Direct Detection of Dark Matter

Frank Calaprice

Dark Matter
Direct Detection Experiments

- The 2009 Report of the HEPAP Particle Astrophysics Assessment Group (PASAG) recommended for the next decade.
  - "2 to 3 second generation (G2) detectors covering major technologies (CDMS and cryogenic liquids) starting construction in 2013, with sensitivity of 10^{-46} cm^2"
  - "2 third generation (G3) detectors with independent targets starting construction in 2017, with sensitivity of 10^{-47} cm^2."

- The 2014 Report of Particle Physics Project Prioritization (P5) Panel
  - "Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, *as well as the ability to confirm or refute current anomalous results*."

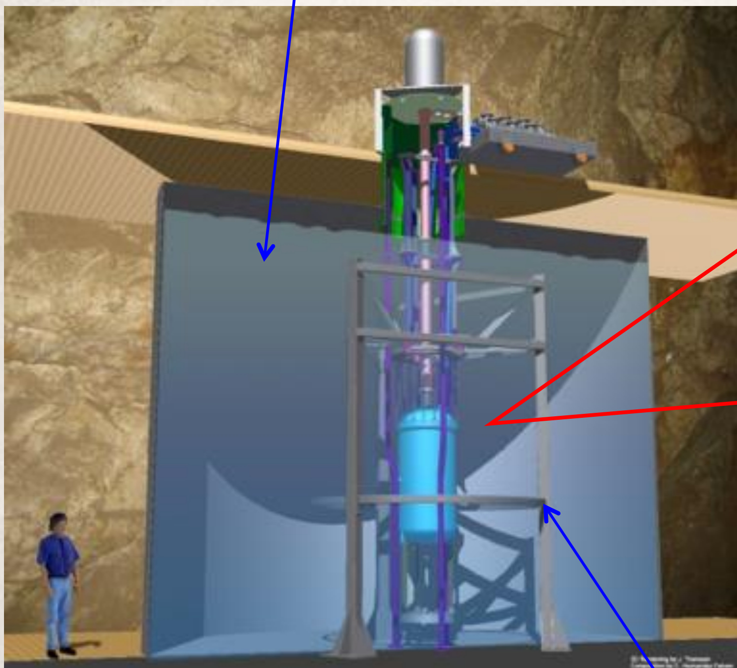
Outline

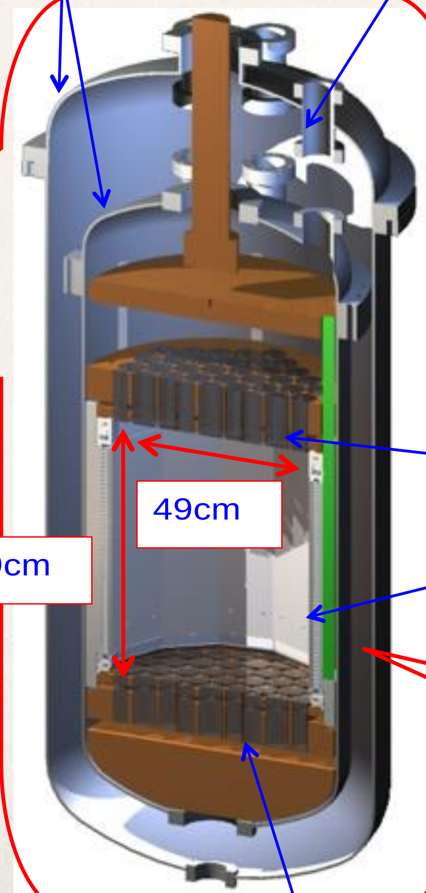
1. Liquid XENON two-phase detectors
   - LUX and LZ
   - XENON-200 and Xenon 1-ton
2. Liquid argon detectors
   - DarkSide 50 and DarkSide 1-ton
   - DEAP 1-ton single phase.
3. Cryogenic crystal detectors
   - CDMS
4. NaI crystal scintillators
   - DAMA/LIBRA anomaly
   - SABRE North and South
5. Summary

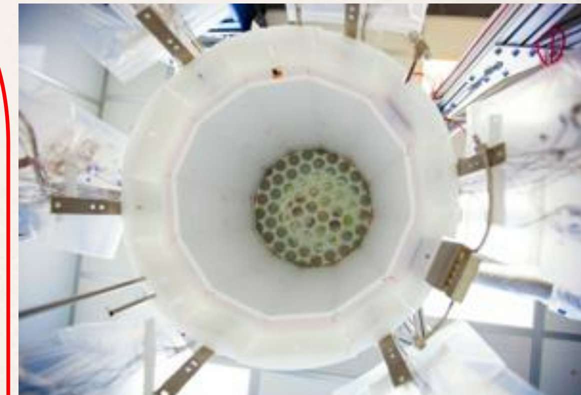
LXe Two-phase TPC Detectors

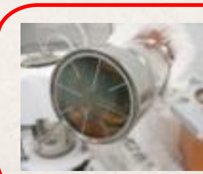
LUX and LZ

Introduction to the LUX Detector









- **370 kg Lxe, 145 kg fiducial (latest)**
- **122 PMTS (QE ~30% @ 175nm**
- **Low radioactivity materials**
- **> 1 kW cooling power from thremosyphons**
- **70,000 gallons of DI water**
- **Rn content <100 mBq/m^3**

Scale Up ≈ 50 in Fiducial Mass

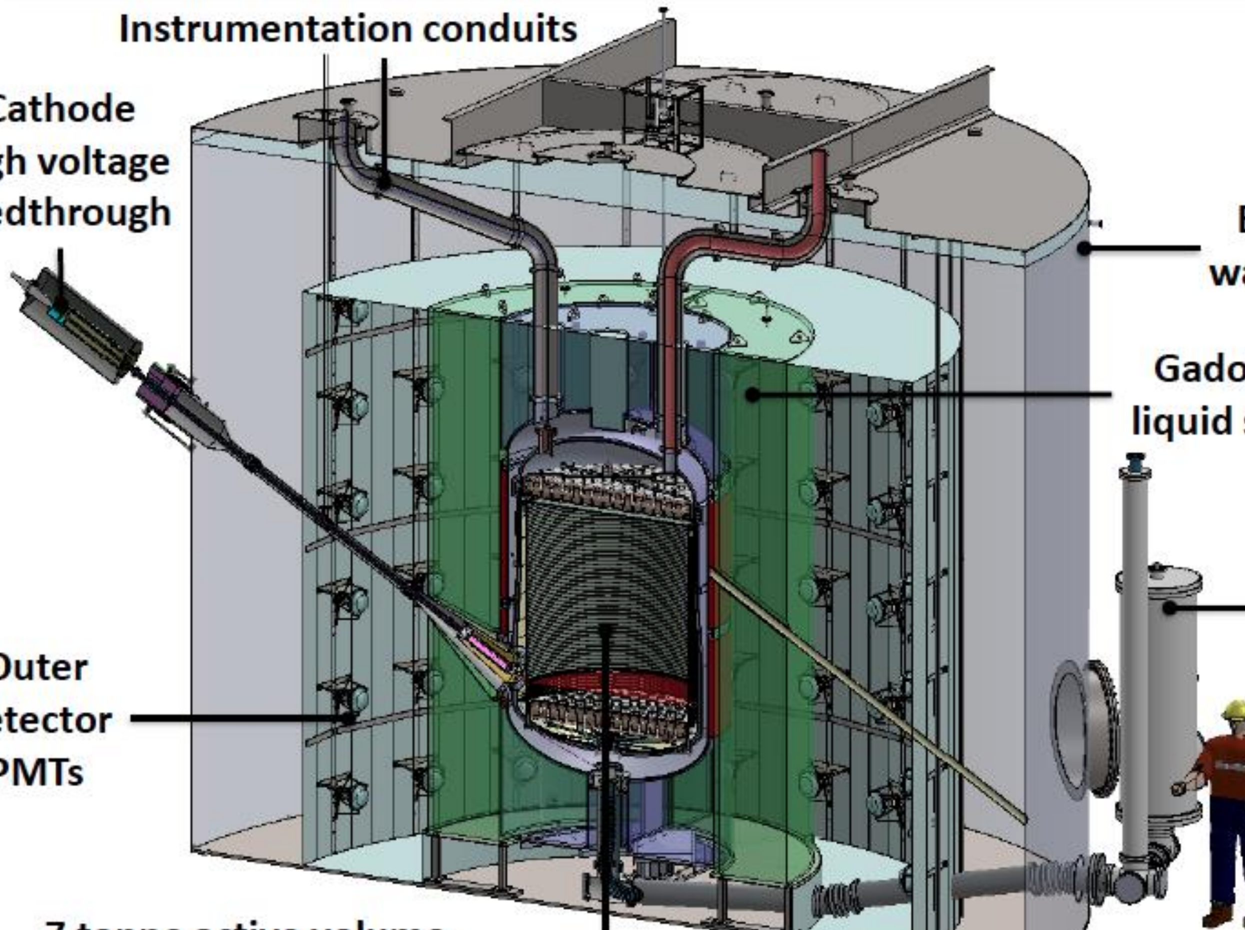
LZ

Total mass – 10 T
WIMP Active Mass – 7 T
WIMP Fiducial Mass – 5.6 T
LZ Surface assembly June 2017
Underground assembly July 2018.
LZ commissioning Feb 2019

LUX

Completed 300 day LUX data
 acquisition– 3x more data.
Achieved new low energy cutoff:
1.1 keVnr, x500 better for 5.6 GeV WIMP
 LUX decommissioning fall 2016.

LZ Detector Overview



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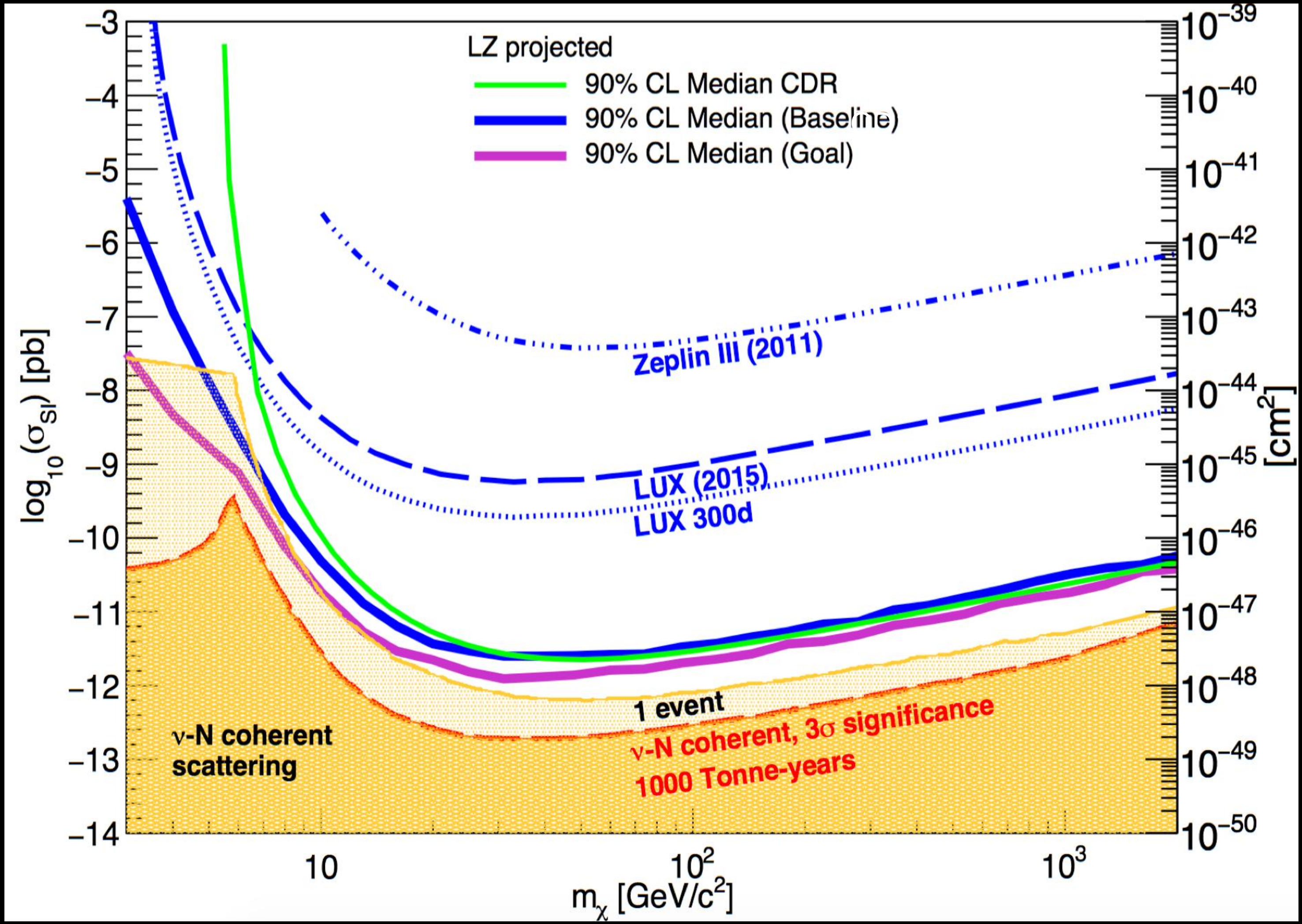
Projected LZ Sensitivity
Spin Independent



