

# WIMP Modulation Detection with SABRE

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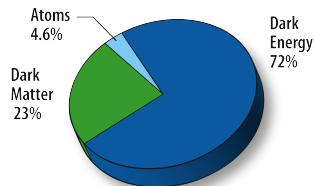
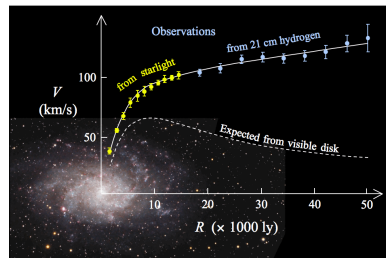


# Overview

- 1 Motivation
- 2 SABRE - The Ingredients
- 3 SABRE - Putting Everything Together
- 4 The Australian Lab

# Evidence for Dark Matter

- Rotation curves of spiral galaxies
- Hot gas in galaxy clusters
- Gravitational lensing of galaxy clusters
- CMB anisotropy
- Structure formation



NASA / WMAP Science Team

# Search for Dark Matter

## Direct Detection

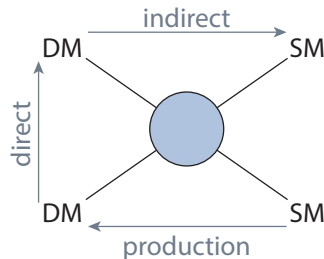
Nuclear recoils of Dark with Standard Matter

## Indirect Detection

Astronomical and cosmological observations

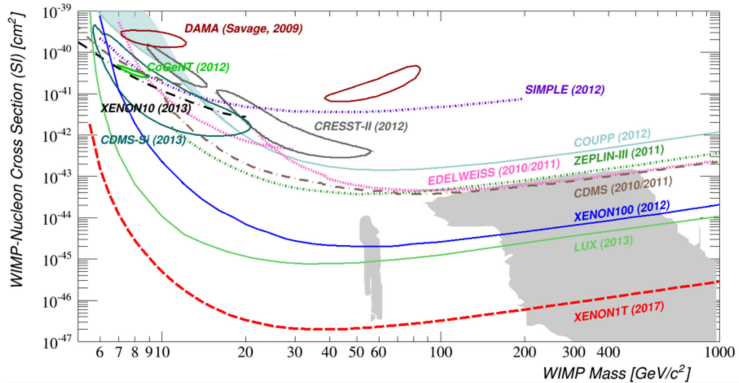
## Production

Production in Accelerators





# The Tension



# Solving the Tension?

## The Recoil Rate

$$\frac{dR}{dE_{\text{nr}}} = \frac{\sigma(q)}{2m\mu} \rho \eta(E_{\text{nr}}, t)$$

$\sigma(q)$

WIMP-nucleus cross section

$\rho$

local WIMP density

$\eta(E_{\text{nr}}, t)$

WIMP velocity distribution

Assumptions

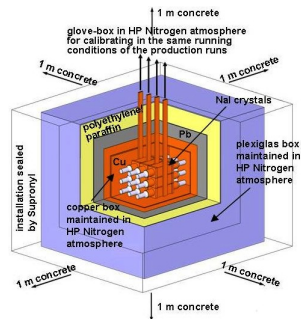
WIMP interactions with n & p  
halo model

number of WIMP species & distribution  
velocities in the galaxy

# The DAMA/LIBRA Experiment

## Setup

- 25 high purity NaI(Tl) crystals with 9.7 kg each
- 2 low background PMTs coupled to each crystal via 10 cm quartz light guide
- Shielding: OFHC Cu, low radioactivity lead, Polyethylene, concrete
- Kept in sealed box continuously flushed with HP N<sub>2</sub>
- Located at LNGS ( $\sim 3200$  m.w.e.)

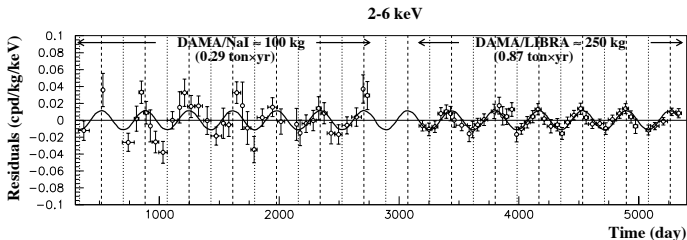
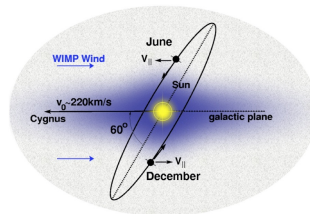


Official DAMA website

# The DAMA/LIBRA Experiment

## Annual Modulation Signal

- Modulation at 2– 6 keV<sub>ee</sub>
- Most prominent at 3 keV<sub>ee</sub>
- Effect  $\sim 2\%$
- Peak end of May / beginning of June
- $9.3\sigma$  C.L.

