Additive manufacturing of scintillators: Status and Opportunities

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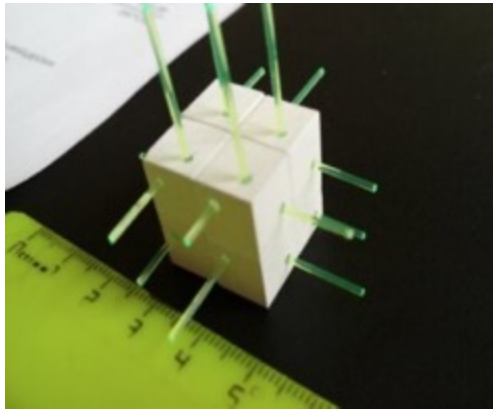
Plastic scintillator needs for next generation experiments

- Plastic scintillator are ubiquitous throughout HEP and NP
- Requirements for next-generation experiments
  - Larger / complex geometries (enhanced optical effects)
  - Finer granularity (large quantities)
  - Embedded components (optical fibers, reflectors, etc)
- New formulations required for tacking new detection channels
  - Lithium loading for anti-neutrino detection
  - Cherenkov vs scintillation light
- *New active low-background materials*
  - *dark matter searches, 0v2b, etc*



https://phys.org/news/2020-06-d-printed-neutrino-detectors.html

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Emerging technology connection – 3D printing

- Additive Manufacturing, such as 3D printing, offers many opportunities for next generation scintillators
- Rapid prototyping of scintillator designs
- Ability to produce simple to very complex geometries
  - Potential large cost reduction
  - Additive manufacturing can produce components not possible by conventional means
- Ability to print multi-material composites or even meta materials
  - Example - scintillator & housing in a single print / heterogenous composites
- And can be valuable tool for producing low-background components for rare event searches

https://www.shapeways.com/product/QNFAKNW9Z/gyroid

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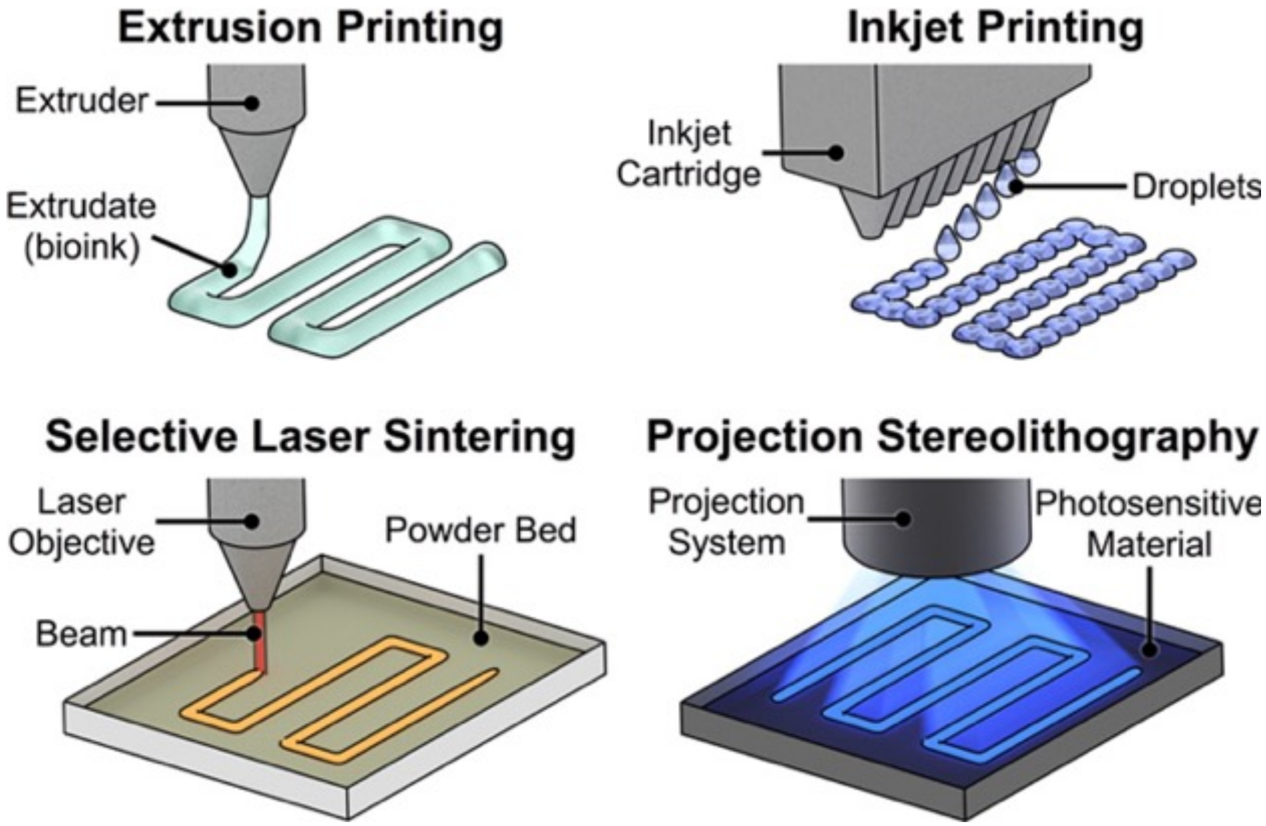
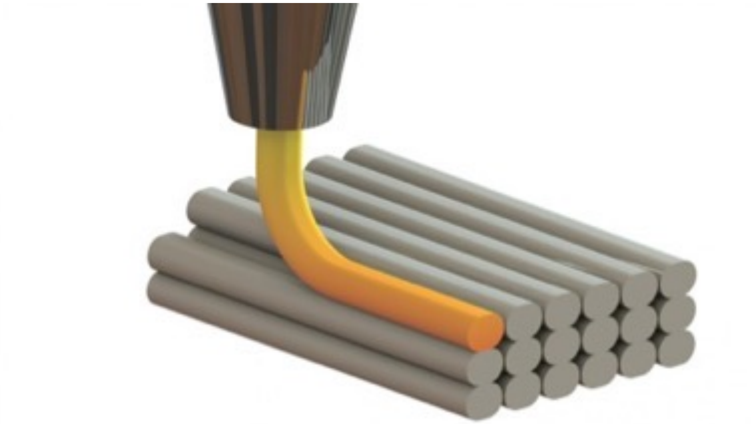
What kind of 3D printing?