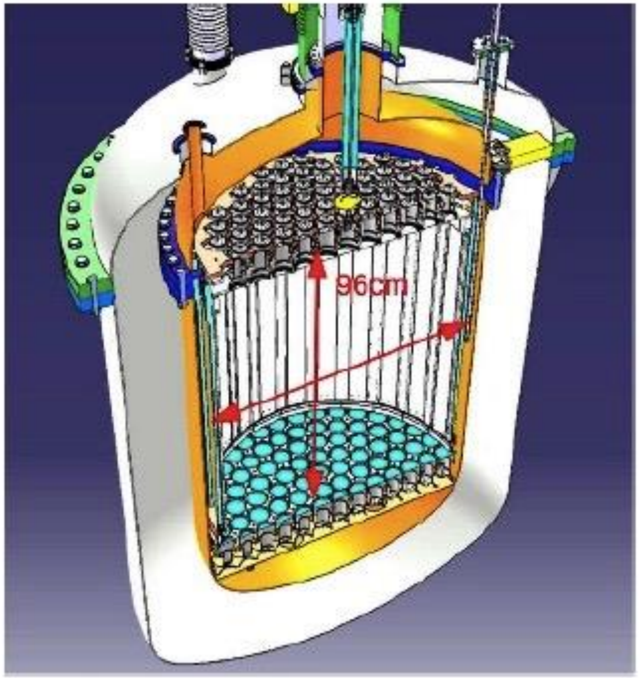
Liquid Xenon Two-Phase TPC

XENON 100 & 1 Ton

XENON1T

- **Science goal:** 100 times more sensitive than XENON100.
- **Target/Detector:** 3.2 tonnes of Xe/ dual-phase TPC readout by 248 PMTs.
- **Shielding:** Water Cherenkov muon veto.
- **Cryogenic Plants:** Xe cooling/ purification/distillation/storage systems designed to handle up to 10 tonne of Xe. Upgrade to a larger detector (XENONnT) planned for 2018
- **Status:** All systems successfully tested. Commissioning of detector ongoing. First science run this Fall.

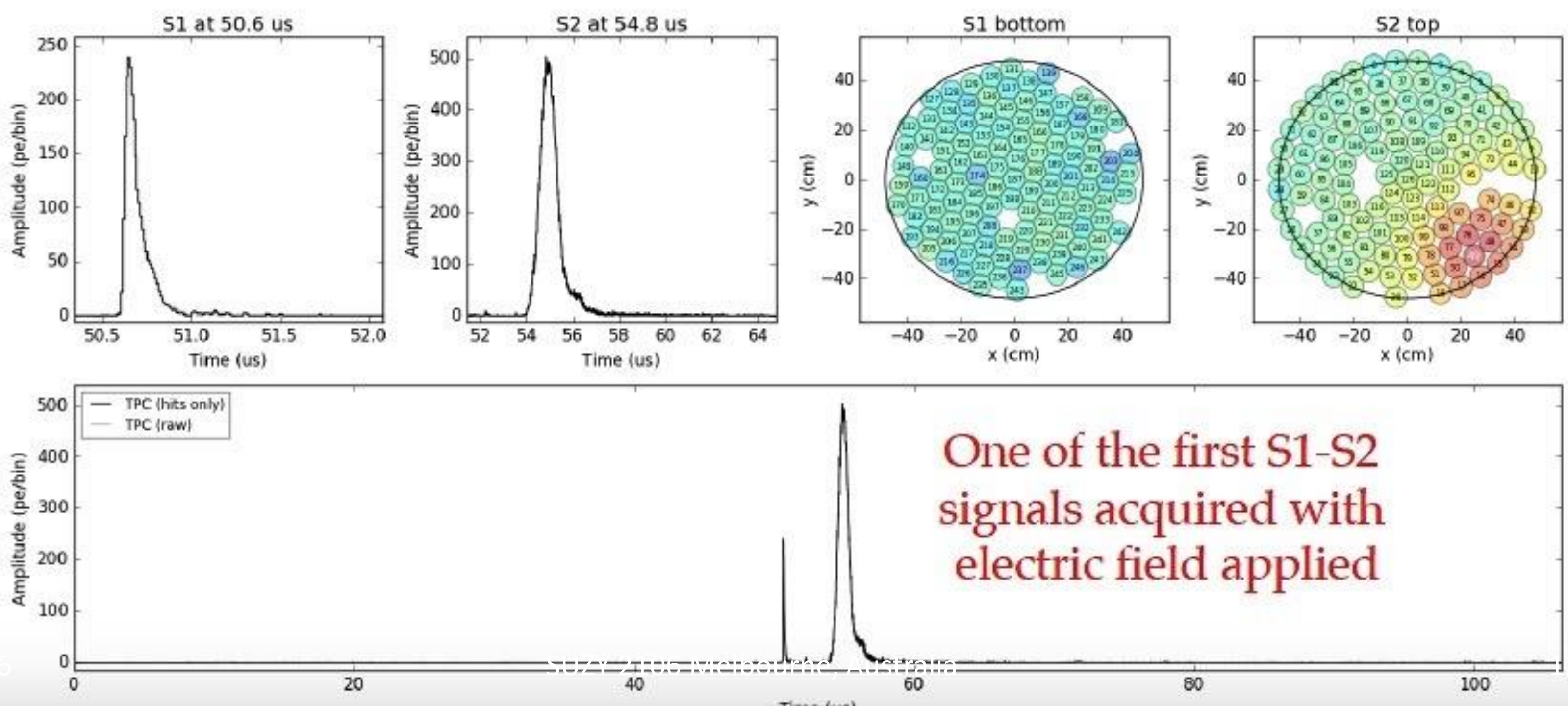
XENON1T TPC



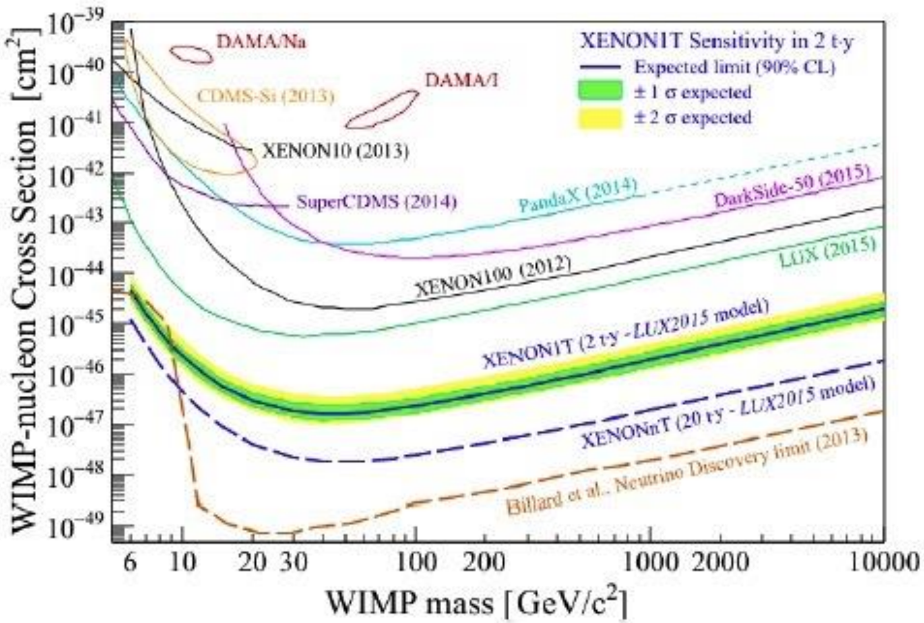
- The XENON1T Time Projection Chamber (TPC) is filled, since April 2016, with 3.2 tonnes of high-purity Xenon.
- 248 low-background 3″photomultipliers (Hamamatsu R11410-21) are reading out the 2-tonne active volume.

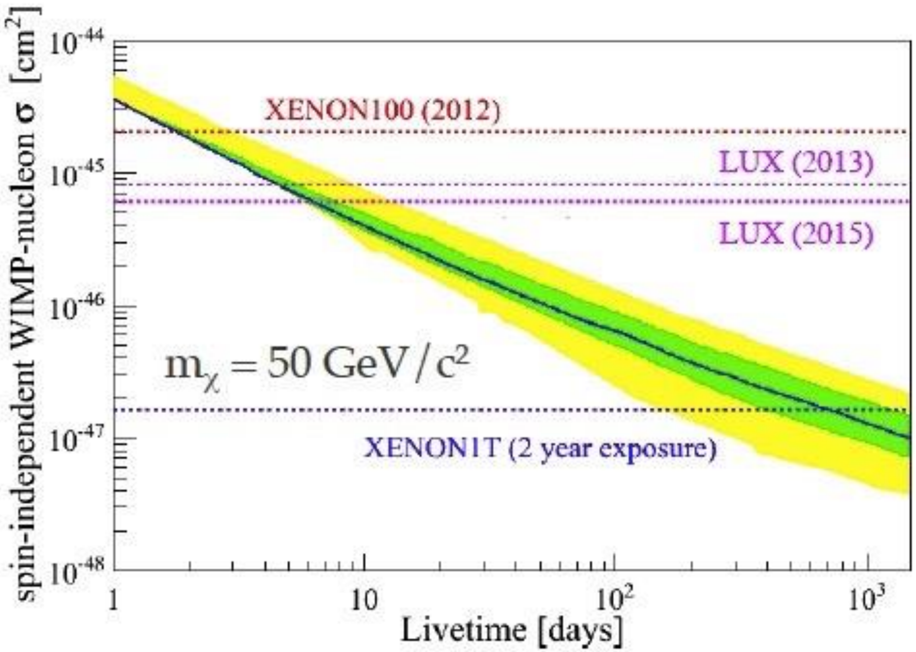
XENON1T TPC COMMISSIONING

- The XENON1T Time Projection Chamber and associated cryogenic system are presently under commissioning.
- Detector is responding to radiation as expected, with both charge and light being detected. The total mass of 3.2 tonnes of LXe is being continuously purified to reach the desired charge yield at the applied field.



XENON1T projected sensitivity



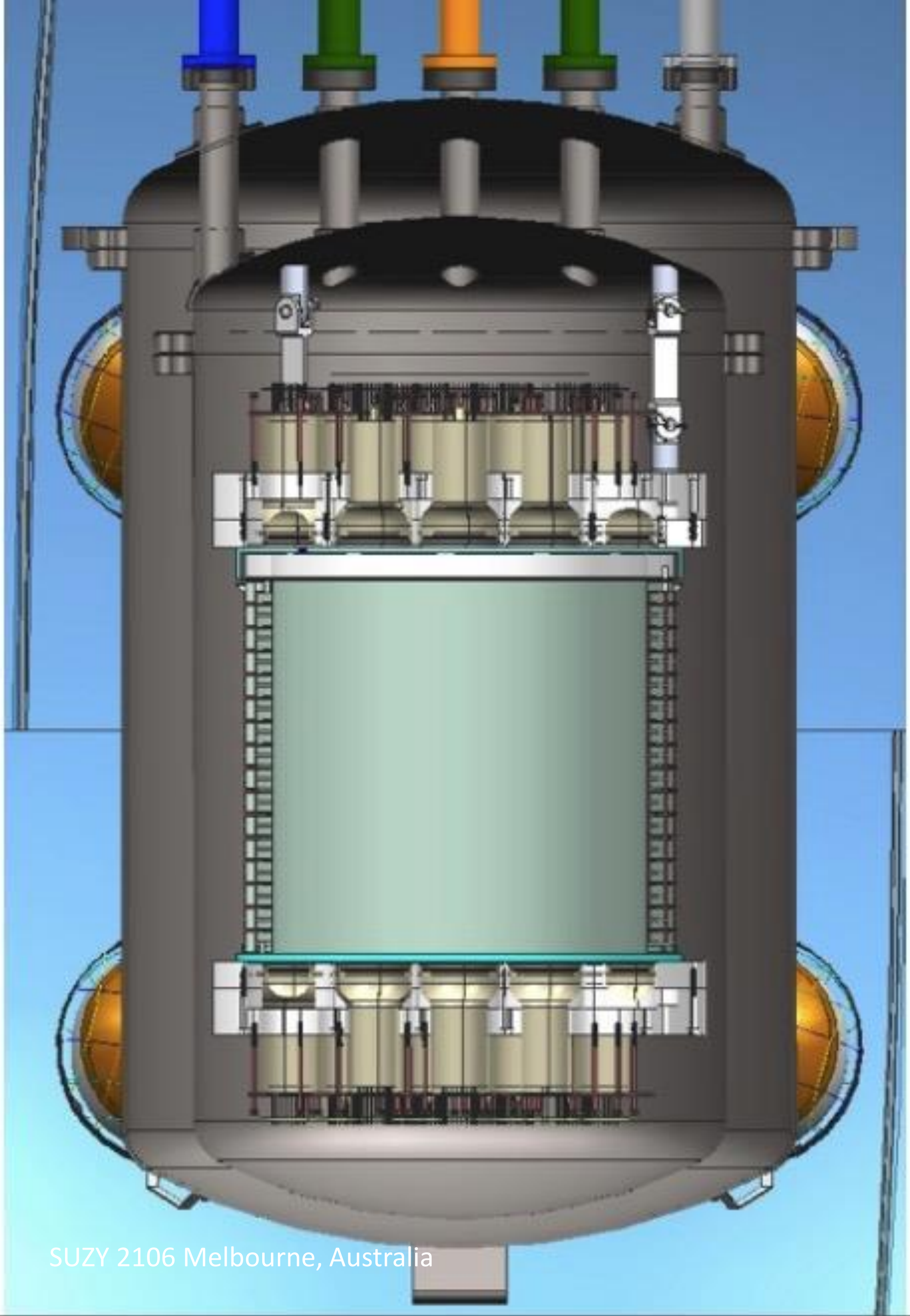


- Expected to reach with a 2 t·y exposure a sensitivity to spin-independent WIMP-nucleon interactions of $1.6\ 10^{-47}\ \mathrm{cm}^2$ for a $50\ \mathrm{GeV}/c^2$ (99.75% ER rejection, 40% acceptance NR and 1 tonne fiducial volume).
- Expected to overcome presently world-leading limits just within 10 days of data taking in dark matter mode.

