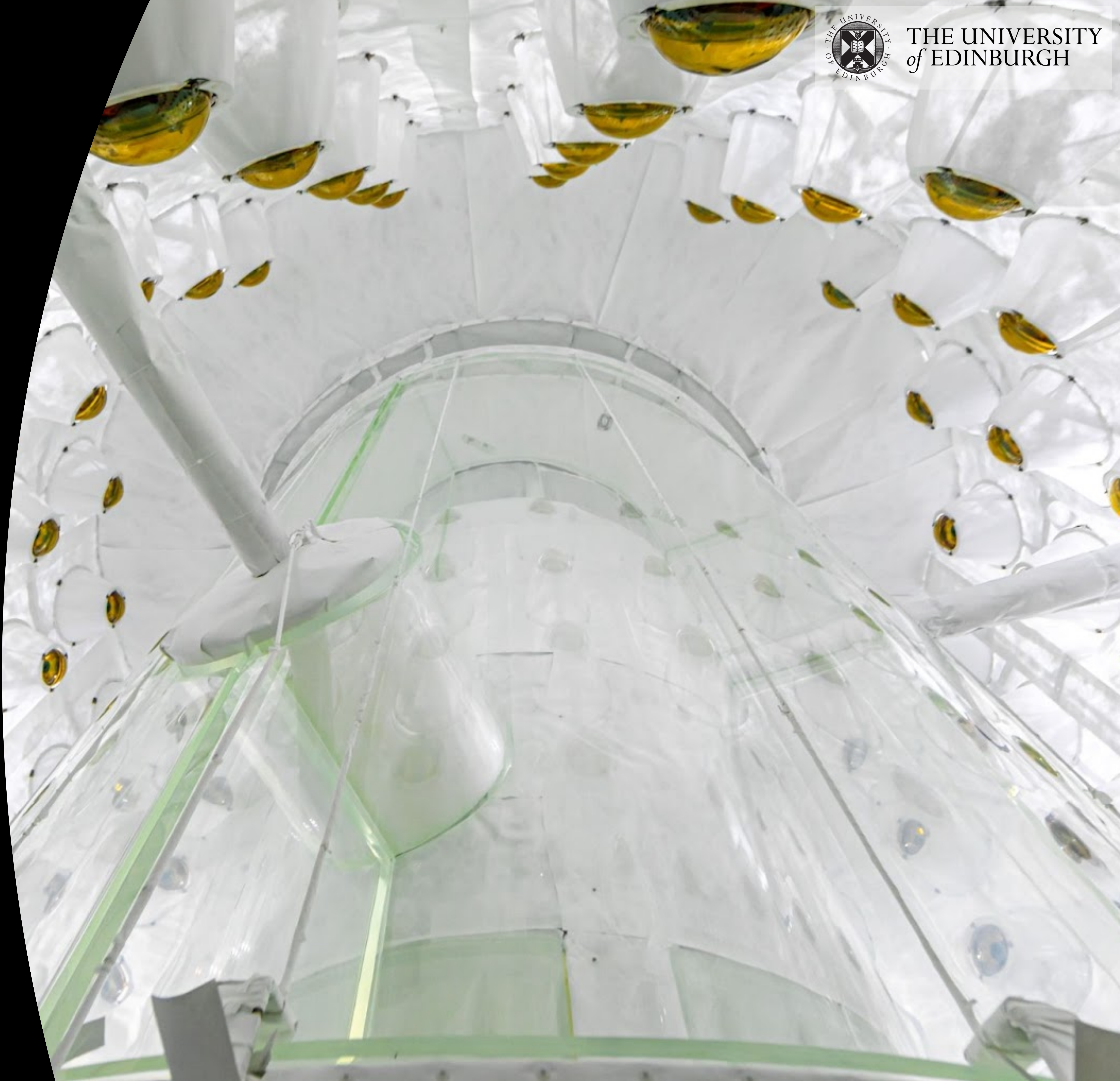
The LZ Outer Detector

IDM 2024

Alberto Uson
on behalf of the LZ Collaboration



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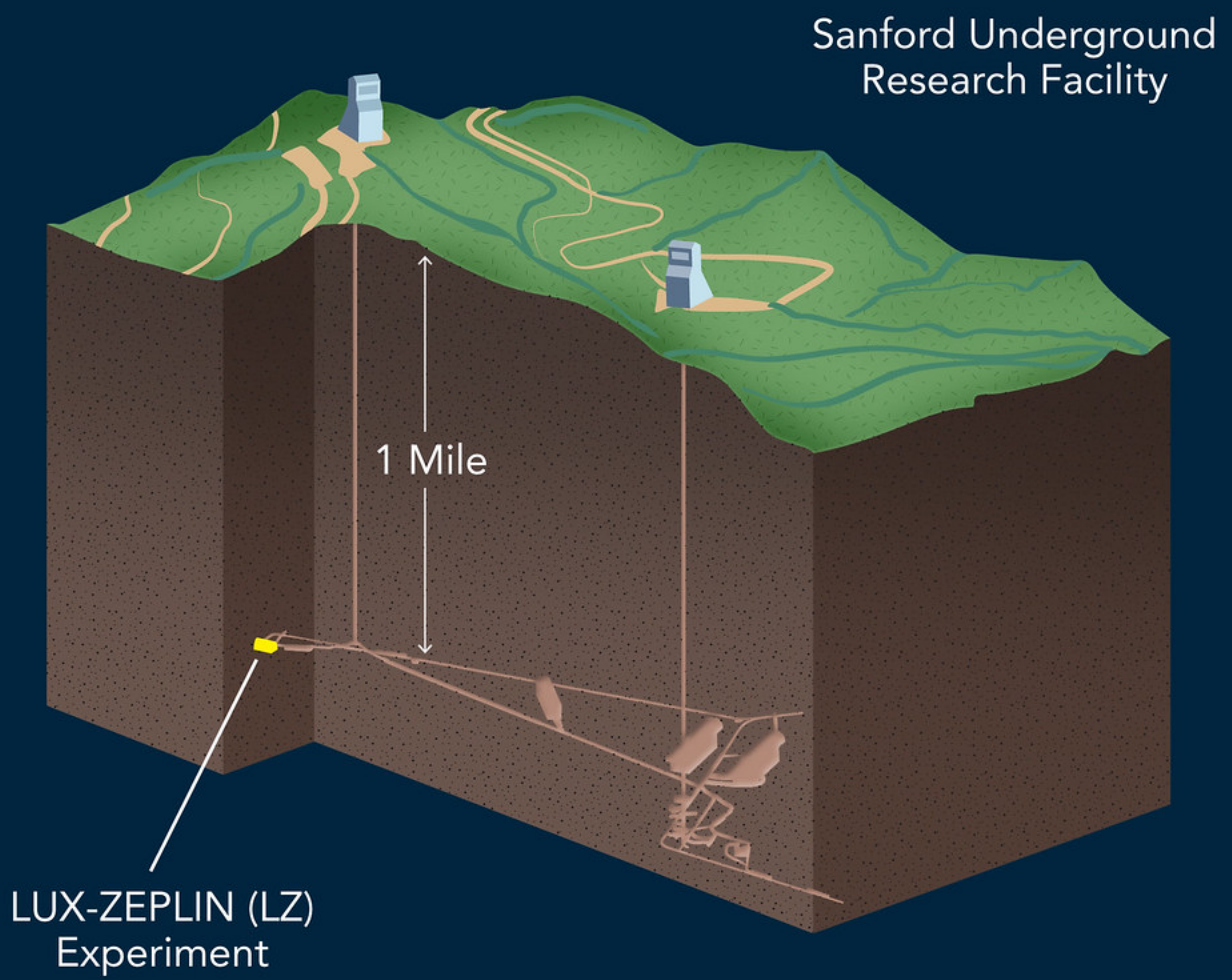
Outline

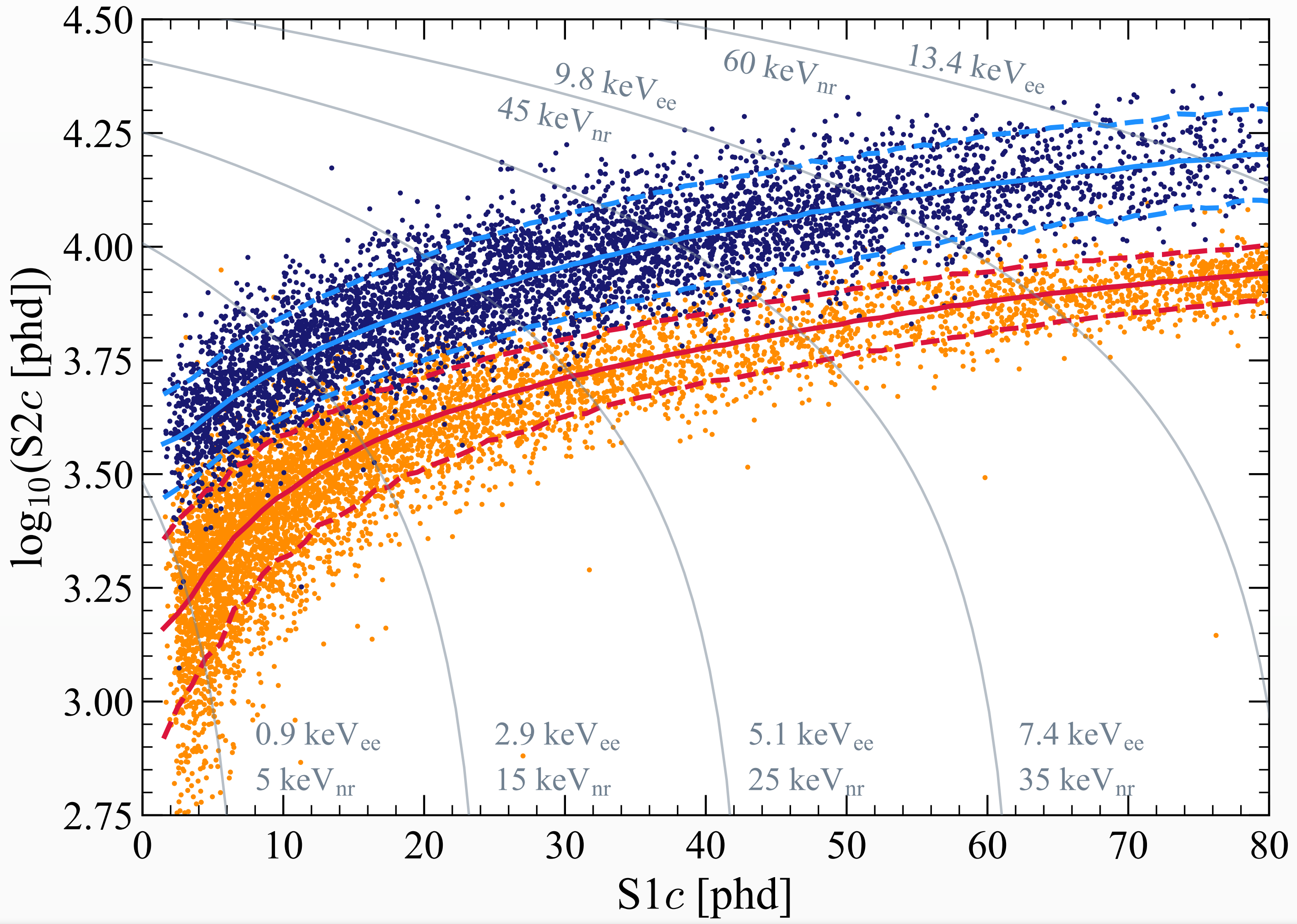
- The LZ experiment and motivation for a veto system
- The Outer Detector and its backgrounds
- Calibration and monitoring
- Neutron tagging efficiency
- Performance during Science Runs



The LUX-ZEPLIN (LZ) experiment

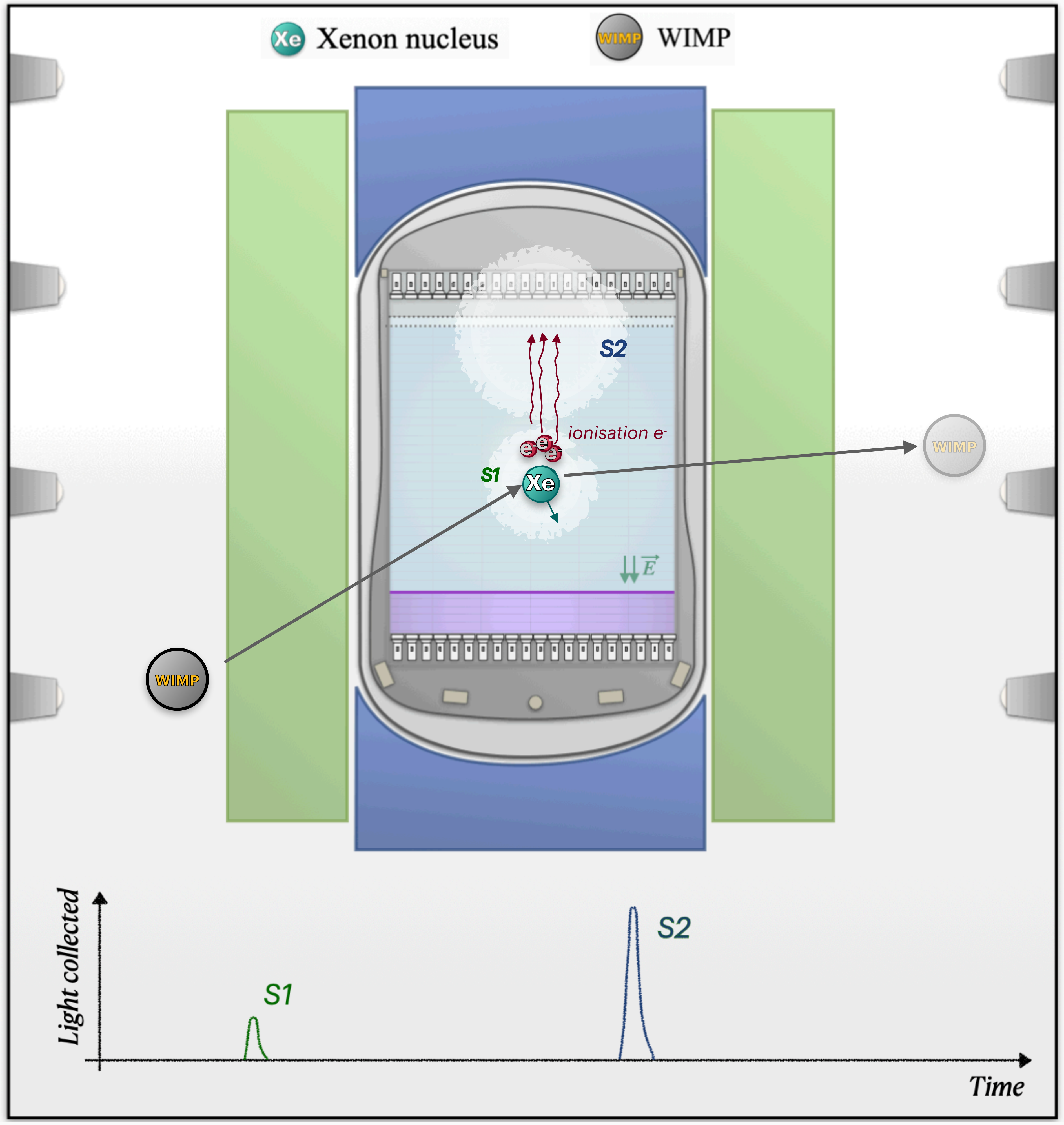
More info in [I. Olcina Talk]

- Optimised for searching **WIMP**s with masses in above ~5 GeV/c²
- Sensitive to additional processes, including BSM physics: solar neutrinos, $0\nu\beta\beta$, axions, etc
- Located in the Davis Cavern of SURF (Lead, South Dakota)
- Detection based on a 7t active mass **dual-phase xenon EL-TPC**: events reconstructed combining scintillation (S1) and ionisation (S2)
- S2/S1 ratio indicates the type of interaction:
  - Nuclear recoils (**NR**) in xenon mostly from WIMPs
  - Most backgrounds are Electron Recoils (**ER**)



Phys. Rev. Lett. 131, 041002 (2023)

Calibration data in $\log_{10}$(S2c) vs S1c space using a tritium source and a DD neutron source



NR backgrounds in LZ: neutrons

- Some backgrounds -e.g. CEνNS neutrinos or leakage ER events- can also produce WIMP-like NR recoils.
- Among them, **neutrons** are the predominant ones, they are mainly produced through:
  - Natural radioactivity in detector components or cavern:
    - (α,n) reactions → single neutrons often without coincident γ's. Main sources being: PTFE, PMT (as they contain low-Z materials)
    - Spontaneous fission from heavy nuclei (^{238}U, ^{235}U, ^{232}Th) → several n's (~2) and coincident γ's (~6)
  - Induced by atmospheric muons
- Some assets can be leveraged to distinguish from WIMP signal:

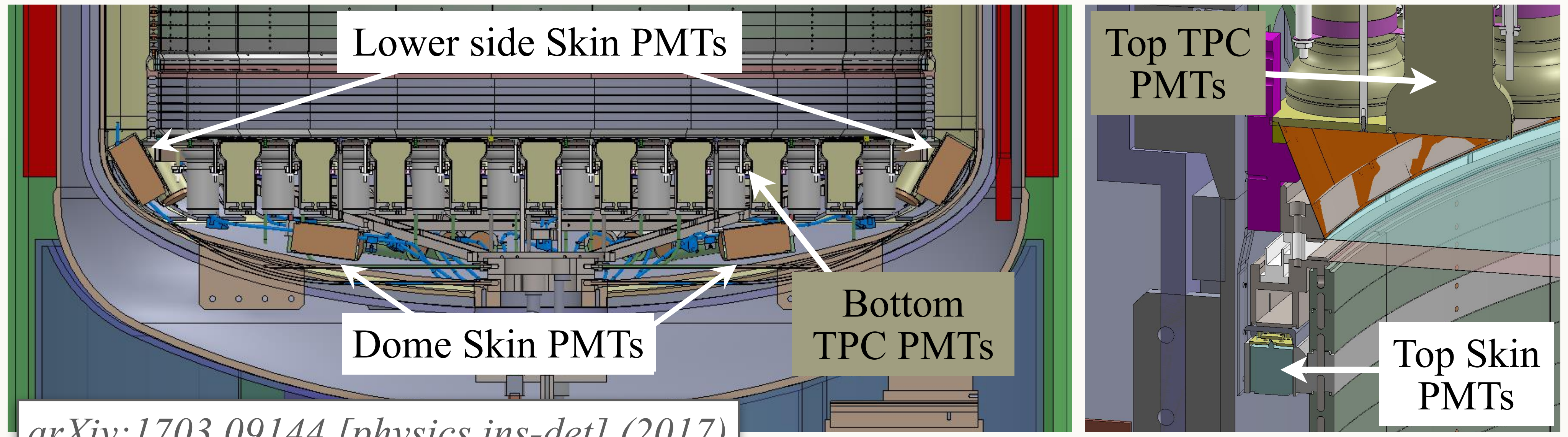
	# interaction in LXe	**Location in active TPC**	**Interaction in surrounding materials**
WIMPs	1	Homogeneous	No
neutrons	1 or more	Closer to TPC boundaries	Yes

The LZ neutron veto system: Skin+OD

- Definition of the “surrounding materials” of previous slide:

Skin detector

1. 2t-LXe region between TPC outer walls and inner cryostat vessel: 93 PMTs at the top and 38 PMTs at the bottom