- A wide-range of 3D printing methods exist
  - Fusion deposition modeling (FDM) most common
- 3D printing method strongly affects bulk optical properties
- Light-based techniques offer very good optical with reduced boundary effects due to layers



https://www.sipri.org/commentary/blog/2019/advances-3d-printing-technology-increasing-biological-weapon-proliferation-risks



https://additive3d.com/extrusion-deposition-fused-deposition-modeling-fdm/

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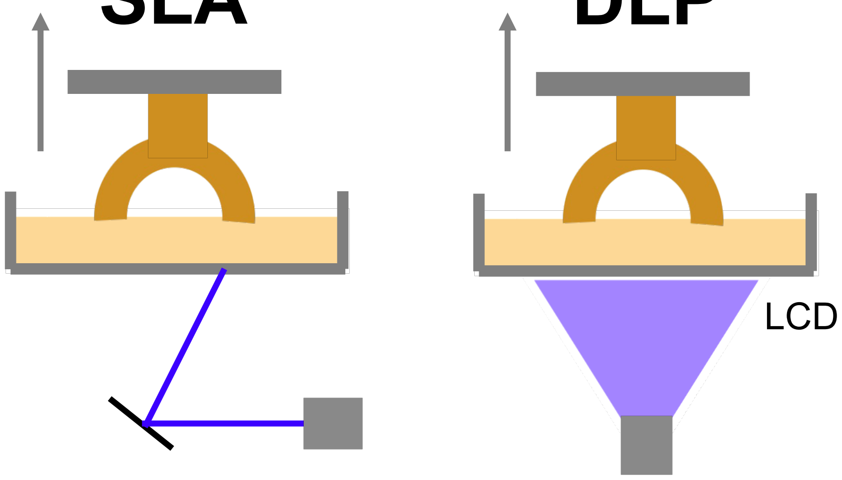
3D printing with *light*

- Light-based 3D printing techniques
  - Stereolithography (SLA)
  - Digital Light Processing (DLP)

- Part is produced layer-by-layer from a liquid resin vat using just ***light***
  - Near ***<u>contactless</u>*** manufacturing!

- Significantly better optical properties than FDM 3D printing



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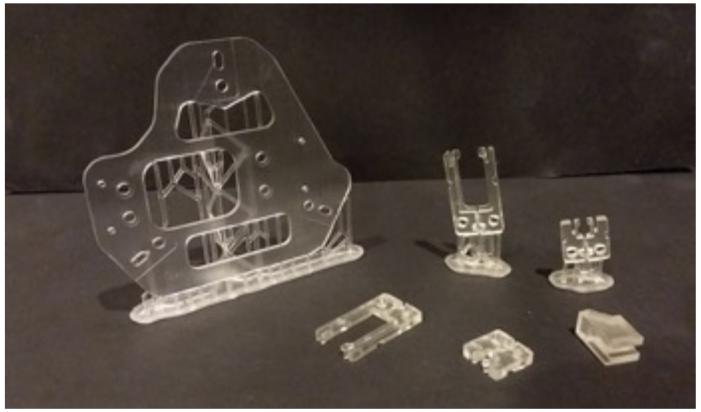

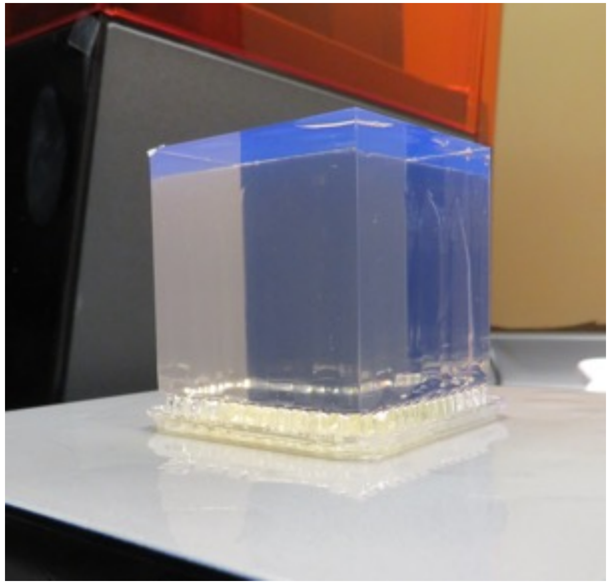

Various SLA printed components (top) and a SLA printed cube (2 in)^3 (right)

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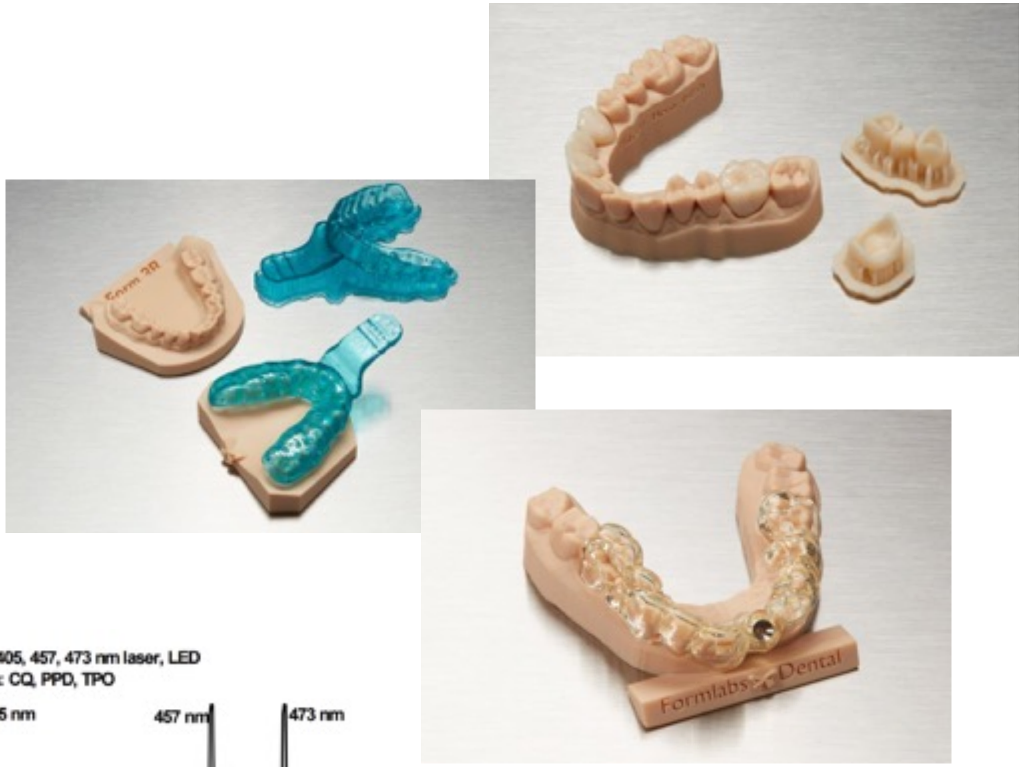
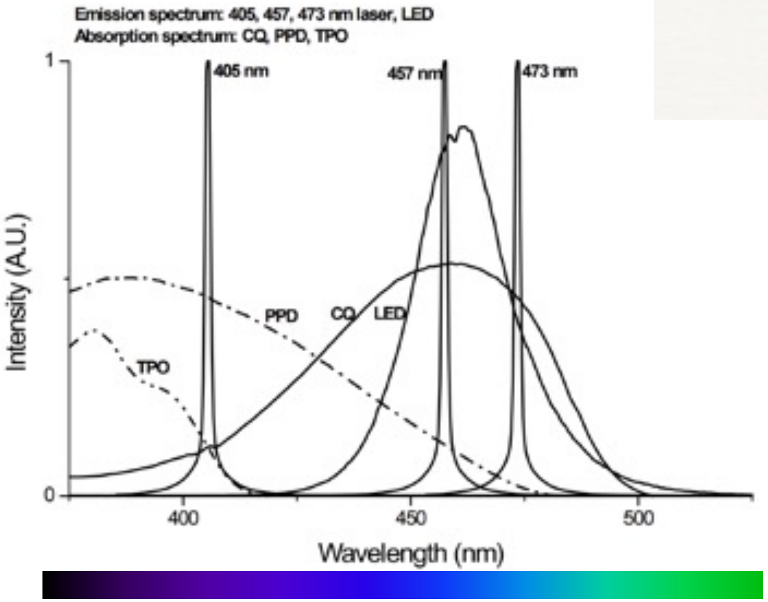
Photoinitiated scintillators

