# SABRE: Direct Dark Matter Detection in the Northern and Southern Hemispheres


F. Nuti*

for the SABRE collaboration

*The University of Melbourne and CoEPP


31st January 2017

CAASTRO-CoEPP Workshop

Picture by M. Volpi

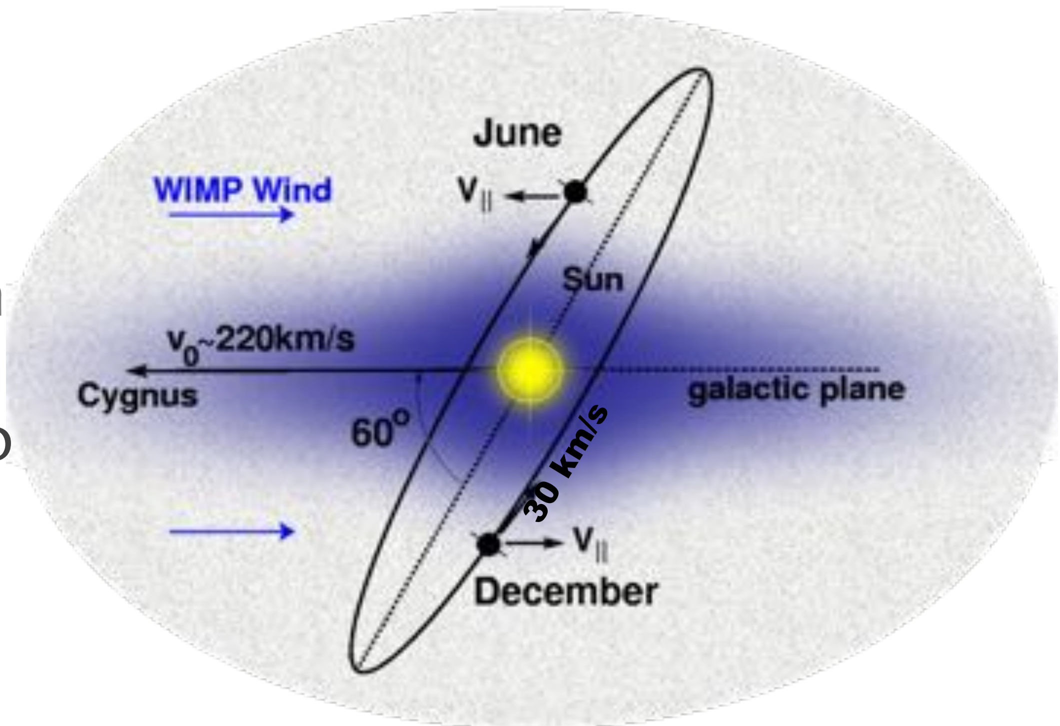
THE UNIVERSITY OF MELBOURNE

STAWELL UNDERGROUND PHYSICS LAB

SABRE

# WIMP FLUX MODULATION

- Hypotheses:
  - Weakly interacting massive particles (WIMPs) permeate our galaxy
  - Small but non-null σ with SM particles
- The earth speed relative to WIMP halo is subject to annual modulation
- DM flux and detection rate have characteristic period and phase important for background discrimination
- Max rate the 02/06, Min the 01/12, T=1 year

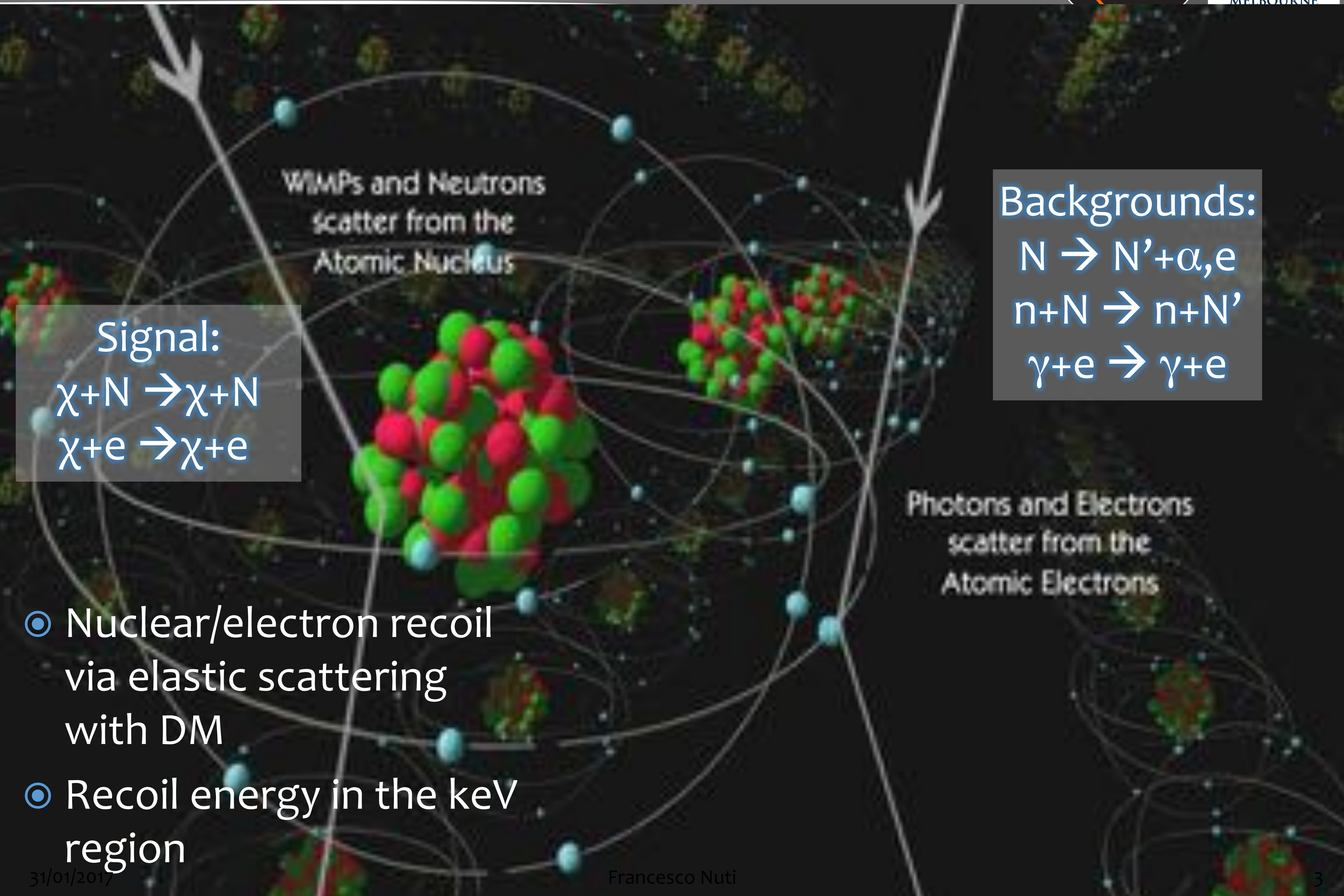



Rate modulation:

$$\frac{dR}{dE}(E,t) \simeq S_0(E) + S_m(E)\cos\omega(t-t_0)$$

arXiv:1209.3339v3

# Direct DM Detection




**Signal:**

$\chi+N \rightarrow \chi+N$

$\chi+e \rightarrow \chi+e$

**Backgrounds:**

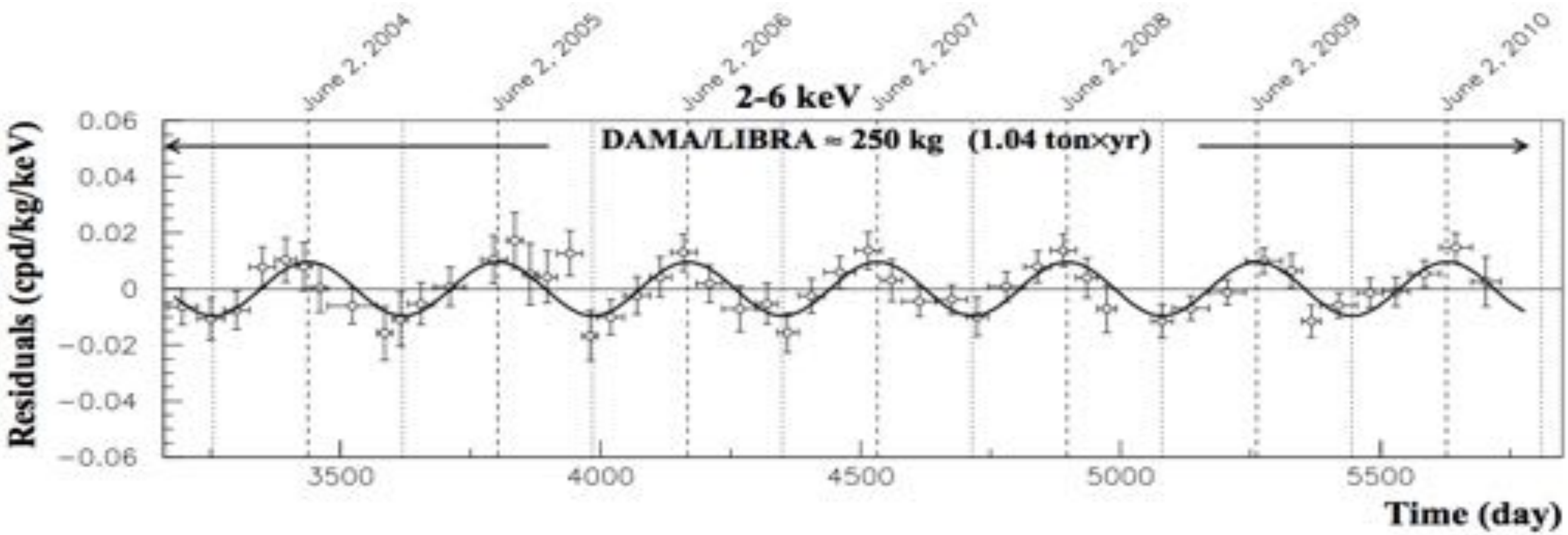
$N \rightarrow N'+\alpha,e$

$n+N \rightarrow n+N'$

$\gamma+e \rightarrow \gamma+e$

- Nuclear/electron recoil via elastic scattering with DM
- Recoil energy in the keV region

# DAMA/LIBRA RESULTS



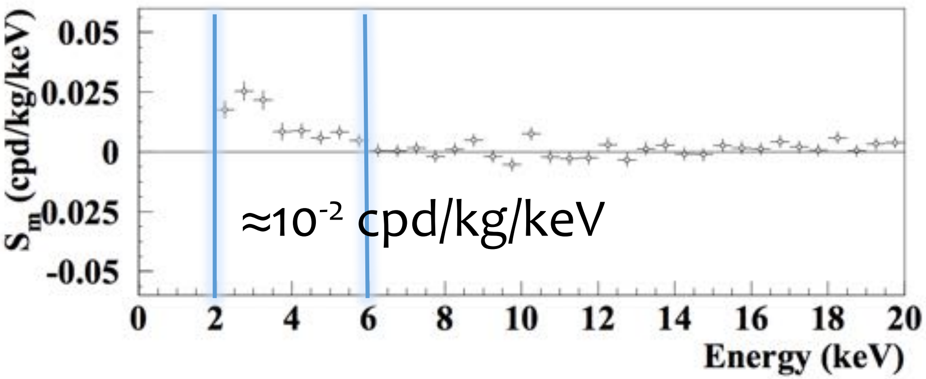

| | $A$ (cpd/kg/keV) | $T = \frac{2\pi}{\omega}$ (yr) | $t_0$ (days) | C.L. |
|---|---|---|---|---|
| DAMA/NaI & DAMA/LIBRA–phase1 | | | | |
| 2-4 keV | (0.0190±0.0020) | (0.996±0.002) | 134±6 | 9.5 $\sigma$ |
| 2-5 keV | (0.0140±0.0015) | (0.996±0.002) | 140±6 | 9.3 $\sigma$ |
| 2-6 keV | (0.0112±0.0012) | (0.998±0.002) | 144±7 | 9.3 $\sigma$ |

arXiv:1308.5109v2

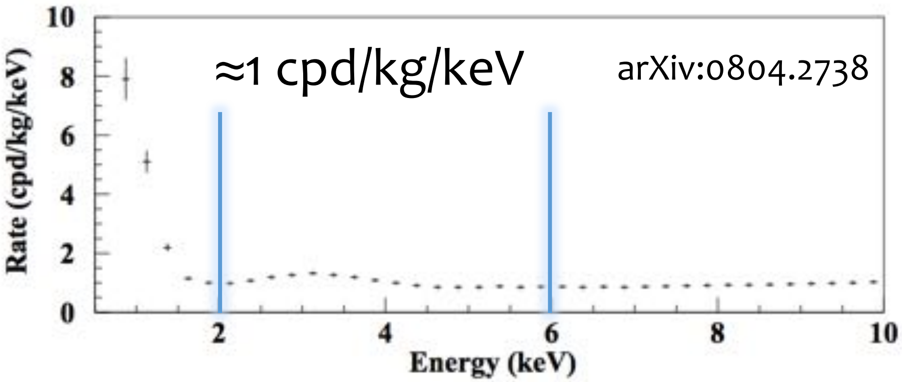
# DAMA/LIBRA RESULTS

## 9.5σ is a strong evidence of modulation but:

Modulation amplitude



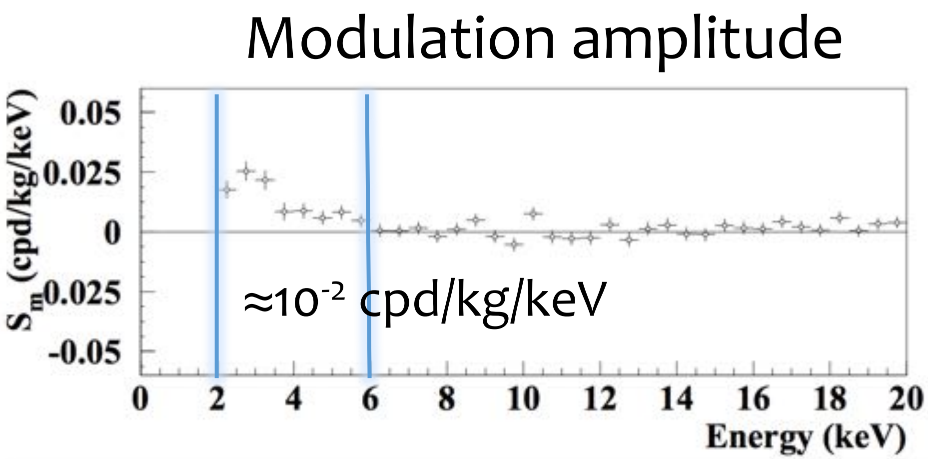

Background

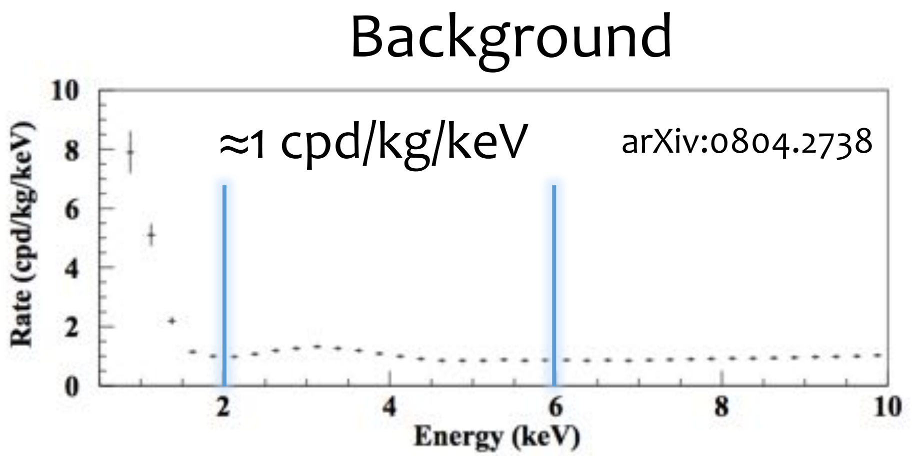



- Observed near to the detector energy limit
- May be due to an accidental local oscillatory source of backgrounds with same phase and period
- Null results with other techniques (see Xenon100/LUX results)

