on extrusion
Yucun Xie, UMD. Looking at new materials better than TiO2 for coating the scintillator.

Cladding. Light yield vs reflectivity. Clear that improved reflectivity of cladding can have big effect on LY



Wrapper.
Measurement of LY for different wrappers around extrusion. Can make big improvement.

Table 5. Light yield relative to TiO_2 co-extruded cladding

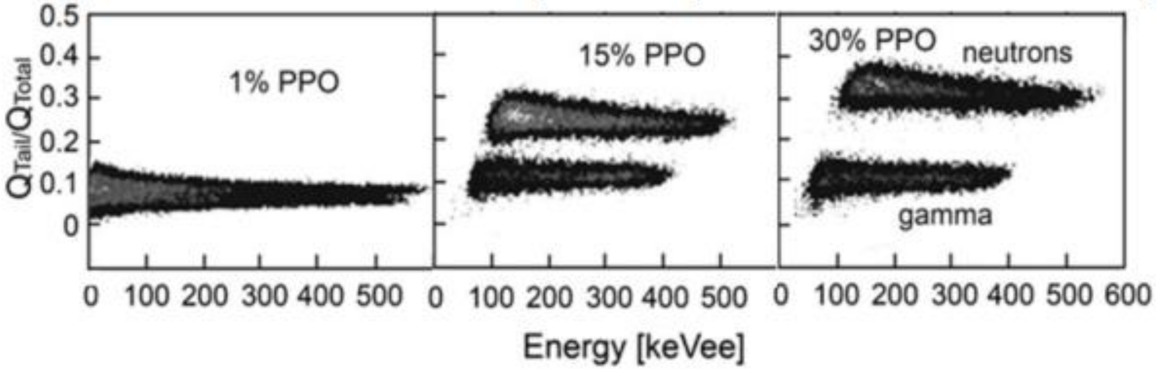
Wrapper	Relative Light Yield
TiO_2 coextruded cladding	1.0
Tyvek	1.08
ESR	1.46
Black wrapper	0.24

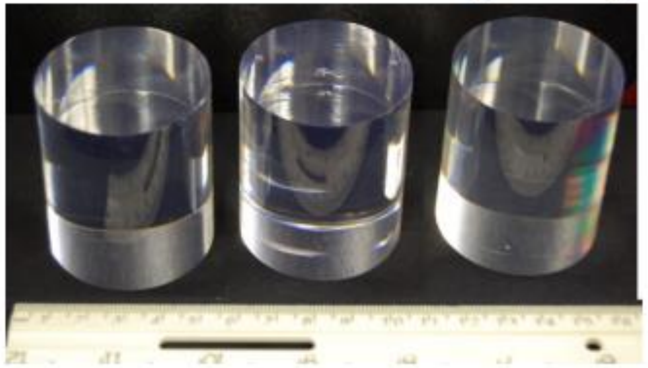
Neutron scintillator: Use injection molding process to study making cheap neutron-sensitive scint. Study using polycarbonate base for improved radiation hardness.

- FNAL, LLNL, Erciyes University (Kayseri, Turkey), Beykent University (Istanbul)
- https://www.sciencedirect.com/science/article/pii/S0168900211021395
- n-scint uses slow response to neutrons to separate gamma-neutron by pulse shape

Plot: Qtail/Qtotal – fraction of pulse in tail of pulse

•High concentrations (>20%) of fluorescent dyes increases fraction of delayed light



