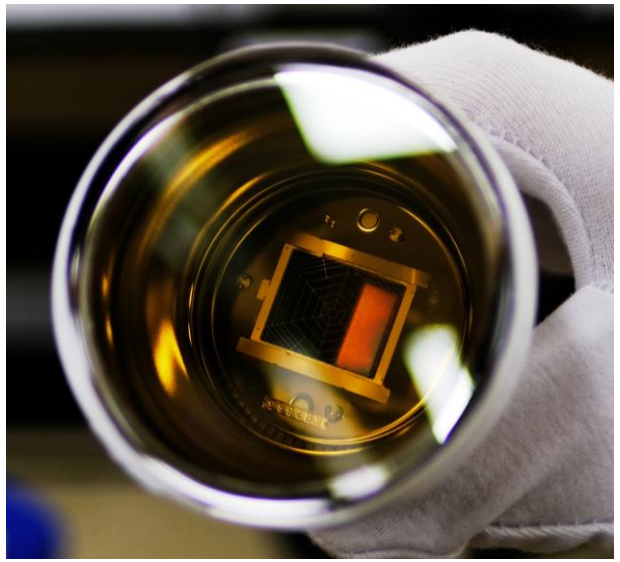
R11065 PMT CONTRIBUTION TO THE SABRE SOUTH EXPERIMENTAL BACKGROUND

William Melbourne

The University of Melbourne

On behalf of SABRE South



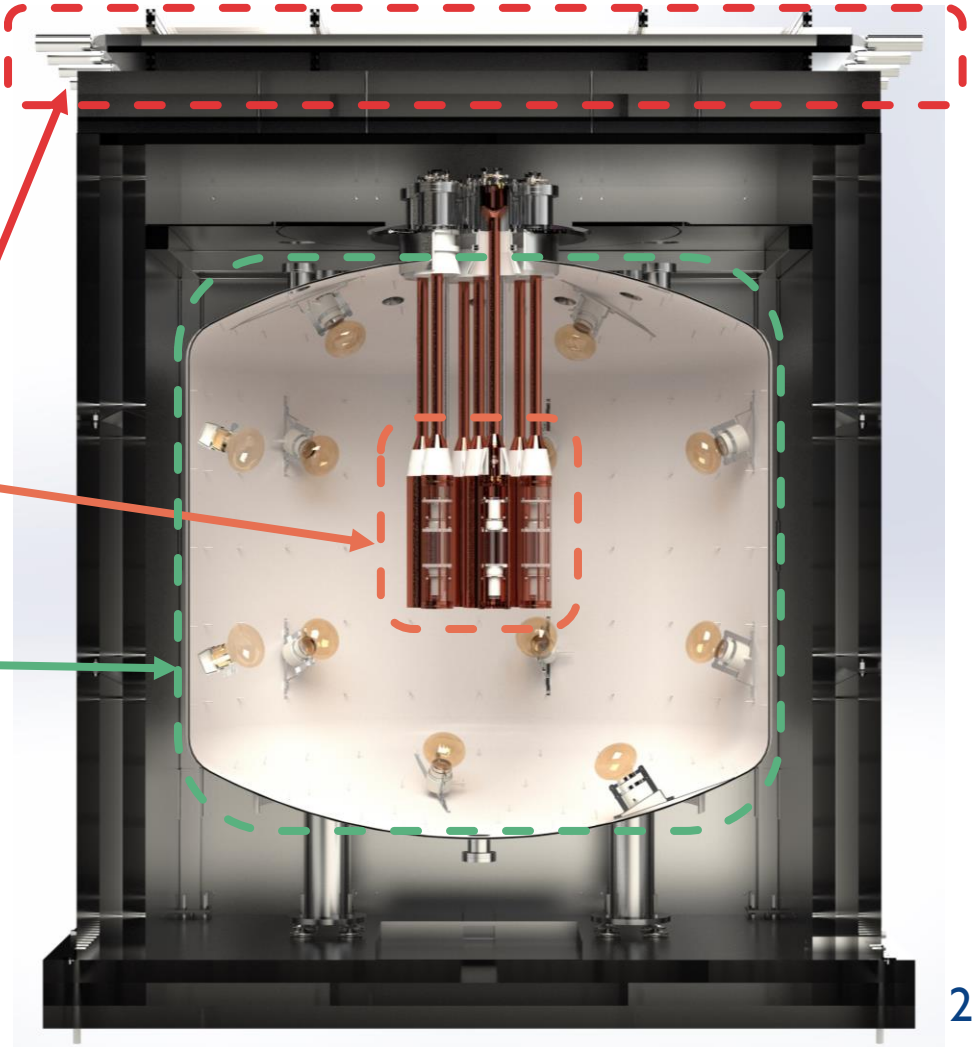
Dark Side of the Universe 2022 - Sydney

SABRE SOUTH

The first direct detection experiment in the Southern hemisphere.

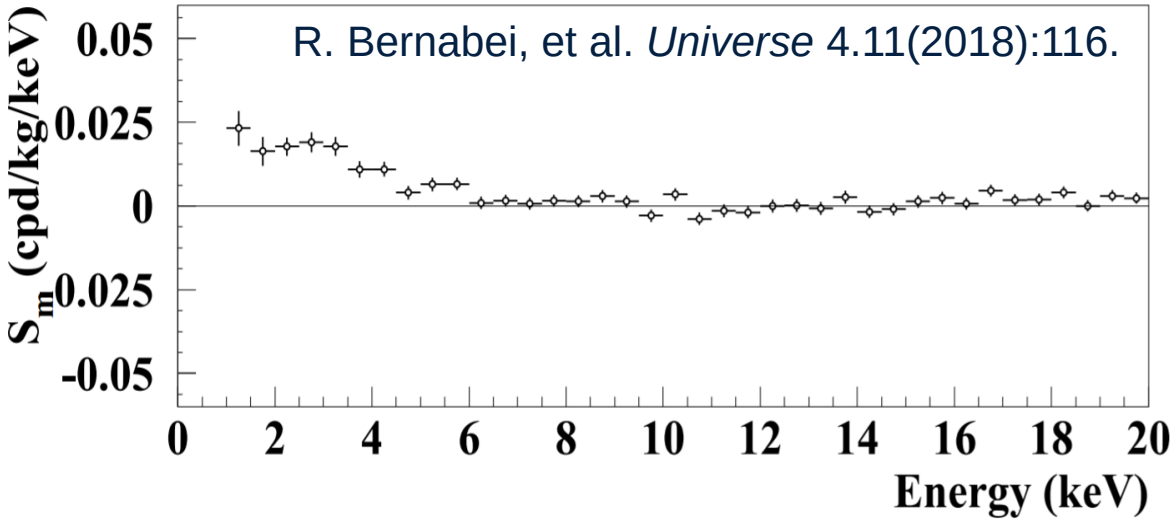
Covered by E. Barberio in plenary.

- NaI array: 7 High purity NaI(Tl) Crystals w PMT readout
- Liquid scintillator veto: 12 kl LAB + PPO & Bis-MSB w 18 oilproof-PMT
- Muon veto: 3x3.2 m array of 8 detectors

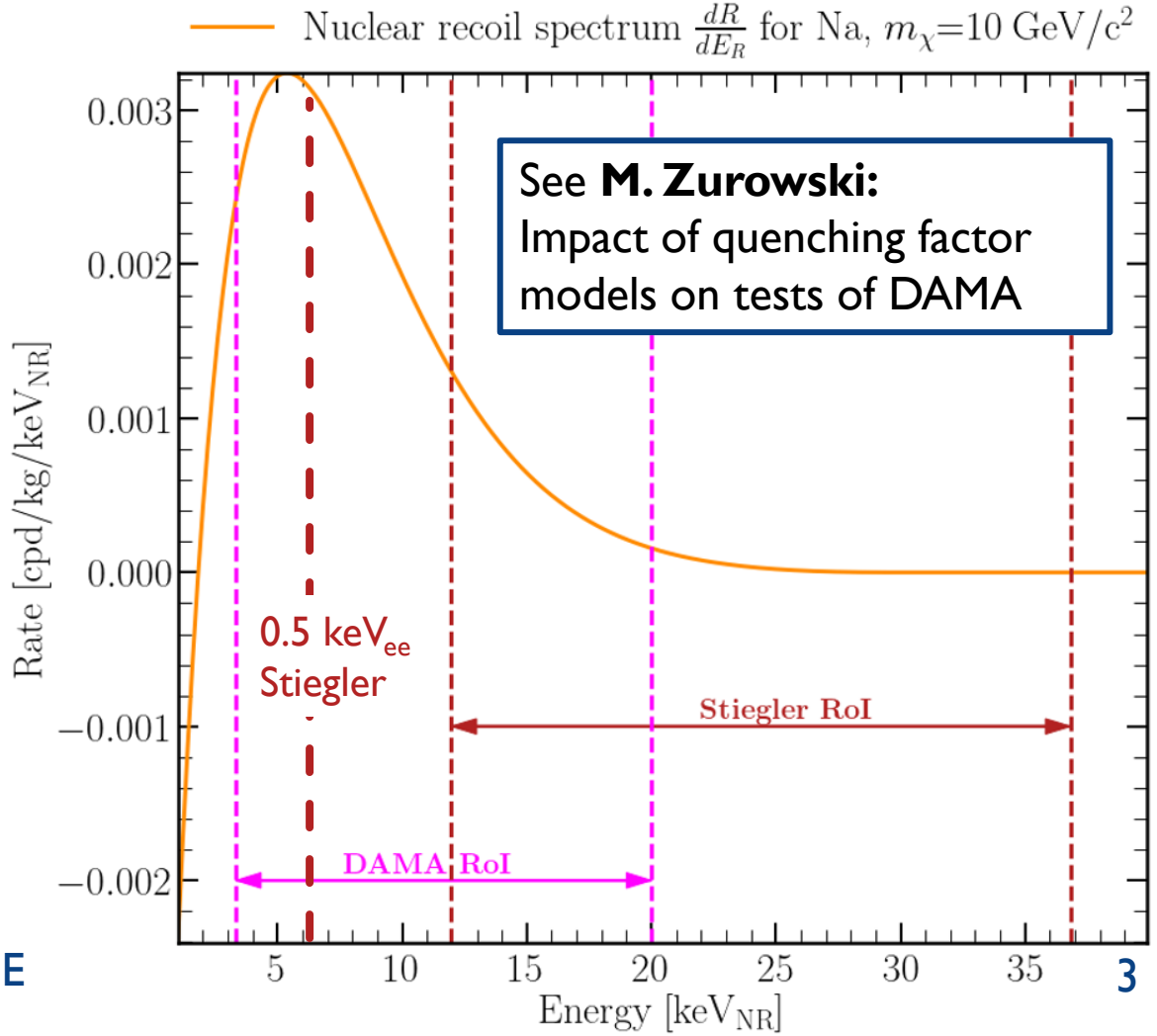


ANNUAL MODULATION SIGNAL

DAMA has 20 year modulation in 2-6 keV_{ee} region (later 1-6 keV_{ee}) with combined significance 12.9σ



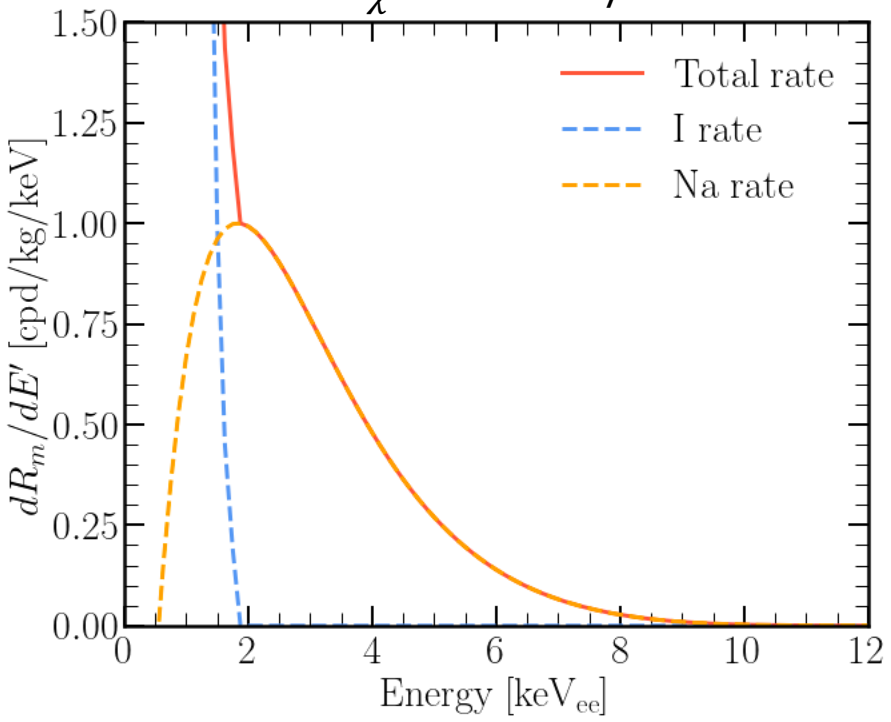
The RoI is complicated by the quenching factor. May be different for SABRE



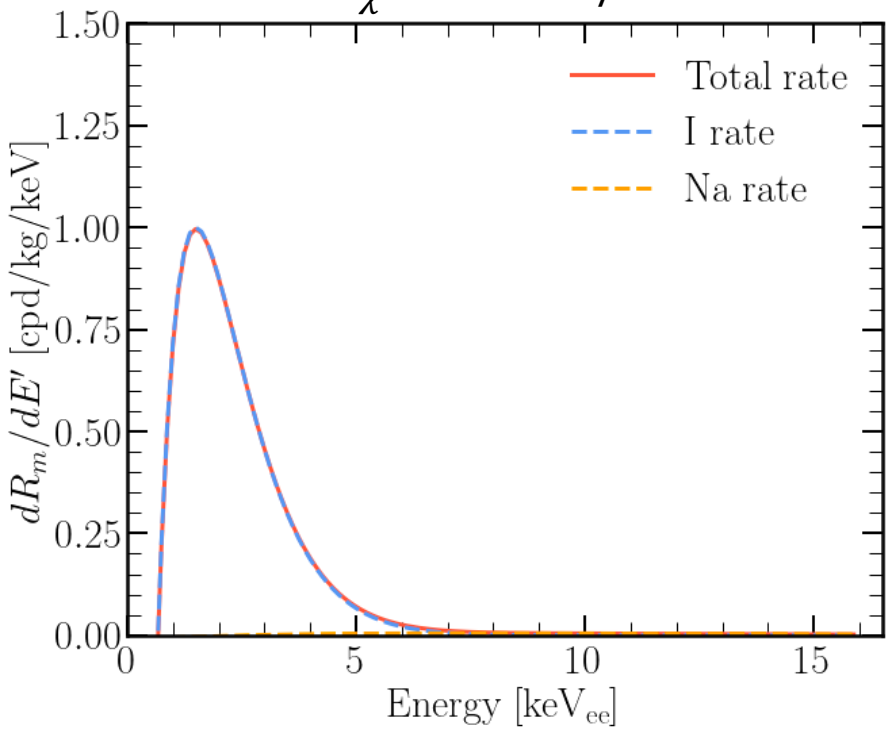
ANNUAL MODULATION SIGNAL

If QE is the same, going below 1 keV has additional physics impact,
Could distinguish if DAMA signal is Na or I recoils.

