Dark matter searches and underground lab in Australia

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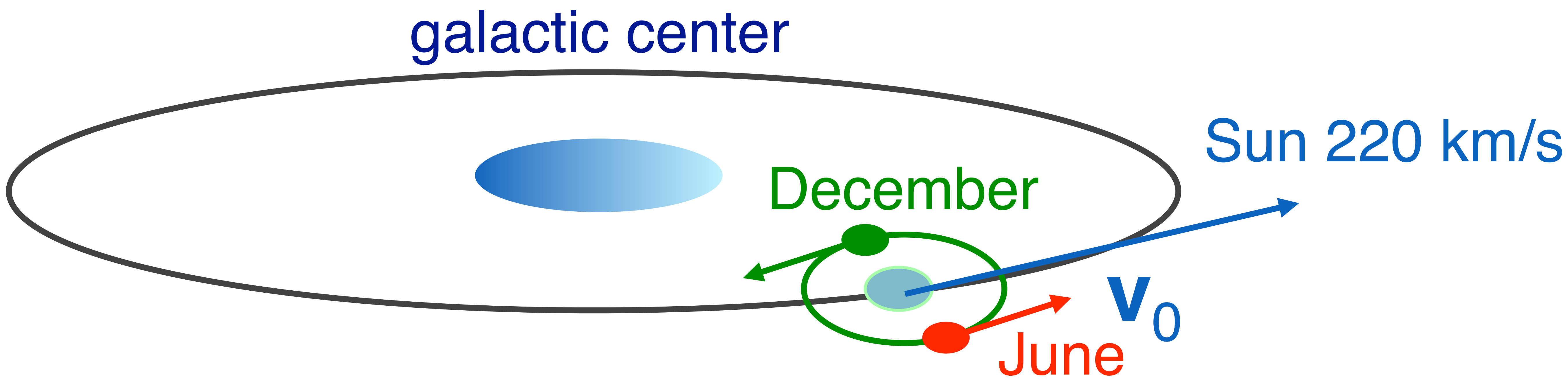
The University of Melbourne
Symposium on science at PAUL , Du Toikloof Mountains, South Africa

Annual modulation of WIMP DM

Astrophysics

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

Particle physics



Annual modulation; maximum on June 2, minimum December 2

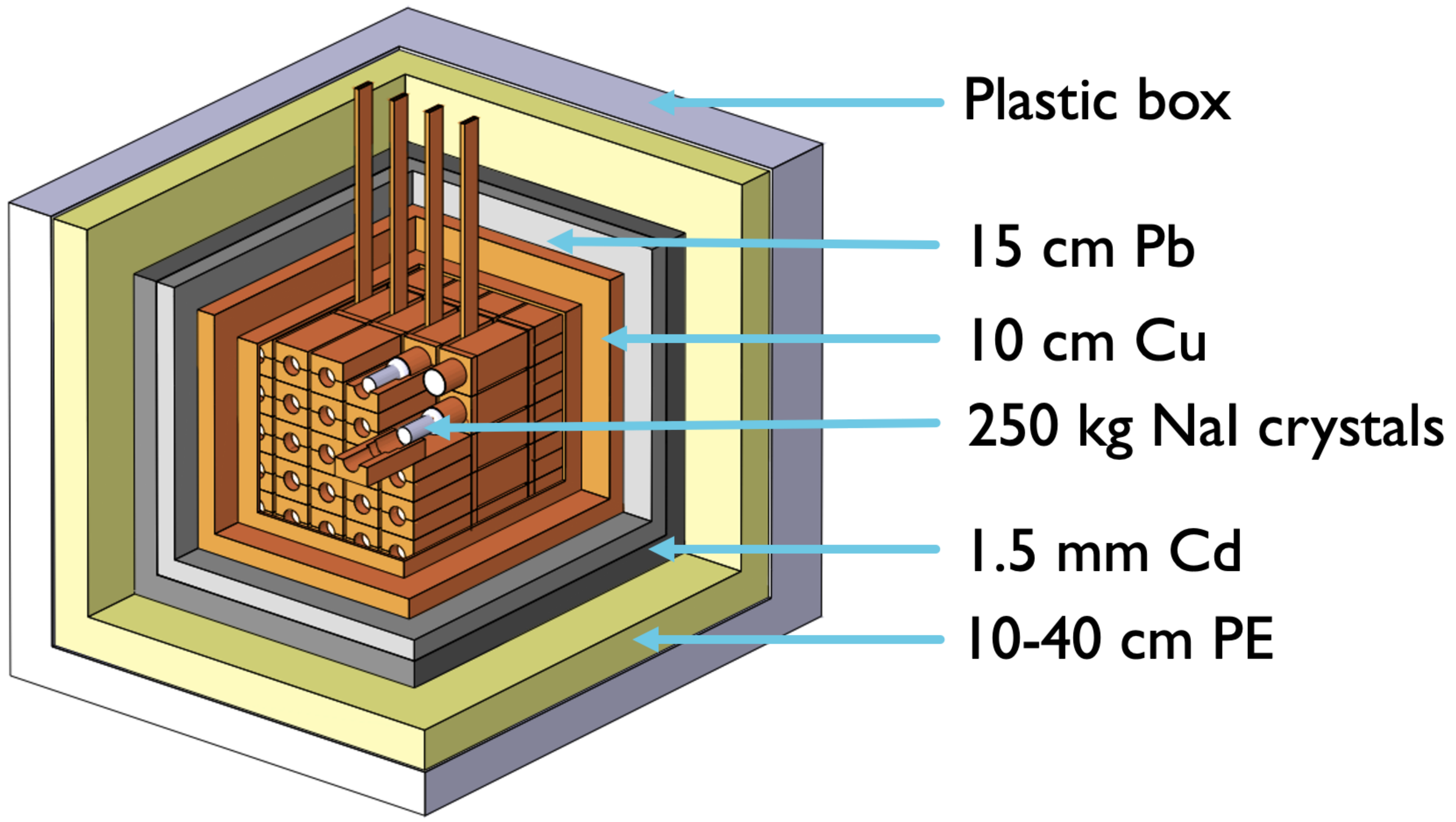
$$R(t) = B + R_0 + \boxed{R_m \cos\left(\omega(t - t_0)\right)}$$

Modulating component ~ 2-10% of R(t)

- **Rare and low energy events**
  - Expected σ(WIMP-nucleon) ~ 10^{-48} – 10^{-40} cm^2
  - Very low expected rate < 1 count/day/kg (few % of which modulates)
  - Expected recoil energy is 1-100 keV for a WIMP of mass 10-1000 GeV/c^2

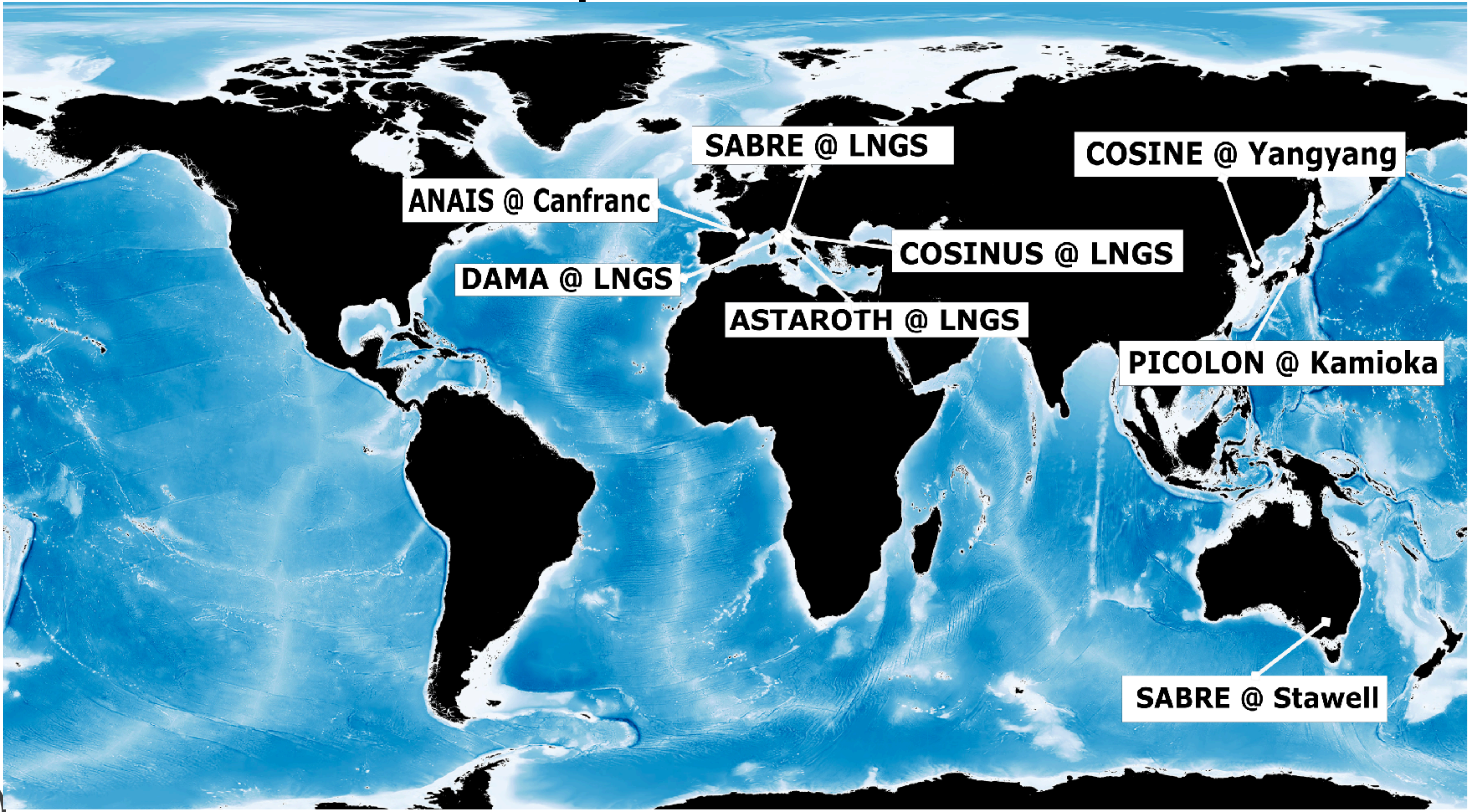
Results from DAMA/LIBRA

250Kg NaI(Tl)



- ~20 years of operations: 12.8 σ CL significance
- Period: (0.998±0.002) y
- Phase: (145±5) days (2-6 keV) and (145±7) (1-3 keV)
  Expected DM phase 152.5 days
- Amplitude: (0.0103±0.0008) cdp/kg/keV
- Observed annual modulation ~ 0.01 cpd/kg/keV (dru) in ROI [1,6]keV

NaI experimental landscape



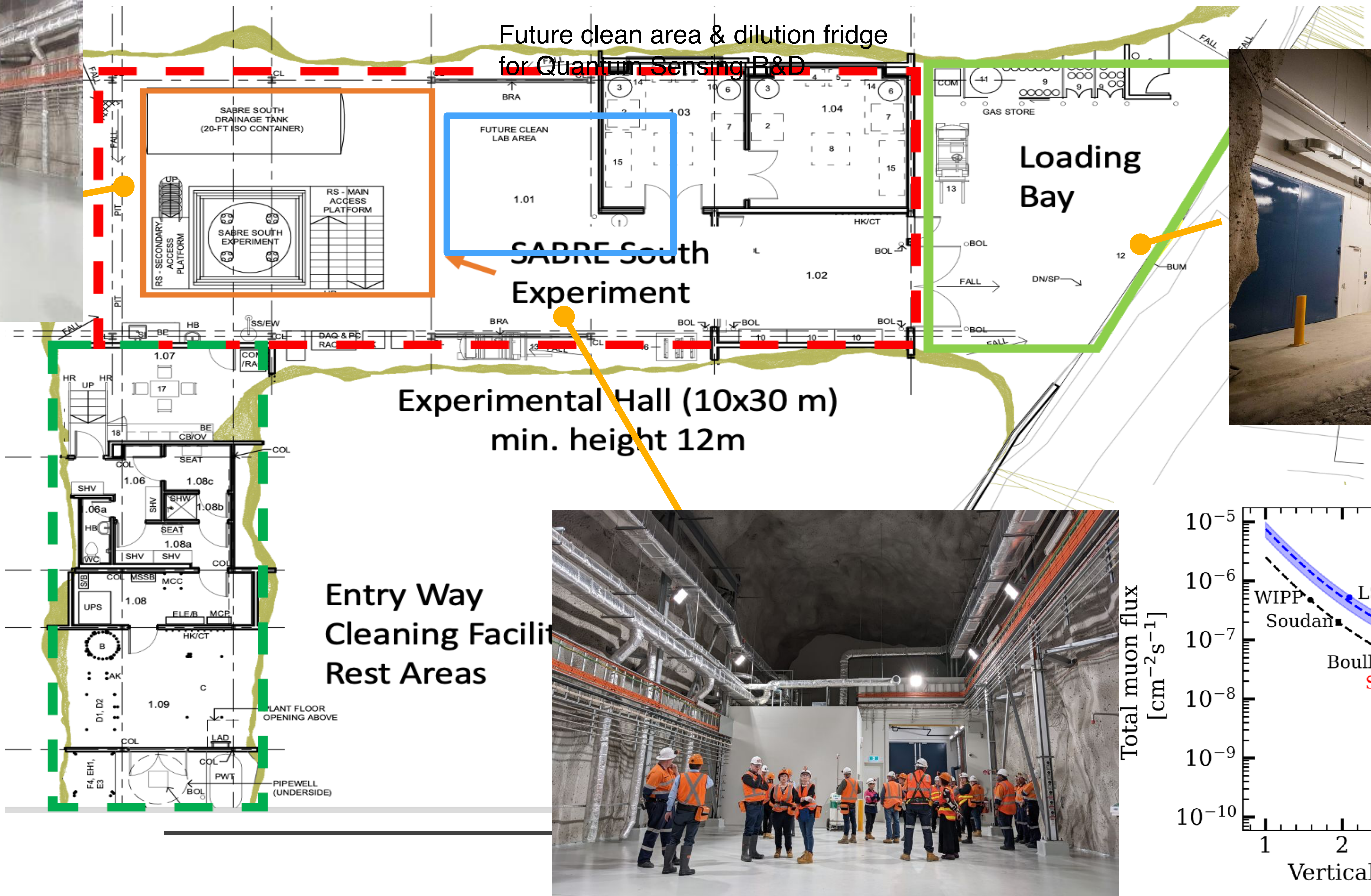
STAWELL UNDERGROUND PHYSICS LAB (SUPL)

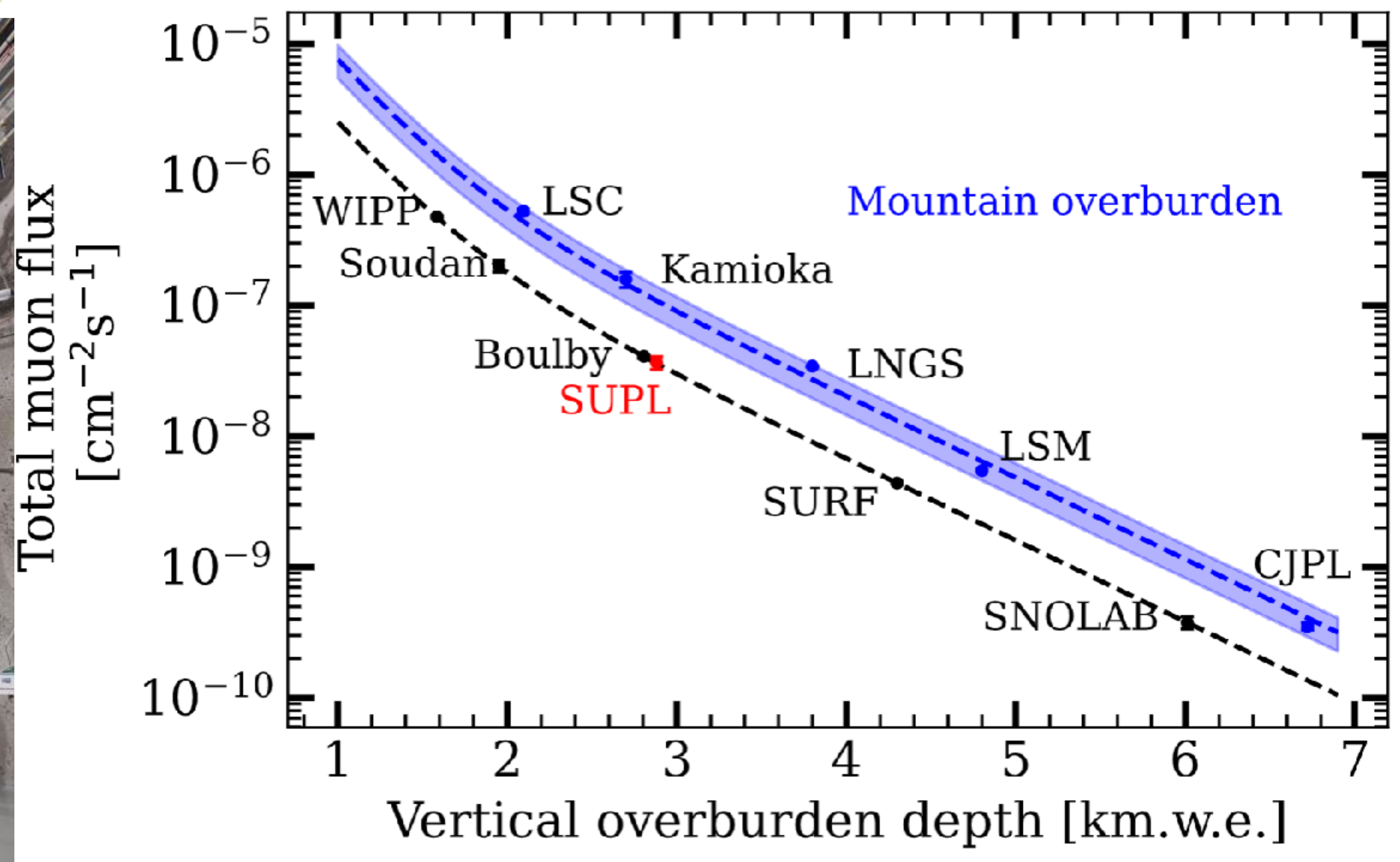
Stage 1 completed in August 2022

SUPL

- 1025 m deep (~2900 m water equivalent) with flat over burden
- Helical drive access

https://www.supl.org.au





SUPL

- Commissioning throughout 2023.
- First major equipment to be delivered in January 2024.
- SABRE collaborators commenced mine safety training (2 days on site, medical testing)