- Conventional scintillators are produced by a ***thermally initiated*** polymerization reaction
- For light-based 3D printing we'll need a ***photoinitated*** polymerization
- Luckily, there is a lot of existing research from the dental industry…



https://dental.formlabs.com/

- Common photoinitators
  - CQ - visible light (450 nm typical)
    - Two-step initiator
    - Camphorquinone
  - TPO – UV-visible light (365 or 405 nm typical)
    - One-step initiator
    - diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide



J. Appl. Polym. Sci. 2019 DOI: 10.1002/APP.47381

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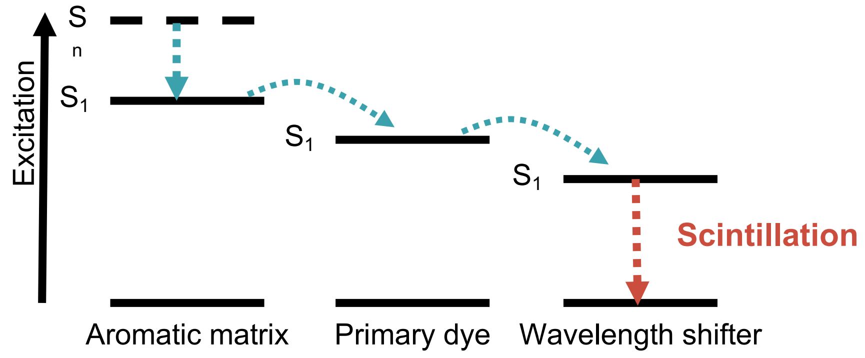
Composition of a 3D printed scintillator

- Differences between thermal and photo curing compositions
  - Requires photo polymerization initiators
  - Higher reactivity species (example acrylates)
- Need fast cure times (≲ 60 sec per printed layer desirable)
- Viscosity and cross linkers are important for good spatial resolution



Ingredient	Role	Example
Monomer / Oligomer	Forms the polymer base. Oligomers increase the viscosity of the resin and aids in achieving good spatial resolution	Acrylate terminated urethane *(Ideally, these would be aromatic!)*
Cross linker / dilutant	Used to reduce the viscosity and increases hardness	Difunctionalized acrylate monomer
Photo initiator	Causes polymerization when exposed to light	TPO
Primary fluorescence dye	Forms the scintillation base and is responsible for PSD	PPO
Secondary dye	Used to shift scintillation light to visible wavelengths.	Bis-MIS, POPOP, Exalite series

