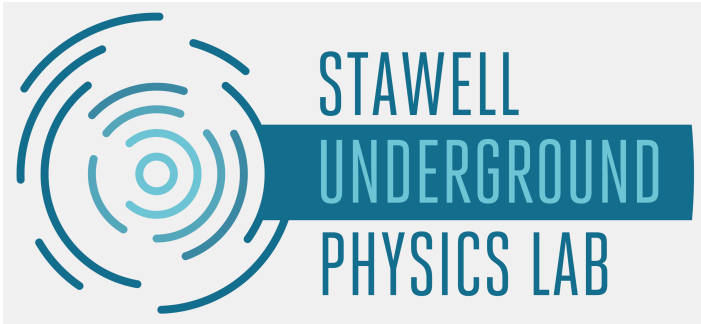
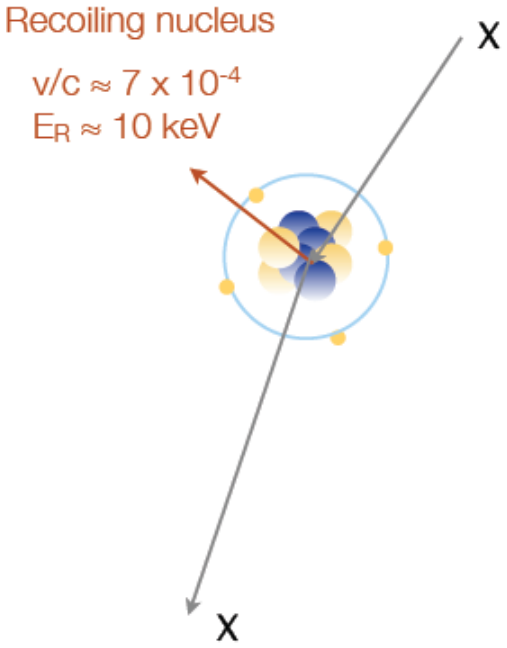
Galactic dark matter search with SABRE, a dual-site detector using ultra-pure NaI(Tl) scintillator

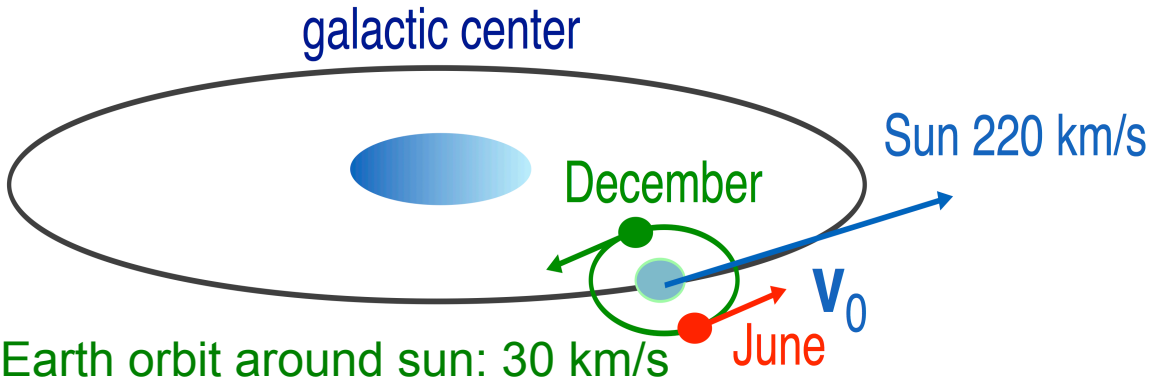
Greg Lane
Australian National University

on behalf of the SABRE collaboration



Dark Matter: WIMPs in the galactic halo



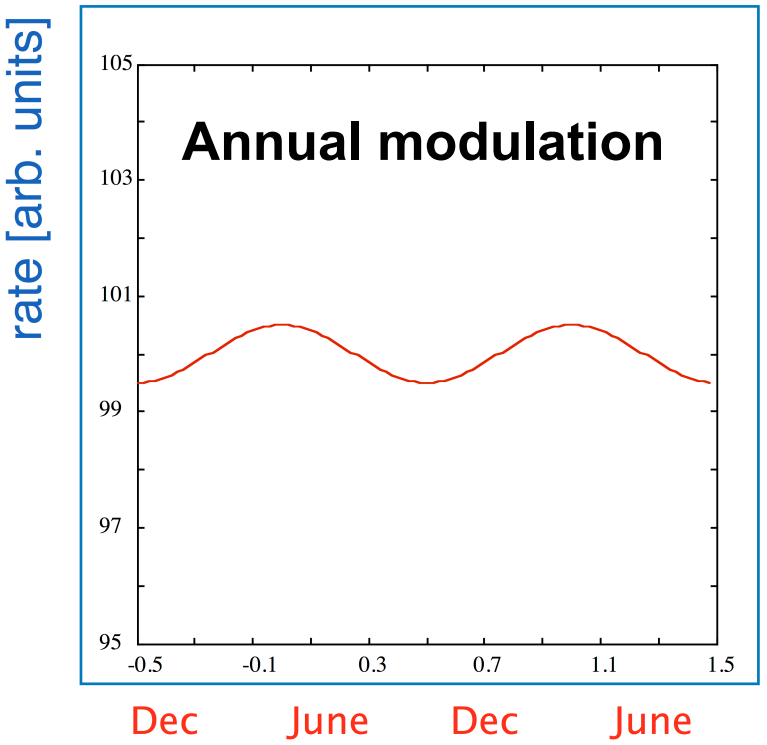


Standard halo model: Spherical halo of cold, dark matter permeating the galaxy with ρ_X~0.3 GeV/cm^3

WIMP interaction rate:

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

$2\pi/\omega$=1 yr and t_0 on June 2nd.



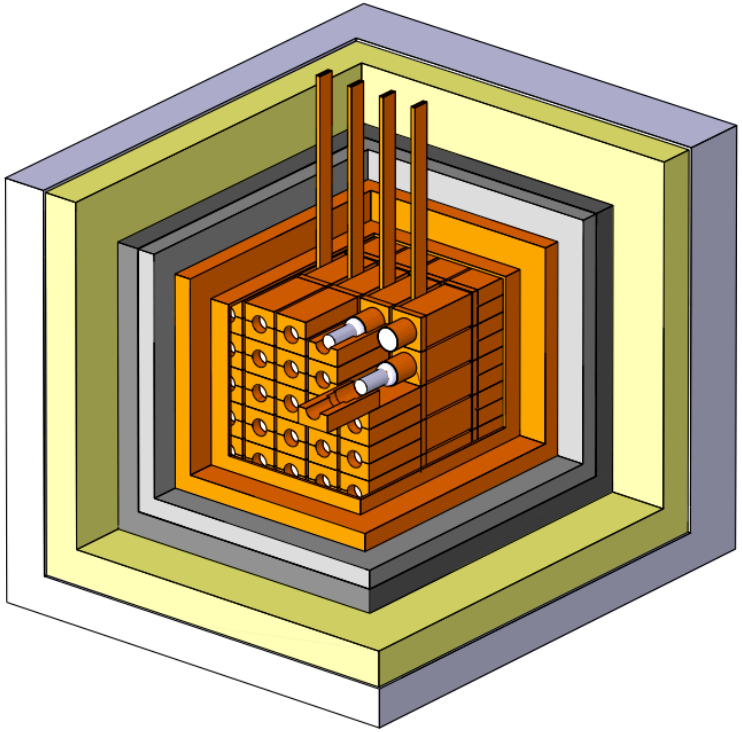
Dark Matter Detectors: Results

Location	Name	Detector	Started	Findings
Gran Sasso mountain, Italy	CRESST-II	3 kilograms of calcium-tungstate crystals	2009	Possible dark-matter signals later shown to be background
	DAMA/LIBRA	250 kg of sodium-iodide crystals	2003	Annual modulation signal, still unexplained
	DarkSide-50	50 kg of liquid argon	2013	No signals
	XENON1T	3,500 kg of liquid xenon	Due spring 2016	No signals from precursor experiments
Homestake mine, South Dakota	LUX	370 kg of liquid xenon	2013	No signals
Mozumi mine, Kamioka, Japan	XMASS-I	835 kg of liquid xenon	2010	No signals
Vale Inco mine, Sudbury, Canada	PICO-60	37 kg of trifluoromethyl iodide	2013	No signals
Soudan mine, Minnesota	CoGeNT	0.5 kg of germanium crystals	2009	Possible dark-matter signals later shown to be background
	CDMS	9 kg of germanium crystals	2012	No signals

Summary from *Nature News*, Nov 2015

- "No signals" means no evidence claimed for DM.
- All in underground labs to achieve low backgrounds.
- All labs are (presently) in the northern hemisphere (N.B. DM-ICE at the south pole is not listed).
- Some initial claims of DM signals subsequently shown to be background.
- Persistent signal from DAMA/LIBRA is still unexplained; tension with other null results.

DAMA/NaI ➔ DAMA/LIBRA



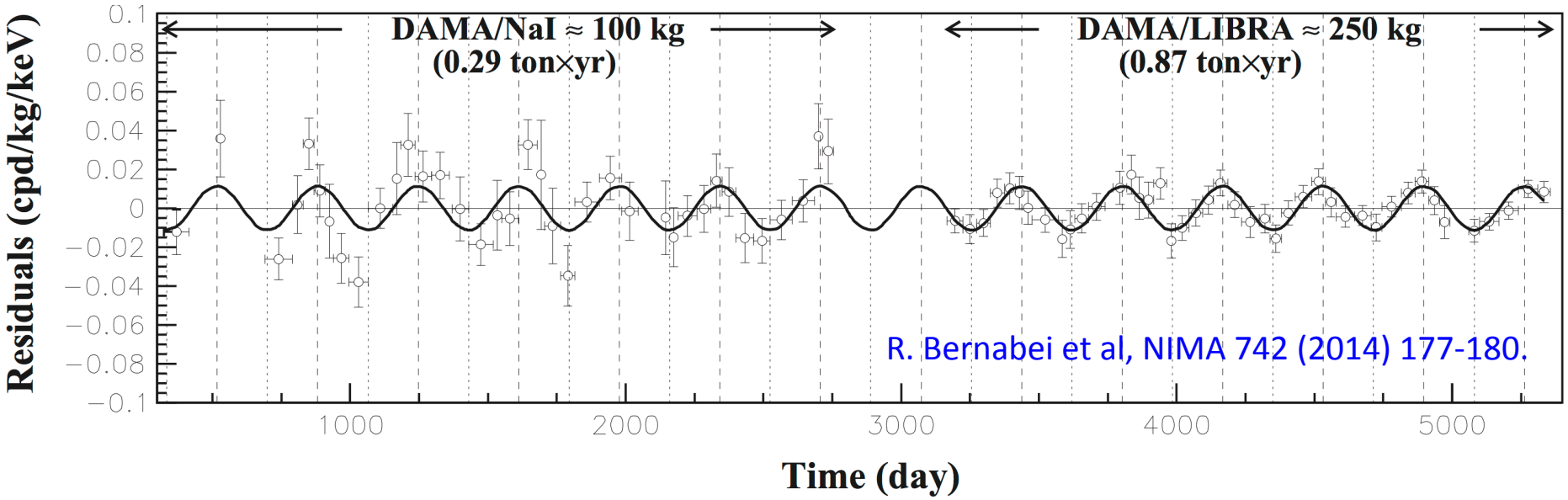
- NaI(Tl) scintillator – WIMPs scatter off sodium and/or iodine nuclei
- LNGS (Italy) since 1995
- 100 kg (DAMA-NaI, 7 years)
- 250 kg (DAMA/LIBRA, 6+ years)
- 25 x 10kg crystals each with two PMTs

