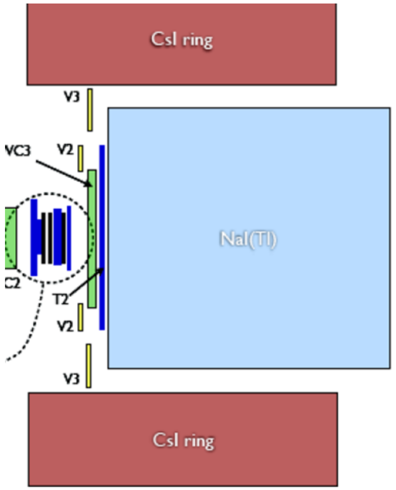
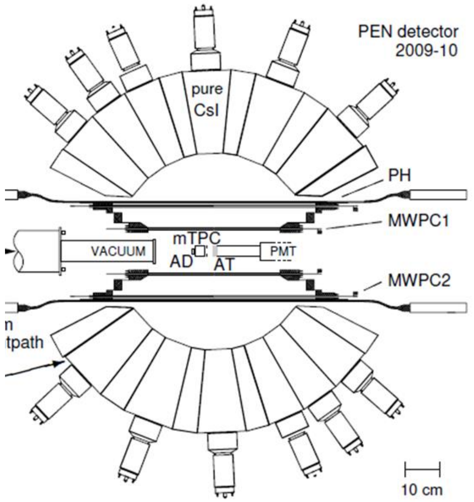
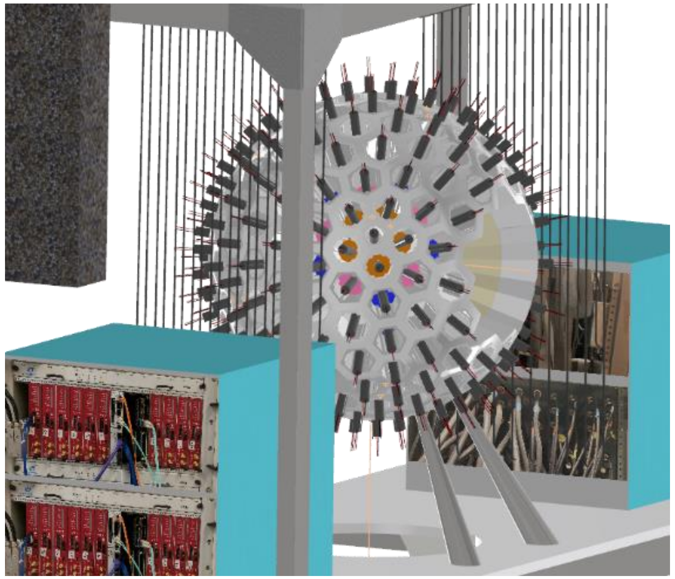
What Calorimeter is needed for PIONEER ?

D. Hertzog







- NaI excellent resolution
- Slow
- Small solid angle
- Unsegmented
- Designed for pienu

~1%

- CsI modest resolution
- Fast
- Large solid angle
- Segmented
- Designed for pi-beta

~5-6%

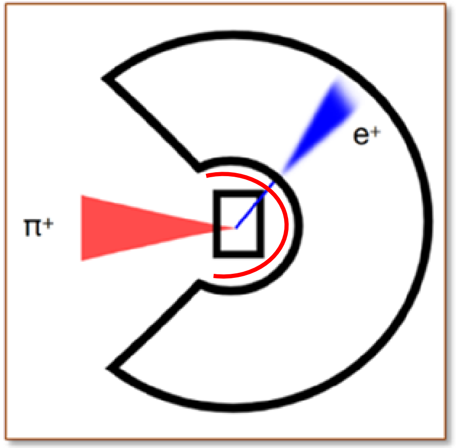
- LXe very good resolution
- Fast
- Large solid angle
- Unsegmented
- Designed for pienu

~2%

- LYSO very good resolution
- Fast
- Large solid angle
- Segmented
- Designed for pienu & pi-beta

