SABRE: DARK MATTER ANNUAL MODULATION DETECTION IN THE NORTHERN AND SOUTHERN HEMISPHERE

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FOR THE SABRE COLLABORATION

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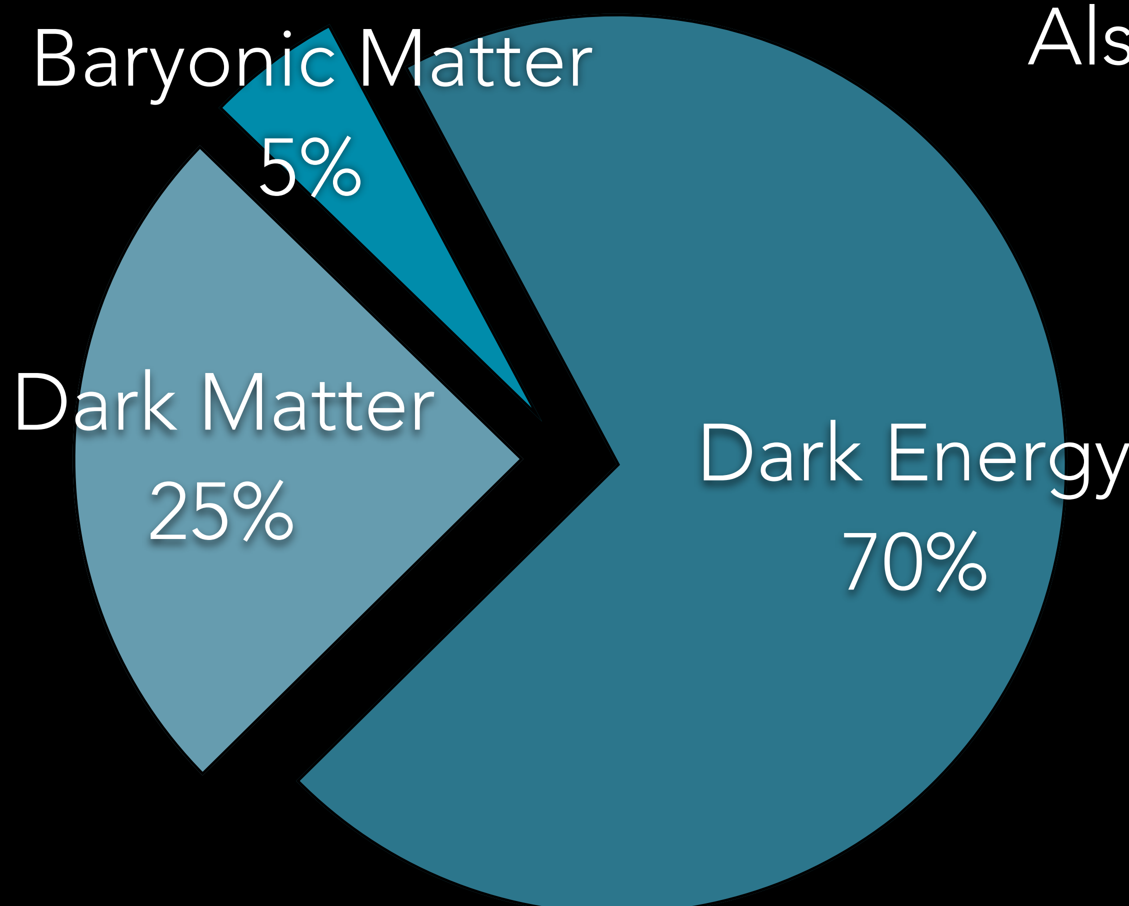
OUTLINE

- Dark Matter and Dark Matter Detection
- The SABRE project
- Results on NaI(Tl) crystal growth
- SABRE PoP
- SABRE in the southern hemisphere
- Conclusions

DARK MATTER IN THE UNIVERSE

Dark matter particles should have the following properties:

- Stable or long-lived
- Neutral



Also usually assumed:

- Density = 0.3 GeV/cm^3
- Maxwellian distribution (v_0 ~ 220 km/s)

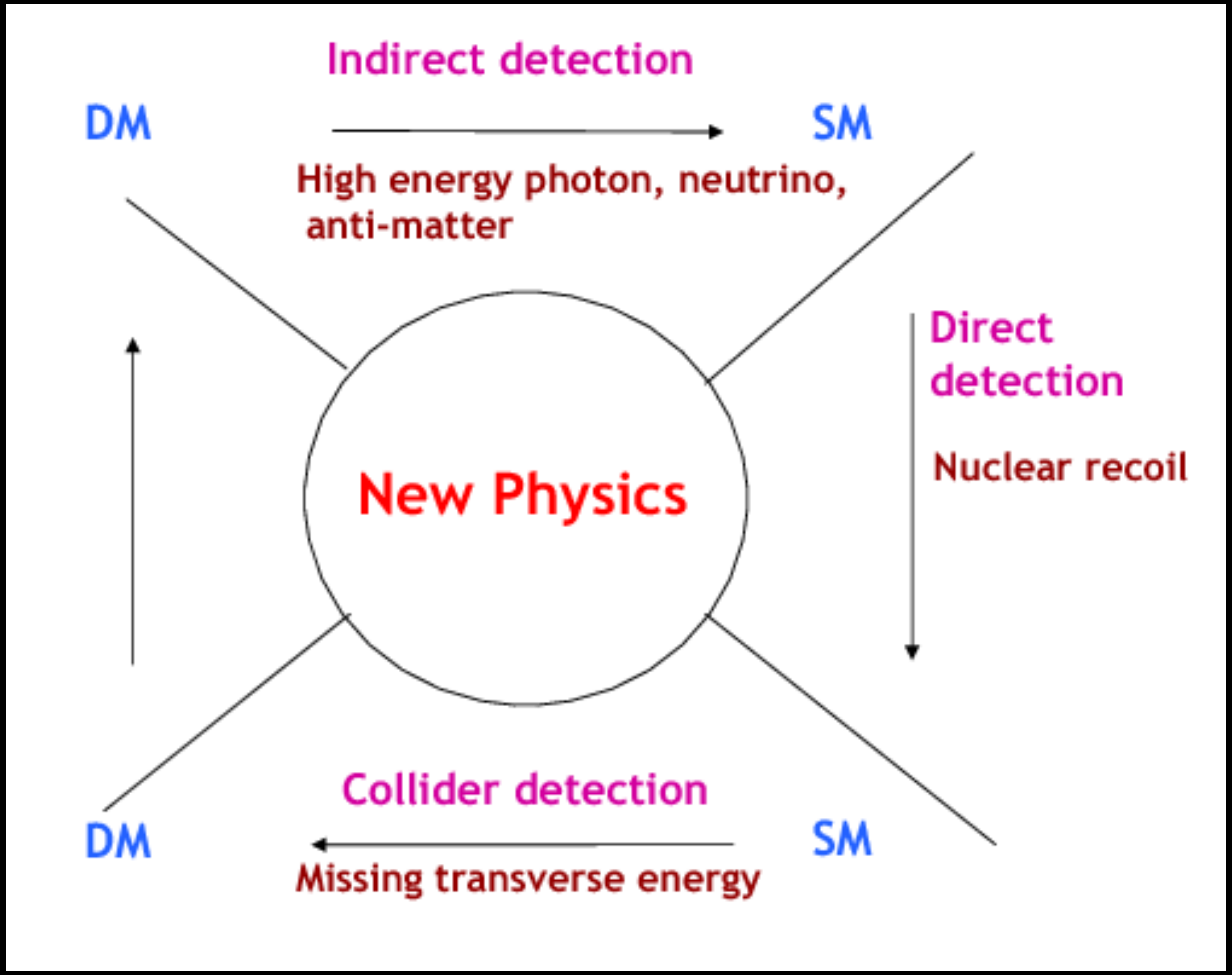
WIMPs (Weakly Interacting Massive Particles) of mass ~100 GeV, are the "miracle" candidates

DARK MATTER DETECTION

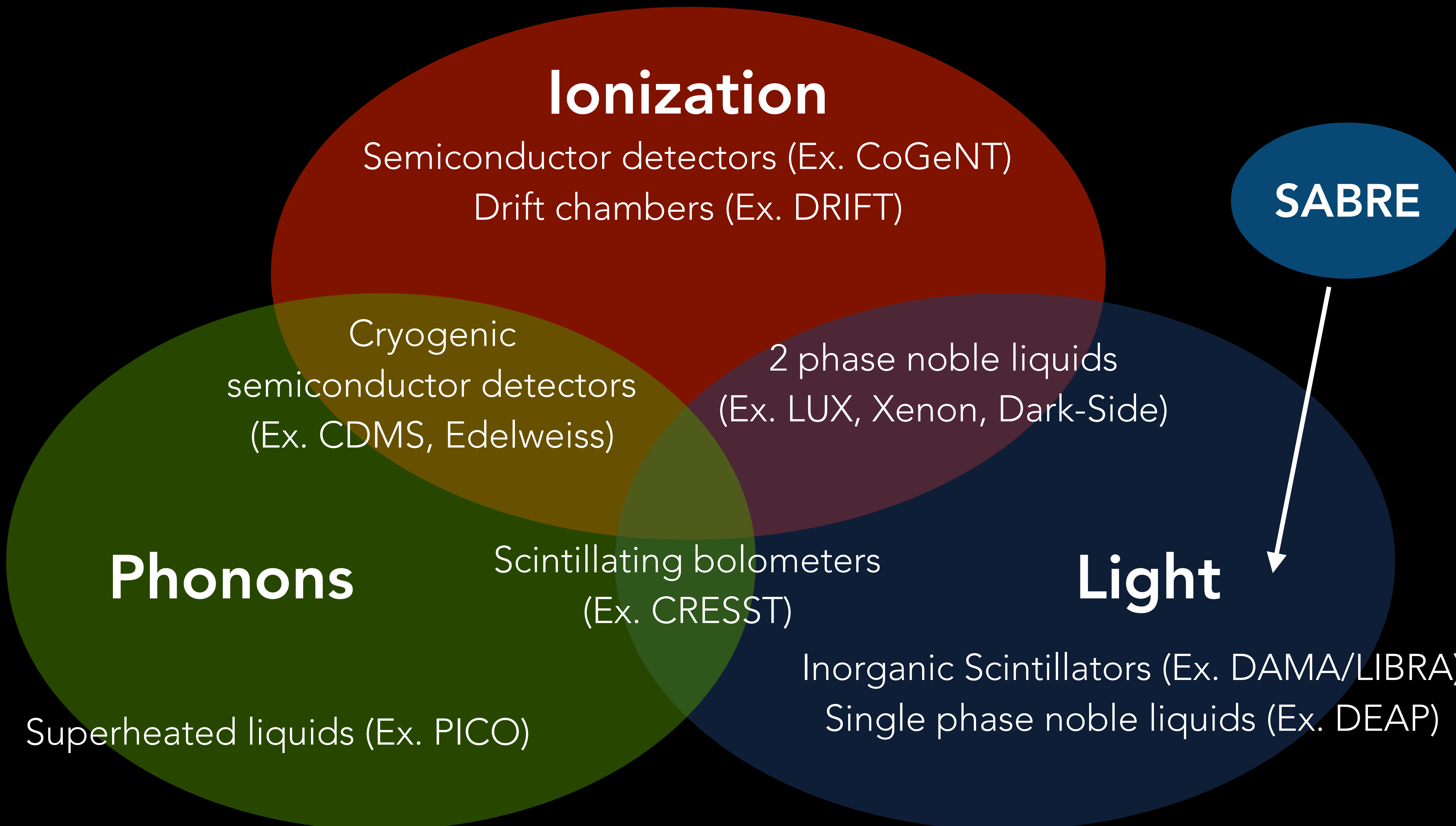
Indirect detection: detect SM particles produced by DM annihilation

Collider detection: DM particles produced at colliders by interaction of SM particles and identified by the transverse missing energy