Detector Apparatus:
Bernabei et al, NIMA 592 (2008) 297– 315

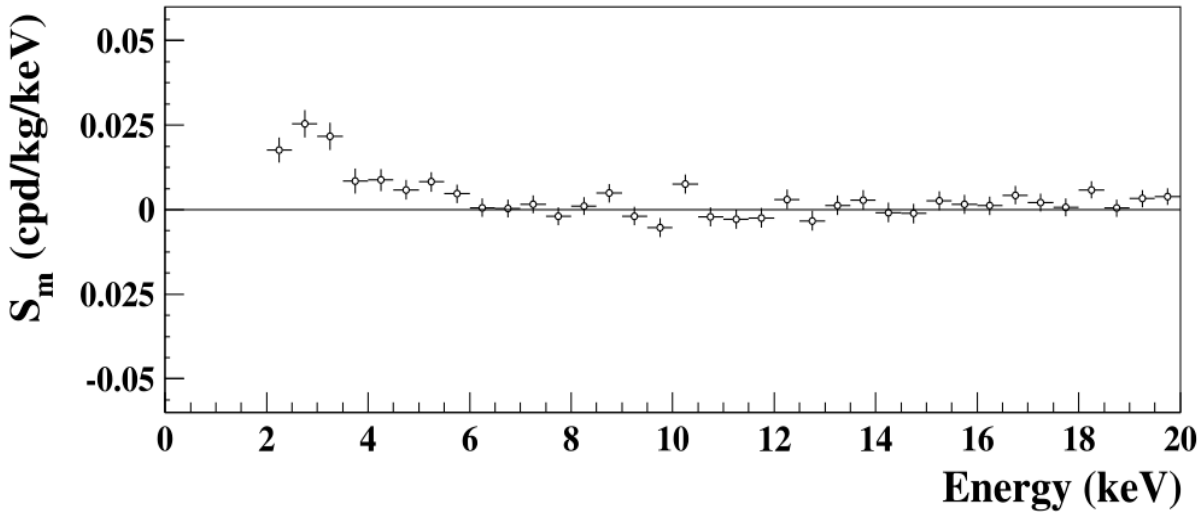
Combined DAMA/NaI – DAMA/LIBRA results:
Bernabei et al, EPJ C 73 (2013) 2648.

Ongoing phase 2 of DAMA/LIBRA:
Bernabei et al, NIMA 742 (2014) 177.

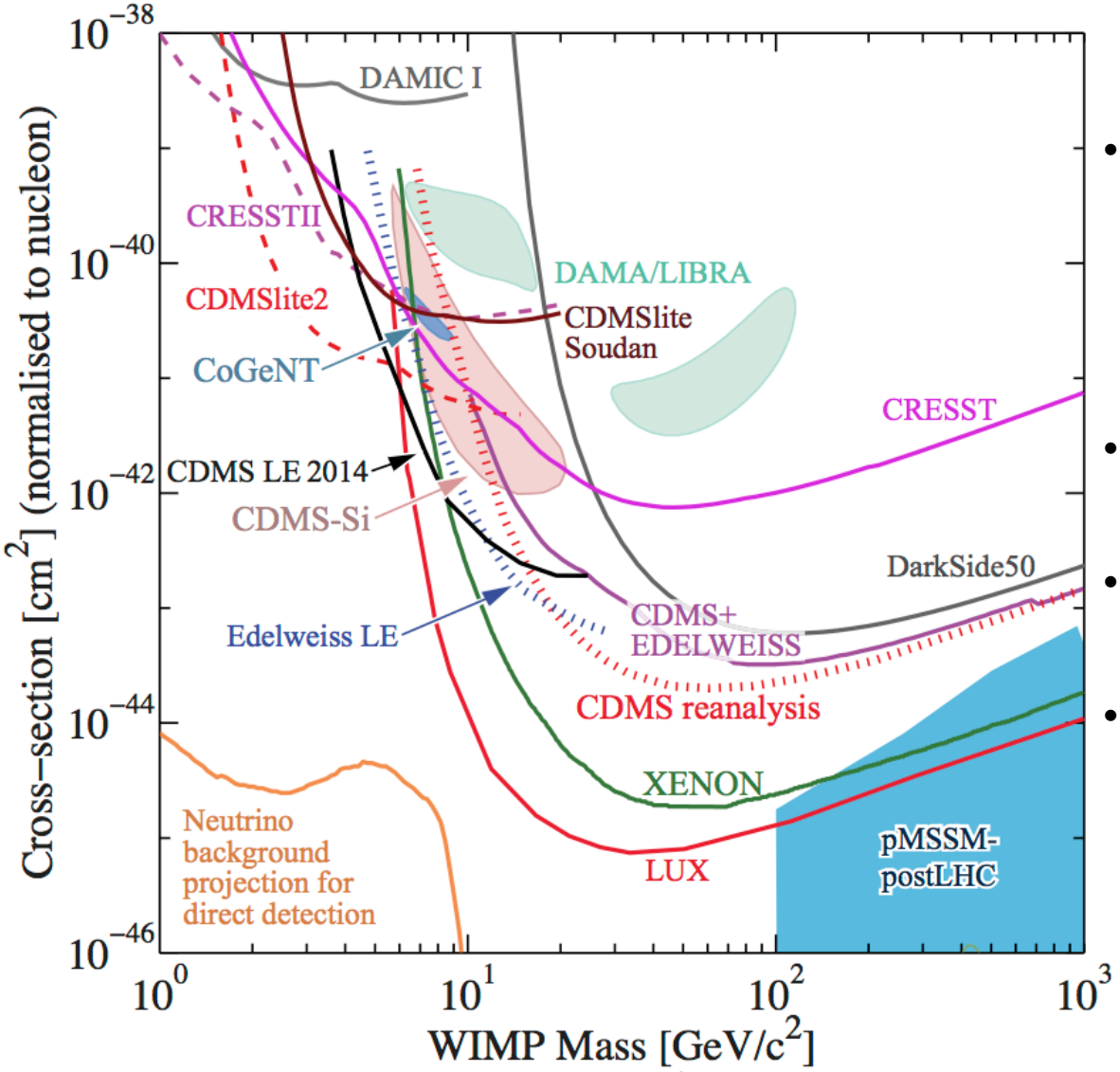
DAMA/LIBRA – 9σ signal – Dark Matter?



- 13 annual cycles
- Amplitude: 0.0112(12) cpd/kg/keV
- Phase: 144(7) days vs expected 152.5 days
- Signal observed in cuts between E_{ee} = 2-6 keV



Limits on WIMP mass/cross-section



Spin-independent WIMP cross sections (normalised to a single nucleon).
C. Patrignani *et al.* [PDG], Chinese Physics C 40 (2016) 100001.

Tension between DAMA/LIBRA and other results… Why?

- Modulation from other seasonal causes?
  – Radon, temperature, pressure, muons, etc, etc, have all been investigated – signal persists.
- Uncertainty in quenching for low energy nuclear recoils?
- DM signal in DAMA near a known 3 keV background from ^{40}K.
- DAMA is (was) unique as the most sensitive NaI–based DM detector – despite extensive investigation of backgrounds, seasonal variations are hard to rule out.

SABRE is a new approach using NaI(Tl) that aims to confirm or refute the DAMA signal.

SABRE – Collaboration

- Collaboration: 11 Institutions from **Italy, US, UK and Australia**

- Princeton University
- Lawrence Livermore National Laboratory (LLNL)
- Pacific Northwest National Laboratory (PNNL)

- Imperial College London

- INFN - Laboratori Nazionali del Gran Sasso
- Sapienza Università di Roma & INFN
- Università degli Studi di Milano & INFN

- Australian National University
- University of Adelaide
- University of Melbourne
- Swinburne University of Technology

SABRE: Sodium iodide with Active Background REjection

Plans and Strategies to Confirm/Refute DAMA Signal

Control seasonality

- Northern/Southern hemisphere detectors – Seasonal backgrounds out of phase, DM signal in phase.
- Gran Sasso and Stawell Underground Physics Laboratory (SUPL).
- SUPL hopes to be the first deep underground lab in the southern hemisphere (c.f. plans for ANDES Lab; South pole (DM-ICE) is not a general purpose lab)

Improved backgrounds via both active and passive approaches

- Active scintillator veto surrounding NaI(Tl) to reduce internal and external background
- NaI(Tl) crystals with higher purity than DAMA
- Low radioactivity enclosures and PMTs