Liquid Argon Two-Phase TPC

Darkside-50 and Darkside 20t

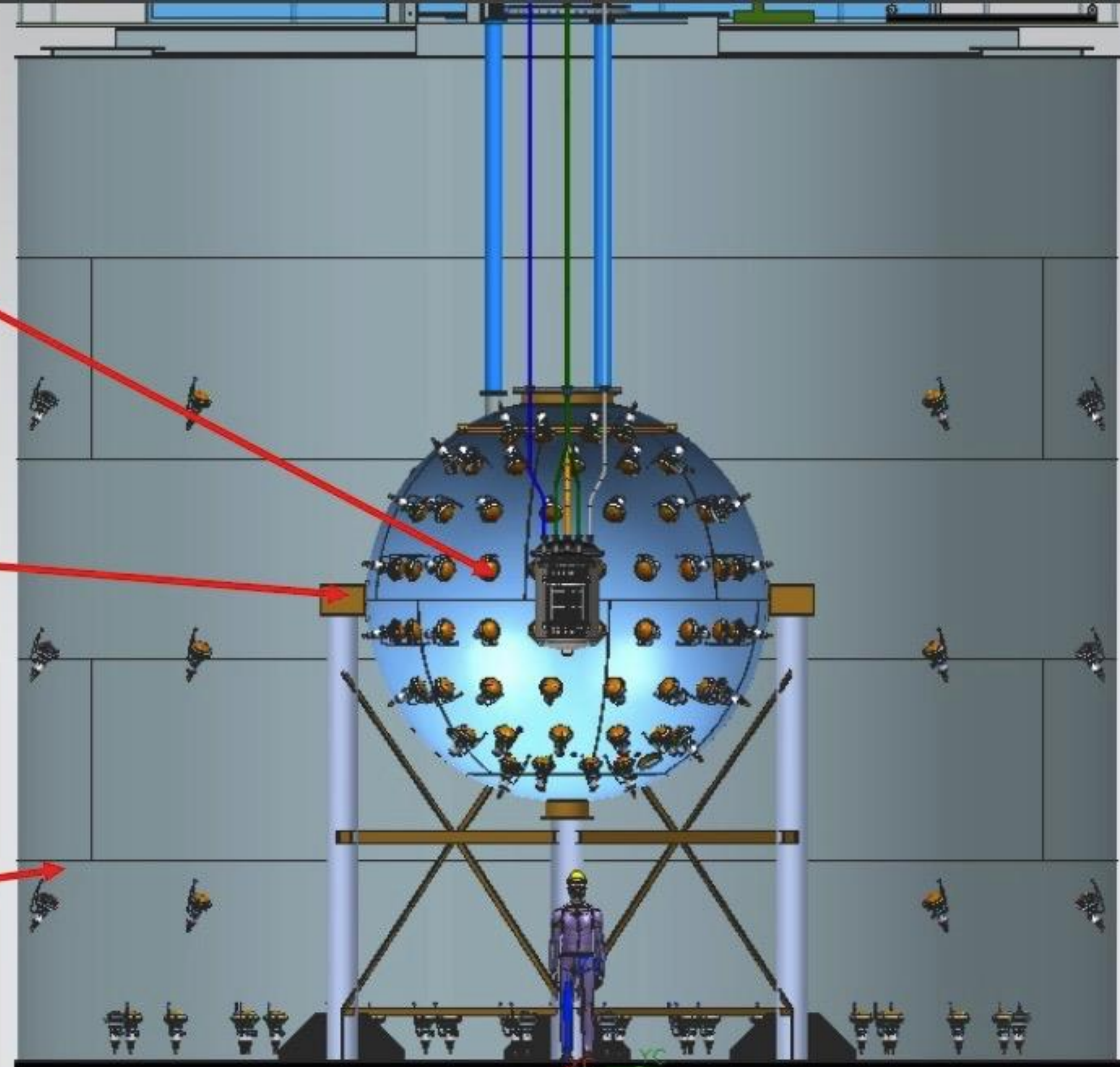
Liquid Argon TPC
153 kg ^{39}Ar-Depleted
Underground Argon
Target

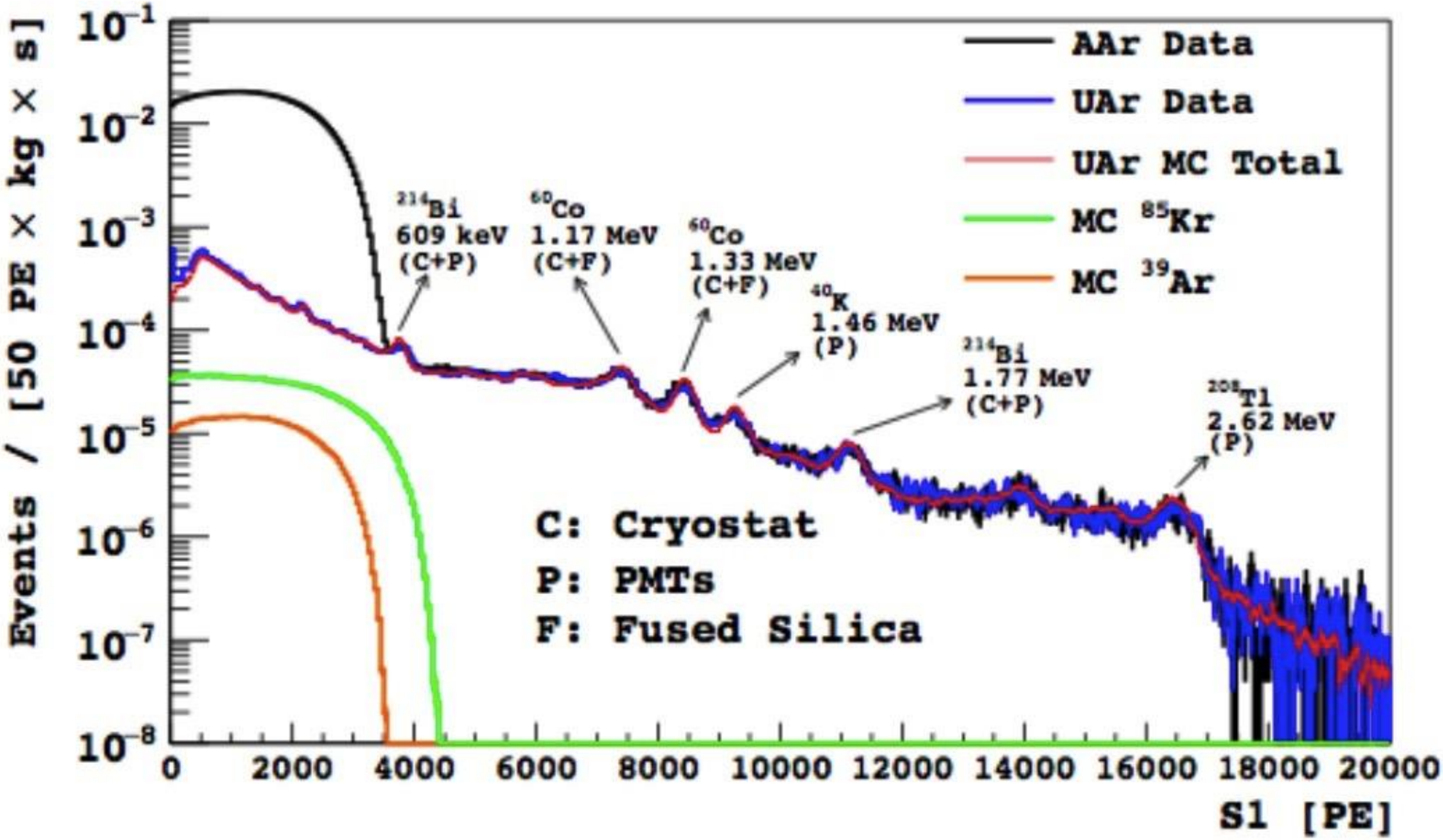


Liquid Argon TPC
153 kg ^{39}Ar-Depleted
Underground Argon
Target

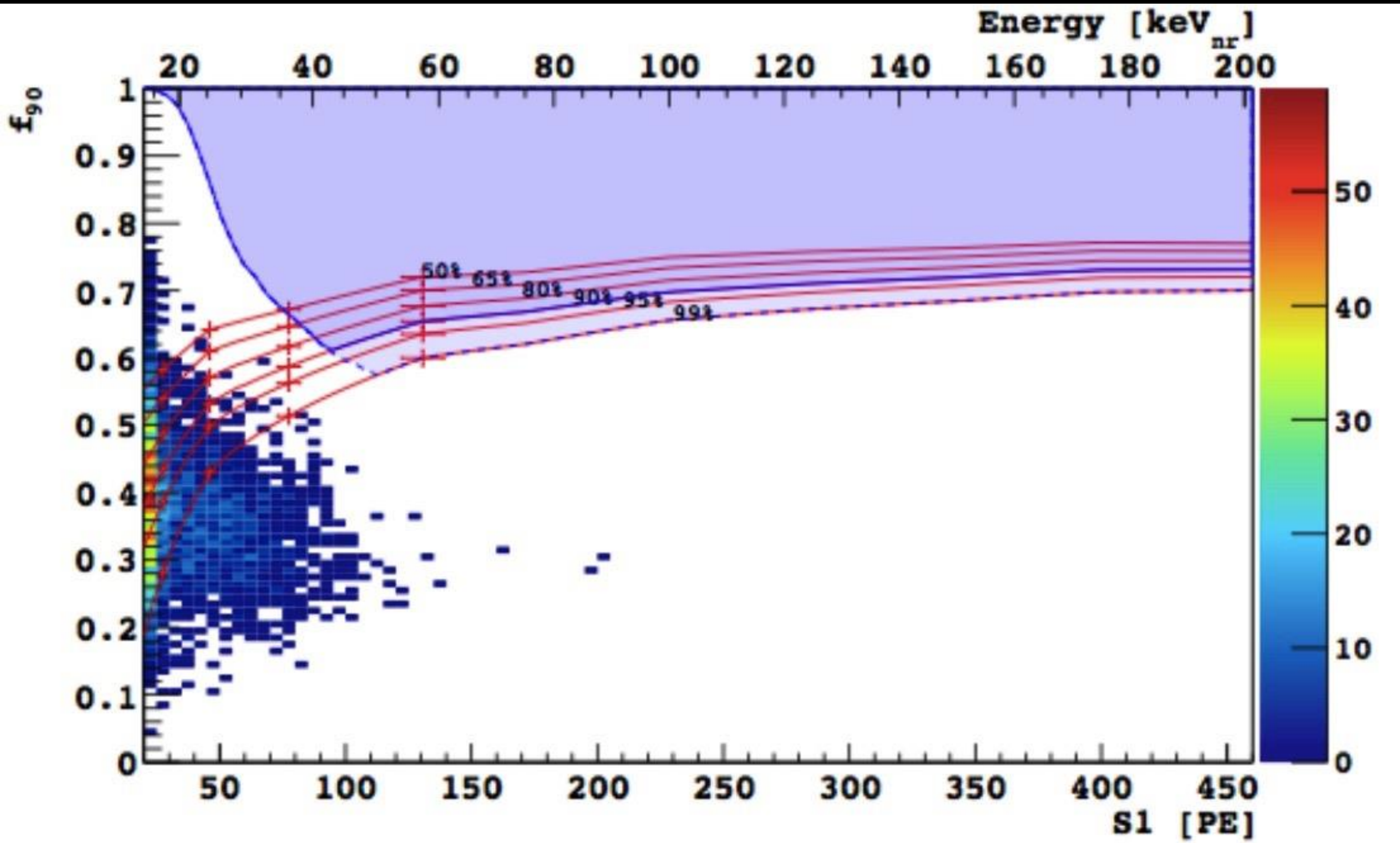
4 m Diameter
30 Tonnes
Liquid Scintillator
Neutron Veto