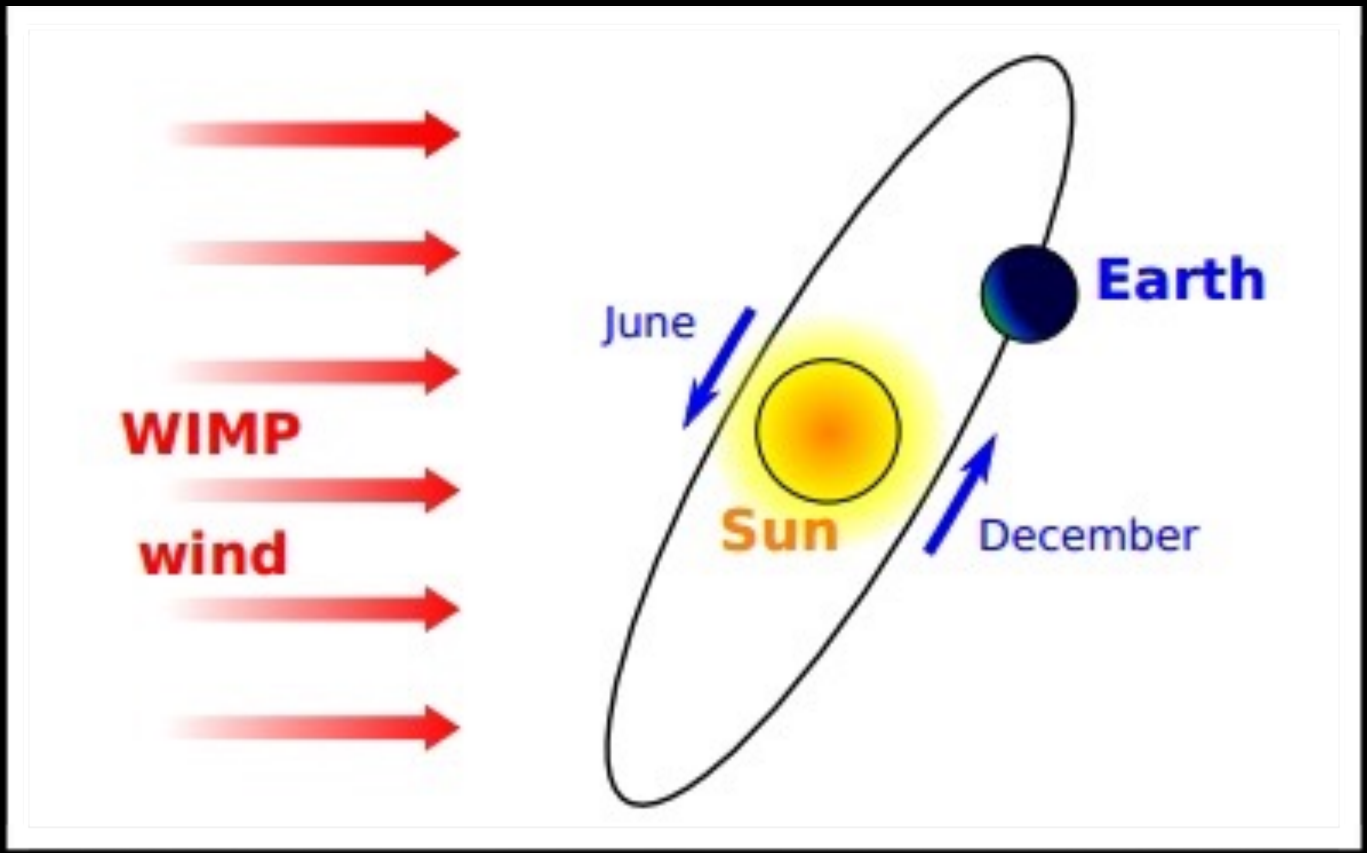
Direct detection: detect DM-induced nuclear recoils in a underground detector



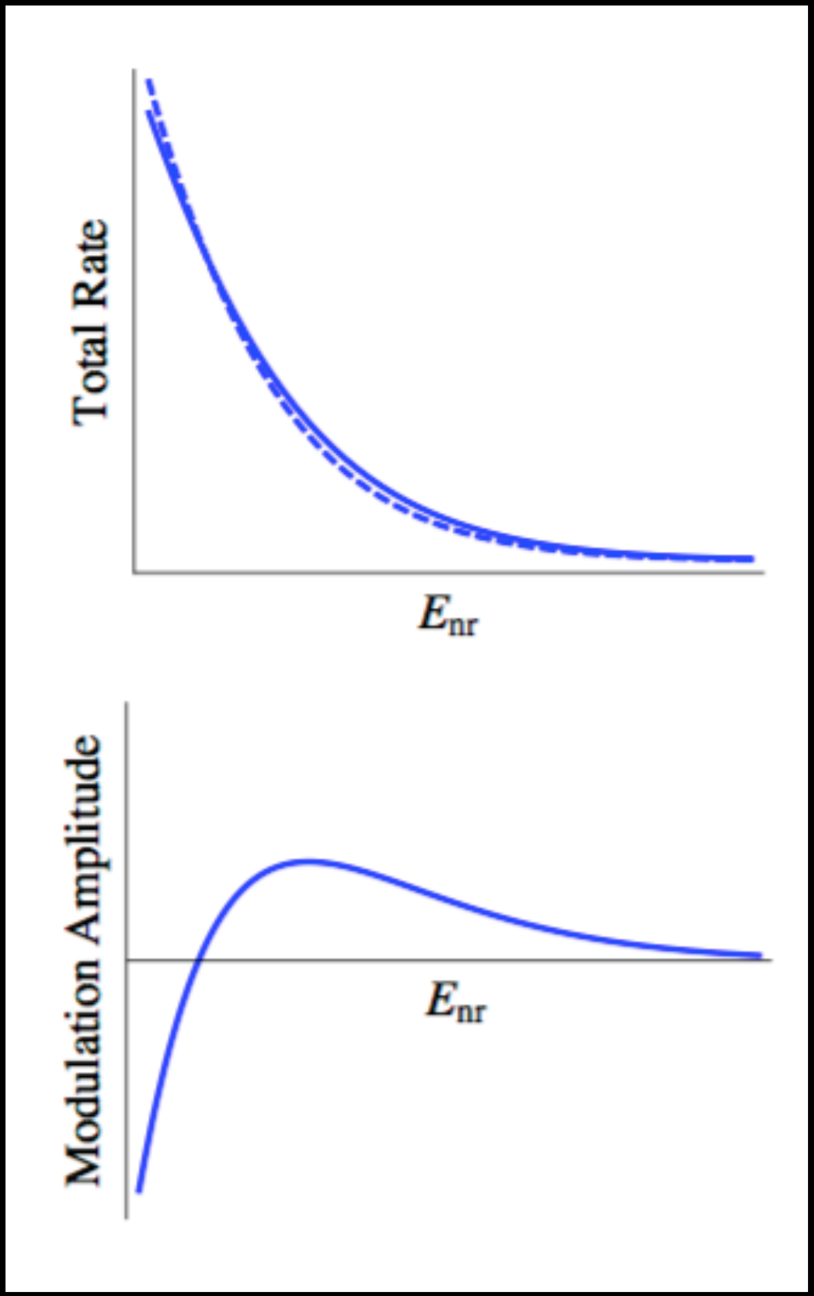
DETECTION CHANNELS



ANNUAL MODULATION



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



Period = 1 year - Maximum ~ June 2nd

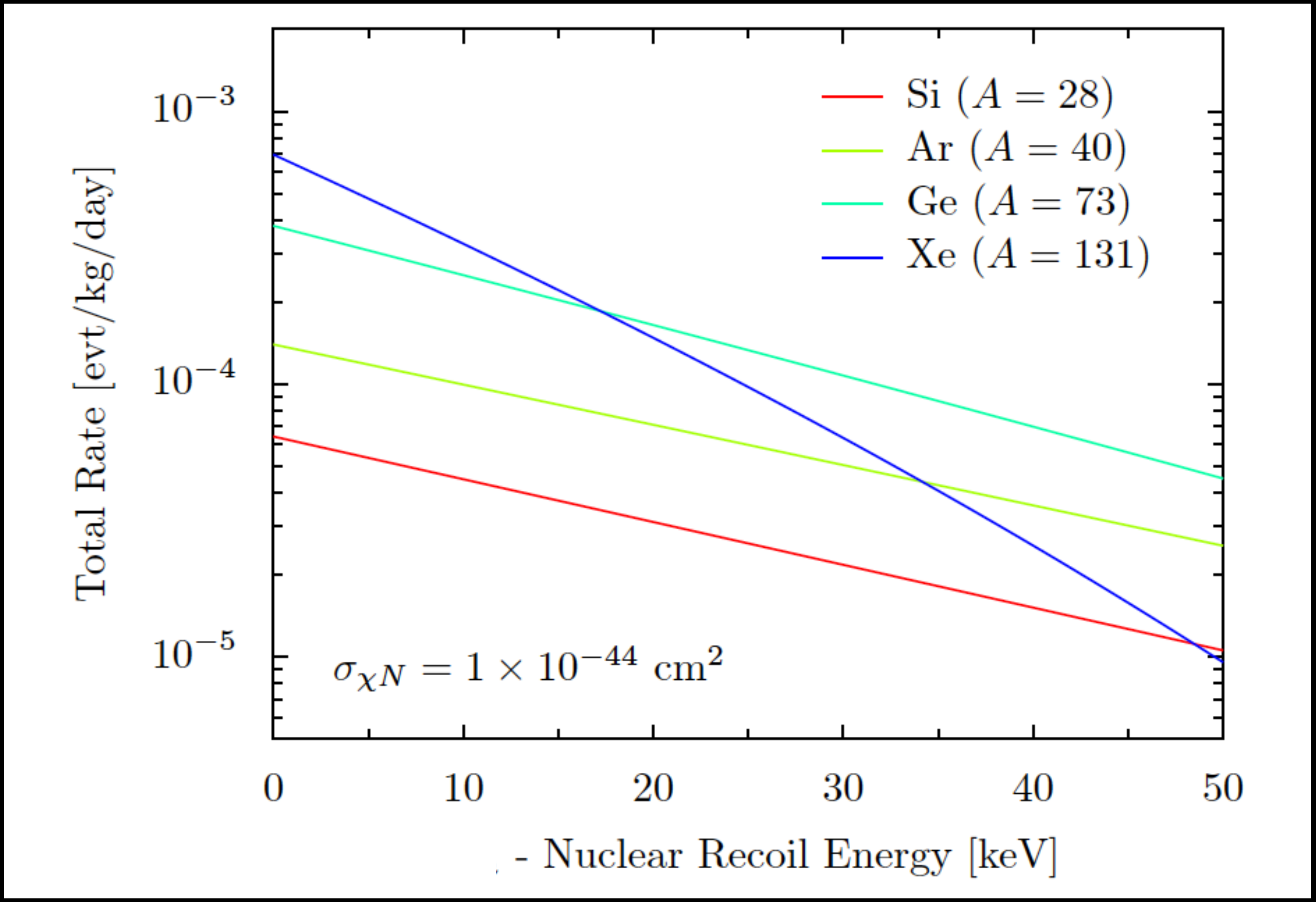
http://arxiv.org/abs/1209.3339

S_m/S_0 (modulation fraction) - for most models is O(1 - 10%)

DM RATE IN A DETECTOR

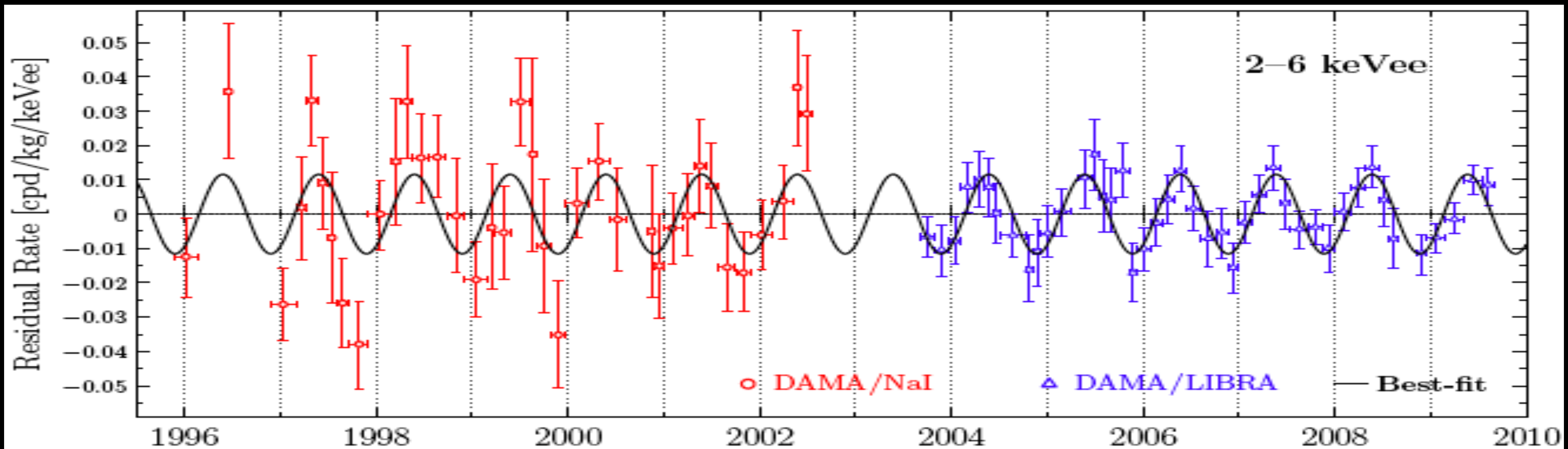
For μ_X = 100 GeV
and A = 100:

- $\sigma_{SI} = 10^{-42} - 10^{-44}$ cm^2
- **Rate = 0.01 - 1 cpd/kg**
- E_{nr} = 0 - 25 keV



Exponential-like shape, increasing at low E (similar to many bkgs...)
Demands O(keV) thresholds and backgrounds close to zero.
All experiments operated in **low radioactivity environments and deep underground.**

