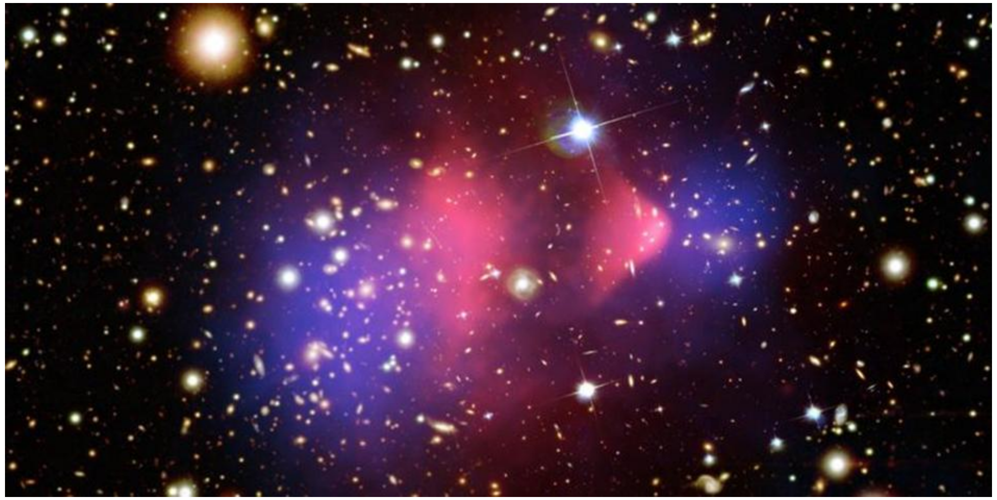
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

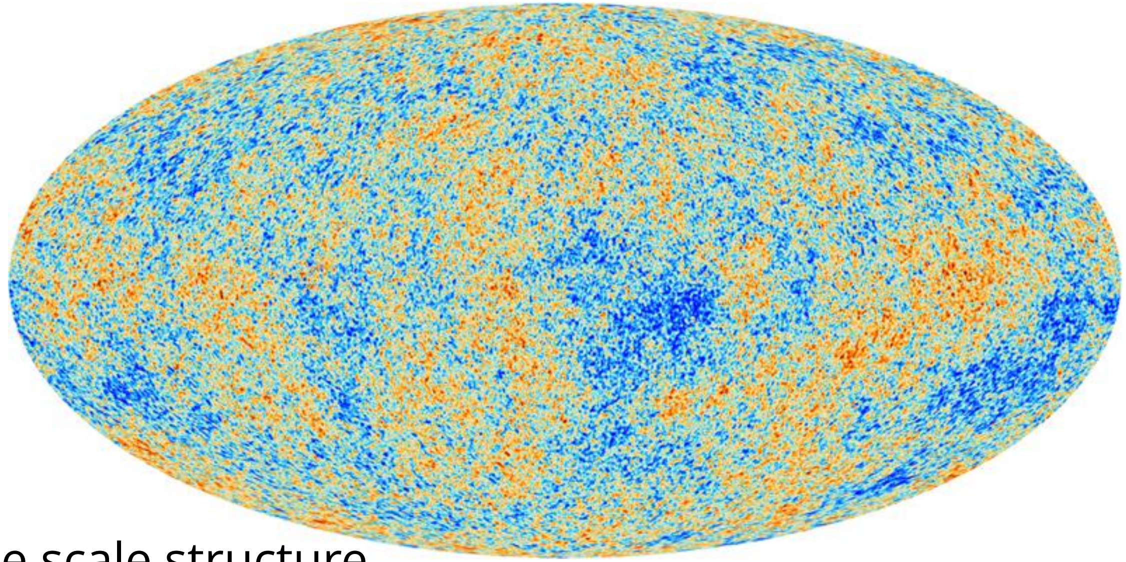
The SABRE South Experiment and the Liquid Scintillator Veto

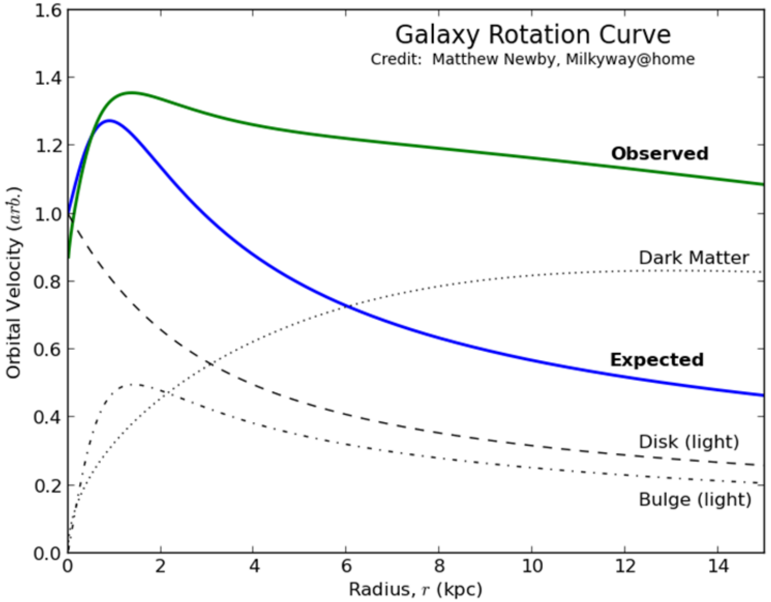
Lachlan Milligan (on behalf of SABRE South)

Dark Matter Evidence



Bullet Cluster



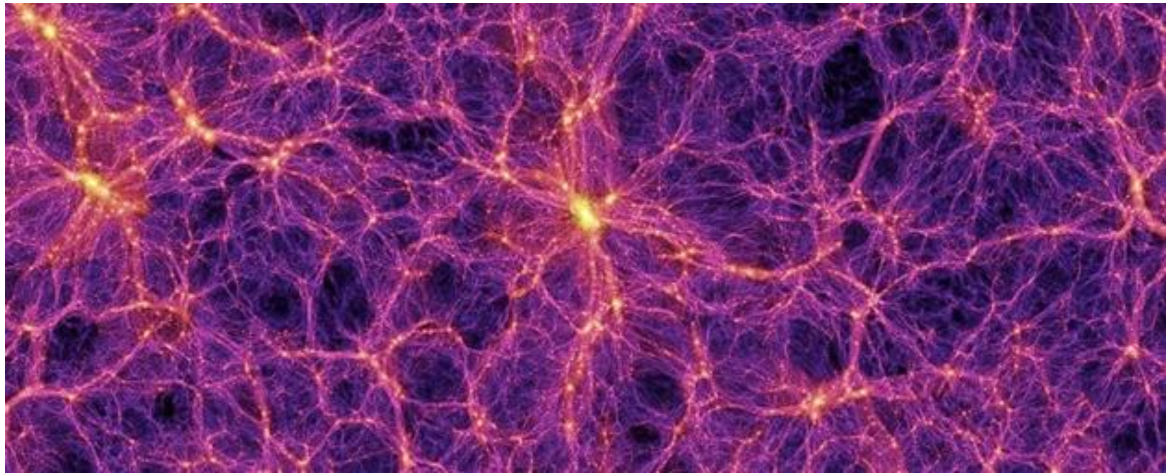


Galaxy Rotation Curve

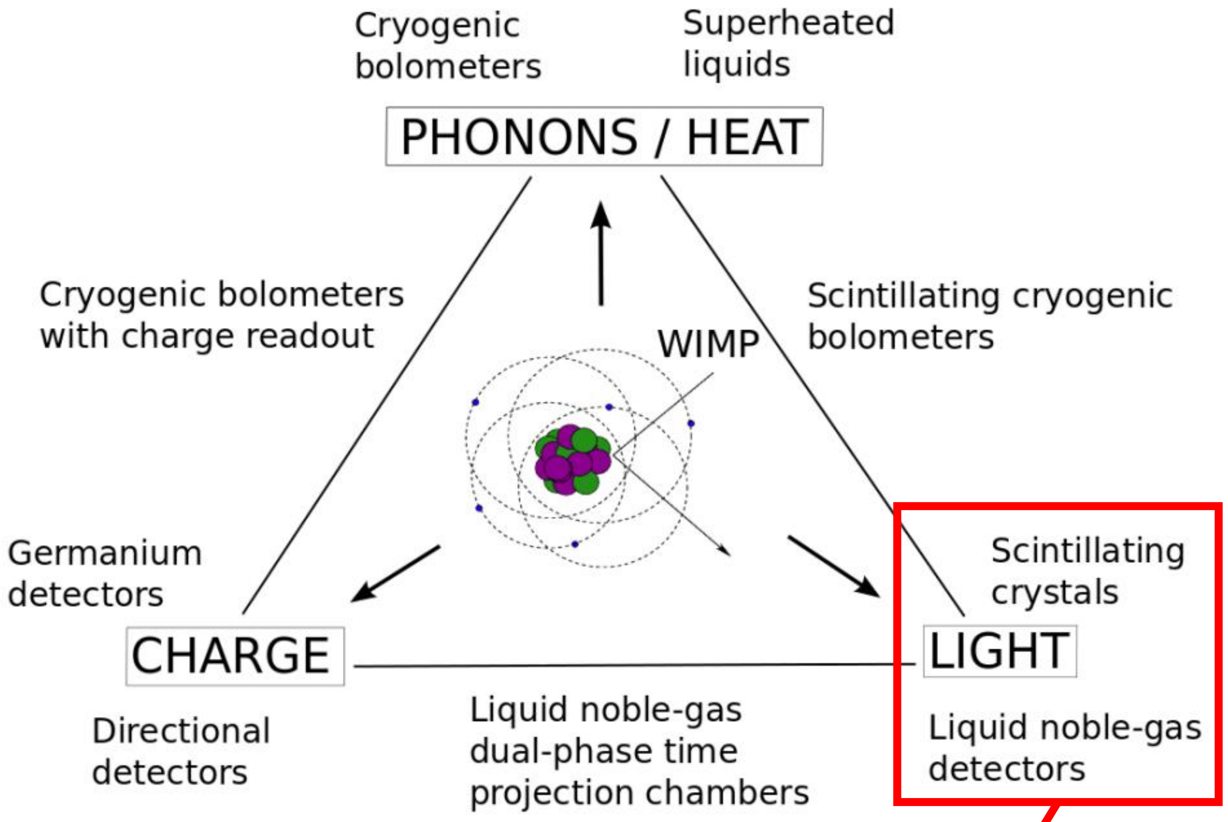
Credit: Matthew Newby, Milkyway@home

Galaxy Rotation Curves

Large scale structure



Dark Matter Direct Detection



Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

WIMP

Scintillating cryogenic bolometers

Germanium detectors

CHARGE

LIGHT

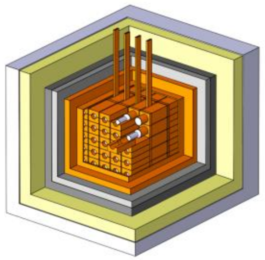
Scintillating crystals

Directional detectors

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

Reported annually modulating signal from DAMA



Direct detection – look for scattering/interactions of DM with SM model matter

Most commonly nuclear scattering following below differential event rate:

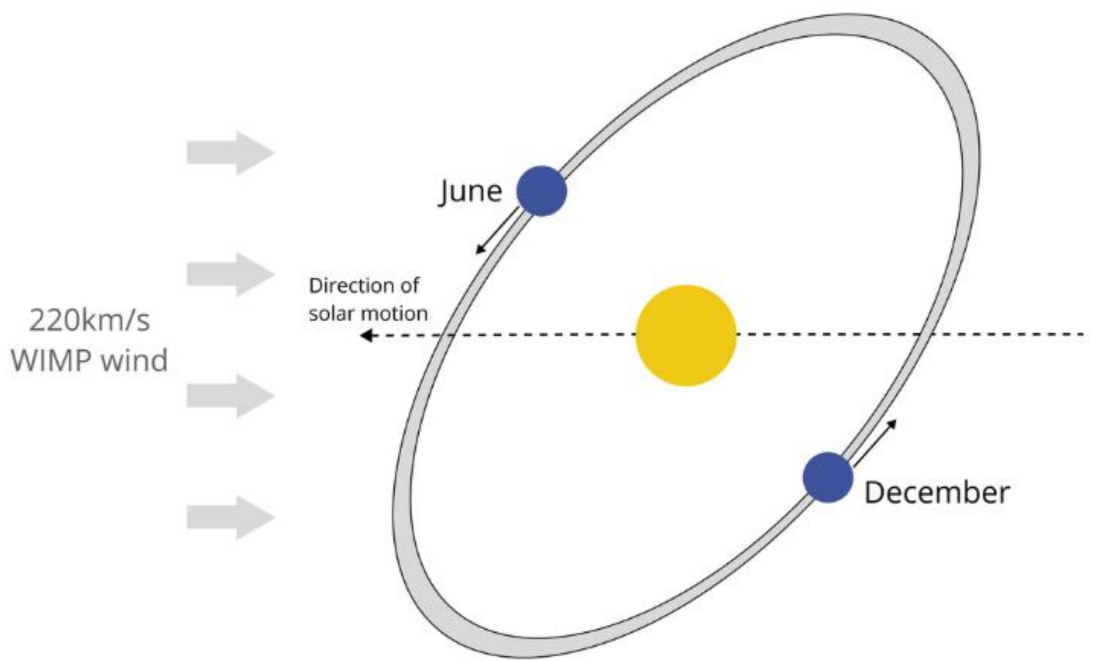
$$\frac{dR}{dE_R}(E_R, t, m_\chi, \sigma) = \boxed{\frac{\rho_\chi}{M m_\chi}} \int_{v_{min}}^{\infty} \boxed{v f(v,t)} \boxed{\frac{d\sigma}{dE_R}(v, E_R)} dv$$

DM/target properties, local DM density

DM halo velocity distribution

Differential cross-section for DM-nucleus elastic scattering

Annual Modulation of DM



A model independent signal for dark matter due to relative motion of earth through DM halo

Period of 1 year, peaking June 2nd
$(\boldsymbol{t_0} = \mathbf{152.5\ days})$

Expect very low modulation amplitude ~0.01 cpd/kg/keV

Single hit events

$$\frac{dR}{dE_R}(t) = S_0(E_R) + \boxed{S_m(E_R)\cos\omega(t - t_0)}$$

What DAMA measures + reports
(“residuals”)

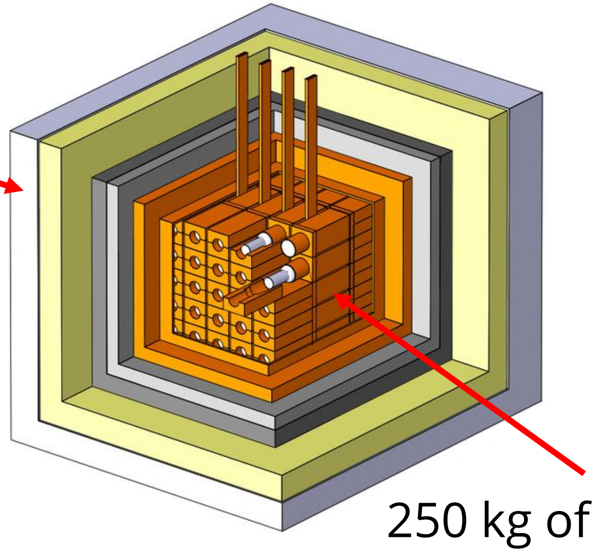
The DAMA Anomaly

The DAMA/LIBRA experiment produced 20 year long observation of annual modulation

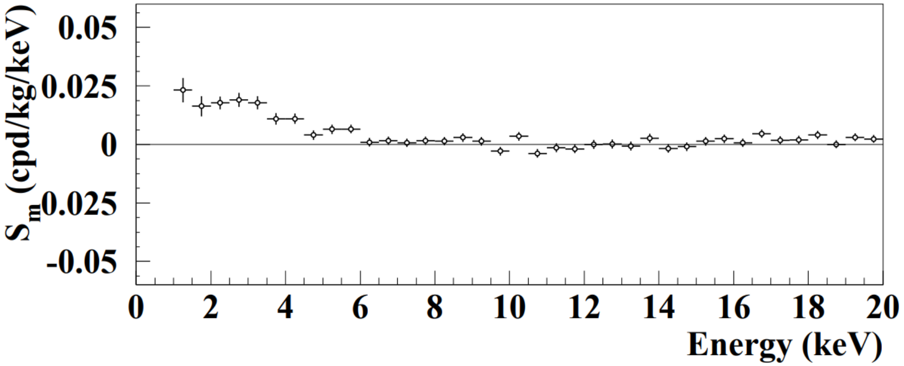
- 1-6 keV nuclear recoils at a significance of 12.9 σ
- **Is currently unresolved**

Background ~0.8 cpd/kg/keV

Cu Pb, HDPE Shielding

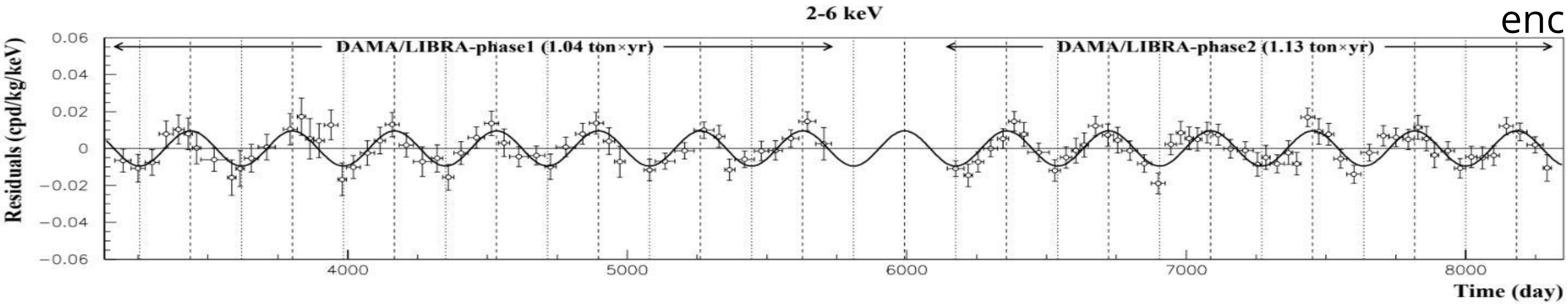


250 kg of NaI(Tl) crystals (25 enclosures)



S_m: 0.01058 ± 0.00090 cpd/kg/keV
Phase: 144.5 ± 5.1 days
Period: 0.999 ± 0.001 yr

Modulation present in 1-6 keV



DAMA/LIBRA, *Nucl.Phys.Atom.Energy* 19 (2018) 4, 307-325

Testing the DAMA Anomaly

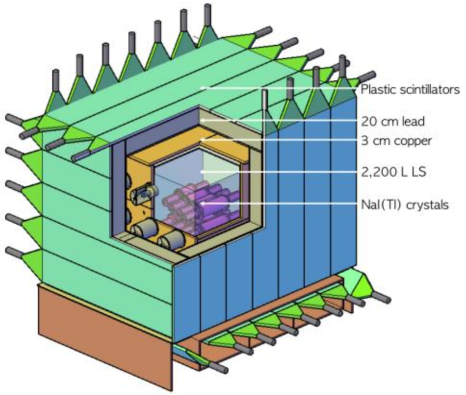
Anomaly best tested by similar, but improved, detectors:

- ANAIS – Canfranc underground lab, Spain
- COSINE100 – Yangyang lab, South Korea
- Cosinus – LNGS, Italy (NaI, cryogenic, no Tl)
- **SABRE – SUPL, Australia and LNGS, Italy**

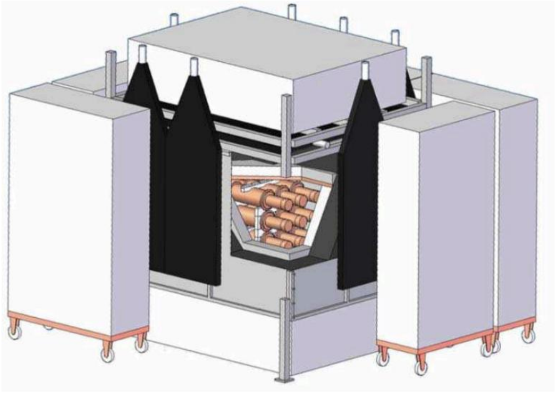
Utilising the same target material (NaI(Tl))

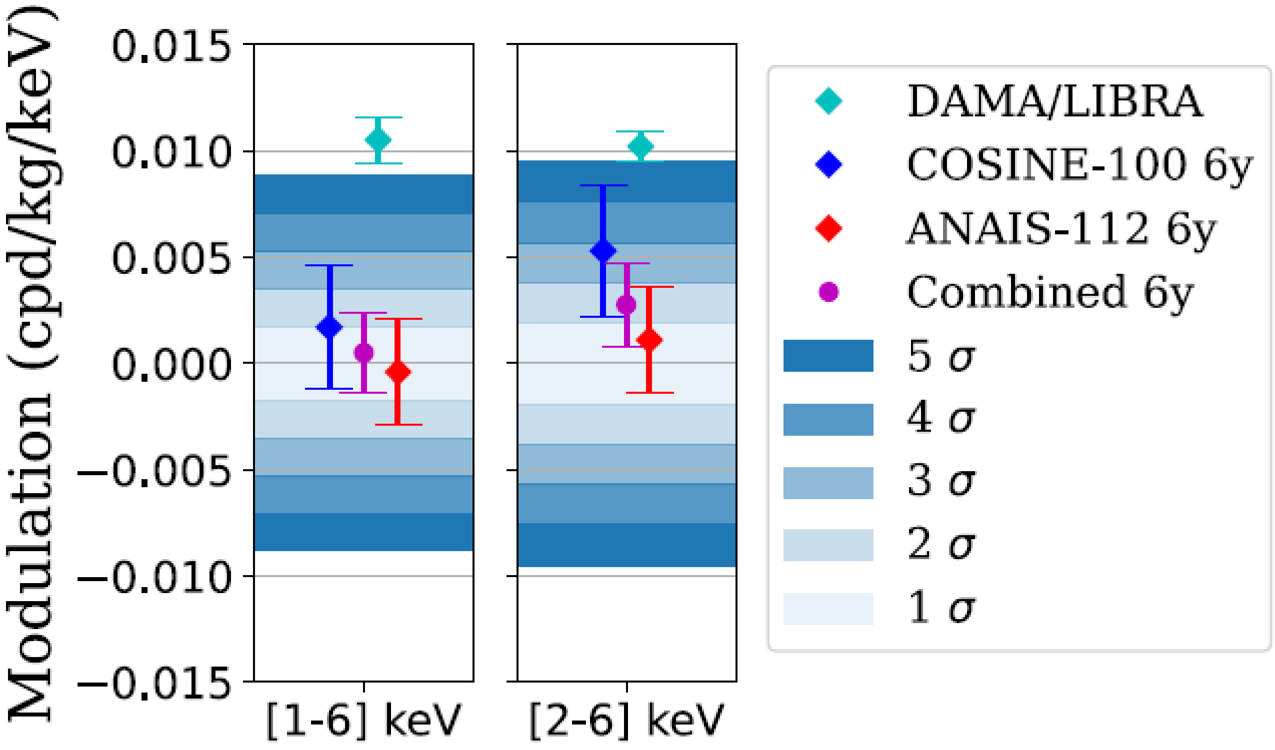
Current tests of DAMA/LIBRA results are inconclusive

COSINE-100 [2]
~2.9 cpd/kg/keV
100 kg of NaI(Tl)



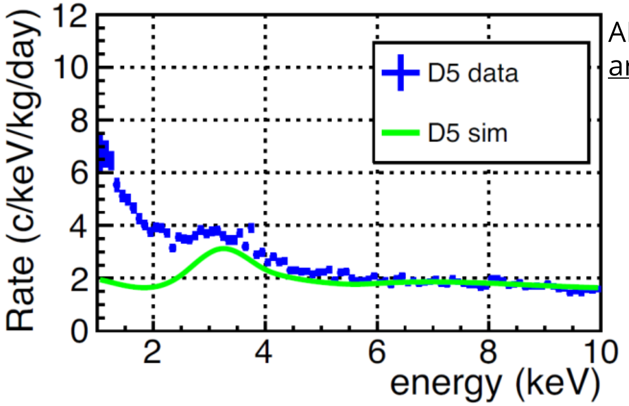
ANAIS-112 [3]
~3.2 cpd/kg/keV
112 kg of NaI(Tl)





COSINE-100, ANAIS-112, Phys. Rev. Lett. 135 (Sep, 2025) 121002

Both have upcoming upgrades with lower backgrounds!