~2%

Guiding principles for the design of the Calorimeter



Required properties

- Very good to excellent resolution for positrons below 70 MeV ($\delta E/E < 2\%$)
- Adequate depth and lateral containment to minimize the tail (~20 X0)
- Highly uniform to avoid polar angle dependent response
- Fast timing (<200 ps), and Short pulse duration (<40 ns)
- Can be used in online pipeline triggering
- Can calibrate to high precision the intrinsic response with e^+ beam
- Calibration program to maintain relative (and absolute) gain throughout long running periods

Desirable parameters **(we will unpack these)**

- Segmented
  - Greatly reduces pileup impact
  - Opens up Radiative Decay measurements
  - Required if we aim to do Pion Beta Decay in Phase II
    - (needs Simulation to establish viability)
  - Significant reduction in online data storage rates (see Lawrence)
  - Provides a (θ,ϕ) hit coordinate of impact e^+
- Cost range "reasonable" (< \$6-10 M) and depends on funding agencies
- Experience in collaboration (exists for both LXe and Crystals)

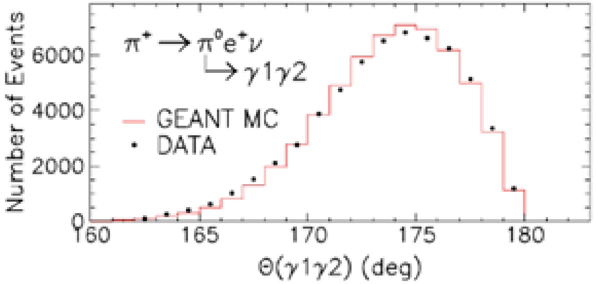
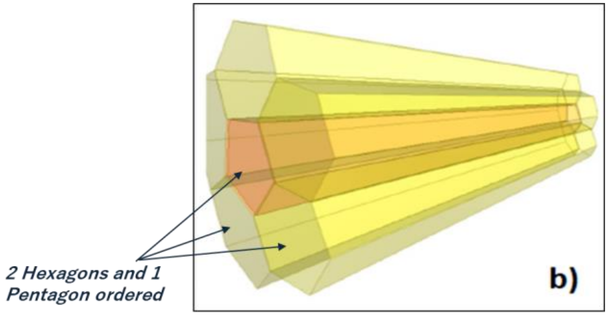