# DAMA/LIBRA RESULTS

## 9.5σ is a strong evidence of modulation but:



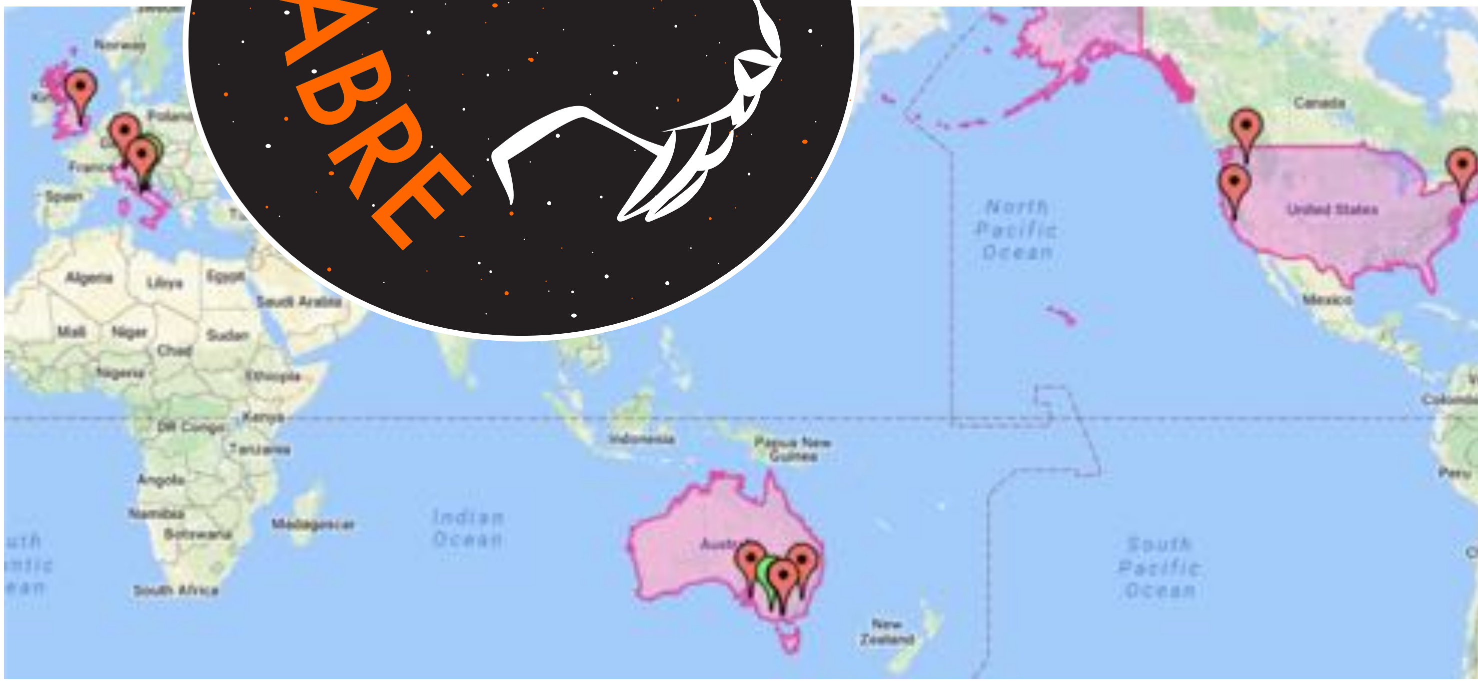




Is DAMA's signal an unconstrained seasonal variation or DM?

Need for another NaI(Tl) experiment for a model-independent verification

# Sodium-iodide with Active Background REjection

SABRE



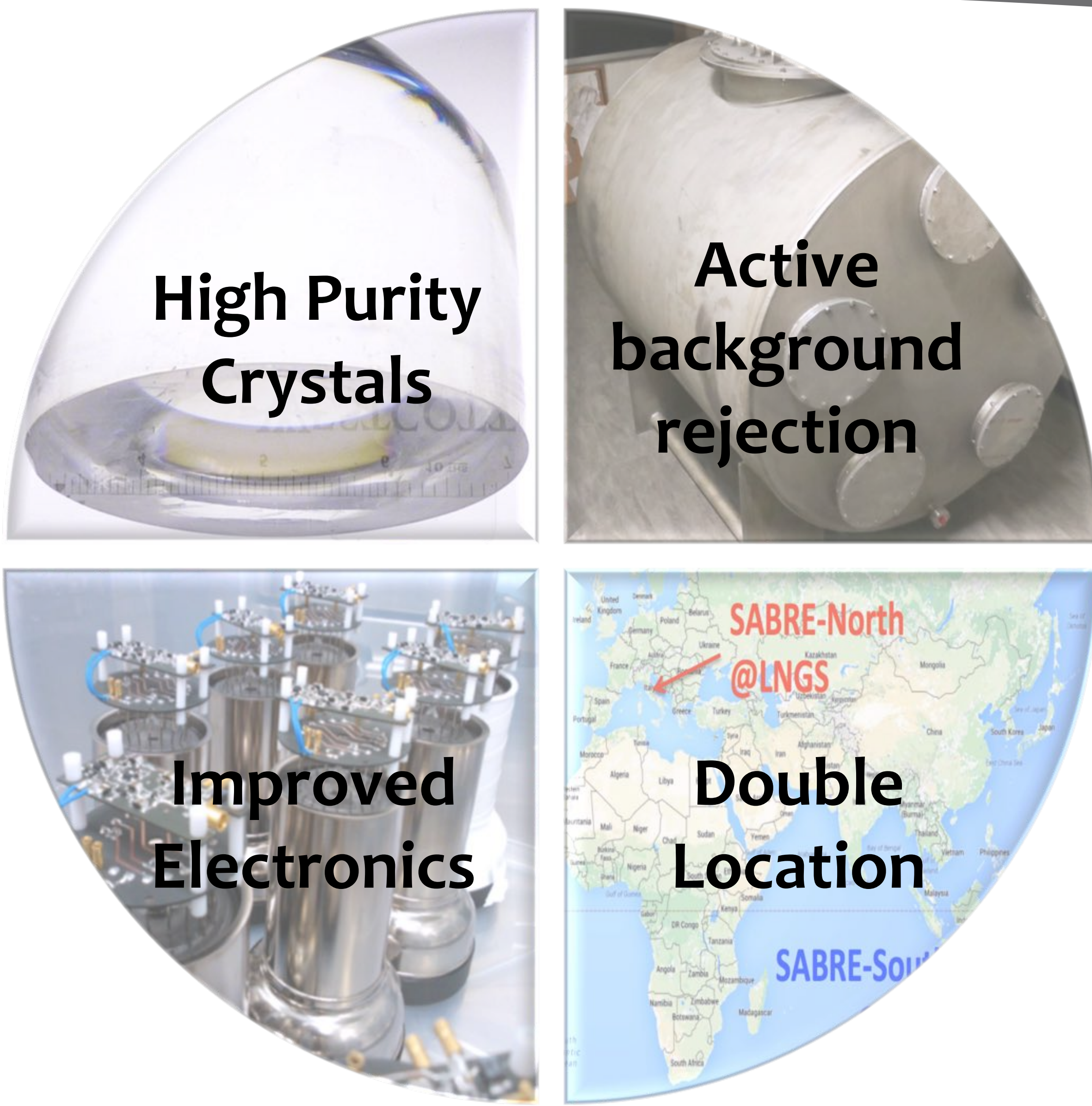

Adelaide University
Australian National University
Swinburne University
University of Melbourne

Imperial College London

LNGS & GSSI
INFN Rome
University of Milano & INFN

LLNL
PNNL
Princeton University

# The SABRE principles



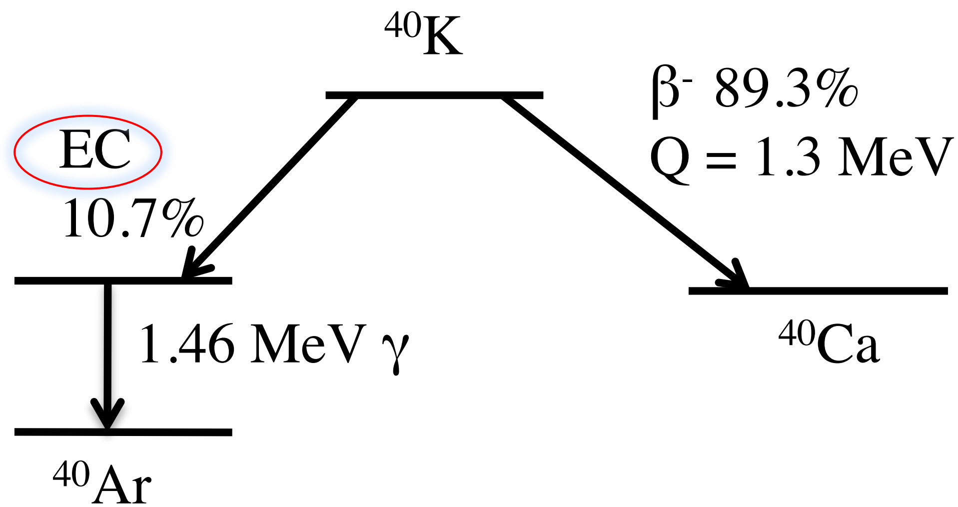

**Unprecedented background rejection and sensitivity with a NaI(Tl) experiment**

# High Purity Crystals

- Main background: crystal radioactivity
- $^{40}K$ Electron Capture

3 keV Auger e$^-$

- Other dangerous contaminations: Rb, U, Th, Pb
- Princeton Uni. and Sigma-Aldrich to obtain Astro-grade powder with reduced contaminations