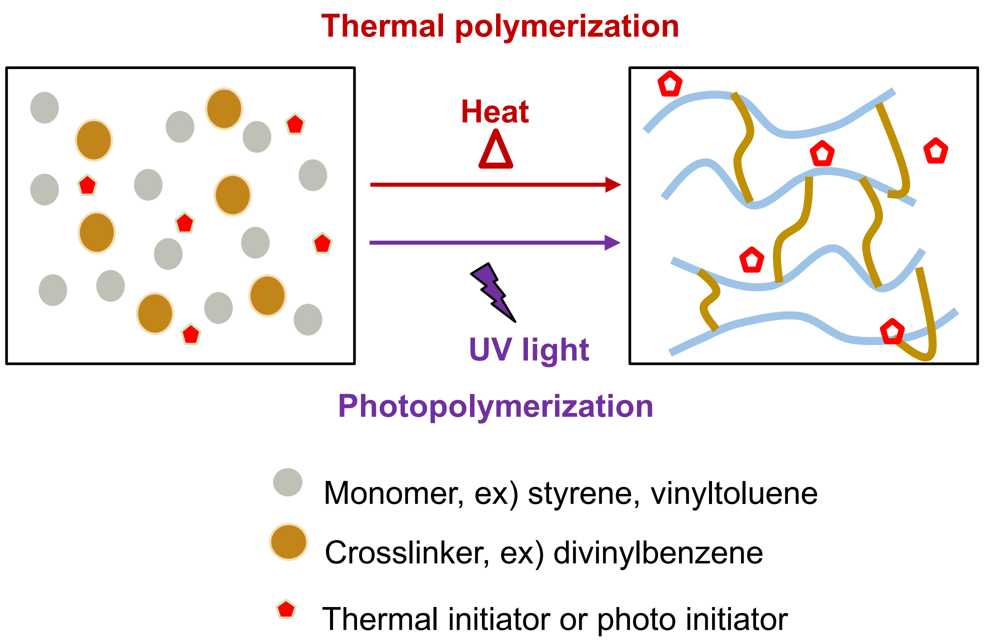


Figure credit - Yongwook Kim

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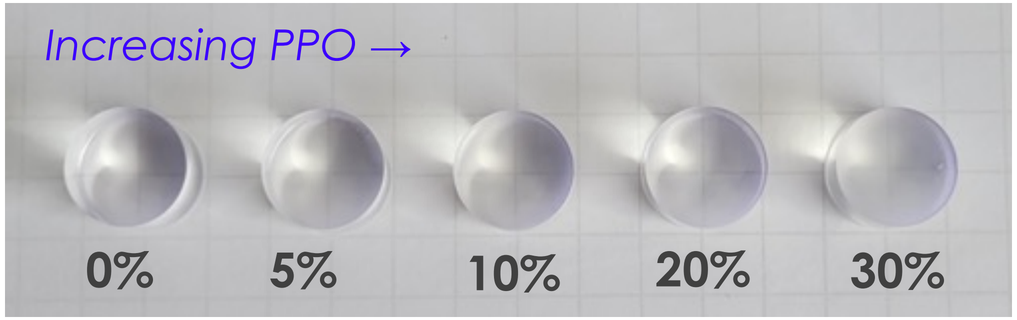
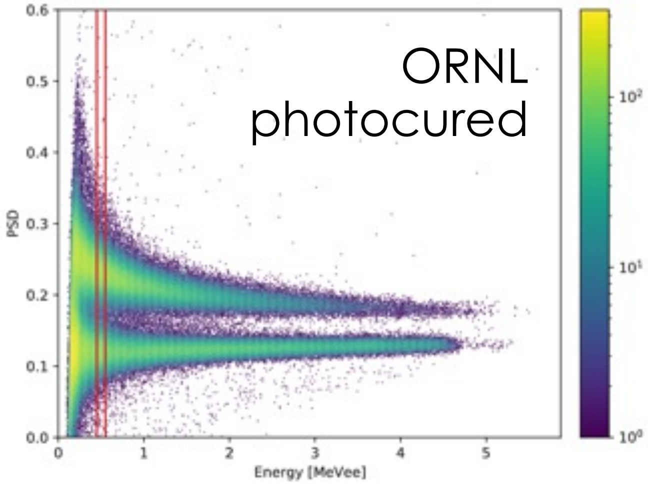
Performance of photocurable scintillators

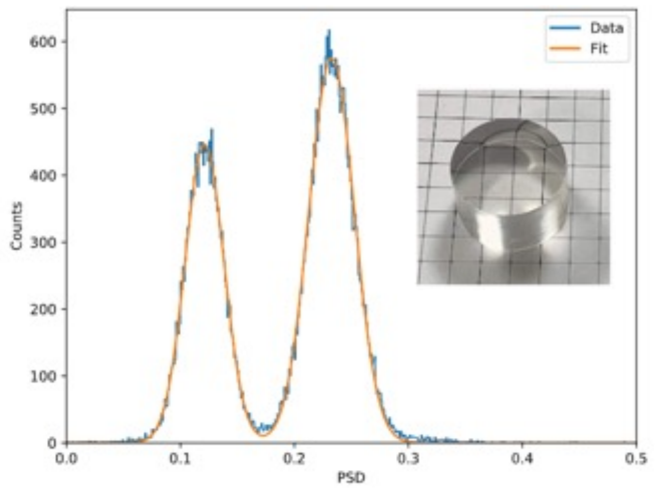
- Light yield and particle discrimination ~75% of commercial scintillators
  - Efforts on further increasing light yield and PSD are underway
- Using non-aromatic matrix, light yield dominated by primary dye concentration
  - Aromatic matrixes are preferred but not as common in reactive acrylate form

Bulk photopolymerized
(12 mm x 25 mm dia.)

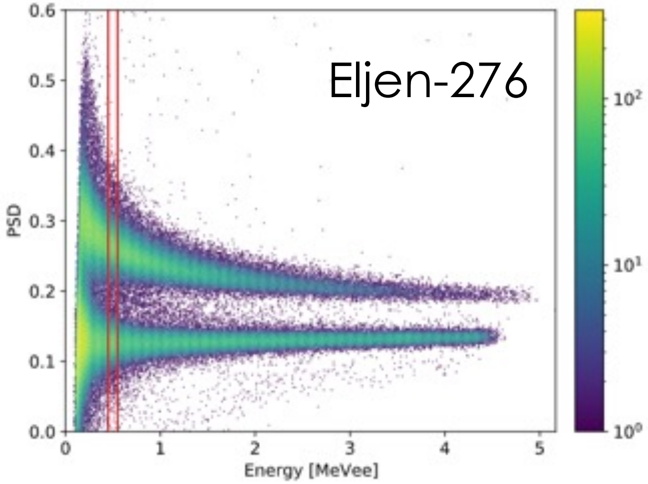




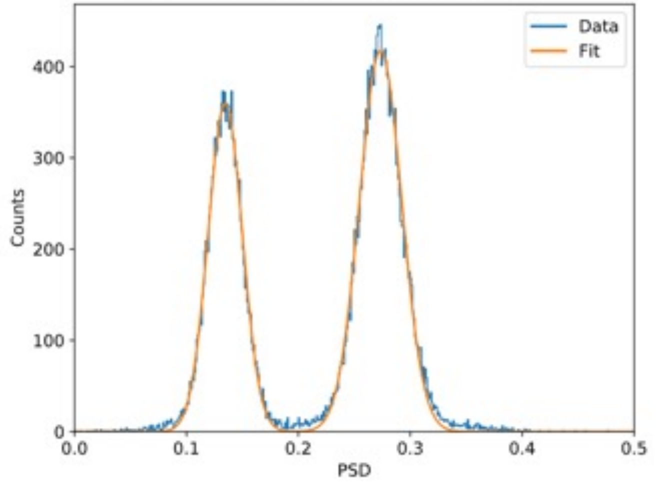
(a) 2D AmBe PSD/energy histogram from AFIT101



