WIMP Modulation Detection with the SABRE NaI(Tl) Experiment

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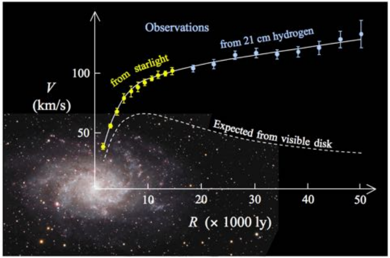
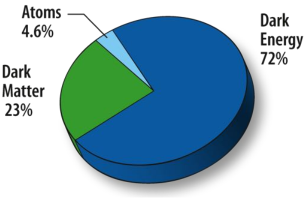
Imperial College London

Overview

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

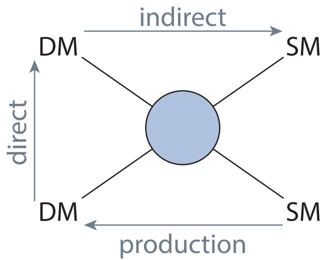
Nuclear recoils of Dark with Standard Matter

Indirect Detection

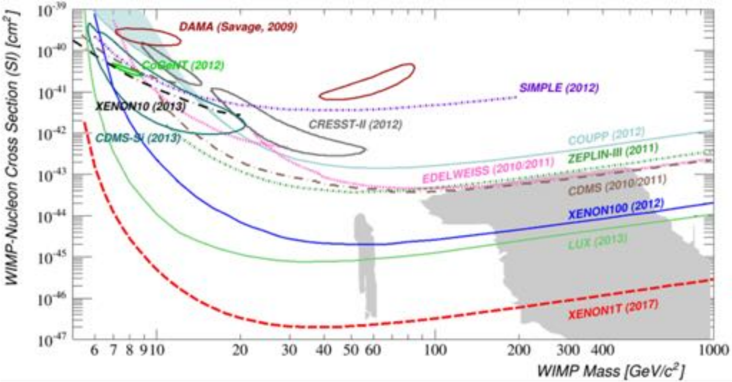
Astronomical and cosmological observations

Production

Production in Accelerators



Not So Current Status - The Tension



Solving the Tension?

The Recoil Rate

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

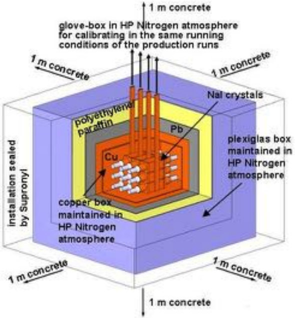
$\sigma(q)$	WIMP-nucleus cross section
ρ	local WIMP density
$\eta(E_{\mathrm{nr}}, t)$	WIMP velocity distribution
Assumptions	WIMP interactions with n & p halo model number of WIMP species & distribution velocities in the galaxy

NaI experiment needed ⇒SABRE

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 quarz light guide
- Shielding: OFHC Cu, low radioactivity lead, Polyethylene, concrete
- Kept in sealed box continuously flushed with HP N_2
- Located at LNGS ($\sim$ 3200 m.w.e.)

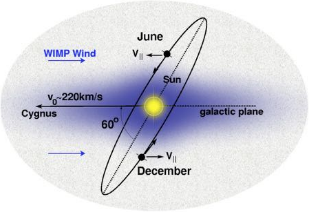


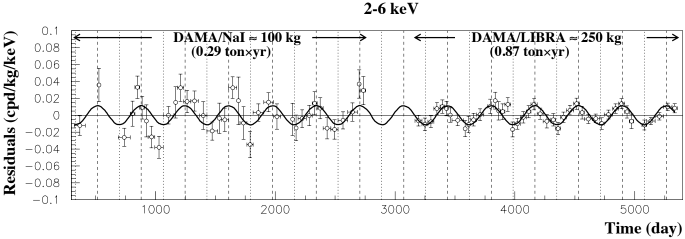
Official DAMA website

The DAMA/LIBRA Experiment

Annual Modulation Signal

- Modulation at 2– 6 $\mathrm{keV_{ee}}$
- Most prominent at 3 $\mathrm{keV_{ee}}$
- Effect ~ 2 %
- Peak end of May / beginning of June
- 9.3σ C.L.





DAMA/LIBRA results and perspectives, Bled 2013

Outline

What Makes SABRE Special?