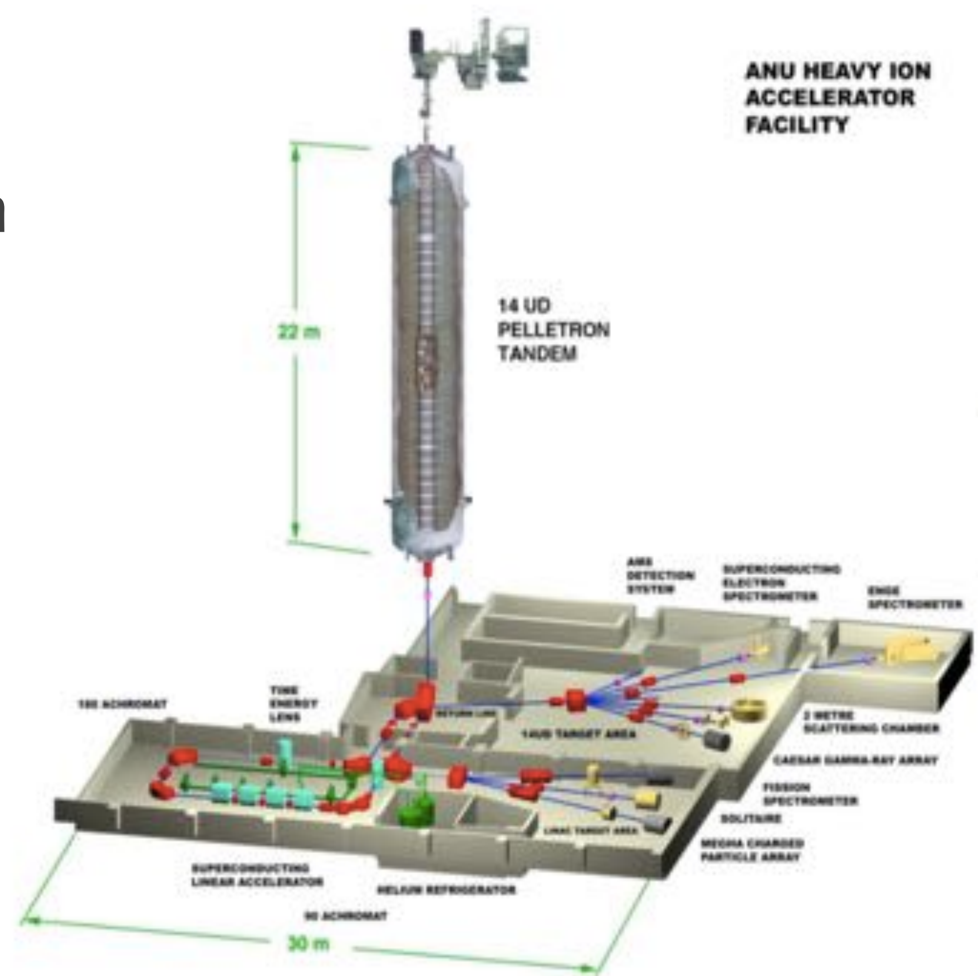

| Element | Sigma-Aldrich [ppb] | DAMA Powder [ppb] | DAMA Crystal [ppb] |
|---|---|---|---|
| K | 3.5 (18)* | 100 | ∼13 |
| Rb | 0.2 | n.a. | < 0.35 |
| U | $< 1.7\ (< 10^{-3})$** | ∼ 0.02 | $0.5 - 7.5\times10^{-3}$ |
| Th | $< 0.5\ (< 10^{-3})$** | ∼ 0.02 | $0.7 - 10\times10^{-3}$ |

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

# Purity Measurements @ ANU

**Atomic mass spectroscopy** to measure radionuclide isotope ratios

- $^{129}$I sensitivity better than $^{129}I/^{127}I = 2*10^{-13}$ ($\lesssim$1mBq/Kg)
- Next challenge: $^{210}$Pb
  - does not easily form negative ions
  - various chemical forms to produce Pb beams investigated.
  - Expected sensitivity to contaminations <10mBq/Kg



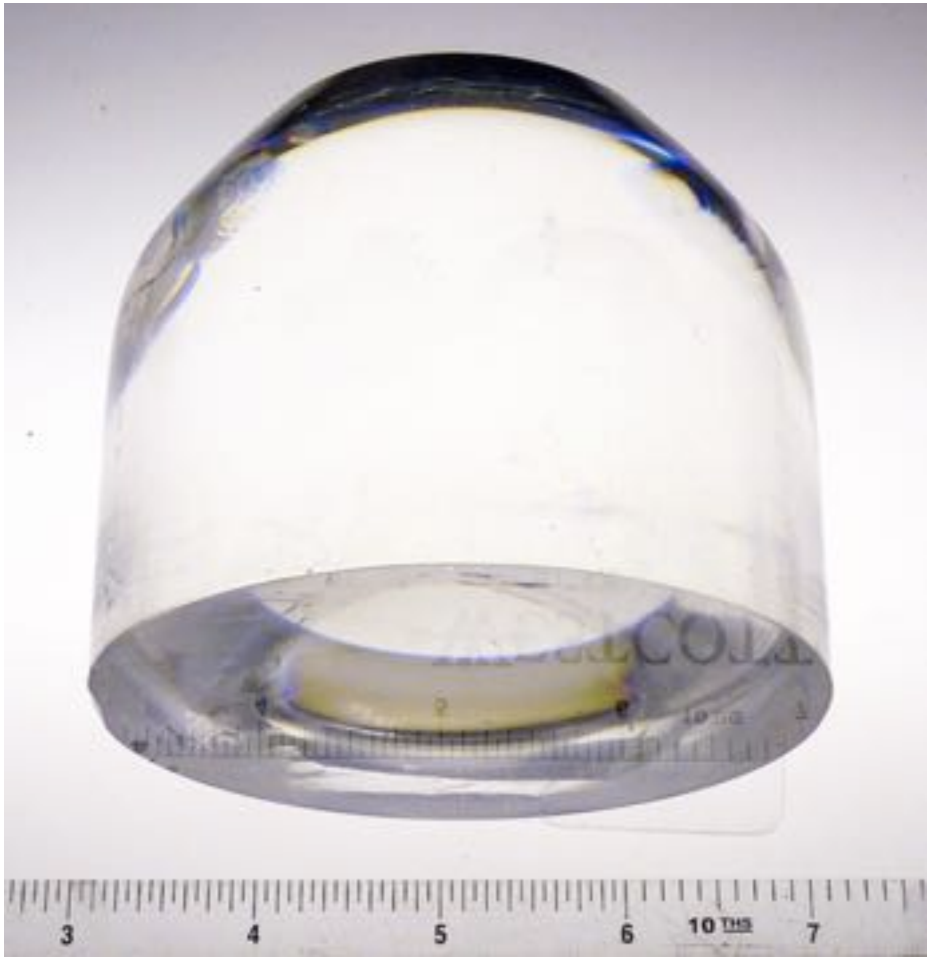
# High Purity Crystals

First large crystal

- 2kg (final des.≈ 5kg)
- 88 mm diameter (final des.≈ 95mm)

| $^{39}$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 |

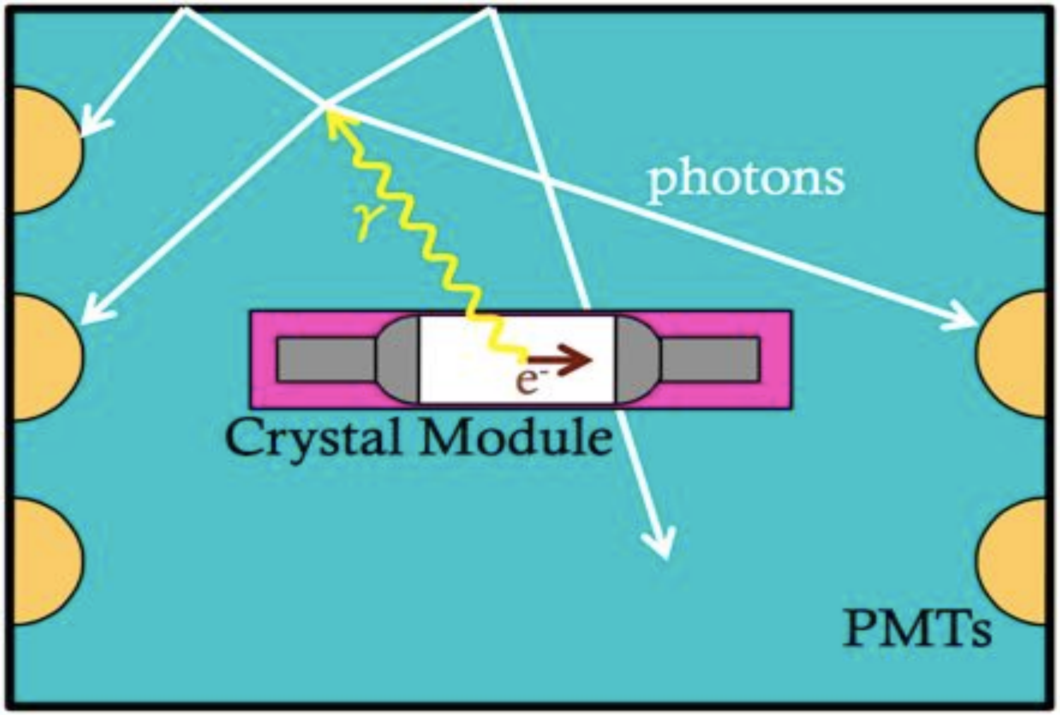
- Rb< 0.1 ppb (DAMA < 0.35 ppb)