10 m Height
11 m Diameter
1,000 Tonnes
Water Cherenkov
Muon Veto





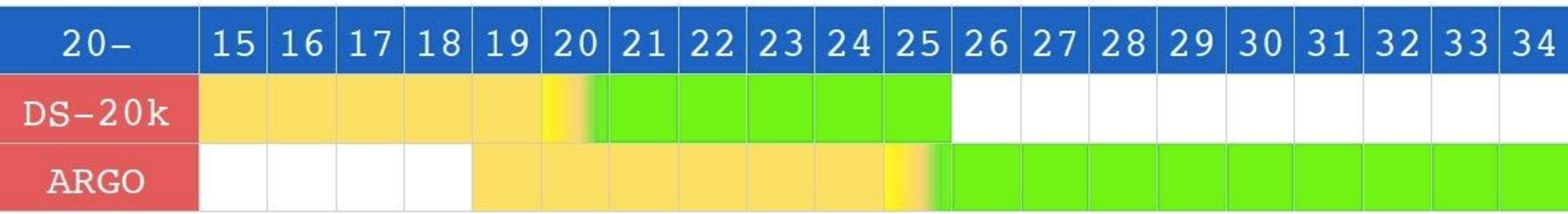
AAr Data
UAr Data
UAr MC Total
MC 85Kr
MC 39Ar
214Bi 609 keV (C+P)
60Co 1.17 MeV (C+F)
60Co 1.33 MeV (C+F)
40K 1.46 MeV (P)
214Bi 1.77 MeV (C+P)
208Tl 2.62 MeV (P)
C: Cryostat
P: PMTs
F: Fused Silica
Events / [50 PE × kg × s]
S1 [PE]



Energy [keV$_{nr}$]
20
40
60
80
100
120
140
160
180
200
f_{90}
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50%
65%
80%
90%
95%
99%
50
40
30
20
10
0
50
100
150
200
250
300
350
400
450
S1 [PE]

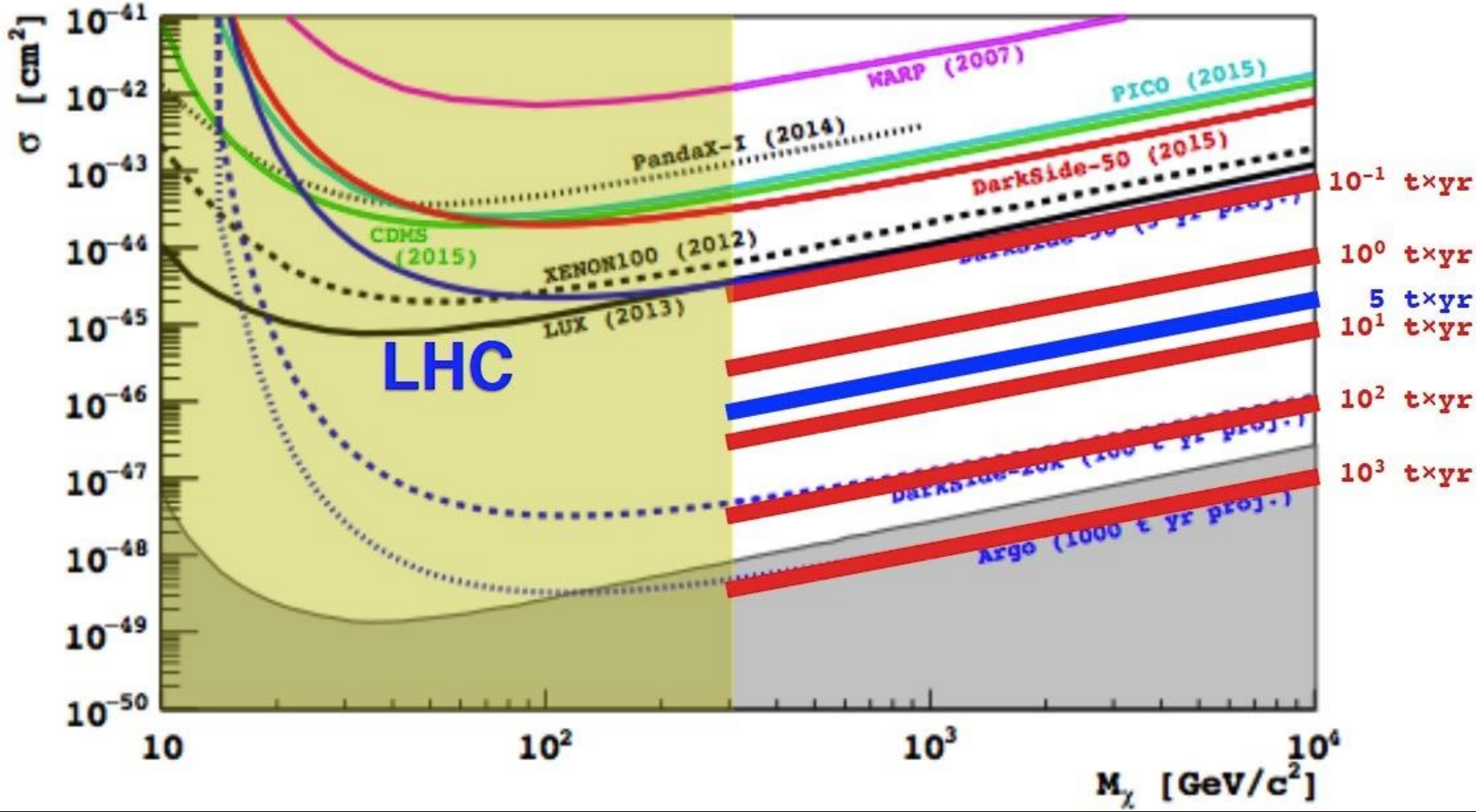
DarkSide-20k

20-tonnes fiducial dark matter detector
start of operations at LNGS within 2020
100 tonne×year background-free search for dark matter



Argo

300-tonnes depleted argon detector
start of operations at LNGS within 2025
1,000 tonne×year background-free search for dark matter
precision measurement of solar neutrinos


σ [cm²]
WARP (2007)
PICO (2015)
PandaX-I (2014)
DarkSide-50 (2015)
CDMS (2015)
XENON100 (2012)
LUX (2013)
LHC
10⁻¹ t×yr
10⁰ t×yr
5 t×yr
10¹ t×yr
10² t×yr
10³ t×yr
Argo (1000 t yr proj.)
Mχ [GeV/c²]

Liquid Argon- Single Phase

DEAP

DEAP-3600 Dark Matter Search at SNOLAB

Project Overview

3.6 tonne liquid argon target in
85-cm radius ultraclean acrylic vessel,
255 8-inch HQE PMTs

1 tonne fiducial mass designed for
< 0.2 background events/year

10^{-46} cm^2 sensitivity for 100-GeV WIMP
with 3-year exposure
with 15 keV_{ee} (60 keV_r) threshold

Start of liquid argon filling June 11, 2016
(approx. 1200 kg July 1, 2016)

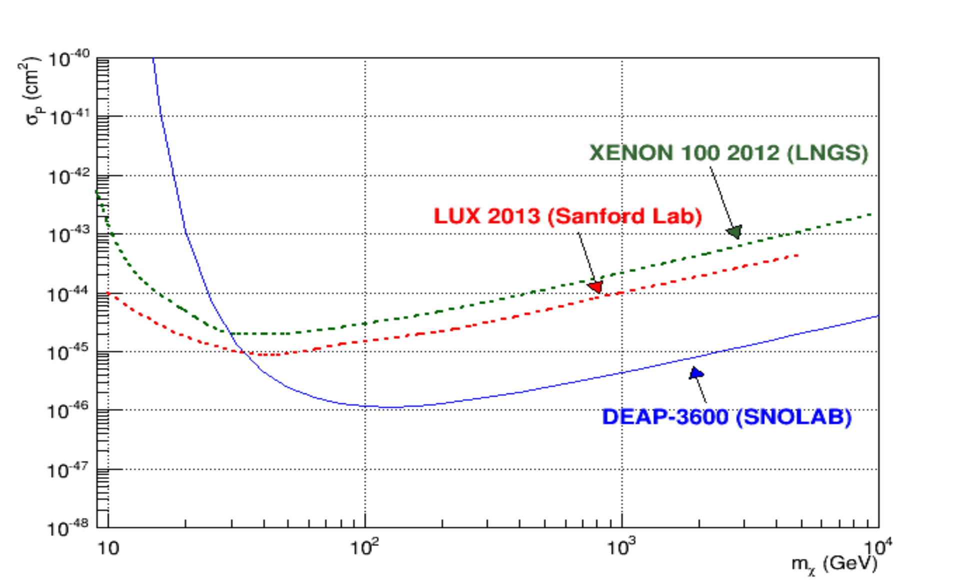
Filling completed by end of July, 2016
(start of physics running)

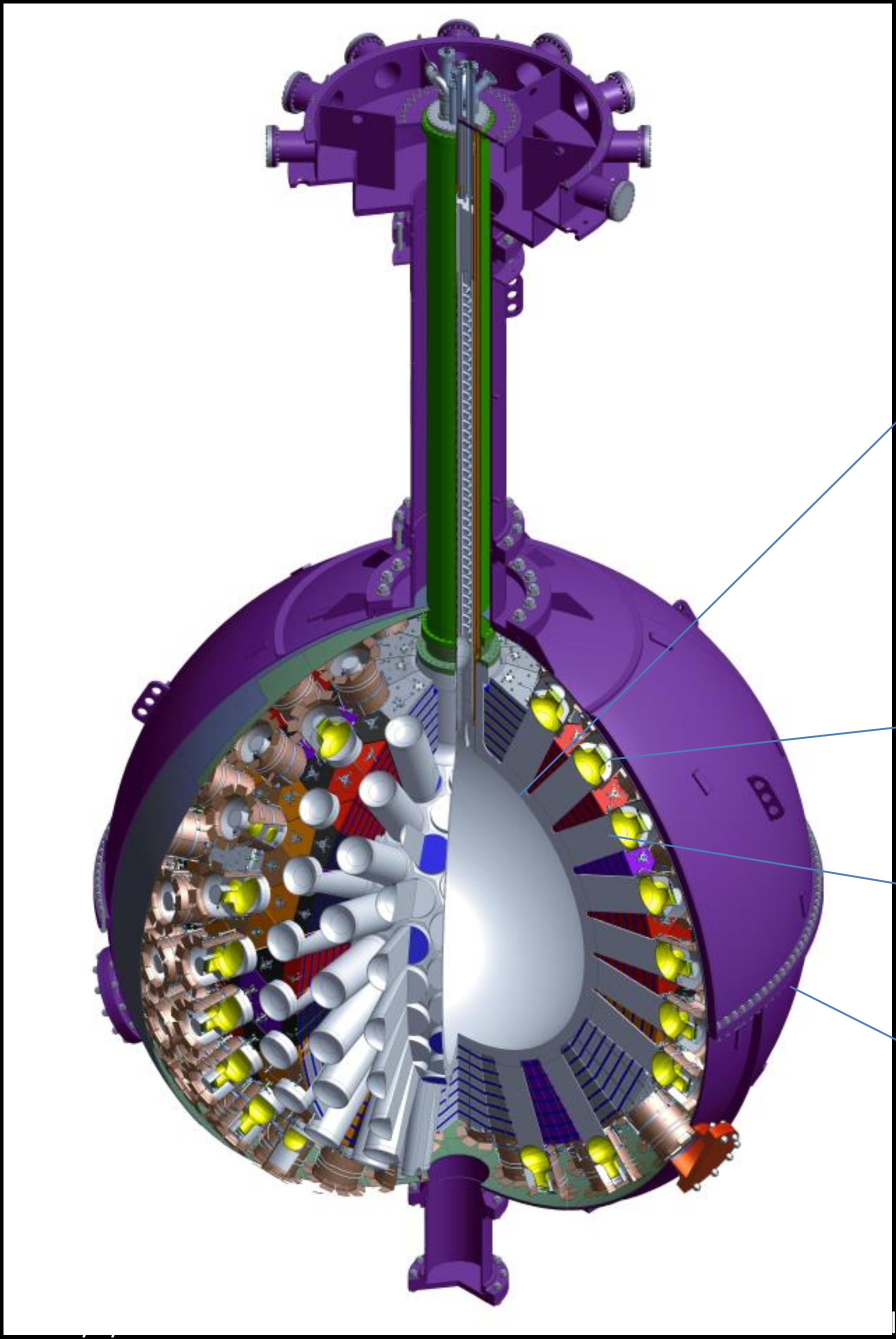
Project Status

PMT commissioning Throughout prep.
inner AV, calibration 2015

Water tank fill Aug. 2015
Cryogenic and purification Aug 2015-
System commissioning Feb 2016

