Optical calibration of SABRE-South veto photomultiplier tubes

Kamiel Janssens
SABRE South Collaboration

QCHS 2024 - Session G
20 Aug 2024

Cairns, Australia

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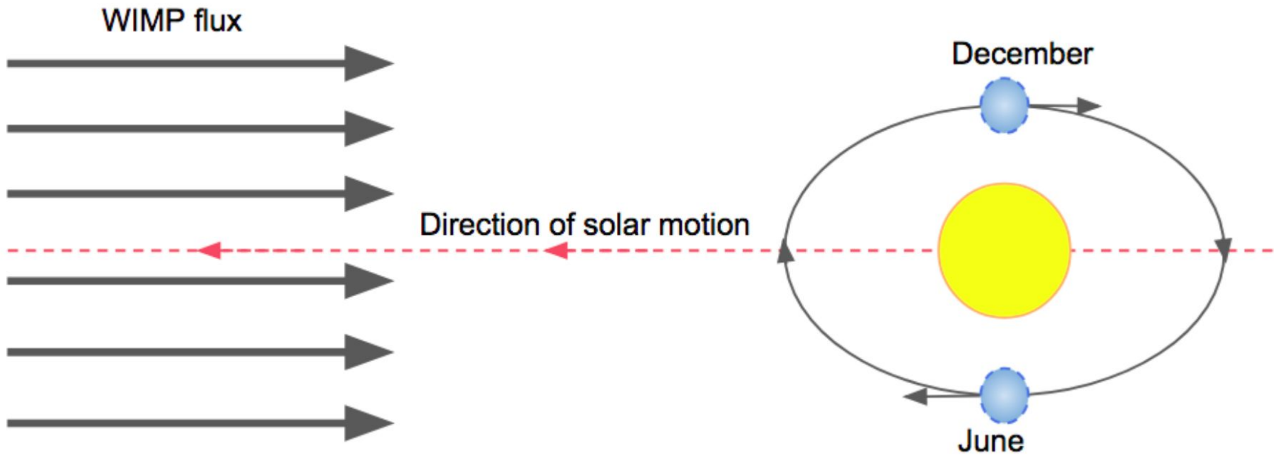
*These **slides** do contain **minimal text** as they support the topics I discuss. For those who are interested: there is a **fully annotated version** of these slides **at the end**.*

Cairns, Australia

Modulating dark matter signal

The DAMA/LIBRA conundrum

See SABRE-South general talk by Irene Bolognino.
Thu 22nd @ 11h20 - Session F



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

2-10%

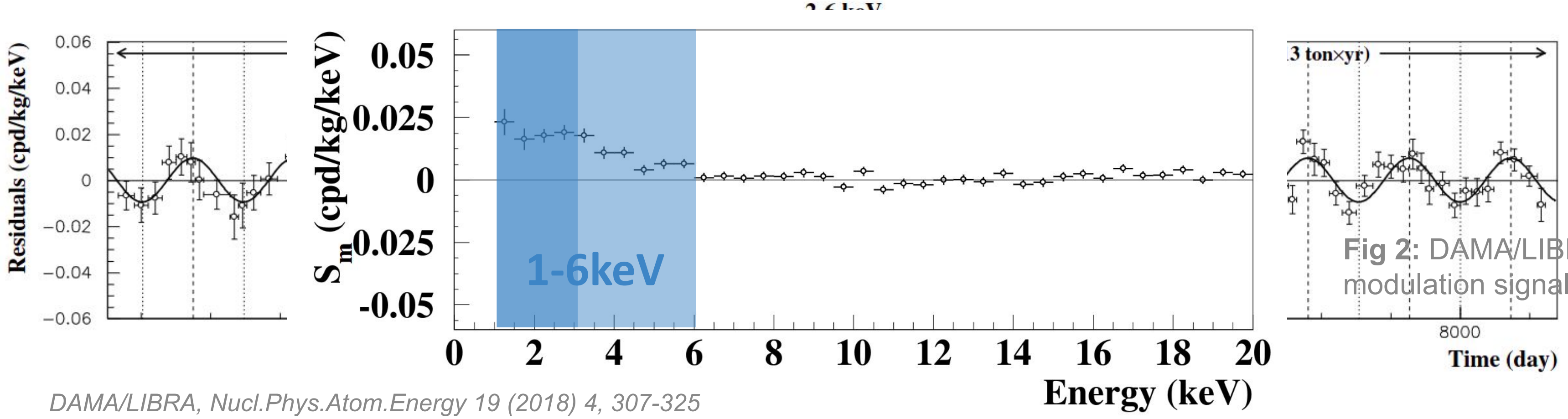
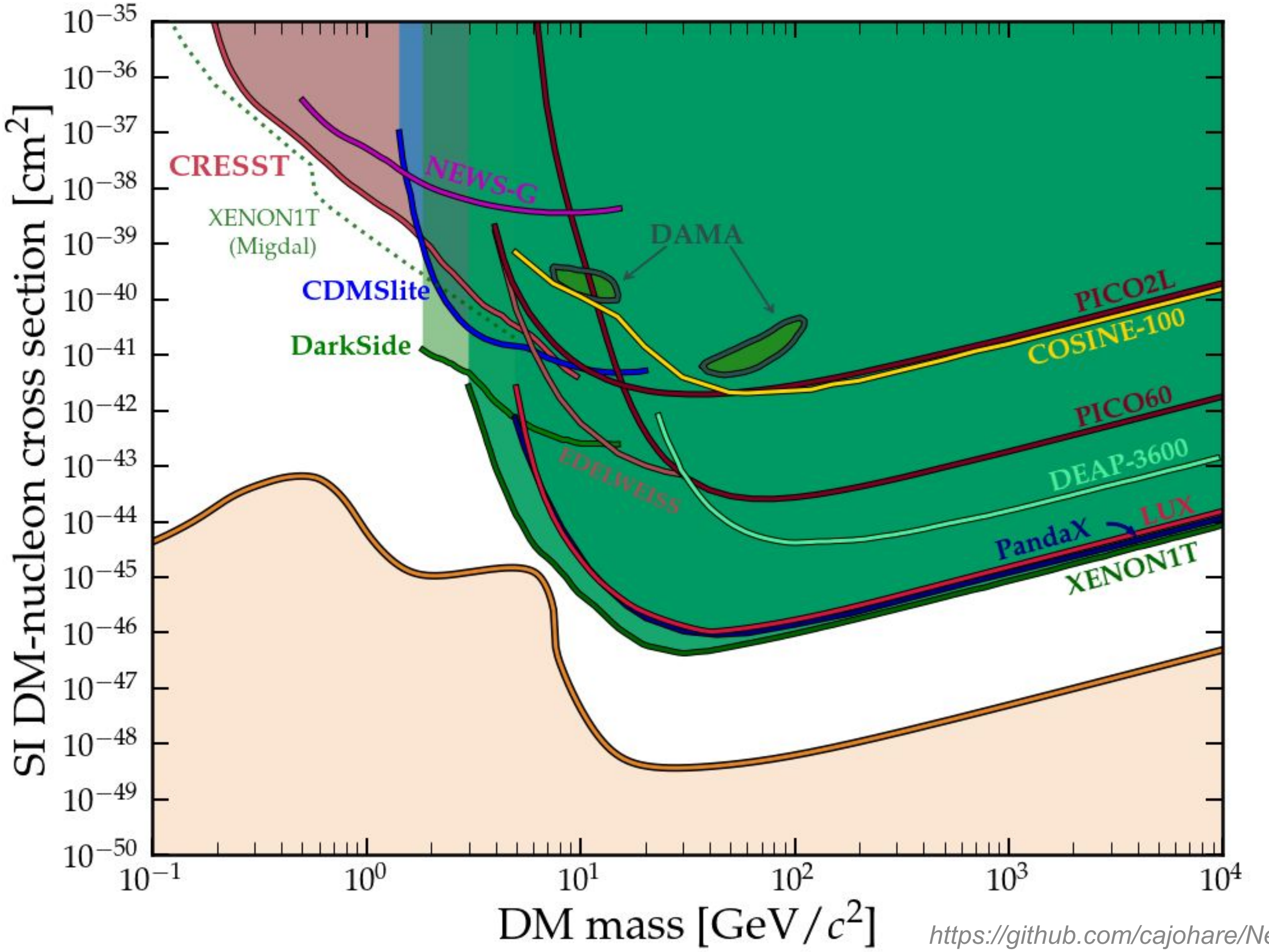


Fig 2: DAMA/LIBRA energy spectrum modulation signal - **Fig 1:** DAMA/LIBRA annual modulation signal

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

Modulating dark matter signal

The DAMA/LIBRA conundrum



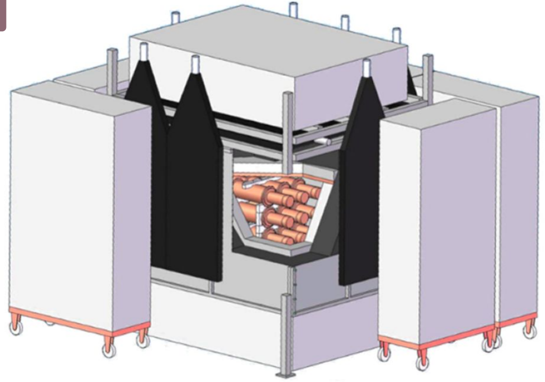
https://github.com/cajohare/NeutrinoFog

Fig 3: Constraints on spin independent DM cross section.

Modulating dark matter signal

NaI experiments & SABRE unique position

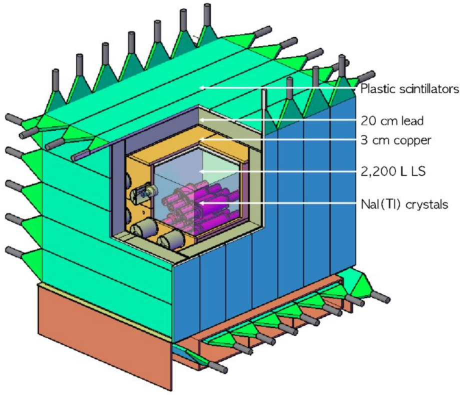
ANAIS



J. Amare, et al, Phys. Sci. Forum 2021

COSINE

H. Prihtiadi et al JCAP02(2021)013

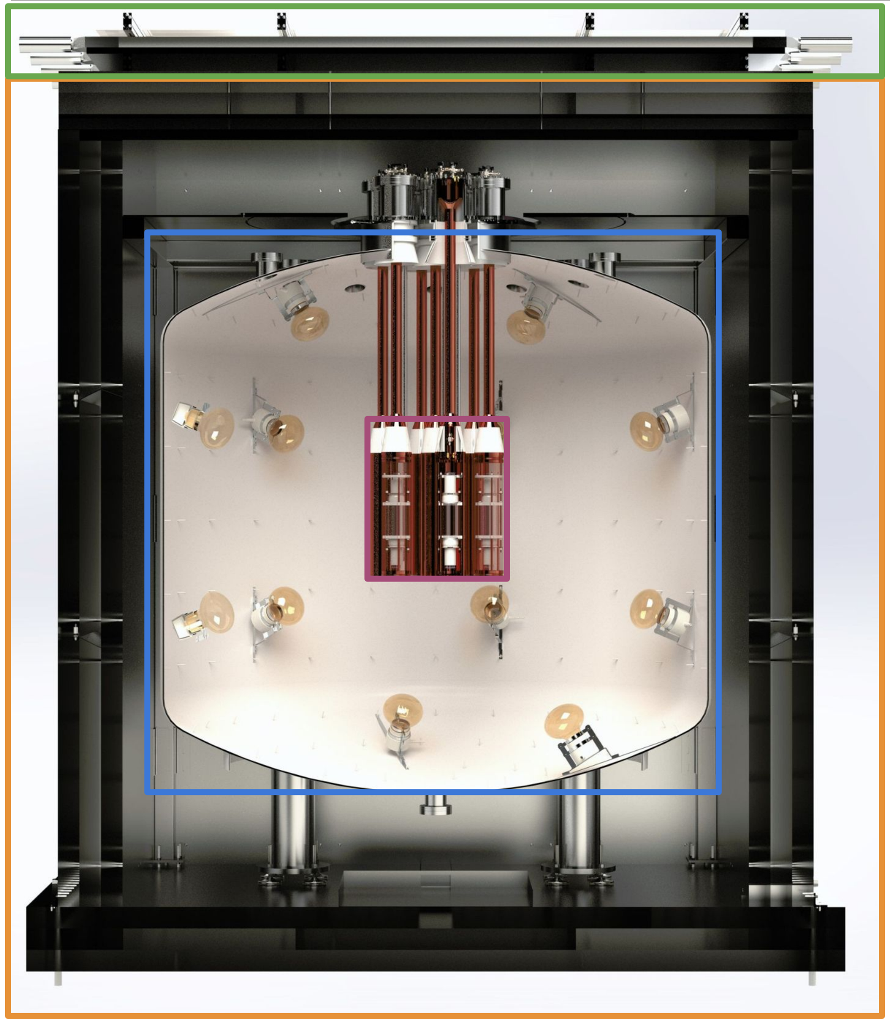


SABRE

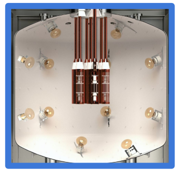
- Ultra pure crystals
- High levels of pass
- Dual experiment s

Modulating dark matter signal

SABRE-South experimental layout



Sensitive detector:
7 NaI crystals + 2x7 R11065 PMTs



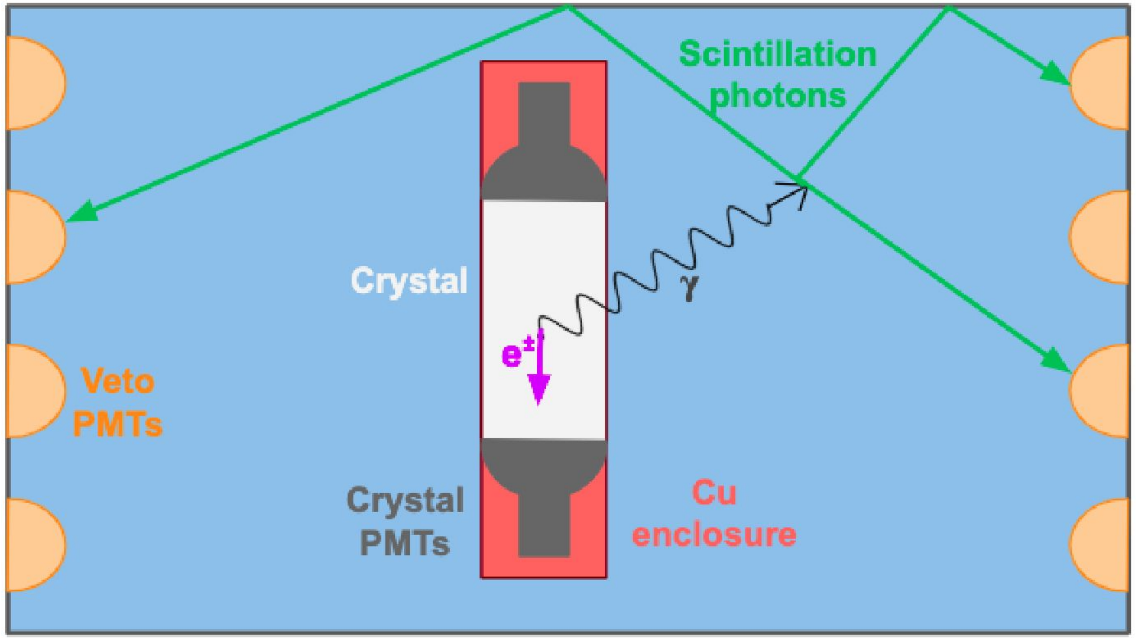
Active veto:
12.000L liquid scintillator (LAB),
18 R5912 PMTs

Passive shielding:
Steel & polyethylene

Muon veto:
9.6 m² detector

SABRE-South active veto

Radioactive decay of **crystal** impurities constitutes **key background**, which can partially be **vetoed** by observing the gamma rays in the liquid scintillator.



