Title: Ugrnd Experiments

Speakers:

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2023/06/27

Underground Science - Day 3

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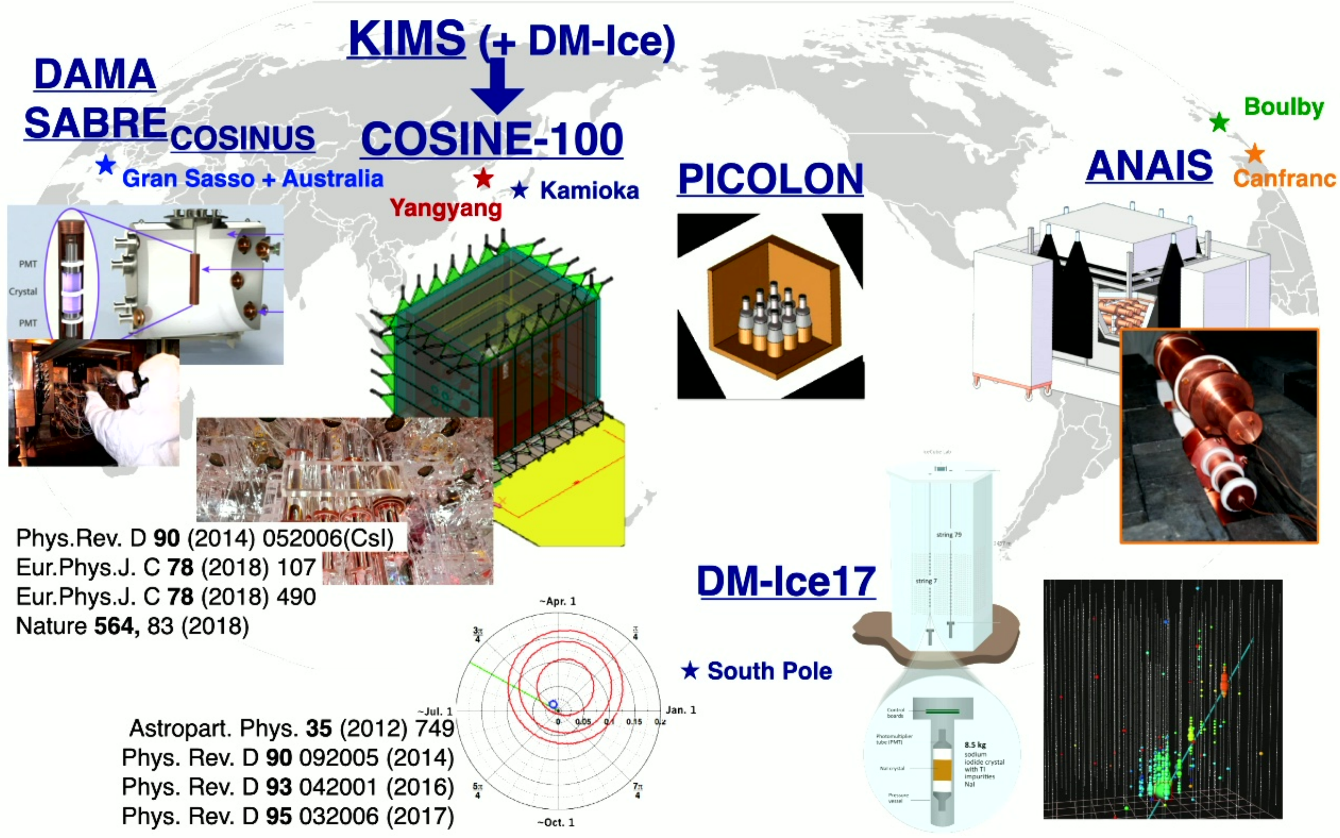
SNOLAB

Last Time:

- Discussed the different backgrounds that come into play in underground physics and the tools and techniques used to understand, mitigate and characterize those backgrounds.
- Discussed the DAMA/LIBRA excess, possible interpretations and their pitfalls.

Worldwide Effort to Test DAMA/Libra



DAMA
SABRE **COSINUS**
★ Gran Sasso + Australia

KIMS (+ DM-Ice)
COSINE-100
★ Yangyang
★ Kamioka

PICOLON

ANAIS
★ Boulby
★ Canfranc

DM-Ice17
★ South Pole

Phys.Rev. D **90** (2014) 052006(CsI)
Eur.Phys.J. C **78** (2018) 107
Eur.Phys.J. C **78** (2018) 490
Nature **564,** 83 (2018)

Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

COSINE-100

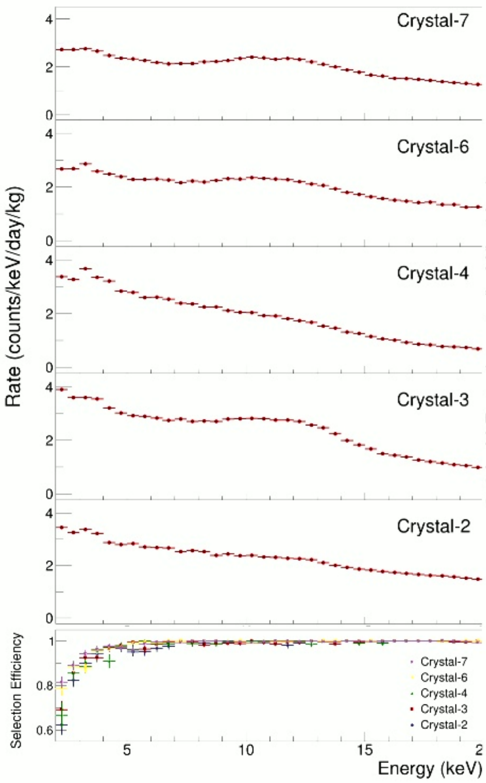
Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS II	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WS III	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WS III	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
Crystal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5

- Located in Yangyang Laboratory, South Korea
- 8 copper encapsulated NaI(Tl) crystals
  - 106 kg total
- Two 3-inch PMTs per crystal
  - trigger at ~0.2 p.e. threshold
- Calibration via sources through tubes
- Total Background: 2 - 4 x DAMA/LIBRA avg. (2.7 cpd/kg/keV on average in 2 - 6 keV ROI)
- U/Th/K below DAMA, ^{210}Po very close
- High light yield