Start of AV cooldown Feb 2016





DEAP-3600 Detector

3600 kg argon target
(1000 kg fiducial)
in sealed ultraclean
Acrylic Vessel

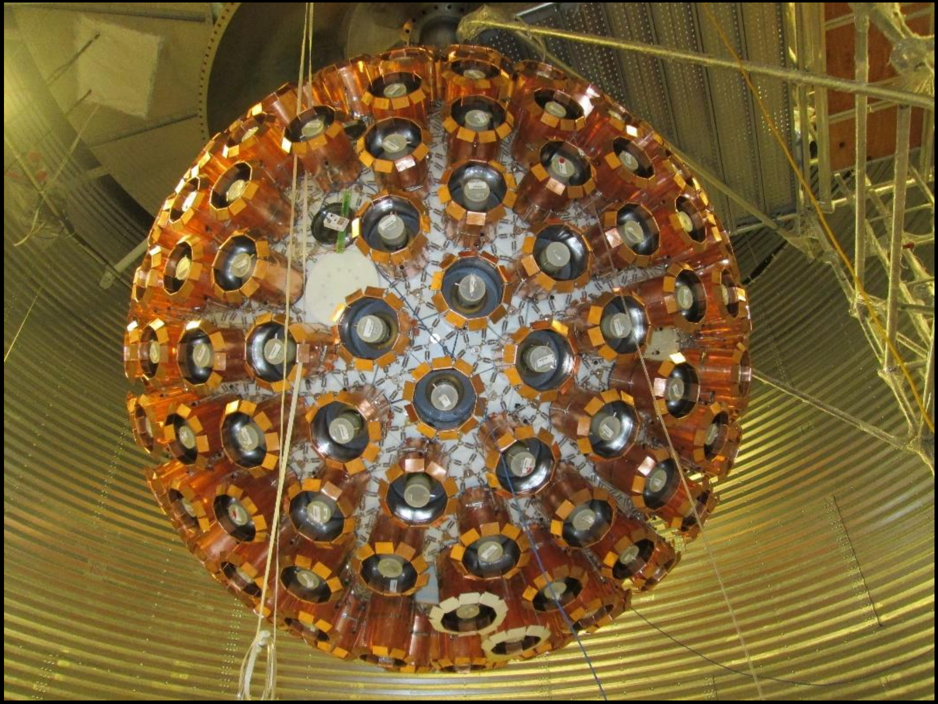
Vessel is “resurfaced”
in-situ to remove
deposited Rn daughters
after construction

255 Hamamatsu
R5912 HQE PMTs 8-inch
(32% QE, 75% coverage)

50 cm light guides +
PE shielding provide neutron
moderation

Steel Shell immersed in 8 m
water shield at SNOLAB

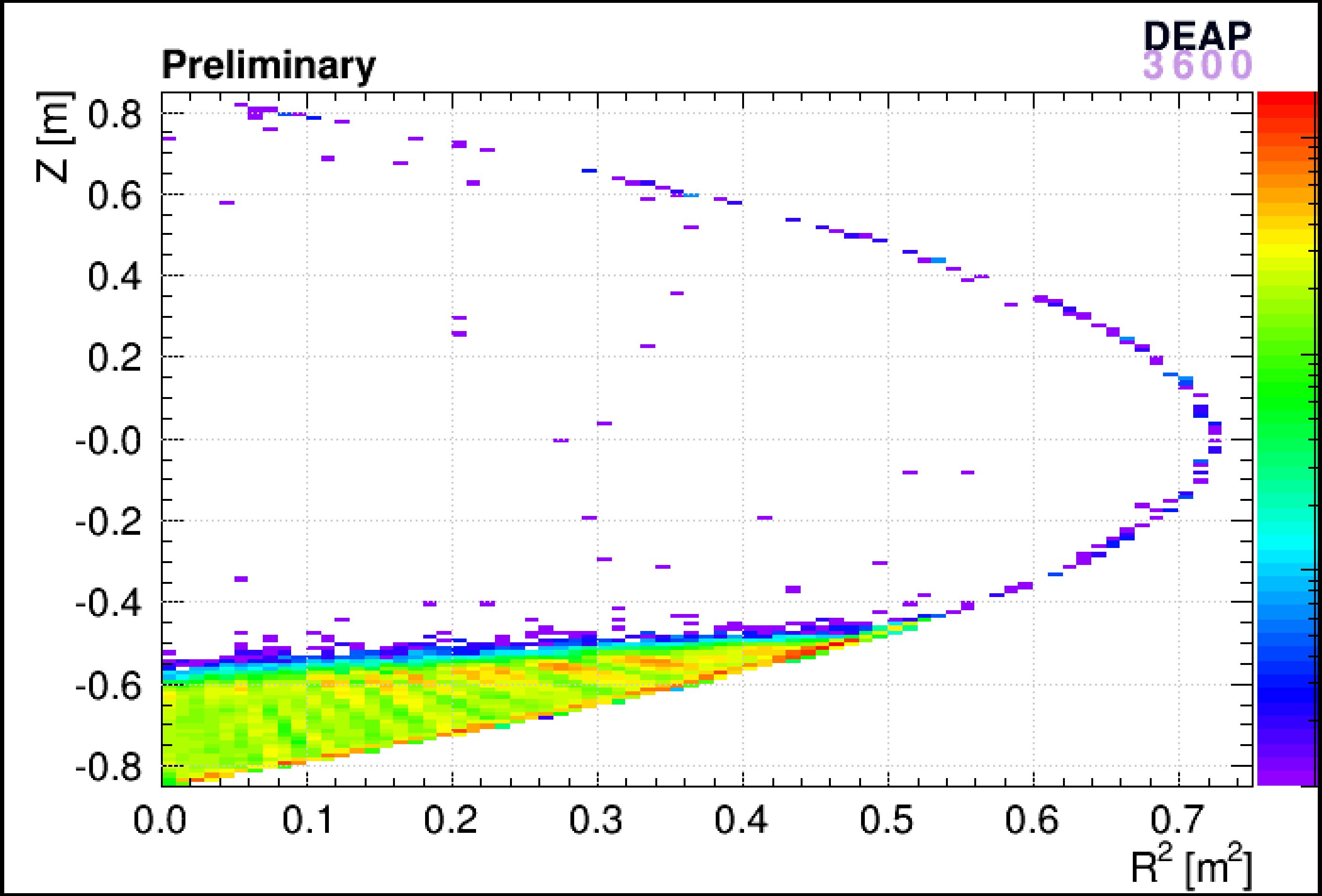
DEAP-3600 Detector at SNOLAB



Completed inner detector
255 8" R5912HQE PMTs
installed in shield tank

Steel Containment Sphere
in 8m diameter water shield tank
(water tank was filled Oct 2015)

Reconstructed event positions, liquid argon argon filling, June 2016



Optical and reconstruction algorithm calibration in progress

Ge and Si Cryogenic Crystals

SuperCDMS at SNOLab

SuperCDMS SNOLAB

Selected as part of the US Generation 2 experiments

Mission: Cover the low WIMP mass region: 0.5-10 GeV/c^2

Low temperature technology sensitivity is unique in this region without requiring very large target mass.

Complementary to LZ and Xenon 1ton/Nton, DarkSide, DEAP3600, XMASS: higher threshold but much larger target mass => focused on WIMP mass above 10 GeV/c^2

Ability to eventually reach the neutrino floor

Project currently being baselined for CD2 in Spring 2017

first data in 2020

DOE ($17.6M),NSF ($12M), CFI (Can$3M)

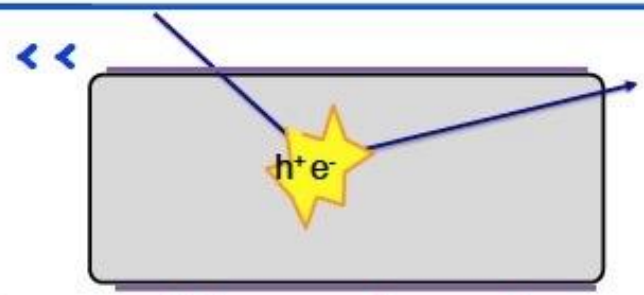
co-managed by DOE and NSF as a single project

CDMS project goals

1) Design, build an experimental infrastructure able to reach the neutrino floor
   - Cryogenic system
   - Shield
   - Ultra low radioactivity tower design able to accommodate next generation HV (improved CDMSLite) and phonon+ionization (iZIP) detectors.
   - + flexibility to adapt to new ideas/discoveries in the next decade.

2) Construct first generation payload able to make impressive progress at low mass in the first two years:e.g. 2HV, 2 iZIP

CDMS:Use of Phonons and Cooper Pairs



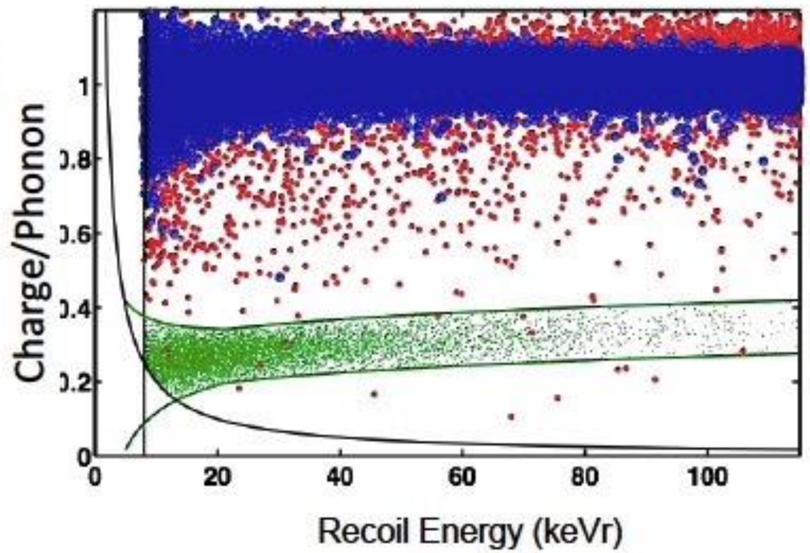
<1meV quanta

=> sensitivity but requires ≈30mK
detailed information about the event

Recognition of nuclear recoils

Nuclear Recoils
- 8% e^-/h^+
- 92% phonons

Electron Recoils
- 25% e^-/h^+
- 75% phonons

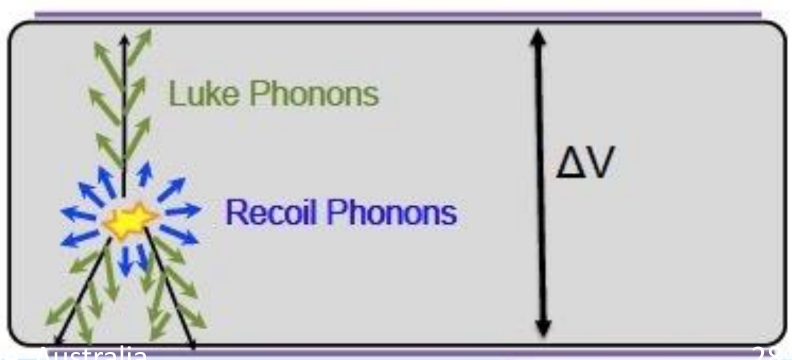


Fiducialization ionization or phonons

We can efficiently get rid of surfaces

Amplification of ionization

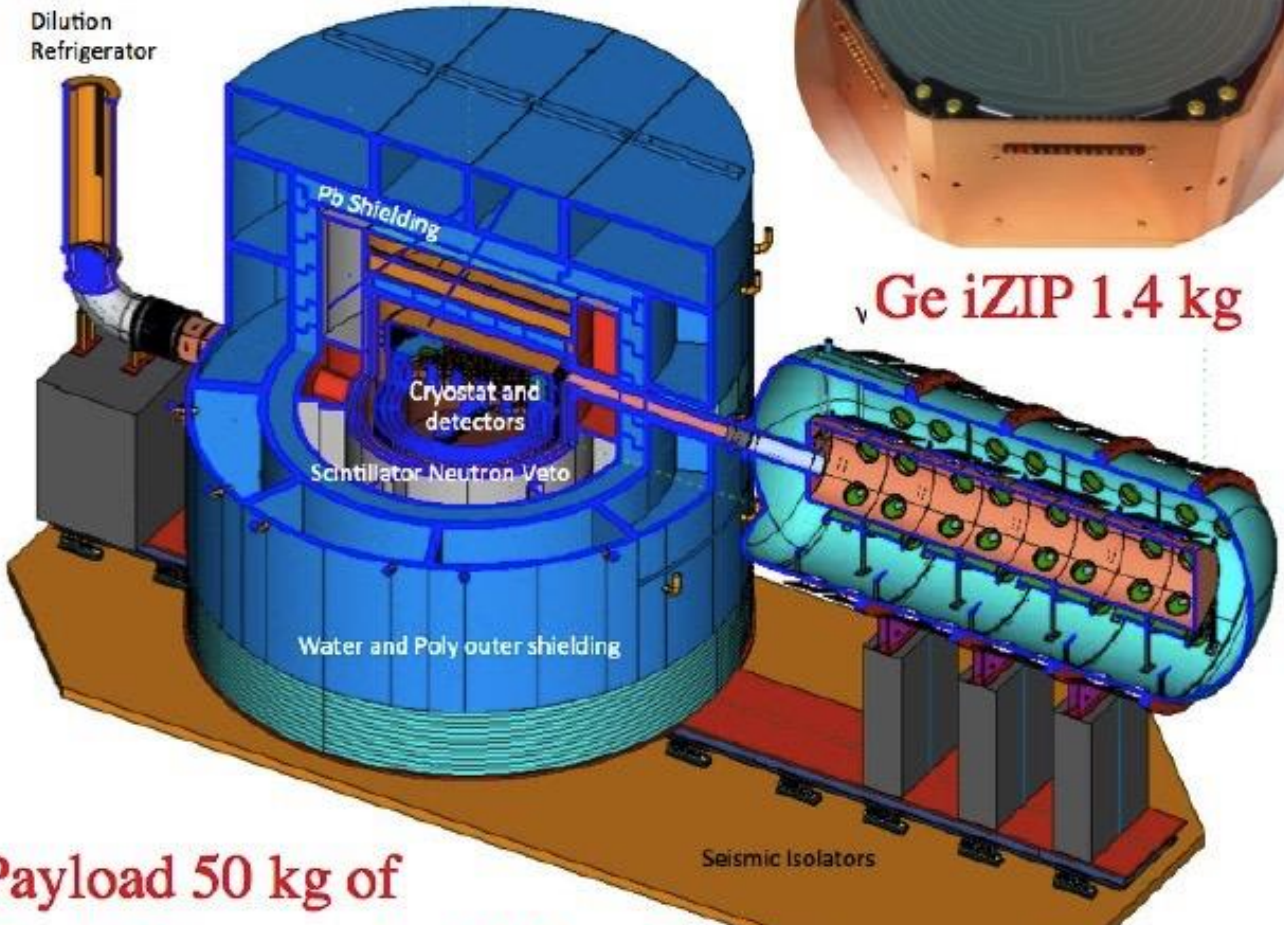
CDMS-HV: give up nuclear recoil ID

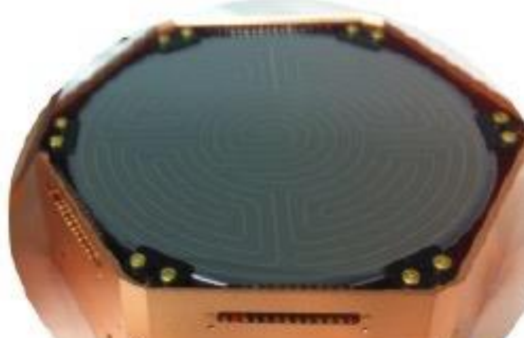


SuperCDMS SNOLAB Experiment

(≈2020)