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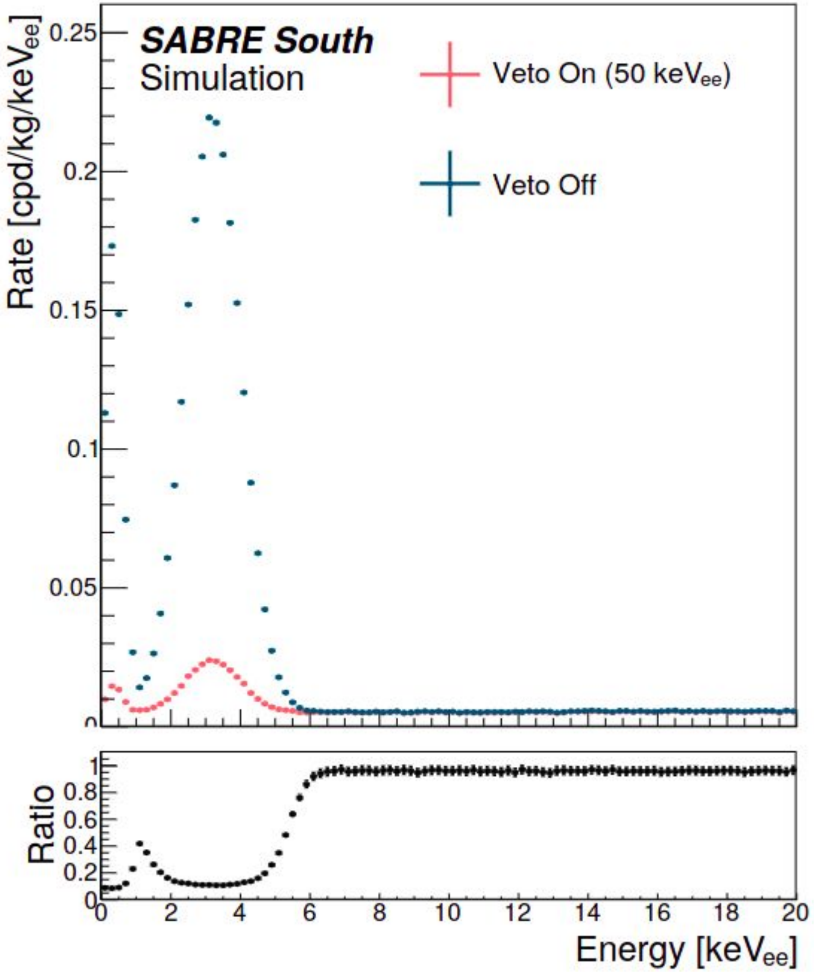


Fig 5: Background from ^{40}K with and without veto.

E. Barberio, et al, Eur. Phys. J. C 83, 878 (2023)

The importance of PMT calibration

SABRE-South

Crystal PMTs

Hamamatsu R11065

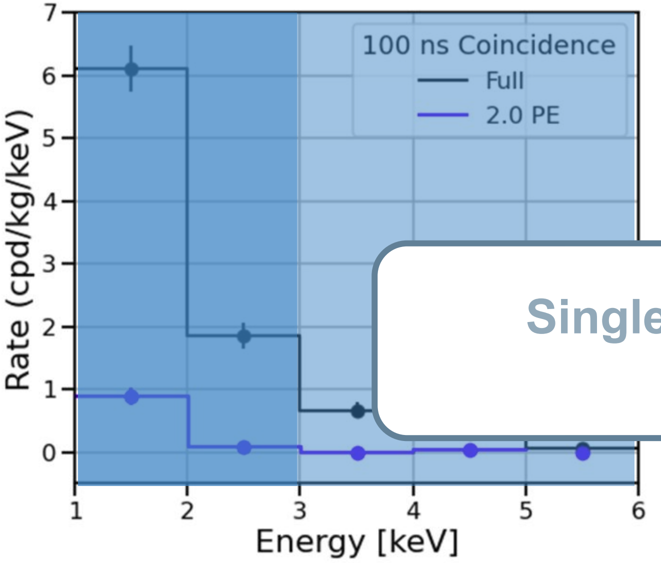
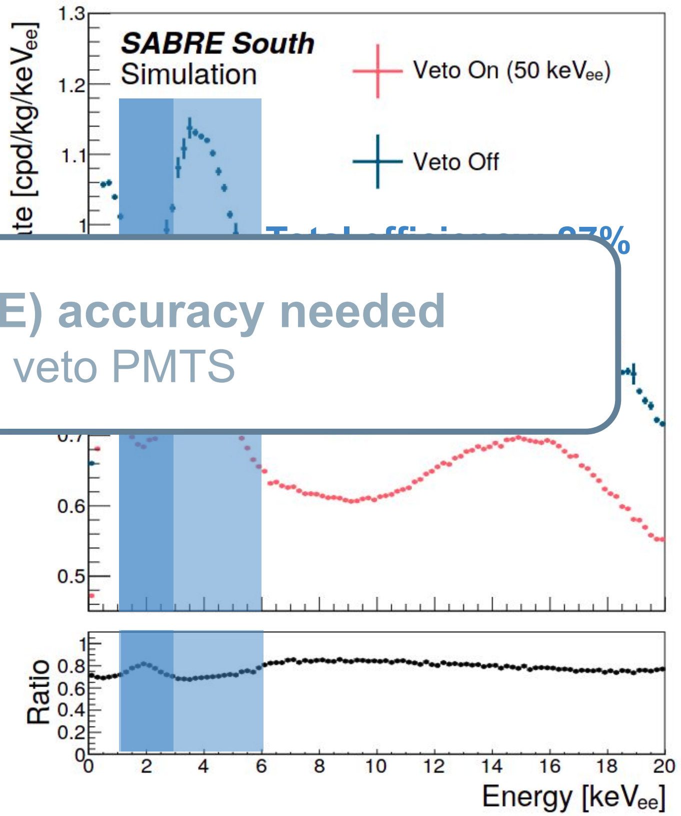


Fig 5: PMT background rates (upper limits) for SABRE with and without 2 photo-electron (PE) selection criteria.

W. Melbourne, et al, SciPost Phys. Proc. 12, 061 (2023)

Veto PMTs

Hamamatsu R5912



Single photo electron (SPE) accuracy needed
for both crystal & veto PMTS

Fig 6: Crystal background energy distribution, with and without active veto.

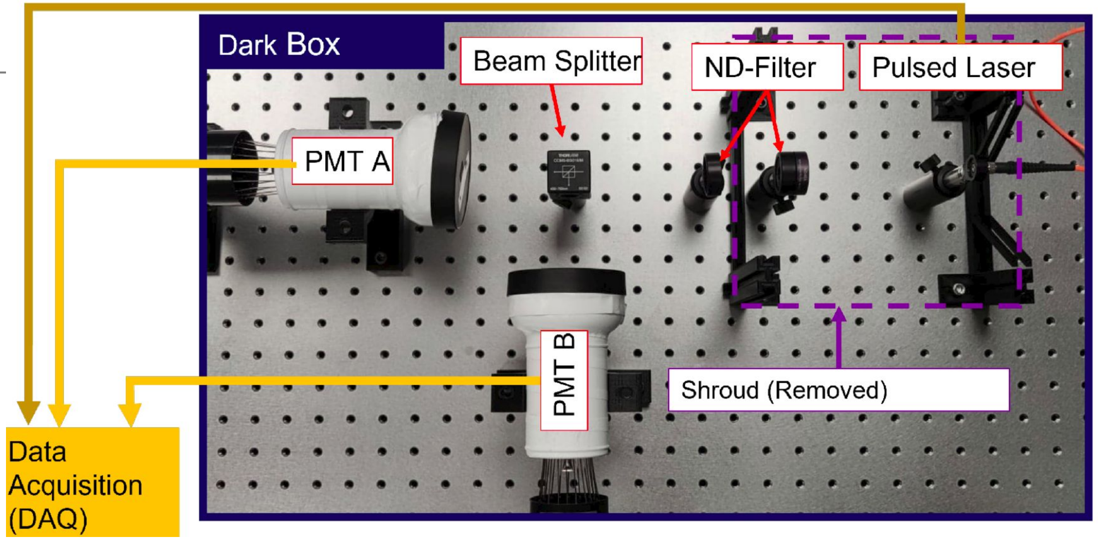
E. Barberio, et al, Eur. Phys. J. C 83, 878 (2023)

Pre-calibration

Current status - veto/crystal PMTs

- ➢ Single photo electron (SPE) charge
- ➢ Dark rate
- ➢ PMT gain
- ➢ Robustness under changing conditions
  - ○ Temperature
  - ○ After-pulsing
  - ○ Non linearity

Pre-calibration results to be published/on arXiv later this year



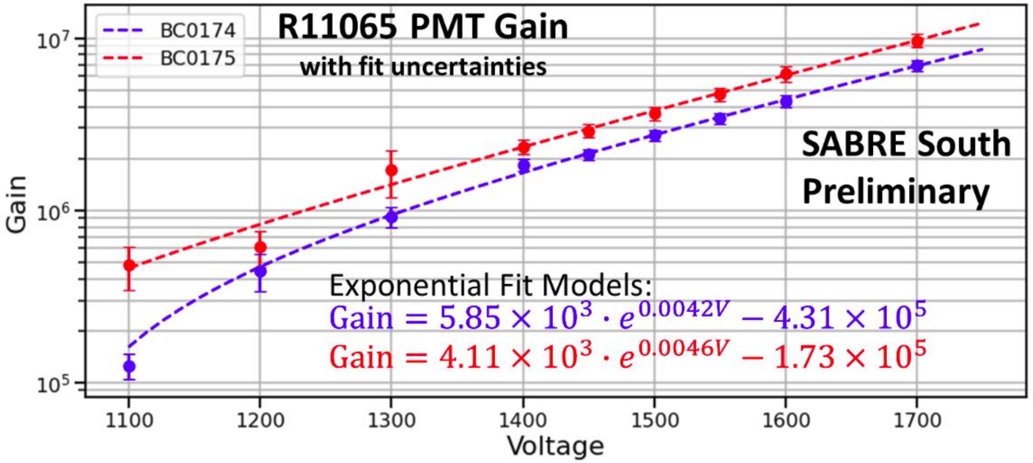


Fig 7: Top: optical layout. Bottom: SABRE's crystal PMTs gain.

W. Melbourne, et al, SciPost Phys. Proc. 12, 061 (2023)

In-situ calibration

The laserball solution (445 nm)

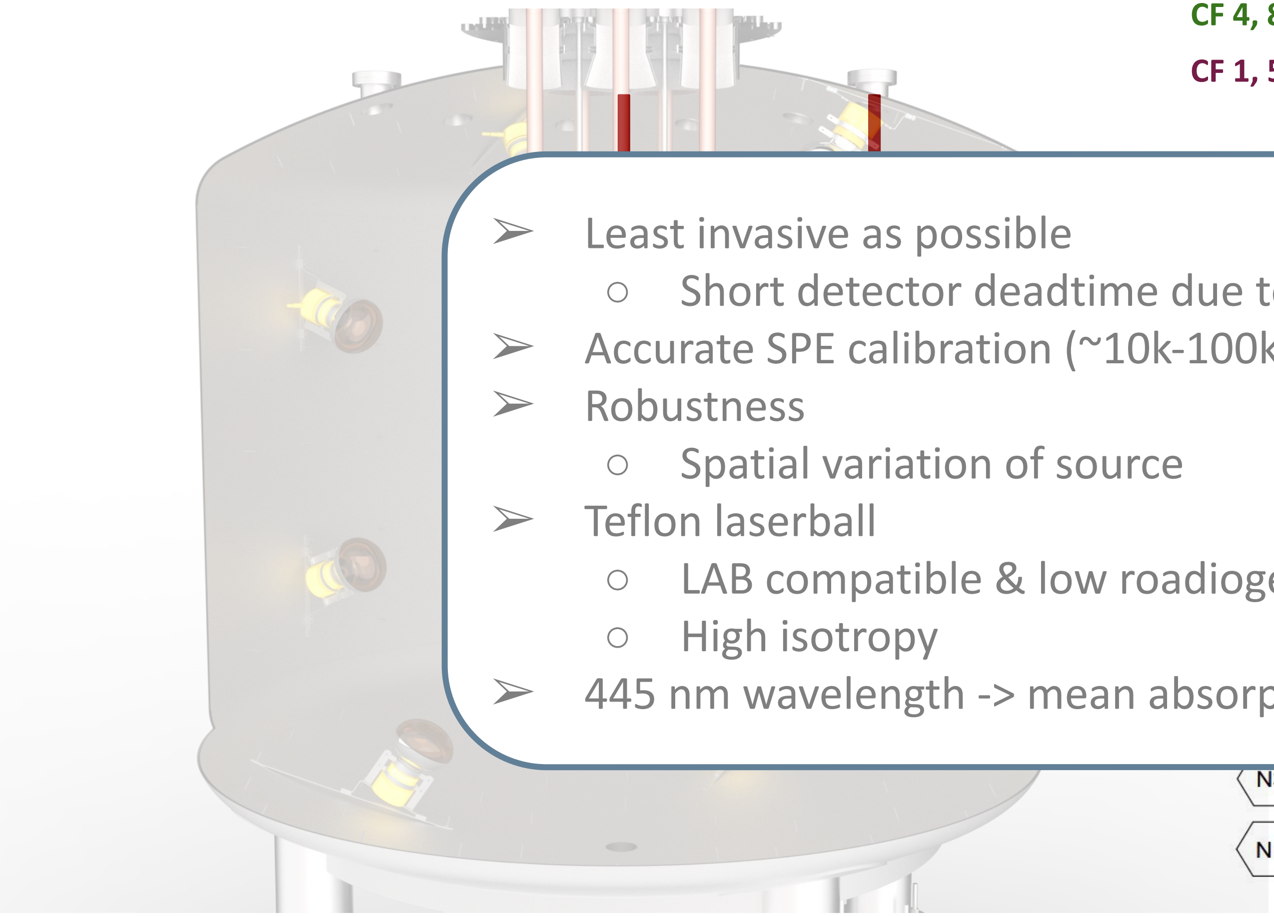
SABRE-South Preliminary results

Altered layout being considered w.r.t. SABRE-South technical design report: https://doi.org/10.26188/14618172.v3