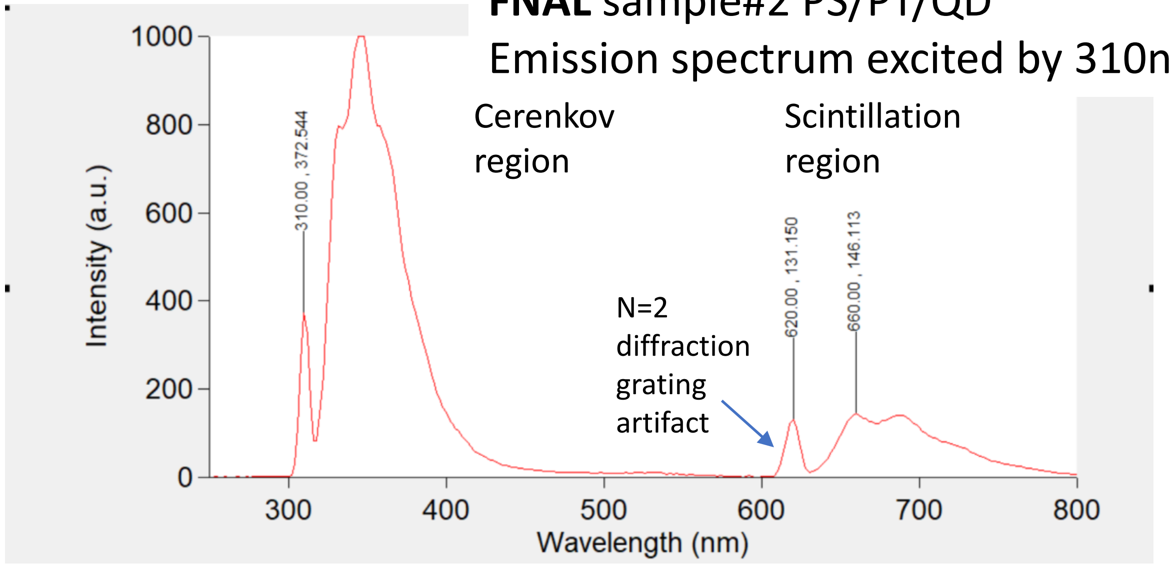


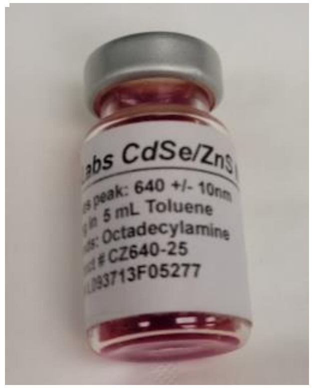
N. Zaitseva et. al., *Nucl. Instrum. Meth. A.*, 668 (2012) 88.

New type of scintillator using long Stokes Shift quantum dots

Polystyrene/PT base. Use in Dual readout calorimetry. Use long stokes shift to move scint light to long wavelength. Use QD decay time to help with C/S separation. Collaboration with CapeSym, Inc.