- SNOLAB 6010 mwe





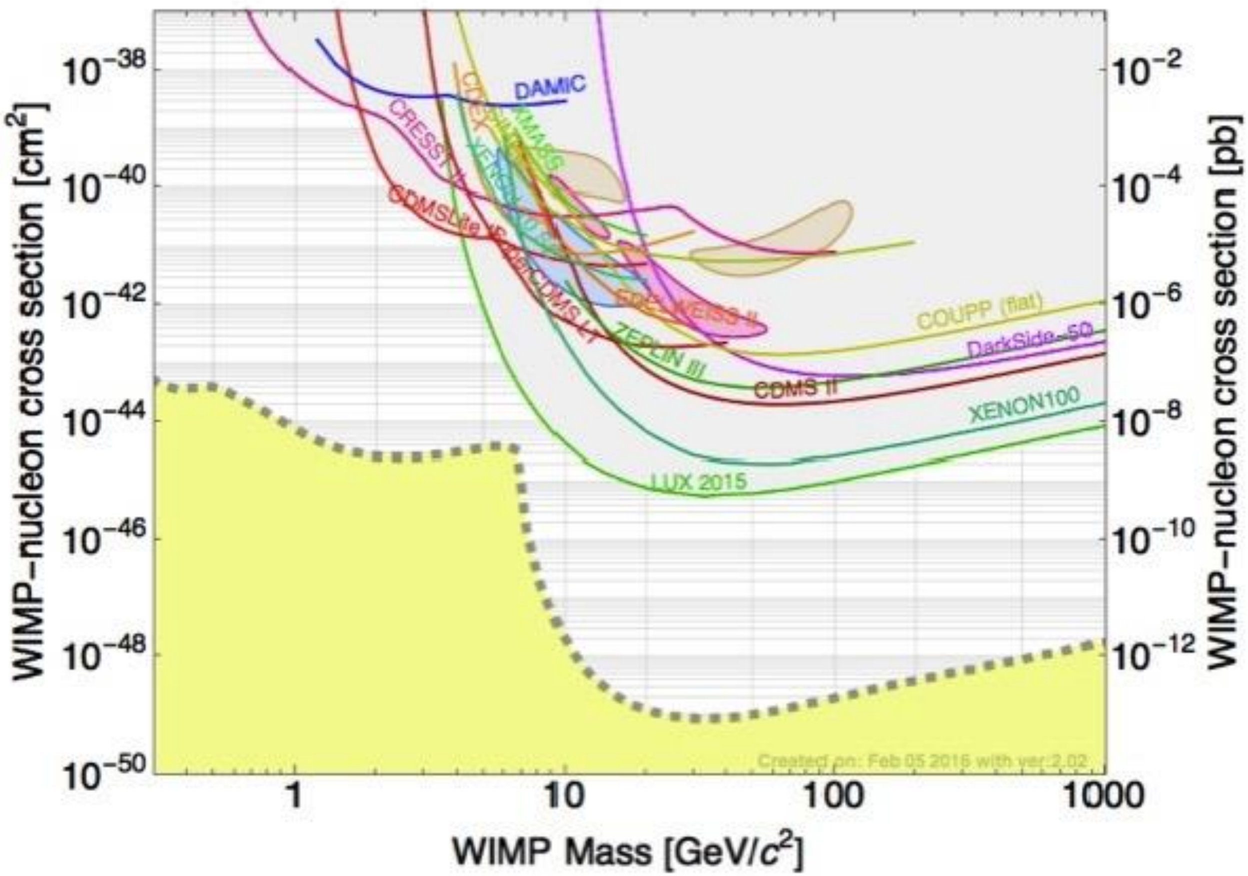
Ge iZIP 1.4 kg

Ge Tower 8.4 kg

Payload 50 kg of Ge & Si - capacity 400 kg Ge

High sensitivity at low mass

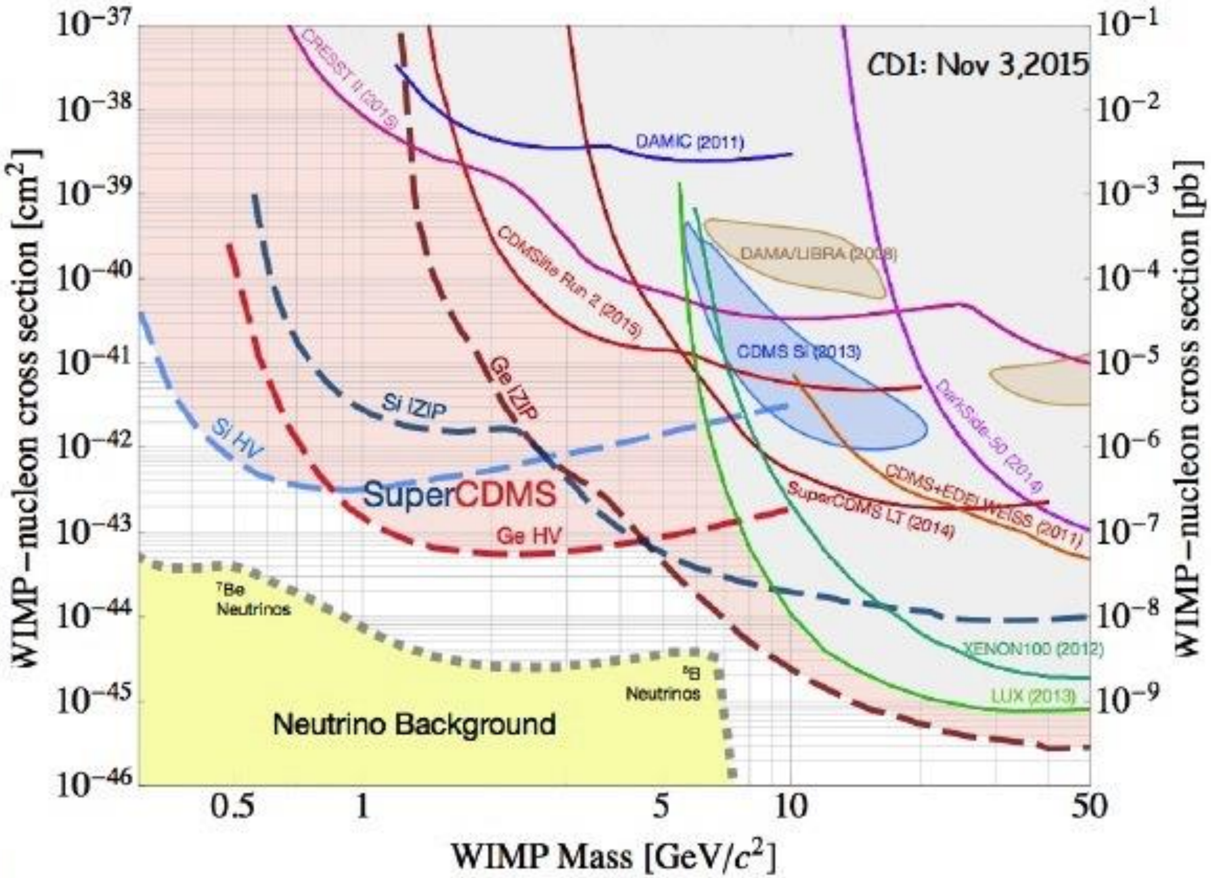
- **High signal to noise ratio for ionization+ phonon (iZIP)**
  - => large amount of information , excellent nuclear recoil discrimination, good fiducialization
- **High sensitivity of Luke Neganov amplification**
  - CDMSLite
  - at the cost of no nuclear recoil discrimination



SuperCDMS Science Goals

First pay load ->

4 iZIPs+ 1HV (CD1)
Background levels as estimated in Fall 2015
Optimal Interval
no background subtraction but will attempt (better by !
no nuclear recoil discrimination for HV
^{3}H dominant for Ge
^{32}Si dominant for Si
^{8}B neutrinos
15 evts in 5 years



Upgrade paths

SuperCDMS+Eureca
Serious discussion of merging at SNOLAB => larger target mass x2-3 e.g., for 4 to 10 GeV/c^2+^{8}B
Recovering nuclear recoil discrimination at low mass, e.g., through ≤10eV rms phonon resolution in HV detectors -> Neutrino Floor

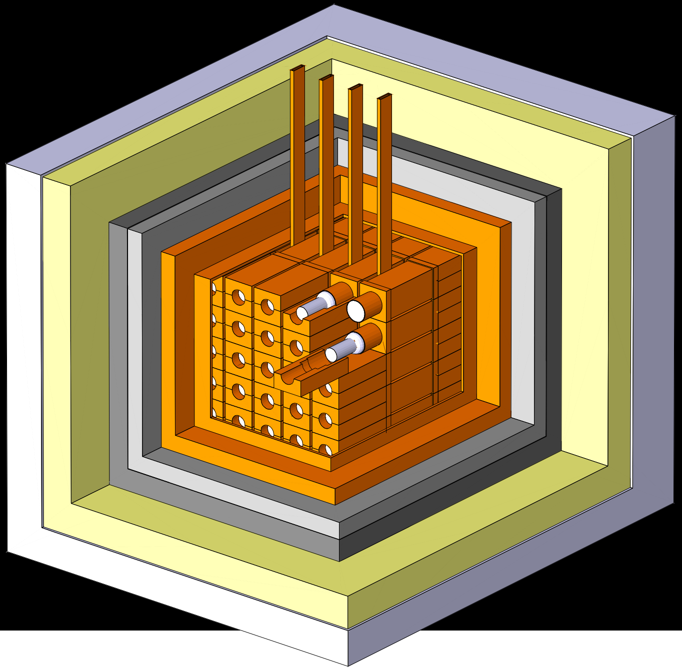
Being updated/optimized: e.g.,
2 HV towers
2 iZIP towers needed to reliably subtract HV background

NaI(Tl) Crystal Scintillator

DAMA-LIBRA

The DAMA/LIBRA Detector

- High purity NaI(Tl) crystals
- OFHC copper
- Low radioactivity lead
- Cu/Pb etched with acid in clean room
- Polyethylene/paraffin-Cadmium
- Flushed with HP N_2 Gas
- No muon veto.