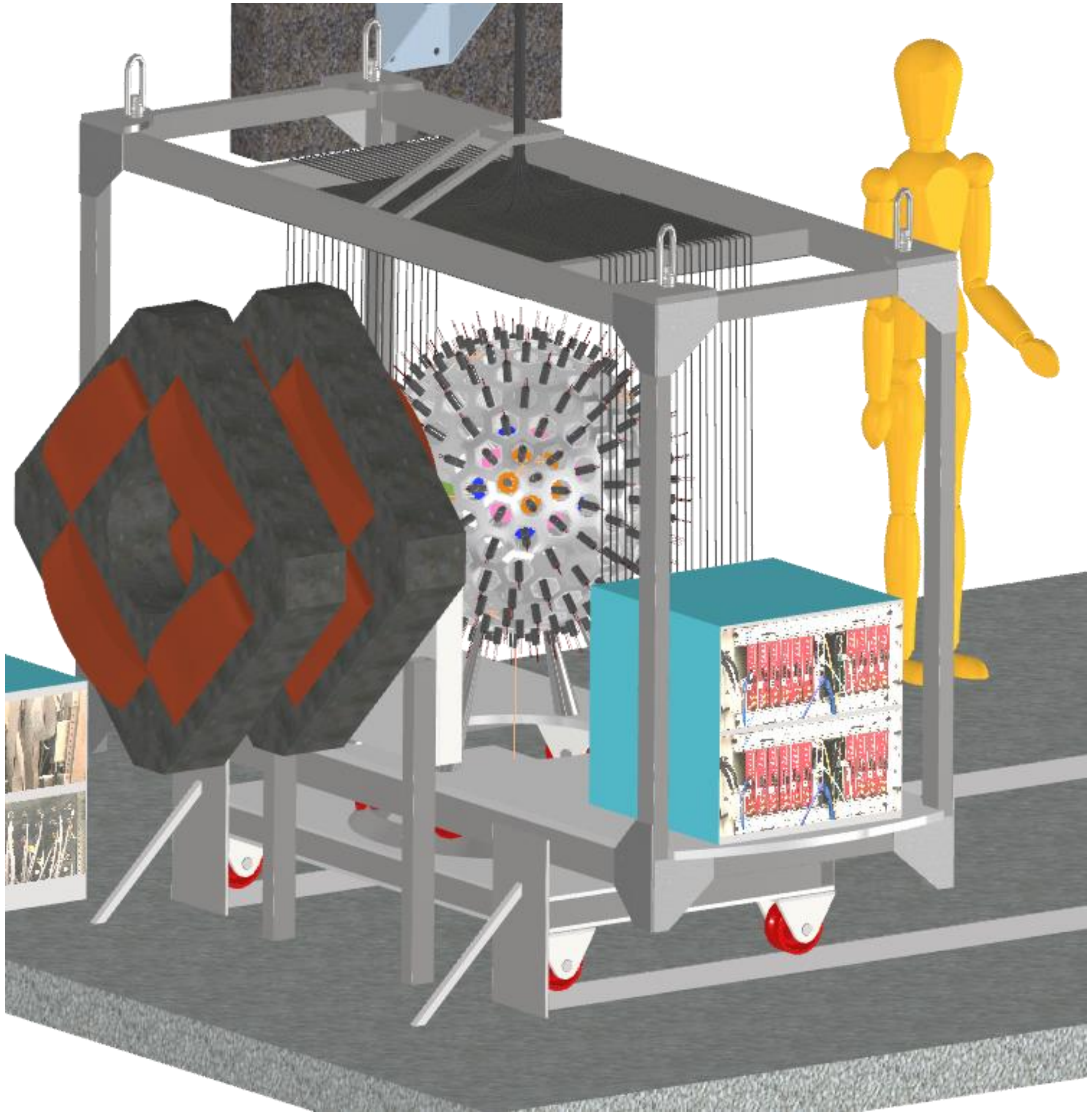
FIG. 5: Histogram of the γ-γ opening angle in π_β decay.

The Case and Cost for LYSO

D. Hertzog on behalf of many others

- the basic geometry in the beamline
- system is on rails,
- can be craned in and out,
- racks represent needed readout





Evaluating LXe and LYSO options at present

Scintillator	X0 (cm)	R_M (cm)	Light Yield (g/MeV)	Peak l (nm)	Decay t (ns)	Density (g/cm^3)
LYSO	1.14	2.07	30,000	420	40	7.4
LXe	2.77	5.22	30,000	178	4/20/45	2.98
NaI(Tl)	2.59	4.13	40,000	410	245	3.67
CsI	1.86	3.57	2000	420 / 310	30/6	4.51