# Active Background Rejection

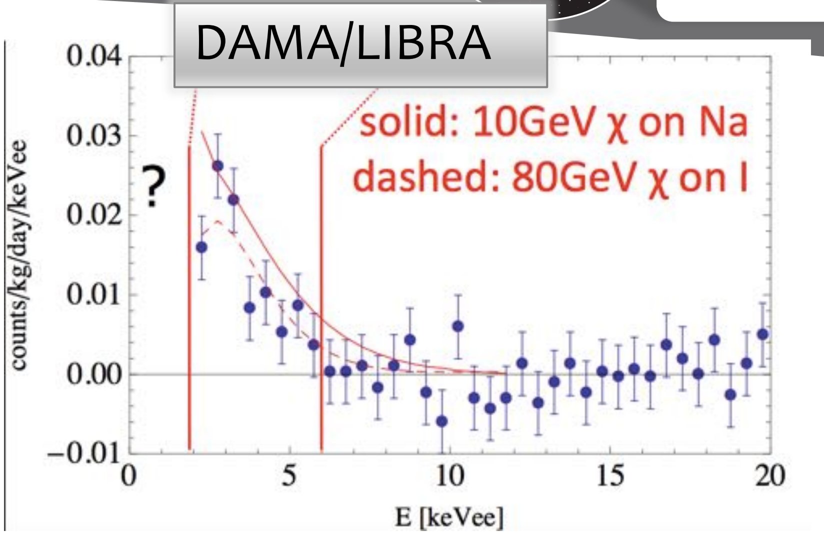
- Goal: Reject non-weakly interacting processes (external+intrinsic backgrounds)
- Crystals immerged in liquid scintillator
- Veto coincident signals in crystals and scintillator
- Additional passive shielding for environmental background

$^{40}K$ electron capture in crystals

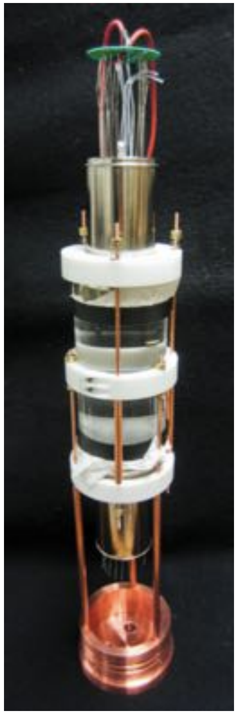


# Improved Electronics

- Goals:
  - High light yield
  - Energy threshold < 2 KeV
  - Reduced radioactivity and noise




- Design:
  - Baseline: Hamamatsu R11065 3" PMTs
  - Direct PMT-crystal coupling
  - Custom pre-amplifiers → less after-glow
  - Contaminations: ≈1 mBq for U, Th, Co; ≈10 mBq for K

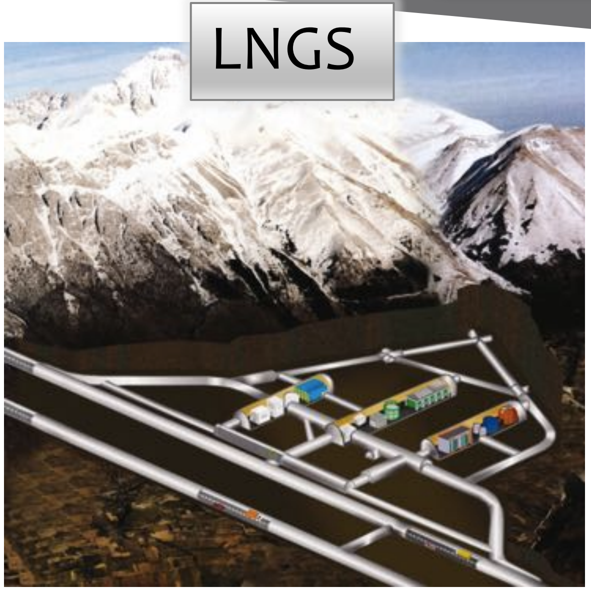


# Double location

- Twin experiments:
  - LNGS (Italy)
  - SUPL (Australia)

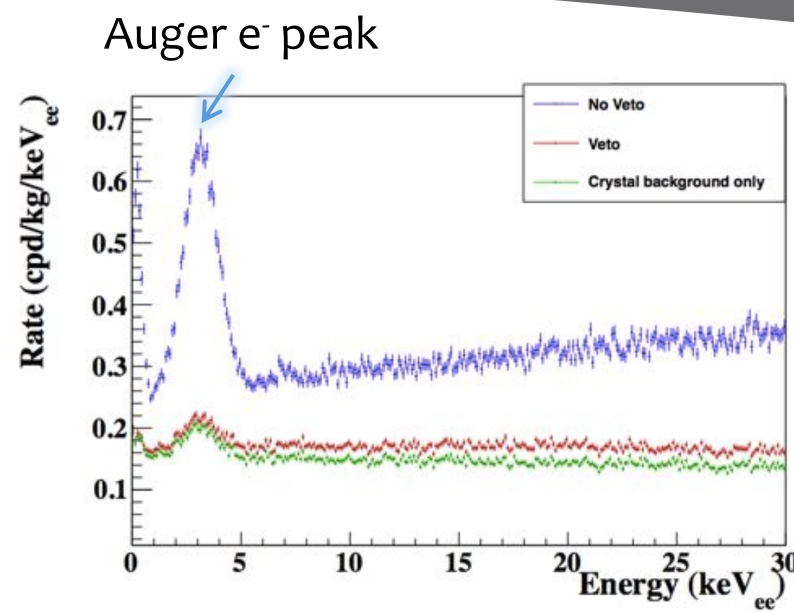
  both ≈ 3000 m.w.e and similar design performance

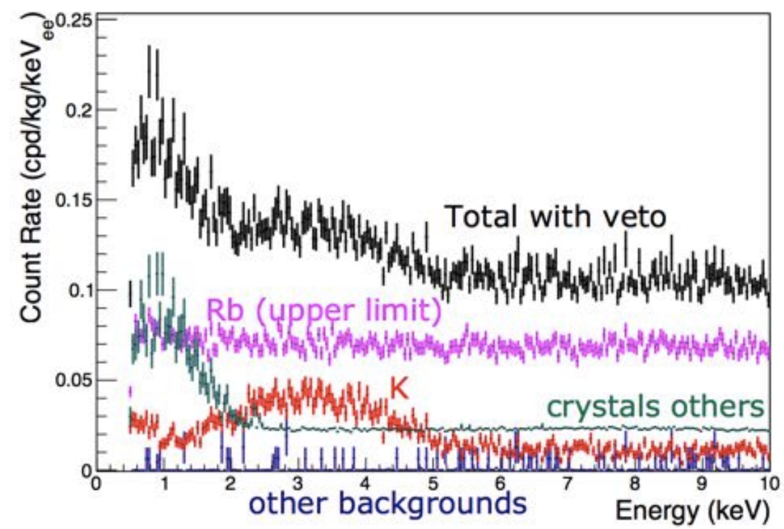
- Different environmental conditions:
  - Seasonal effects with opposite phase
  - Rock composition and radiopurity
  - Independent radon, temperature, pressure control systems and power supply




