Simulation of the SABRE Experiment Physics

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The University of Melbourne

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Picture by M. Volpi

THE UNIVERSITY OF MELBOURNE

STAWELL UNDERGROUND PHYSICS LAB

SABRE

OUTILINE

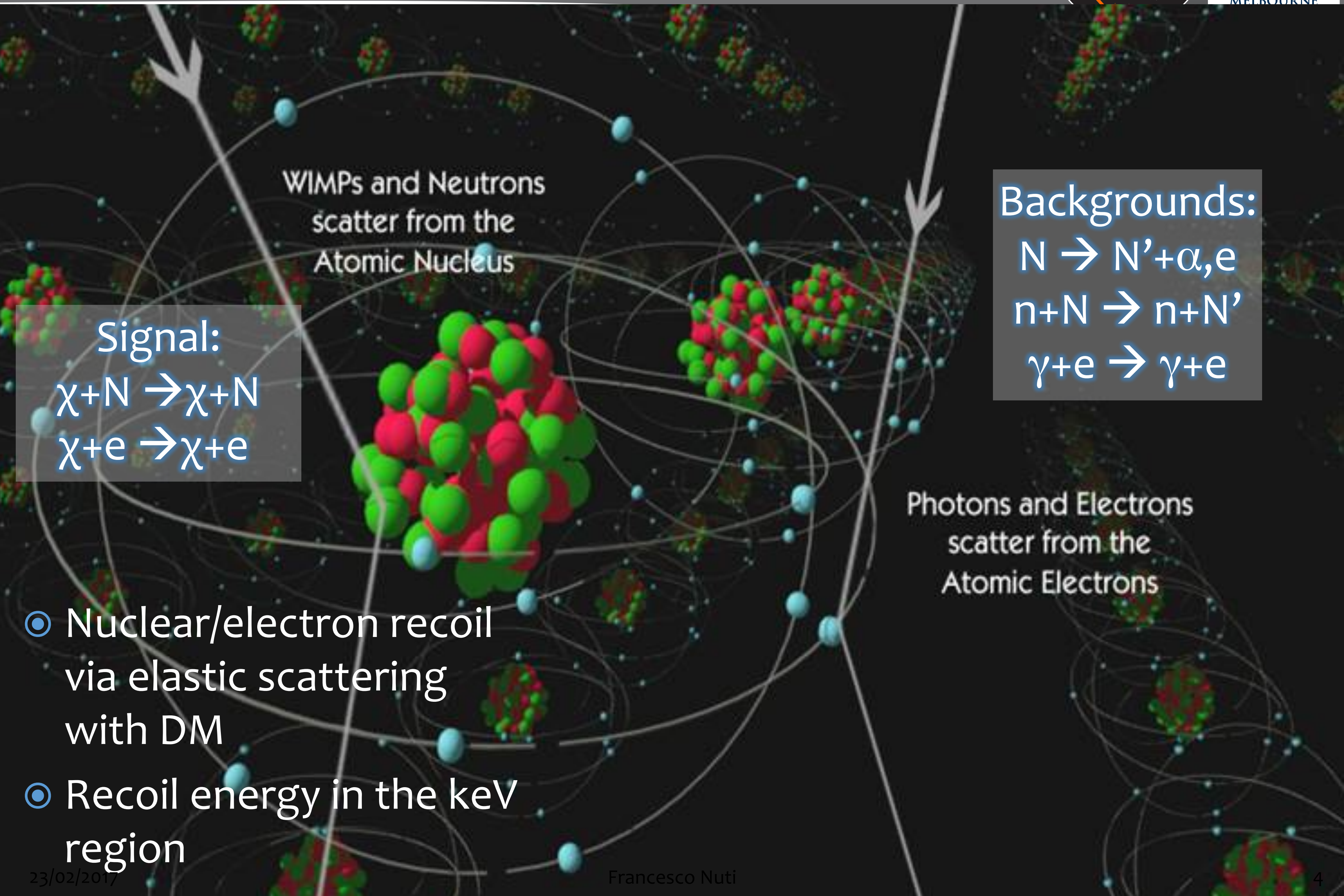
- Estimate of the expected backgrounds
  - Radiogenic environmental+intrinsic (F. Nuti, C. Tomei*, P. Montini*, G. D'Imperio*, M. Antonello*)
  - Muon-Induced (F. Zhang)

*INFN group

- Development of the SABRE@SUPL experiment
  - Active rejection studies: vessel design, PMT number and disposition (M. Zurowski)
  - Passive shielding studies (I. Mahmood)

Background estimate

Direct DM Detection



Signal:

$\chi + N \rightarrow \chi + N$

$\chi + e \rightarrow \chi + e$

Backgrounds:

$N \rightarrow N' + \alpha, e$

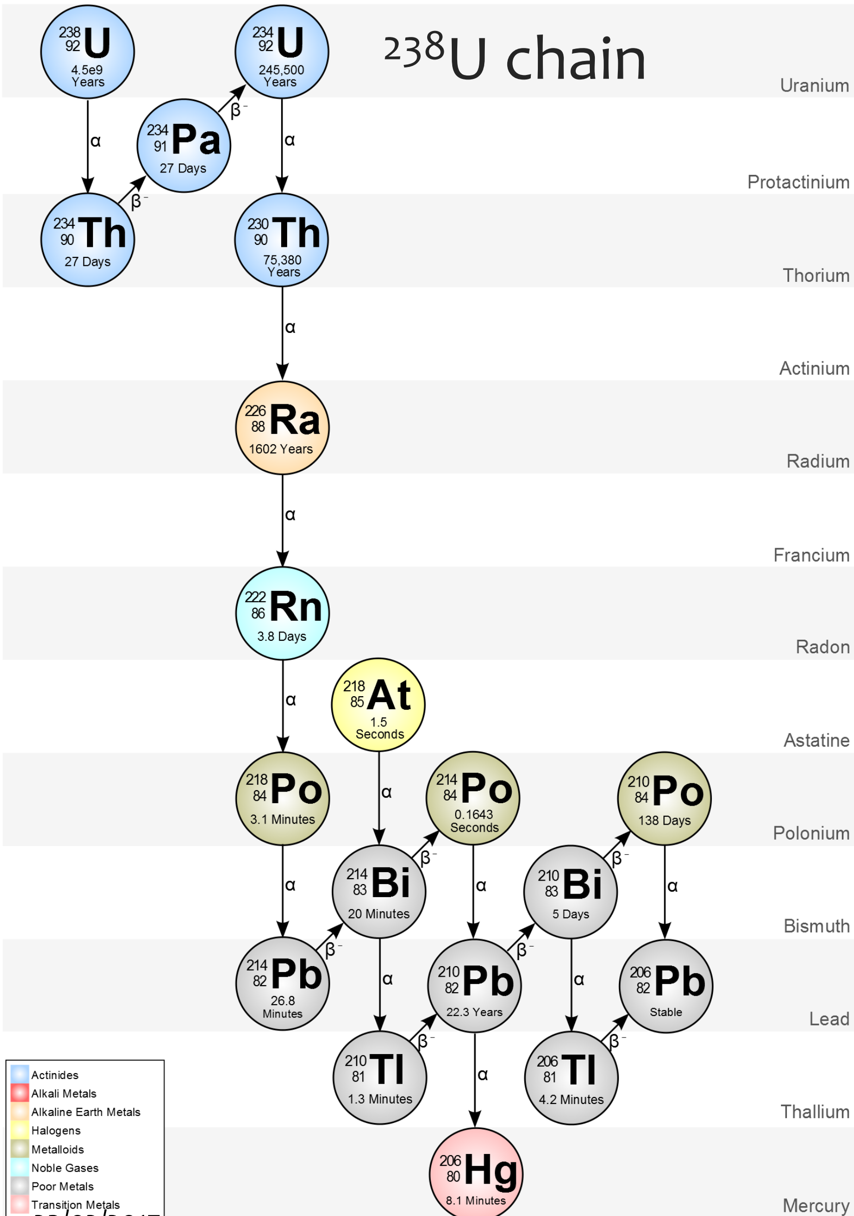
$n + N \rightarrow n + N'$

$\gamma + e \rightarrow \gamma + e$

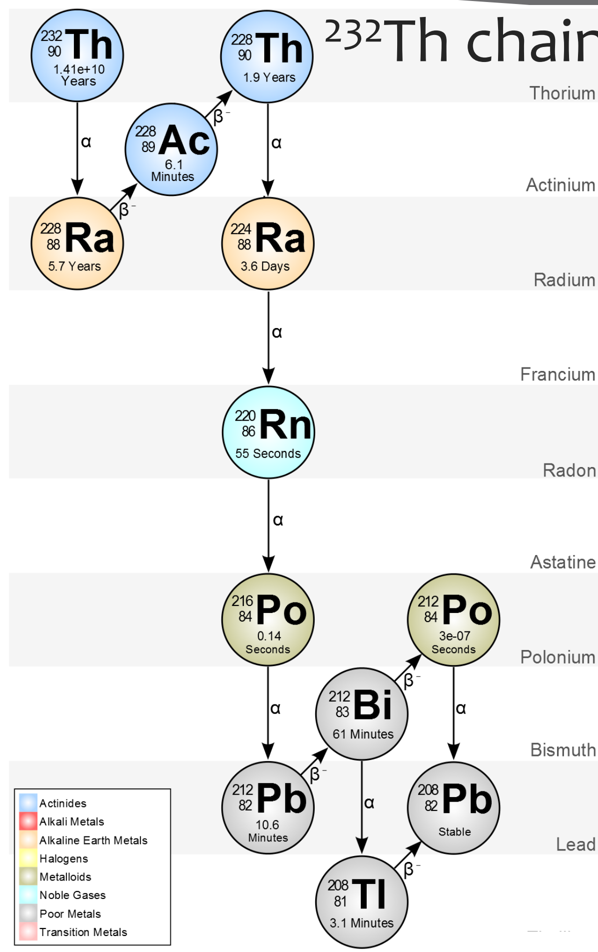
- Nuclear/electron recoil via elastic scattering with DM
- Recoil energy in the keV region

RADIOGENIC BACKGROUND

^{238}U chain



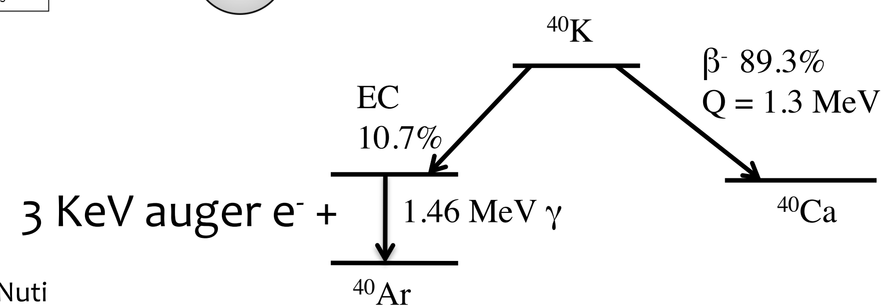
^{232}Th chain



^{235}U chain negligible contaminations

Others:

