Dark Matter direct detection at the Stawell Underground Physics Laboratory

Irene Bolognino
The University of Adelaide

INFN Laboratori Nazionali di Frascati - 27th September 2023

Research Activities

Astroparticle Physics

Dark Matter:

- SABRE: SABRE North (LNGS, Italy), University of Milan, Italy. SABRE South, (SUPL, Australia), University of Adelaide, Centre of Excellence for Dark Matter and Particle Physics, Australia.
- Cygnus (SUPL, Australia), University of Adelaide, Centre of Excellence for Dark Matter and Particle Physics.

Cosmic-rays:

- LAGO (South America), University of Turin, Italy.
- ARGO-YBJ (YangBaJing China), University of Pavia, Italy.

Neutrinos:

- SoLid (BR2, Belgium), University of Nantes and SUBATECH laboratory, Nantes, France.
- Borexino (LNGS, Italy), University of Milan, Italy.


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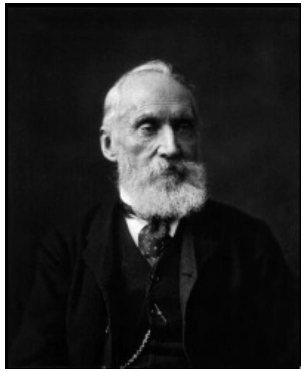
Irene Bolognino

Outline

- Dark Matter.
- Direct detection through Dark Matter modulation.
- The SABRE South experiment at SUPL laboratory (Australia).

Dark matter: a problem with a long history…



Lord Kelvin (1904)

Found a difference between the estimated mass of the galaxy (from observed velocity dispersion of the stars) and the stars we can see.
There was a difference between that mass and the stars we can see.

"Many of our stars, perhaps a great majority of them, may be dark bodies."

Henri Poincaré (1906)

"Since [the total number of stars] is comparable to that which the telescope gives, then there is no dark matter, or at least not so much as there is of shining matter."

Albert Einstein (1921)

Studied star clusters.

"The non luminous masses contribute no higher of an order of magnitude to the total mass than the luminous masses."

Dark matter: a problem with a long history…

Fritz Zwicky (1933)

Studied the COMA cluster, cluster of galaxies

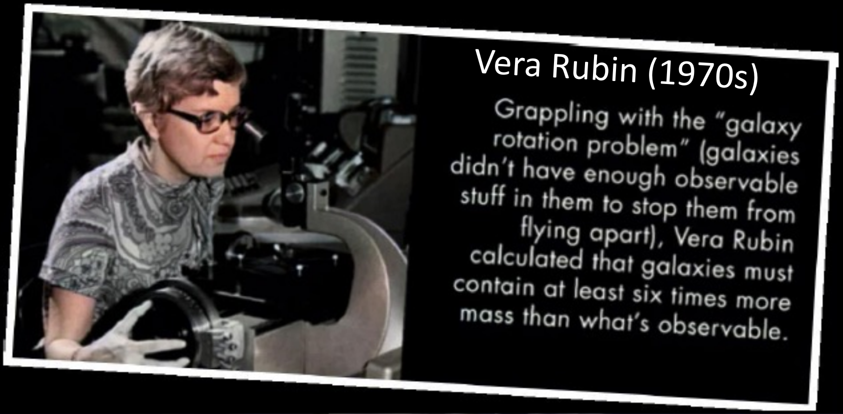
"According to present estimates the average density of dark matter in our galaxy and throughout the rest of the universe are in the ratio 100,000."

Collection of more than a thousand galaxies that are gravitationally bound together.

They all orbit around their collective centre of mass.

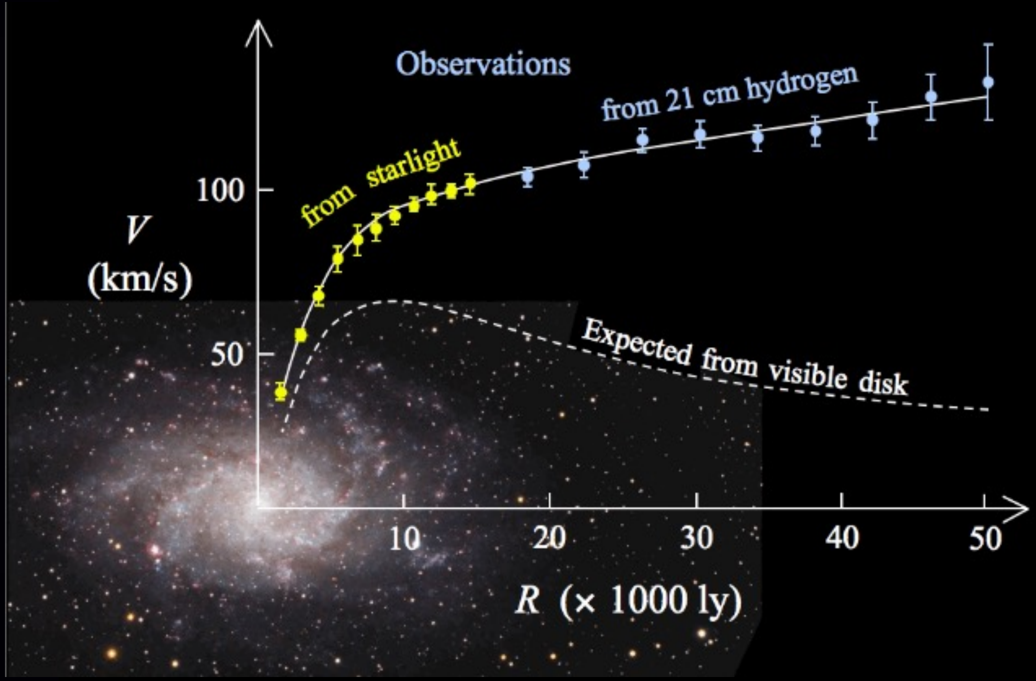
Measurements of the orbital speed of these galaxies showed that somewhere objects were moving faster than he expected as there was a lot more matter in the cluster than he could see.

Dark matter: further strong evidence



Without additional mass in the galaxy, to pull those stars in, they should be flung off into space!

The result was the same in other galaxies.



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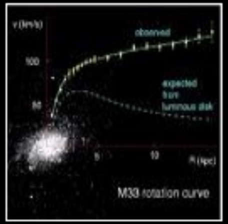
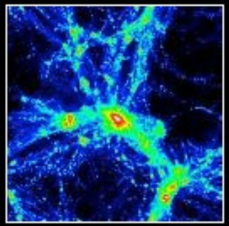
What is the Universe made of?

What is the Universe made of?

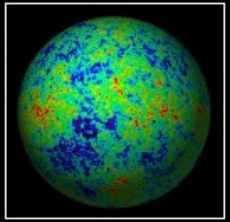
OBSERVATIONS



• Rotation Curves

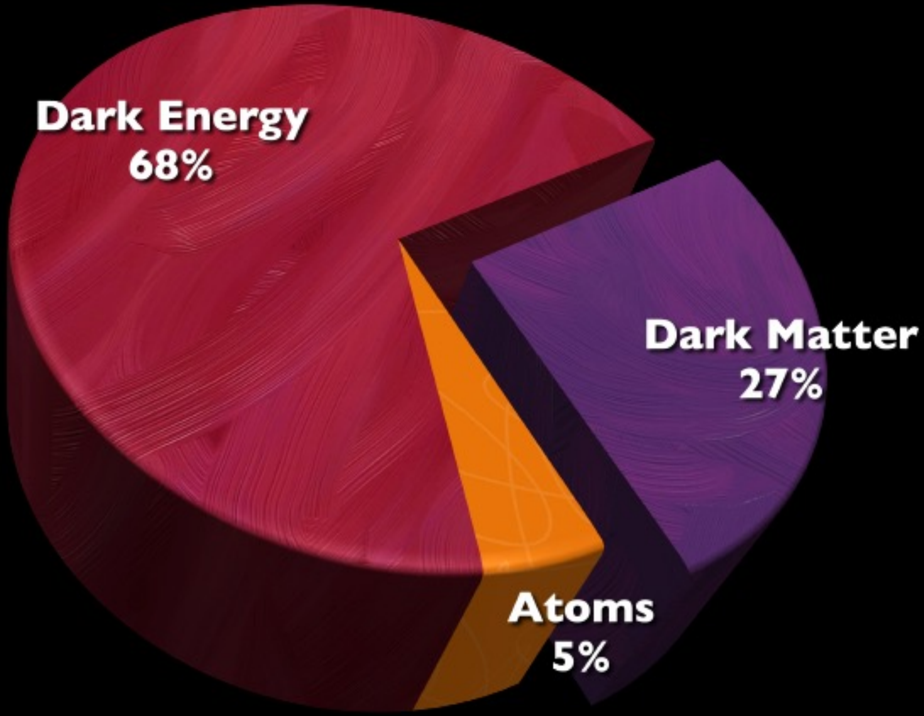


• Clusters of galaxies



• CMB

• Type Ia Supernovae

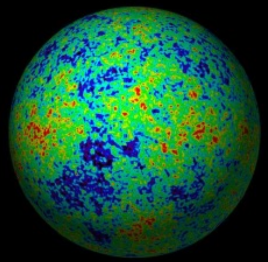


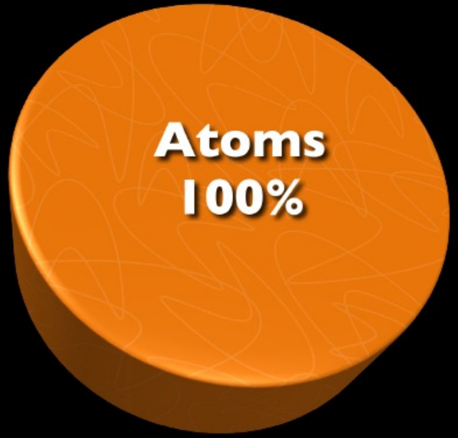
Dark matter is approx. 5 times the ordinary matter!

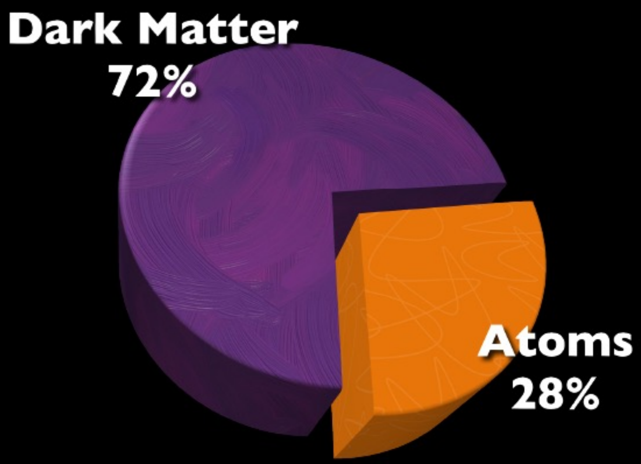
[statement valid *now*, and on *very large scales*]

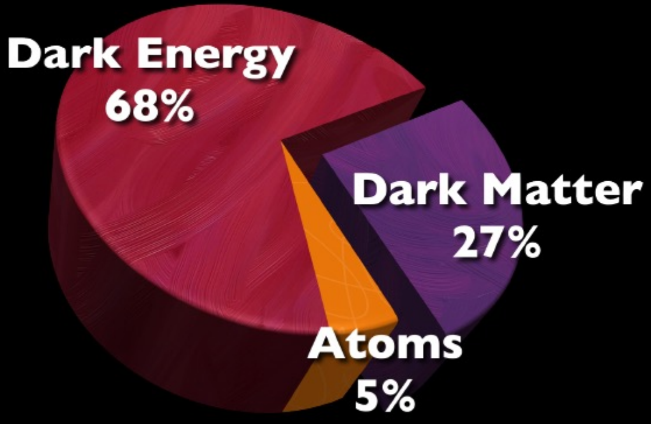
What is the Universe made of?

Posti & Helmi, A&A 621,A56 (2019)



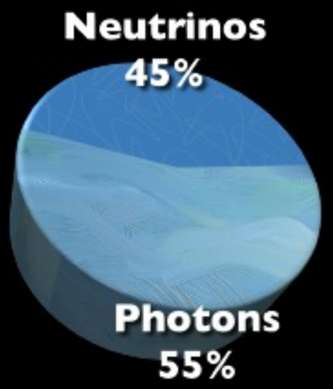






What was the Universe made of?

At BBN

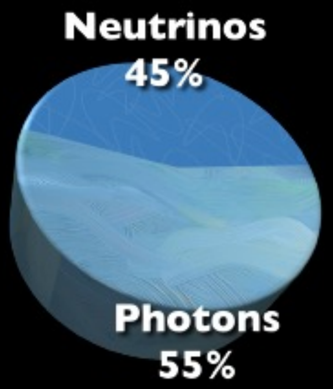


What was the Universe made of?

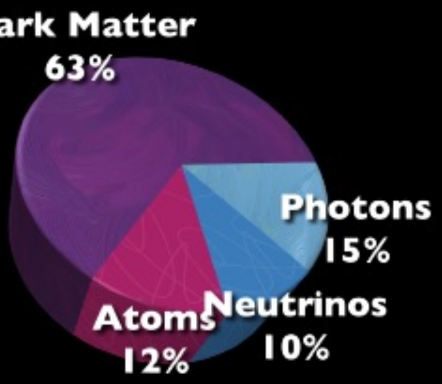
About 380,000 years after the Big Bang, matter cooled enough for electrons to combine with nuclei to form neutral atoms (recombination). The light that was released at this time is detectable today in the form of radiation from the Cosmic Microwave Background.

What was the Universe made of?

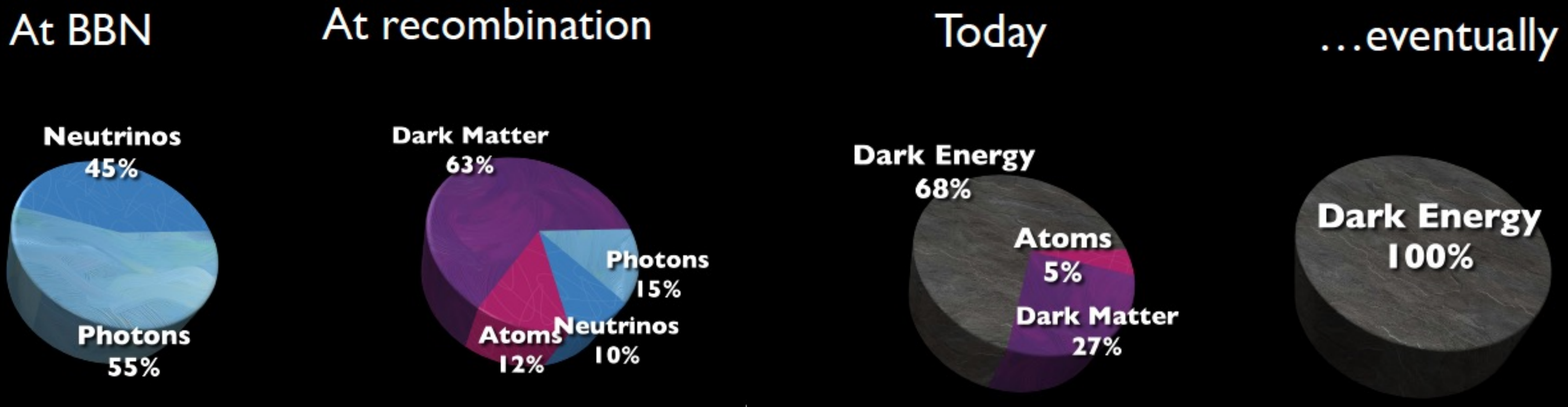
At BBN



At recombination



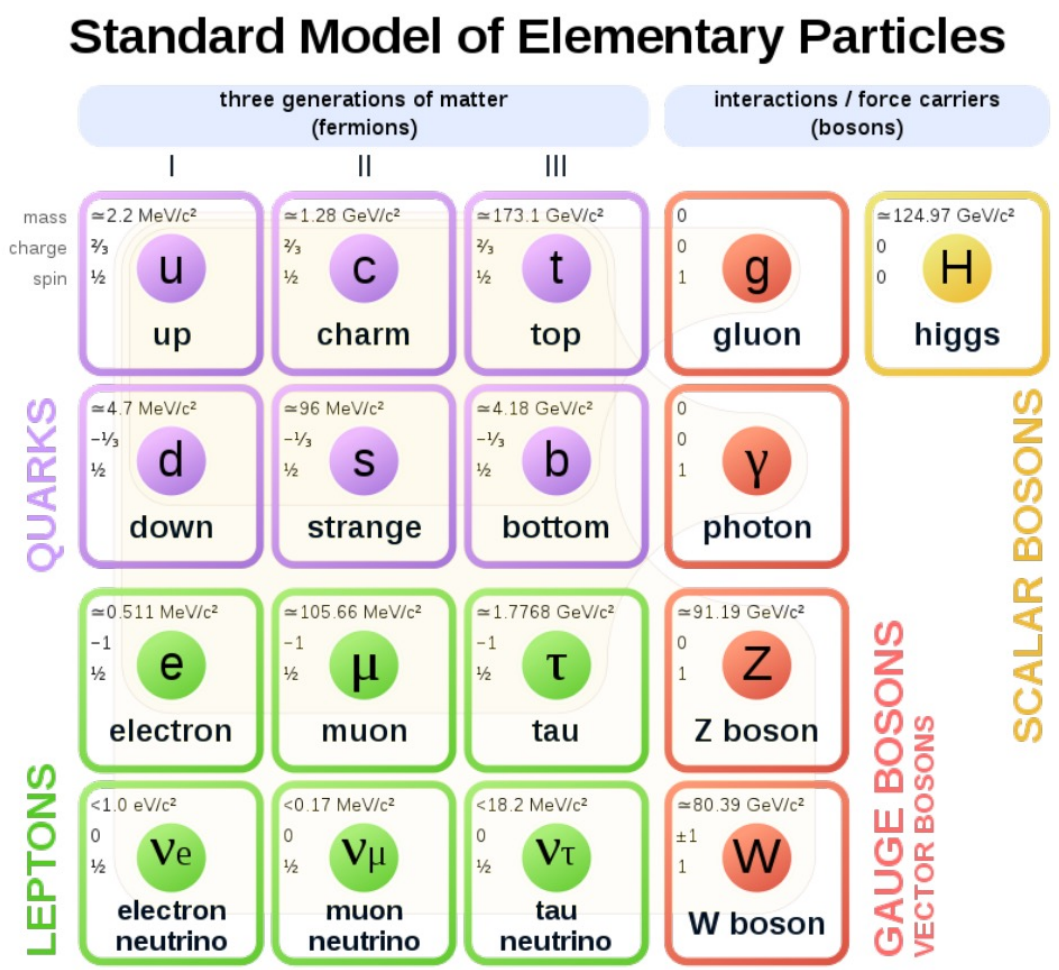
What was the Universe made of?