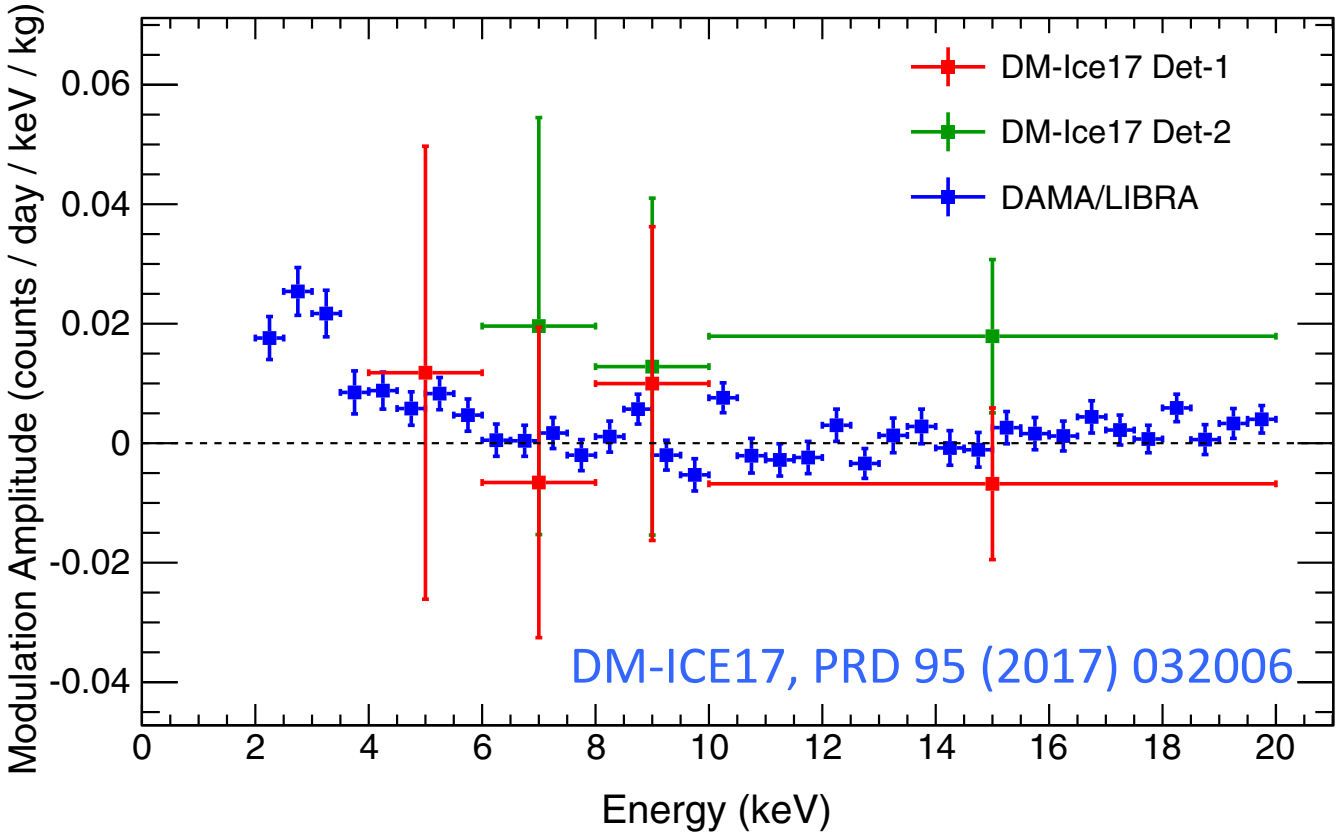
Lower WIMP energy threshold

- High QE PMTs directly coupled to NaI(Tl) crystals
- Fully digital DAQ with PSD based data analysis to give improved backgrounds.
- Clarify conflicting quenching factor measurements that don't affect experimental E_{ee} threshold, but do impact E_{NR} and the implied WIMP energies.

Testing DAMA and confronting seasonal backgrounds

Other NaI-based DM detectors can test DAMA, but possibly the best test is to use similar detectors in both the northern and southern hemispheres.

Northern Detectors: ANAIS, PICO-LON, KIMS-NaI/COSINE, SABRE NORTH
Southern Detectors: DM-ICE, SABRE SOUTH



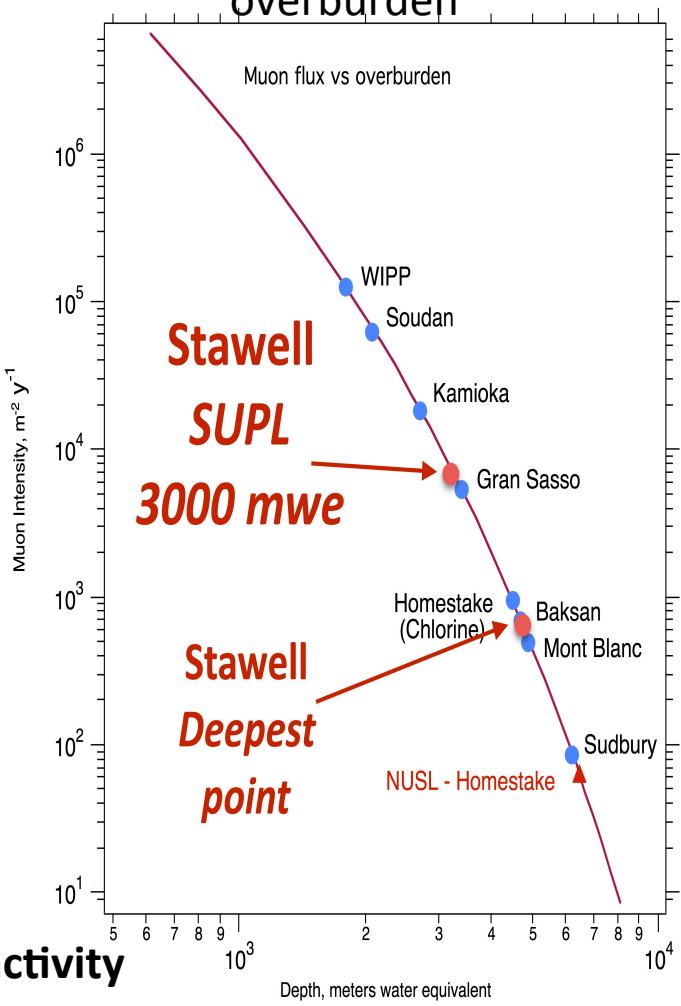
DM-ICE17 (17kg of NaI at the south pole) has published results.

Not yet at sensitivity to test the DAMA result.

Only SABRE plans to operate essentially equivalent detectors in both hemispheres.

SUPL – Stawell Underground Physics Laboratory

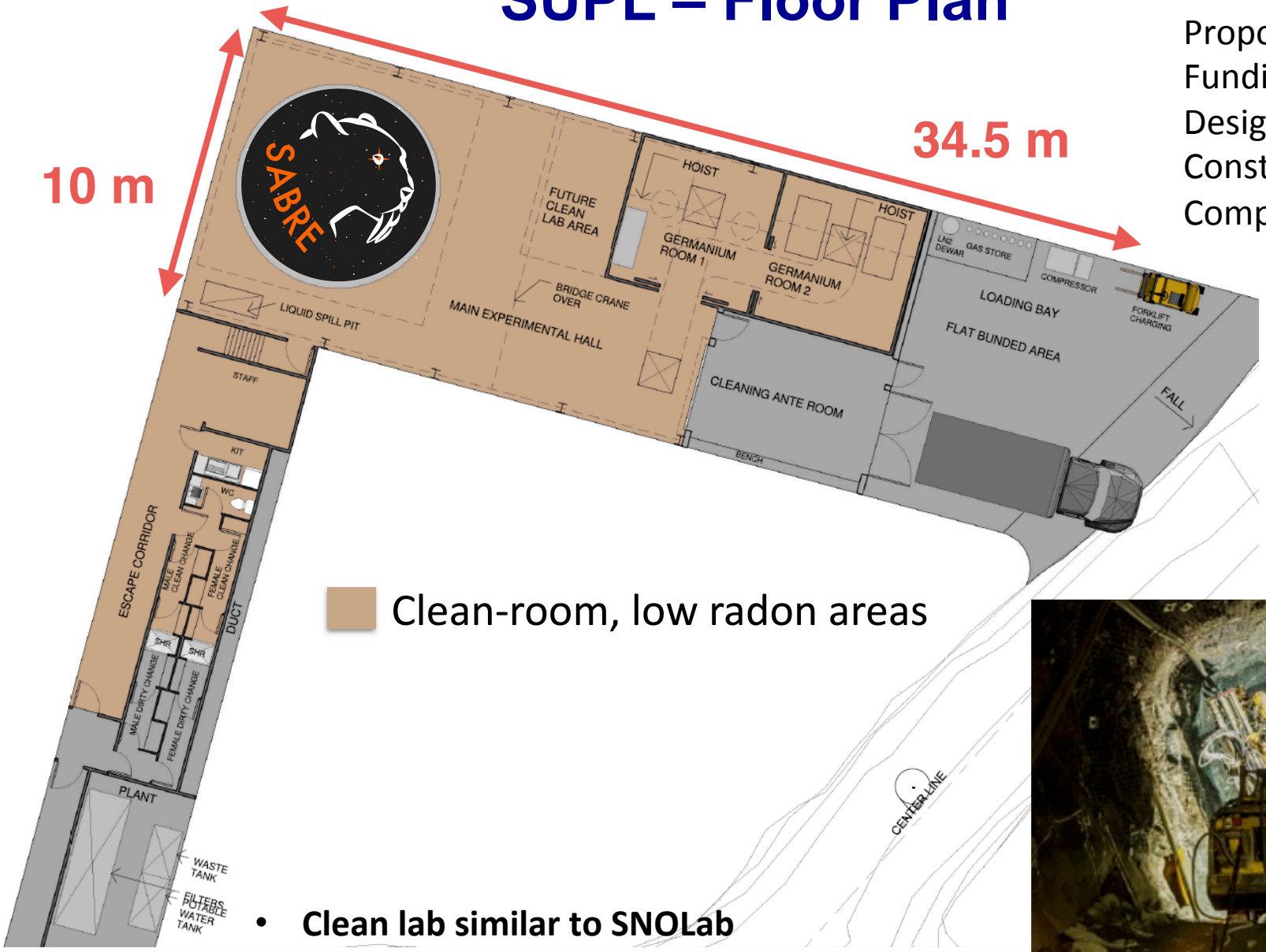
Gold mine with decline construction, accessible by car/truck, basalt rock, flat overburden



Effective depth and environmental radioactivity broadly comparable to Gran Sasso

SUPL – Floor Plan

Proposed: Sep 2014
Funding: May 2015
Design: 2016/2017
Construction: 2017
Completion: 2018



Clean-room, low radon areas

- **Clean lab similar to SNOLab**
- **Designed to have Rn activity < 100 Bq/m^3**

