LYSO Bench Tests

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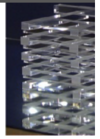
Outline

- Here’s the idea: use the PEN calorimeter with added stopping power as an alternative to liquid Xenon - pictures
- Pros and cons of our choice of LYSO crystals
- Intrinsic characteristics of LYSO that affect energy resolution – can they be overcome?
- Testing capabilities at UW
- Overcoming intrinsic beta radioactivity in LYSO crystals
- Measurements with 60Co gamma radiation and cosmic muons
- Summary

Why we chose LYSO crystals

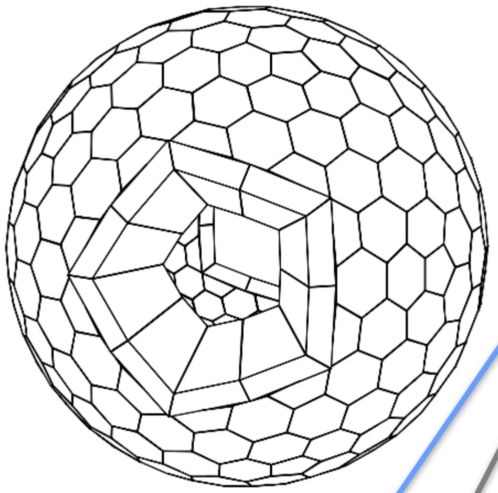
From Ren-Yuan Zhu's presentation, LYSO is a good candidate

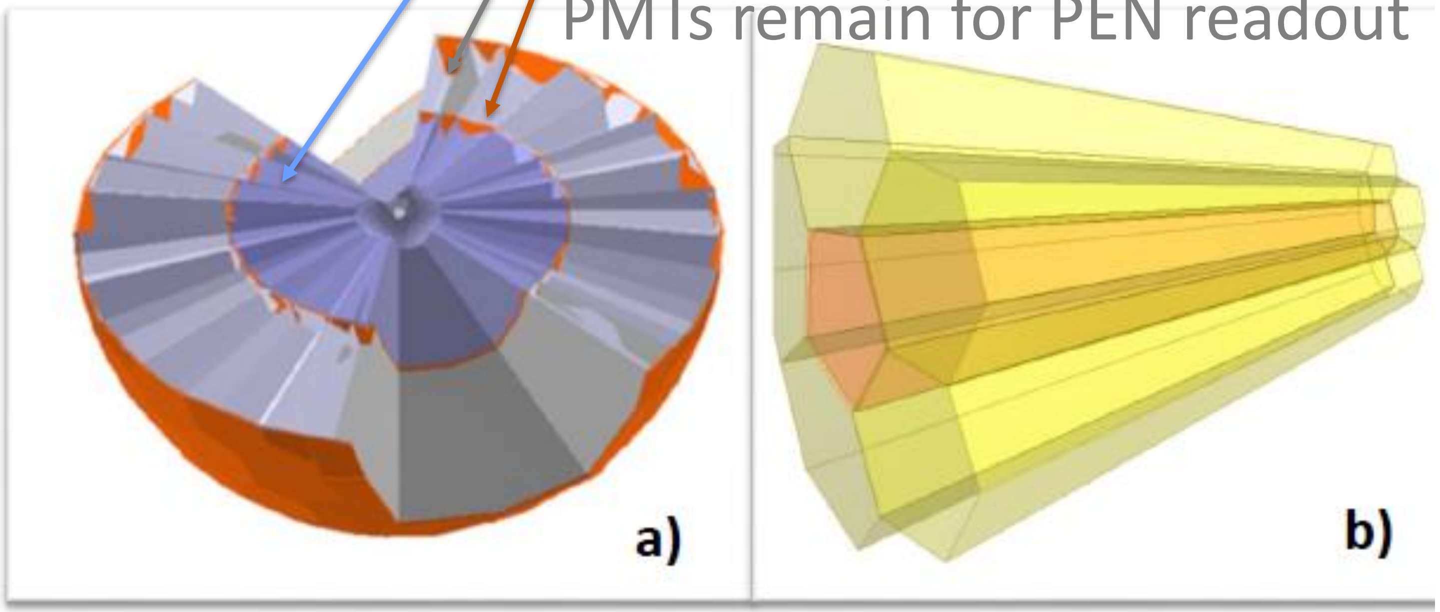
Crystals with Mass Production Capability



Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (ºC)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
$\lambda_{peak}{}^a$ (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index^b	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield^{a,c}	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time^a (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No

The CALO Xtal Hybrid Idea



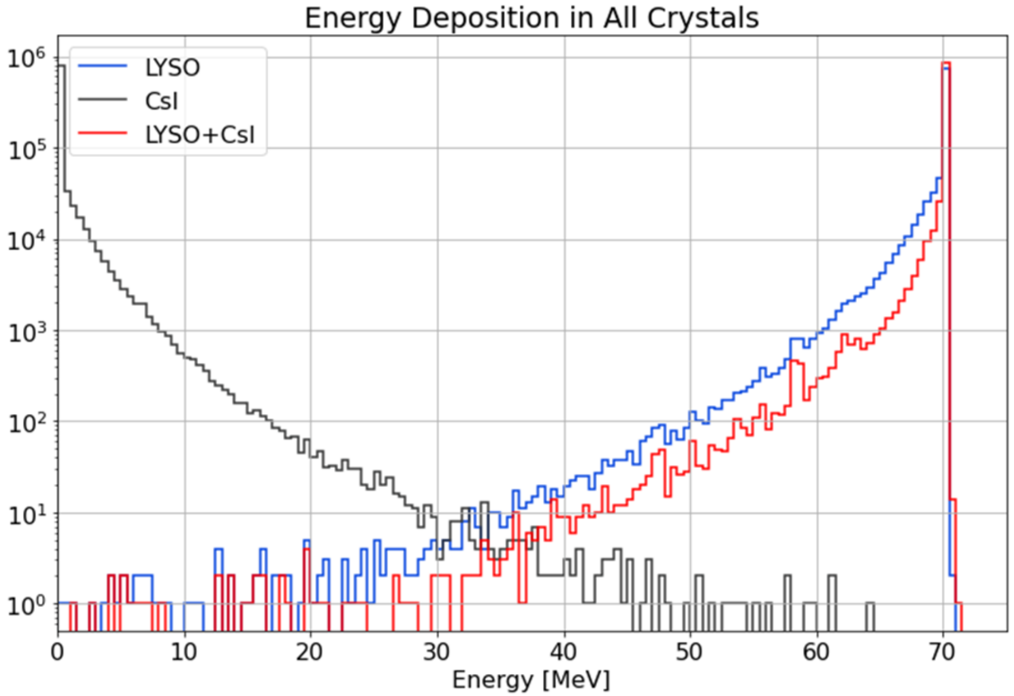


16 X_0 LYSO

PEN Calorimeter (12 X_0 CsI)

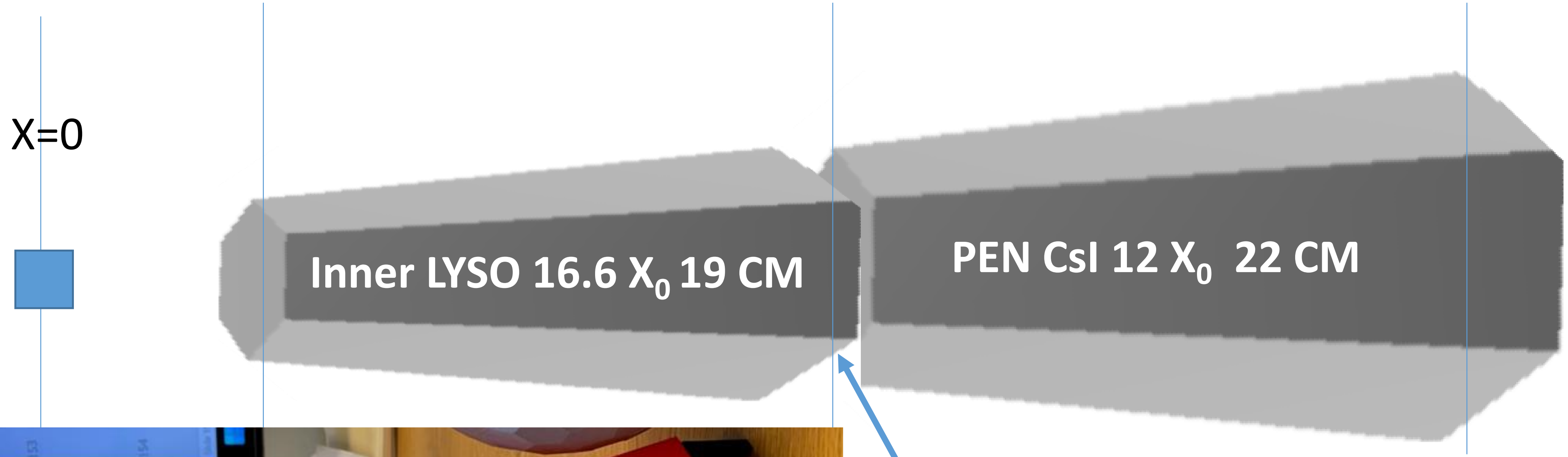
SiPM readout of LYSO;