THE DAMA/LIBRA MODULATION



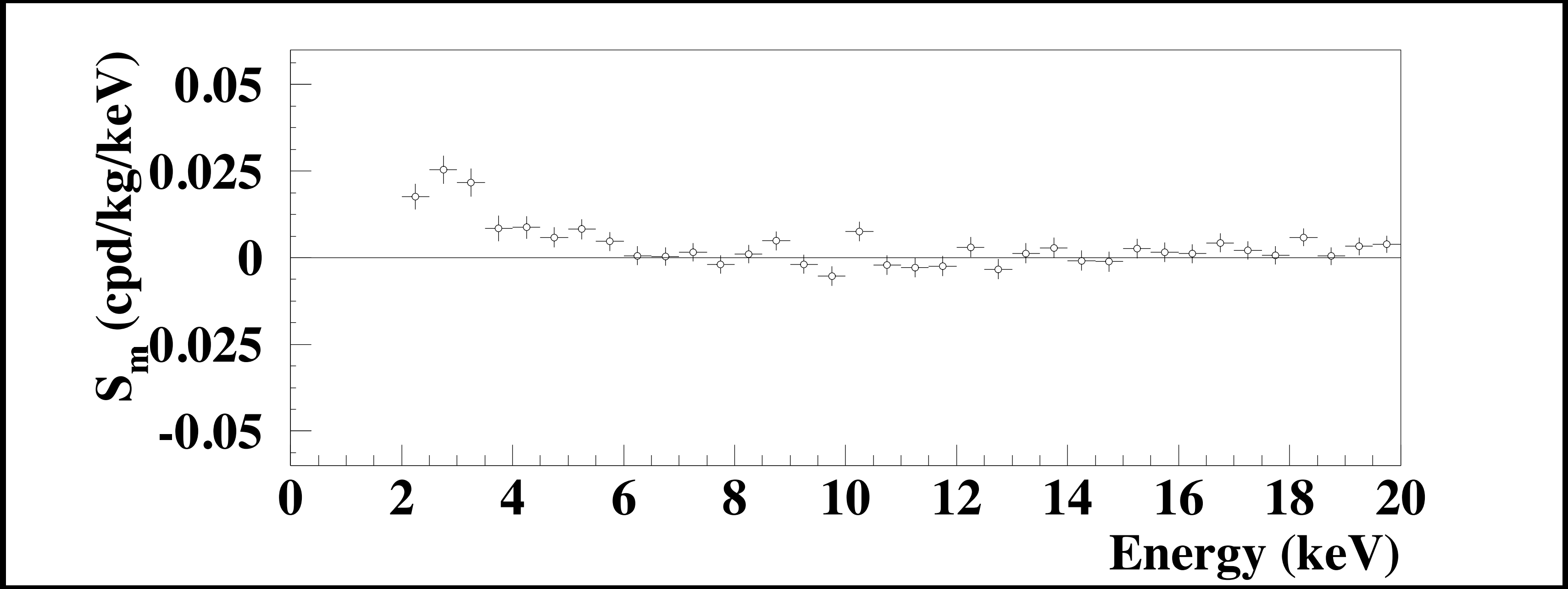
R. Bernabei et al. (DAMA coll.), EPJ C (2013) 73:2648

- 13 annual cycles (DAMA/NaI + DAMA/LIBRA)
- χ^2/ndf = 70.4/86
- 9.3 σ significance
- Period: (0.998±0.002) y
- Phase: (144±7) days vs. Expected DM phase 152.5 days
- Modulation Amplitude: (0.0112±0.0012) cdp/kg/keV

THE DAMA/LIBRA MODULATION

Sources of modulations other than Dark Matter have been investigated and excluded:

- ✓ radon
- ✓ temperature
- ✓ gas pressure
- ✓ electronic noise
- ✓ energy scale
- ✓ efficiencies
- ✓ environmental neutrons



R. Bernabei et al. (DAMA coll.), EPJ C (2013) 73:2648

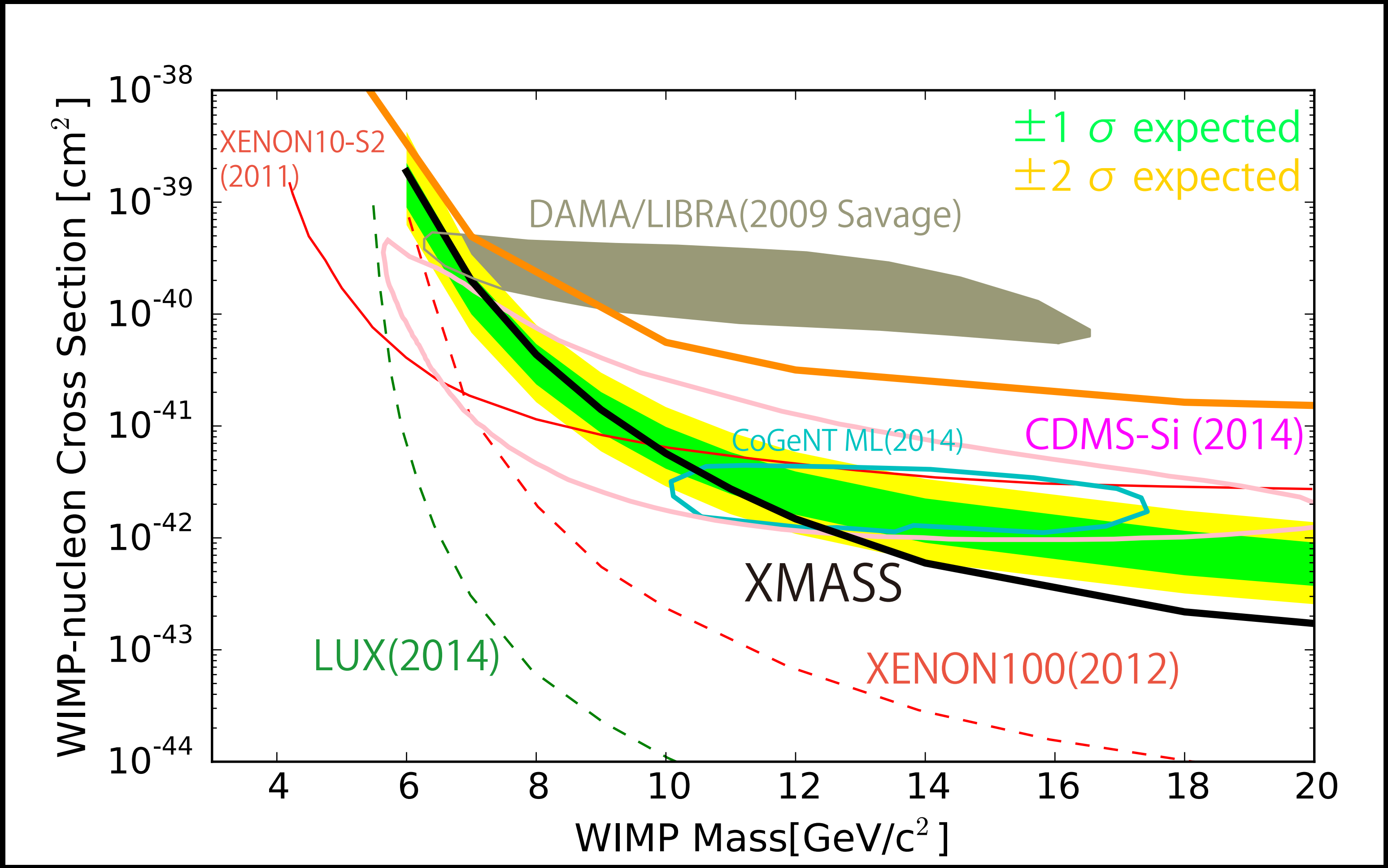
No explanation of the modulation due to effects from known particles (neutrons, muons, neutrinos)

No modulation > 6 keV - No modulation in multi-hit events

THE LOW-MASS POSITIVE RESULTS

When interpreted in the WIMP framework (model dependent), tension with other results from experiments using different targets (XENON, LUX, CDMS, etc…)

No other NaI experiment so far has studied the annual modulation effect with similar sensitivity. Confirmation of DAMA/LIBRA results still missing.



XMASS Collaboration: arXiv:1511.04807

SABRE: SODIUM IODIDE WITH ACTIVE BACKGROUND REJECTION

WHAT

An experiment based on NaI(Tl) scintillating crystals and focused on the achievement of a very low background via crystal purity and active rejection through liquid scintillator veto.

WHY

Search for Dark Matter through the well known effect of the annual modulation of the experimental rate.

WHERE

To be installed underground at LNGS (Italy) and Stawell gold mine (a future underground site in Australia).

In the southern hemisphere seasonal modulations have opposite phase: an effective way to disentangle this kind of background.

THE SABRE APPROACH

Grow NaI(Tl) crystals with higher purity than DAMA/LIBRA.

- Develop ultra-high purity NaI powder
- Develop high purity NaI(Tl) crystal growth method
- Develop NaI(Tl) crystal detectors with higher light yield and lower energy threshold than DAMA/LIBRA

High purity, high Q.E. Hamamtasu PMTs

High purity materials for steel vessel and copper enclosures

Operate NaI(Tl) detectors in liquid scintillator (LS) veto + passive water shielding

- Reject dangerous ^{40}K background and other internal/external backgrounds

Twin detectors in northern and southern hemisphere

- Powerful tests against environmental backgrounds

ULTRA-HIGH PURITY NAI POWDER

First investigation started in 2010 at Princeton by J. Benziger, F. Calaprice and A. Wright.

Identification of high-purity powder in collaboration with Sigma-Aldrich and Seastar.

High sensitive ICPMS by Seastar and PNNL to monitor progress in crystal development.

Element	Seastar [ppb]	Sigma-Aldrich [ppb]	DAMA powder [ppb]	DAMA crystal [ppb]
K	12	3.5 (18*)	100	~ 13
Rb	14	0.2	n.a.	< 0.35
U	<0.2(0.0035**)	<1.7(0.001**)	~ 0.020	0.0005 - 0.0075
Th	<0.1(0.005**)	<0.1(0.005**)	~ 0.020	0.0007 - 0.010

* Independent measurement, not from Sigma Aldrich

** Preliminary measurement at PNNL; full validation needed

NAI(TL) CRYSTAL GROWTH

Small high purity crystal growth tests using different methods.

Approaches:
1) careful material screening,
2) precision cleaning,
3) ultra-sensitive chemical analysis.

Procedure found for not introducing impurities.

Facility at RMD suitable to make ~5kg crystals (Φ = 10cm).

RMD
A Dynasil Company

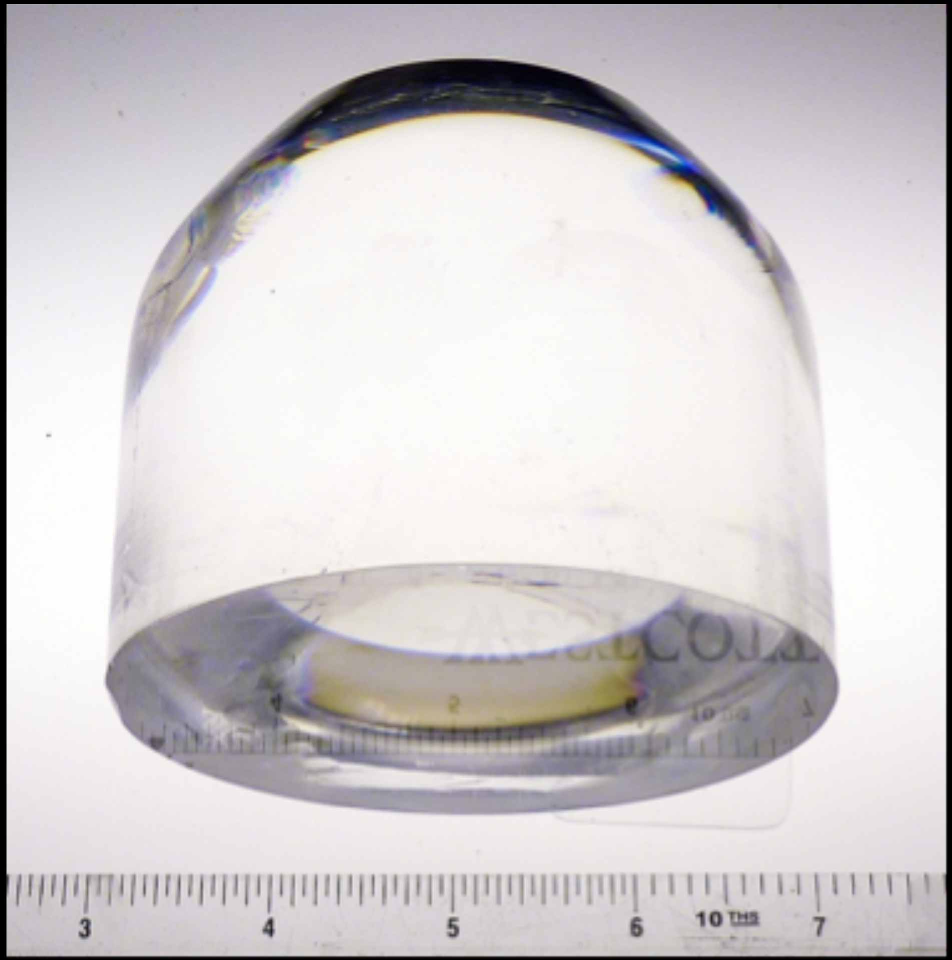
NAI(TL) CRYSTAL GROWTH

2.0 kg, 88 mm diameter crystal (close to the planned diameter for the ~5kg crystals in SABRE) grown from Sigma-Aldrich Astrograde powder

- Photo yield: 41 ph/keV
- Pe yield: 14 pe/keV
- 39K in NaI powder: 10 ppb

Crystal was cut into four slabs for chemical analysis
– ICP-MS, calibrated with gamma-counting

K in crystal below the DAMA level



	This crystal	DAMA crystal
K*	9 ppb	13 ppb
Rb	< 0.1 ppb	<0.35 ppb

*using veto effective [K] is below 1 ppb.

