Optical simulations analysis

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Light detection in LEGEND-200

- Modeled after the GERDA system
- Detects light generated in LAr by natural scintillation*
  - *After wavelength shifting the light
- Plastic fibers trap light and guide photons to SiPMs for detection

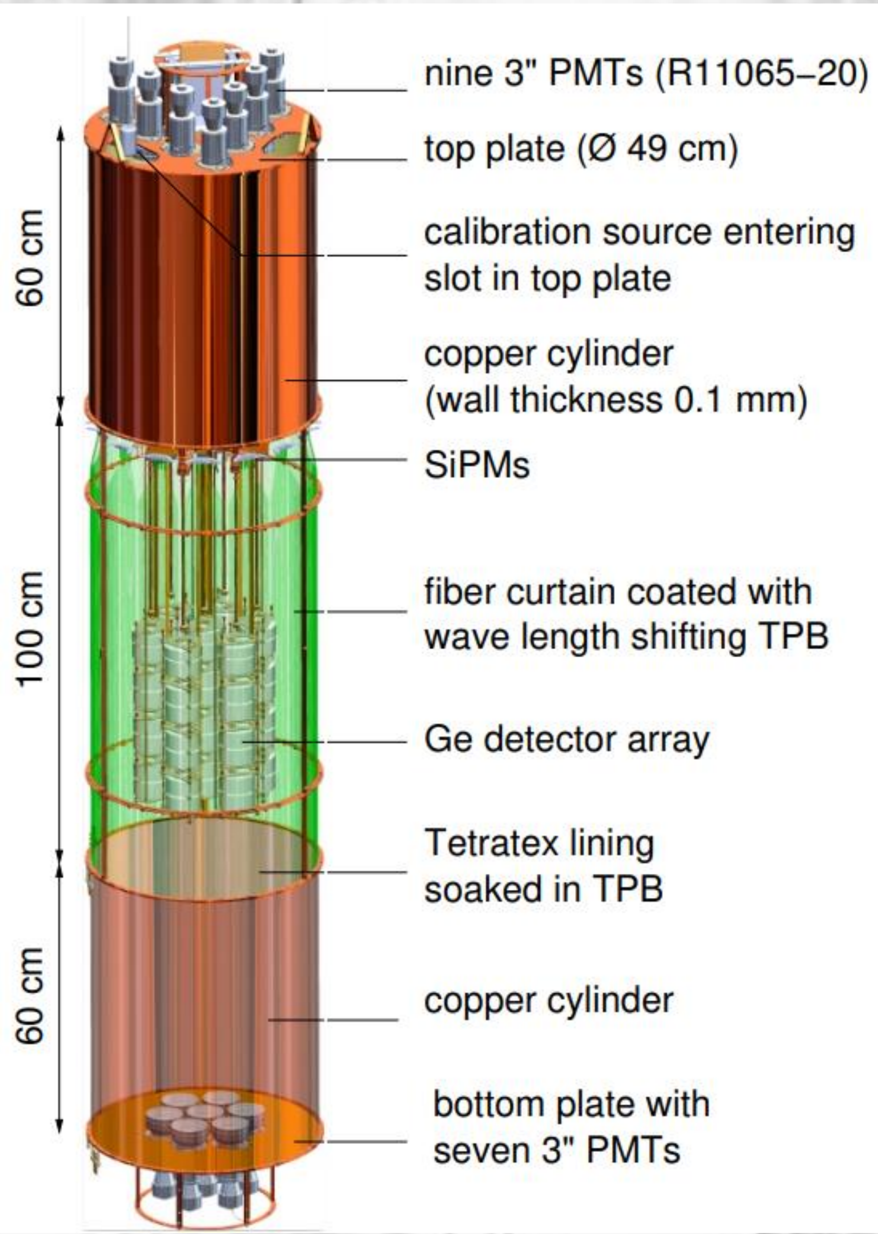
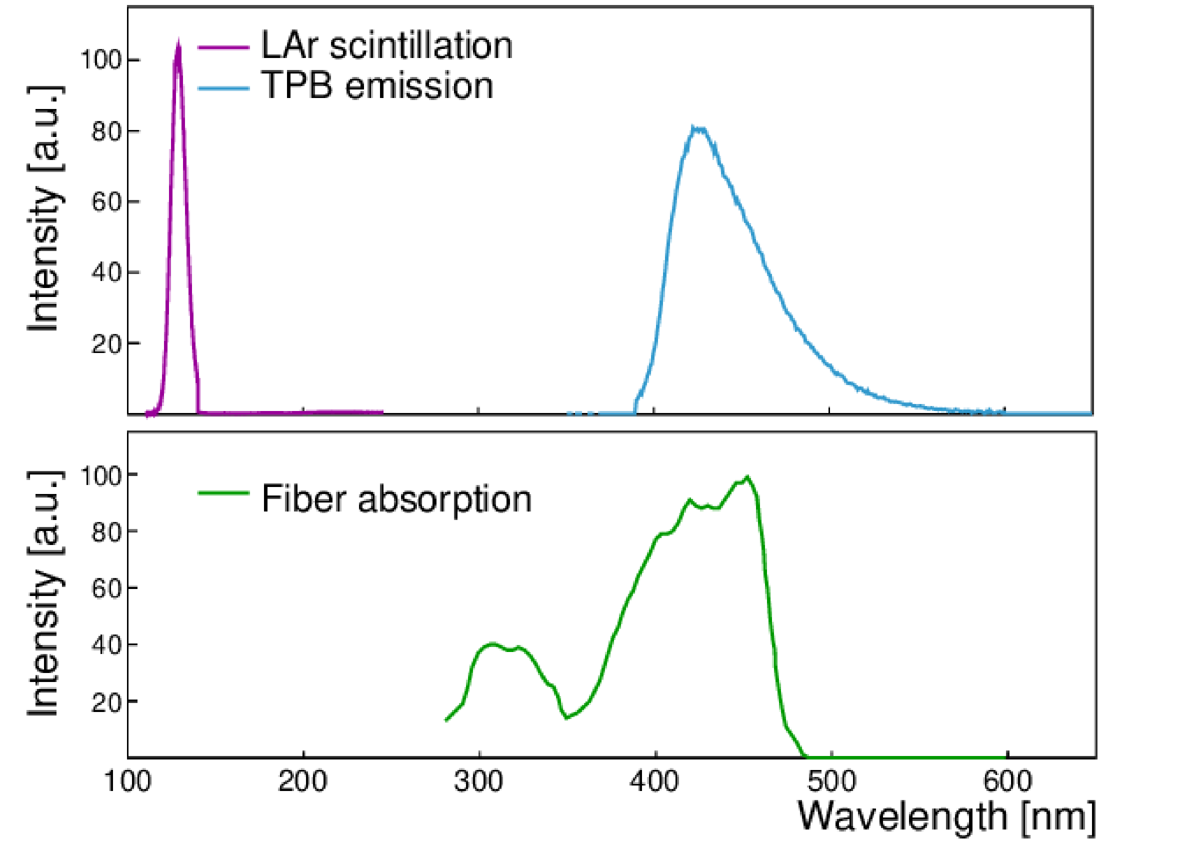