# EXPECTED BACKGROUND

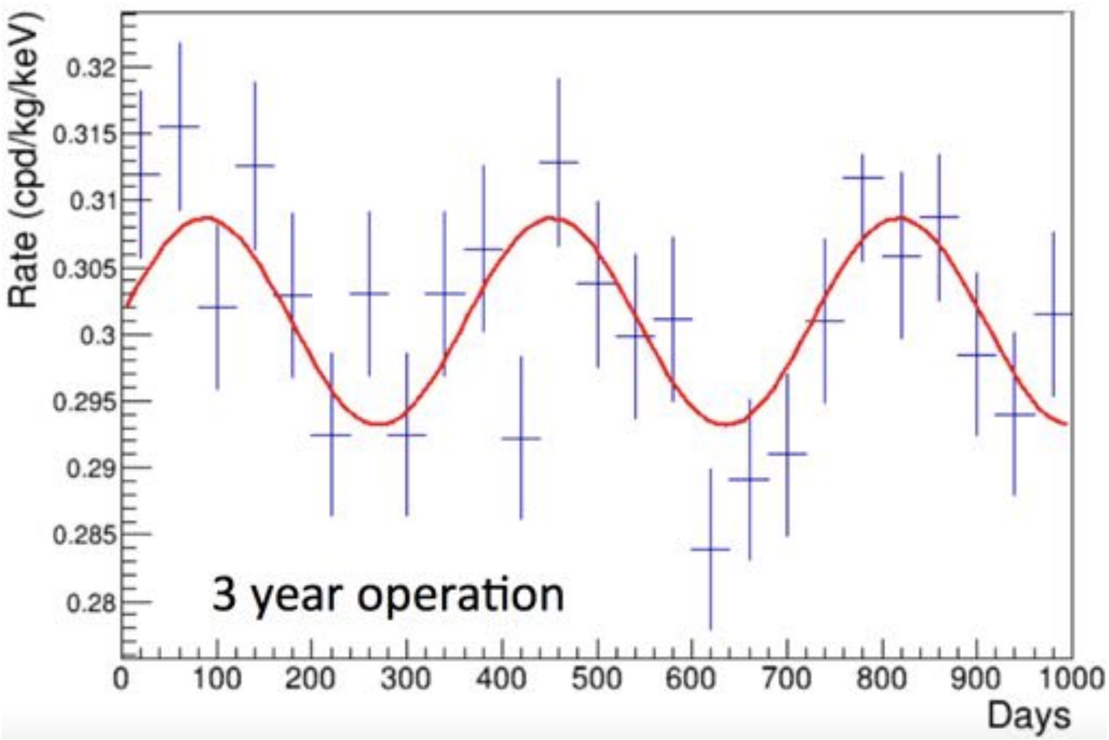
- Background from crystal is dominant
- Veto reduces effectively background (4 times less auger e$^-$)
- K and Rb dominates in 2-6 KeV
- Other contaminations below 2 KeV
- Expected backgrounds one order of magnitude smaller than in DAMA/LIBRA



# EXPECTED SENSITIVITY

- 50 Kg total crystal mass
- 3 years of exposition
- Background 0.15 cpd/kg/keV




- 4σ power to confirm DAMA/LIBRA
- 6σ to refute

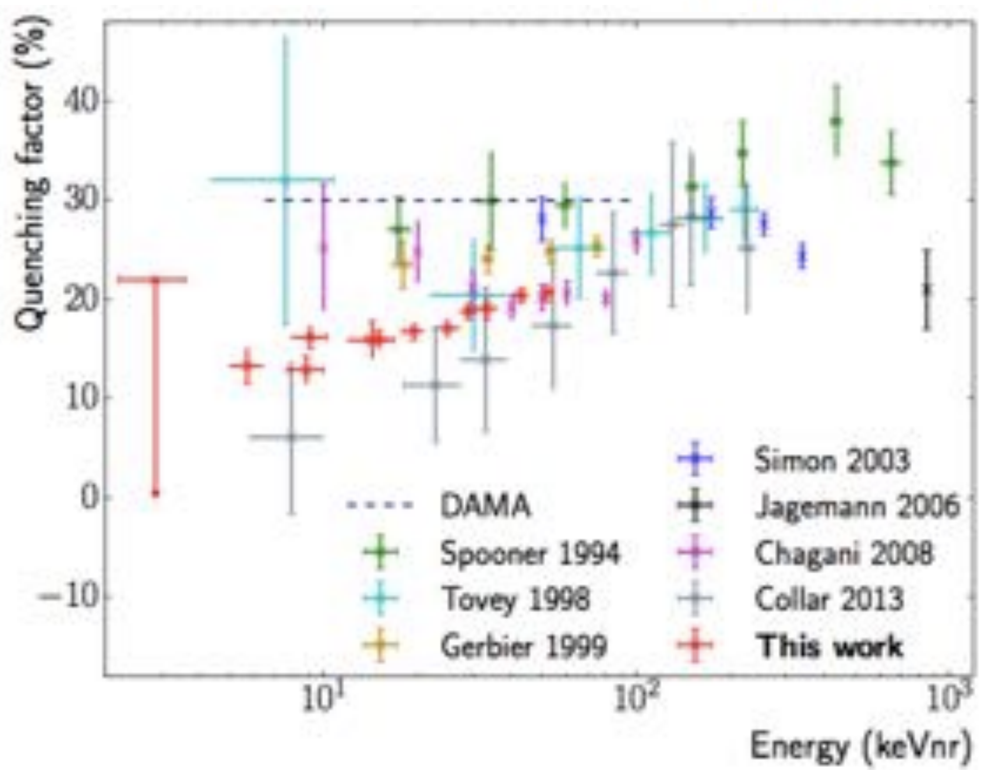
# Nuclear Recoil quenching

New results on quenching factor

- lower quenching at lower recoil energies
- The region 2 – 6 keVee corresponds to higher nuclear recoil energies
- 9 keVnr ←→ 0.9 keVee
- ANU could measure the QF with higher precision and reach lower energies

J. Xu et al

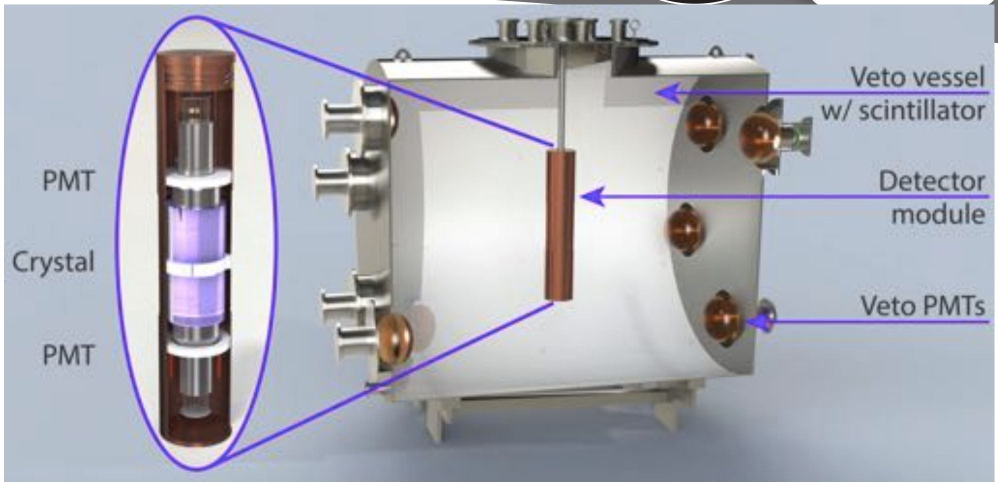
Phys. Rev. C 92, 015807 (2015)



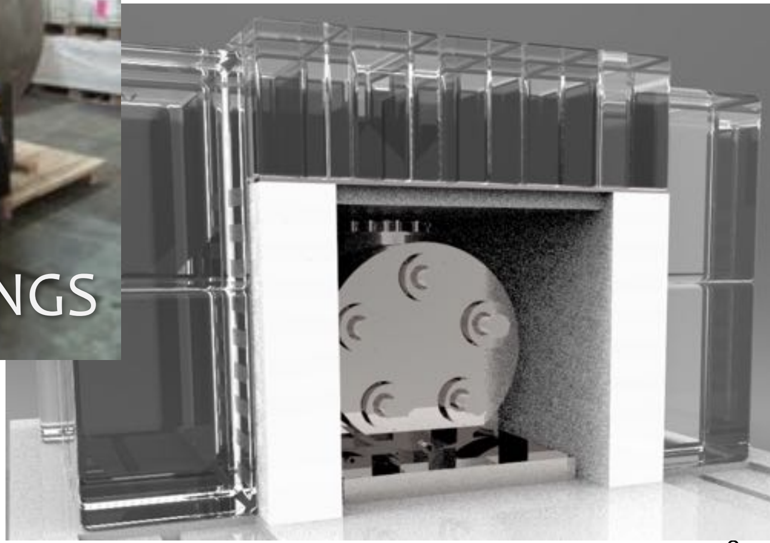
SABRE Proof of Principle is about to start @ LNGS