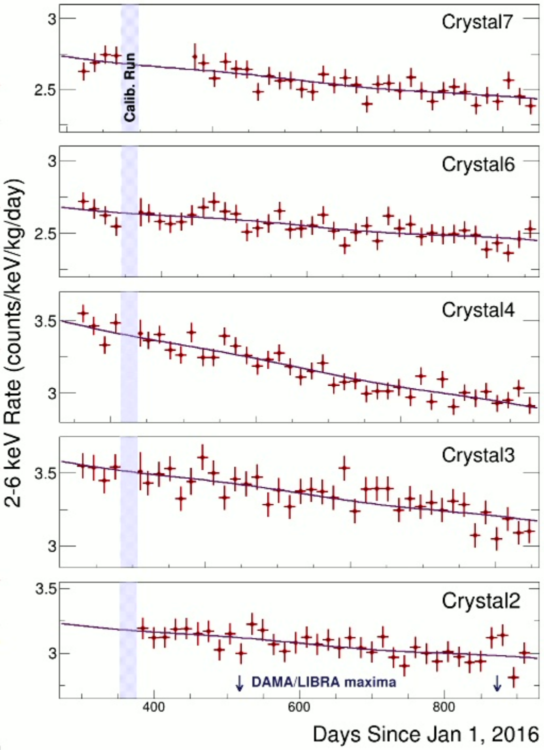
SNOLAB

PRL 123.031302

COSINE-100 Modulation Search



Energy spectra between 2 - 20 keV and signal efficiency using ^{60}Co source

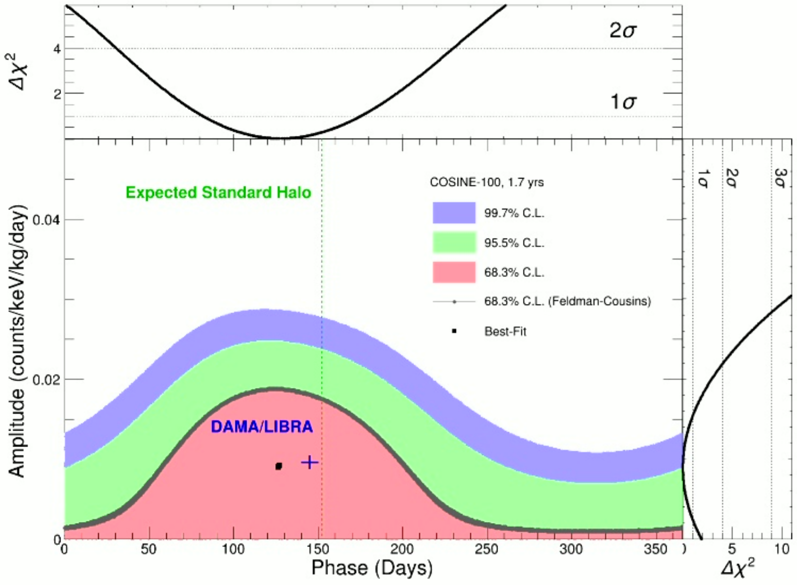


Rate vs time for the 2-6 keV ROI

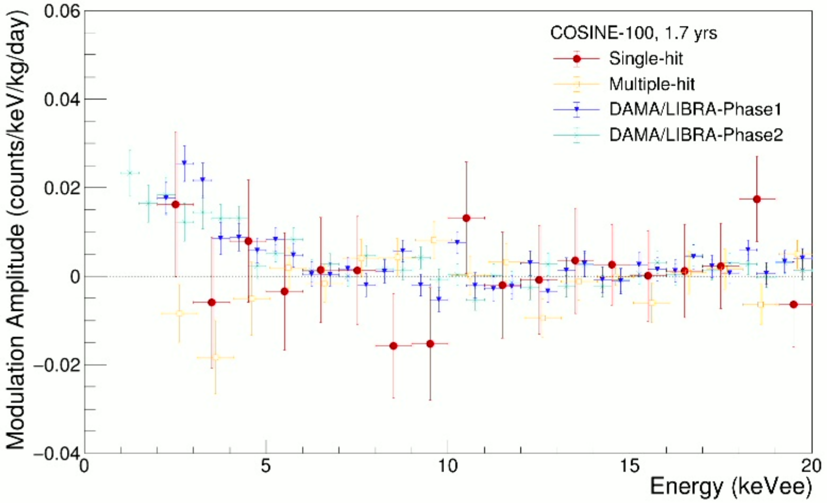
- 1.7 years (97.7 kg x years) exposure
- Global fit using cosmogenic and sinusoidal components simultaneously for crystals
- Crystal 1, 5, and 8 excluded in this analysis due to low light yield and excessive PMT noise
- Sideband events decrease exponentially, agrees with known cosmogenic components

PRL 123.031302

COSINE-100 Results



Configuration	χ^2	*d.o.f.*	p-value	Amplitude (counts/keV/kg/day)	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092±0.0067	127.2±45.9
DAMA/LIBRA (Phase1+Phase2)	–	–	–	0.0096±0.0008	145±5
COSINE-100	175.6	175	0.473	0.0083±0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.143	0.0024±0.0071	152.5 (fixed)
ANAIS-112	48.0	53	0.67	-0.0044±0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1+Phase2)	71.8	101	0.988	0.0095±0.0008	152.5 (fixed)

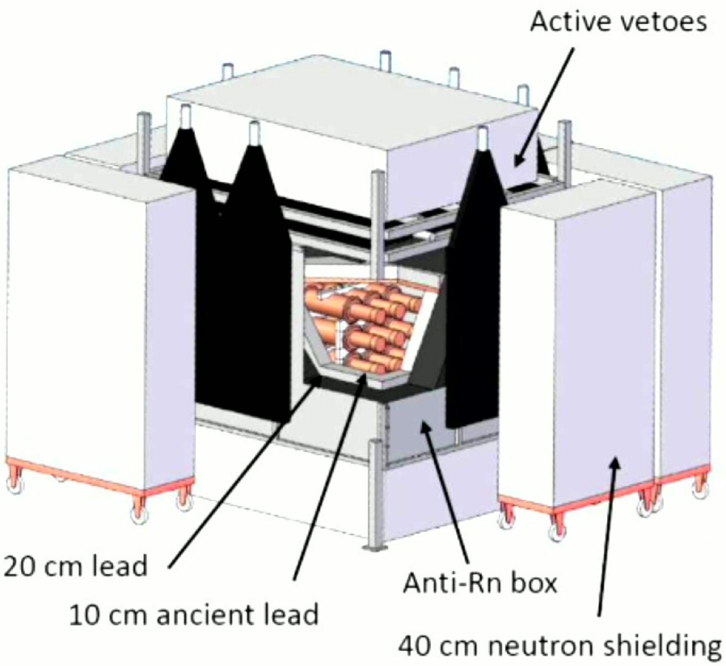


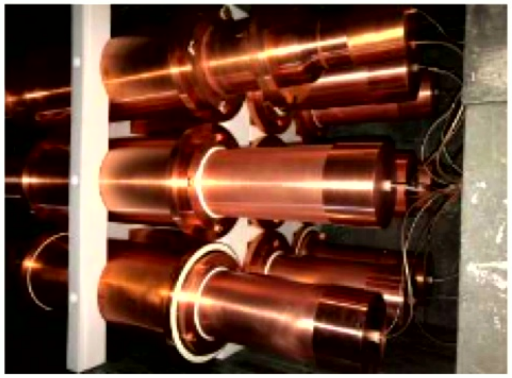
- Best fit amplitude and phase for 2 - 6 keV
  - 0.0092 ± 0.0067 cpd/kg/keV
  - 127.2 ± 45.9 days
- The result is consistent with both the null hypothesis and DAMA/LIBRA's best fit value
- Expect 3σ coverage of DAMA region within 5 years of data exposure
- Future analyses will utilize at least a 1 keV threshold and improved event selection to reduce the exposure required for 3σ coverage.