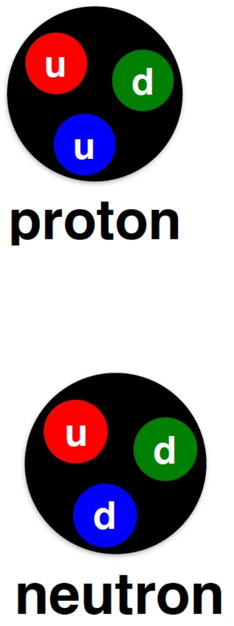


Beyond the Standard Model (BSM)

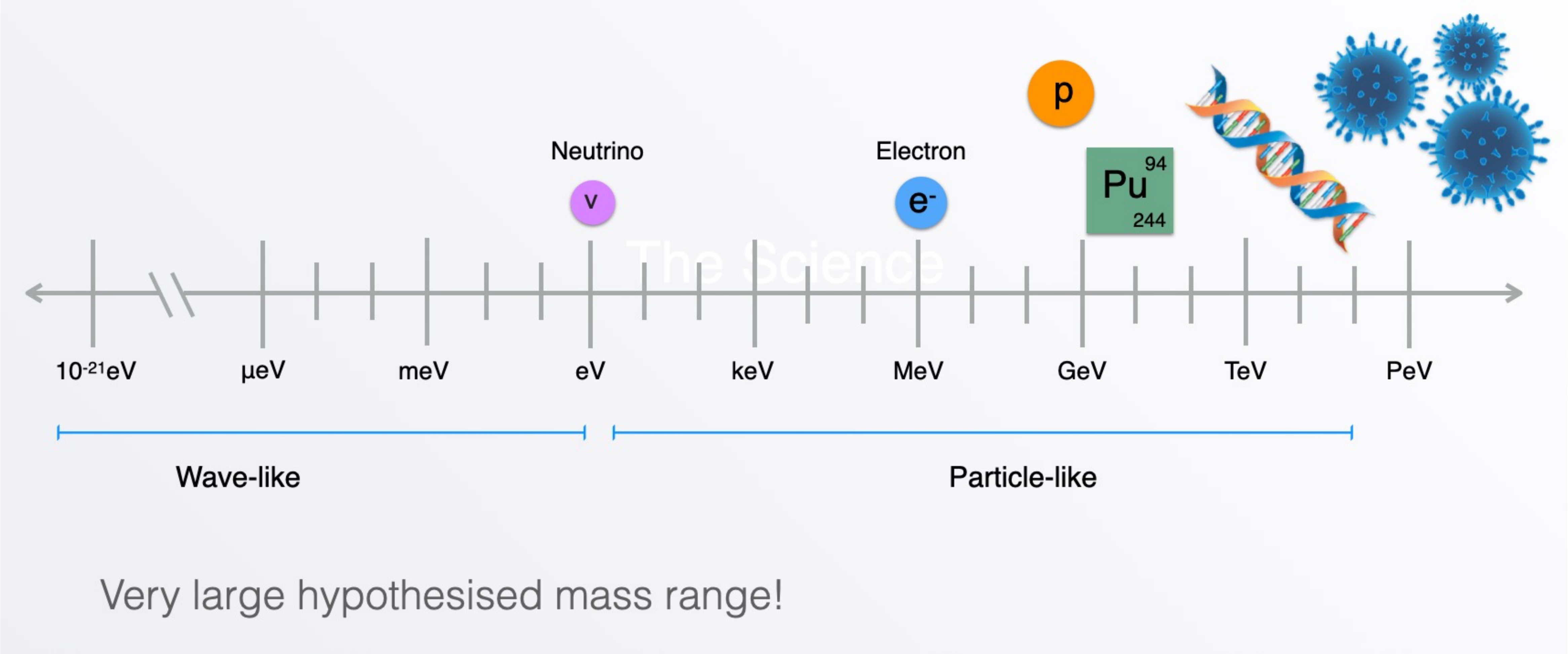
- The Standard Model describes three of the four known fundamental forces (electromagnetic, weak and strong interactions) in the Universe and classifies all known elementary particles.

- It does not explain:
  - Gravity;
  - Neutrino masses;
  - Dark Matter.





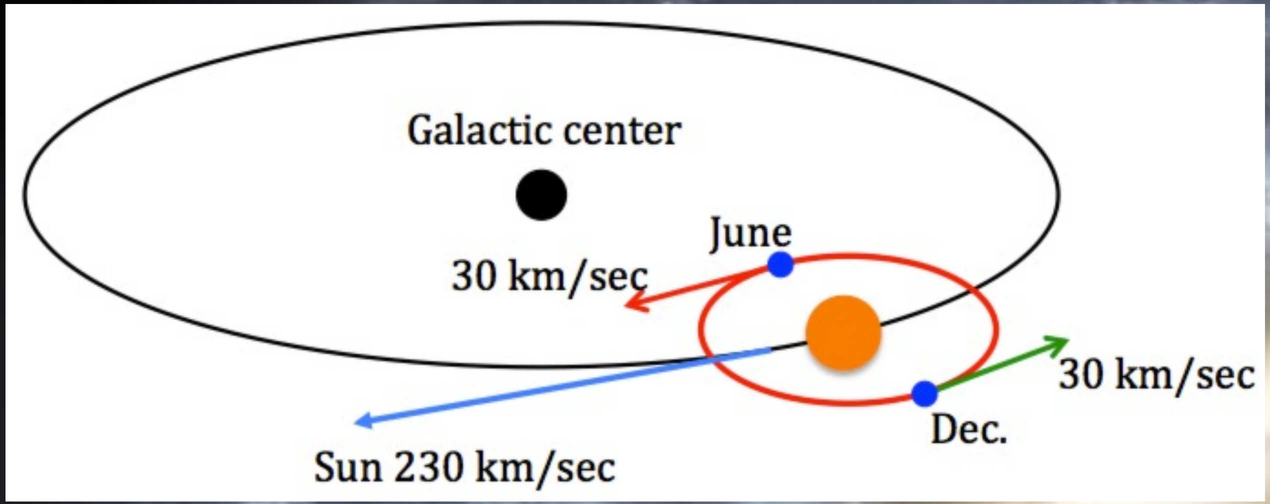
The challenge



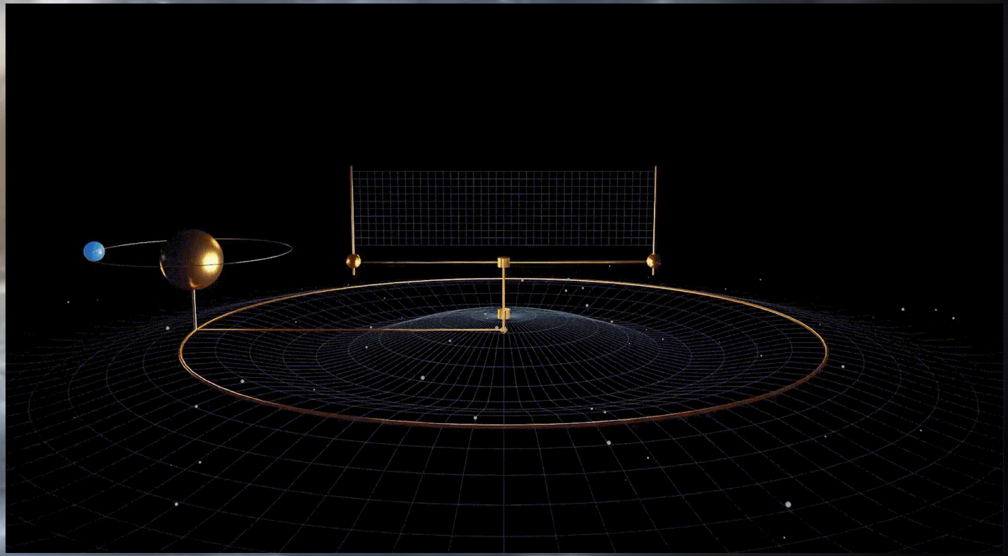
Dark matter candidates

Dark matter is expected to form a stationary halo around the galaxy

Dark Matter Annual Modulation



- Annual modulation having 1 year as a period due to the Earth motion around the Sun.
- Maximum and minimum expected on 2nd June and on 2nd December.



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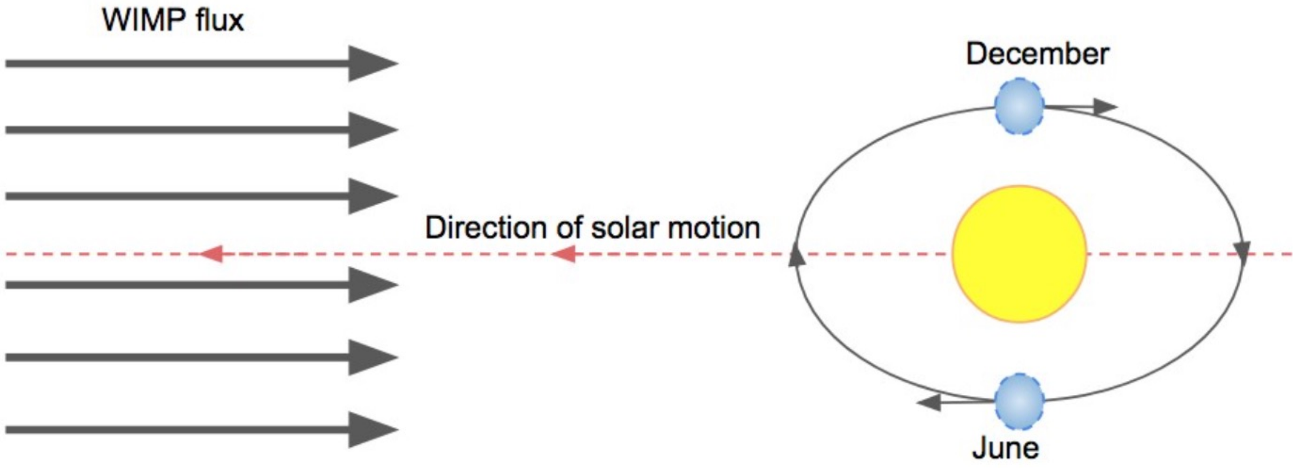
Dark Matter Annual Modulation



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

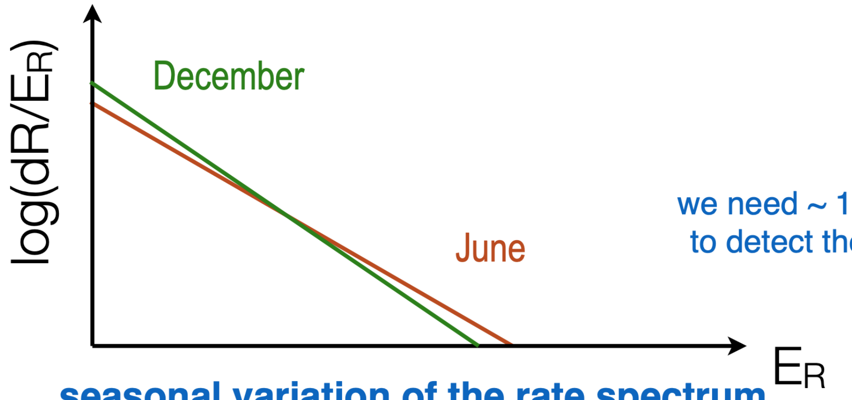
Rare and low energy events:

- expected WIMP-nucleon $\sigma \sim 10^{-48}$ - 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

- Standard halo model hypothesis: spherical halo of cold, dark matter (WIMP particles) permeating the galaxy
- Local energy density $\rho_{WIMP} \sim 0.3$ GeV/cm^3
- Maxwell velocity distribution

⇩

Annual modulation: maximum and minimum expected on June 2nd and on 2nd December



we need ~ 1000 events to detect the variation

seasonal variation of the rate spectrum

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Annual modulation is a <u>model independent</u> signature of Dark Matter interaction, but control of modulating background is key

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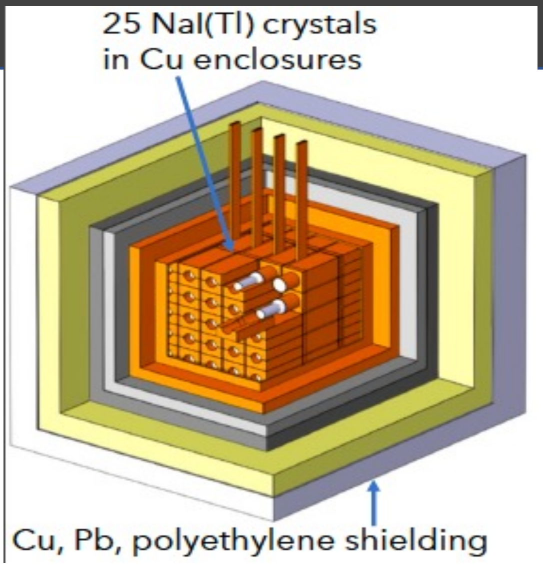
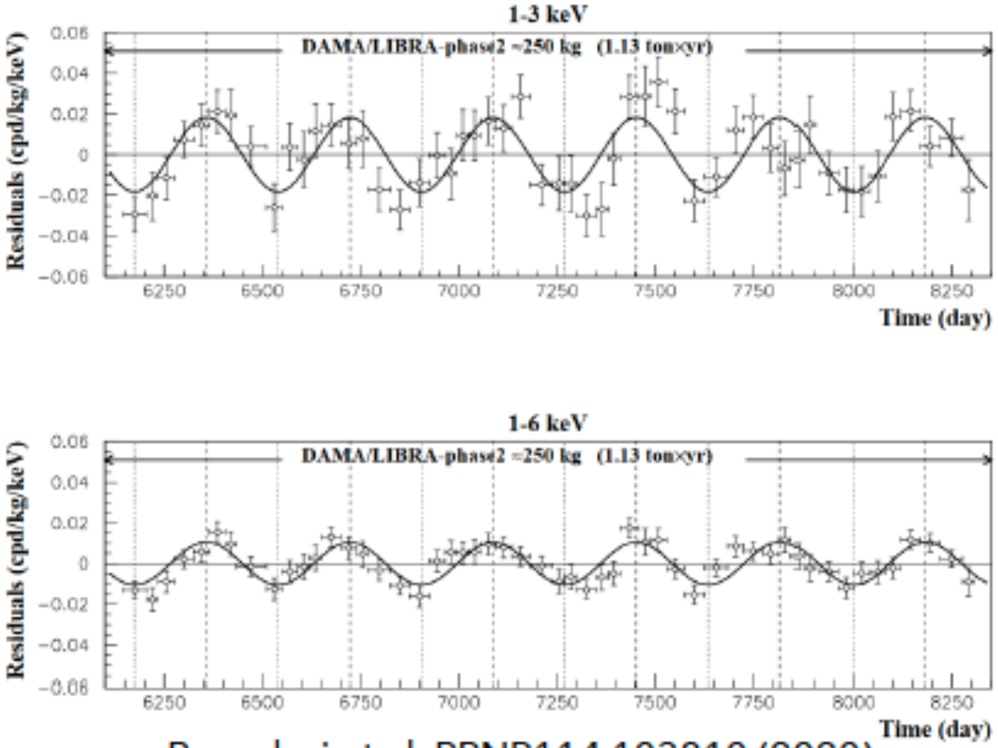
The DAMA/LIBRA claim

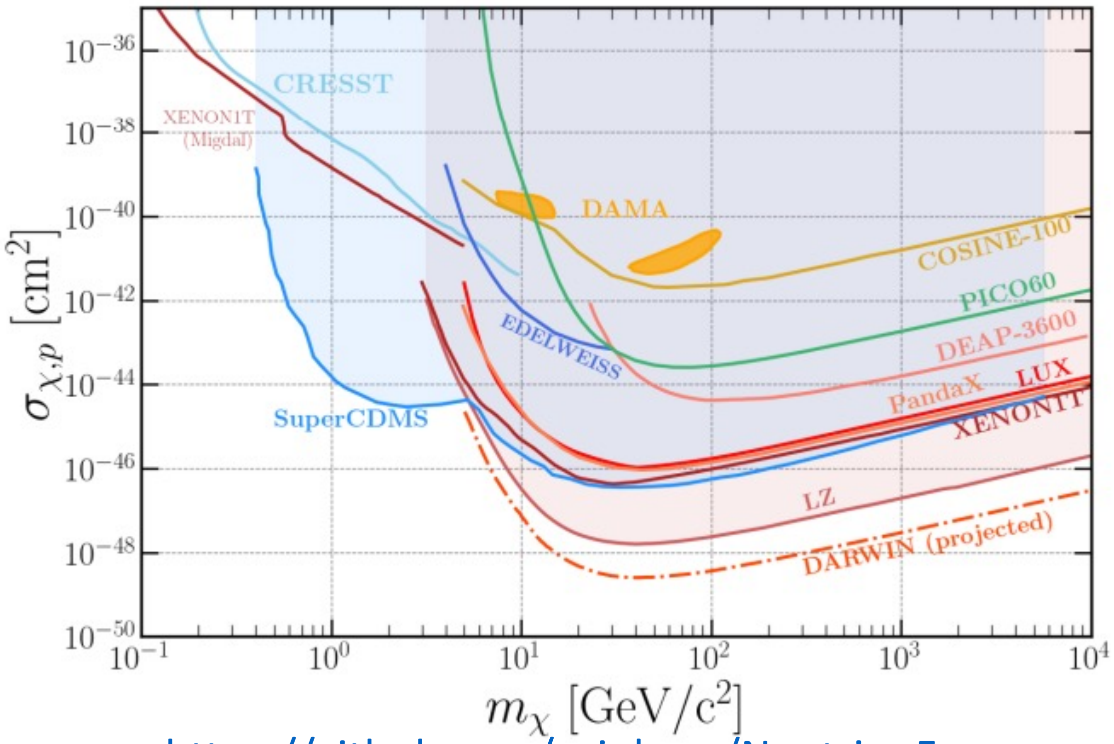
The **DAMA/LIBRA** experiment has observed a modulation for about 2 decades:

- located at Laboratori Nazionali del Gran Sasso, Italy
- total mass: 250 kg of NaI (Tl).
- observed **~0.01 cpd/kg/keV** modulation in the 1-6 keV (second phase) energy range
- 12.9 σ significance



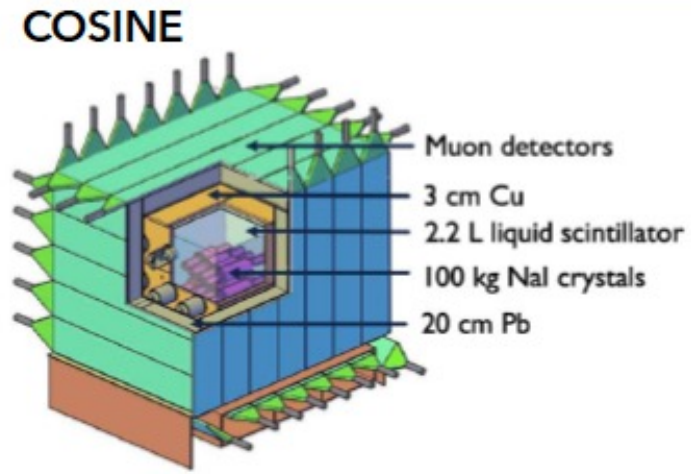


Bernabei et al. PPNP114 103810 (2020)