The "SUPL researcher" starter kit

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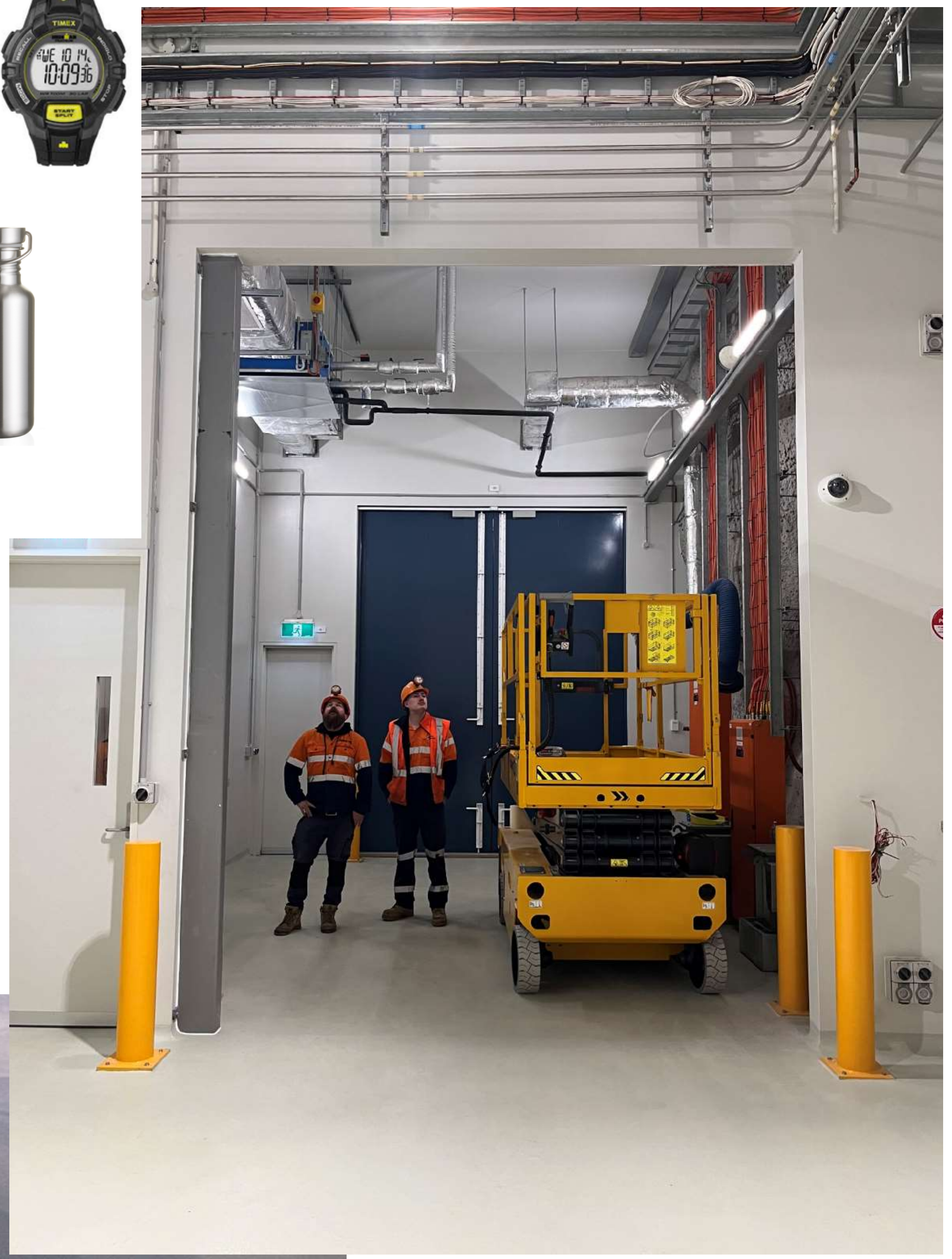
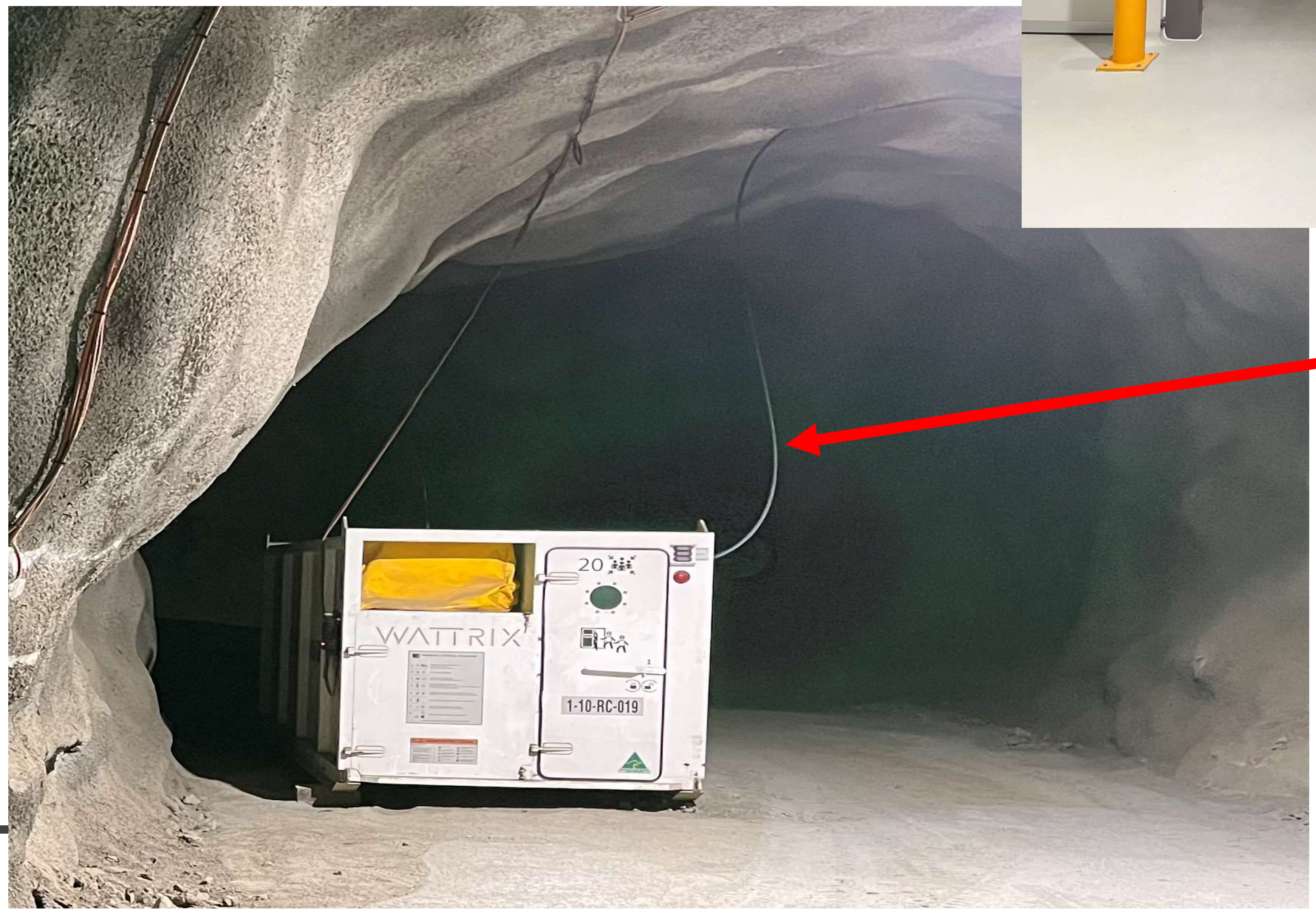


SUPL will provide	**Individual Researchers**
1. Self-rescuer 2. Cap lamp 3. Gloves 4. Ear protection 5. Safety glasses 6. SGM Information Card	Must have your own: 7. High-visibility clothing 8. Steel capped boots as specified by SGM. **SUPL or Individual Researcher** 9. Miner's belt 10. Miner's helmet



SGM Compressed Air Line

Preparing for work in SUPL

- **Actions to move equipment to SUPL**
  - SUPL and SABRE Agreement
  - Delivery and installation
    - Planning
    - Arrival at SGM
    - Transport to SUPL
    - Off-loading at SUPL
    - Allocated research space
    - Equipment register
    - Services and consumables
  - Undertaking research activities
    - Risk assessments
    - Standard Operating Procedures
    - Work instructions or O&M manuals

- **Documents for approval to move equipment to SUPL**
  - Equipment register
  - Task risk assessment
  - Process risk assessments
  - Approval to work at SUPL
  - Standard operating procedures
  - Work instructions
  - Training, mine safety, heights, confined spaces etc.

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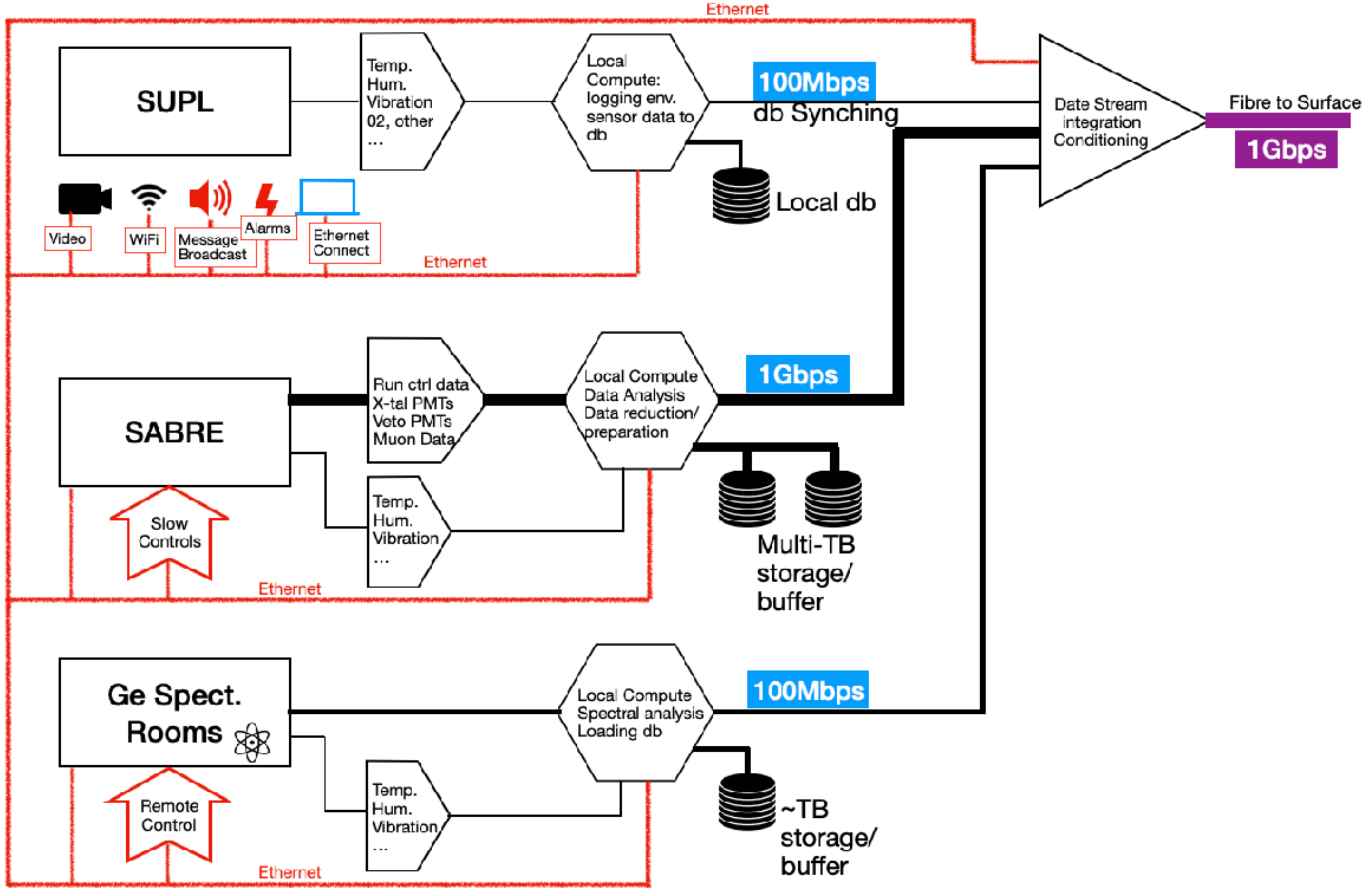
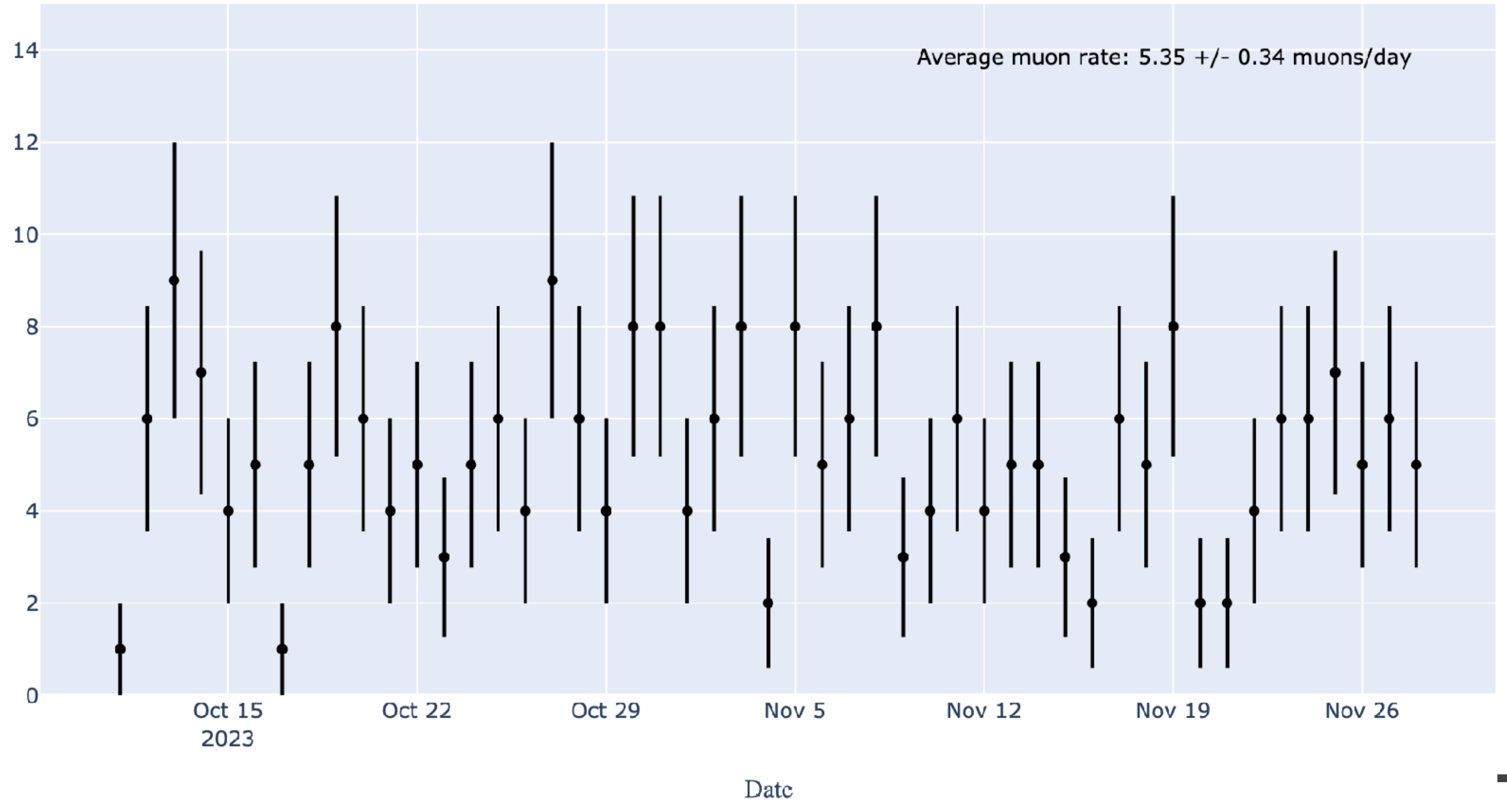
Computing

First SUPL measurement of muon flux, October 2023





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SUPL

- Located in the **active** Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia
- First underground lab in the southern hemisphere

STAWELL UNDERGROUND PHYSICS LAB

https://www.supl.org.au

Strong support of the local community

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

SUPL TIMELINE

- ***2014*** Lab proposed, Project Leaders E. Barberio (University of Melbourne), J. Mould (Swimburne)
- ***2015*** Federal Stronger Region grant to NGSC for the Lab design
- ***2016*** Lab design by WOOD ready
- ***2017*** Hiatus - SGM in caretaker mode
- *2018* the project restart: ARETE capital acquires SGM
- ***2019*** construction starts by H.Troon (Ballarat)
- ***2022*** August SUPL finished and commissioning start
- ***2023*** December SUPL ready to be used
- **2024** January SABRE starts construction

THE HISTORY

A delegation of Italian scientists, visited SGM and suggested to build an underground laboratory to test the dark matter signal seen in Italy

SGM and NGSC enormously supportive and help to generate government funding for SUPL

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STRONG SUPPORT FROM SGM

SCHOOL ENGAGEMENT

- 50% increase in STEM enrolments in Stawell and Ararat schools since SUPL announced;

Foster innovation culture and an entrepreneurial mindset with the help of the innovation lab @ Swinburne

Explore

Particle Detector, Master classes, Innovation Kit

Educate

Lessons on special relativity and subatomic physics

Engage

Mobile device VR of experiments to engage at home

Evaluate

Centre supports schools in evaluation

STRONG SUPPORT FROM INFN

We don't want you to just host the (SABRE) experiment; we want you as collaborators in the experiment

2014 workshop @ Stawell on dark matter

Prof. Sandro Bettini helped to set the requirements and help with the lab design

OUTREACH AND MEDIA

LAB CONSTRUCTION

Stawell Underground Laboratory construction

$5 million

Federal Government funding (Education)

Stawell Underground Laboratory construction

$5 million

Victoria State Government (Regional Development)

Stawell Underground Laboratory construction

$1.8 million

SUPL ltd. manages the lab

Dr Sue Barrel (chair SUPL ltd.)

Running cost from university funding.
Requested 17M for 5 years running cost from the federal government

SABRE Capital Funding:
ARC, via ANU, UM, …

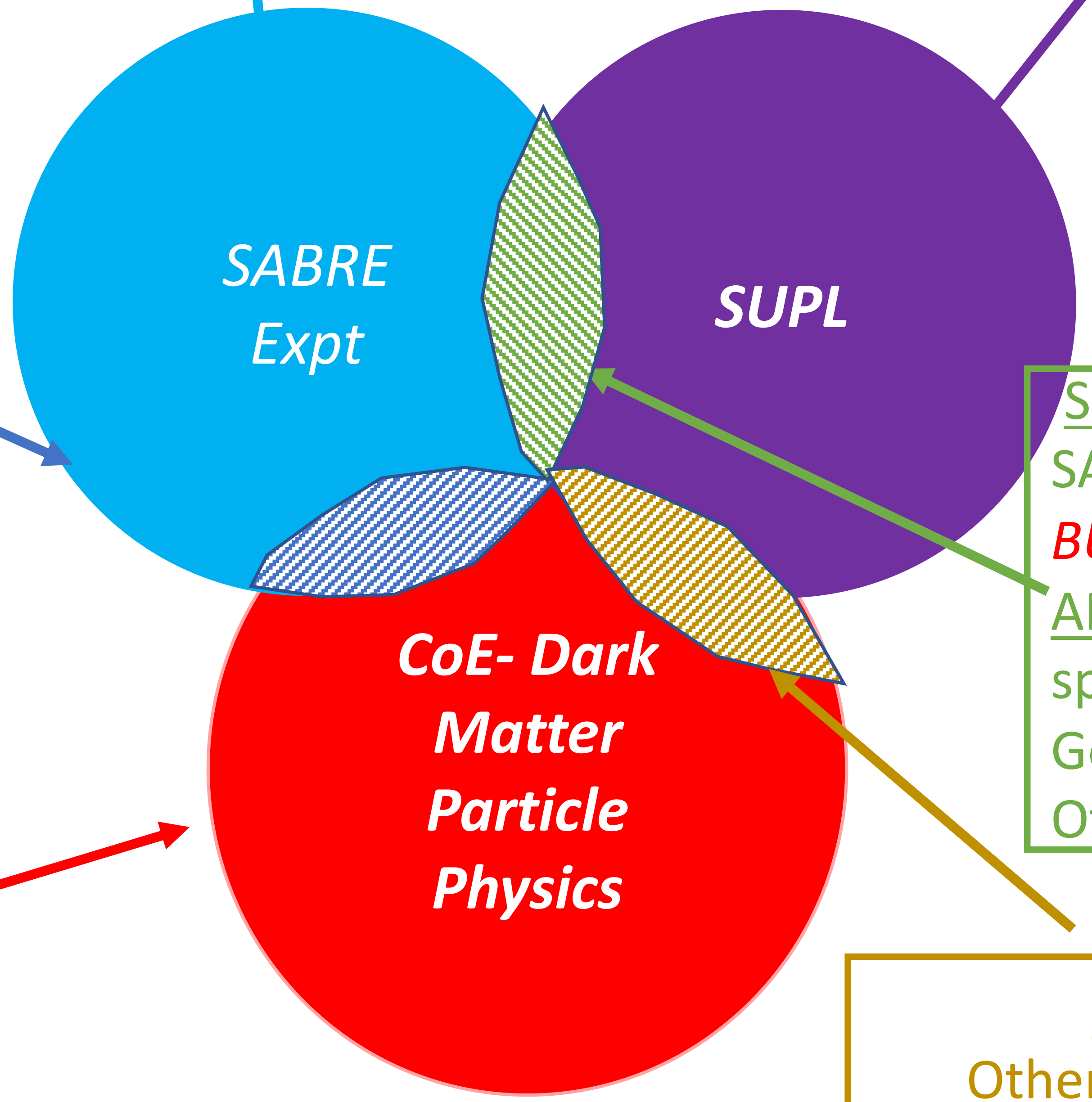
Collaborators:
UM, ANU, UA, Swinburne, INFN, Princeton, …

SUPL Capital Works Funding:
Commonwealth Govt.
Victoria Govt.

Operational Funding:
SUPL Partners - UM, ANSTO, ANU, UA, Swinburne

Independent funding ~$6M

SABRE: key component of the CoE Scientific Program
BUT only a part of it.
Other projects include:
Searches for Axions (UWA);
Search for DM production at the LHC (UM, UA) ; Theory; etc.



SUPL: Future National Facility
SABRE is initial Key experiment
BUT also:
ANSTO low background Gamma spectroscopy facilities;
Geology & biology experiments;
Others …

CoE Funding:
ARC, UM, UWA, UA, ANU, Swinburne.

CoE Funding:
Other DM experiments, Cygnus, Cryo exp.