$M_\chi = 10\ GeV/c^2$



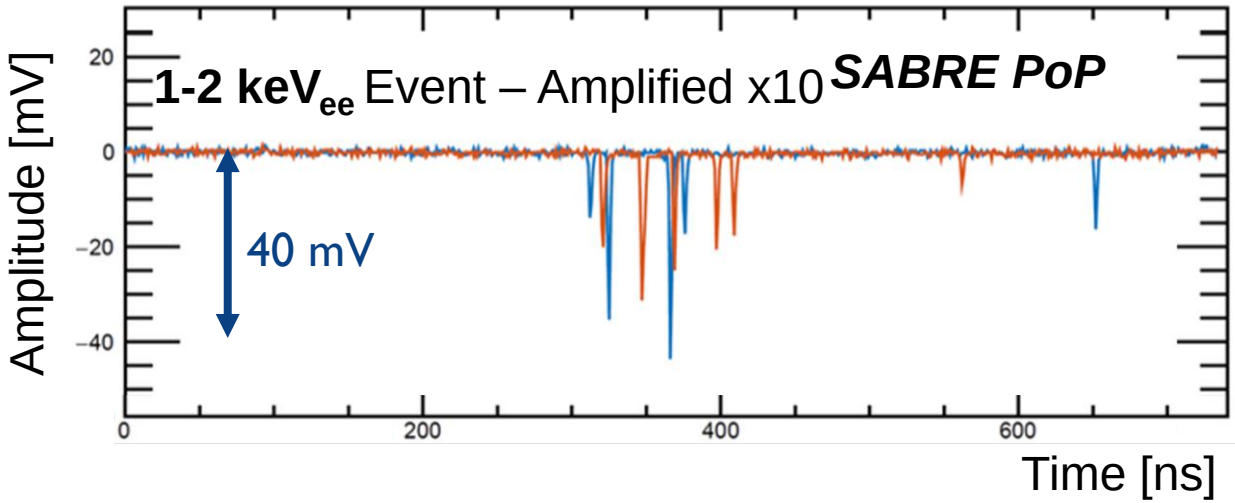
$M_\chi = 40\ GeV/c^2$



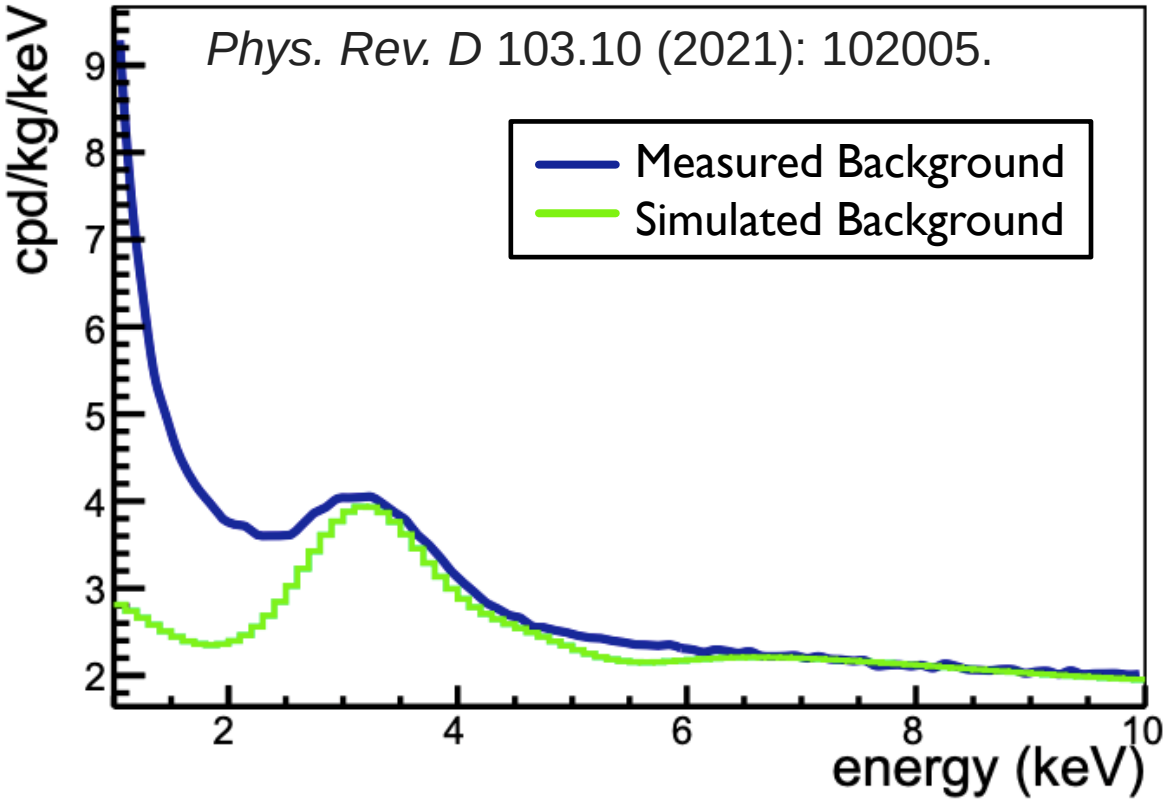
ANNUAL MODULATION SIGNAL

What does 1 keV_{ee} look like?

- Expect ~12 detected photons (PE)
- Spread over 100's of ns

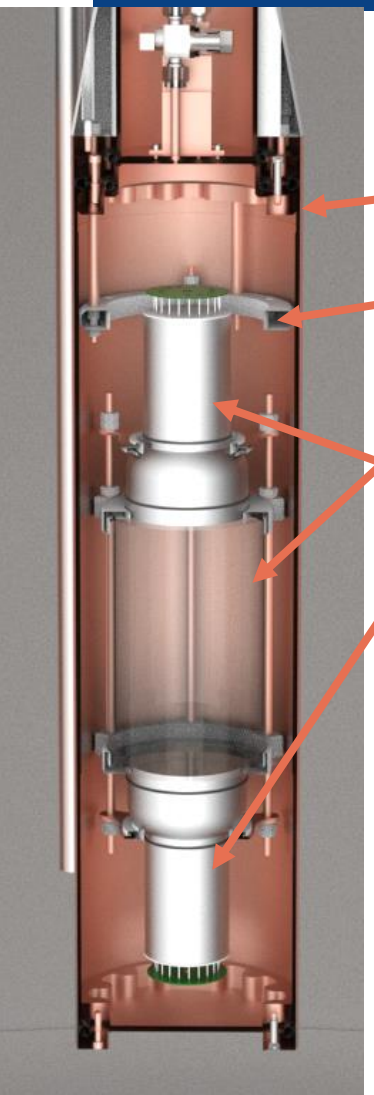


ANAIS NaI(Tl) Background



1 keV_{ee} events are a series of individual photons.
Background is not just radioactive

NaI(TI) DETECTORS



Array of 7 NaI(TI) detectors in the liquid veto.

- OFHC Copper enclosure purged with dry N_2.
- PTFE internal structure
- High purity NaI(TI): LY ~12 PE/keV
- 2 x 76mm R11065 PMTs
  - QE>30%
  - Low radioactivity body
  - 500 MS/s readout
  - Threshold ~0.3 SPE peak

	K [ppb]	^{238}U [ppt]	^{232}Th [ppt]
SABRE[1] NaI-33	4.7±1.4	<1	<1
DAMA [2]	13	<10	<10
COSINE-100 [3]	17.8	<20	0.6

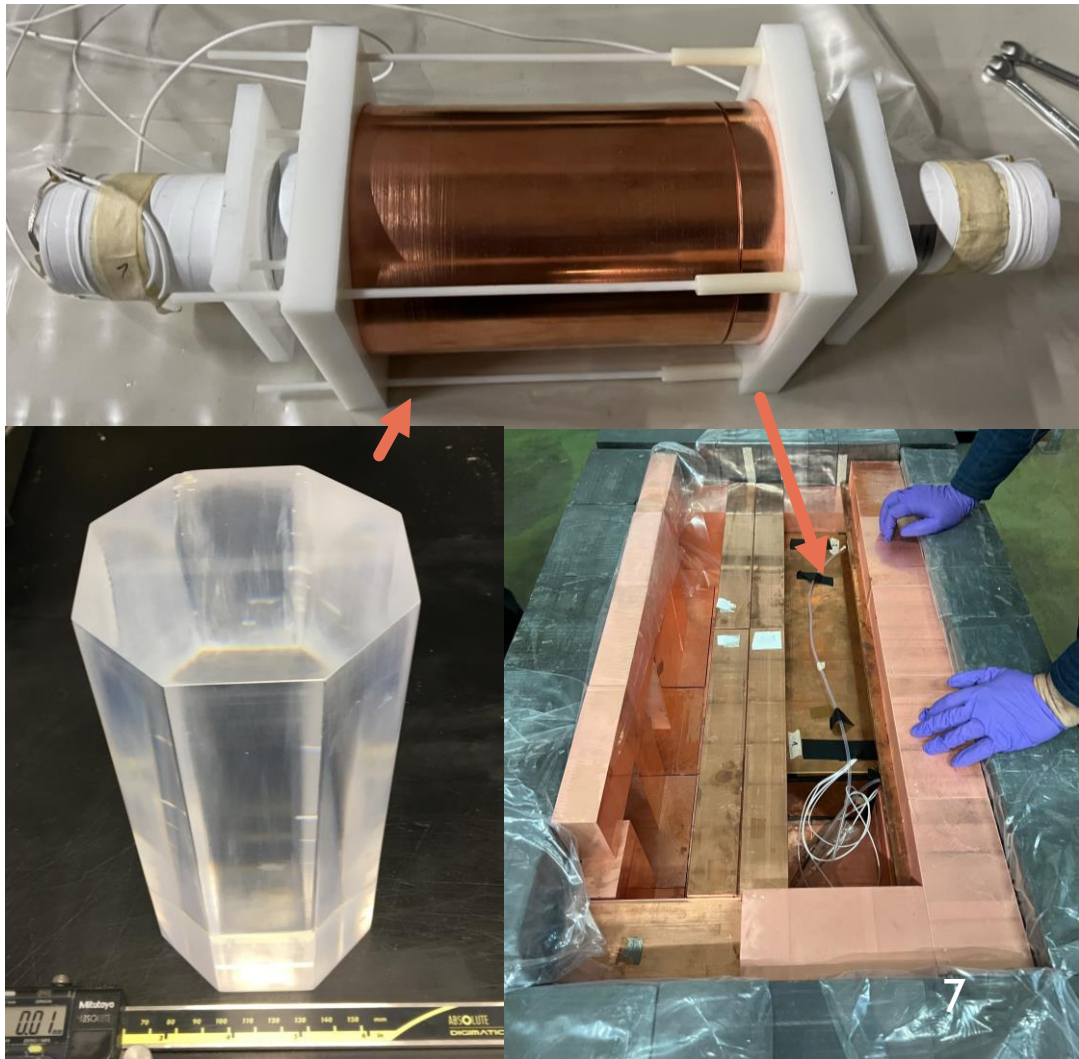
SABRE has grown highest purity NaI(TI)

[1] – M. Antonello, et al.," Characterization of SABRE crystal NaI-33 with direct underground counting." *Eur. Phys. J. C* 81, 299 (2021)
[2] – R. Bernabei, et al. "The DAMA/LIBRA apparatus." Nucl. Instrum. Methods Phys. Res. A: 592.3 (2008): 297-315.
[3] – G. Adhikari, et al. "Initial performance of the COSINE-100 experiment." The European Physical Journal C 78.2 (2018): 1-19.

NAI-35

First SABRE South Test crystal:

- Grown at RMD using "Astro-grade" NaI
- 3.7 kg post cut & polish
- Encapsulated w Suprasil windows
- Currently being characterised at LNGS by direct counting



Preliminary results used to set LY for background studies

NAI-35 LIGHT YIELD

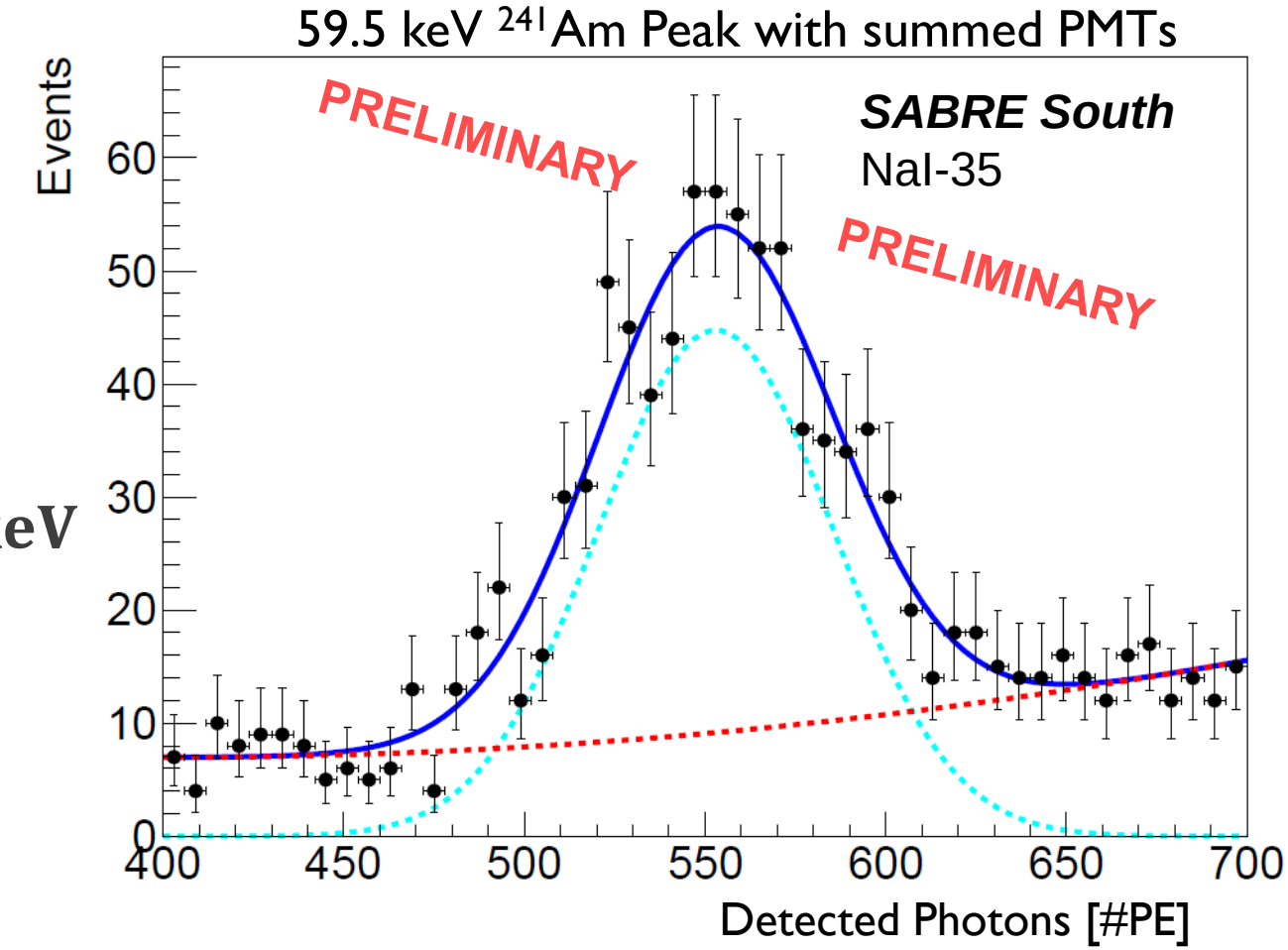
Using 59.5 keV gamma from ^{241}Am.