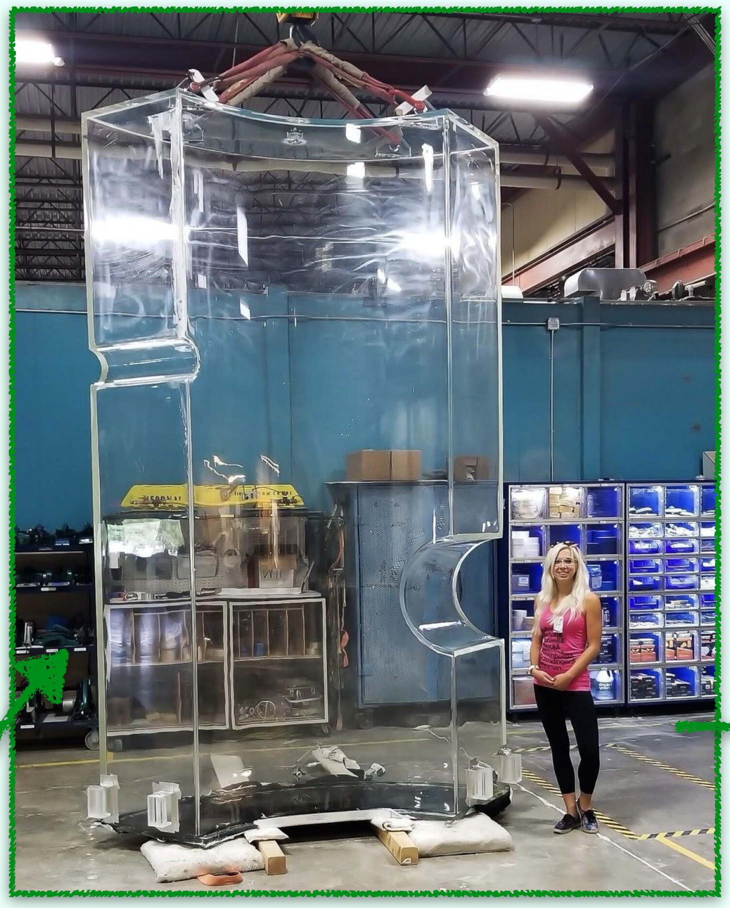


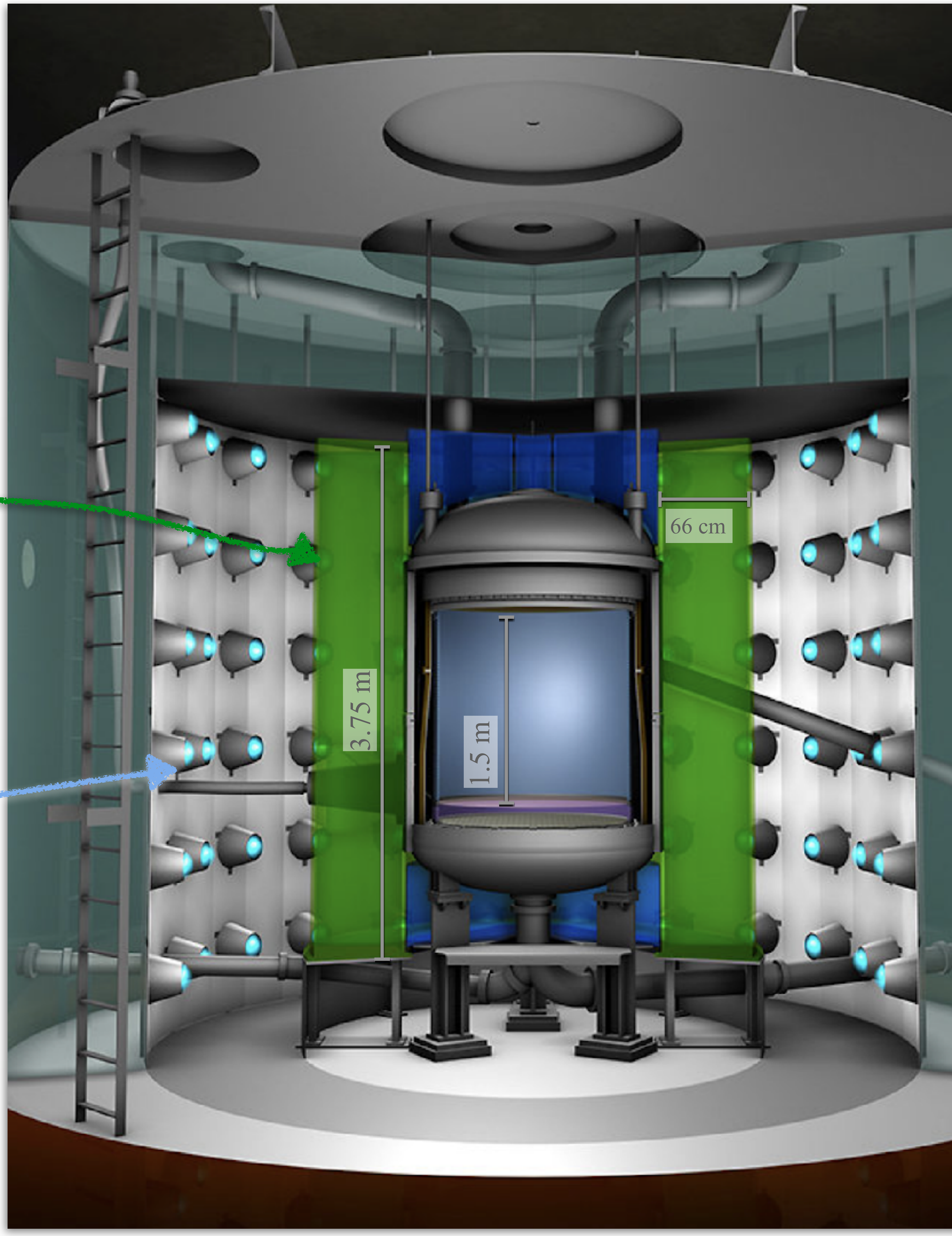
arXiv:1703.09144 [physics.ins-det] (2017)

Outer detector (OD)

2. 10 UV-transparent acrylic tanks with 17t of Gadolinium-loaded (0.1% by mass) liquid scintillator to increase n-capture efficiency

3. A tank filled with ~238t of ultra-pure water instrumented with 120 8-inch PMTs

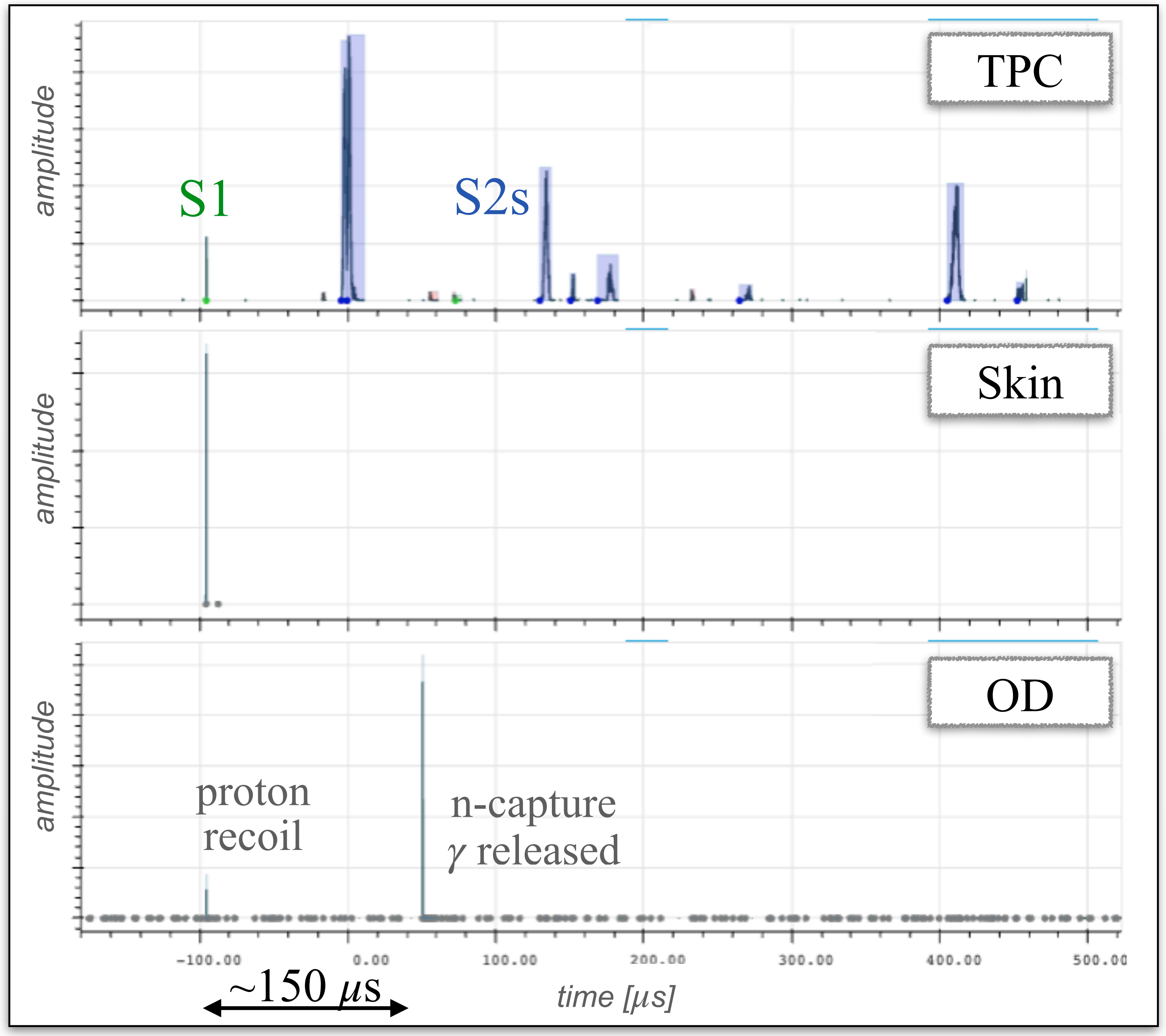




The LZ neutron veto system

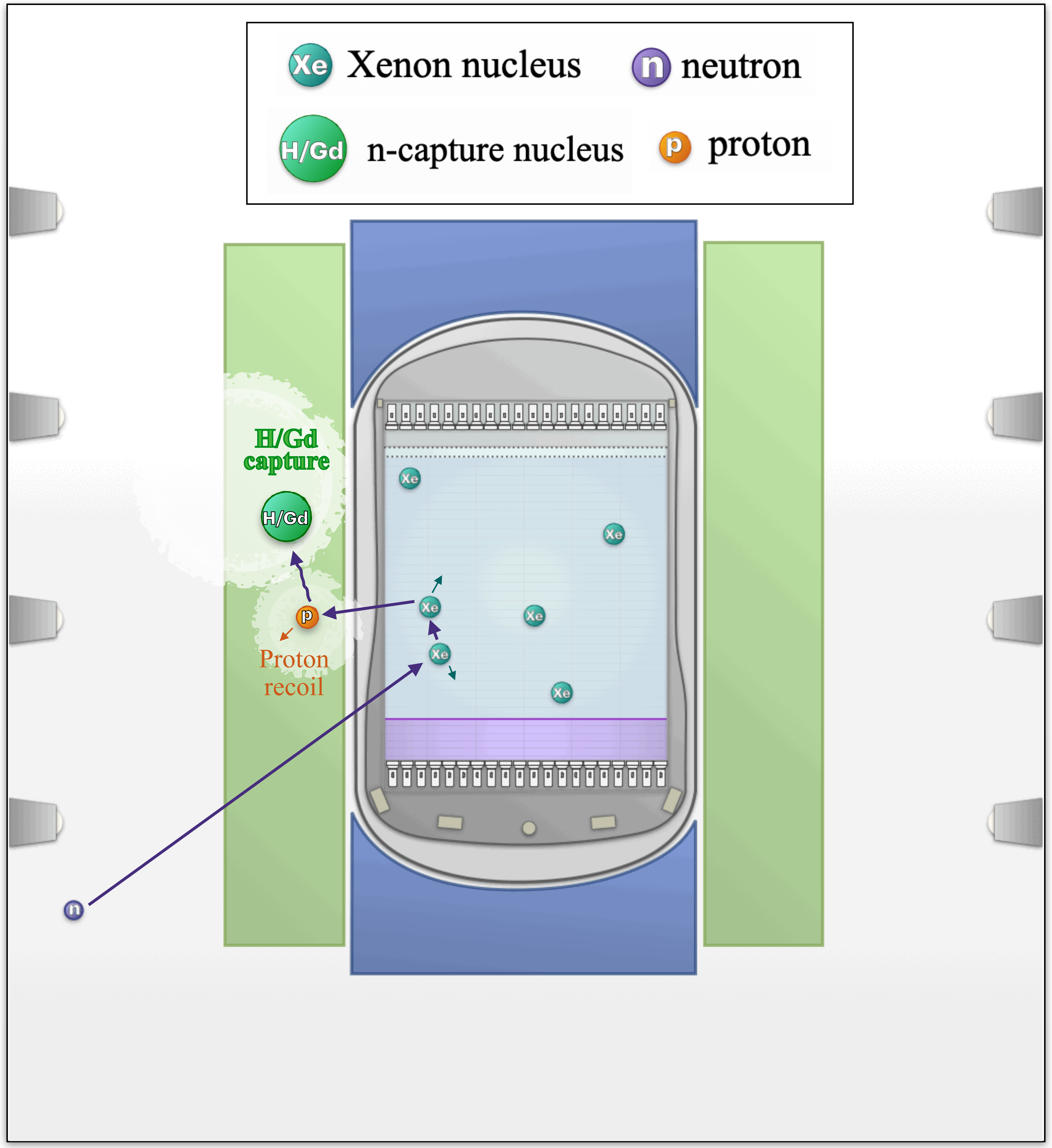
Signature of neutron events in the detector system:

1. Single or multiple scatters in TPC
2. Once out, thermalise through collisions with H → prompt pulse in OD
3. Captured later (~28 μs on average, reduced from ~218 μs thanks to Gd in LS):
   - In **H** → Single 2.2 MeV γ
   - In ^{157}**Gd**/^{155}**Gd** → cascade of ~4-5 γ's up to 7.9/8.5 MeV



Resulting waveforms

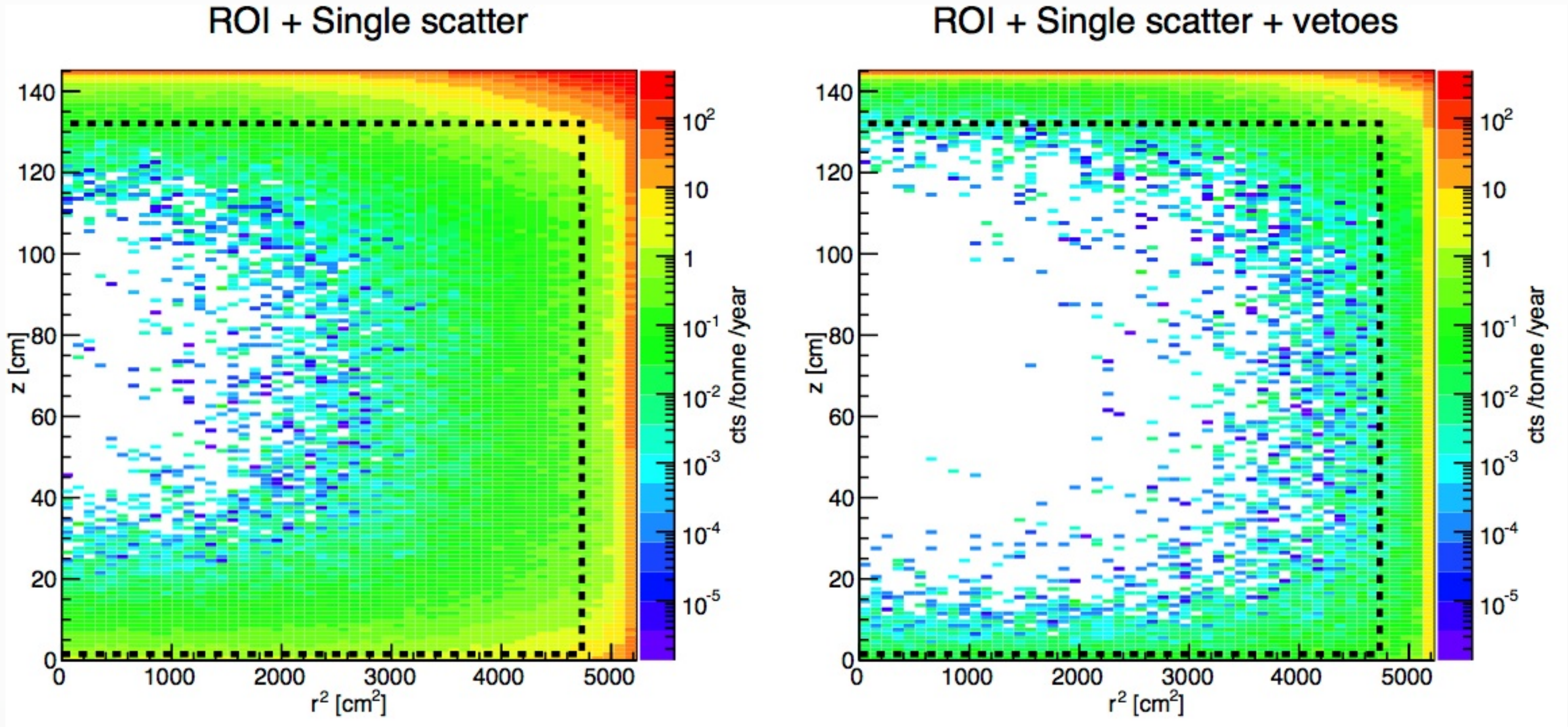
We expect "delayed" pulse from eventual n-capture γ's, plus a possible "prompt" (S1-coincident) one from proton recoil



The LZ Outer Detector

- Then, the outer detector is a fundamental piece in the experiment to tag and reduce the number of neutrons (main NR background contribution) and gamma backgrounds
- Likewise, the OD allows increasing the TPC fiducial volume, with a direct consequence in the exposure

Total NR background (+ER leakage) from detector materials simulations



arXiv:1703.09144 [physics.ins-det] (2017)

➡ Amount of LXe needed to meet LZ background requirements for >~5.5t FV:

11t (no veto) vs 7t (with veto)

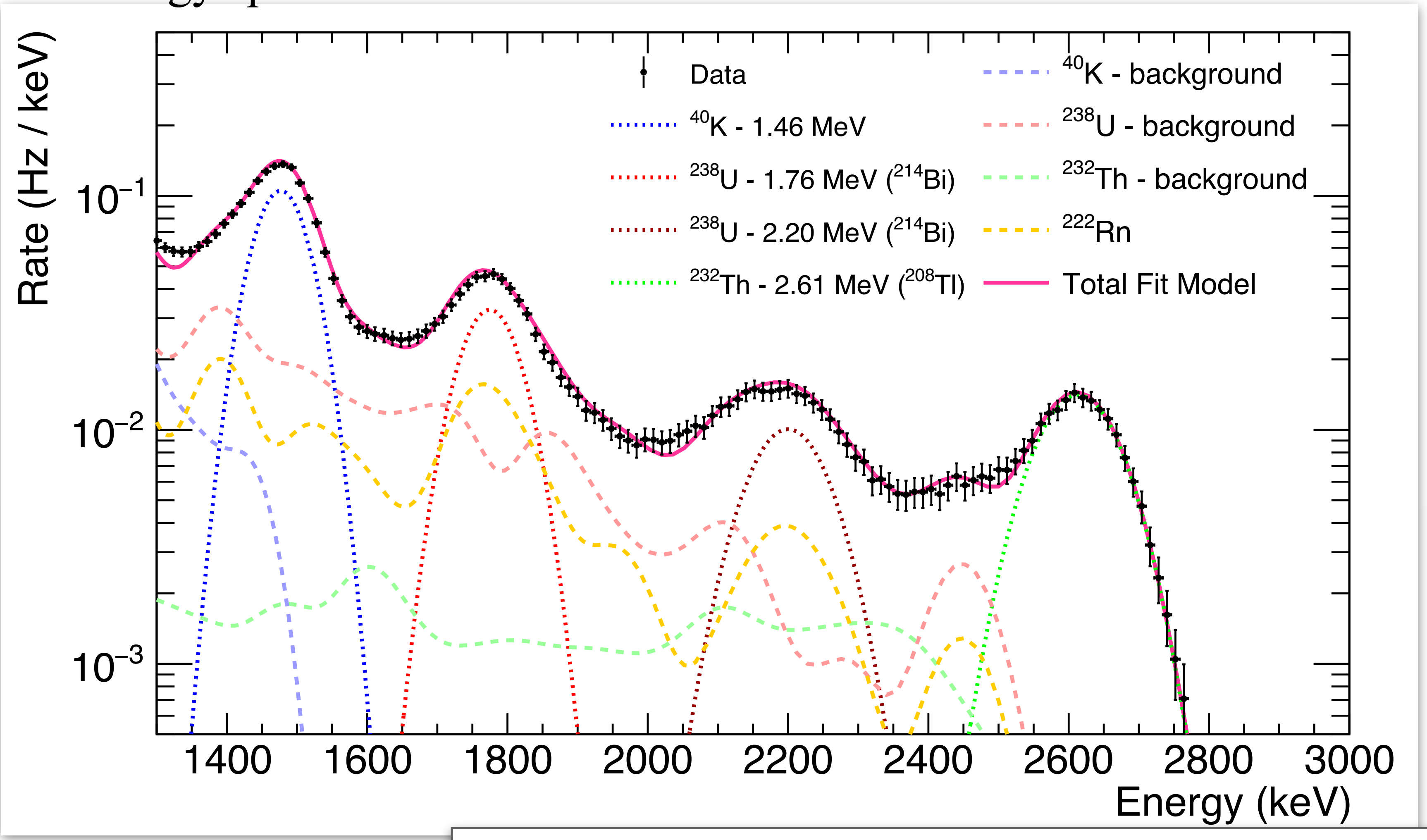
OD backgrounds

- Events with OD depositions that are neutrons/gammas uncorrelated with TPC
- Main sources:
  - **Davis Cavern γ's** from intrinsic radioactivity of cavern walls
    - Dominates OD event rate above 200 keV
    - NaI detector @ 9 different positions used to measure flux →