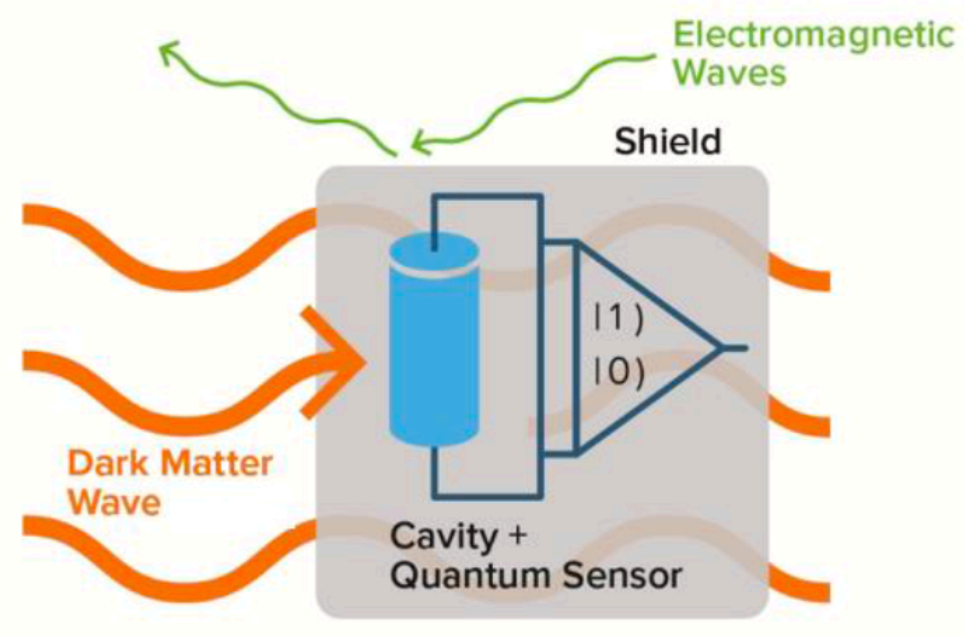
Independent funding ~$47M

ARC Centre of excellence for DM

- Prof Elisabetta Barberio director
- 7 years projects (midd-2020—midd-2027)
- 21 Chief investigators (Australian) over 6 Australian Universities (10 theorists, 10 experimentalists)
- 3 new academics (direct detection experimentalists)+ 1 position almost filled (direct detection experimentalist)
- 13 partner investigators (formal agreement) - INFN, Caltec, Amsterdam, Washington, Stockholm, MIT, Sheffield; locally ANSTO and DSTG
- 30 associate investigators (less formal association) from many other countries
- 24 postdocs supported by the centre
- 100 students
- 14 admin staff supported by the centre

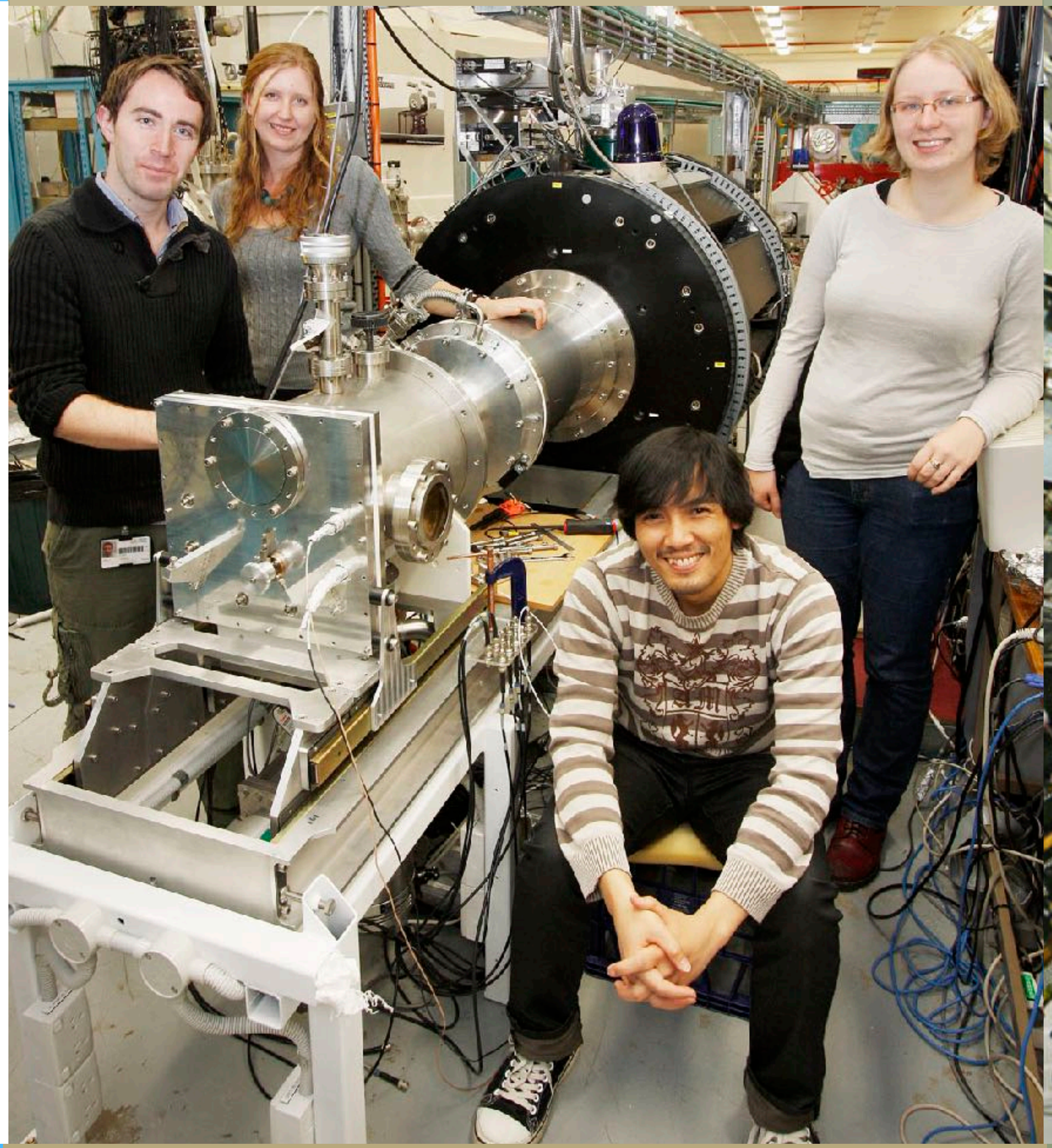
RESEARCH THEMES

Direct Detection



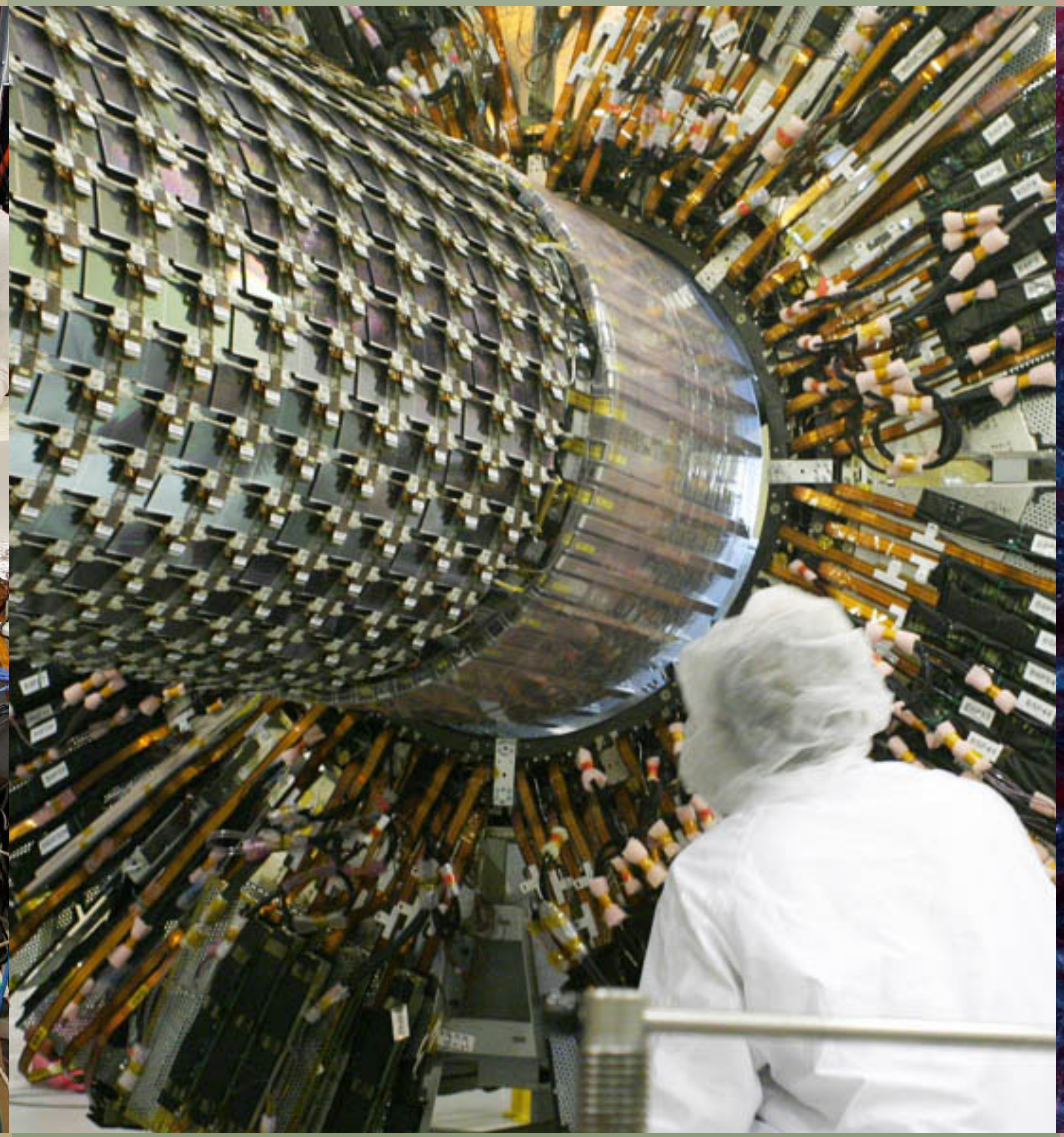
WIMP-like, Axion-like

Metrology



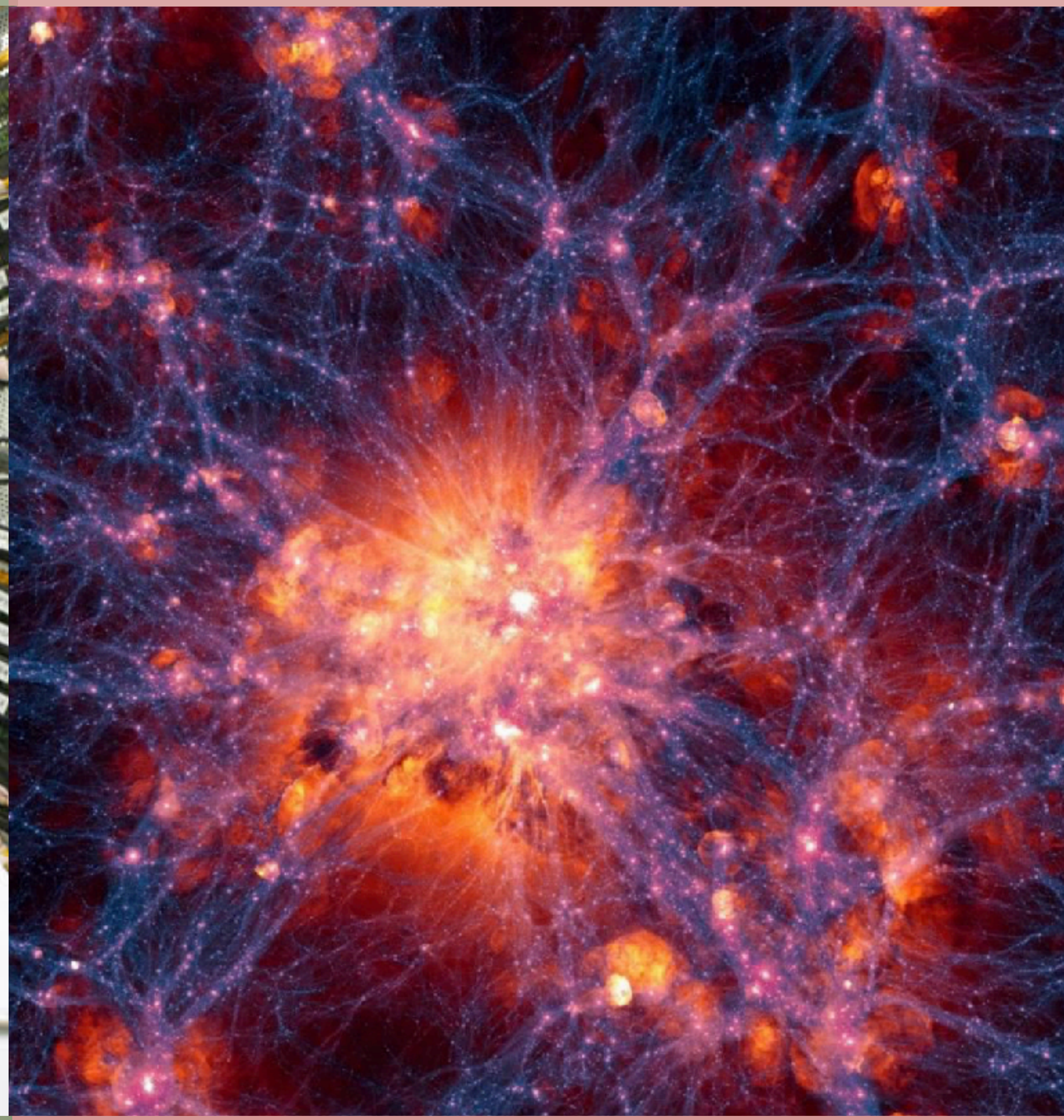
Nuclear and quantum techniques

Large Hadron Collider



Dark matter analyses

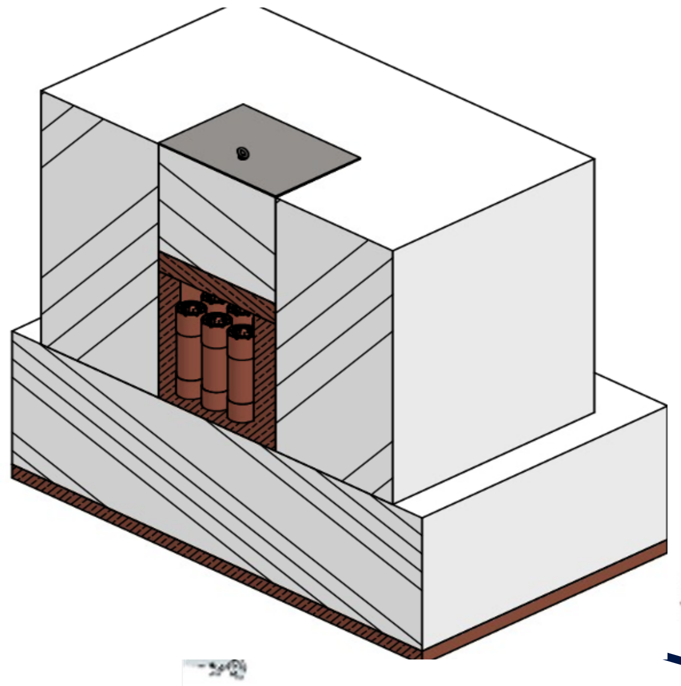
Theory

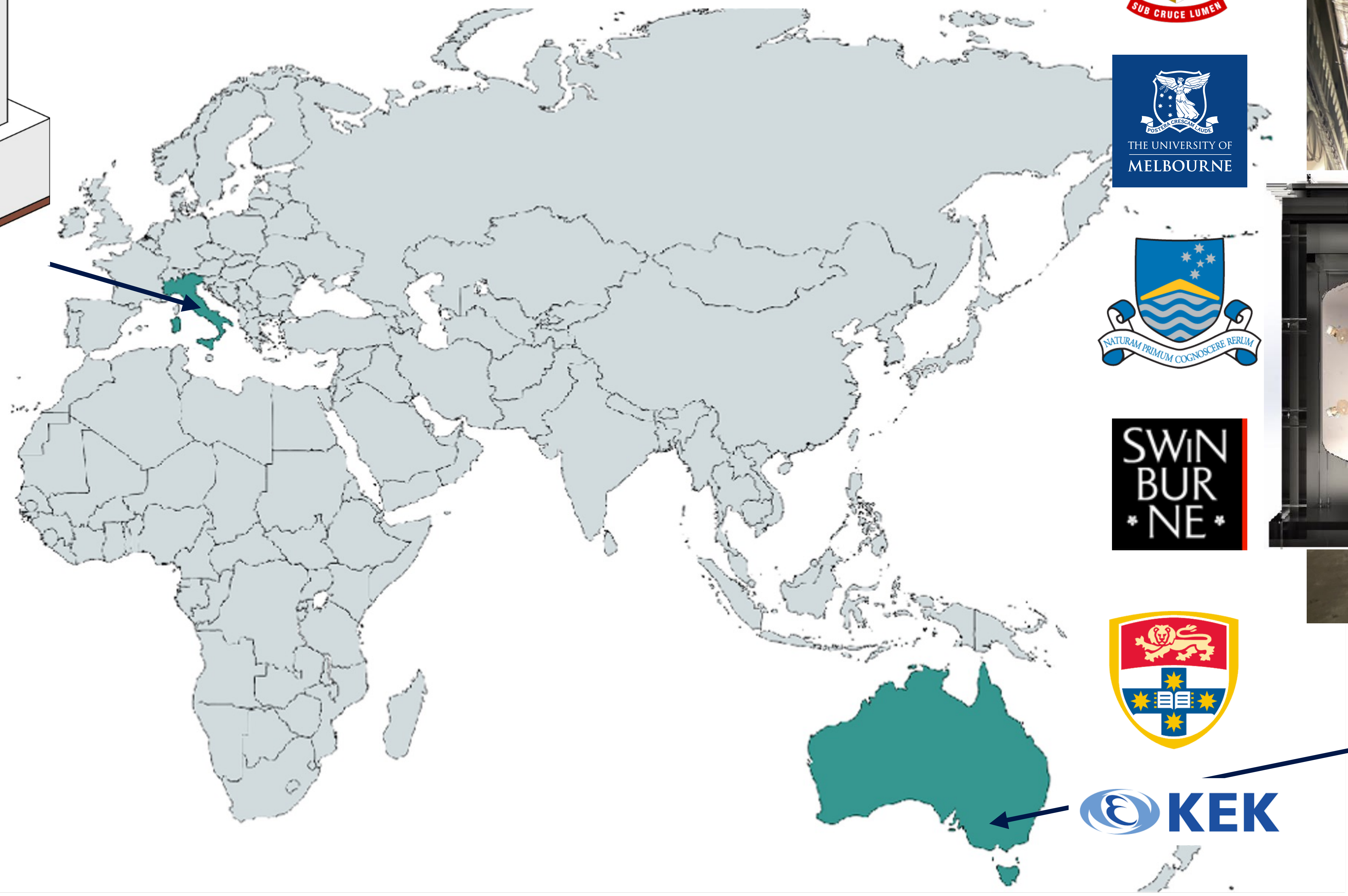


Indirect detection, astro simulation,

SABRE

- **Two similar detectors in two underground locations in opposite hemisphere:**
  - SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
  - SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia





Requirements for SABRE

SABRE South TDR

- Main requirement - outperform DAMA/LIBRA.
- Same stringent crystal requirements for North (no LS veto) and South (with an LS veto).

Table 1. Annual modulation in the 1-6 keV region reported by DAMA [2], COSINE [3], and ANAIS [4] in units of DRU (cpd/kg/keV). The χ^2/ndf for the global average is 10.8/2.

Setup	Mass (kg)	Background (dru)	Modulation (dru)	Uncertainty (dru)
DAMA	250	0.8	0.0105	0.0011
COSINE	61.3	2.7	0.0064	0.0042
ANAIS	112.5	3.2	-0.0034	0.0042
Global average	-	-	0.0094	0.0010

Table 2. Purity levels of NaI(Tl) crystals of various experiments.

Experiment	^{39}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Pb (mBq/kg)
DAMA/LIBRA [6]	13	0.7 – 10	0.5 – 7.5	$(30-50)\times10^{-3}$
ANAIS-112 [7]	31	<0.81	0.36	1.53
COSINE-100 [8]	35.1	<0.12	<2.4	1.74
SABRE (NaI-033) [9]	4.3	0.4	0.2	0.34

Table 3. Key performance parameters of SABRE.