FNAL sample#2 PS/PT/QD
Emission spectrum excited by 310nm





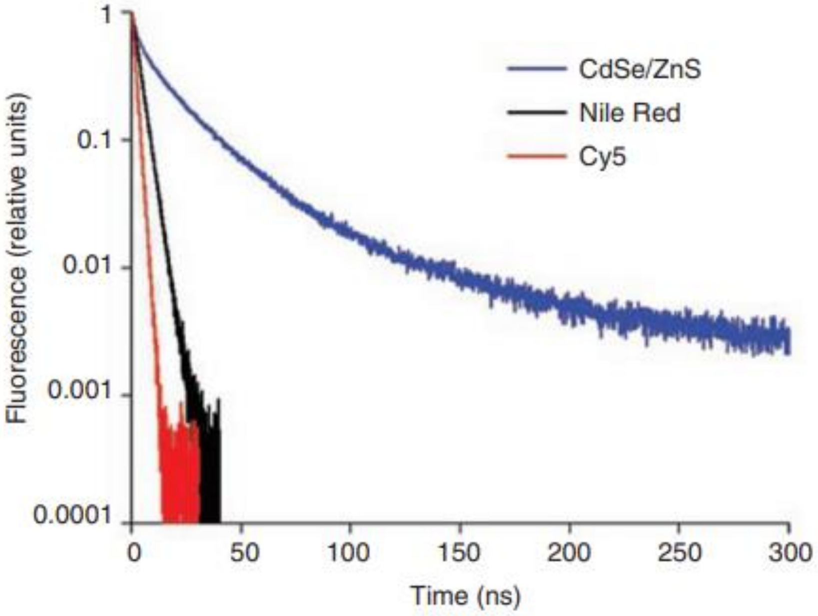
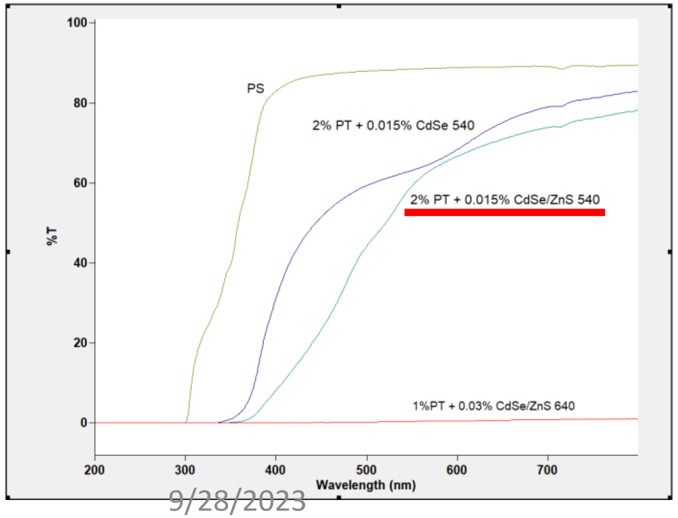
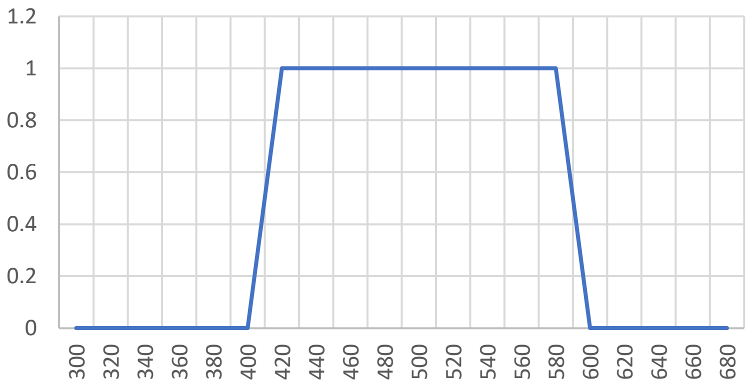


Figure 2 | Fluorescence decay behavior. Fluorescence decay behavior of typical organic fluorophores (mono-exponential, lifetimes of 1.5 ns (Cy5) and 3.6 ns (Nile Red)) in comparison to a typical QD (CdSe/ZnS, multi-exponential, mean lifetime ($\tau_{1/e}$) of 10.3 ns).

https://pubs.acs.org/doi/10.1021/acsami.7b19144

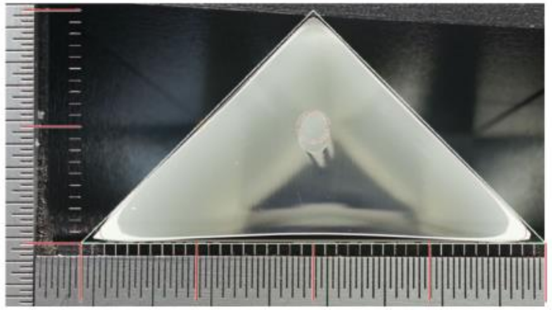


filter transmission for Cerenkov light



Stokes-Shift-Engineered Indium Phosphide Quantum Dots for Efficient Luminescent Solar Concentrators
•Sadra Sadeghi