Peak fit with Gaussian + 2nd order Chebyshev polynomial for bkg.

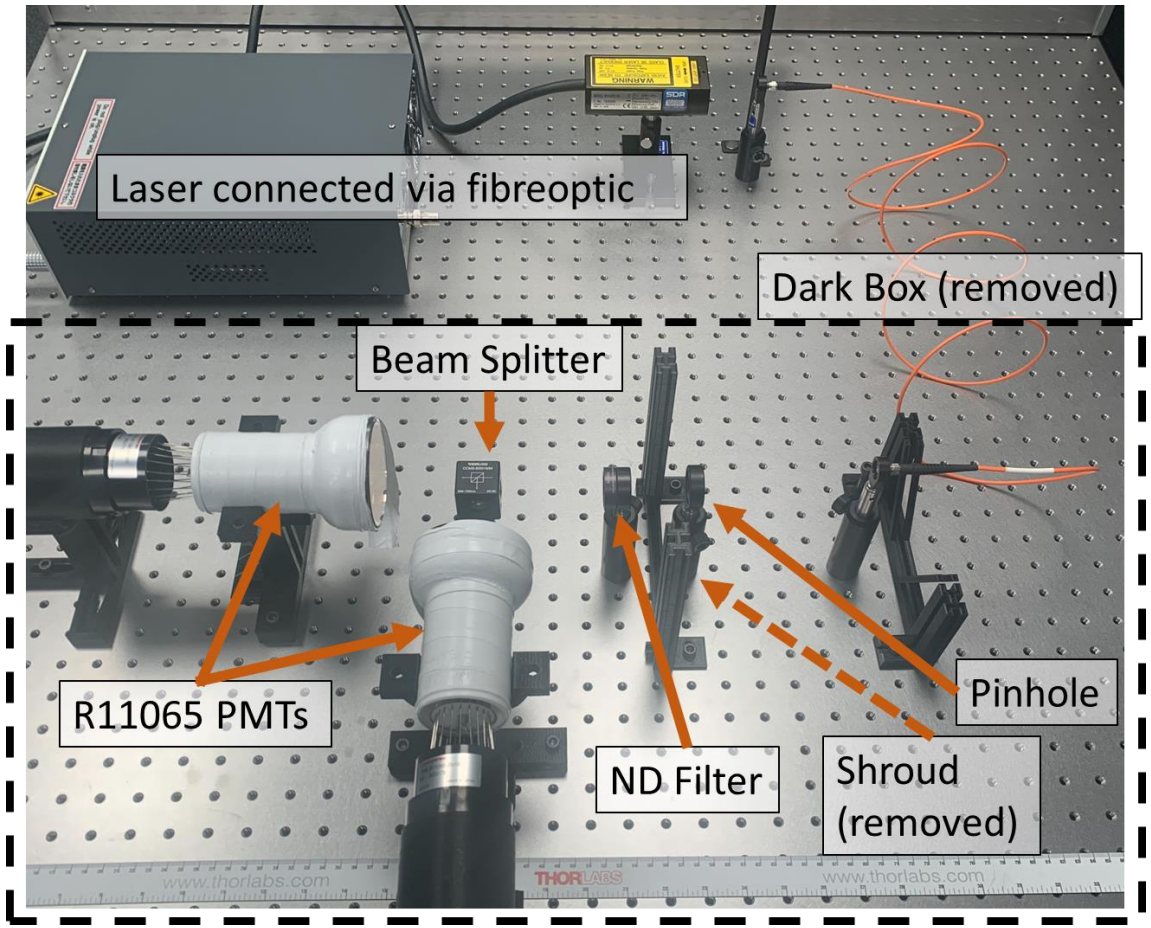
Preliminary measured light yield:

$$\mathbf{L.Y.} = \mathbf{9.29 \pm 0.03_{fit} \pm 0.11_{Q_{SPE}}\ PE/keV}$$

- Lower than expected but <u>no direct coupling of PMT and NaI(Tl)</u>
- So use NaI-33 LY to set energy scale



PMT CHARACTERISATION



Developed PMT test bench to measure:

- Single PhotoElectron (PE) response
- Dark rate
  - Temperature dependence
  - Correlated/uncorrelated
- Quantum Efficiency (QE)
- Transit time mean & spread
- Spatial uniformity

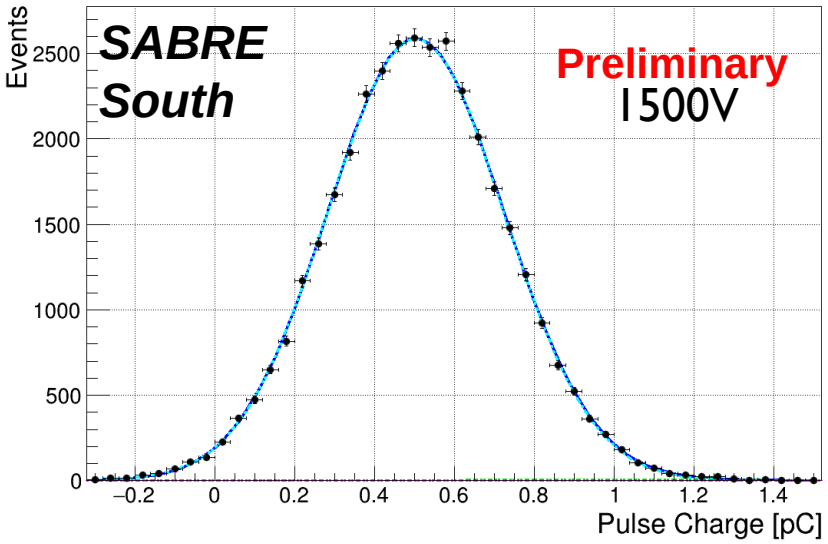
All 32 PMTs (+4 spares) are in process of being characterised.

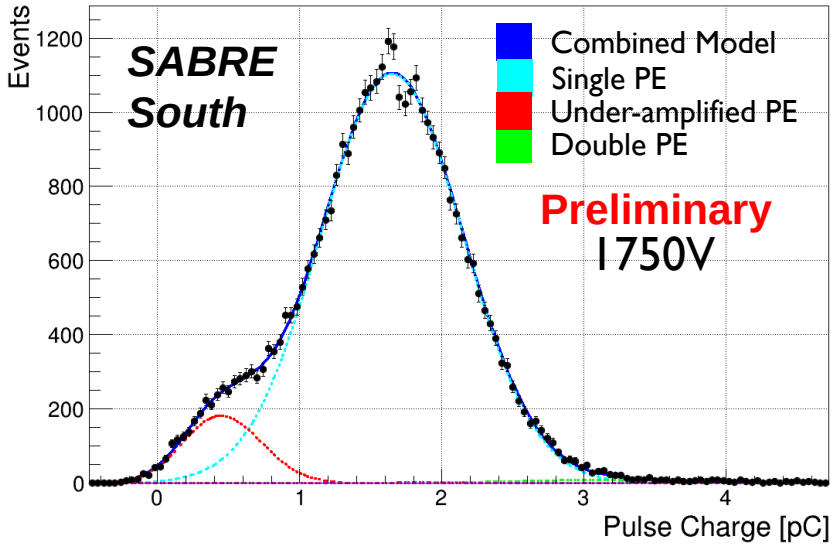
SPE RESPONSE

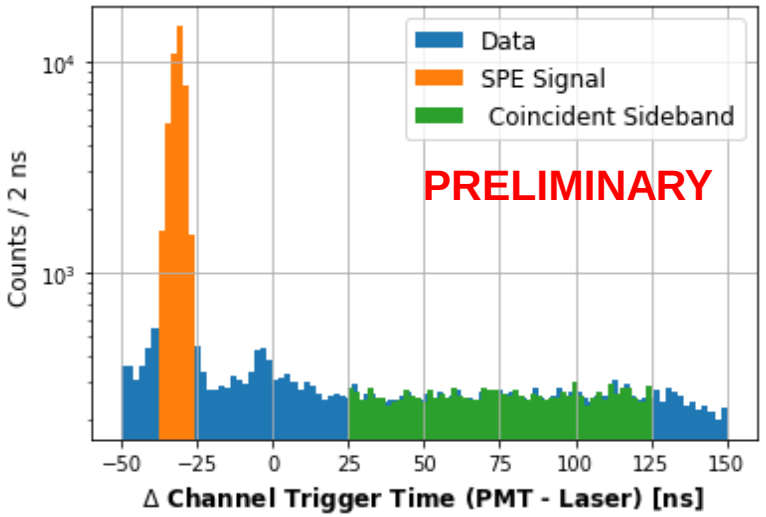
Use attenuated picosecond pulsed laser with mean occupancy ~0.05 photons/pulse
Coincidence timing cut can obtain >99% pure single photoelectron sample.

Charge distribution fit with multi PE convolved fit

$$\sum_{n=1}^{4} C'_n\left(\mathrm{P_U}\cdot \mathrm{Gauss}(\delta\cdot q_{SPE}, \delta\cdot\sigma_{SPE}) + (1-P_U)\mathrm{Gauss}(q_{SPE},\sigma_{SPE})\right) *^n$$

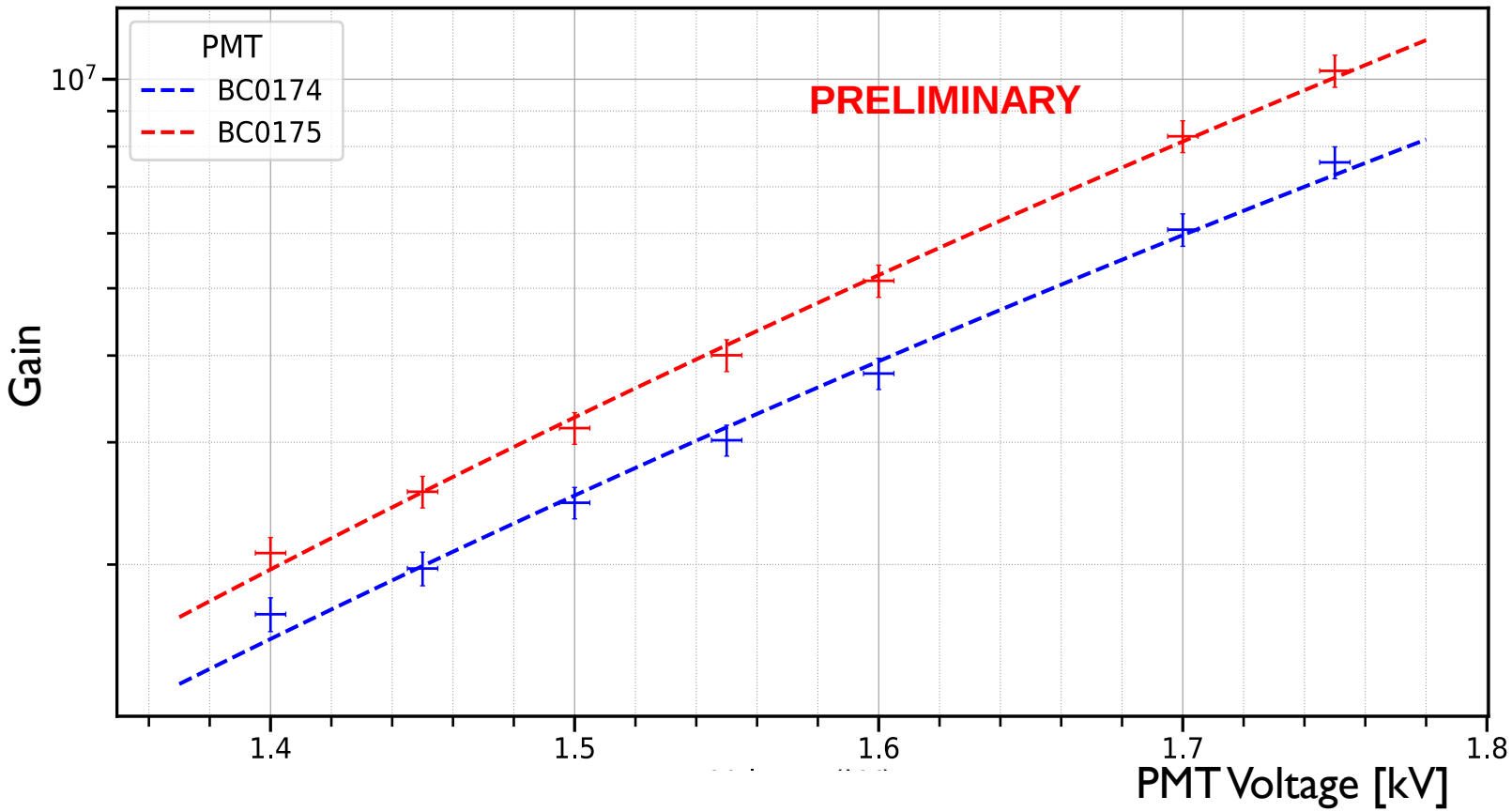






SPE RESPONSE

From SPE Measurements we get gain curves



Good agreement with Hamamatsu parametrisation

$\text{Gain} = a \cdot V^b$

$b \approx (0.6\text{–}0.7)\text{N}_{\text{dynode}}$

$\approx 7\text{–}8.4$

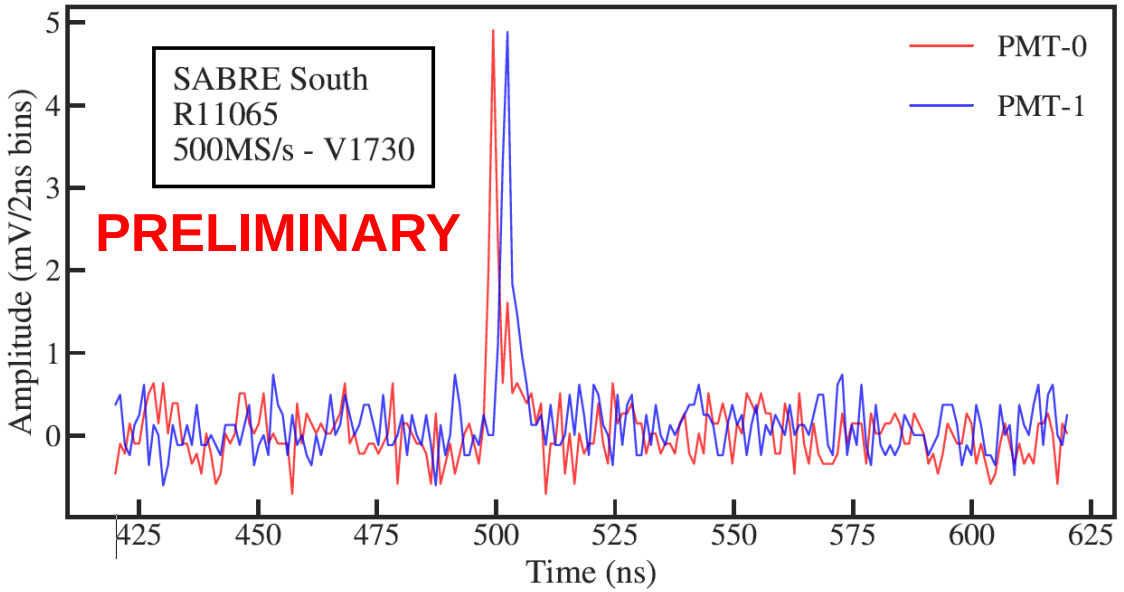
Fit Model	$\chi^2/\text{N}_{\text{DoF}}$
$0.153 \cdot V^{6.90}$	$4.31/5$
$0.168 \cdot V^{7.31}$	$2.30/5$