Parameter	**Value**
Light yield	11.1 ± 0.2 PE/keV [10]
Energy resolution	13.2% (FWHM/E) at 59.5 keV [10]
Efficiency	
Crystal energy threshold	1 keV
Veto energy threshold	50 keV
Total active mass	35 - 50 kg
Background rate (PoP)	0.36 cpd/kg/keV [11]
Background rate (South)	0.72 cpd/kg/keV [12]

Large (> 4 kg) Na(Tl) Crystals background & mass

Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active mass (kg)
DAMA [1]	13	0.7-10	$(5\text{-}30)\times10^{-3}$	0.5-7.5	250
ANAIS [2]	31	<0.81	1.5	0.36	112
COSINE [3]	35.1	<0.12	1-1.7	<2.4	~60
SABRE [4]	4.3	0.4	0.49	0.2	~35+40=75 (total goal)
PICOLON [5]	<20	-	$<5.7\times10^{-3}$	-	~20 (goal)

[1] R. Bernabei et al., NIMA 592(3) (2008)
[2] J. Amare et al., EPJC 79 412(2019)
[3] P. Adhikari et al., EPJC 78 490 (2018)
[4] B. Suerfu et al., Phys. Rev. Research 2, 013223 (2020), , Eur.Phys.J.C 81 (2021) 4, 299 , Phys. Rev. D 104, 021302 (2021)
[5] K. Fushimi et al., PTEP 4 043F01 (2021)

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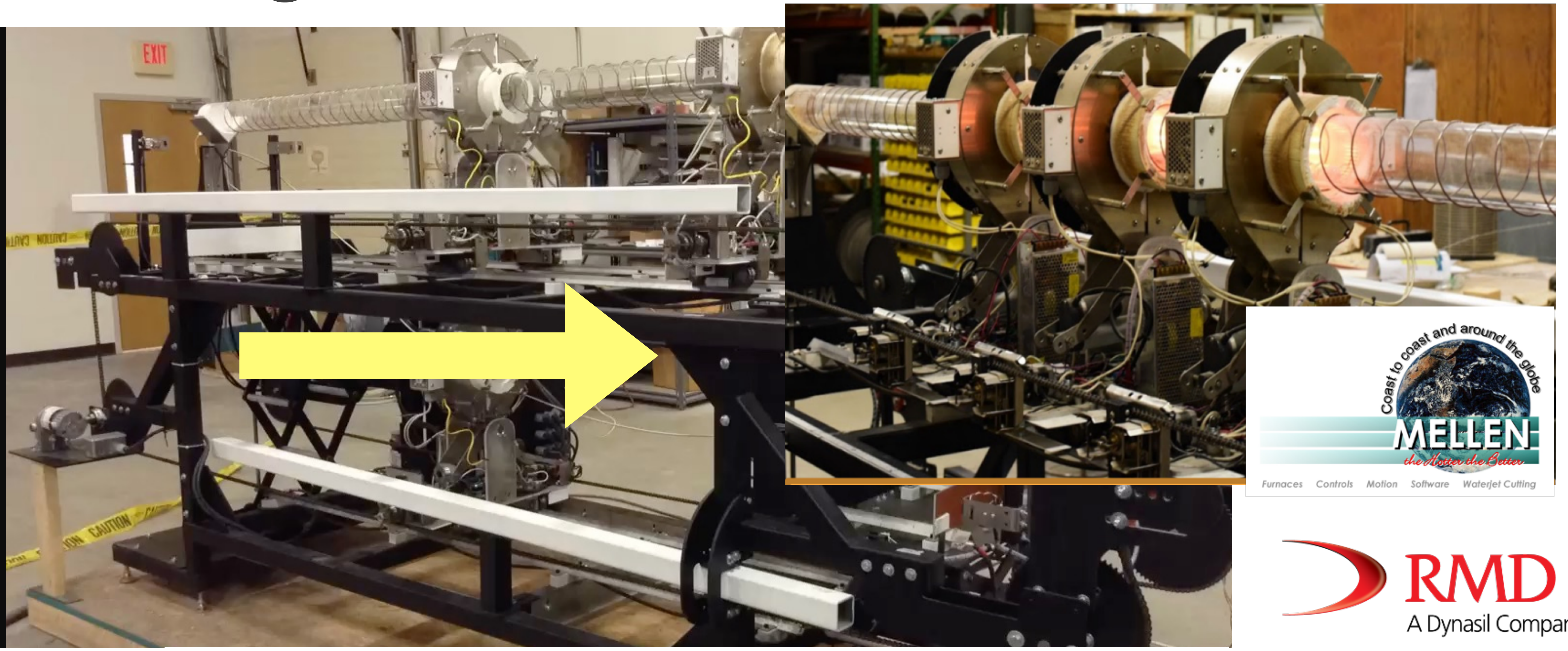
Na(TI) Crystals: Zone Refining Purification

- Strategic and unique to the SABRE project is the idea to zone refine the powder prior to growth
- A zone refiner suitable for order of 100 kg crystal production has been built in collaboration with MELLEN
- The zone refiner is being moved to RMD for growing a test crystal by the end of the summer



Impurities are pushed to the end of the refining tube and removed from the ingot before the crystal growth. Reduction factors of

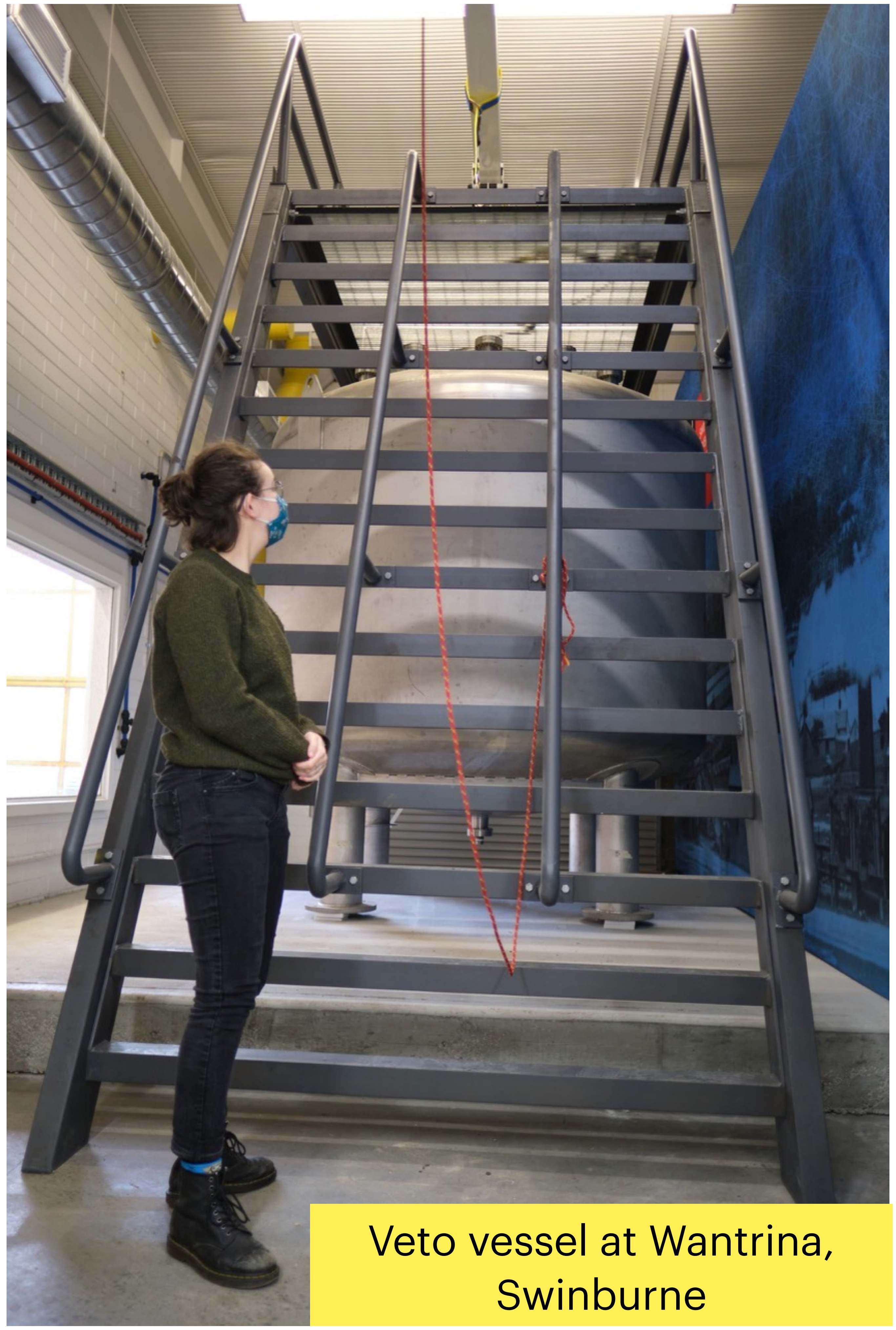
- ^{40}K: 10-100
- ^{87}Rb: 10-100
- ^{210}Pb: 2

Final crystal intrinsic background ~0.3 cpd/kg/keV

Isotope	Impurity concentration (ppb)					
	Powder	Sample location (mm)				
		7±7	325±9	492±10	635±20	783±30
^{39}K	7.5	<0.8	<0.8	1	16	460
^{85}Rb	<0.2	<0.2	<0.2	<0.2	<0.2	0.7
^{208}Pb	1.0	0.4	0.4	<0.4	0.5	0.5
^{65}Cu	7	<2	<2	<2	2	620
^{133}Cs	44	0.3	0.2	0.5	23.3	760
^{138}Ba	9	0.1	0.2	1.4	19	330

B. Suerfu, Phys. Rev. Applied 16, 014060 (2021)

SABRE South Collaboration



Veto vessel at Wantrina, Swinburne

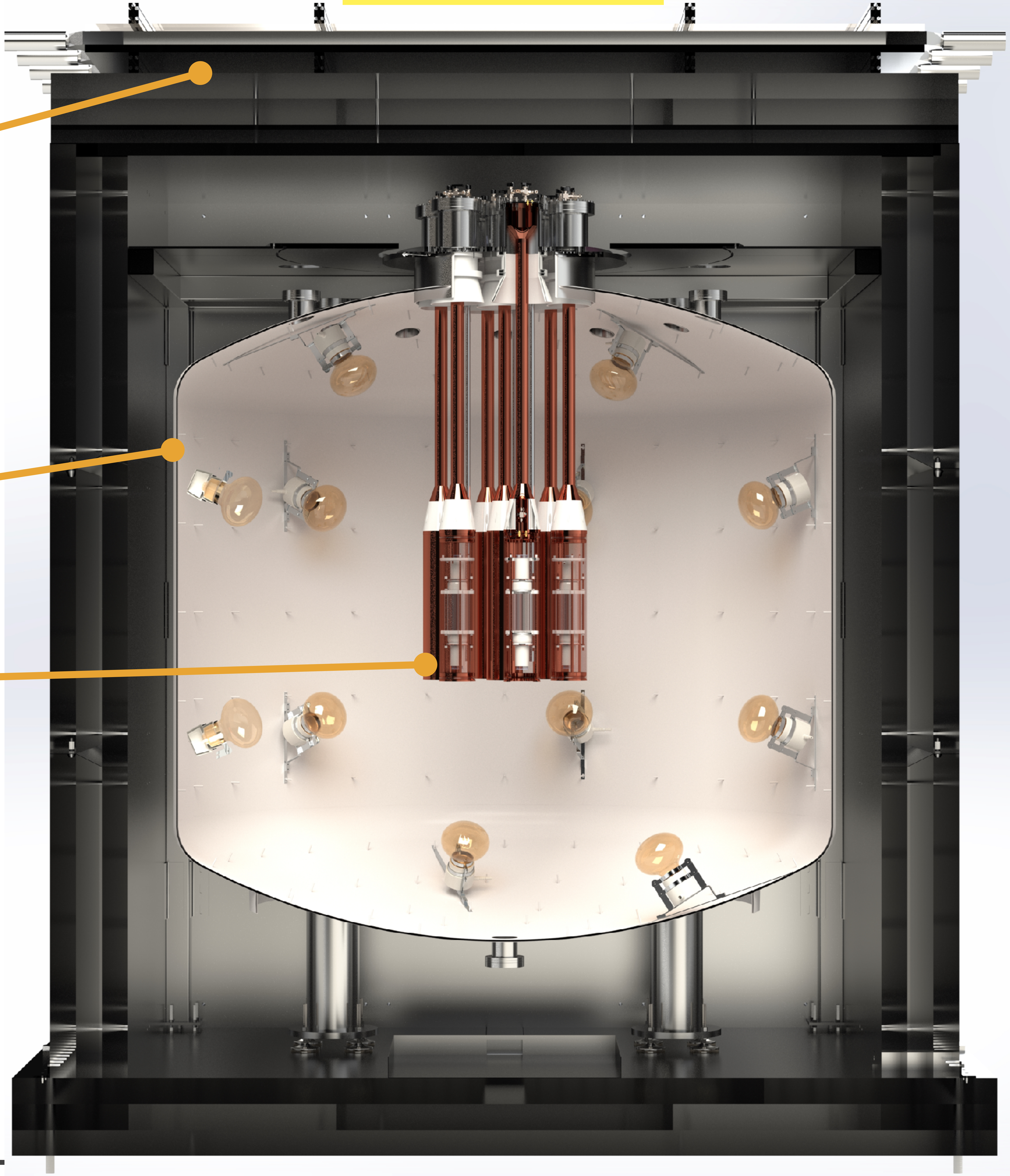
SABRE south collaboration meeting at Stawell (Victoria)

SABRE South @ SUPL

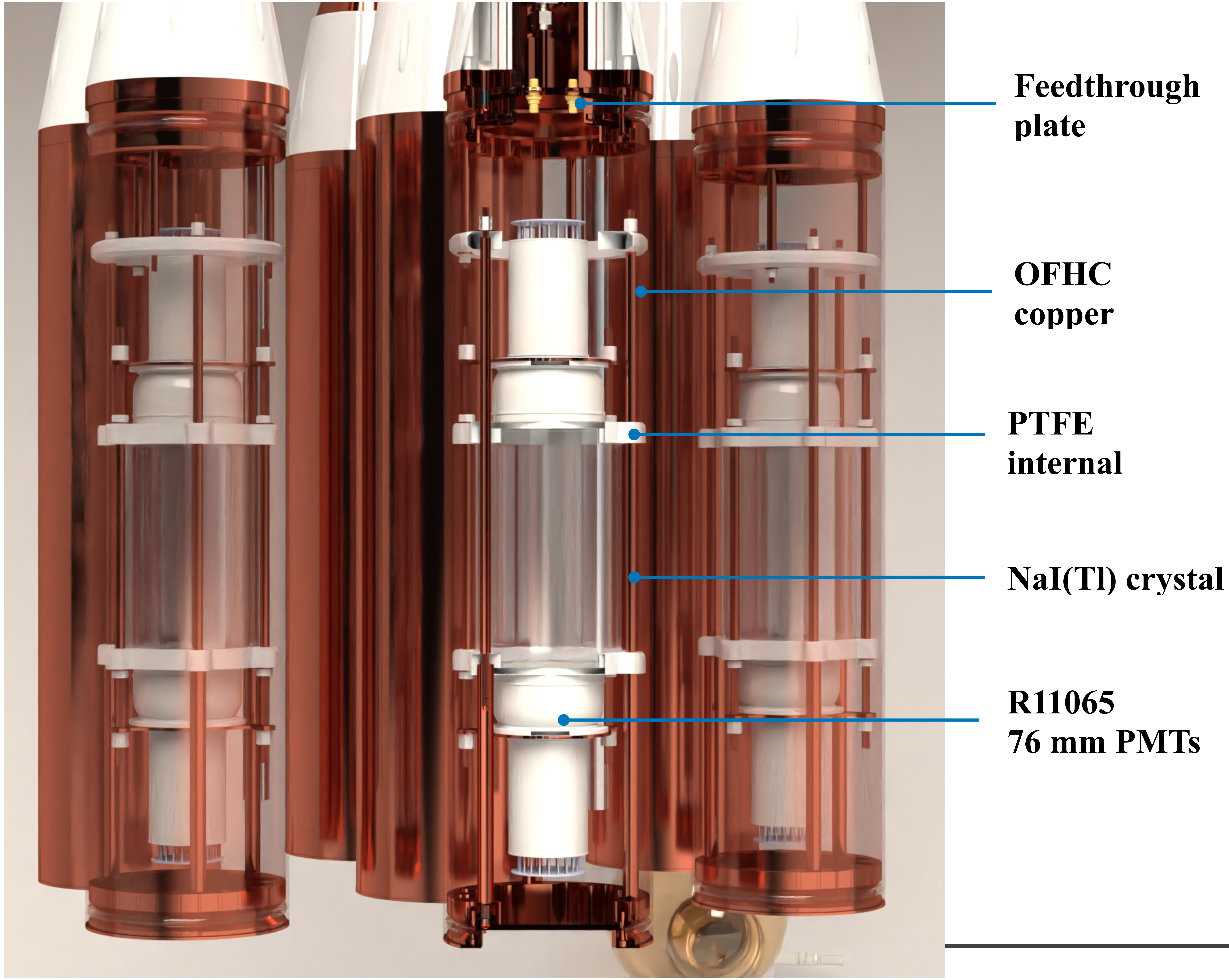
- **Muon System**
  9.6 m^2 x 5 cm EJ200
  R13089 PMT x 16 @ 3.2 GS/s
- **Passive shielding, Steel + HDPE**
- **Liquid Scintillator Veto System**
  12k litres Linear Alkyl Benzene + PPO & Bis-MSB
  Stainless steel, non-thoriated welds, lumirror coating
  Oil-proof base R5912 PMT x 18 @ 500 MS/s
- **DM Target Detector**
  NaI(Tl) Crystals, HPN2 flushed
  R11065 low radioactivity PMT x ~14 @ 500 MS/s