SABRE: Sodium iodide with Active Background REjection

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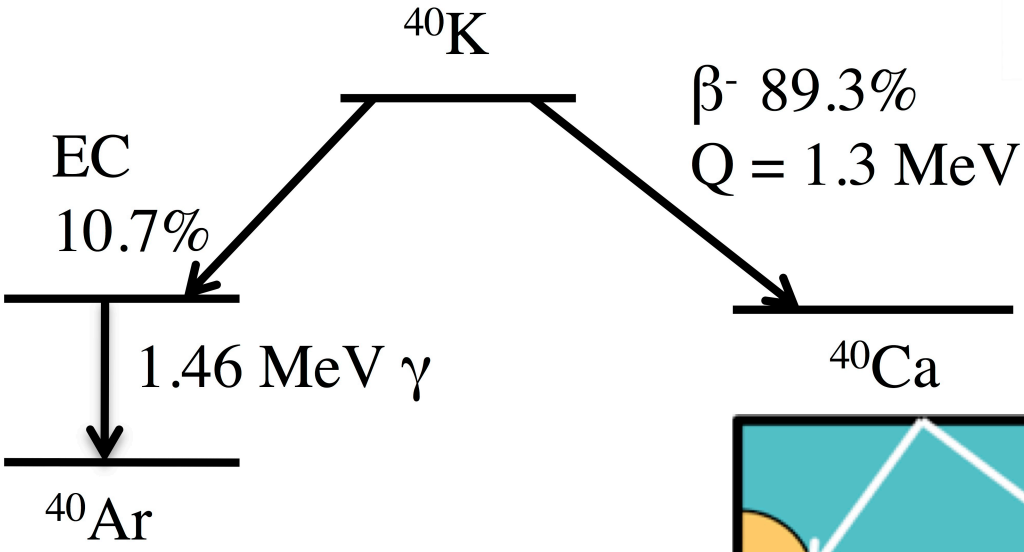
SABRE – Active Background Rejection

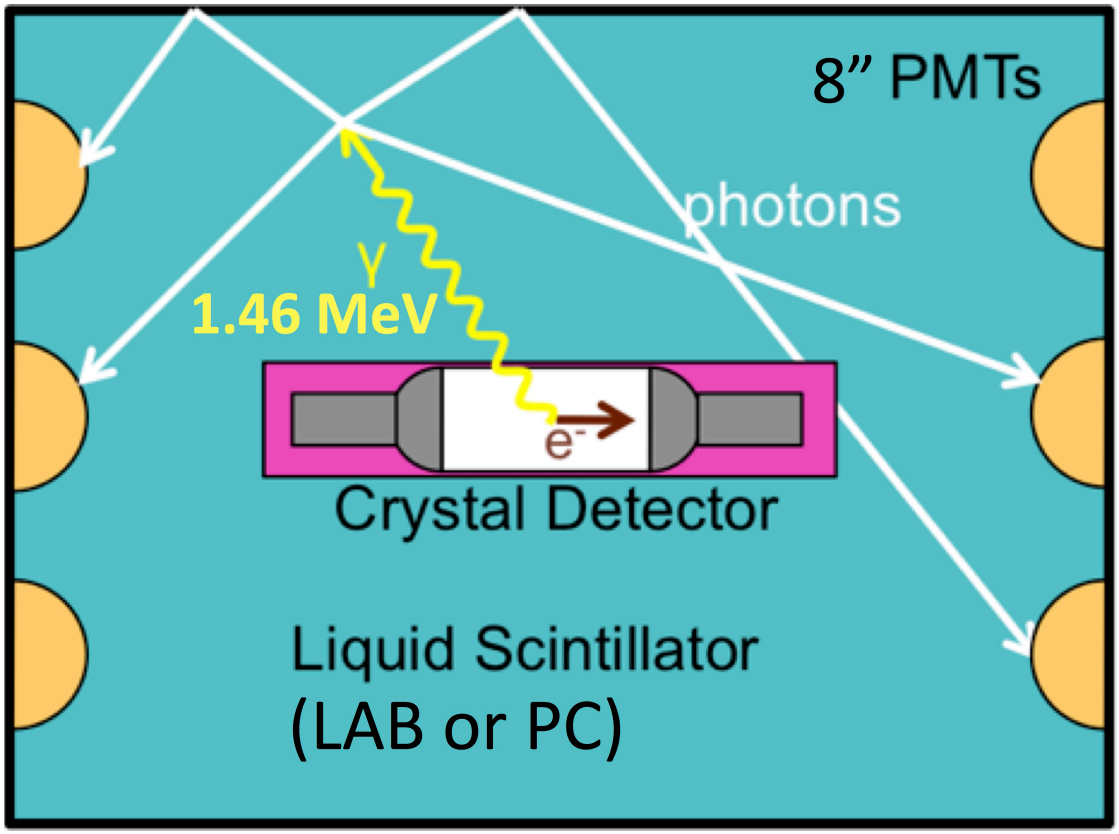


EC leaves hole in K-shell, giving 3 keV Auger electron

Dominant background in DAMA and lies in the DM signal region

Liquid scintillator to veto 3 keV Auger in crystal by coincidence with Eγ=1.46 MeV.

Can also veto external, incoming radiation



SABRE – Passive background removal

High-purity NaI Powder

- Developed at Princeton with Sigma-Aldrich and Seastar
- ICP mass spectroscopy by Seastar and PNNL
- Accelerator Mass Spectrometry (AMS) for ultra-sensitive measurements at Australian National University (ANU)

High Purity Crystals

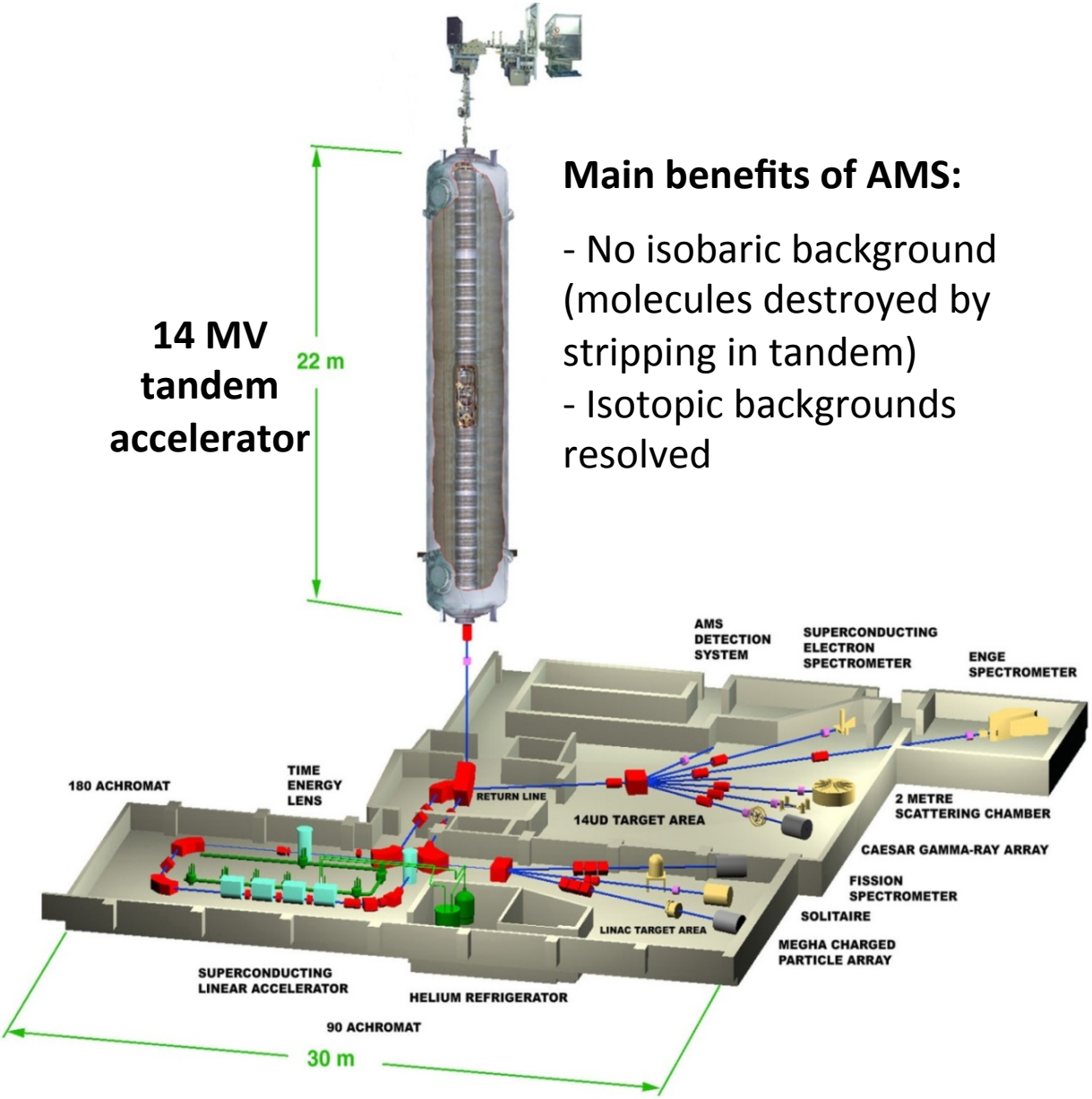
- Crystal growth (Princeton in collaboration with RMD, Radiation Monitoring Devices)
- 2kg, high-purity with 88mm diam achieved
- Good scintillation properties
- <K> ~9 ppb and still improving (DAMA ~ 13 ppb)
- <Rb> < 0.1 ppb (DAMA < 0.35ppb)

Actual Detector Crystals

- Require 5kg
- Full-scale crystal for proof of principle test at Gran Sasso is in production.

High-purity, 2kg test crystal

Accelerator Mass Spectrometry (AMS) at ANU



Main benefits of AMS:

- No isobaric background (molecules destroyed by stripping in tandem)
- Isotopic backgrounds resolved

- Measure contaminant radionuclide isotope ratios through atom counting
- **Ultrasensitive**
- Unstable/stable atom ratio sensitivity of 10^{-12} – 10^{-17}
  - Requires sample-dependent chemistry

- Pacific Northwest National Laboratory (USA) performs high performance ICPMS (Inductively Coupled Plasma Mass Spectrometry).
  - Broader application but can have less sensitivity.

SABRE AMS measurements so far

Limitations:

- Need to be able to dissolve sample and extract the element of interest.
- Measures atom ratios – isotopic spike may be needed to convert to an absolute yield.

Application 1: ^{129}I, $T_{1/2}$=15.7 Myr, produced through activation.

- Q(β)=189 keV ➔ produces low energy β- and a 40 keV γ.
- Sensitivity of ^{129}I/I < 10^{-14} has been demonstrated ➔ 56 μBq/kg of NaI.
- ^{129}I/I measured in growth- and astro-grade NaI powder: 2.0(1)x10^{-13} (c.f. DAMA value of 1.7x10^{-13} inferred from ^{129}I decay in their crystals).