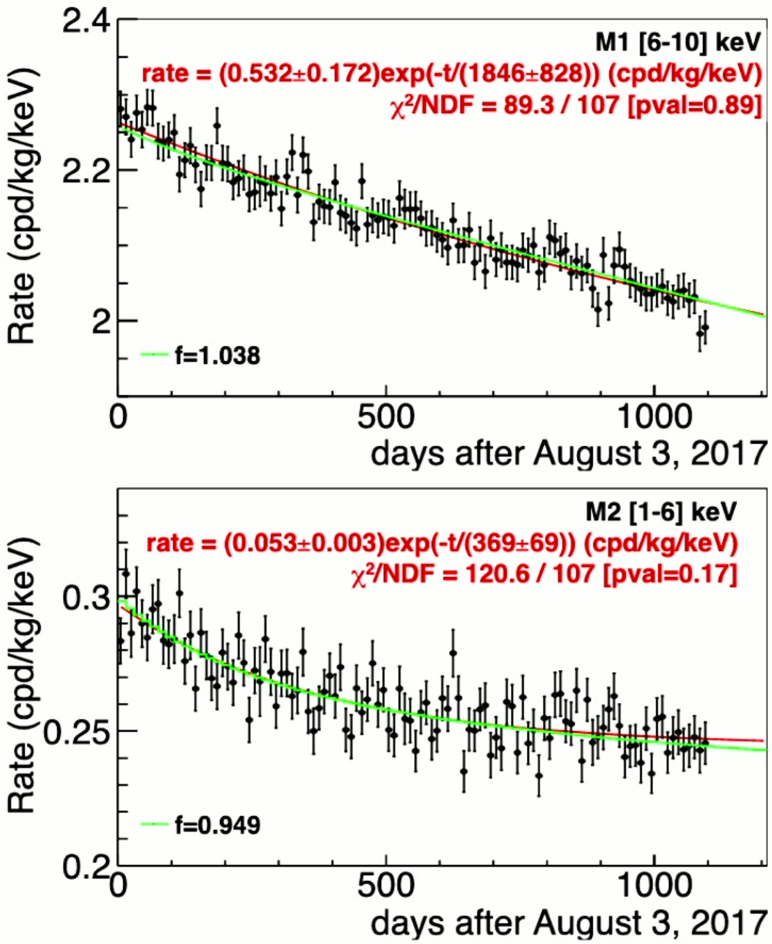
Phys. Rev. D 103, 102005

ANAIS 112

- Located in Hall B at the Canfranc Laboratory (2450 mwe).
- NaI(Tl) crystals (12.5 kg each) grown from ultra pure NaI powder and housed in OFE copper.
  - 112.5 kg of NaI(Tl), distributed in a 3×3 array of modules.
- Mylar window for low energy calibration
- Two Hamamatsu R12669SEL2 photomultipliers
  - Low background, high quantum efficiency.





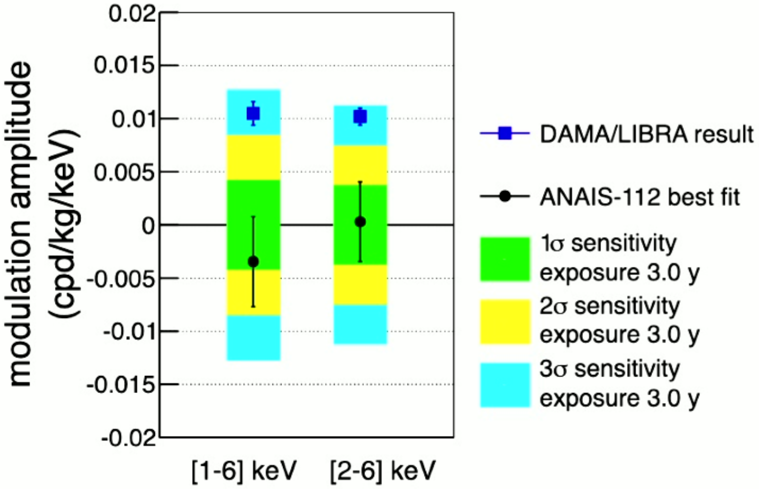


ANAIS 112:
3-Year Background Models

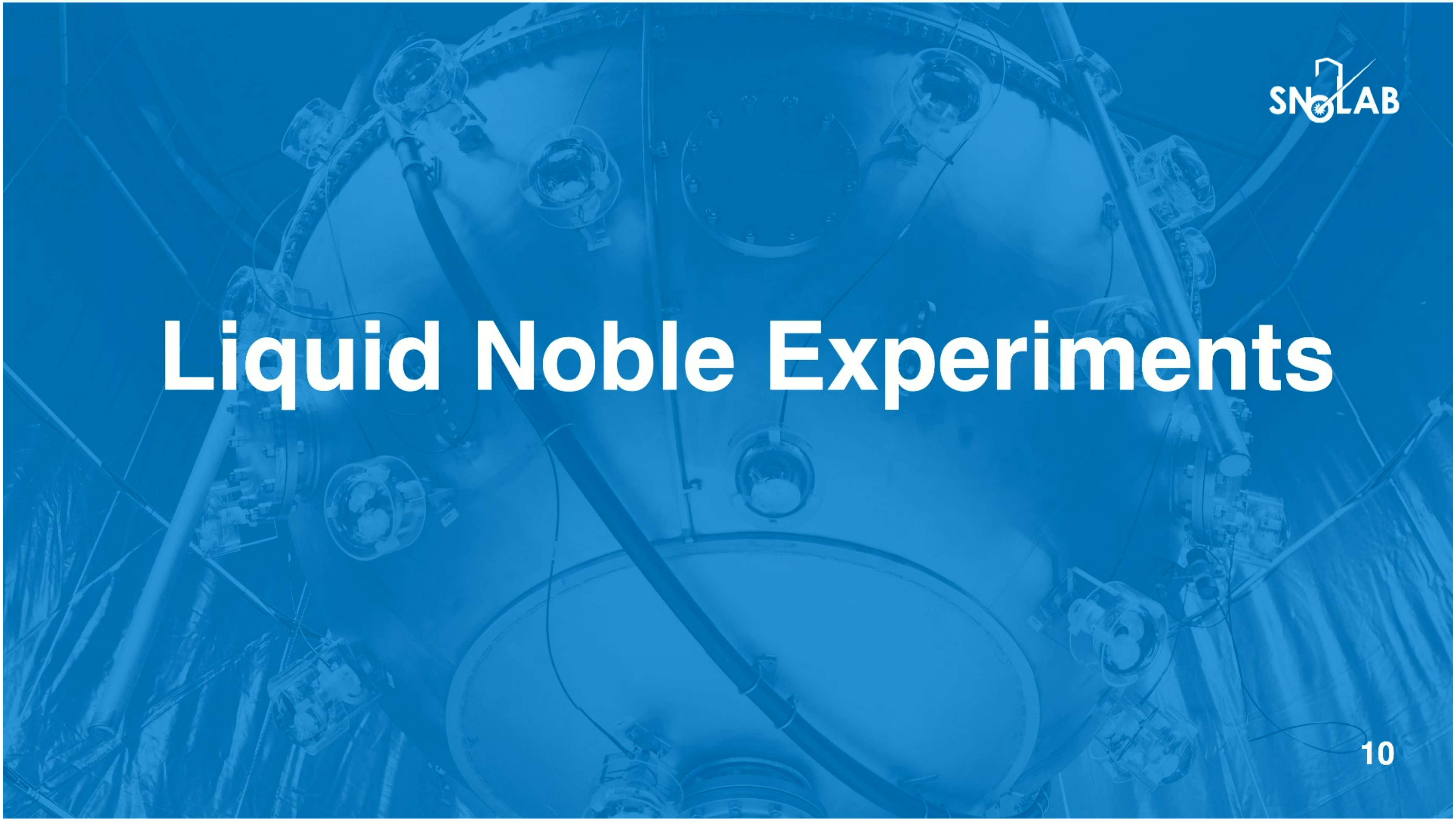
- Three independent background modeling procedures:
  - Exponentially decaying background
  - Probability distribution function derived from background model
  - Probability distribution function for every detector to account for possible systematic effects related with the different backgrounds and efficiencies of the different modules.