Liquid Xenon option

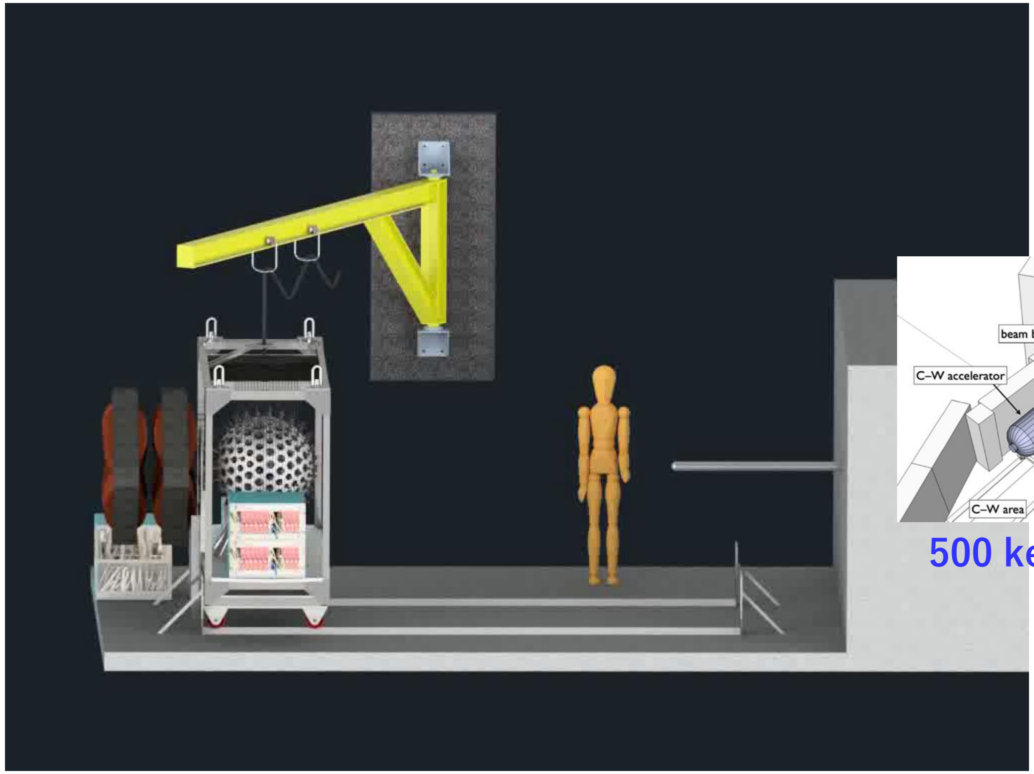
- Single volume, 1000 VUV PMTs viewing volume
- Intrinsically homogeneous response
- MEG II demonstrated resolution for gammas at 50 MeV with inner SiPM and outer PMTs
- Need to test with positrons, summing 1000 waveforms, and across a wide energy range
- Windows and safety/recovery are engineering challenges

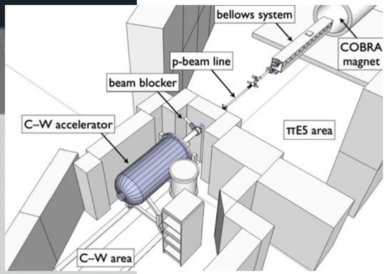
LYSO option

- Segmented, 236 (or 330) "blue" PMTs viewing individual crystals
- Very dense, non hygrophobic and no temp dependence
- Resolution for 10 array excellent, but …
- Need to test tapered crystals and build a larger array

Calibration is critical. LYSO plan (250-350 PMTs)

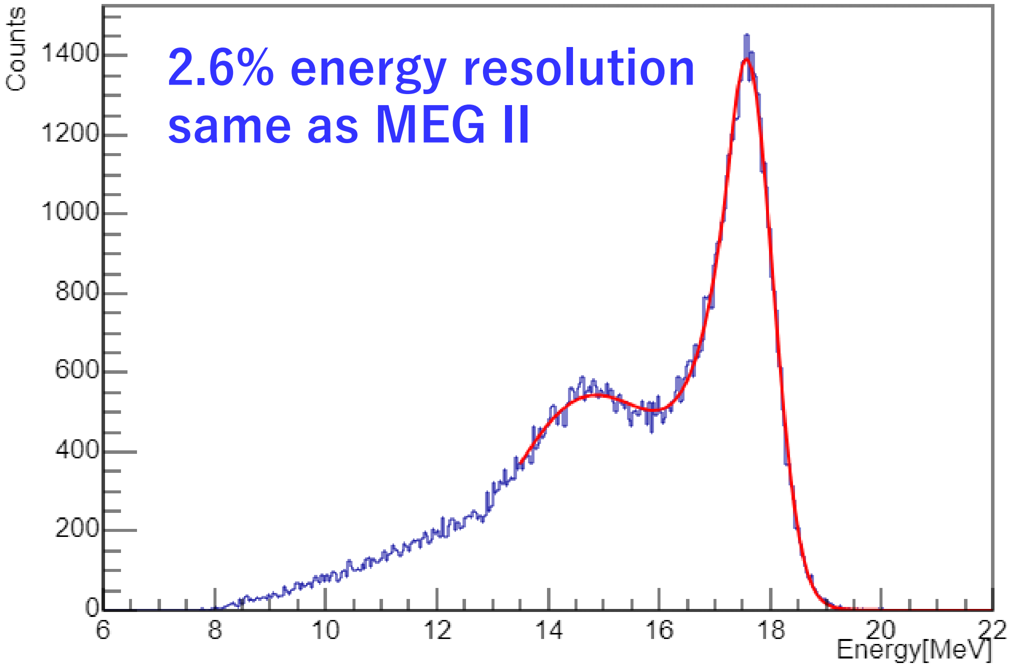
1) p-Li 17.6 MeV γ; absolute Energy, 3 times per week for 1 hour
2) $\pi^- p \rightarrow n\pi^0 \rightarrow \gamma\gamma$; once per cycle; absolute Energy at high end
3) UV laser excites each xtal; (relative gain stability); see Erik