Application 2: ^{210}Pb, $T_{1/2}$=22.2 yr, environmental contamination, important background

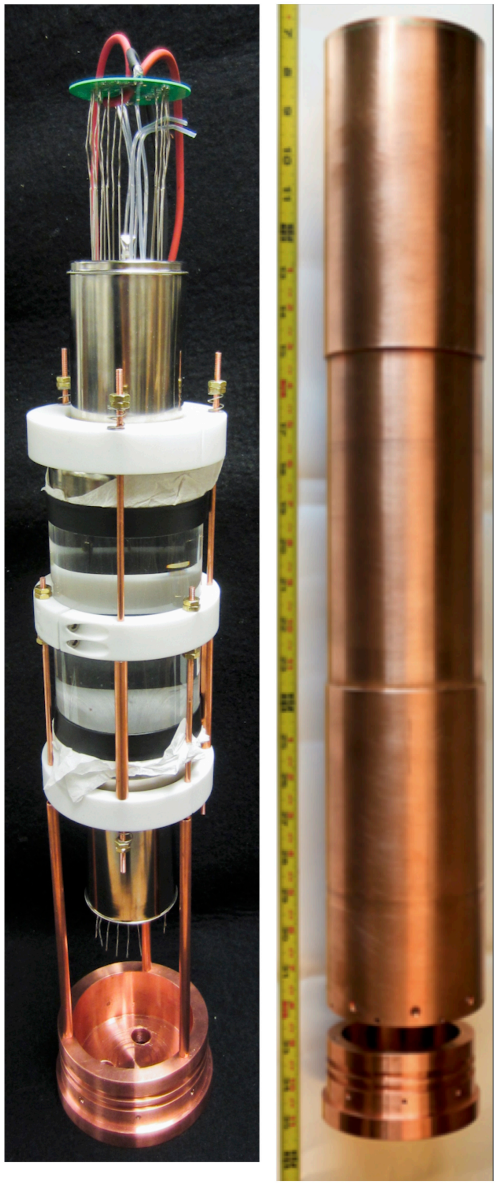
- Pure Pb samples have demonstrated ^{210}Pb/Pb ratios of 10^{-14}
  - ➢ Measurement sensitivity of 1 mBq/kg under ideal conditions.
- However, efficiency/purity of the chemical extraction of Pb also matters…
- A single test measurement for **^{210}Pb in NaI** has been made:
  - Much of the extracted material was not Pb, diluting the beam current
  - ~100 mBq/kg sensitivity achieved under these very unfavourable conditions.
- Significant improvements will be possible, but the ultimate sensitivity is not yet clear.

Other applications?

Encapsulation and PMTs

Hamamatsu R11065-20 3-inch PMTs with direct optical coupling to crystals

- QE 35% (c.f. 12% in DAMA/LIBRA)
- Low radioactivity per PMT
  - ~3 mBq U, ~0.5 mBq Th/Co and ~2 mBq K
- New PMT stem: Ceramic feedthroughs with ultra-high purity alumina
- Packaged in air- and light-tight, low-radioactivity, ultra-pure copper.



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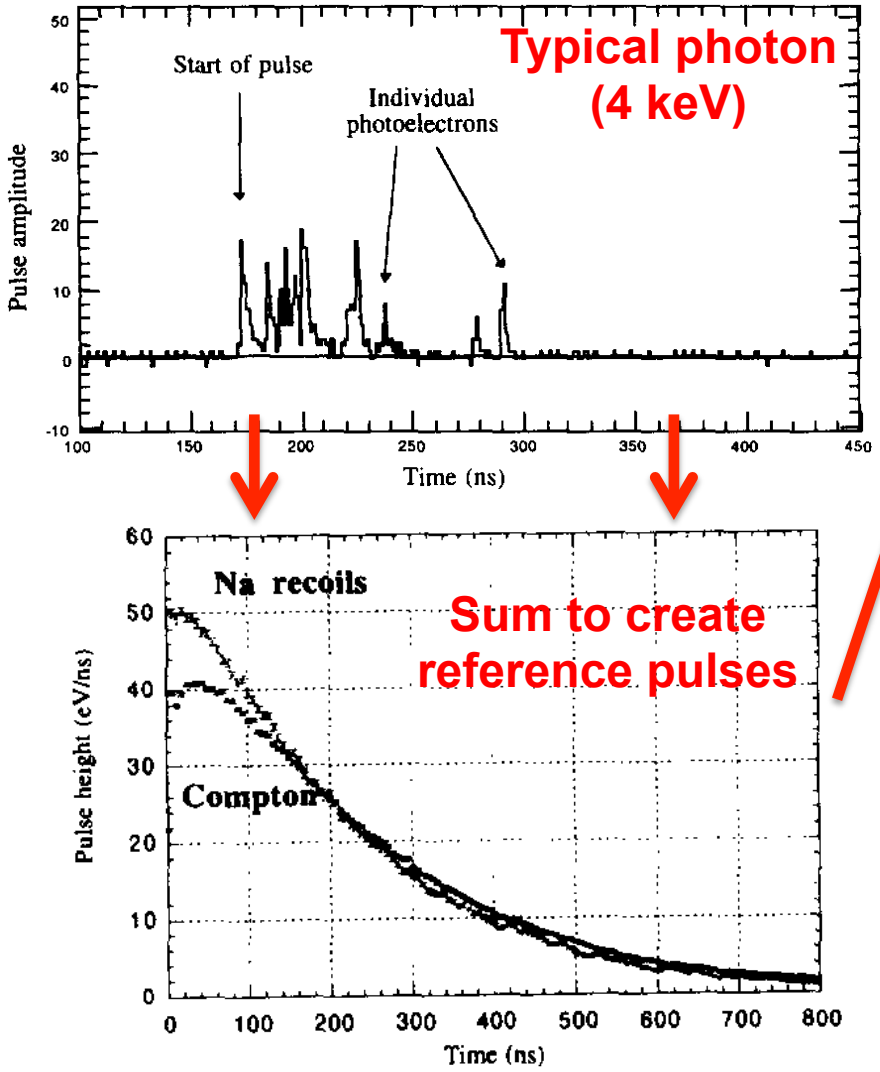
Pulse Shape Discrimination

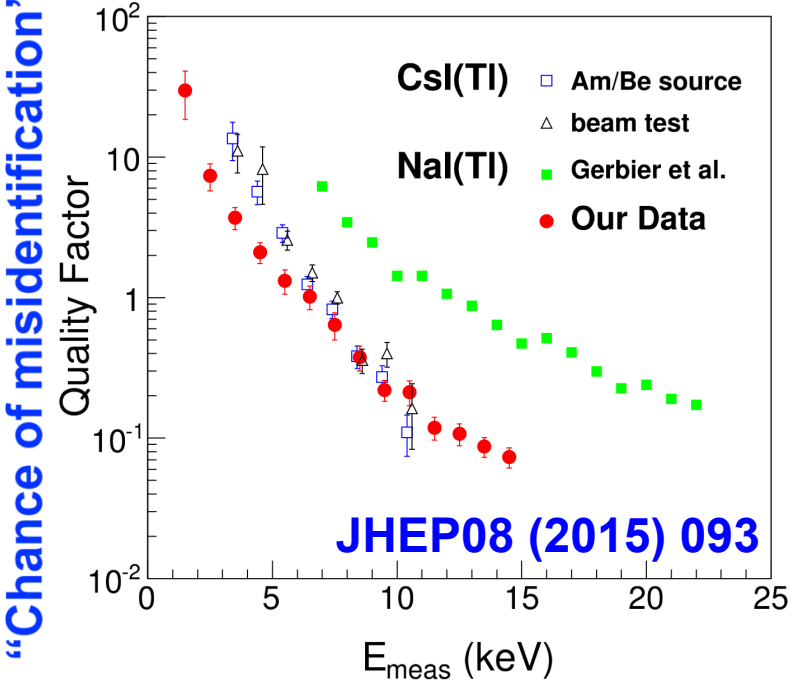
PSD in NaI for LSM, Gerbier et al AP 11 (1997) 287



Time behaviour of signal provides NR/e$^-$ discrimination (see also, e.g. NAIAD, AP 19 (2003) 691).

No PSD used in DAMA. PSD planned for SABRE.

PSD also in other new NaI expts, e.g. KIMS-NaI/COSINE (below).

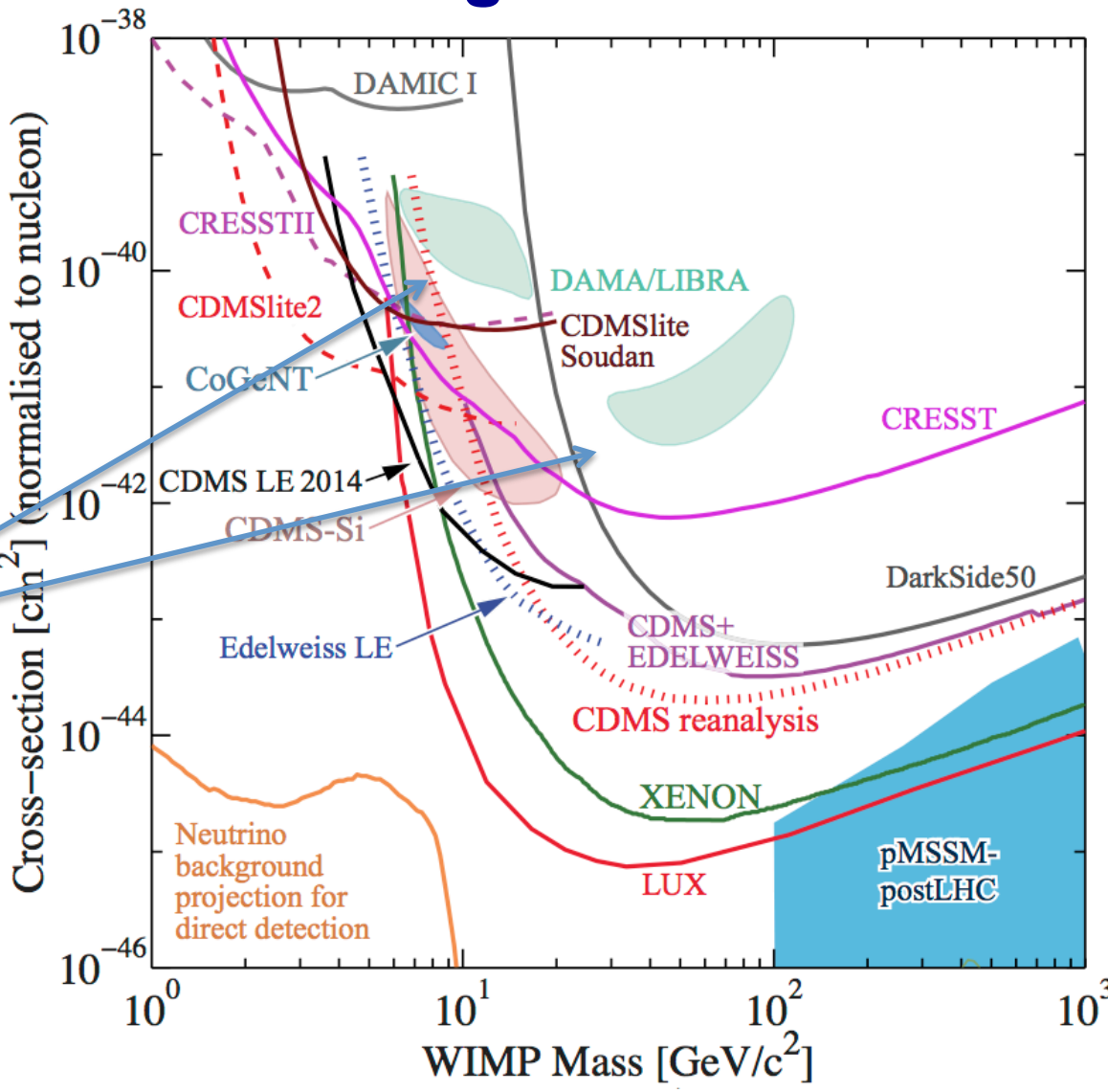


Importance of Quenching Factor

Only part of the nuclear recoil energy, E_{nr}, is transferred to electrons, $E_{ee}=Q\,E_{nr}$
(Q is poorly determined)

Position in exclusion plot depends on whether interaction is assumed to be with Na or I nuclei.