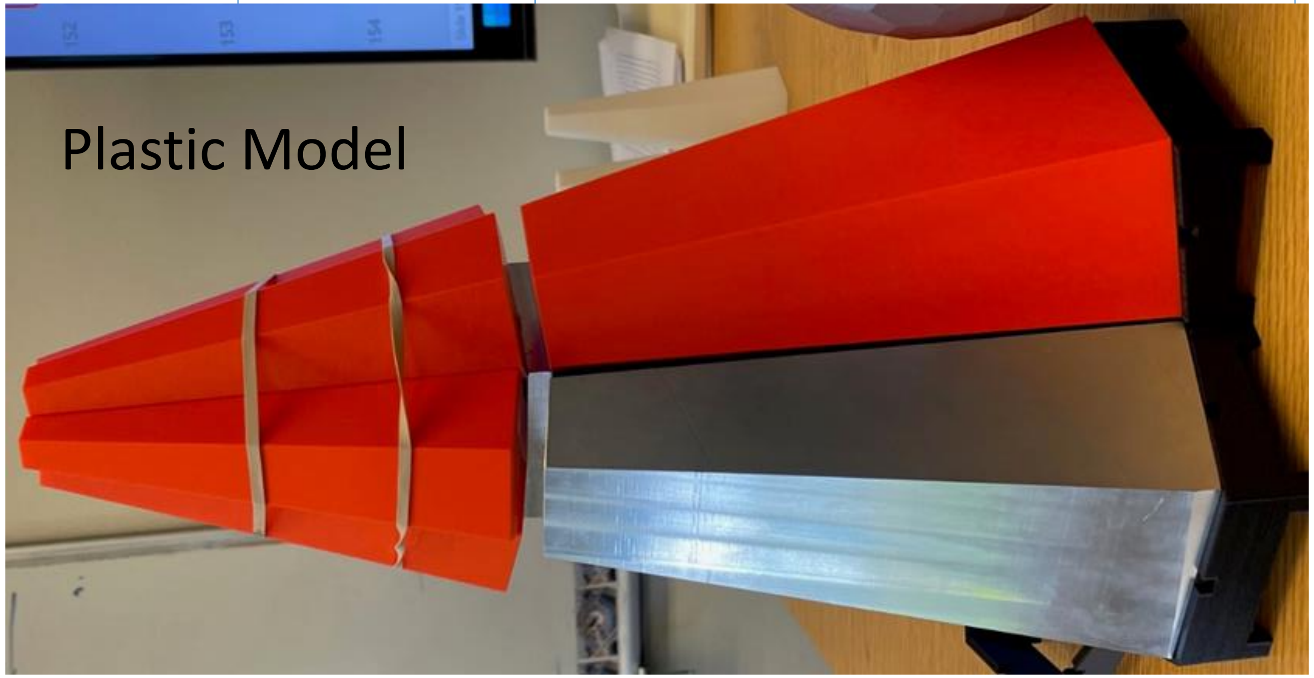
PMTs remain for PEN readout

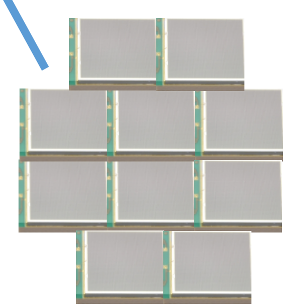


With "2" Calorimeters at the same time ($16\ X_0 + 28\ X_0$) gives unique handle on the low energy tail

Here’s the concept “to scale”