Diagram of GERDA's light collection

Scintillation in LAr

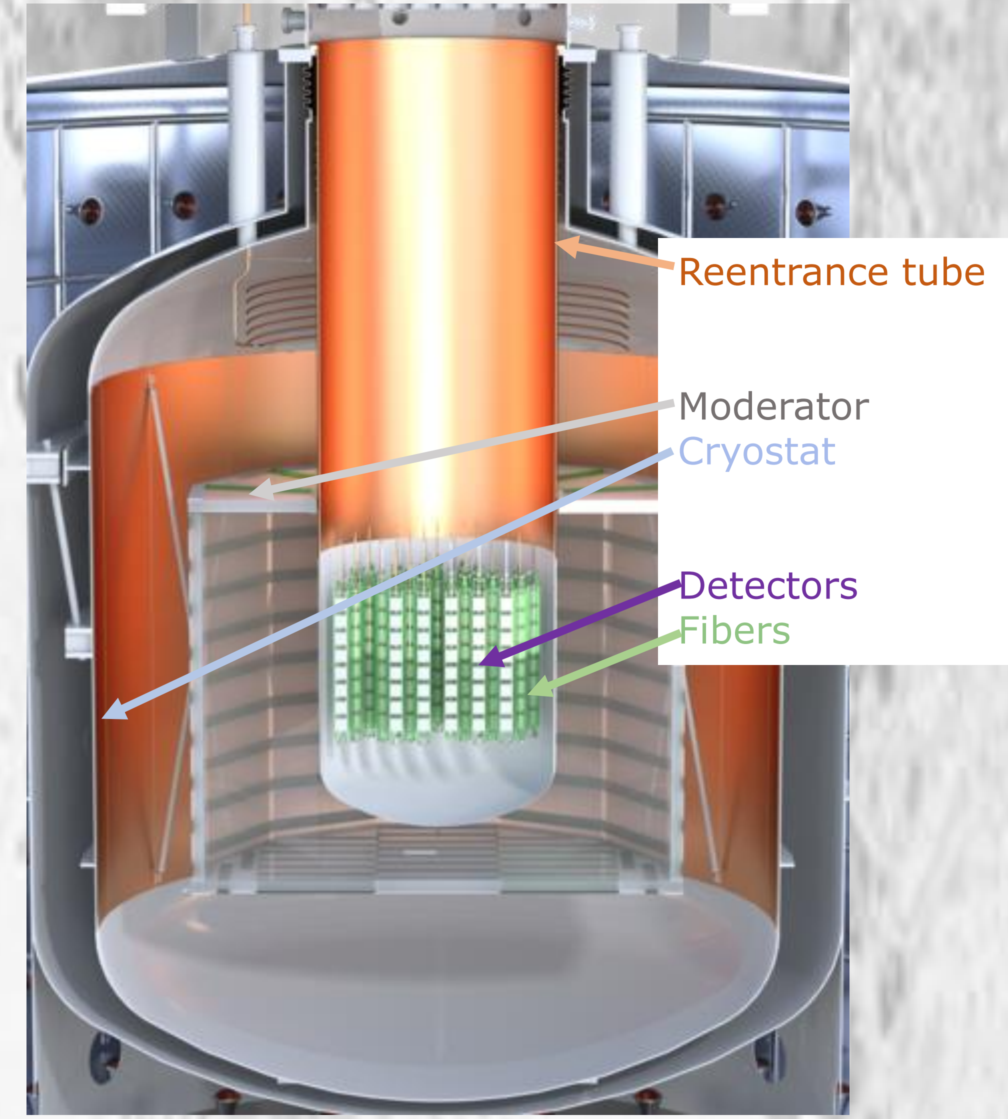
- Strong natural scintillator
- Scintillation light is produced at the VUV (vacuum ultra-violet) wavelengths, spectrum peaks at 128 nm
- Wavelength shifters absorb ~128 nm light and re-emit at 400-500 nm wavelengths (visible light)



From this L200 paper

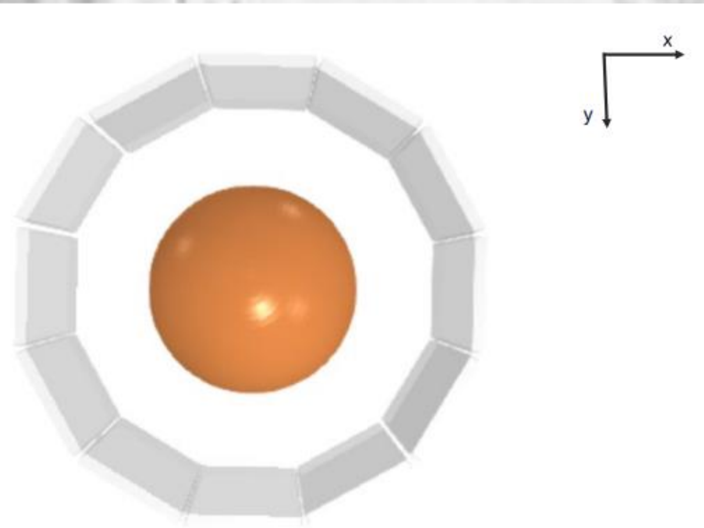
Light detection in L1000

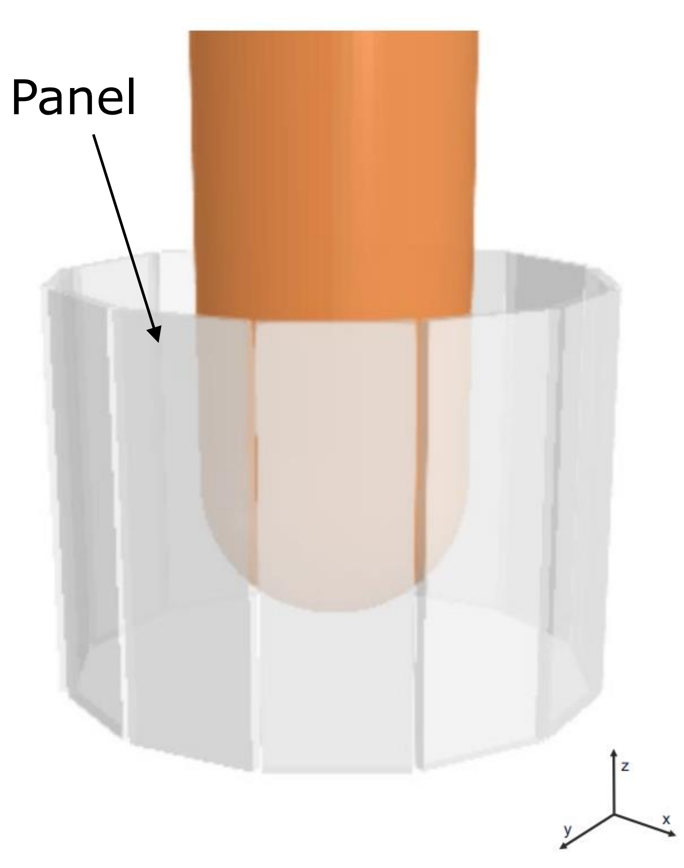
- Still an open question
  - Certainly, there will be light detection near the Ge detectors
  - What about far away from the detectors?
  - Can we equip the moderator with light detection instrumentation?
    - The reentrance tube separates the "underground argon" (UGLAr) light + fibers from the "atmospheric argon" (AAr)



The L1000 moderator

- Large, thick (10 cm) plastic shield
- Designed to moderate neutrons, which are then captured passively in LAr or in the plastic
- Currently 12 side panels, + top and bottom (not pictured here)
- Reduces neutron-induced background in simulations by ~50%