500 keV p

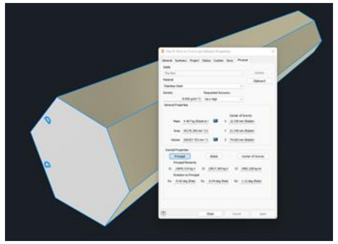
p-Li method following L3 @ LEP and MEG-II

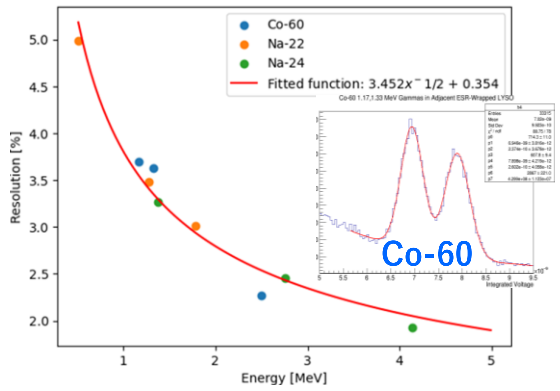


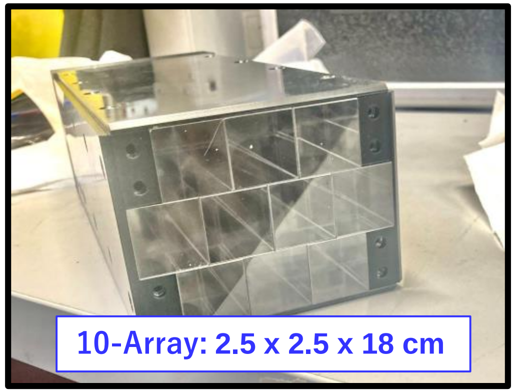
We used our 1.4 MeV proton beam degraded and impinging on a LiF foil. **@440 keV** it excites a resonance, which decays with a **17.6 MeV gamma**

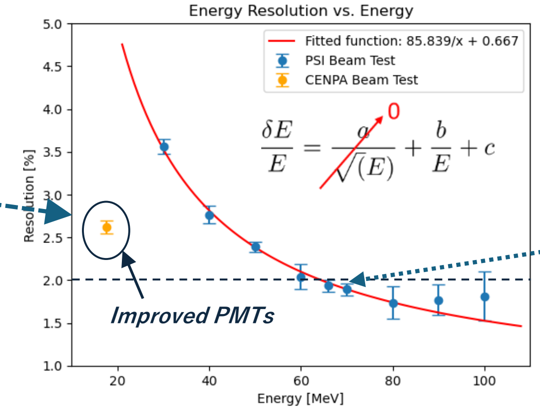
Evaluating the LYSO option: Our systematic approach

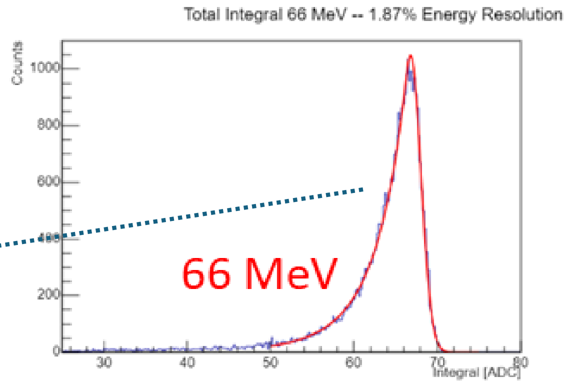
- Extensive single crystal tests with sources and uniformity scans
- p-Li 17.6 MeV γ test with array at CENPA
- 10 Days @ PSI: 30 – 100 MeV e^+
- Energy resolution: 1.8% @ 70 MeV;
  - Resolution impacted by PMT noise issues
    - Later resolved, see the post-PSI measurement
  - Timing resolution <200 ps above 10 MeV
  - Longitudinal crystal light variation <4%
    - <0.2% contribution to energy resolution
  - Position resolution: ~0.7cm from 10 array
- Fully integrated into the Simulation
- Recon and Clustering codes written
- Planned Lab work for 2024
  - Awaiting 3 tapered Crystals
  - PMT and lightguide tests
  - Wrapping optimization