(b) 1D AmBe PSD histogram from AFIT101

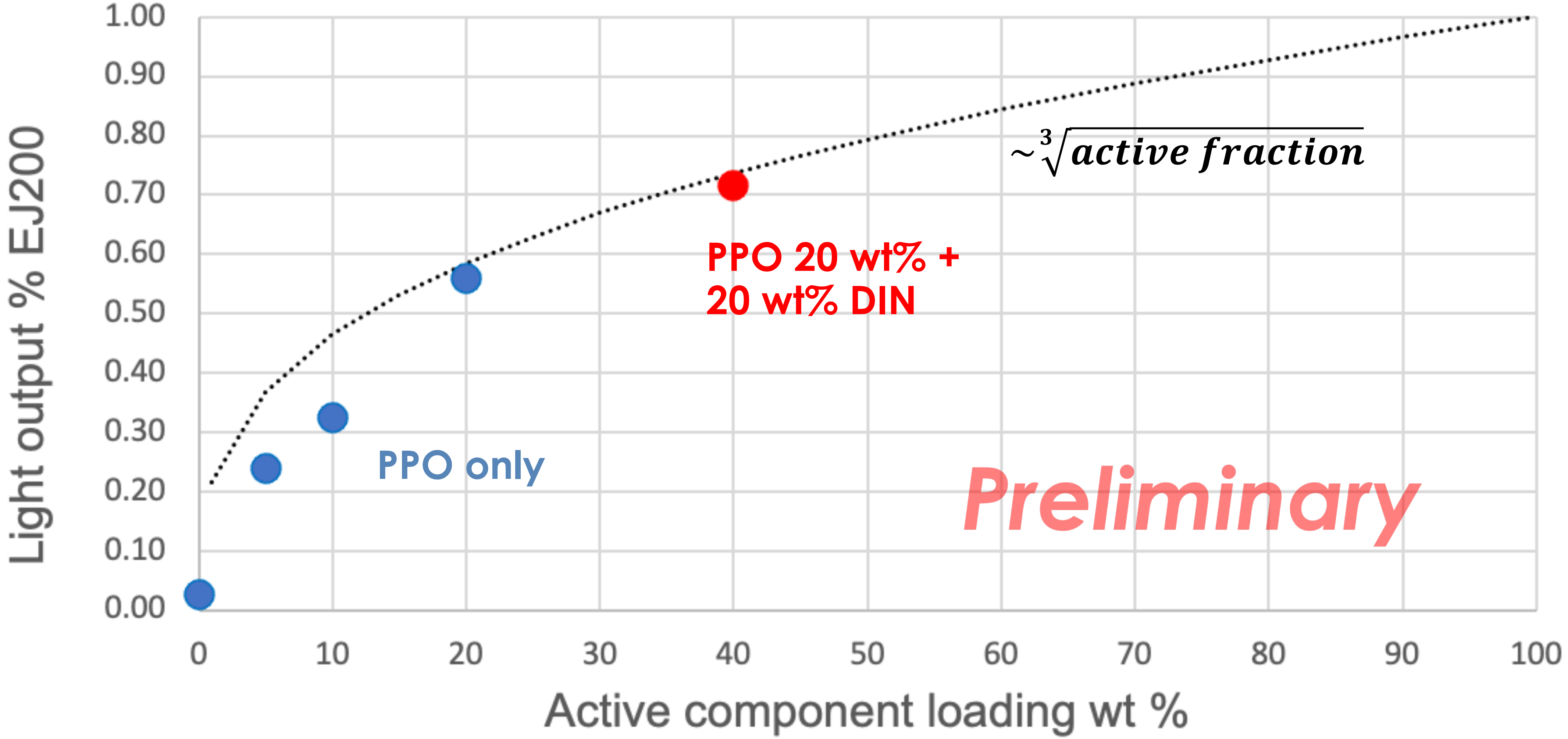


(c) 2D AmBe PSD/energy histogram from EJ-276



(d) 1D AmBe PSD histogram from EJ-276

Light yield comparison