R&D at Roma Tre + GSSI

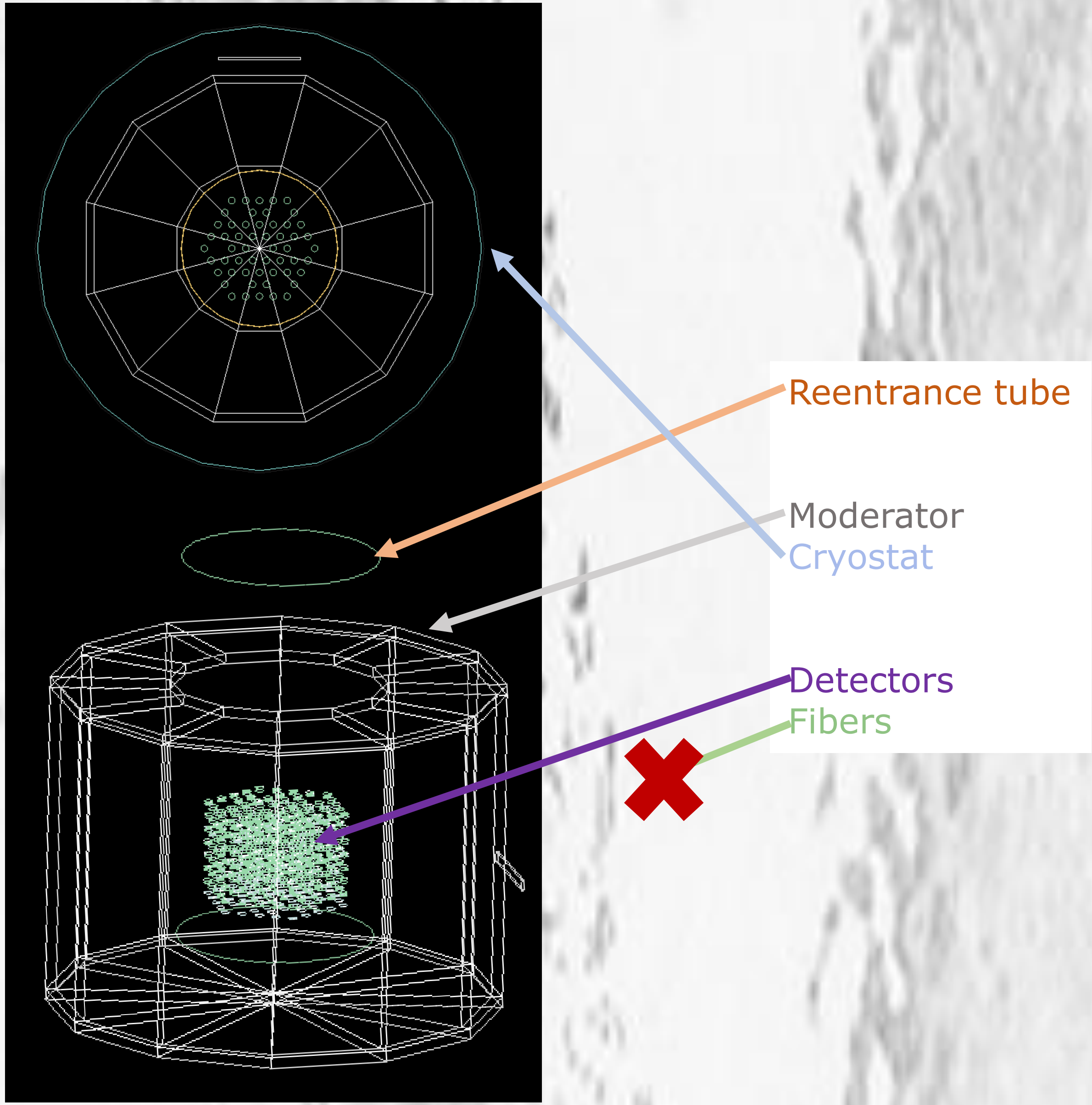
- Can we equip the moderator with light detection instrumentation?

- …Or rather, *should* we
- Top-level goal: use detailed simulations to assess the capabilities of light instrumentation in the outer (atmospheric) argon of L1000
  - This is shortened to AAr-inst sometimes

What one panel with AAr-inst might look like

The warwick-legend simulation module

- Geant4-based module
- Created by the Warwick group, later adapted by the TUM group, now adapted by the ItalSim group (mostly me lol)
- Works best for backgrounds which cover large areas
  - Muons, neutrons, and now scintillation
  - https://github.com/ItalSim/warwick-legend/tree/master



Optical map

- Simulating optical photons is very intensive on the processor and the memory of the system
- To save time, build a 'map' which covers the entire LAr volume, simulate all the optics at once, and then reference the map

Normal process: energy->scintillation->detection->analysis

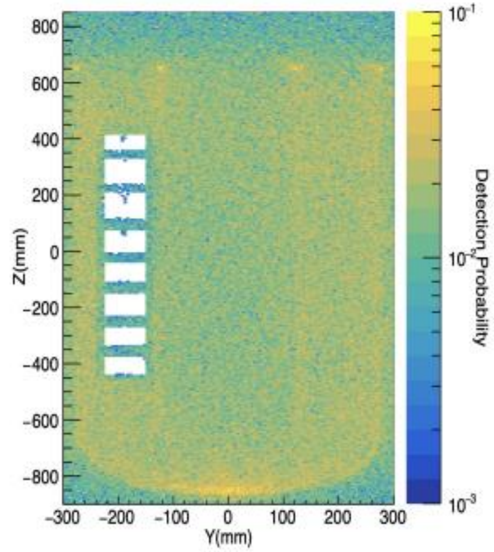
New process: energy->optical map->analysis

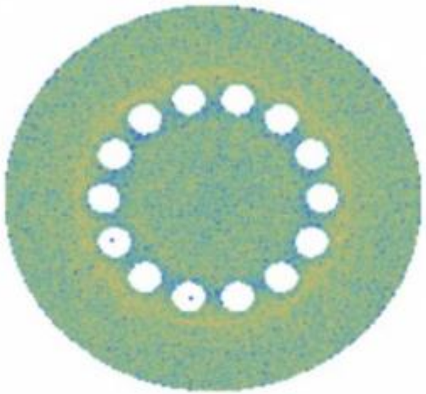
Optical maps in MaGe (L200 only)

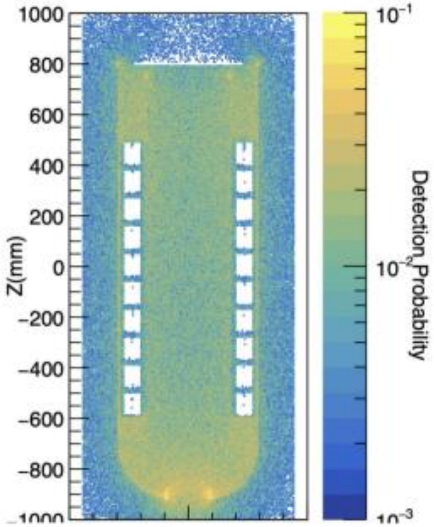
- LAr volume is broken up into small cubes, called 'voxels'
- Many photons are simulated within each voxel
- Photons collected by the fibers are counted, and detection probability for photons in that voxel can be determined

$$Detection\ probability = \frac{\#\ photons\ detected}{\#\ photons\ simulated}\ \text{(per voxel)}$$

- Information is stored for each voxel (position, detection prob.)