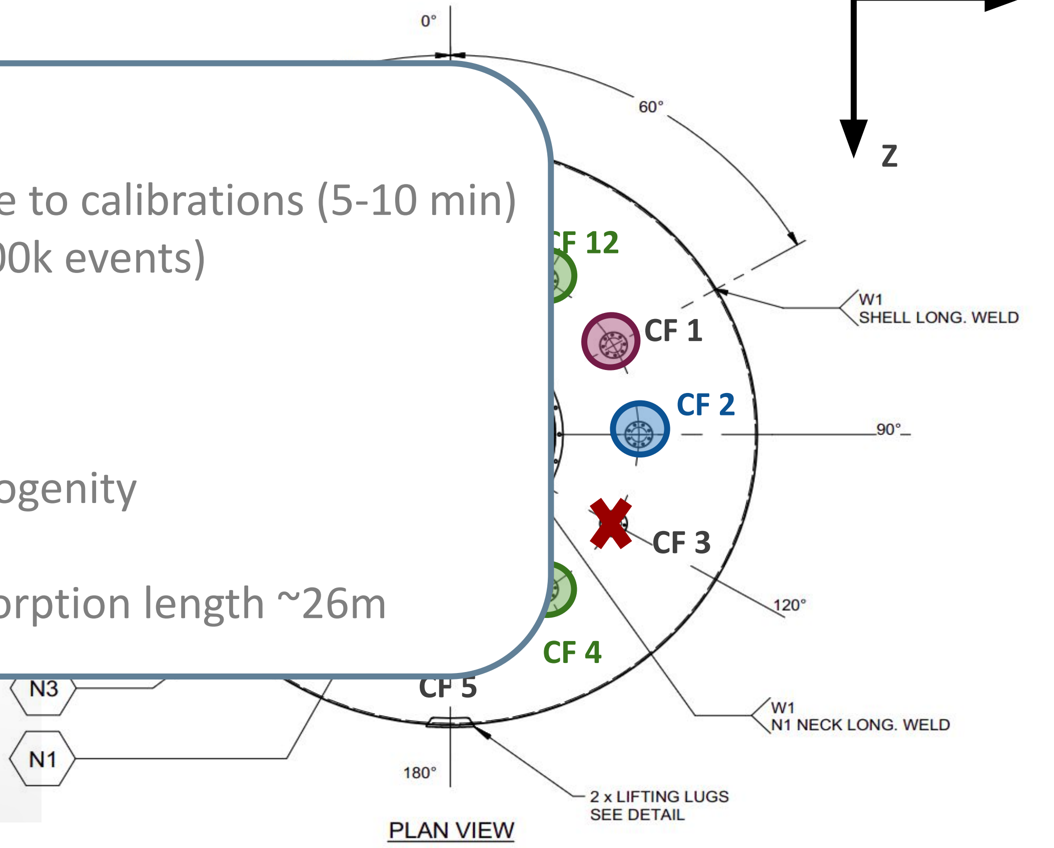
CF 2, 6, 10 : Radioactive calibration system

CF 4, 8, 12 : PMT feedthrough

CF 1, 5, 9 : partially blocked by PMT cable



- Least invasive as possible
  - Short detector deadtime due to calibrations (5-10 min)
- Accurate SPE calibration (~10k-100k events)
- Robustness
  - Spatial variation of source
- Teflon laserball
  - LAB compatible & low roadiogenity
  - High isotropy
- 445 nm wavelength -> mean absorption length ~26m



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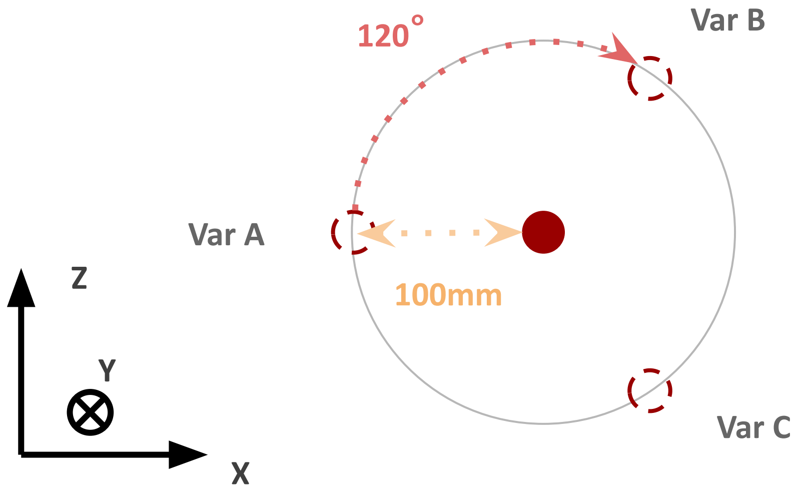
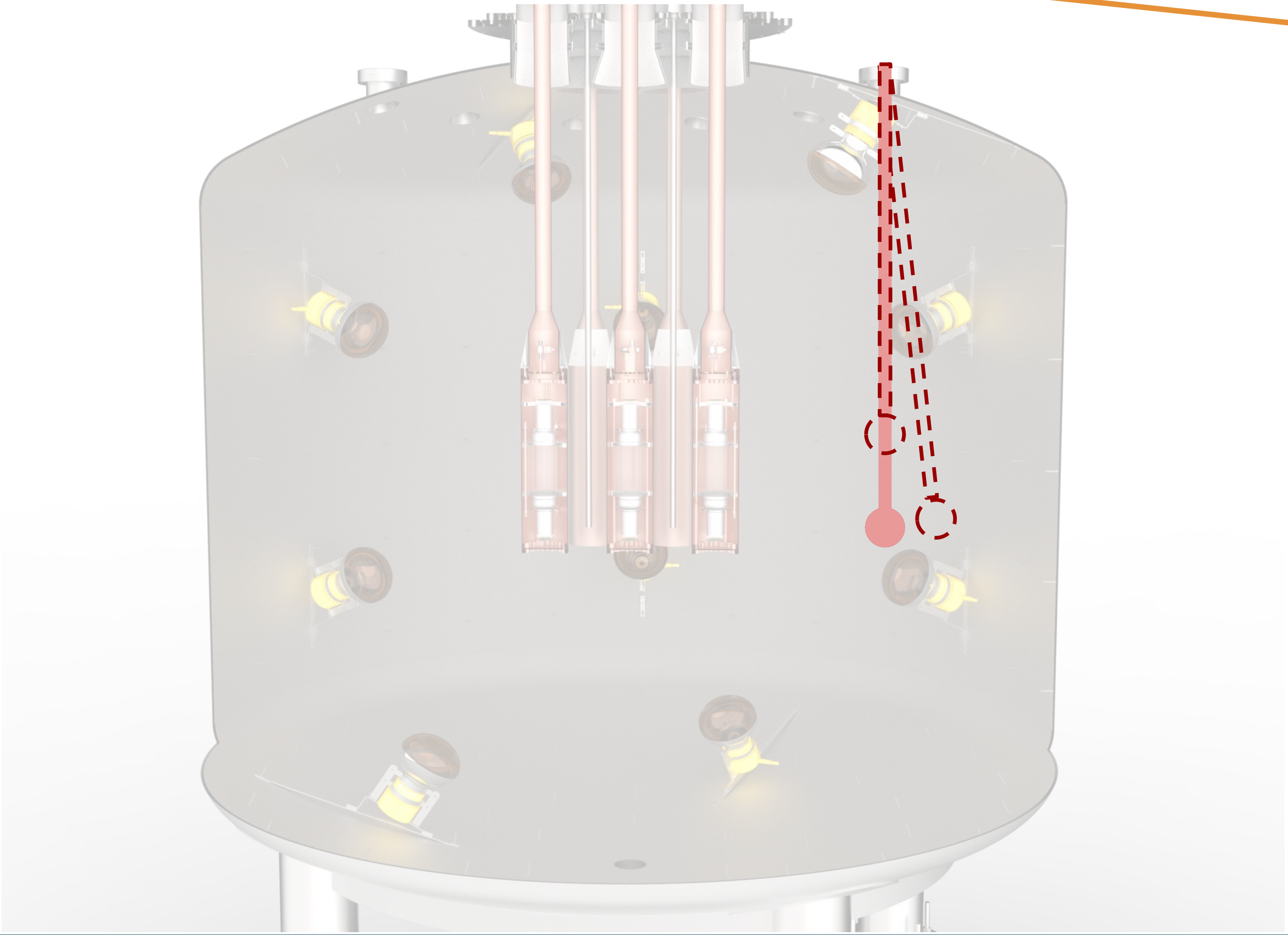
- Spatial variation of source
  - Variation 1:
    - Change suspension length
  - Variation 2:
    - Consider drift ~ pendulum





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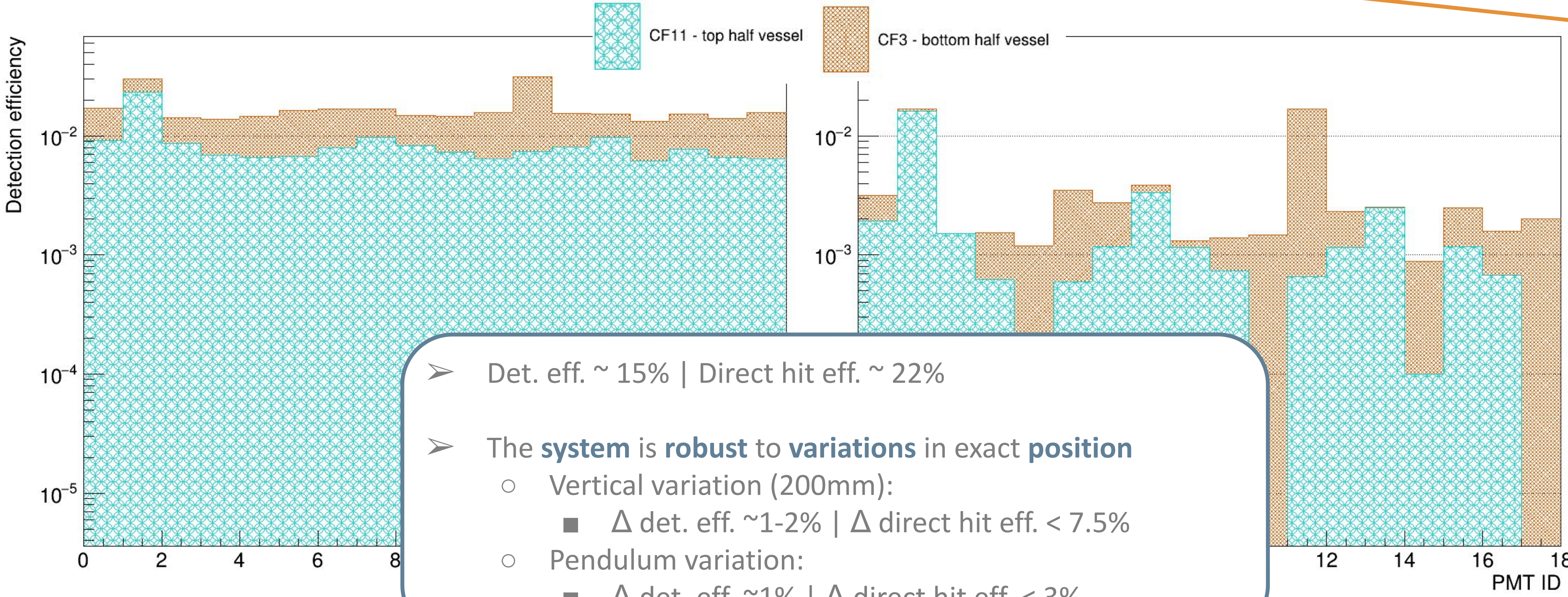


- Det. eff. ~ 15% | Direct hit eff. ~ 22%
- The **system** is **robust** to **variations** in exact **position**
  - Vertical variation (200mm):
    - Δ det. eff. ~1-2% | Δ direct hit eff. < 7.5%
  - Pendulum variation:
    - Δ det. eff. ~1% | Δ direct hit eff. < 3%

Fig 8: Detection effi... ...ections (right).

Conclusion

See SABRE-South general talk by Irene Bolognino. Thu 22nd @ 11h20 - Session F

SABRE is uniquely positioned to **contribute** to **solving** the **DAMA/LIBRA DM-conundrum**.

- ➢ Ultra
- ➢ Dual
- ➢ Passi

Accurate **PMT**

- ➢ **Pre-**

In-situ calibrat

- ➢ **Seve**
- ➢ All sy
  - ○ lo
  - ○ high statistic (10k-100k events)
  - ○ robust

successful calibration process @ the single photo electron level

Interested in more details?

Check out our SABRE-South technical design report:

https://doi.org/10.26188/14618172.v3

South

- Australian Government – Australian Research Council
- KEK-JAPAN
- SWINBURNE
- The University of Sydney
- ARC Centre of Excellence for Dark Matter
- The University of Melbourne
- The University of Adelaide
- Australian National University

North

- INFN LNGS – Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Gran Sasso
- INFN – Istituto Nazionale di Fisica Nucleare
- Università degli Studi di Milano
- Sapienza Università di Roma
- Princeton University
- Università del Salento

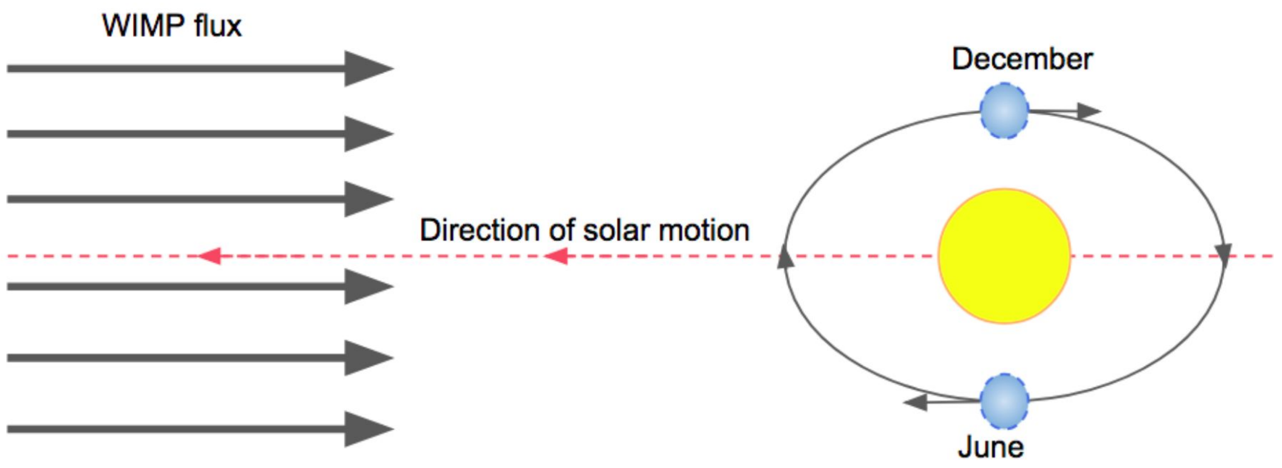
SABRE - Partner institutions

Annotated slides

Modulating dark matter signal

The DAMA/LIBRA conundrum

See SABRE-South general talk by Irene Bolognino.
Thu 22nd @ 11h20 - Session F



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

2-10%

- Standard model halo hypothesis: spherical halo of cold, dark matter permeating the galaxy
  - -> leads to annual modulation in DM signal (~2-10% of total amplitude)
  - Peaks June 2nd

Modulating dark matter signal

The DAMA/LIBRA conundrum

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- ➢ The DAMA/LIBRA experiment has observed signal consistent with DM modulation signal for the past 2 decades.
- ➢ Observed ~0.01 counts per day/kg/keV in range 1-6 keV, totalling to 12.9σ
- ➢ Largest contribution of signal arrives from 1-3keV.