DARK RATE

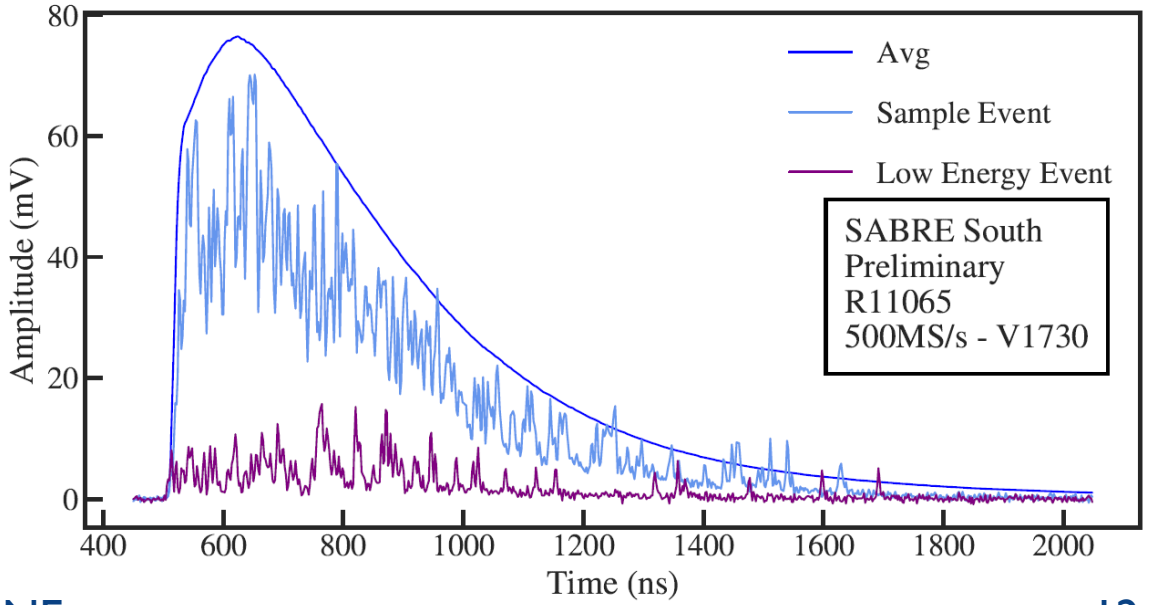
"Dark" events are any event not caused by NaI(Tl) scintillation – no light.

Dominated by thermionic emissions (~1 PE with Temperature dependence)
These contribute outside the RoI. Coincidence in RoI driven by other effects.

Coincident thermionic noise 2 x 1 PE ~ 0.15 keV_{ee}



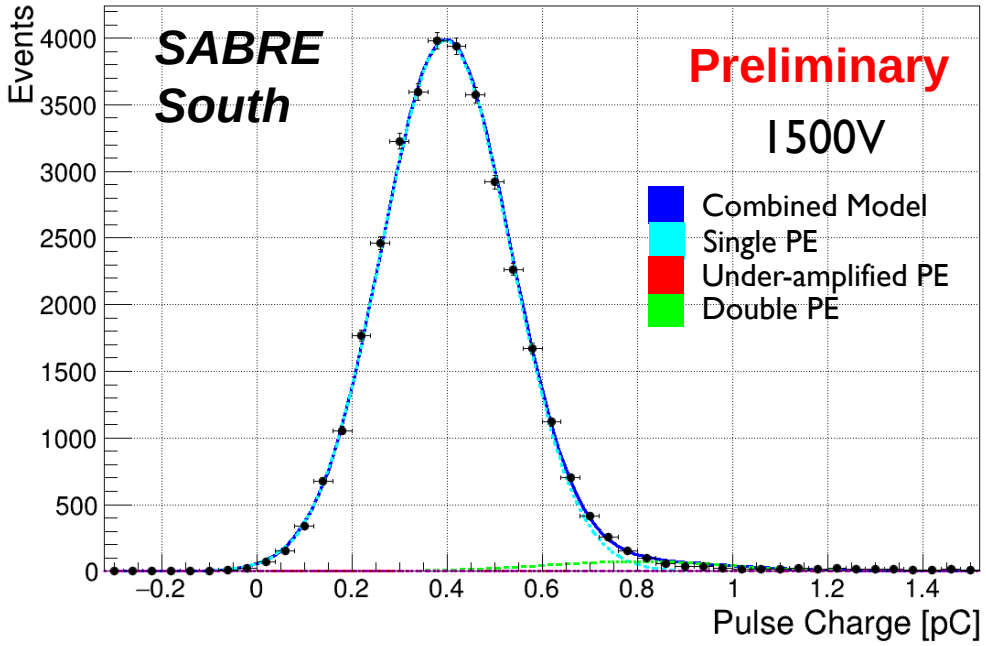
Average + high and low energy NaI(Tl) pulses

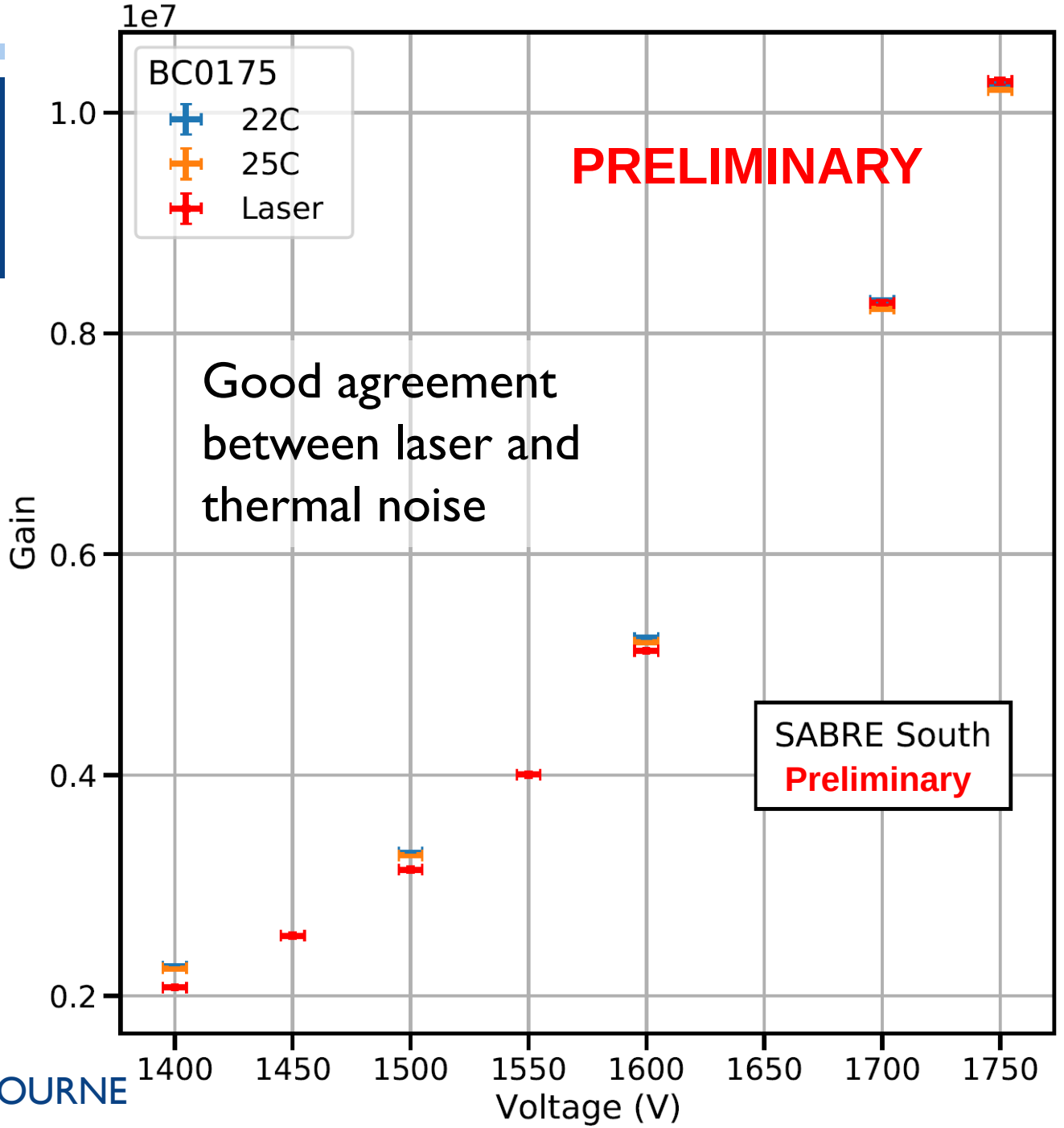


DARK SPE RESPONSE

Also measured SPE response from thermal noise events. No temperature effect.

Will be used for continuous gain monitoring





DARK RATE

Show promising separation with single PMT.

Use ratios to minimise energy dependence

$$X1 = \frac{Q_{(100,\,600)}}{Q_{(0,\,600)}} \qquad X2 = \frac{Q_{(0,\,50)}}{Q_{(0,\,600)}}$$

$$CAP_x = \frac{Q_{(0,\,x)}}{Q_{(0,\,t_{max})}}$$

ANAIS: *JCAP* 11 (2022) 048

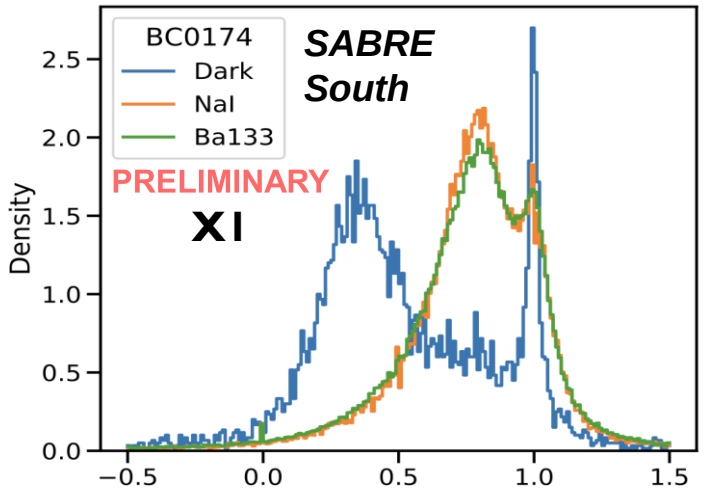
$Q_{(t1,\,t2)}$ is the charge in a specific window.

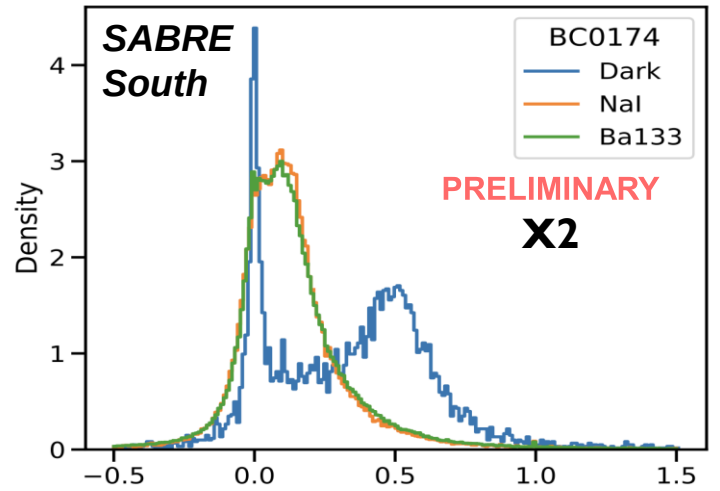
$$Q_{(t1,\,t2)} = \sum_{t=t1}^{t2} h(t)$$

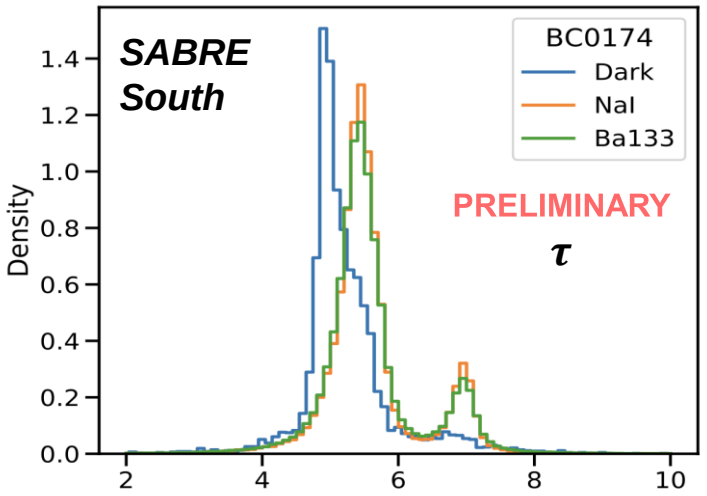
Amplitude at time t

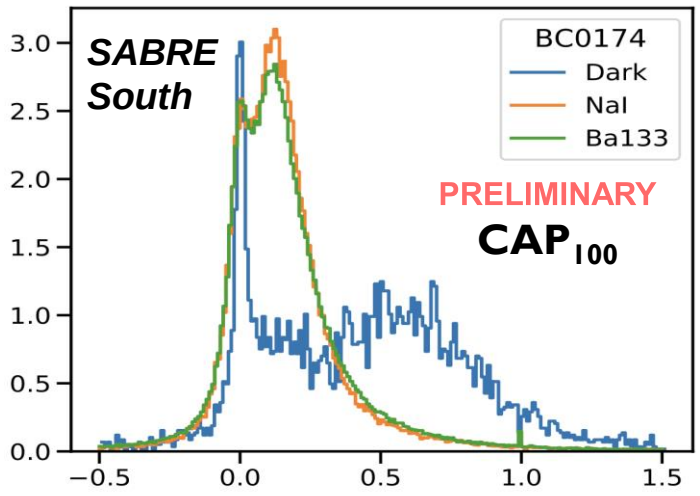
$$\tau = \frac{\sum_{t=0\ ns}^{600\ ns} h(t) \cdot t}{\sum_{t=0\ ns}^{600\ ns} h(t)}$$

What happens with pair of PMTs?