ANAIS 112: 3 Year Results

Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	1	132 / 107	3	-0.0045±0.0044	0.051	0.051
	2	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	3	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	1	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	2	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	3	1018 / 972	18	0.0003±0.0037	0.14	0.15

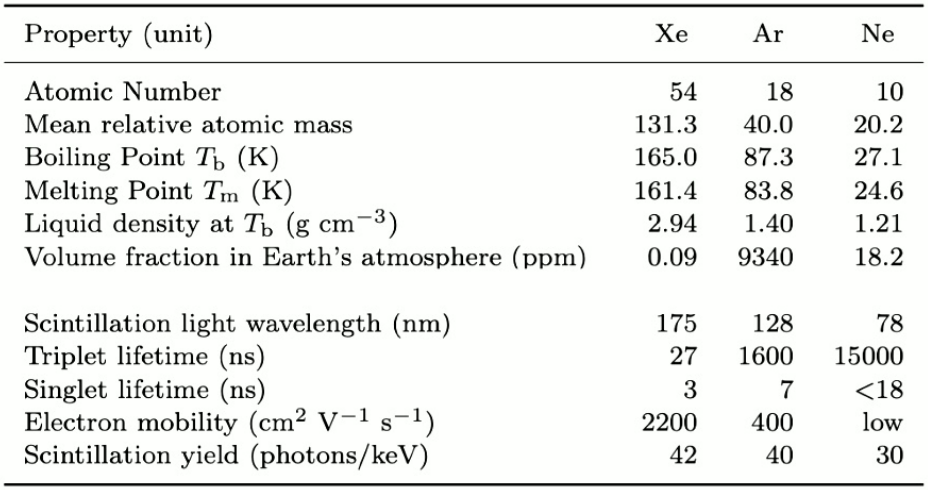


- Data support the absence of modulation in both energy region and three background models.
- Best fits are incompatible with DAMA/LIBRA at 3.3 σ in the [1-6] keV region and 2.6σ in the [2-6]keV region

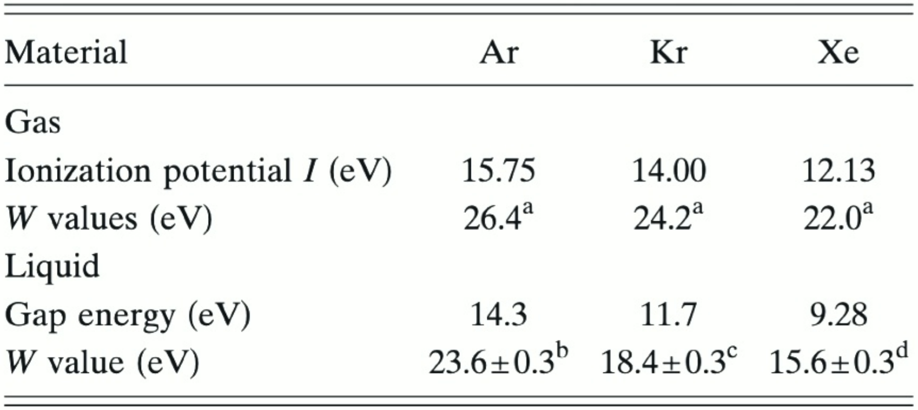


Liquid Noble Experiments

Liquid Noble Properties



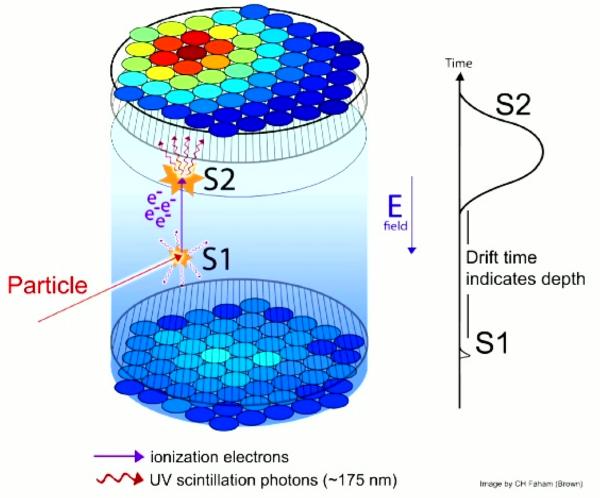
Property (unit)	Xe	Ar	Ne
Atomic Number	54	18	10
Mean relative atomic mass	131.3	40.0	20.2
Boiling Point T_b (K)	165.0	87.3	27.1
Melting Point T_m (K)	161.4	83.8	24.6
Liquid density at T_b (g cm^{-3})	2.94	1.40	1.21
Volume fraction in Earth's atmosphere (ppm)	0.09	9340	18.2
Scintillation light wavelength (nm)	175	128	78
Triplet lifetime (ns)	27	1600	15000
Singlet lifetime (ns)	3	7	<18
Electron mobility (cm^2 V^{-1} s^{-1})	2200	400	low
Scintillation yield (photons/keV)	42	40	30

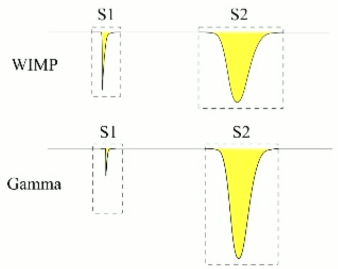


Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

- Three different noble liquids have been considered for dark matter detection over the past few decades.
- Properties of the noble liquids determine many practical aspects of the detectors. For example, Xe has a high density and a large target mass (favorable) but it is not very abundant in the atmosphere (more expensive).
- The energy loss of an incident particle in noble liquids is shared between excitation, ionization and sub-excitation electrons liberated in the ionization process
- The average energy loss in ionization is slightly larger than the ionization potential or the gap energy, because it includes multiple ionization processes
- As a result, the ratio of the W-value (average energy required to produce an electron-ion pair) to the ionization potential or gap energy equals 1.6 - 1.7