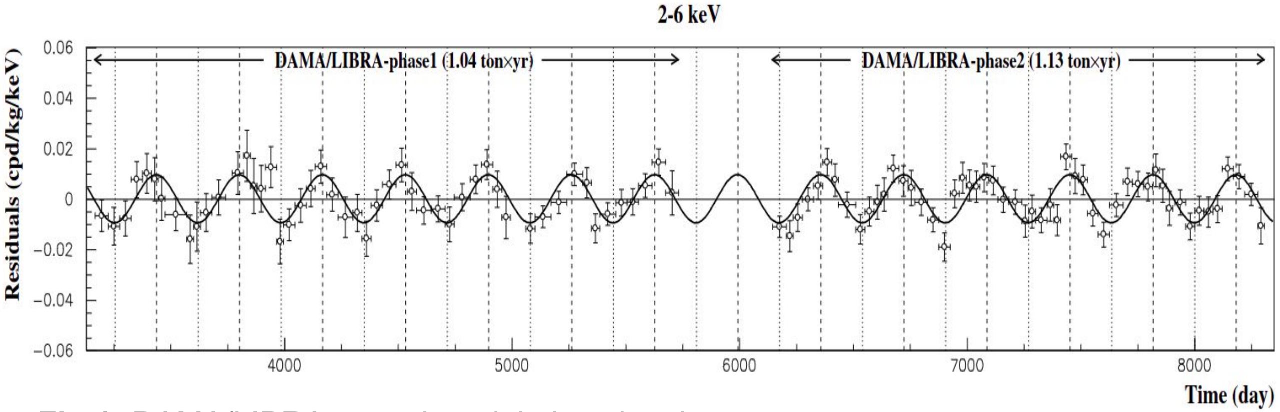

Fig 1: DAMA/LIBRA annual modulation signal

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

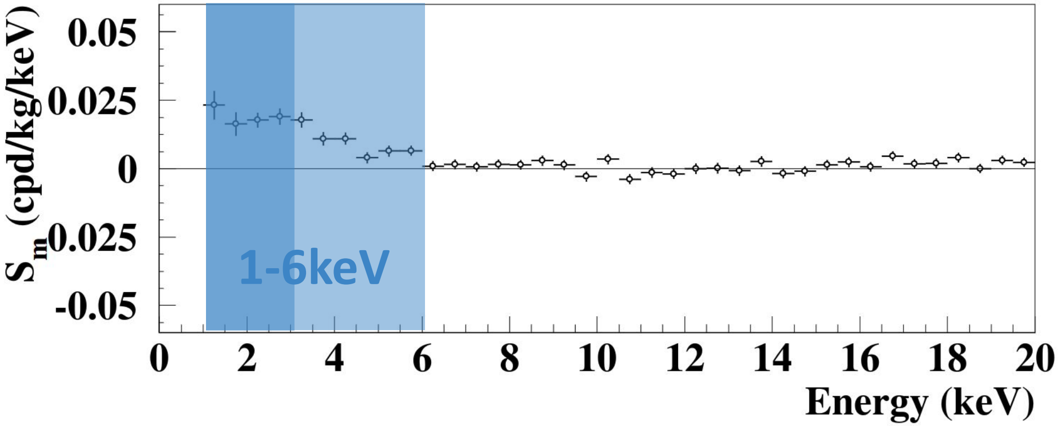

Fig 2: DAMA/LIBRA annual modulation signal - energy spectrum

Modulating dark matter signal

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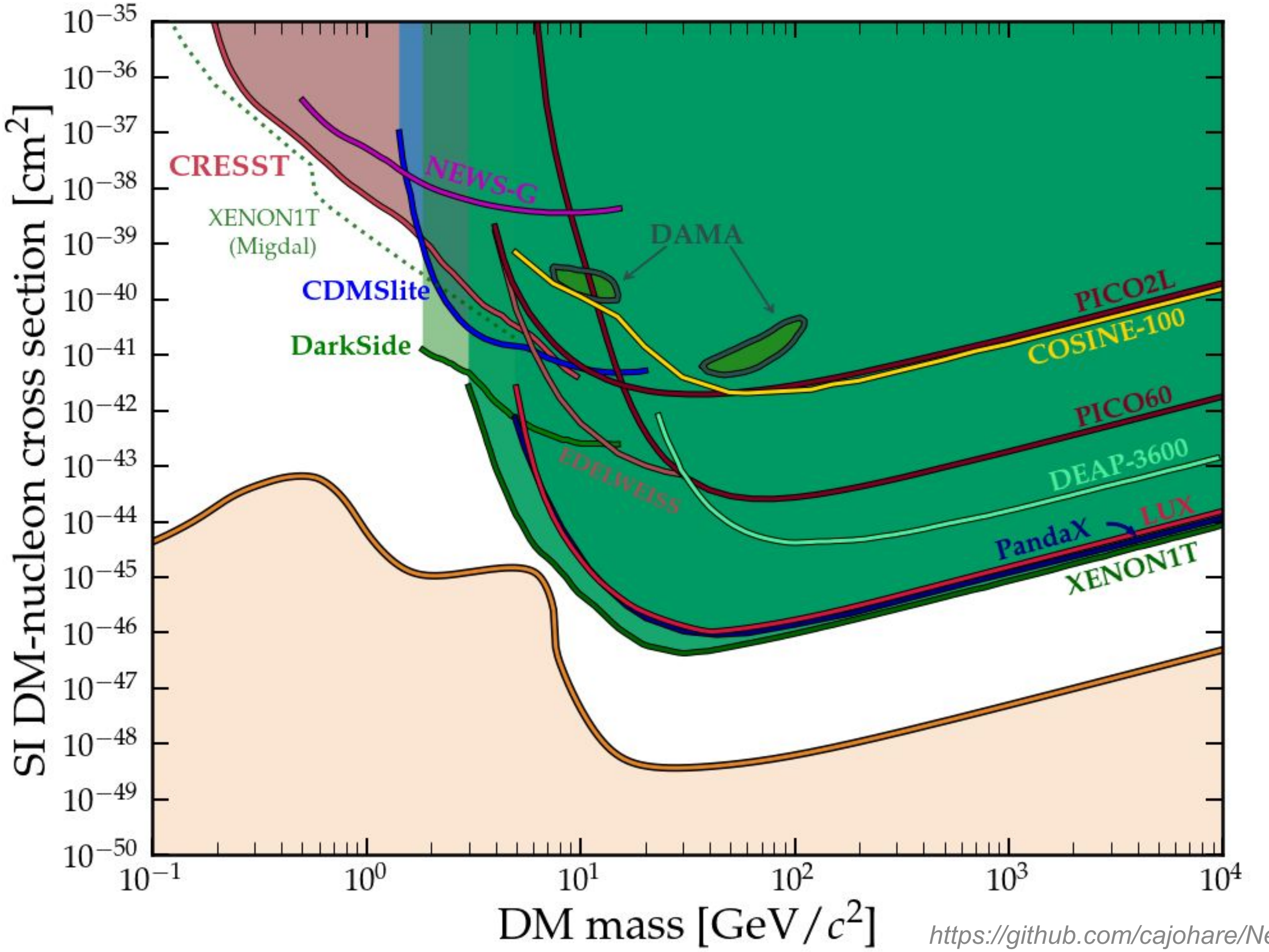

https://github.com/cajohare/NeutrinoFog

- Signal in direct tension with null results of wide variety of different experiments.
- We need experiments using the same material (NaI) to confirm/refute the DAMA/LIBRA results

Fig 3: Constraints on spin independent DM cross section.

Modulating dark matter signal

NaI experiments & SABRE unique position

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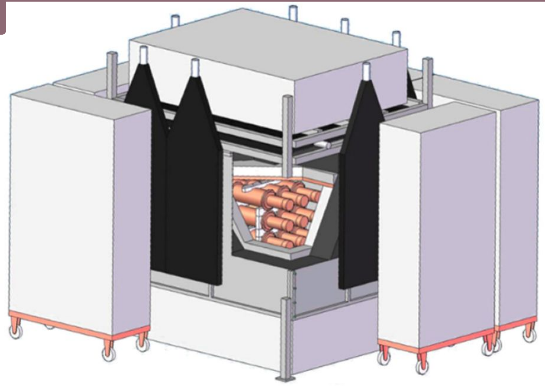
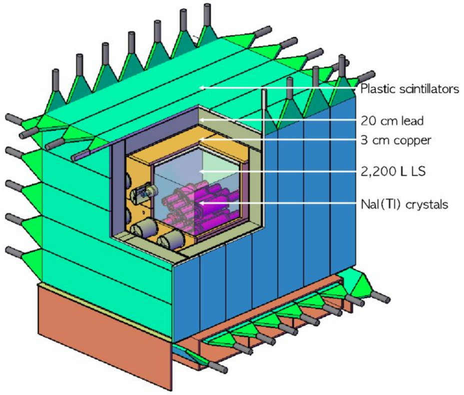
ANAIS



J. Amare, et al, Phys. Sci. Forum 2021

COSINE



H. Prihtiadi et al
JCAP02(2021)013

- ANAIS & COSINE take data since a number of years
- Until today results are consistent with both null hypothesis as well as DAMA/LIBRA at ~<3σ

Modulating dark matter signal

NaI experiments & SABRE unique position

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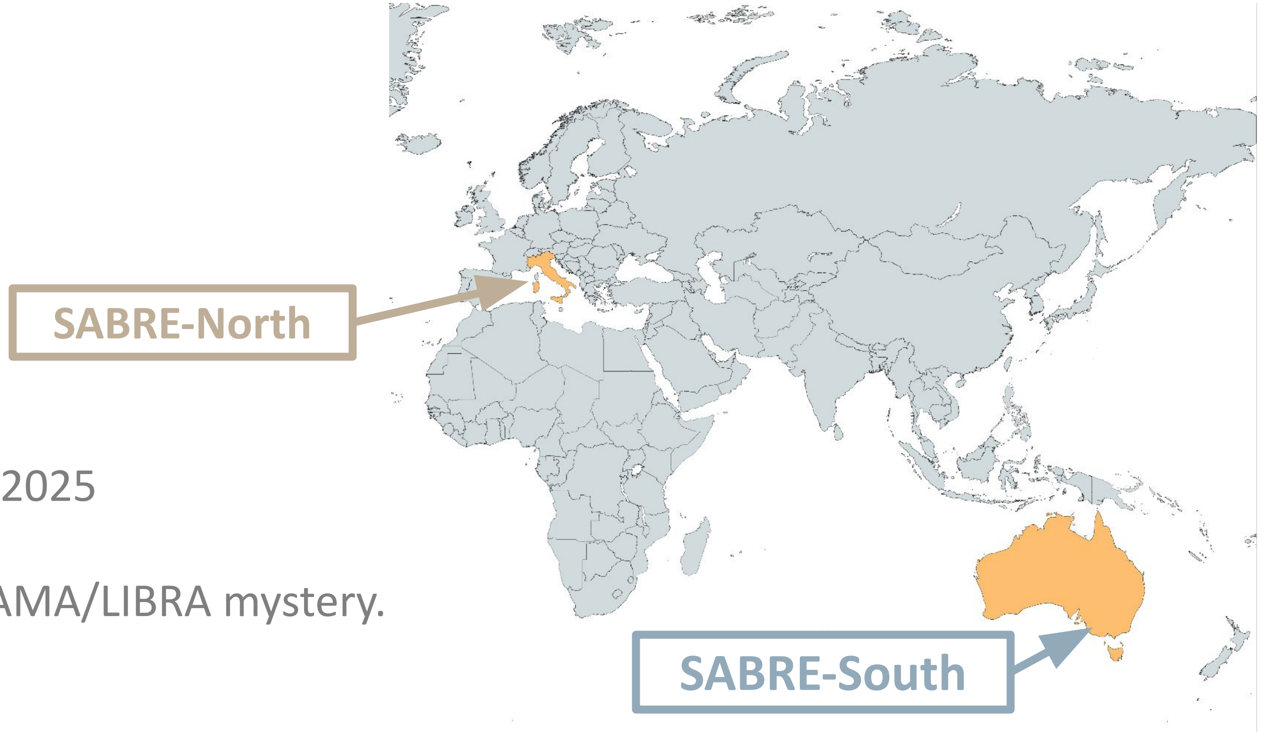
SABRE

- ➢ Ultra pure crystals
- ➢ High levels of passive and/or active shielding
- ➢ Dual experiment set-up -> control for seasonal effects

SABRE-South detector deployment planned for 2025

Aim to significantly contribute to unravel the DAMA/LIBRA mystery.