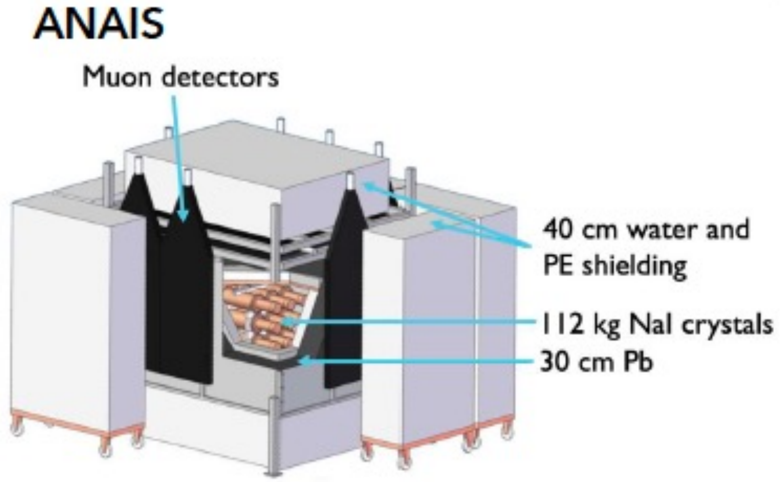


https://github.com/cajohare/NeutrinoFog

Current running NaI(Tl) detectors



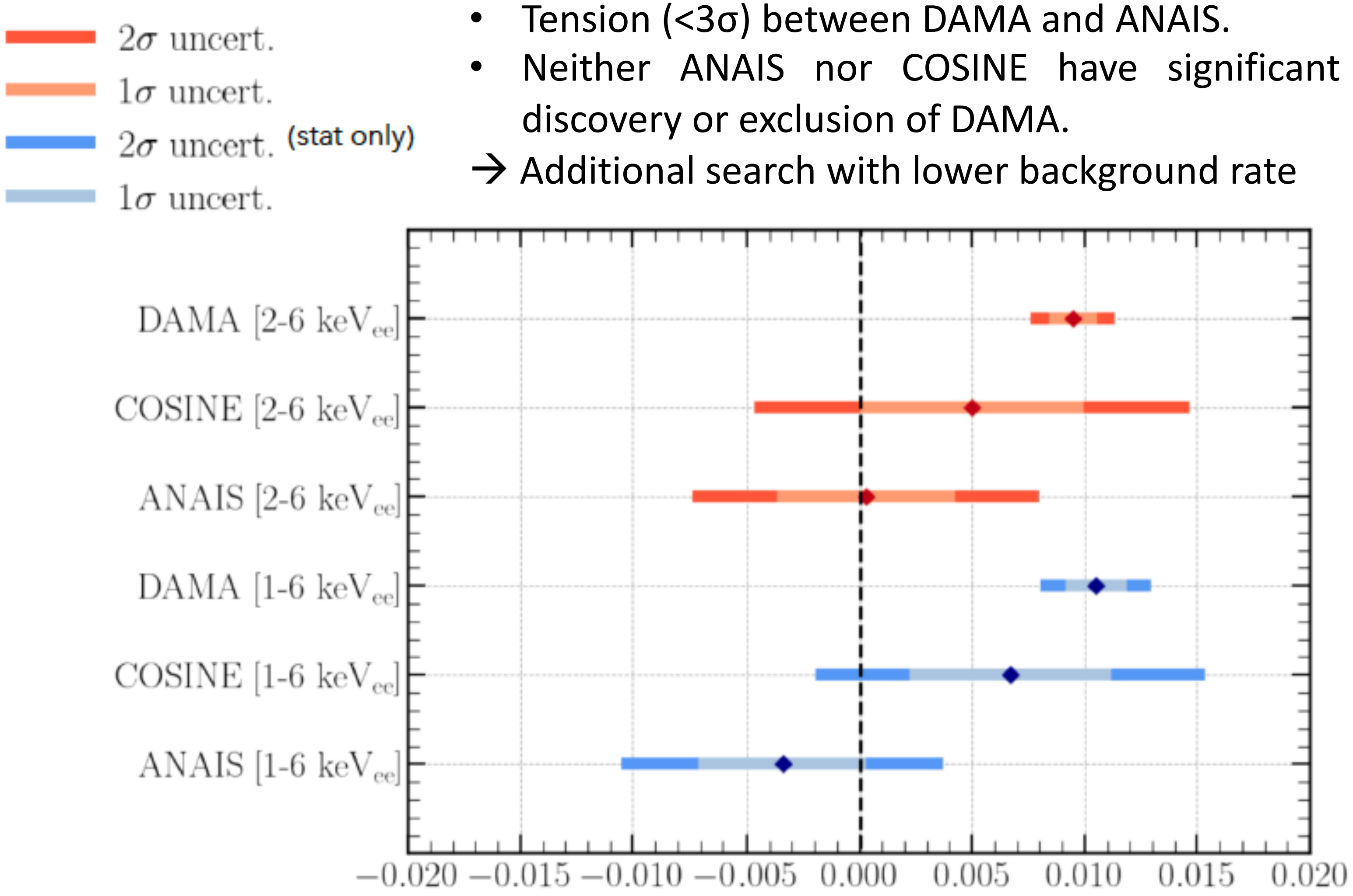
Phys. Rev. D 106,052005 (2022)



Phys.Rev.D 103 (2021) 10,102005

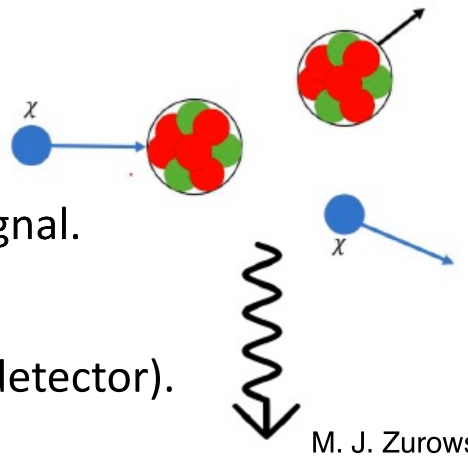
- Tension (<3σ) between DAMA and ANAIS.
- Neither ANAIS nor COSINE have significant discovery or exclusion of DAMA.

→ Additional search with lower background rate



DAMA results: Bernabei et al. PPNP114 103810 (2020)

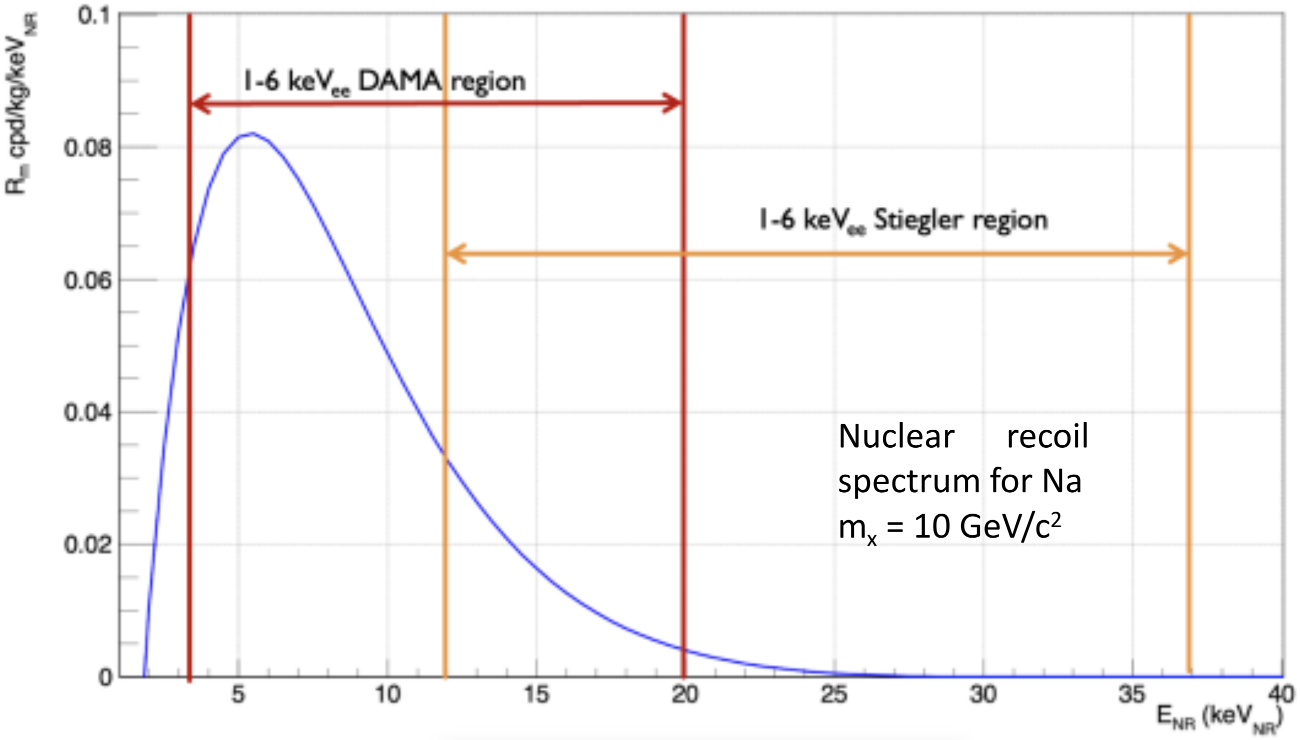
Interaction Mechanism



M. J. Zurowski, arXiv: 2211.15861

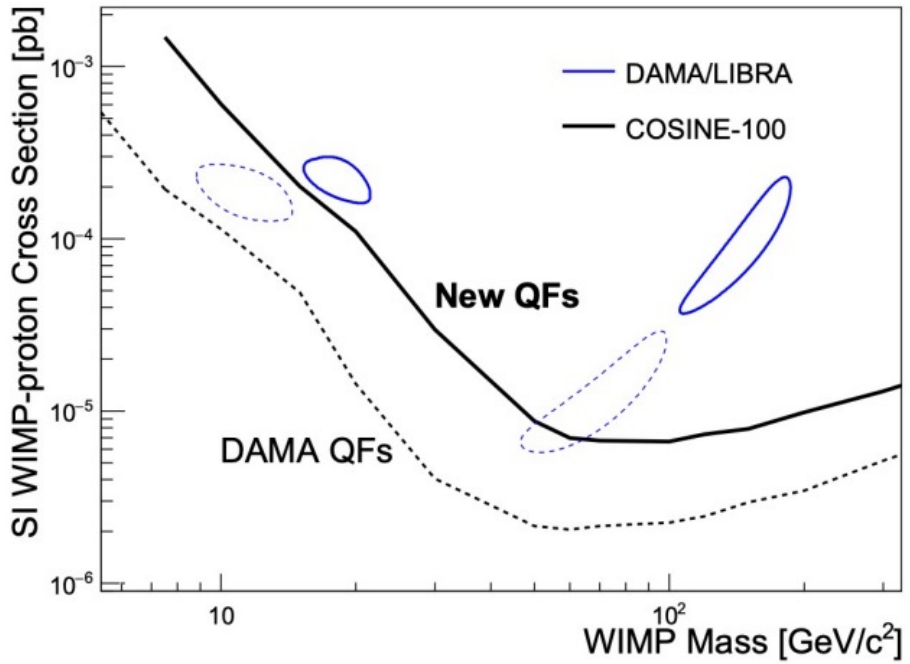
- Not all of the energy imparted into the recoiling nucleus is transformed into a detectable signal.
- Reconstruction of recoil energy -> understanding of quenching factor (QF).
- QF converts the nuclear recoil energy into the electron equivalent energy (the units of the detector).
- Change of QF has a strong influence on the observable rate.

- Changing relationship between NR and observed energy means the 1-6 keVee observable region of interest is "accessing" different parts of the nuclear recoil energy spectrum.
- This effect will impact any nuclear recoil signal in a NaI(Tl) detector, not just DM.
- It is possible that this effect depends strongly on the optical properties of the crystal, and if so then different growth methods can impact results.

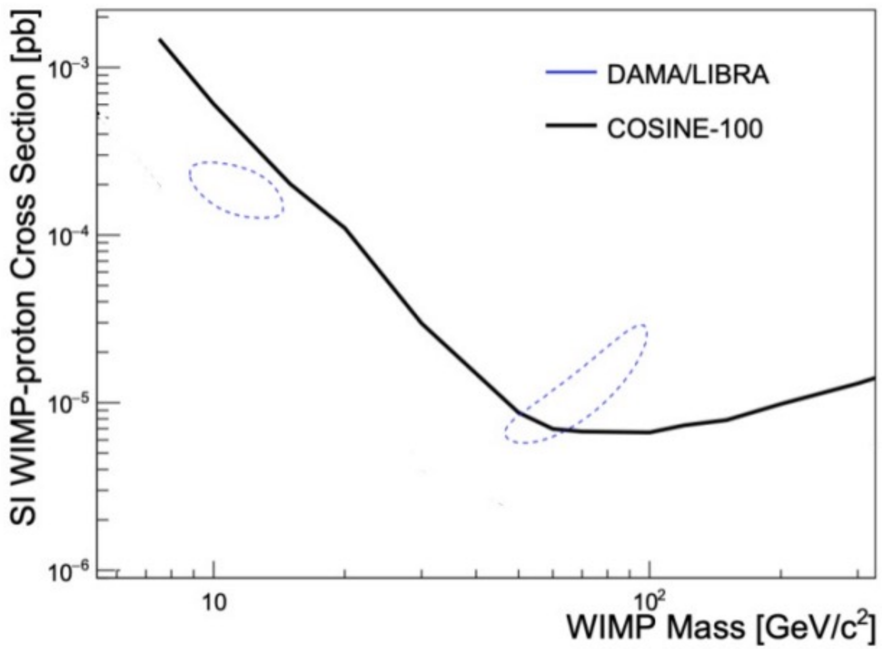


Quenching Factor Impact

Can use results presented by COSINE [1] to understand how different QF combinations impact exclusion of DAMA



Assuming detectors have the same QF (either the solid or dotted lines)



Assuming detectors have different QFs

[1] Adhikari et al. JCAP 11 (2019)


SABRE
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DARK MATTER
PARTICLE PHYSICS
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The SABRE Collaboration

The ambitious program of SABRE foresees two detectors in two underground locations:

- SABRE North at Laboratori Nazionali del Gran Sasso (LNGS) in Italy
- SABRE South at Stawell Underground Physics Laboratory (SUPL) in Australia

PRINCETON UNIVERSITY

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO

UNIVERSITÀ DEL SALENTO

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

STAWELL UNDERGROUND PHYSICS LAB

SWINBURNE

KEK High Energy Accelerator Research Organization

THE UNIVERSITY OF MELBOURNE

Australian National University

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY of ADELAIDE

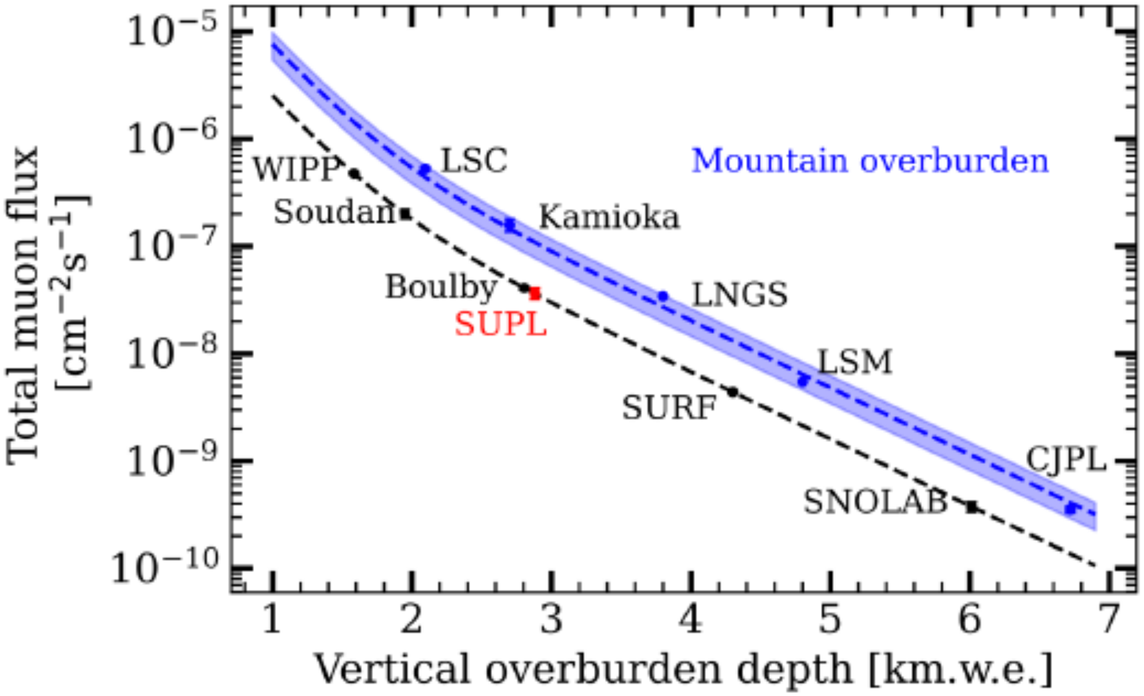
The Stawell Underground Physics Laboratory

- SUPL is the first deep underground lab in the Southern Hemisphere (37° South) located in western Victoria, 500 km from Adelaide.
- Lab is about 1 km below ground with flat over burden within the Stawell Gold Mine → The muon flux expected at the SUPL laboratory is one million times less than what detected at the ground level.
- Lab construction finished in mid June 2022, ready in 2022/2023.

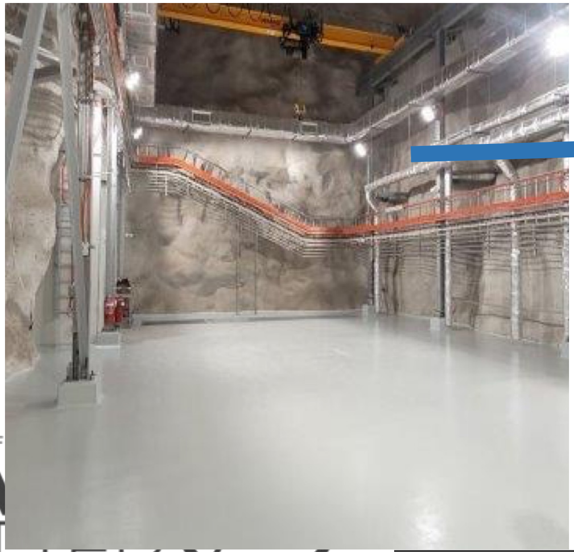
- The walls of the mine contain trace amounts of radioactive elements like Uranium and Thorium which decay into radon gas that produces additional counting rates (gamma-ray) in the detector through its daughters.
- Walls pinned with steel, sprayed with low radioactivity shotcrete and coated with Tekflex.
- Environmental background measurements.