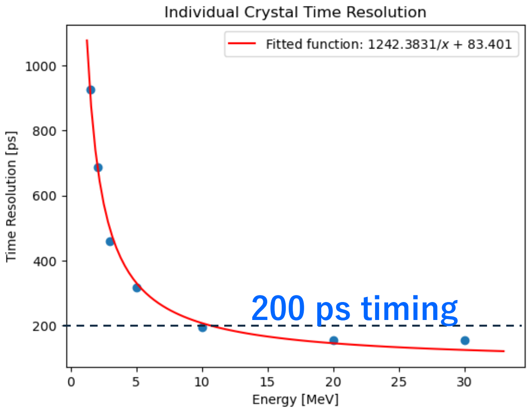


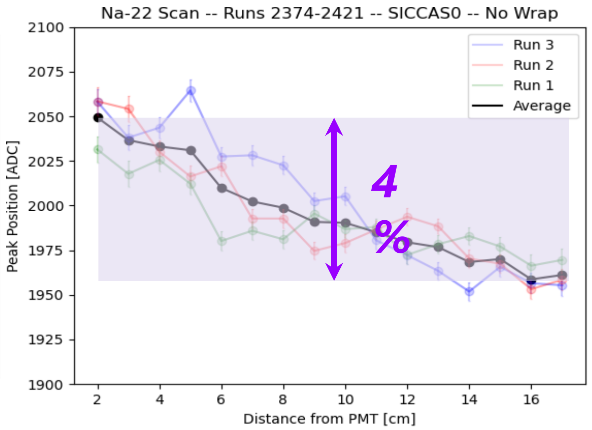




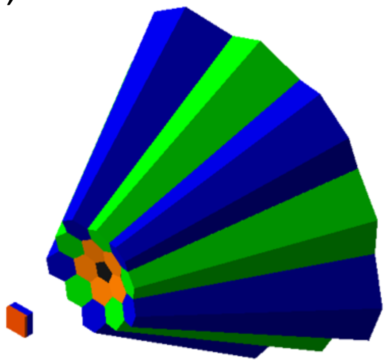








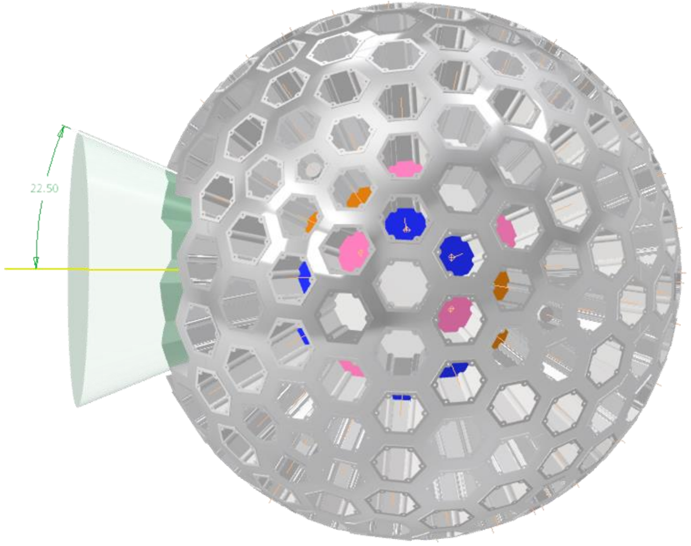
LYSO vs "required" **Black** = meets specs, TBD = work in progress, Bonus = Advantage