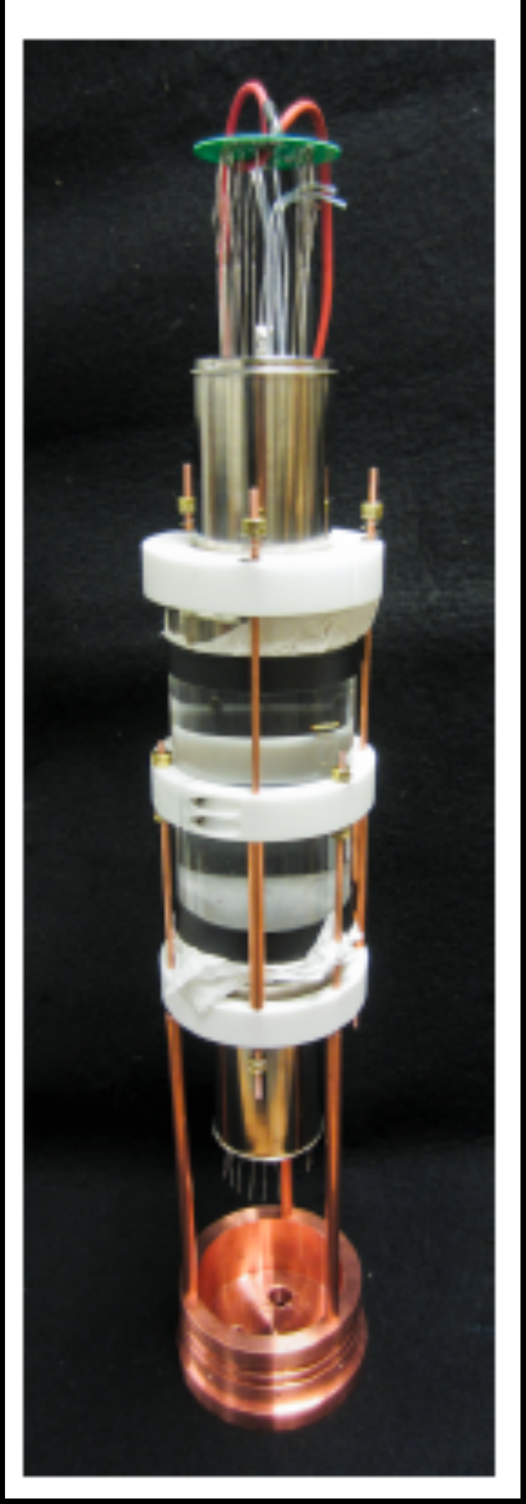
SABRE DETECTOR MODULE

Ultra-high purity NaI(Tl) crystal ~ 5kg

Optically coupled to two 3-inch diameter high Q.E. PMTs (direct coupling)

PMTs:
High quantum efficiency: 35 %
Low radioactivity: ~ 3 mBq/PMT U, ~ 0.5 mBq/PMT Th, Co and ~ 2 mBq/PMT K
Further improvements in development with Hamamatsu

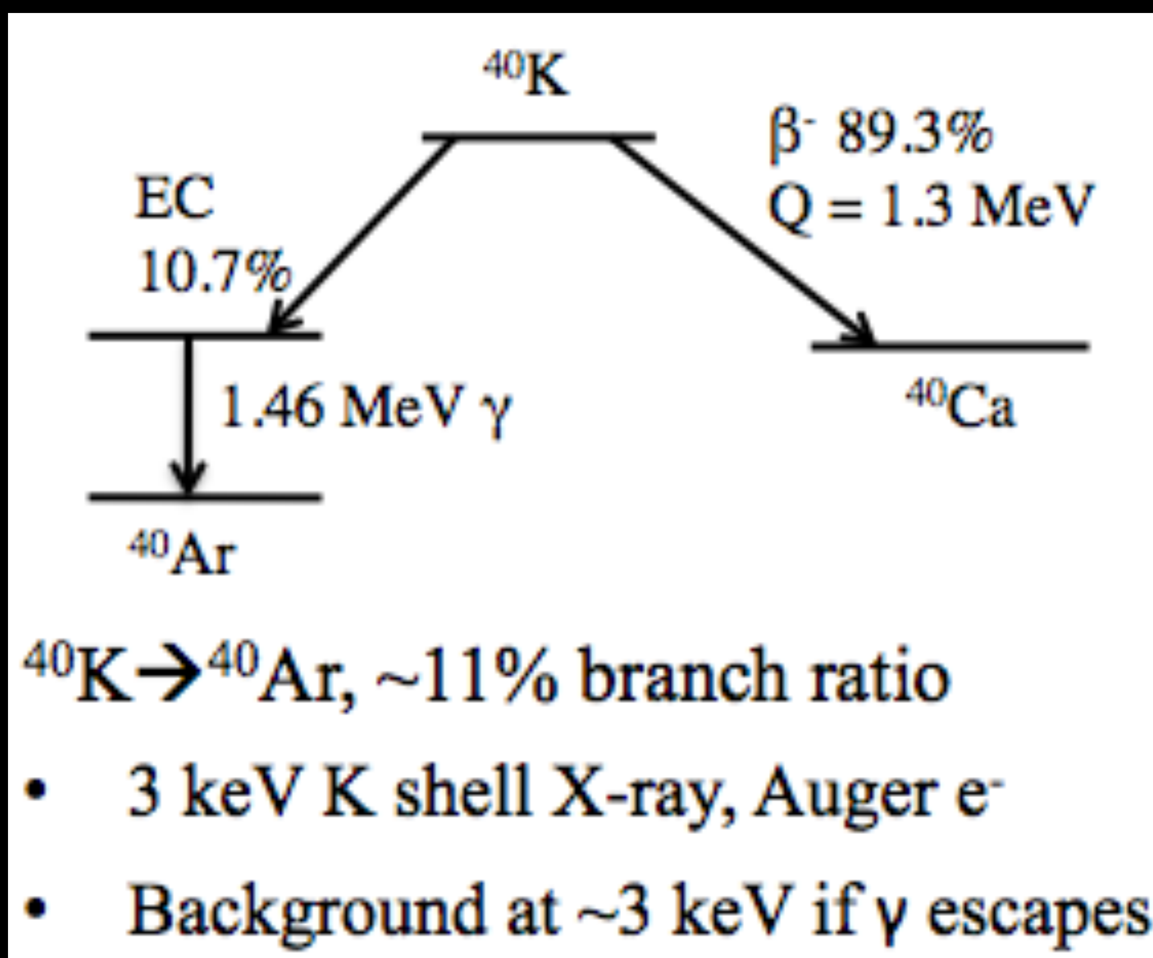
Packaged in a low radioactivity, air- and light-tight, high purity copper enclosure.

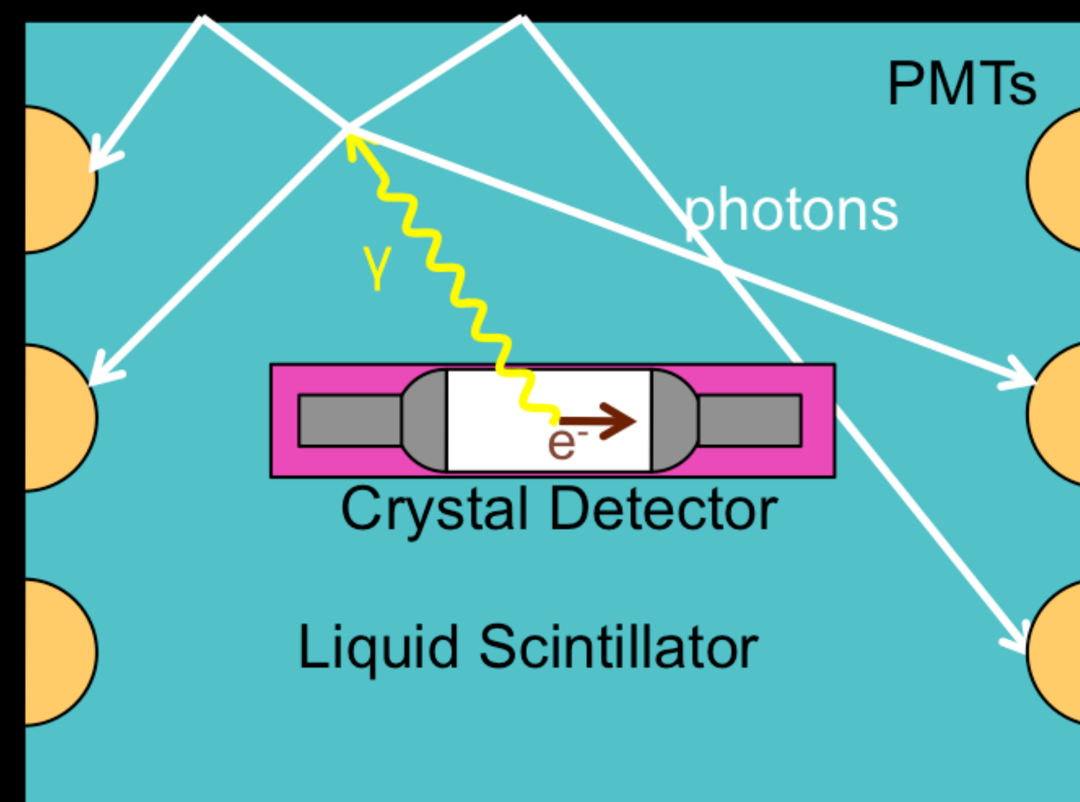


SABRE VETO PRINCIPLE

A significant background for DM searches with NaI(Tl) crystals arises from ^{40}K decays due to trace concentration of potassium in the crystals

ULTRA-HIGH PURITY NAI(TL) DETECTOR + ACTIVE VETO DETECTOR





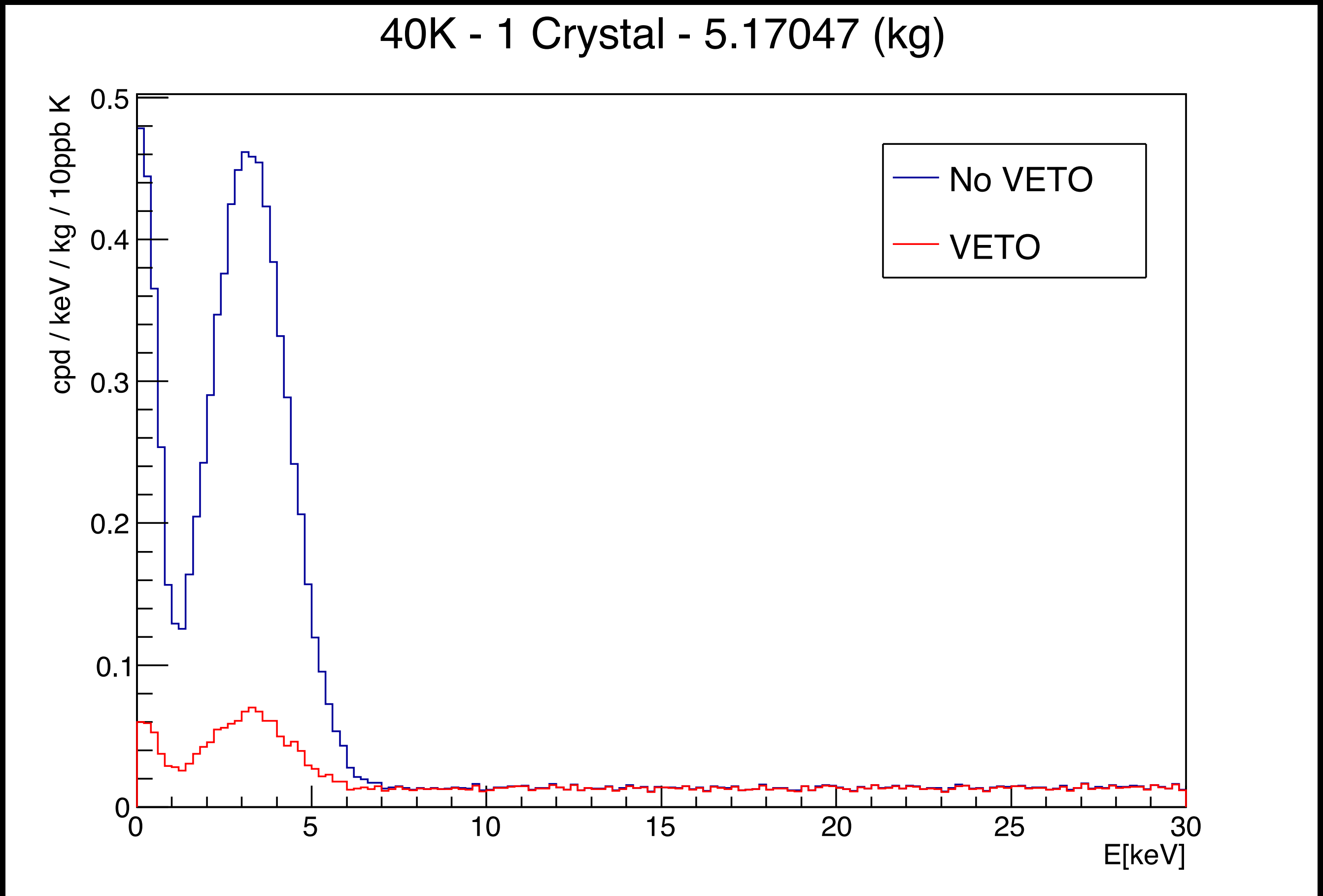
If 1.46 MeV gamma is detected by a LS veto, ^{40}K background can be rejected

LIQUID SCINTILLATOR VETO

Goal: veto ^{40}K background in crystals, shielding of external radiation.
Inner surface cleaned and coated to avoid degradation, high reflectivity.
Equipped with 10 8" high QE Hamamatsu PMTs.
Liquid Scintillator is pseudocumene PC or LAB.
Expected Light Yield ~ 0.2 p.e./keV.