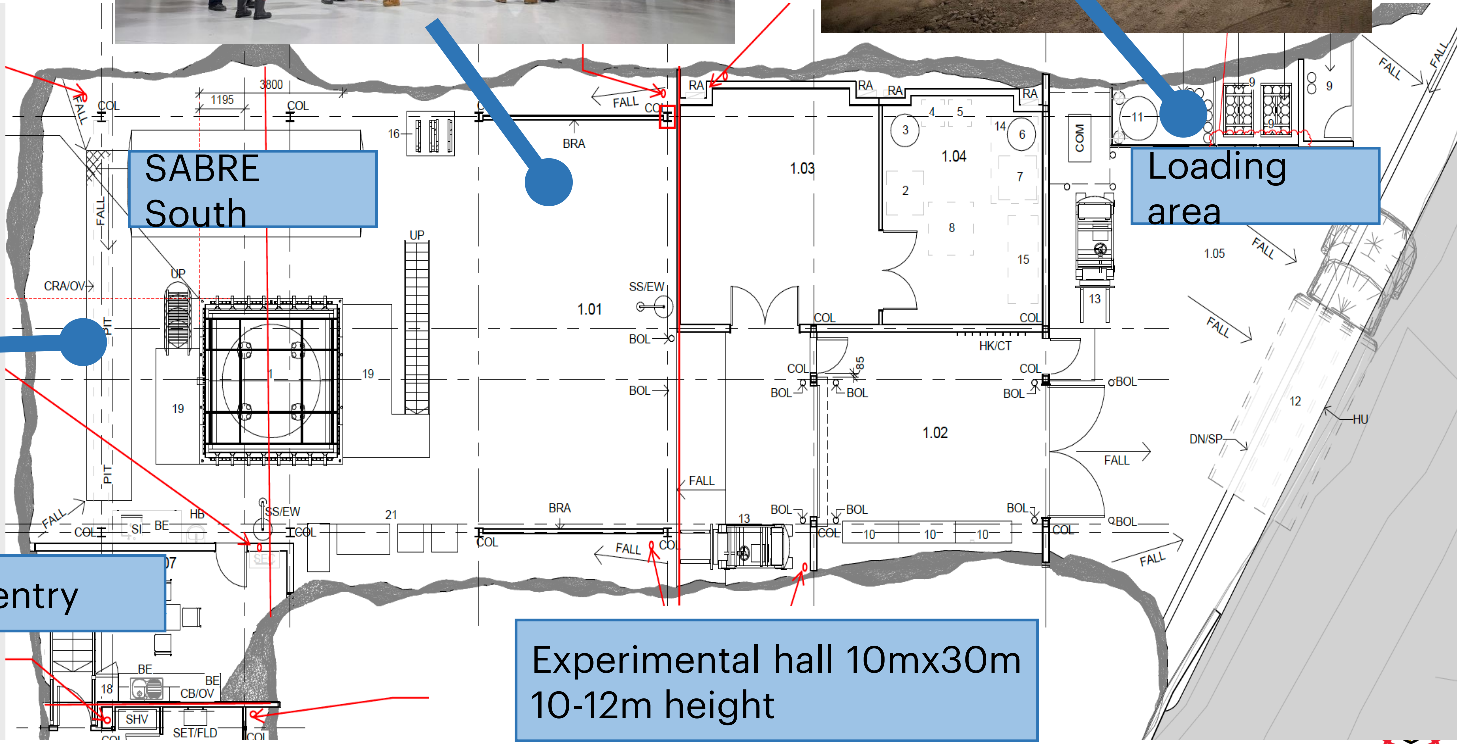
Very Low Background Radiation Environment

- Direct Dark Matter Detection.
- Other low background Particle Physics Detector Development
- Low background nuclear spectroscopy laboratory
  - HPGe spectrometers.
- Quantum device measurement (reduction of cosmic ray upsets)
  - Proposal for multi-user Dilution Refrigerator installation underway.
- Possible low-radiation studies in biological systems.
- Geology and seismic studies.



The Stawell Underground Physics Laboratory





The SABRE Collaboration

SABRE North and South detectors have **common core features**:

- Same crystal production and R&D.
- Same detector module concept (ultra-pure crystals and HPK R11065 PMTs).
- Common simulation, DAQ and data processing frameworks.
- Exchange of engineering know-how with official collaboration agreements between the ARC Centre of Excellence for Dark Matter and the INFN.

SABRE North and South detectors **have different shielding designs:**

- SABRE North has opted for a fully passive shielding due to the phase out of organic scintillators at LNGS. Direct counting and simulations demonstrate that this is compliant with the background goal of SABRE North at LNGS.
- SABRE South will be the first experiment in SUPL, the liquid scintillator will be used for in-situ evaluation and validation of the background in addition of background rejection and particle identification.

A MoU for the full SABRE experiment has been drafted and will be signed in the following months.

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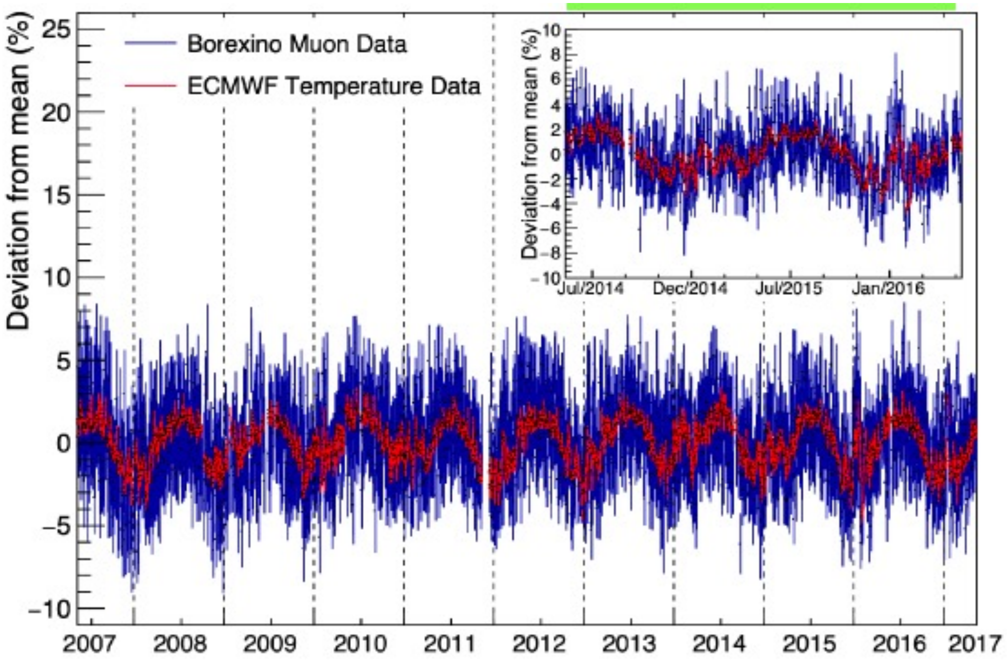
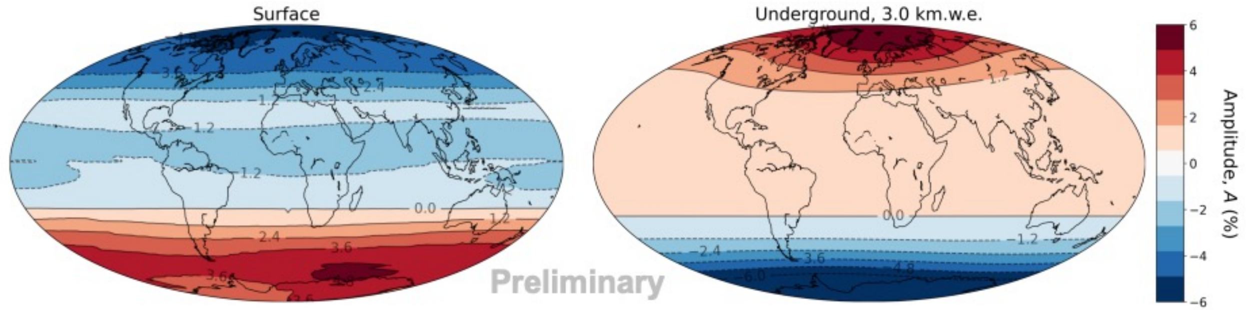
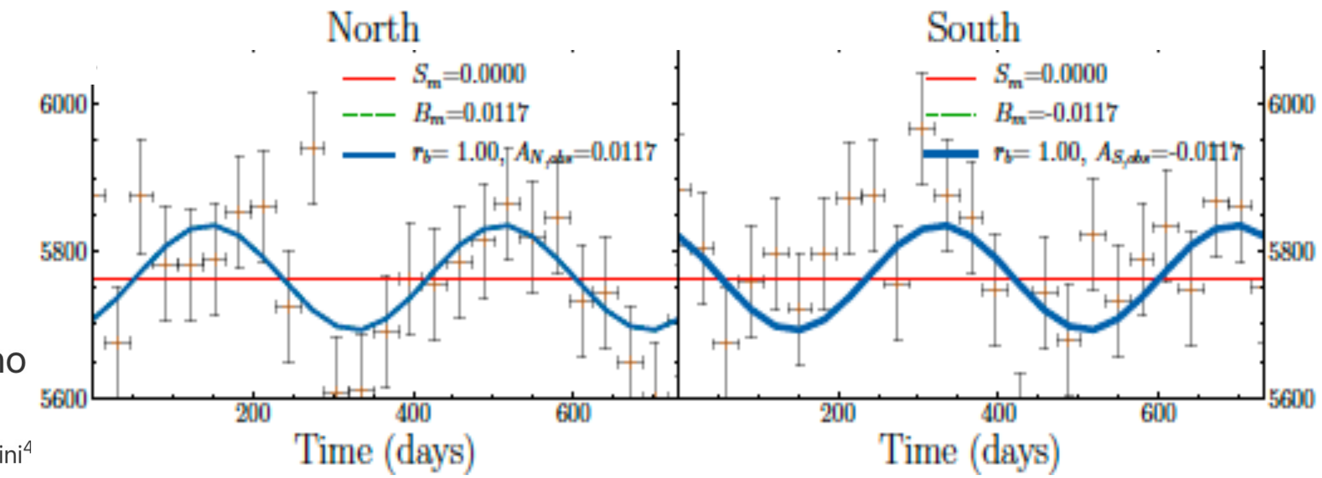
Exclusion of seasonal effects

- The site in the Southern hemisphere is important to exclude seasonal effects.
- The seasons are reversed from those in the Northern Hemisphere → muon modulation maximum is on 2nd December; minimum is on 2nd June.



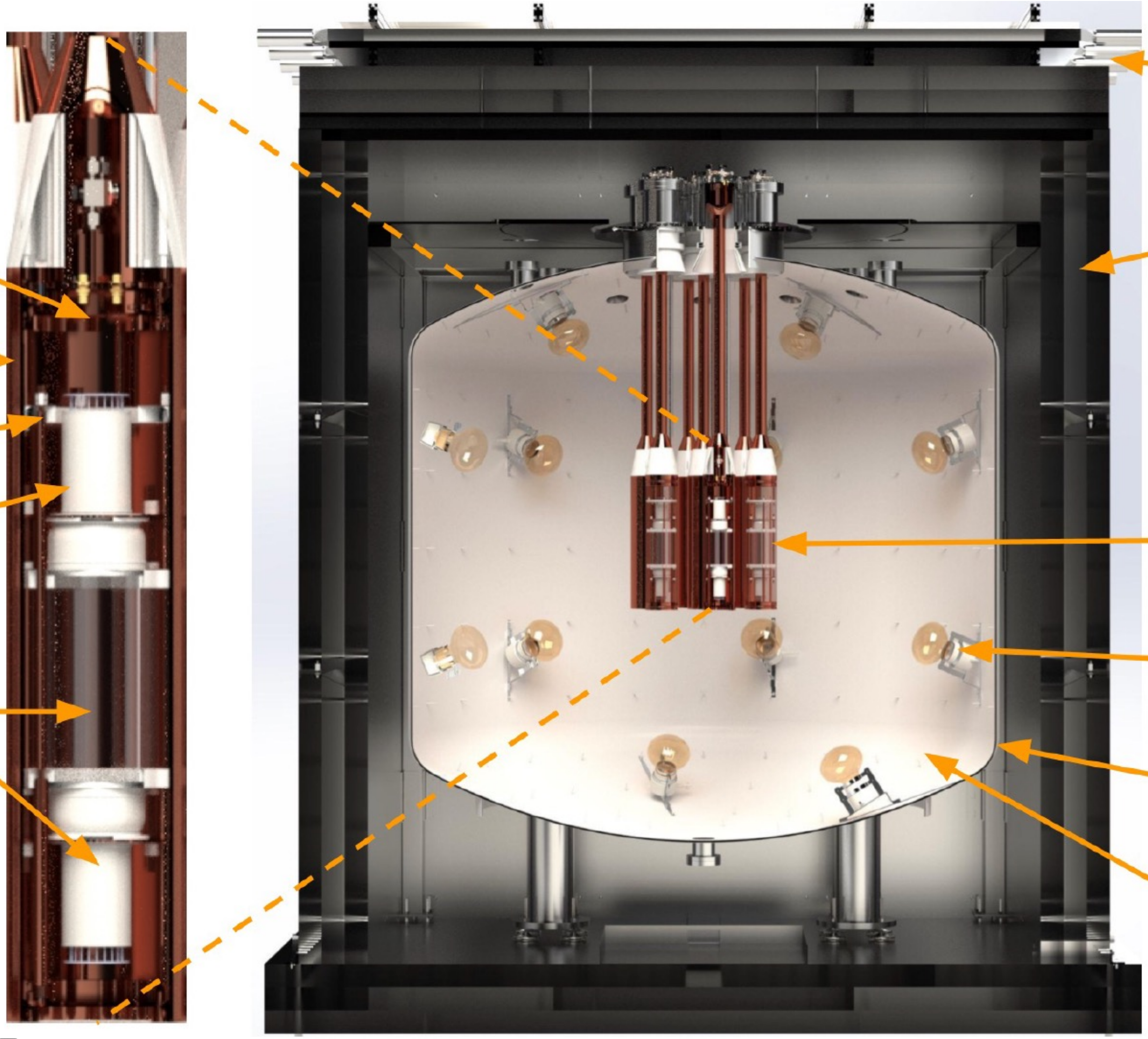




Modulations of the cosmic muon signal in ten years of Borexino data

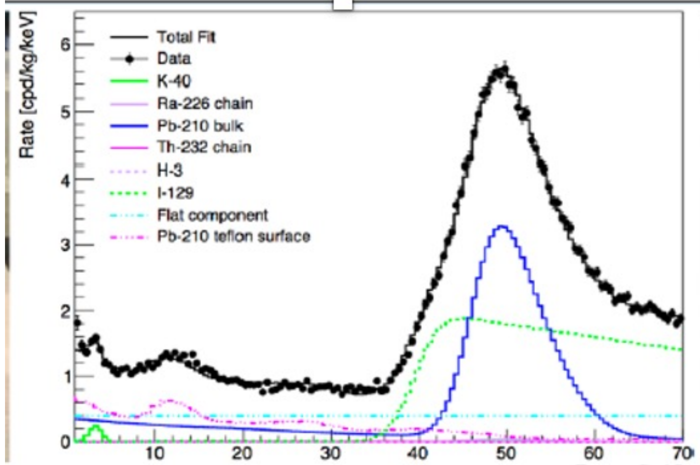
M. Agostini[1], K. Altenmüller[1], S. Appel[1], V. Atroshchenko[2], Z. Bagdasarian[3], D. Basilico[4], G. Bellini[4]
J. Benziger[5], D. Bick[6] I. Bolognino[4] + Show full author list

SABRE (Sodium iodide with Active Background REjection) South



High-purity NaI(Tl) crystals

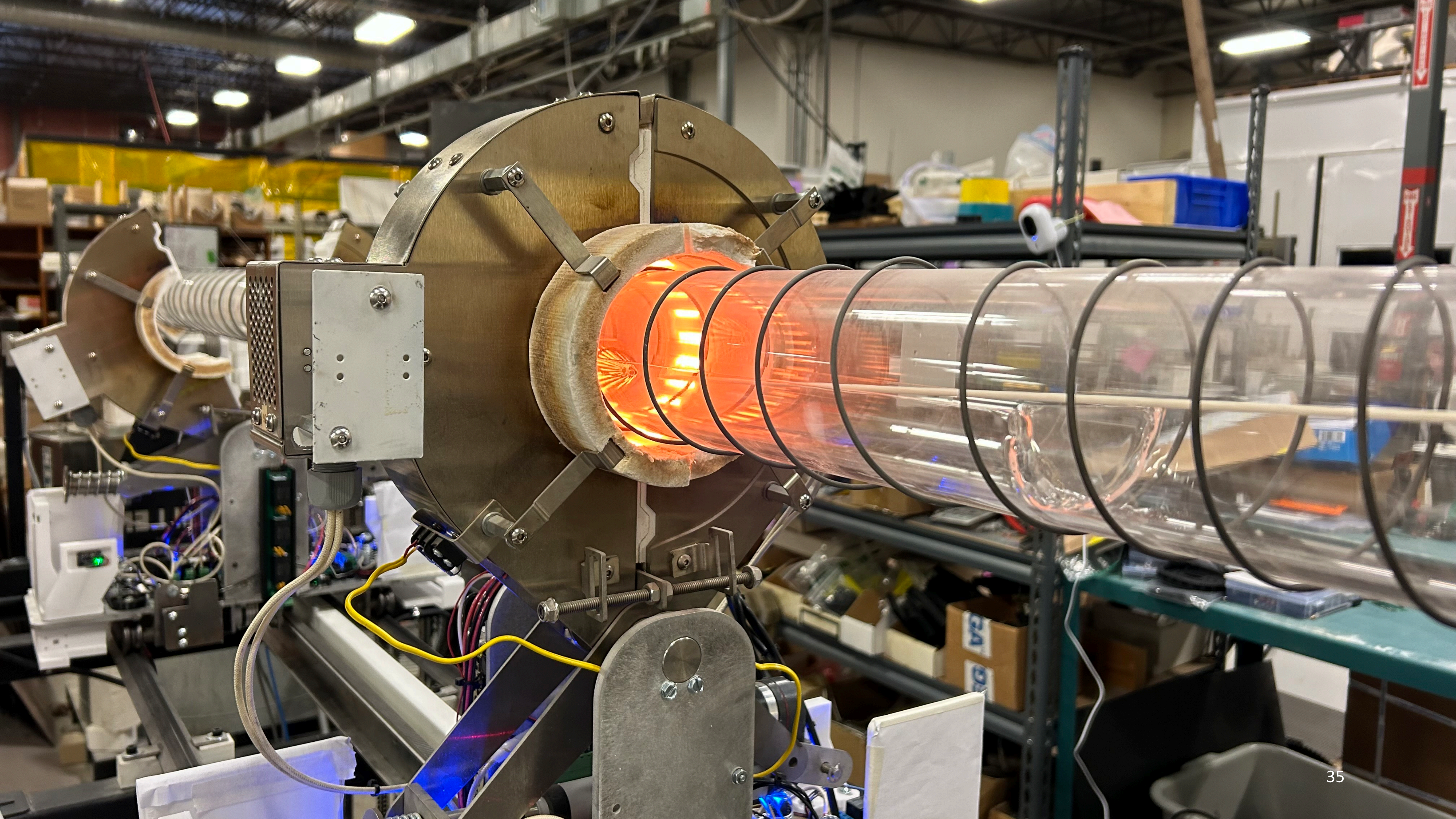
- Ultra-pure Astrograde NaI powder from R&D with Merck.
- High-purity, low background crystals are being grown in collaboration with Princeton and RMD.
- Four crystals have been tested at LNGS.
- Light yield 9-12 phe/keV.
- Two more crystals are arriving in the next months to complete the testing phase.