ANAIS-112, arXiv:2404.17348

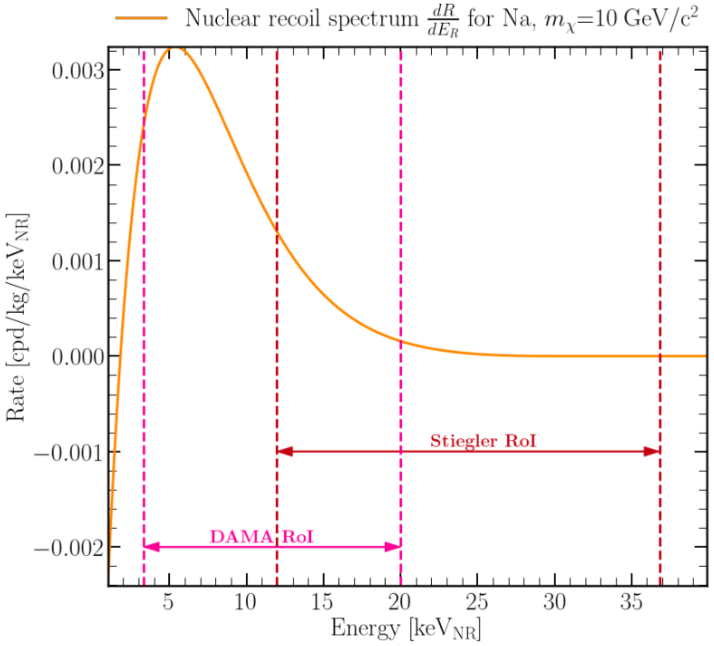
Comparing Results: Quenching Factor

Accurate comparison of results dependent on quenching factor to ensure consistent energy scale

Quenching factor: Conversion factor of nuclear recoil energy to electron-equivalent, due to energy losses in recoil process

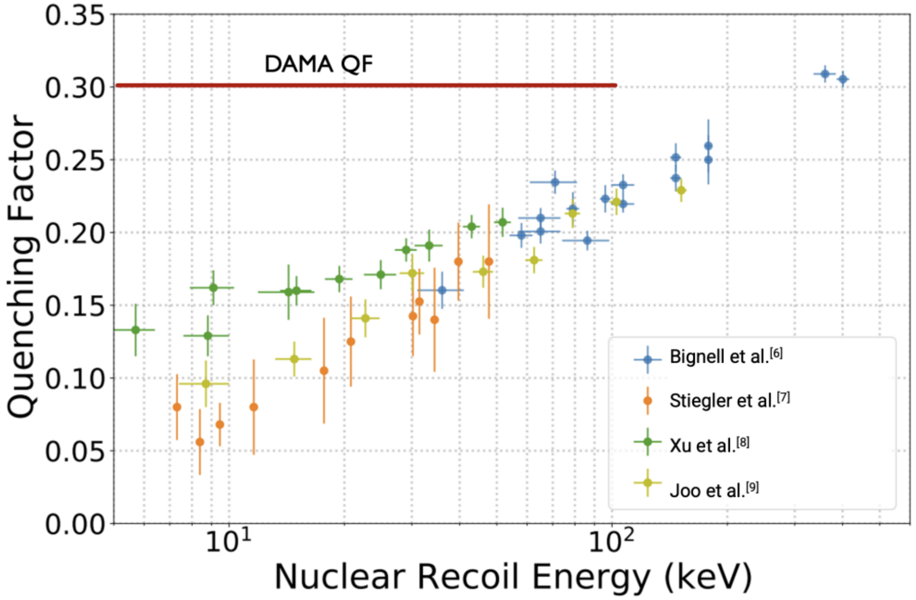
Stiegler vs. DAMA QF yield different energy regions – evidence QF also varies based on crystal growth process

Require accurate QF measurements to ensure proper comparability across experiments



M. J. Zurowski, arXiv: 2211.15861

$$E_{ee} = Q(E_{NR})E_{NR}.$$



The SABRE Collaboration

Detectors in two locations:

- SABRE North: Laboratori Nazionali del Gran Sasso (LNGS), Italy
- *SABRE South: Stawell Underground Physics Laboratory (SUPL), Australia*

Dual hemisphere – seasonal backgrounds opposite phase i.e. Muon induced

North

INFN Istituto Nazionale di Fisica Nucleare

Sapienza Università di Roma

Princeton University

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

Università degli Studi di Milano

Università del Salento

South

Dark Matter Particle Physics

The University of Melbourne

Swinburne

Crystals

RMD A Dynasil Company

SICCAS Since 1928

Screening

UKRI Science and Technology Facilities Council

Boulby Underground Laboratory

Australian Government ANSTO

UCL

Veto LS & PMTs

Institute of High Energy Physics Chinese Academy of Sciences

SABRE South is a first for Australia:

- **First deep underground laboratory at 1025 m in southern hemisphere**
- **First underground dark matter experiment**

SABRE South assembly beginning in late **2025/early 2026**

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

Stawell Underground Physics Lab

The Stawell Underground Physics Lab

SABRE South Collab, Astropart.Phys. 179 (2026) 103240

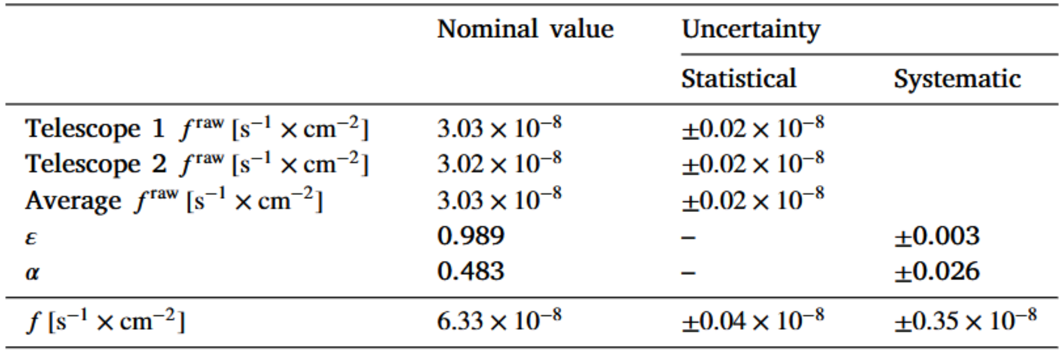
Lab completed in 2022/2023, and first detectors commissioned in 2024

Muon detectors installed in **“telescope mode”** to measure flux, angular spectrum

First muon flux measurement published, see: *SABRE South Collab, Astropart.Phys. 179 (2026) 103240*

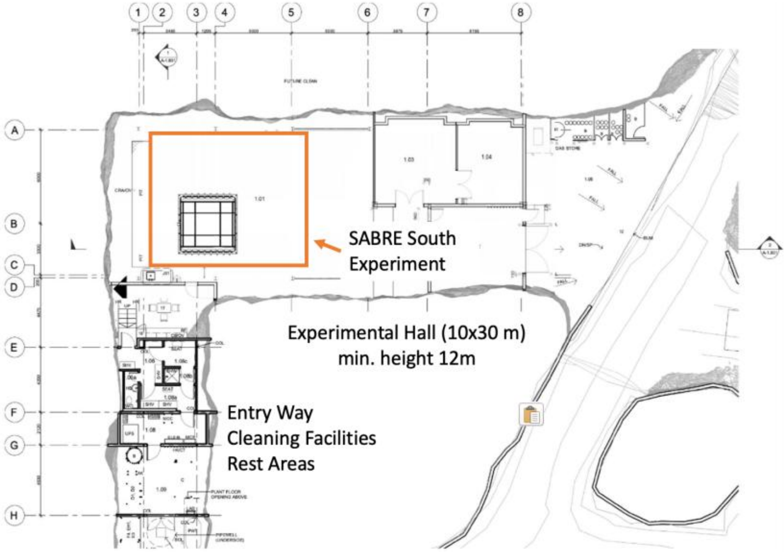
ε - efficiency
α – geometric acceptance

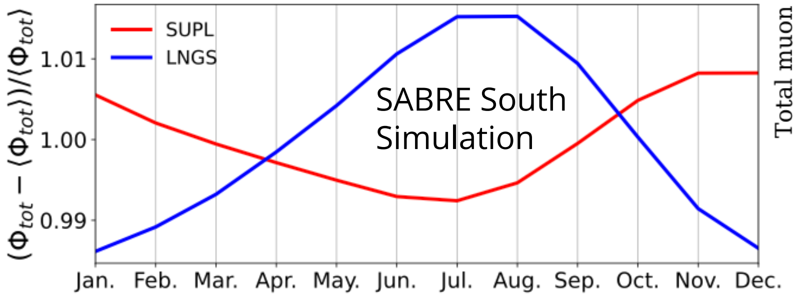
$$f = \frac{f_{\text{raw}}}{\varepsilon\ \alpha}$$

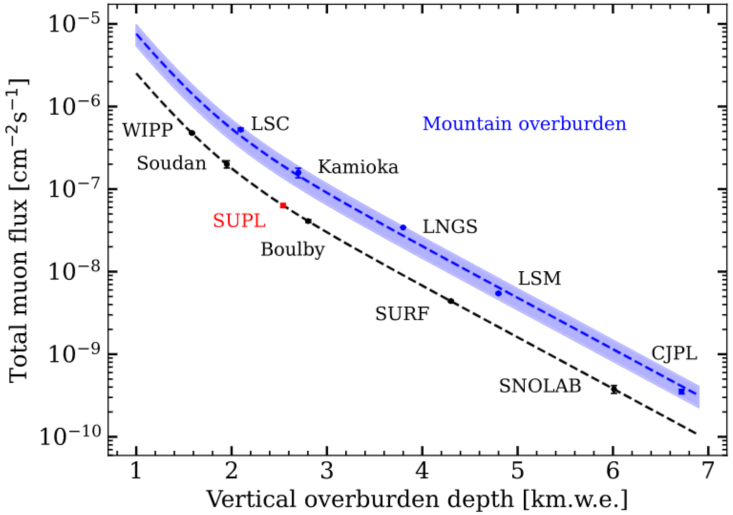


	Nominal value	Uncertainty	
		Statistical	Systematic
Telescope 1 f^{raw} [$\text{s}^{-1} \times \text{cm}^{-2}$]	3.03×10^{-8}	$\pm 0.02 \times 10^{-8}$	
Telescope 2 f^{raw} [$\text{s}^{-1} \times \text{cm}^{-2}$]	3.02×10^{-8}	$\pm 0.02 \times 10^{-8}$	
Average f^{raw} [$\text{s}^{-1} \times \text{cm}^{-2}$]	3.03×10^{-8}	$\pm 0.02 \times 10^{-8}$	
ε	0.989	–	± 0.003
α	0.483	–	± 0.026
f [$\text{s}^{-1} \times \text{cm}^{-2}$]	6.33×10^{-8}	$\pm 0.04 \times 10^{-8}$	$\pm 0.35 \times 10^{-8}$

$$f_{\text{sim}} = (4.8 \pm 2.3) \times 10^{-8}\ [\text{s}^{-1} \times \text{cm}^{-2}],$$







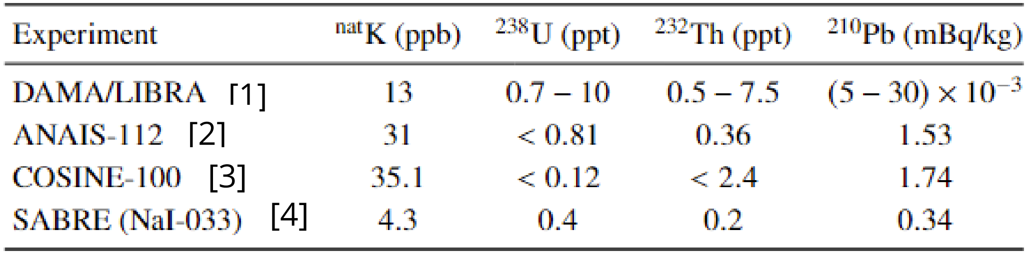
The SABRE South Concept

SABRE South Collab 2025 *JINST* **20** T04001

To effectively test DAMA/LIBRA, an **ultra-low background** is required to be sensitive to **0.01 cpd/kg/keV**

Backgrounds dominated by radiogenic background in crystals – SABRE South backgrounds comparable to DAMA/LIBRA with high radiopurity

Utilise an **active veto detector** to drastically reduce external backgrounds - **<10% of background external to crystals by design**

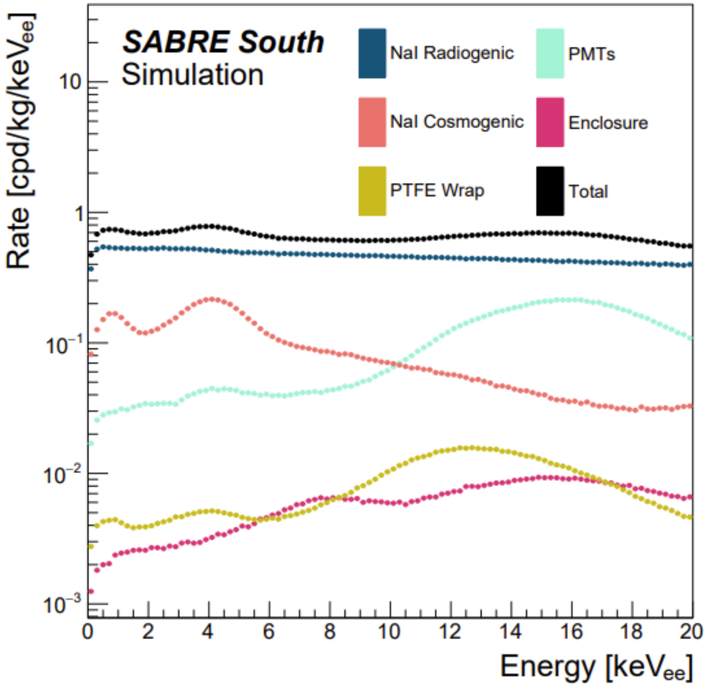


Experiment	^{nat}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Pb (mBq/kg)
DAMA/LIBRA [1]	13	0.7 – 10	0.5 – 7.5	$(5 - 30) \times 10^{-3}$
ANAIS-112 [2]	31	< 0.81	0.36	1.53
COSINE-100 [3]	35.1	< 0.12	< 2.4	1.74
SABRE (NaI-033) [4]	4.3	0.4	0.2	0.34

[1] DAMA Collaboration, R. Bernabei et al., The DAMA/LIBRA apparatus, NIMA
[2] ANAIS Collaboration, J. Amaré et al., Analysis of backgrounds for the ANAIS-112 dark matter experiment, EPJC
[3] COSINE Collaboration, P. Adhikari et al., Background model for the NaI(Tl) crystals in COSINE-100, EPJC
[4] B. Suerfu et al., Growth of ultra-high purity NaI(Tl) crystals for dark matter searches, Physical Review Research

Component	Rate (cpd/kg/keV)	Veto efficiency (%)
Crystal intrinsic	$<5.2 \times 10^{-1}$	13
Crystal cosmogenic	1.6×10^{-1}	45
Crystal PMTs	3.8×10^{-2}	57
Crystal wrap	4.5×10^{-3}	11
Enclosures	3.2×10^{-3}	85
Conduits	1.9×10^{-5}	96
Steel vessel	1.4×10^{-5}	>99
Veto PMTs	1.9×10^{-5}	>99
Shielding	3.9×10^{-6}	>99
Liquid scintillator	4.9×10^{-8}	>99
External	5.0×10^{-4}	>93
Total	**0.72**	**27**

SABRE South – 0.72 cpd/kg/keV
ANAIS112 – 3.2 cpd/kg/keV
COSINE100 – 2.9 cpd/kg/keV
DAMA/LIBRA – 0.8 cpd/kg/keV



The SABRE South Detector

SABRE South Collab 2025 *JINST* **20** T04001

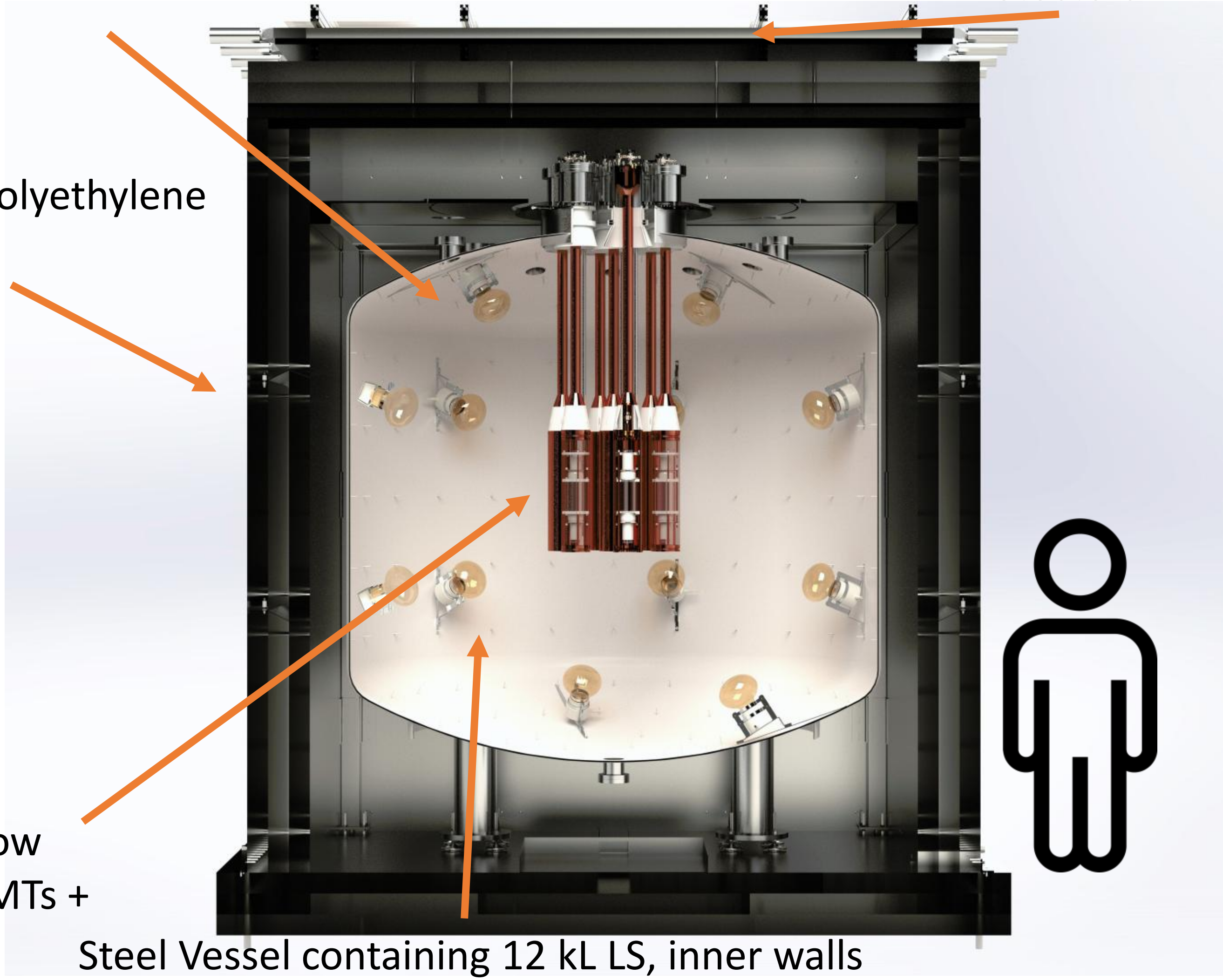
Improvement on similar detectors:

- Higher purity, low background crystals
- **Southern hemisphere location**
- **Active background veto**
- Particle ID, some position reconstruction capabilities

Total background: **0.72 cpd/kg/keV** for 50 kg of NaI(Tl)

1 keV energy threshold for 1-6 keV ROI in NaI(Tl)