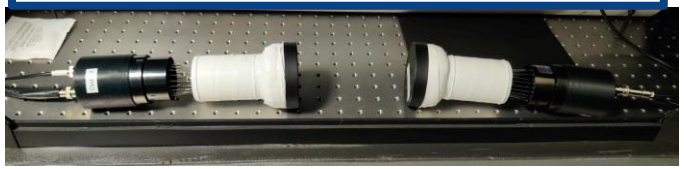




CORRELATED DARK EVENTS

PMT dark runs taken with pair on PMTs in coincidence (1600 ns) with <SPE trigger (1.7 mV)

Blocked PMTs

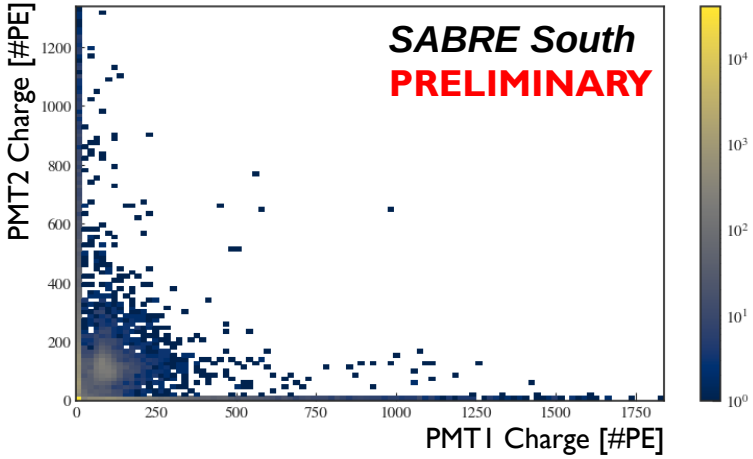


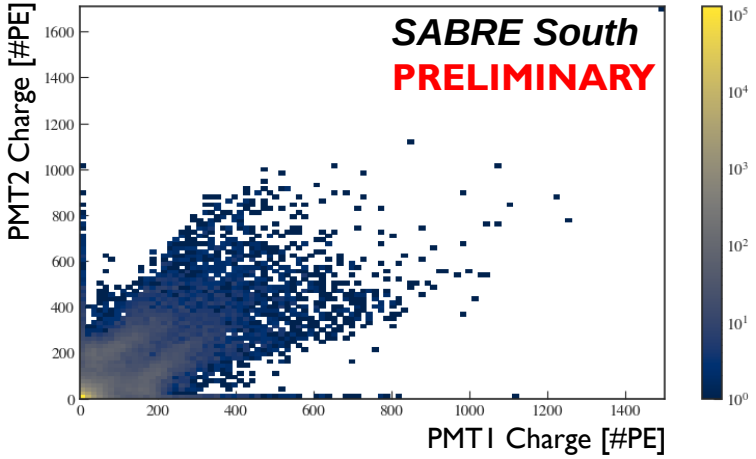
Mainly Asymmetric Events
Some random coincidences

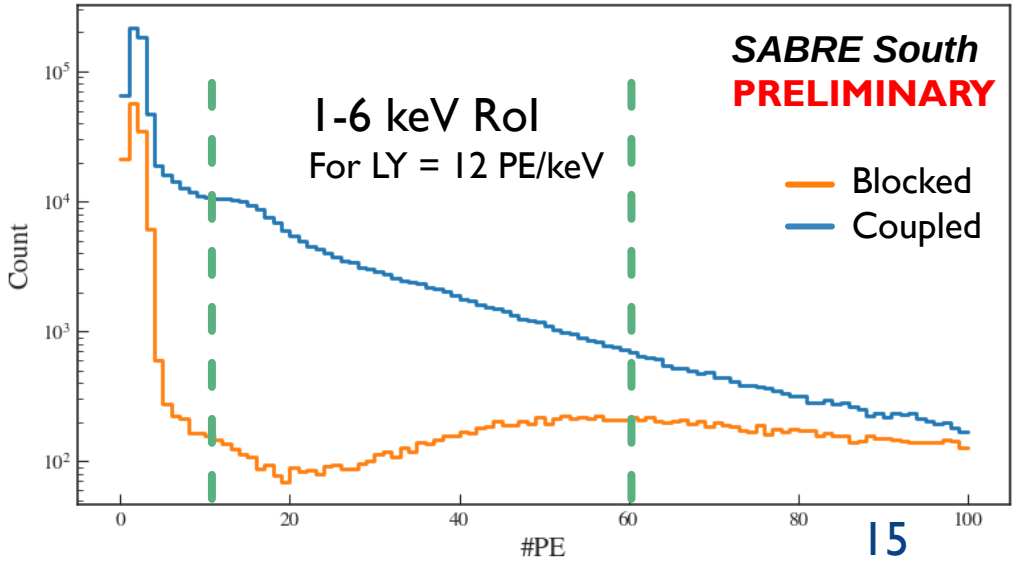
Coupled: Optical Pad + Grease

See exponential structure in RoI
Higher counts potentially due to:

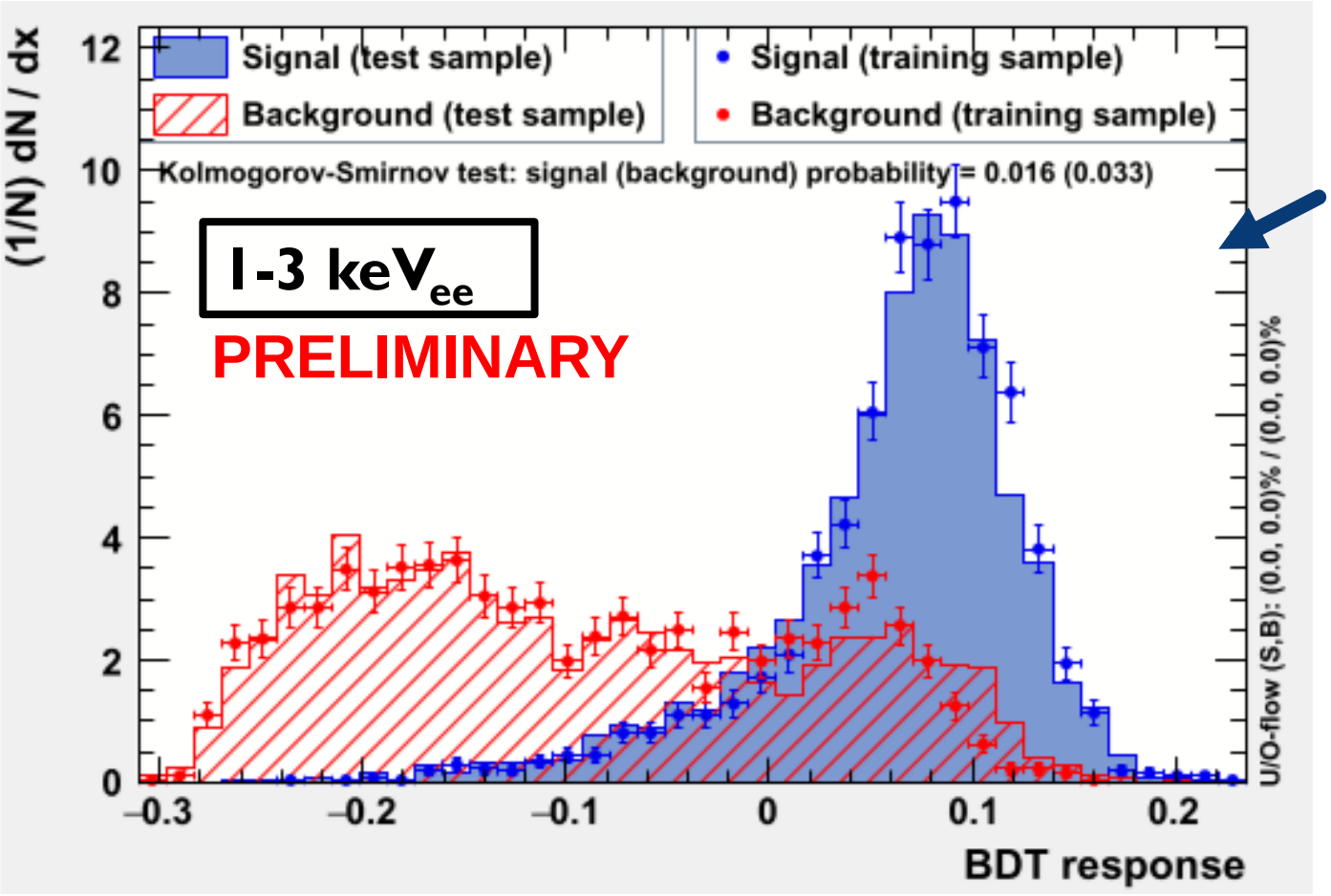
- Dynode glow
  NIM A *545*(1-2), pp.225-233.
- Surface muon flux







BACKGROUND SUPPRESSION



First classifier trained on data (NaI ER & PMT Bkg) looks promising

- DAMA X1 & X2,
- Amplitude weighted mean-time
- ANAIS CAP$_X$ (100, 200,300,400,500,600)

1-3 keV: 90% bkg rejection for 50% signal eff

3-10 keV: 96% bkg rejection for 50% signal eff

More information to be exploited from pair of channels

Cannot quantify exact impact on background yet. Need:

- Underground measurements
- Effective BDT

SUMMARY

SABRE South is Southern Hemisphere's first direct detection experiment and independent replication of DAMA/LIBRA

- 1 keV_{ee} region is crucial to replicate DAMA
- <1 keV_{ee} can deepen understanding of DAMA result
- PMTs make a non-negligible contribution to experimental background
- Can be effectively reduced through pulse shape based classifiers

BACKUP SLIDES

SABRE – A DUAL SITE EXPERIMENT

SABRE (Sodium iodide with Active Background REjection) is an independent replication of DAMA/LIBRA with dual detectors in both hemispheres.

SABRE South - at the Stawell Underground Physics Laboratory (SUPL)

SABRE North - at the Gran Sasso National Laboratory (LNGS)

SABRE Proof of Principle in Hall C, LNGS

Experiments share:

- Same NaI(Tl) detector module with Ultra-pure crystals
- Common simulation, DAQ and analysis framework
- Extensive joint engineering efforts between INFN and CDMPP

Divergence on veto/shielding designs due to restriction of liquid organic scintillators at LNGS

SABRE NORTH STATUS

Two low background NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.
Proof-of-principle phase (1 crystal + active veto) concluded.

Results:

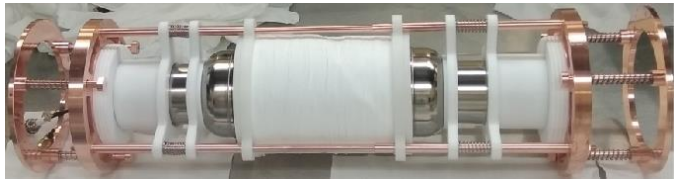
- Full Monte-Carlo simulation model to identify background components
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, lowest since DAMA/LIBRA.

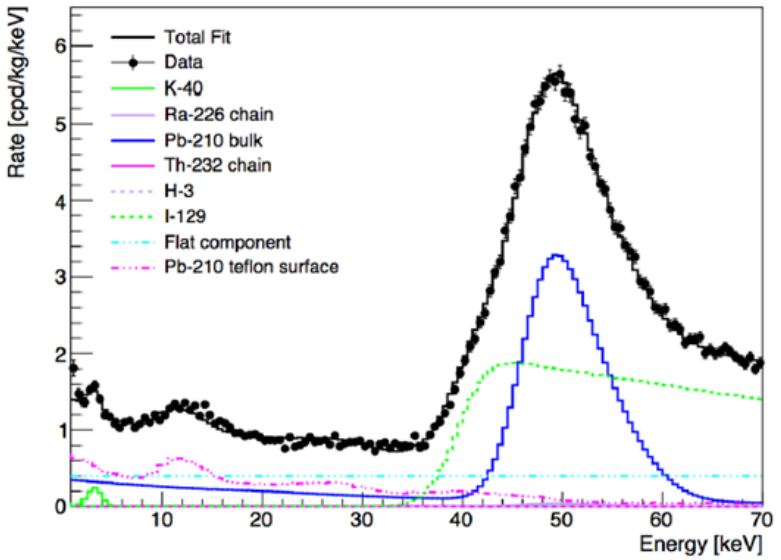
Goals for near future:

Test the same crystal (NaI-33) with a lower radioactivity reflector

- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.

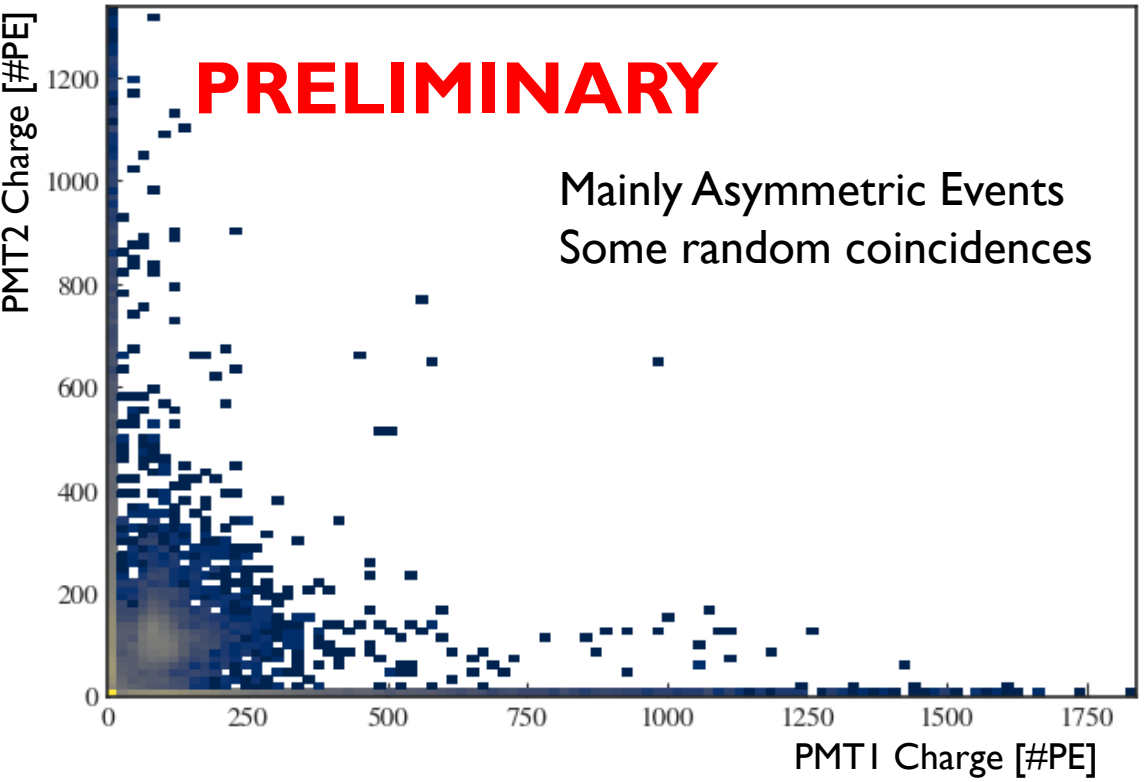
Demonstrated feasibility of full scale experiment without active veto