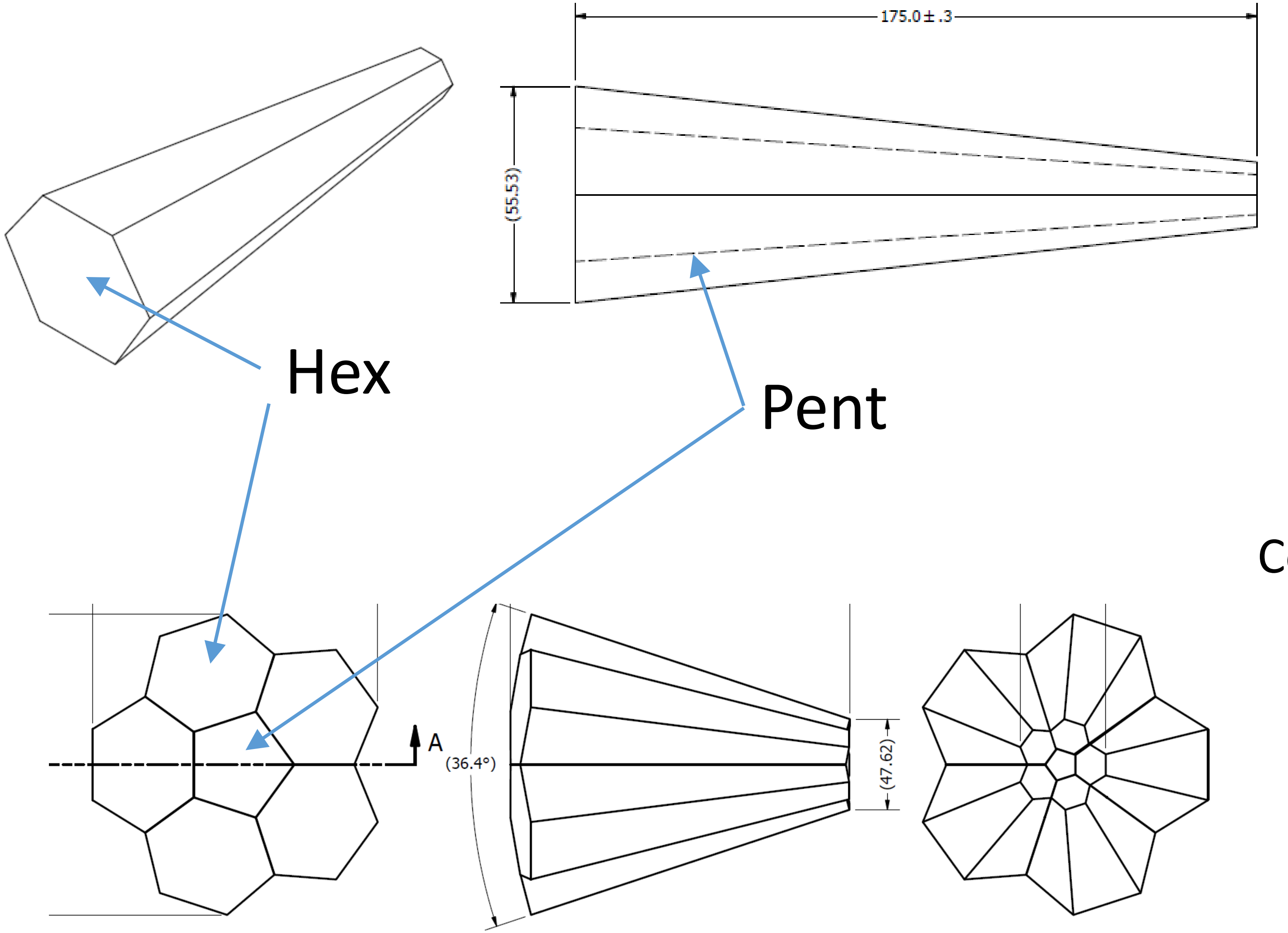


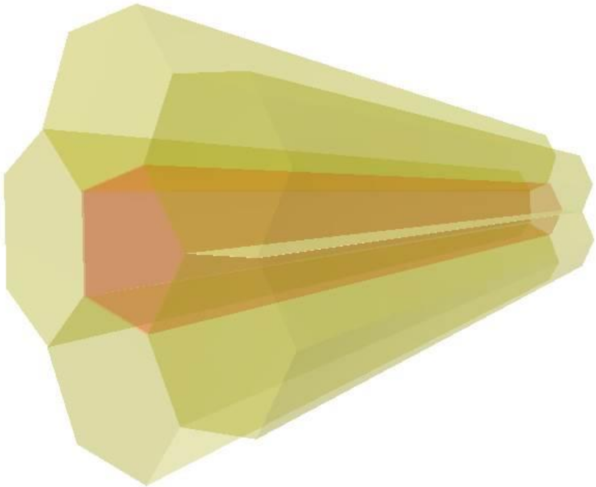




SIPM layer 1cm gap

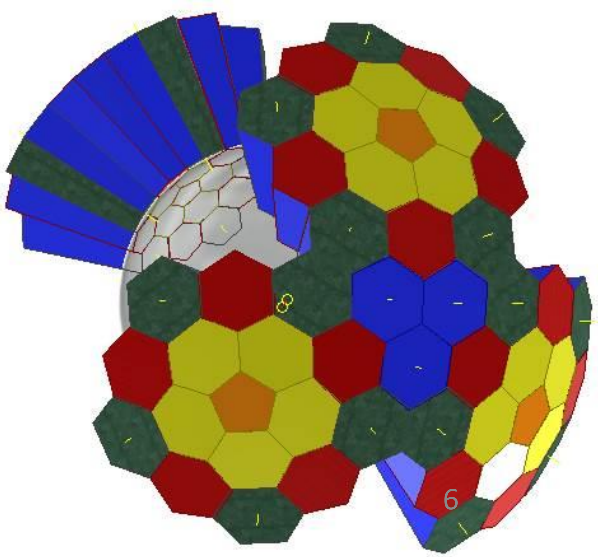
Images and Models that Fit



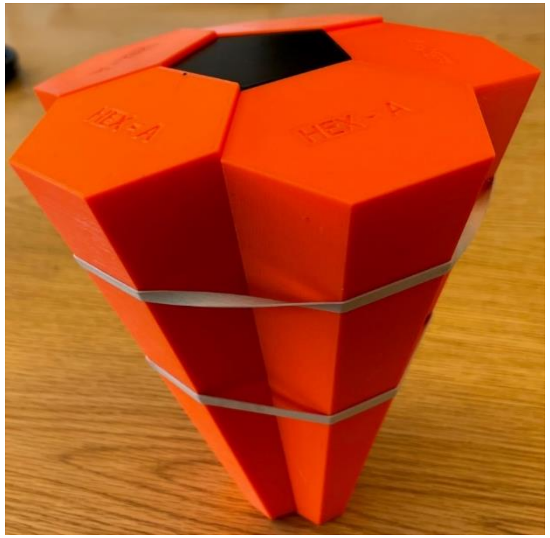


Small array

Conceptual with PEN outer CsI

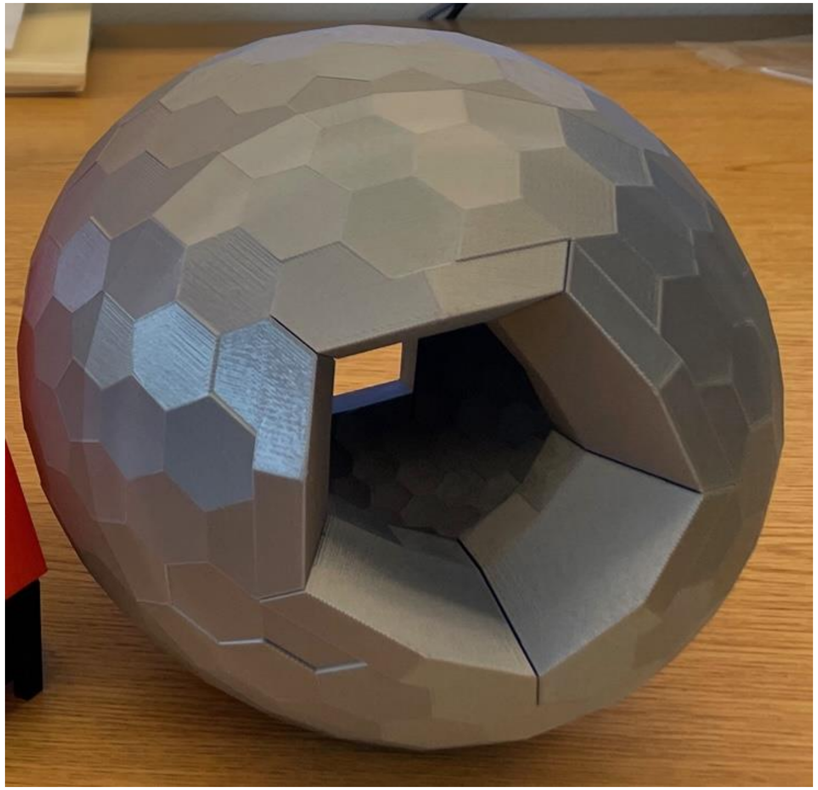


Useful 3D models address the mechanical design issues. Inner Xtals match PEN CsI 1:1 with 1 cm gap for SIPM layer

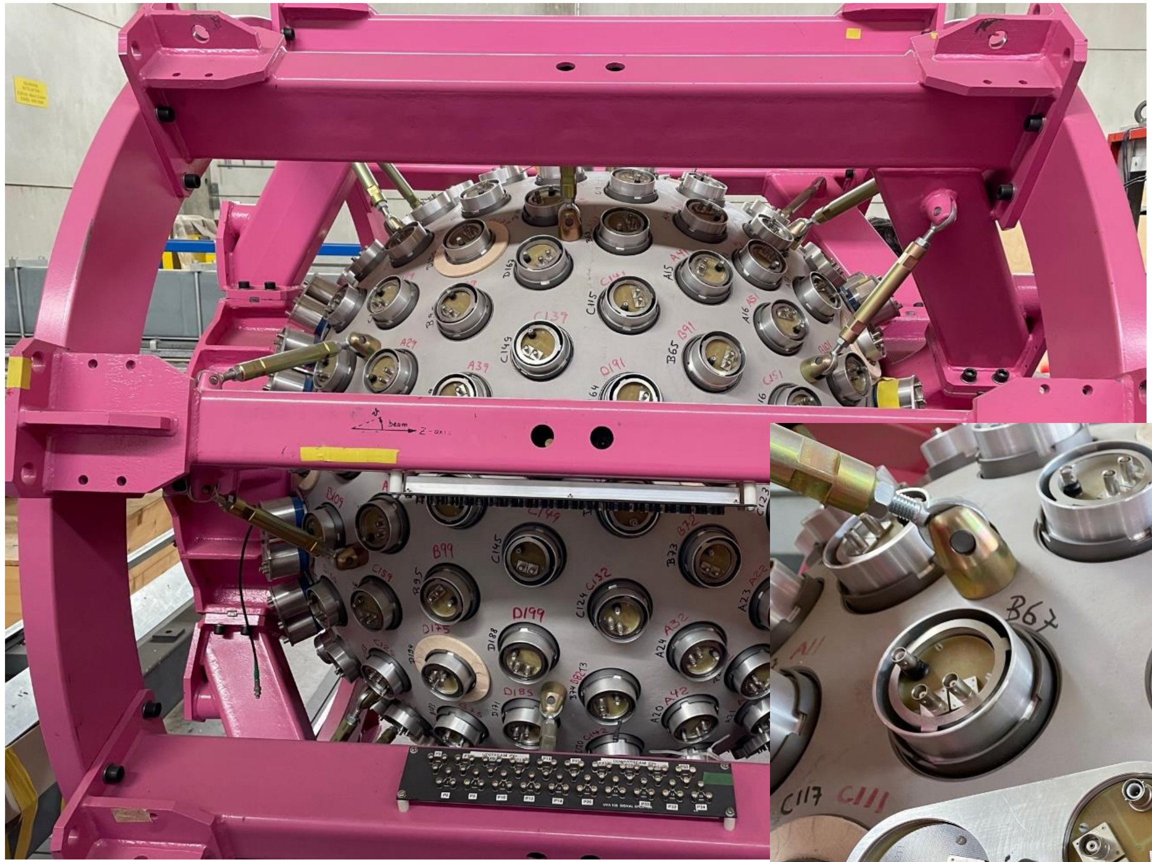


Actual Size

PEN to Scale



Reminder: PEN CsI array exists at PSI; we will need to evaluate its status with Dinko's help next spring/summer



LYSO crystals in HEP experiments

Energy and time resolution of a LYSO matrix prototype for the Mu2e experiment

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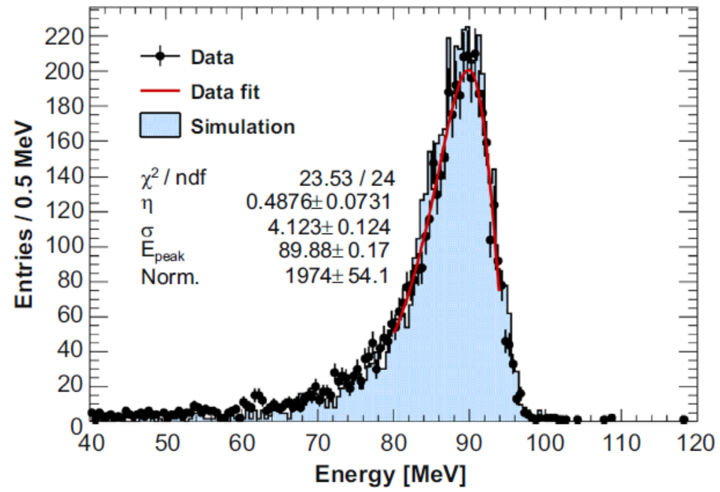
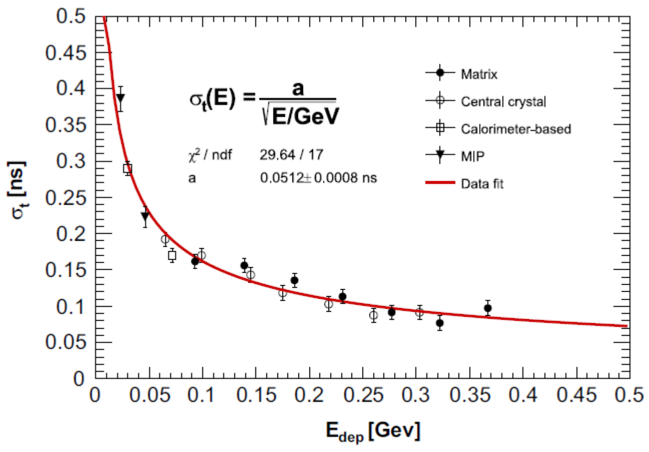


Fig. 1. Energy distribution for 90 MeV photons (dots) compared with GEANT4 simulation (filled histogram). MC spectrum includes 2 mm beam spread and an additional 2.6% Gaussian smearing accounting for miscalibration, non-uniformity and non-linearity. Energy resolution is obtained from a fit with a Lognormal distribution (solid line).

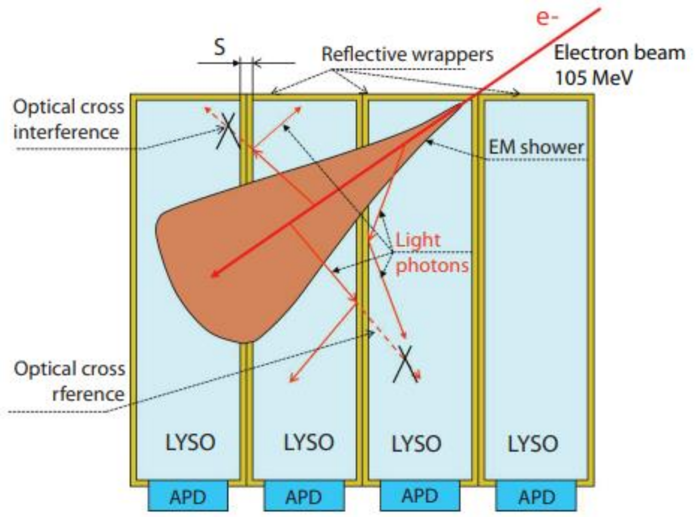
Timing is good



ig. 3. Time resolution for e⁻ as a function of the deposited energy. The jitter due o the trigger has been subtracted. The σ_T value has been obtained with the whole natrix (dots), the central crystal (circles) and the difference of two crystals when he beams hit in the middle of the two (open squares). The low energy region has een exploited with minimum ionizing particles (triangles).

$$\frac{\sigma_E}{E_{dep}} = \frac{a}{\sqrt{E_{dep}(\text{GeV})}} \oplus b. \qquad (1)$$

The extracted parameters are: $a = (0.6 \pm 0.1)\%$, $b = (3.6 \pm 0.2)\%$. The same parametrization on Monte Carlo (MC) events provides $a = (0.52 \pm 0.04)\%$, $b = (2.86 \pm 0.09)\%$.