Also depends on values used for Q.



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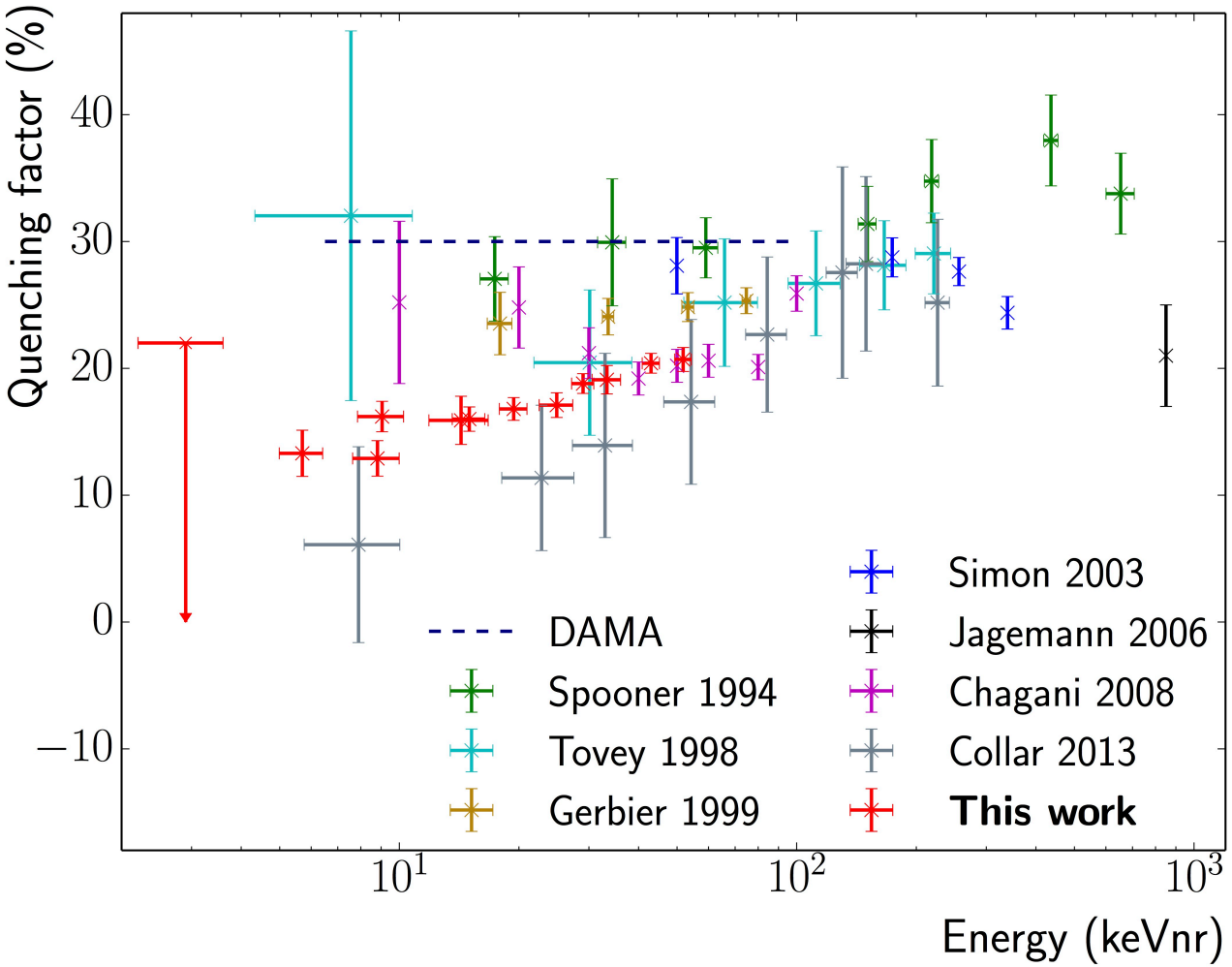
Measurements of the Quenching Factor



DAMA used constant Q=0.3 for Na scattering.

Q is definitely lower and energy dependent, see Xu et al (2015, red data points)

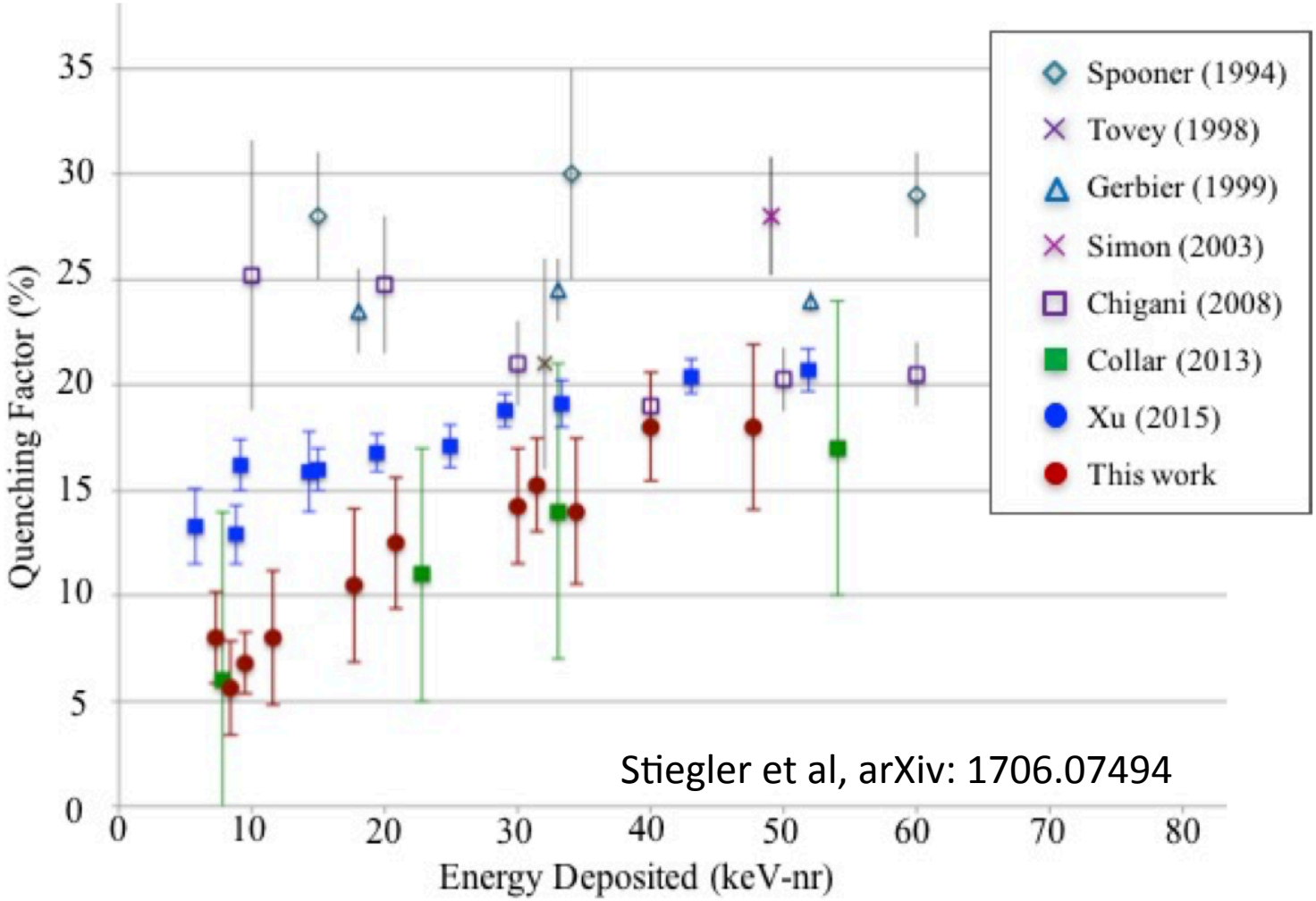
Multiple papers have looked at how changes in Q affect the WIMP exclusion plots.

Have we reached a level of confidence in the energy dependent quenching?

J. Xu et al, Phys. Rev. C 92, 015807 (2015)

Pulsed neutron beam via ^{7}Li(p,n). Q from scattering neutrons in NaI(Tl), kinematics, E and TOF.

Measurements of the Quenching Factor



Maybe not…

Very recent paper gives values lower than the 2015 results.

Crystal dependence?

New ANU measurements are planned:

Better beam pulsing (1ns pulse width). Lower energy threshold. Multiple crystals.