Goals:
- Characterize crystal background
- Test veto performance

Design:
- One 5.5 kg crystal
- 1.4m x 1.5m cylindrical vessel
- External shielding: lead basement and Polyethylene+Water walls







# Conclusion

- SABRE can perform an *independent high sensitivity* verification of the DAMA/LIBRA modulation
- SABRE features:
  - Higher purity NaI(Tl) crystals
  - Active background rejection
  - Low background high gain electronics
  - Twin detectors
- Proof of Principle to start in 2017
- 3 years of data for first full-scale experiment results

# backup

# SUPL CHARACTERISTICS

- Clean lab similar to SNOLab
- Rn activity < 100 Bq/m$^3$ in "clean area". Surface coating to inhibit Rn.
- Temp.: 19±2 °C, Relative humidity 40% - 50%, remote monitoring & control.
- Low radiation concrete and finishing; sampling all sand and cement.

| | Gran Sasso Lab. Reference | Stawell |
|---|---|---|
| Neutron Flux | $4 \times 10^{-6}$ n/s/ | $<7 \times 10^{-6}$ n/s/cm$^2$ UL |
| Gamma-ray flux below 3 MeV | 0.73 γ/s/cm$^2$ | <2.5 γ/s/cm$^2$ UL |
| Radioactivity levels of rock | | |
| Rock $^{238}$U (ppm) @ 880m | 2.63 | 0.64 |
| Rock $^{232}$Th (ppm) @ 880m | 0.72 | 1.63 |
| Refuge Radon Bq/m$^3$ (12 day accumulation, ventilated) | *O*(50) | 36±5 21°C, 1056 kPa, 21% humidity |

## Diurnal modulation signal from dissipative hidden sector dark matter


R.Foot[1], S.Vagnozzi[2]

*ARC Centre of Excellence for Particle Physics at the Terascale,*
*School of Physics, University of Melbourne,*
*Victoria 3010 Australia*



We consider a simple generic dissipative dark matter model: a hidden sector featuring two dark matter particles charged under an unbroken $U(1)'$ interaction. Previous work has shown that such a model has the potential to explain dark matter phenomena on both large and small scales. In this framework, the dark matter halo in spiral galaxies features nontrivial dynamics, with the halo energy loss due to dissipative interactions balanced by a heat source. Ordinary supernovae can potentially supply this heat provided kinetic mixing interaction exists with strength $\epsilon \sim 10^{-9}$. This type of kinetically mixed dark matter can be probed in direct detection experiments. Importantly, this self-interacting dark matter can be captured within the Earth and shield a dark matter detector from the halo wind, giving rise to a diurnal modulation effect. We estimate the size of this effect for detectors located in the Southern hemisphere, and find that the modulation is large ($\gtrsim 10\%$) for a wide range of parameters.


arXiv:1412.0762

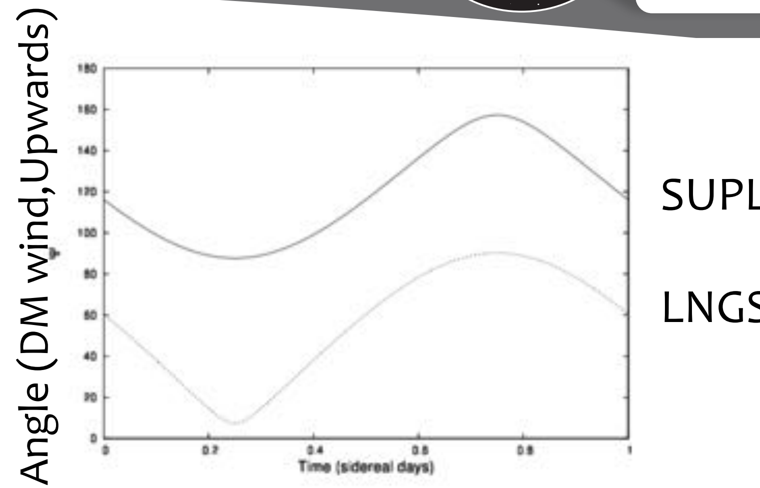



Figure 2: Variation of $\psi(t)$ during the course of a sidereal day for a detector located in the Stawell mine (solid line) and under the Gran Sasso d'Italia (dashed line).

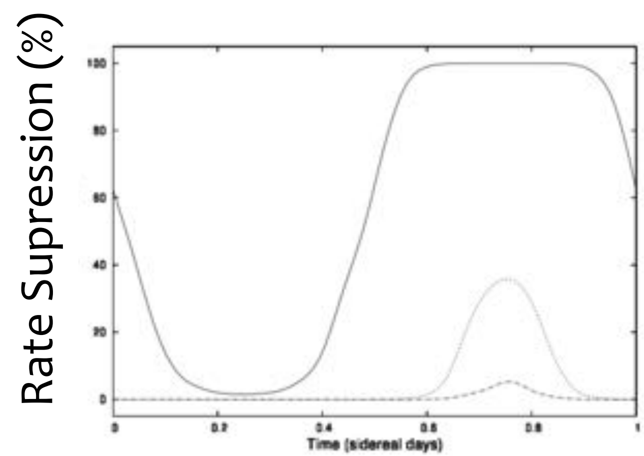
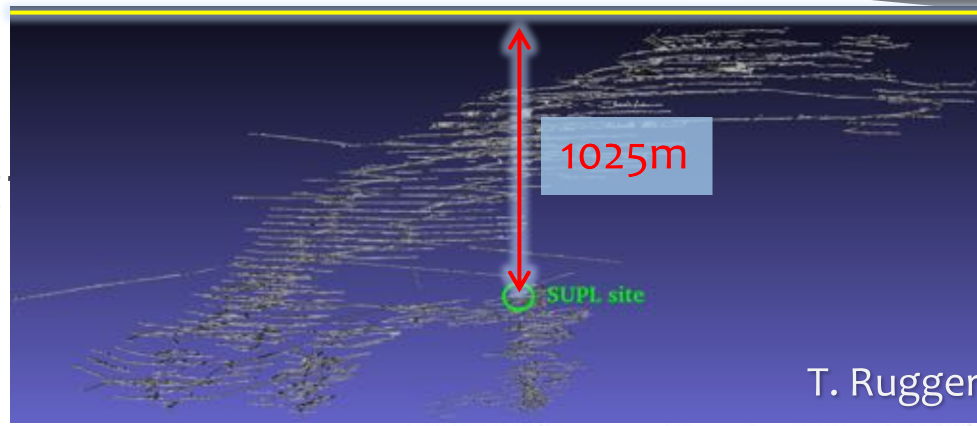



Figure 3: Percentage rate suppression for a detector situated in the Stawell mine for $m_{F_2} = 10$ GeV (solid line), $m_{F_2} = 100$ GeV (dashed line), $m_{F_2} = 1$ TeV (dot-dashed line). We have assumed $\alpha' = 10^{-2}$, $|Z'| = 10$, a recoil energy of 2 keV and an Na target ($m_T \simeq 23 m_p$).

# Stawell Undeground Physics Laboratory

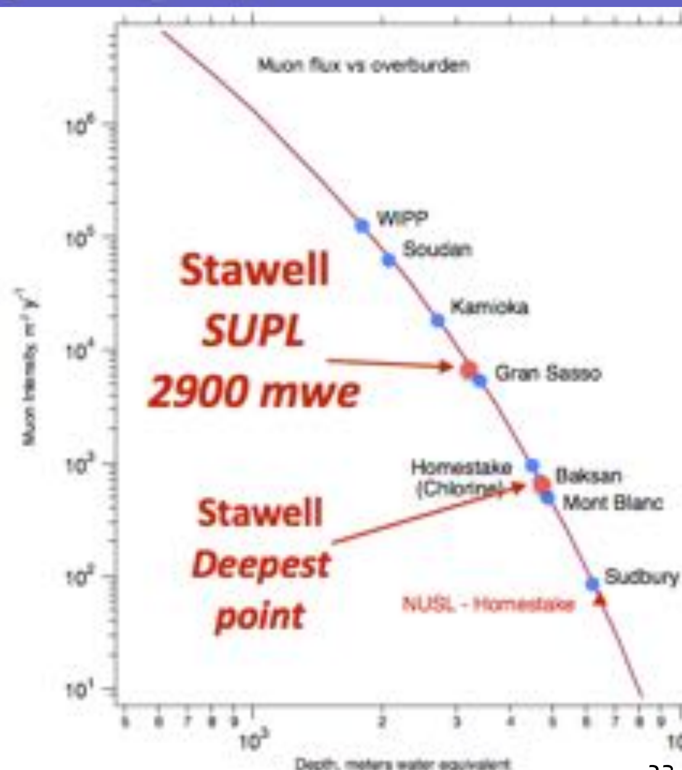
See Anthony Williams' talk

- Clean laboratory @ 1025m
- Design completed
- Construction to start in early 201
- Host SABRE and other experiments