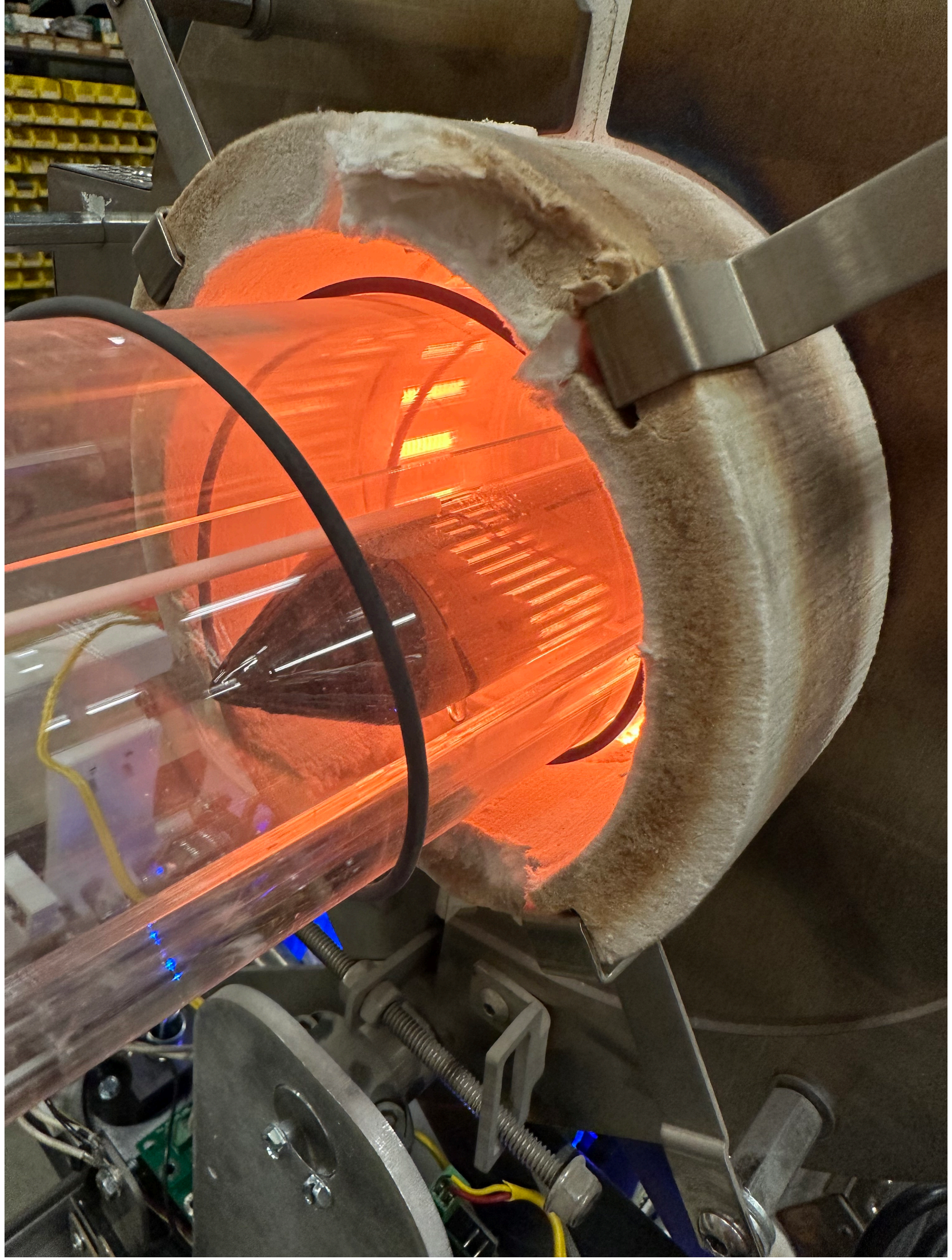
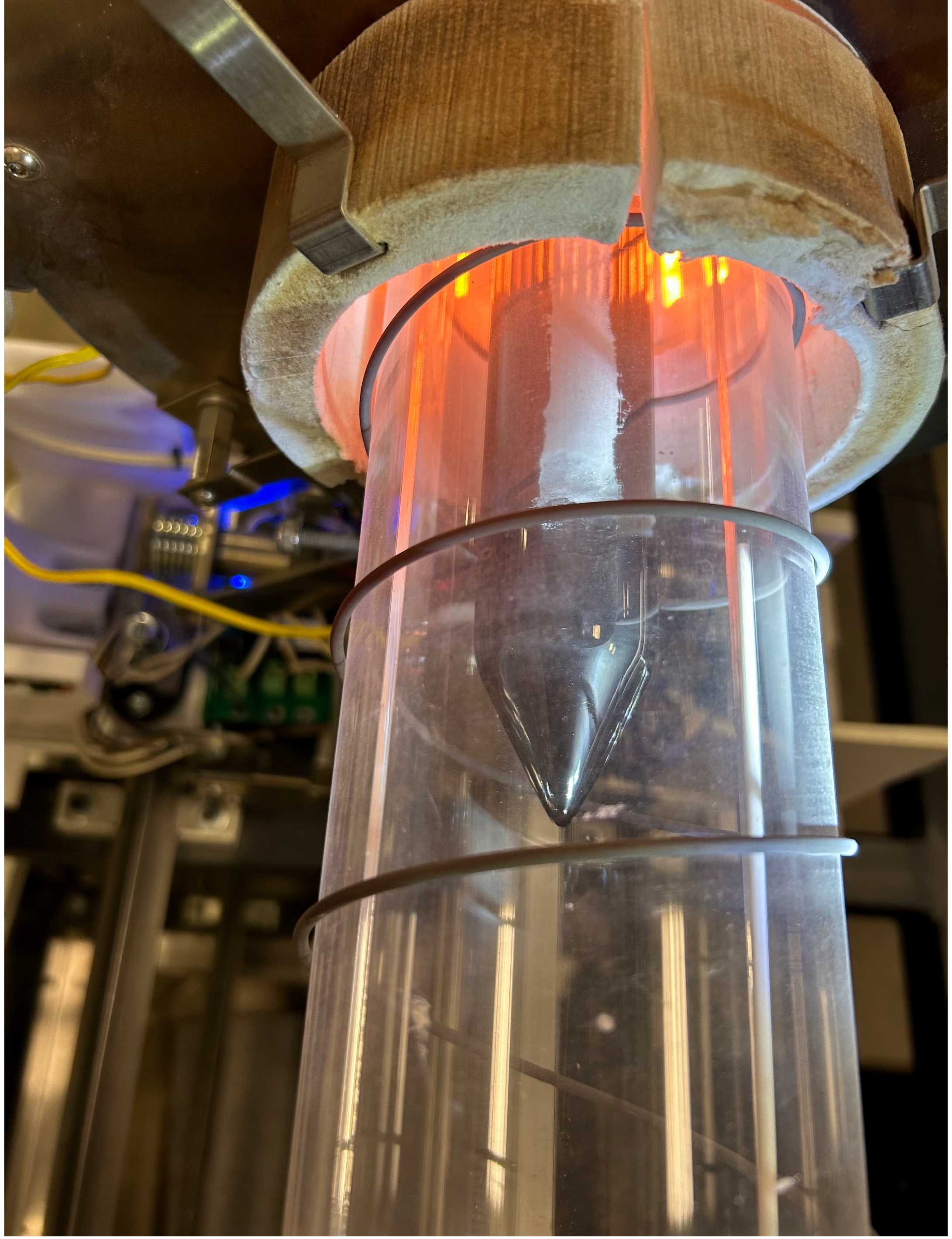


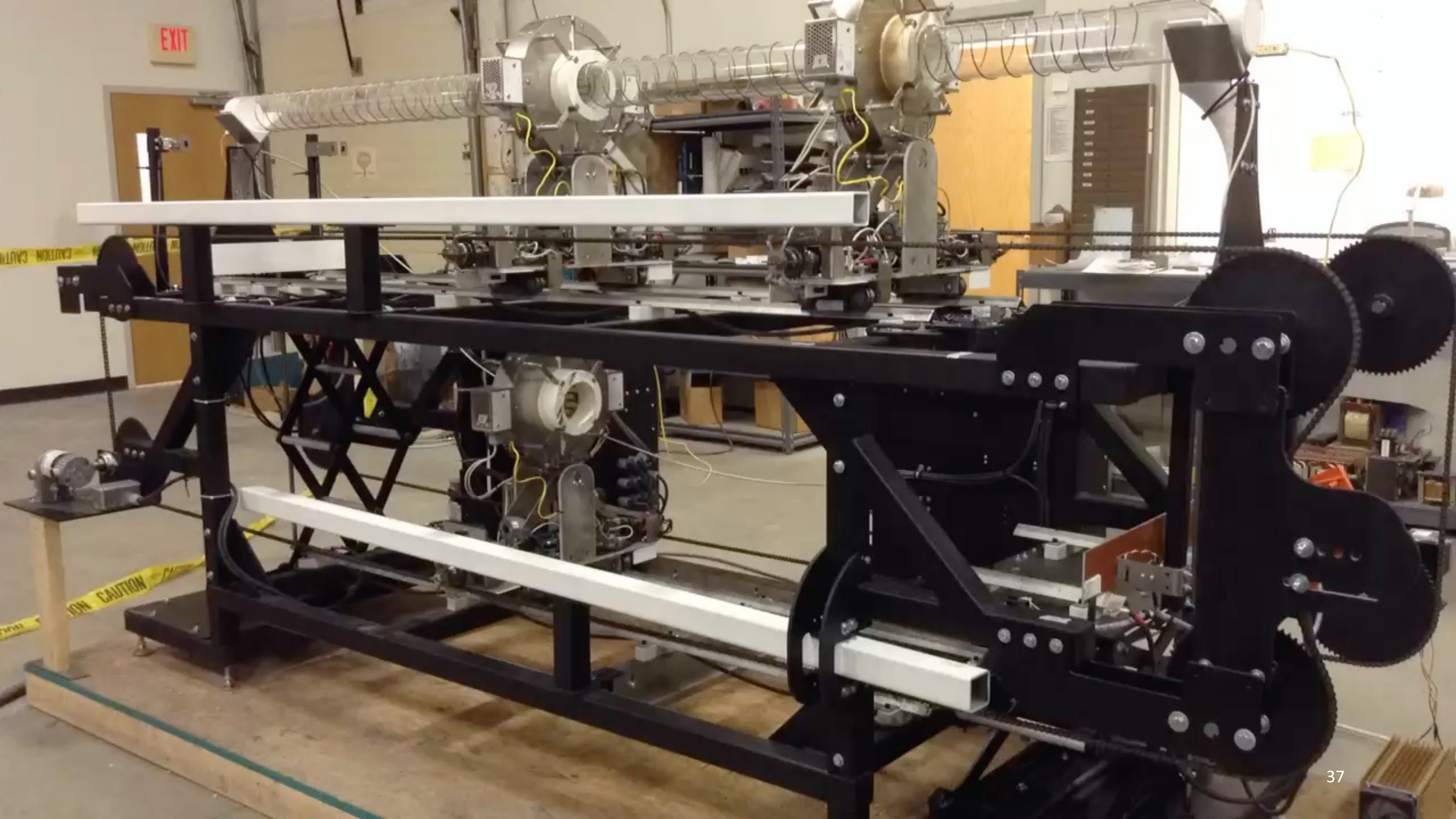
Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{210}Pb (mBq/kg)	^{232}Th (ppt)	Active mass (kg)
DAMA [1]	13	0.7-10	$(5\text{-}30)\times10^{-3}$	0.5-7.5	250
ANAIS [2]	31	<0.81	1.5	0.36	112
COSINE [3]	35.1	<0.12	1-1.7	<2.4	~60
SABRE [4]	4.3	0.4	0.49	0.2	~35+40=75 (total goal)
PICOLON [5]	<20	-	$<5.7\times10^{-3}$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

SABRE crystal mass = 3.4 kg

[1] R. Bernabei et al., NIMA 592(3) (2008)
[2] J. Amare et al., EPJC 79 412(2019)
[3] P. Adhikari et al., Phys. Rev. Lett. 123, 031302 (2019)
[4] B. Suerfu et al., Phys. Rev. Research 2, 013223 (2020)
[5] K. Fushimi et al., PTEP 4 043F01 (2021)

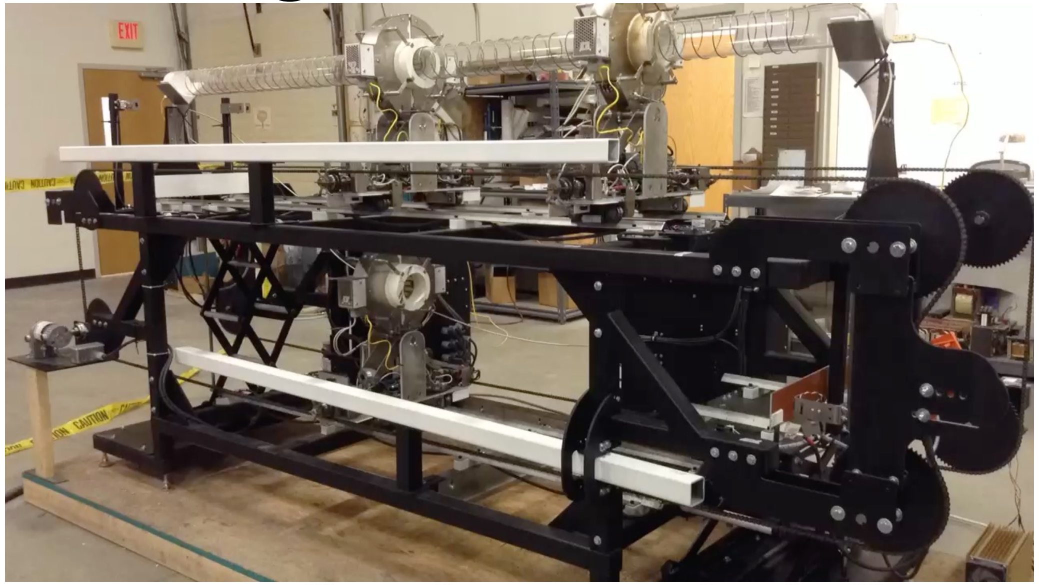



EXIT
CAUTION

High-purity NaI(Tl) crystals – Zone Refining

- Strategic and unique to the SABRE project is the idea to zone refine the powder prior to growth.
- Zone refining 100 kg of crystal powder prior to crystal growth has been built in collaboration with MELLEN.
- Impurities are pushed to the end of the refining tube and are then removed. Reduction factors of:
  - ^{40}K: 10-100
  - ^{87}Rb: 10-100
  - ^{210}Pb: 2
- Being used at RMD to prepare a final test crystal.



Isotope	Powder	Impurity concentration (ppb) – 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)

Active Background Rejection

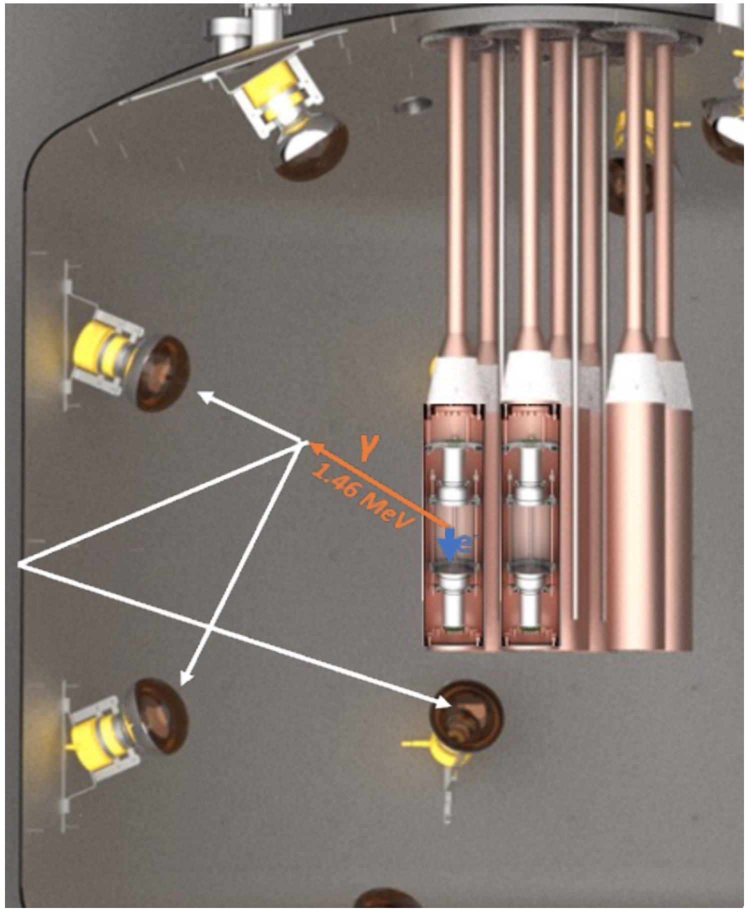
SABRE South also uses an external tagging system to remove high energy decay products observable in the liquid scintillator.

System has 4π coverage made up of:

- 12 kL (10 tons) linear alkyl benzene (LAB) doped with PPO and Bis-MSB.
- LAB is sourced from JUNO.
- 18 Hamamatsu 20.4 cm R5912 PMTs sampled at 500 MS/s.

Average light yield of ~0.17 PE/keV, though strong position dependence.

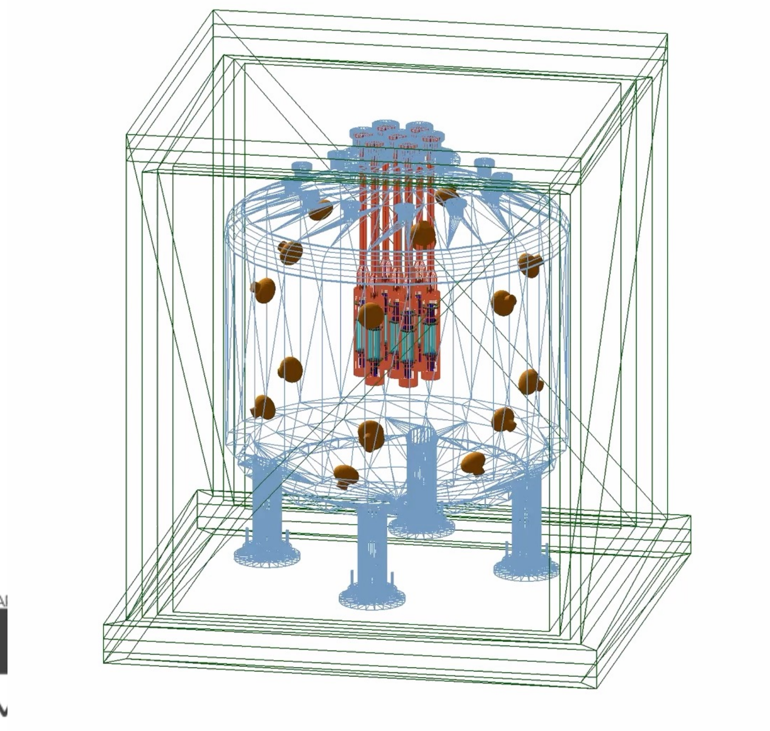
Energy threshold of 50 keV which is able to reduce the background by 25%, giving a total background of <1cpd/kg/keV.