^{40}K, ^{60}Co, ^{137}Cs

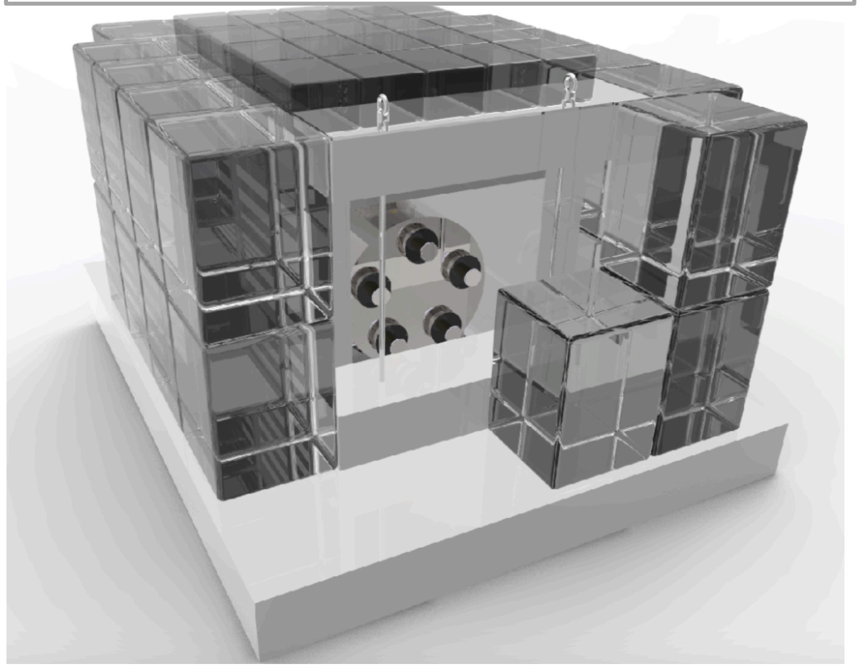


RADIOGENIC BACKGROUND

- Radioactive sources:
  - Any element constituting the detector
    - NaI(Tl) crystals
    - Crystal wrapping
    - Crystal enclosure
    - Crystal PMTs
    - Liquid Scintillator
    - Steel Vessel (Here shown as example)
    - Veto PMTs
    - External Shield
  - Lab and surrounding rocks (not in this talk)

- Background estimated for the Proof of Principle (PoP) setup soon online at LNGS
- Same procedure can be applied to estimate the background for SABRE at SUPL
- Results for
  - Potassium measurement mode (KMM)
  - Dark Matter measurement mode (DMM)

Proof of Principle (PoP) setup



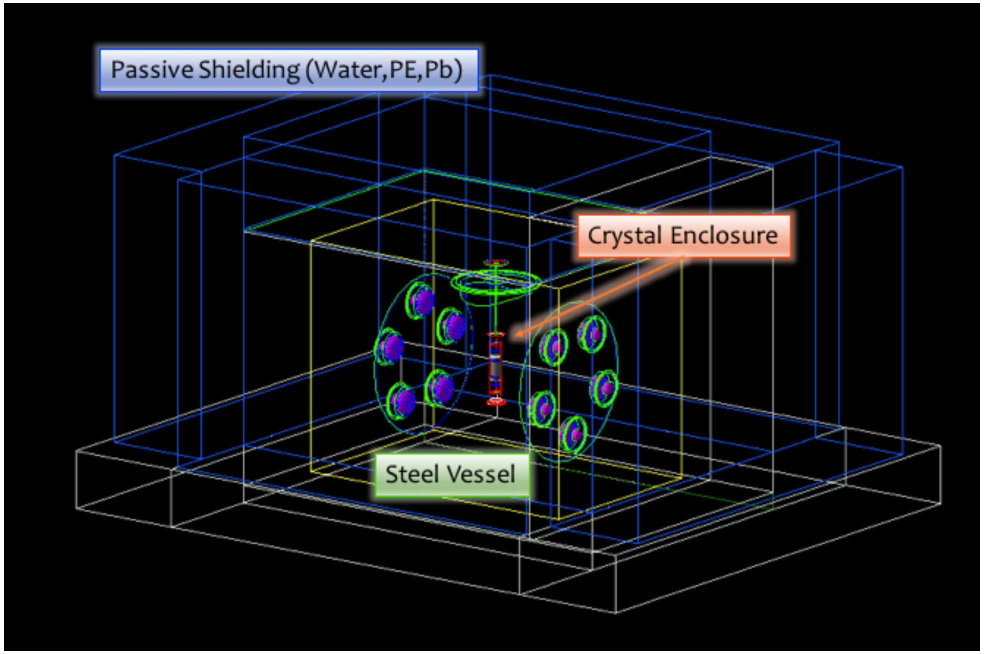
BACKGROUND ESTIMATE PROCEDURE

- Measurements of radio-purity for each detector element

Steel Vessel Contaminations

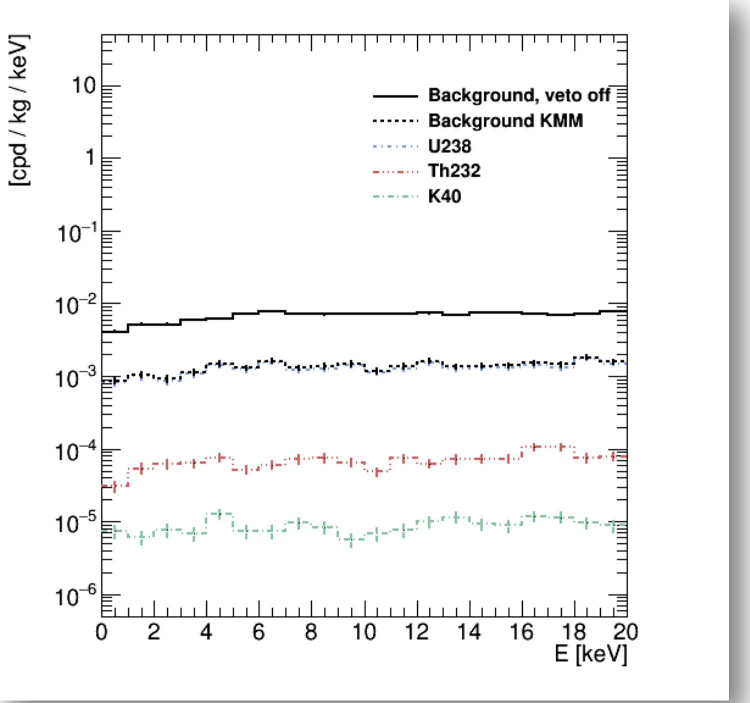
Lot Number	Thickness	U		Th		K		Pb	Comments
	inch	ppb	mBq/kg	ppb	mBq/kg	ppb	mBq/kg	ppb	default units if not specified
S536	3/8	0.3	3.7	<0.1	<0.4	4	0.12	10	

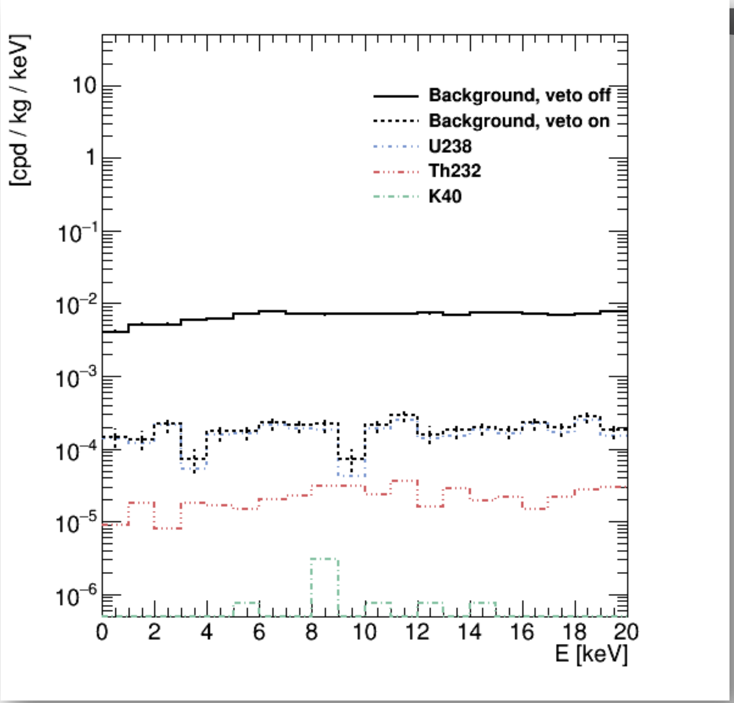
- GEANT4 Simulation of
  - Experimental setup
  - Decay processes
  - Particle propagation and interaction in the detector



- Evaluation of the signal of interest (KMM,DMM) counts per day (cpd) expected from each source

Vessel expected Background





Potassium Mode:

Energy deposition in Liquid Scintillator in [1280,1640] keV

Background in [2,4] KeV:

(2.27 ± 0.18)e-03 cpd/kg

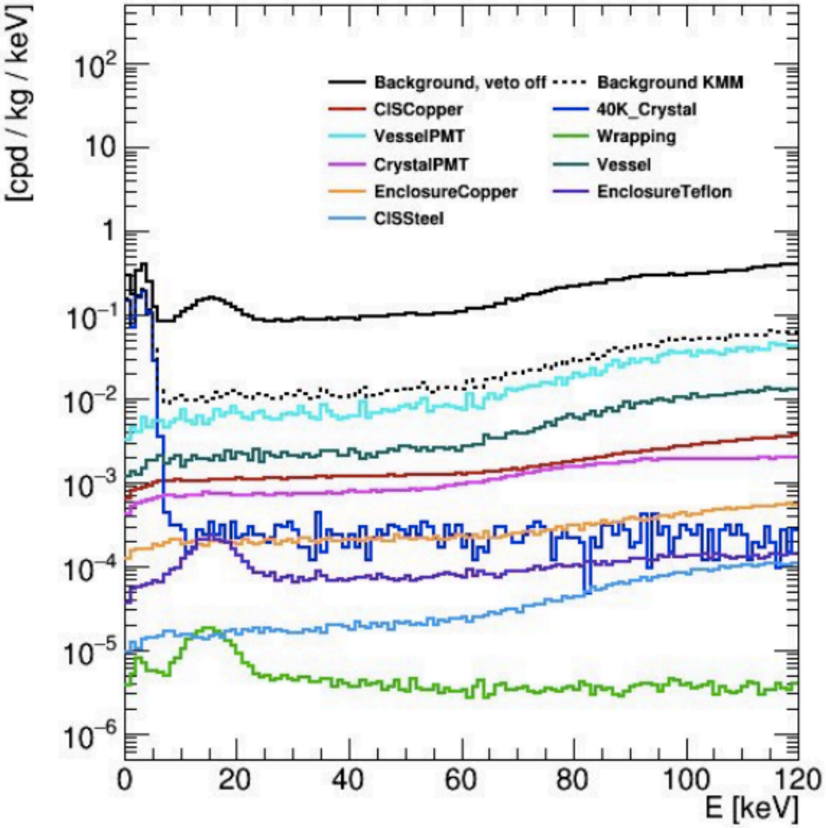
DM detection mode:

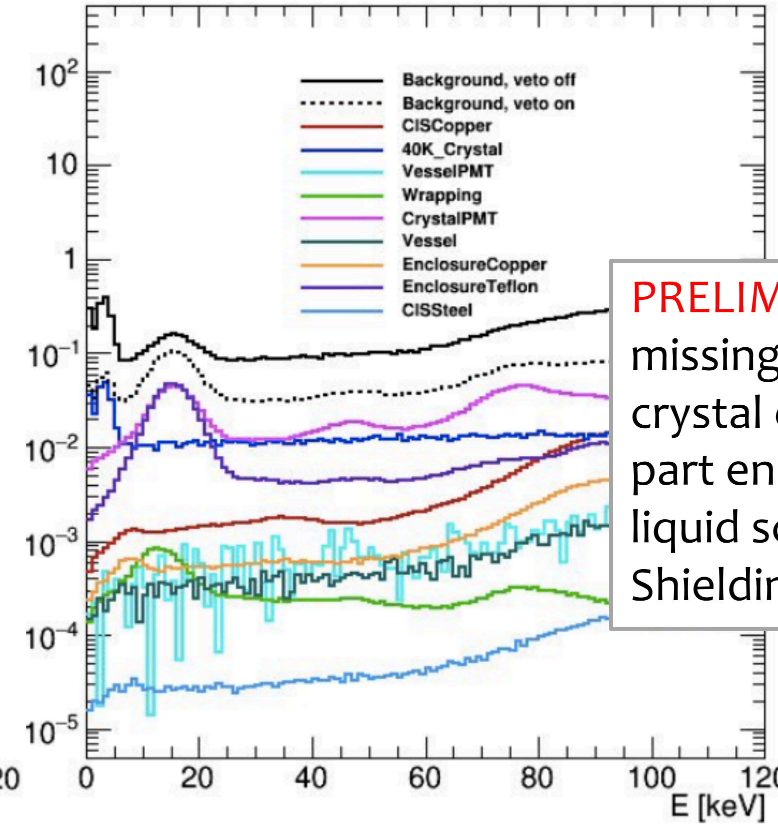
Energy deposition in Liquid Scintillator <100 keV

Background in [2,6] KeV:

(7.27 ± 0.97)e-04 cpd/kg

Total expected Background

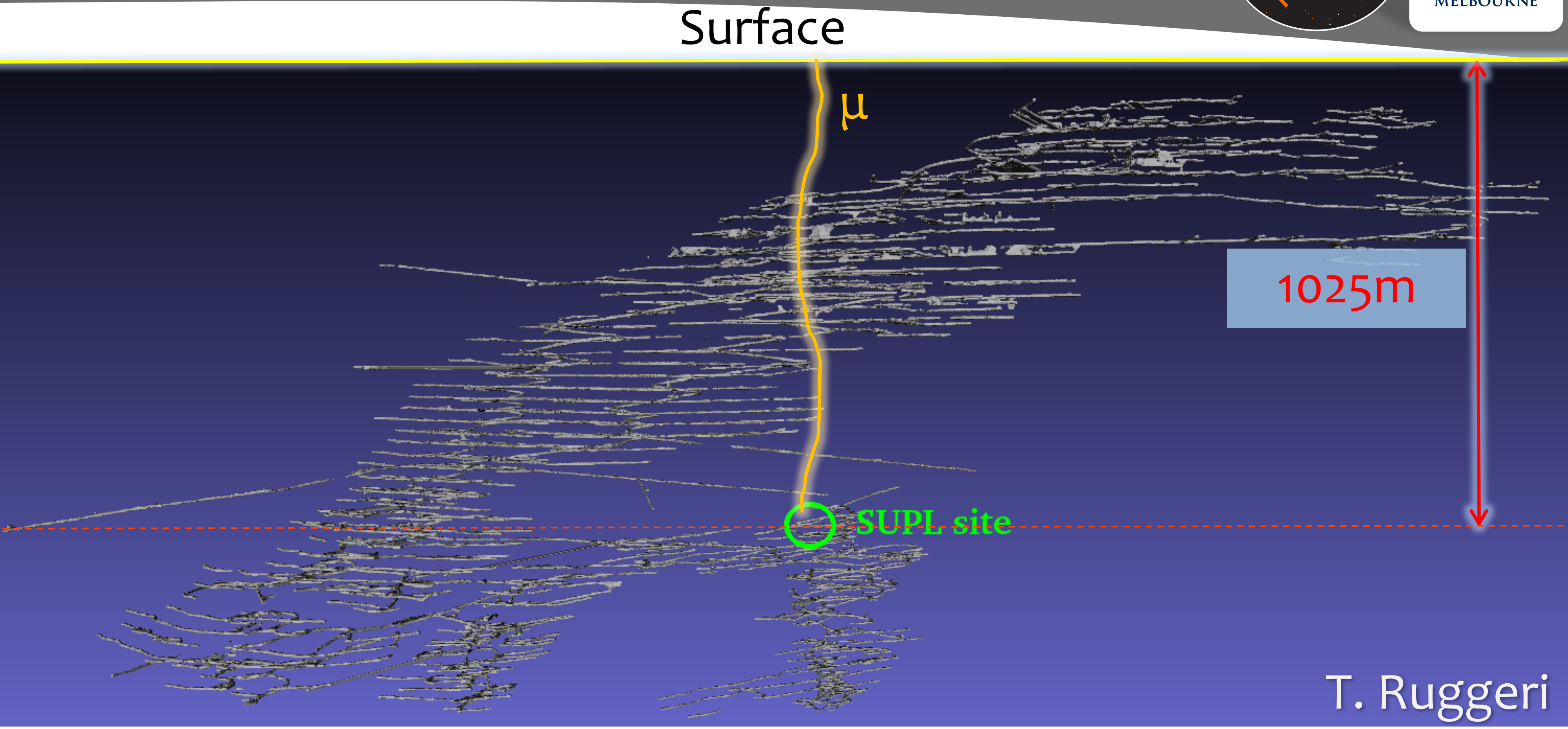




PRELIMINARY!
missing:
crystal except for ^{40}K
part enclosure
liquid scint.
Shielding

	Potassium Mode	DM detection mode
Crystal contamin.	0.379 ± 0.003 cpd/kg	0.144 ± 0.002 cpd/kg
Others	(1.1± 0.1)e-02 cpd/kg	(6.0± 0.1)e-02 cpd/kg

Muon-induced background



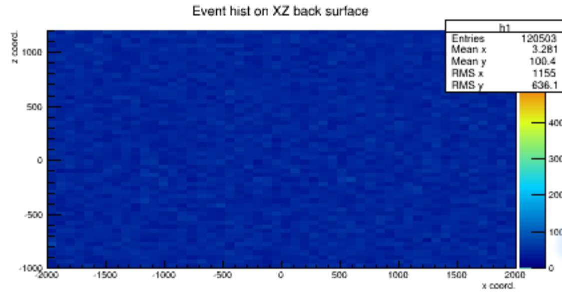
- Energetic muons (>600 GeV) produced in cosmic ray showers can reach the SUPL site depths
- Interaction of muons with matter (rocks, lab, detector) can cause activation → Additional radiation → Additional background

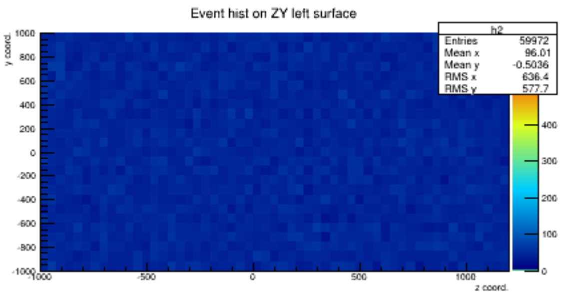
Muon-induced background

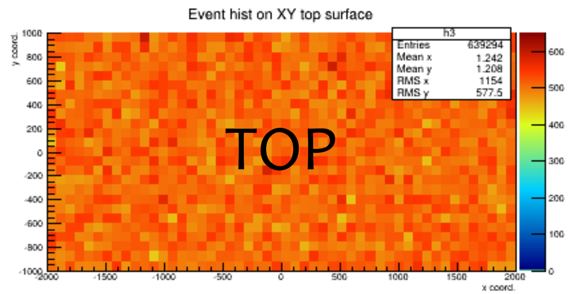
- Study propagation of muons underground with MUSIC-MUSUN (arXiv:0810.4635v1)
- Setup:
  - Gaisser's formula for muon spectrum at sea level modified for large zenith angles
  - Basalt rock with density 2.7 g/cm^3
  - Muon propagated at depths of the SUPL site (1025m)
- Goal: Characterize the muon flux at the surface of a box 40x20x22 m^3 surrounding the SUPL site
- Ultimate goal: use the estimated flux to calculate the activation induced by muons and the resulting background for the experiment