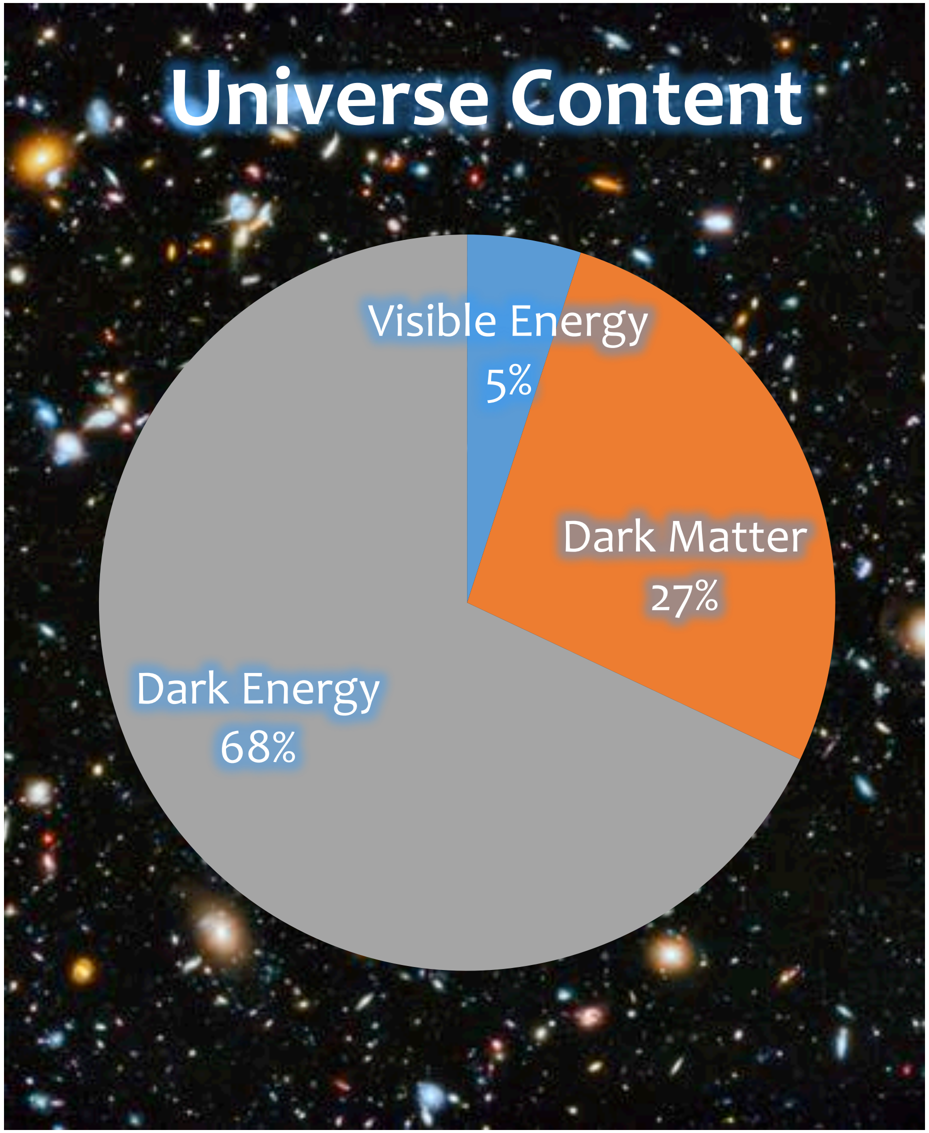




Clean-room, low radon areas



# THE DARK MATTER PROBLEM




Dark Matter properties:

- Stable (half life > universe age)
- Cold (non-relativistic)
- Non-baryonic
- No EM and Strong interactions

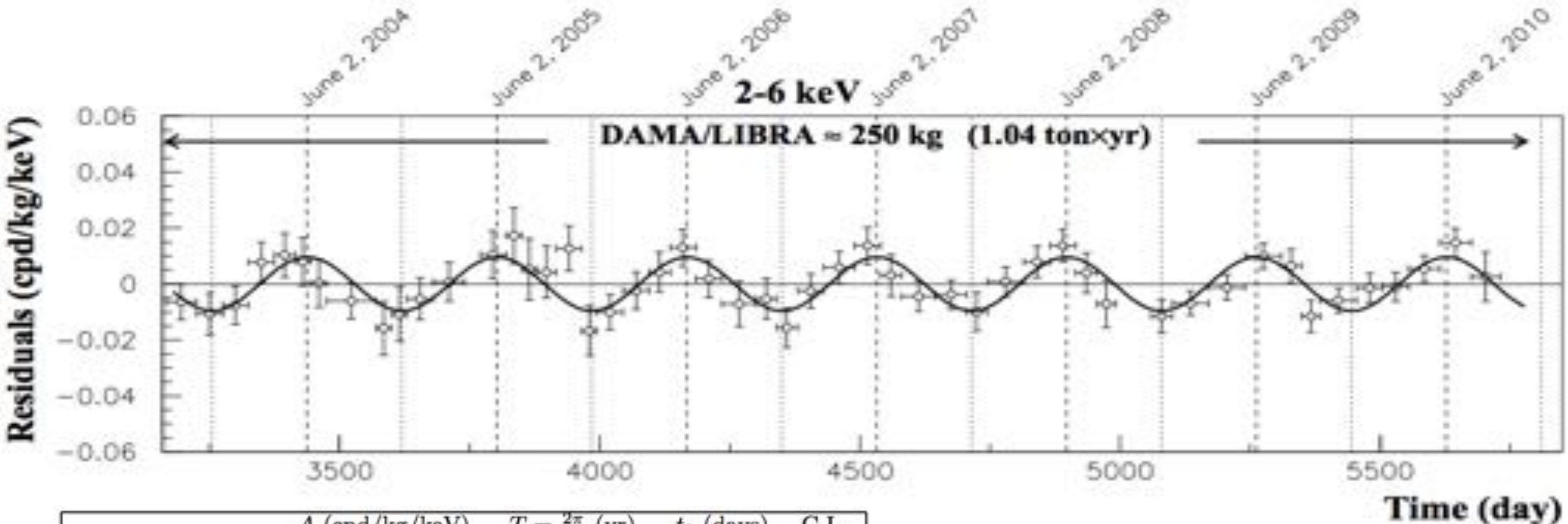
Possible Candidate:

## WIMPs

Weakly interacting massive particles:

- Masses > GeV
- Low self-annihilation and SM scattering cross-sections via weak interaction or new weaker interactions

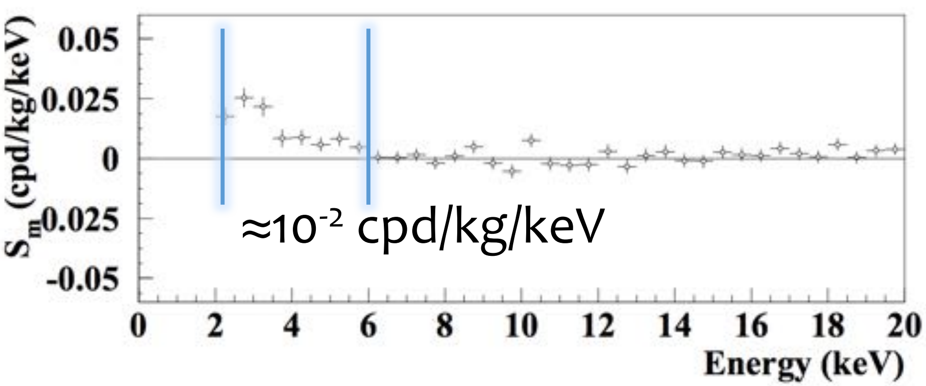
# DAMA/LIBRA RESULTS




| | $A$ (cpd/kg/keV) | $T = \frac{2\pi}{\omega}$ (yr) | $t_0$ (days) | C.L. |
|---|---|---|---|---|
| DAMA/NaI & DAMA/LIBRA–phase1 | | | | |
| 2-4 keV | (0.0190±0.0020) | (0.996±0.002) | 134±6 | 9.5 $\sigma$ |
| 2-5 keV | (0.0140±0.0015) | (0.996±0.002) | 140±6 | 9.3 $\sigma$ |
| 2-6 keV | (0.0112±0.0012) | (0.998±0.002) | 144±7 | 9.3 $\sigma$ |

arXiv:1308.5109v2

## Modulation amplitude




## Background