Vessel: 1.4 m diameter, 1.5 m length

^{40}K decays uniformly distributed inside the crystal
90% of 3keV decays are rejected by the veto.



THE SABRE PHASED STRATEGY

Grow high purity crystal.

Validate procedure to produce crystals and validate efficiency of LS veto with preliminary measurements at LNGS

SABRE Proof of Principle (PoP)

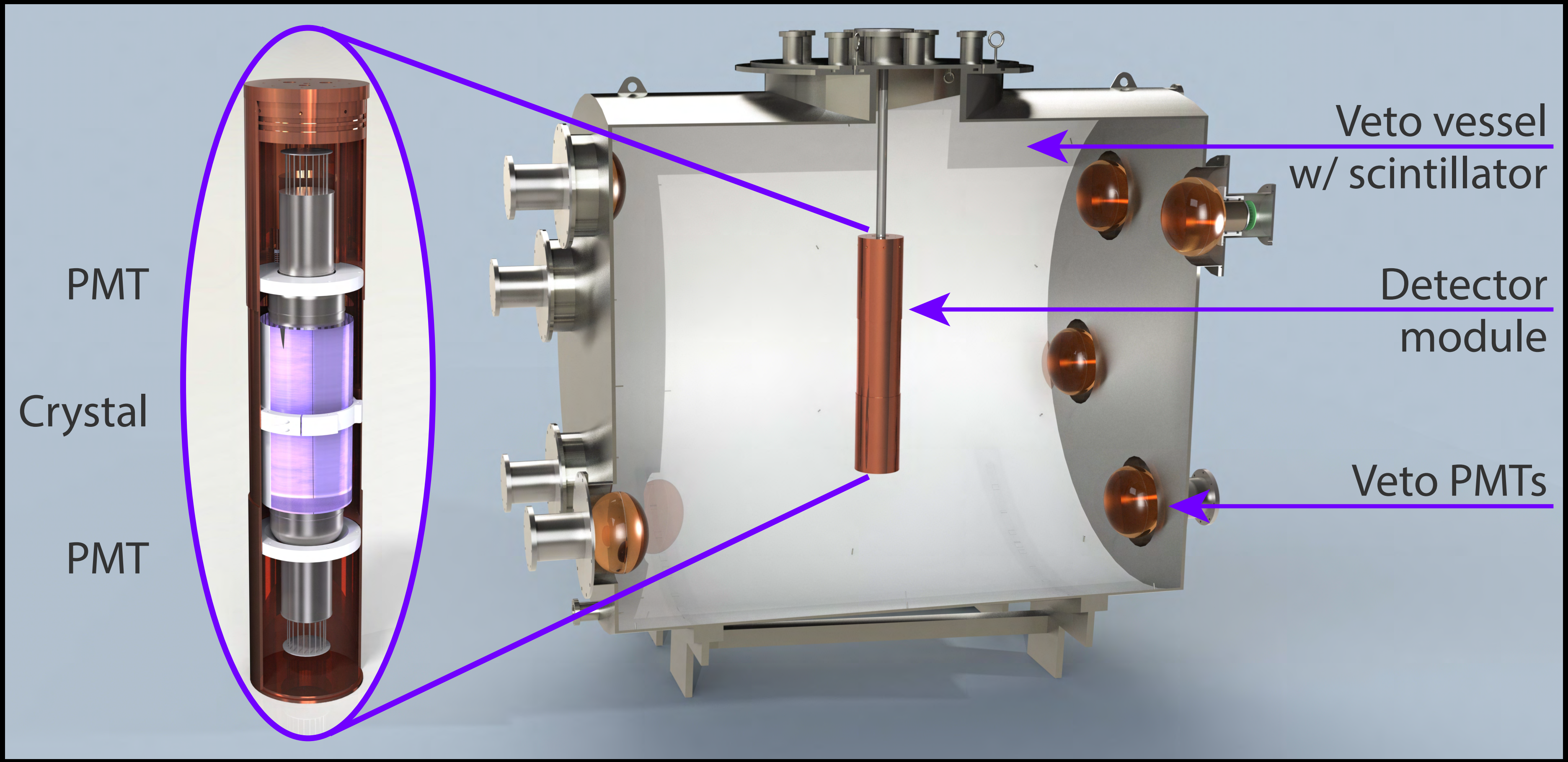
In parallel prepare underground installation for the full scale detector setup

Full scale detectors @ LNGS and Stawell

SABRE

SABRE PROOF OF PRINCIPLE

Asses the radiopurity of the NaI(Tl) crystals grown for SABRE and show that this is compliant to the requirements needed to the full SABRE project.



Demonstrate the feasibility to operate high purity NaI(Tl) crystals inside a liquid scintillator veto and test the veto efficiency and its background reduction capability.

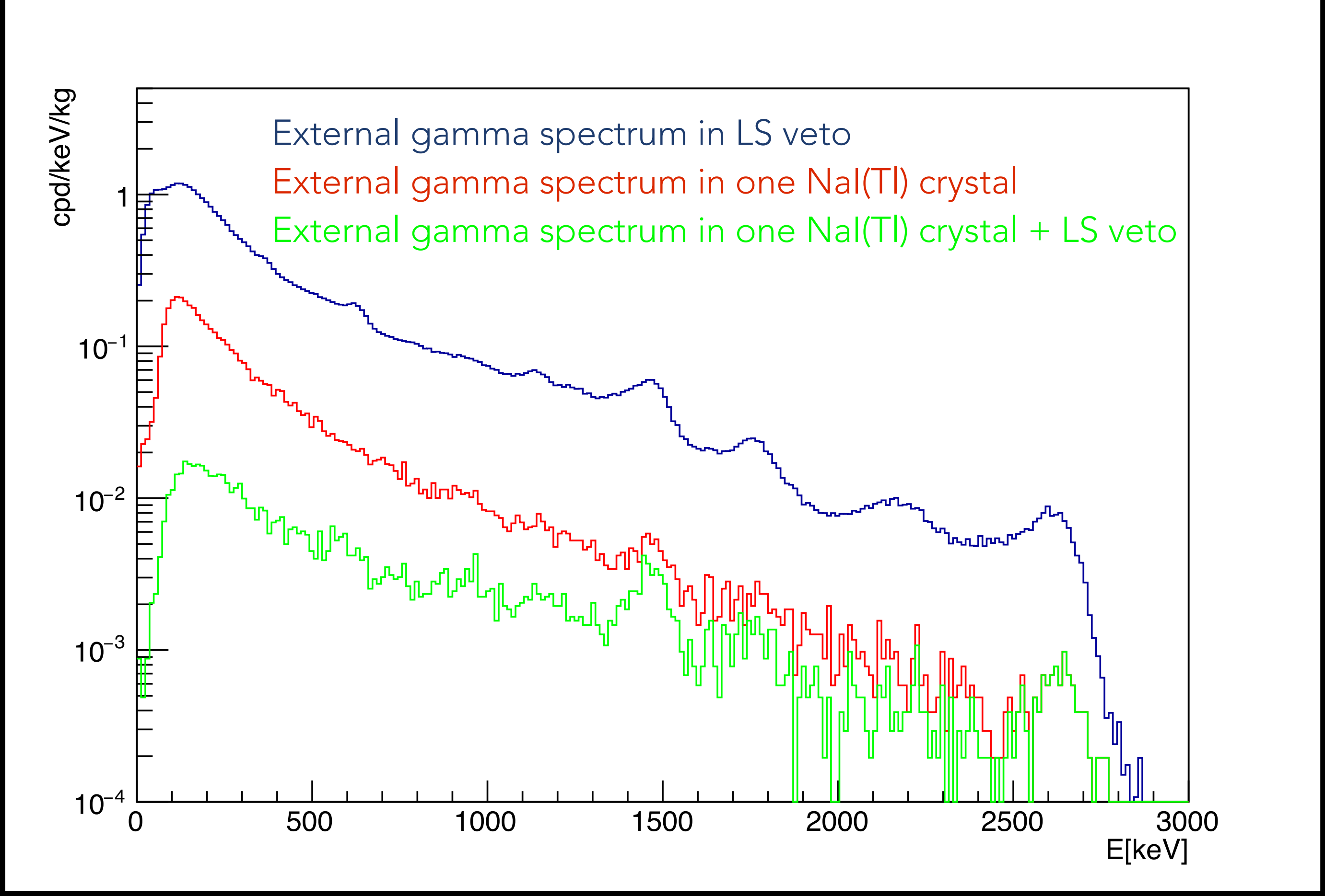
Study in details the background:

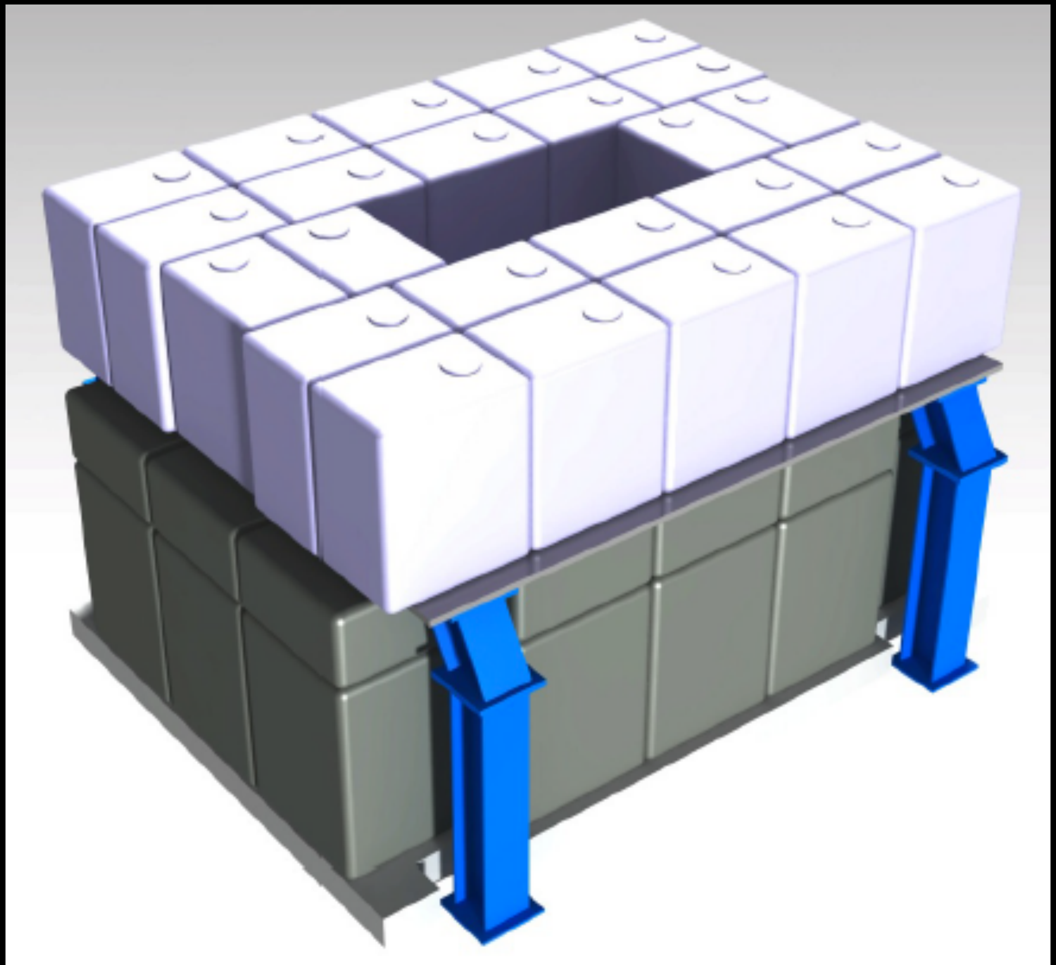
- intrinsic contaminations of the crystals, including cosmogenic activation;
- background from other components of the setup outside the crystals, that is PMTs, enclosure, liquid scintillator, etc…;
- background from external sources;

SABRE POP @ LNGS

In order to shield the PoP-setup from external radioactivity (mainly the gamma flux from the experimental hall) and maintain the counting rate of the liquid scintillator veto at an acceptable level, the steel vessel has to be provided with an external shielding.

We adopted a hybrid solution, involving both lead and water for an equivalent shielding effect of at least 90 cm of water along all the directions.