Liquid Noble Detectors

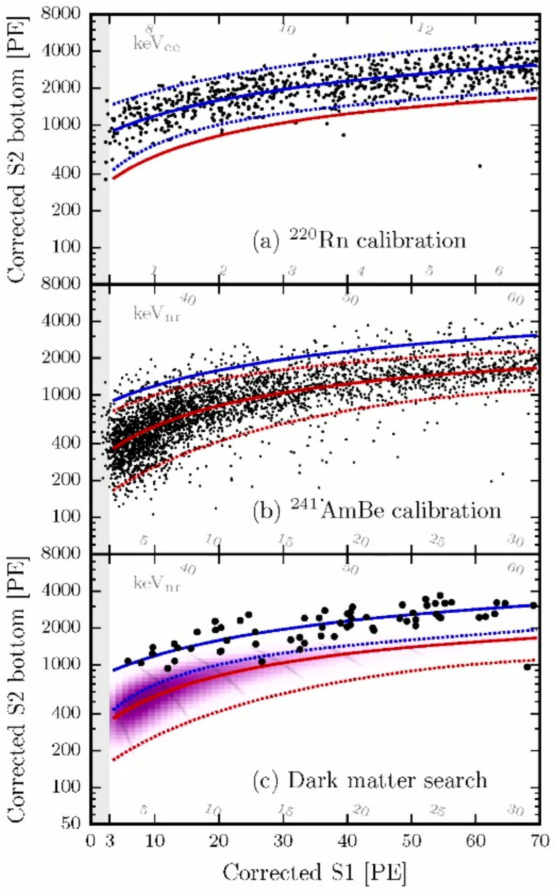




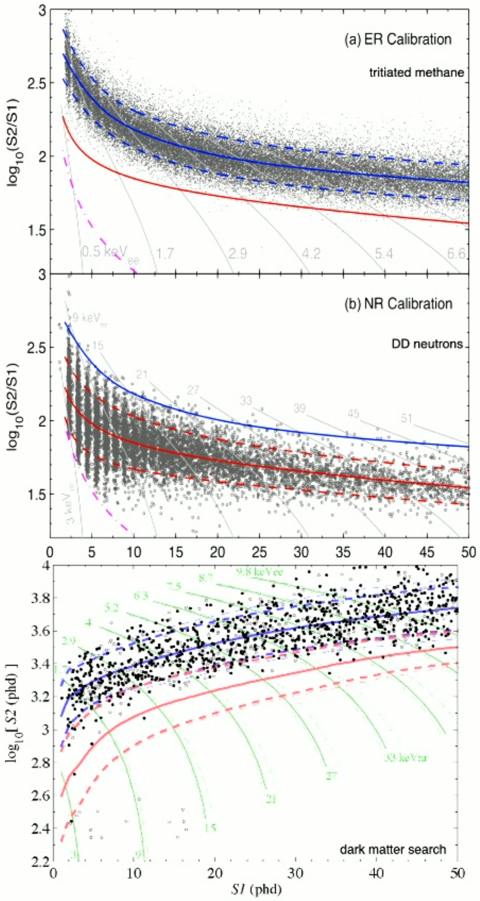
Dual Phase TPCs (XENON, LUX/LZ, Darkside PandaX, etc)

- Interactions in the liquid produce excitation and ionization.
- Excitation leads to scintillation light emission
- Ionization electrons are drifted with an applied electric field into the gas phase (S1).
- In the gas phase, electrons are further accelerated producing proportional scintillation (S2).
- PMTs on the bottom and top of the chamber record scintillation signals.
- Distribution of S2 give xy coordinates, drift time gives z coordinates
- Ratio of S2/S1 discriminates electron and nuclear recoils

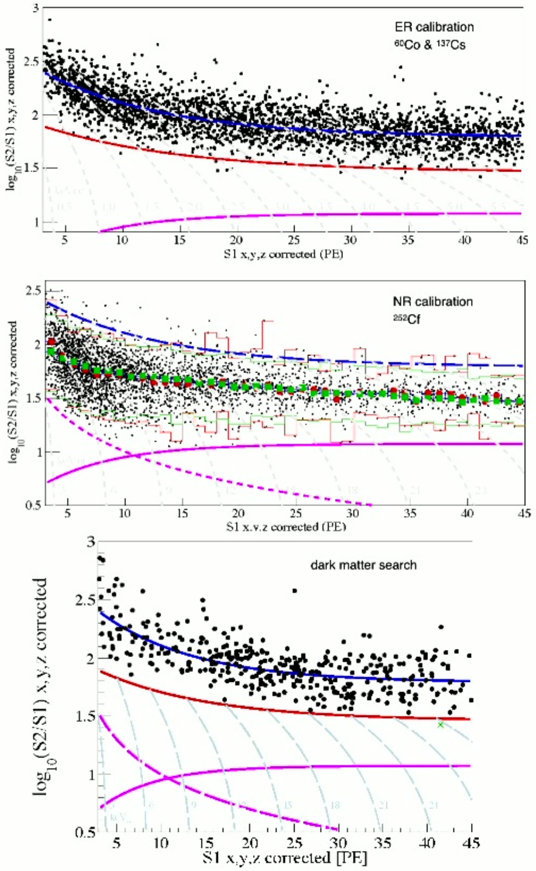
Xenon1T



LUX



PandaX-II



Energy

Nuclear recoils are measured through a combination of scintillation light and ionization. The nuclear recoil energy is related to S1 by

observed
scintillation [PE]

[keV$_{\mathrm{nr}}$]

$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

suppression of scintillation
signal from electric field for
ER and NR events

light yield
[PE/keVee]

scintillation efficiency
of NR in LXe

Energy

Nuclear recoils are measured through a combination of scintillation light and ionization. The nuclear recoil energy is related to S1 by

[keV$_{nr}$]

observed scintillation [PE]

$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

suppression of scintillation signal from electric field for ER and NR events

light yield [PE/keVee]

scintillation efficiency of NR in LXe

The nuclear recoil energy is related to S2 by

observed scintillation [PE]

$$E = \frac{S2}{Y} \frac{1}{Q_y(E)}$$

[keV$_{nr}$]

number of free electrons per unit energy

secondary amplification factor [pe/e$^-$]

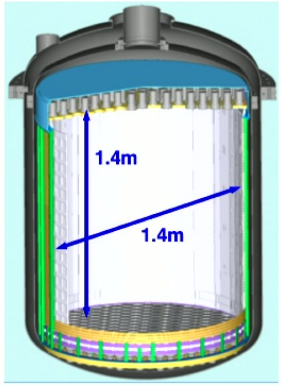
L$_{eff}$ accounts for the quenching of the scintillation signal for a nuclear recoil.