SABRE: Sodium iodide with Active Background REjection

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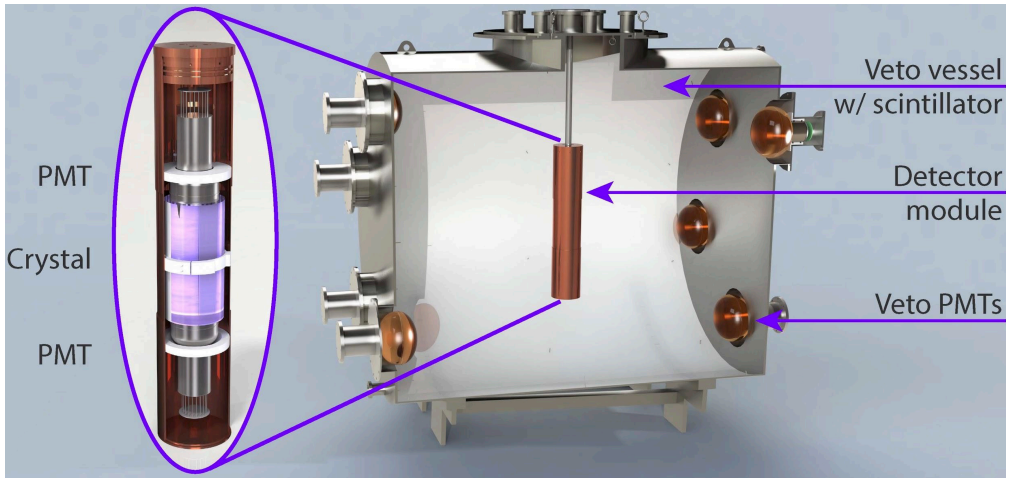
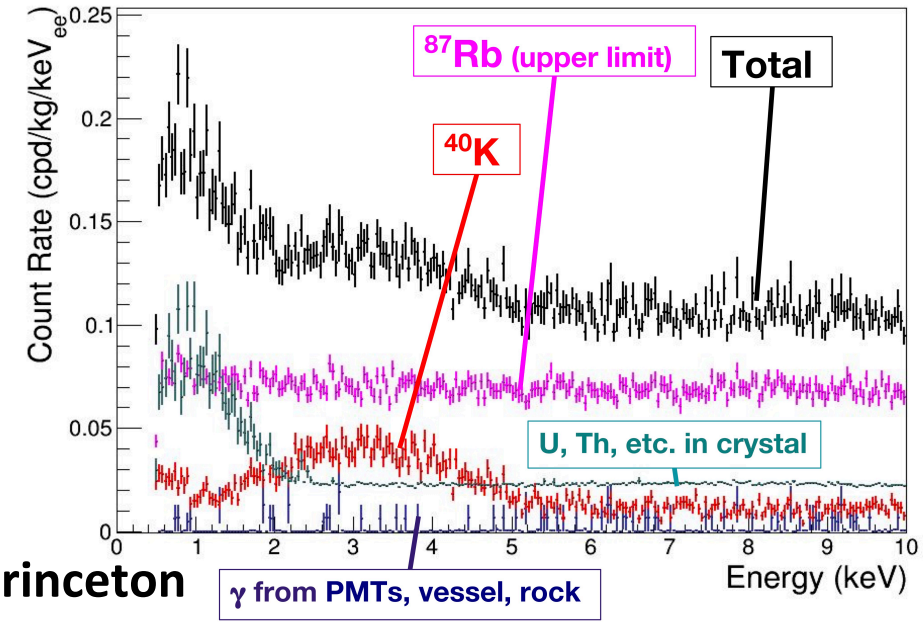
WHAT EXACTLY IS SABRE AND HOW WILL IT PERFORM?

SABRE Proof of Principle – Expected Performance

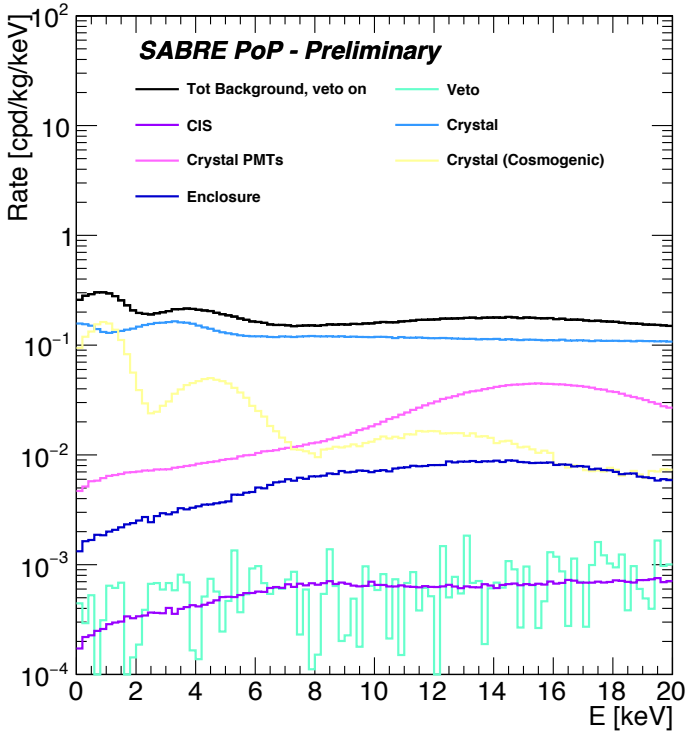


Proof of principle (PoP) at LNGS: 5-kg NaI(Tl) and a 1.4x1.5m veto filled with ~2 ton pseudocumene (PC).

Independent modelling of the background at **Princeton** and at **Rome/Milan/Melbourne**



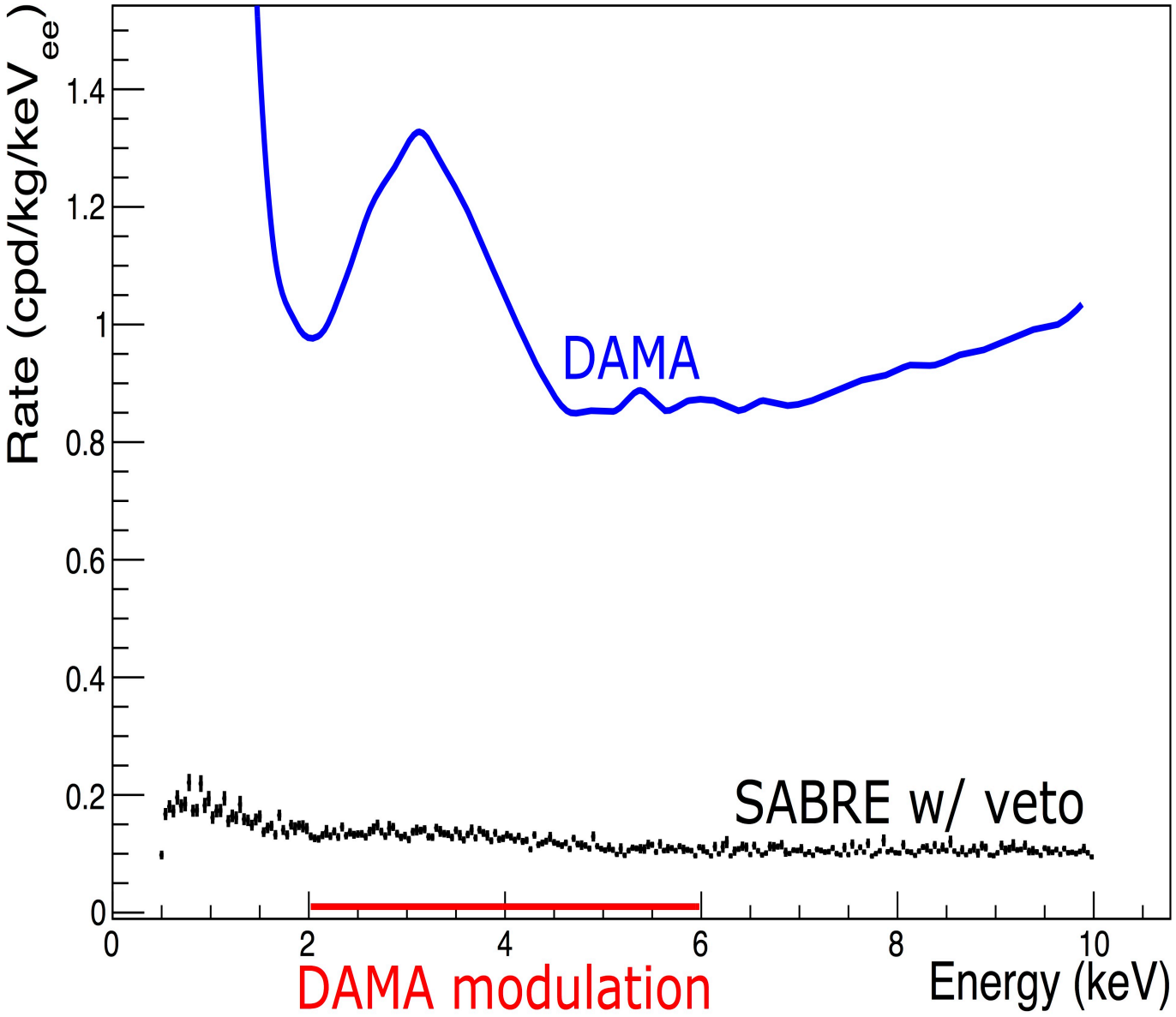
Princeton



Rome/ Milan/ Melb.

Somewhat different assumptions, but essentially excellent agreement

SABRE Performance – Backgrounds



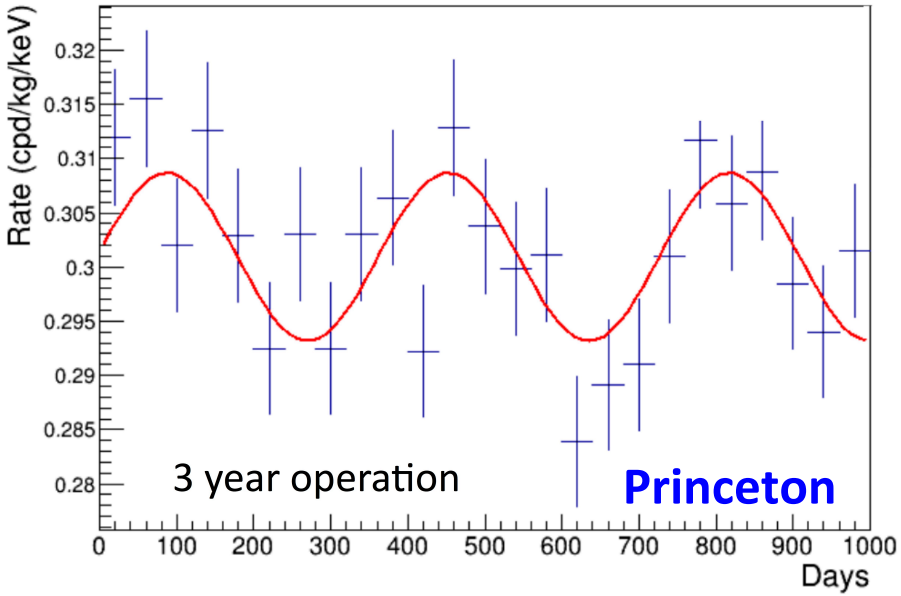
Comparison with measured DAMA response suggests we will have:

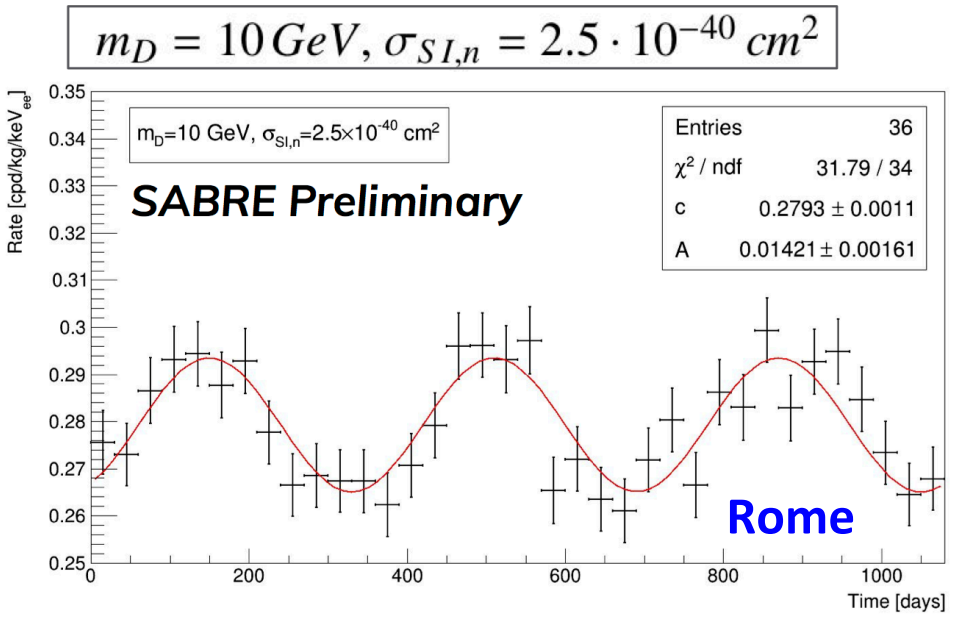
- Increased overall sensitivity
- Lower threshold and hence sensitivity to low-mass WIMPs

SABRE Performance – Expected modulation signals

Independent modelling of the expected modulation signals.
Each based on the respective background modelling and a standard galactic halo.

Both based on 50 kg of NaI(Tl) in the PoP vessel





- Good agreement.
- 3 year measurement should give either a 6σ refutation or a 4σ verification.
- SABRE North and South can be combined if the signal is DM related and not a seasonal background.

SABRE PoP – Status

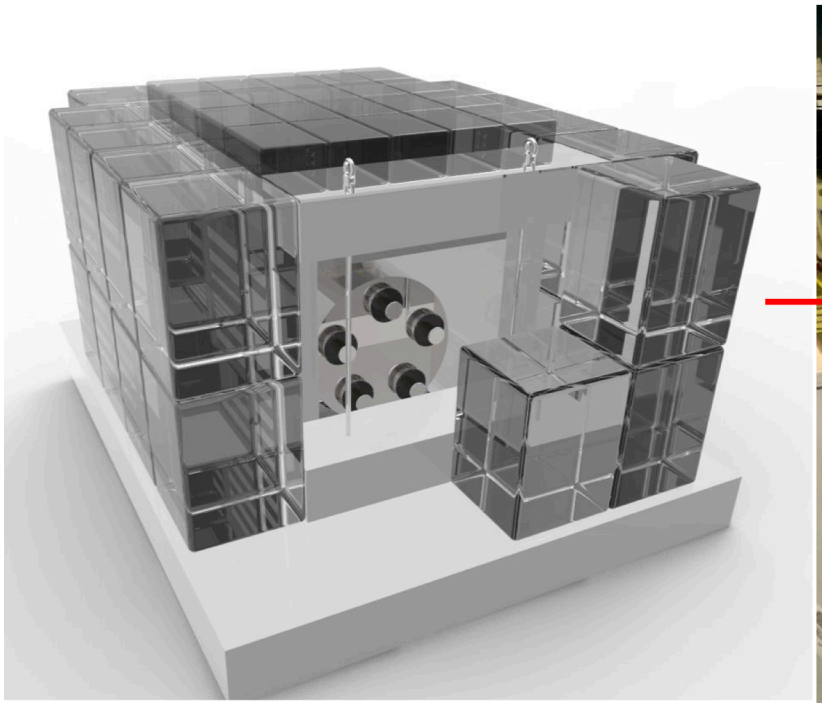
PoP vessel arrived at LNGS in Nov 2016

Temporary location in Hall B is being used for preliminary (ongoing) tests:

- PMTs, DAQ, Trigger logic, water run, etc,

High-purity, full-size crystal currently being prepared at Princeton and RMD. Hope to have at LNGS within next few months.

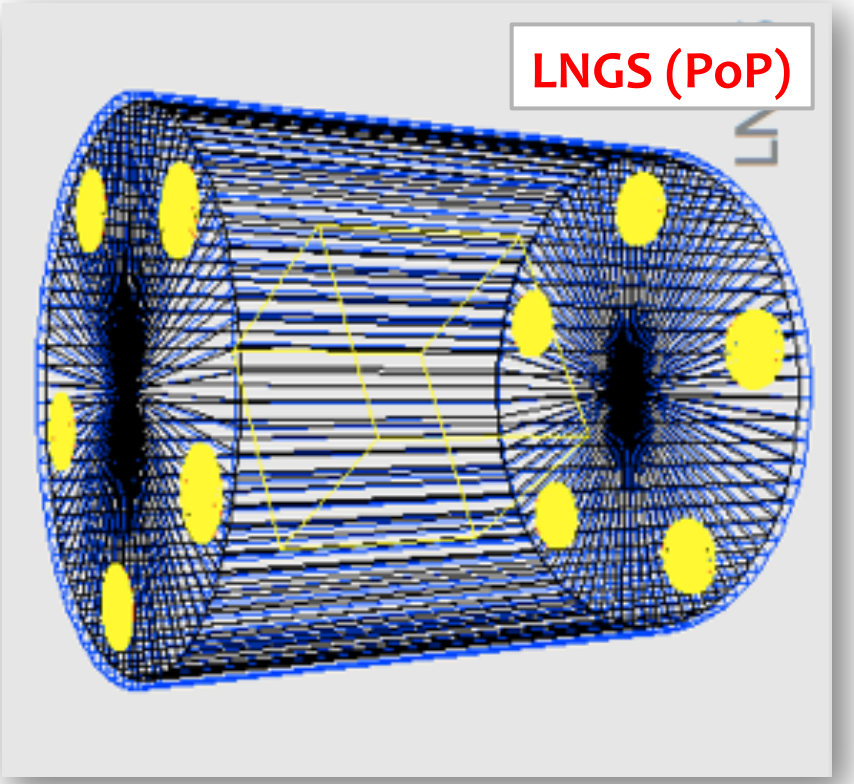
SABRE PoP – Permanent home

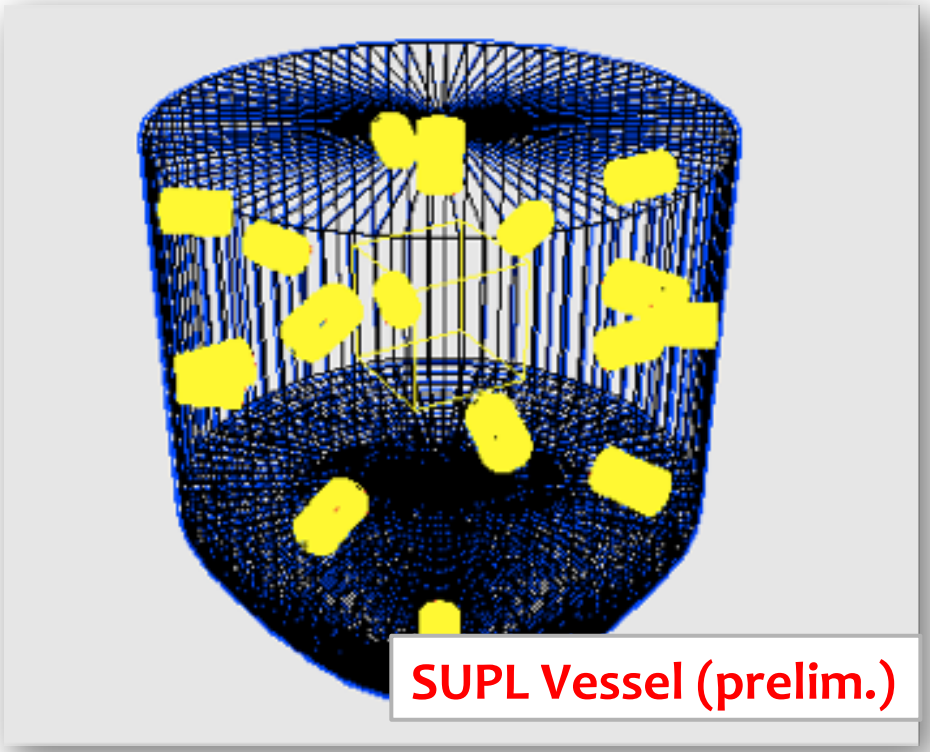


Hall C at LNGS

- Refurbishment completed and floor prepared.
- Installation of water, polyethylene and lead shielding is underway.
- Move of PoP vessel, insertion of high-purity crystal, and commissioning/initial data collection by the end of 2017.

Full SABRE – Status and activities





- SABRE North will proceed at LNGS after successful operation of the PoP.
- SABRE South is moving straight to a full detector.
  - Australian mine regulations prevent use of PC. Will instead use linear alkyl benzene (LAB) for the veto.
  - Different vessel design, modelling is ongoing, talking to suppliers.
  - Measurement of backgrounds in mine is ongoing.

SABRE – Summary and the future

DAMA/LIBRA DM Signal

- DAMA's long-standing and statistically significant signal is in considerable tension with other DM measurements – warrants testing and explanation.
- Conclusive test from twin detectors in both north and south hemispheres.

Stawell Underground Physics Laboratory

- Plan to be the first deep underground lab in the southern hemisphere
- Environmental, shielding and radioactivity characteristics broadly comparable to Gran Sasso
- Design completed – construction negotiations are underway. Hope for completion in 2018

SABRE

- We believe we have the highest-purity NaI(Tl) crystals ever made.
- Twin detectors with these crystals and active veto systems to be sited in both Gran Sasso (Italy) and Stawell (Australia).
- SABRE PoP to be deployed in Gran Sasso in 2017.
- Full experiments to be installed in 2018/2019 – both SUPL and LNGS.
- 3 years of operation for a definitive test of the DAMA/LIBRA DM signal.

Acknowledgments:
SABRE Collaboration

Industrial Partners:
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