In-situ optical (in LS) and radioactive calibration possible



9.6 m^2 Muon Detectors

> 18x R5912 Veto PMTs

Steel and Polyethylene Shielding

High quantum efficiency and low radioactivity R11065 Crystal PMTs + ultra pure NaI(Tl) crystals

Steel Vessel containing 12 kL LS, inner walls covered in Lumirror reflector

The SABRE South LS Veto

12 kL of linear alkyl benzene (LAB) procured via JUNO experiment production line, doped with PPO and bisMSB

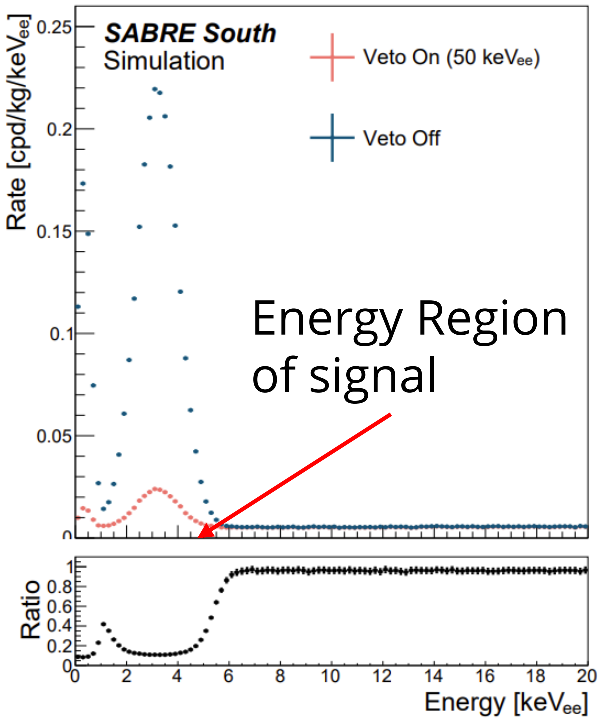
Two key requirements:

- Reduce ^{40}K background by factor of 10
- Provide some degree of event reconstruction – particle ID or position reconstruction

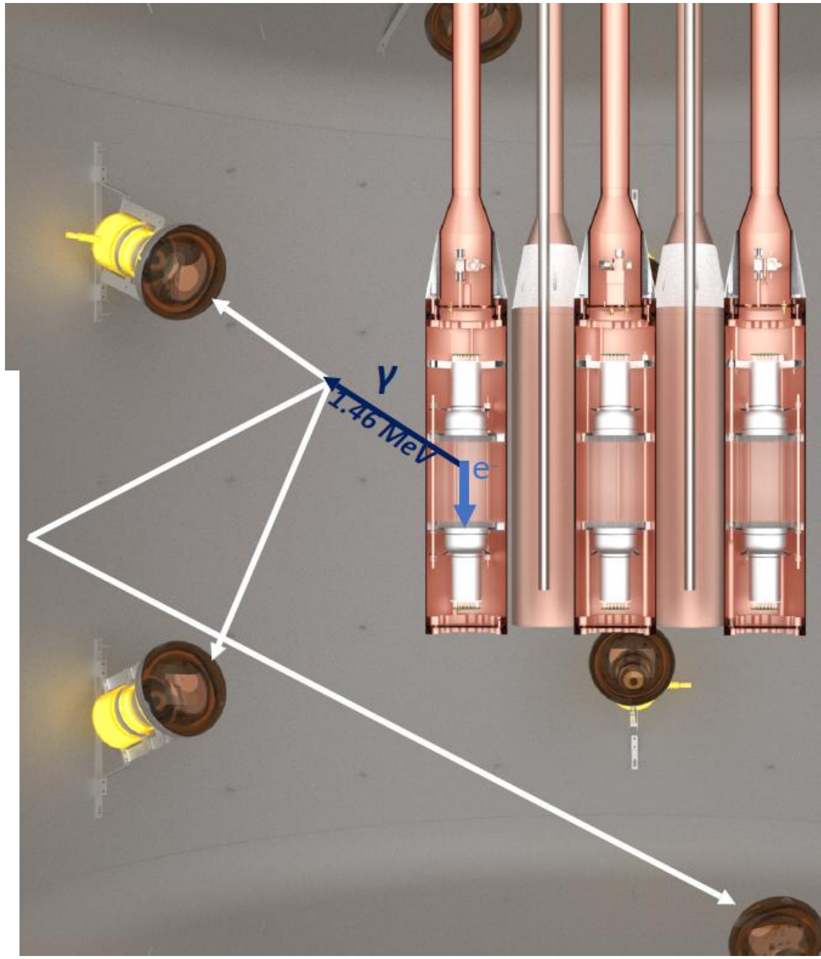
Desire to extract as much physics/information from the veto

To achieve requirements demands deep understanding of detector response

^{40}K Rate



Energy Region of signal



SABRE South Collab. EPJC, Vol 83, 878 (2023)
https://doi.org/10.1140/epjc/s10052-023-11817-z

Full Detector Response

L.J. Milligan *et al* 2025 *JINST* **20** P07049

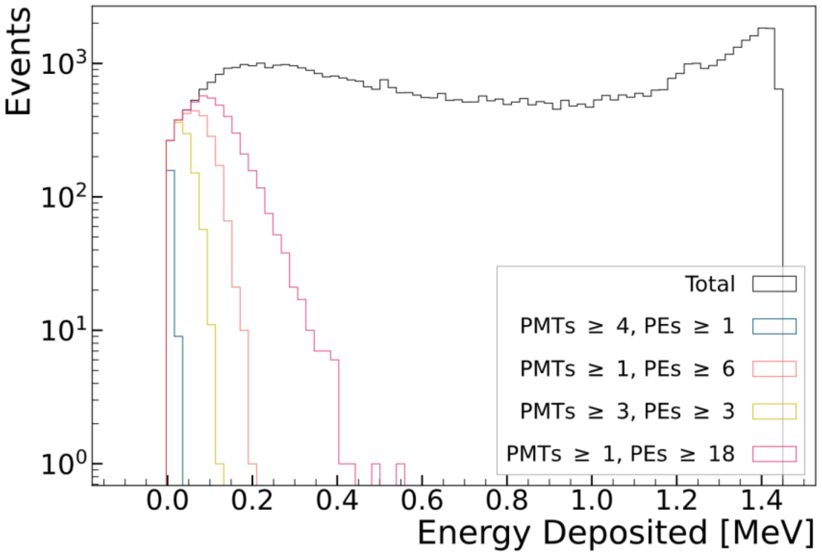
Light yield of of LS ~12 photons/keV

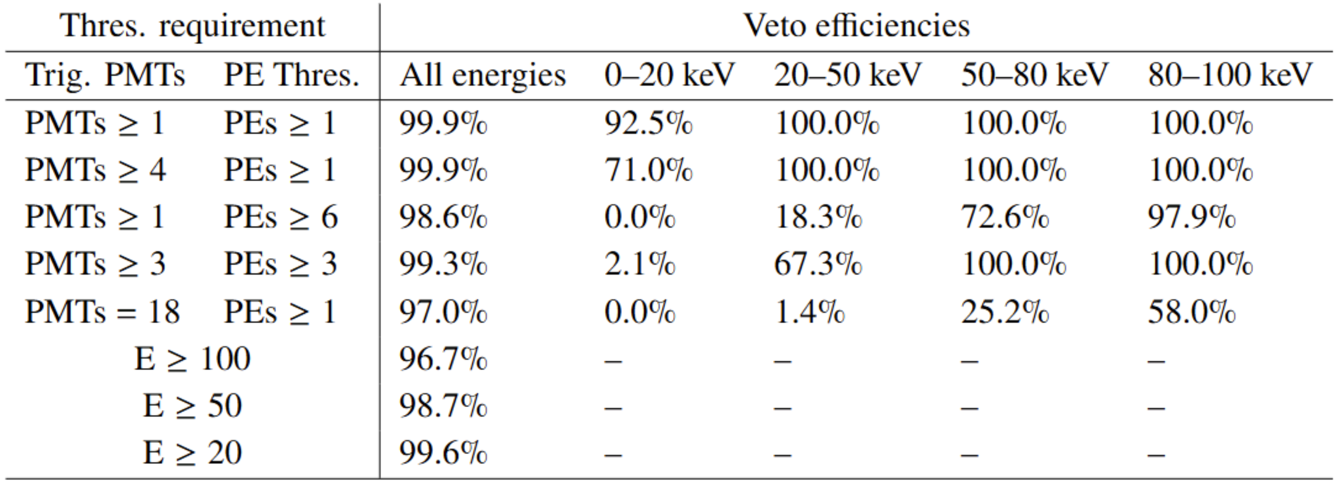
Average of 0.75 PE/keV detectable by any PMT

Simulated analysis of triggers indicate threshold between **20-50 keV (>15 PE)** possible – expect low amounts of detectable photons at keV energies

Understanding of PMT response/noise imperative

Considering ^{40}K decays that interact with LS





Thres. requirement		Veto efficiencies				
Trig. PMTs	PE Thres.	All energies	0–20 keV	20–50 keV	50–80 keV	80–100 keV
PMTs ≥ 1	PEs ≥ 1	99.9%	92.5%	100.0%	100.0%	100.0%
PMTs ≥ 4	PEs ≥ 1	99.9%	71.0%	100.0%	100.0%	100.0%
PMTs ≥ 1	PEs ≥ 6	98.6%	0.0%	18.3%	72.6%	97.9%
PMTs ≥ 3	PEs ≥ 3	99.3%	2.1%	67.3%	100.0%	100.0%
PMTs = 18	PEs ≥ 1	97.0%	0.0%	1.4%	25.2%	58.0%
E ≥ 100		96.7%	–	–	–	–
E ≥ 50		98.7%	–	–	–	–
E ≥ 20		99.6%	–	–	–	–

PMT Performance Parameters

L.J. Milligan *et al* 2025 *JINST* **20** P07049
O. Stanley *et al* 2025 *JINST* **20** P07052

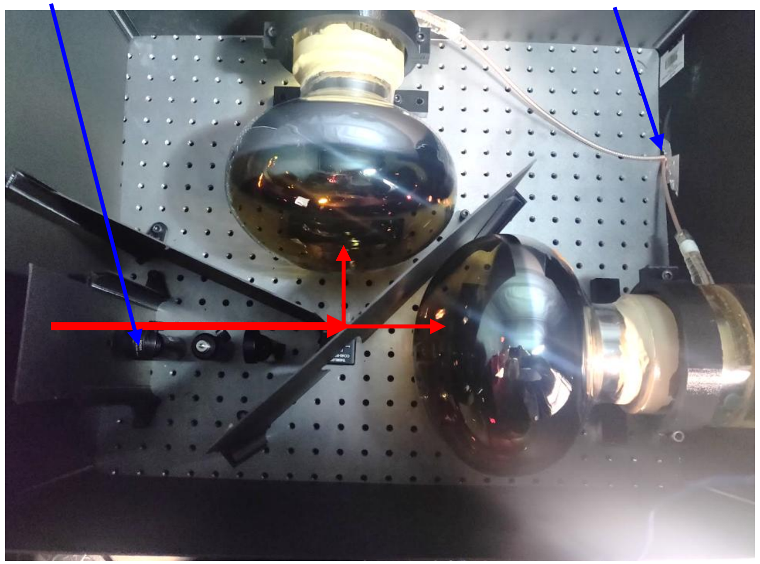
Broadly, PMT performance parameters can be split in two ways:

- **Signal** and **noise** related parameters
- Parameters important for **configuring the detector**, and for doing **reconstruction in the detector**

Measure these for the PMTs in our SABRE South LS Veto

Challenge: Consistently dark environment, experimental setups capable of single photon sensitivity

Large light-proofed dark boxes mounted on optical table

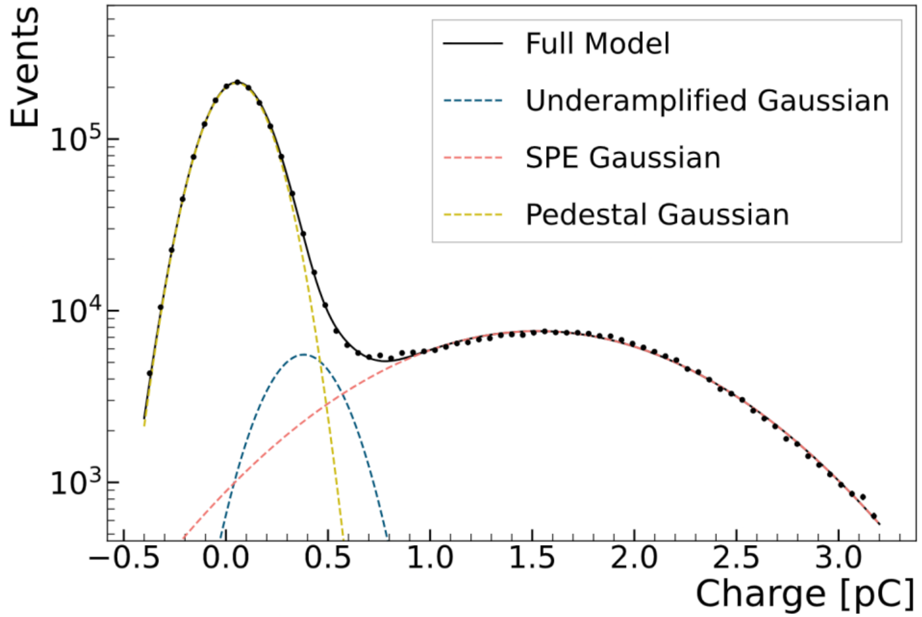


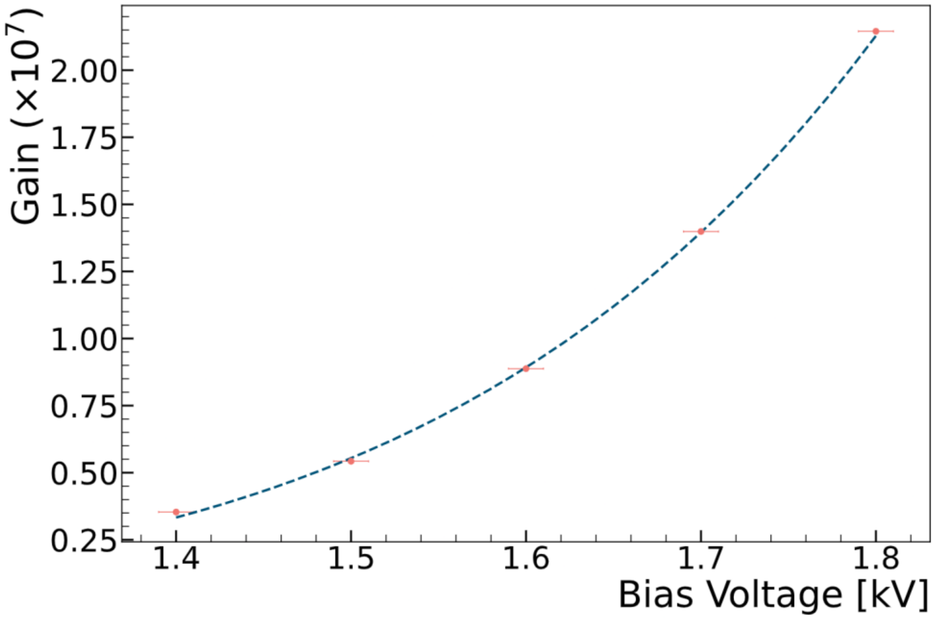
Stacked ND filter and pinhole (attenuation)

Out to V1730 digitizer with 2 ns precision

Dark optical setup with **picosecond pulsed laser** capable of attenuating to single photons

Pre-calibration: SPE Response/Gain





Isolated single photoelectron (PE) charge spectra through coincidence with laser signal

Fit: $$F(x, N_1, N_2, \mu_{1\mathrm{PE}}, \sigma_{1\mathrm{PE}}, \mu_{\mathrm{ped}}, \sigma_{\mathrm{ped}}, \delta) = N_1 G(x, \mu_{\mathrm{ped}}, \sigma_{\mathrm{ped}}) + N_2 G(x, \mu_{1\mathrm{PE}}, \sigma_{1\mathrm{PE}}) + (1 - N_1 - N_2) G(x, \delta \times \mu_{1\mathrm{PE}}, \delta \times \sigma_{1\mathrm{PE}}),$$

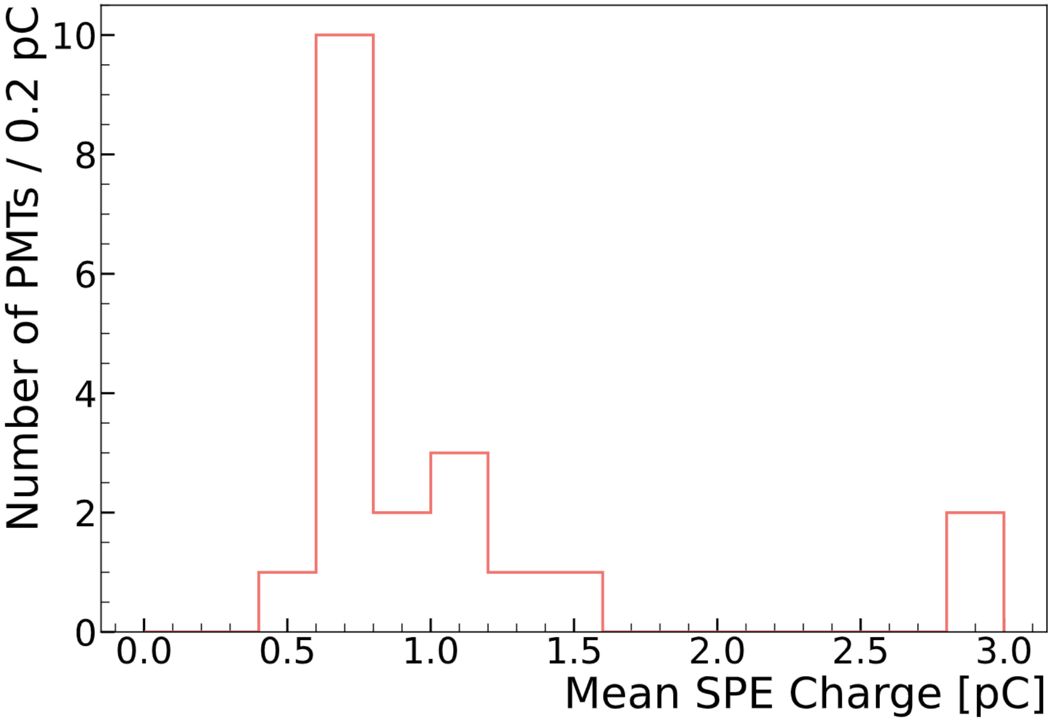
1PE mean = mean SPE charge

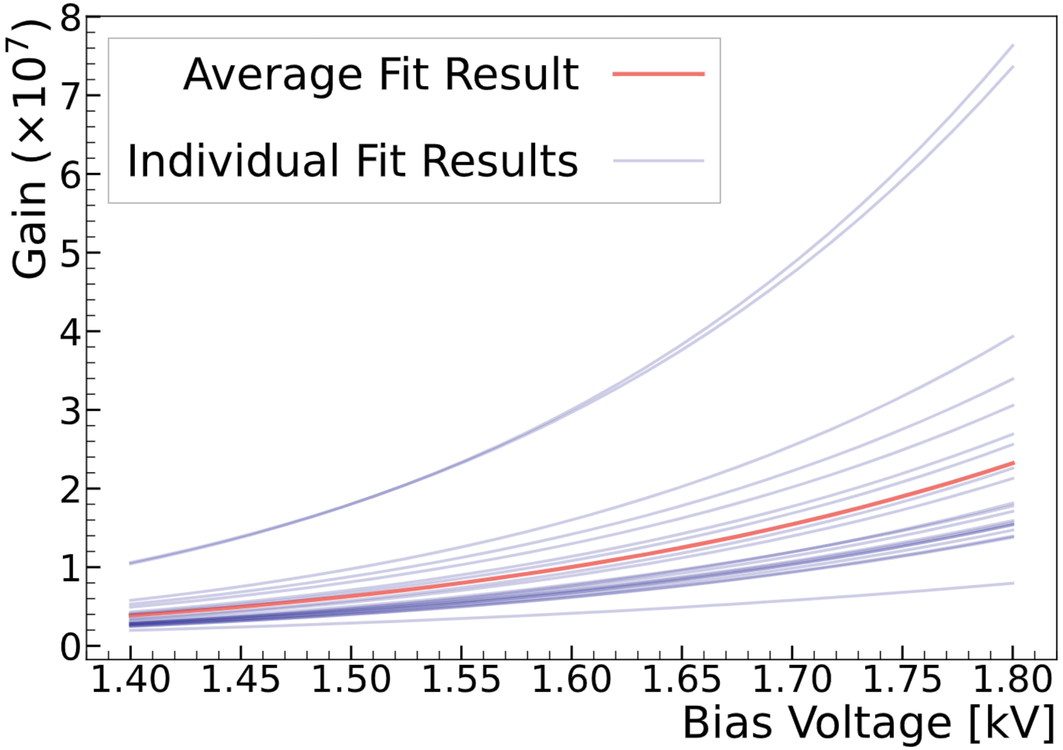
Repeat for range of bias voltages, extract gain curve

Fit according to: $$\mu = AV^{kN}$$

A, k floated, N no. of dynodes (10)