https://www.veritasium.com/videos/2022/6/2/the-absurd-search-for-dark-matter

SABRE South TDR



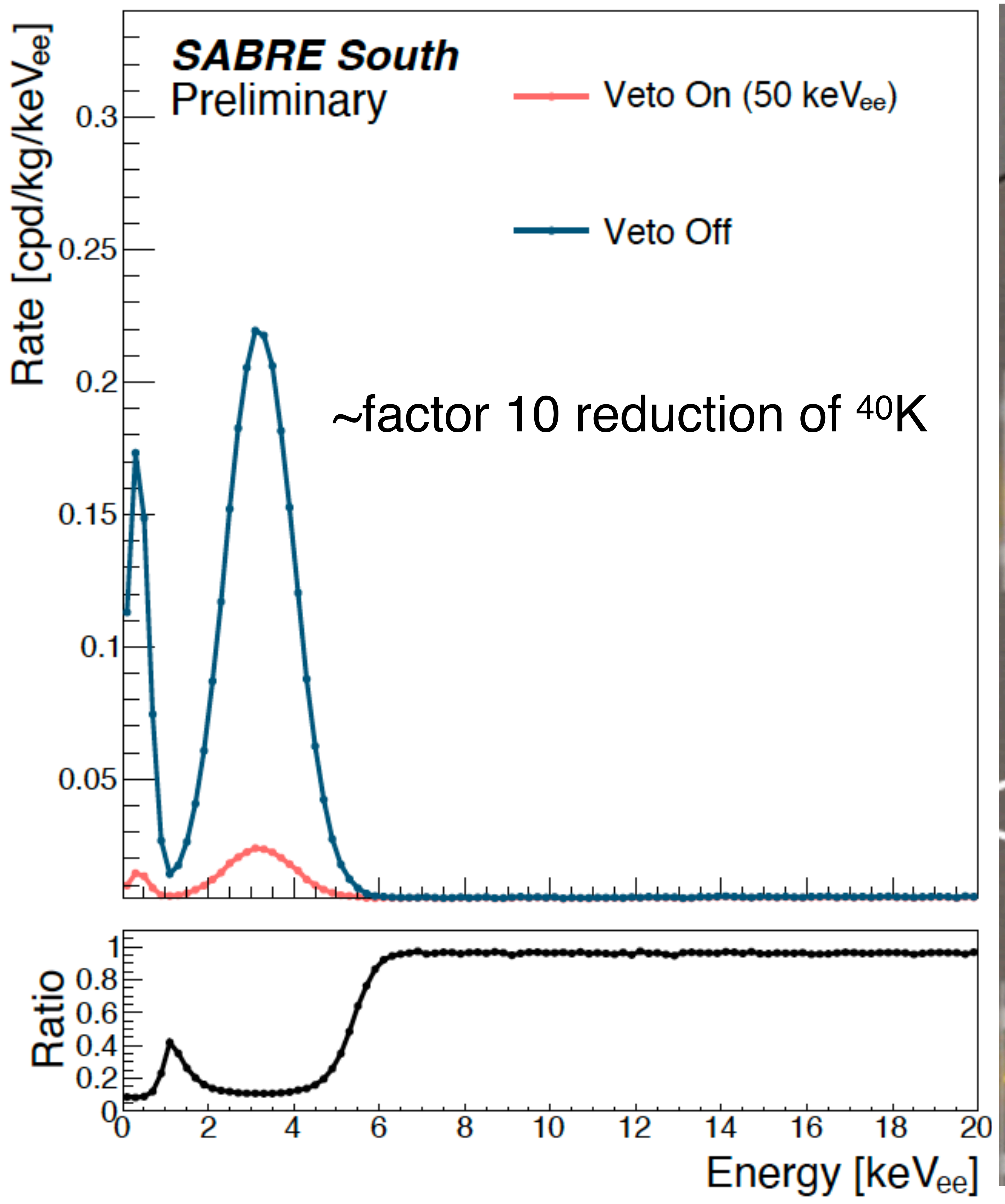
SABRE South crystals modules

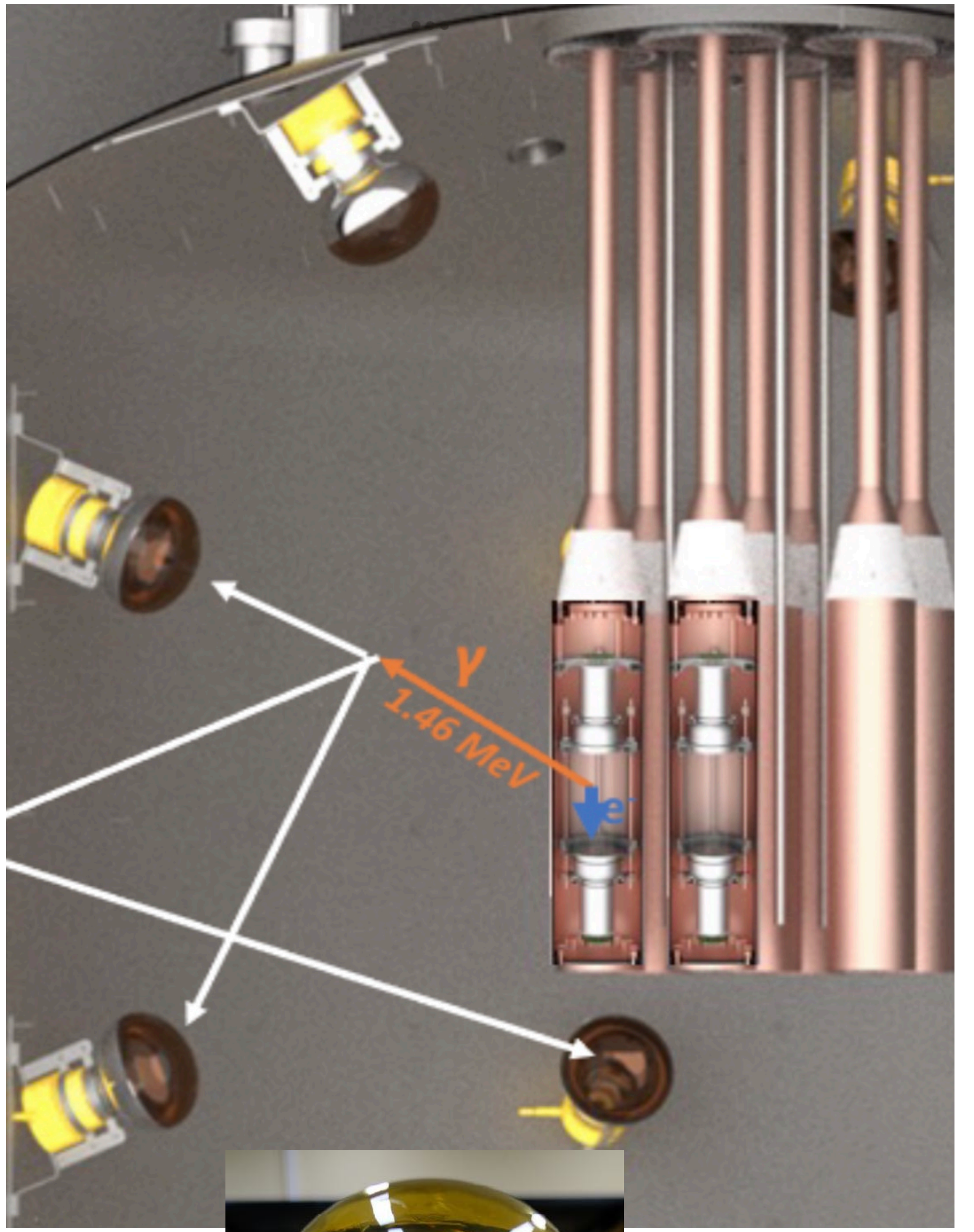


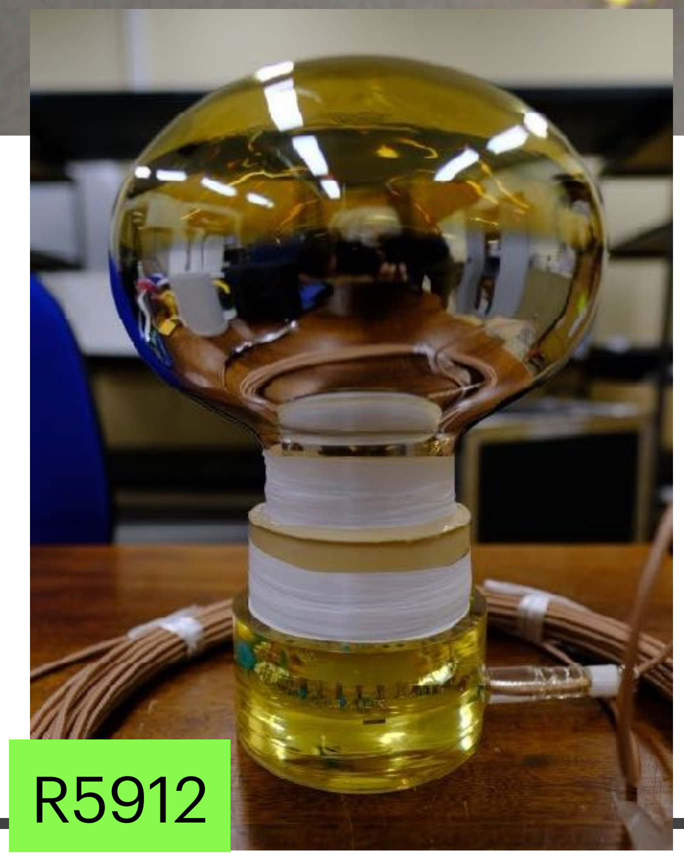
LS System

4π coverage:

- 12 kL Liquid alkibenzene from JUNO doped with PPO and Bis-MSB
  - Photon attenuation > 20m
  - $^{238}U/^{232}Th<10^{-15}$ g/g, $^{40}K<10^{-17}$ g/g
- 18 204 mm PMTs (Hamamatsu R5912) oil proof
- 16 PMTs from Daya Bay for testing and possible integration in the LS Veto system.







Any radioactive decay with gamma > 100 keV can be detected

Timeline

2023				2024				2025			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

Crystal production, transport, cool-down

Clean room, glove box

NaI enclosure assembly, testing

NaI installation

Veto tank prep.

Installation

Fluid handling manufacturing

Installation

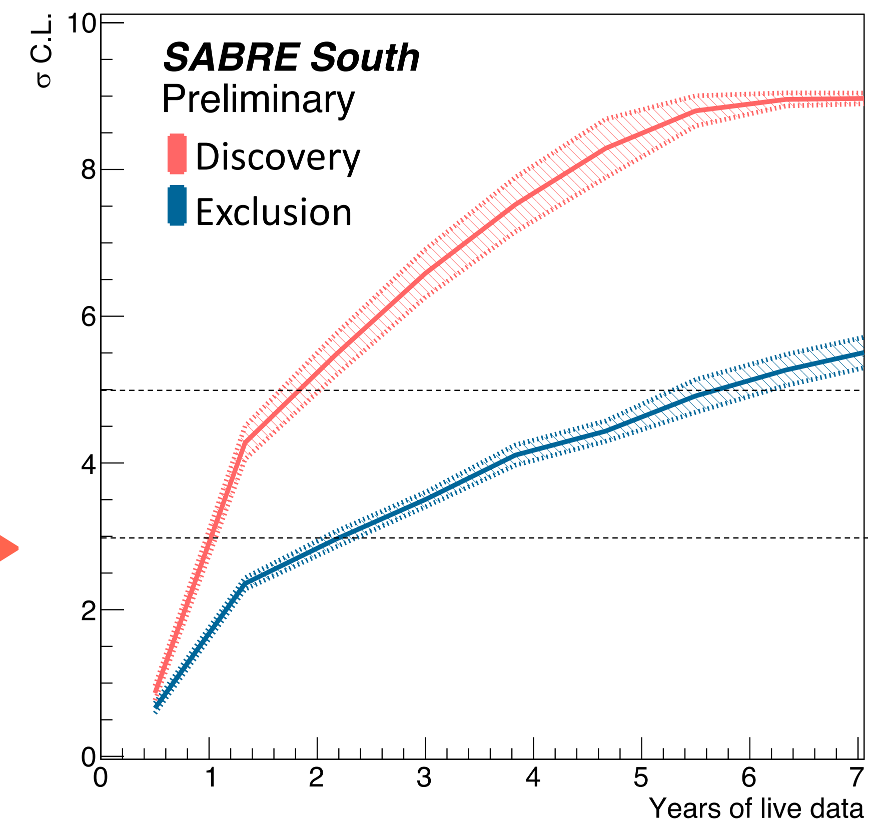
LS installation

Shielding stage 1

Shielding Stage 2

SUPL access and μ flux

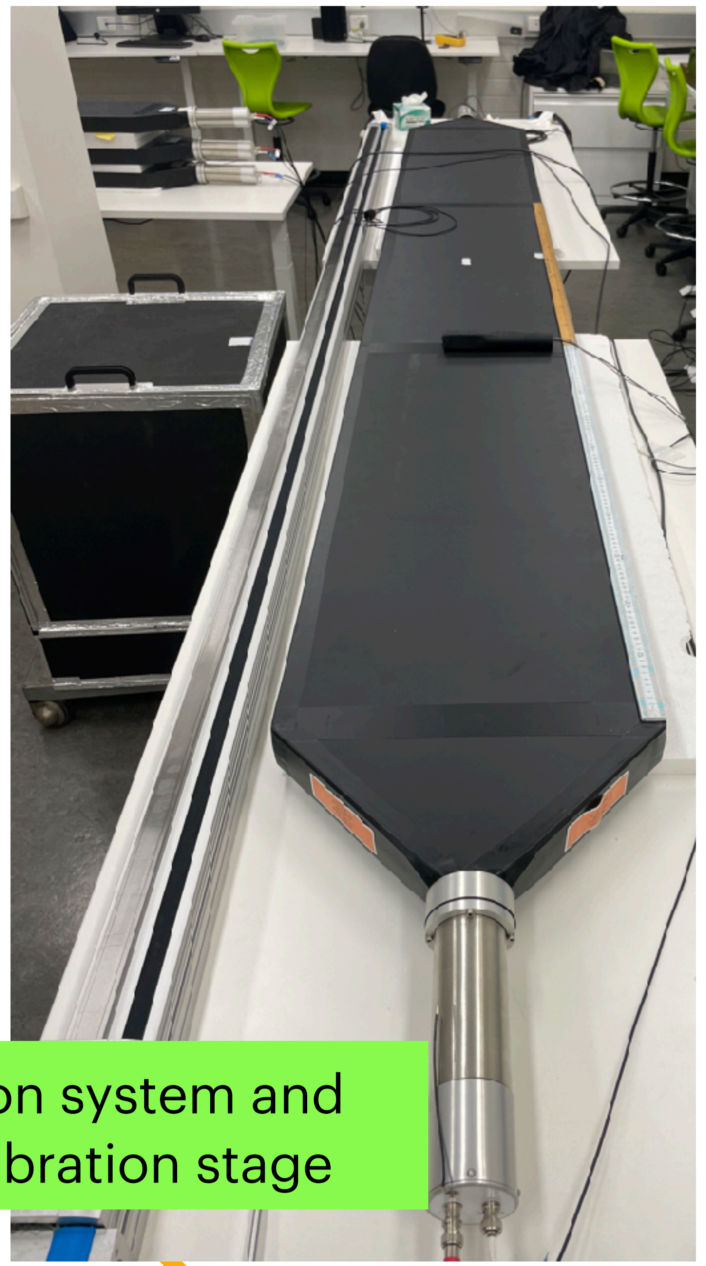
μ installation



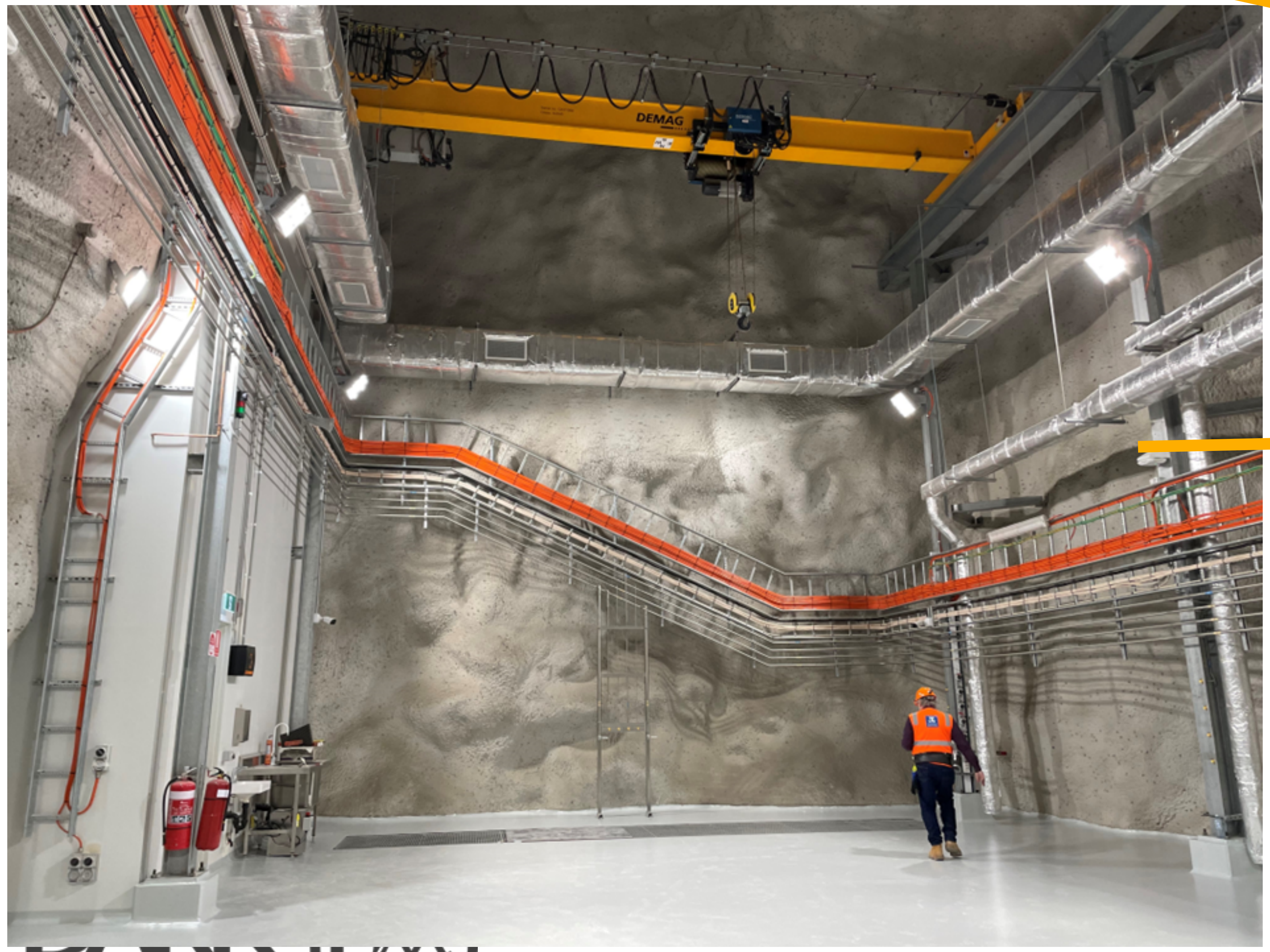
SUPL activities (near term)

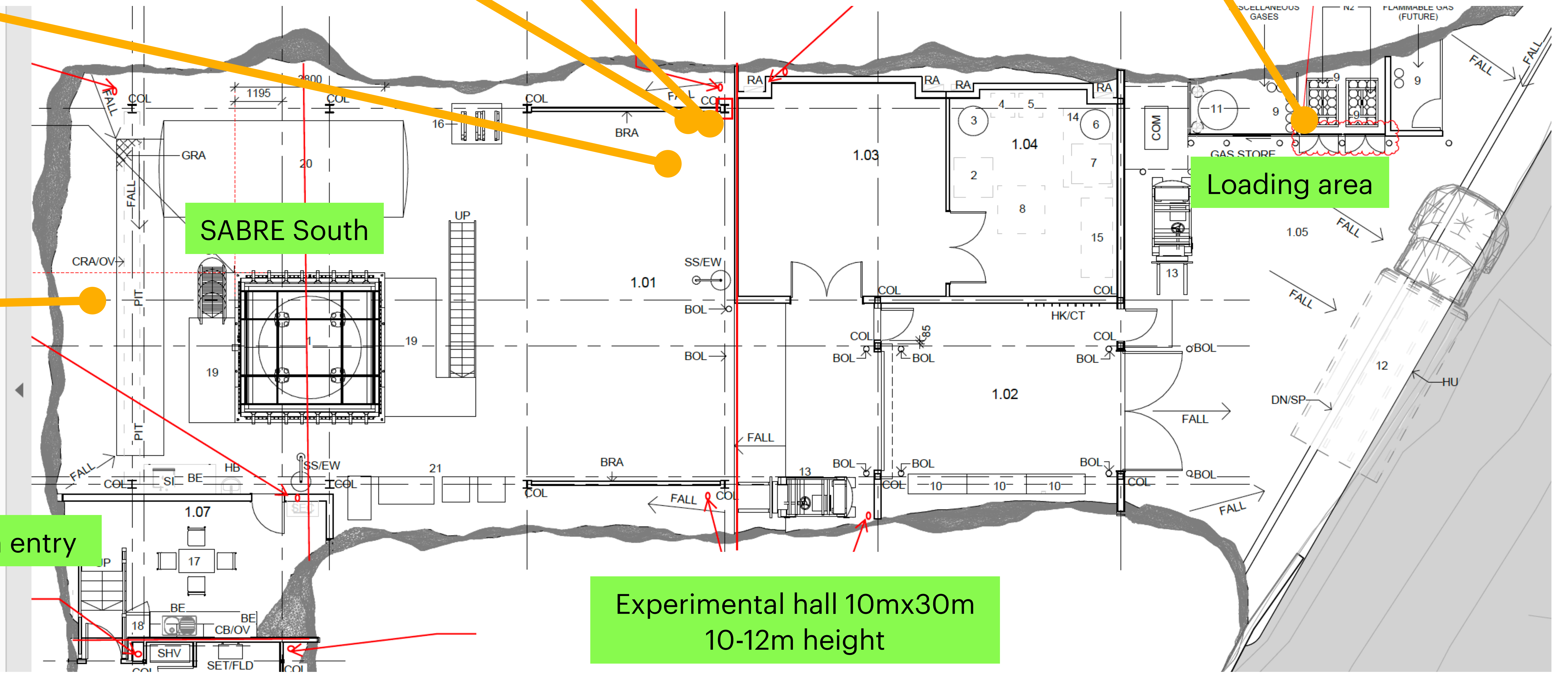
Lead castle for crystal assembly testing (pictured LNGS)

DAQ system



Muon system and calibration stage





SABRE South

Loading area

Clean entry

Experimental hall 10mx30m 10-12m height

Clean spaces

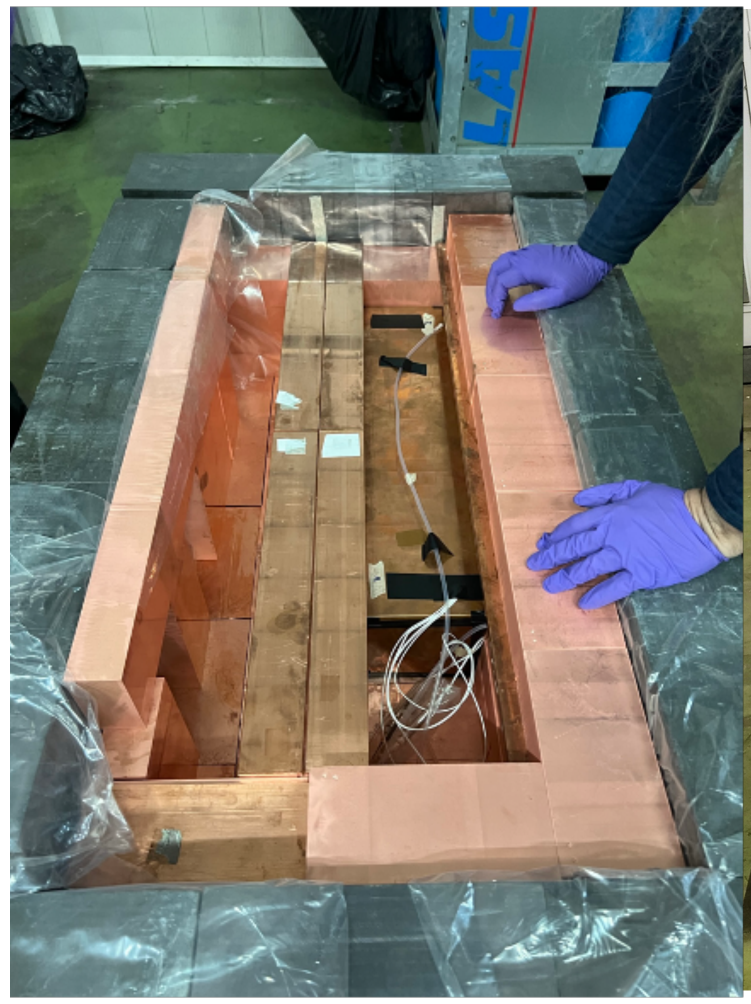
- 2 Main facilities (Figures shown are from LNGS) with ISO-7 performance.

