



# Single Photon Template Creation for the LZ

## & Development of the XLZD Outer Detector

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# Introduction and Motivation

- Evidence motivating the search for DM
- The LZ detector overview
- LZ Single Photon Template Task:
  - **Motivation:** Facilitate **photon counting** using a convolutional neural network (CNN)
    - Improve **energy resolution**
    - Improve pulse shape discrimination
    - **Improve sensitivity** of low energy NR search
- XLZD Testbench Task:
  - Evaluate different media including **4-MU**
  - **Motivation:** To evaluate the how different media effect **light collection efficiency.**
    - **Inform XLZD OD design**
    - Location depended - Gran Sasso, Italy, **does not allow liquid scintillators**

# A Brief Intro to Dark Matter

- **Fritz Zwicky** Coma cluster observations 1933: observed missing mass he called 'Dunkle Materie'

## Main Evidence:

- **Flat rotation curves** - Vera Rubin and Kent Ford 1970
- Total matter vs X-ray emitting matter disagreement - **Gravitational lens** and X-ray observations.
- **CMB**
- **Big Bang Nucleosynthesis**

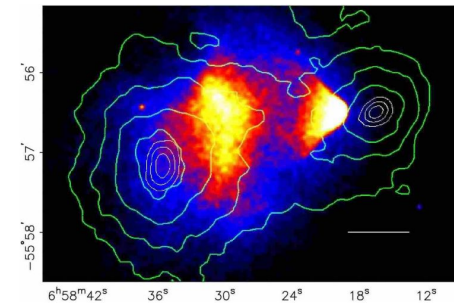
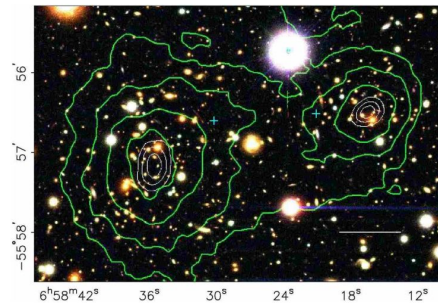
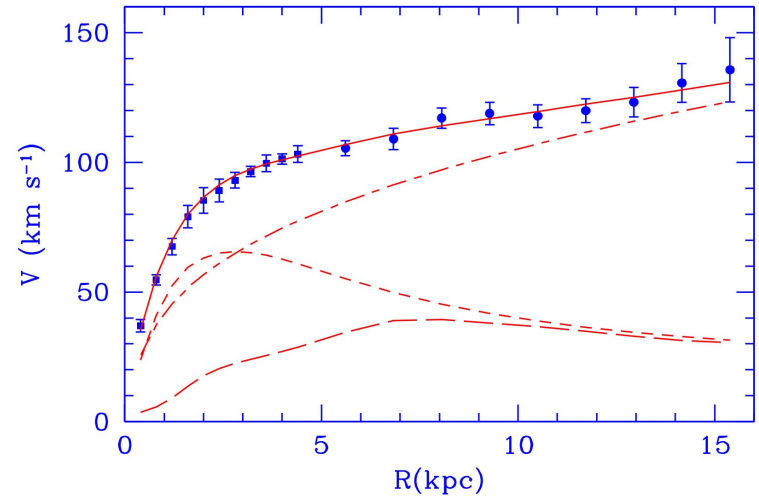
## Favoured model:

Weakly Interacting Massive Particles - WIMPS

## Detection Mechanisms:

**Nuclear Recoils - NRs** and **Electronic Recoils - ERs**

Note: In LZ ERs are a background



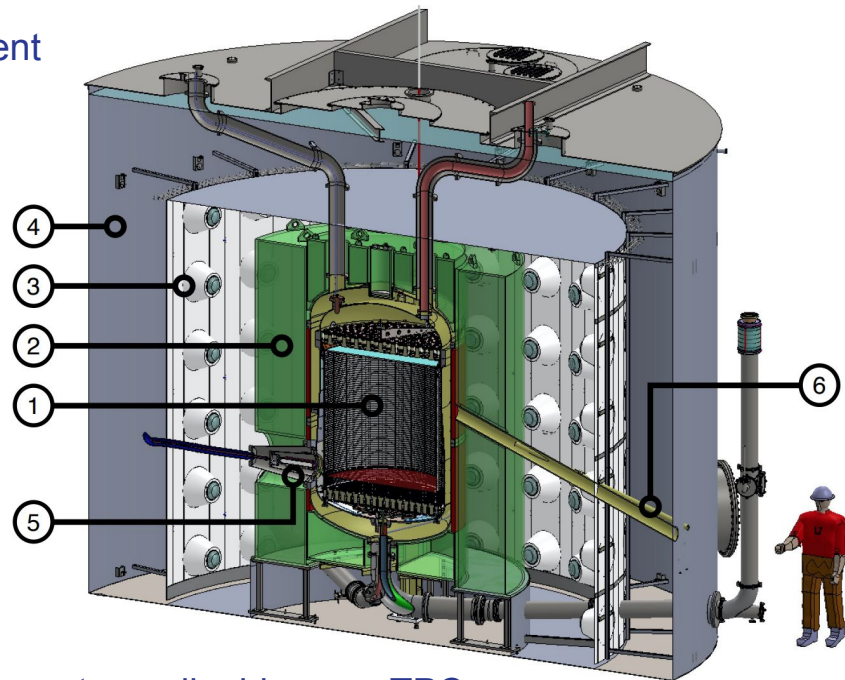
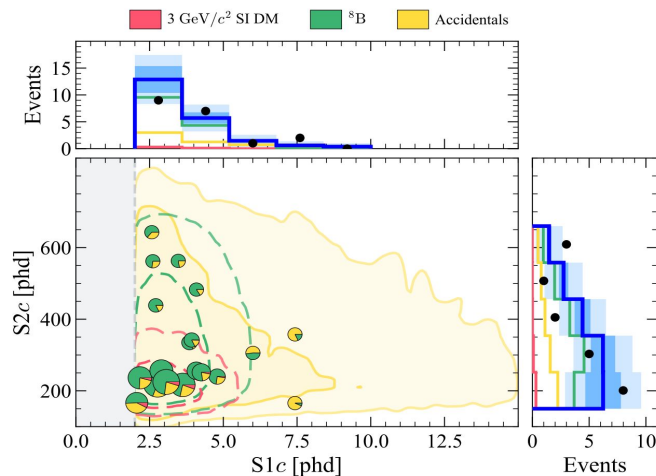
# The LZ detector and NRs and ERs

**Goal:** Observe **DM-SM Nuclear Recoil (NR)** scattering event using a **Liquid Xe TPC** and 2 active veto systems

**Outer Detector (OD) - Neutrons & Gammas**  
Skin - Gammas

ERs and NRs differentiation:

- TPC observes 2 signals
  - **Scintillation - S1s**
  - **Ionization - S2s**
- **ERs larger S1:S2 value - NRs quenched**



- 1 - Seven-tonne liquid xenon TPC
- 2 - Gadolinium loaded liquid scintillator OD
- 3 - 120 veto PMTs
- 4 - Water tank
- 5 - High-voltage feedthrough for the TPC and Skin
- 6 - Neutron beam-pipe

# Photon Template Task: Selecting single photons from data

Data set: **WIMP search background data**

Single photon PMT pulse selection:

Stage 1: Select **single electron (SE) pulses**  
(array level)

Stage 2: From SE pulses select **single photon pulses** (PMT level)

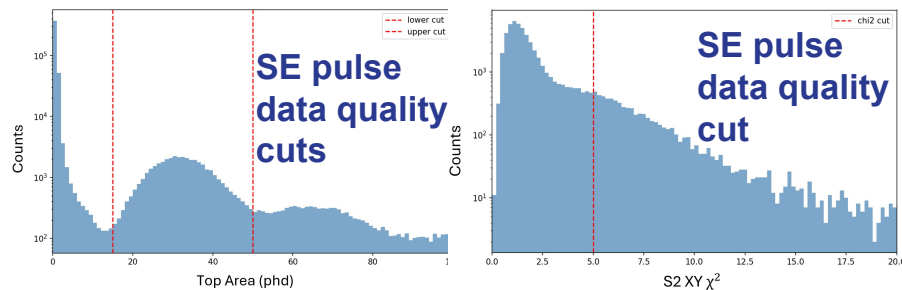
Stage 2 selection process:

- **Light Response Model (LRM) gives spatial response of the detector**
- Event location and PMT location
- Use to find probability event/pulse originates from multiple photons in 1 PMT
- **Pulse with less than 0.05 probability kept**

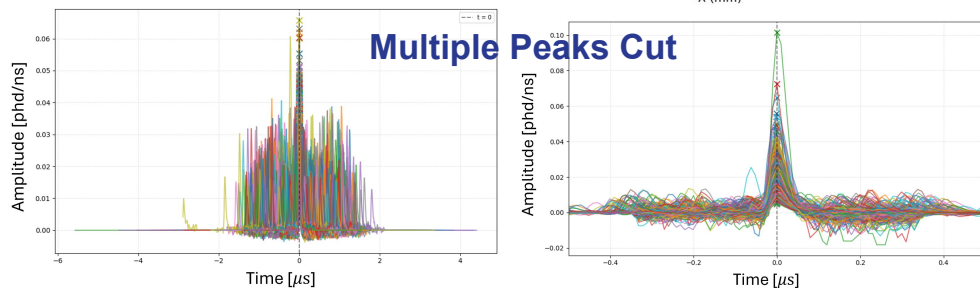
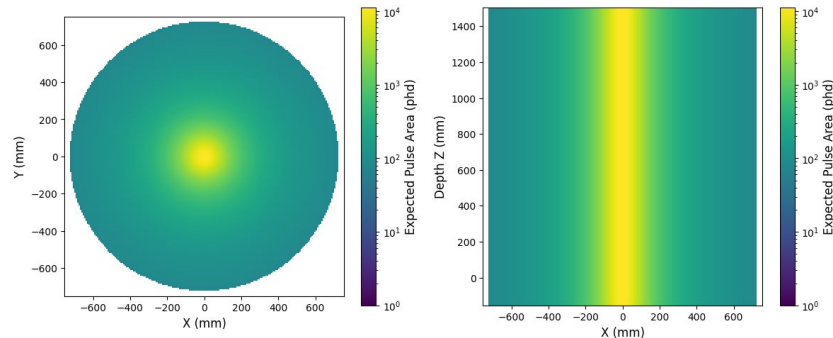
Lots of waveforms still with multiple peaks

-> **Apply multiple peak cut**

- Peak above a defined background level.
- **Not within 4 samples (40ns) of another peak.**



**LRM for channel 0**



# Photon Template Task: Aligning waveforms

Pulses roughly aligned (chPeakTime RQ). **Data digitised in 10ns windows** -> Need to **align waveforms**

Created an **iterative process** to align photon waveforms **using FFTs**  
Use FFTs to shift waveform by **fractional number of samples**

**Fourier shift theorem:**

$$\mathcal{F}\{f(t - \tau)\} = \hat{f}(\omega)e^{-2\pi i\omega\tau}$$

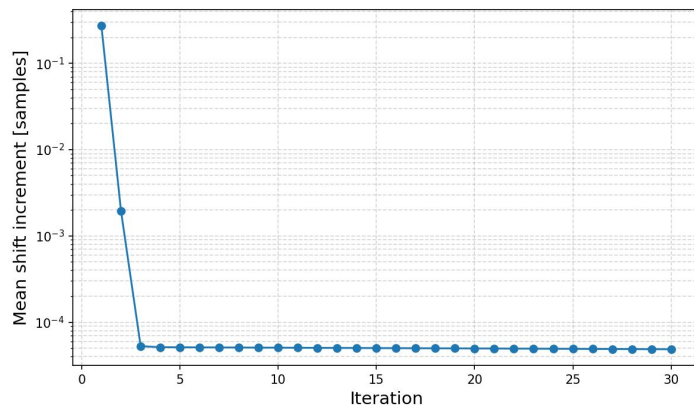
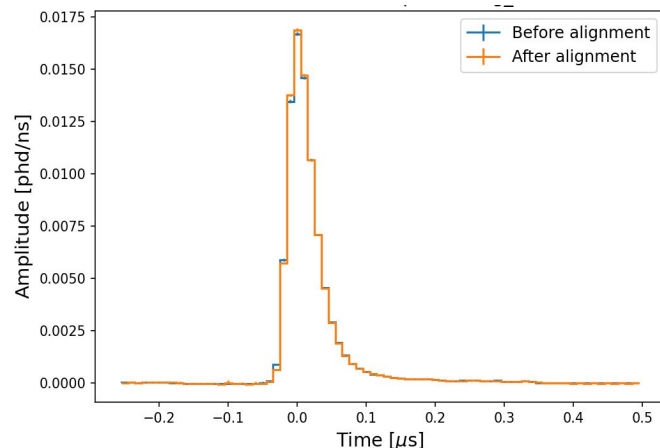
Each Iteration:

- **Shift the waveforms**
- Remake the template
- Until the shift evolution is no longer significant

$\mathcal{F}$	-	Fourier transform
$\tau$	-	Fractional shift
$\hat{f}$	-	Frequency domain
$f$	-	Input waveform (time domain)
$t$	-	Time
$\omega$	-	Frequency
$\sigma_i^2$	-	Variance

The shift value found by **minimising**  $\chi^2$ , between the waveform and the template (i is the index of the sample)

$$\chi^2(\tau) = \sum_{i=1}^N \frac{(W_{\tau,i} - T_i)^2}{\sigma_i^2}$$



# Photon Template Task: Creating a Simulated Template

Single photon pulses **simulated** using **DER** software package  
DER = **D**etector **E**lectronic **R**esponse

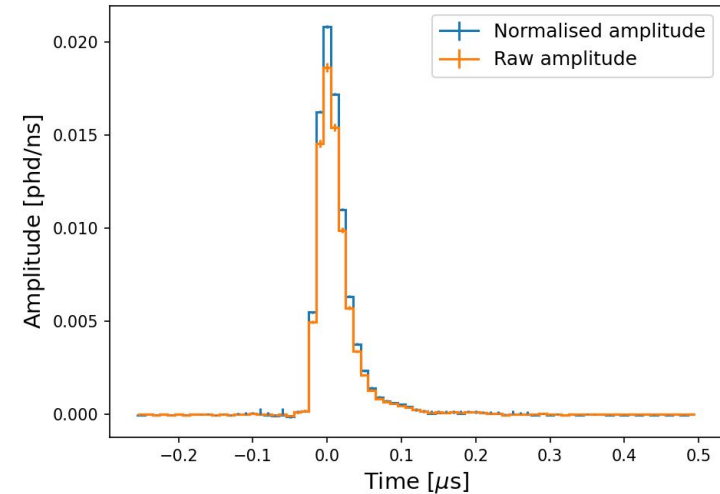
Simulated data passed directly through **LZAP**  
LZAP = **L**Zs **A**nalysis **P**ackage

**No selection** is needed on the simulated single photons

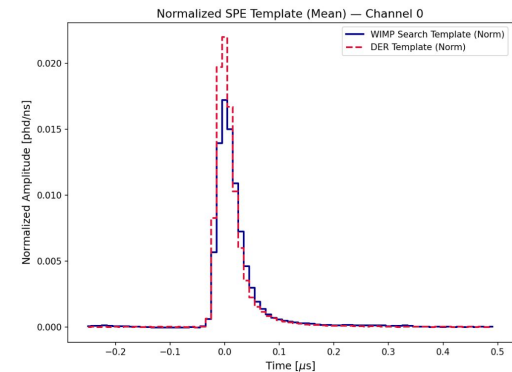
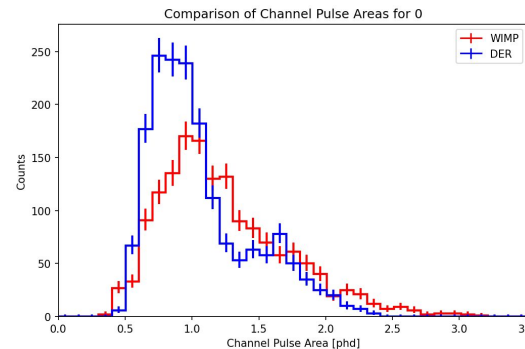
Simulated **data digitised** in 10ns window -> **Waveforms need to be aligned**

## Next steps:

- **Compare** simulated and observed templates - **KS tests**
- If simulated template verified: **Photon counting** in WIMP search data using **ML**
- If simulated template disagree: **Evaluate simulations parameters** and improve.