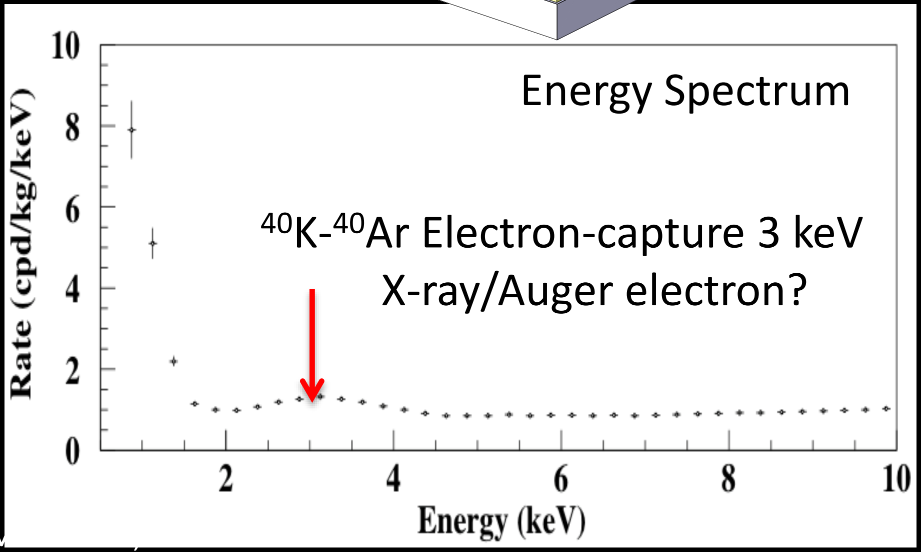


Residual ^{40}K background

~13 ppb ^{nat}K

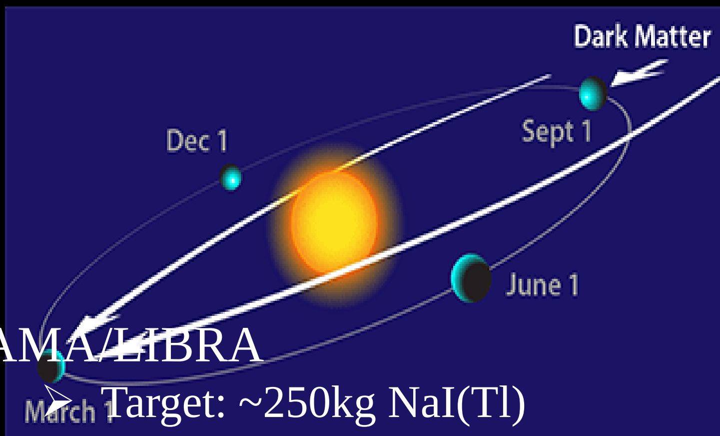
$^{40}K \rightarrow {}^{40}Ar$, ~11% branch ratio

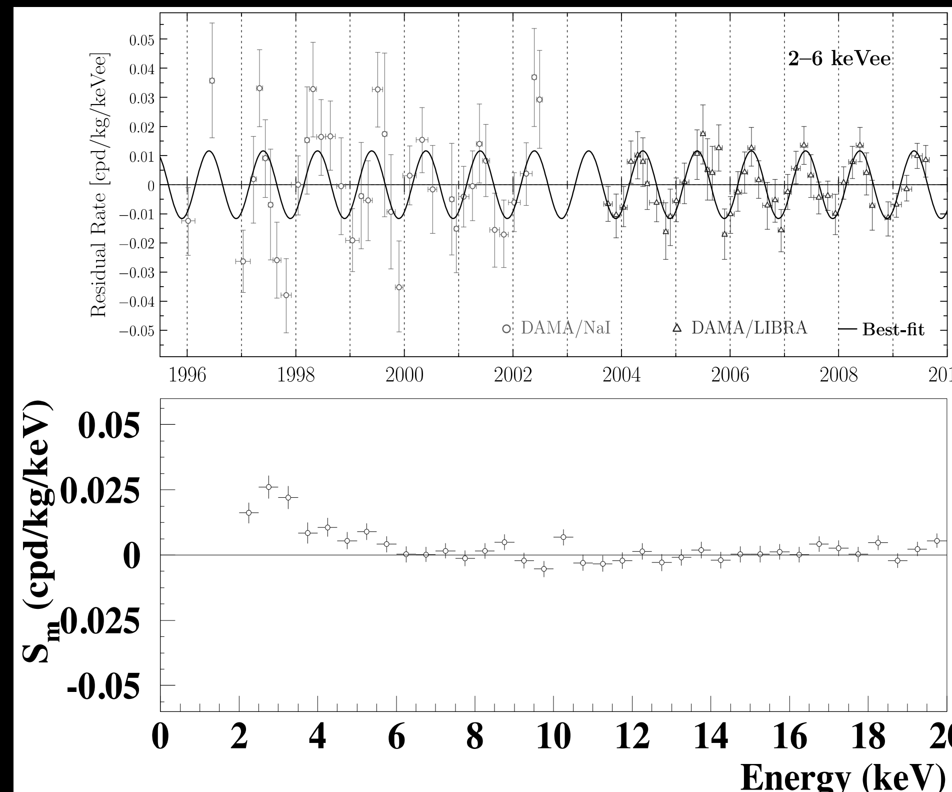
3 keV K shell X-ray, Auger e^-



Hints of dark matter from DAMA-LIBRA

- DAMA/LIBRA observed low energy rate modulation





DAMA/LIBRA

- ➢ Target: ~250kg NaI(Tl)
- ➢ Signal: Annual modulation
  - ➢ Modulating: ~0.0112 (12) cpd/keV/kg
- ➢ Signal region: 2-6 keV_{ee}
  - ➢ Non-modulating: ~ 1 cpd/keV/kg
  - ➢ No modulation above 6 keV.
- ➢ ~9.3σ significance 14 cycles (2013)

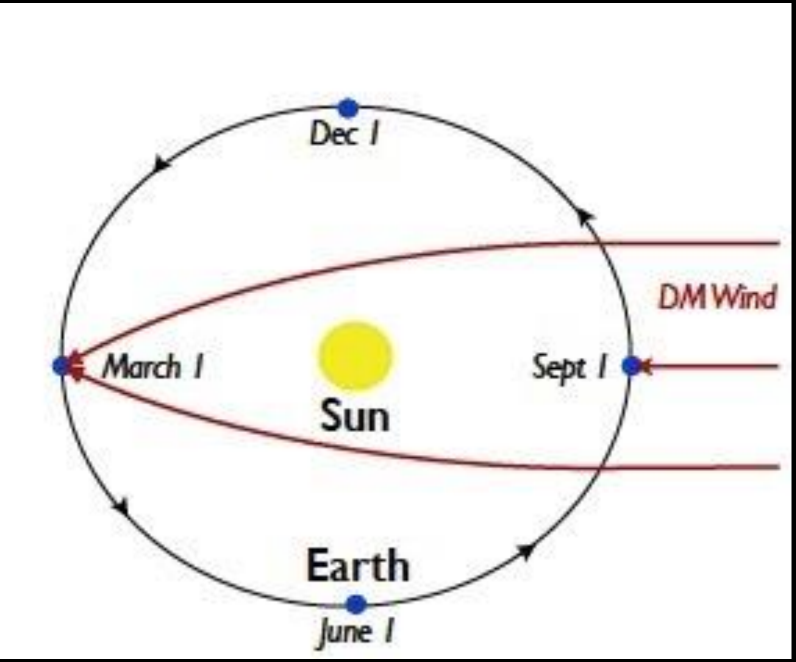
- Is this signal from dark matter interactions?

DAMA-LIBRA

- The annual modulation observed by DAMA-LIBRA is consistent with motion of Sun-Earth system through dark matter halo.
  - The amplitude is ~1%.
  - The period is one year.
  - The rate is maximum on day 144 ± 7 d (May 24),
  - This is within uncertainty of June 2, the expected peak rate in dark matter.
- Significant background due to radioactivity in crystal means modulation of WIMP rate is larger than 1%.
  - Could be explained by threshold effect for light WIMPs.
- Results are inconsistent with experiments using other targets. (LUX, XENON, CDMS)
- An independent experiment with NaI is needed.

Gravitational Focusing Phase Shift. Cosmogenic backgrounds.

- Maximum annual WIMP rate is expected on June 2.
- DAMA observes max rate on May 24 (± 7d), 9 days earlier than expected.
- Gravitational focusing shifts the peak rate earlier, towards March, could explain the DAMA phase.
- Background from cosmogenic muon flux modulates seasonally by 1.29 % with max rate on June 28 (± 6 d).
  - This is too late to explain DAMA's modulation.



S. K. Lee, M. Lisanti, A. H. G. Peter, and B. R. Safdi, Effect of Gravitational Focusing on Annual Modulation in Dark-Matter Direct-Detection Experiments," Phys.Rev.Lett. 112 (2014) no. 1, 011301

NaI(Tl) Crystal Scintillator

SABRE

SABRE

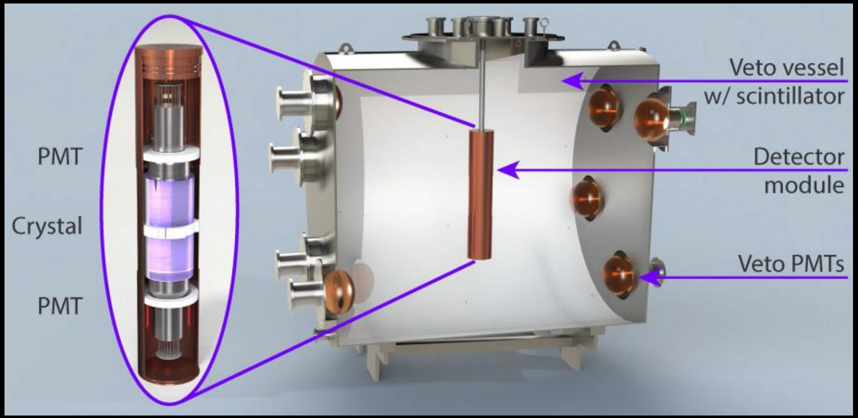
(Sodium iodide with Active Background REjection)

Testing the DAMA-LIBRA Annual Modulation for Dark Matter

Strategy

1. Reduce NaI(Tl) crystal radioactivity
   - Develop radio-pure NaI powder and special crystal growth technique.
   - Employ active scintillator veto
2. Lower threshold energy
   - High Q.E PMTs directly on crystals.
   - Reduce PMT dynode afterglow.
3. Eliminate seasonal effects.
   - Detectors in North and South Hemispheres.
   - North: LNGS, Italy
   - South: SUPL, Australia

Liquid Scintillator Veto



- Veto β–γ radioactivity in NaI crystal by detecting γ-ray in liquid scintillator.
  - ^{40}K 3-keV EC-γ (largest background)
  - ^{22}Na, ^{126}I, in NaI.
- PMT γ-Compton background, etc.
- Rock and cosmogenic backgrounds.

Main Background: NaI(Tl) Radioactivity

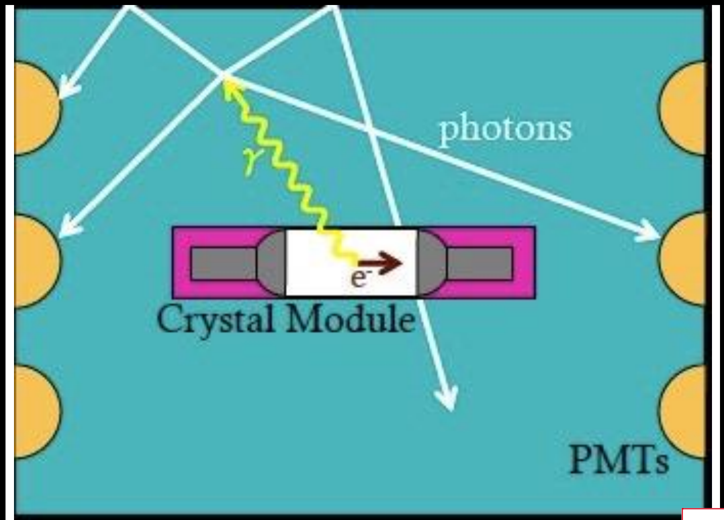
Research to reduce and measure trace levels of naturally occuring radioactive K, Rb, U, Th paid off.

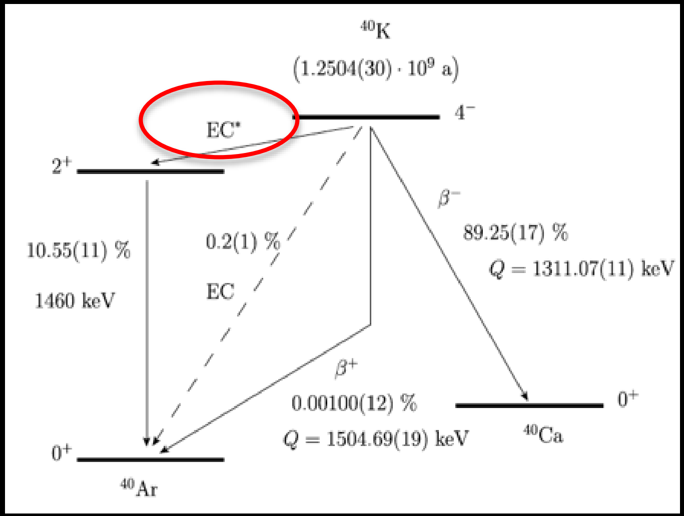
2-kg radio-pure NaI(Tl)

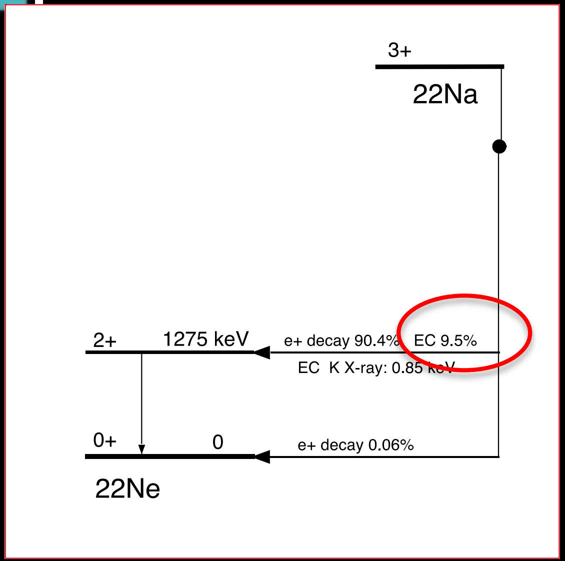
Sample	K(ppb) -Seastar Jan 2016	K(ppb)- PNNL Apr 2016
2A	9 ± 1	10.0 ± 0.7
2B	7 ± 1	9.1 ± 0.3
2D	11 ± 1	9.7 ± 0.4
2E	9 ±1	9.8 ± 0.4
Average	9	9.6

Good agreement for [K] between independent ICP-MS measurements.
[Rb] upper limit <0.1 ppb. [U], [Th] ~ 0.5 ppt
[K] here is lower than 13 ppb in DAMA/LIBRA.
Effective concentration of K is further reduced by veto.