- **NaI assembly clean room/tent**
  - Clean room under muon parking frame
  - Assembly glove box.
  - Storage for materials
- **Facility for characterisation necessary at SUPL. Shielded volume: lead with N2 or compressed air flushed box**

- **Veto Tent**
  - Cover to prevent Radon plate-out in the vessel during lumirror, PMT, calibration system mounting

- For both Rn mitigation is our primary concern. We are discussing with SGM to use “compressed airline” delivering low Rn air from the surface for use in refuge chambers near SUPL.

Veto vessel tent for SABRE PoP at LNGS




NaI(Tl) detector characterisation castle at LNGS

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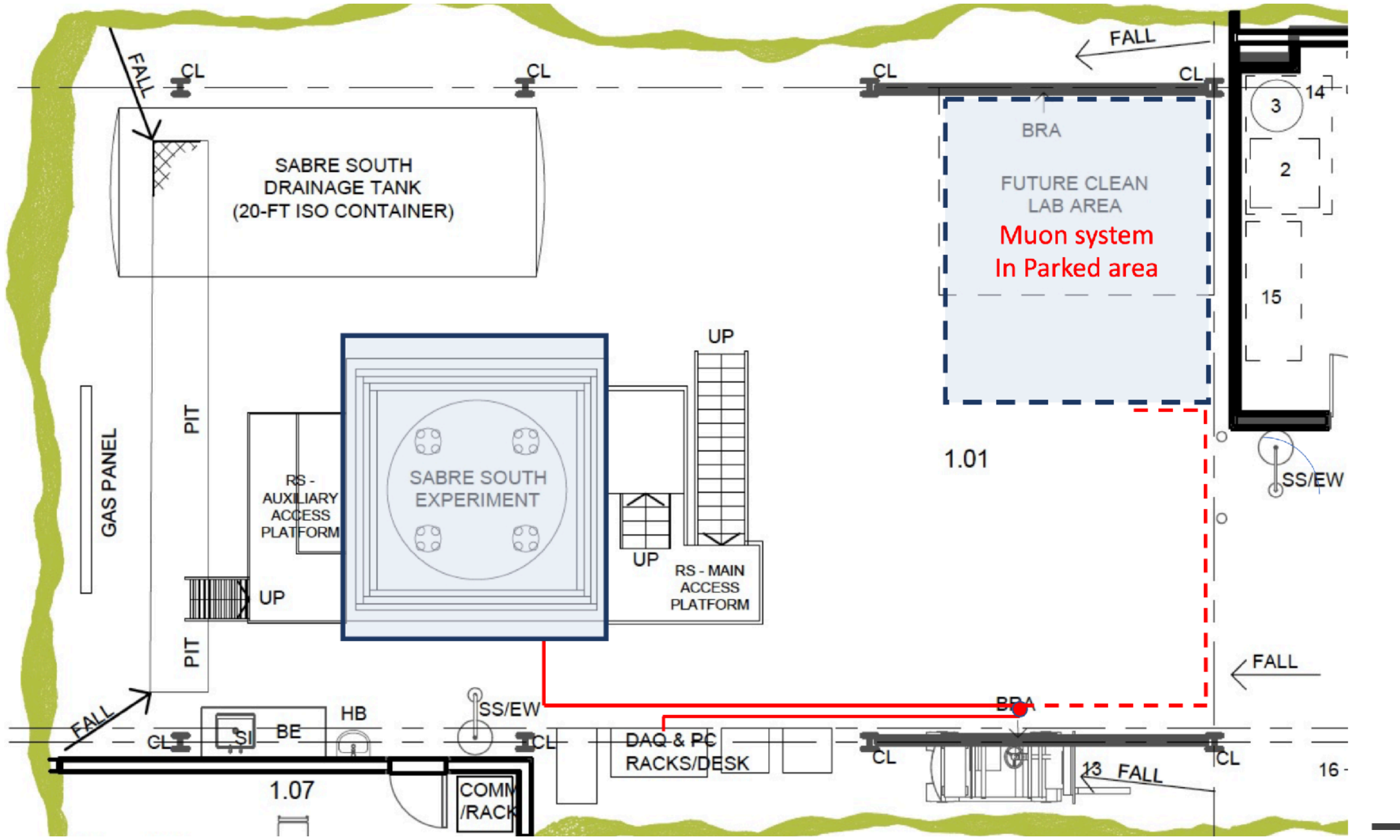
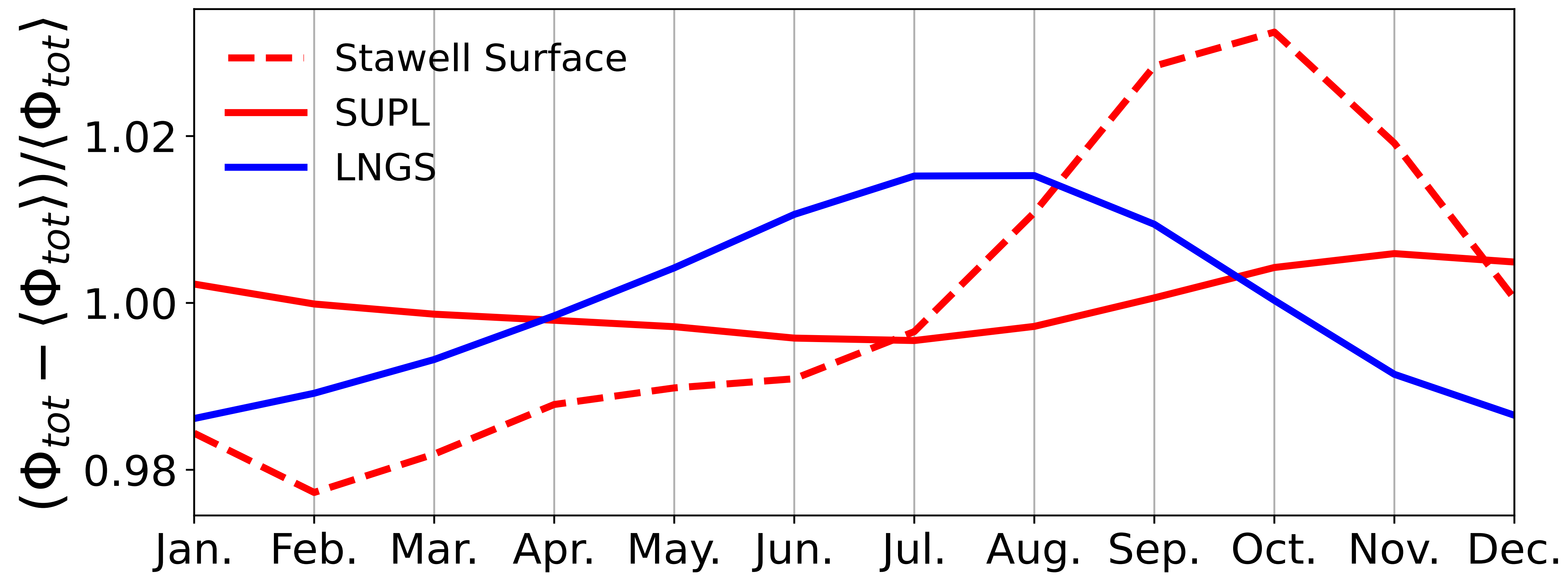
First to go down: Muon System

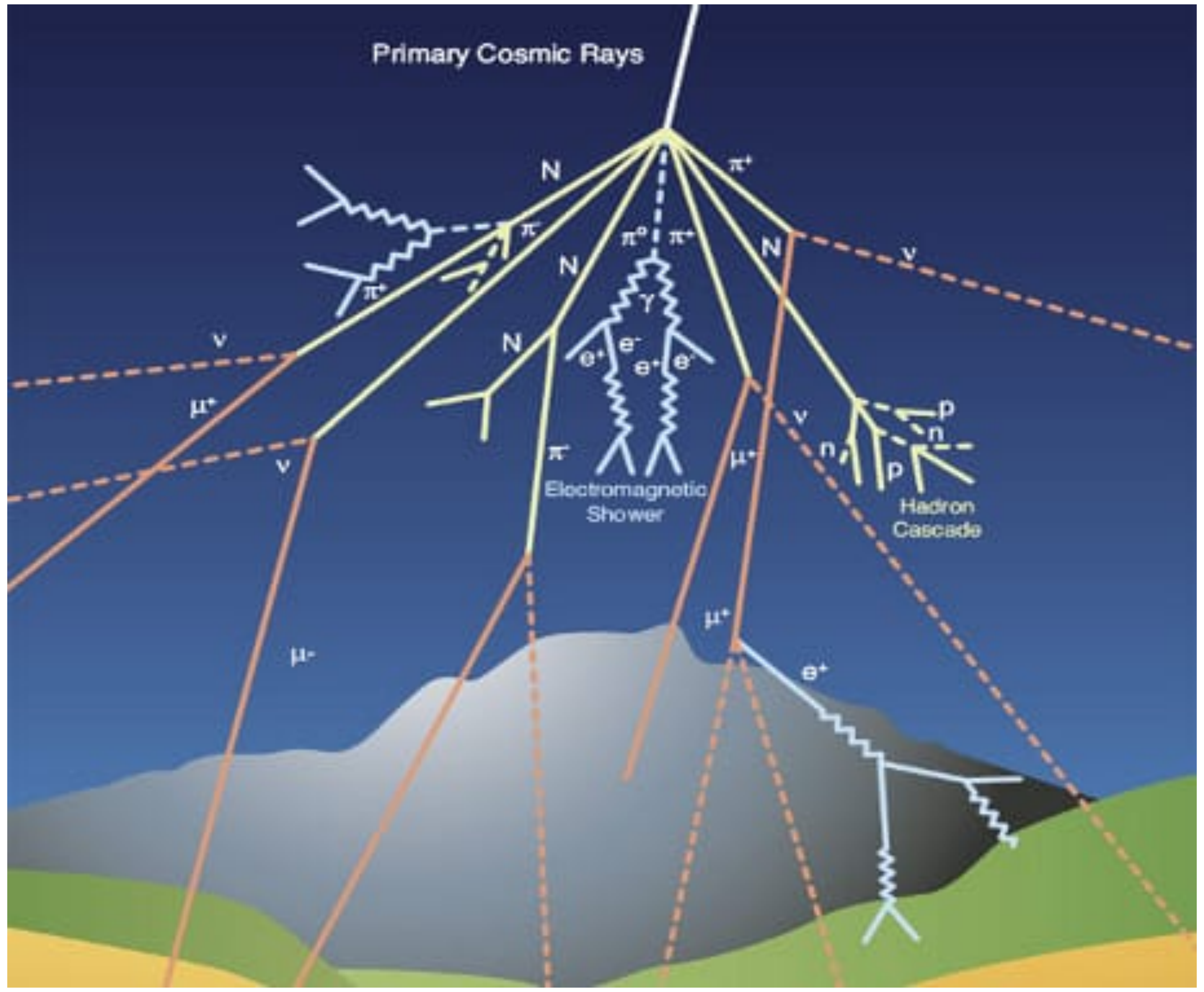
- **Geometry:** 3m x 0.4m EJ200 x 8 modules. 2-PMT readout ToF-type system with ~5cm position resolution along detector.
- Veto for background directly above crystals (avoiding LAB), and for muon flux.

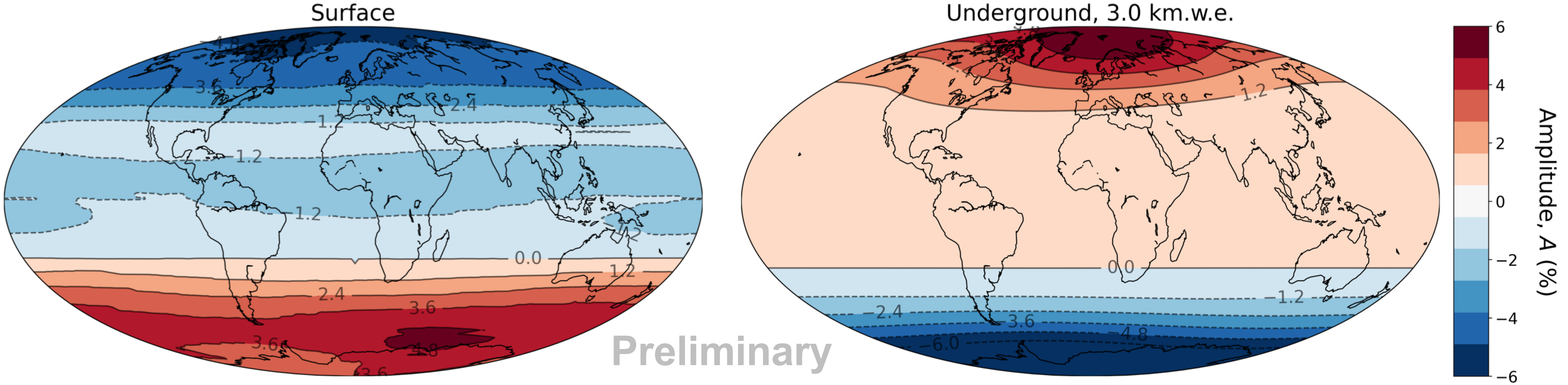


- **Stage 1**: 2 layer configuration for μ flux vs. direction at SUPL (1025 m)
  Ready for deployment in January 2024.
- **Stage 2**: SABRE μ Veto and muon flux modulation studies.

Muon flux

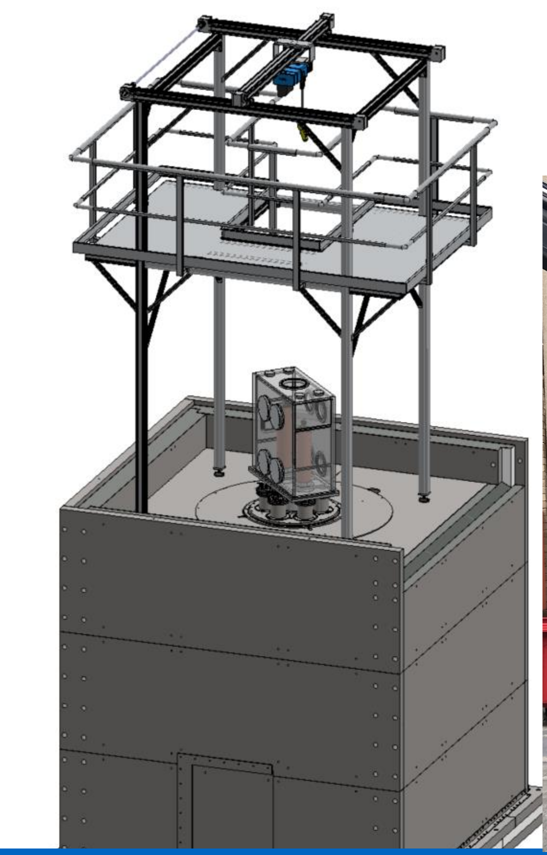




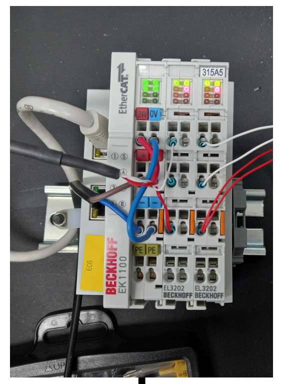


Preliminary

Other achievements

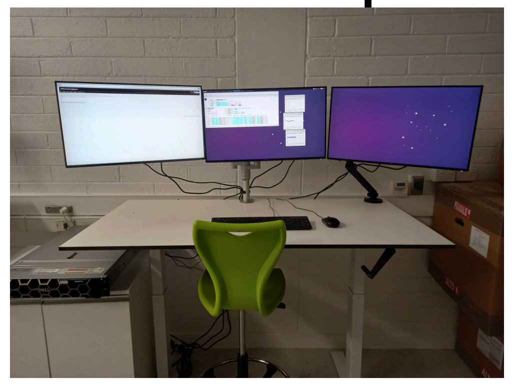
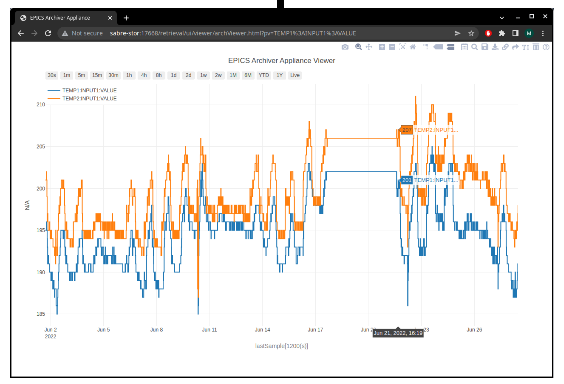