Modulating dark matter signal

SABRE-South experimental layout

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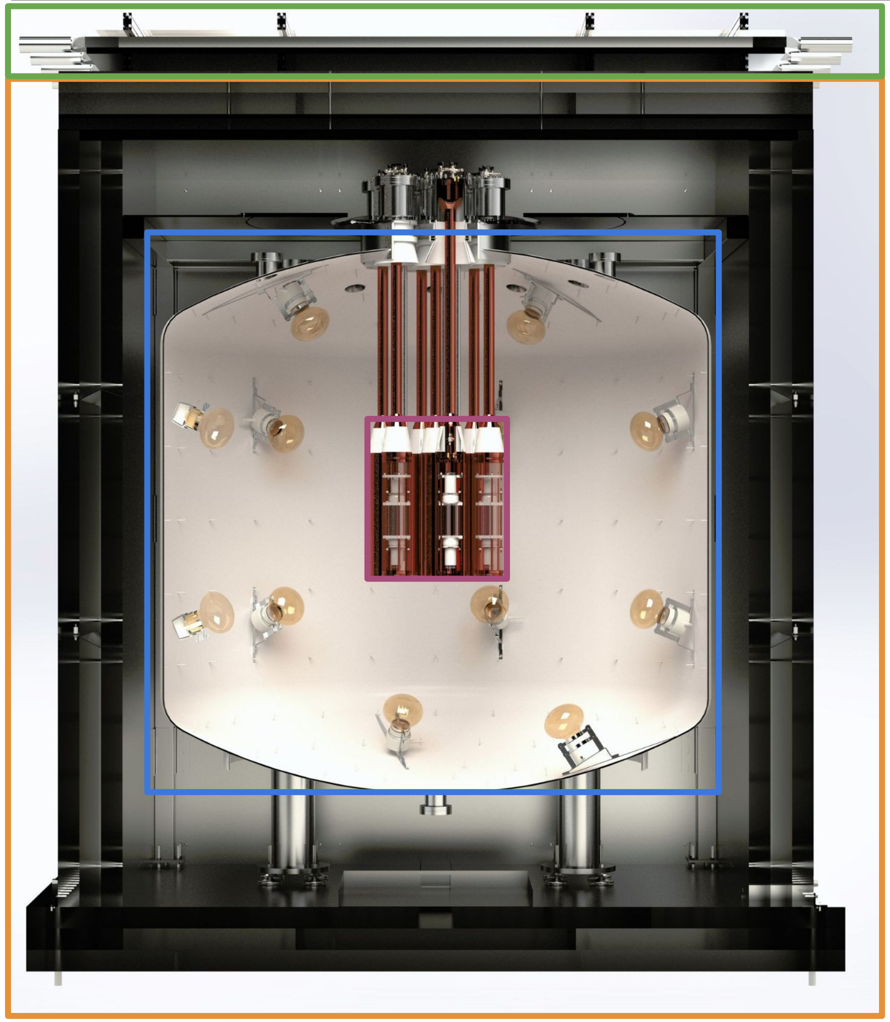

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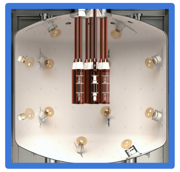

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SABRE-South active veto

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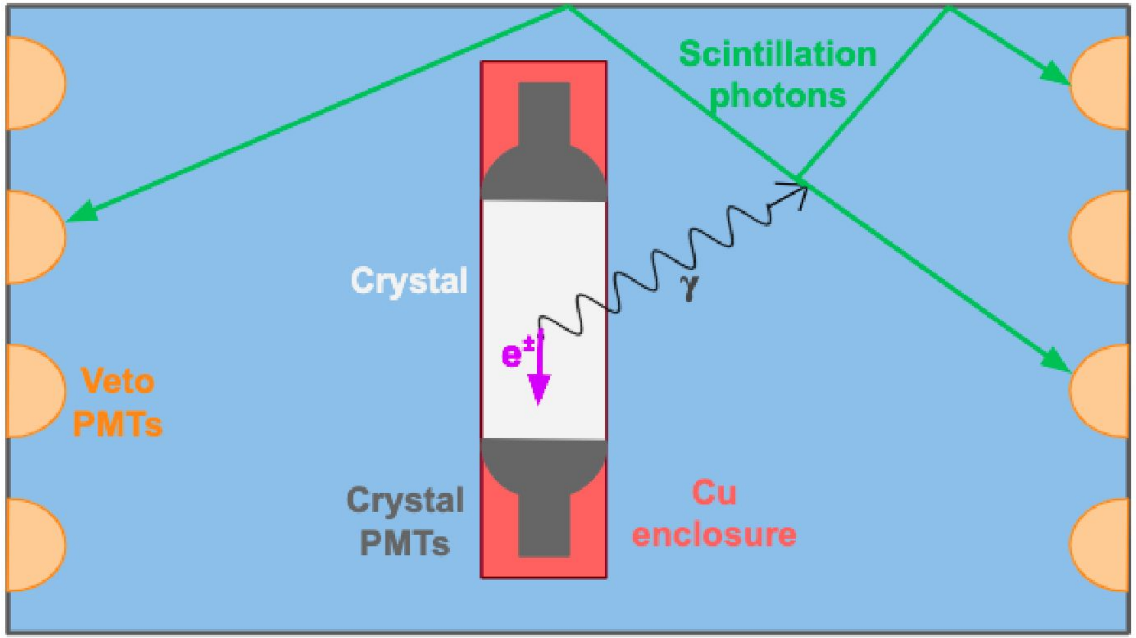


Fig 4: Illustration of active veto.

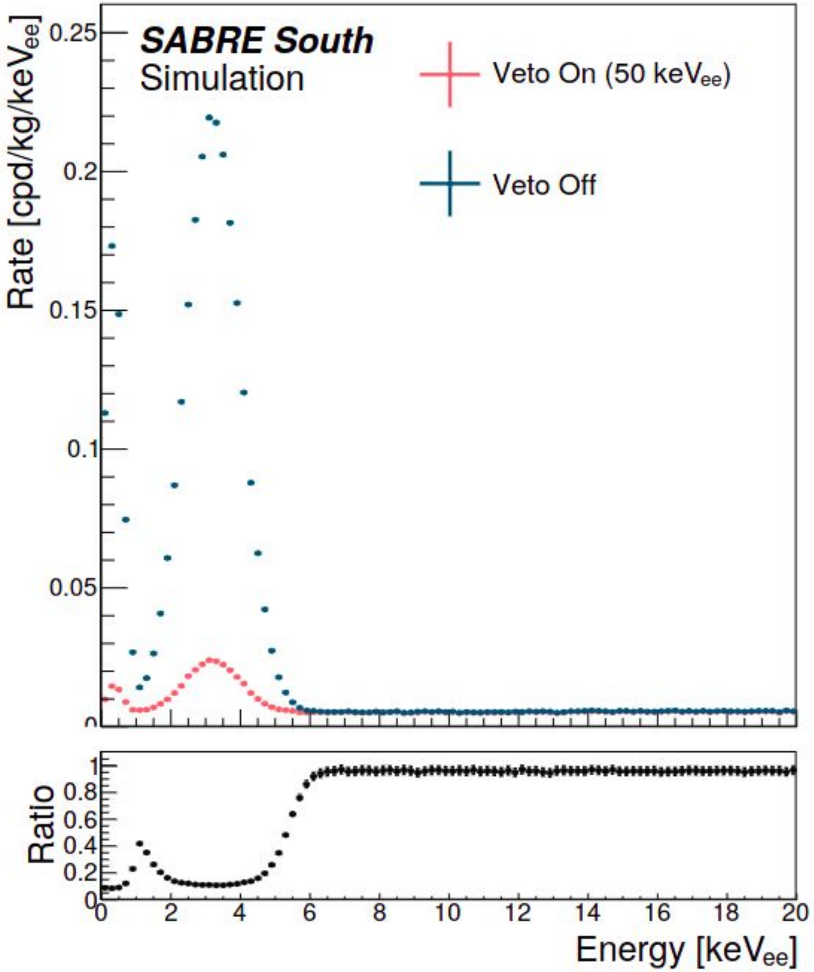


Fig 5: Background from ^{40}K with and without veto.

E. Barberio, et al, Eur. Phys. J. C 83, 878 (2023)

SABRE-South active veto

Breakdown of crystal backgrounds from radiogenic and cosmogenic contributions with and without veto system.

Radiogenic		
Isotope	Rate, veto ON [cpd/kg/keV$_{ee}$]	Rate, veto OFF [cpd/kg/keV$_{ee}$]
^{210}Pb	$2.8 \cdot 10^{-1}$	$2.8 \cdot 10^{-1}$
^{87}Rb	$< 2.2 \cdot 10^{-1}$	$< 2.2 \cdot 10^{-1}$
^{40}K	$1.3 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
^{238}U	$< 5.4 \cdot 10^{-3}$	$< 5.7 \cdot 10^{-3}$
^{85}Kr	$< 1.9 \cdot 10^{-3}$	$< 1.9 \cdot 10^{-3}$
^{232}Th	$< 3.4 \cdot 10^{-4}$	$< 3.9 \cdot 10^{-4}$
^{129}I	$9.2 \cdot 10^{-5}$	$9.2 \cdot 10^{-5}$
Total	$< 5.2 \cdot 10^{-1}$	$< 6.0 \cdot 10^{-1}$

Cosmogenic		
Isotope	Rate, veto ON [cpd/kg/keV$_{ee}$]	Rate, veto OFF [cpd/kg/keV$_{ee}$]
^{3}H	$7.8 \cdot 10^{-2}$	$7.8 \cdot 10^{-2}$
^{113}Sn	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$
^{127}Te	$2.9 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$
^{109}Cd	$1.4 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
^{121}Te	$9.1 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$
^{22}Na	$5.2 \cdot 10^{-4}$	$1.4 \cdot 10^{-2}$
^{125}I	$2.3 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$
^{113m}In	$7.5 \cdot 10^{-5}$	$5.2 \cdot 10^{-4}$
^{127m}Te	$4.9 \cdot 10^{-5}$	$4.9 \cdot 10^{-5}$
^{126}I	$4.1 \cdot 10^{-5}$	$6.2 \cdot 10^{-5}$
^{121m}Te	$1.8 \cdot 10^{-5}$	$6.0 \cdot 10^{-5}$
^{123m}Te	$7.3 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$
^{109m}Ag	$2.8 \cdot 10^{-6}$	$2.8 \cdot 10^{-6}$
^{125m}Te	$1.6 \cdot 10^{-6}$	$1.7 \cdot 10^{-6}$
Total	$1.6 \cdot 10^{-1}$	$2.7 \cdot 10^{-1}$

The importance of PMT calibration

SABRE-South

Crystal PMTs

Hamamatsu R11065

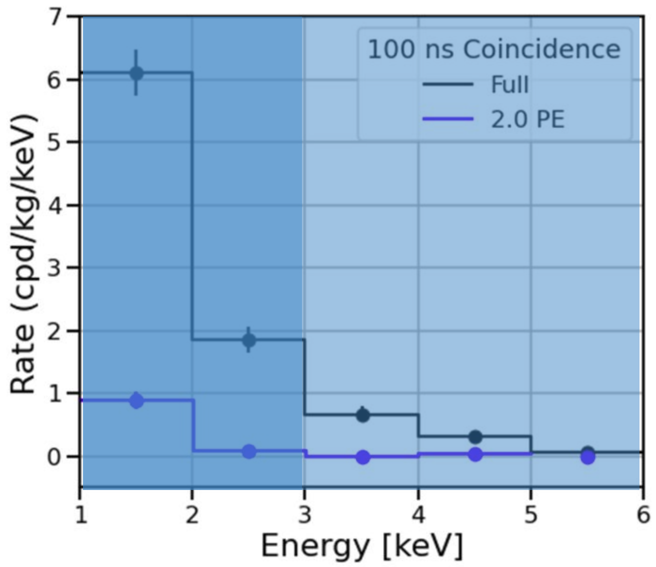


Fig 4: PMT background rates (upper limits) for SABRE with and without 2 photo-electron (PE) selection criteria.

W. Melbourne, et al, SciPost Phys. Proc. 12, 061 (2023)

- ➢ PMT noise forms a significant contribution to the overall noise budget in the key 1-3keV signal region
- ➢ Accurate calibration, both before and during the experiment, are crucial to prevent a potential DM signal to be buried below PMT noise/uncertainties.

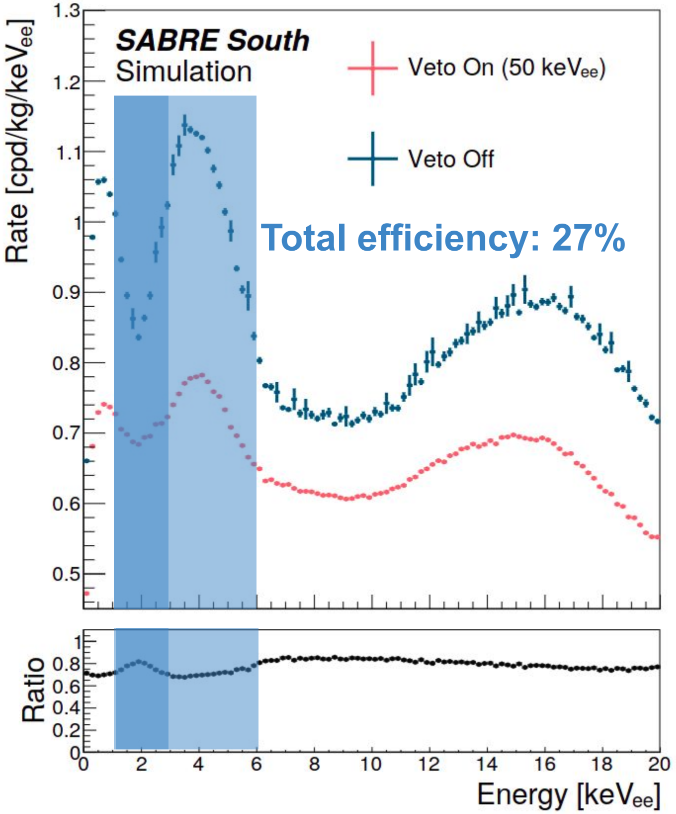
The importance of PMT calibration

SABRE-South

- The active veto system can deliver a 27% background reduction in the signal region (1-6keV).
- Achieving such veto perromances requires ~ single photon electron resolutions and response from PMTS, as well as detailed calibration.

Single photo electron (SPE) accuracy needed
for both crystal & veto PMTS

Veto PMTs
Hamamatsu R5912



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Single photo electron (SPE) accuracy needed
for both crystal & veto PMTS

	Rate [cpd/kg/keV$_{ee}$]	Veto Efficiency [%]
Crystal radiogenic	$5.2 \cdot 10^{-1}$	13
Crystal cosmogenic	$1.6 \cdot 10^{-1}$	40
Crystal PMTs	$3.8 \cdot 10^{-2}$	60
PTFE wrap	$4.5 \cdot 10^{-3}$	13
Enclosures	$3.2 \cdot 10^{-3}$	85
Conduits	$1.9 \cdot 10^{-5}$	96
Liquid scintillator	$4.9 \cdot 10^{-8}$	> 99
Steel vessel	$1.4 \cdot 10^{-5}$	> 99
Veto PMTs	$1.9 \cdot 10^{-5}$	> 99
Shielding	$3.9 \cdot 10^{-6}$	> 99
External	$O(10^{-4})$	> 99
Total	$7.2 \cdot 10^{-1}$	27

Table 12 Background rate in the dark matter measurement region for the SABRE South components after a 6 month cool-down period, and the corresponding veto efficiency.