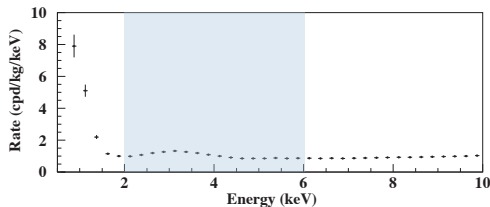
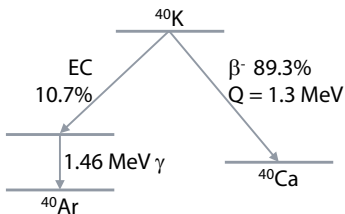


DAMA/LIBRA results and perspectives, Bled 2013

# Potassium Obsession

## $^{40}\text{K}$ Decay

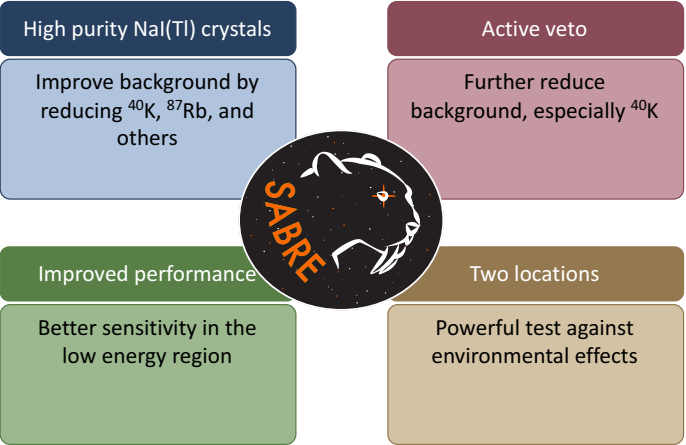
- $\text{natK} \simeq 93\% \text{ } ^{39}\text{K} + 0.012\% \text{ } ^{40}\text{K} + 7\% \text{ } ^{41}\text{K}$
- 3 keV Auger  $e^-$  accompanying 1.46 MeV  $\gamma$  after electron capture  
 $\Rightarrow$  Right in the region of interest
- DAMA reports 13 ppb  $\text{natK}$  contamination in their crystals



# Outline

- 1 Motivation
- 2 **SABRE - The Ingredients**
- 3 SABRE - Putting Everything Together
- 4 The Australian Lab

# What Makes SABRE Special?



# Pure Crystals

## The NaI(Tl) Crystal

- Crystal should have at least purity of DAMA crystals, preferably better
- Crystal size a few kg
- Very good scintillation properties

## The Challenge

- DAMA's crystals cannot be bought
- Growing process has to be newly developed
- Purity difficult to reach





# High Purity Crystals

The NaI Powder

## Development of Ultra High Purity Powder

- Collaboration with 2 industrial partners for production
- Independent high sensitivity impurity measurements
- R&D on further purification ongoing

Element	Sigma-Aldrich [ppb]	DAMA Powder [ppb]	DAMA Crystal [ppb]
K	3.5 (18)*	100	~13
Rb	0.2	n.a.	< 0.35
U	< 1.7 ( $< 10^{-3}$ )**	~ 0.02	$0.5 - 7.5 \times 10^{-3}$
Th	< 0.5 ( $< 10^{-3}$ )**	~ 0.02	$0.7 - 10 \times 10^{-3}$

\* Independent measurement

\*\* Preliminary measurement at PNNL; full validation needed.  
Bernabei et al., NIM A592 (2008) 297-315

# Crystal Growth

## Crucible Tests

- Test growth of small crystals in different crucibles and ampules
- Careful material selection
- Precision cleaning

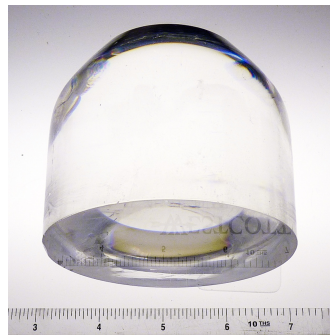


Crucible Ampules	Cleaning procedure	Contamination due to crystal growth [ppb]			
		K	Rb	Th	U
# 1, # 1	Standard	$65 \pm 10$	N.D.	0.2– 0.4	0.1– 0.2
# 1, # 2	Precision	$41 \pm 10$	N.D.	N.D.	N.D.
# 2, # 2	Precision	$63 \pm 10$	N.D.	N.D.	N.D.
# 3, # 3	Precision	$6 \pm 10$	N.D.	N.D.	N.D.
Blank test	Precision	1.5	$4 \times 10^{-3}$	$0.4 \times 10^{-3}$	$0.14 \times 10^{-3}$