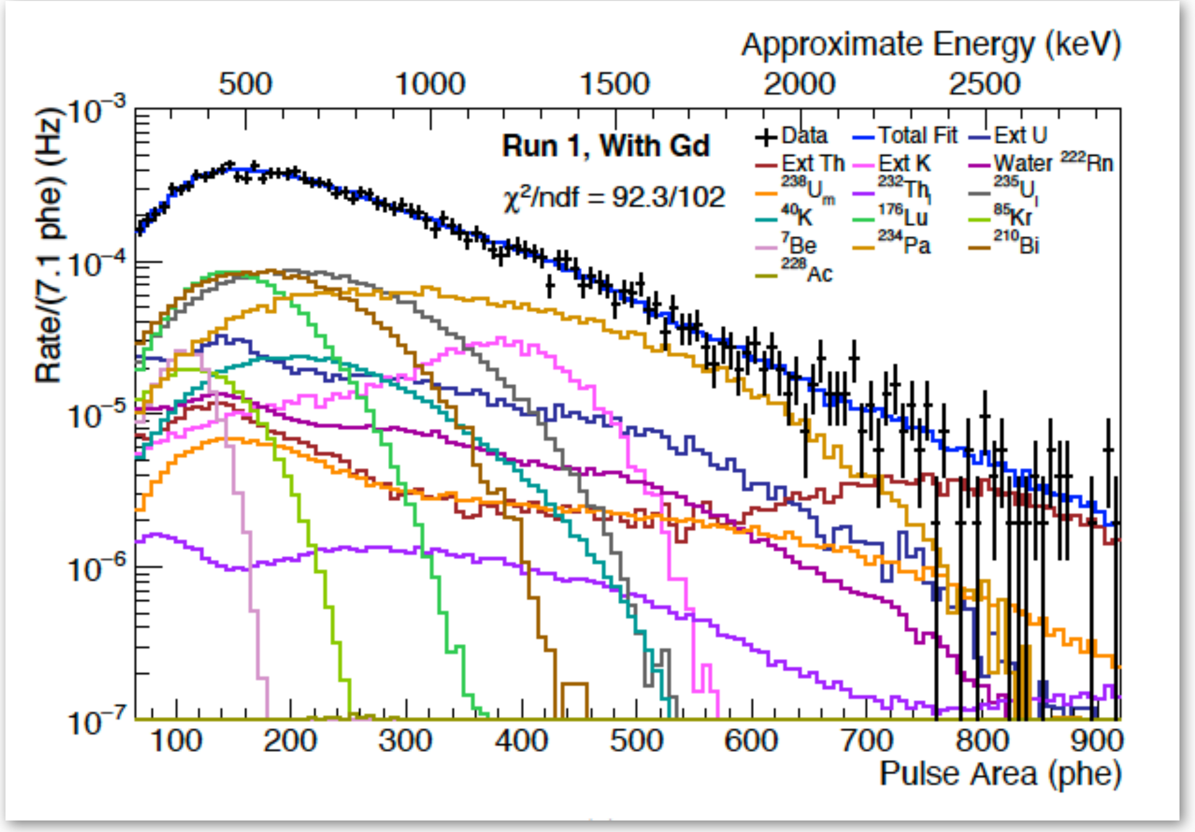
	^{40}K - 1461 keV	**^{238}U - 1764 keV**	**^{232}Th - 2614 keV**
Average activities [Bq/kg]	220 ± 60	29 ± 15	13 ± 3

  - **Detector components** radioactivity
    - Main contributions: OD PMTs, Acrylic and supports, and cryostat vessel
  - $\alpha/\beta/\gamma$ decays from **radioimpurities** dissolved in **GdLS**
    - Activities measured with custom-made screener
    - Most significant sources of background:
      - → ^{238}U chain, ^{235}U chain, ^{14}C, ^{152}Gd, ^{147}Sm, ^{172}Lu

Energy spectra measured on the floor at the centre of water tank



Astroparticle Physics, Volume 116, Pages 102391 (2020)



β/γ fits

Nucl. Inst. Meth. A (2019) (148-163)

OD backgrounds

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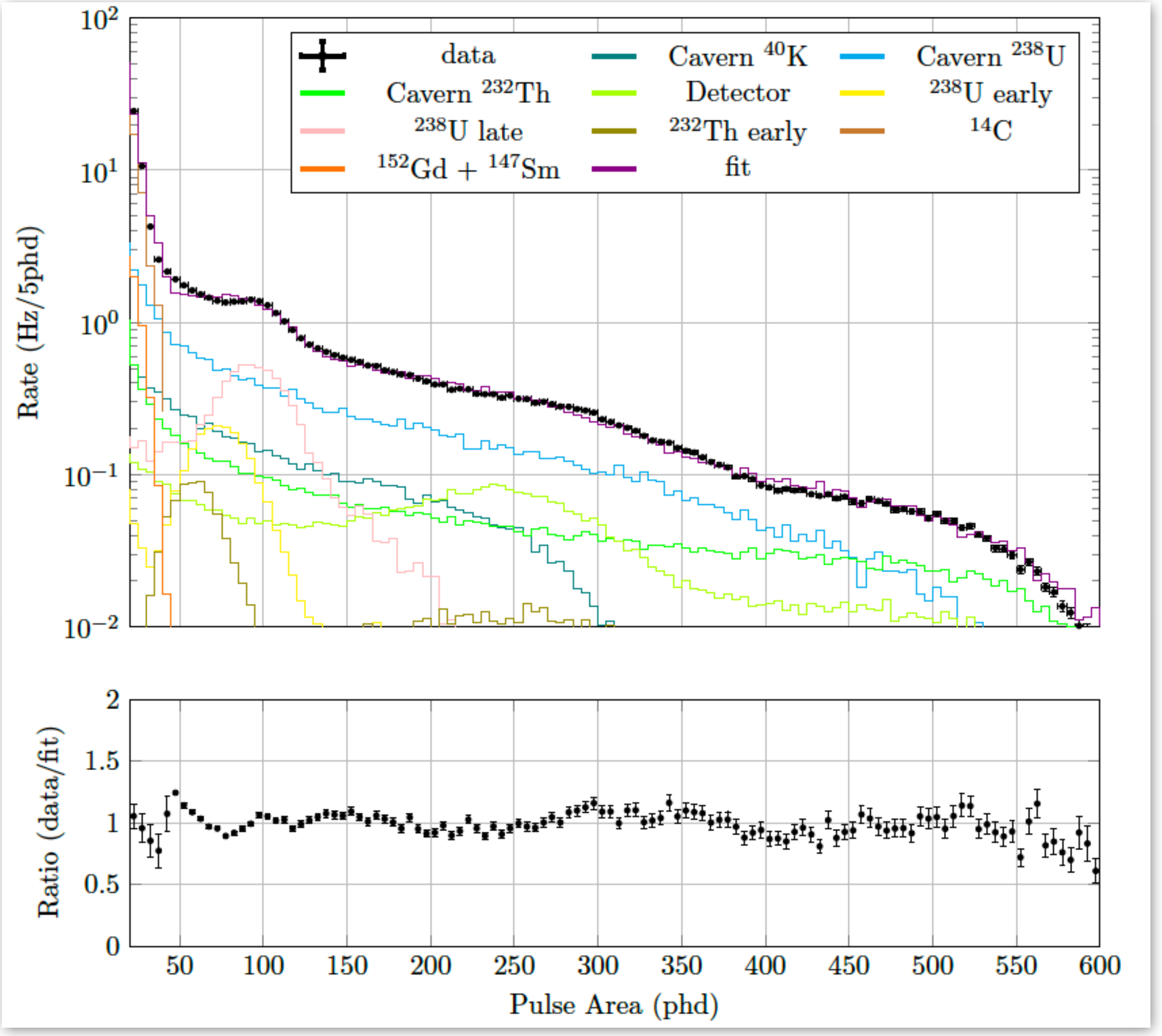
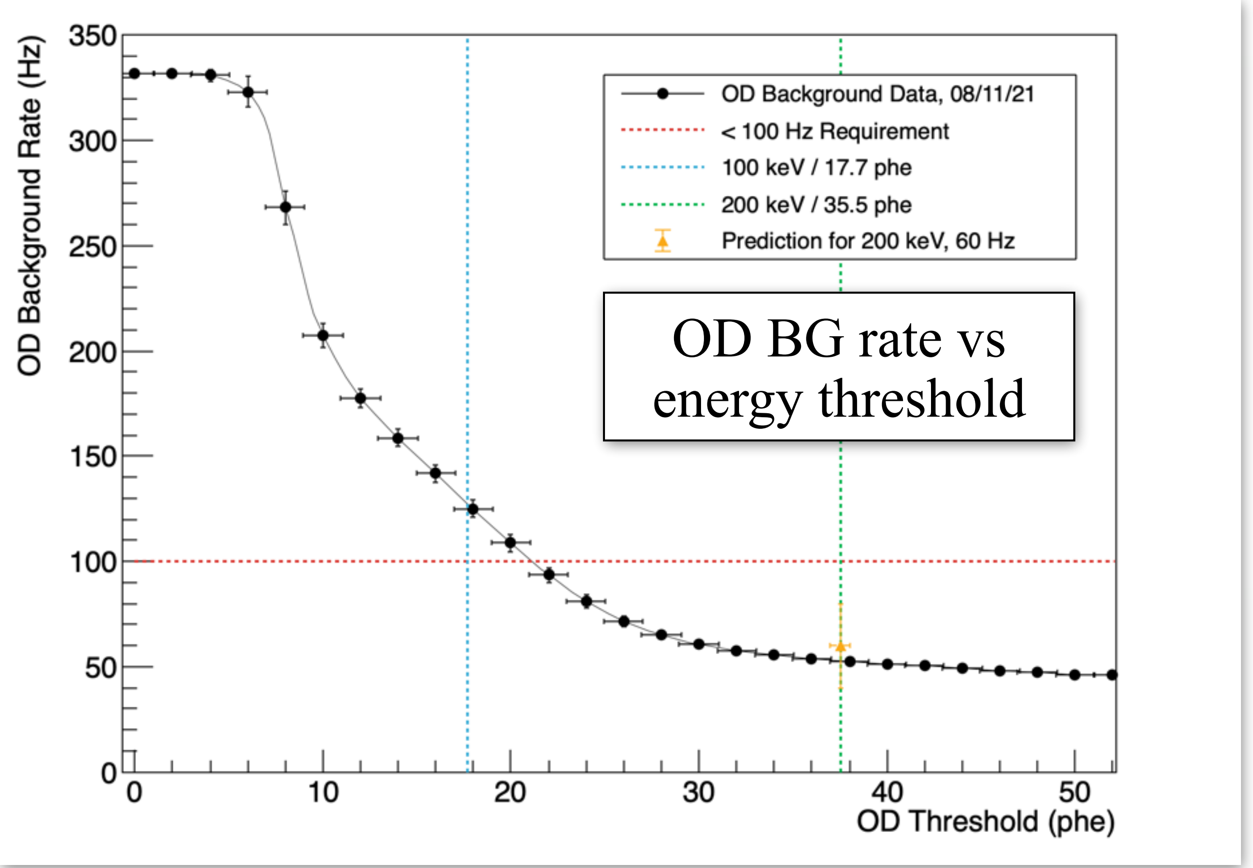
$\rightarrow$ ^{238}U chain, ^{235}U chain, ^{14}C, ^{152}Gd, ^{147}Sm, ^{172}Lu