E. Barberio, et al,
Eur. Phys. J. C 83, 878 (2023)

Pre-calibration

Current status - veto/crystal PMTs

- ➢ Single photo electron (SPE) charge
- ➢ Dark rate
- ➢ PMT gain
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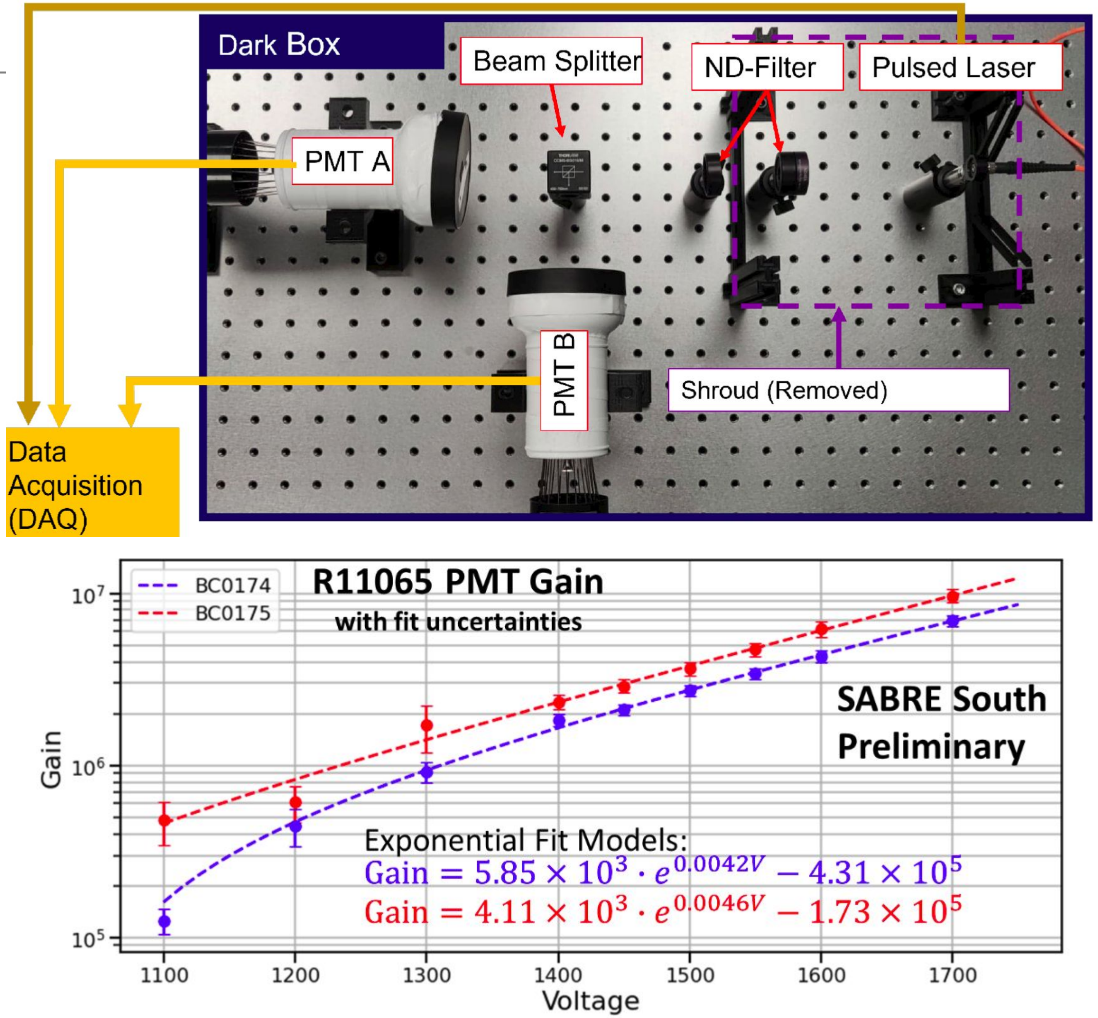
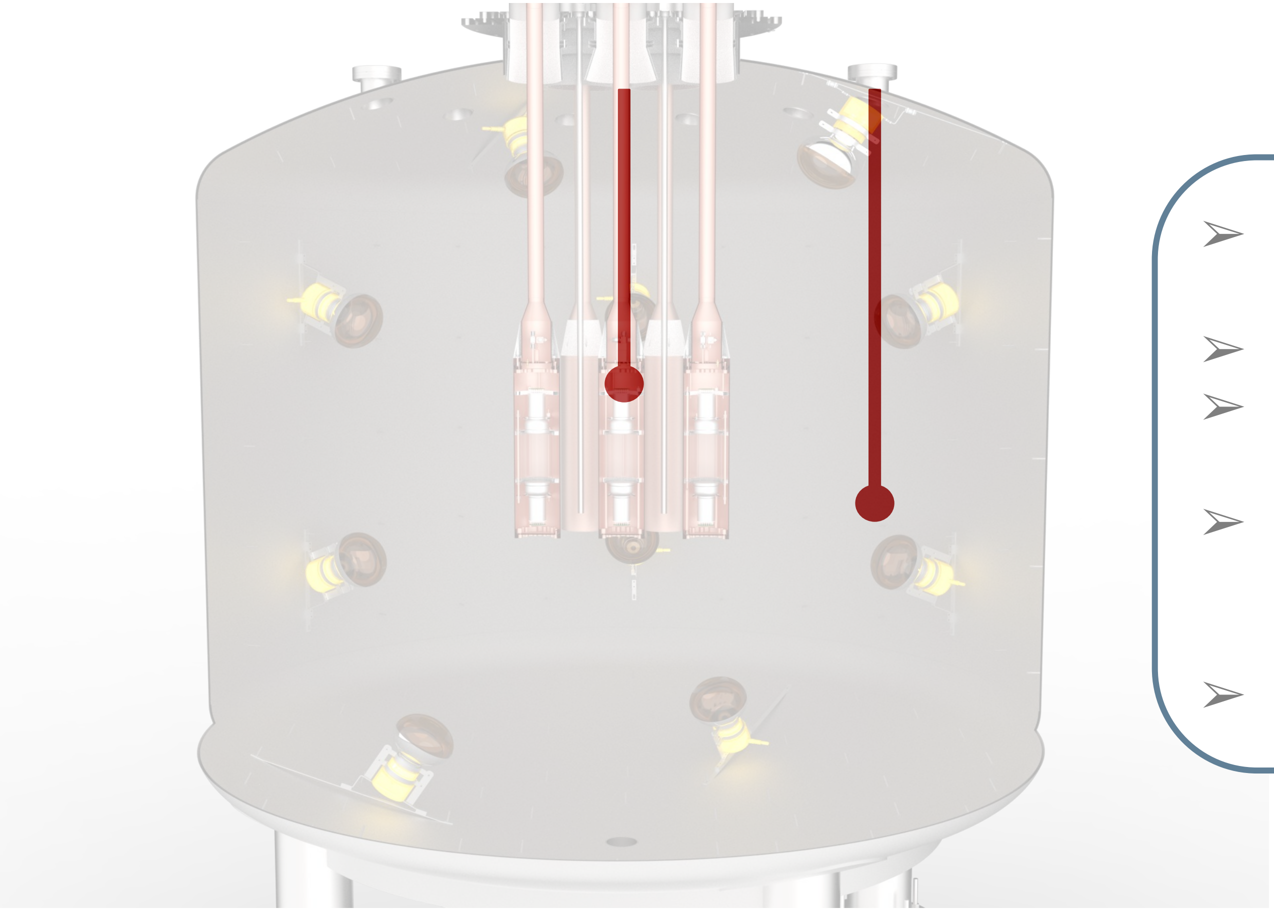


Fig 6: Top: optical layout. Bottom: SABRE's crystal PMTs gain.

W. Melbourne, et al, SciPost Phys. Proc. 12, 061 (2023)

In-situ calibration during experiment operation

The laserball solution (445 nm)



- Least invasive as possible
  - Short detector deadtime due to calibrations (5-10 min)
- Accurate SPE calibration (~10k-100k events)
- Robustness
  - Spatial variation of source
- Teflon laserball
  - LAB compatible & low roadiogenity
  - High isotropy
- 445 nm wavelength -> mean absorption length ~26m

In-situ calibration during experiment operation

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CF 2, 6, 10 : Radioactive calibration system

CF 4, 8, 12 : PMT feedthrough

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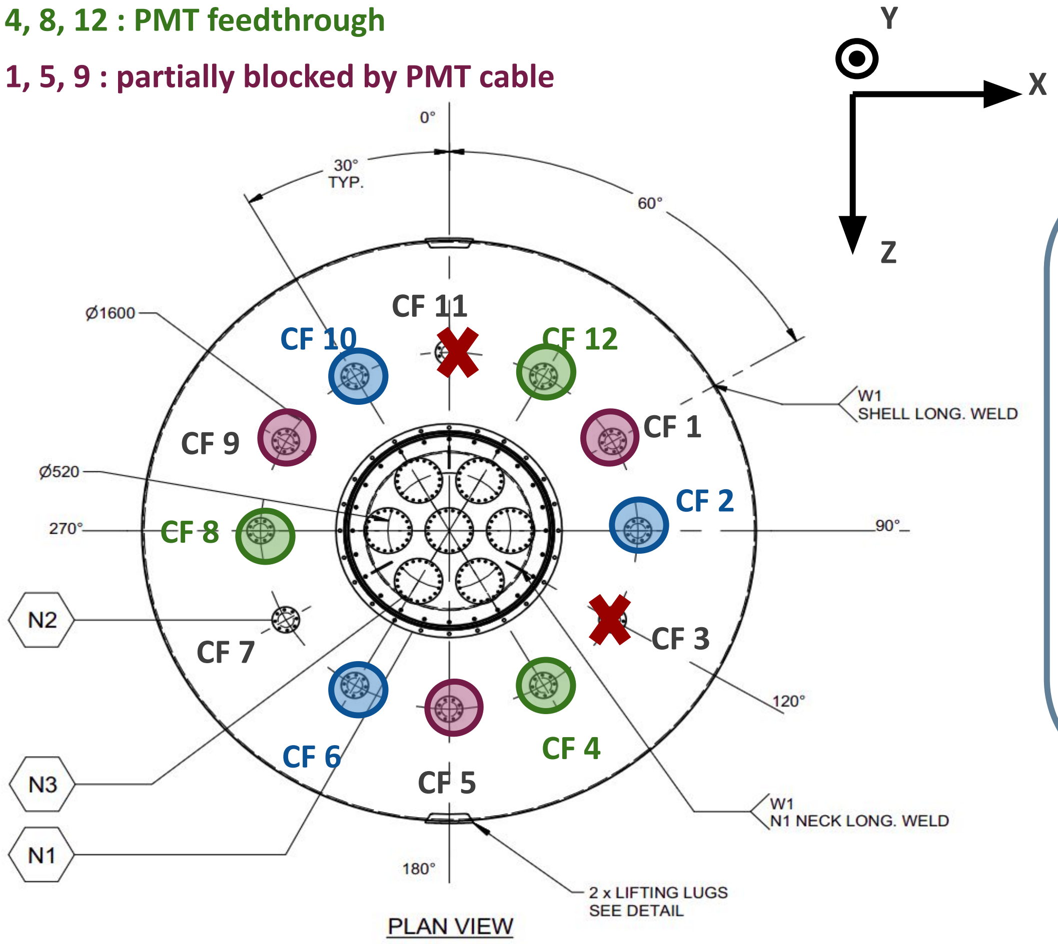

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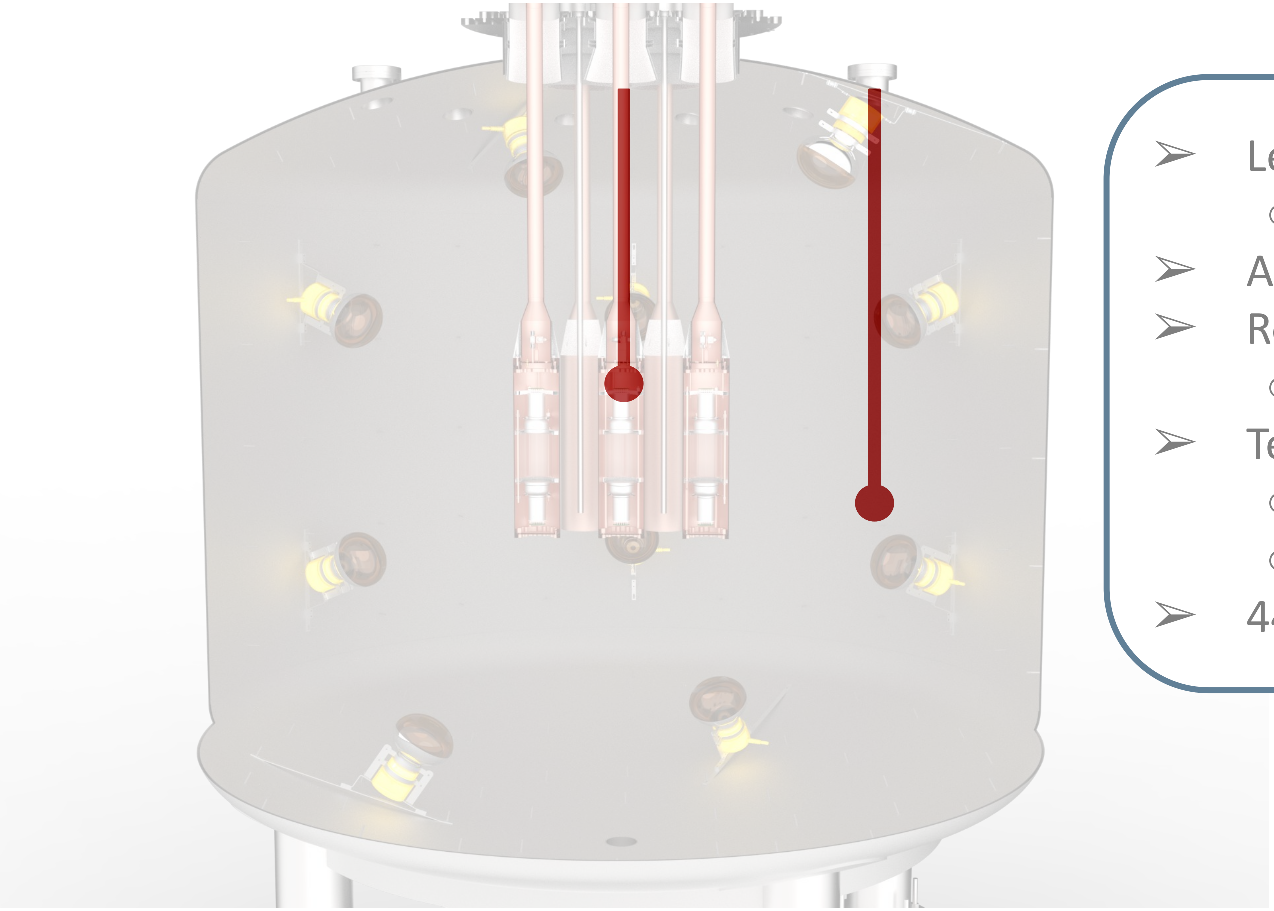
In-situ calibration during experiment operation

The laserball solution (445 nm)