# High Purity Crystal

## First Larger Crystal

- 2-kg crystal made out of Astrograde powder
- 88-mm diameter similar to final crystals
- Good scintillation properties
- $\langle \text{Rb} \rangle < 0.1 \text{ ppb}$  (DAMA  $< 0.35 \text{ ppb}$ )

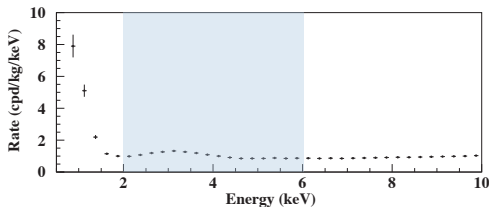
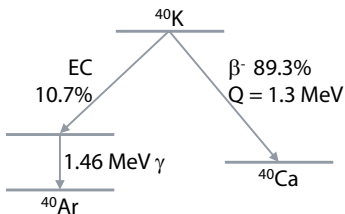


$^{39}\text{K}$ [ppb]	Seastar	PNNL	DAMA
A	$9 \pm 1$	$10.0 \pm 0.7$	
B	$7 \pm 1$	$9.1 \pm 0.3$	
D	$11 \pm 1$	$9.7 \pm 0.4$	
E	$9 \pm 1$	$9.8 \pm 0.4$	
Average	9	9.6	13

# Active Veto: The Principle

## $^{40}\text{K}$ Decay

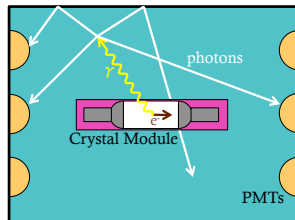
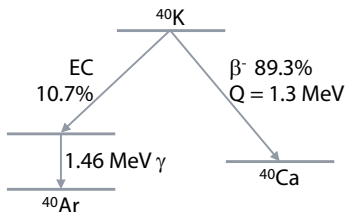
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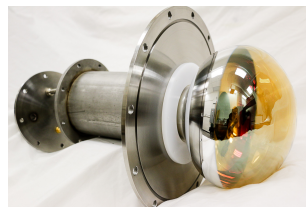
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- 3 keV Auger  $e^-$  accompanying 1.46 MeV  $\gamma$  after electron capture  
 $\Rightarrow$  Right in the region of interest  
 $\Rightarrow$  Coincidence between  $e^-$  and  $\gamma$  can be used to veto such events
- DAMA reports 13 ppb  $\text{natK}$  contamination in their crystals



# The Active Veto

## The Portable Veto Vessel

- 1.4 m diameter  $\times$  1.5 m length
- Made out of low radioactivity steel
- $\sim 2.3$  tons of scintillator (probably PC+PPO)
- 10 veto PMTs (Hamamatsu R5912)
- Expected light yield  $\sim 0.2$  p.e./keV



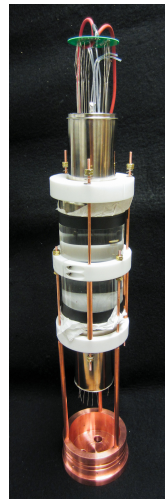
# Improved Performance

## Improved PMTs

- High quantum efficiency:  $\sim 35\%$
- Low radioactivity:  $\sim 1$  mBq U, Th, Co;  $\sim 10$  mBq K
- Development by Hamamatsu in collaboration with Princeton
- Further improvements in development

## Higher light yield, lower threshold

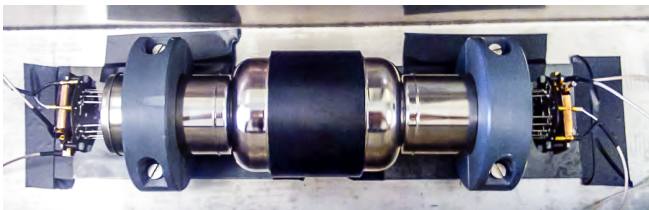
- PMTs directly coupled to crystal
- Very good reflector around crystal