Total OD BG during first Science Run



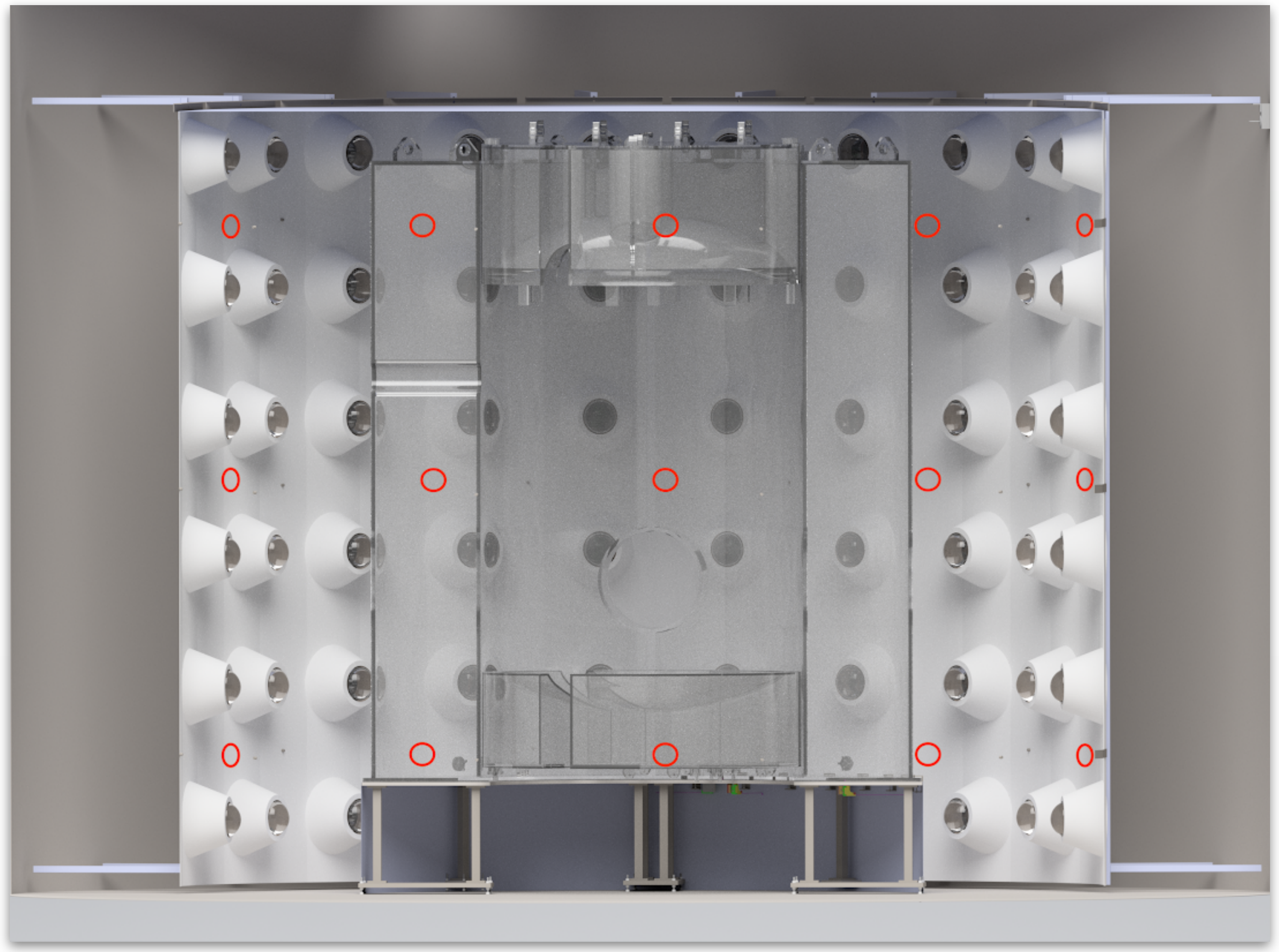
S. Eriksen (2022), U. Bristol

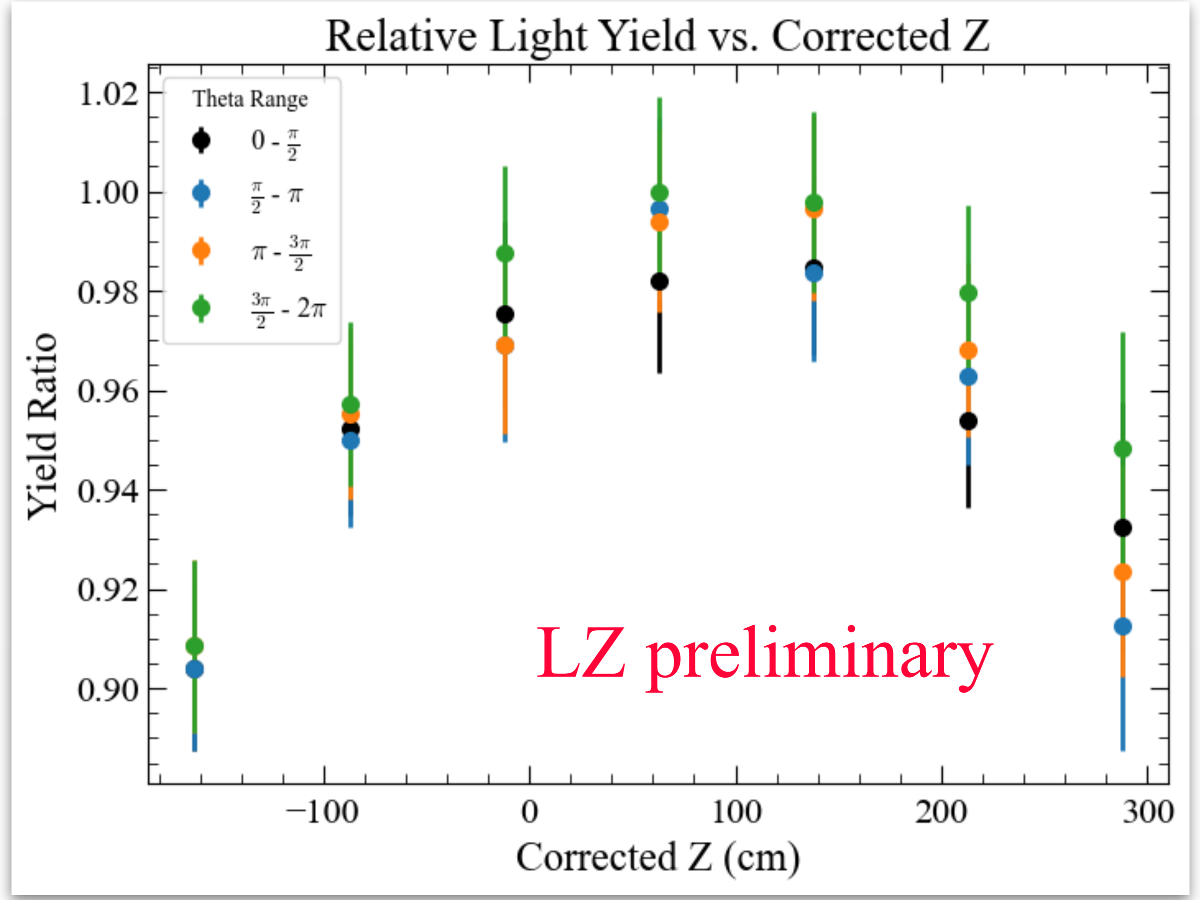


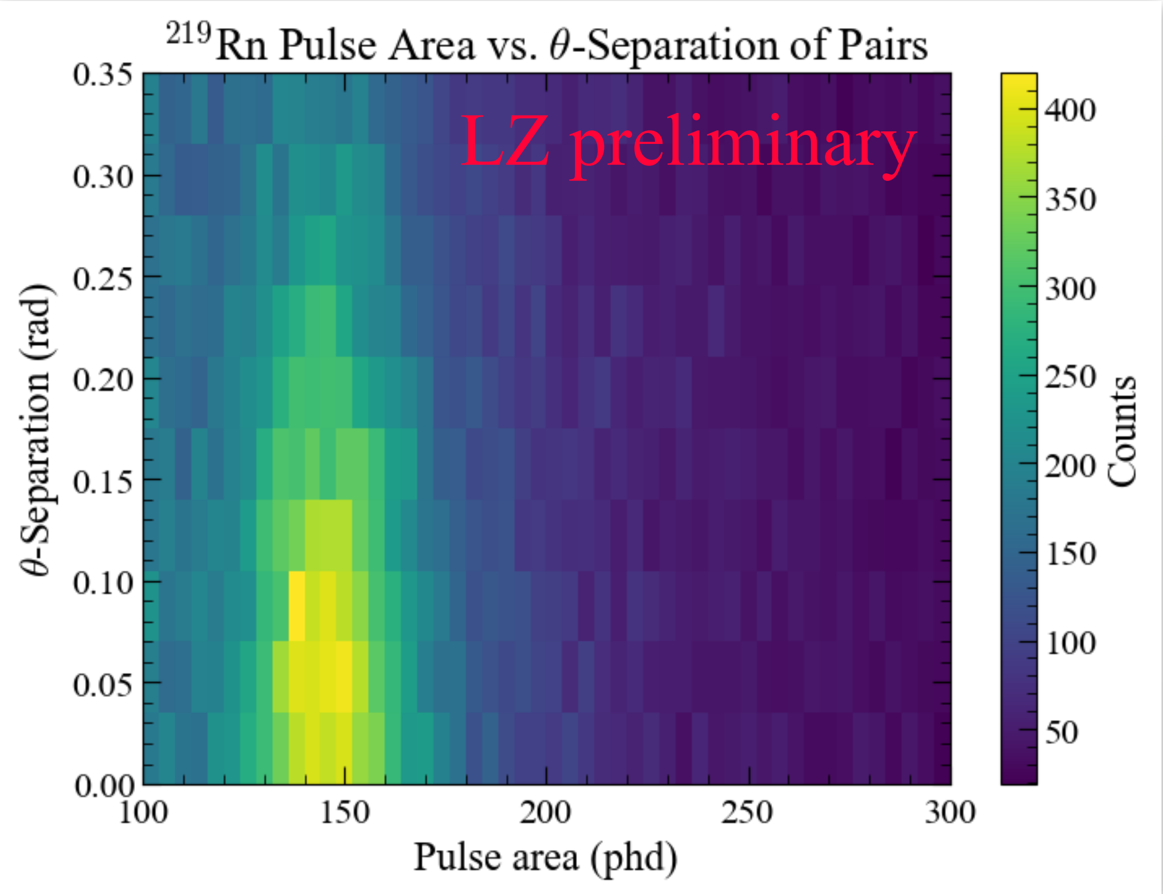
OD BG rate vs energy threshold

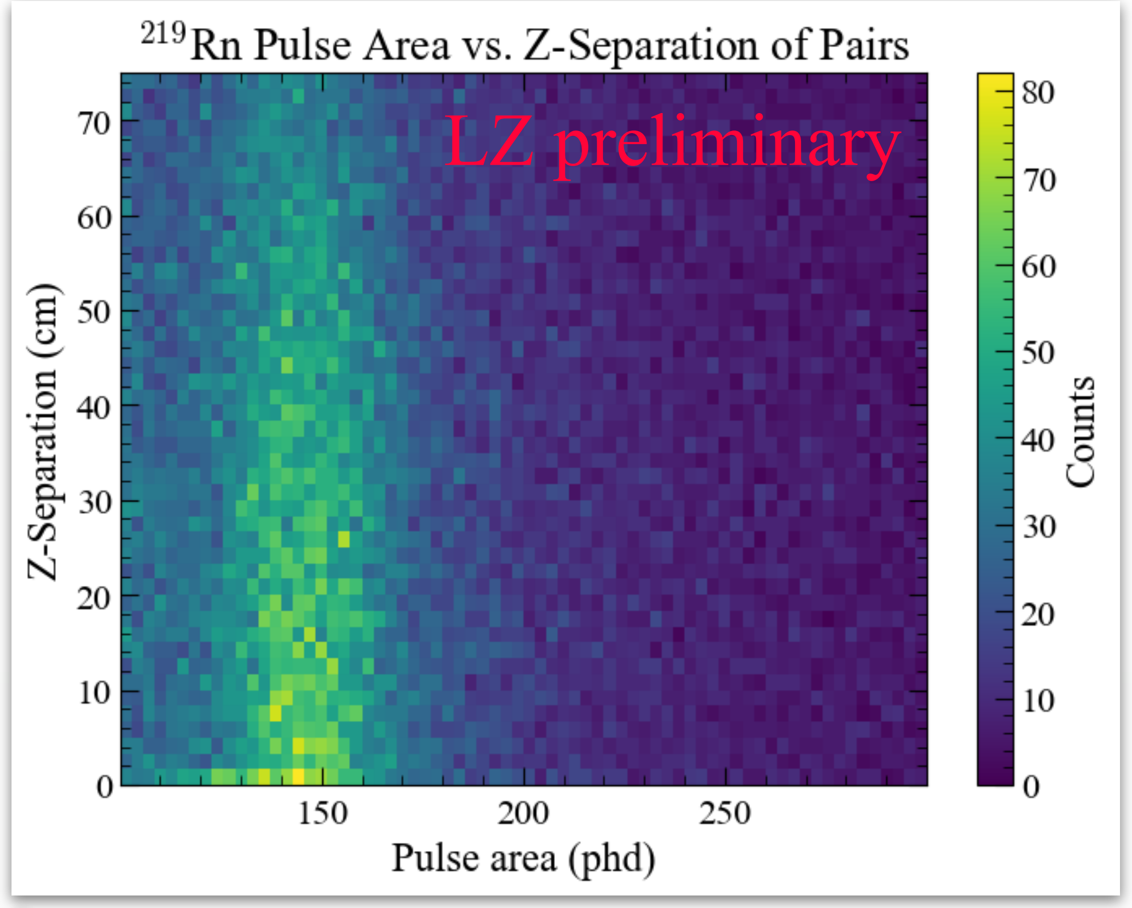
OD calibration and light yield studies

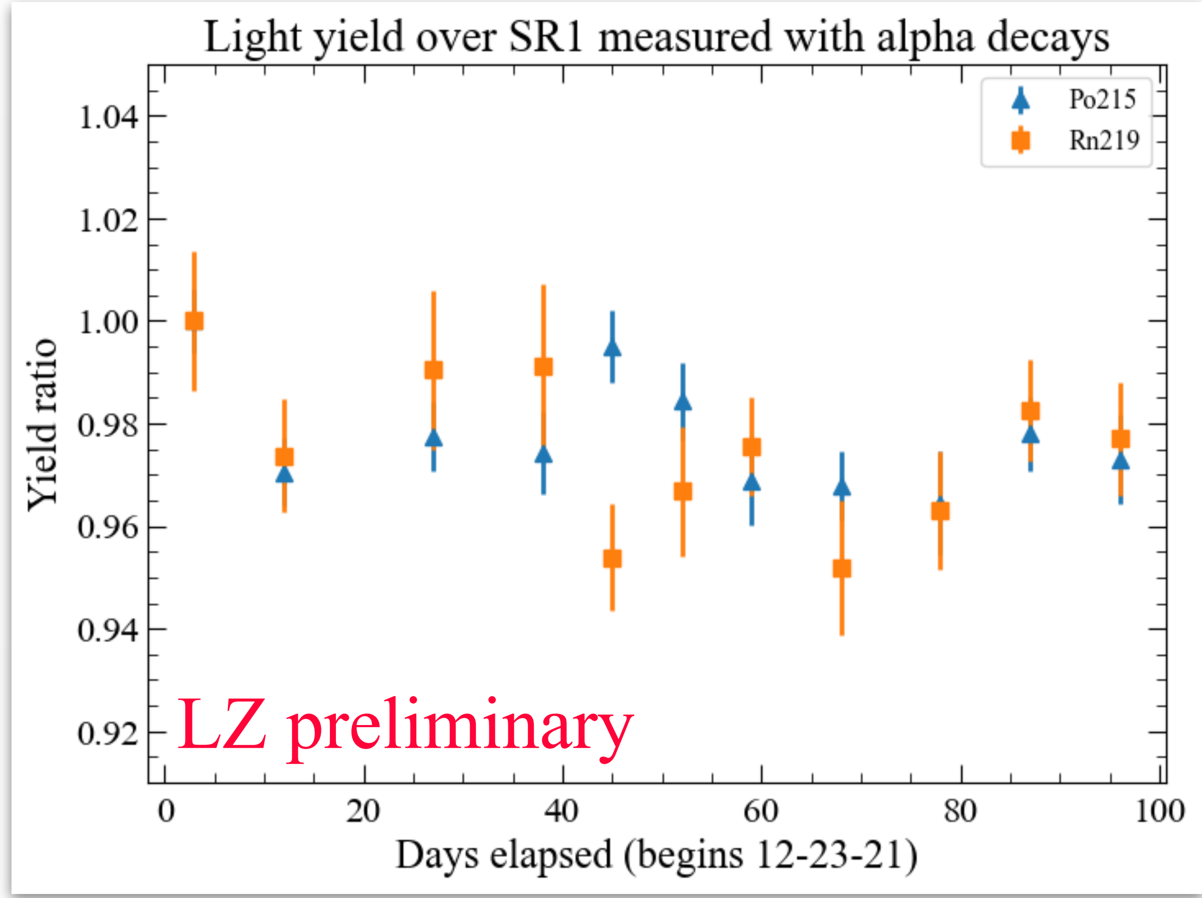
- 35 LED-driven optical fibres used to calibrate and monitor PMT single photon response Nucl. Inst. Meth. A (2021) 165551
- Uniformly distributed ^{219}Rn and ^{215}Po alphas from backgrounds used for:
  - Studying light yield position dependence → ~10% maximum variation with Z
  - OD Z (74.8 cm) and θ (0.24 rad) spatial resolution
  - Checking time stability during Science Runs







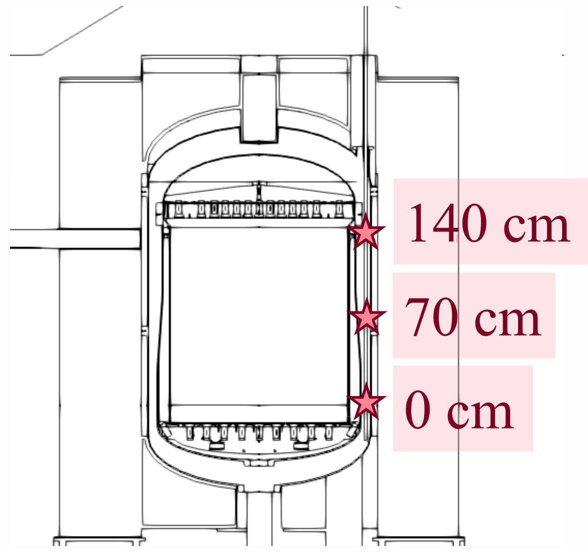




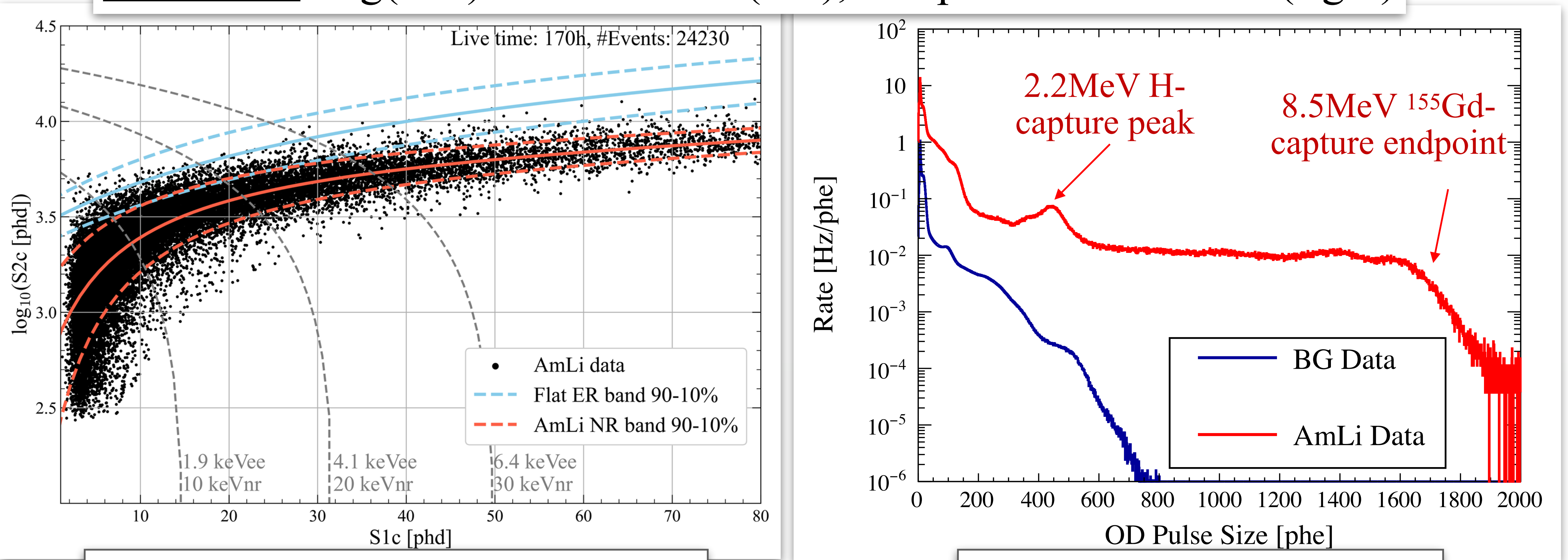
Neutron tag studies with OD

- OD neutron tagging efficiency performed in LZ with a variety of neutron sources. Main ones:
  - **AmLi**: low-energy (<1.5MeV ≡ ~45 keV_{nr}) neutrons
  - **AmBe**: energies up to ~11 MeV (≡ ~330 keV_{nr})
    → around 58% accompanied with prompt 4.4 MeV gamma.

Both deployed in CSD tubes (3 azimuth angles) at configurable positions along the TPC height

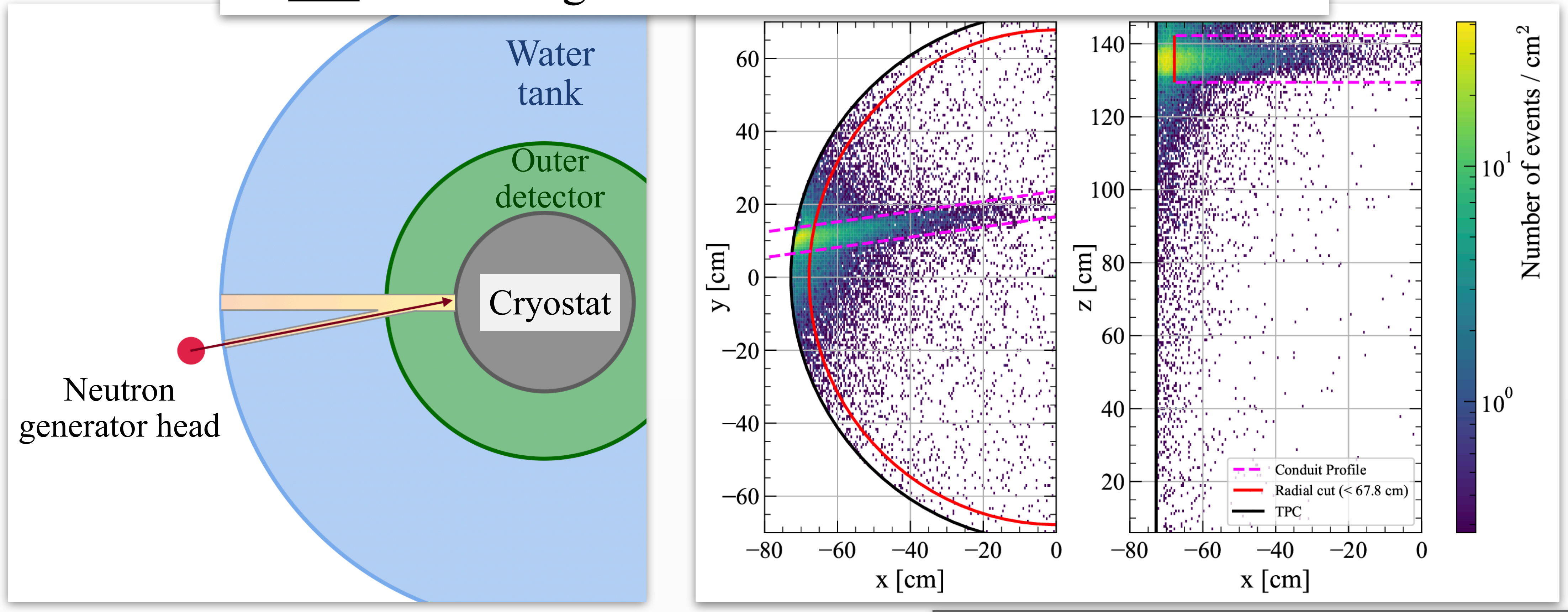


AmLi data: log(S2*c*)vsS1*c* in TPC (left), OD pulse area vs BGs (right)



arXiv:2406.12874 [physics.ins-det] (2024)
Phys. Rev. D 108, 012010 (2023)