$$L_{eff} \equiv \frac{S1(E_{nr})/E_{nr}}{S1(122keV_{ee})/122keV_{ee}}$$

122 γ line from ^{57}Co source

Status Of Current TPC Dark Matter Experiments

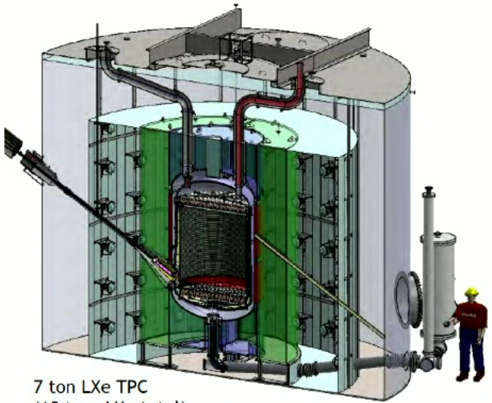
XENONnT



2019-2025

8T LXe

LZ



7 ton LXe TPC
(10 tons LXe total)

2021-2025

7t LXe

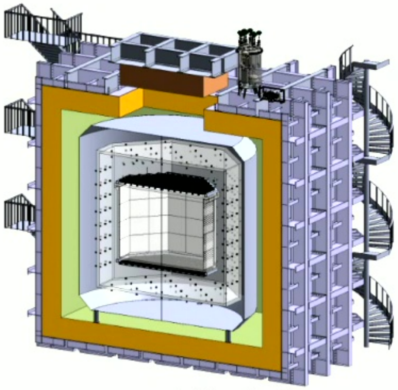
PandaX-4T

2020 - ?

4t LXe

Taking Data

DarkSide-20K



50t LAr

2026 - ?

Under Construction

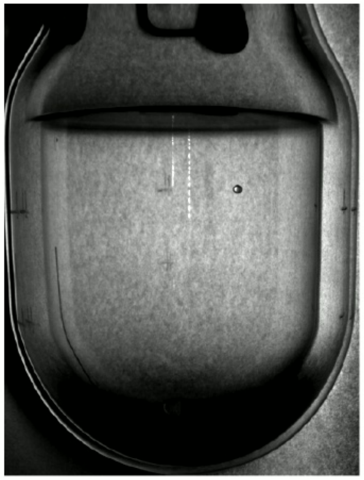
Darwin

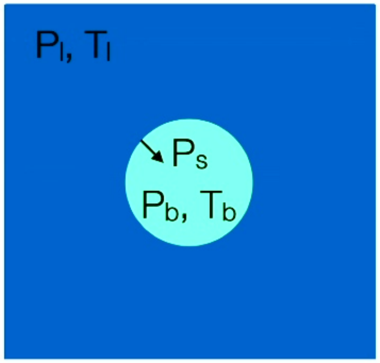
50T LXe

XLZD

50T LXe

Taking Data





NIM A 781(2015) p96

How Do Bubble Chambers Work?

- Start with a bubble in a liquid in thermal and chemical equilibrium

$$T_l = T_b$$

- If $P_b > P_l$ the bubble will expand (assuming no surface tension).
- Include surface tension, $P_s = 2\sigma / r$, bubble grows when

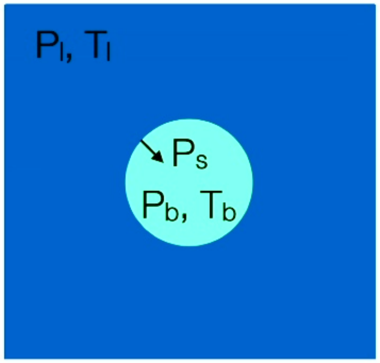
$$P_b > P_l + P_s$$

$$\text{and} \qquad r > r_c = \frac{2\sigma}{P_b - P_l}$$

- Bubbles that do not meet this criteria collapse

NIM A 781(2015) p96

How Do Bubble Chambers Work?



- The threshold for bubble nucleation is given by

$$E_T = \underbrace{r\pi r_c^2\left(\sigma - T\left[\frac{d\sigma}{dT}\right]_\mu\right)}_{\text{surface energy}} + \underbrace{\frac{4\pi}{3}r_c^3\rho_b(h_b - h_l)}_{\text{bulk energy}} - \underbrace{\frac{4\pi}{3}r_c^3(P_b - P_l)}_{\text{reversible work}}$$

ρ = *density and* h = *specific heat*

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$$\text{and} \quad r > r_c = \frac{2\sigma}{P_b - P_l}$$

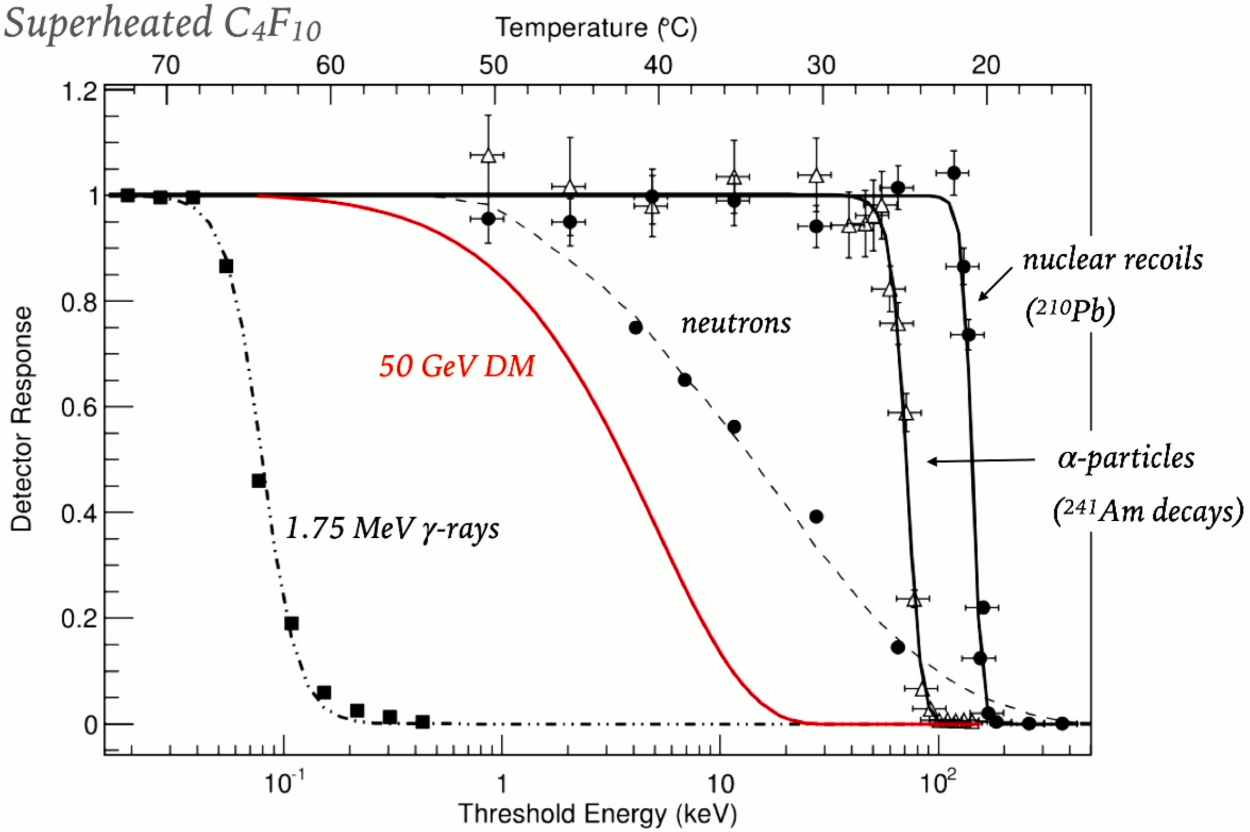
- Bubbles that do not meet this criteria collapse

Physics Letters B 711 (2012) 153–161

Detector Response

- Heavier particles have higher thresholds
- Tune the chamber to be unresponsive to most backgrounds(ER).
- Underground location and shielding to mitigate neutrons.
- But what about alphas?