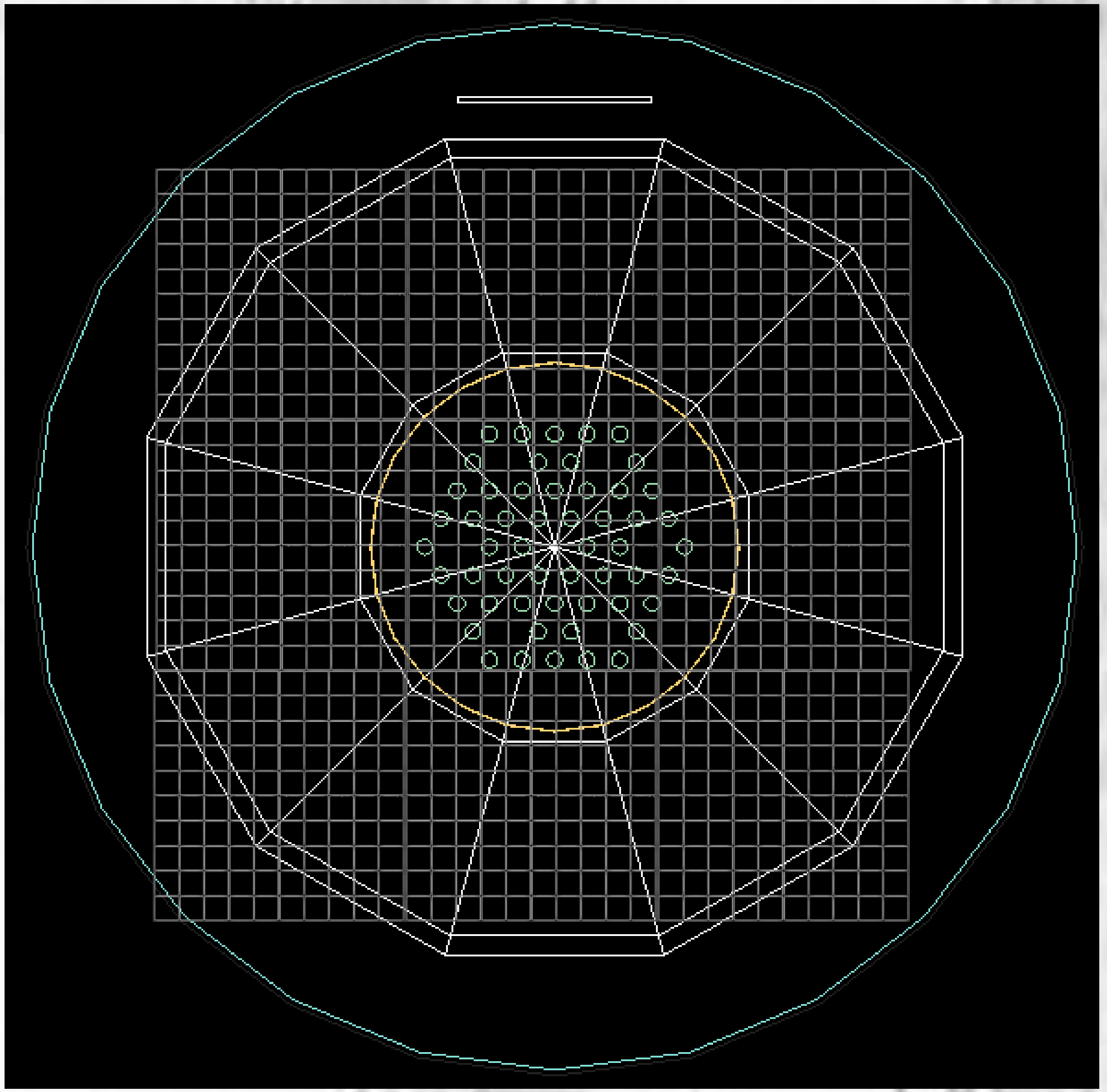






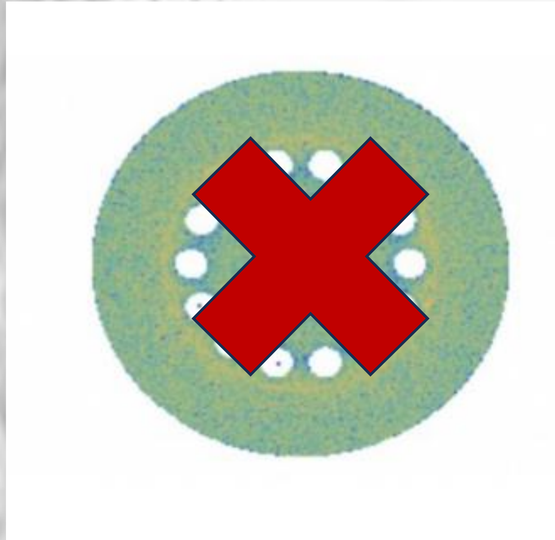
Optical maps in L1000

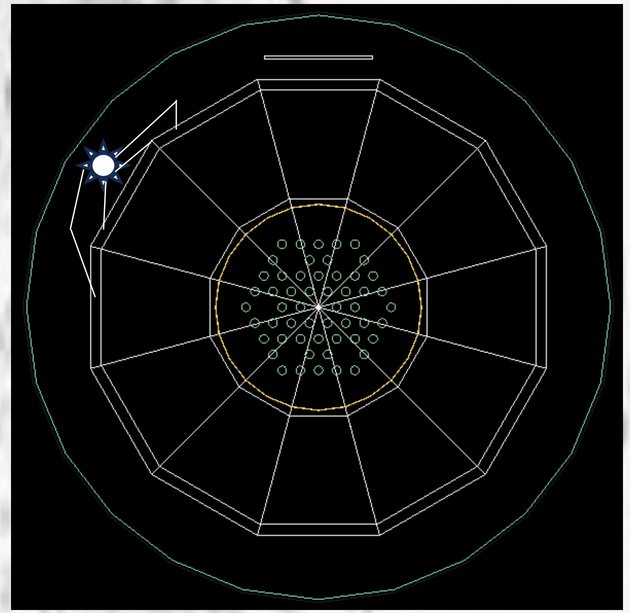
- LAr volume is broken up into small cubes, called 'voxels'
- Many photons are simulated within each voxel
- What do we do about the fibers/light collection?



Optical maps in L1000

- We do not know what the Aar-inst might look like for L1000
  - Will it be fibers? Panels? Groups of bare SiPMs? How many? Which dimensions?
- Instead of saving a probability for each voxel like MaGe, save the location of *every* photon which arrives at the moderator