DD source aligned with conduit as in direct more

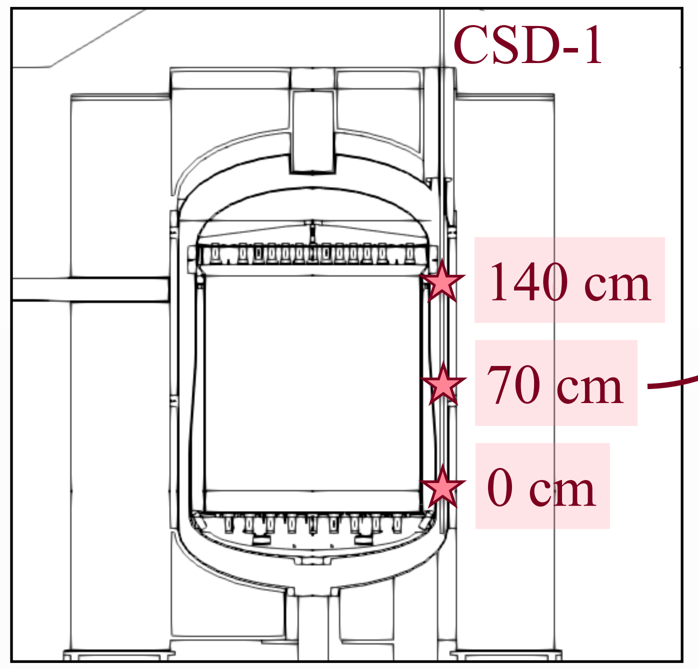


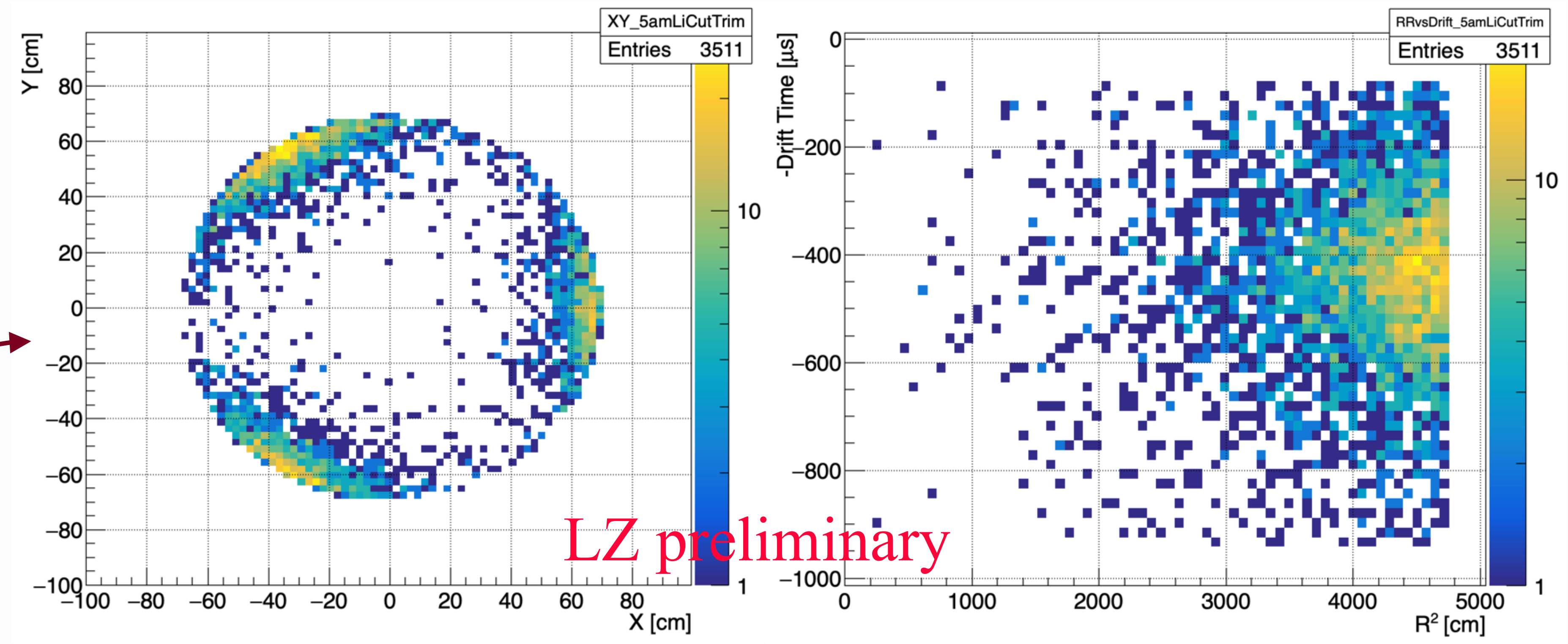
arXiv:2406.12874 [physics.ins-det] (2024)

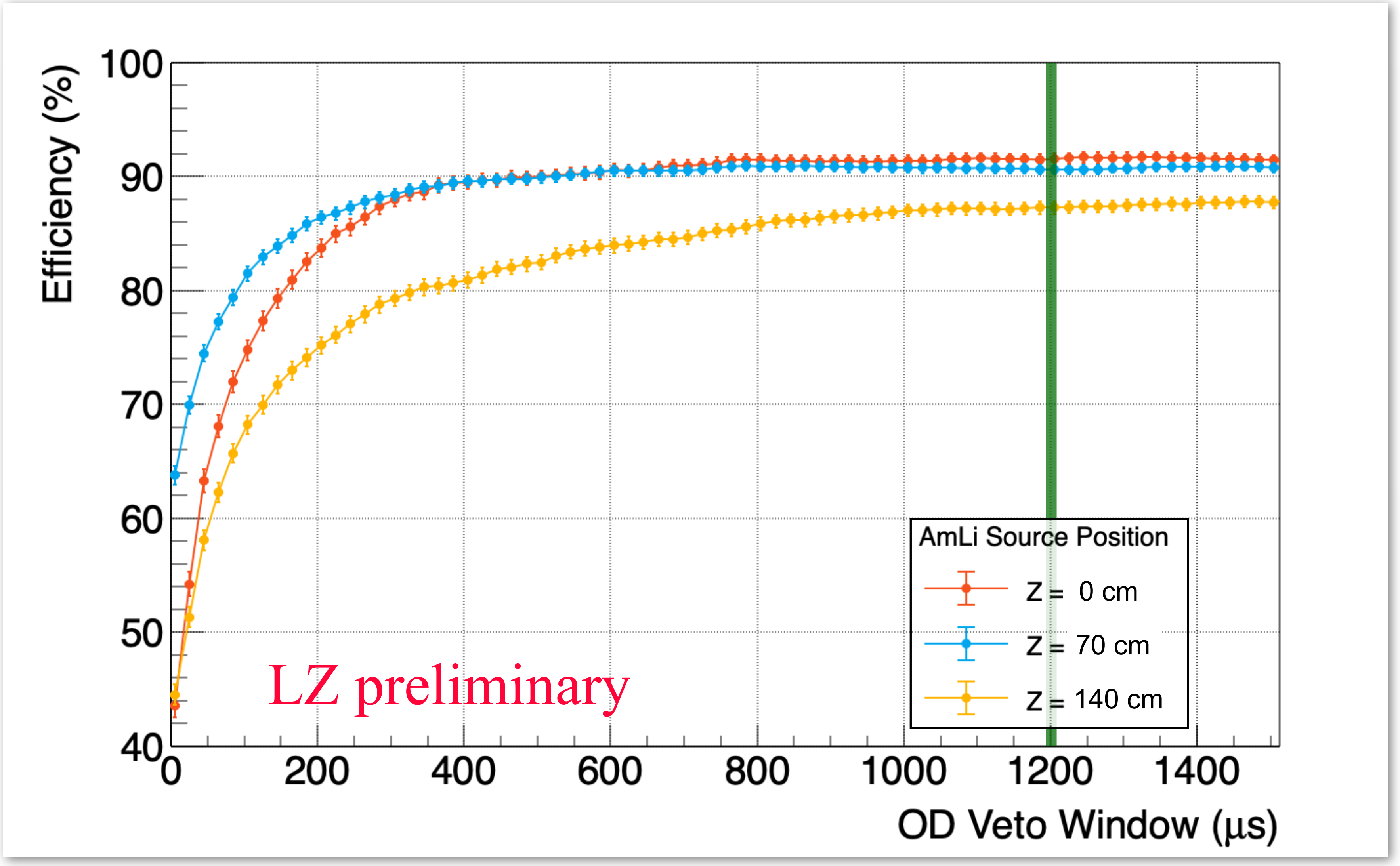
- **DD** generator with configurable neutron energy distributions close to the top of TPC (fixed)
  - e.g. direct mode → monoenergetic 2.45 MeV (~74 keV_{nr})

Neutron tagging efficiency for First Science Run (SR1)

- 3 AmLi sources at different azimuthal angles used for given Z positions: 0, 70, and 140 cm (from TPC bottom)
- E.g. $Z = 70$ cm:







- 1σ cut around SS NR band to ensure neutron sample
- Events vetoed if contain pulses in any of these 4 windows (configured for 5% deadtime):
  - Skin Prompt: >2.5phe pulses with *ΔT_{skin} in (-0.5, 0.5) μs
  - OD Prompt: pulses with ΔT_{OD} in (-0.3, 0.3) μs
  - Skin Delayed: >50phe pulses with ΔT_{skin} in (0.5, 1200) μs
  - OD Delayed**: >37.5phe pulses with ΔT_{OD} in (0.3, 1200) μs

Total neutron tagging efficiency averaged across Z positions with AmLi source: **89 ± 3%**

*$\Delta T_{skin,OD} \equiv t_{S1} - (t_{pulse})_{skin,OD}$

**Rate of accidental pulses (due to windows size) accounted for in the associated tagging efficiency

OD constraints for SR1 WIMP Search (WS)

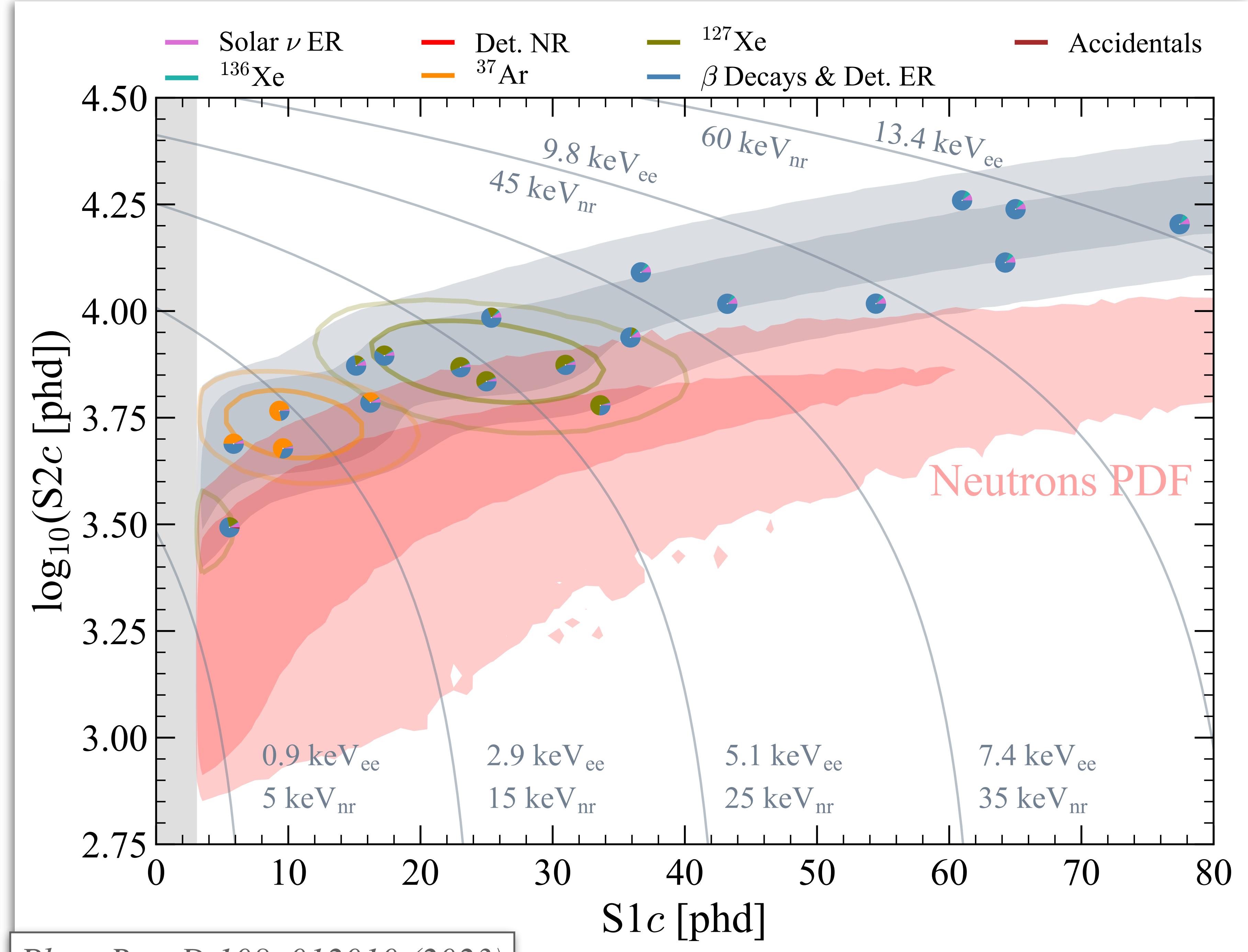
Neutron background for WIMP search [I. Olcina talk] constraint assessed via two ways:

1. Auxiliary fit (and analogous to WS) to events passing all cuts except OD veto:
   - Non-neutron events with accidental OD-TPC coincidence taken into account (5%)
   - Best-fit values for each contribution in 60 days:

OD-tagged events

Source	Expected Events	Fit Result
Solar ν ER	1.44 ± 0.03	1.43 ± 0.03
Detector neutrons	0.8	$0.0^{+0.8}$
^{37}Ar	2.9 ± 0.5	2.8 ± 0.5
^{136}Xe	0.79 ± 0.12	0.79 ± 0.12
^{127}Xe	1.6 ± 0.2	1.6 ± 0.2
β decays + Det. ER	10.7 ± 2.6	11.3 ± 2.2
Accidentals	0.09 ± 0.03	0.10 ± 0.03
Total	18.2 ± 2.7	18.1 ± 2.4

   - Which corresponds to $\mathbf{0.0^{+0.2}}$ neutrons in 60 days × 5.5 t exposure in the WIMP fit region



Phys. Rev. D 108, 012010 (2023)

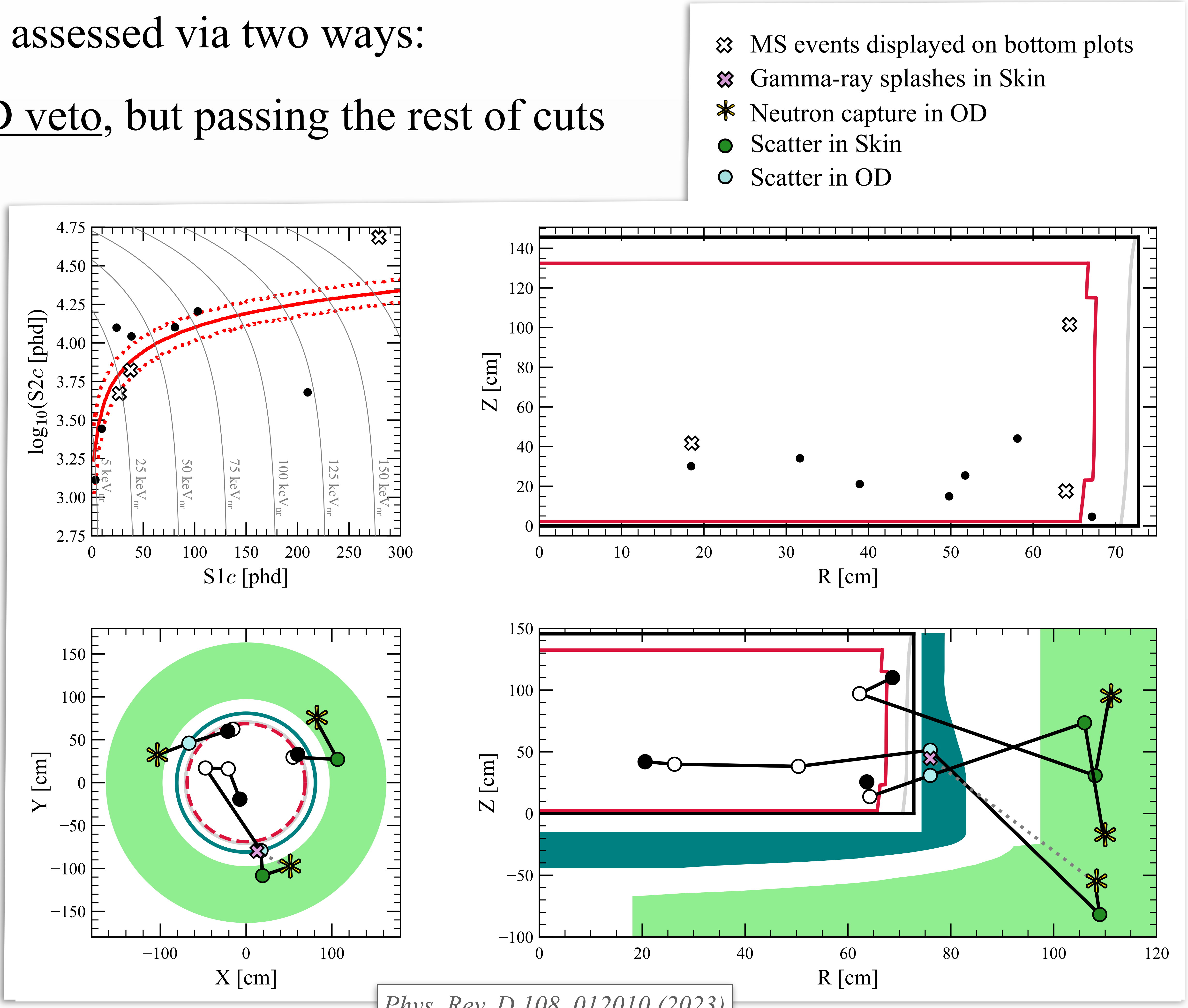
OD constraints for SR1 WIMP Search (WS)

Neutron background for WIMP search [I. Olcina talk] constraint assessed via two ways:

1. Auxiliary fit (and analogous to WS fit) to events failing OD veto, but passing the rest of cuts
2. Conversion from sideband MS potential neutrons:
   - OD delayed window reduced from 1200 μs to 400 μs
   - OD pulse area threshold from 37.5 phe to 400 phe
   - Wider S1c ROI, extended up to 500 phd
   - As a result: **10 MS** neutron candidates in SR1

- MS:SS ratio = 2.3:1 (from sims)
- 49% OD veto eff. for sideband selection (from AmLi)
- 20% OD veto inefficiency for WS sel. (from AmLi)
- Survival fraction for FV and ROI (from sims)

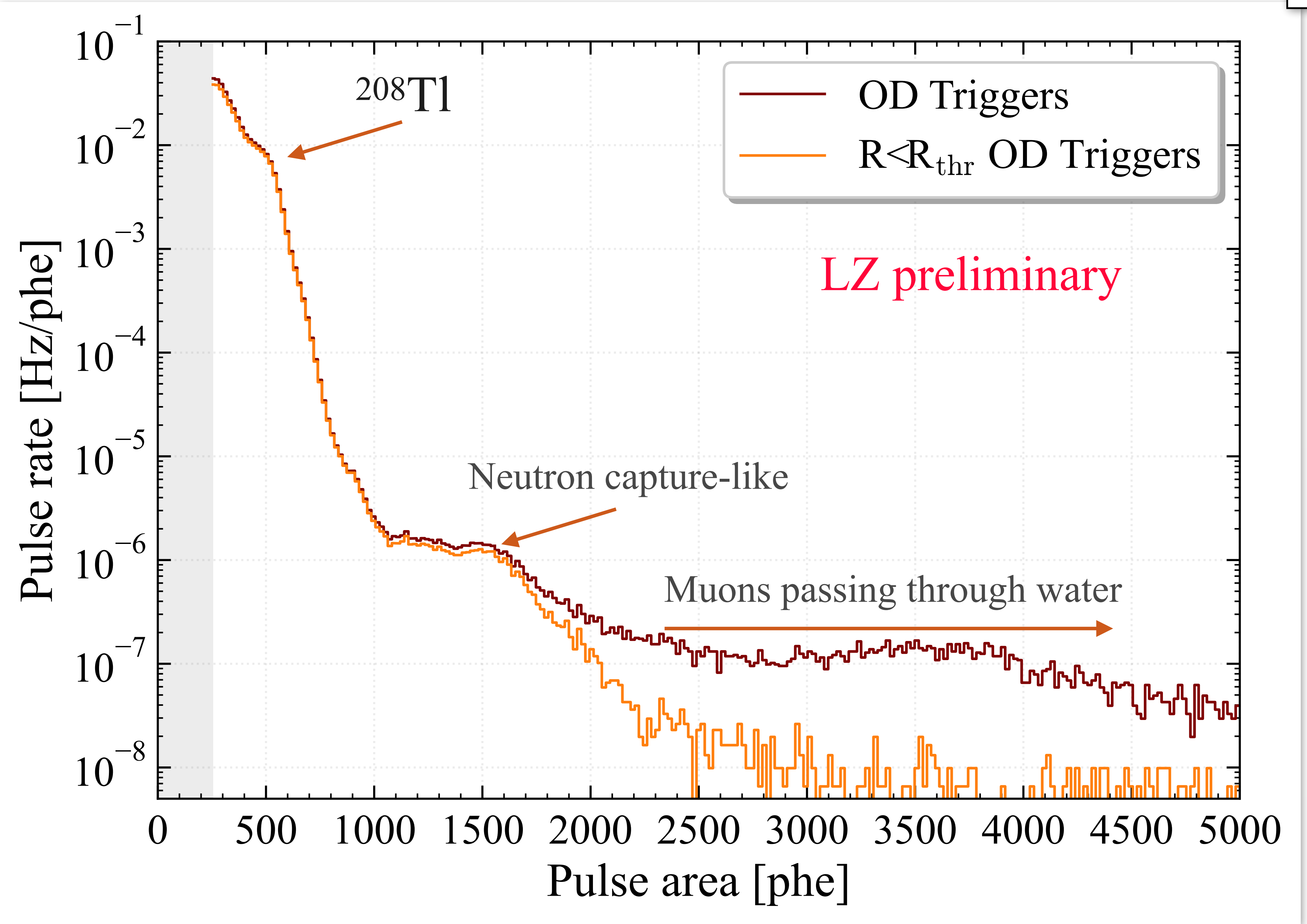
- **0.29** events in the WS surviving OD veto, and **1.1** tagged by veto (in 60 days)