# Improving Performance

## Afterglow

- Requiring coincidence between 2 PMTs reduces dark count
- Light generated in one PMT can be picked up in other  $\Rightarrow$  Afterglow
- Lower HV reduces afterglow
- Pre-amplifier developed by LNGS enables operation at such low HV reduces afterglow to level of random coincidences

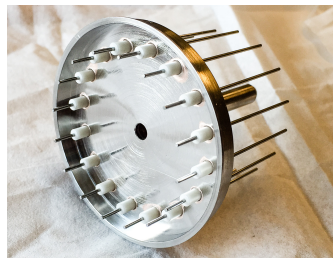
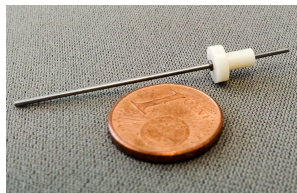




# Improving PMTs

## New Stem

- Designed to reach higher radio-purity and better stability
- Ceramic feedthroughs use ultra high purity alumina ( $\text{Al}_2\text{O}_3$ )
- Special brazing of feedthroughs to Kovar plate by PPPL
- High QE PMT to be built with this stem by Hamamatsu



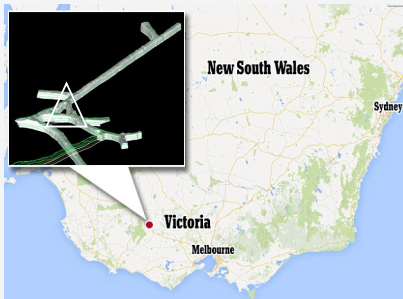
## Two Locations: Northern and Southern Hemisphere

- $\sim 3000$  m.w.e shielding at both locations
- Twin detectors for optimum comparability
- Both detectors will run in parallel

LNGS, Italy



SUPL, Australia

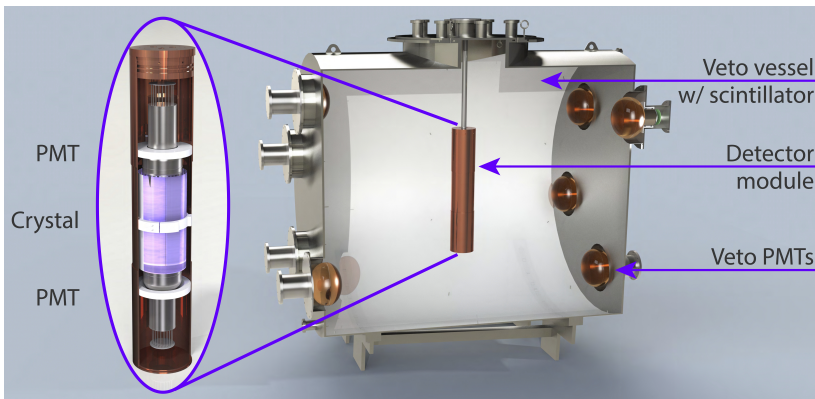


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# SABRE

- Proof-of-Principle: 5.5-kg ultra high-purity NaI(Tl) crystals
- Full scale experiment: 40 – 50 kg target mass at each location
- Additional water / lead / polyethylene shielding around the veto



# Proof of Principle

## Goals

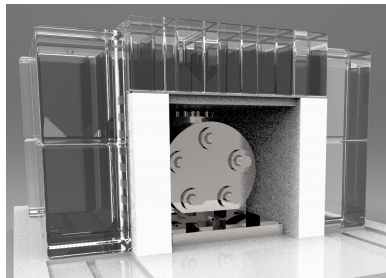
- Measure impurity levels of first high-purity crystal(s)
- Determine effectiveness of veto

## Setup

- Location: LNGS
- 1-2 crystals (5.5 kg)

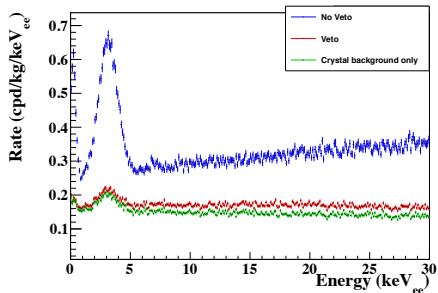
## Status

- Most components available
- Vessel on its way to LNGS
- Preparations at LNGS in progress
- Start next spring