Crystal Insertion system

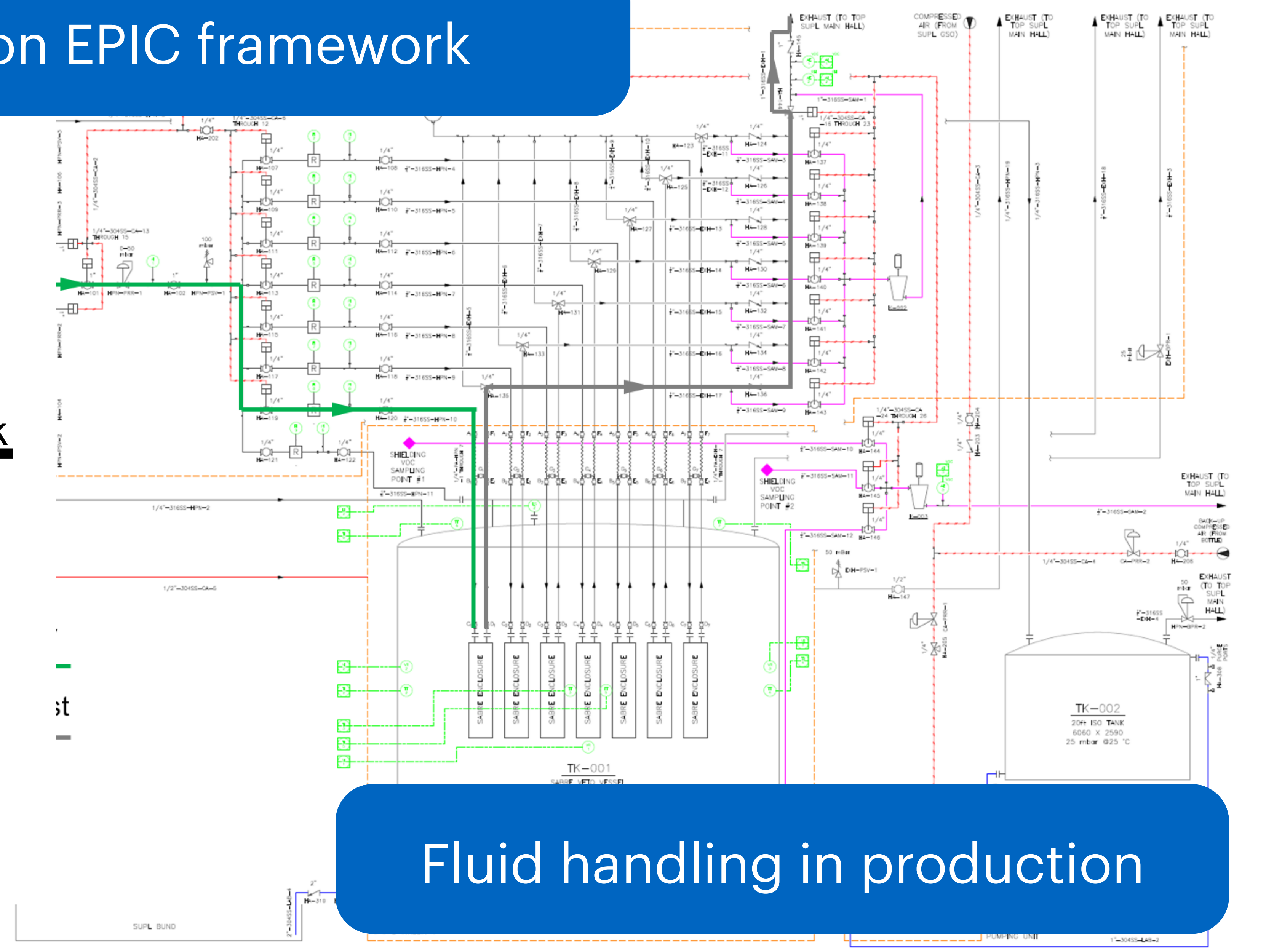



DAQ & Monitor

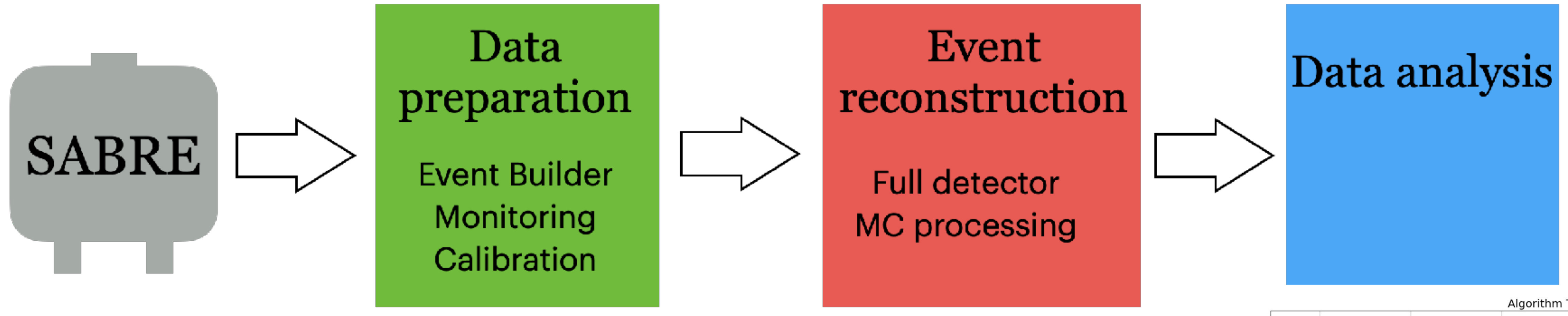
Network

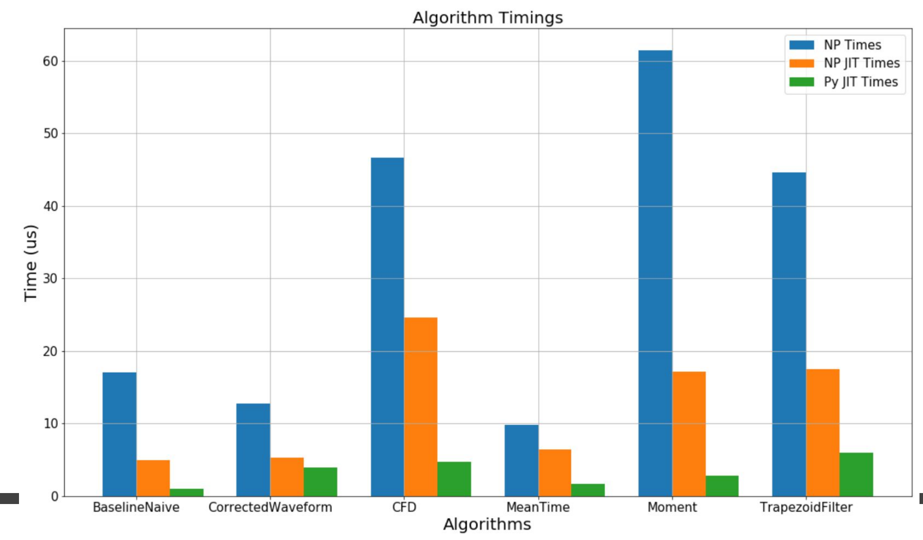
Common EPIC framework

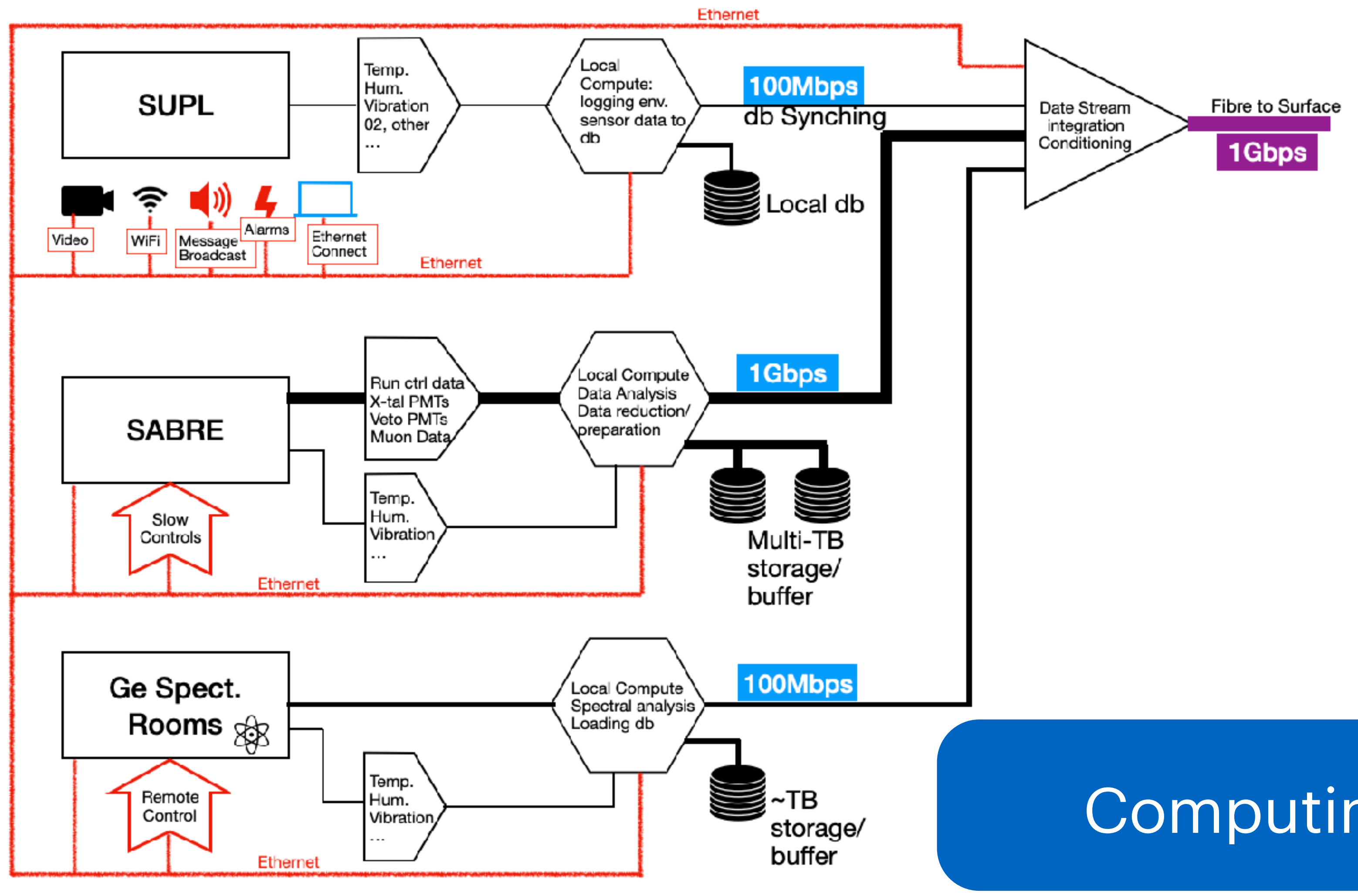


Fluid handling in production



Offline software framework

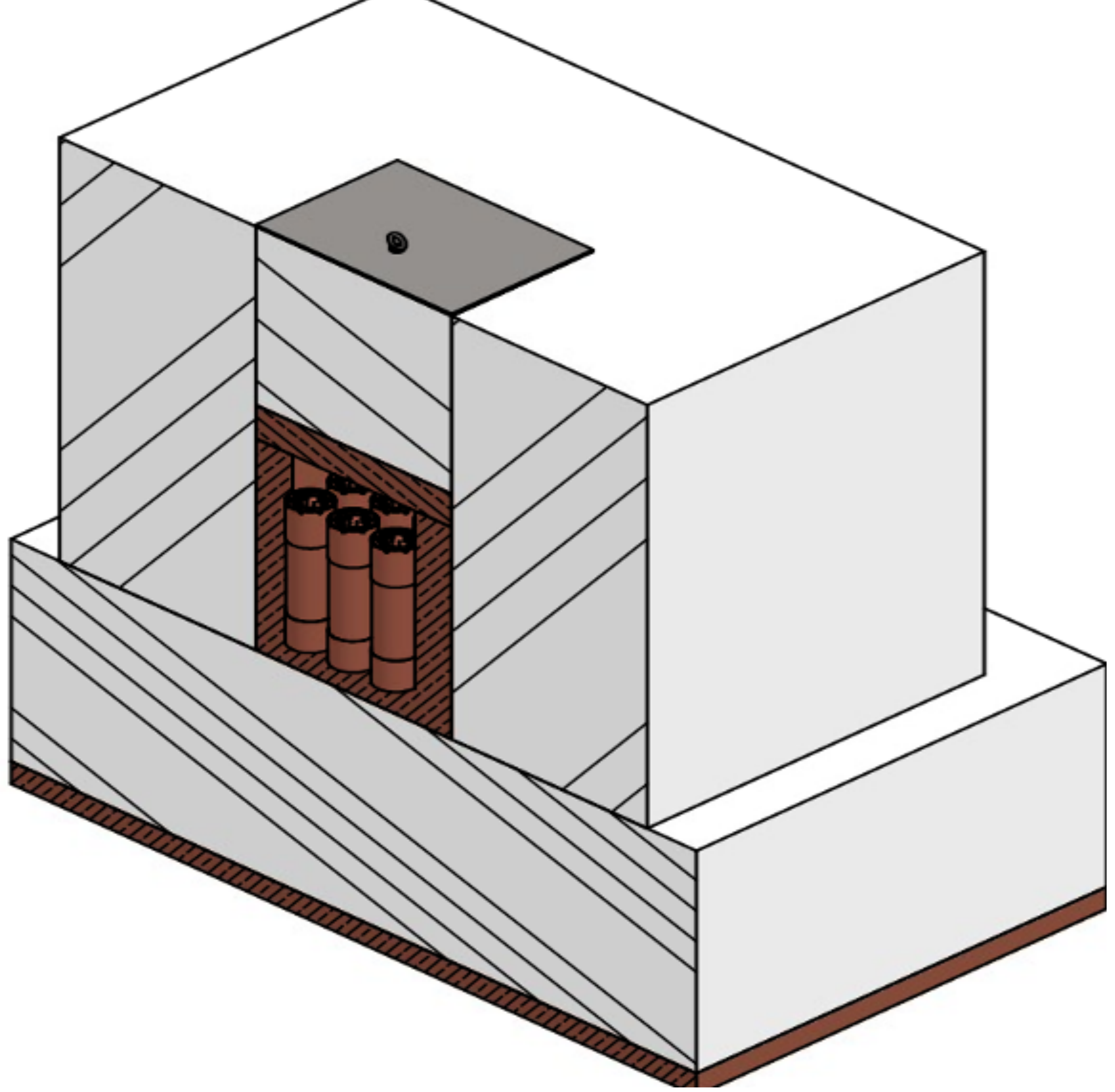


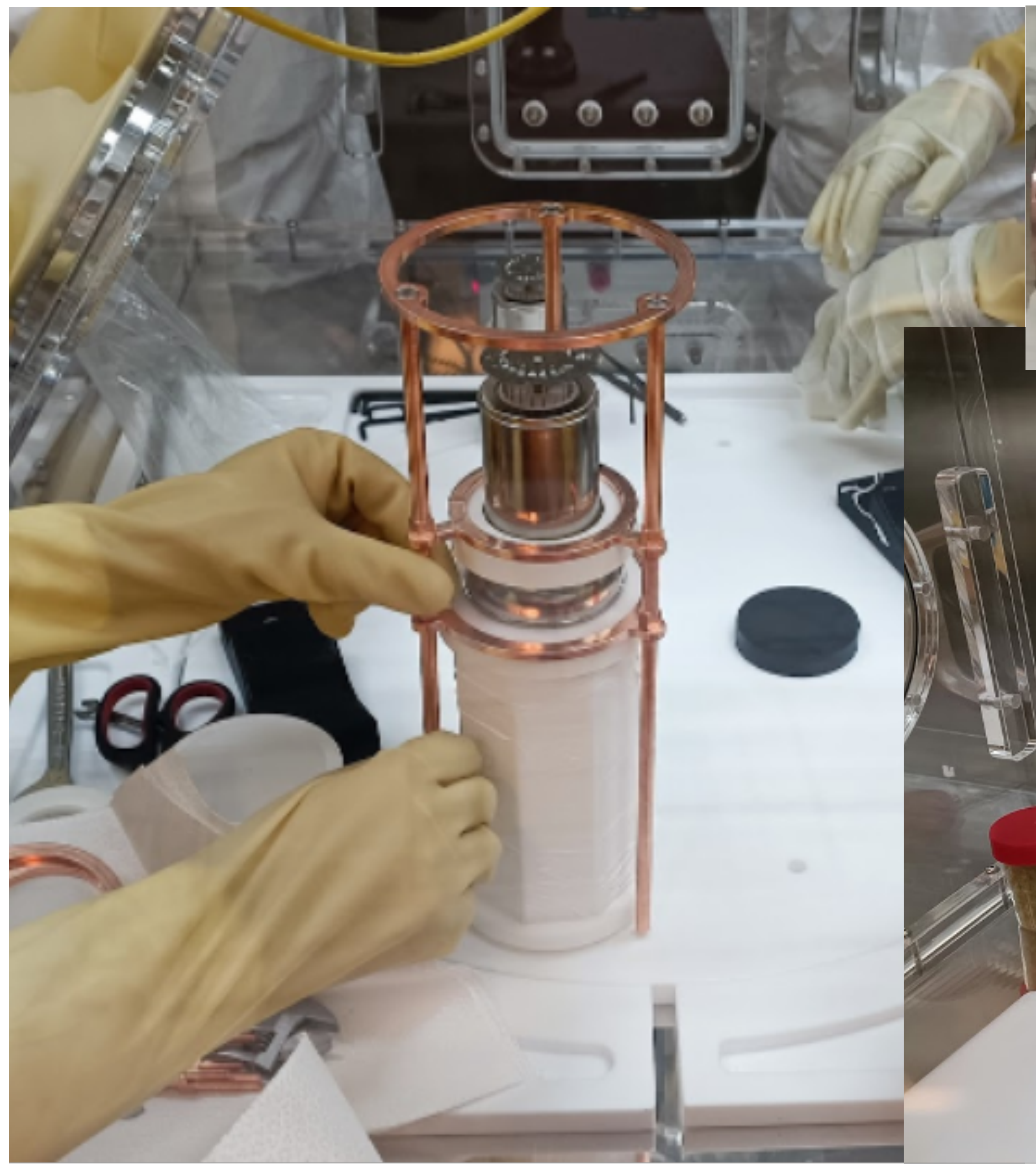


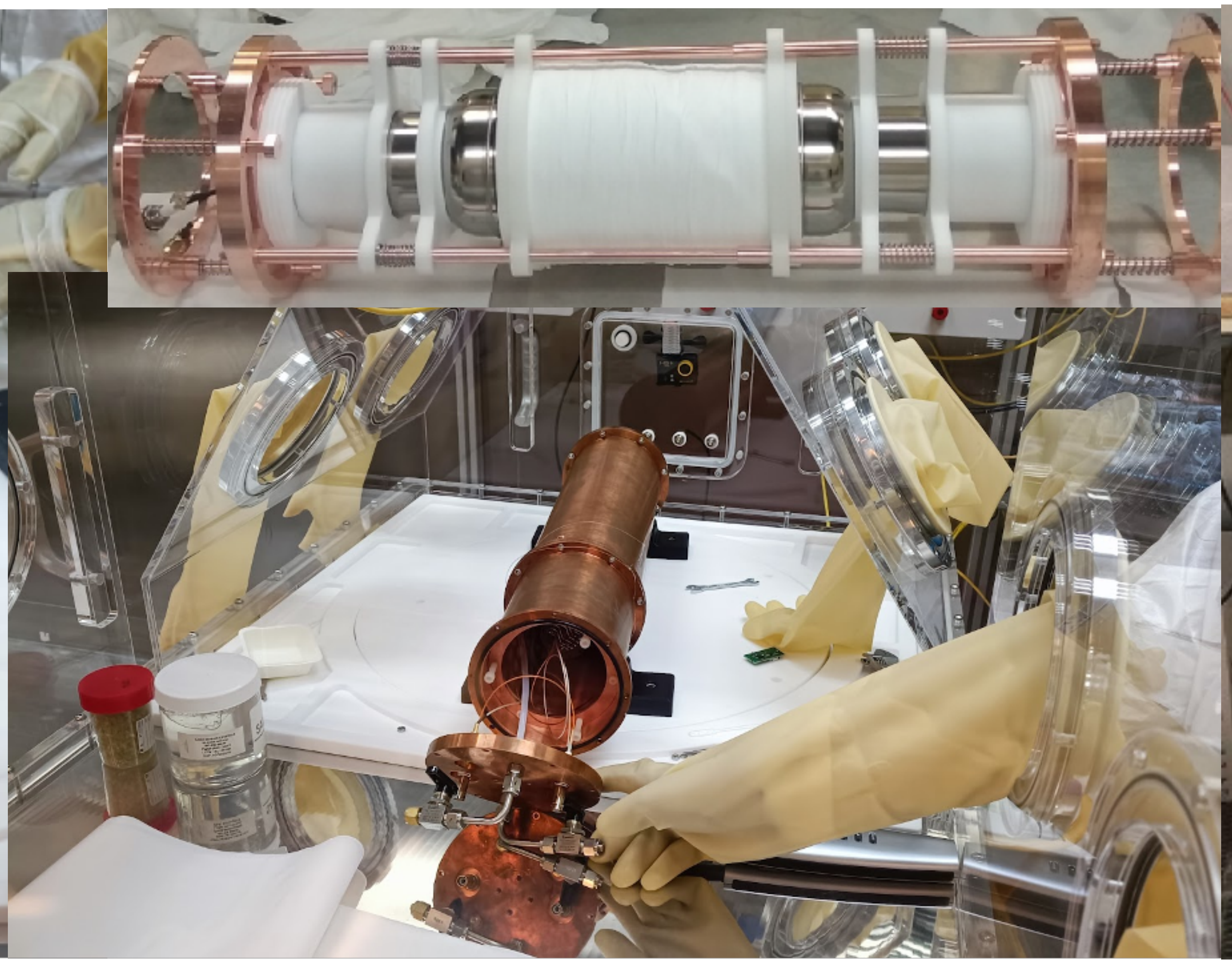
Computing

SABRE North status

- 3 x 3 matrix of ≈ 5 kg NaI detectors (40 kg)
- Inner 5 mm thick ultra pure Cu box
- 10-15 cm Cu and 80 cm PE shielding structure (~ 30t)
- Predicted background from environmental gamma and neutrons ~0.01 dru in the ROI