- Resolution:
  - Measured <1.8% in 10 array; will likely improve with "linear" PMTs. Concerns raised:
  - TBD: uniformity of tapered crystals (will know answer in 6 months)
  - TBD: more precise evaluation of boundaries and wrapping
  - TBD: more complete simulation of <MeV activity in crystals unrelated to shower
- Geometry
  - Optimized following Omar's parametric study, adequate depth and lateral containment (same for LXe)
  - Higher density means 15 x smaller, 2x smaller R_M; Bonus: larger Fiducial Volume for same geometry
  - Uniformity vs angle is not biased.
- Timing
  - Measured fast timing (<200 ps) and Short pulse duration (<40 ns)
- Calibration methods
  - **Intrinsic tail at 0-degree with e+ beam (same for LXe)**
  - **p-Li for 17.6 γ works naturally (see animation) Bonus**
  - **$\pi^- p \rightarrow n\pi^0 \rightarrow \gamma\gamma$ works with removed downstream crystal plug Bonus**
  - **LASER-based optical excitation of scintillation per crystal used for Gain stability, Relative timing, & Pileup simulation**
- **DAQ considerations (from Lawrence) Bonus; all of these**
  - Many few channels to read out per trigger (e.g, 10 vs 1000 for LXe)
    - the DAQ rate question becomes much more reasonable
  - Energy sum algorithms for triggering can become much cleaner because there will be smarts to do more localized sums — we don't have to add the noise/activity from every crystal into every sum.
  - It will fit into one Apollo, which simplifies triggering / sparsification questions

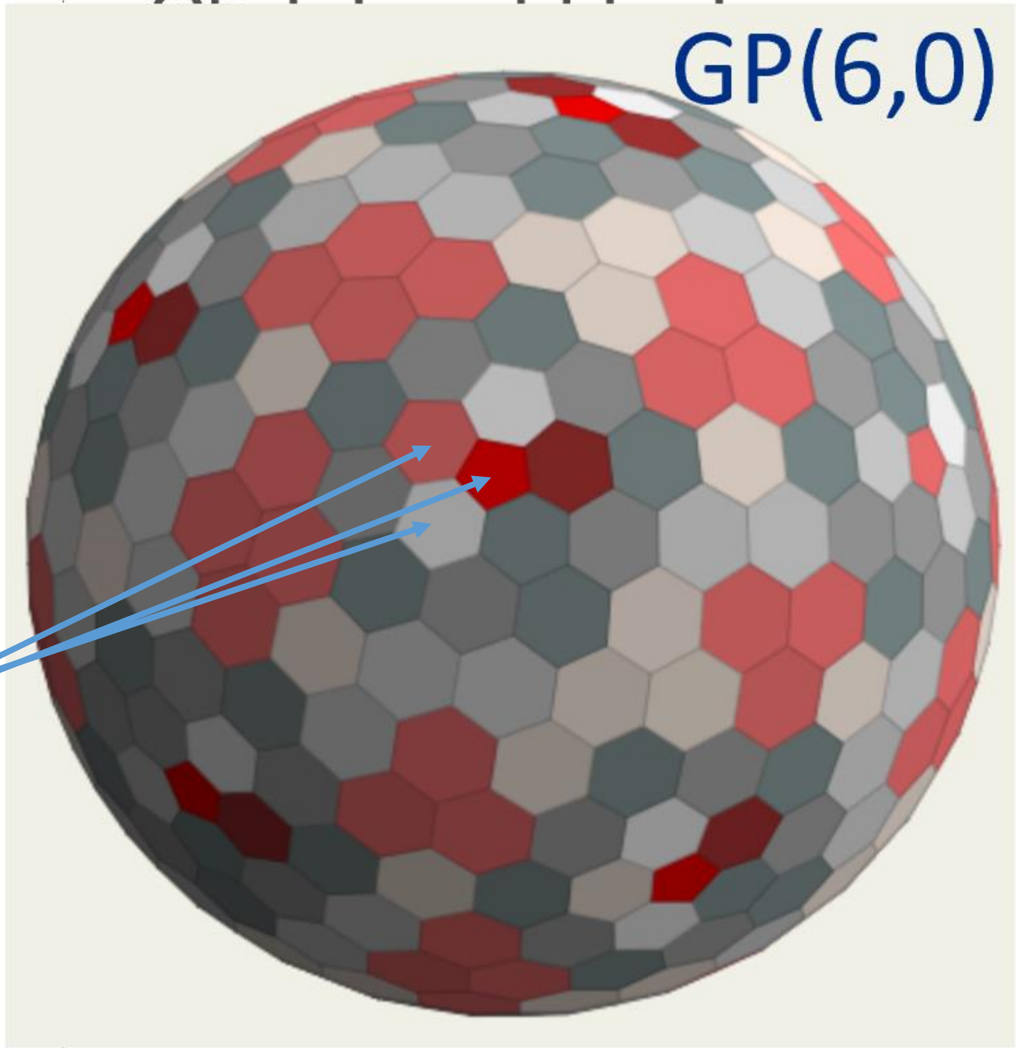
LYSO vs "Desirable" **Black** = meets specs, TBD = work in progress, Bonus = Advantage