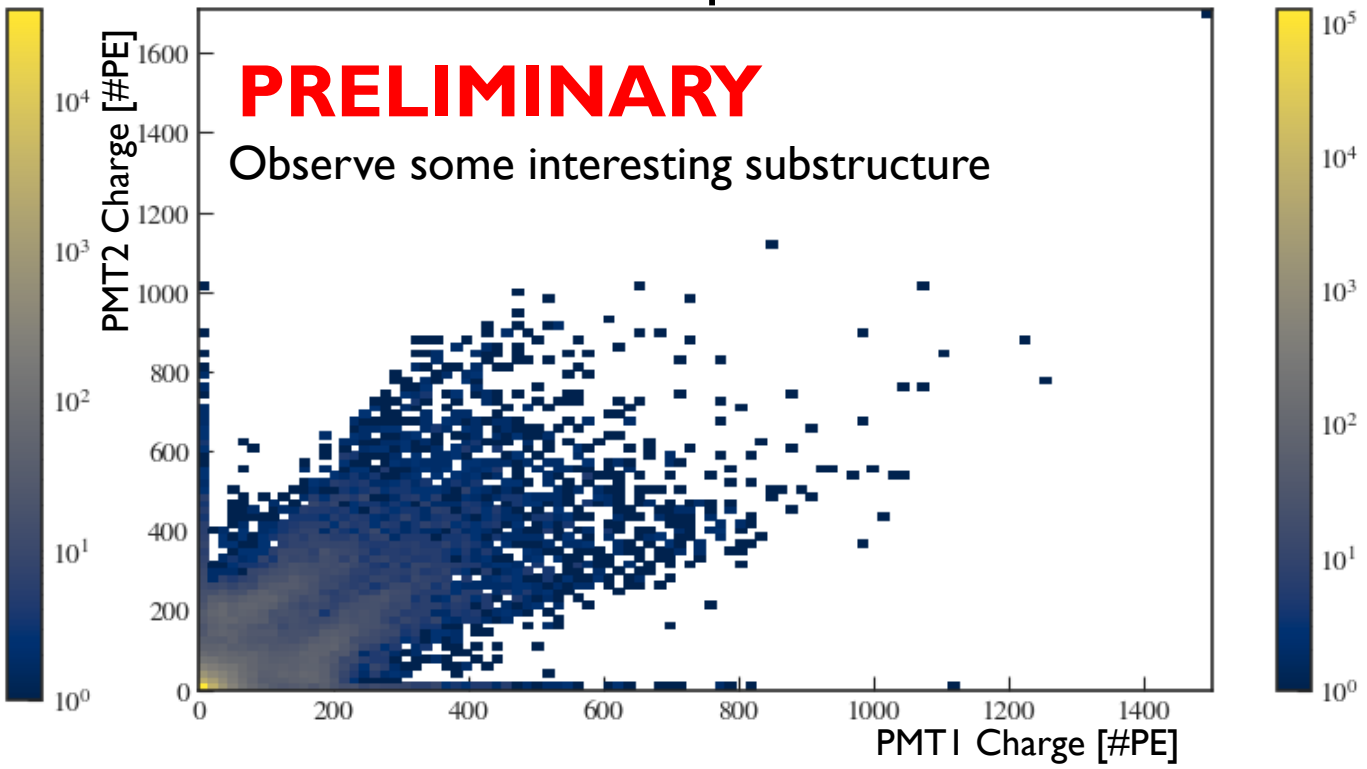


CORRELATED DARK EVENTS

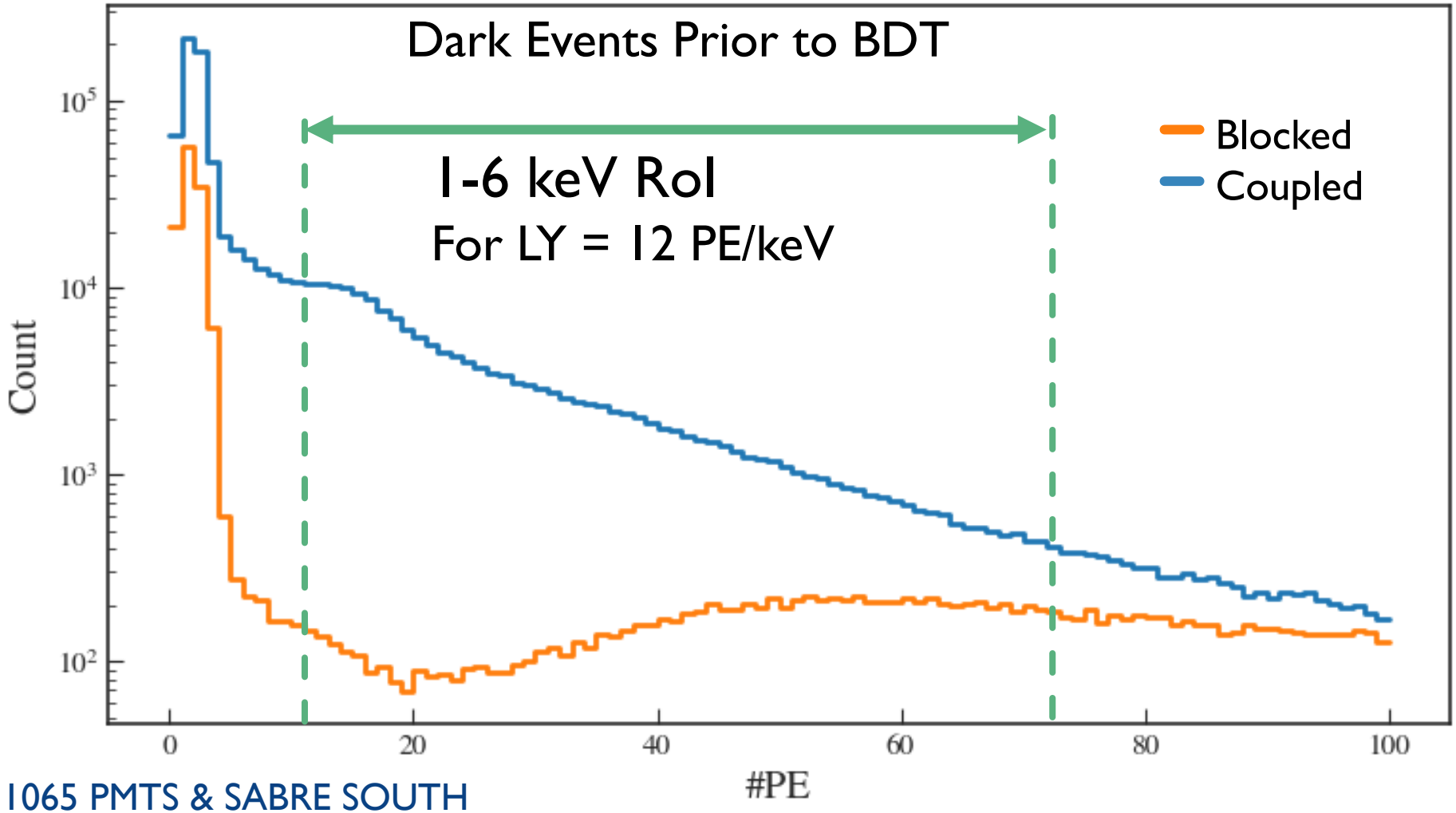
Blocked

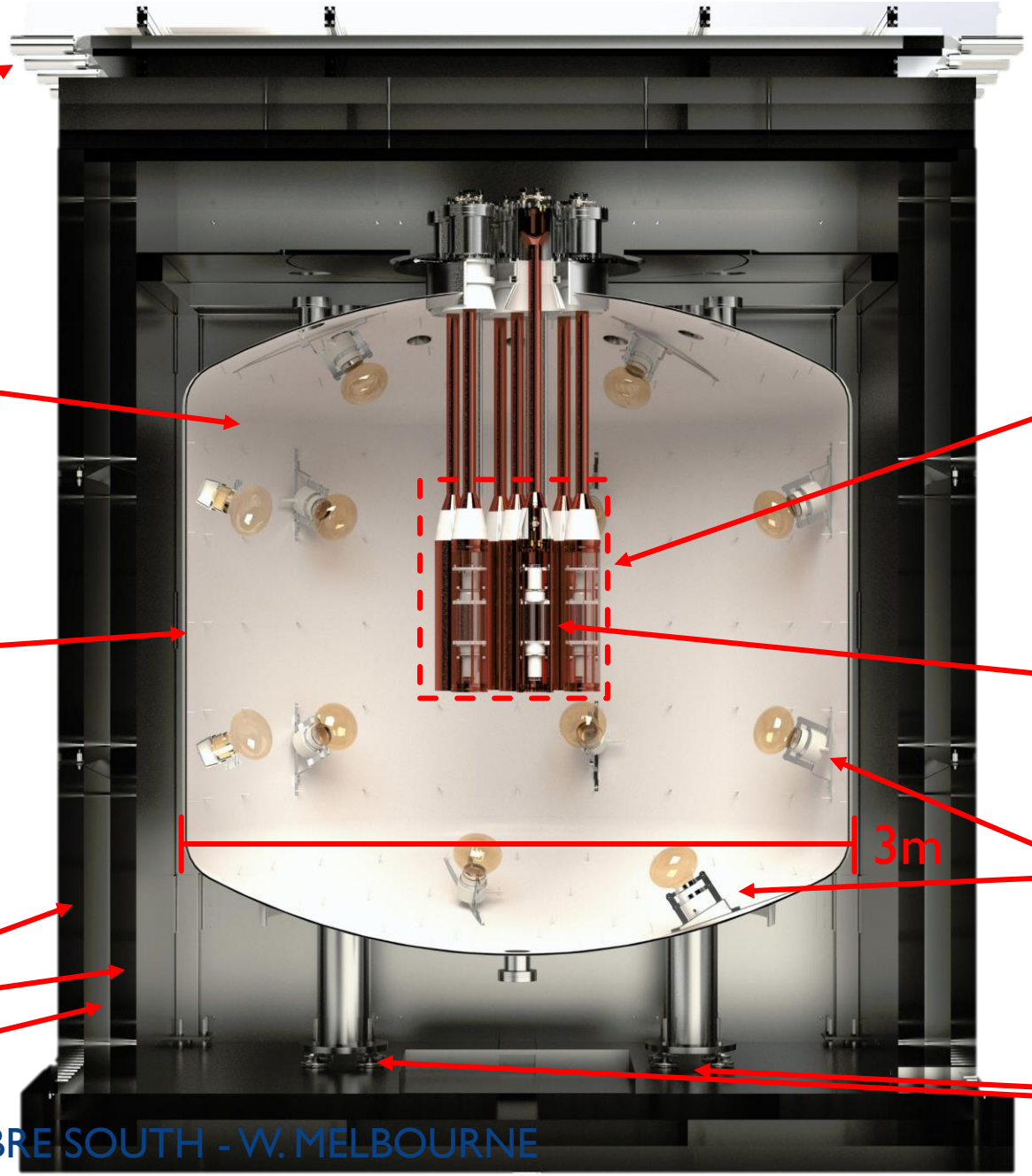


Coupled



IMPACT ON BACKGROUND





Muon Veto
(9.6 m² array)

12,000 L
LAB with
PPO & Bis-MSB

Veto Vessel
Stainless-Steel
Lumirror coating

External Shielding
Steel
Polyethylene

Crystal Array:
- **NaI(Tl) crystal**
- **2x 76mm R11065 Hamamatsu PMTs**

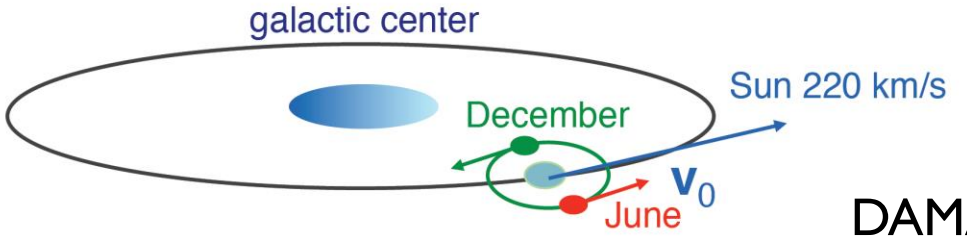
Calibration Sources

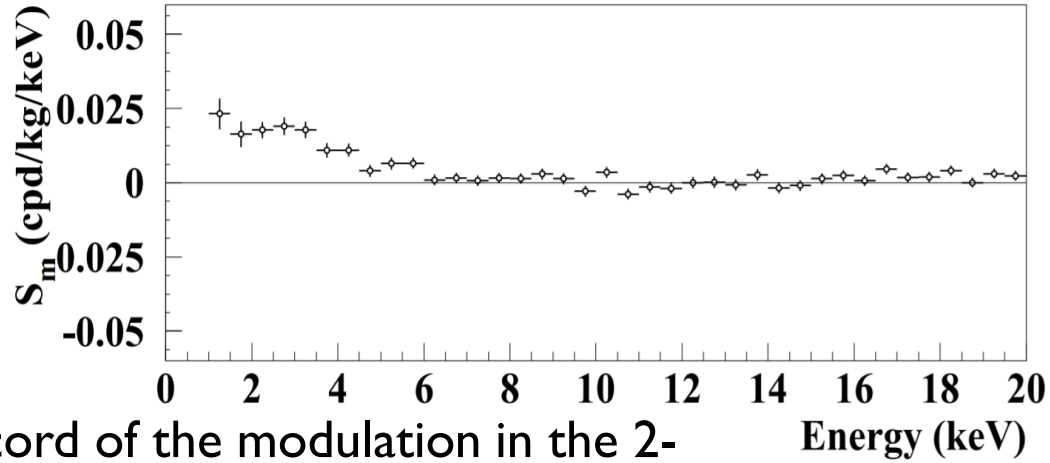
Veto PMTs
18xHamamatsu R5912

Passive Damping System

ANNUAL MODULATION & DAMA/LIBRA

Unique model independent signal for dark matter caused by relative motion of the earth through galactic halo





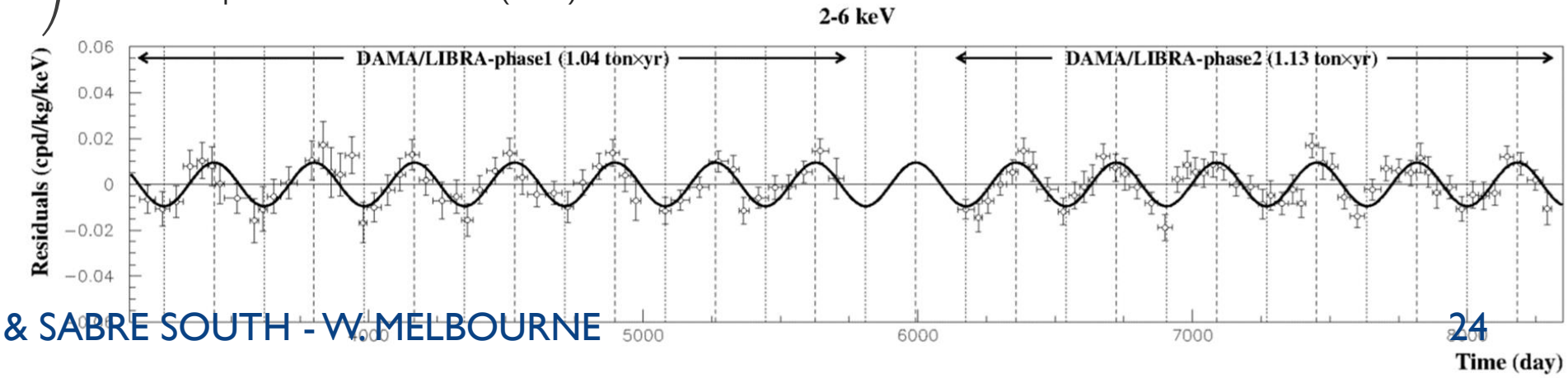
DAMA has a 20-year record of the modulation in the 2-6 keV energy range with combined significance of 12.9 σ

R. Bernabei, et al. "First model independent results from DAMA/LIBRA–phase2." *Universe* 4.11 (2018): 116.

$$R = R_0 + S_m \cdot \cos\left(\frac{2\pi(t - t_p)}{1\ yr}\right)$$

Modulating Signal signatures:

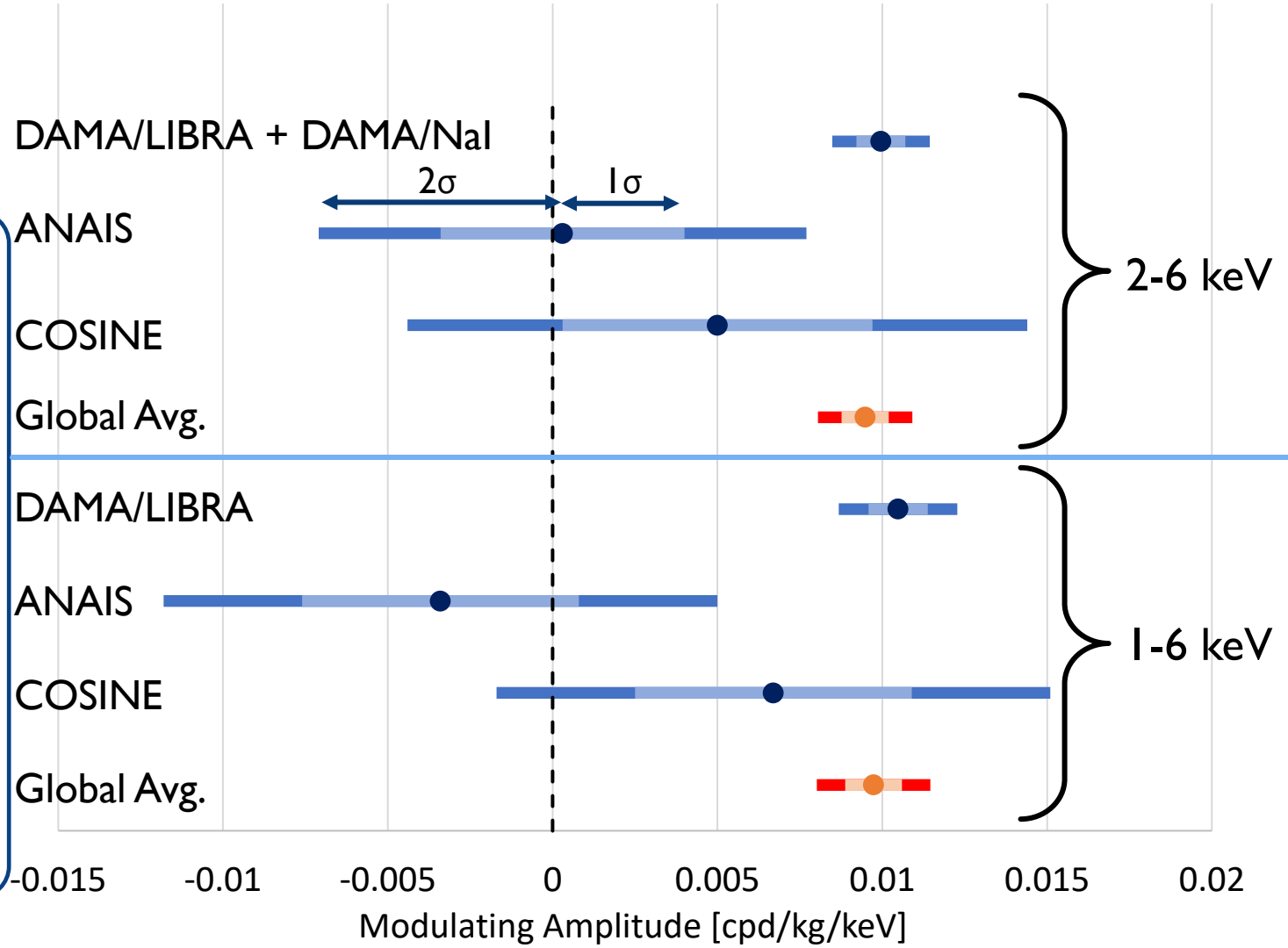
- Period of one year
- Peaks on June 2nd $(t_p = 152.5\ days)$
- $S_m/R_0 \approx 0.01 - 0.03$



MODULATION RESULTS & GLOBAL AVERAGE

ANAIS: 110 kg of NaI(Tl) with muon veto at Canfranc underground laboratory (Spain).
Background: ~3-4 dru,
Exposure: 314 kg x yr.
Phys.Rev.D 103 (2021) 10, 102005

COSINE100: 60 kg of NaI(Tl) used for analysis, with veto system at Yang Yang underground lab (Korea).
Background: ~3 dru,
Exposure: 173 kg x yr.
Arxiv:2111.08863



Global fit shows tension(<3σ)

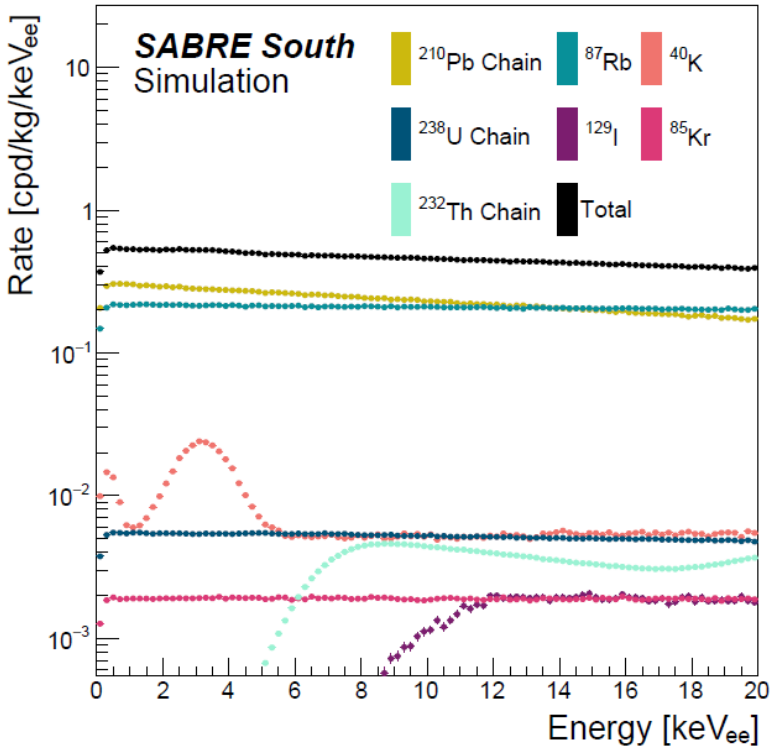
ANAIS or COSINE yet to have significant discovery or exclusion of DAMA.

Motivates additional low-background search in Southern Hemisphere

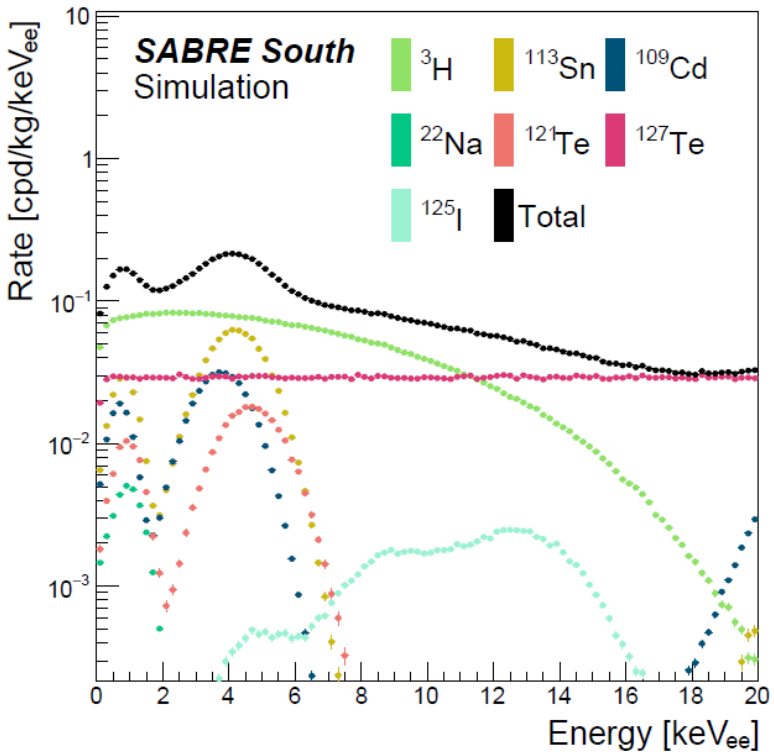
NAI(TL) BACKGROUND SIMULATION

- Using direct counting of NaI-33 and ICP-MS, have simulated background of SABRE South crystals.
- ^{40}K effectively suppressed by veto, main radiogenic background are ^{210}Pb, ^{87}Rb (very conservative upper limit)
  Cosmogenic background after 180 days mainly ^{3}H (12.4 yrs) and ^{113}Sn (115 days)

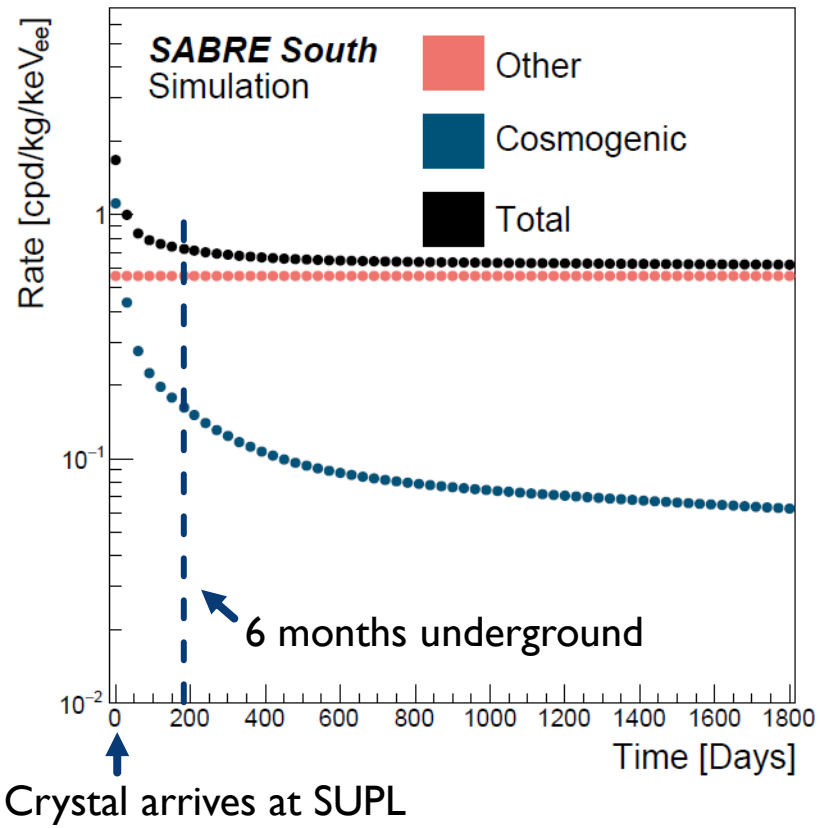
Radiogenic Background



Cosmogenic Background
(6 months underground)



Time Dependence of Background



ACTIVE VETO SYSTEM

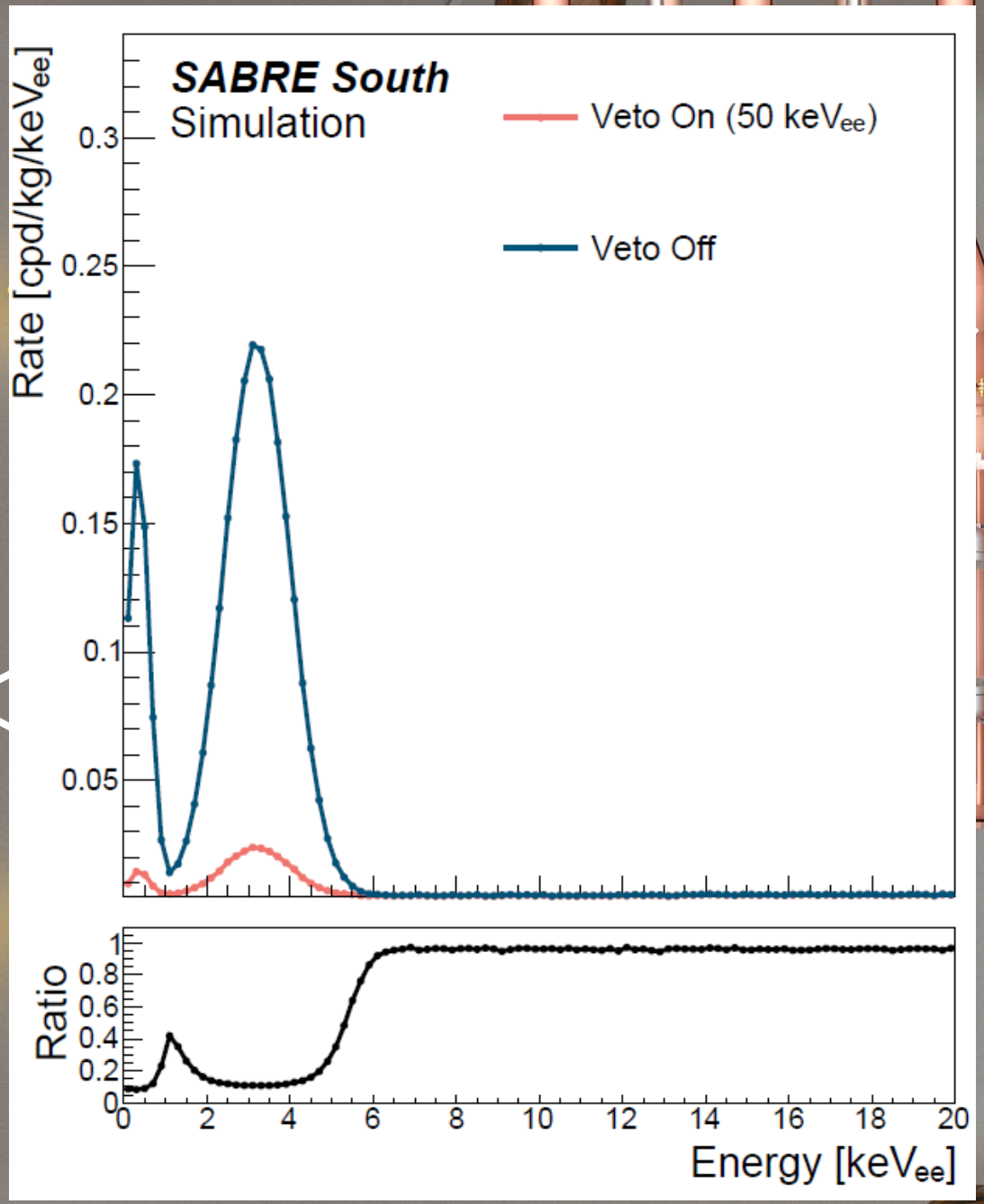
The active veto is designed to:

- Veto ^{40}K decays in NaI(Tl) with >85% efficiency.
- Be sensitive to >50 keV energy deposition
- This reduces some key backgrounds by factor 10, including some cosmogenics.

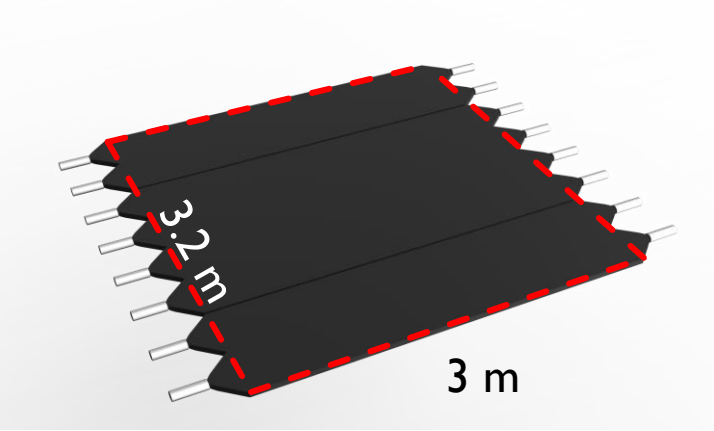
Veto trigger on coincident single photons in 2+ PMTS so actual threshold likely to be lower.