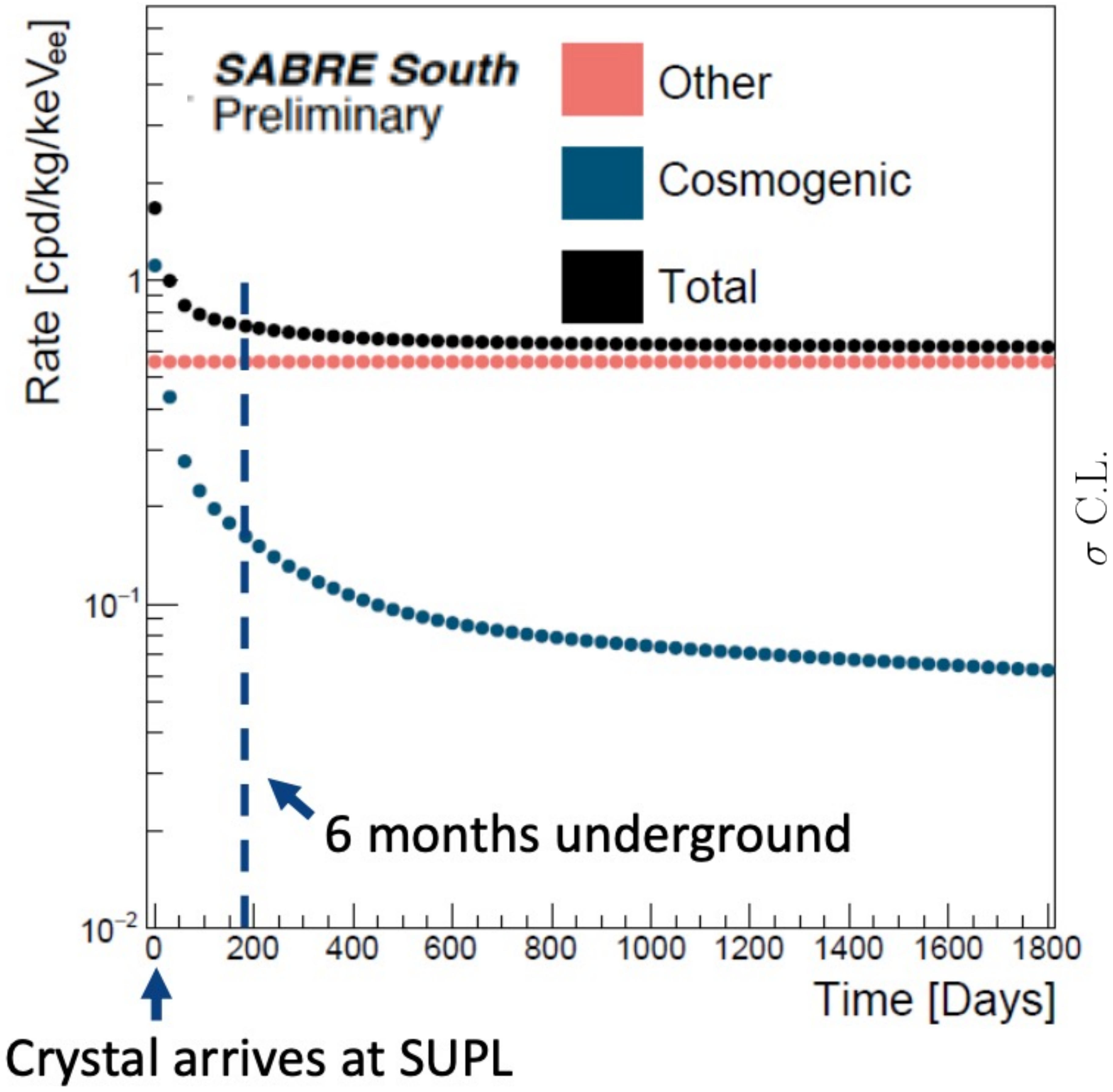


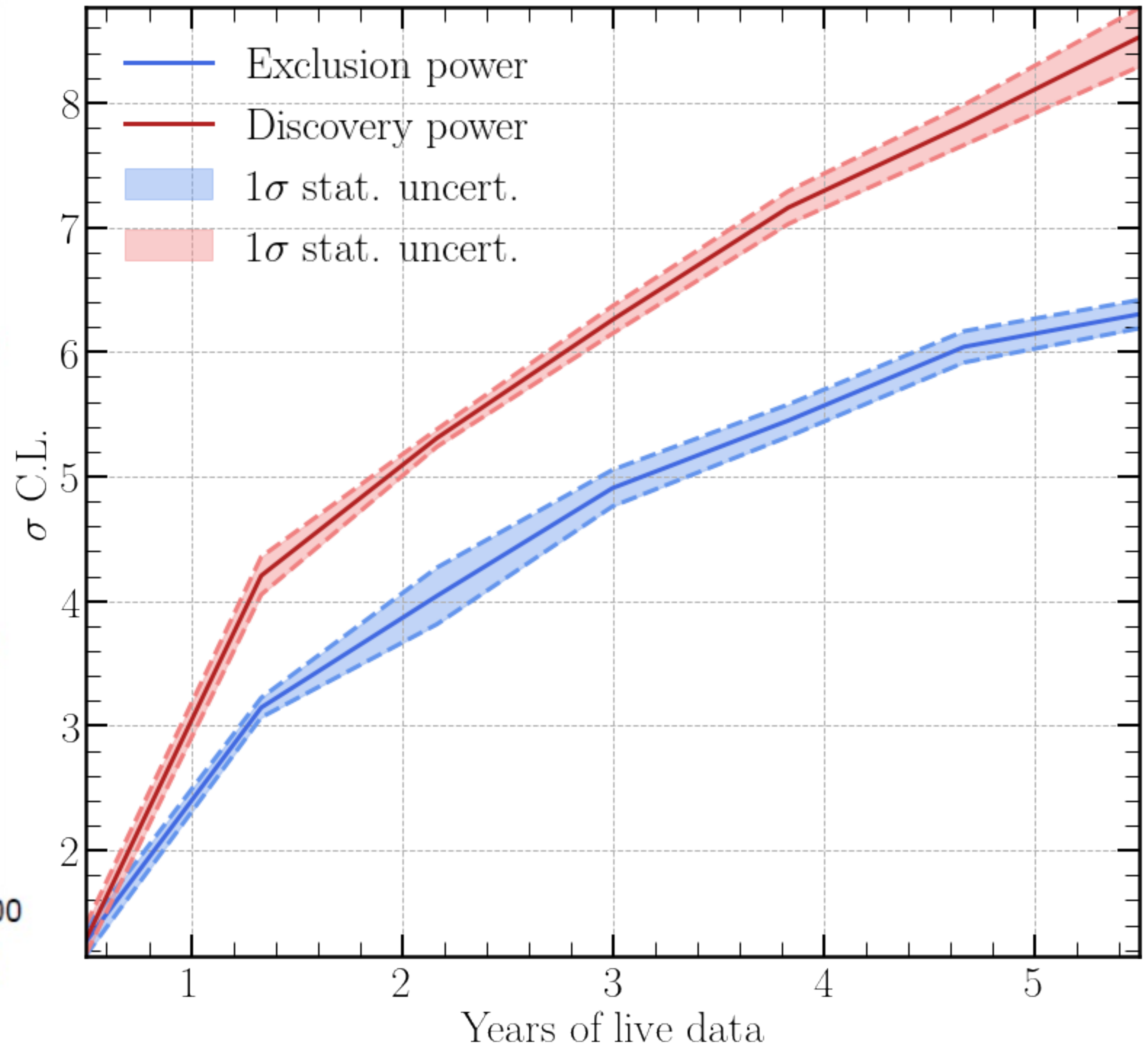
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

SABRE Impact

SABRE South arXiv: 2205.13849

- Crystal background from NaI-33
- Cosmogenic background ^3H (half life 12.4 yrs)





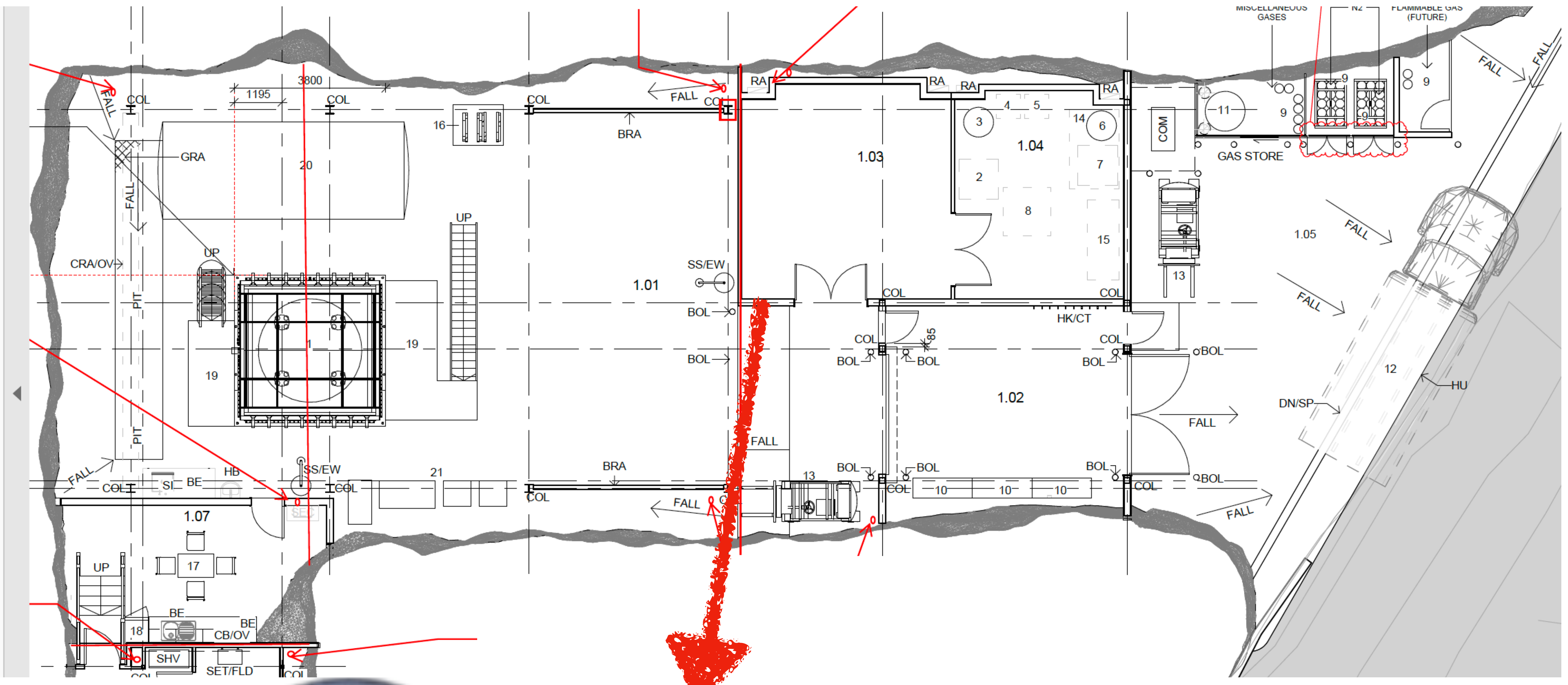
Assuming total crystal mass of 35 kg and background of 0.5 cpd/kg/keV

Sensitivity ~$\sqrt{M/R_b}$,

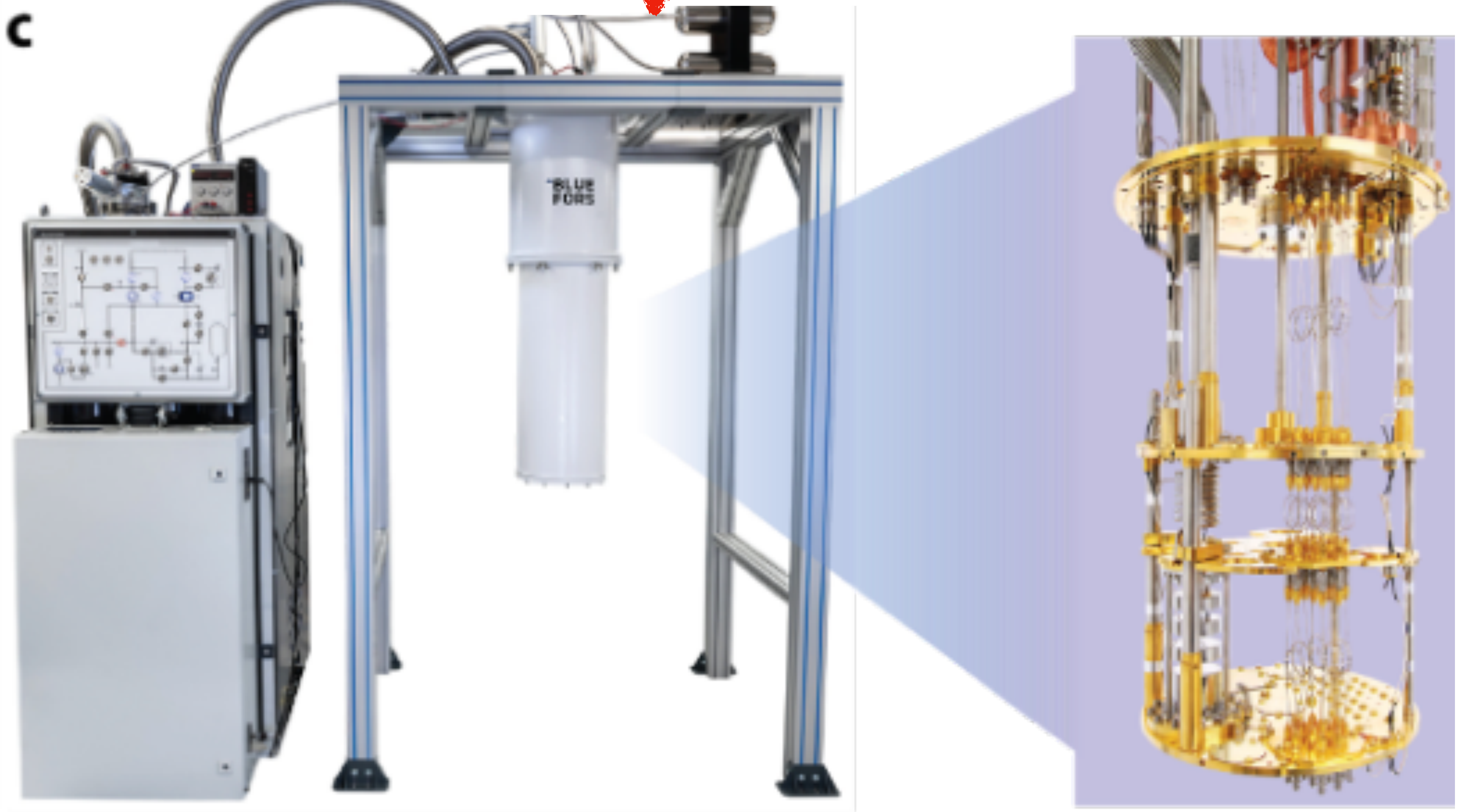
Statistically significant results with 2-3 years of exposure

CELLAR

- Dilution refrigerator (10 mK base) in SUPL
- Another at Swinburne (30 mK base)
- Rare combination of deep underground lab and cryogenics
- Enable extremely low background research
- Research areas: quantum tech, gravitational waves, dark matter, etc
- Open-access facility for Australian researchers



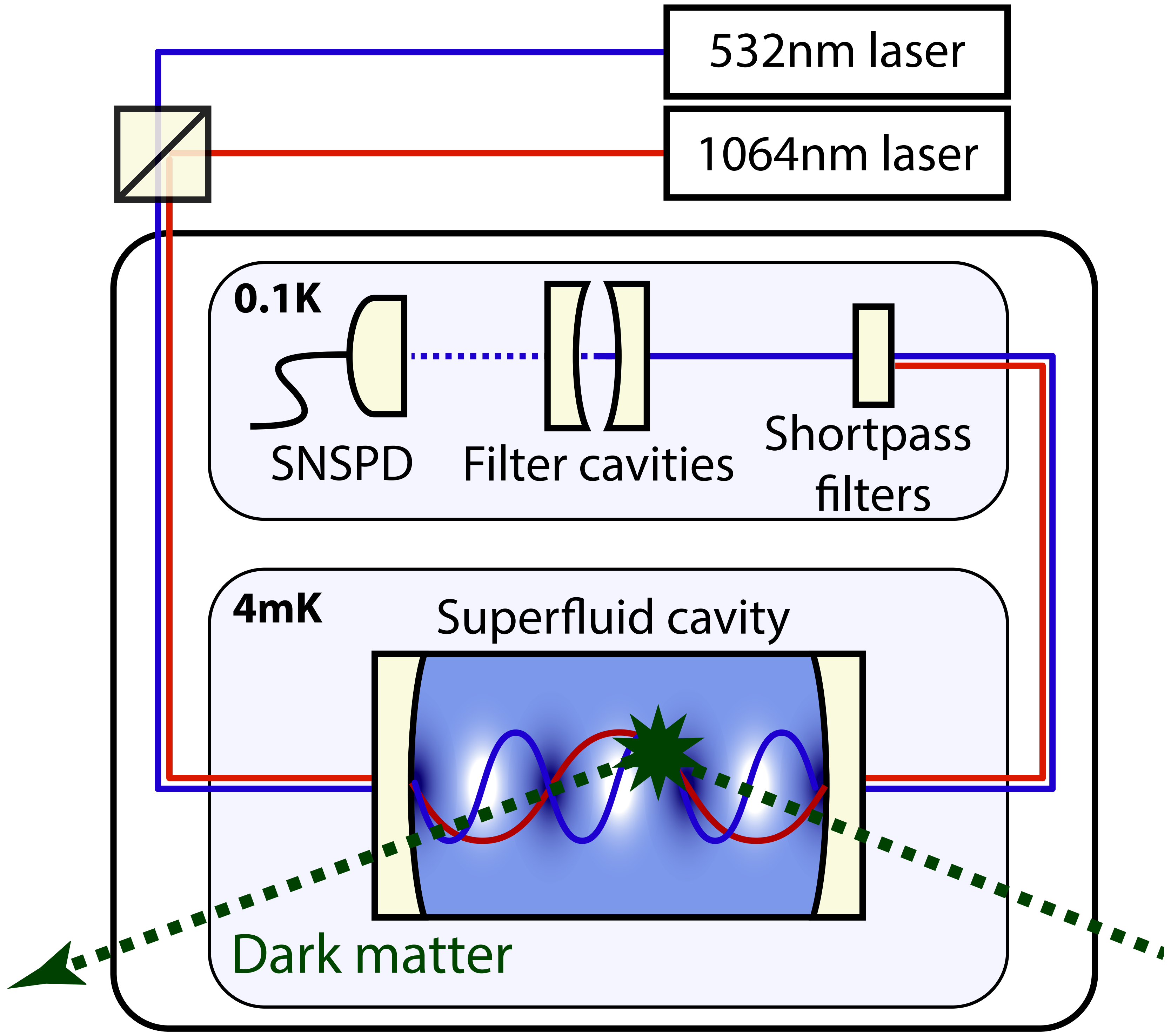
c



Ultra-low-mass DM reaches

https://arxiv.org/pdf/2306.09726.pdf

Optomechanical Dark Matter Direct Detection: ODIN



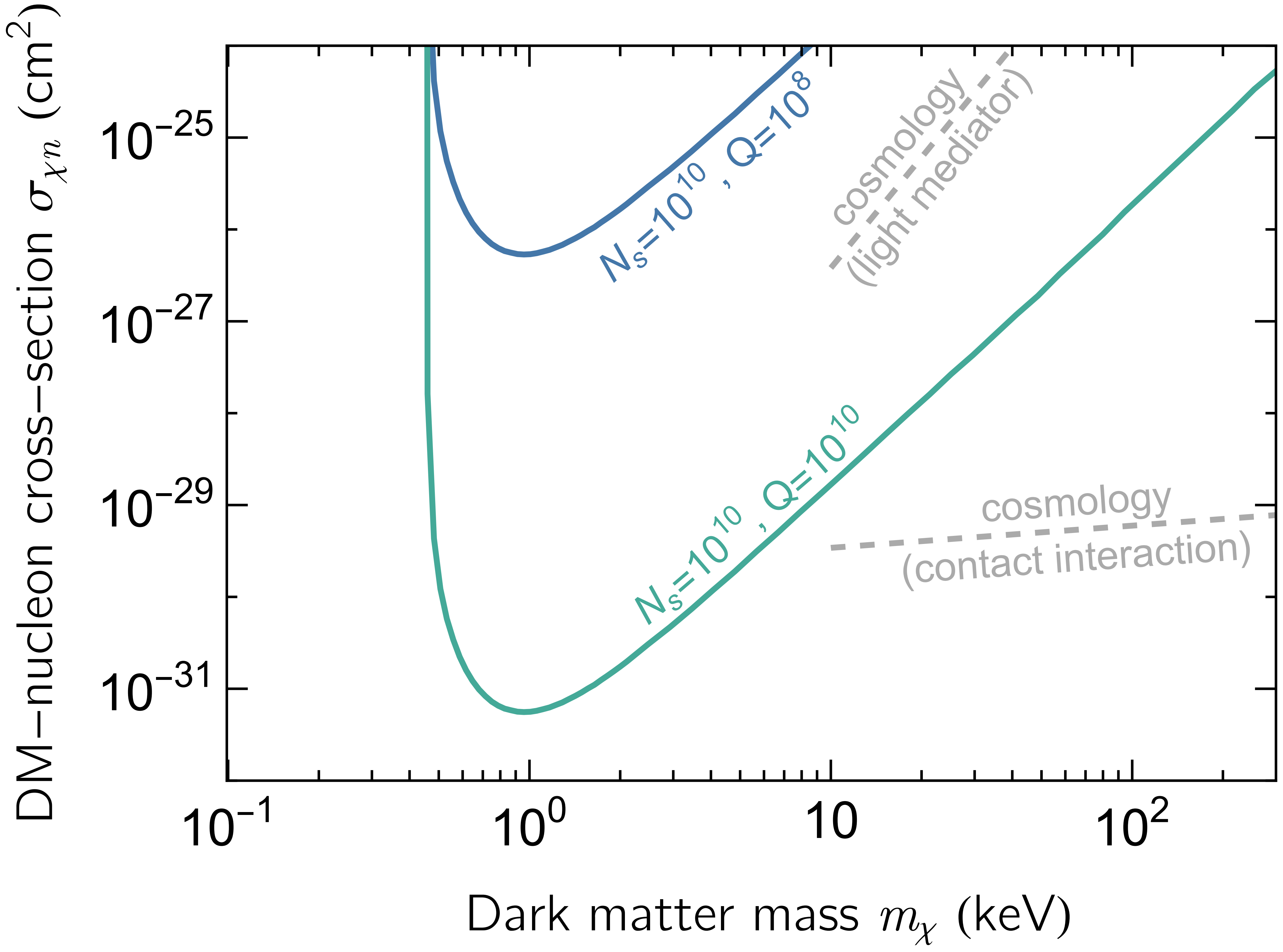


FIG. 4. Projected 90% C.L. upper limits on the dark matter–nucleon cross-section at ODIN, $\sigma_{\chi n}$, assuming a run time of 100 days.

OTHER ACTIVITIES AT SUPL

Planned:

- Ultra-low background Ge counting facility

- R&D facility for cryogenics dark matter detectors & TPC detector prototypes

- Geophysics

Woking on it:

- Low background radiation biophysics : Study the biological effects of very low background radiation.

- Extremeophile astrobiology – life in extreme environments (no oxygen, high T, high p)