## Preliminary Comparison



# XLZD and the The Testbench Task

**Next generation detector** planned by the XENON, LZ and DARWIN collaborations

**Aim:** Active Lq Xe mass between 60 and 80 tonnes

Outer detector (OD) as in LZ will be a **neutron active veto system**

- Tags and vetos neutron TPC signals

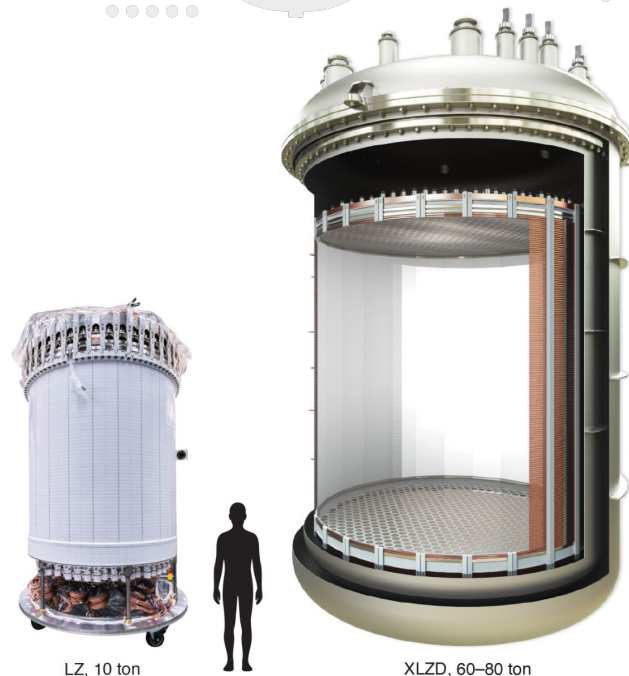
**Testbench aim:** To investigate the light yield of various media (for use in the XLZD OD)

**Task 1:** Compare Gadolinium-loaded Water-based Liquid Scintillator against deionised (DI) water

**Task 2:** Use wavelength filters to investigate light yield of DI water with 0 ppm, 0.2ppm, 0.4ppm and 1 ppm of 4-MU

**4-Methylumbelliferone (4-MU)** - Soluble wavelength-shifting chemical

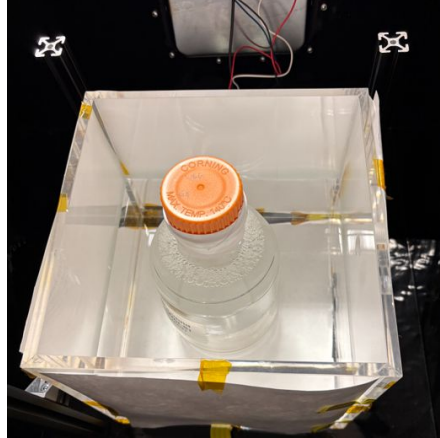
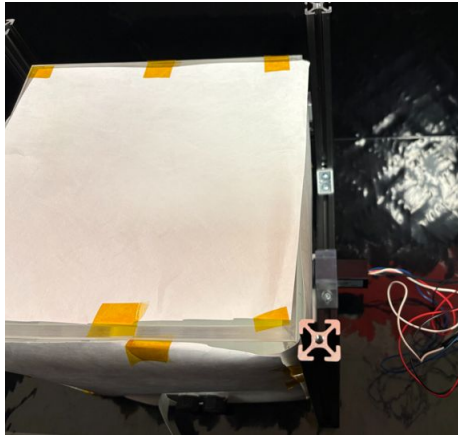
- Absorbs and **re-emits photons at a higher wavelength** to a **higher QE region of PMT**