Veto performance position dependent.

Makes exact threshold complex, requires simulation digitisation to study precisely.

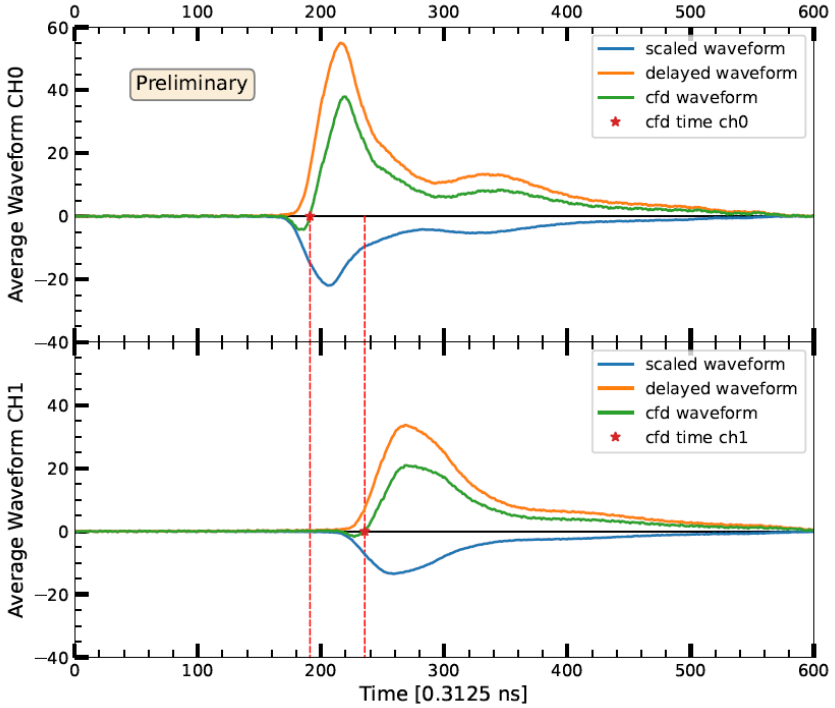


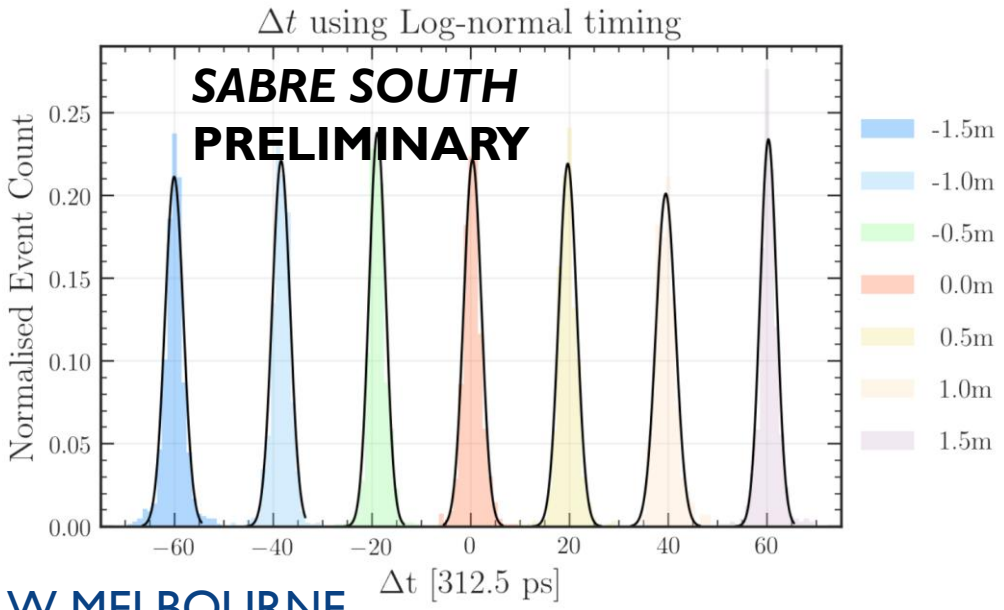
MUON VETO SYSTEM



Provides additional tagging of cosmic muons, and measurements of muon modulation at SUPL (with LS veto)

- 8 x EJ200 organic scintillator panels (3x0.4x0.05 m) with PMTs at opposite ends. Readout at 3.2 GS/s which gives longitudinal position resolution of 3.2 cm using CFD trigger.
- l localisation in LS



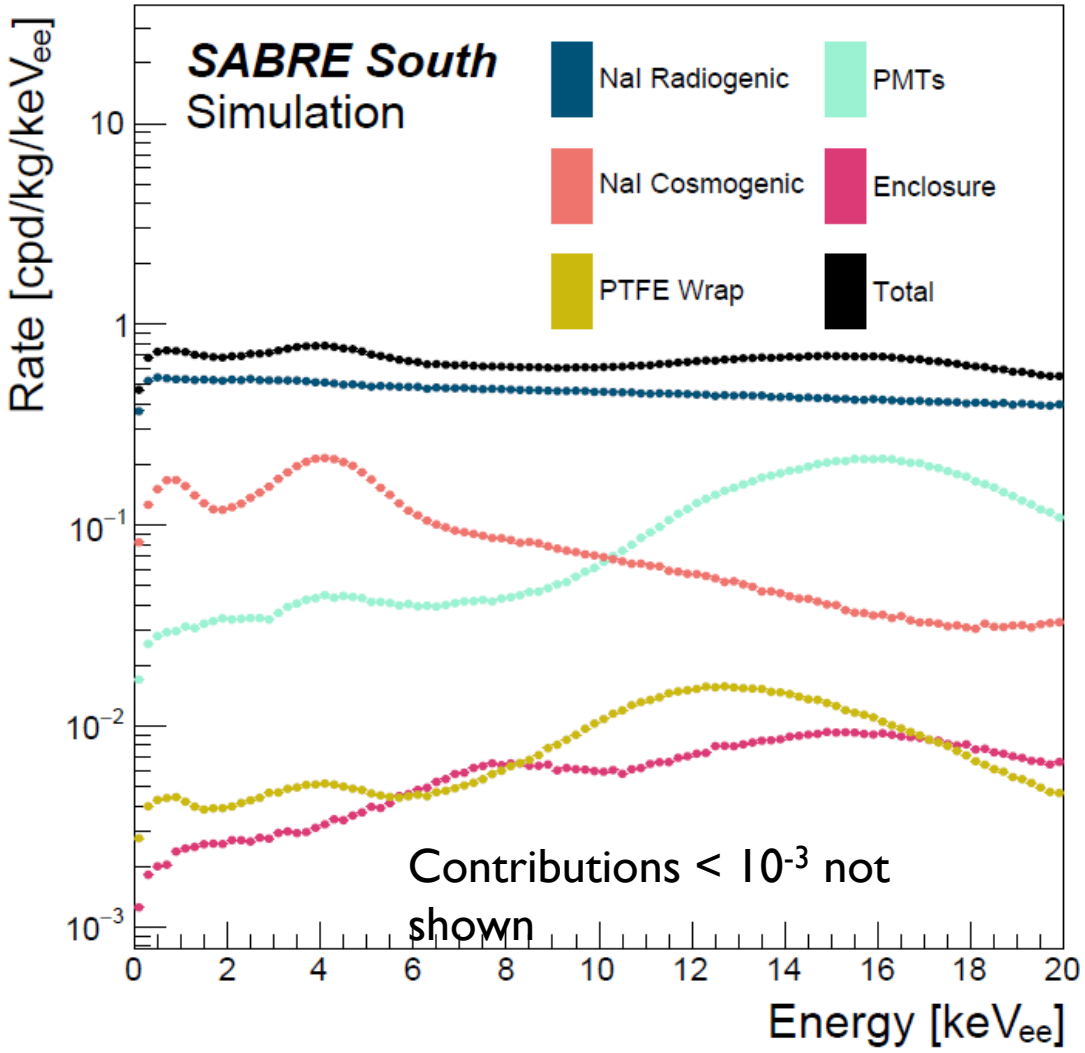


Each panel is being characterised for timing and efficiency on surface

BACKGROUND SIMULATION

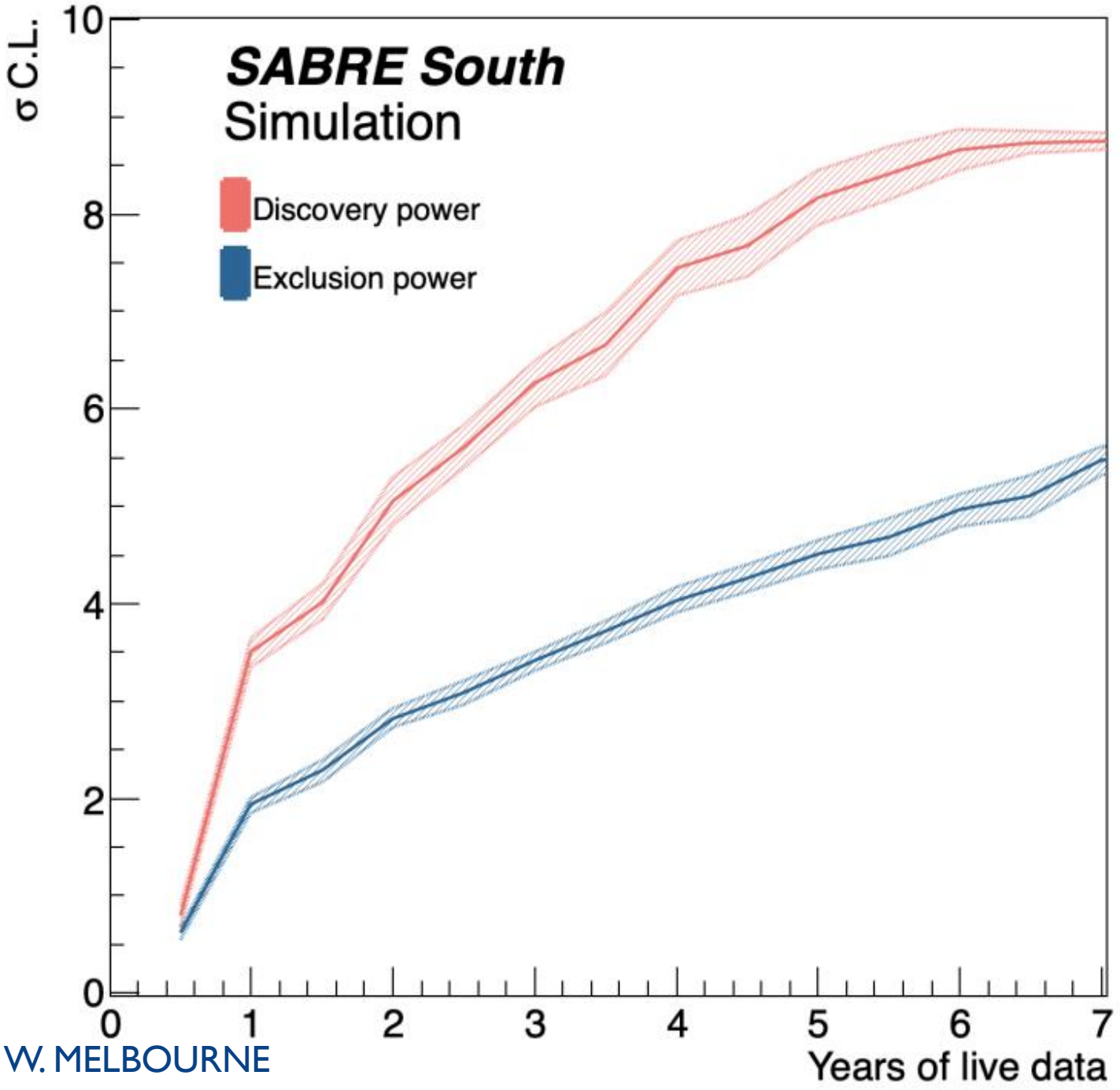
- Total experimental radioactive background has been simulated (arXiV:2205.13849).
- We expect an overall background of **0.72 cpd/kg/keV$_{ee}$**
- Dominated by NaI background (radiogenic and cosmogenic) with ^{40}K effectively suppressed.

- Satisfy SABRE South goal of <10% of background from non-crystal sources.
- External backgrounds, shielding, LS bulk, and veto PMTs contribute less than 10^{-3} cpd/kg/keV



SENSITIVITY

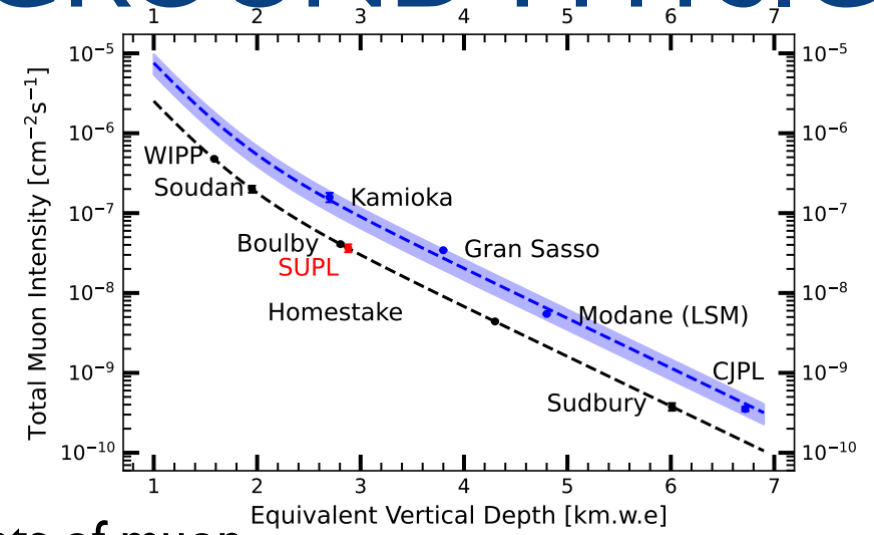
With 50 kg of NaI and target background in 1-6 keV SABRE South will have 5σ discovery (3σ exclusion) power to a DAMA-like signal with 2 years of data taking.

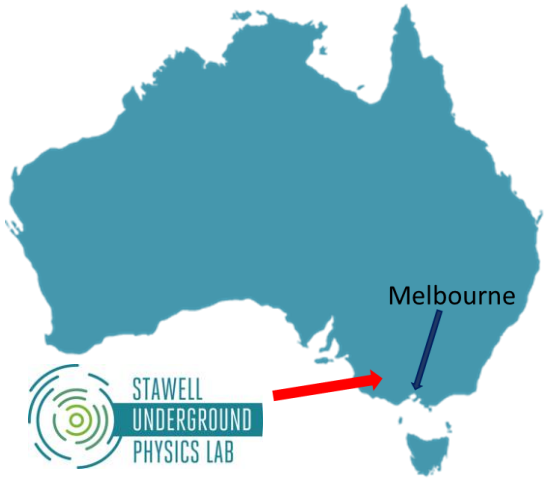


STAWELL UNDERGROUND PHYSICS LAB

SUPL is the first deep underground lab in Southern Hemisphere (37° South).
1025 m below the surface with flat overburden (2900 mwe).

Lab opened this year currently commisioning





SABRE South will make detailed measurements of muon, neutron, and gamma backgrounds later this year