- Experience of group
  - JETSET segmented Pb/SciFi calorimeter for LEAR (similar tapered array)
  - BNL monolithic Pb/SciFi calorimeters (24 stations)
  - Muon g-2 segmented PbF2 arrays (24 stations) [includes SiPMs, electronics, calibrations, recon]
  - PIONEER LYSO development (several test beams so far + extensive lab work)
- Segmentation **Bonus for all of these**
  - Greatly reduces direct pileup in the Calorimeter (factor of ~25 ?)
  - Allows pattern-based Radiative Decay measurement in combination with Tracker
  - Provides a (θ,ϕ) hit coordinate of impact e^+ at the ~0.7 cm precision to be used in event tracking
  - Can be used for Pion Beta Decay in Phase II (**needs Simulation**)
- Practical considerations **Bonus for all of these**
  - Uses conventional blue-sensitive PMTs
  - Simple mechanical engineering; build it, run it, move it, rotate it, …
    - Does not require on-site staff and expert operators/engineering
  - Practical calibration methods as mentioned
  - No safety issues and no cryogenics; no temp dependence
  - Can be placed close to last Quad (better for rate)
  - Can be placed on rail system for easy access to ATAR etc
  - Each crystal can be evaluated with a vigorous QC program
  - No windows for energy loss



Aiming at PiBeta & Rad Decays

- Ideally, push inner radius out "as far as you can afford" to get better angular separation between showers, lower rates, improve spatial angular measurements, etc.
- We are moving from 10 cm to 15 cm and evaluating in our simulations the advantages vs the cost
- We will have SICCAS cut these shapes for our 3 ordered crystals
- Secondary, but probably important:
  - Larger inner radius is good for the interior detector placement and maintenance



C500du6I

362 faces

Complete Cost estimate

(the calorimeter is "everything" including calibration, PMTs, and digitization)

- Crystals
  - SICCAS is preparing 3 tapered crystals now at $30 k / each, which includes their R&D for new tooling, various test growths they are making now and their risk. Jianglai is negotiating with them on our behalf and, for now, he suggest using $20k/xtal for a bulk order of 230 - 340
  - **Net: $4600 - 6800 k** [depends on our final Rinner radius choice]
- PMTs and HV
  - Using conventional blue PMTs, we estimate $1000/ch for PMT, divider, and HV.
  - **Net: $250 - 350 k**
- Mechanical support and tools
  - Must simply carry the weight and have flexible installation aspects and rotation; local engineering done.
    - **Net: $100 k**
- Calibration Systems
  - Cockcroft Walton system (Important: **assume we can inherit this from MEG**)
  - LH2 system; (assume PSI can provide)
  - Dual UV LASER based distributed calibration system, including laser enclosure, monitor detectors, and so on.
    - **Following g-2 roughly: $250 k**
- DAQ digitizers and electronics (not the entire DAQ)
    - **250 – 350 Channels; Net: $250 – 350 k**
- **Net for entire Calorimeter, readout, mechanics, calibration, digitization:**
  - **NET SUM: $5450** for current geometry; and, **$7850 for larger array with 15-cm inner radius**