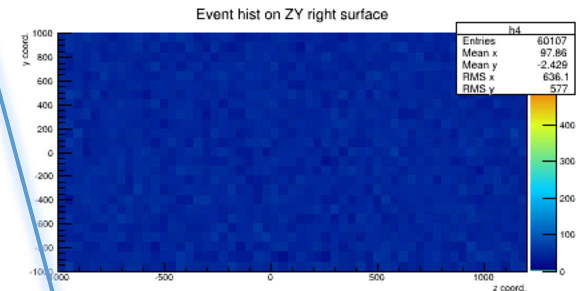
MUON FLUX

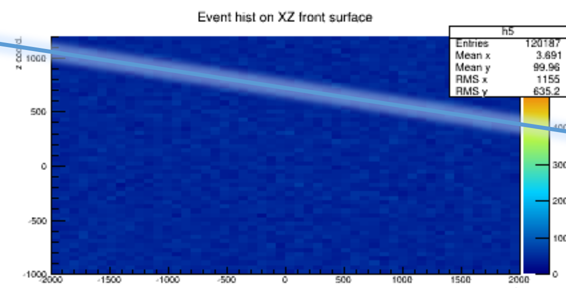
- Uniform flux on each surface









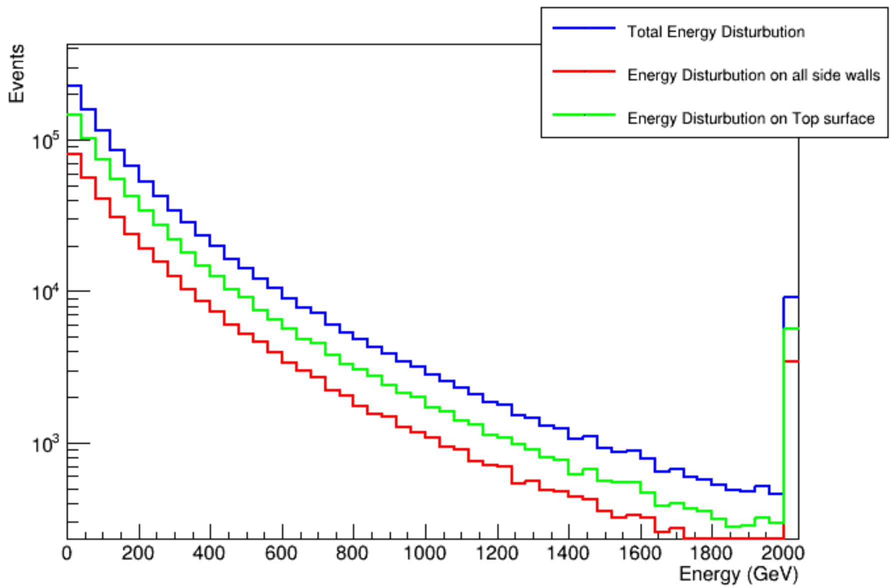


SIDE Walls

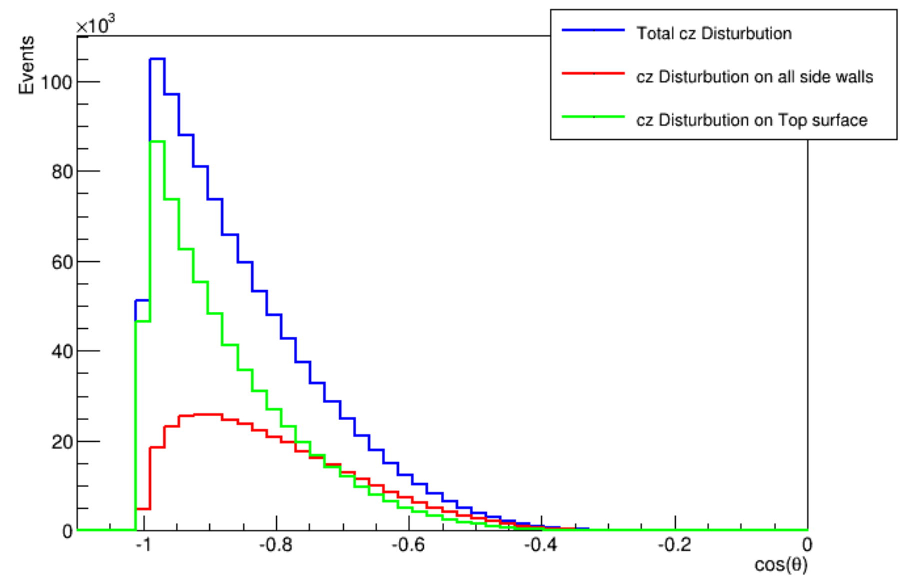
- 64% of the flux from top
- 36% from the side walls
- ~0% from the bottom

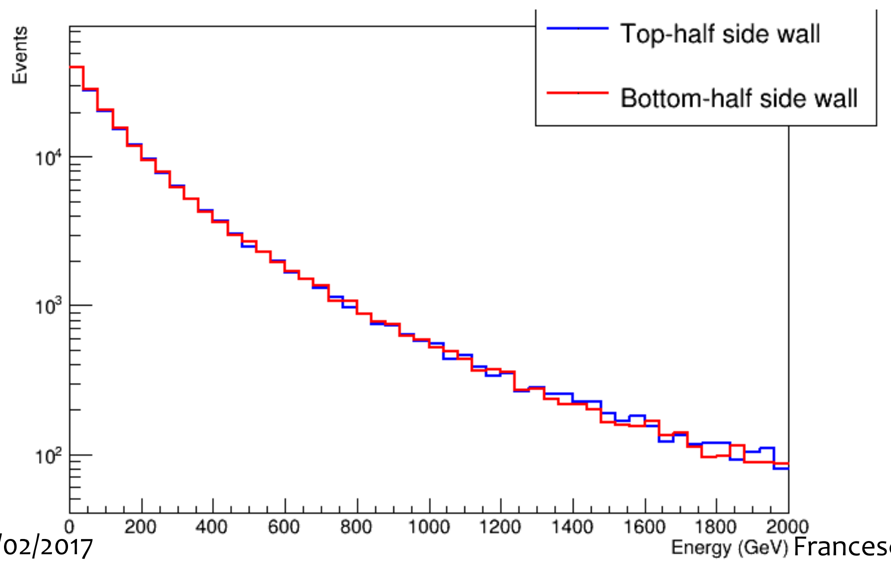
Muon Energy and Direction

Final muon energy



Final muon polar angle





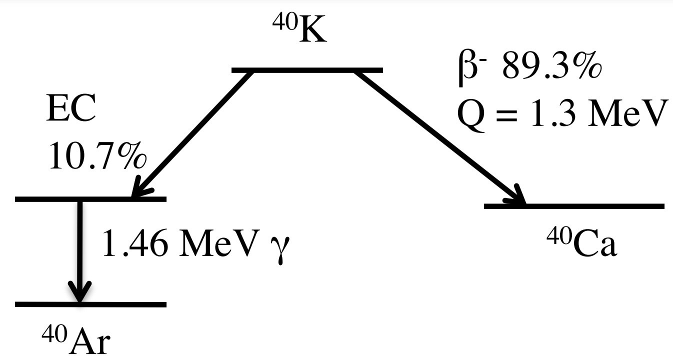
- Energy profile seems not to be affected by the final position
- Polar angular distribution clearly surface-dependent

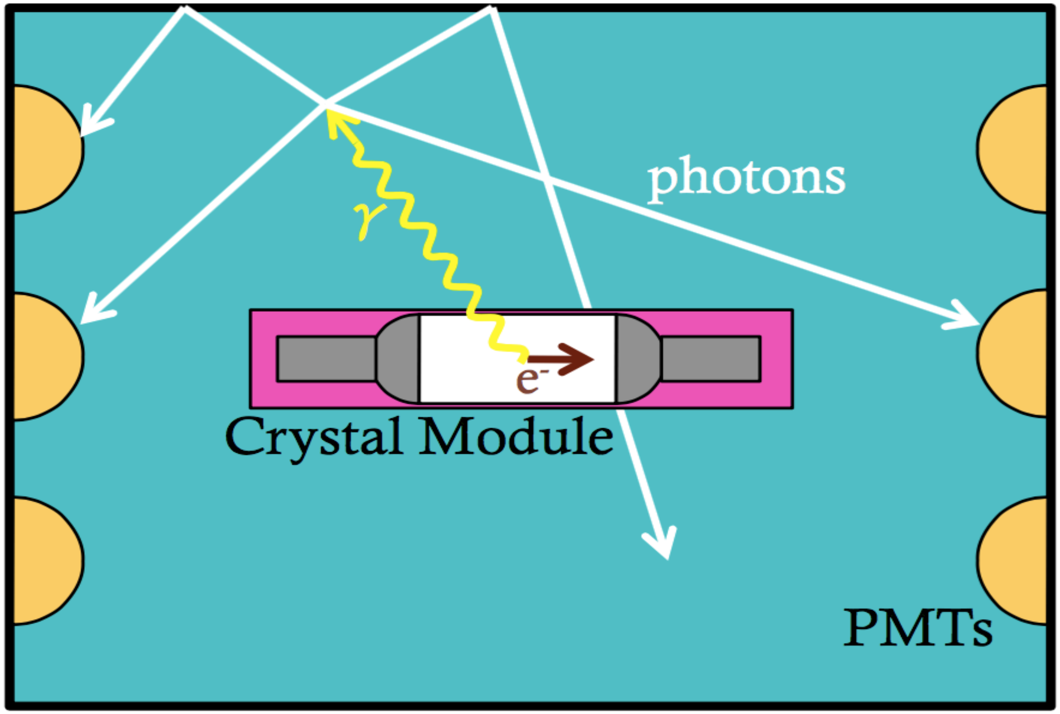
Optimization studies

Active Background Rejection

- NaI crystals immerged in liquid scintillator
- Goal: reject external+intrinsic backgrounds (radioactive, cosmic-induced processes)
- Veto processes with significant signals in the scintillator (>100KeV)

^{40}K electron capture in crystals

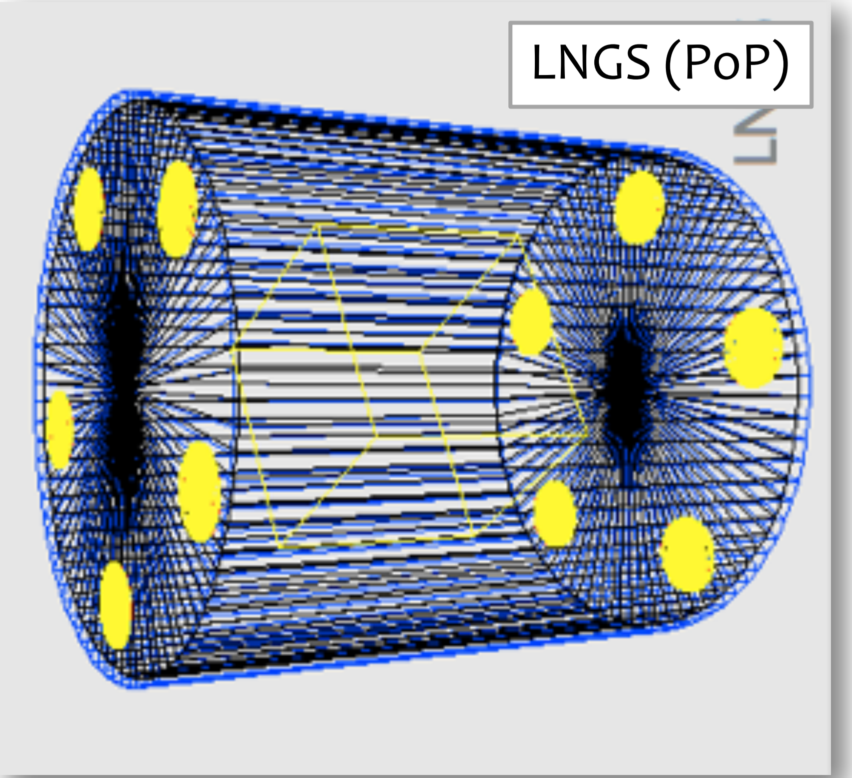


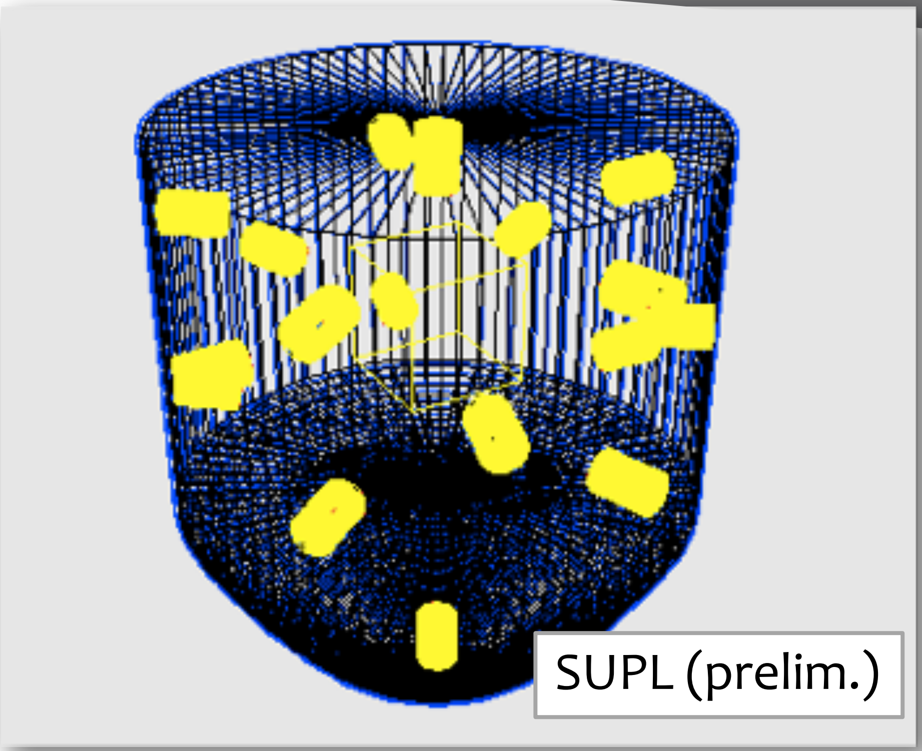


VESSEL STUDIES

- **SLitrani** simulation of the light production/collection (https://crystalclear.web.cern.ch/crystalclear/SLitraniX/SLitrani/index.html)
- Sensitive surfaces based on Hamamatsu R5912 PMTs (max efficiency ~25% at wavelength of ~400nm)
- Radiation source in a 0.6x0.6x0.6 m^3 box:
  - 1.46 MeV γ (from ^{40}K)
  - 0.1 MeV γ (target energy sensitivity)
- Studied performances vs. Vessel size, PMT position and number