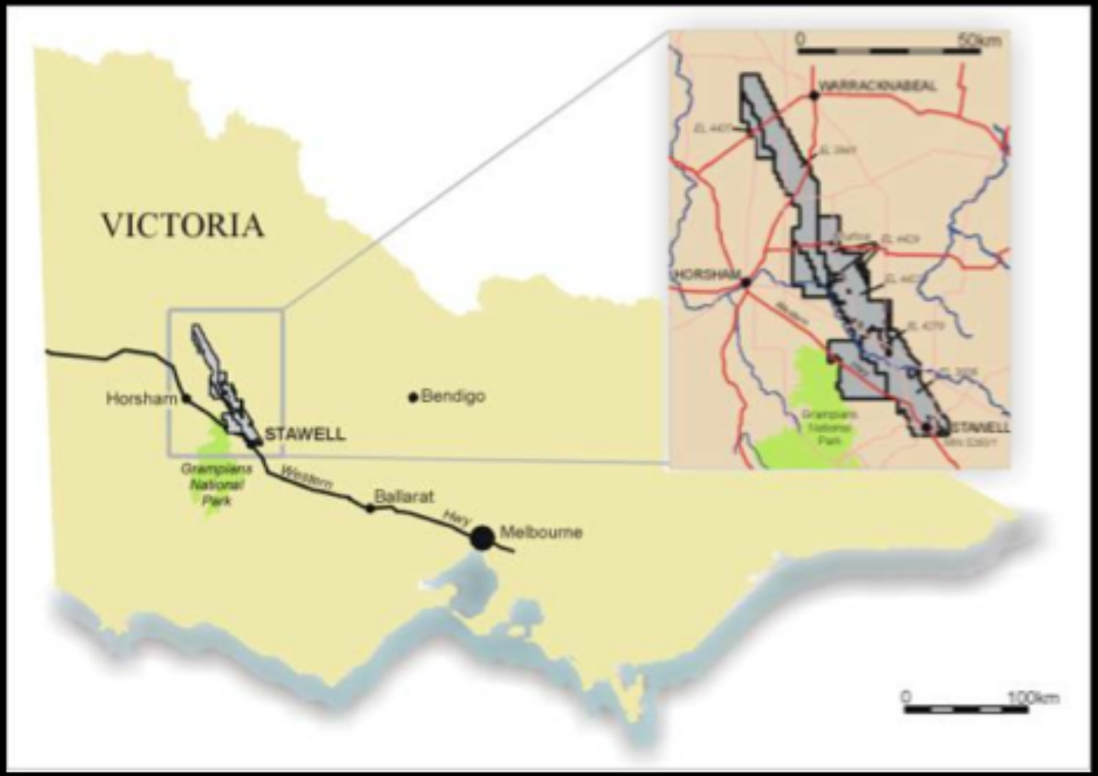




SABRE IN THE SOUTHERN HEMISPHERE

SUPL: STAWELL UNDERGROUND PHYSICS LABORATORY

Stawell gold mine ~240 km west of Melbourne, in 2017 will host the first ready to be used underground laboratory in the Southern hemisphere.



State of Victoria, ~ 240 km west of Melbourne, ~3h drive.

Chosen lab site: cavern 1km underground,
~3.1 km w. e. (flat surface, basalt density of the mine ~ 2.86 t/m^3), similar to LNGS.

Decline mine, 1.6 km maximum depth, with all caverns served with electricity, optical fibre, compressed air, reached by car/truck.
The mine is operational.

TIMELINE

2014:
Lab proposed

2015:
Funding secured (May)
Design consultant appointed (Oct)
Complete design (Dec/Jan 2016)

2016:
Design Review (Jan/Feb)
Start construction (Feb/Mar)
Facility ready (Dec)

2017:
Lab ready to use (Jan/Feb)

SABRE COLLABORATION

Australian National University
Gregory Lane, Cedric Sinemel, Andrew Stuchbery, Anton Wallner

INFN, LNGS
Maddalena Antonello, Giuseppe Di Carlo, Graham Giovanetti, Aldo Ianni, Donato Orlandi, Michela Paris, Chiara Vignoli

University of Roma "Sapienza" and INFN Roma
Ioan Dafinei, Marcella Diemoz, Valerio Pettinacci, Giancarlo Piredda, Shahram Rahatlou, Claudia Tomei

Lawrence Livermore National Laboratory (LLNL)
Jingke Xu

Pacific Northwest National Laboratory (PNNL)
Isaac Arnquist, Eric Hoppe, Todd Hossbach, John Orrell, Cory Overman

Princeton University
Jay Benziger, Frank Calaprice, Francis Froborg, Graham Giovanetti, Burkhant Suerfu, Masa Wada

Swinburne University of Technology
Jeremy Mould, Alan Duffy

University of Melbourne
Elisabetta Barberio, John Koo, Chunha Li, Peter McNamara, Francesco Nuti, Phillip Urquijo

University of Milano and INFN
Davide D’Angelo

CONCLUSIONS

- DAMA/LIBRA signal highly significant. Model-independent test of DAMA/LIBRA is necessary.
- SABRE is well equipped for a definitive test:
  - Ultra-high purity NaI powder developed
  - High purity NaI(Tl) crystal growth method proved effective
  - Low background detector enclosure in design
  - Higher light yield, lower energy threshold can be expected
  - Liquid scintillator veto to reject residual background
- SABRE PoP approved by INFN (2016/2017)
- Start of PoP within mid 2016
- Soon after the PoP characterisation phase, start the first physics run.
- International competition, very exciting field!

BACKUP SLIDES

EXPECTED SENSITIVITY

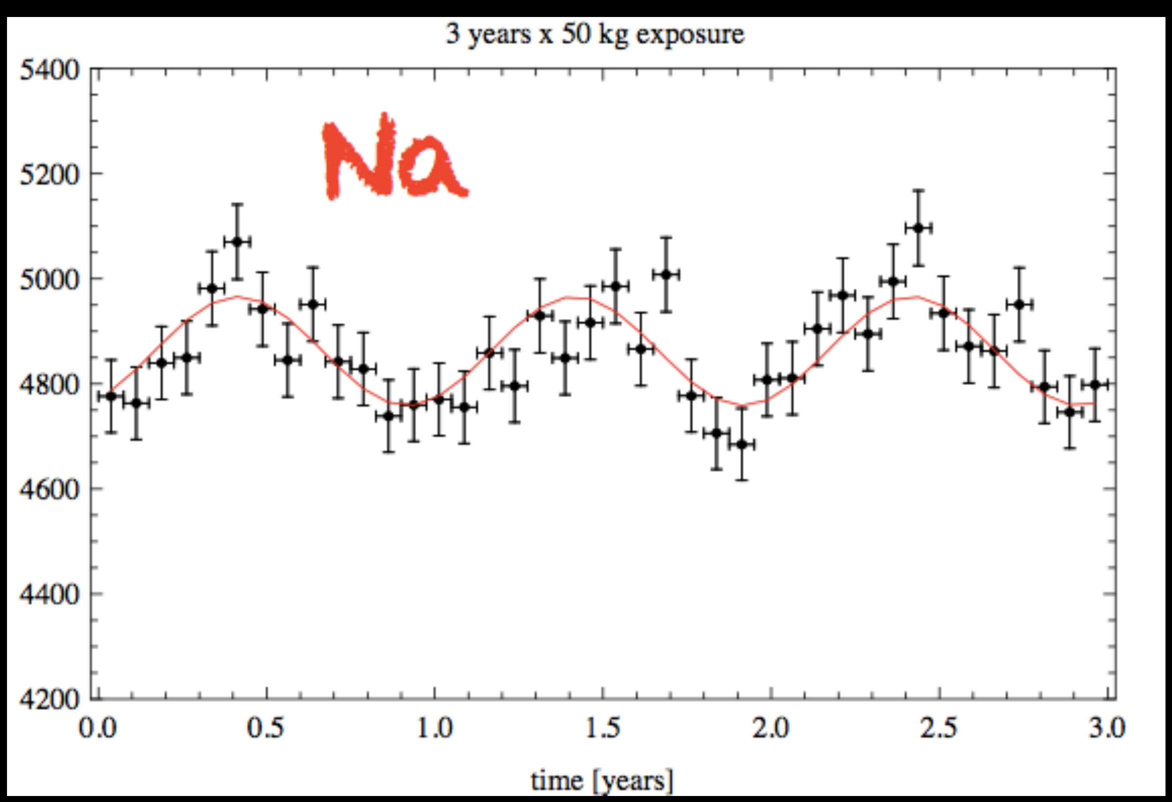
Assume "standard" WIMPs reference model and best fit values from DAMA/LIBRA

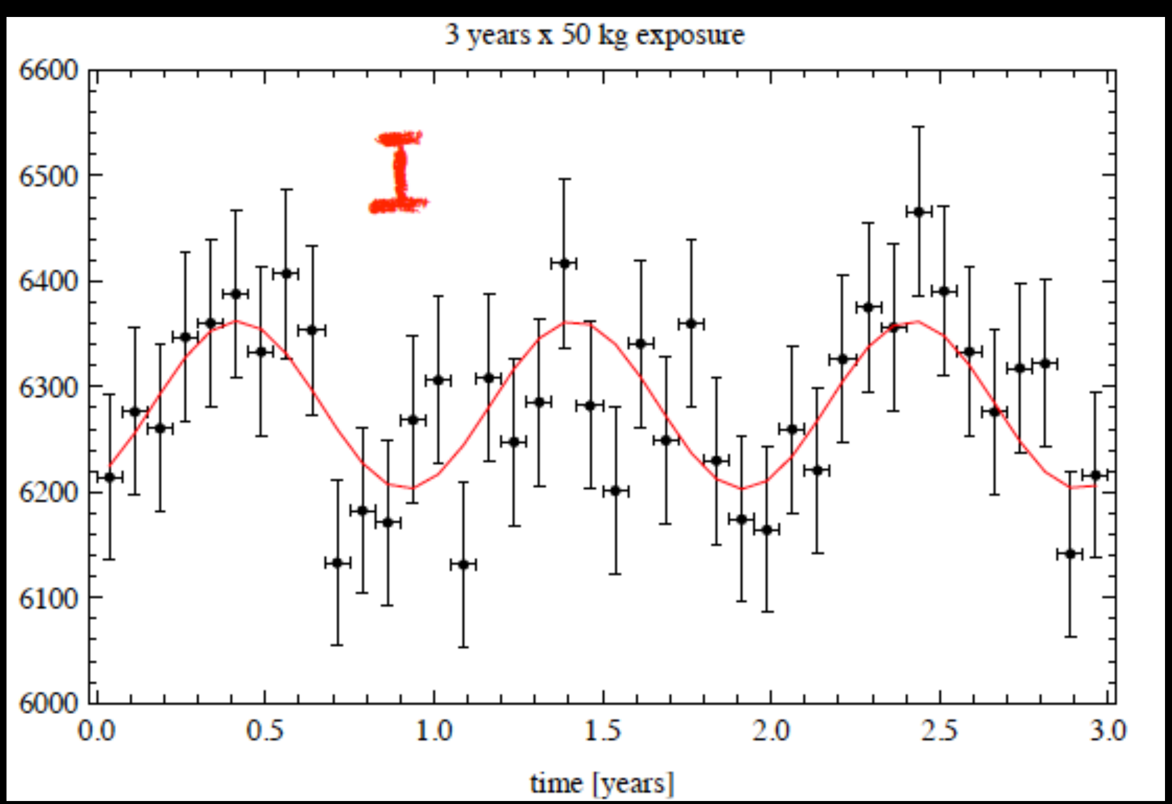
Assume a background level ~ 0.2 cpd/keV/kg (crystal internal contaminations at the level of DAMA and 90% veto rejection)

Assume stable detector operations

Signal + background in [2,6] keV_{ee} window for 3 years and 50 kg exposure

5σ sensitivity for the Na case, 4σ for the Iodine case.

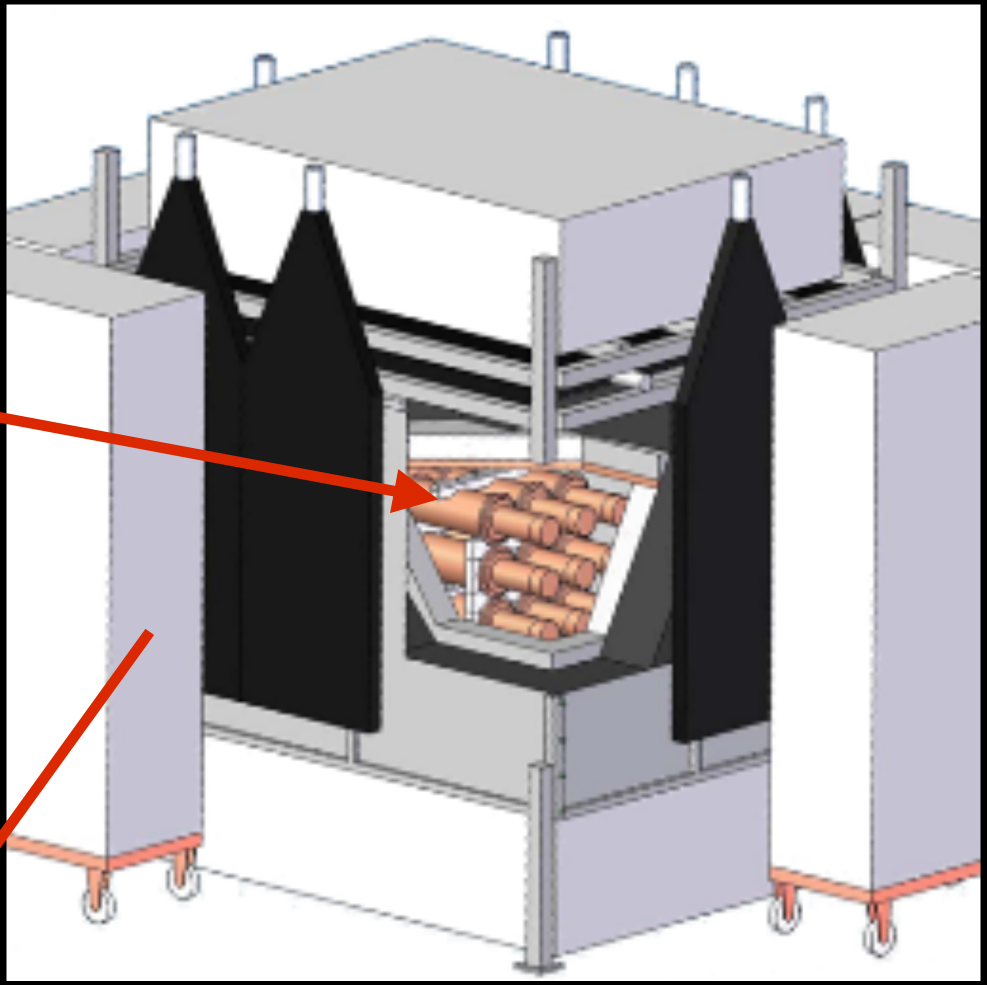




OTHER NAI EXPERIMENTS - ANAIS

ANAIS: search for DM annual modulation at Canfranc Underground Laboratory (LSC) in Spain.