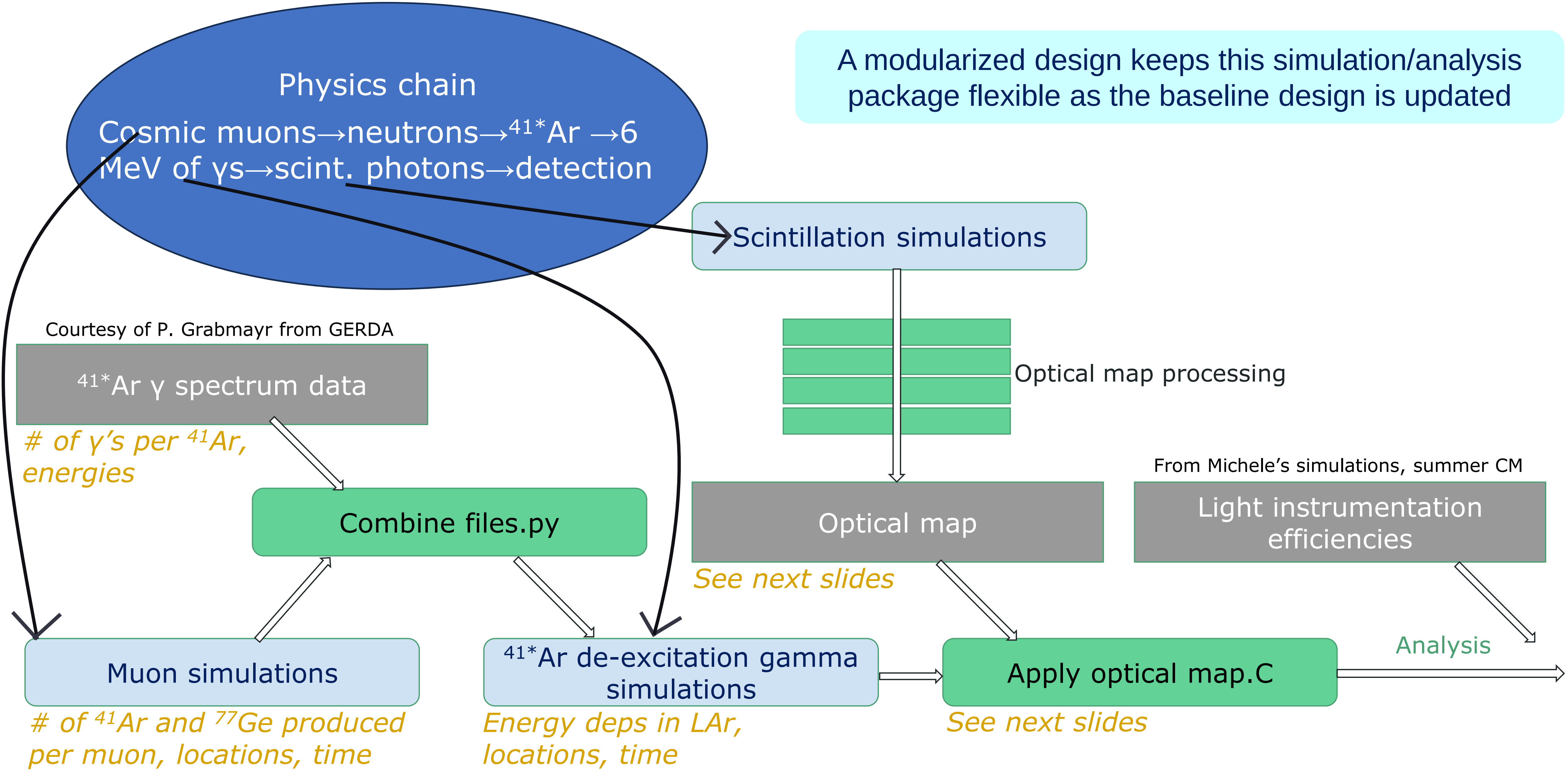




Case study: ^{41}Ar

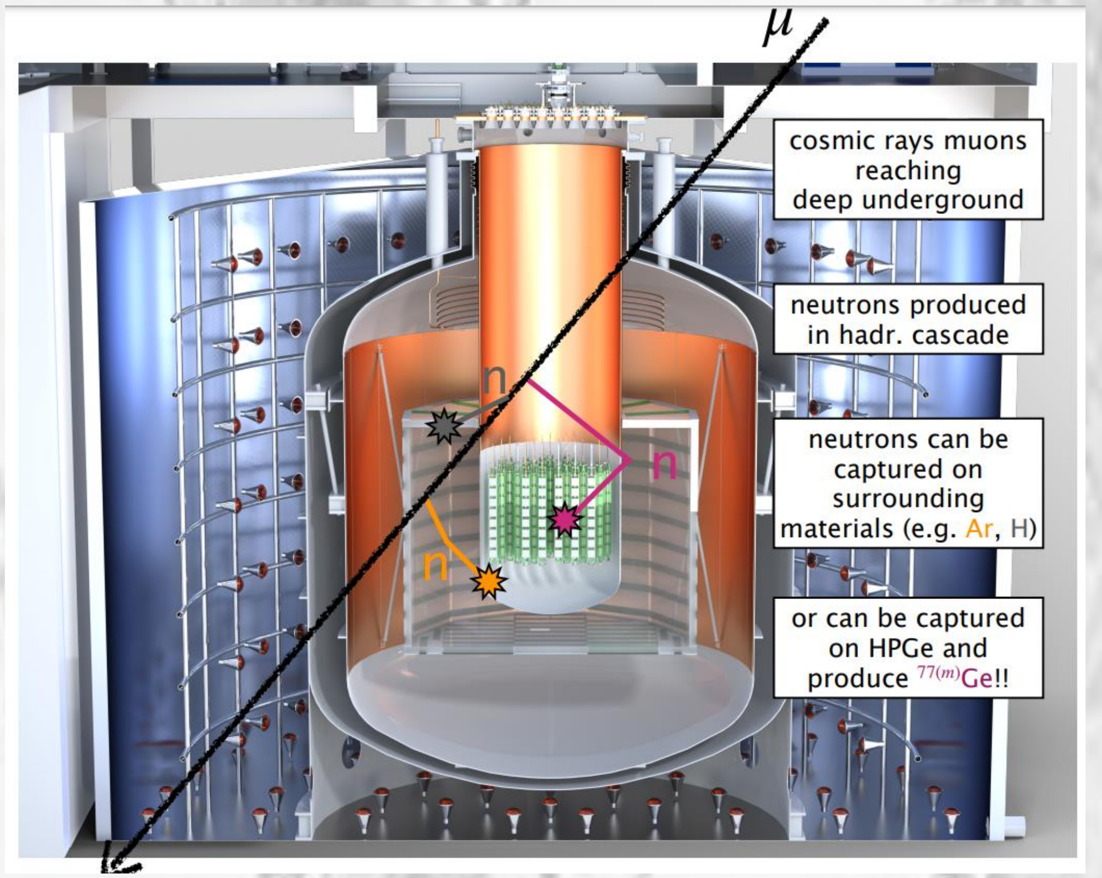
- Muon-induced neutrons represent a serious background for LEGEND-1000 if it is hosted at LNGS
- Moderator is effective, but not perfect
  - Muon-induced neutrons produced *inside* the moderator can still capture on the Ge detectors
- Goal: identify muons which produce neutrons -> apply an extended cut

A modularized design keeps this simulation/analysis package flexible as the baseline design is updated



Muon simulations at LNGS

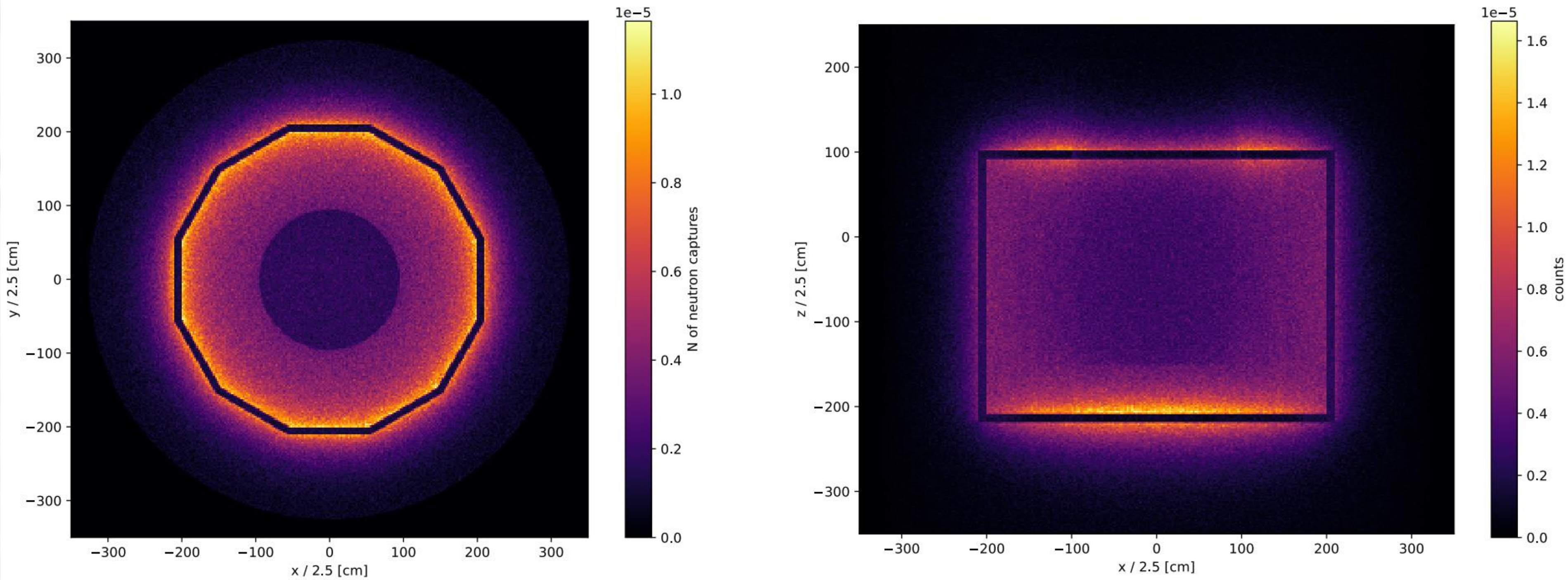
- Muon energy/angular distribution sampled from the LNGS option of MUSUN (MUon Simulations UNderground)
- Event information about muons which produce at least one ^{41}Ar are saved