Pre-calibration: SPE Response/Gain





Mean SPE charge and gain at fixed 1500V bias voltage for every PMT

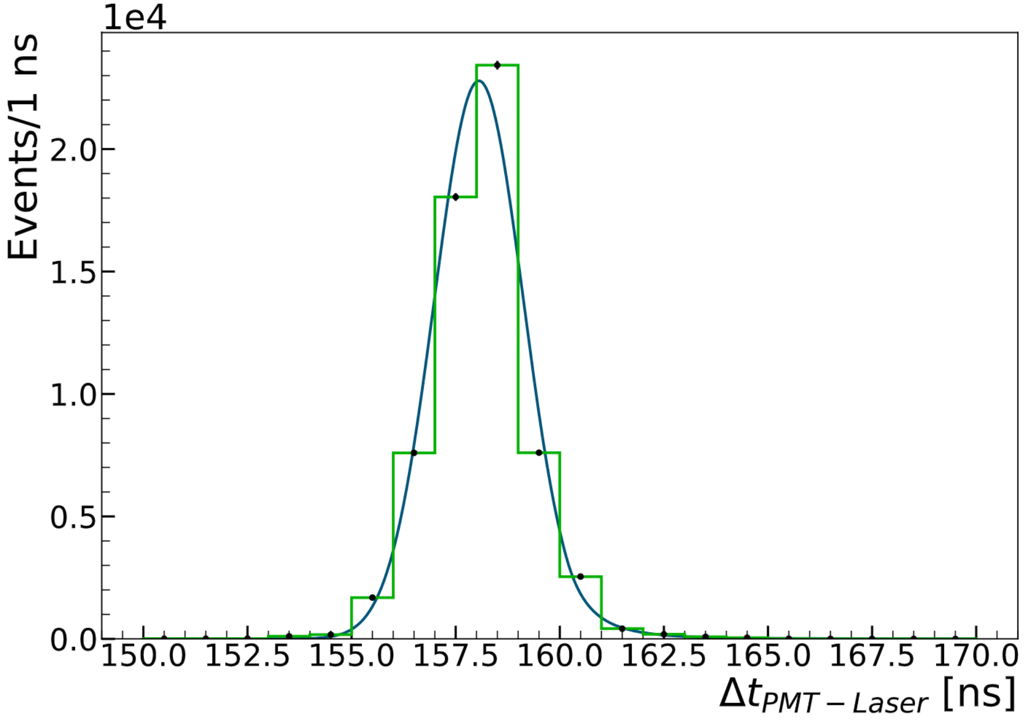
Expected gain from Hamamatsu is ~1x10^7 – slightly below expected

Gain curves, and mean SPE for each PMT, allow for individual configuration of LS veto instruments

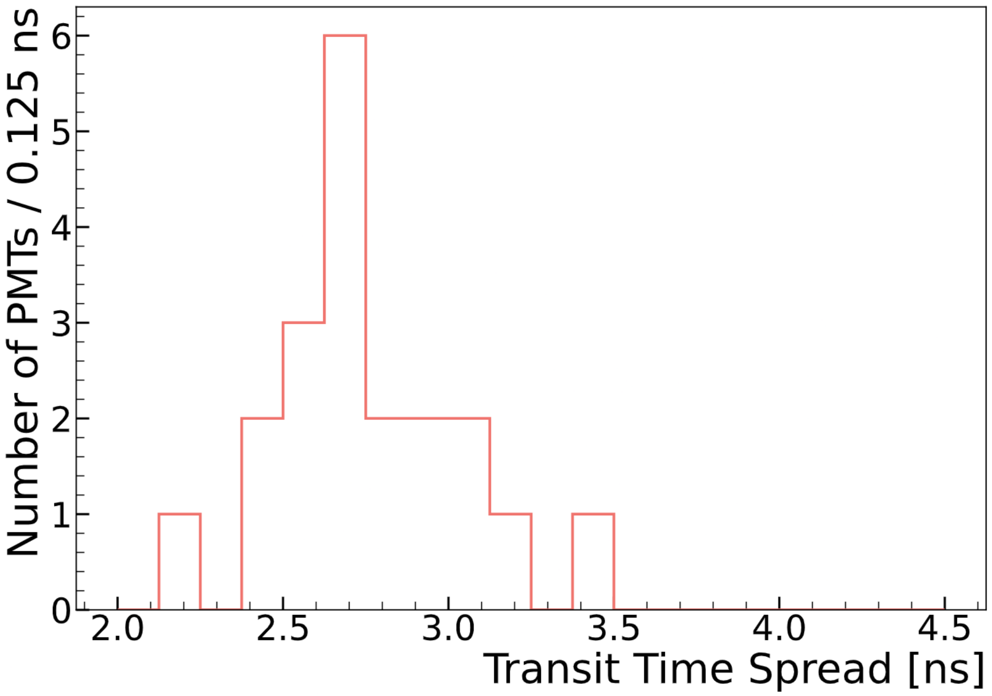
Pre-calibration: Timing Properties

Transit time spread (TTS) – spread of time for signal to traverse PMT (FWHM of timing dist.)

Timing dist. acquired relative to laser trigger time

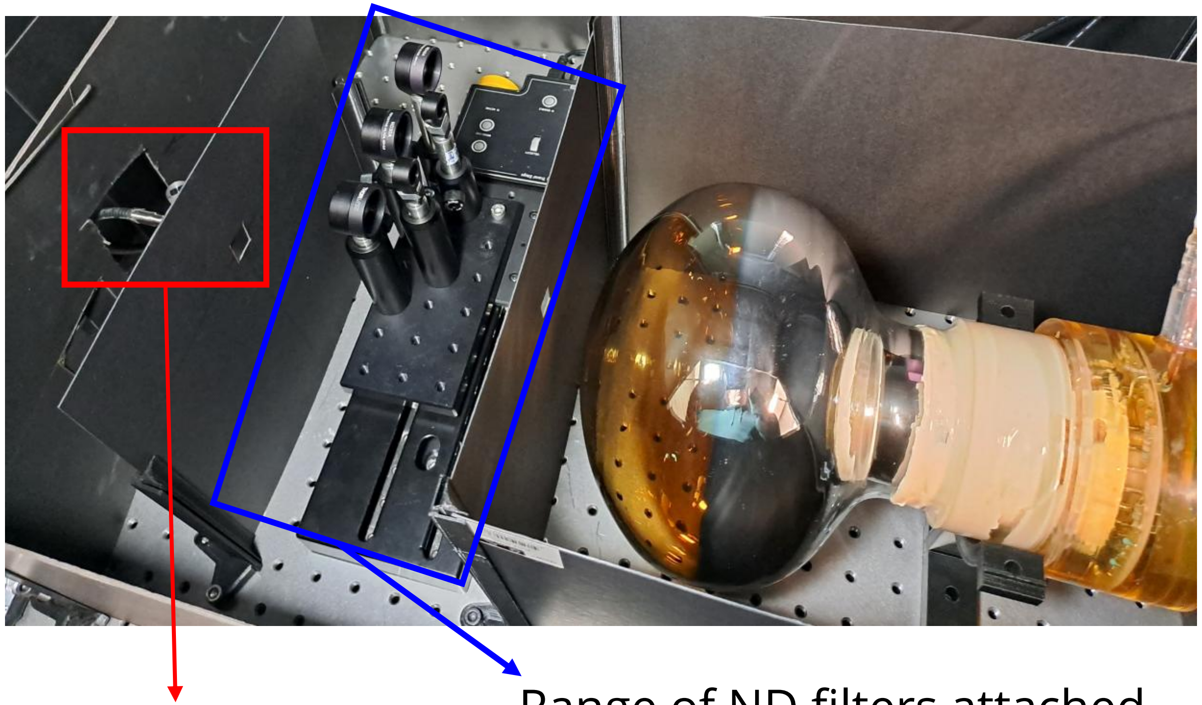


Dist. Fit with a crystal ball function,
FWHM extracted from PDF



Hamamatsu nominal TTS ~ 2.4 ns
Majority of PMTs consistent, spread above due to resolution of laser

Pre-calibration: Response Linearity



Laser in via collimator, adjustable aperture, at high intensity

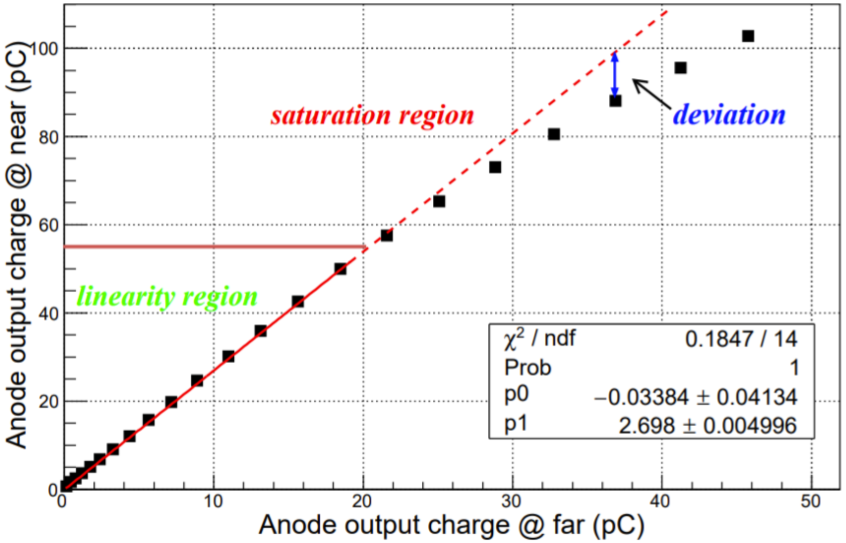
Range of ND filters attached to motorized stage

Can reach range of intensities, data collection automated

Linear PMT response is when the **measured** number of PEs determined via PMT response matches the **expected** number from physics

At intensity where this match is no longer 1:1 – PMT response has **saturated**

Determining point at which response saturates, is important for reconstructing high energy events



X. Wang *et al* 2021 *JINST* **16** P04008

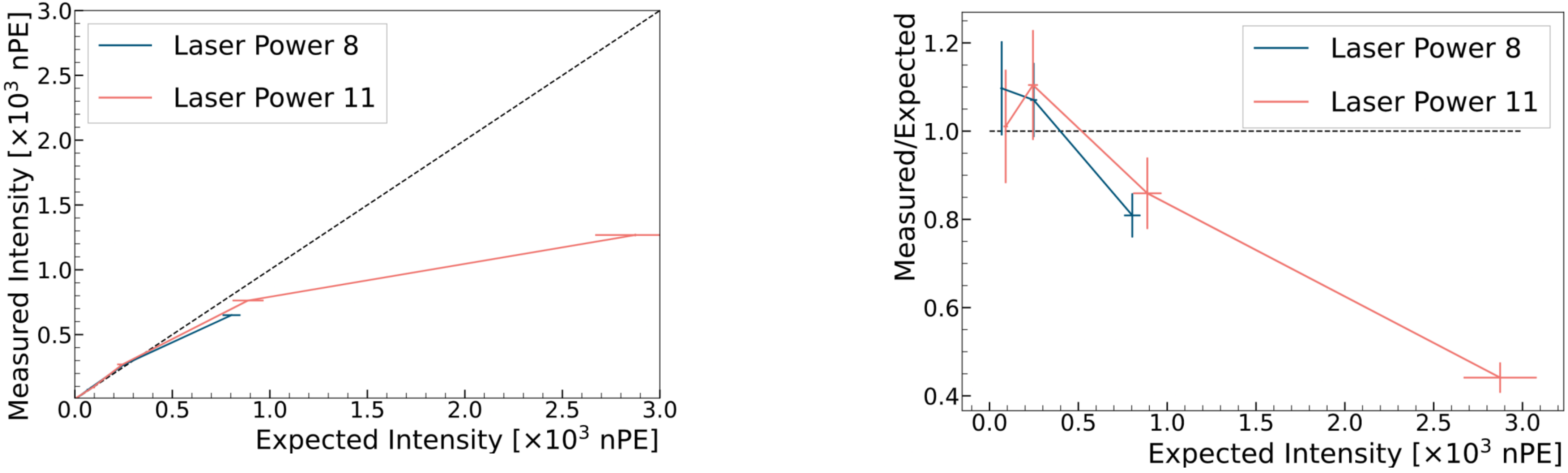
Pre-calibration: Response Linearity

Expected intensity: number of PEs determined from attenuation of ND filter at each intensity, applied to low intensity reference in linear regime

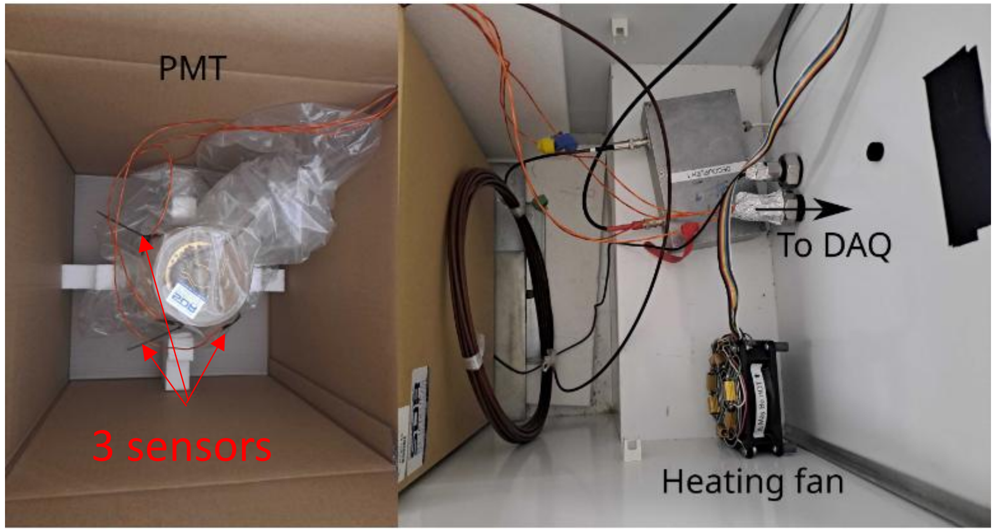
Measured intensity: number of Pes determined from PMT charge at each intensity

Large error bars from ND filter tolerance

Saturation onset determined at intensity of ~500 PEs



Pre-calibration: Dark Rate



PMT placed in temperature-controlled/insulated environment (fridge)

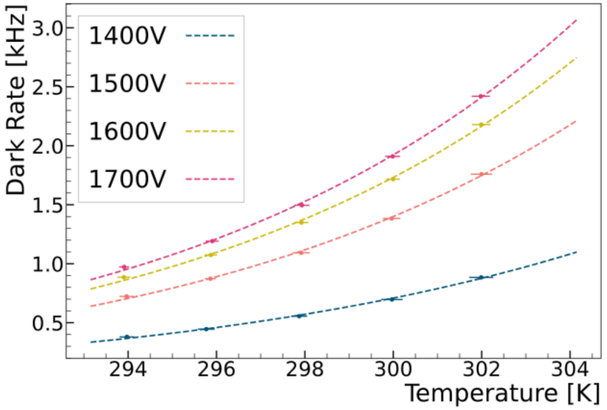
Temperature adjusted by heating fan/fridge remotely w/ wifi controller, recorded via ethercat

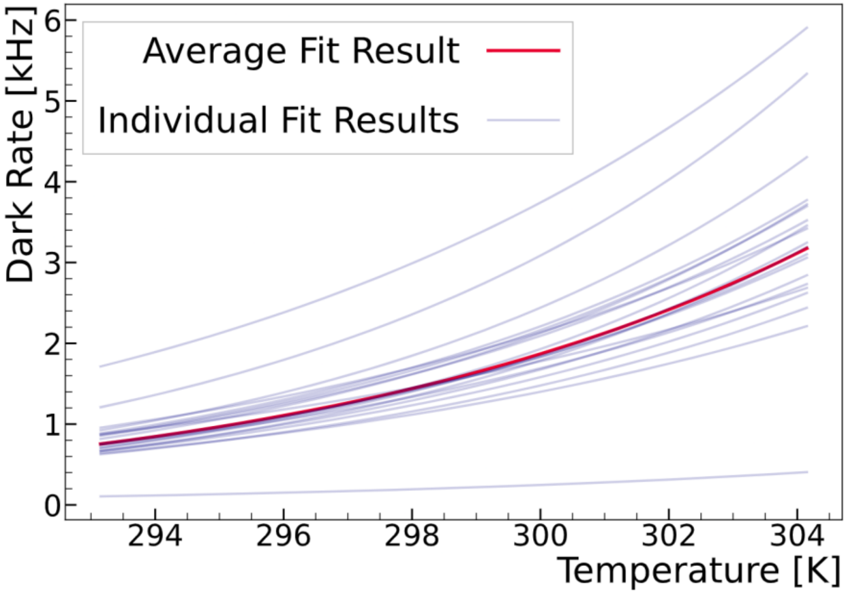
5 temperatures at 4 voltages, with 4 hour thermalization between temps

Variability key to understand if temperature varies w/ time

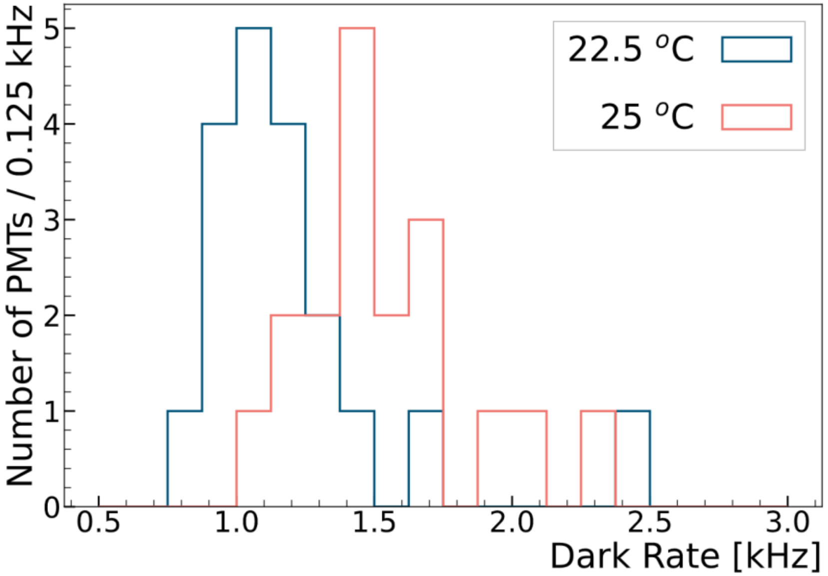
$$R = \boxed{A} T^{5/4} e^{-\boxed{e\psi/K} T}$$

Floated





DR at 1500V, approx. SUPL temps

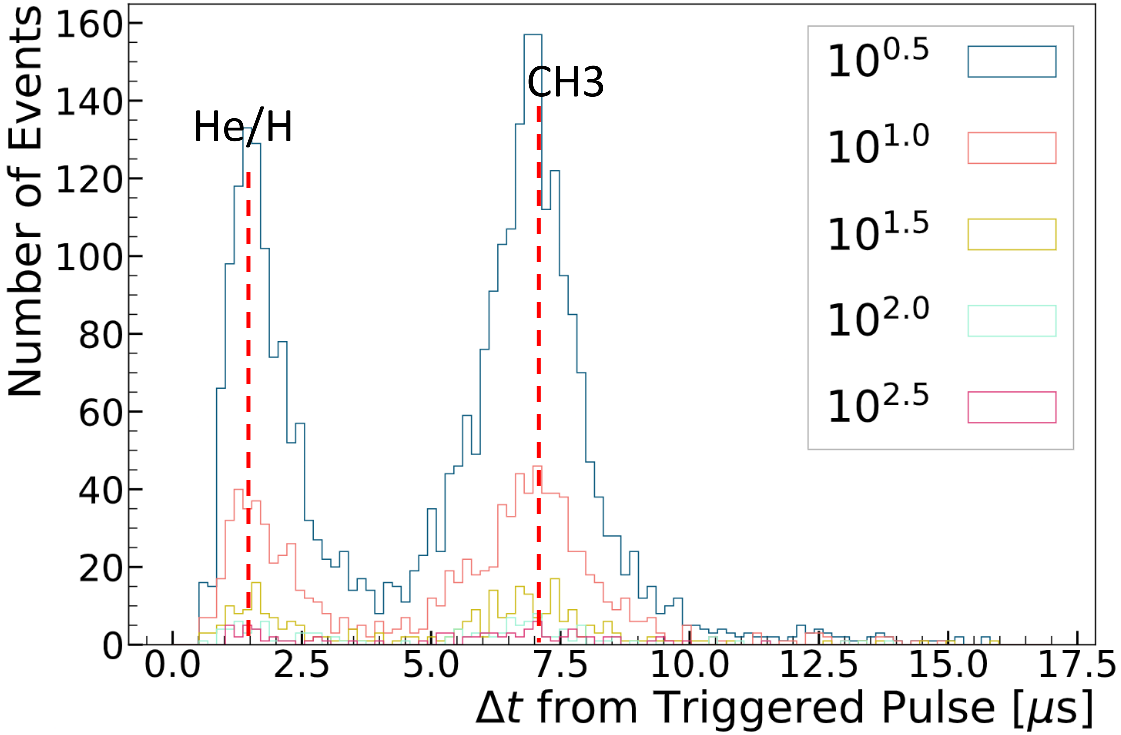


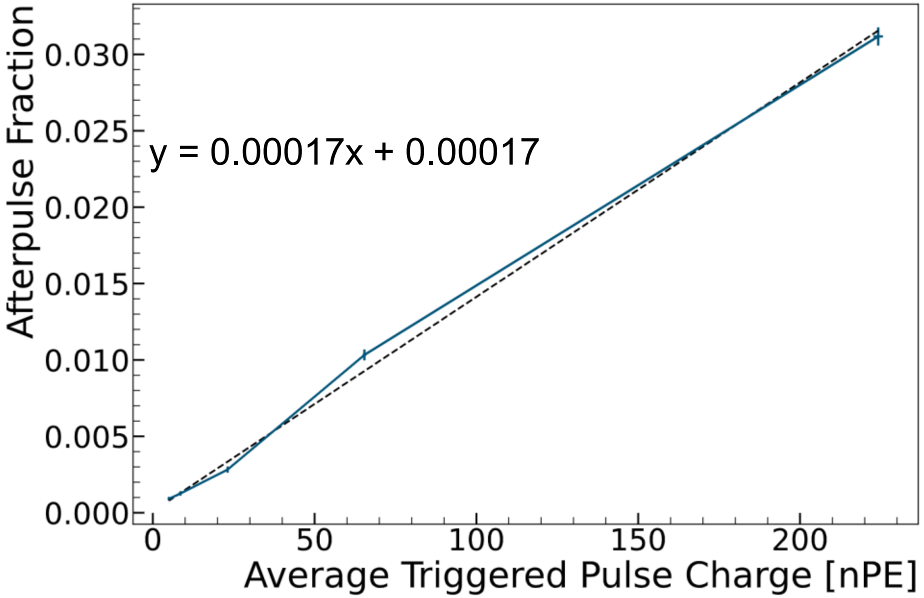
Pre-calibration: Afterpulsing

Afterpulsing: noise effect at high intensities where small "afterpulses" occur after high intensity pulse after characteristic time