Superheated C_4F_{10}



Physics Letters B 711 (2012) 153–161

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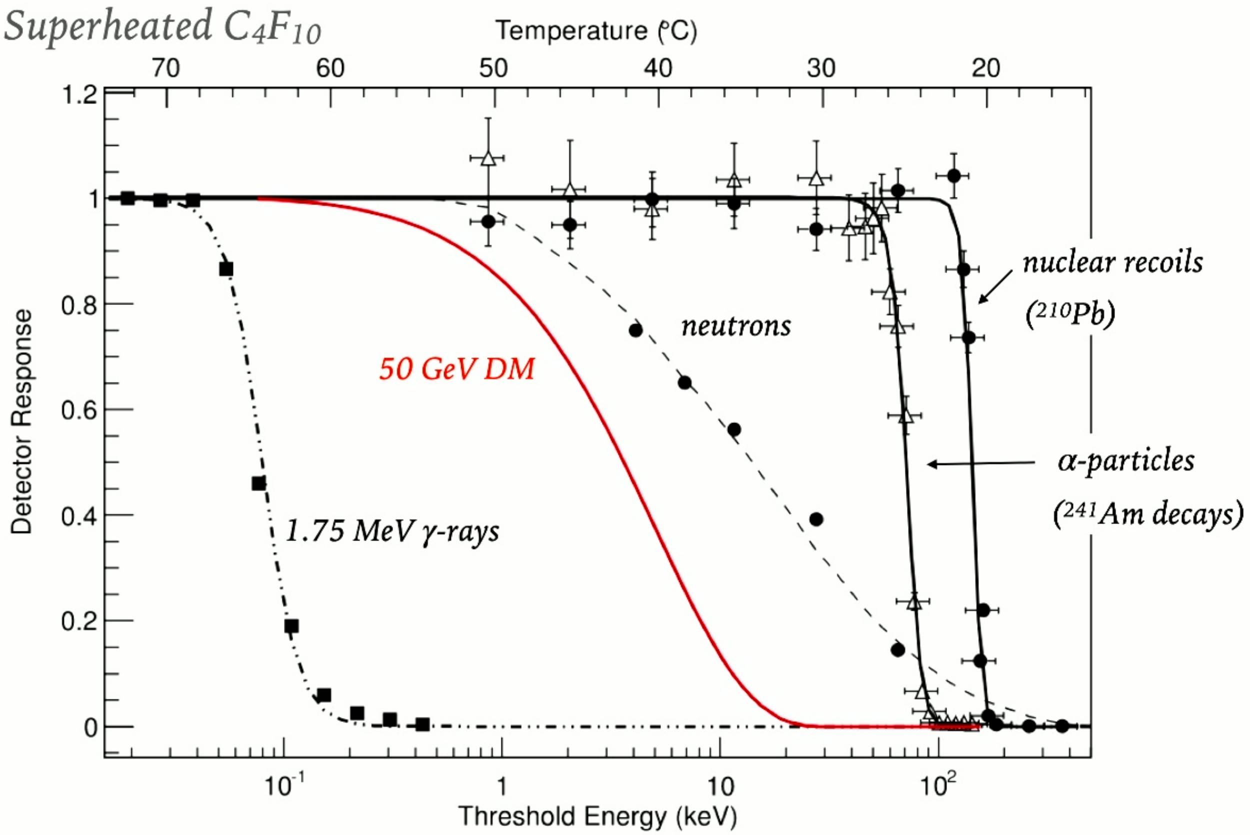
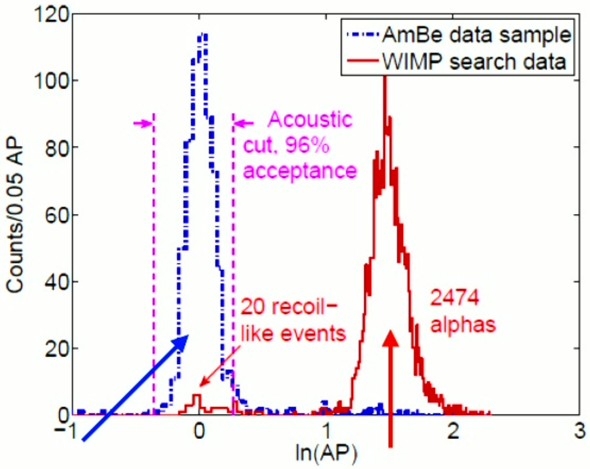
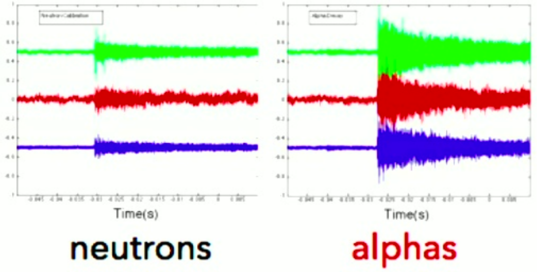
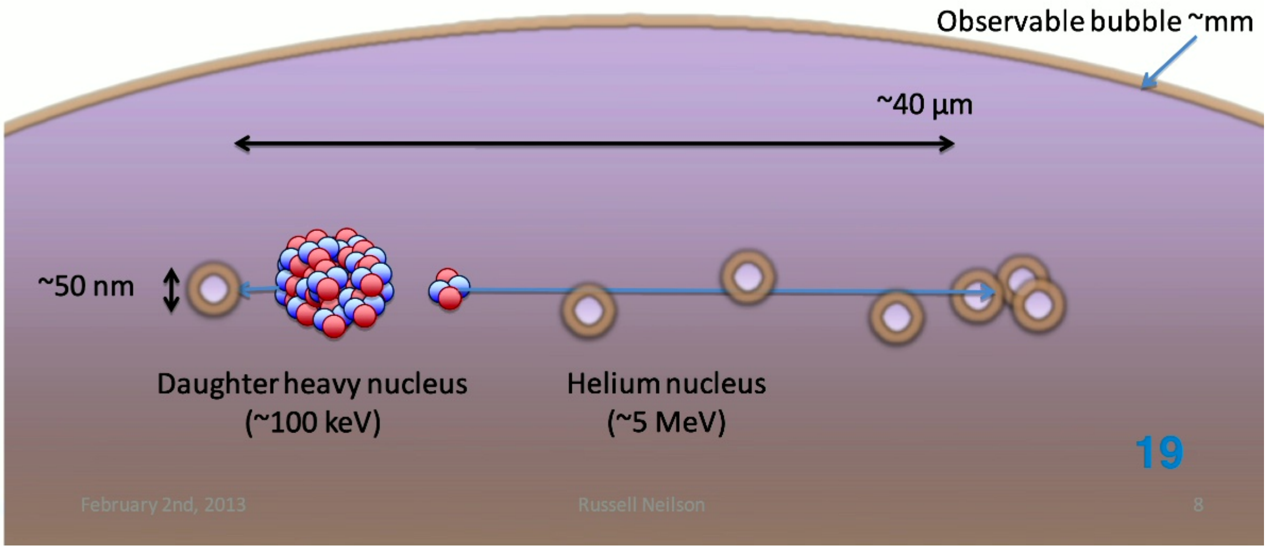