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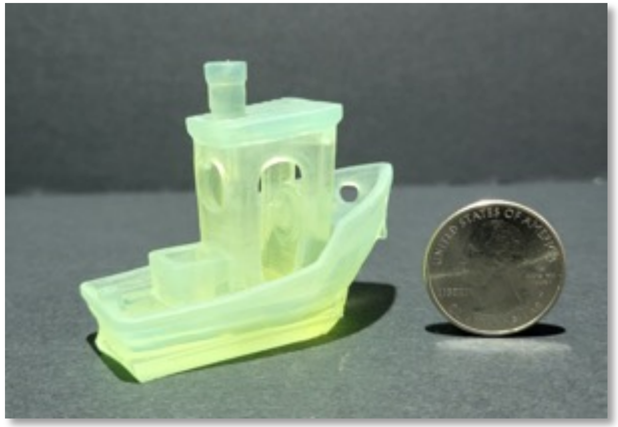
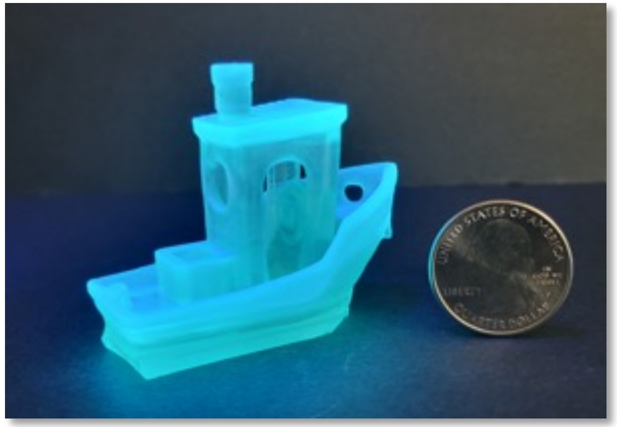
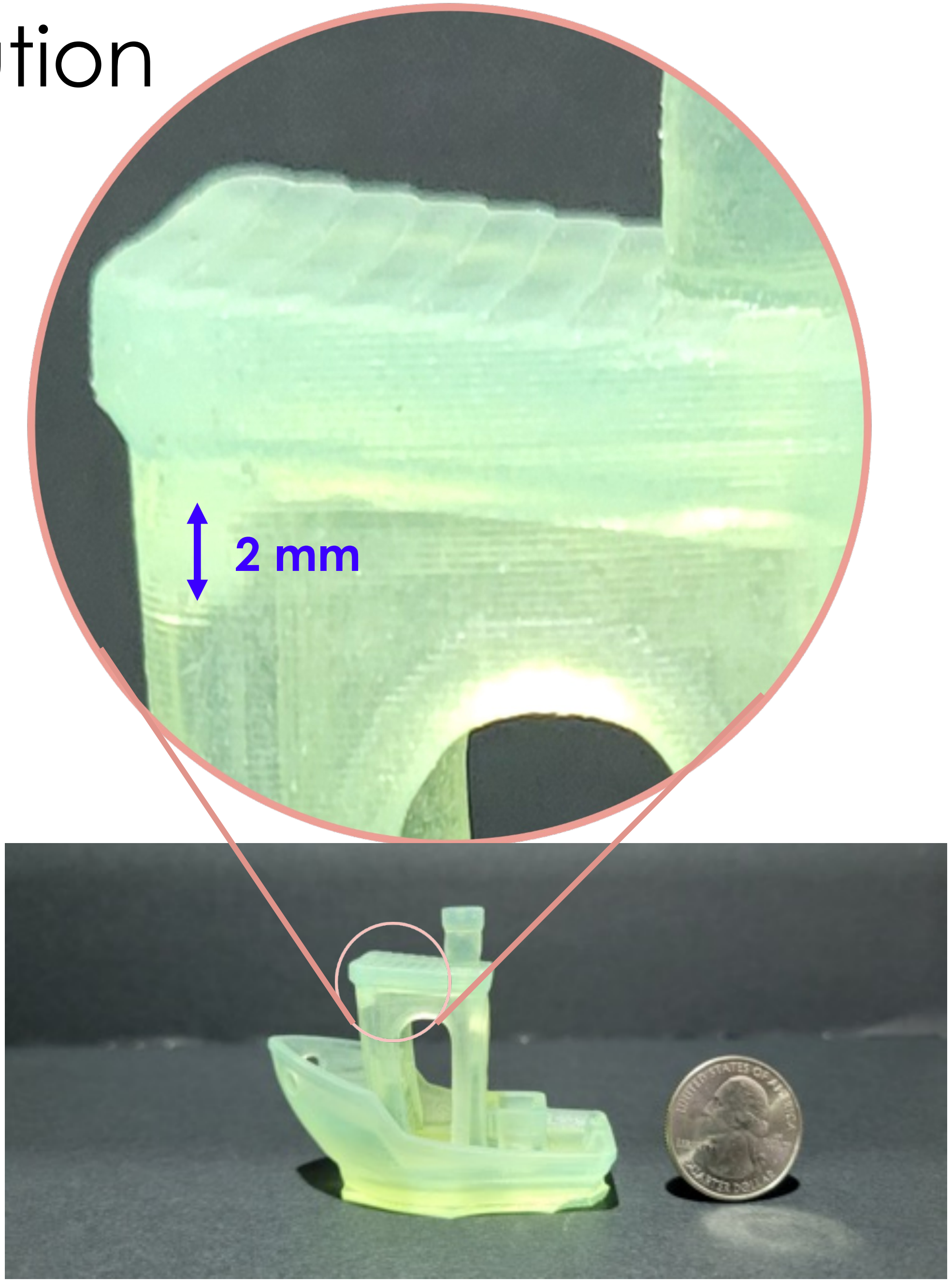
Improving 3D printing spatial resolution