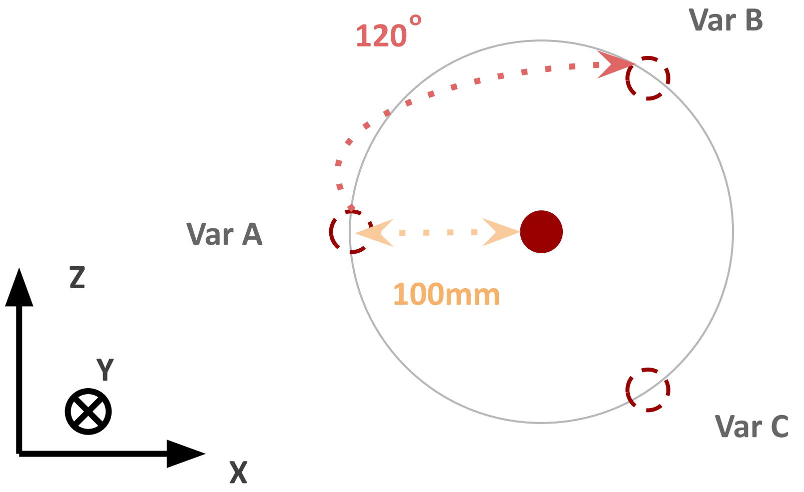


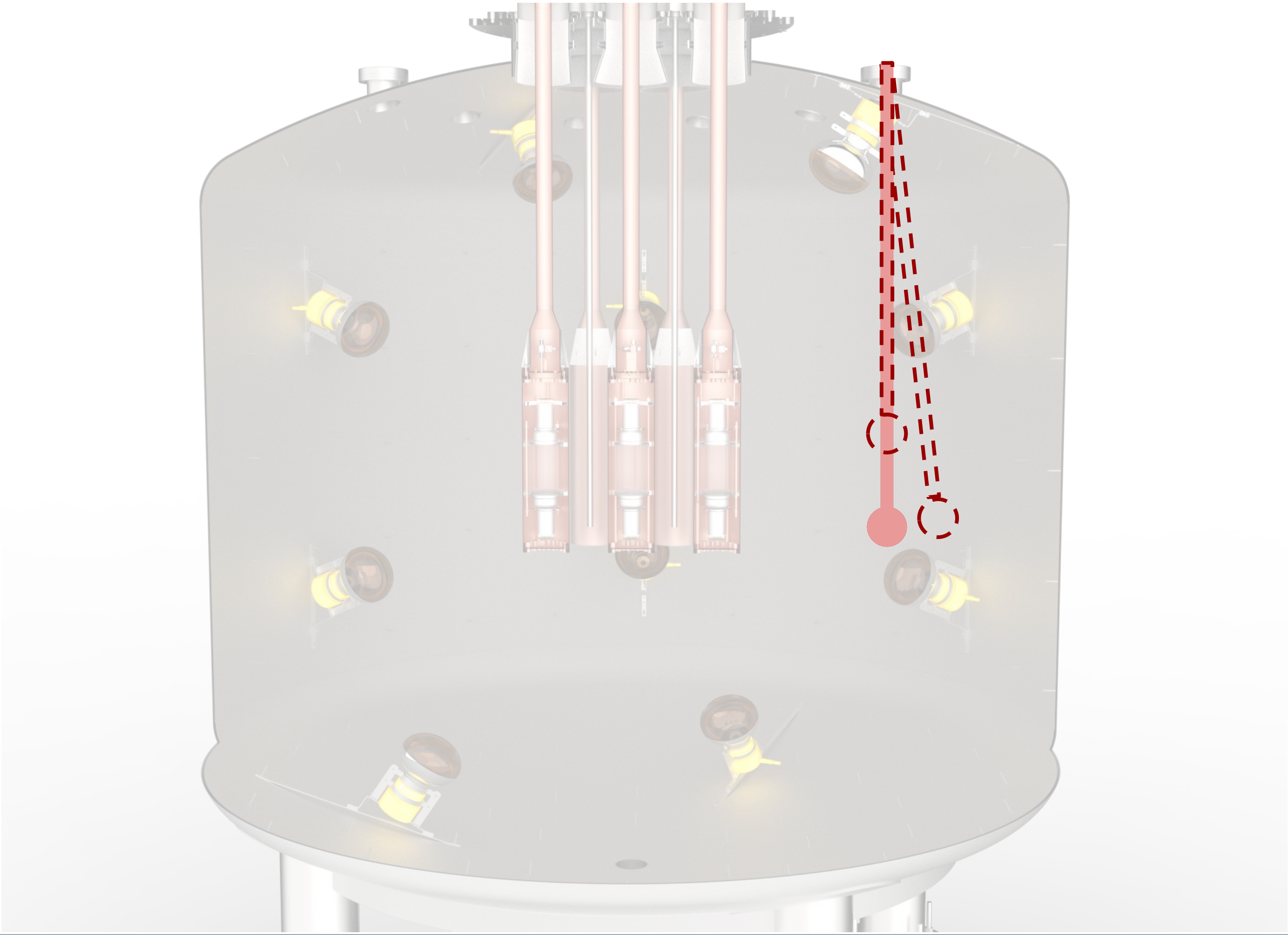
- ➢ Least invasive as possible
  - ○ Short detector deadtime due to calibrations (5-10 min)
- ➢ Accurate SPE calibration (~10k-100k events)
- ➢ Robustness
  - ○ Spatial variation of source
- ➢ Teflon laserball
  - ○ LAB compatible & low roadiogenity
  - ○ High isotropy
- ➢ 445 nm wavelength -> mean absorption length ~26m

In-situ calibration during experiment operation

The laserball solution (445 nm)

- Spatial variation of source
  - Variation 1:
    - Change suspension length
  - Variation 2:
    - Consider drift ~ pendulum





In-situ calibration during experiment operation

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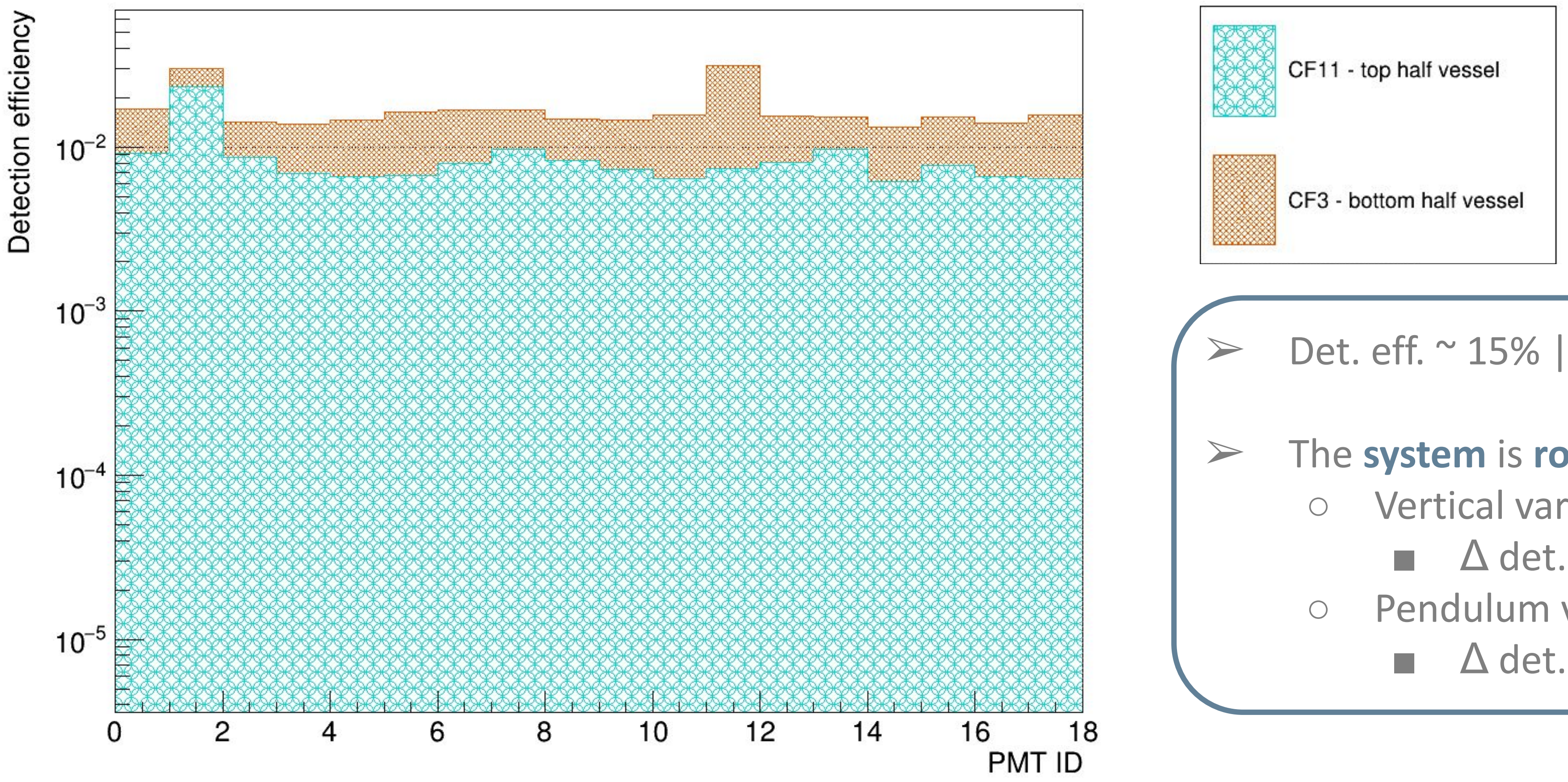

Fig 7: **Detection efficiency** for in-situ calibration system.

- Det. eff. ~ 15% | Direct hit eff. ~ 22%
- The **system** is **robust** to **variations** in exact **position**
  - Vertical variation (200mm):
    - Δ det. eff. ~1-2% | Δ direct hit eff. < 7.5%
  - Pendulum variation:
    - Δ det. eff. ~1% | Δ direct hit eff. < 3%

In-situ calibration during experiment operation

The laserball solution (445 nm)

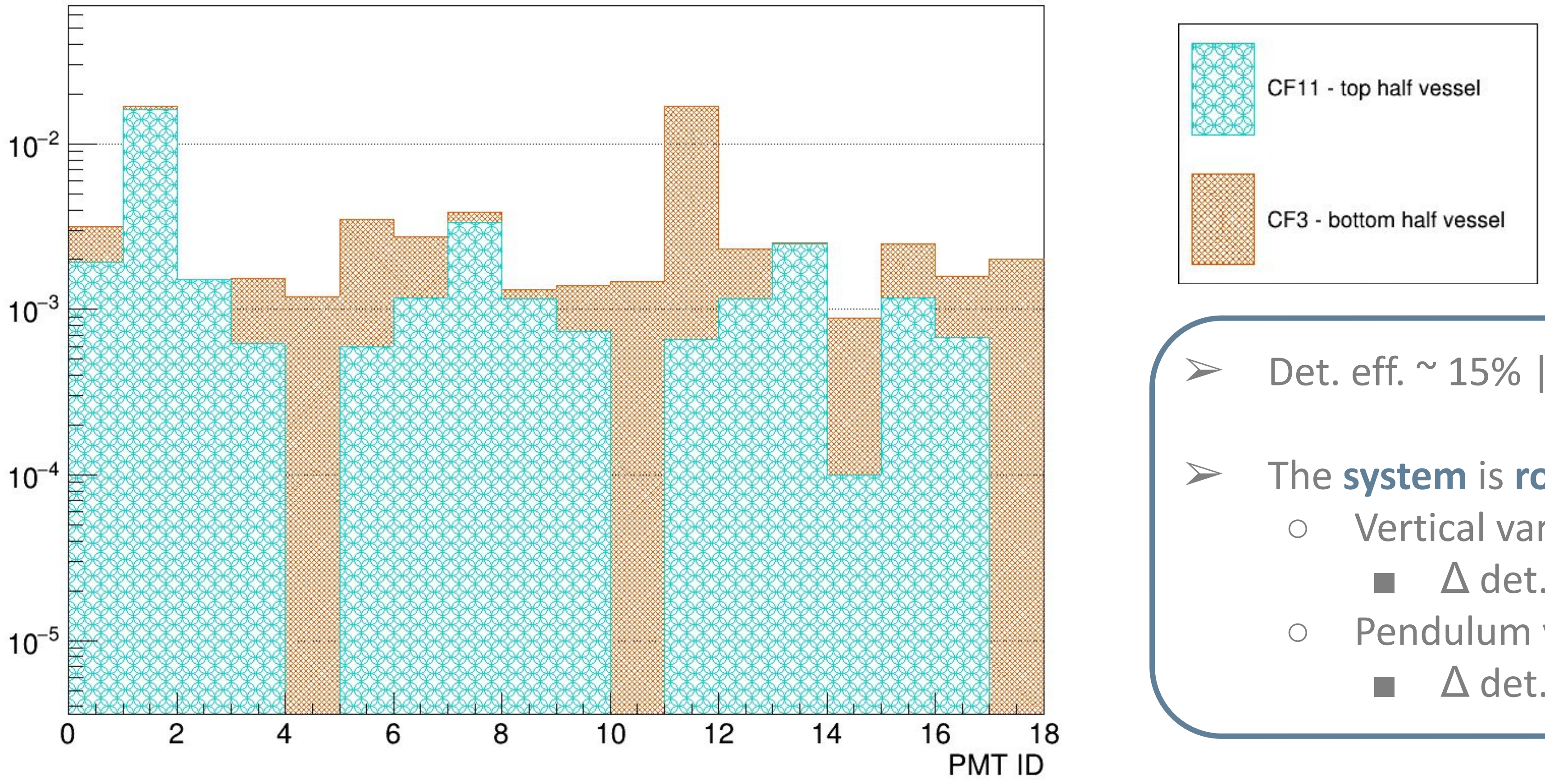

Fig 7b: **Direct hit efficiency** for in-situ calibration system.

- Det. eff. ~ 15% | Direct hit eff. ~ 22%
- The **system** is **robust** to **variations** in exact **position**
  - Vertical variation (200mm):
    - Δ det. eff. ~1-2% | Δ direct hit eff. < 7.5%
  - Pendulum variation:
    - Δ det. eff. ~1% | Δ direct hit eff. < 3%

Conclusion

See SABRE-South general talk by Irene Bolognino. Thu 22nd @ 11h20 - Session F

SABRE is uniquely positioned to **contribute** to **solving** the **DAMA/LIBRA DM-conundrum**.

- ➢ Ultra pure crystals
- ➢ Dual detector set-up (Northern & Southern hemisphere)
- ➢ Passive & active shielding

Accurate **PMT calibration** is **crucial**

- ➢ **Pre-calibration** results expected to be published/on arXiv **later this year**

In-situ calibration:

- ➢ **Several layouts** under **final consideration**
- ➢ All systems are able to **deliver** on a
  - ○ low invasive (5-10 min)
  - ○ high statistic (10k-100k events)
  - ○ robust

  successful calibration process

Conclusion

See SABRE-South general talk by Irene Bolognino. Thu 22nd @ 11h20 - Session F

SABRE is uniquely positioned to **contribute** to **solving** the **DAMA/LIBRA DM-conundrum**.

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Accurate **PMT**

- **Pre-**

In-situ calibrat

- **Seve**
- All sy
  - lo
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  - robust

successful calibration process

Interested in more details?