Assembly of 12.5 kg NaI(Tl) crystals encapsulated in copper. Nine modules in a 3×3 matrix are expected to be set-up at LSC along 2016.



Crystals produced by Alpha Spectra
K ~ 40 ppb and 0.5 mBq/kg alpha background (not yet at equilibrium)

Light Yield ~ 15 p.e./keV
1 keVee threshold

Shielding: 10 cm of archaeological lead, 20 cm of low activity lead, 40 cm of neutron moderator, anti-radon box, active muon. Experimental hut already operative at LSC.

OTHER NAI EXPERIMENTS - DM-ICE

DM-ICE: search for DM annual modulation exploiting the peculiar location of the South Pole (under ice)

Goal: operate a 250 kg detector in the northern hemisphere (Boulby Underground Laboratory, UK) and, if a signal is observed, move it to the South Pole.

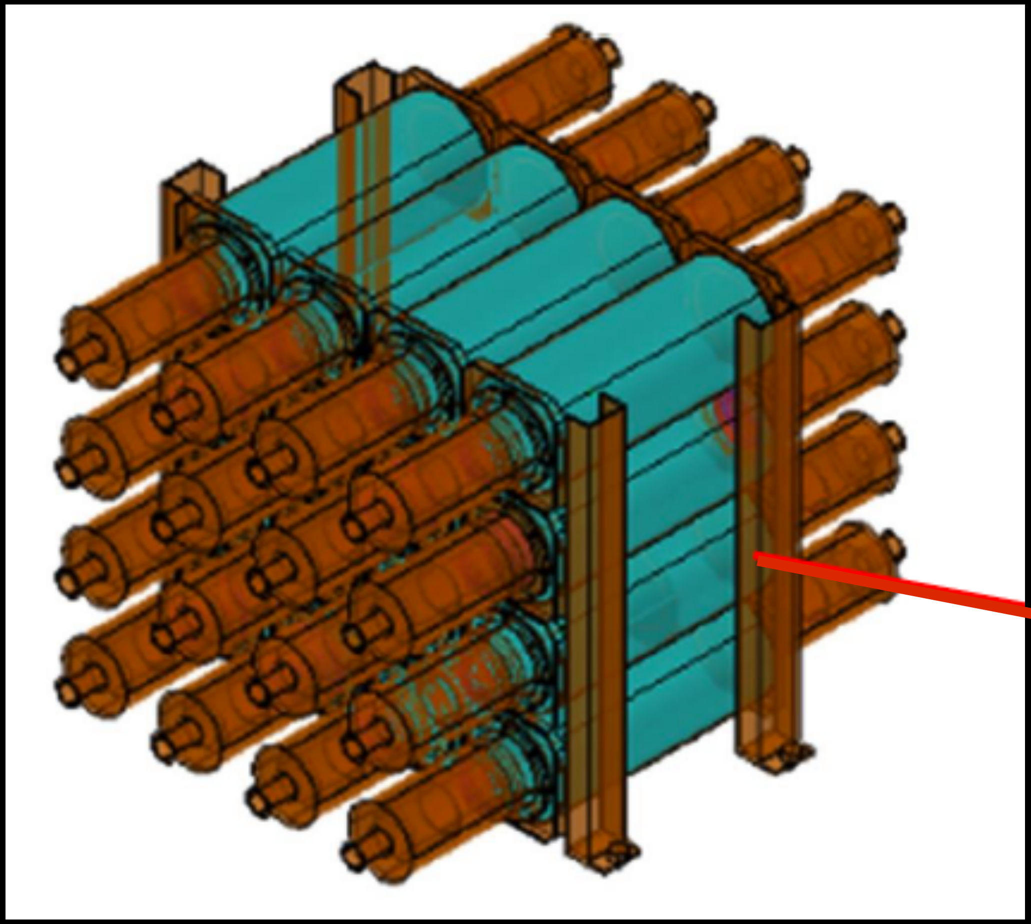
DM- Ice17 (17 kg) successfully deployed in the South Pole ice in December 2010 and operated since then. Potassium level well above the DAMA/LIBRA value (about a factor 30). Light yield ~ 5 p.e./keV.

DM-Ice37/55 setup: 2 x 18.3 kg crystals grown by Alpha Spectra in operation at Boulby since Jan. 2015.

The growth strategy at Alpha Spectra is shared between the ANAIS, DM-Ice and KIMS experiments)

OTHER NAI EXPERIMENTS - KIMS

KIMS NaI: search for DM annual modulation with a 200 kg NaI(Tl) crystal array operated at the Yangyang underground laboratory in Korea.



Six R&D stage crystals tested so far. Crystals grown by Alpha Spectra and Beijing Hamamatsu using a variety of NaI powders (from AS itself and from Sigma Aldrich) and operated inside the same experimental apparatus used for the previous KIMS-CsI experiment.

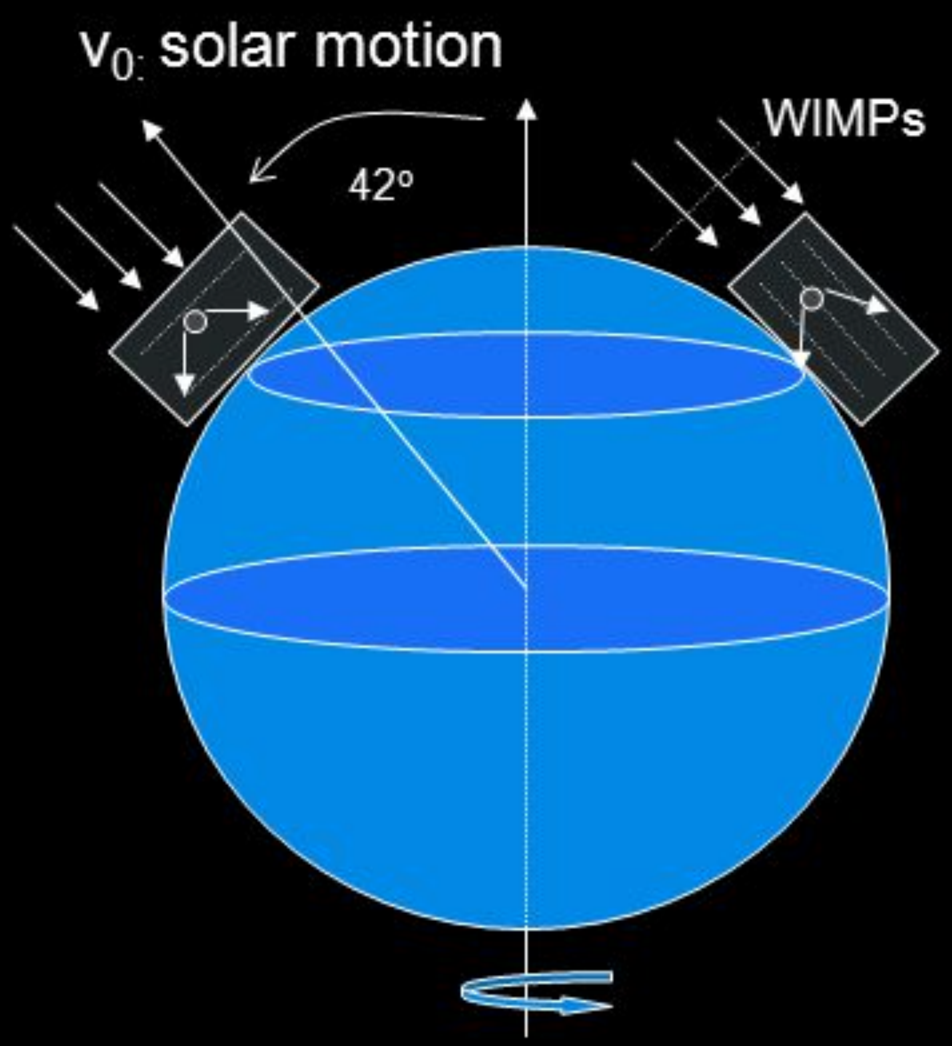
Future NaI crystal array
12.5kg X 16 crystals=200kg

Plan to use LS veto

Light yield: 11 - 15 p.e./keV
^{40}K contamination: ~ 25 ppb (Astro Grade powder) - ~ 40 ppb (AS powder)
^{210}Po contamination ~ 0.5 mBq/kg
Next step: assembly of the shielding for the 200 kg experiment and operation of the available 50 kg of NaI crystals of different radio-purity.

DIURNAL MODULATION

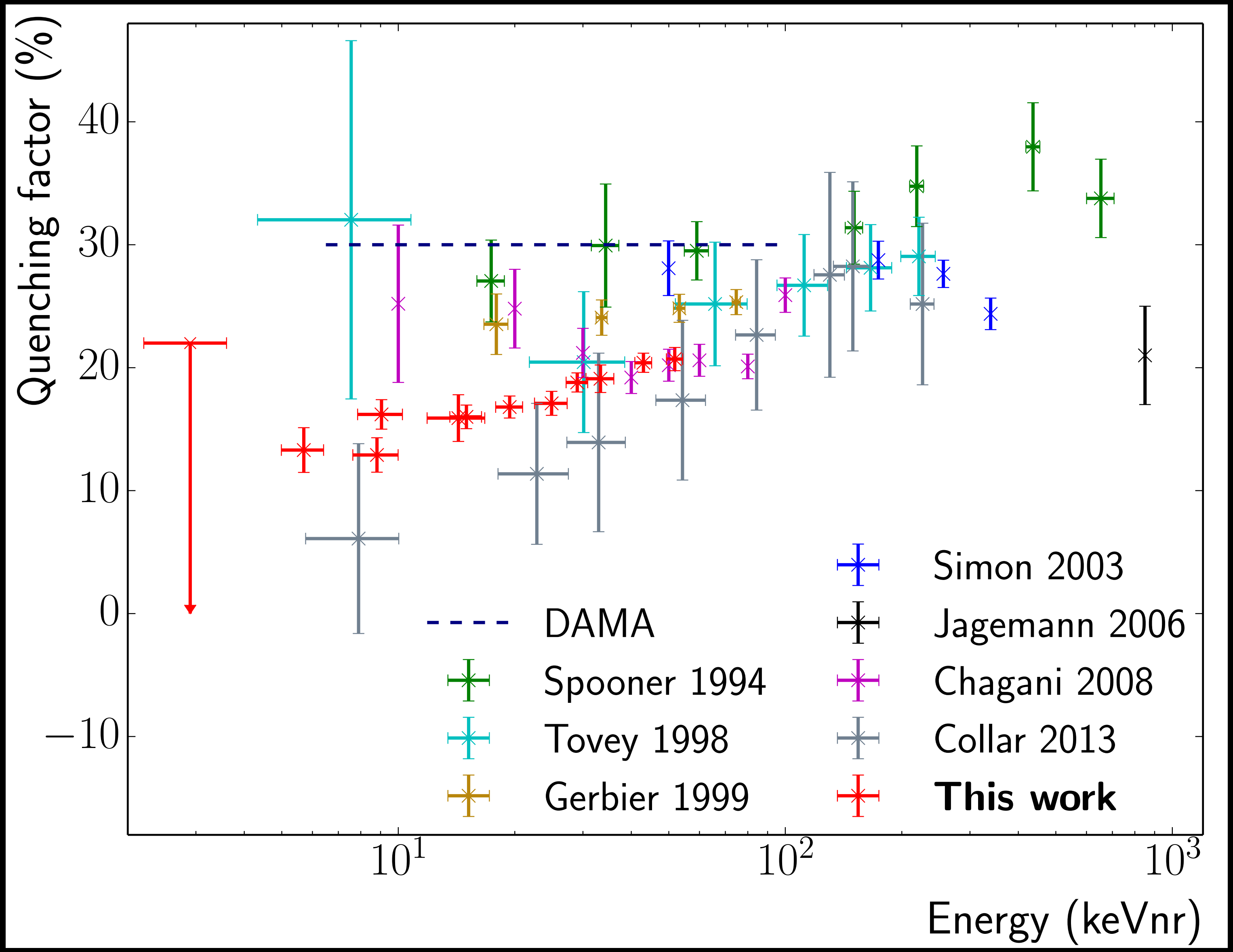
A diurnal modulation of the DM signal is expected as a function of the sidereal time due to Earth rotation velocity contribution.



Moreover, during a sidereal day the Earth shields a terrestrial detector with a varying thickness, and this induces a variation of the flux of the DM candidates impinging the detector.