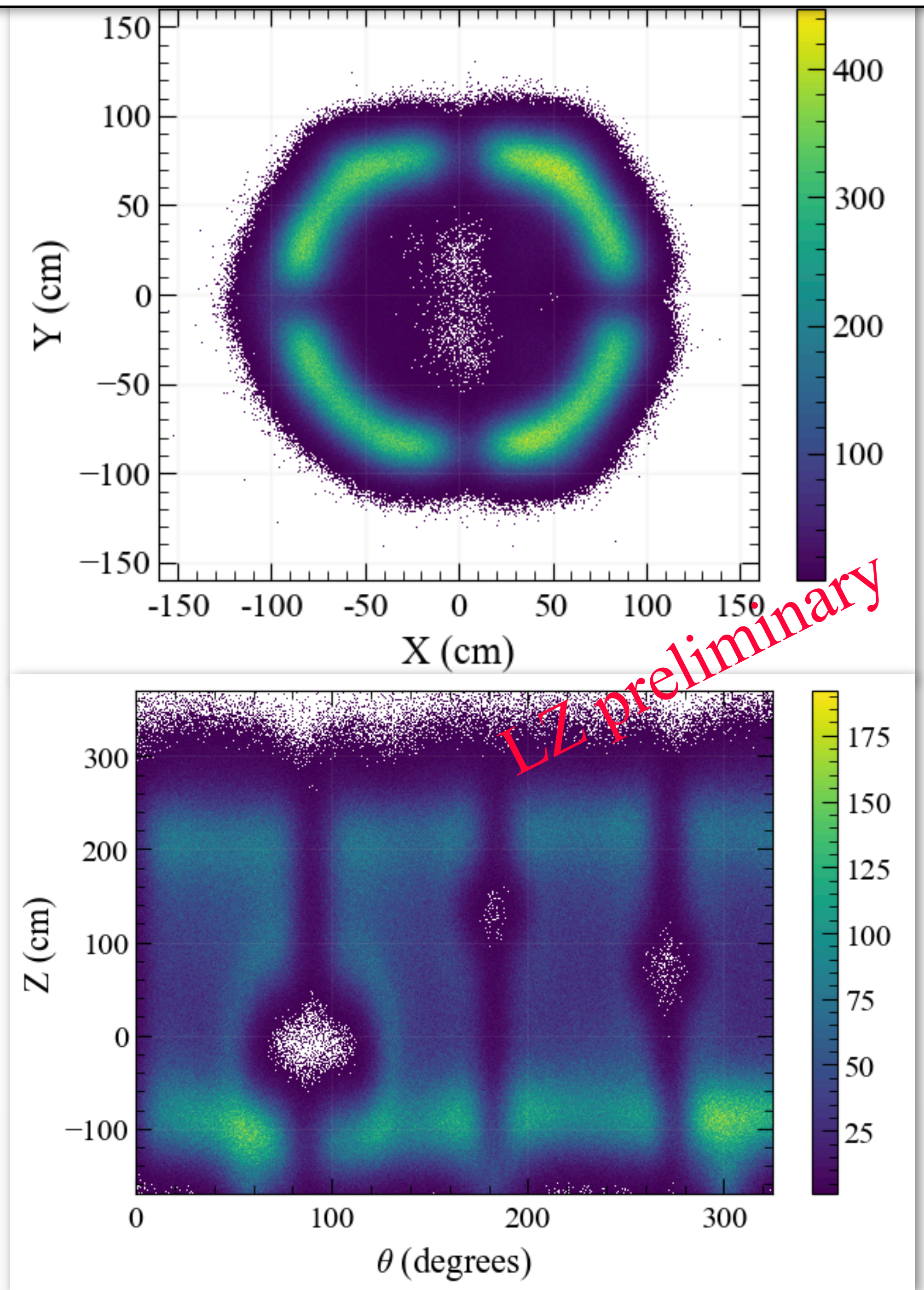
Phys. Rev. D 108, 012010 (2023)

post-SR1 OD performance

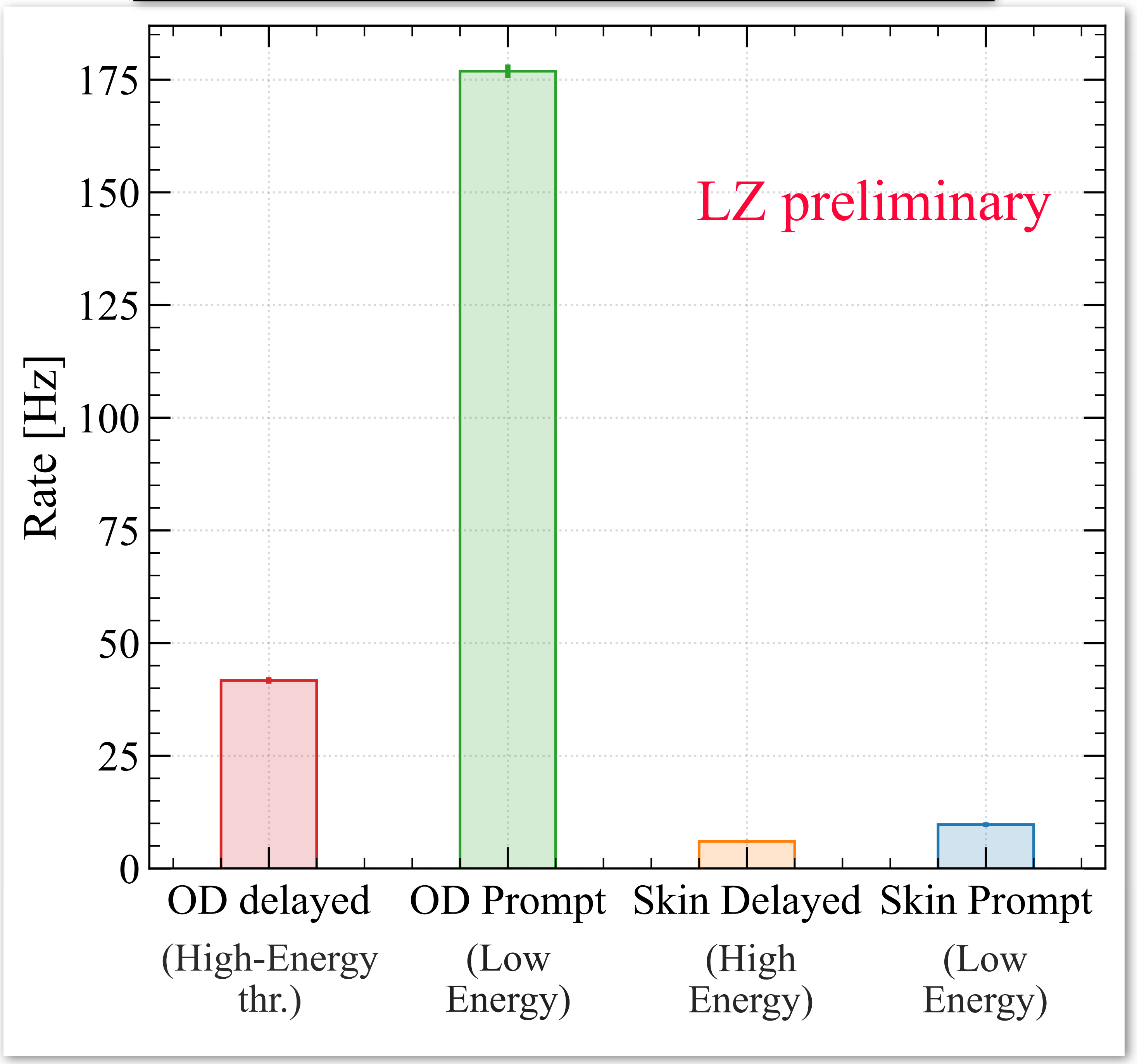
- Very good performance of the Outer Detector during SR1 WS, really useful to understand neutron backgrounds
- The LZ Outer Detector keeps informing about neutrons in current science run → Stay tuned for upcoming results!
- Currently, more extended studies: with more sources employed, and better understanding of the detector



Spatial dsts. of OD pulses in ^{208}Tl area range for OD-triggers



Rate of pulses in the different veto windows



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And don't forget to check all the LZ contributions in the conference!:

"*An update on the LUX-ZEPLIN (LZ) experiment's search for dark matter*" (talk)
I. Olcina

"*Electric fields & their effects in the LUX-ZEPLIN detector*" (Poster)
S. Dey

"*Optimisation of fast likelihood functions for dark matter and rare event searches*" (Poster)
J. Green

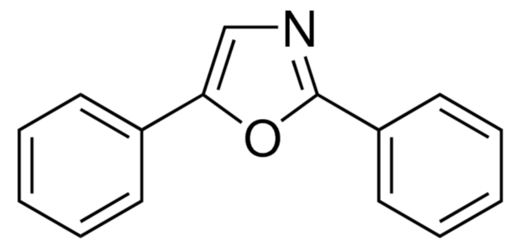
"*Bringing back the senses to LUX-ZEPLIN*" (Poster)
A Swain

LZ Collaboration Meeting at SURF, June 2023

Back up

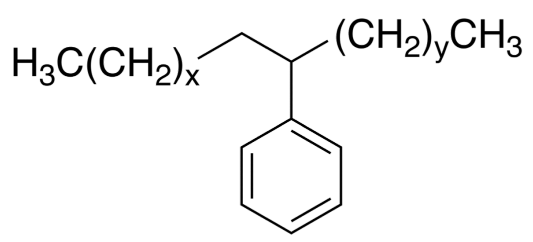
GdLS composition

GdLS



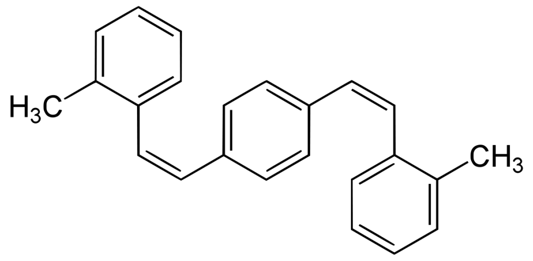
Linear Alkylbenzene (LAB)

- Energy deposited in LS excites LAB
- LAB transfer energy to the PPO fluor



2,5-Diphenyloxazole (PPO)

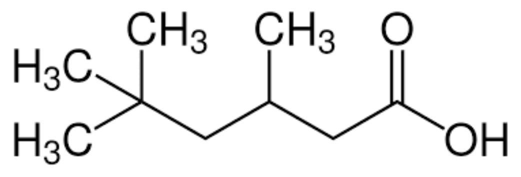
- Emits <380 nm wavelength light



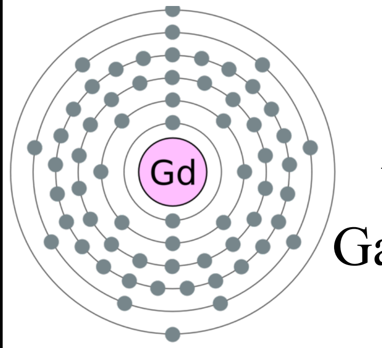
1,4-bis(2-methylstyryl (benzene)) (bis-MSB)

- Shift light to 410-425 nm to reduce self-absorption and match PMT response

Regular LS

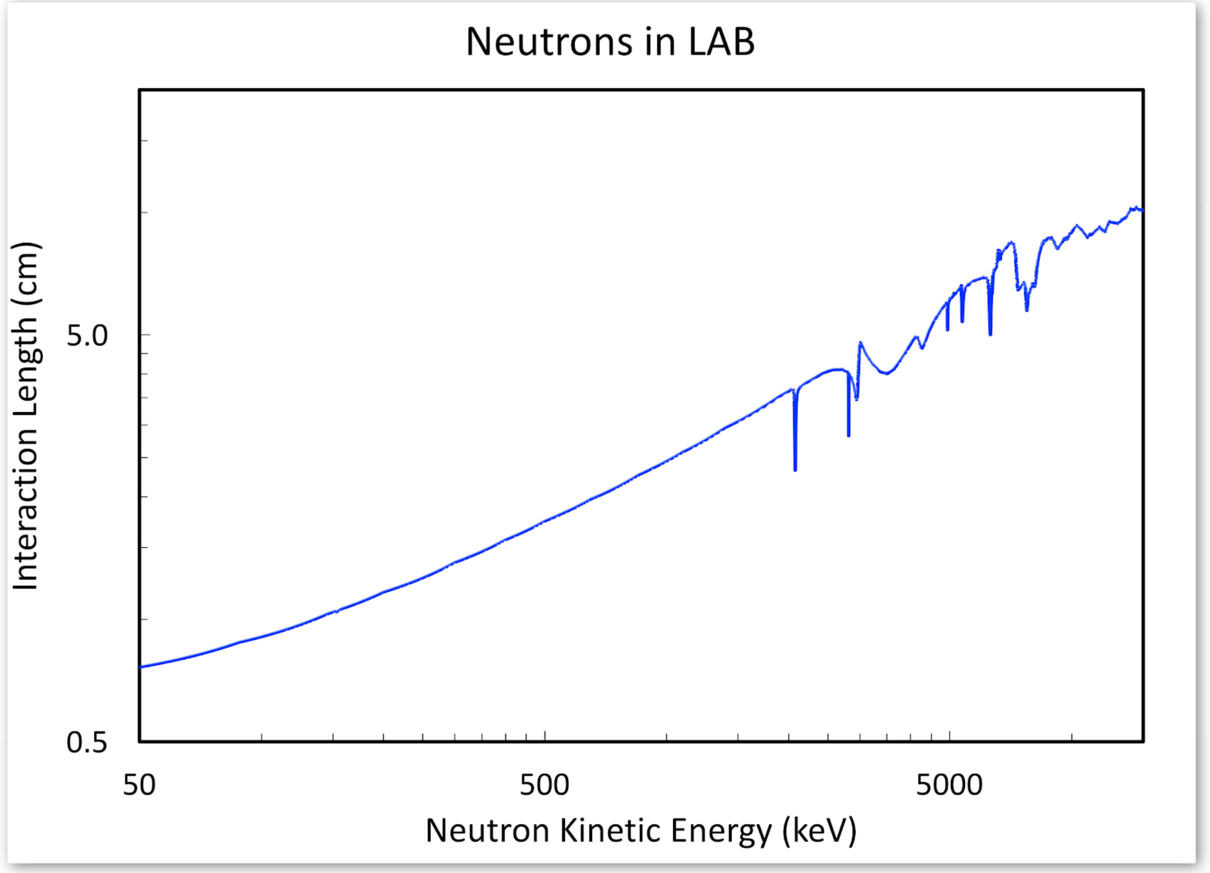


3,5,5-trimethylhexanoic Acid (TMHA)

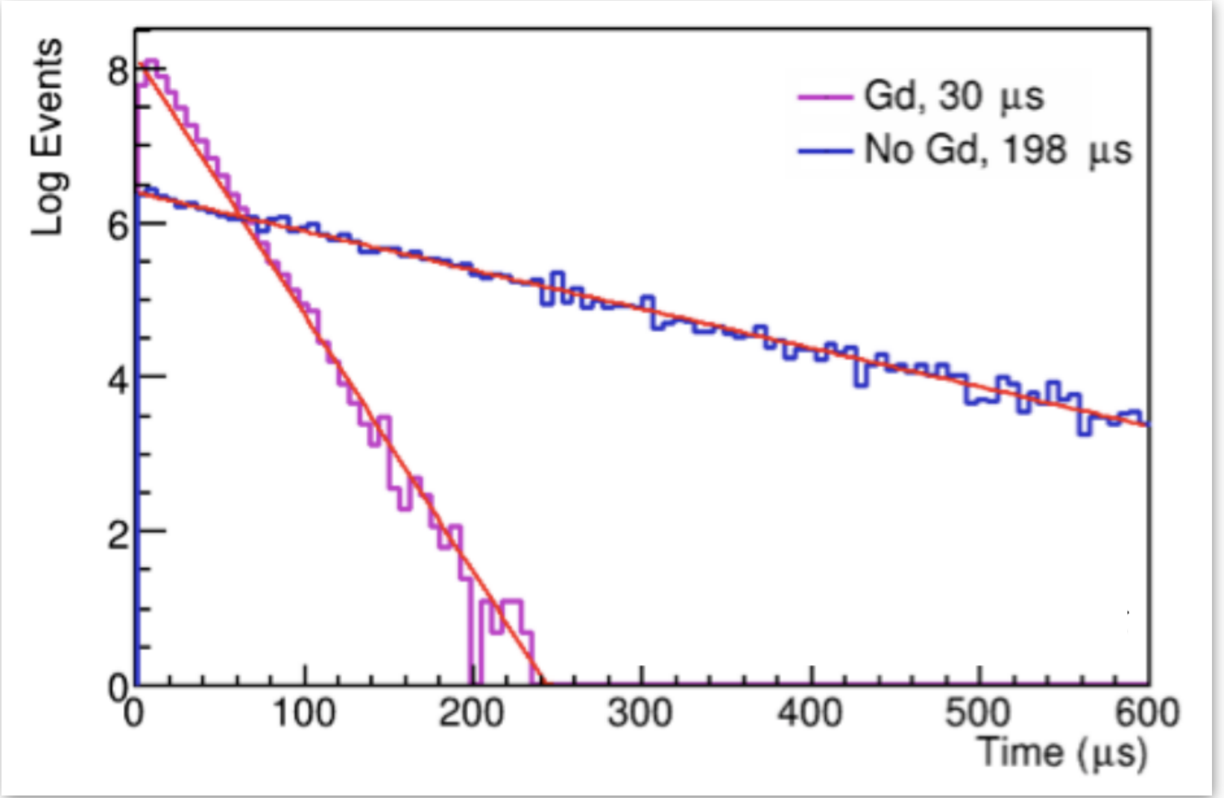


Neutral Gadolinium (Gd)

- LS doped with 0.1% by mass of Gd (dissolved into the LS via the chelating agent TMHA)