- 3D printing formulations showing high spatial resolution
  - Test prints using "*3DBenchy*"
  - *Better than 200 um resolution achievable*
- *3DBenchy print parameters*
  - *200 um layer thickness*
  - *60 seconds per layer*
  - *Printed on a modified Anycubic mono X*

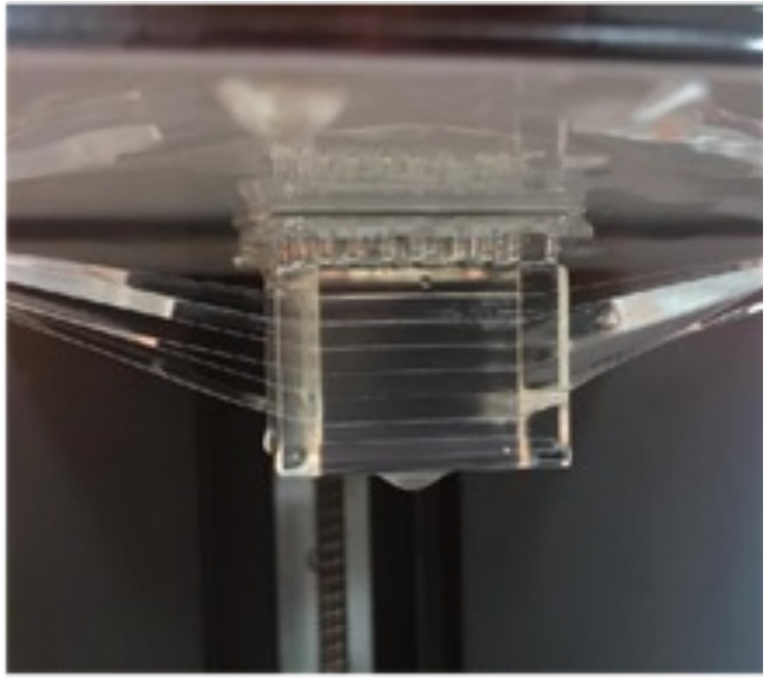


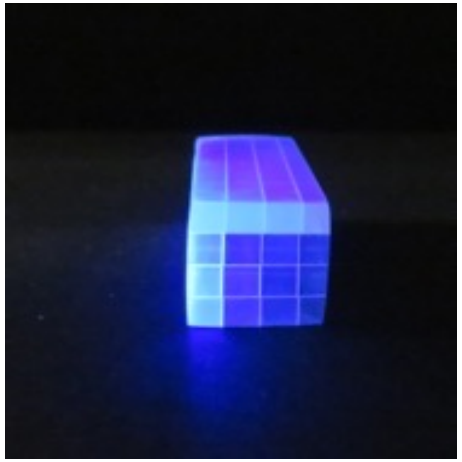


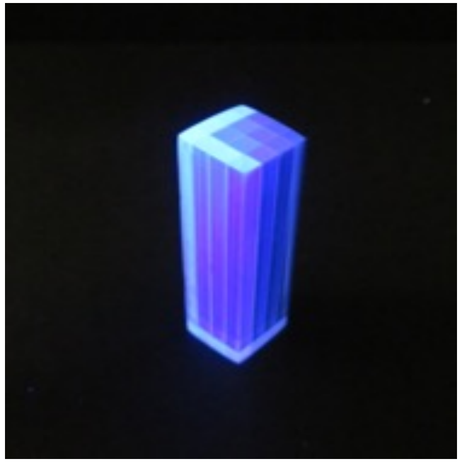


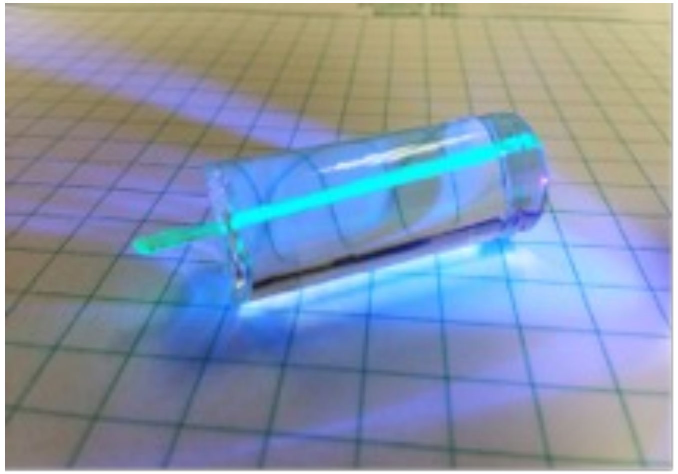
Embedding

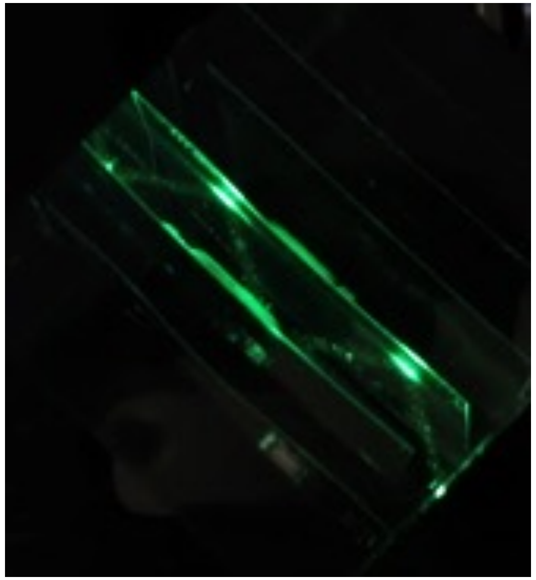
- Direct embedding of optical reflectors and other materials possible during 3D printing
- Compact, optically segmented arrays are desired for wide-range of experiments
- Useful for particle tracking detectors and fiducialization
  - 3D scintillation tracking array, reactor antineutrino experiments?











Adding new detection channels

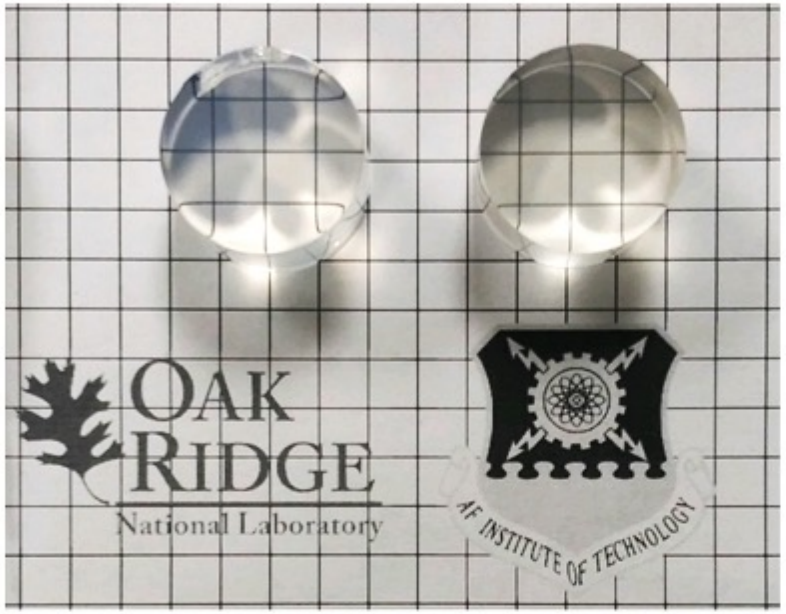
- Electron antineutrinos can be detected in scintillators using using inverse beta decay
  - Electron antineutrinos interact with hydrogenous materials
  - Neutron can then be captured using a dopant with a high neutron capture cross section
    - ^{6}Li, ^{10}B, Gd
- ^{6}Li is an ideal candidate
  - Recent formulations makes it relativity simple to added to a scintillator
  - Reaction products do not experience lower scintillation quenching compared to ^{10}B
- Metal loading also possible
  - Bismuth loading for improved gamma-ray sensitivity
- *Other interesting dopants???*