Active Background Rejection

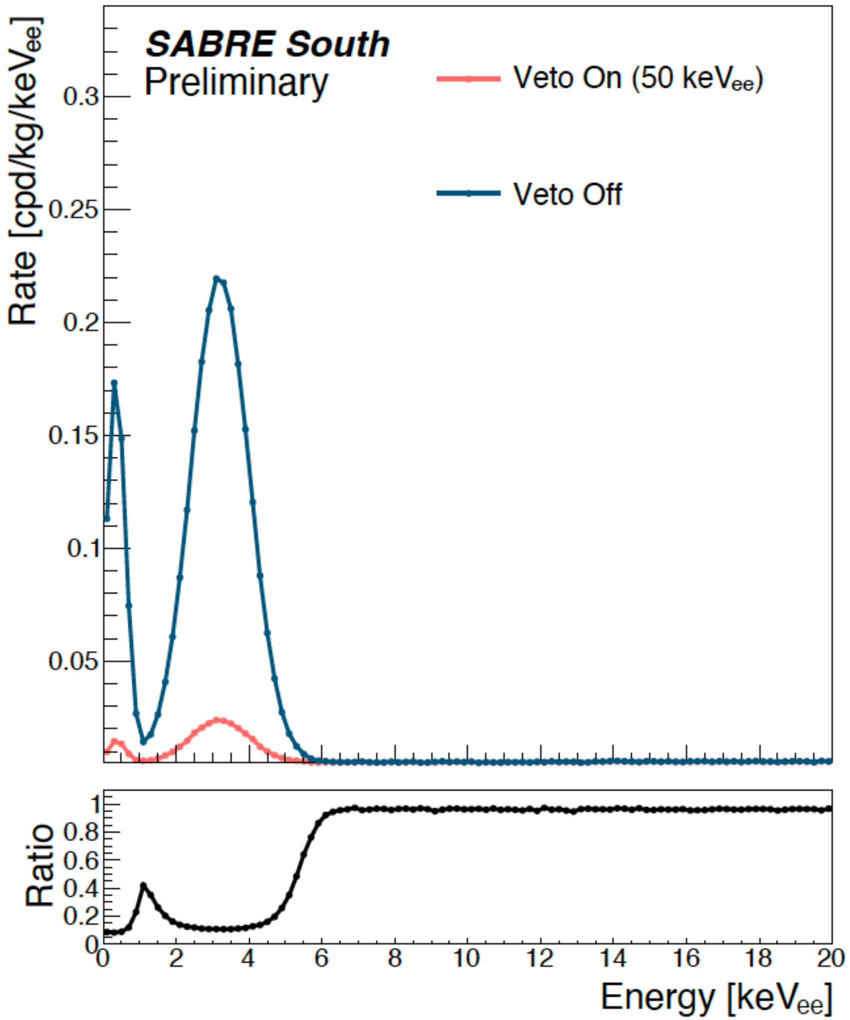
Any radioactive decay with gamma >100 keV can be vetoed.

cpd/kg/keV per mBq/kg	^{238}U	^{232}Th	^{210}Pb	^{85}Kr	^{87}Rb	^{40}K
1-6 keV no veto	0.963	0.250	0.681	0.191	0.695	0.650
1-6 keV with veto	0.921	0.216	0.681	0.191	0.695	0.095
Veto efficiency	4.3%	13.3%	0.0%	0.0%	0.0%	85.4%



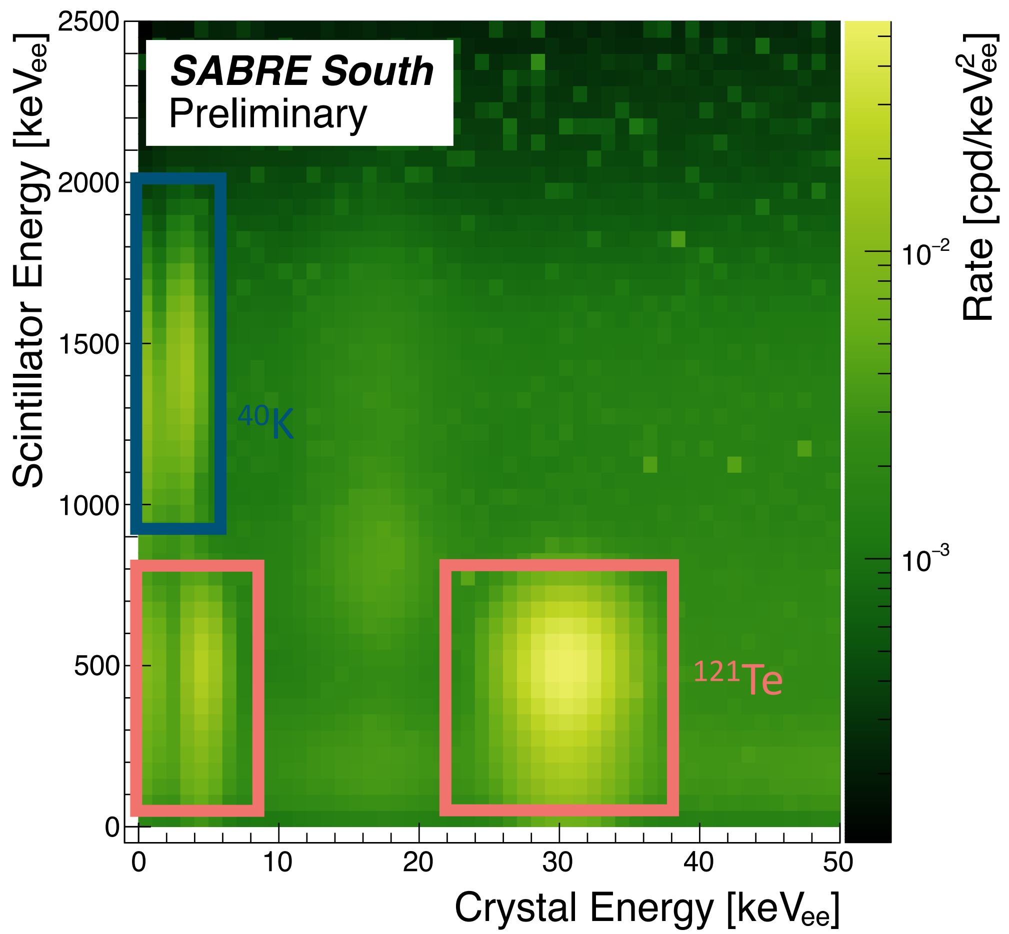
Collaboration paper submitted to EPJC about full background characterisation by using GEANT4 Monte Carlo simulations.
http://arxiv.org/abs/2205.13849
(accepted to EPJC)

Background spectrum of ^{40}K decays in the crystal with and without the veto requirement

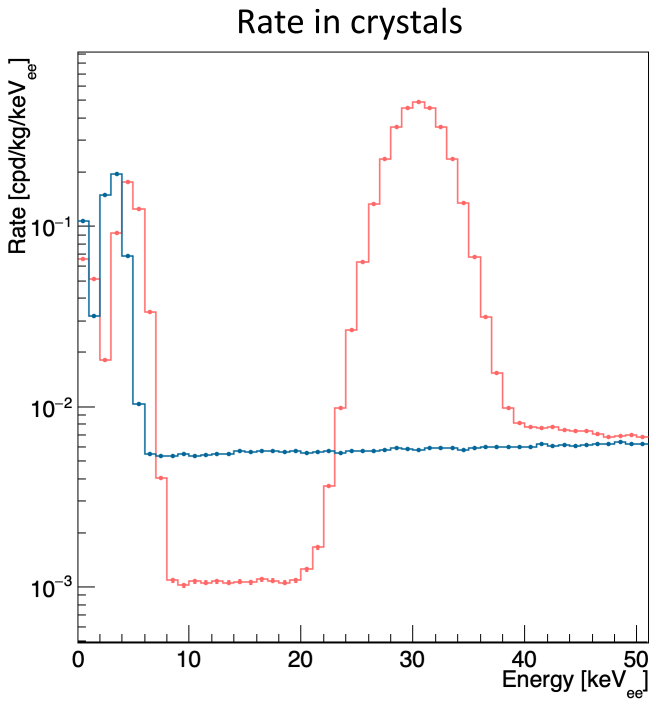


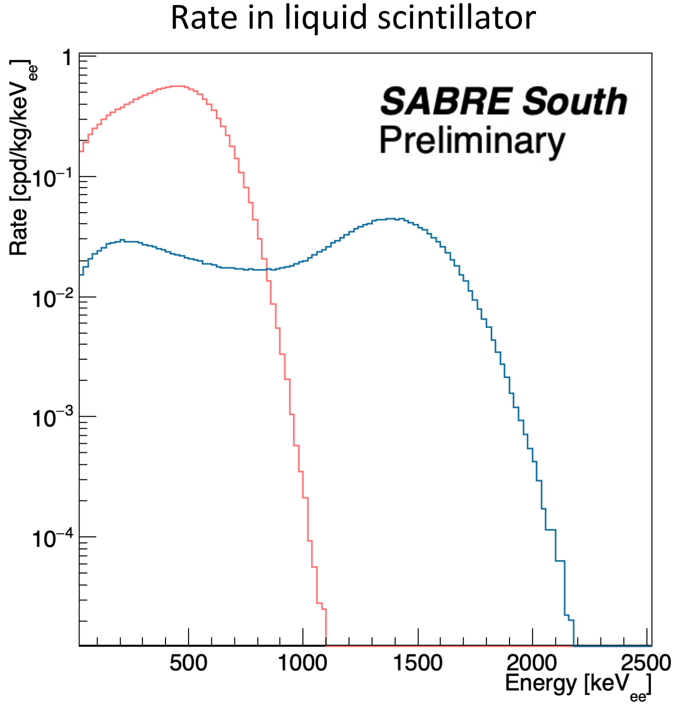
Total Background Model

Veto system not only reduces background but also allows for in situ measurements and particle ID.



E.g., ^{40}K and ^{121}Te both have distinct islands in crystal-scintillator energy plane



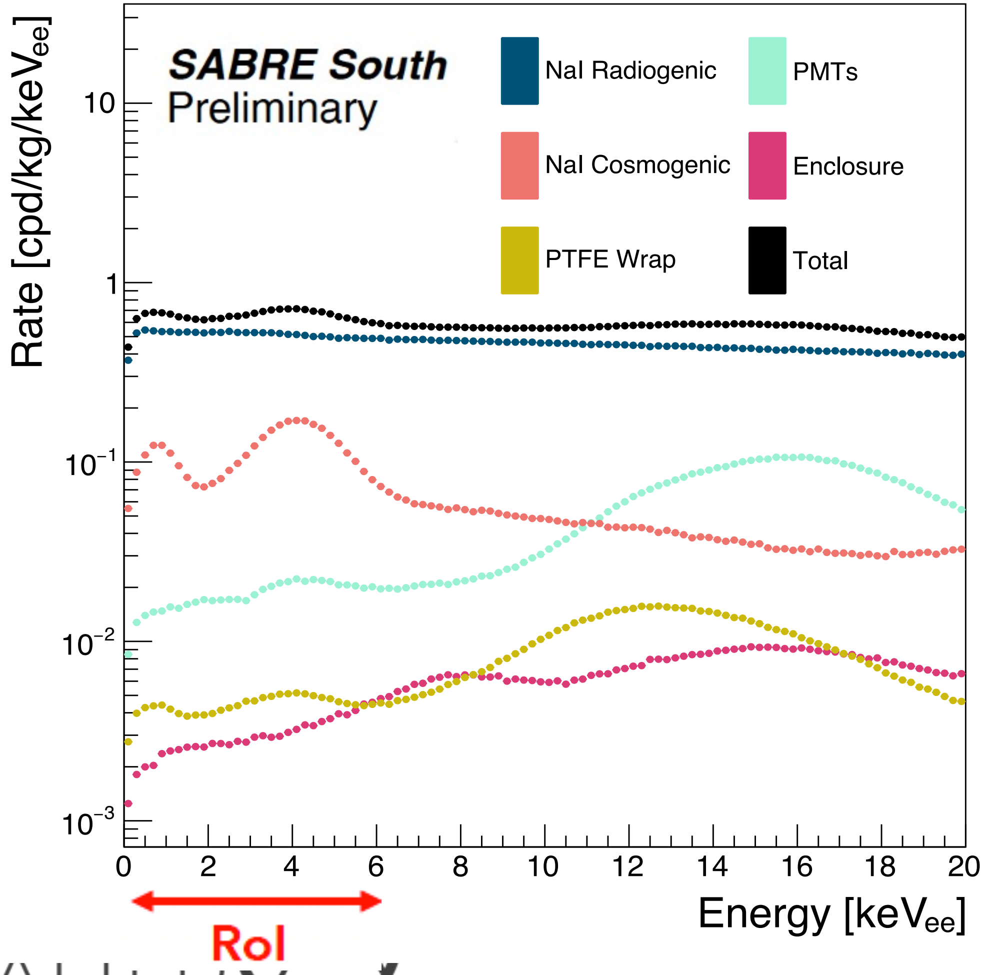


SABRE South Collab. arxiv:2205.13849
(accepted to EPJC)

Total Background Model

Using background from NaI-33, with 50 kg of NaI, expect 0.72 cpd/kg/keV in RoI.

SABRE South Collab. arxiv:2205.13849 (accepted to EPJC)



Component	Rate (cpd/kg/keV$_{ee}$)	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**

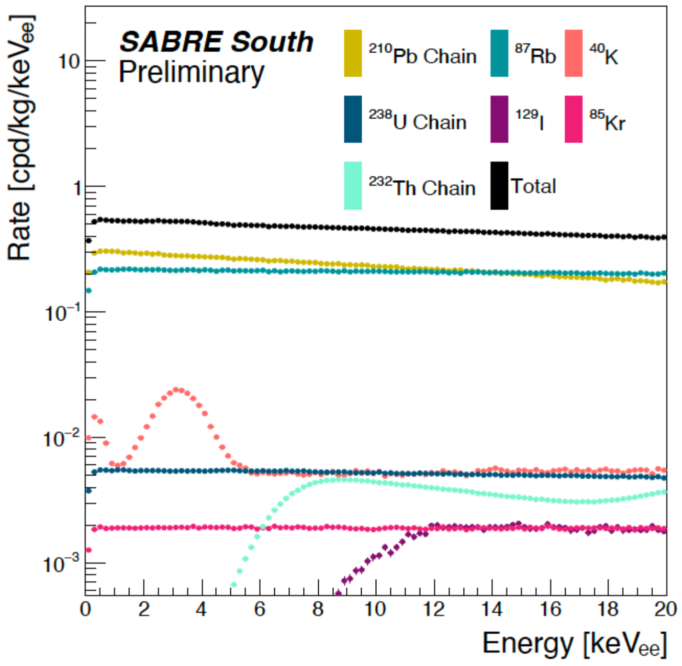
< 10% of background from non-crystal sources.

NaI(Tl) Background Simulations

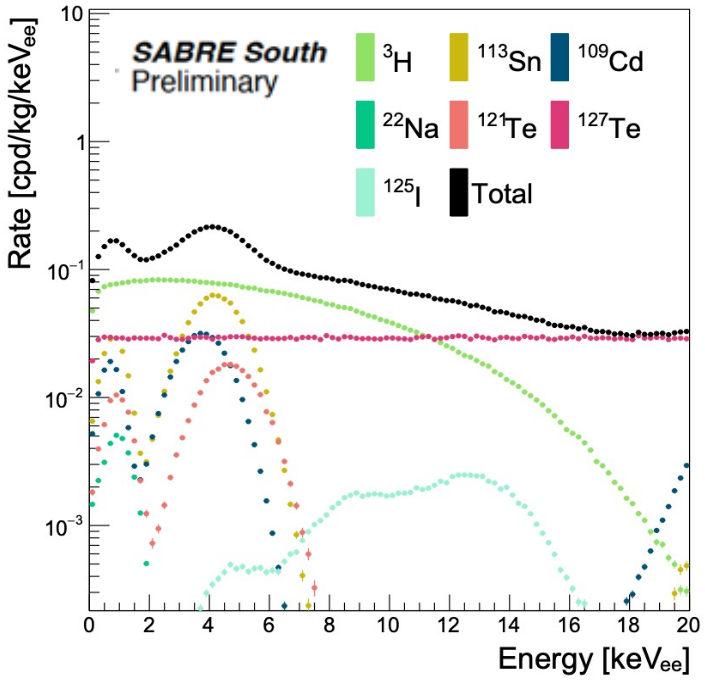
SABRE South Collab. arxiv:2205.13849 (accepted to EPJC)

- Background of SABRE South crystal have been both simulated and directly measured (on NaI-33) with Inductively coupled plasma mass spectrometry (ICP-MS).
- Main radiogenic background represented by ^{210}Pb, ^{87}Rb (very conservative upper limit). No ^{87}Rb was found with the ICP-MS measurement, and the order of magnitude of this contamination is currently unknown.
- Cosmogenic background after 180 days underground mainly due to ^{3}H (12.4 yrs) and ^{113}Sn (115 days).