Check out our SABRE-South technical design report:

https://doi.org/10.26188/14618172.v3

SABRE - Partner institutions

SABRE

South

Australian Government
Australian Research Council

KEK-JAPAN

SWINBURNE

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

THE UNIVERSITY OF MELBOURNE

THE UNIVERSITY of ADELAIDE

Australian National University

North

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

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

SAPIENZA UNIVERSITÀ DI ROMA

PRINCETON UNIVERSITY

UNIVERSITÀ DEL SALENTO

Backup slides

SABRE-South's exclusion/discovery potential

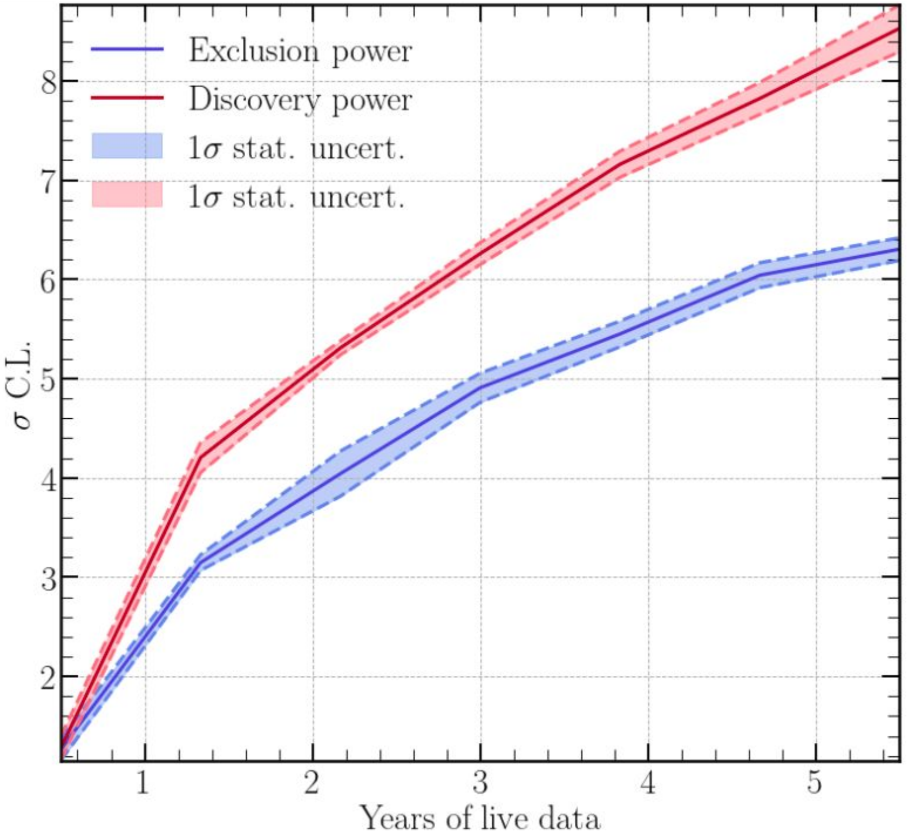


Figure 4. The exclusion and discovery power of SABRE South for a DAMA-like signal. The shaded regions indicate 1σ statistical uncertainty bands.

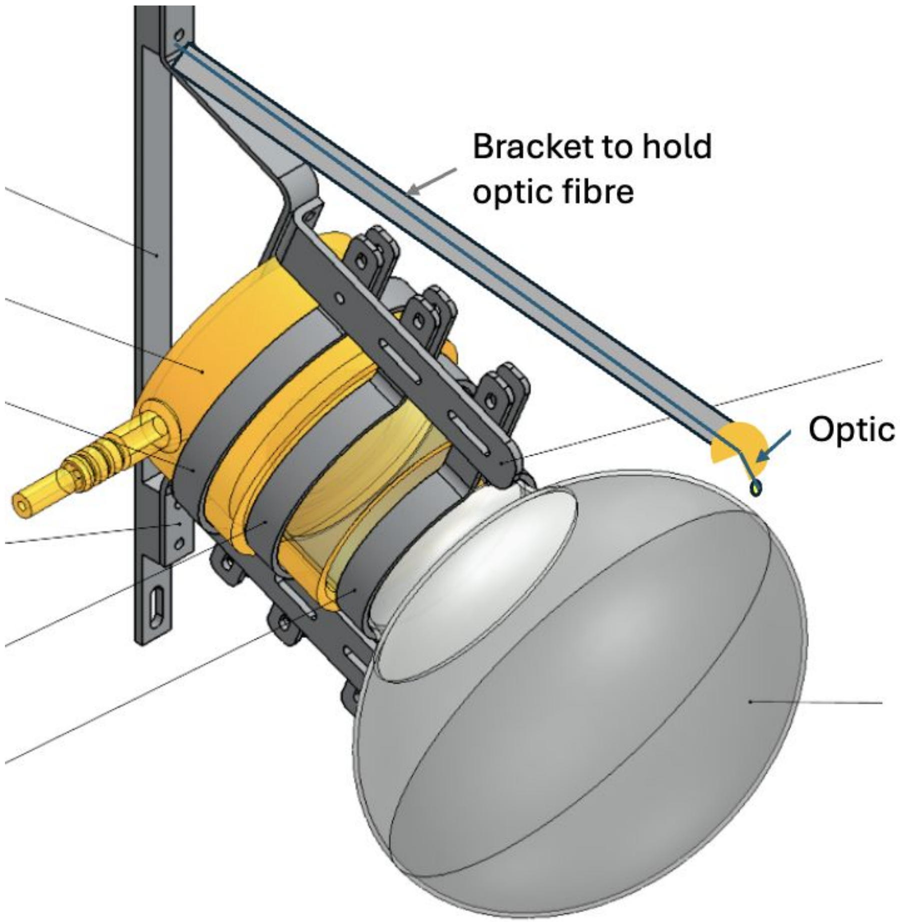
SABRE-South TDR
https://doi.org/10.26188/14618172.v3

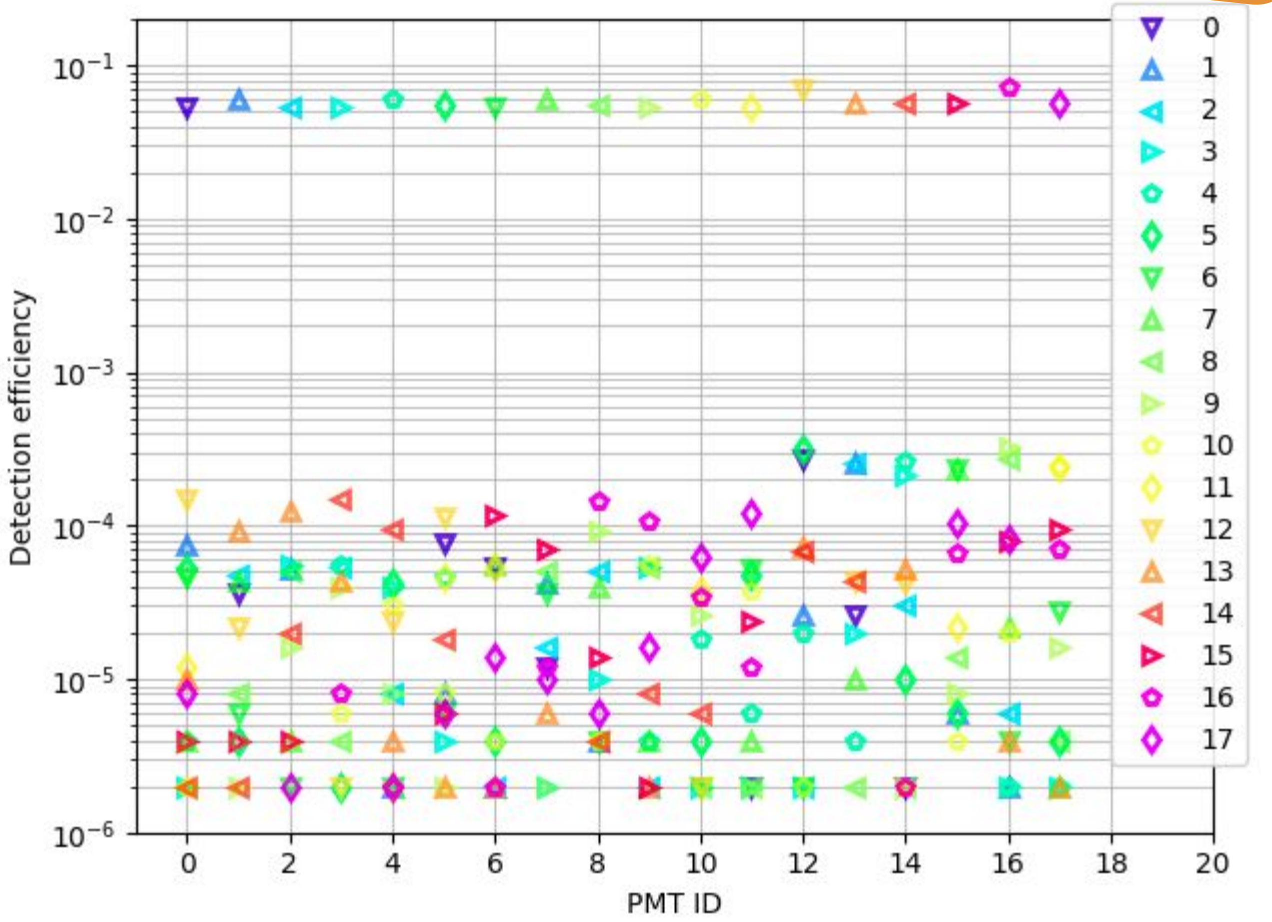
In-situ calibration

Alternative solution: direct coupling (405 nm)

SABRE-South Preliminary results

Altered layout being considered w.r.t. SABRE-South technical design report: https://doi.org/10.26188/14618172.v3





In-situ calibration

Alternative solution: direct coupling (405 nm)

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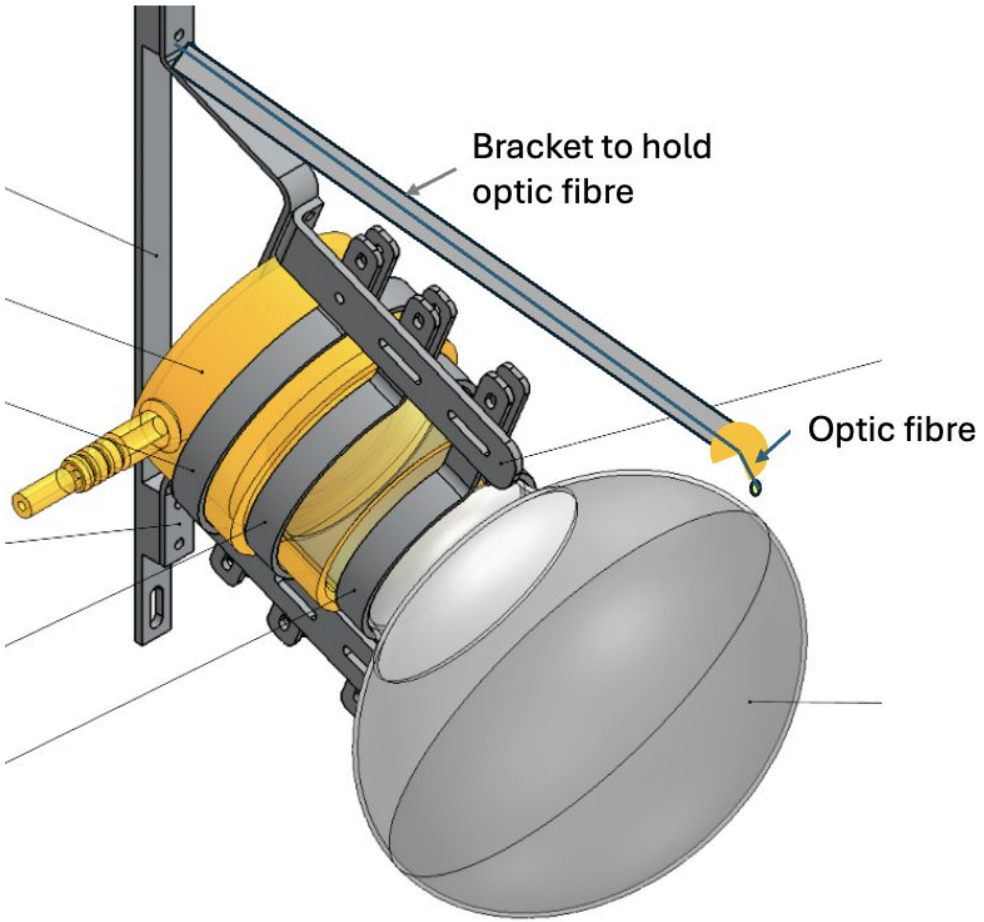

Alternative in-situ calibration method

- Optic fibre directly attached to PMT bracket
- 405 nm wavelength for short absorption length in LAB
- Benefits:
  - Higher level of control and predictability
  - More accurate timing measurements
- Downsides:
  - Longer calibration times as laser intensity needs to be lower to ensure single photon electron events

In-situ calibration

Alternative solution: direct coupling (405 nm)

SABRE-South Preliminary results

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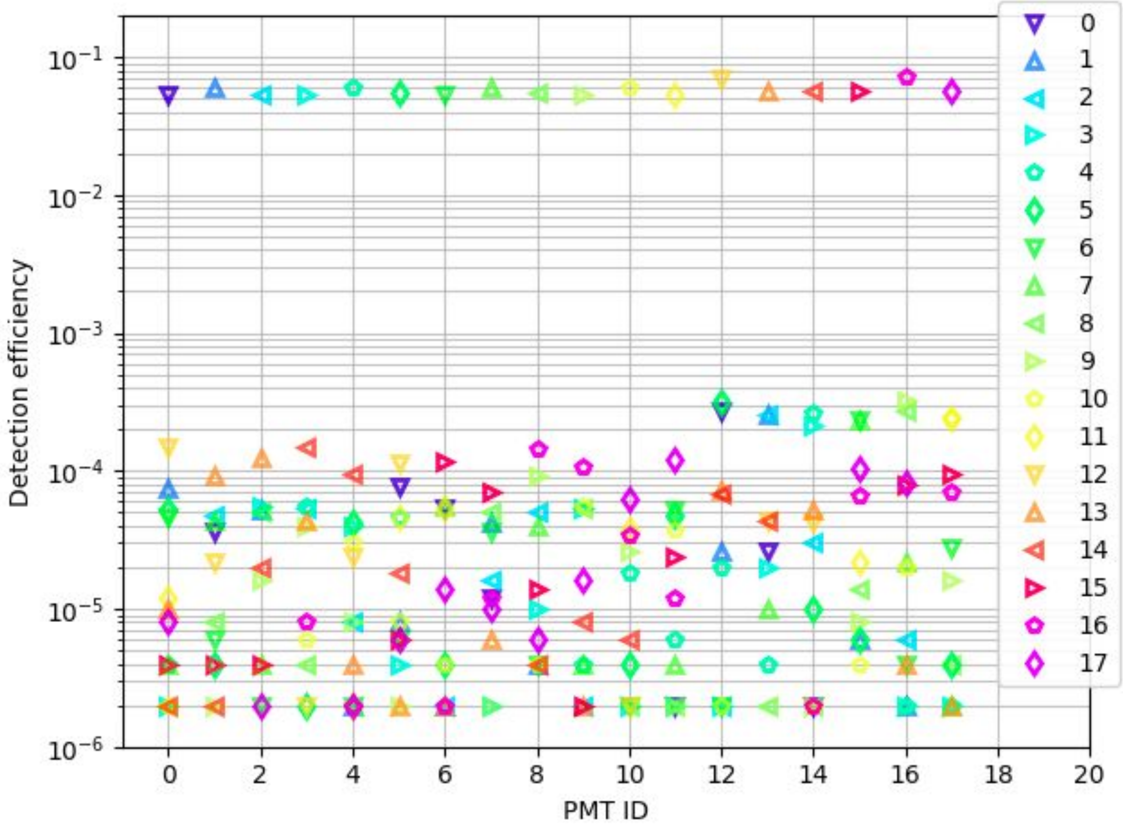

Alternative in-situ calibration method

- Would enable successful single photon calibration of all PMTs
- Low level of cross-talk between the calibration source of different PMTs

Preliminary simulations indicate that **both solutions** should enable **in-situ PMT calibration**, each with their own pros and cons.