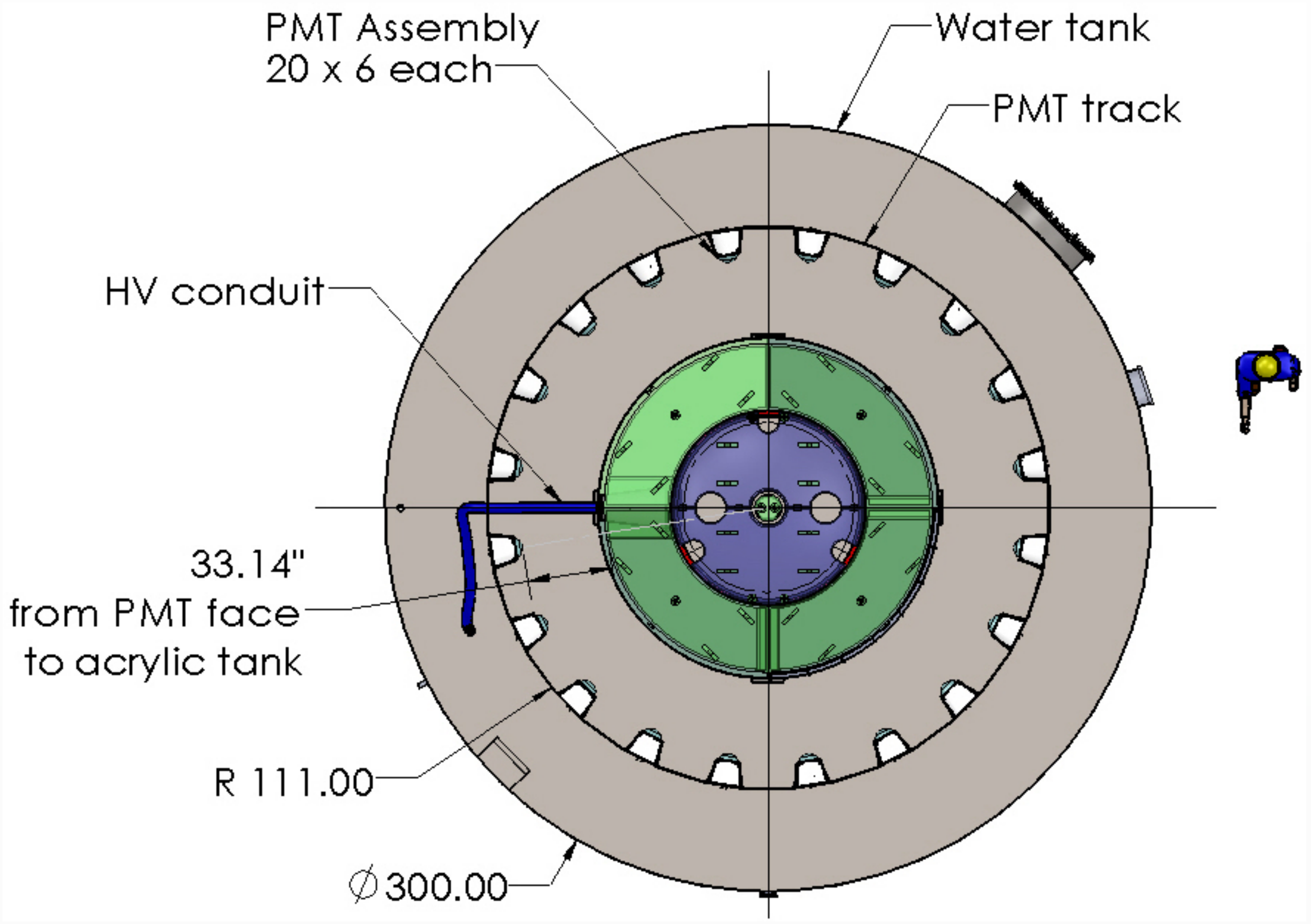


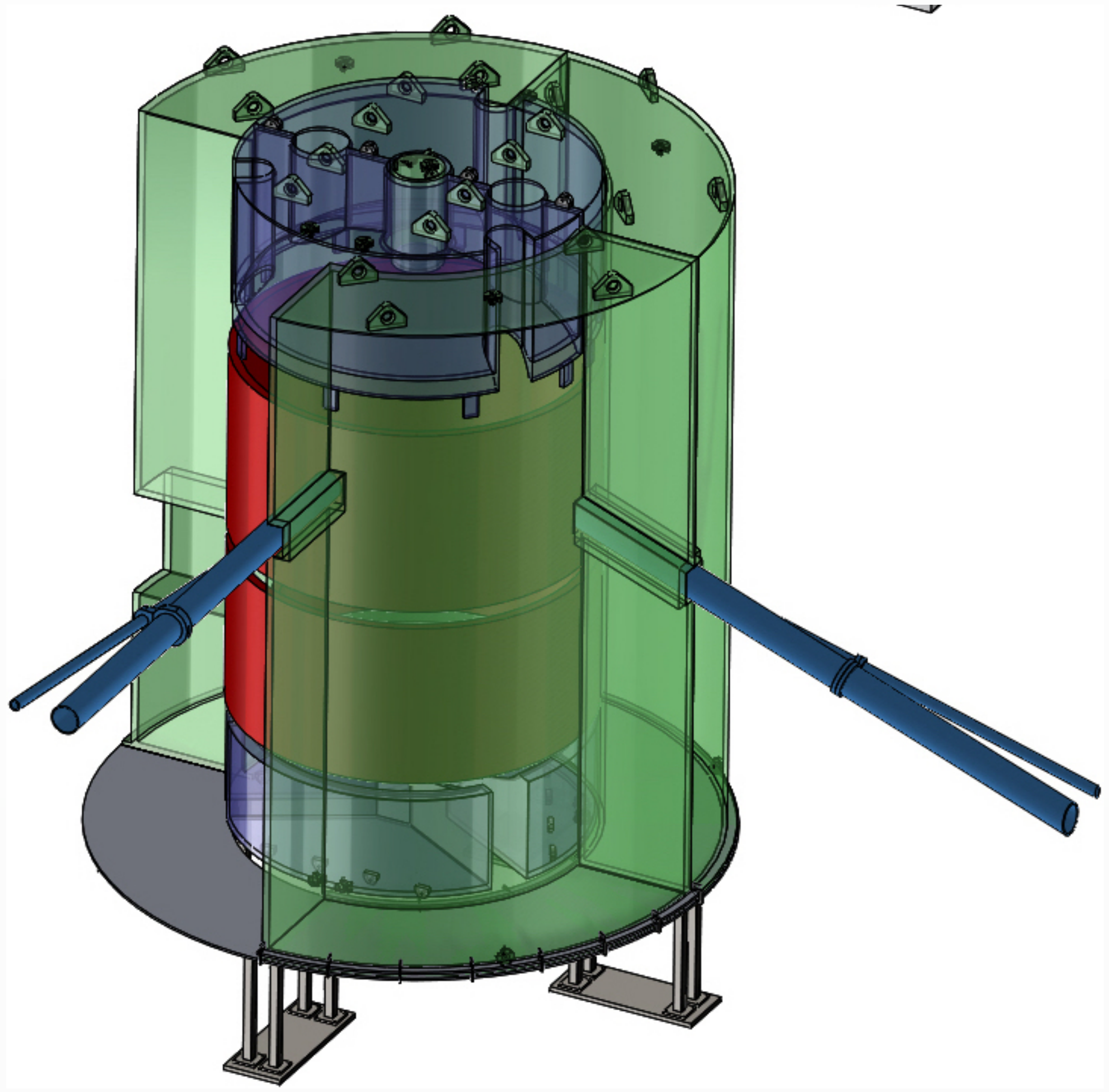
Effect of Gd in capture time

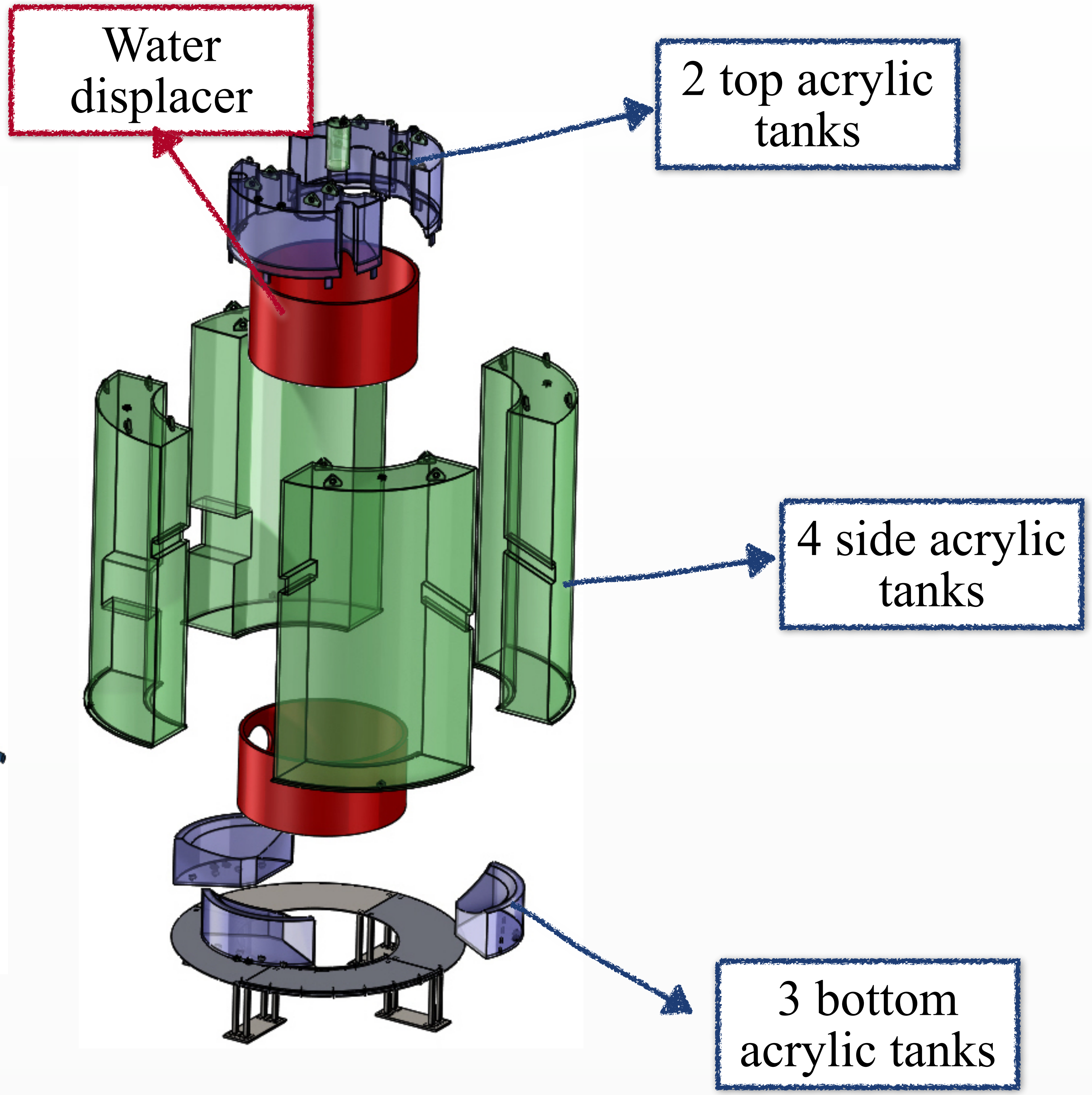


0.1% of Gd sufficient to reduce neutron capture time from 218μs to ~28μs

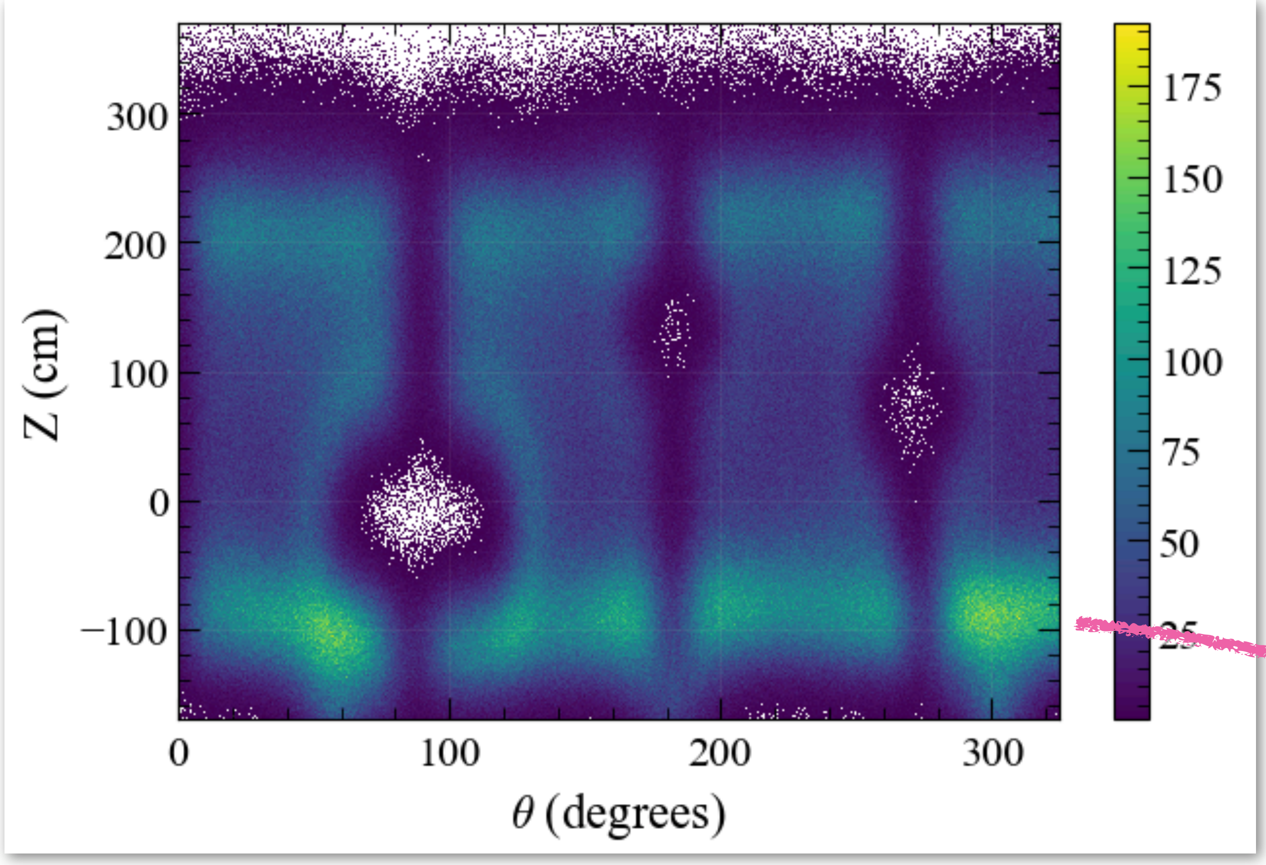
Outer detector



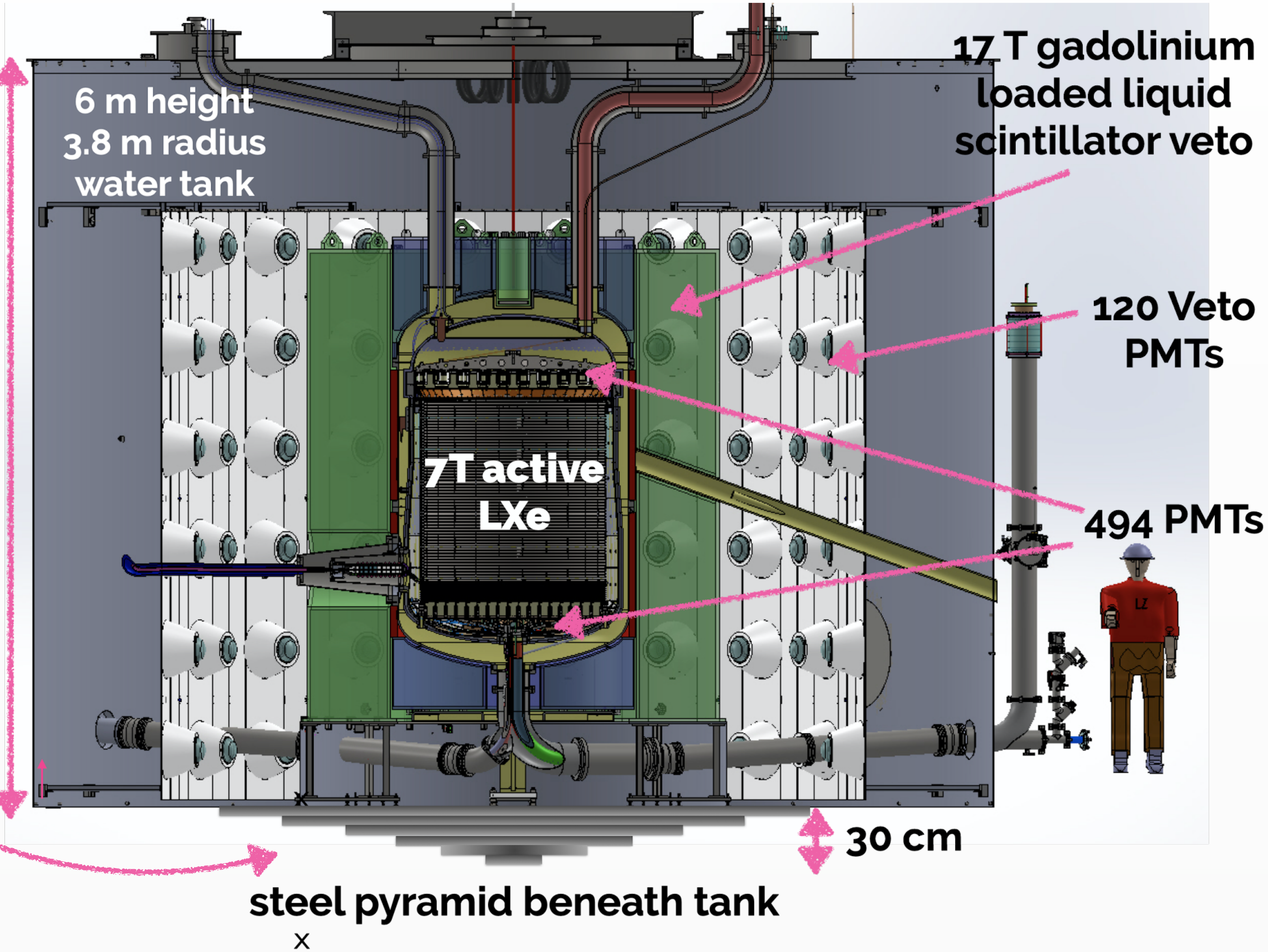




OD backgrounds spatial distribution



More events at low Z due to the smaller shielding



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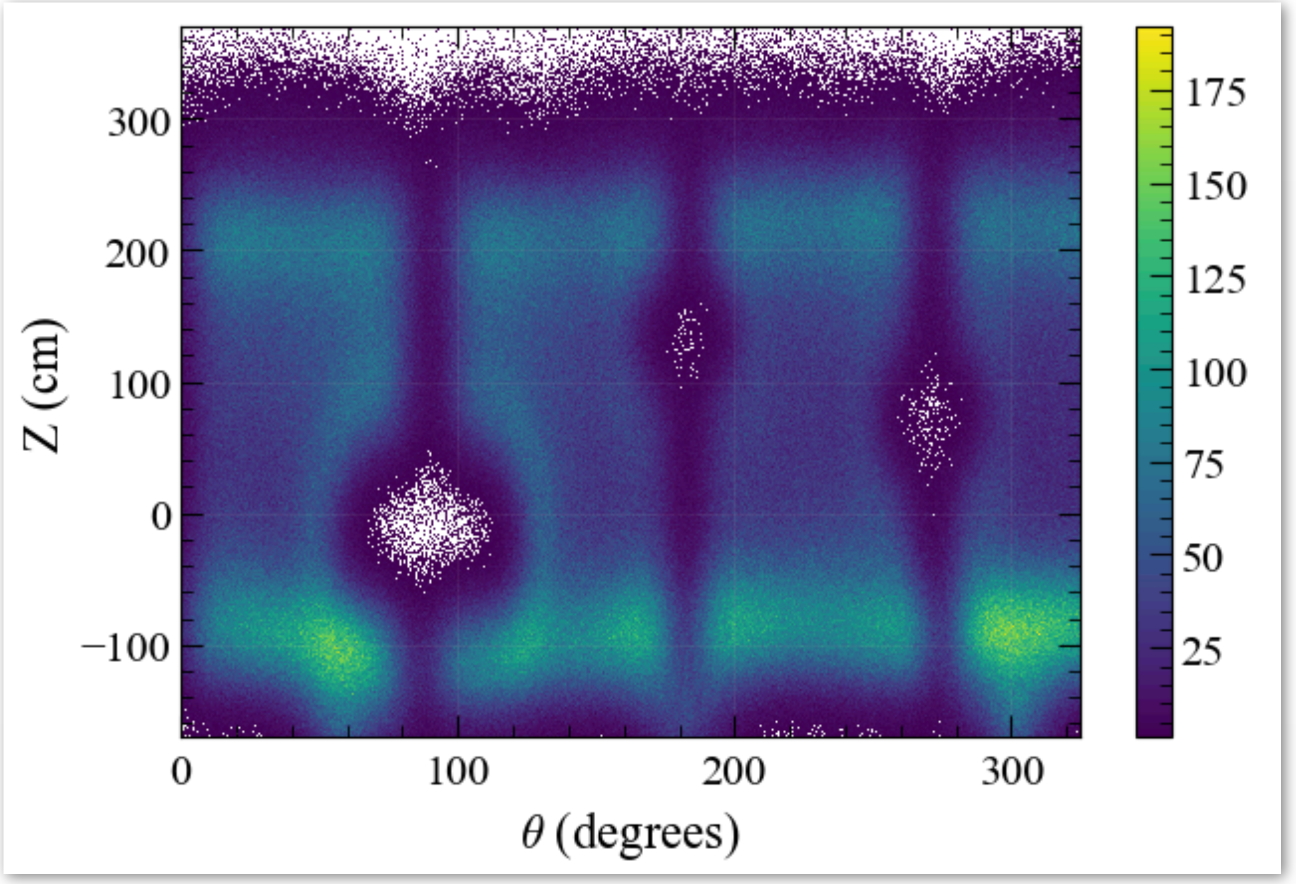