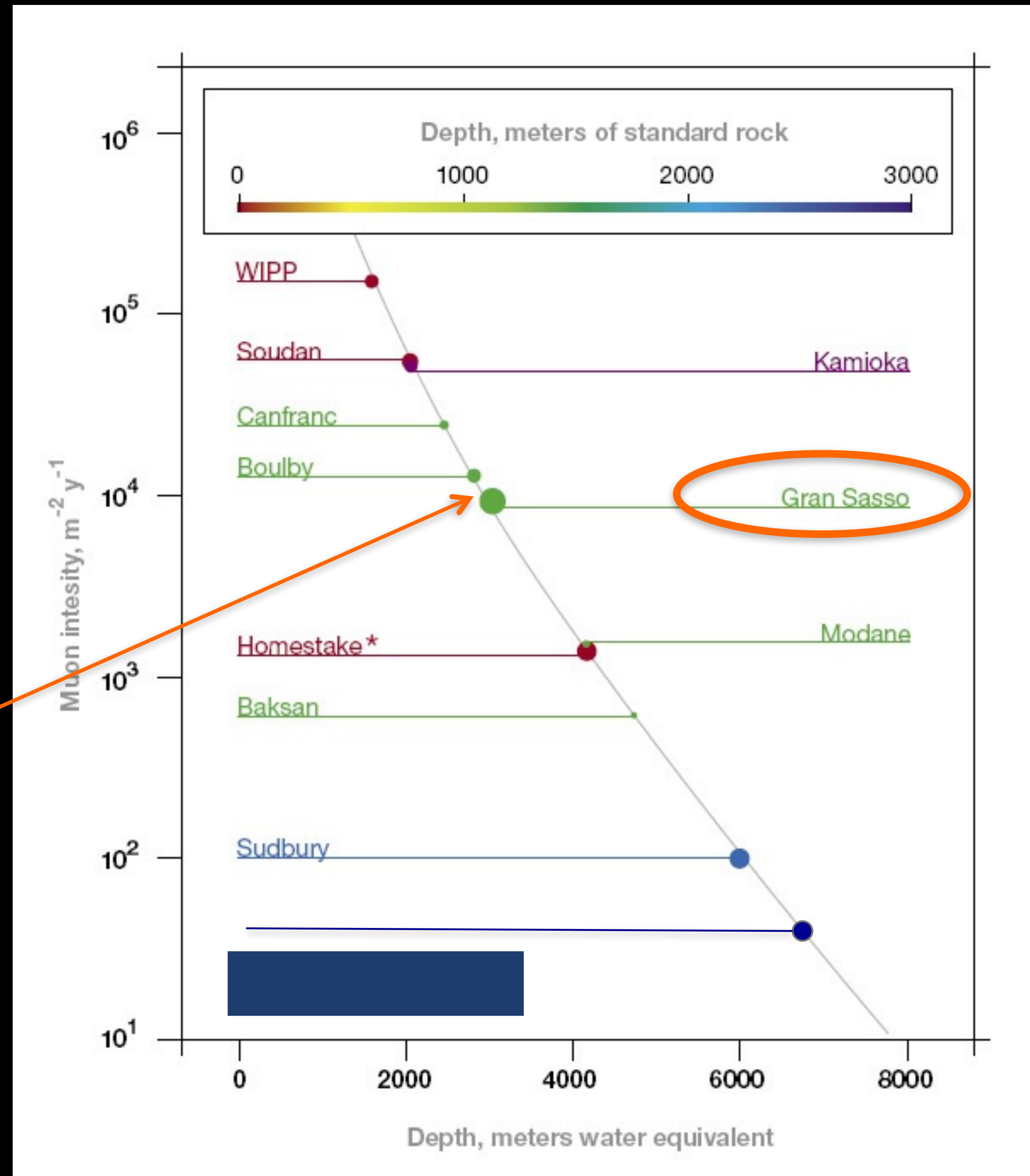
The rotational velocity (at most 0.5 km/s, near the equator) is significantly smaller than the orbital velocity (30 km/s), making the daily modulation signal much smaller than the annual modulation signal and, unfortunately, much more difficult to detect.

NUCLEAR RECOIL QUENCHING



Results show more quenching at low recoil energies than previously found.
Trend agrees with measurements of J. Collar.
Region of interest in D-L (2 – 6 keVee) corresponds to higher nuclear recoil energies than previously thought: e.g., 9 keVnr is about 0.9 keVee.

UNDERGROUND LABS



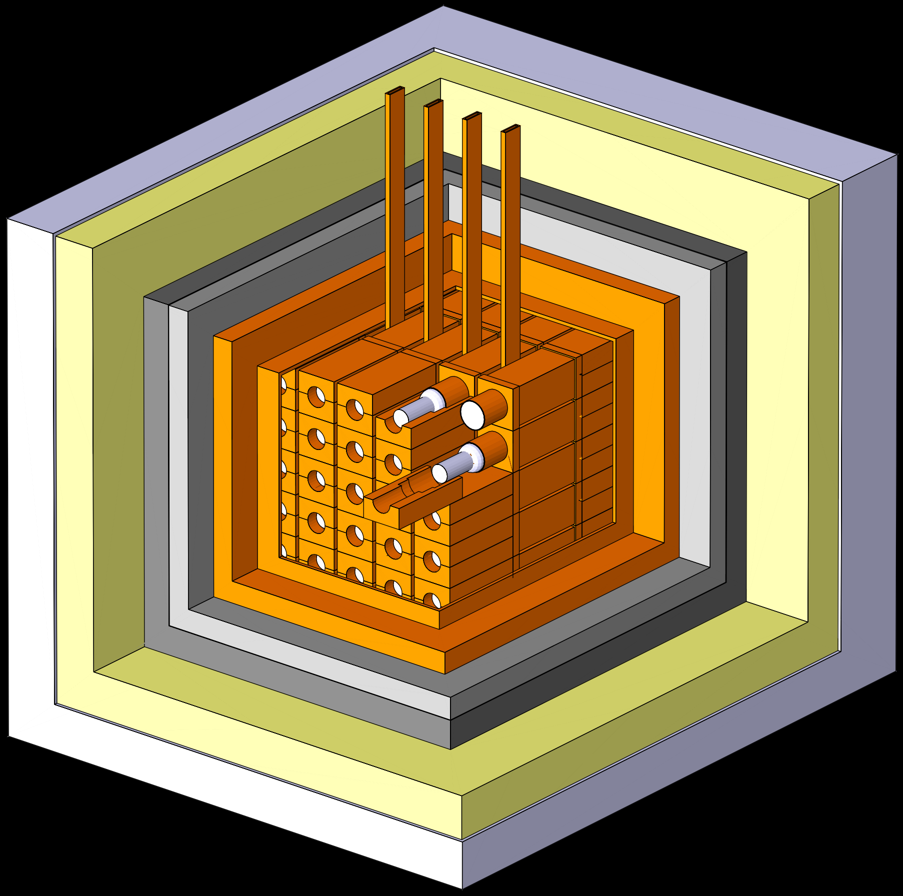
Stawell Gold Mine

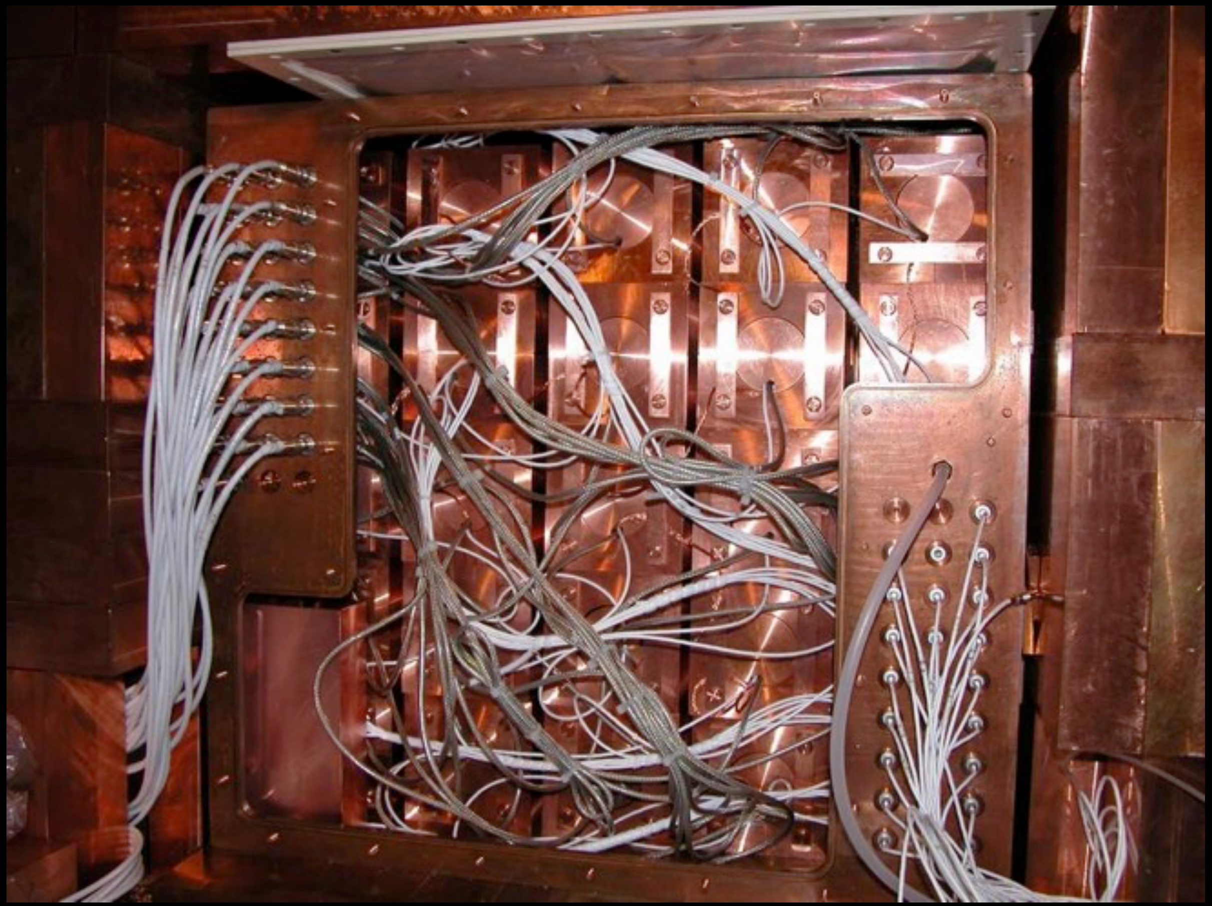
THE DAMA/LIBRA EXPERIMENT

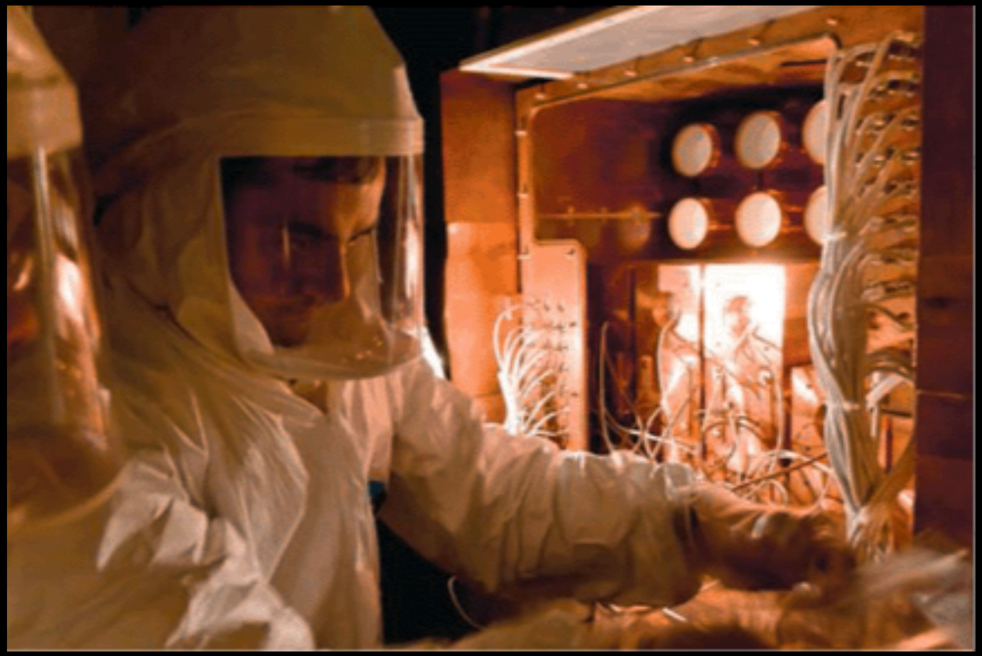
High Purity NaI (Tl) crystals

Located at LNGS:

1. DAMA (100kg) 1996-2002
2. DAMA/LIBRA (250kg) Phase I: 2003-2010
3. DAMA/LIBRA (250kg) Phase II: 2011-…







NAI CRYSTAL @ SICCAS

Powder purification and crystal growing is also being investigated at SICCAS (Shanghai Institute of Ceramics – Chinese Academy of Sciences) that grew TeO_2 crystals for the CUORE experiment.

Powder produced at Kunshan Chemical (partner lab)
< 3 ppm K (HPGe)
~0.45 ppm K (ICP-MS)

Started R&D in 2015

Four NaI crystals grown (not Thallium doped)
1.2 kg, Ø5 cm, h 12 cm
Crystals #1 and #2 —> measured by HPGe and ICPMS at LNGS, show a ~4 purification factor wrt the powder
Crystals #3 and #4 —> melted and regrown at SICCAS to study purity improvement through successive crystal growth
Before being shipped to Italy they will undergo polishing tests