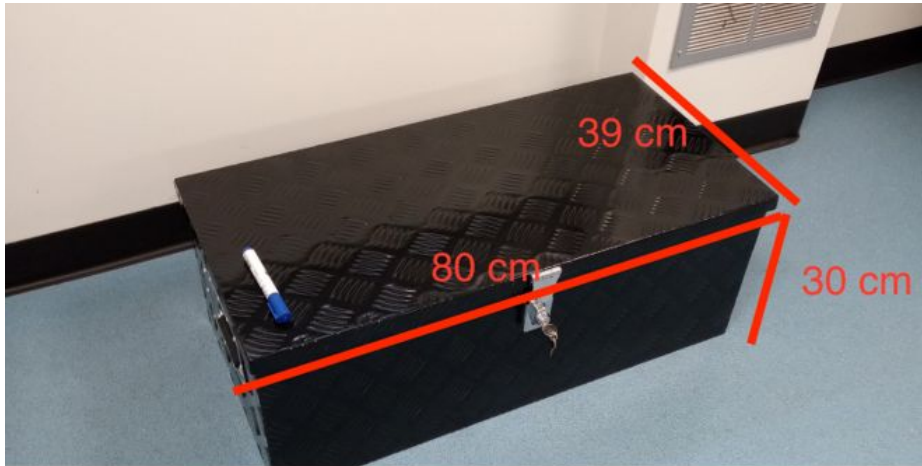
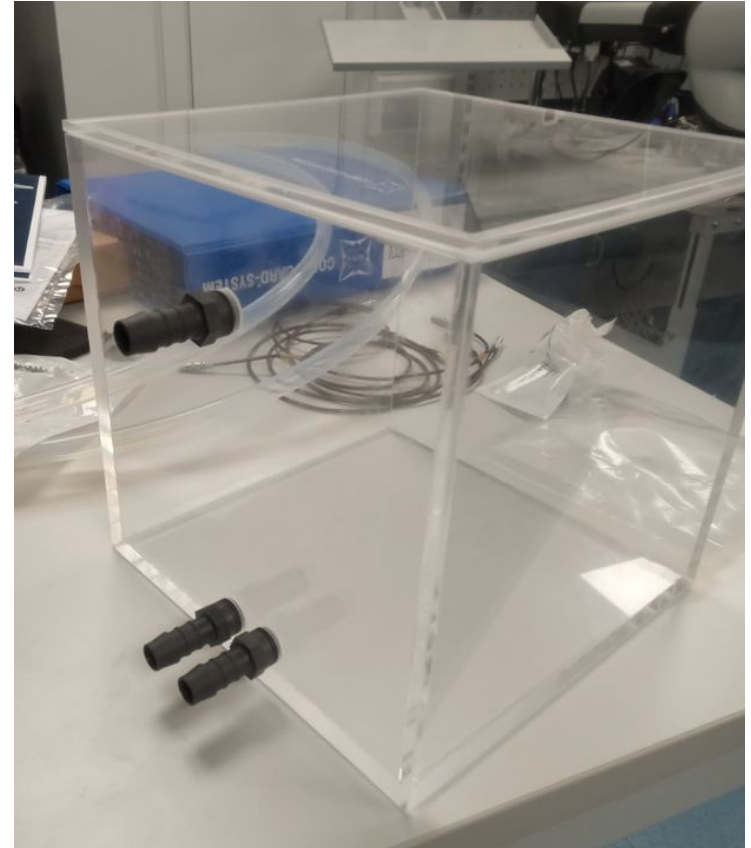
LZ, 10 ton

XLZD, 60-80 ton

# The Testbench Setup



AmBe neutron source used



# The Testbench Task: The Results

## Dark Noise:

- **Dark Count** - Mimics photon signals
- **Electronic Pedestal** - Causes a Background level of noise in all waveforms

If PMT not left in darkness for sufficient time, the rate artificially increased.

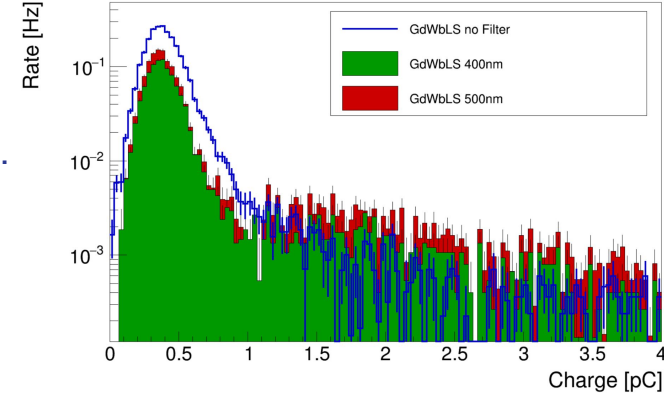
- **Monitor rate of data sets over time**