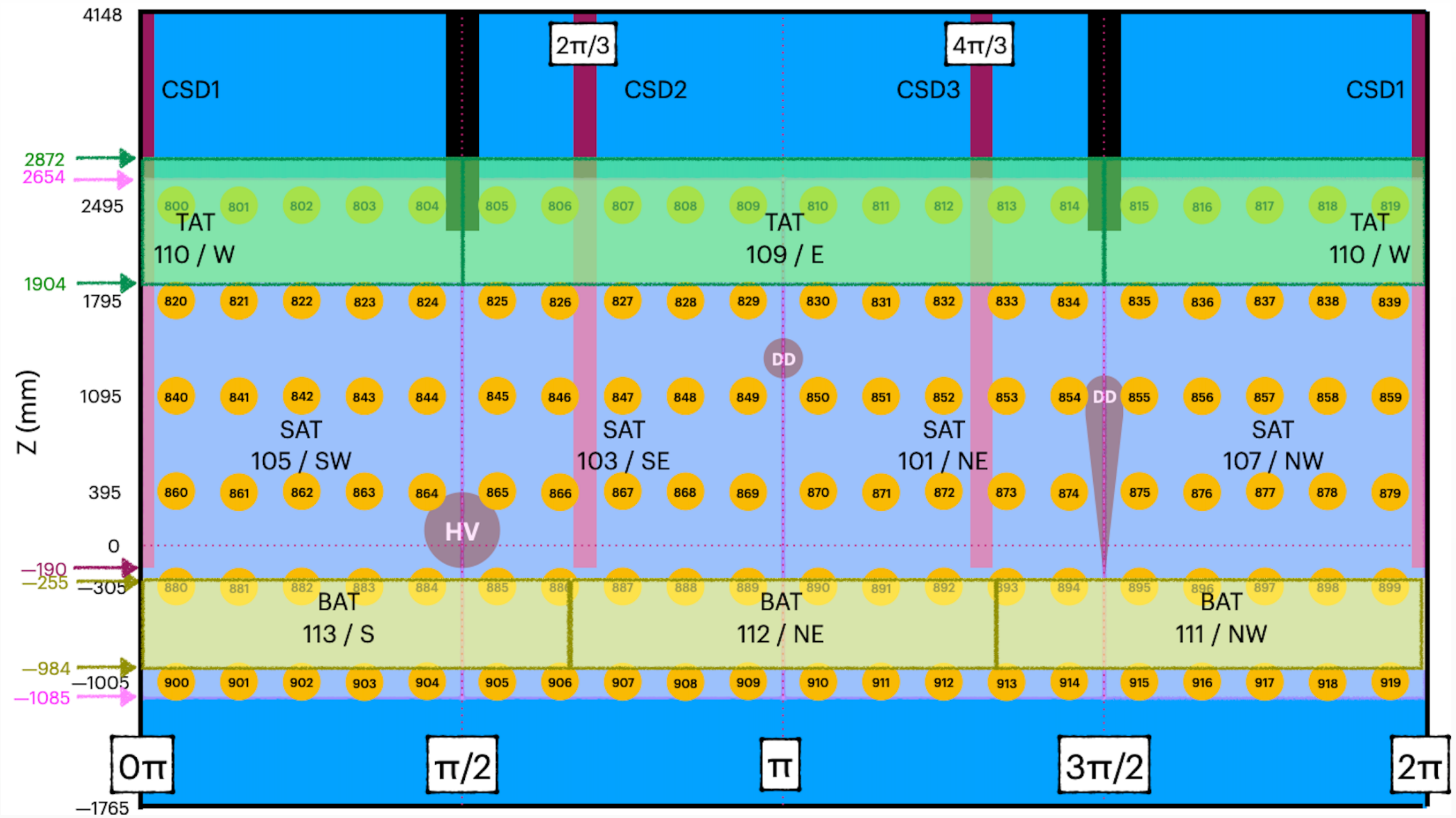
OD geometry





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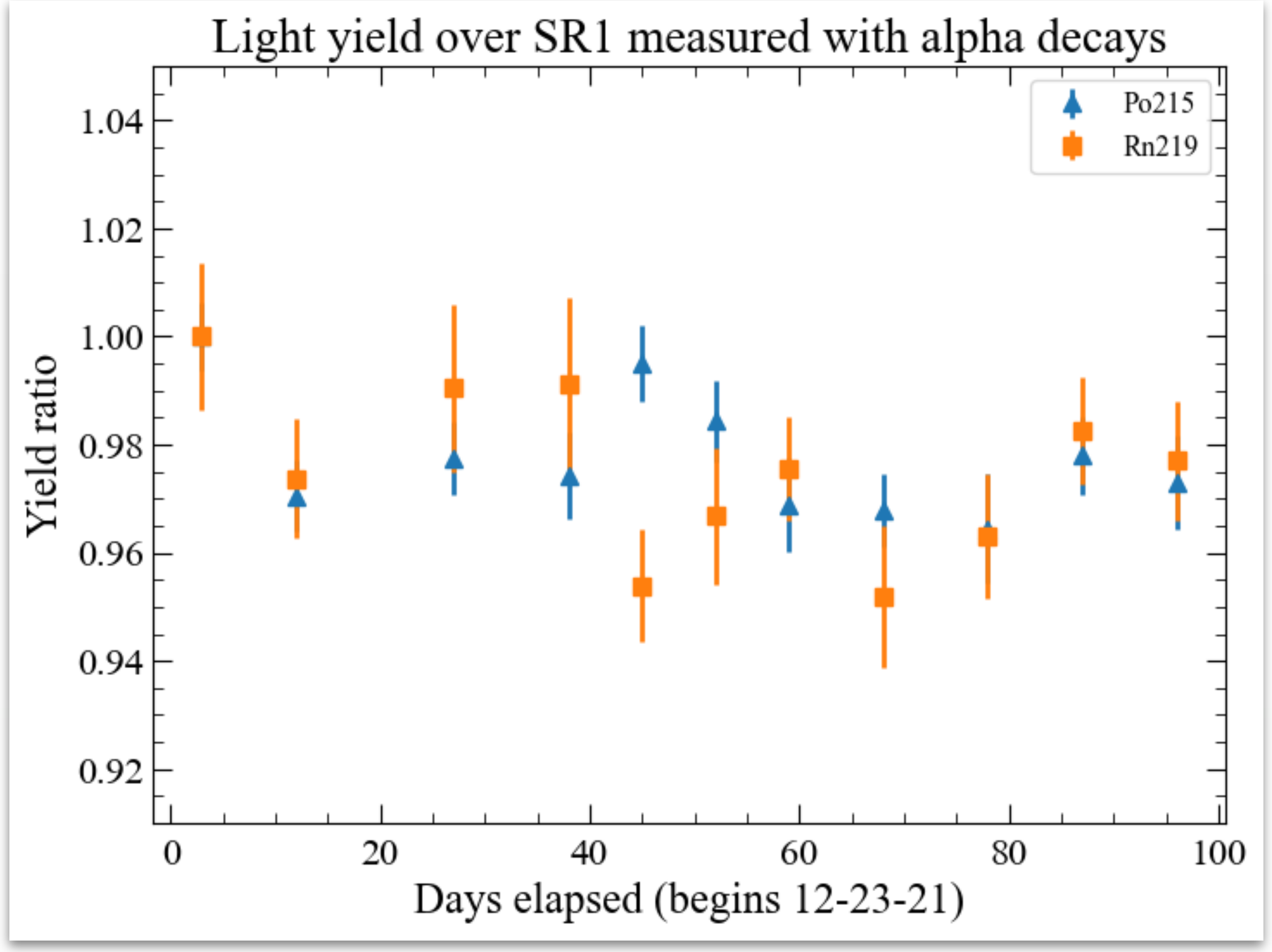
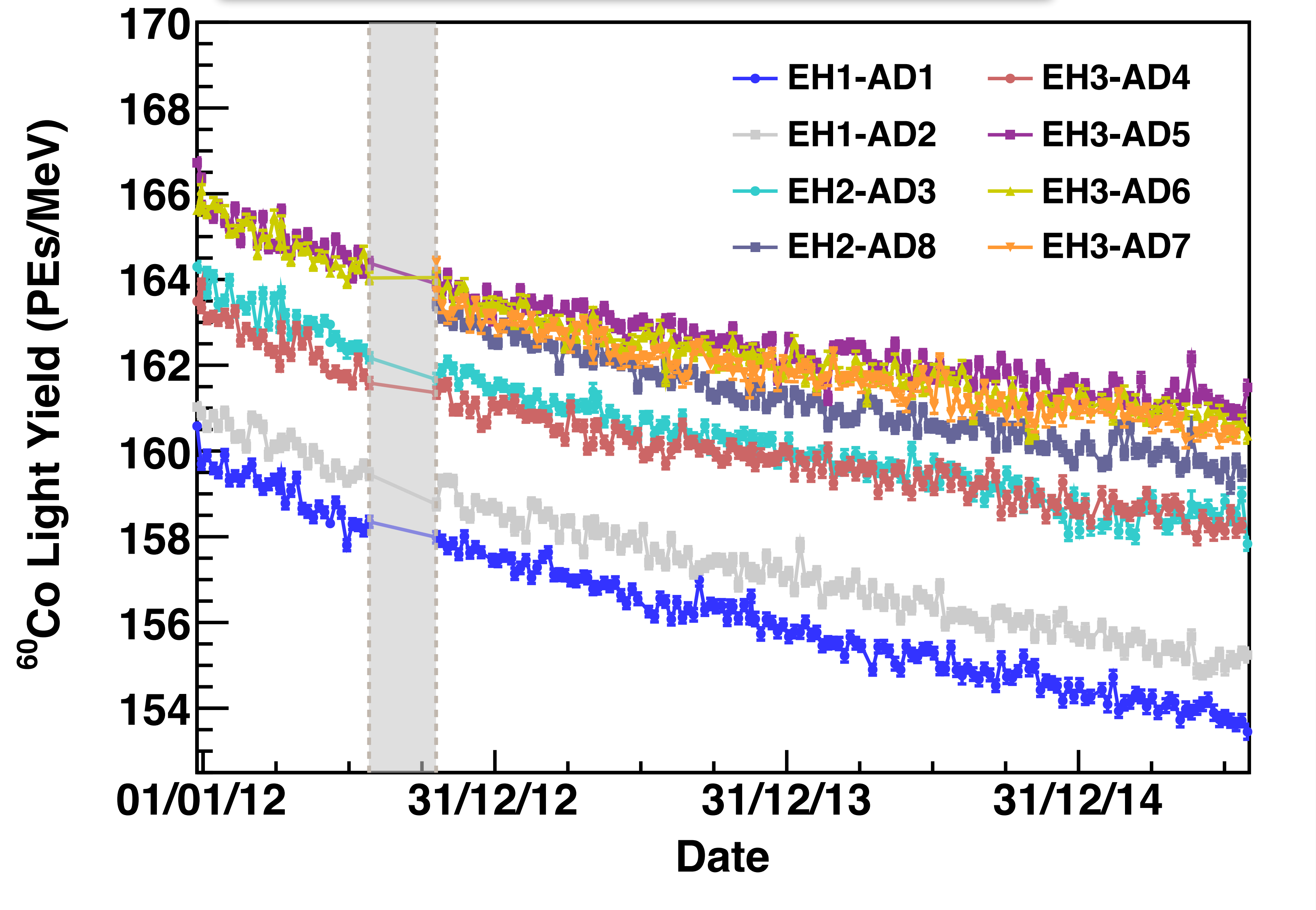
OD light yield temporal evolution



Observed light yield vs time in Daya Bay scintillator



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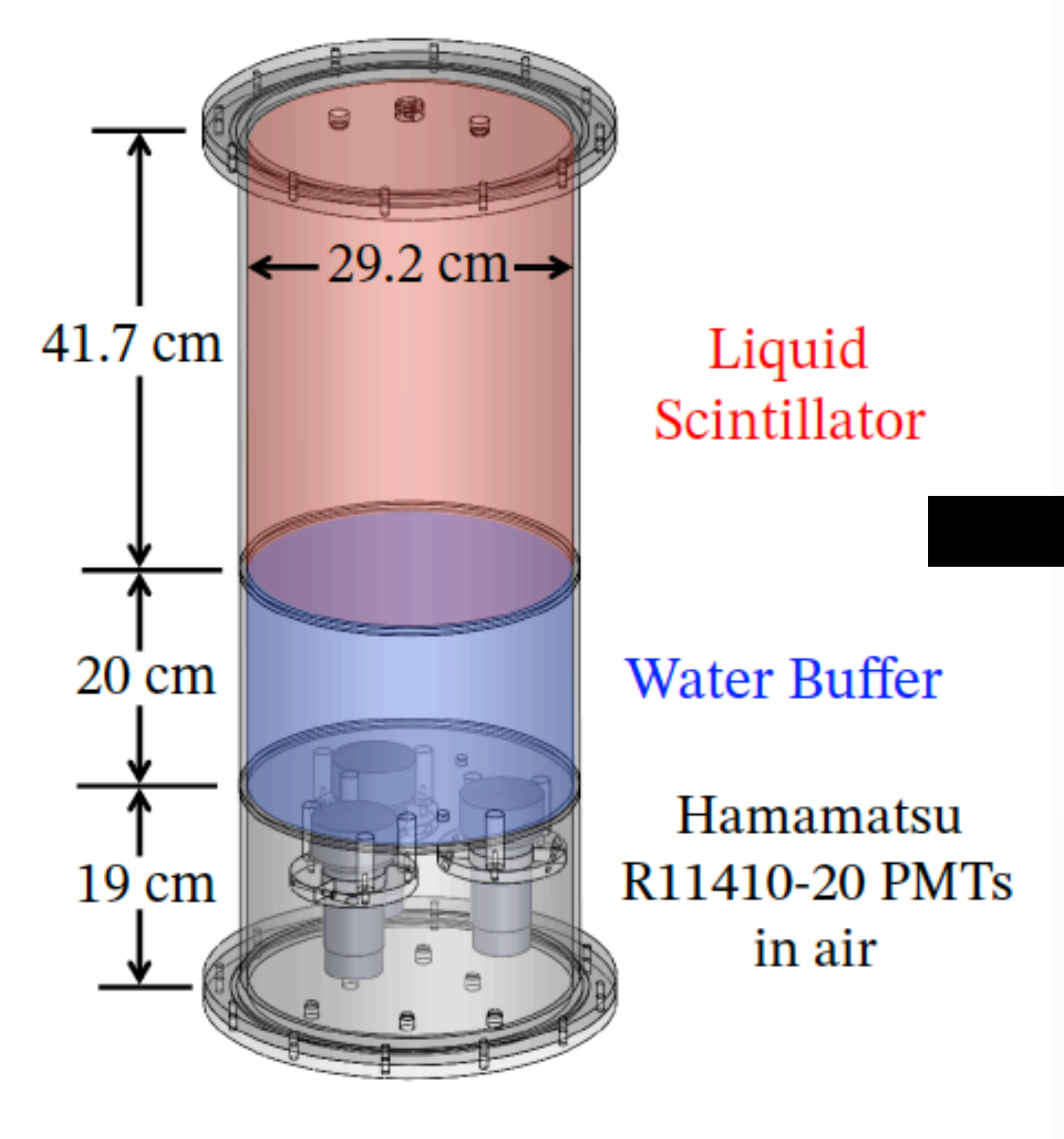
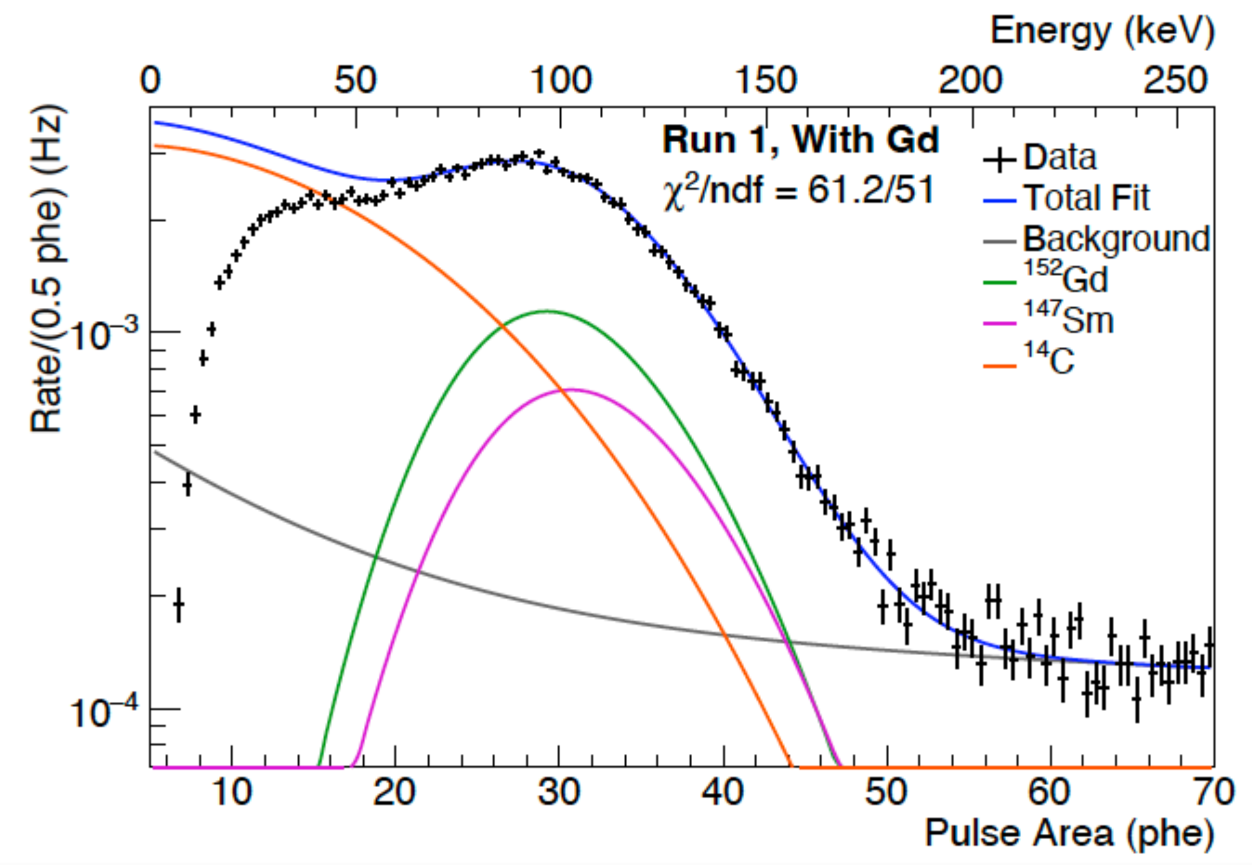
GdLS radioimpurities measurement



Low pulse area region (dominated by C-14)



High pulse area region (dominated by C-14)