EGP Explore Great Pyramid



The EGP Collaboration

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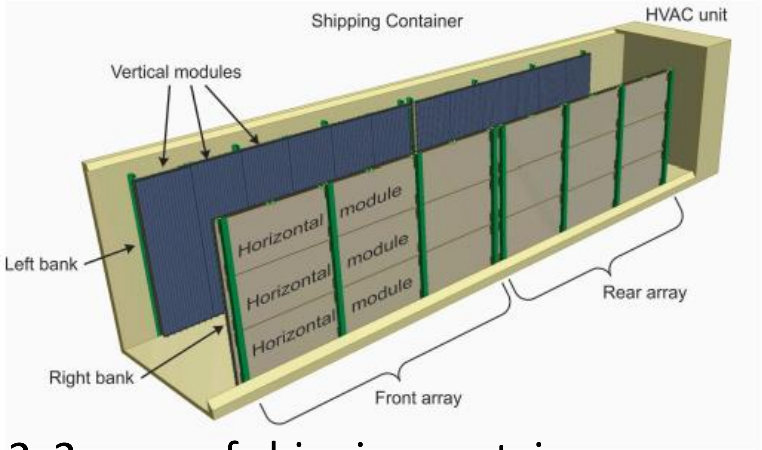
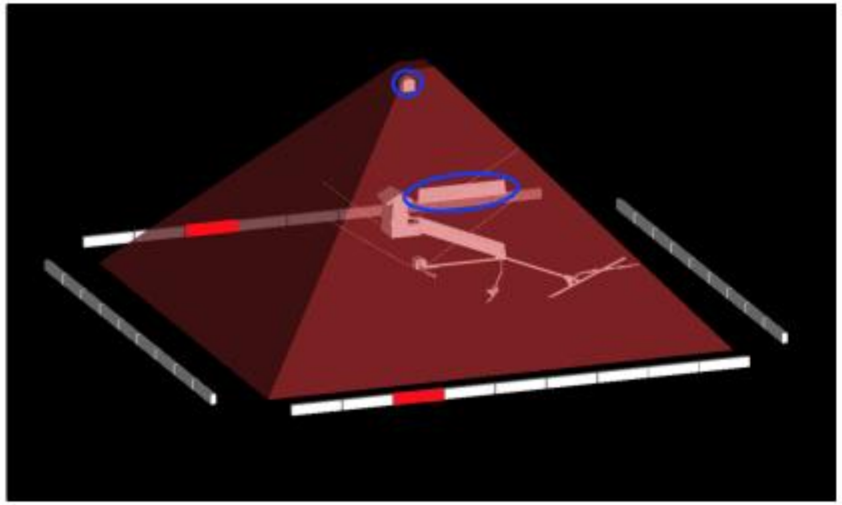
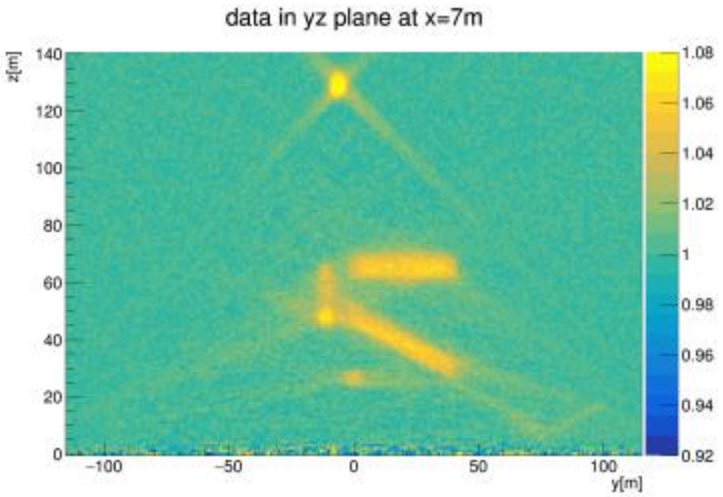


2x2 array of shipping containers with 4 planes of triangular scintillator extrusions in each container. Each plane ~3mx12m ~10 tons for total experiment.





Left: GEANT model of Great Pyramid. Right: simulated results of 3 year run.
4 container array moved to adjacent white region every 2 months.
36 regions → 18 * 2 = 36 month run. Anticipate 100X increased sensitivity to ScanPyramid

Summary

- Organic plastic scintillator very versatile and robust.
- It can be used in many applications.
- Fermilab has lots of resources and experience making scintillator for wide diversity of applications.
- We have interesting R&D and future programs plans.
- We are ALWAYS looking for new collaborators to work with.