Caused by ionisation of gas molecules inside PMT volume (increases over time)

Utilise afterpulse data, 18 us waveforms with peak finder to find afterpulses





Fraction of events w/ afterpulses vs. intensity of initial pulse

Afterpulsing rate:
0.00017 pulses/PE

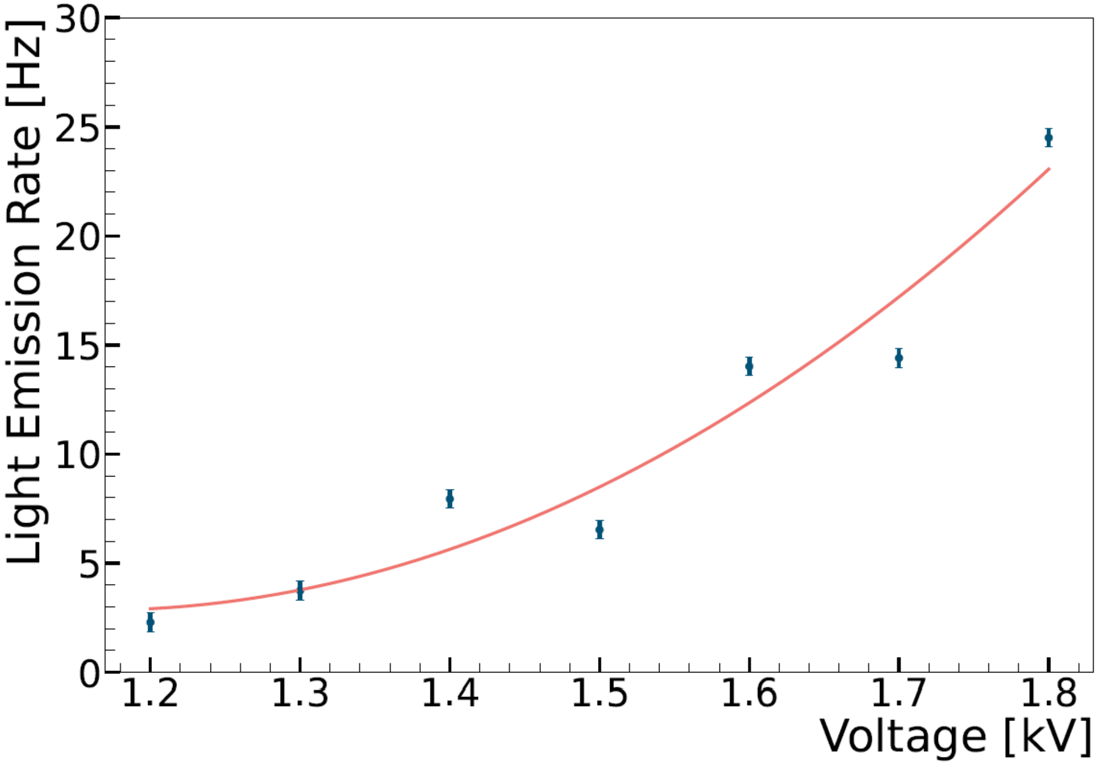
Pre-calibration: Spontaneous Light Emission

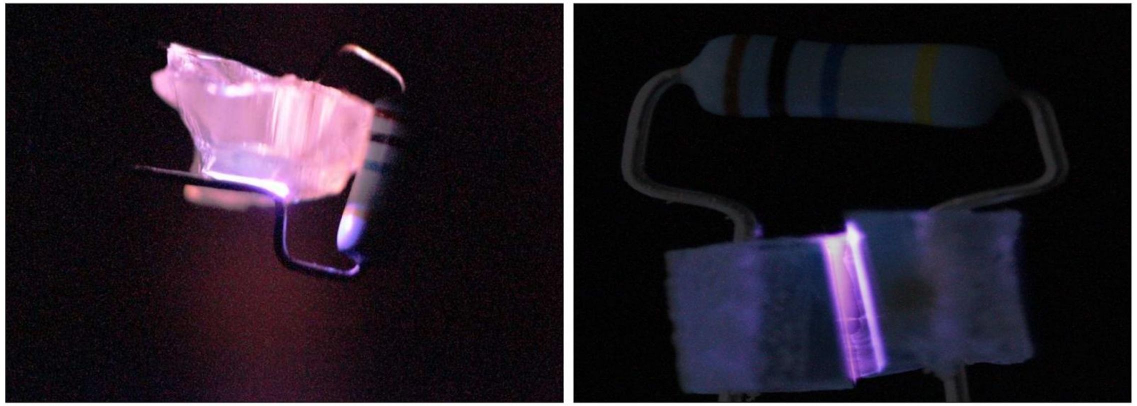
Spontaneous, low rate of “flashes” observed from oilproof PMT bases

Coronal discharge in air gaps between wiring and epoxy compound in oilproof base

Measured for SABRE South veto PMTs, low rate detected w/ voltage dependence

Necessitating wrapping of PMT bases w/ lumirror/foil





Double Chooz Collaboration, JINST, arXiv:1604.06895

Pre-calibration: Daya Bay PMT QA

Lots of PMT properties measured to optimise for our veto efficiency, allow for reconstruction capabilities

Best way to achieve these goals – **increase photosensor coverage, increase light collection/detection efficiency**

16 decommissioned R5912 PMTs acquired from Daya Bay for use in SABRE South

Quality assurance on old PMTs before installation – 13/14 can be used

Shipped from Daya Bay Experiment, China

Daya Bay R5912

SABRE South R5912

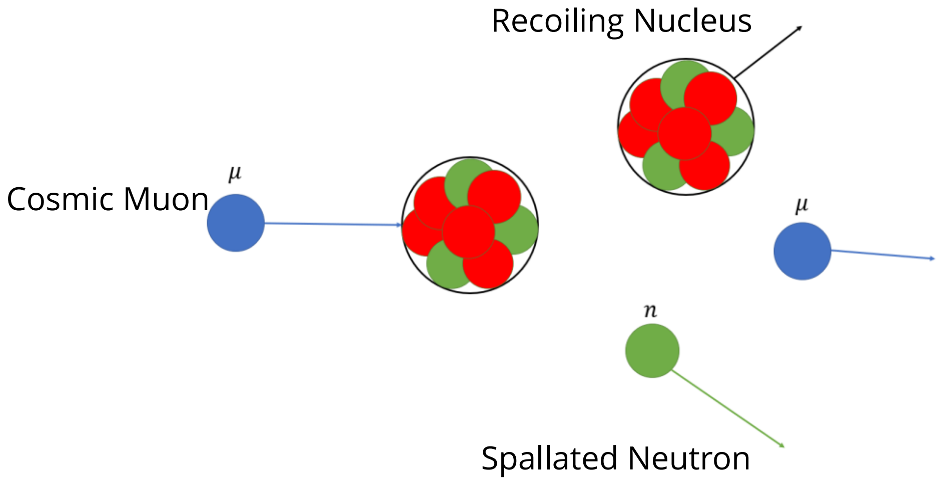
Example of what can be achieved

Can we study the backgrounds detected? → Background Reconstruction and identification

Identify neutron vs. gamma backgrounds in veto?

Spallation neutrons from cosmogenic muons can mimic DM – important background

^{40}K background important as it is in the region of interest of our signal

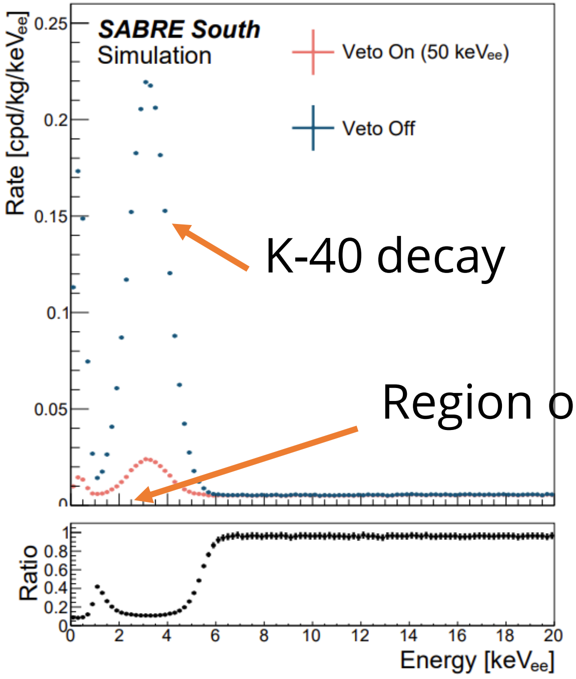


Recoiling Nucleus

Cosmic Muon

Spallated Neutron

vs.



K-40 decay

Region of signal

Pulse Shape Discrimination

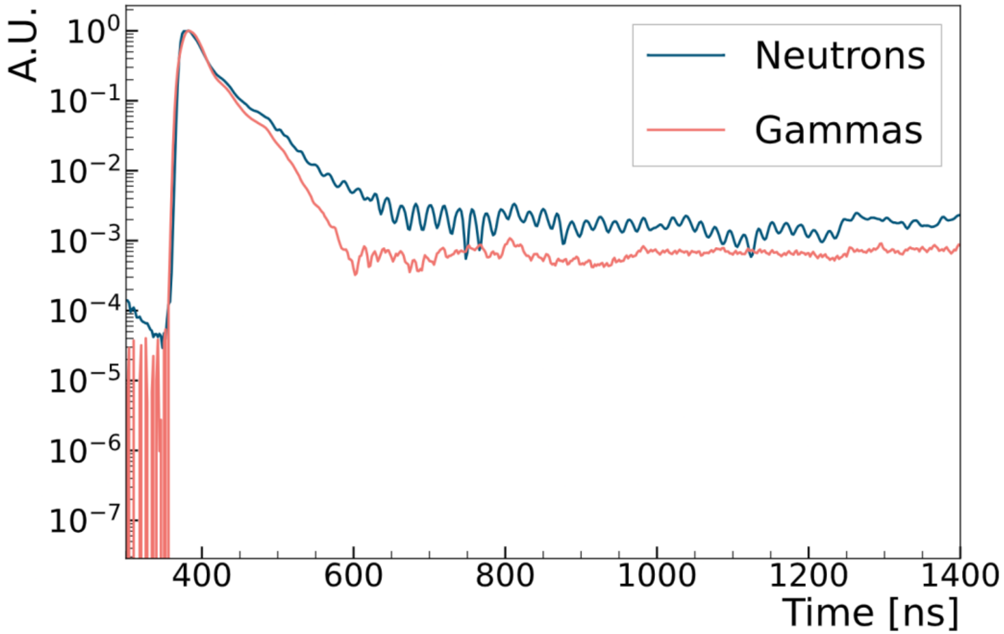
L.J. Milligan *et al* 2025 *JINST* **20** P07049

Particular form of **signal processing** producing variables exploiting interaction physics of particles

Differing interaction mechanisms ➜ Differing proportions of light in pulse

- Neutron vs. Gamma (nuclear vs. electronic interactions)

Pulse shape variables typically exploit different amounts of light in tail for different particles



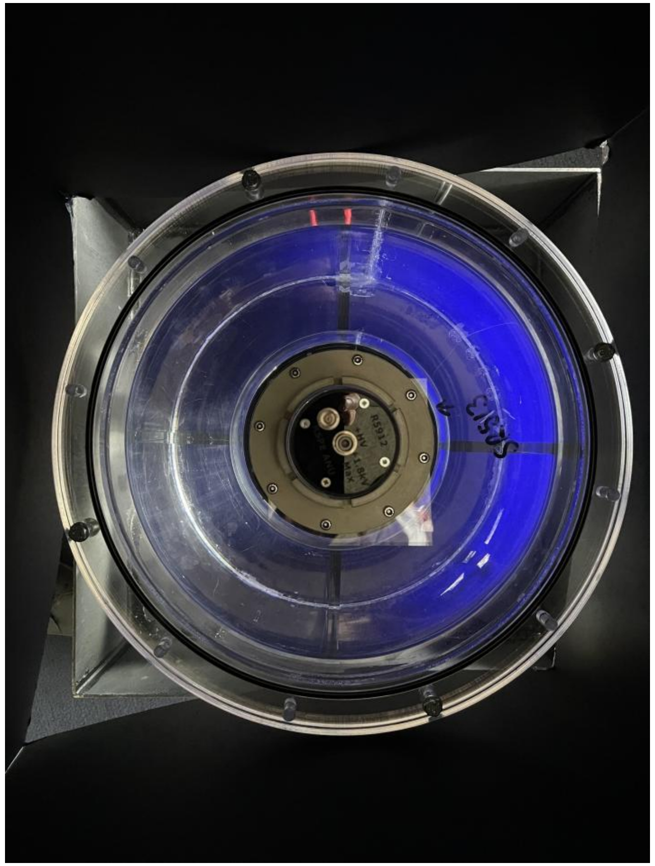
e.g. Charge ratio variables exploit higher proportion of delayed light emission in neutron interactions

$$\mu_t = \frac{\Sigma_i A_i t_i}{\Sigma_i A_i}, \qquad Q_{ratio} = \frac{Q_{delayed}}{Q_{prompt}}$$

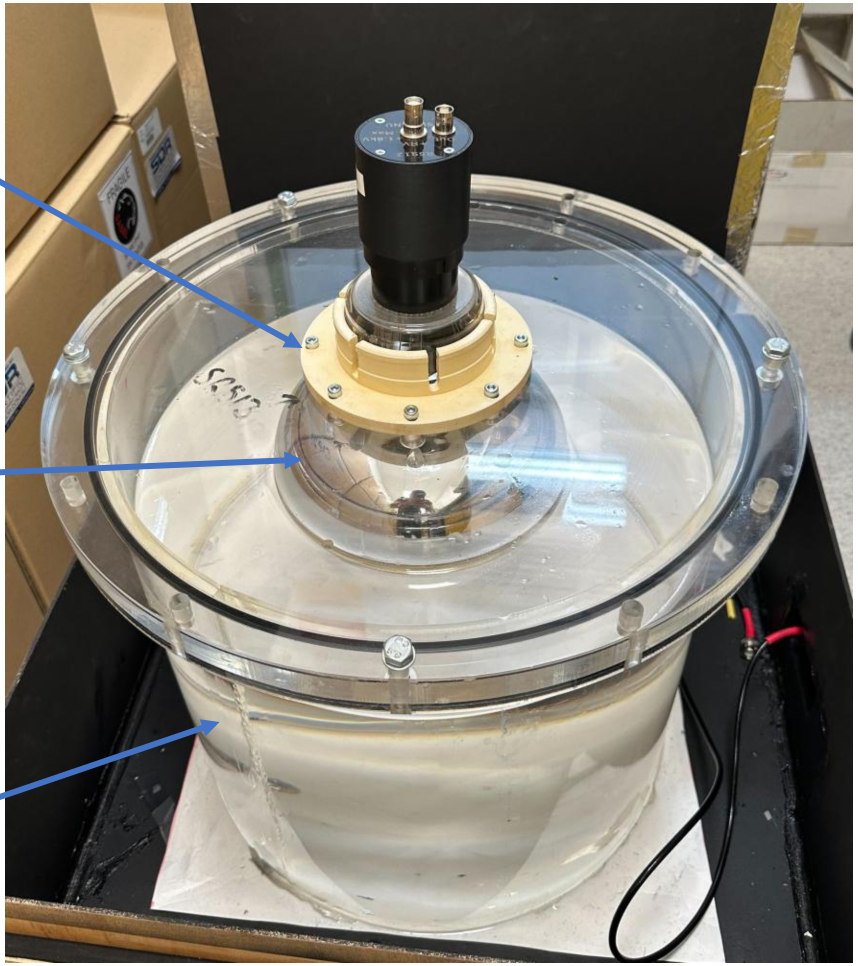
$$\mathrm{CAP}_x = \frac{\sum_{t=t_0\ \mathrm{ns}}^{t=x\ \mathrm{ns}} A(t)}{\sum_{t=t_0\ \mathrm{ns}}^{t=t_{max}\ \mathrm{ns}} A(t)},$$

Pulse Shape Discrimination with Prototype

Simplified prototype of veto: SABRINA (little SABRE) – study discrimination b/w gammas/neutrons



Lumirror reflector (not shown)



3D printed flange holding up PMT with rubber O-ring

Directly coupled Hamamatsu R5912 PMT

LAB-based LS, with 3g/L of PPO and 15mg/L of bisMSB

Pulse Shape Discrimination with Prototype

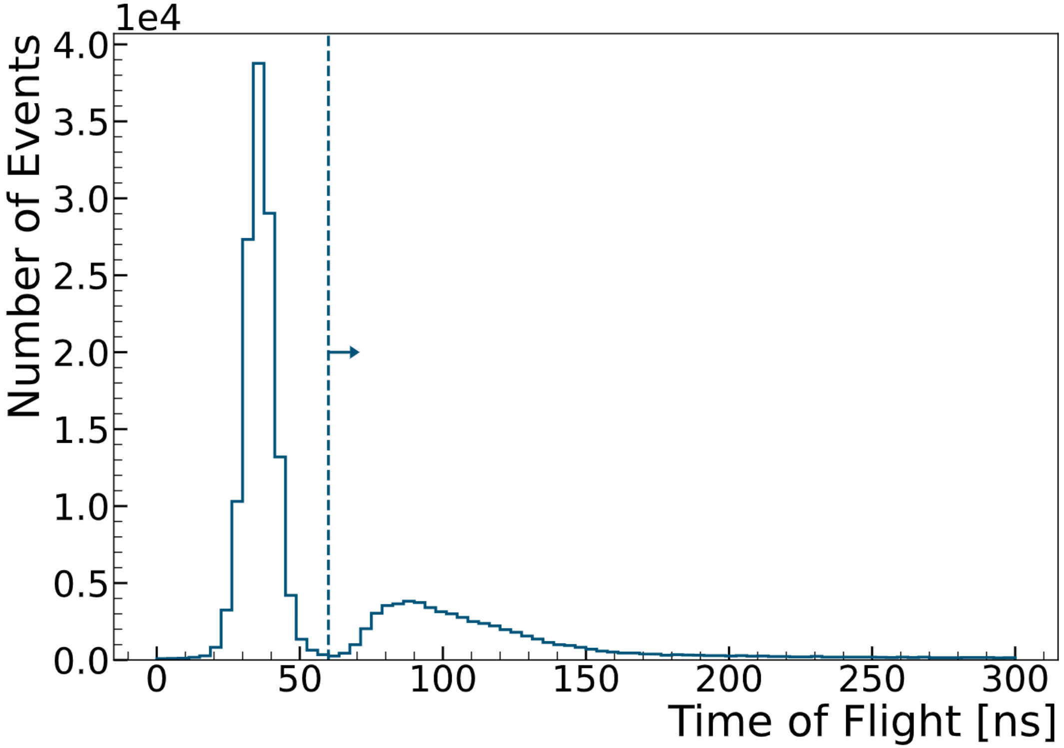
Am-Be neutron/gamma source + Co-60 gamma source

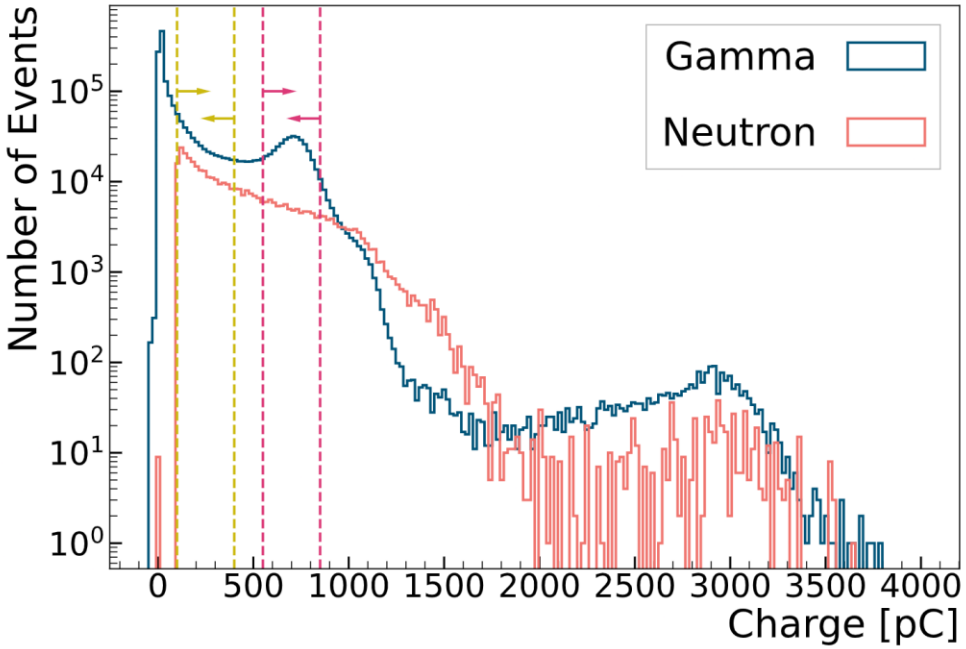
Clean neutron sample required

- Utilise time-of-flight between SABRINA and a muon detector

Gamma sample from Co-60 source

Prepare variables for each sample, combine in BDT





Isolate two energy samples

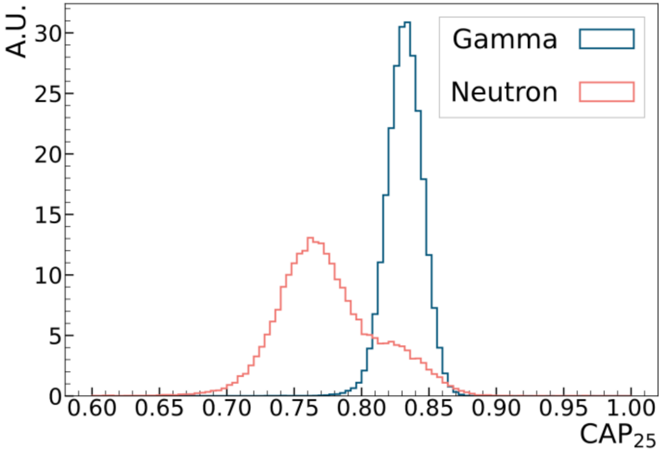
MeV-scale at Co-60 (~1 MeV) peak

keV-scale in lower region of charge spectra

Applicability to Full LS Veto

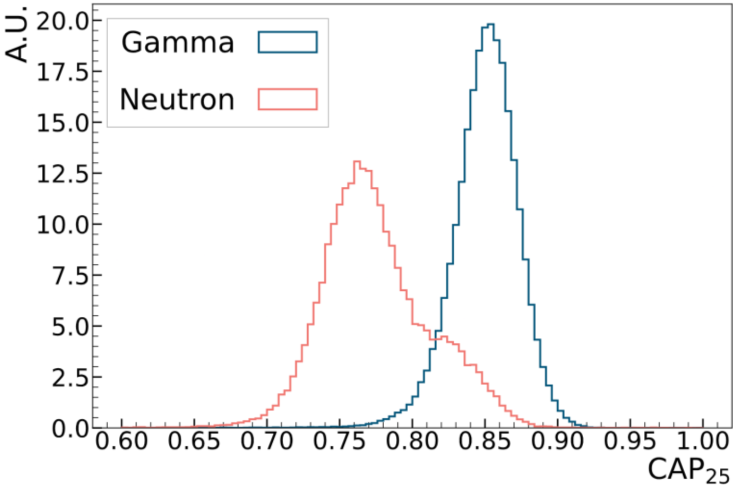
In prototype:

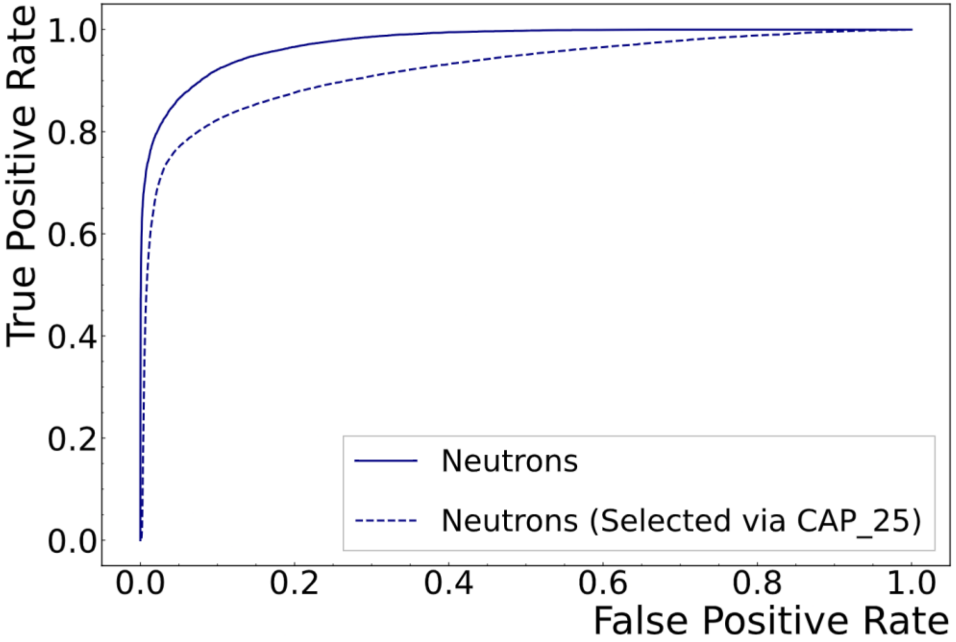
- Compare performance of best variable with total BDT
- Full multivariate BDT capable of 90% efficiency at same rejection as single variable (neutrons)



MeV-scale

keV-scale





In full veto we expect prototype results to correspond to ~100s of keV energy deposits

Extrapolate this to full LS veto - **capable of particle ID down to 100s of keV**

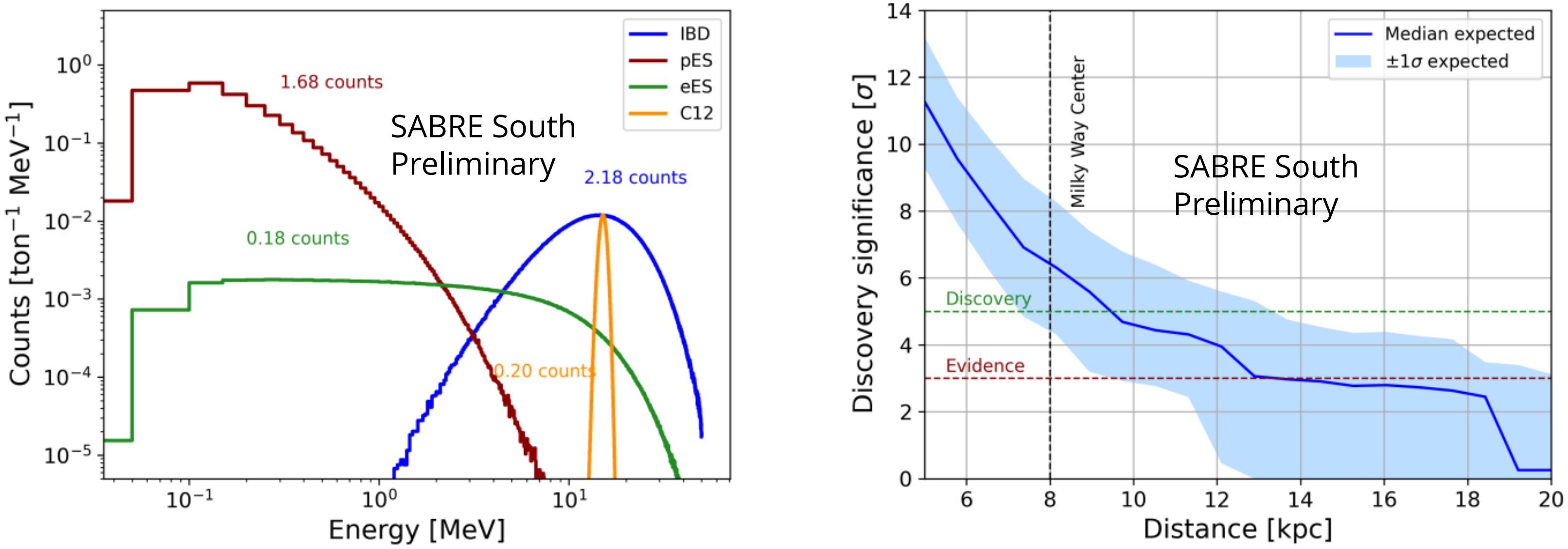
Application to Physics

Beyond identifying particles for the purpose of disentangling our background contributions, particle identification useful for physics analyses

Preliminary sensitivity studies of LS veto to supernovae neutrinos indicate ability to detect supernovae out to center of milky way

Inverse beta decay interaction mechanism results in neutrons – utilize particle ID to tag these events

Potential inclusion in SNEWS!



Recent Developments and Physics Reach

Crystal Development and Screening

Large Dia. Crystals grown by SICCAS w/ seedless Bridgman method

Smaller high-purity astrograde crystals from SICCAS sent to Melbourne

Testing/background characterisation in SUPL with 160mm thick pre-WW2 steel shielding

Full production soon!

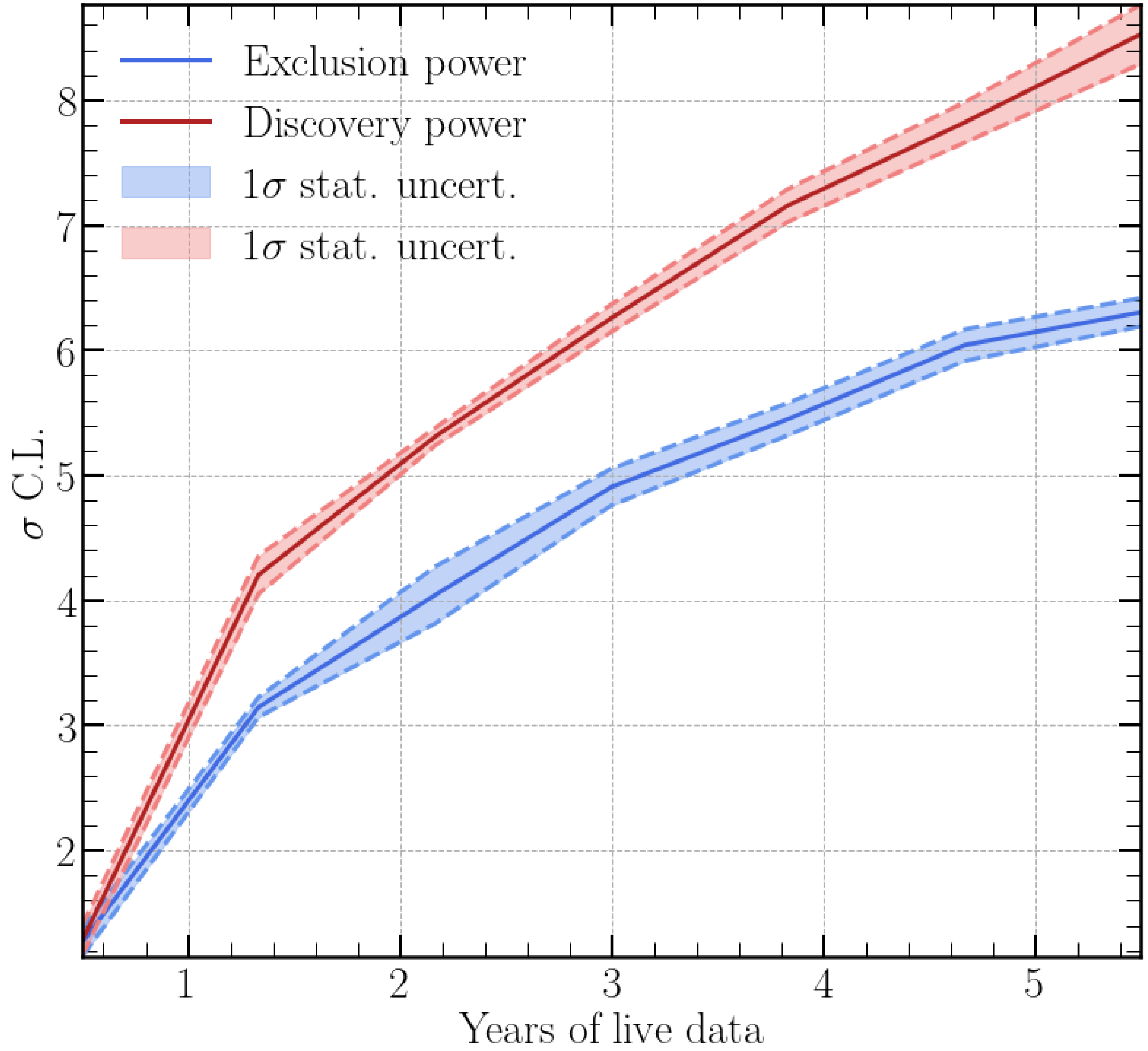
Clean Spaces and Assembly

Materials for clean tents, and glove-box for NaI(Tl) handling delivered to SUPL (for radon control)

Clean area assembly beginning

Crystal testing clean tent assembled, ready for testing

Annual Modulation Sensitivity

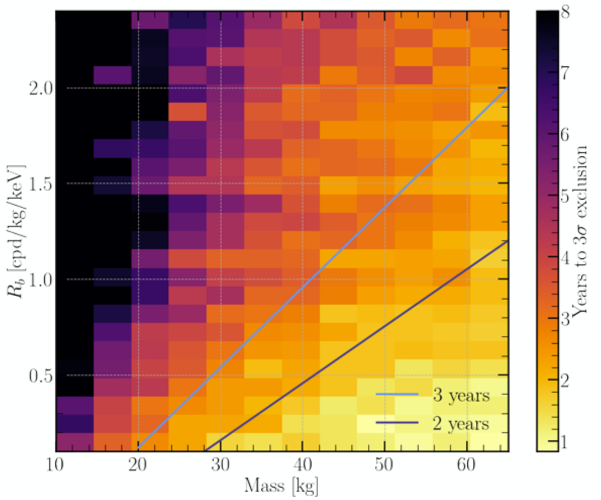


Statistically significant results in 2-3 years live time

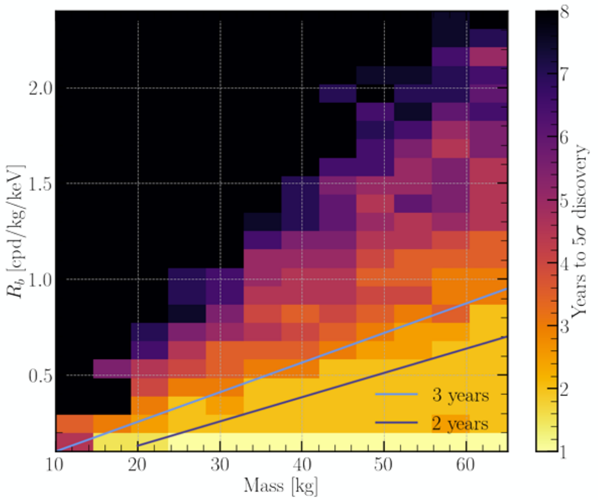
- Exclude DAMA to 5σ in 3 years data
- Confirm DAMA to 5σ in 2 years data

Sensitivity ~$\sqrt{M/R_b}$

3σ exclusion



5σ discovery



Summary

SABRE South aims to test the DAMA/LIBRA anomaly with a **background of 0.72 cpd/kg/keV**, by measuring a **0.01 cpd/kg/keV modulation amplitude**

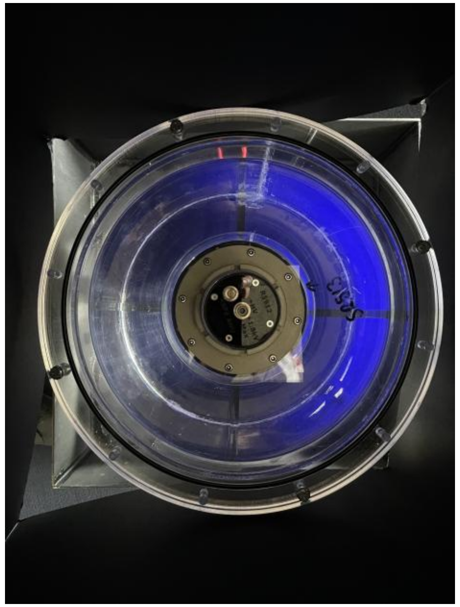
This is driven by **high crystal radiopurity** and an active veto that ensures **<10% of background is external**

To achieve it's requirements, the **LS detector performance needs to be well understood**, which means PMT performance needs to be well understood

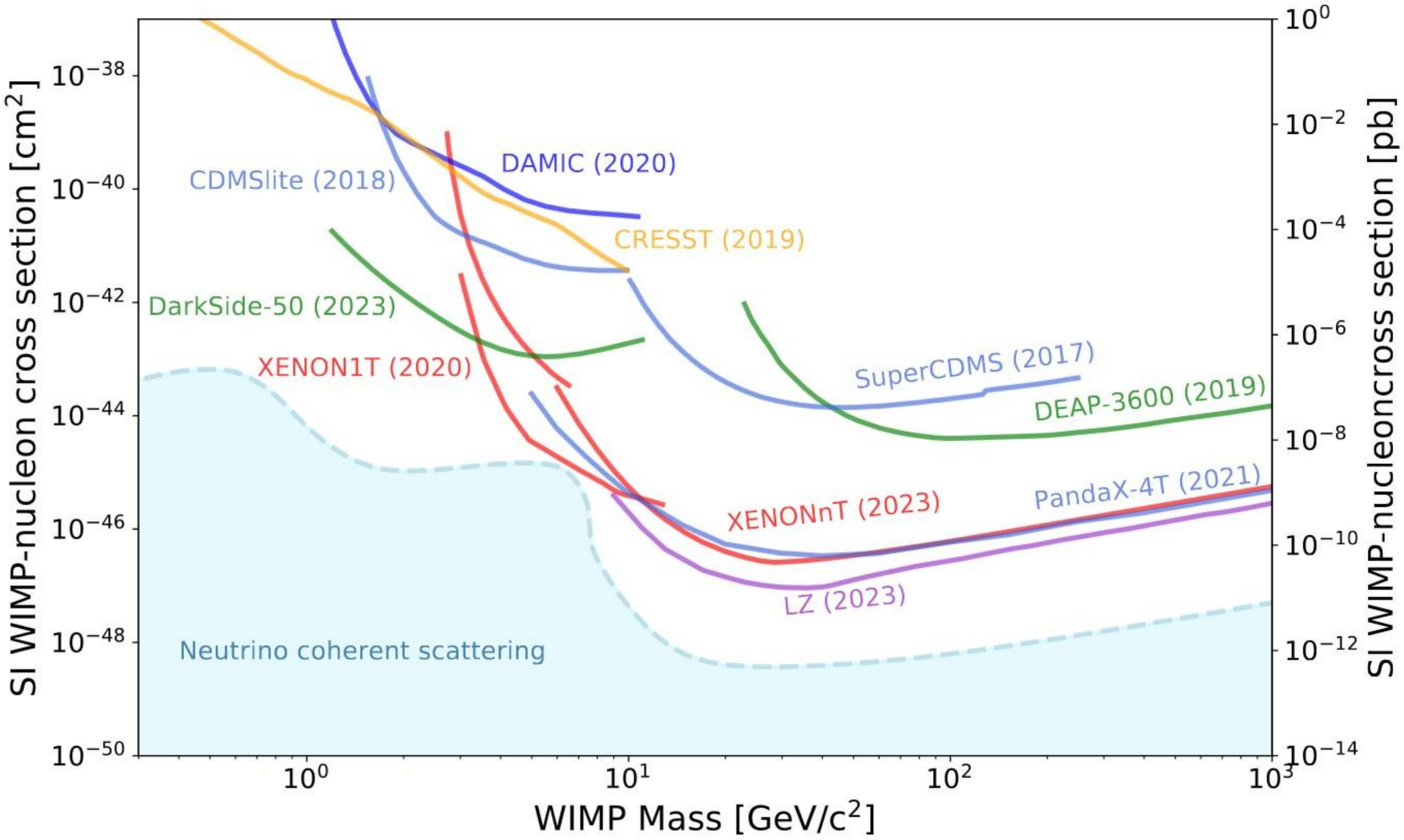
Wide range of PMT parameters measured, to both allow for detector configuration and reconstruction

Example of this with **gamma/neutron discrimination**, possible to perform in LS veto, and apply to **real physics example in the veto**

SABRE South to test reliably test DAMA after 2-3 years data-taking

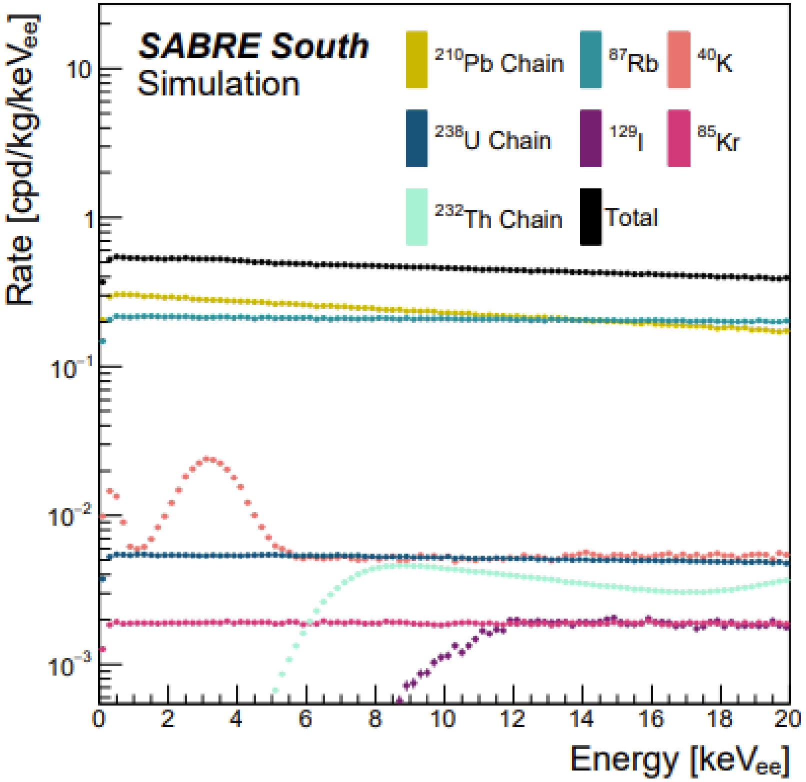


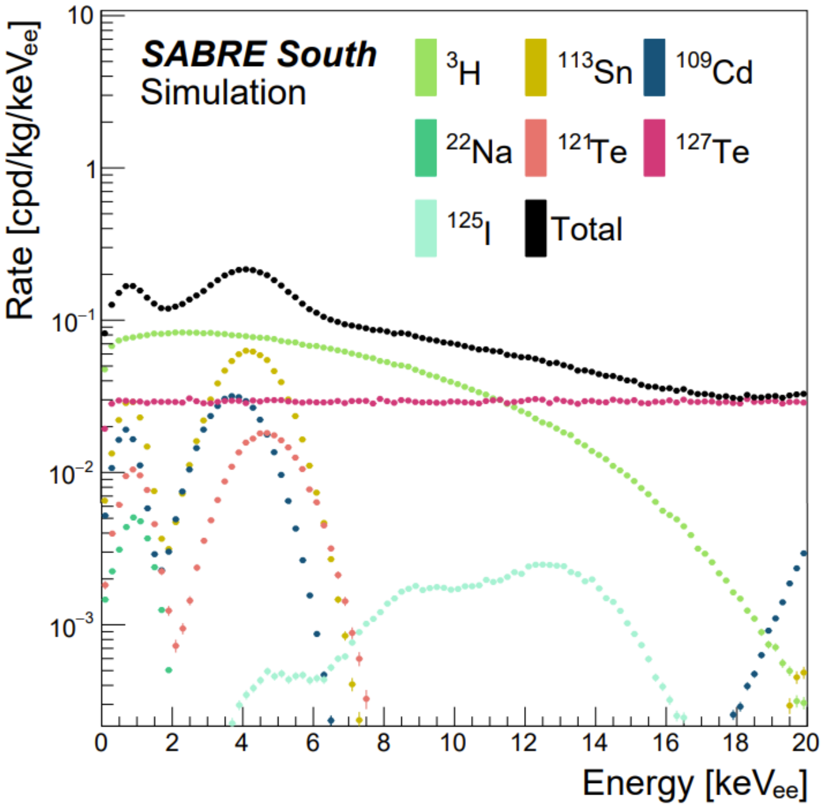
Back ups

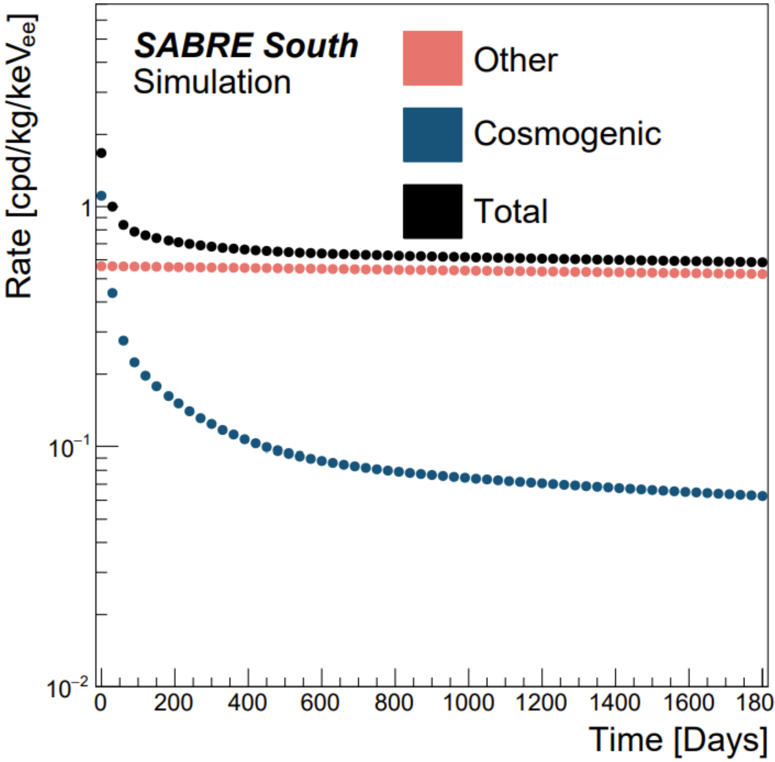


SI WIMP-nucleon cross section [cm^2]
SI WIMP-nucleoncross section [pb]
WIMP Mass [GeV/c^2]
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{0}
10^{1}
10^{2}
10^{3}
DAMIC (2020)
CDMSlite (2018)
CRESST (2019)
DarkSide-50 (2023)
XENON1T (2020)
SuperCDMS (2017)
DEAP-3600 (2019)
PandaX-4T (2021)
XENONnT (2023)
LZ (2023)
Neutrino coherent scattering