SABRE: Sodium iodide with Active Background REjection

High purity NaI(Tl) crystals

Improve background by reducing ^{40}K, ^{87}Rb, and others

Active veto

Further reduce background, especially ^{40}K

Improved performance

Better sensitivity in the low energy region

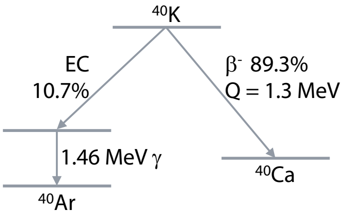
Two locations

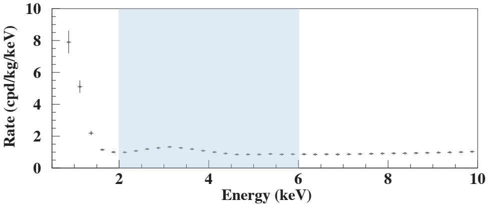
Powerful test against environmental effects

Active Veto: The Principle

^{40}K Decay

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





Active Veto: The Principle

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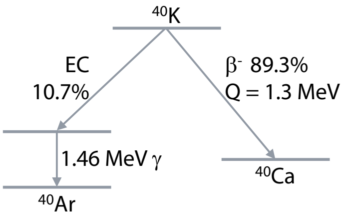
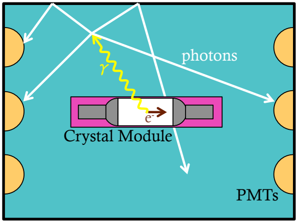
- 3 keV Auger e^- accompanying 1.46 MeV γ after electron capture
  $\Rightarrow$ Right in the region of interest
  $\Rightarrow$ Coincidence between e^- and γ can be used to veto such events
- DAMA reports 13 ppb ^{nat}K contamination in their crystals





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	$\sim$13
Rb	0.2	n.a.	< 0.35
U	< 1.7 ($< 10^{-3}$)**	~ 0.02	$0.5 - 7.5\times10^{-3}$
Th	< 0.5 ($< 10^{-3}$)**	~ 0.02	$0.7 - 10\times10^{-3}$

* 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 ± 10	N.D.	0.2– 0.4	0.1– 0.2
# 1, # 2	Precision	41 ± 10	N.D.	N.D.	N.D.
# 2, # 2	Precision	63 ± 10	N.D.	N.D.	N.D.
# 3, # 3	Precision	6 ± 10	N.D.	N.D.	N.D.
Blank test	Precision	1.5	4×10^{-3}	0.4×10^{-3}	0.14×10^{-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
- $\langle \text{Rb} \rangle < 0.1$ ppb (DAMA < 0.35 ppb)

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

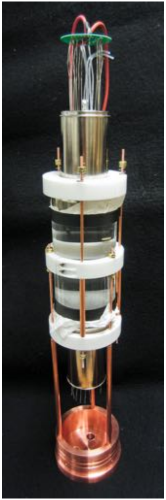
Improved Performance

Improved PMTs

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

Higher light yield, lower threshold

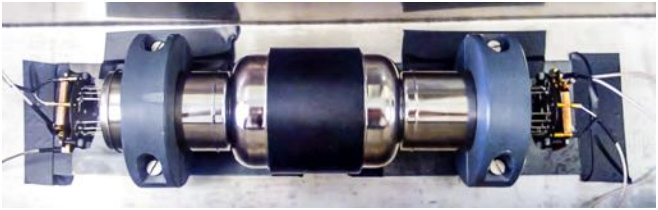
- PMTs directly coupled to crystal
- Very good reflector around crystal



Improving Performance

Afterglow

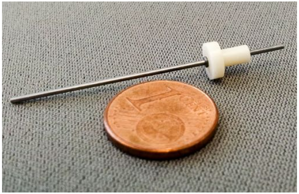
- Requiring coincidence between 2 PMTs reduces dark count
- Light generated in one PMT can be picked up in other ⇒ Afterglow
- Lower HV reduces afterglow
- Pre-amplifier developed by LNGS enables operation at such low HV reduces afterglow to level of random coincidences

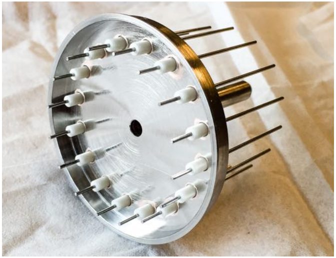


Improving PMTs

New Stem

- Designed to reach higher radio-purity and better stability
- Ceramic feedthroughs use ultra high purity alumina (Al_2O_3)
- Special brazing of feedthroughs to Kovar plate by PPPL
- High QE PMT to be built with this stem by Hamamatsu