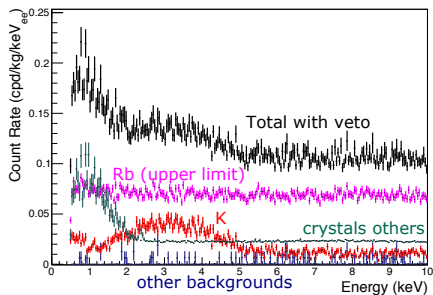


# Background Expectations

## Total Background



## Crystals

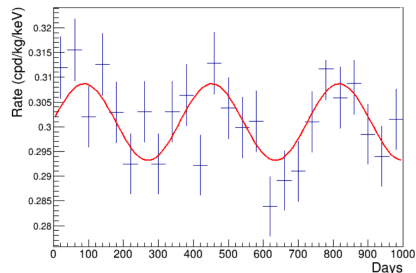


# Expectations

## Sensitivity

### Sensitivity

- 3 years stable detector operations
- No other seasonal effect in ROI (2-6 keV<sub>ee</sub>)
- 50 kg NaI(Tl) array
- 0.15 cpd/kg/keV total background in ROI
  - ⇒ 6 $\sigma$  to refute modulation
  - ⇒ 4 $\sigma$  to verify modulation



# Collaboration



Adelaide University  
Australian National University  
Swinburne University  
University of Melbourne



LNGS & GSSI  
INFN Rome  
University of Milano & INFN



Imperial College London



LLNL  
PNNL  
Princeton University





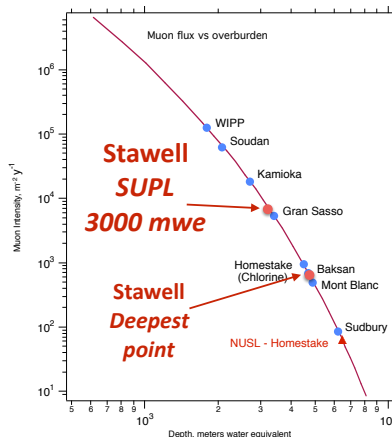
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# Stawell Underground Physics Laboratory (SUPL)

## Overview

- First underground lab in southern hemisphere
- ~ 240 km west of Melbourne
- Decline gold mine
- Site 1.02 km deep (~ 3 km.w.e. similar to LNGS)
- Electricity & optical fibre available
- Can be reached by truck/car
- Clean room design similar to SNOLab



# SUPL Floor Plan




# Lab Characteristics

- Rn activity  $< 100 \text{ Bq/m}^3$  in “clean area”; surface coating to inhibit Rn
- Temp.:  $19 \pm 2^\circ\text{C}$ , remote monitoring & control
- Relative humidity 40% - 50%, remote monitoring & control
- Low radiation concrete and finishing; sampling all sand and cement

	LNGS	SUPL
Neutron flux	$4 \times 10^{-6} \text{ n/s}$	$< 7 \times 10^{-6} \text{ n/s/cm}^2 \text{ UL}$
Gamma flux $< 3 \text{ MeV}$	$0.73 \gamma/\text{s/cm}^2$	$< 2.5 \gamma \text{ n/s/cm}^2 \text{ UL}$
Rock $^{238}\text{U}$ [ppm] @ 880m	2.63	0.64
Rock $^{232}\text{Th}$ [ppm] @ 880m	0.72	1.63
Refuge Rn [ $\text{Bq/m}^3$ ] (12 days accumulated, ventilated)	$O(50)$	$36 \pm 5 \text{ } ^\circ\text{C}$ $1056 \text{ kPa, } 21\% \text{ humidity}$

# Timeline

- 
- 2014**    Lab proposed (Sep)  
Project Leaders: E. Barberio, J. Mould
- 2015**    Funding secured (May)  
Design commenced (Aug)
- 2016**    Design review (Feb)  
Start construction (July)  
**Cavern excavation (Sep)**
- 2017**    Lab surfacing (early 2017)  
Lab ready to use (late 2017)  
Planned experiments:
- SABRE-South (2017)
  - **TPC-experiment:** CYGNUS Directional Dark Matter, Neutrinoless  $\beta\beta$  R&D
  - *Other possibilities **Non HEP:** Astrobiology, Cancer research*

# Conclusions & Outlook

## Conclusions

- WIMP interpretation of DAMA modulation signal in tension with other experiments
- Independent NaI(Tl) experiments needed  $\Rightarrow$  SABRE
- Ultra high purity NaI(Tl) in preparation  $\Rightarrow$  first breakthrough!
- Low background with high purity materials and active veto
- High light yield & lower threshold due to improved, pre-amplified PMTs directly coupled to crystal

## Outlook

- First high-purity NaI(Tl) crystal grown
- Proof of principle at LNGS in preparation
- Full-scale twin detectors in preparation at LNGS (Italy) and SUPL (Australia)