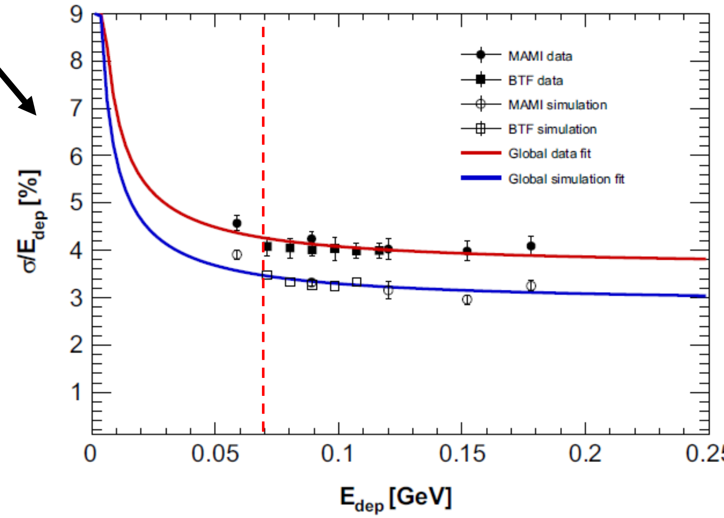


Fig. 2. Energy resolution as a function of the deposited energy for γ's (dots) and e⁻ (full squares). Corresponding MC expectations are reported in circles and open squares, respectively. Simulation points are obtained without the 2.6% Gaussian smearing needed to describe real data.

33200 γ/MeV → 2.3 M γ/70 MeV

For our 70 MeV signal

Collect (?) 75% at QE (?) = 20%

→ 350K → 0.2% "resolution

Motivation and Concerns

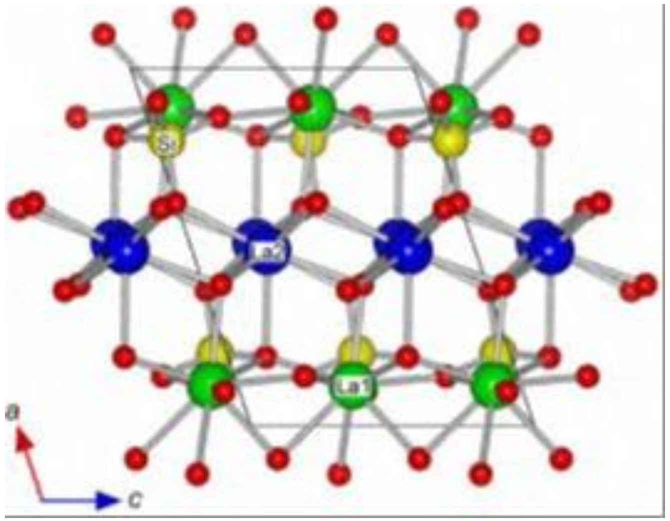
- Advantages (if it works)
  - Simple compared to LXe to maintain in the long run
  - Much cheaper (~$6-7 M for xtals) + 240 readout channels
  - Much lower pileup given intrinsic segmentation
  - Triggering options better for Phase II
  - Can calibrate segments directly in electron beams to characterize fully
- Disadvantages (i.e, it might not be good enough)
  - No really good example of success from other experiments (except PET)
  - We will have to demonstrate that next-gen xtals can be uniform enough
  - Intrinsic resolution worse than LXe by x2, even with high light yield (puzzling)
  - Will require significant Quality Control program to minimize constant terms
  - Not that cheap to do basic conceptual R&D (same problem for LXe though)
  - Intrinsic radioactivity (LYSO xtals have about 37 kBq each)

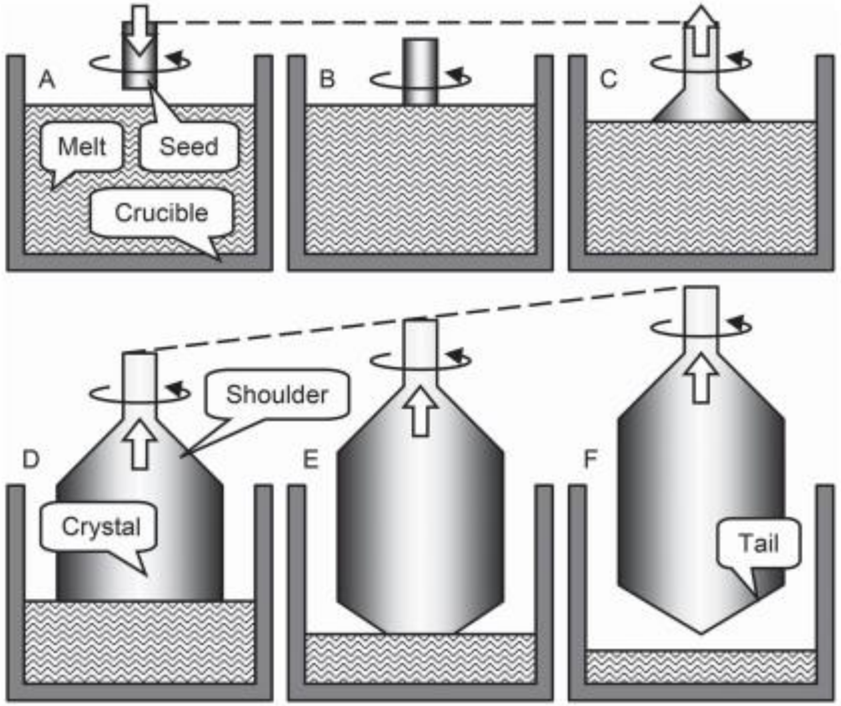
LYSO light output – why excess variance over root N_p?

Non-uniformity in light production

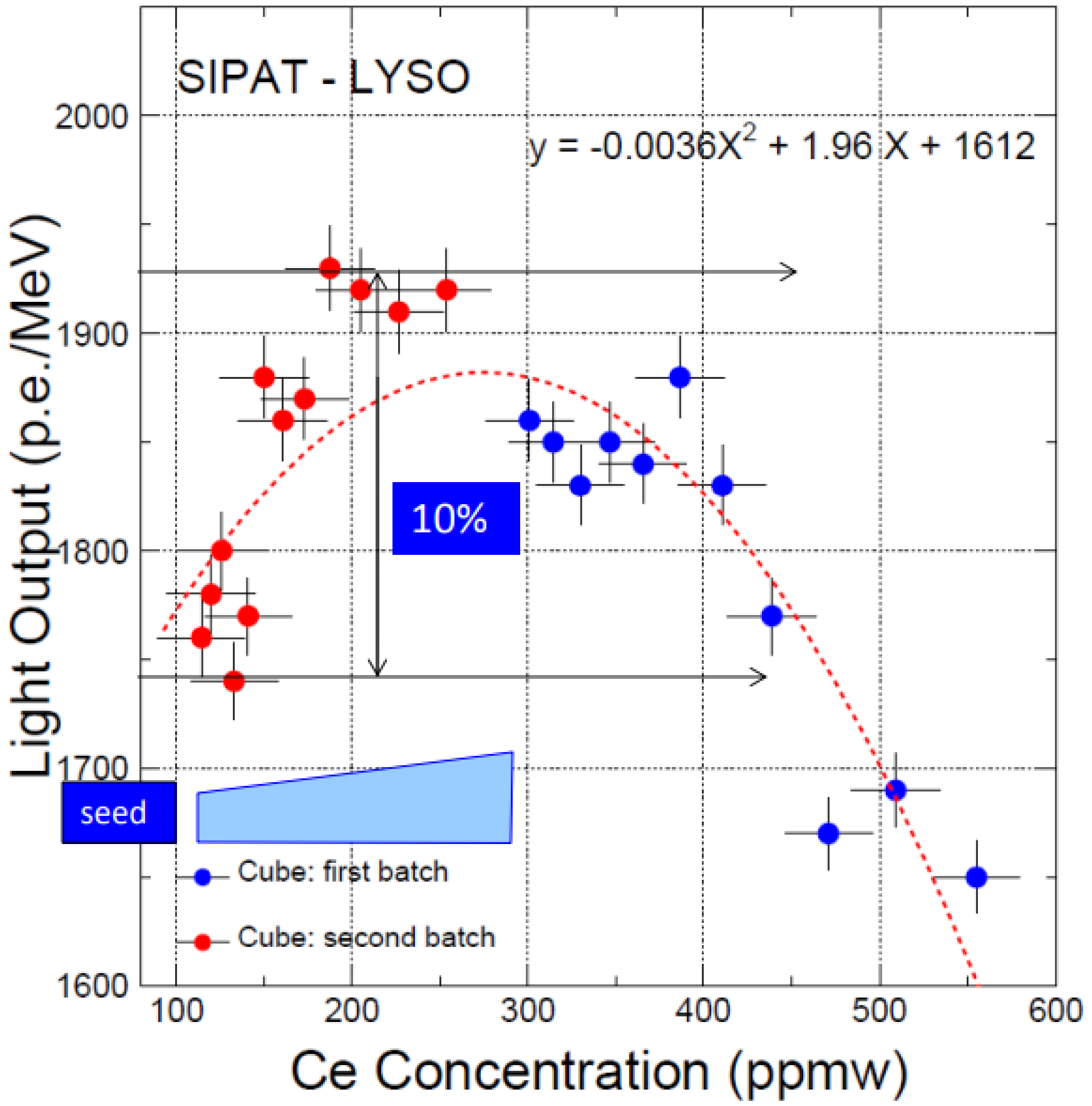
- Ionic sizes: Lu^{3+} = 0.85, Y^{3+} = 0.89, Ce^{3+} = 1.04 (larger)
- Ce^{3+} produces light – most (95%) occupies green Lutecium sites
- Actual Ce composition in crystal < 20% of melt composition
- Ce concentration in xtal grows along length of pull