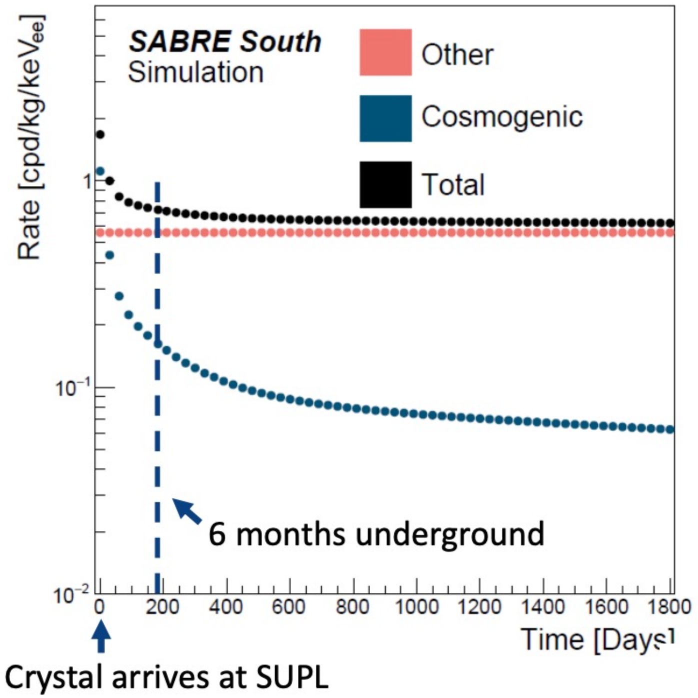
Radiogenic Background



Cosmogenic Background (6 months underground)



Time Dependence of Background



MATTER PARTICLE PHYSICS

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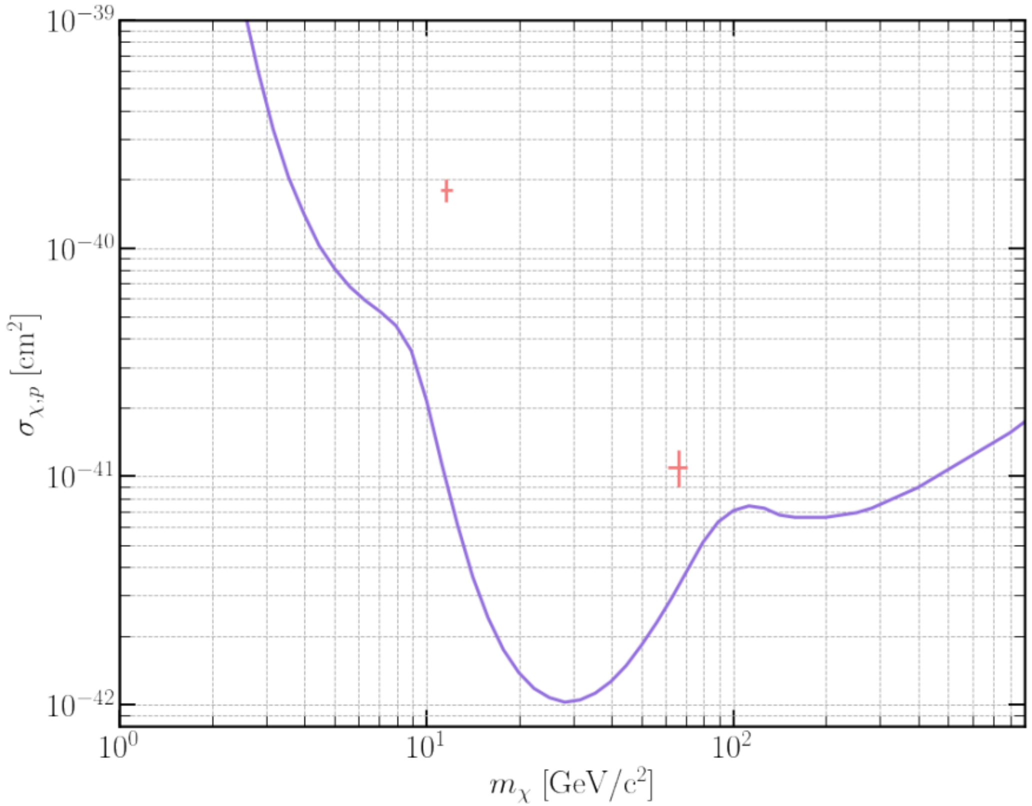
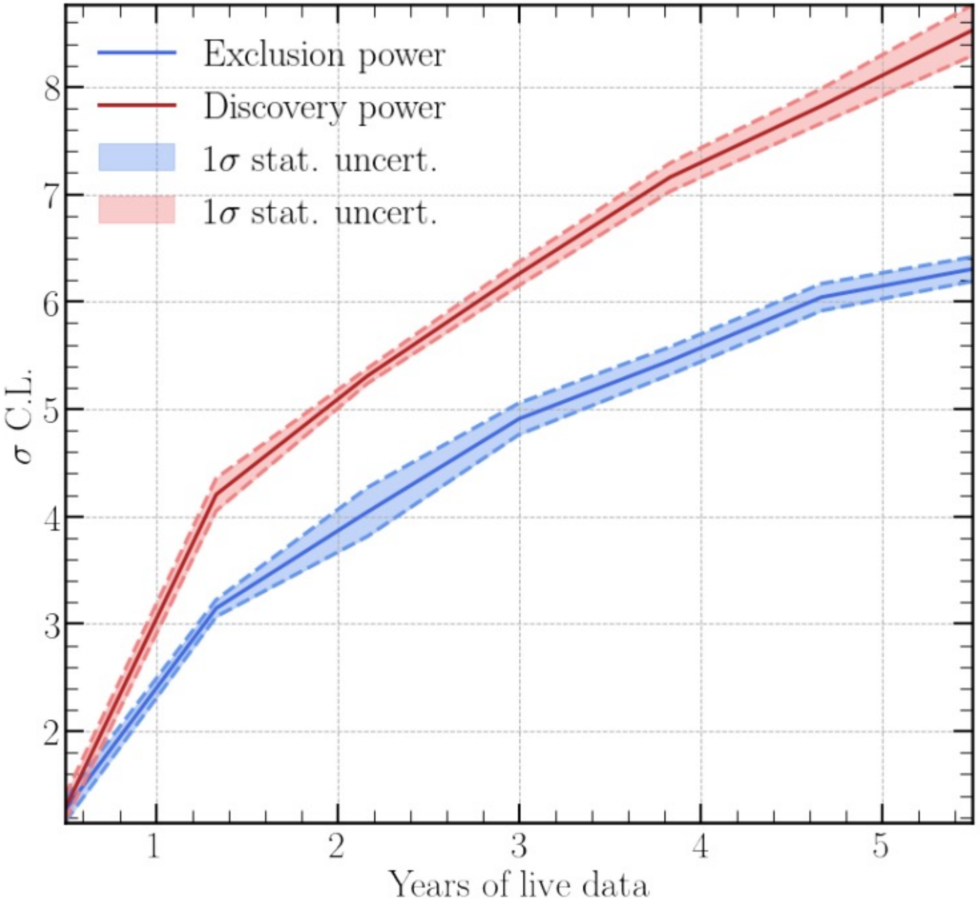
Sensitivity

Assuming total crystal mass of 50 kg and background of 0.72 cpd/kg/keV$_{ee}$ from simulated radioactivity.

90% exclusion curve for the SABRE South experiment after 3 years of data taking .

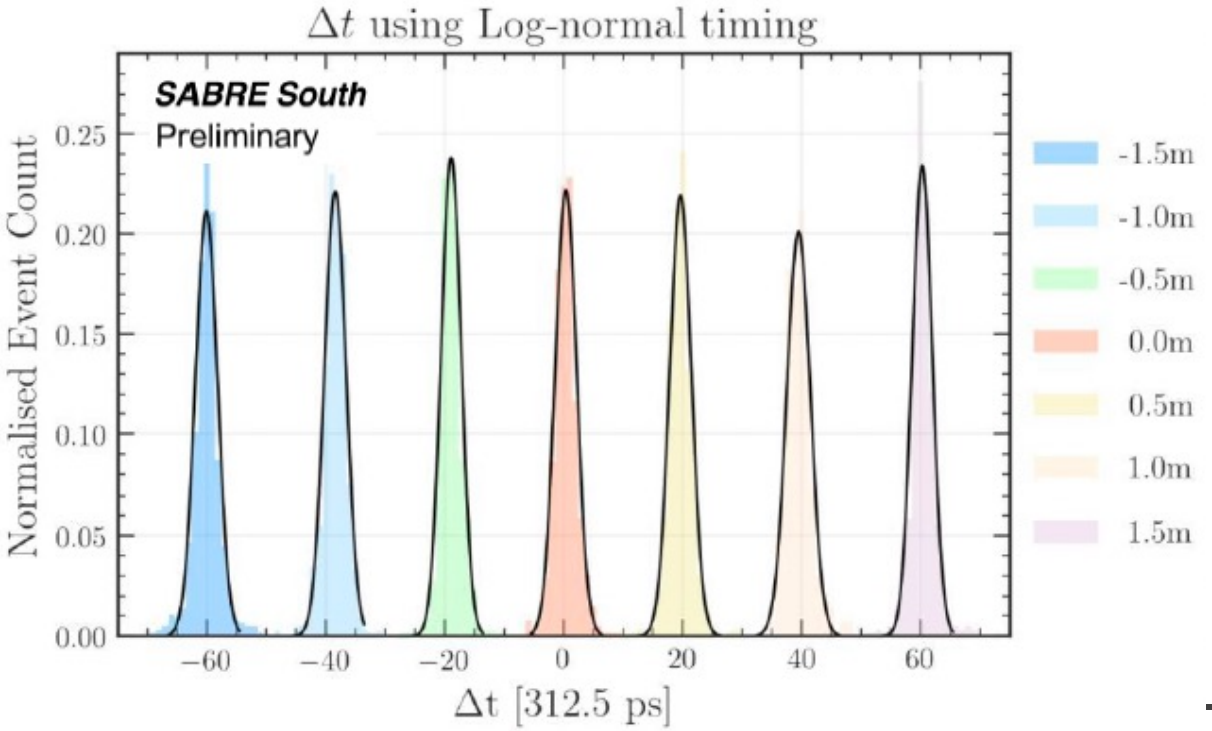


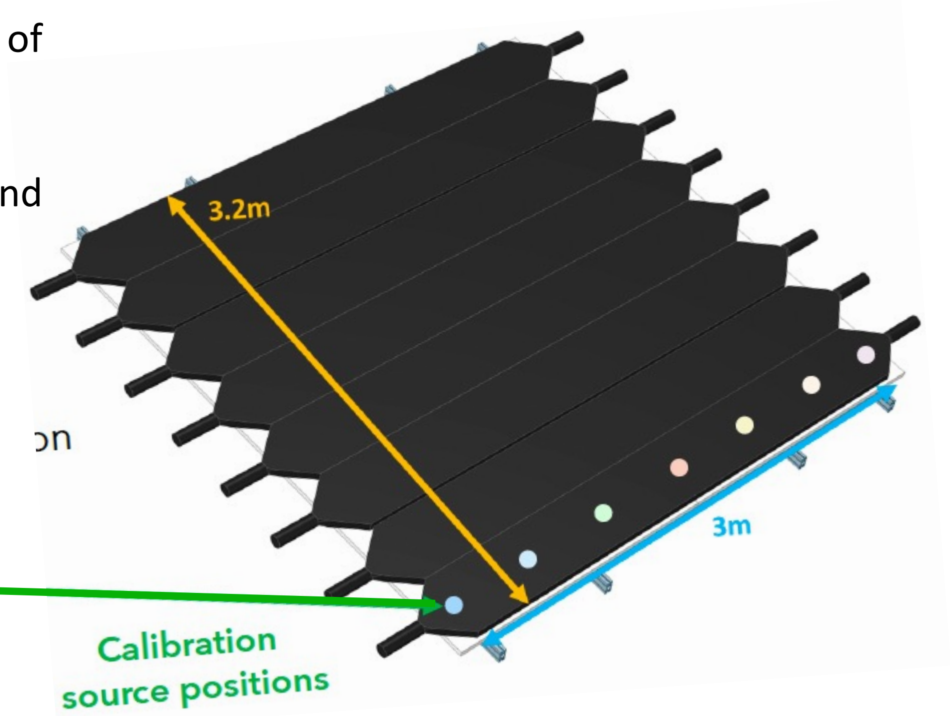
Evolution of discovery/exclusion power as a function of live time.

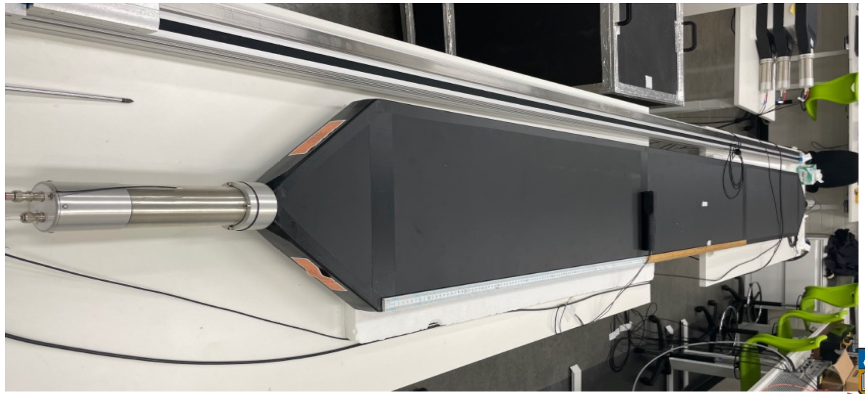


Muon Detector System

- Provides additional tagging of cosmic muons, and long-term measurements of muon modulation at SUPL.
- Will be used to improve particle ID and localisation in LS Veto.
- 8 x EJ200 organic scintillator panels (3x0.4x0.05 m) with PMTs at opposite ends and sampled at 3.2 GS/s.
- Longitudinal position resolution of 3.2 cm using CFD trigger.
- Total coverage 9.6 m^2 above main vessel.
- Each panel is being characterised for timing and efficiency on surface.





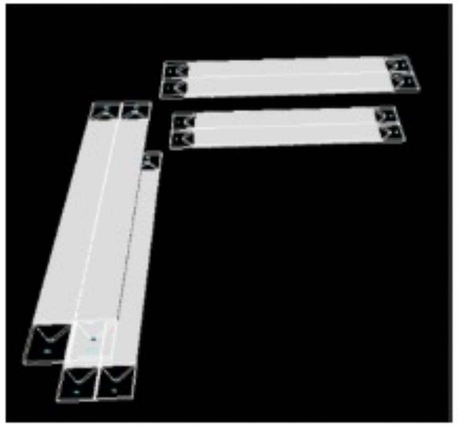


Underground Muon Measurements

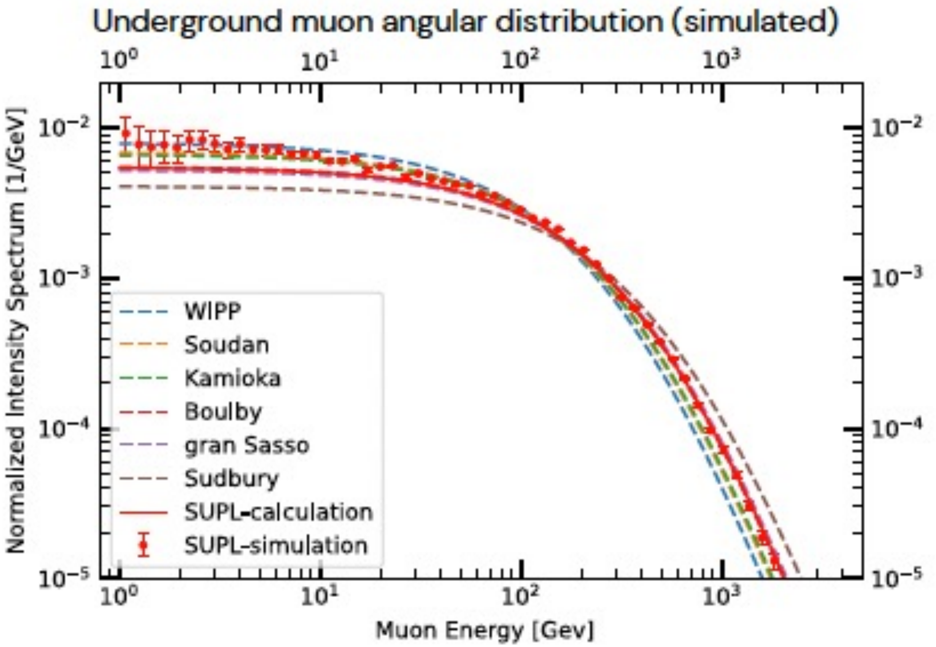
Muon detectors ready to be installed in SUPL in the coming months.

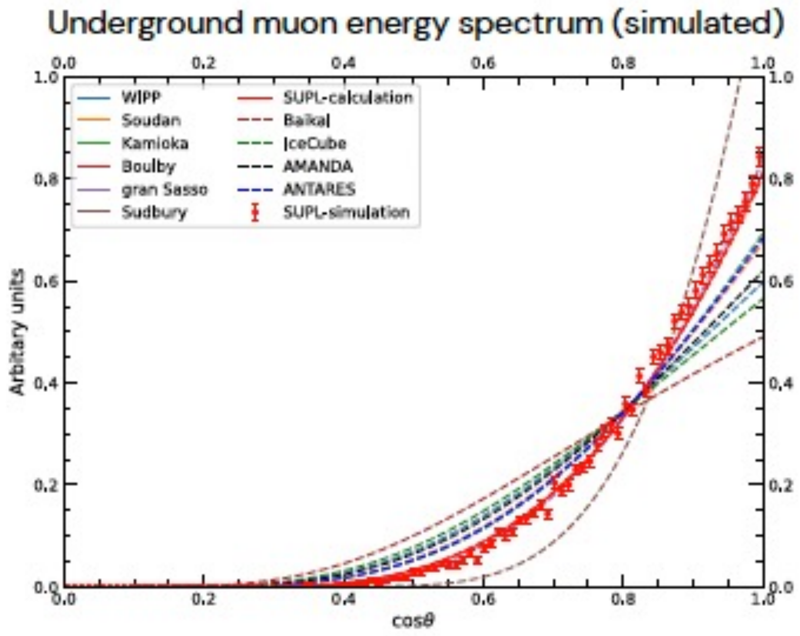
As the first detector in SUPL, this system will:

- measure the muon flux and its angular distribution;
- provide the first test of the remote data acquisition and processing pipeline.

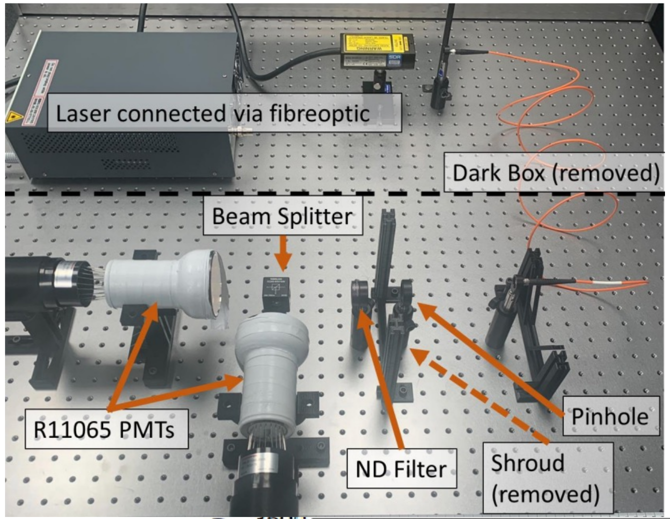


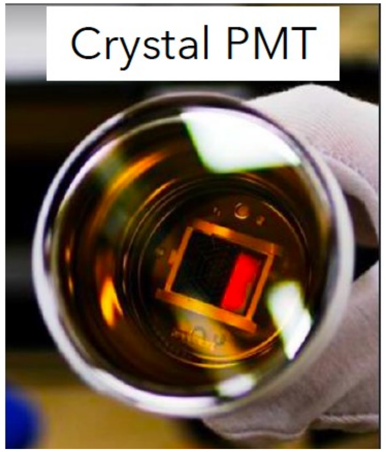
Layout of muon detectors in simulation and proposed SUPL configuration





PMT Characterisation



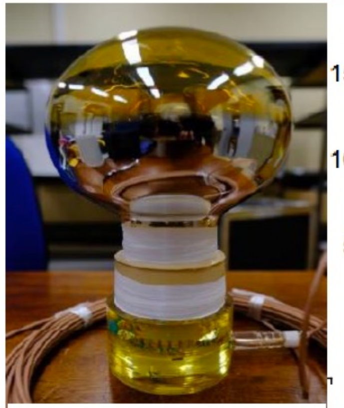


Extensive program to test and pre-characterise PMTs

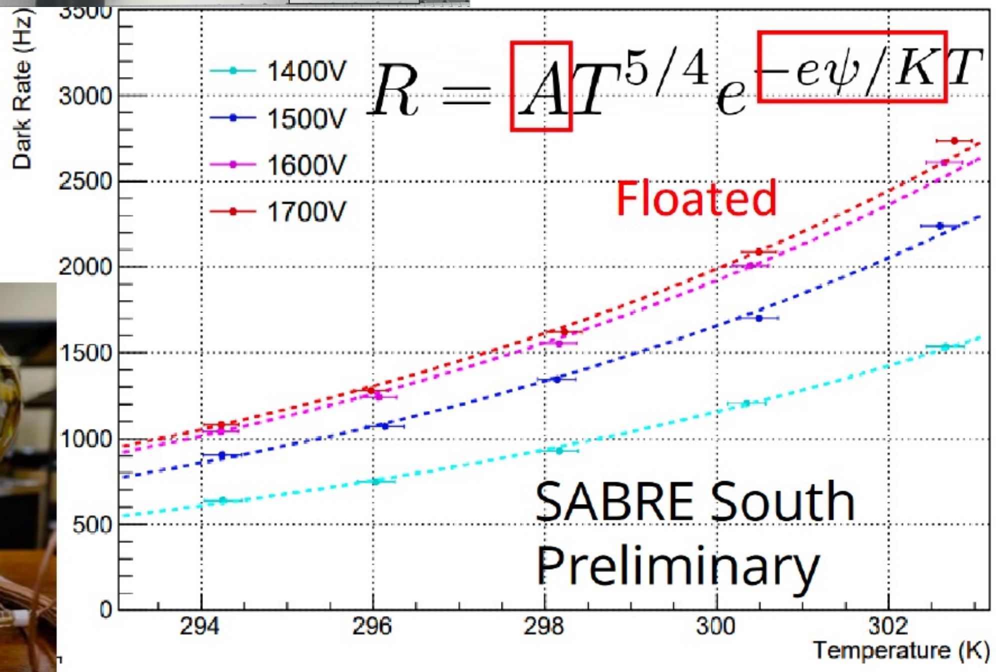
- Understand response of PMTs and their noise characteristics
  - Important for achieving reliable results and low thresholds