$$\overline{\nu_e} + p^+ \rightarrow e^+ + n$$

Prompt: e^+

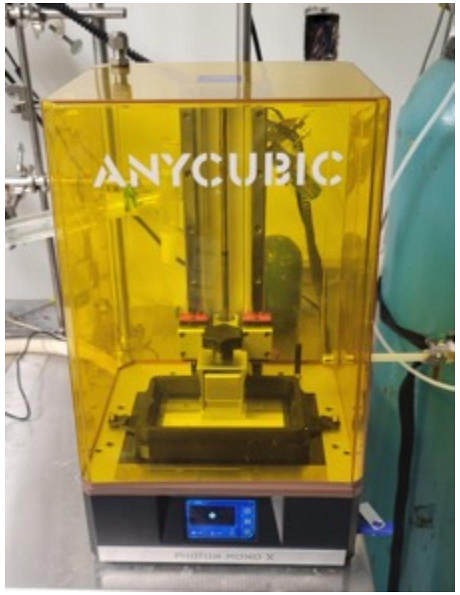
Delayed: $^{6}Li(n,t)^{4}He$

Standard light curable | Bismuth - loaded

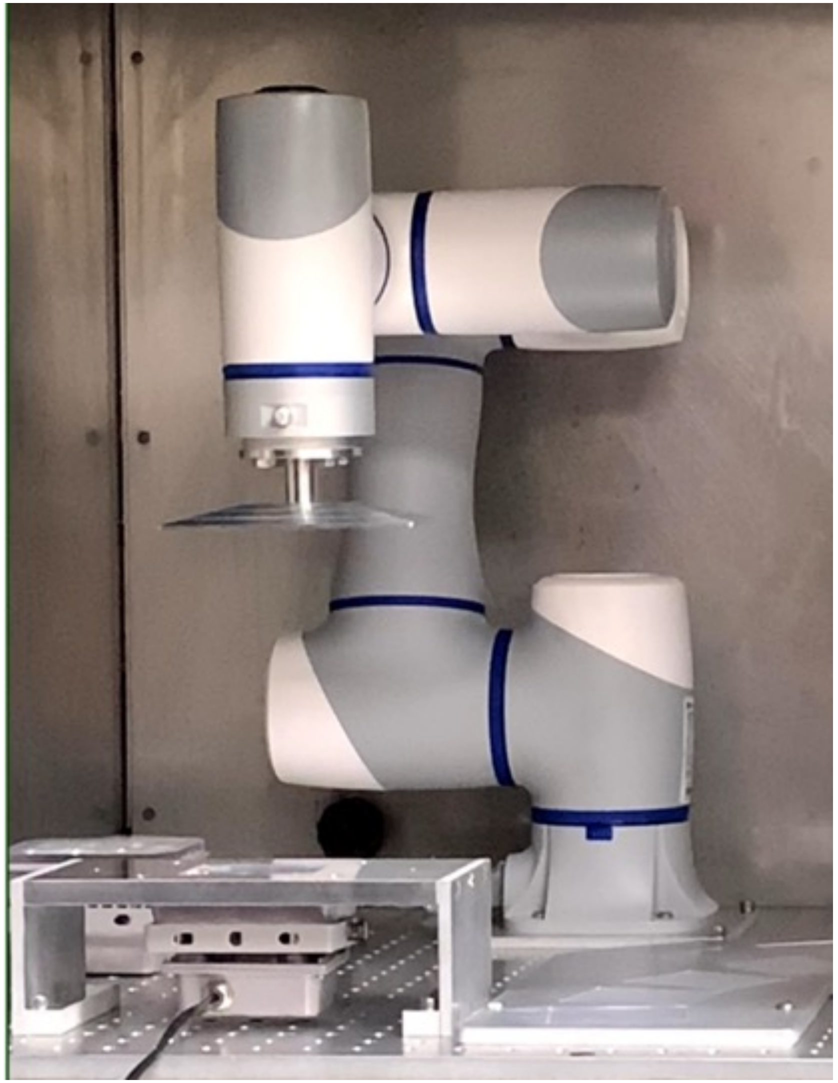


Towards a dedicated 3D scintillator printer

- High performance scintillator should be prepared in an inert environment
  - Improves light output *and printability*
- Requires 3D printer to operate in inert environment such as N_2
- Work underway to develop a dedicated 3D printer for scintillators based on a 6-axis robotic arm



Current 3D printer – Modified Anycubic mono X

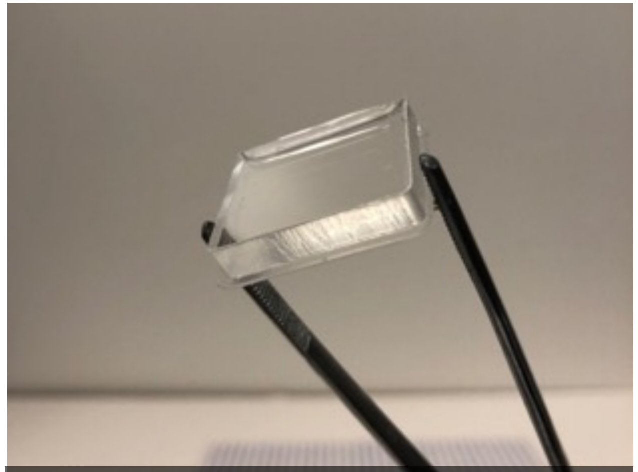


Prototype 6-axis 3D printer for scintillators

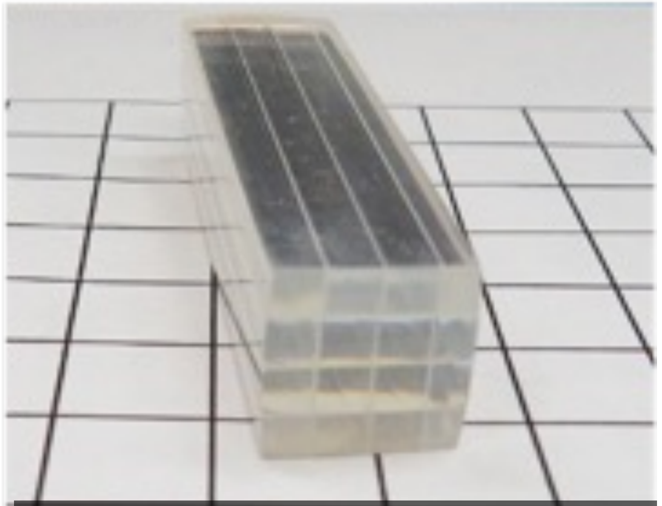
Photo credit – Chandler Moore

Opportunities

- Light-based curable scintillator resins open up a wide range of exciting possibilities
  - 3D printing / bulk photocuring
  - Wavelength shifting adhesives and coatings
  - New materials and dopants



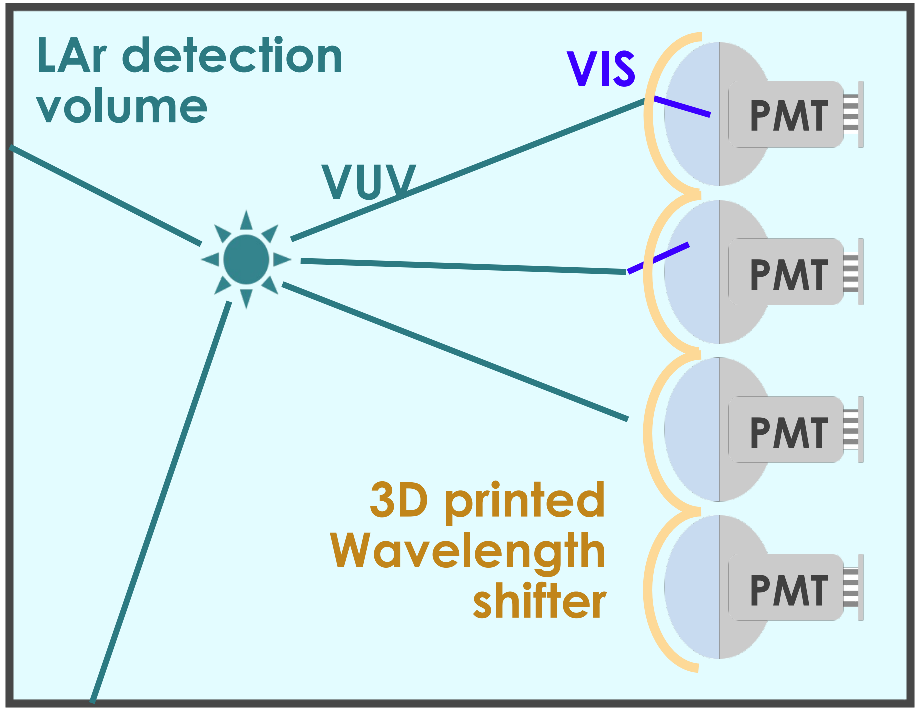
PSD – formulation
Deuterated polystyrene scintillator



Optically segmented PSD plastic scintillator

- Low background materials

- Multi-material composites



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Conclusion

- Photocurable resins offer exciting opportunities for new physics instrumentation
  - Scintillators, wavelength shifters, adhesives
  - Low-background materials and/or scintillators
- Opens the possibility for light-based 3D printing
  - Significant improvement in optical performance compared to FDM based printing
  - Near contactless manufacturing for low background applications
  - < 200 um spatial resolution
- Open question – What applications should be targeted?

Questions ?

ORNL
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LLNL
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Yongwook Kim

AFIT
Juan Manfredi
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