^{41}Ar* de-excitation simulations

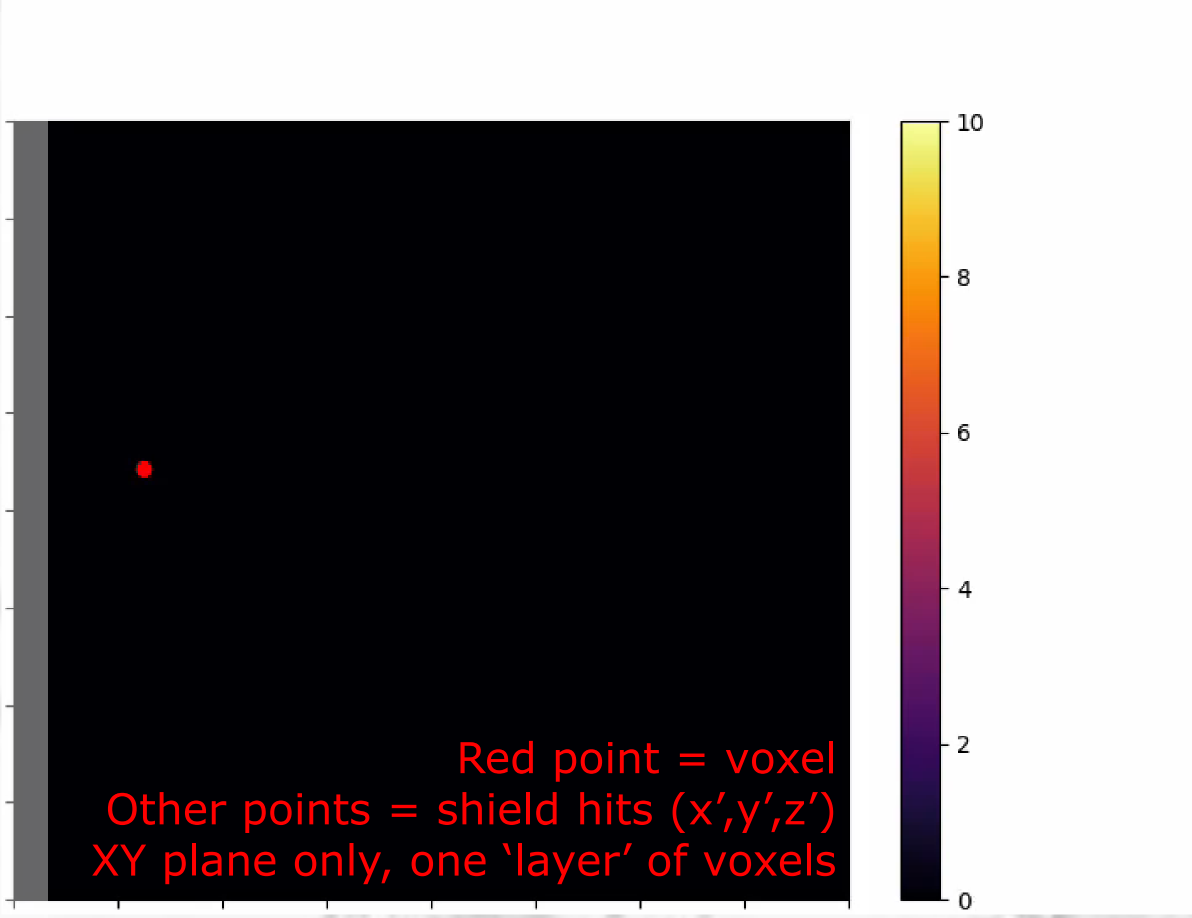
- Locations from muon-induced neutron capture on Ar are saved
- ^{41}Ar* de-excitation gamma spectrum calculated using the MAURINA code, courtesy of P. Grabmayr

Location of ^{41}Ar* produced



Applying the optical map

- Each voxel contains ~1000 photons, with the saved information about where each photon hits the neutron moderator/shield



atmAr optical mapping

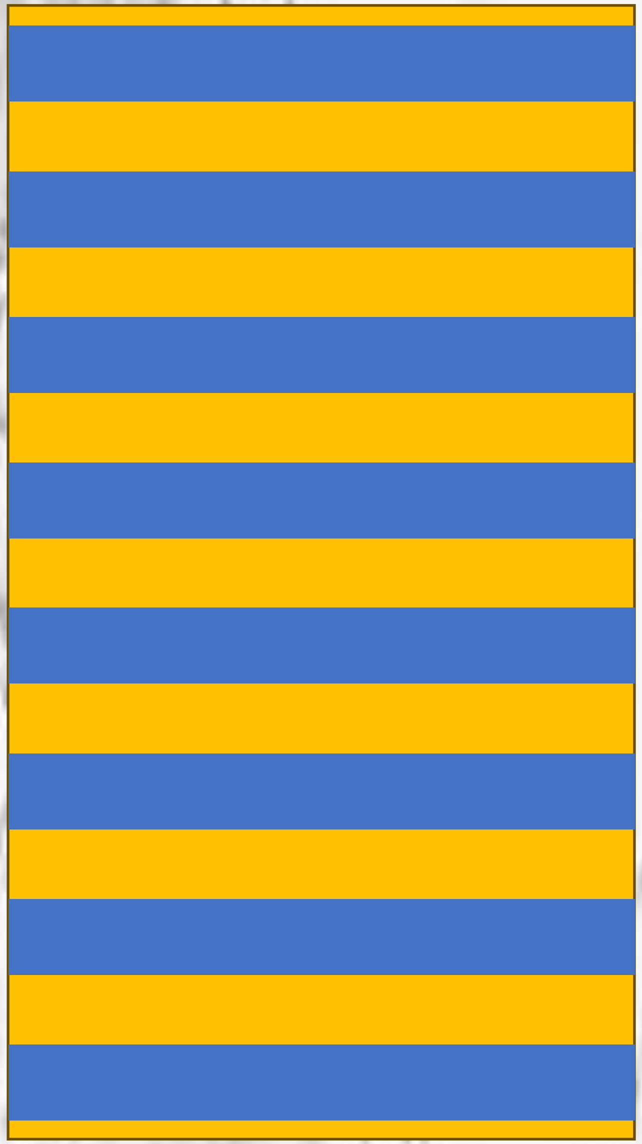
One panel of the shield

Generic implementation allows ‘virtual placement’ of light instrumentation at any locations on the shield with one set of maps

atmAr optical mapping

One panel of the shield
Example light instr.

Generic implementation allows 'virtual placement' of light instrumentation at any locations on the shield with one set of maps



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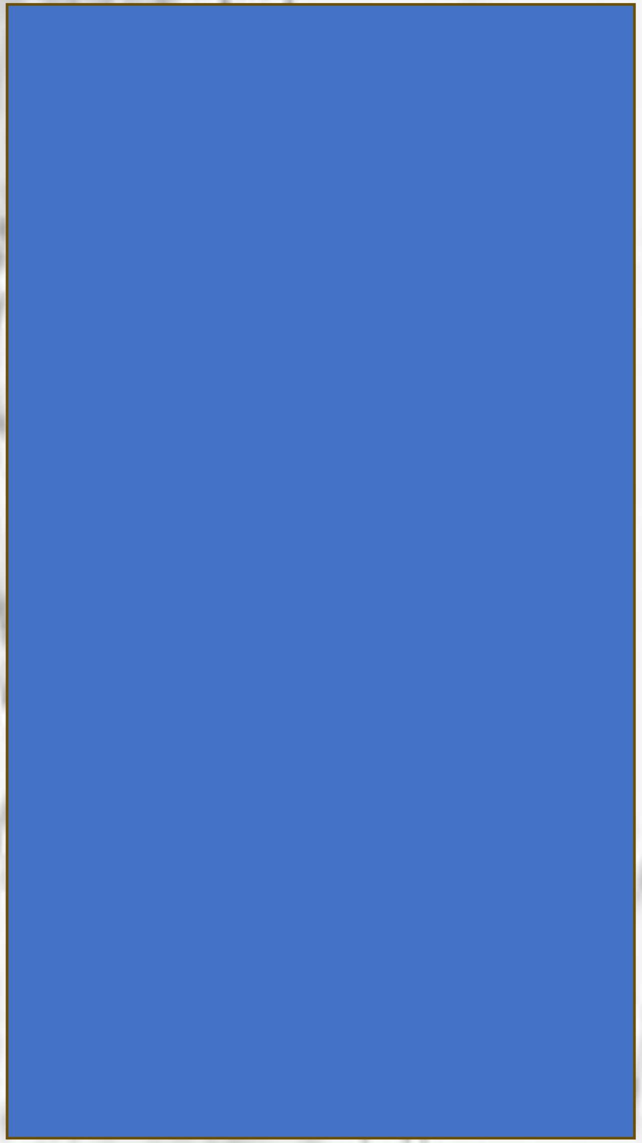