Measuring / Testing:

- Quantum efficiency
- Single phe response and gain
- Dark rate and temperature dependence
- Linearity/saturation
- Afterpulsing
- Dynamic range



Veto PMT

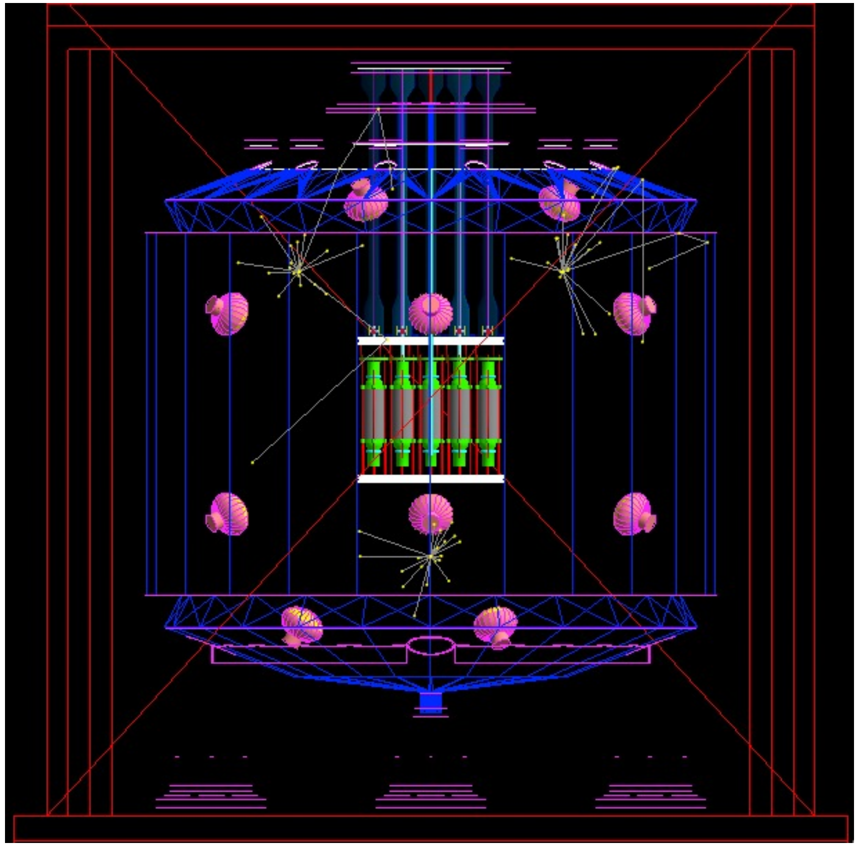


Detector calibrations

All detector components must be carefully calibrated.

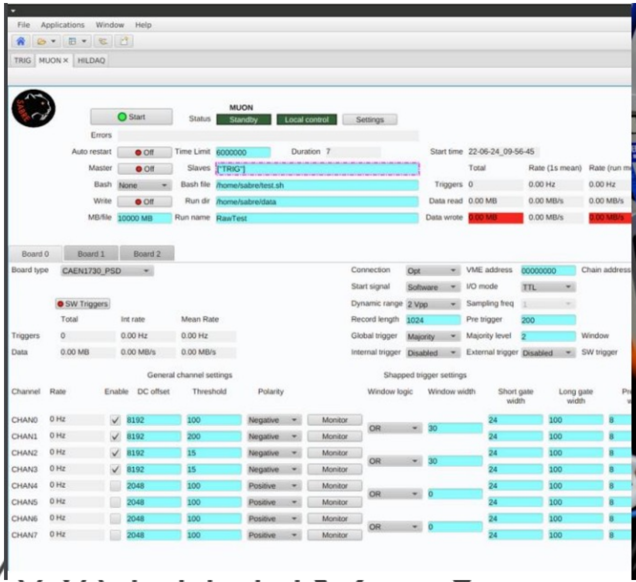
Optical calibration, veto PMTs:

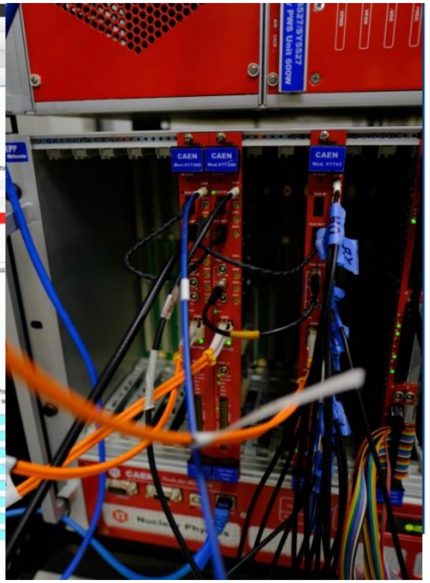
- Definitions of suitable set-ups also from mechanical point of view (e.g. installation of fibre optics and feedthrough).
- Simulations to assess the best set-up and the expected signal.
- Prototype development and tests.
- Calibrations on the full-scale detector.
- Check detector stability over time.

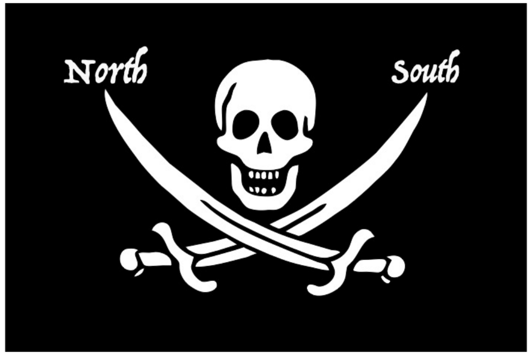


DAQ & Software

- SABRE South has developed DAQ for the SABRE collaboration: independent EPICS based instances for each subdetector (crystal, veto, & muon).
- Global trigger managed by CAEN V2495 FPGA with custom firmware.
- Prototype currently running NaI test at LNGS.

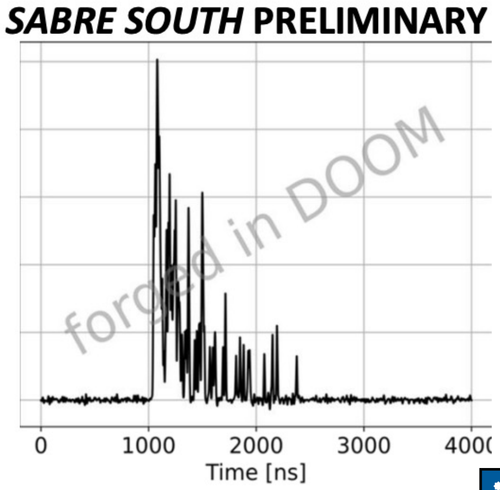






- SABRE South has developed a flexible python-based tool for data processing and analysis code called Pyrate.
- This reconstruction code will be used by the whole SABRE collaboration.

- Designed to process many digitised channels, currently in use for PMT and NaI characterisation. DOI:10.5281/zenodo.6257646



PARTICLE PHYSICS

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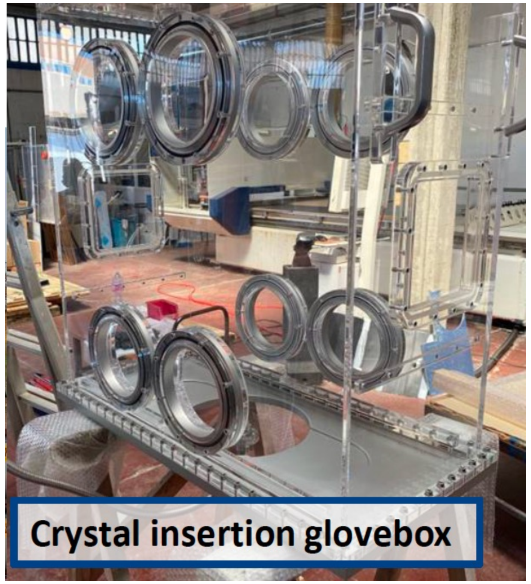
Possible outcomes from SABRE:

1. SABRE doesn't observed any signal $\Longrightarrow$ DAMA/LIBRA detects some false signal introduced somehow;
2. SABRE North and South detect modulation out of phase $\Longrightarrow$ strong evidence that some seasonal background exists and needs to be understood;
3. SABRE North and South detect annual modulation in phase $\Longrightarrow$ some non-seasonal source that is somehow not seen in any other Dark Matter experiments.

All outcomes are interesting.

Summary

- Dark Matter represents the 85% of the mass of the Universe and it is still a mystery.
- A way to detect it, is through its annual modulation which is a model independent signature, but it requires an ultra-low background.
- Currently only one experiment, DAMA/LIBRA claimed to have detected Dark Matter.
- DAMA/LIBRA result is in tension with other experiments which use other target materials. The signal can be due to muons which have the same annual modulation period as Dark Matter.
- For these reasons, an experiment having the same target material of DAMA/LIBRA is essential.
- Australia is building a leading-edge experiment, SABRE South, which will be located at SUPL, the first underground laboratory in the Southern hemisphere.
- SABRE South will reach an ultra-high sensitivity and will be able to exclude seasonal effects.
- SABRE South construction/commissioning to start towards the end of this year, completing in 2024. Vessel, LAB, PMTs, muon detectors, DAQ, crystal insertion system all ready.
- It will be able to confirm or reject the DAMA/LIBRA claim after 2 years.



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MIT

Stockholm University

INFN

The University Of Sheffield.

HZDR

University of Washington

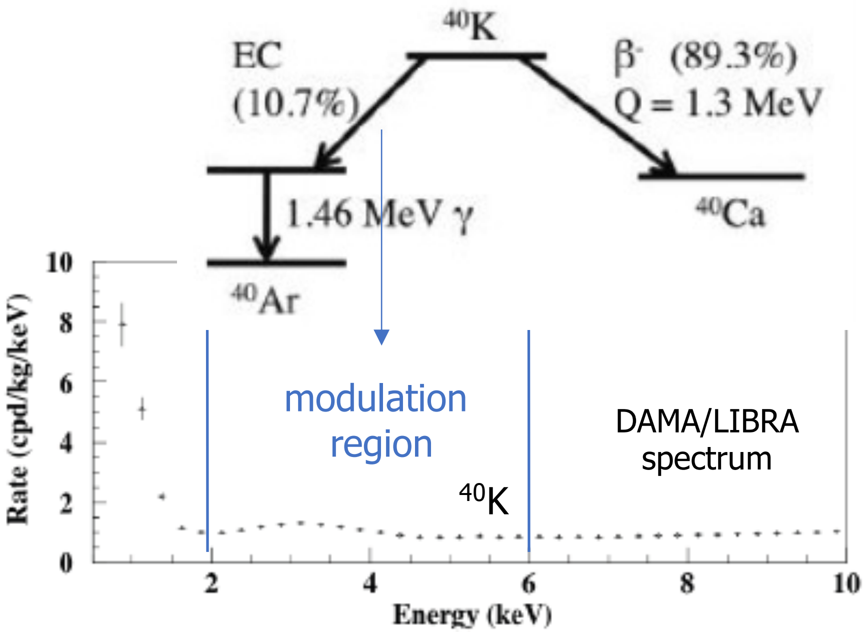
Caltech

Back up

Background from ^{40}K

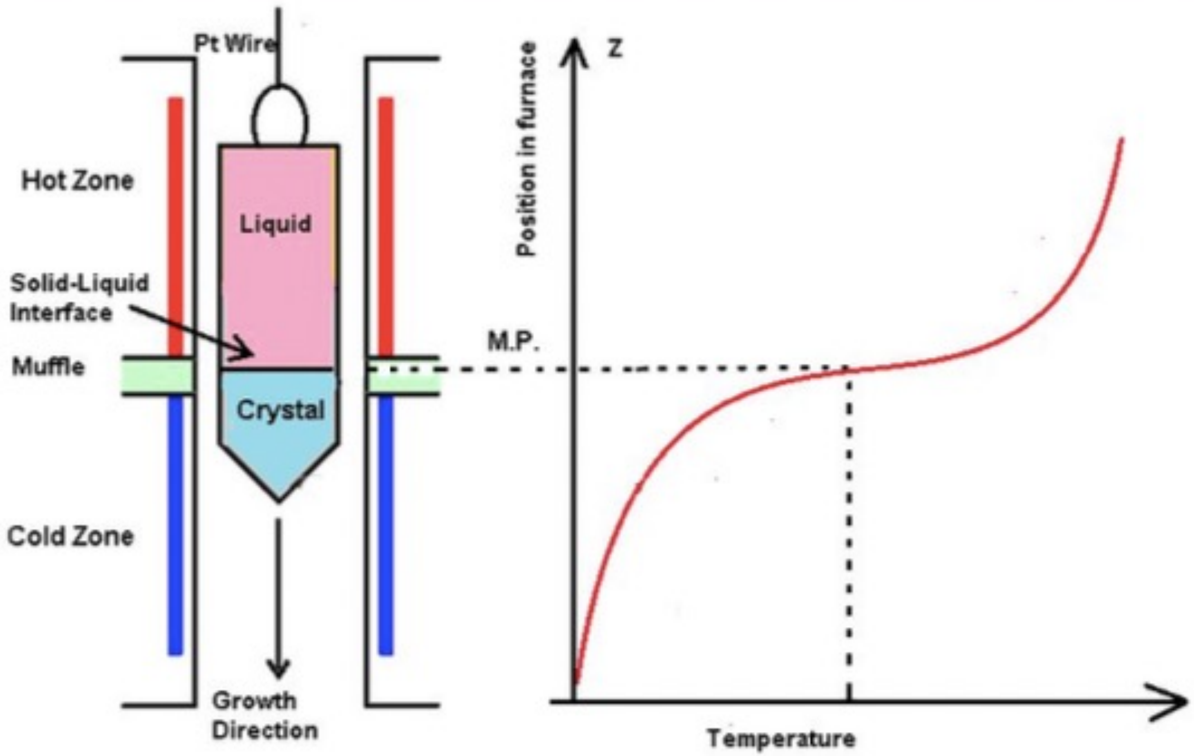
Most dangerous long-lived background in the Region of Interest:

- **^{40}K** decays by e^- capture (BR~11%)
- excited state of ^{40}Ar emitting a 1461 keV gamma
- Auger e^- or X-ray with a total energy of 3.2 keV



Crystal growth

- Crystals are grown in a precision-cleaned carbon coated synthetic fused quartz crucible, using the vertical Bridgman method.
- Furnace is headed to 750 °C over a few days, then crucible is slowly lowered into cold zone (500 °C) at a rate of 7-10 mm/day. The furnace is then cooled to room temperature over a week before crystal is removed.
- The dry NaI powder is mixed with high-purity thallium iodide (TlI) powder (99.999%) and sealed inside a high-purity crucible. To prevent contamination, the crucible is carefully cleaned with high-purity acids.



Vertical Bridgman Tube Furnace   Temperature Profile

FHB (Copyright)

SABRE North status

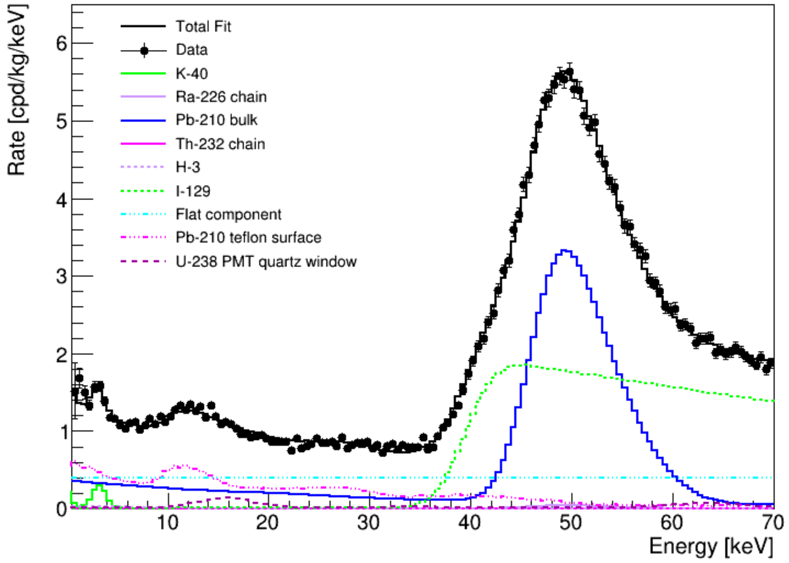
Proof-of-Principle phase (1 crystal + active veto) concluded

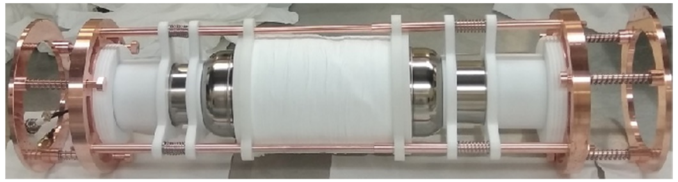
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, lowest since DAMA/LIBRA.

Goals for near future:

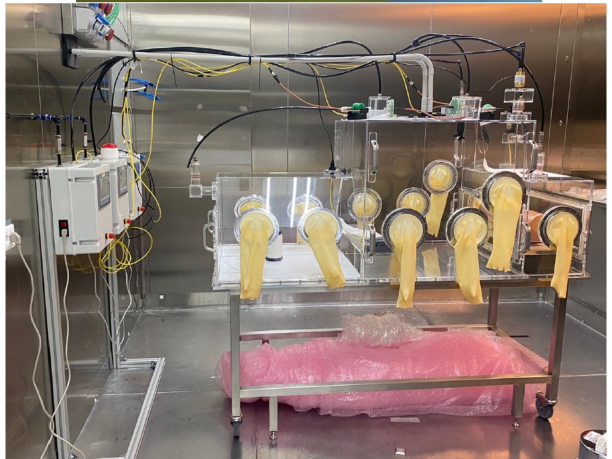
- Test reproducibility of crystal radiopurity
- Demonstrate lower background with zone refining of NaI powder

Full Monte-Carlo simulation model of crystal NaI-33 to identify background components





Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding



Other Physics

New physics	Potential observable/s
Pauli exclusion principle	Proton emission above 10 MeV
Solar axions	Axion to photon conversion, electron scattering
MIMPs (heavy DM, boosted DM)	Excess events in crystal or LS
Charge non conserving decays in Na or I	Electron disappearance, gamma excess
Sub GeV DM	Particle ID fro ER-DM events, Migdal effect
Supernova neutrinos	Scattering in crystal or LS