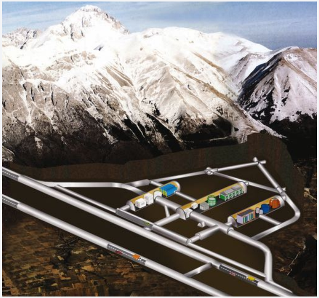




Two Locations: Northern and Southern Hemisphere

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

LNGS, Italy

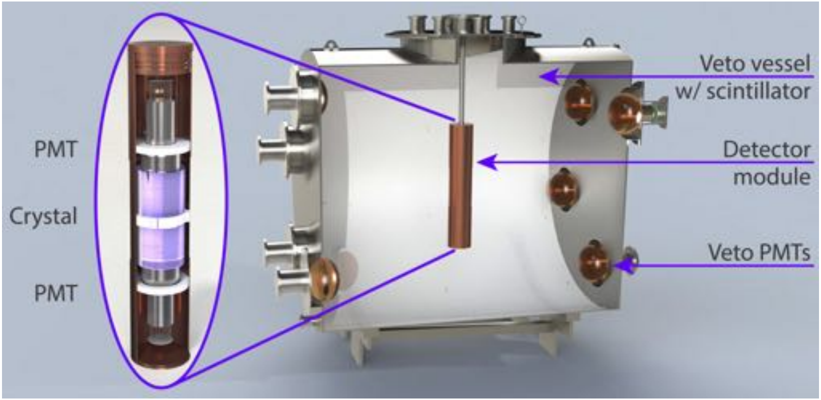


SUPL, Australia

Outline

SABRE North: Proof of Principle

- Measure impurity levels of first ~5.5 kg ultra high-purity NaI(Tl) crystal
- Determine effectiveness of the veto



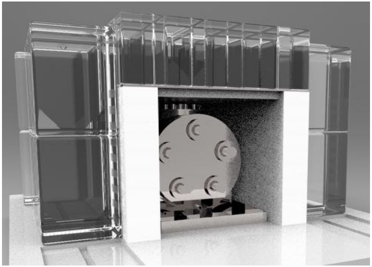
SABRE North: Proof of Principle

The Portable Veto Vessel

- 1.4 m diameter $\times$ 1.5 m length
- $\sim$ 2.3 tons of scintillator (PC+PPO)
- 10 veto PMTs (Hamamatsu R5912)
- Expected light yield $\sim$ 0.2 p.e./keV
- Initial commissioning in Princeton completed, delivered to LNGS

Other Components

- Site in Hall C in preparation
- Design of all components completed, procurement in process
- Start data taking planned in summer



Full Scale Experiments

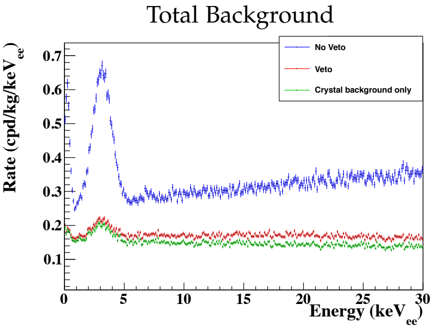
Design Goal: Maximum Compatibility

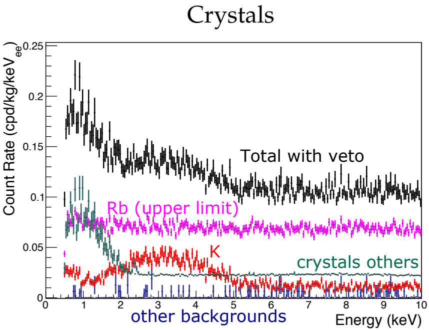
- Crystals from same raw material grown through same procedure
  - Grow in US and fly to AUS?
  - Develop enough expertise to grow in AUS?
- Scintillator: Probably switch to LAB

Strategy

- $\sim$50 kg target mass each
- Upgrade of PoP to SABRE North
  - New crystal insertion system, improved crystal enclosure,...
- Crystal growing (partially) sequential
  - Scenario 1: Deploy complete array first on one site, then other
  - Scenario 2: Upgrade each detector one by one

Background Expectations





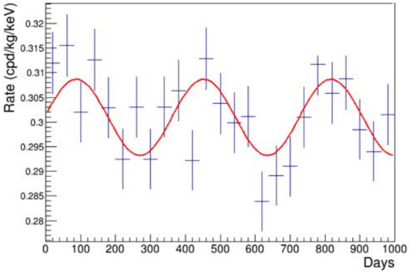
Expectations
Sensitivity

Sensitivity

- 3 years stable detector operations
- No other seasonal effect in ROI (2-6 keV_{ee})
- 50 kg NaI(Tl) array
- 0.15 cpd/kg/keV total background in ROI

$\Rightarrow$ 6σ to refute modulation

$\Rightarrow$ 4σ 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

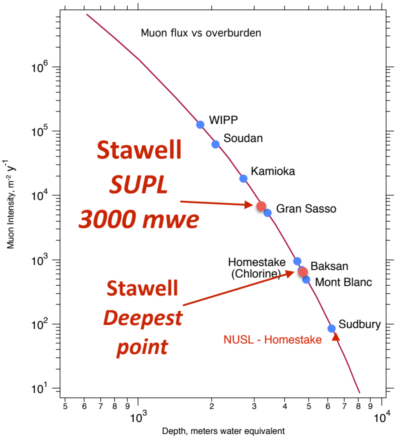
Outline

Stawell Underground Physics Laboratory (SUPL)

Overview

STAWELL UNDERGROUND PHYSICS LAB

- 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

Future expansion
allowed in design

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)