VESSELS (LNGS VS SUPL)





- Pseudocumene
- 10 PMTs
- r x h = 0.675 x 1.50 (m^2)

- Linear Alkyl Benzene (LAB)
- 16 PMTs
- r x h = 1.30 x 1.85 (m^2)

VESSEL SIZE VARIATION

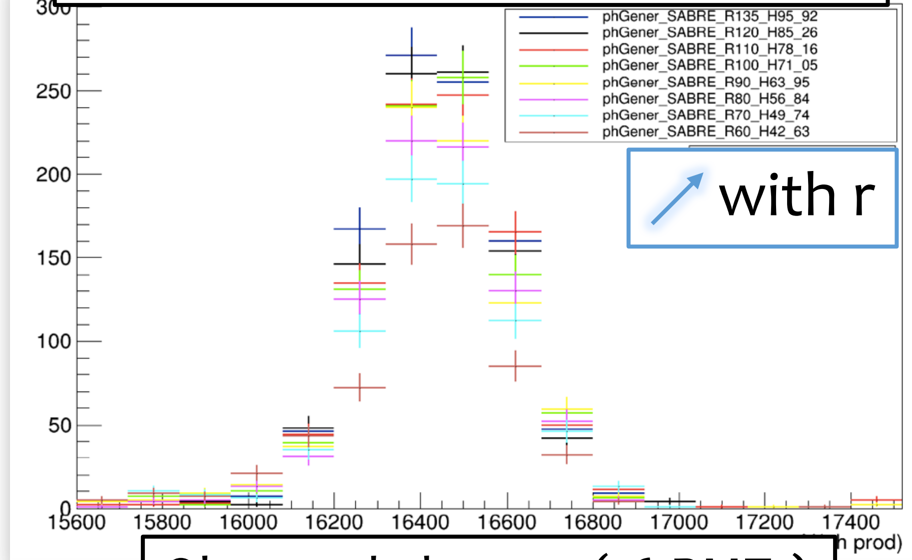
Setup:

- Radius varied 0.6m→1.35m
- Radius/height constant
- PMTs installed on the cylindrical surface of the vessel

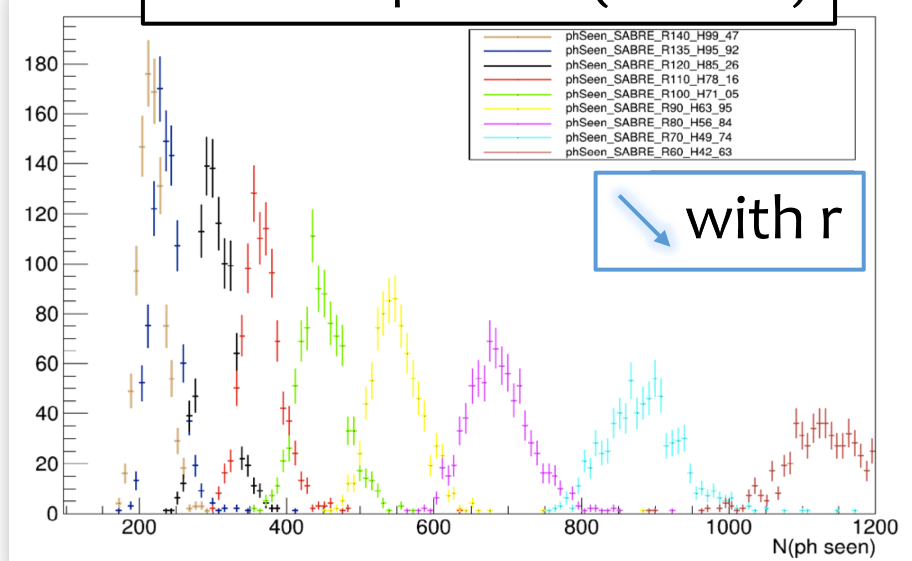
Results: for a smaller vessel

- Less optical photon produced
- More photons collected (greater geometrical acceptance, less absorption)
- Broader peak

Produced photons for a 1.46 MeV γ



Observed photons (16 PMTs)



Collected Photons

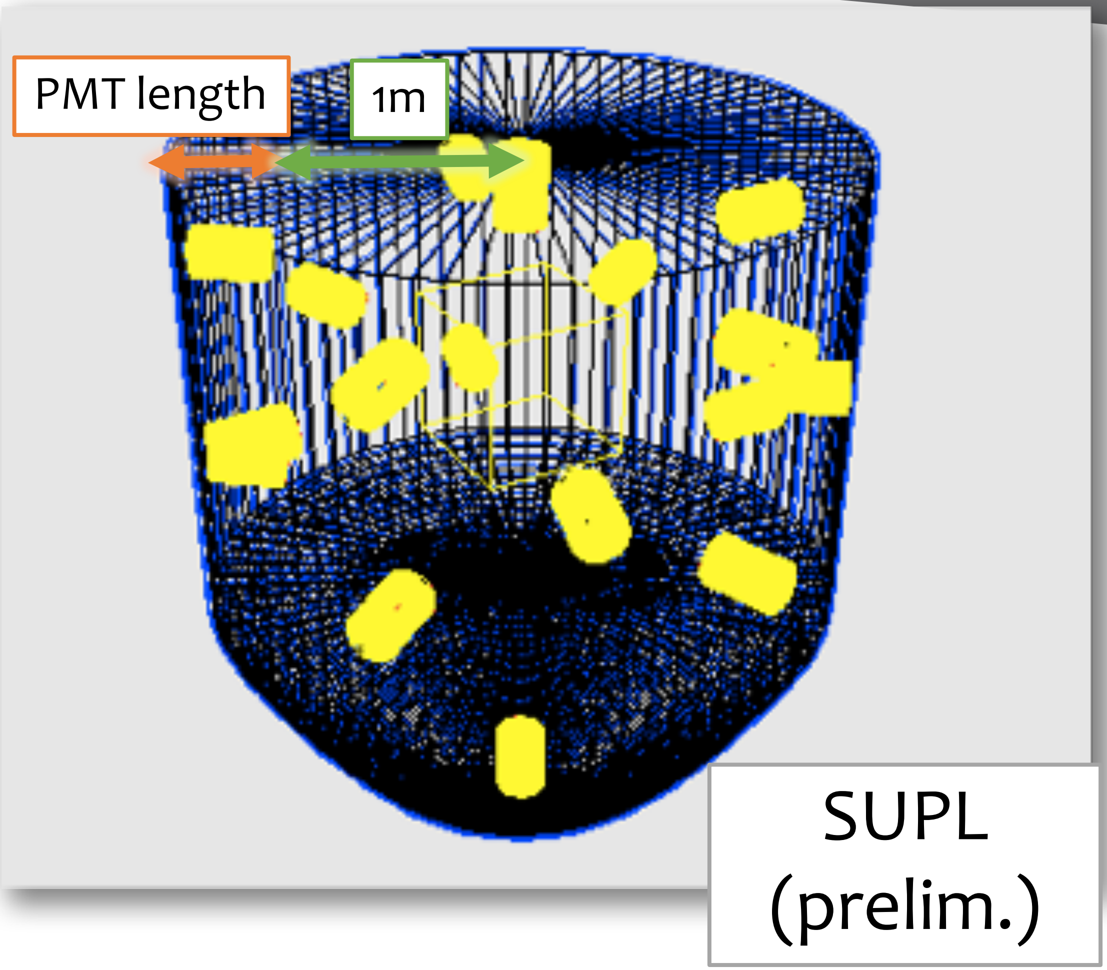
Radius (cm)	Mean	σ/Mean	Peak population* (%)
60	950.96	0.31	90.0
70	804.37	0.25	89.9
80	645.04	0.20	91.7
90	518.92	0.20	93.6
100	433.47	0.16	95.2
110	357.93	0.14	95.7
120	296.84	0.15	97.2
135	232.93	0.12	97.8
(LNGS) 67.465	396.43	0.23	94.6

- Peak population increases with radius
- r=1m offers light yields compatible with the LNGS vessel, compatible peak population and better resolution
- Studied variations of PMT number and position keeping the PMT radial distance fixed at r=1m

* Peak population refers to the number of simulated events in the interval ± 3σ around the mean value

PMTs POSITION AND NUMBER

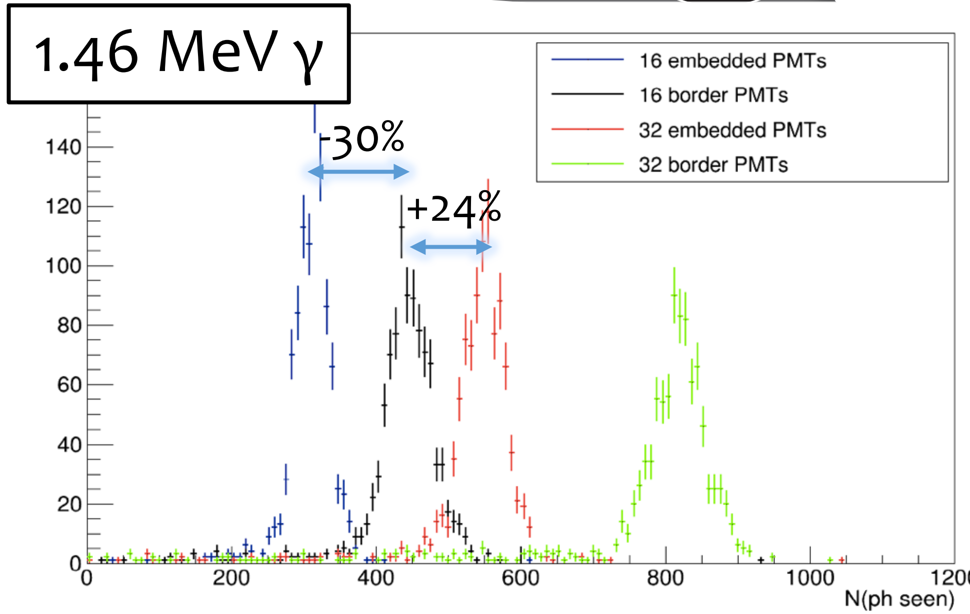
- So far, PMTs sensitive surface (8'' flat disk) on the vessel cylindrical surface
- What if PMTs are fully immerged in the scintillator and anchored to the vessel?
  - Technical Pros&Cons.
  - Expected lower reflection light
- What if we use more PMTs?
  - 16, 32 and 48 PMTs tested