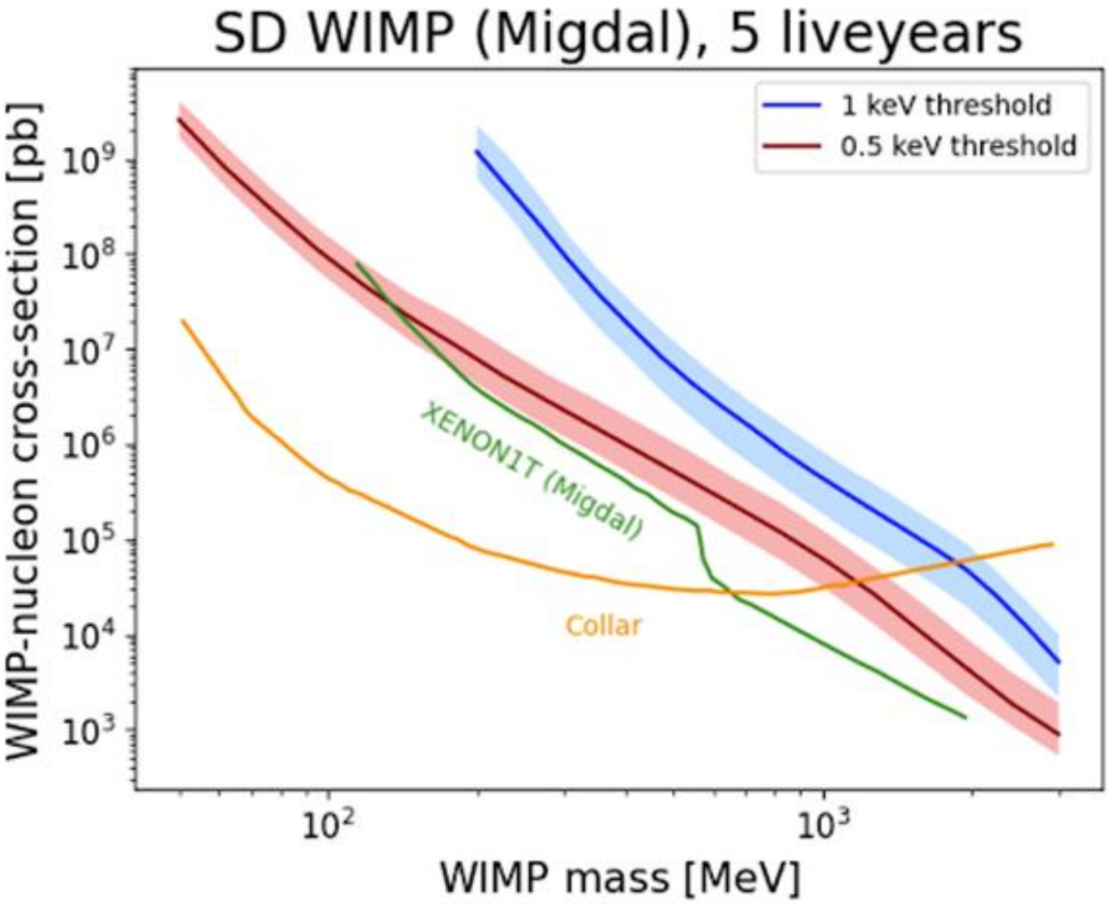
Key Backgrounds

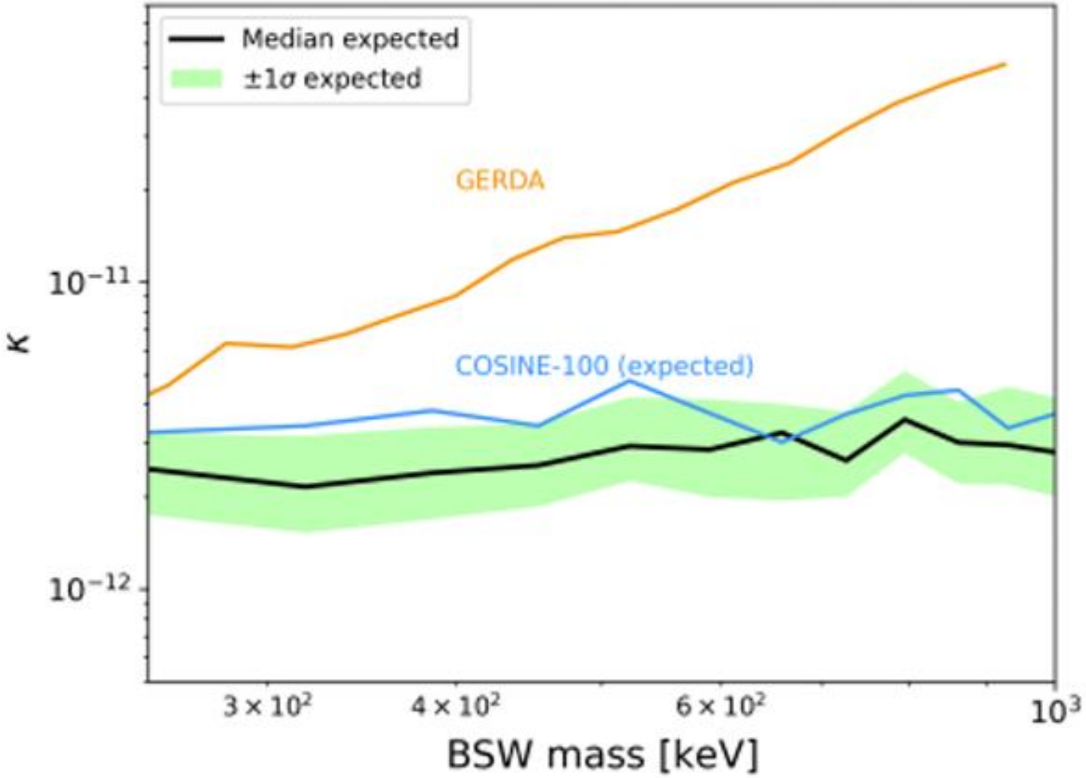






Recent Developments and Physics Reach





Preliminary sensitivity studies on SD WIMP (w/ Migdal) and Bosonic Super-WIMPs

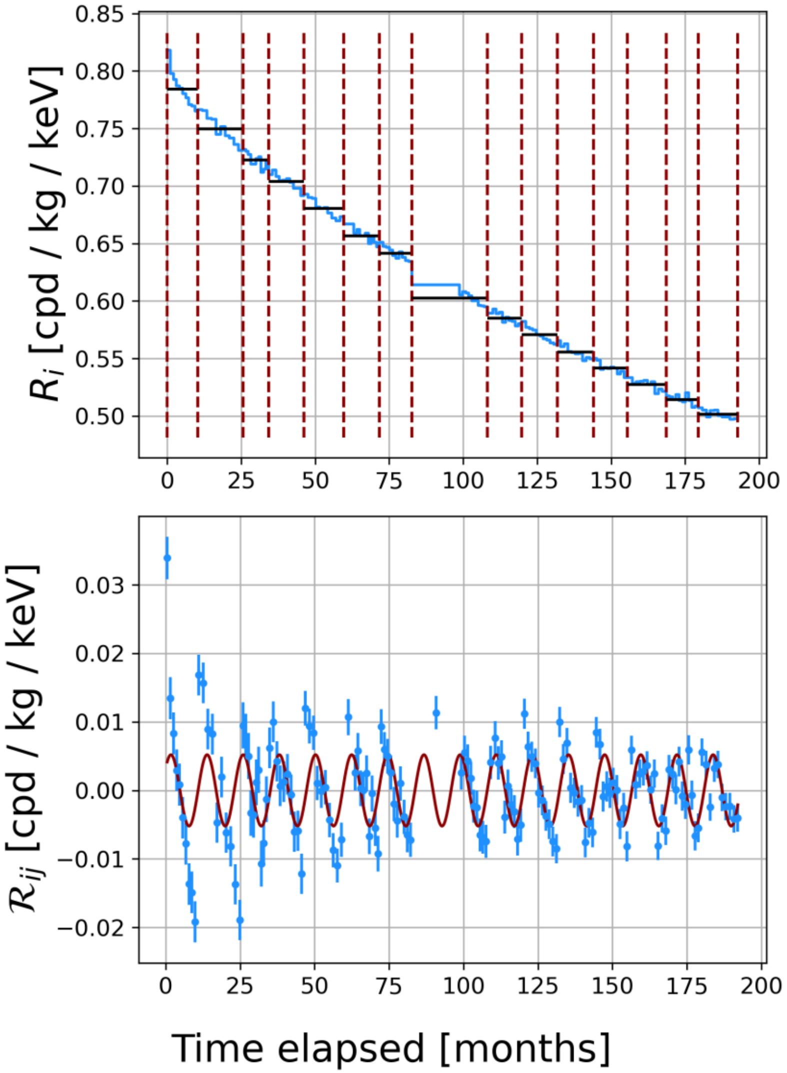
Induced Modulation

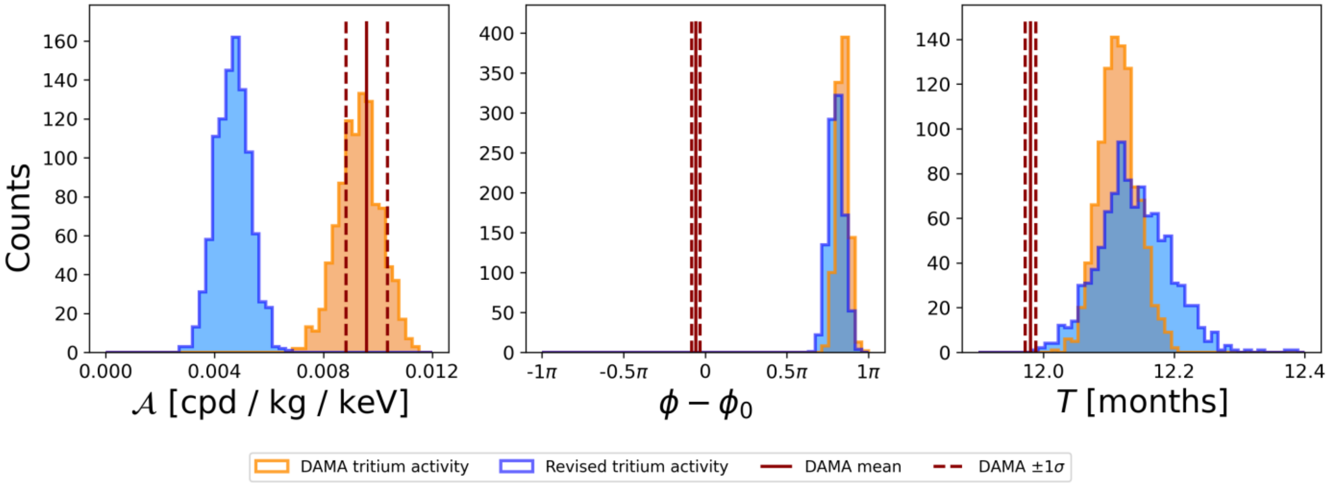
Study potential of induced modulation from DAMA/LIBRA's background subtraction technique **using best faith reproduction of their backgrounds**

DAMA tritium activity likely over-estimated

- Revised activity found by using SABRE South simulated tritium activity and revised calculation of exposure
- Induced modulation is lower amplitude, out of phase

Key takeaway: DAMA/LIBRA background is low enough that shape of background/subtraction method doesn't matter, there is no induced modulation



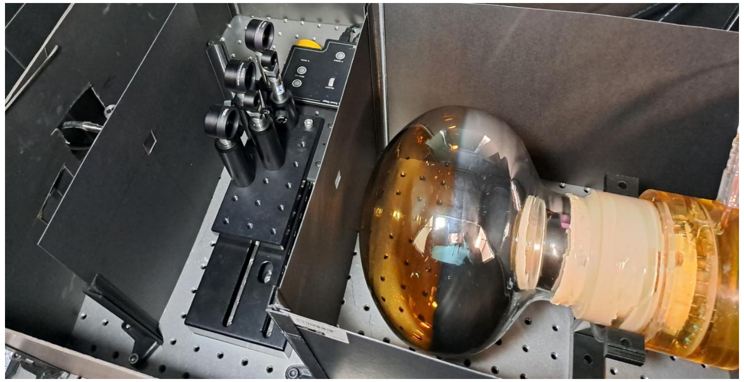


A: Amplitude
Φ: Phase
T: Period

R5912 PMT Pre-Calibration

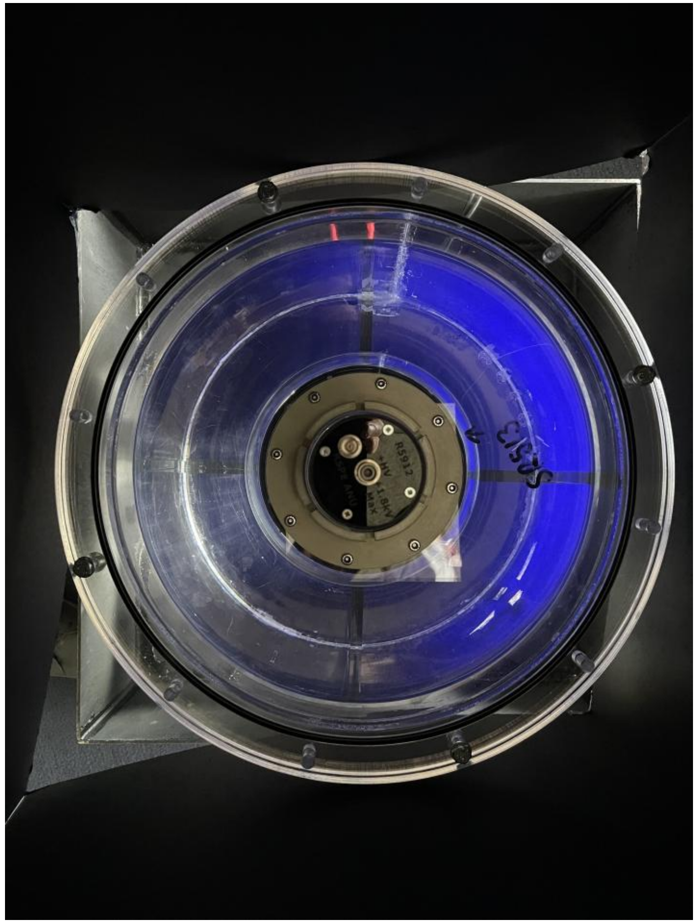
R5912 bulk pre-calibration **(understanding veto detector response)**:
20 PMTs in total with a range of properties to characterise for each

- **Single photoelectron (SPE) response and gain**
- Transit time and transit time spread,
- Relative quantum efficiency
- **Dark rate/dark rate as a function of temperature**
- Spontaneous light emission from oilproof base



- Linearity, and charge response saturation
- Afterpulsing rates

Results in under-prep paper to be submitted to JINST



Particle ID studies with small-scale prototype detector to disentangle backgrounds, expand physics reach

Particle ID w/ Prototype Detector

How well can we identify or discriminate backgrounds within the LS veto? And particle ID in general?

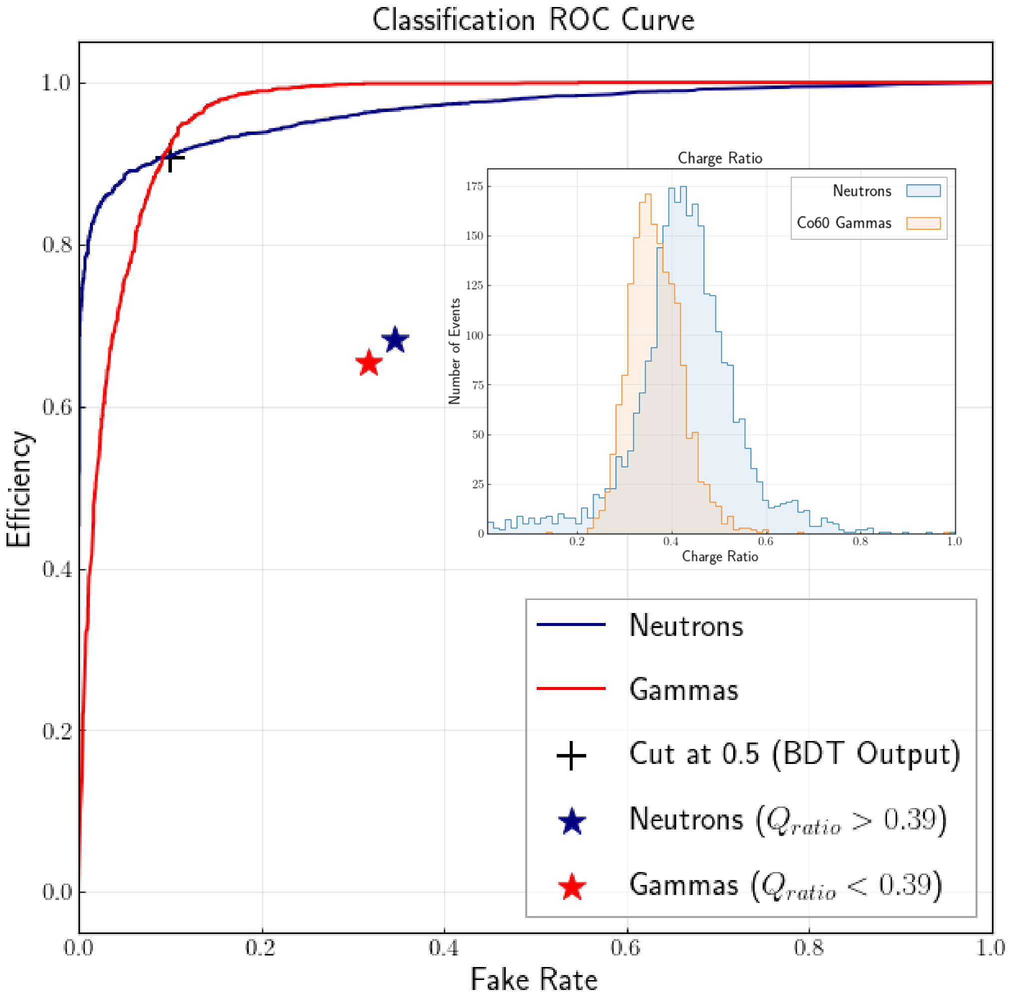
- i.e. gamma ray (^{40}K) vs. neutrons (from spallation via muons)

Use prototype detector study as **testbed for inclusion of particle ID algorithms in veto detector** – for broader physics reach (e.g. **supernovae neutrino detection, models of boosted DM, background disentanglement**)

Small scale prototype detector used:

- 40 L of LS – same to be used in SABRE
- Gammas from ^{60}Co source
- Neutrons from Am-Be source
- R5912 PMT directly coupled