Deionised Water Peak: Rate =  $0.164 \pm 0.008$  Hz

GdWbLS Peak: Rate =  $0.268 \pm 0.006$  Hz

**63.4 % increase in rate of GdWbLS peak**

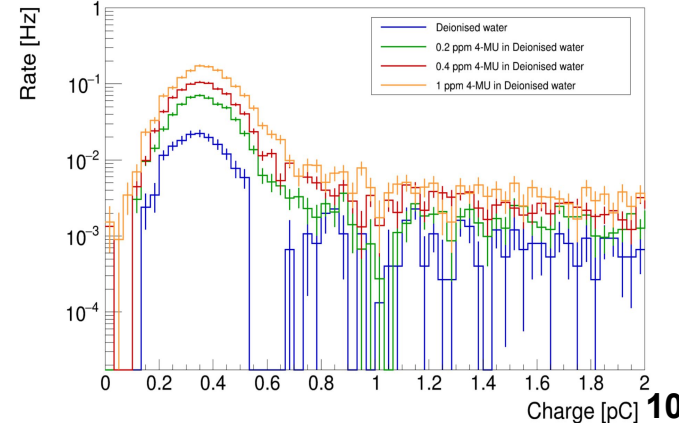
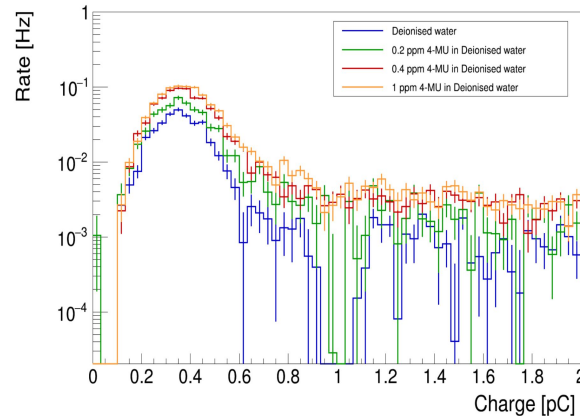
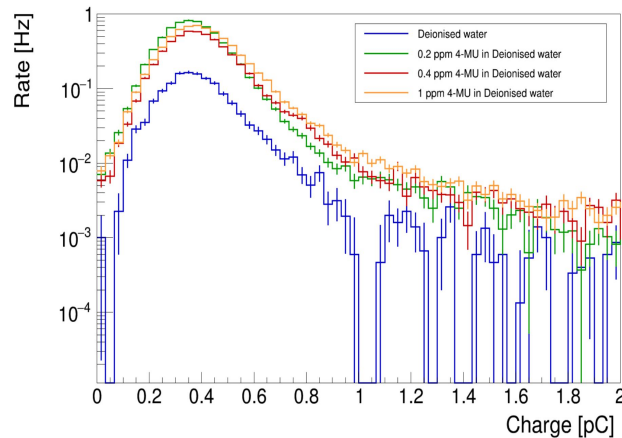
## GdWbLS



## All wavelengths

## 380 nm - 420 nm wavelength band

## 480 nm - 520 nm wavelength band



# Summary and Future Work

Template Created from **WIMP search background data**:

- Selected SE pulse (Array level)
- Selected Single Photon pulses (PMT level)
- **Multiple wavelength peak cut** developed and applied
- **Waveforms aligned** using iterative fast fourier transforms

Template Created from **simulated data**

## Future work:

- **Compare** model template and WIMP search data template
- If verified use model template for **ML photon counting in WIMP search data** - improve low energy search energy resolution
- If disagreement investigate why

Working testbench set up with AmBe neutron source

GdWbLS shown to be significantly better than deionising water even when using a smaller volume.

- 63.4 % increase peak rate seen

4-MU increases detectable light yield from deionised water

## Future work:

- **Continue 4-MU investigation.** Take **more data** with AmBe neutron source
- Complimentary investigating into **winston cone PMTs** to increase OD light yield
- Results contribute to the **XLZD conceptual design report**

**Any Questions?**