Vessel extended to a radius of 1m+PMT length in the immerged case

PMTs position and number

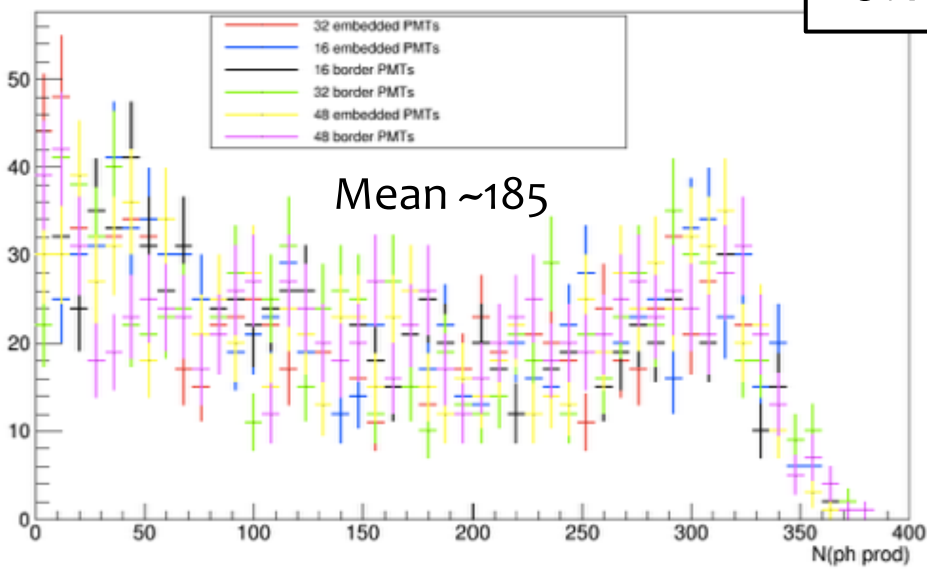
- Embedded solutions have smaller light yields
- Deficit can be recovered with the use of more PMTs
- Is the system sensitivity to low energy photons (~0.1 MeV)?

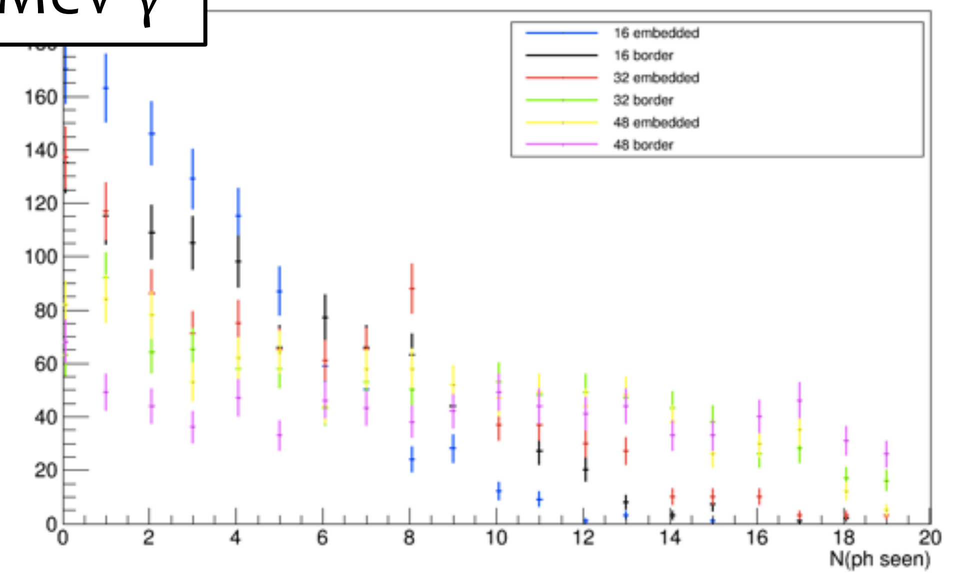


No. PMTs	Radius (cm)	Height/2 (cm)	Mean	σ/Mean	Peak population (%)
16	129(emb)	91.65	307.99	0.13	97.9
16	100	71.05	433.47	0.16	95.2
32	129(emb)	91.65	535.71	0.14	95.0
32	100	71.05	772.34	0.19	95.0
LNGS (10)	67.46	75.24	396.43	0.23	94.6

PMTs position and number

0.1 MeV γ



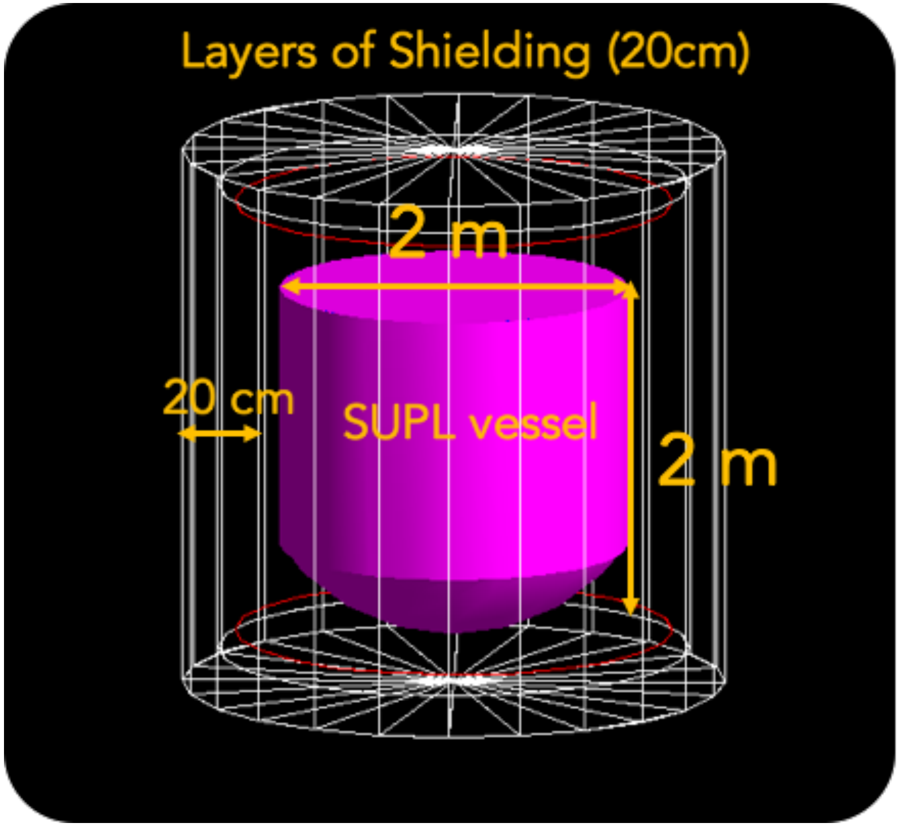


No. PMTs	Radius (cm)	Mean	0 photon evts (%)	1 photon evts (%)
16	129(emb)	3.91	17.0	16.2
16	100	5.46	13.5	11.5
32	129(emb)	6.57	13.7	11.7
32	100	9.14	6.3	9.2
LNGS (10)	67.46	4.44	13.5	12.0

- Large variations in the # of produced photons
- Border PMTs and more PMTs reduces # of undetected processes
- Non-null probability to observe 0 or 1 photons

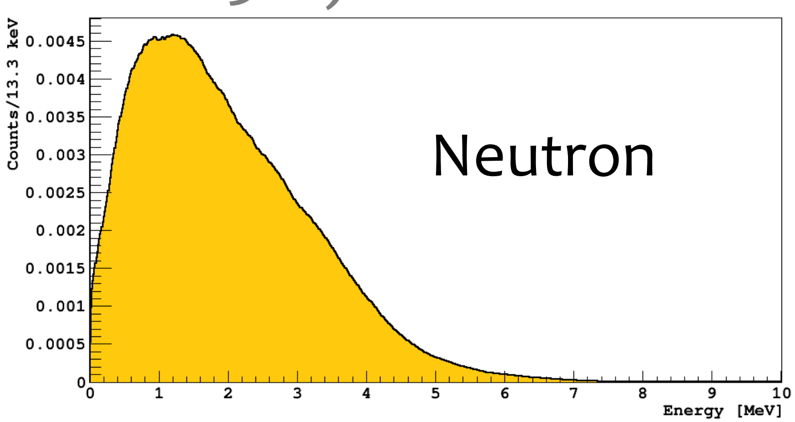
Passive shielding studies

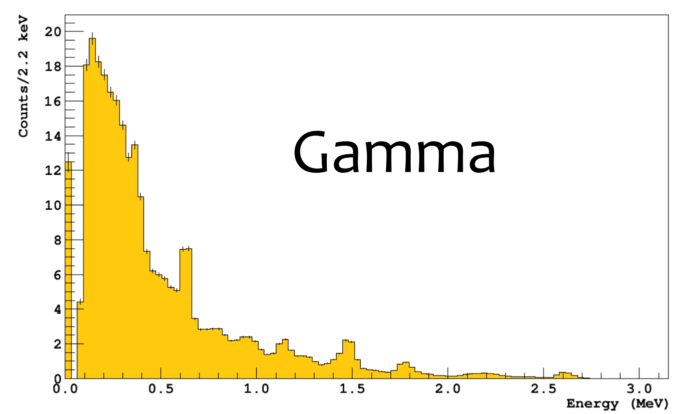
- Characterize the performances of several shielding solutions
- Rejection power against environmental gammas and neutrons
- Studied combinations of
  - Lead (Pb)
  - polyethylene (PE)
  - polyethylene enriched with Lithium/Bismuth (PE-Li/Bi)
- Total thickness 20 cm



Simulation Setup

- SUPL vessel and shielding implemented in GEANT4
- 1 million particles are generated on surface of 2.2 m radius sphere surrounding the detector and pointing towards the centre
- Initial particle energies:
  - LNGS neutron energy spectrum
  - SUPL photon energy spectrum (refuge measurement at 1025m)





Attenuation power (any signal)

- Survival probability with the worst shielding: 18% for neutrons and 1.66% for gammas