LYSO - $(Lu,Y)_2SiO_5$:Ce





Effect of the Cerium Segregation

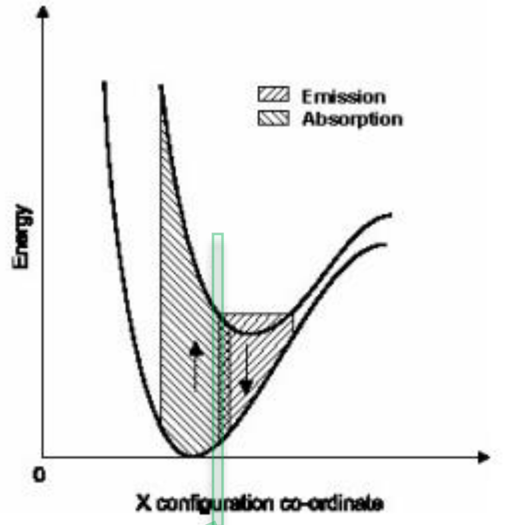


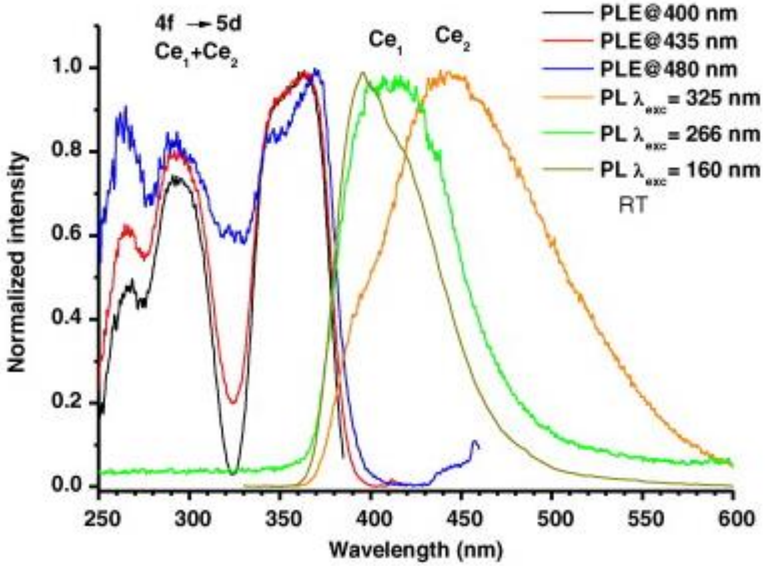
It is known that the cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in δ is possible because of the cerium segregation.

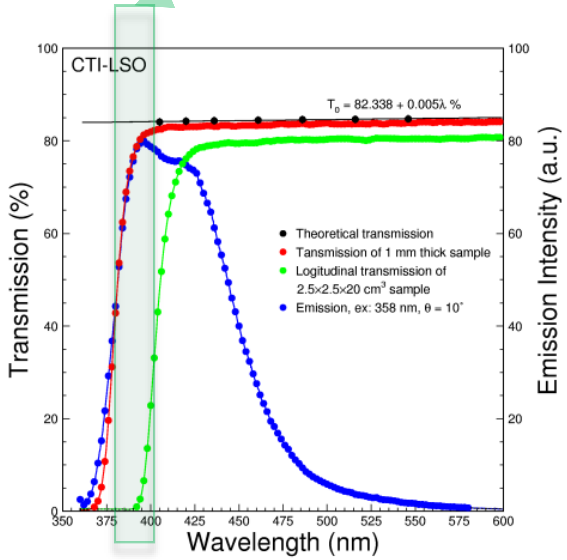
LYSO light output – why excess variance over root N_p?

Non-uniformity in light detection

- Emission peak shifted from absorption peak
- But not far enough – some overlap remains
- Ce re-absorption greater with longer photon paths
- Also reduced transmission from defects and traps
- Lots of internal reflection, n = 1.84 leads to long paths

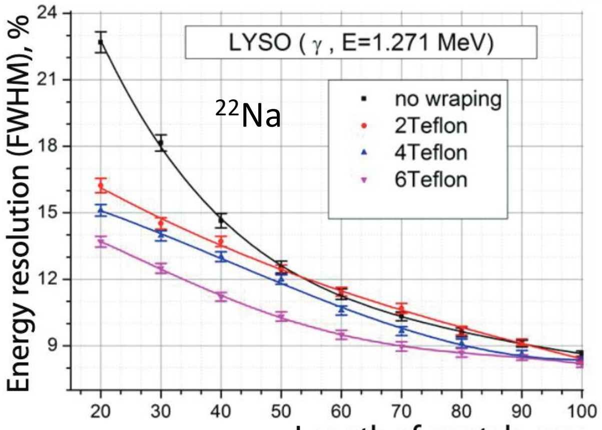




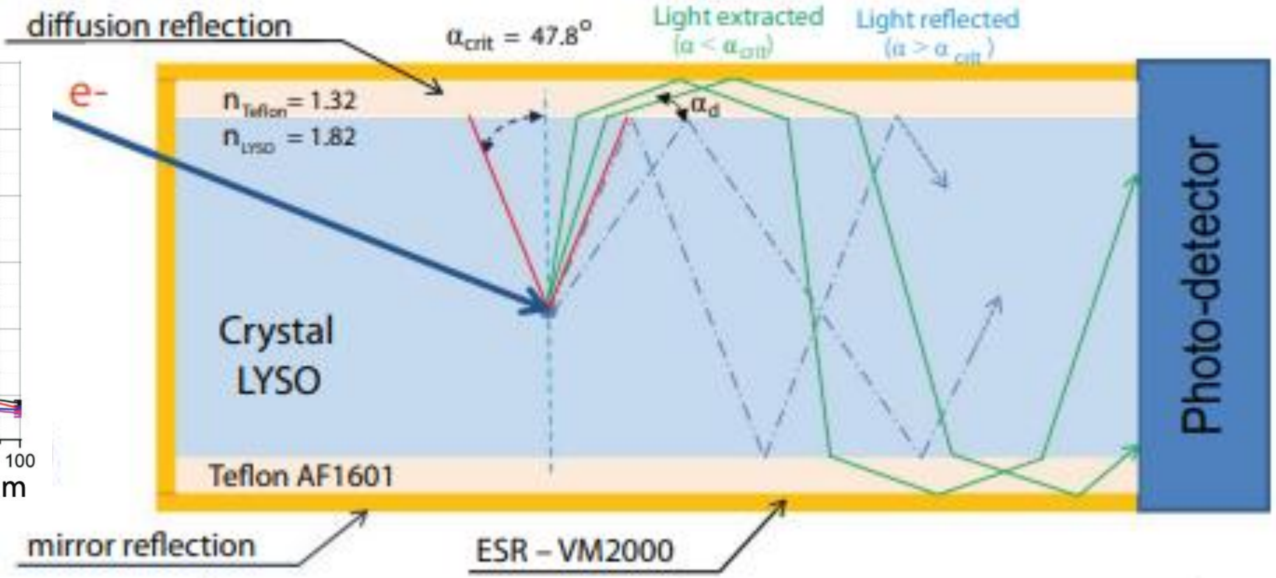


Red – transmission traversing short dimension
Green – transmission traversing along xtal axis

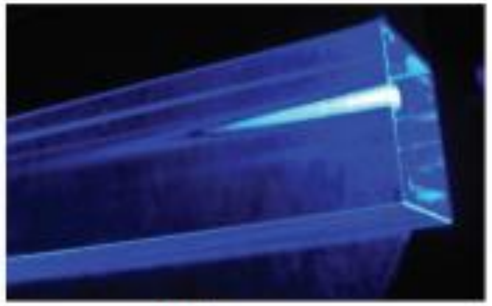
- Reduction of losses can be achieved by creating a diffusive surface on the crystal
- Lapping crystals to a specified surface roughness or chemical etching is one way
- The COMET collaboration wraps their crystals with layers of Teflon tape (TEFLON AF1601, thickness of 60 µm with reflectivity 0.98) and an additional outer layer of reflective tape to prevent light from diffusing into adjacent crystals (ESR VM2000)



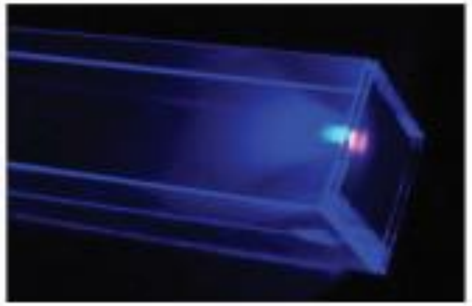
a)



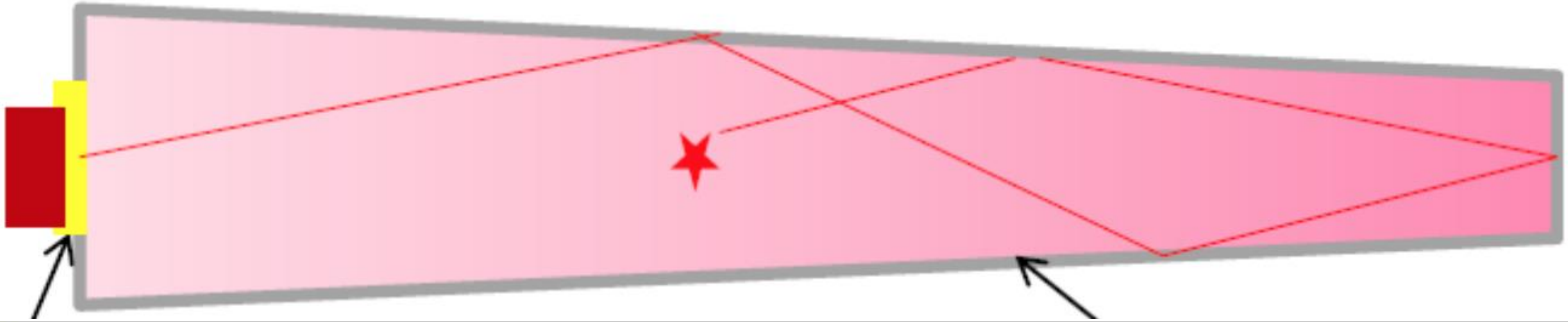
Diffuse wrapped crystal [c] shows less scattering from optically trapped photons