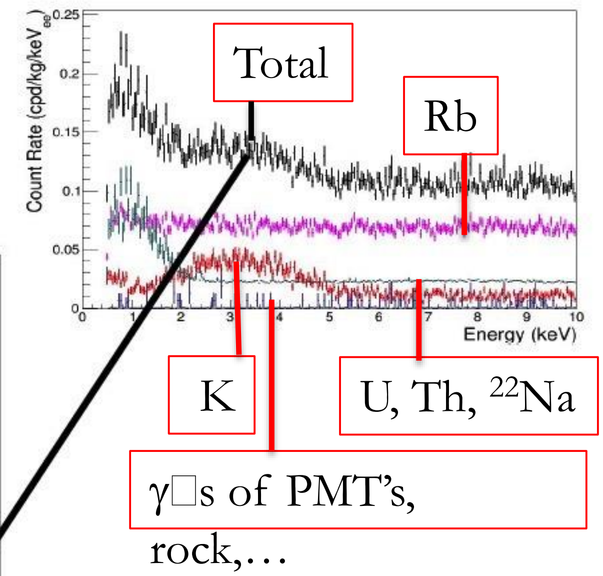
Liquid Scintillator Detects γ-rays and vetos X-rays from ^{40}K and ^{22}Na

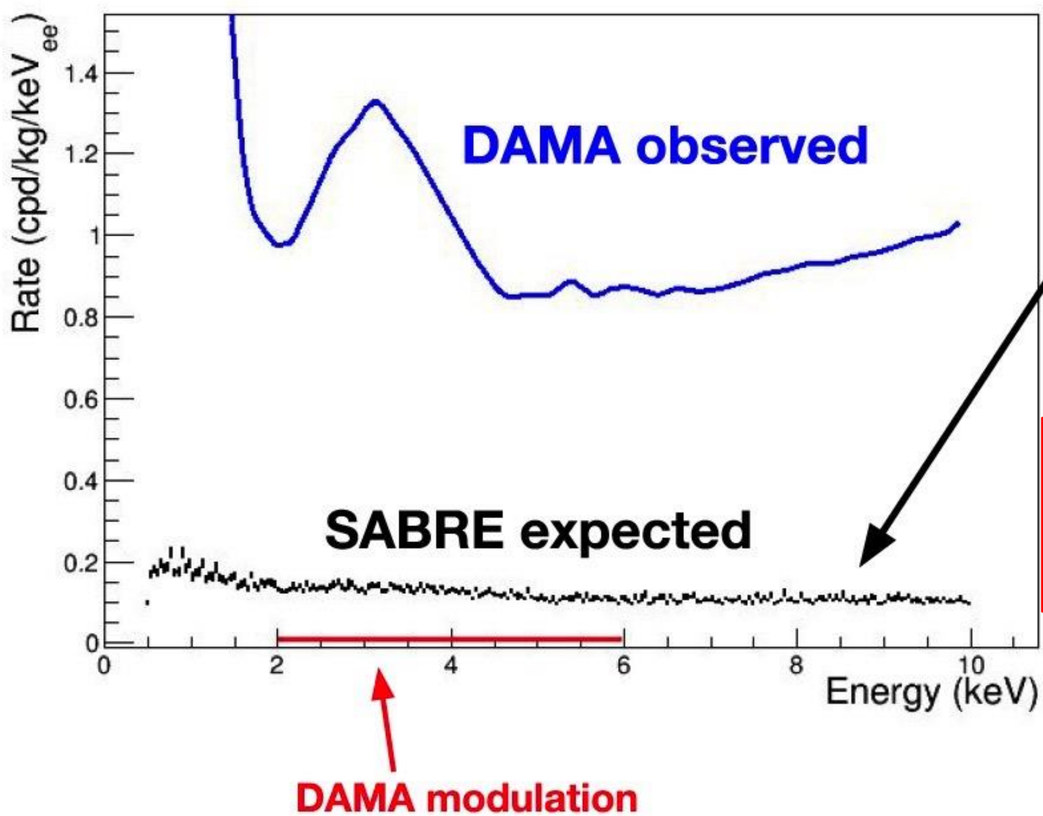






Expected background with veto





The radio-pure NaI crystals and veto result in x10 lower background than DAMA.

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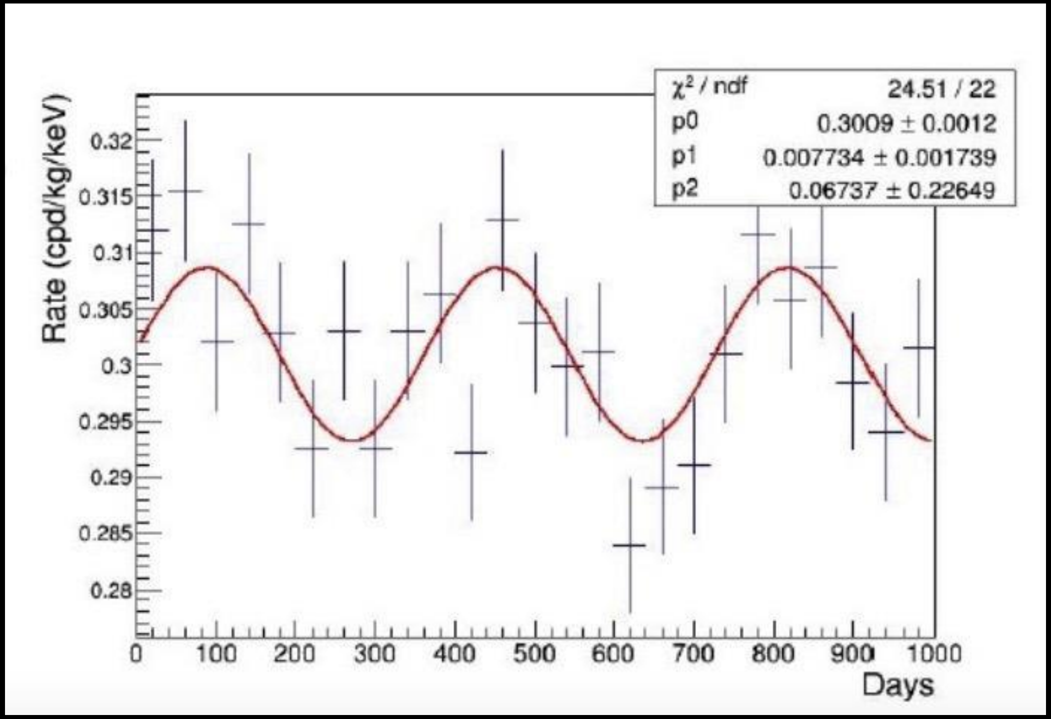
Sensitivity to DAMA-LIBRA Modulation

With expected backgrounds, SABRE can refute (6σ) or confirm (4σ) DAMA-LIBRA modulation with 50 kg x 3 yrs exposure



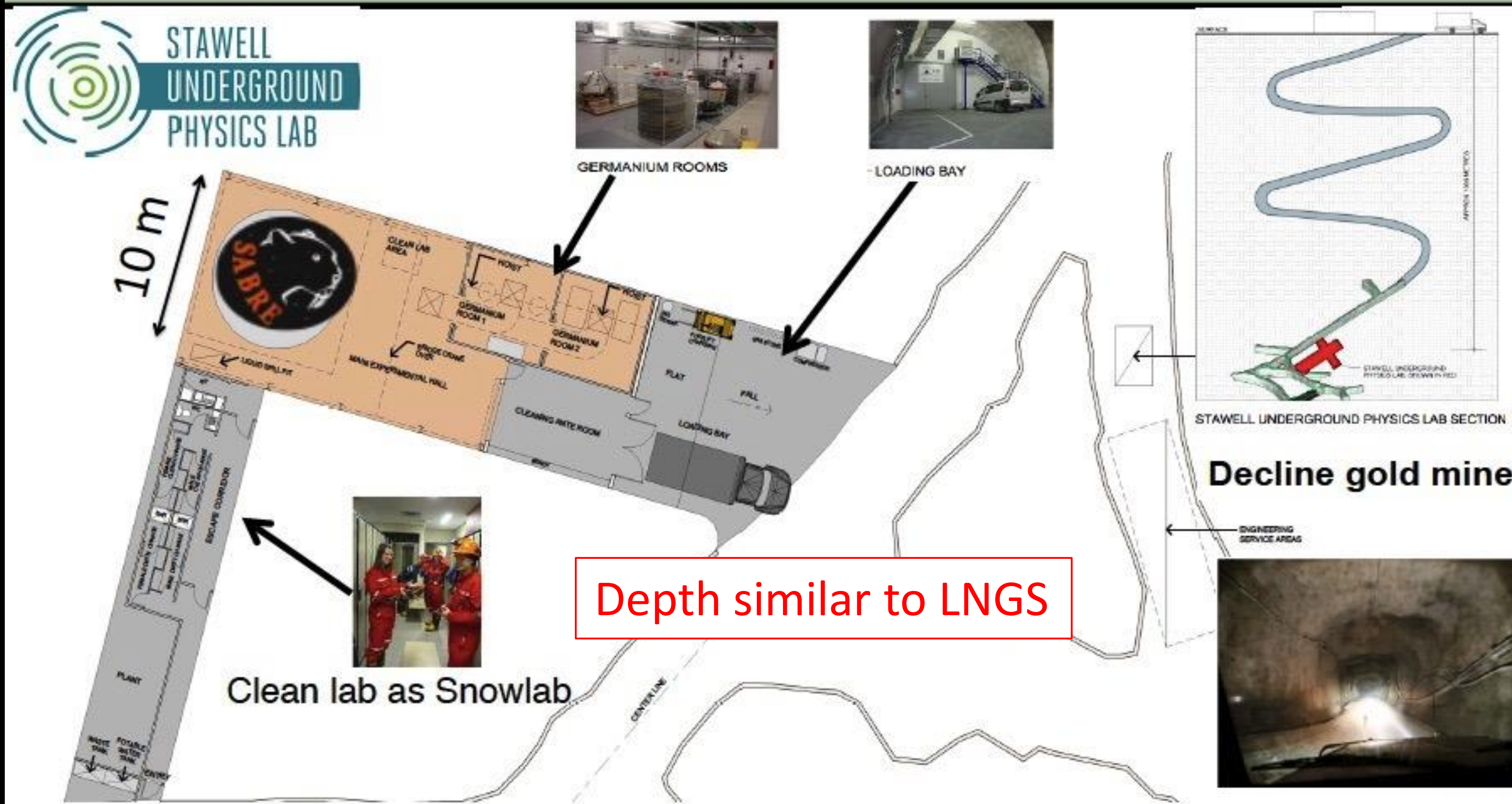
Direct proof of backgrounds by counting in veto will take place in coming months.

SABRE South

A SABRE Twin in a Gold Mine

Near Stawell, Australia

Laboratory design SUPL: Stawell Underground Physics Laboratory



University campus on surface very close by (~ 1.5 km) already fitted for the purpose.

Northern Grampians Shire Council · Australian Government ansto Australian Nuclear Science and Technology Organisation · Newmarket Gold · The University of Melbourne · CoEPP

2014: Lab proposed. 2015: Funding secured from Fed and State. 2017: Lab ready.

Summary and Conclusions

Searches for dark matter by direct detection are being carried out by a robust suite of innovative experiments, only partially covered here.

- Two LXe experiments.
  - XENON 1-ton starts 2017. Goal of $1.6 \times 10^{-47} cm^{2.}$ 50 GeV/c^2
  - LZ 5.6-ton builds on LUX 145-kg. Goal is 1.5×10^{-48} cm^2 50 GeV/c^2
- Two LAr experiments.
  - LAr 1-ton (DEAP) filling, taking data 2017 with goal of 1×10^{-46} cm^2 .
  - LAr-50 (Darkside) achieved background free data. A 20-ton detector is planned. with goal of 4×10^{-48} cm^2 at 300 GeV/cm^2.
- Super-CDMS SNOLab
  - Mass of 50 kg with Ge and Si focuses on light WIMPS: 0.5-5.0 GeV/c^2.
  - First to study largely unexplored region.
- New NaI(Tl) experiments (SABRE, COSINE, ANAIS)
  - Anomalous results of DAMA-LIBRA to be checked in few years.

Poised for Discovery?

The End

No koala bears, nor kangaroos, but another rare creature in Australia.

Prof. Elisabetta Barberio,

the force behind SUPL, getting ready to mine dark matter.

The SABRE Collaboration

(11 Institutions)

SABRE North

Italy

- LNGS
- University of Rome
- Milan University

United Kingdom

- Imperial College

United States

- Pacific Northwest Nat. Lab.
- Princeton University

SABRE South

- Australian National Laboratory
- Australian Nuclear Science and Technology
- Swinburne University
- University of Adelaide
- University of Melbourne