Percentage of Detected Background of Worst Performing Shield

Shield Material (outside to inside)	Lead Thickness (cm)	Neutrons	Photons
5cm Lead, 5cm PE, 5cm Lead, 5 cm PE	10	71.01%	3.74%
10cm Lead, 10cm PE	10	85.23%	3.98%
3cm PE, 7cm Lead, 3cm PE, 7cm Lead	14	98.31%	0.50%
7cm Lead, 3cm PE, 7cm Lead, 3cm PE	14	100.00%	0.65%
5cm PE, 3cm Lead, 8.25cm PE, 3.75cm Lead	6.75	24.45%	55.51%
7cm PE, 3cm Lead, 3cm PE, 7cm Lead	10	20.38%	100.00%
3cm PE, 7cm Lead, 7cm PE, 3cm Lead	10	31.09%	8.84%
5cm PE, 5cm Lead, 5cm PE, 5cm Lead	10	63.56%	3.52%
5cm PE, 3cm Lead, 6cm PE-Bi, 2.25cm PE-Li, 3.75cm Lead	6.75	21.42%	9.79%
3cm PE, 5cm Lead, 6cm PE-Bi, 2.25cm PE-Li, 3.75cm Lead	8.75	26.84%	3.82%

- Stat. error on the table values <1%
- Solutions with enriched PE better for neutrons (as found in **arXiv:nucl-ex/0607032**)
- 3PE:7Pb:7PE:3Pb and 5PE:5Pb:5PE:5Pb are the best otherwise

Attenuation power (DM-like signal)

Percentage of Particles Depositing < 200 keV in Scintillator & > 0 keV in Crystal of Worst Performing Shield

Shield Material (outside to inside)	Lead Thickness (cm)	Neutrons	Photons
5cm Lead, 5cm PE, 5cm Lead, 5 cm PE	10	74.62%	6.07%
10cm Lead, 10cm PE	10	106.71%	1.95%
3cm PE, 7cm Lead, 3cm PE, 7cm Lead	14	64.41%	0.65%
7cm Lead, 3cm PE, 7cm Lead, 3cm PE	14	100.00%	0.44%
5cm PE, 3cm Lead, 8.25cm PE, 3.75cm Lead	6.75	30.77%	57.82%
7cm PE, 3cm Lead, 3cm PE, 7cm Lead	10	24.70%	100.00%
3cm PE, 7cm Lead, 7cm PE, 3cm Lead	10	44.90%	11.71%
5cm PE, 5cm Lead, 5cm PE, 5cm Lead	10	61.40%	5.10%
5cm PE, 3cm Lead, 6cm PE-Bi, 2.25cm PE-Li, 3.75cm Lead	6.75	14.27%	11.11%
3cm PE, 5cm Lead, 6cm PE-Bi, 2.25cm PE-Li, 3.75cm Lead	8.75	17.13%	1.25%

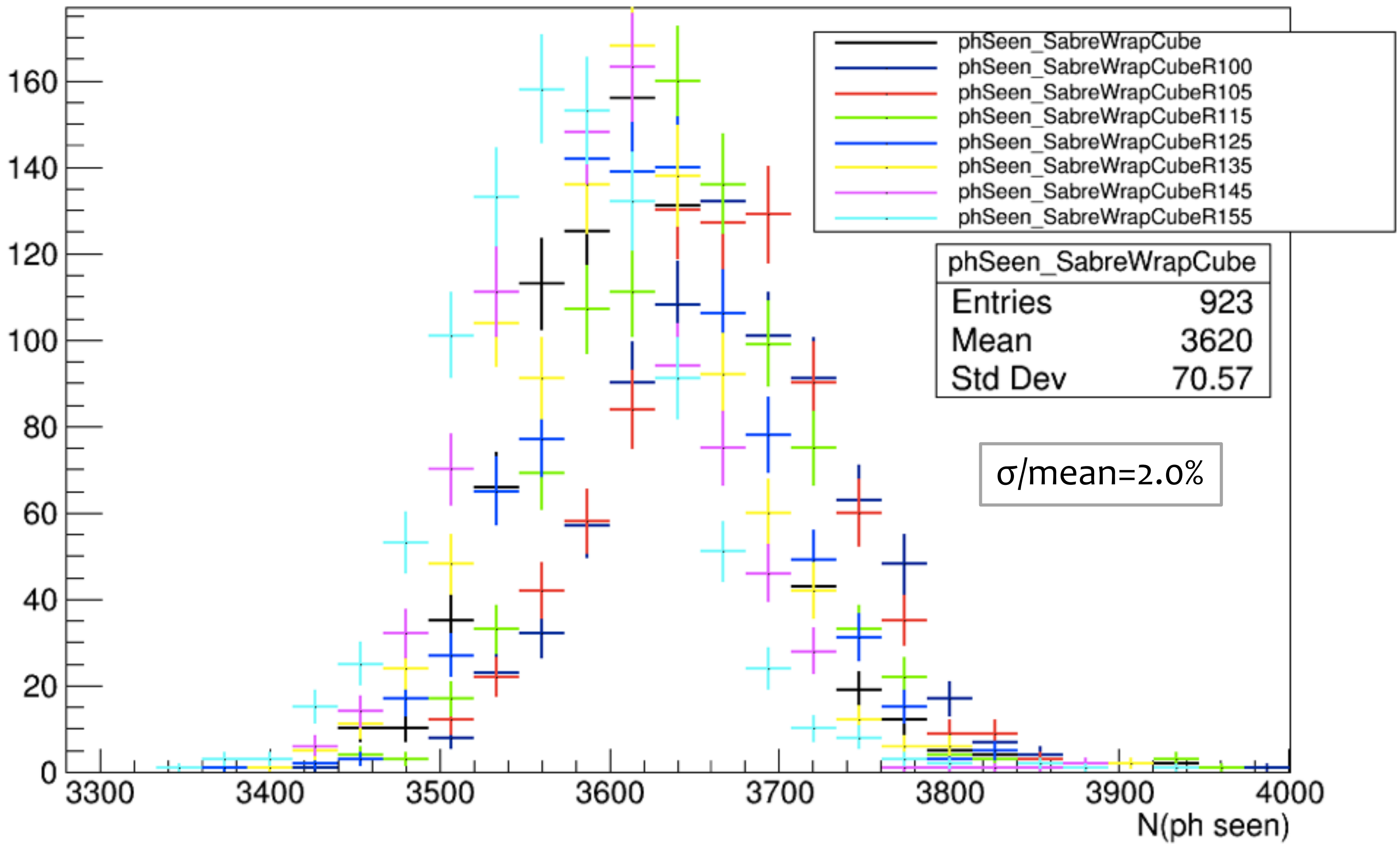
- Survival probability with the worst shielding: 41% for neutrons and 1.04% for gammas
- Stat. error on the table values ~5%
- Same conclusions
- Need to estimate total neutron/gamma flux at SUPL, material costs and availability to take a final decision

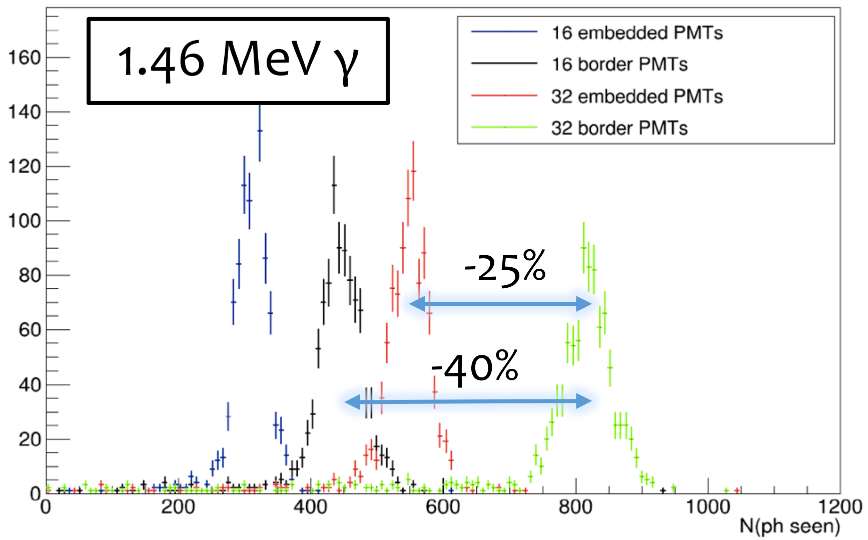
Conclusion

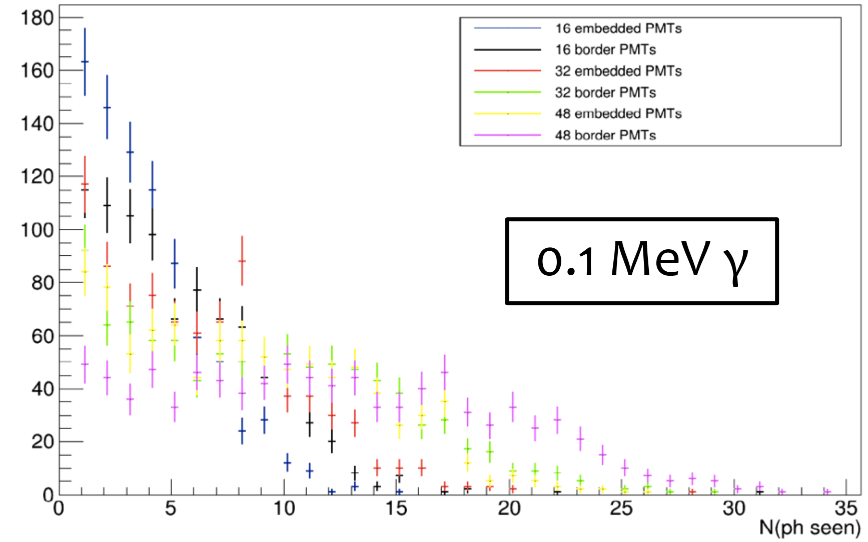
- Background:
  - Radiogenic backgrounds are almost totally characterized for the PoP. Simulation adjustable for a SABRE@SUPL estimate
  - Muon flux @ SUPL characterized; NEXT: simulation of the rock and experiment activation
- SABRE@SUPL development:
  - Studies for the optimization of the vessel and shielding designs are ongoing
  - NEXT:
    - determination of energy sensitivity requirements for the active background rejection
    - determination of gamma flux and neutron flux at SUPL to optimize passive shielding
    - investigate costs/feasibility of the tested solutions