To be included in Veto PMT paper



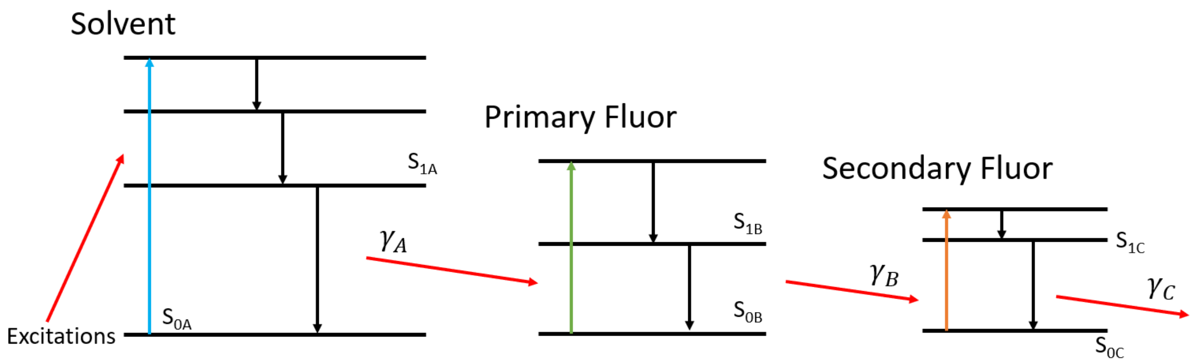
LS Response/Physics

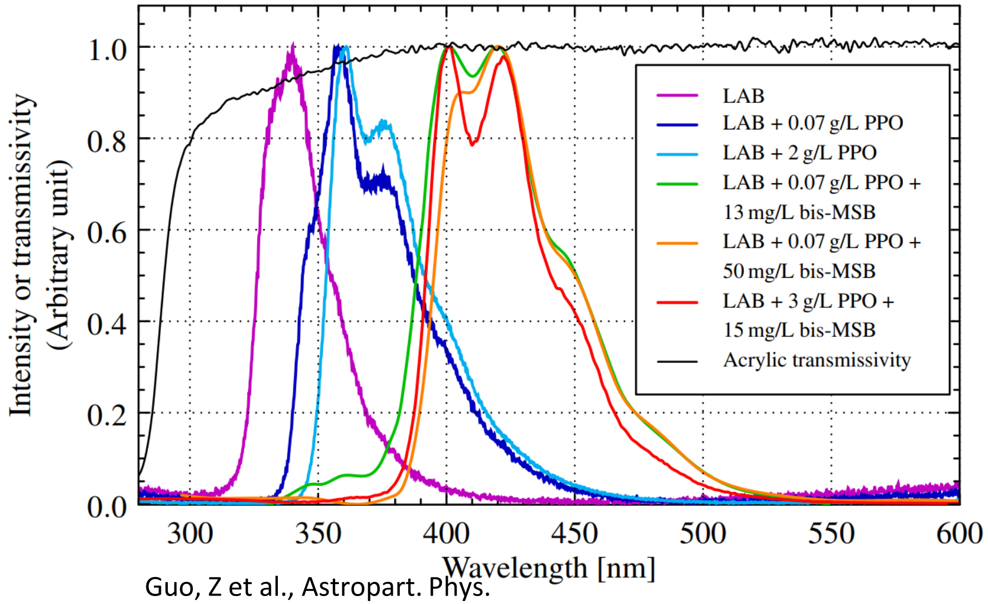
LAB (solvent), and PPO+bis-MSB for fluorophores

Intensity/transmissivity is wavelength dependent

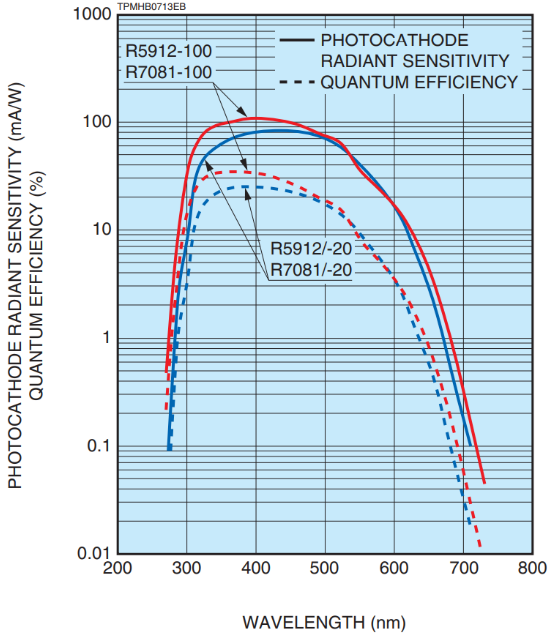
PMT choice/fluorophore choice partly motivated by peak wavelength

From JUNO, expect LS light yield to be ~12 photons/keV



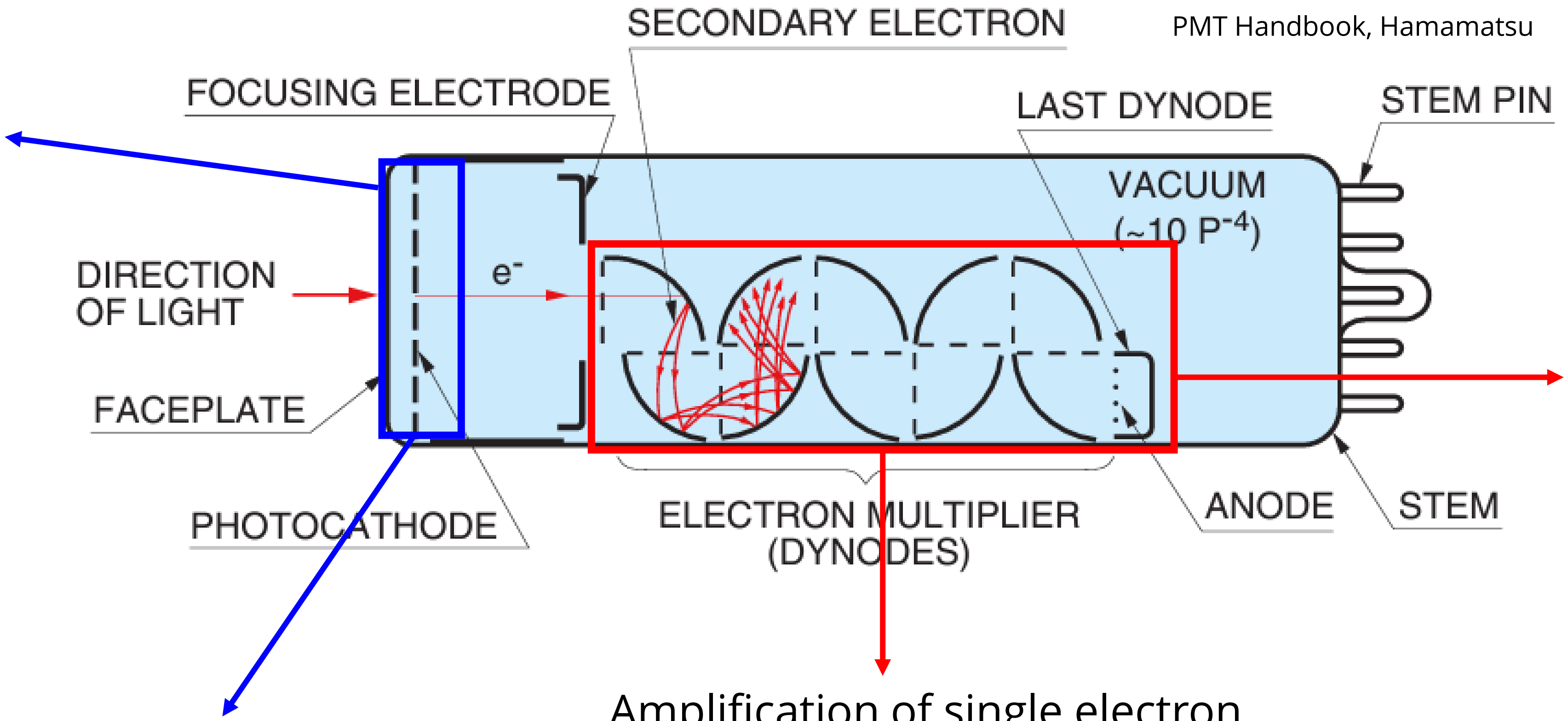


Guo, Z et al., Astropart. Phys.



Overview: Photomultiplier Tubes

Cathode emits primary electron via photoelectric effect



PMT Handbook, Hamamatsu

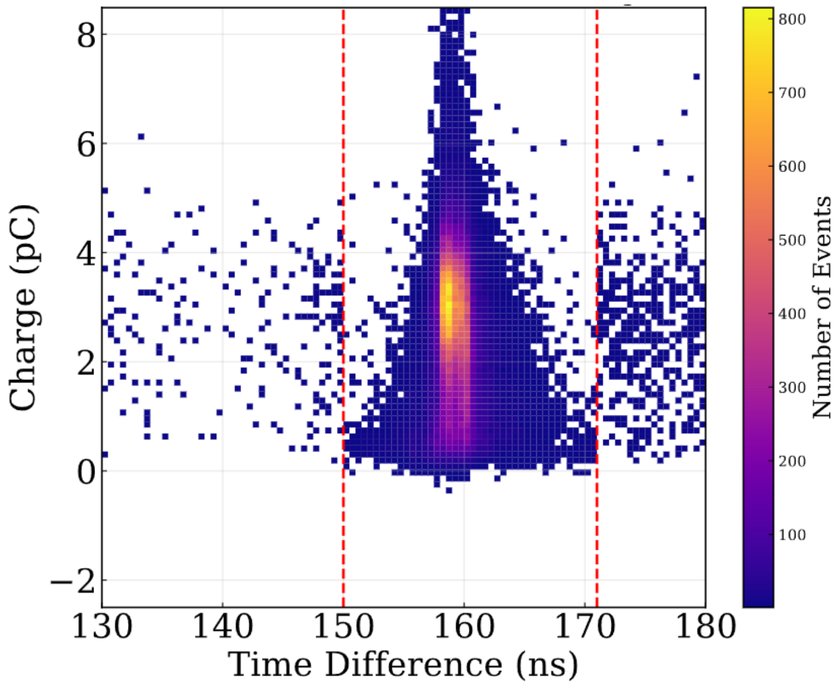
Readout off anode as voltage/current at DAQ

Spontaneous thermionic emission off cathode defines dark rate

Amplification of single electron determines gain/single photoelectron response (SPE)

Traversal time defines transit time and transit time spread

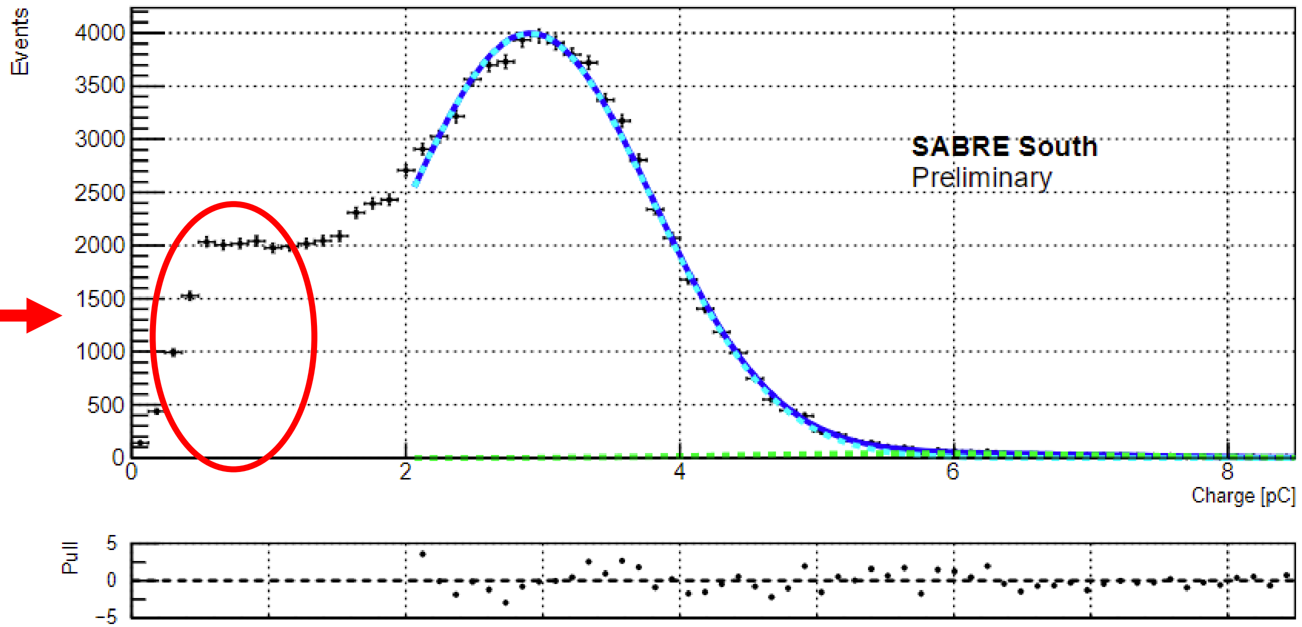
Pre-calibration: SPE Response/Gain



Laser capable of outputting trigger signal

Ensure data is predominantly single photon by cutting on coincidence

Coincidence found in Δt spectra b/w laser and PMT



Isolated single photoelectron (PE) charge spectra through coincidence with laser signal

Fit: $p \times G_{1PE}(\mu_{1PE}, \sigma_{1PE}) + (1-p) \times G_{2PE}(2\mu_{1PE}, \sqrt{2}\sigma_{1PE})$

1PE mean = mean SPE charge

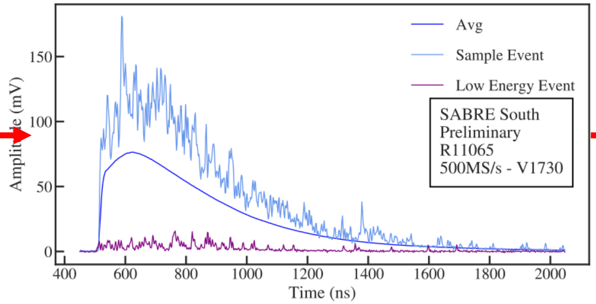
Signal Processing: From Raw Data to Physics

Exploit understanding of detector and PMT response by applying **signal processing** to well understood detector response

Signal processing: conversion of hard-to-parse data (waveforms) to useful summary variables

Signal chain in SABRE South:

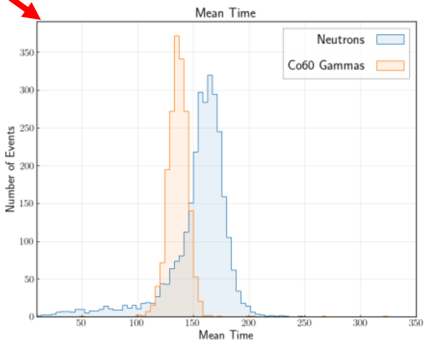
Raw detector data digitised at DAQ



Digitised waveforms from DAQ processed by software to produce useful variables

Software framework

$$\langle t \rangle = \frac{\sum_i A_i t_i}{\sum_i A_i}.$$

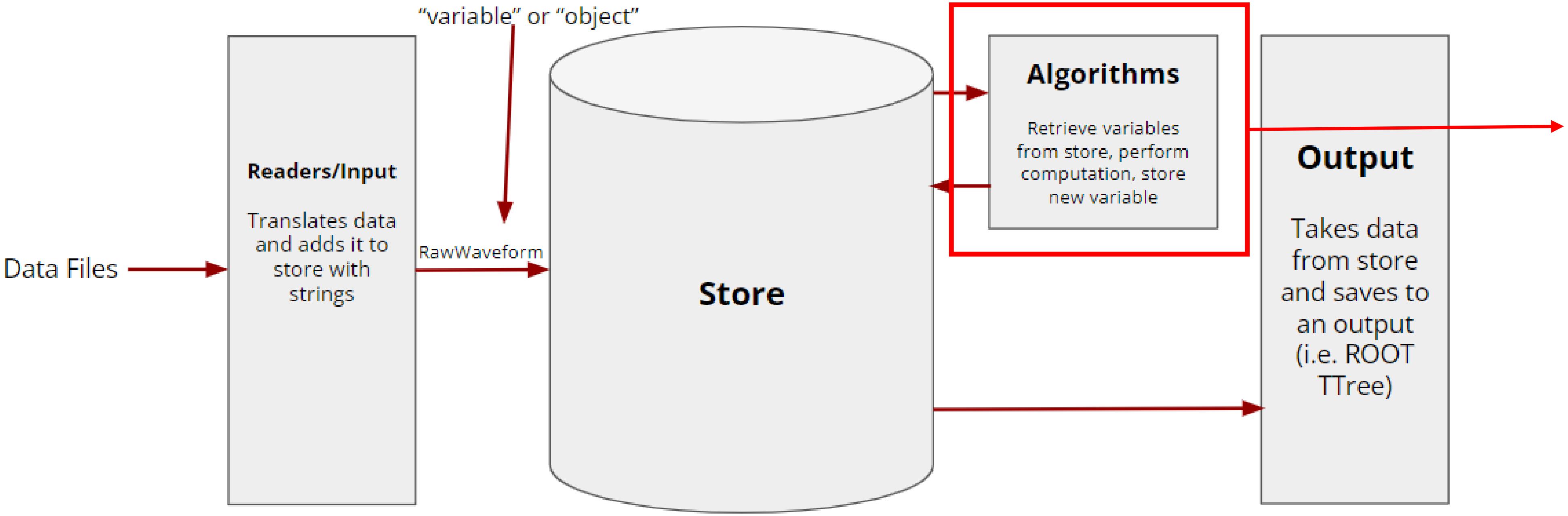


SABRE South Software Framework

To accommodate for signal processing in SABRE in consistent, repeatable way software framework is developed

Designed to be modular w.r.t algorithms used/developed, essentially a collection of useful variables within the framework

Operation of framework:



Looped over events

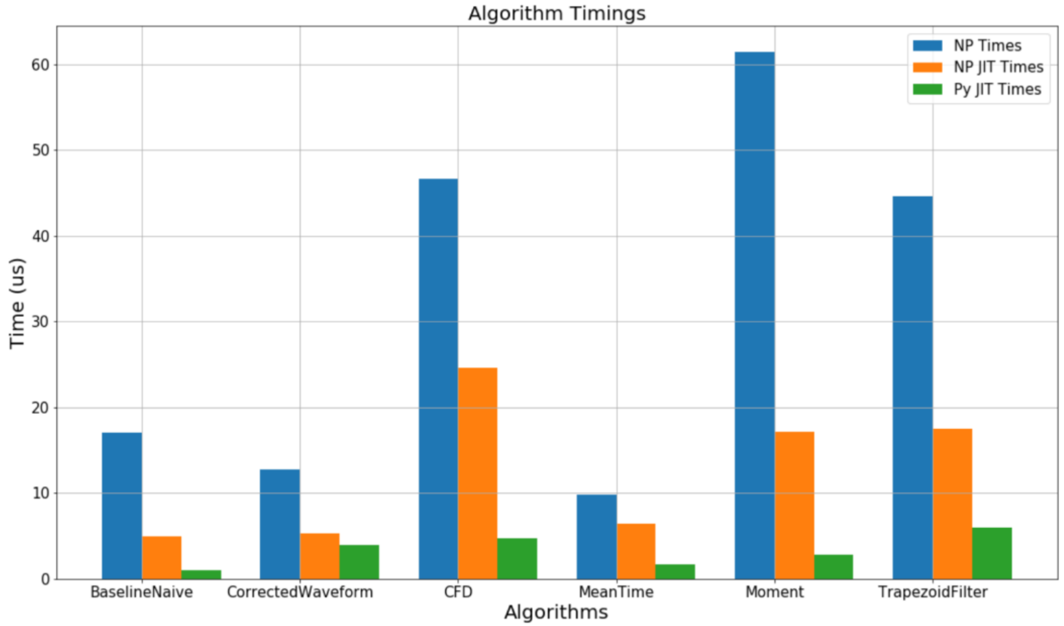
Large amount of variables – optimisation is important

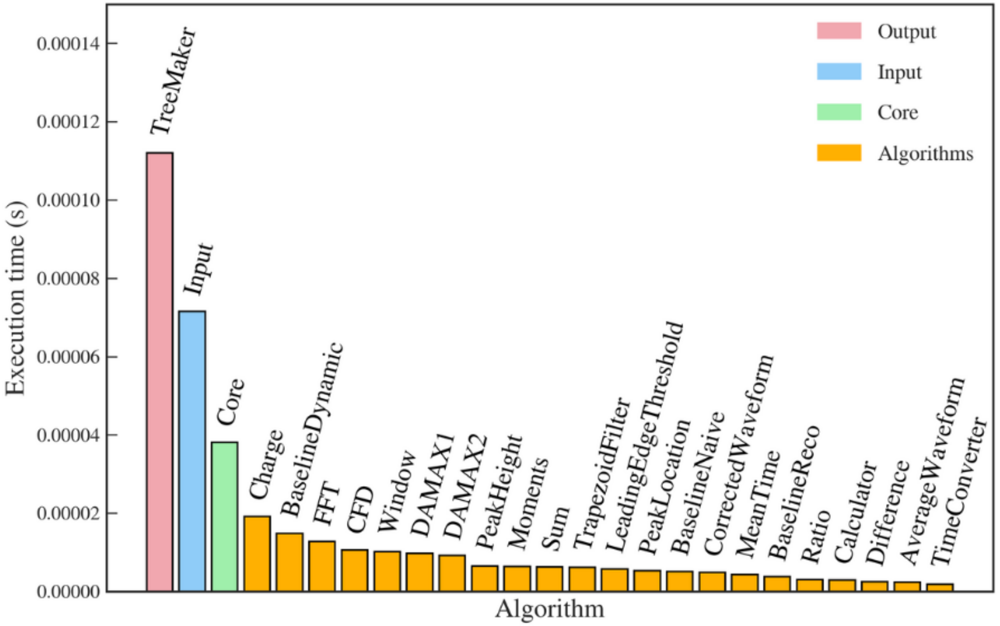
Optimising the Framework

To allow for optimally performing framework that produces relevant signal variables, time optimisation is important

Algorithms optimised using just-in-time compilation package (numba), with python code written to resemble C++ executing faster

Optimisation of algorithms in this way makes them the fastest component of the framework





Pre-calibration: Summary/Motivation

To optimise veto efficiency and meet requirements for background model, deep understanding of detector performance required

Thus, understanding of LS response and **PMT performance parameters** are needed

With low amounts of PEs detectable (< 0.2 PE/keV), each PMT gain and noise properties measured to allow each to be configured to achieve required thresholds

To achieve desired reconstruction capabilities, relevant PMT parameters (linearity, afterpulsing) measured

Drastic improvement to LS veto performance with **increased photosensor coverage from Daya Bay PMTs**, **up to 32 PMTs** in vessel now possible

But how/what can we do to exploit this
deep understanding for reconstruction?