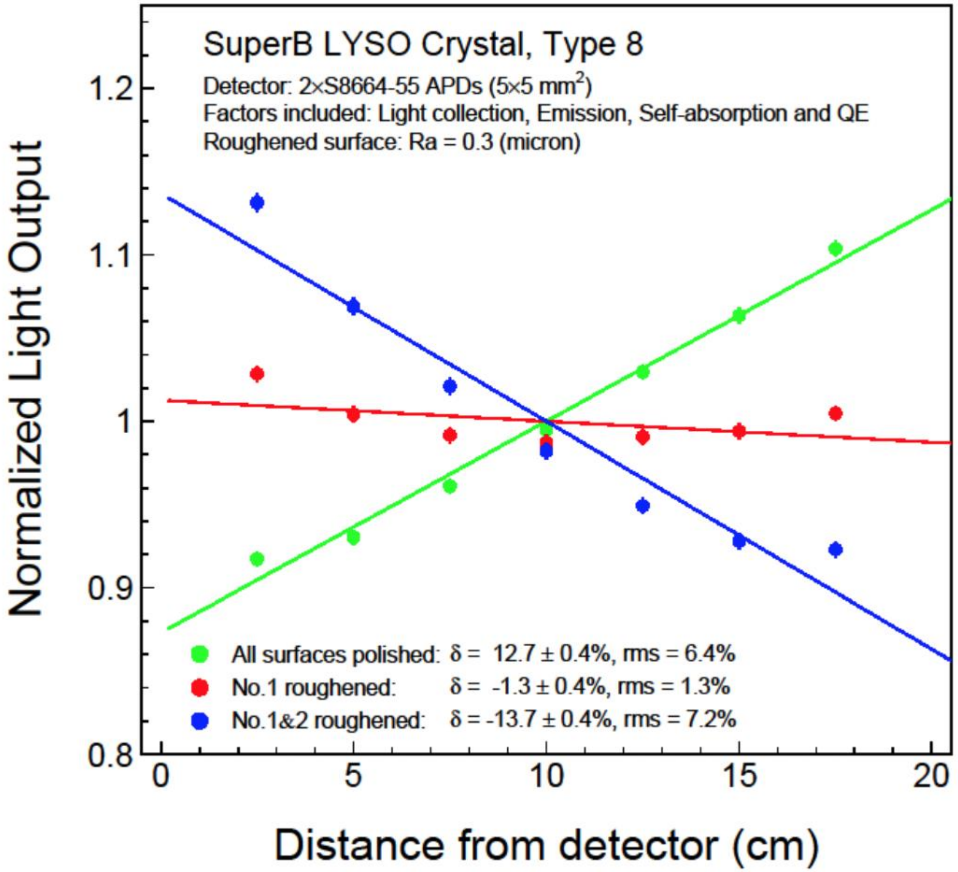
b)



c)



Polished and Roughened Surfaces



The optical focusing, effect dominates non-uniformity: δ is about 13% for all polished surfaces.

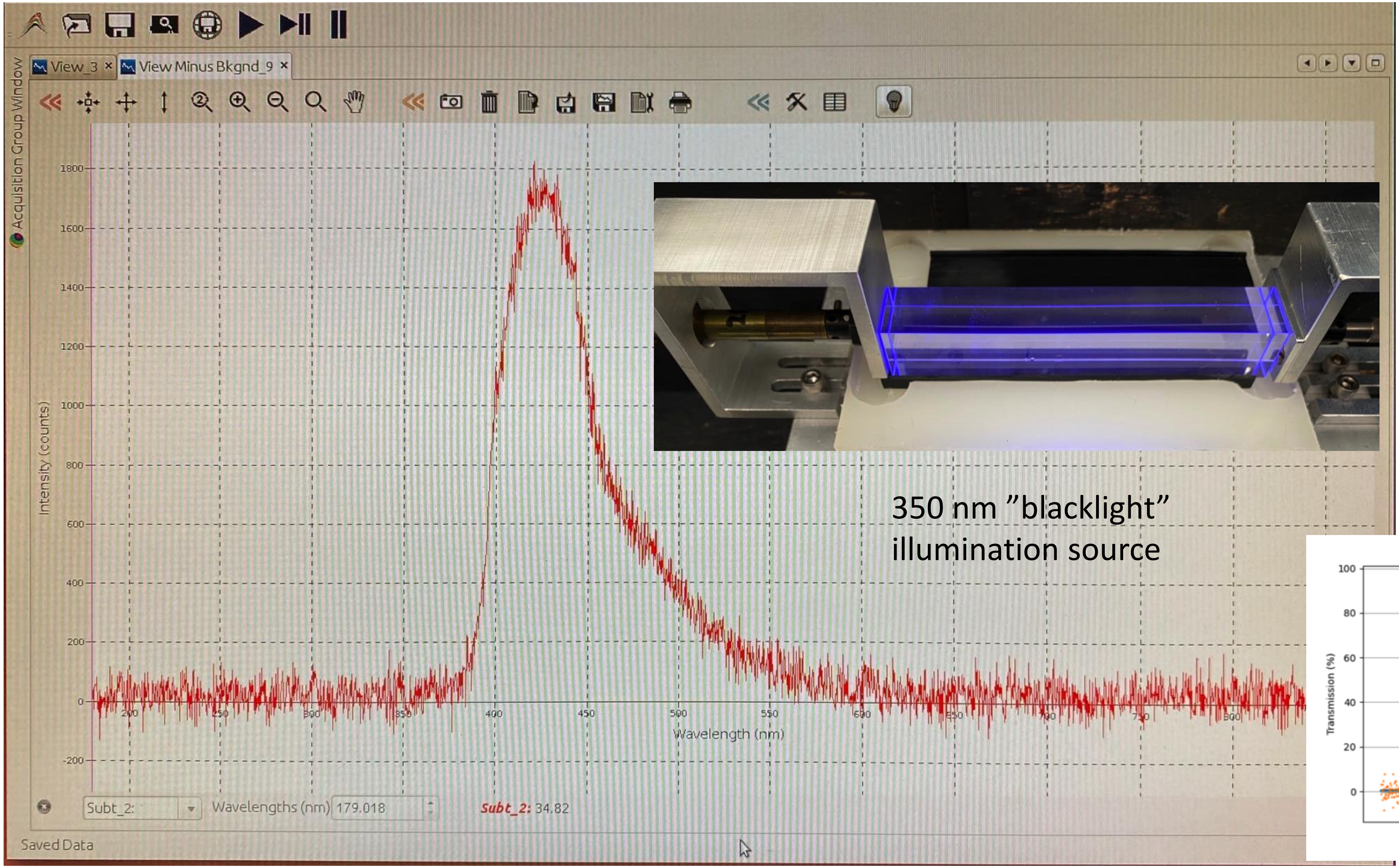
Roughened surface(s) can compensate the optical focusing effect.

The best result is achieved by roughening only one side surface.

Measurement Instrumentation at UW

- Ocean Optics 200nm to 600nm optical spectrometer and Xenon light source. Measures light transmission and fluorescence.
- Various Photomultipliers, NaI and Germanium detectors.
- Laser and neutral density filters for PM calibration
- SiPM modules and readout electronics

LYSO emission spectrum – Ocean Optics Spectrometer

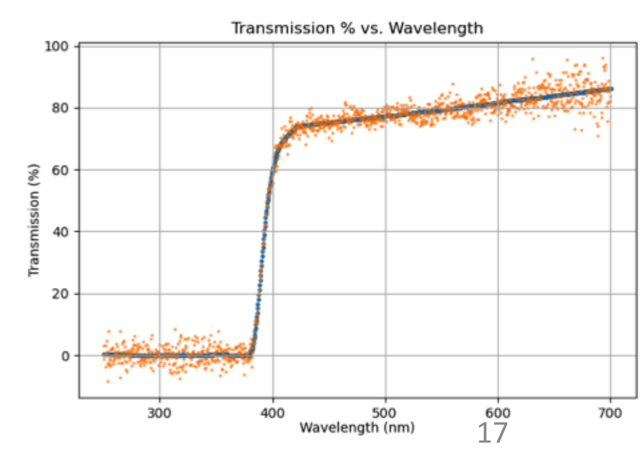


350 nm "blacklight" illumination source

<u>Ocean Optics Spectrometer</u>

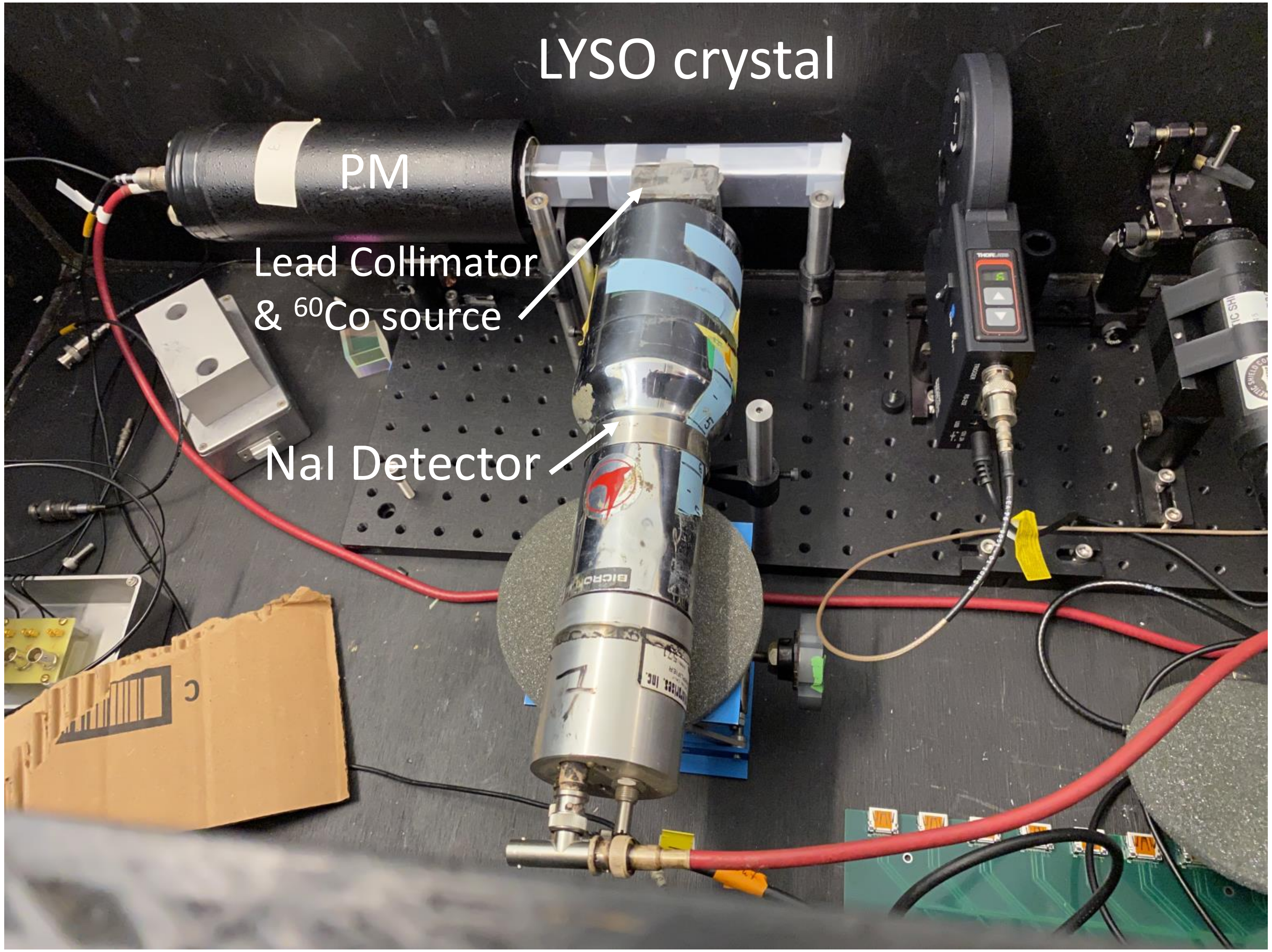
With Xenon light source Measures:

Transmission spectra



Light tight box with photon counting detectors for resolution measurements

- LYSO emits a beta which is contained within the crystal
- Measurements of external radiation sources are used to determine scintillator resolution.
- Sources like ^{60}Co have a gamma cascade to tag the radiation going to the LYSO crystal.
- Performing a coincidence between the NaI and PM separates the extrinsic and intrinsic sources.
- The gamma source, collimator and NaI detector are scanned along the LYSO crystal.

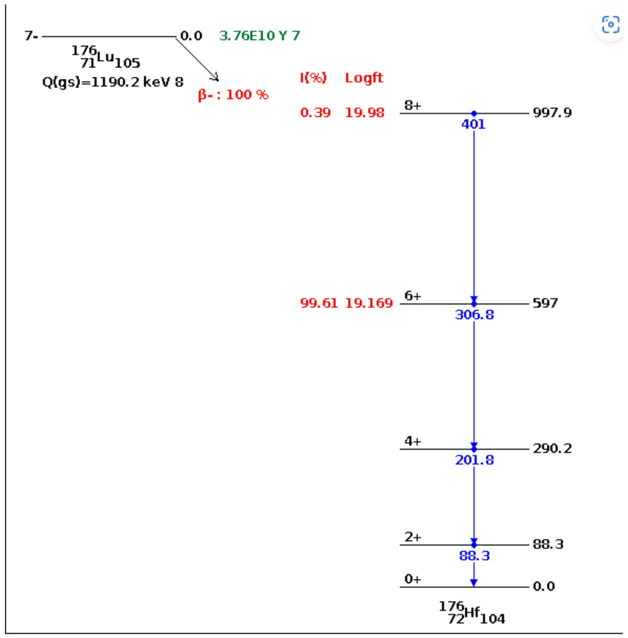


Natural Lutecium contains 2.6% of the radioactive isotope ^{176}Lu

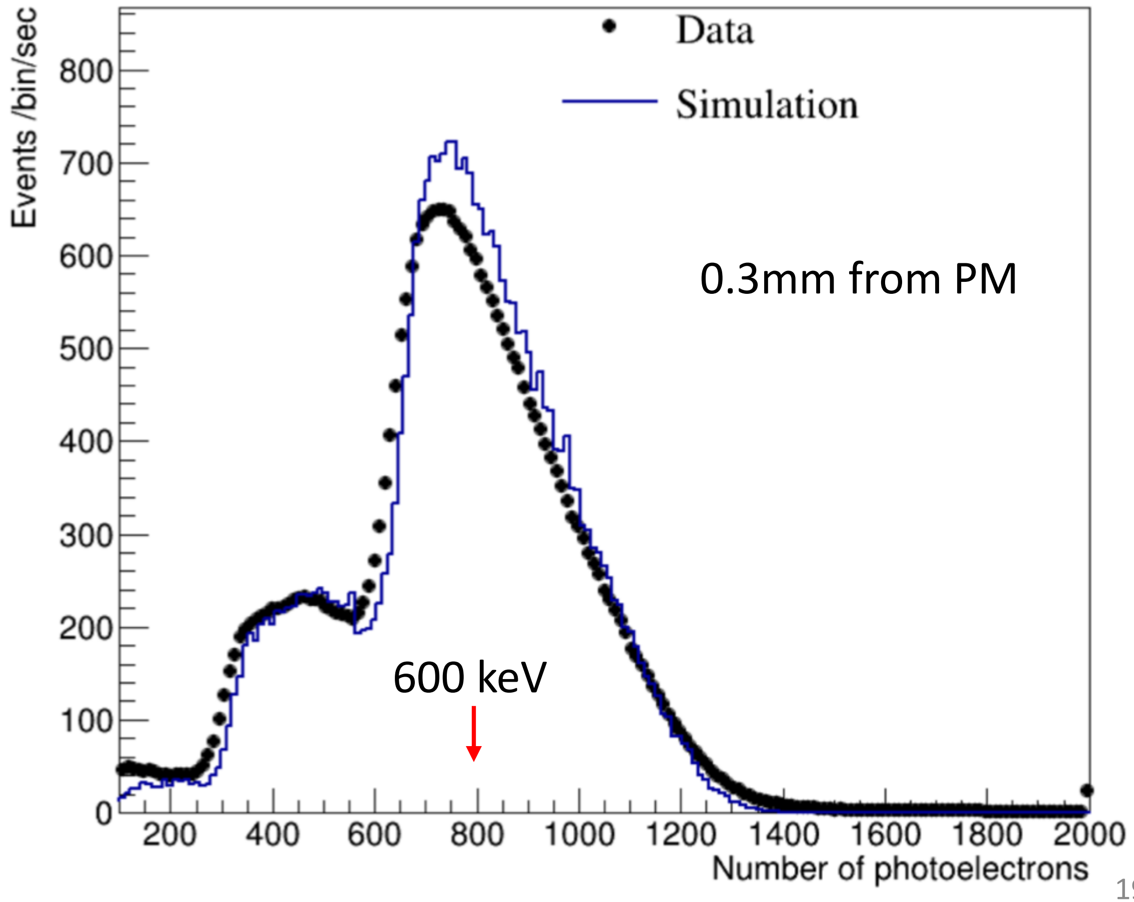
The source strength of the SICCAS LYSO crystal is about 26 kBq
Probing energy resolution with external radioactive sources benefits from cascade gammas that can tag one of the gammas with another detector

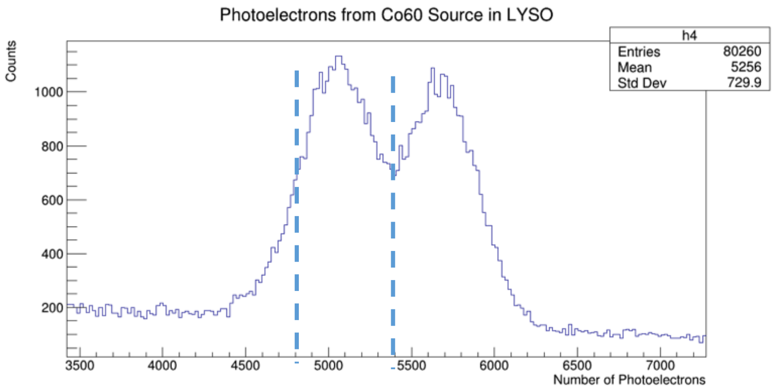
100% beta decays to excited states in ^{176}Hf followed by 88 keV, 200 keV and 300 keV gamma cascade