Backup

Fully instrumented detector

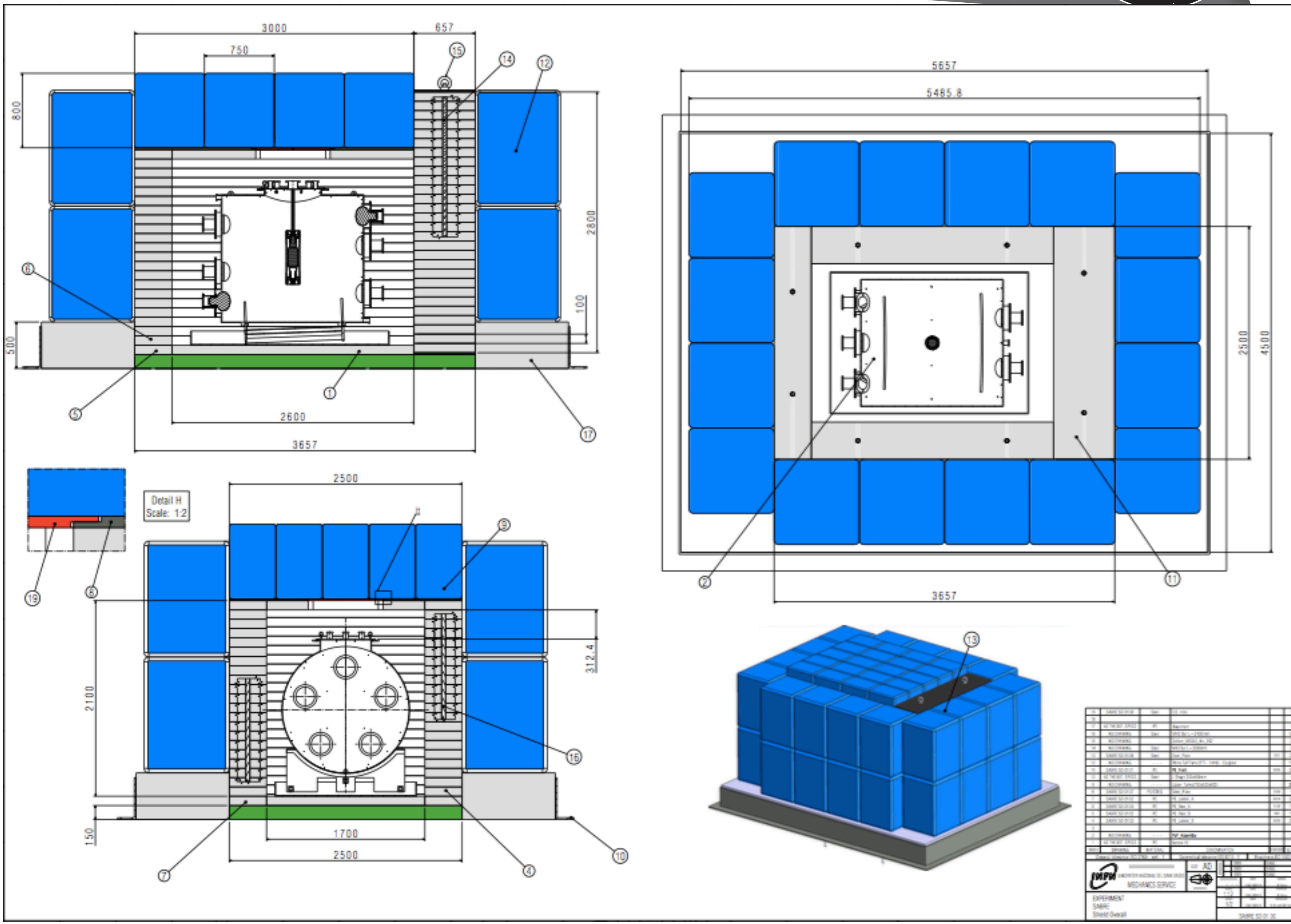






			1.46 MeV γ			0.1 MeV γ		
No. PMTs	Radius (cm)	Height/2 (cm)	Mean	σ/Mean	Peak population (%)	Mean	σ/Mean	Peak population (%)
16	129(emb)	91.65	307.99	0.13	97.9	3.91	0.74	82.7
16	100	71.05	433.47	0.16	95.2	5.46	0.77	85.9
32	129(emb)	91.65	535.71	0.14	95.0	6.57	0.82	85.2
32	100	71.05	772.34	0.19	95.0	9.14	0.79	93.0
LNGS (10)	67.46	75.24	396.43	0.23	94.6	4.44	0.63	82.1

PoP DESIGN



3000
657
750
800
2800
100
500
2600
3657
5657
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2500
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Scale: 1:2
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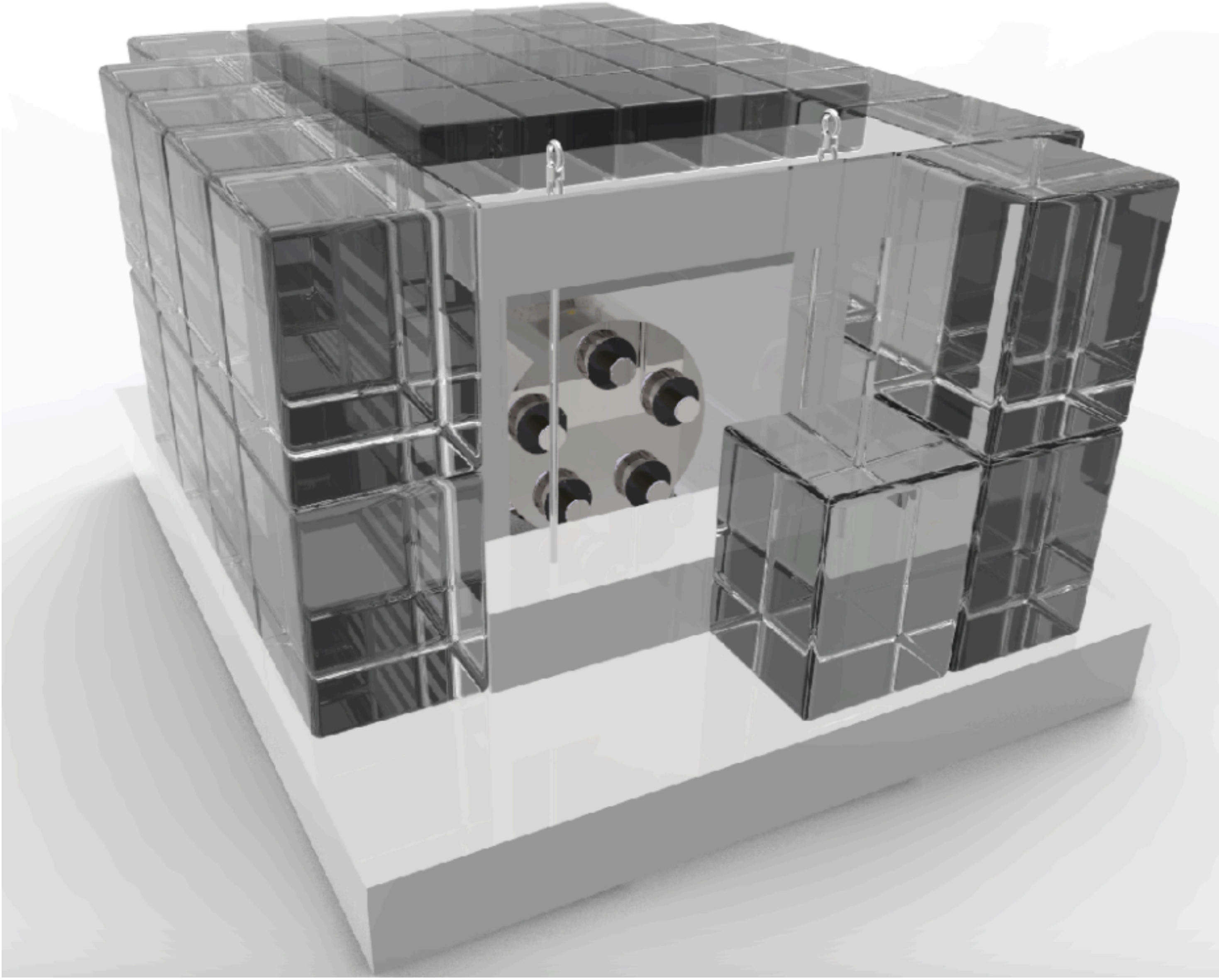
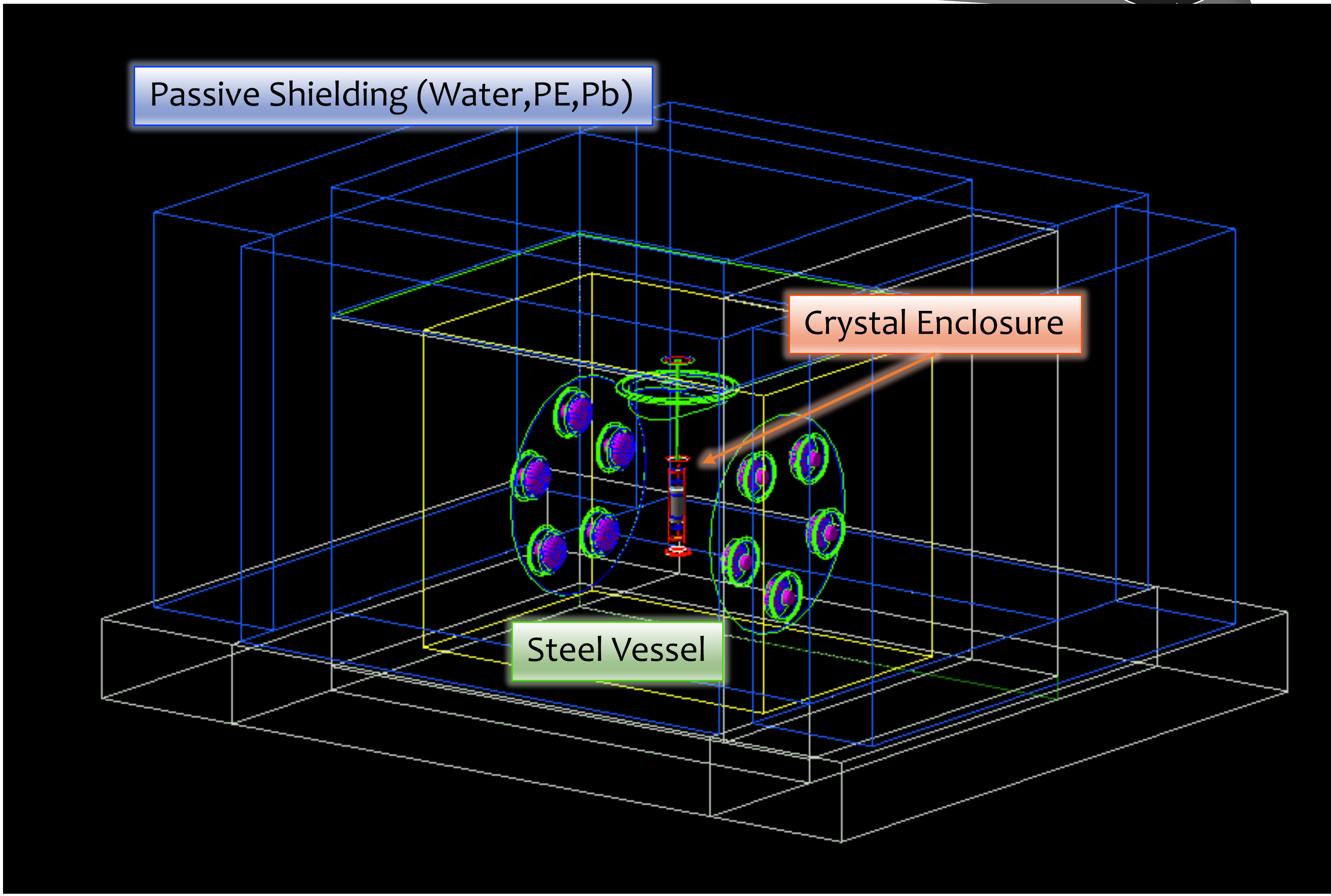
312.4
2100
150
1700
2500

PoP DESIGN



PoP design in simulation



Initial energy Cosmogenic Muons