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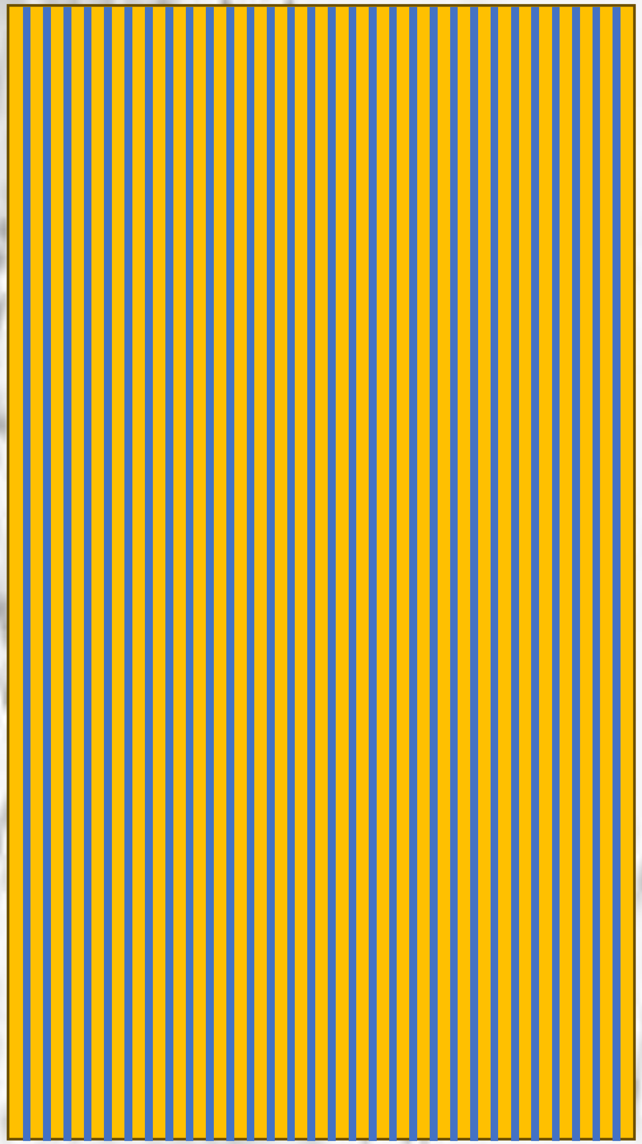

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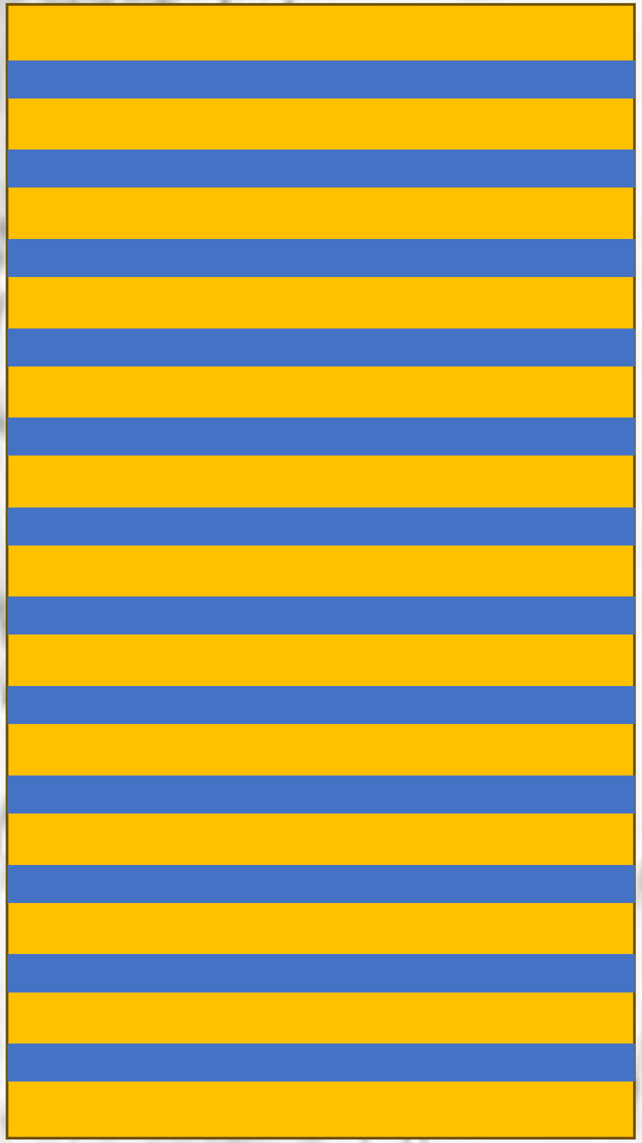


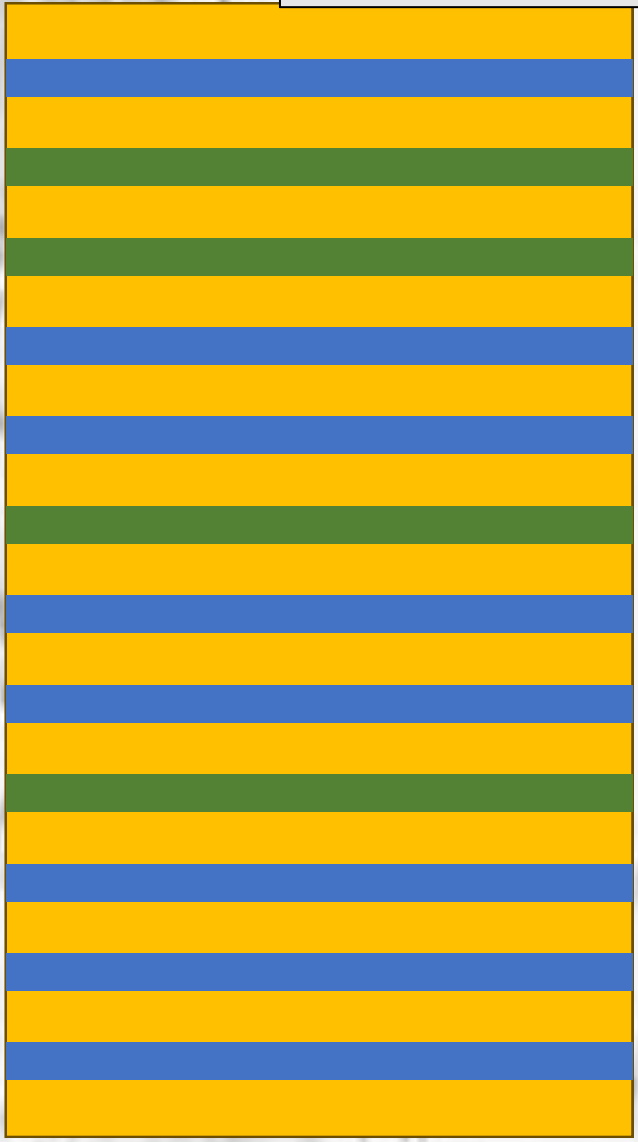
“BASELINE” DESIGN

atmAr optical mapping

Generic implementation allows 'virtual placement' of light instrumentation at any locations on the shield with one set of maps