^{176}Lu decay scheme



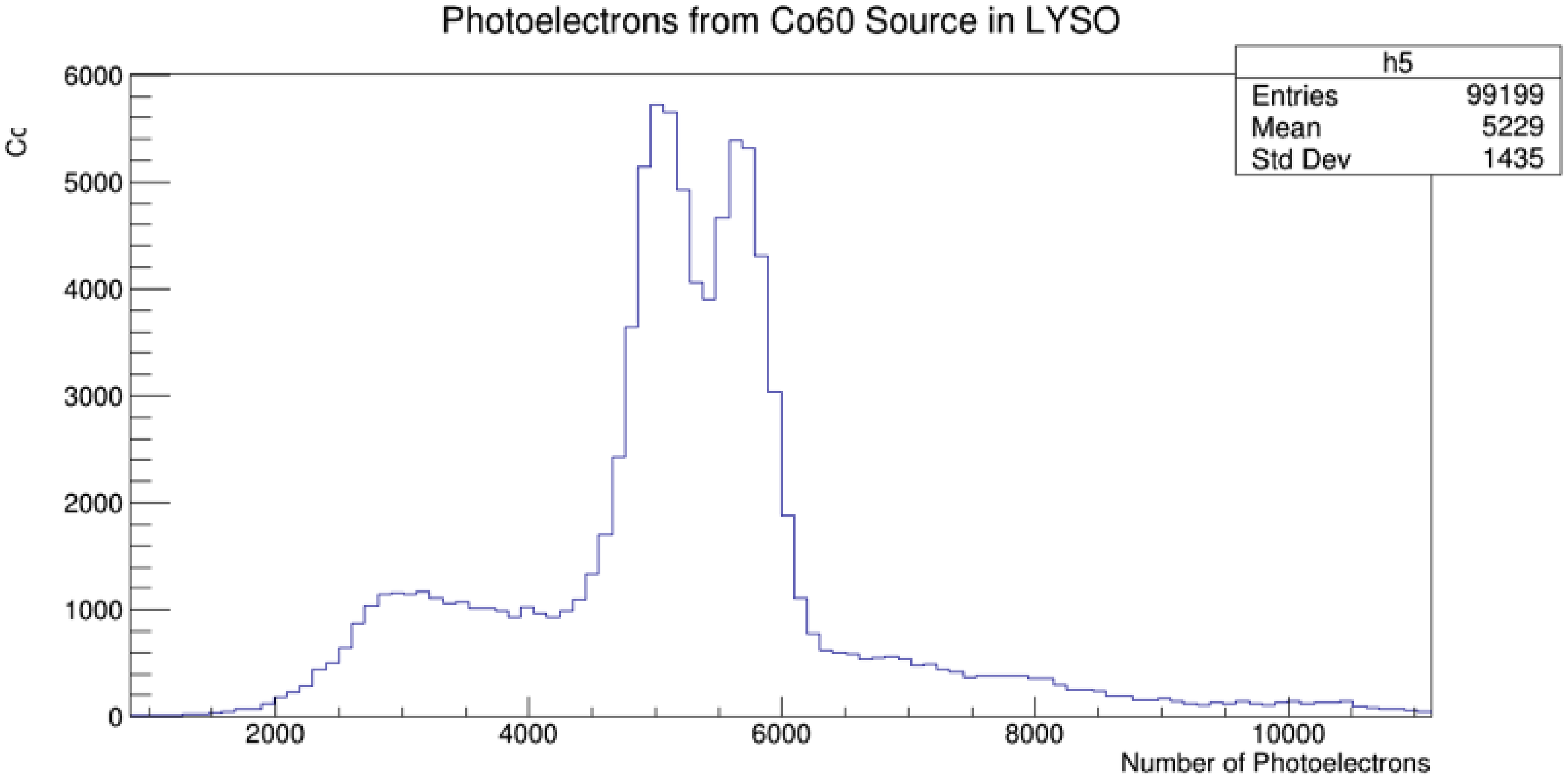
Yong Yang presentation



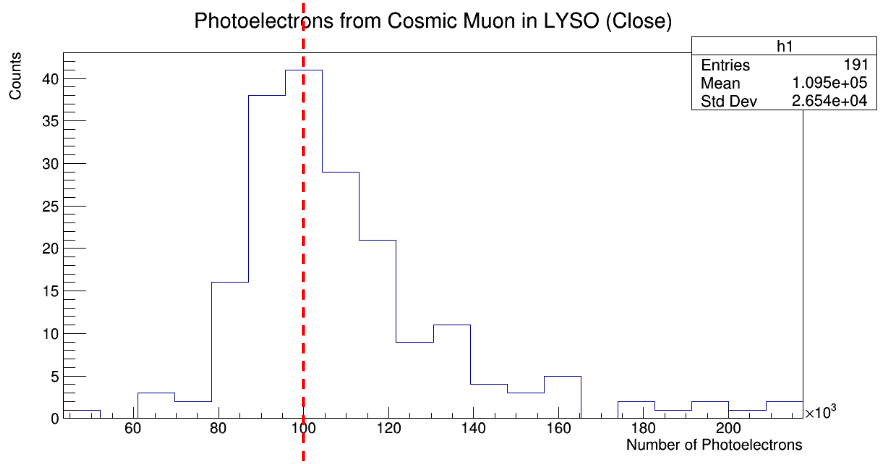


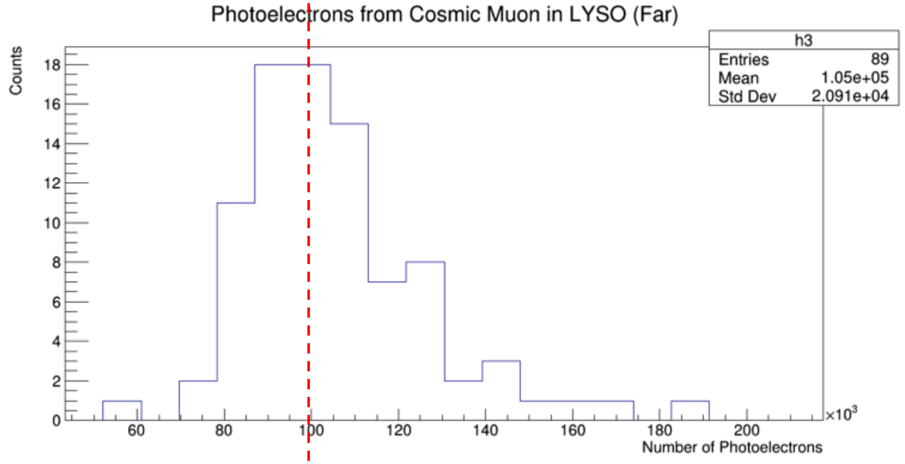
Results of ^{60}Co coincidence with NaI detector

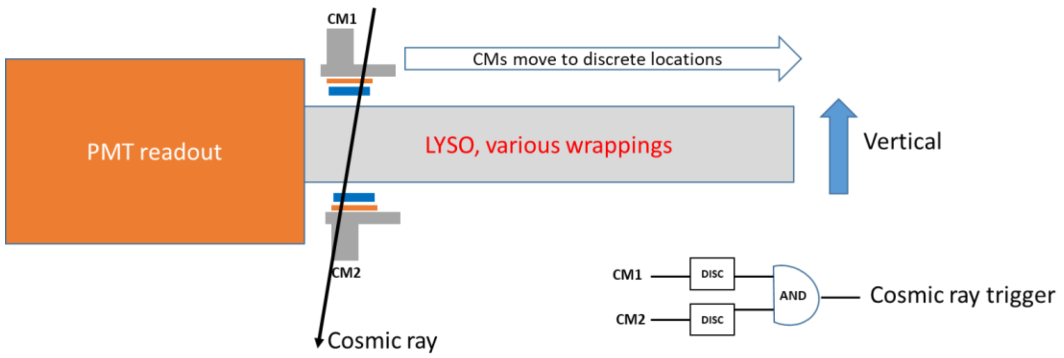
(gamma-rays): 1.1732,1.3325

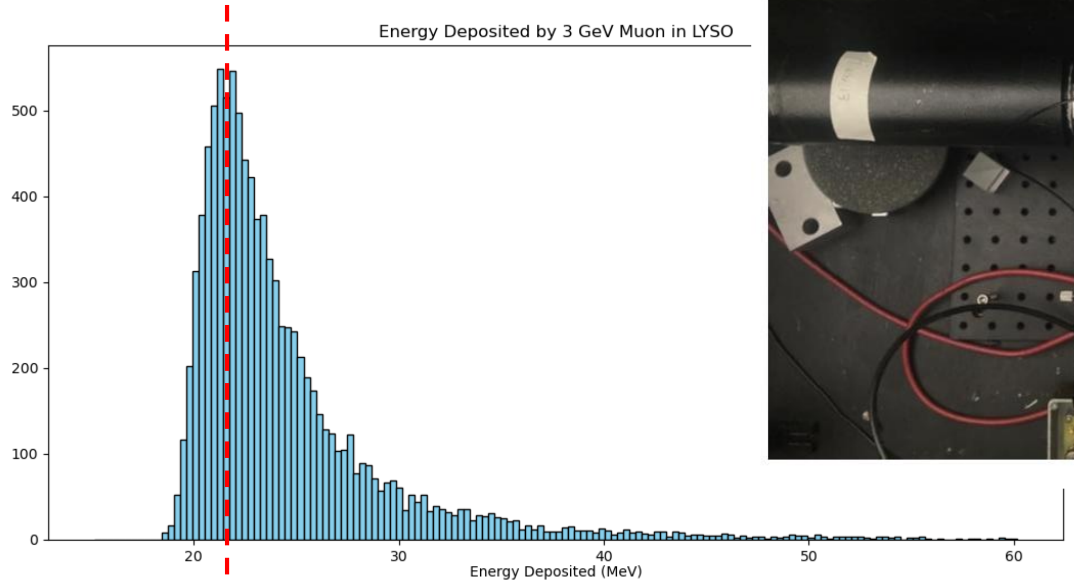


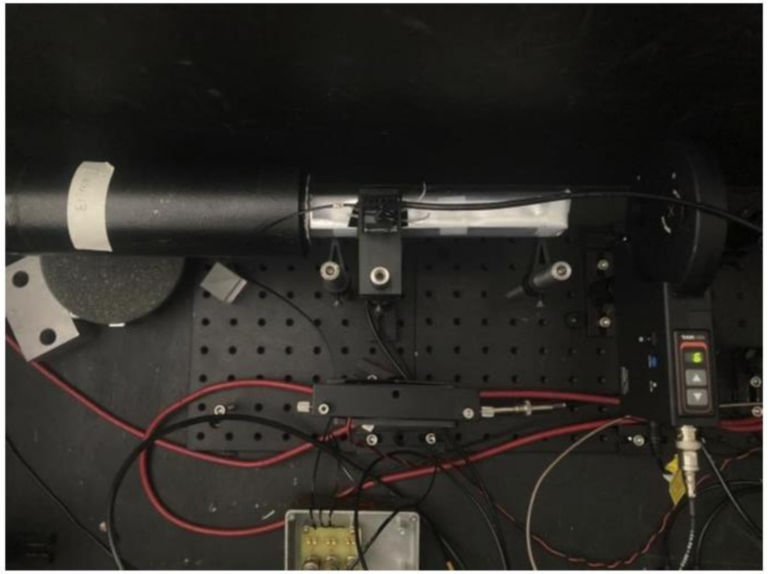
Cosmic Muon Tomography











Reflective Wrapping

4.2% loss of light from far to near end of xtal

Summary

- The concept of a combination CsI and LYSO calorimeter was described.
- LYSO has good stopping power, 40ns timing and high light output but
- The light output has an excess variance which prevents the energy resolution from achieving root N_{pe} statistics.
- Non uniform Ce concentration was given as a likely cause of poor resolution with ways to mitigate some of the affects
- Energy resolution measurements at UW were described as was LYSO’s intrinsic radiation source.