Keeping photon hit locations allows topological/positional analysis of channels

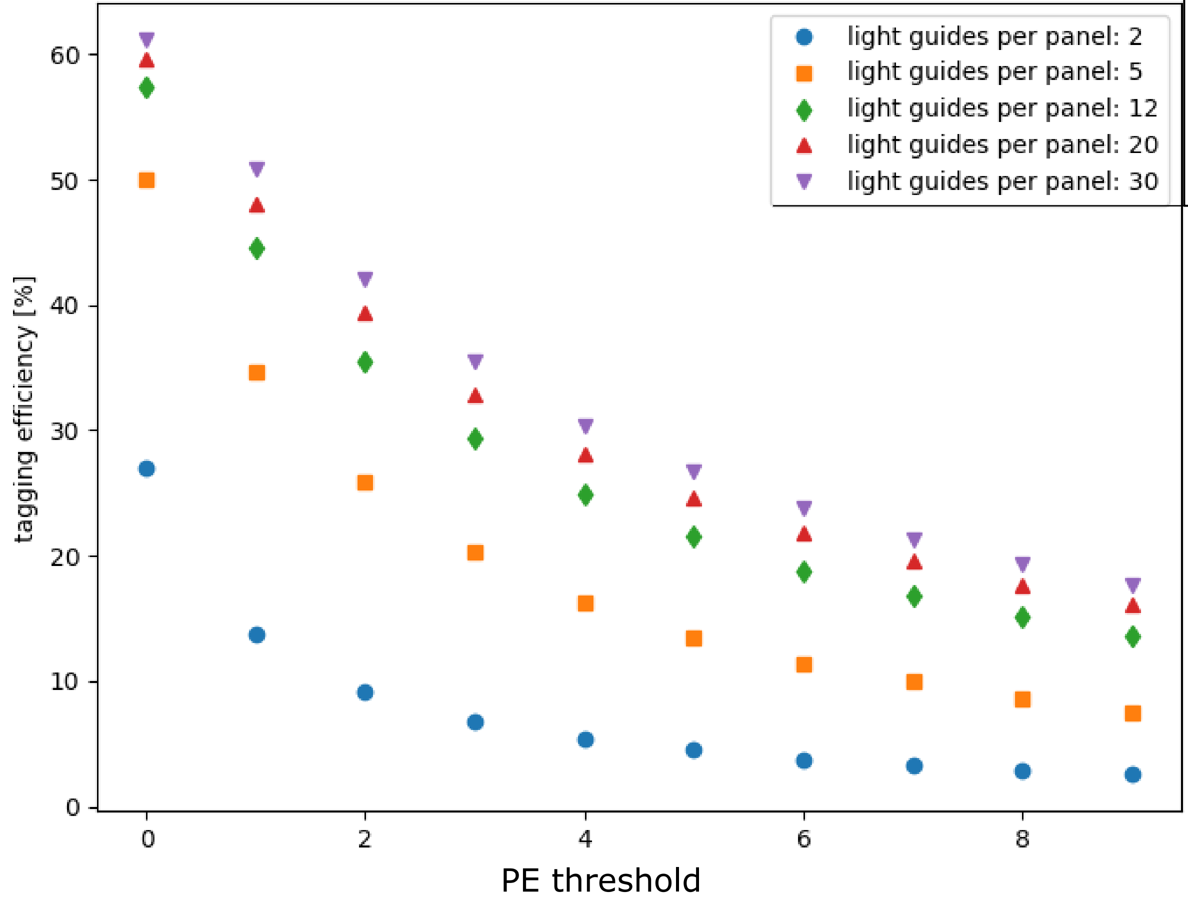
One panel of the shield
Example light instr.
Example channel 'hits'



"BASELINE" DESIGN

Efficiency to tag muon events which produce ^{41}Ar

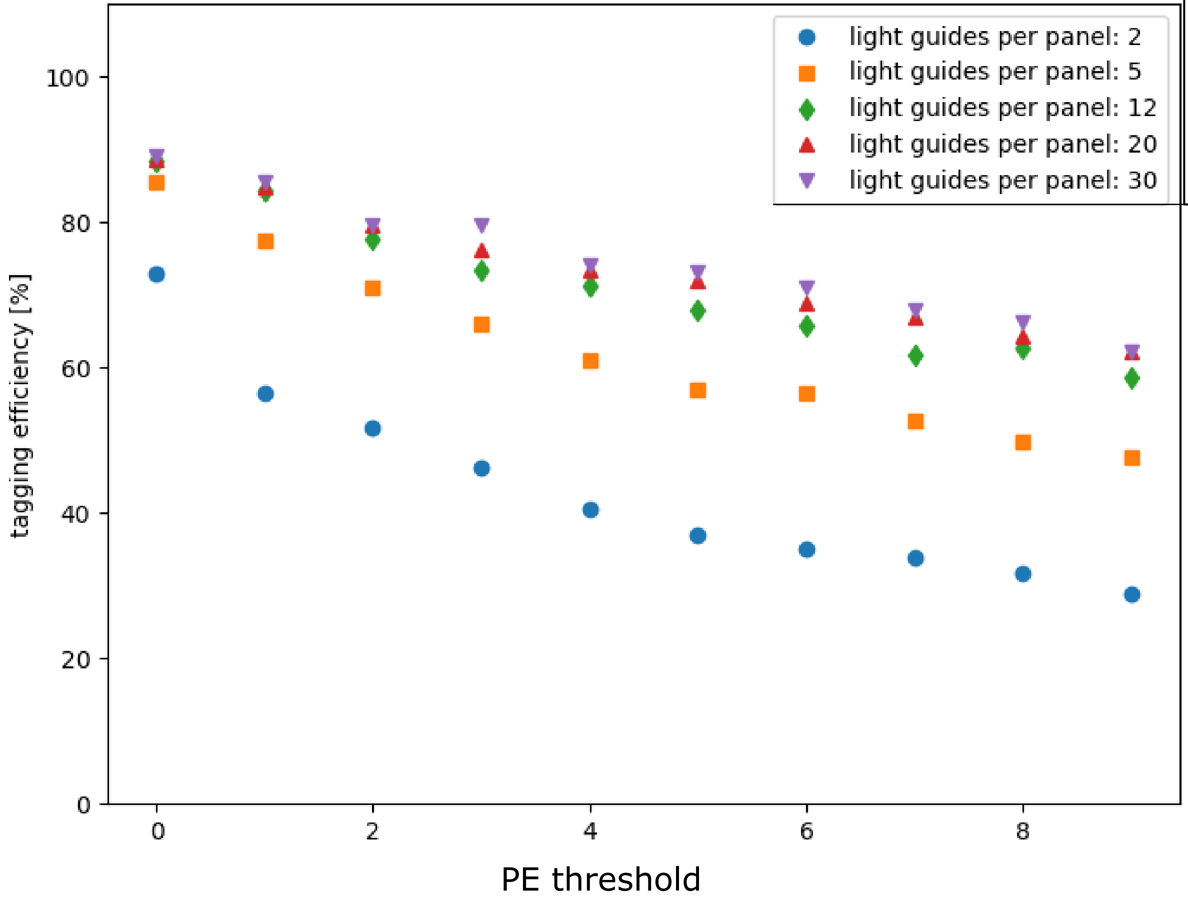
$$\text{Efficiency} = \frac{\#\text{muon events above threshold}}{\#\text{muon events which produce}^{41}\text{Ar}}$$



%coverage
6.7
16.7
40
67
100

Efficiency to tag muon events which produce ^{41}Ar and ^{77}Ge

$$\text{Efficiency} = \frac{\#\text{muon events above threshold}}{\#\text{muon events which produce}^{41}\text{Ar}}$$



%coverage
6.7
16.7
40
67
100

Outlook

We have created and applied an advanced optical map for LEGEND-1000 design considerations

This work is ongoing, but preliminary results suggest that we can identify 70% or more of ^{77}Ge-producing muons

Future studies will include ^{39}Ar decays and the U and Th radioactive decay chains