Liquid Noble Properties

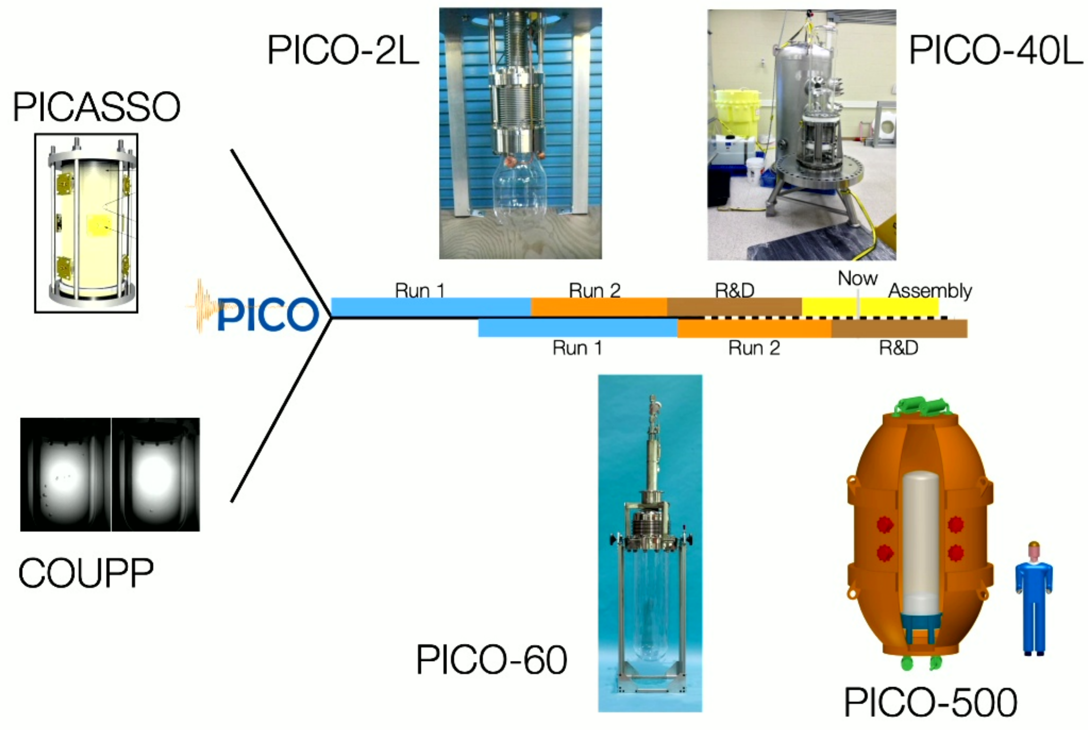


- Alphas deposit their energy over 10s of microns
- Nuclear recoils deposit their energy over 10s of nanometers
- Alpha particles are ~4 times louder than NR. This can be measured by piezoelectric sensors





PICO Program



PICASSO

PICO-2L

PICO-40L

PICO

Run 1

Run 2

R&D

Now

Assembly

Run 1

Run 2

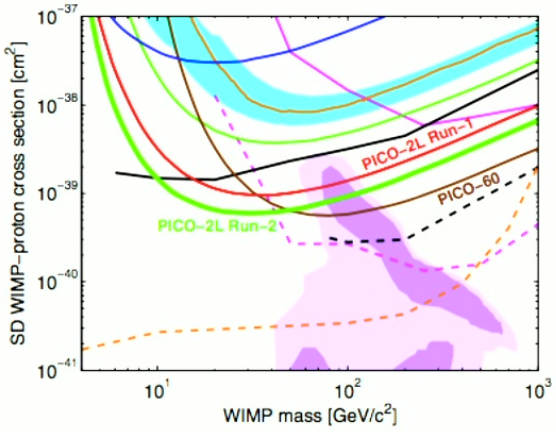
R&D

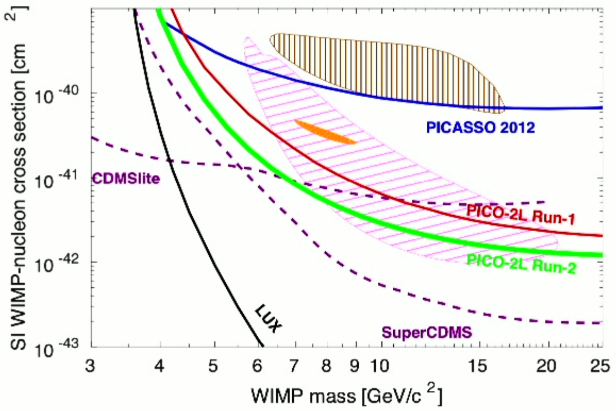
COUPP

PICO-60

PICO-500

PICO-2L Results

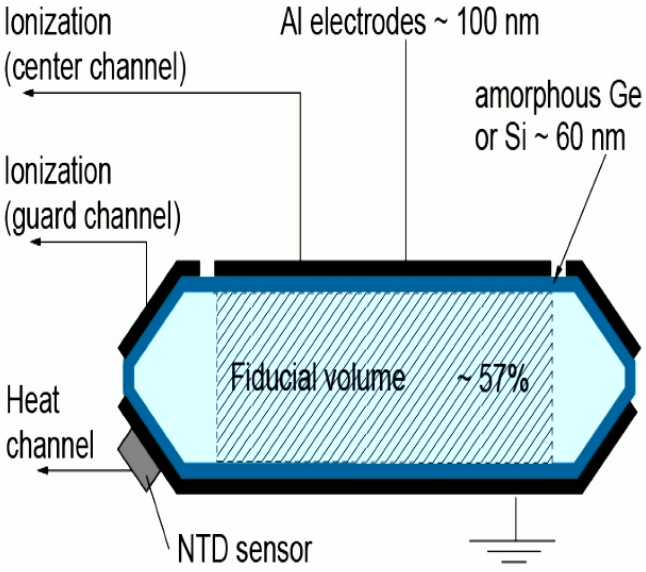




Ken Clark

SNOLAB

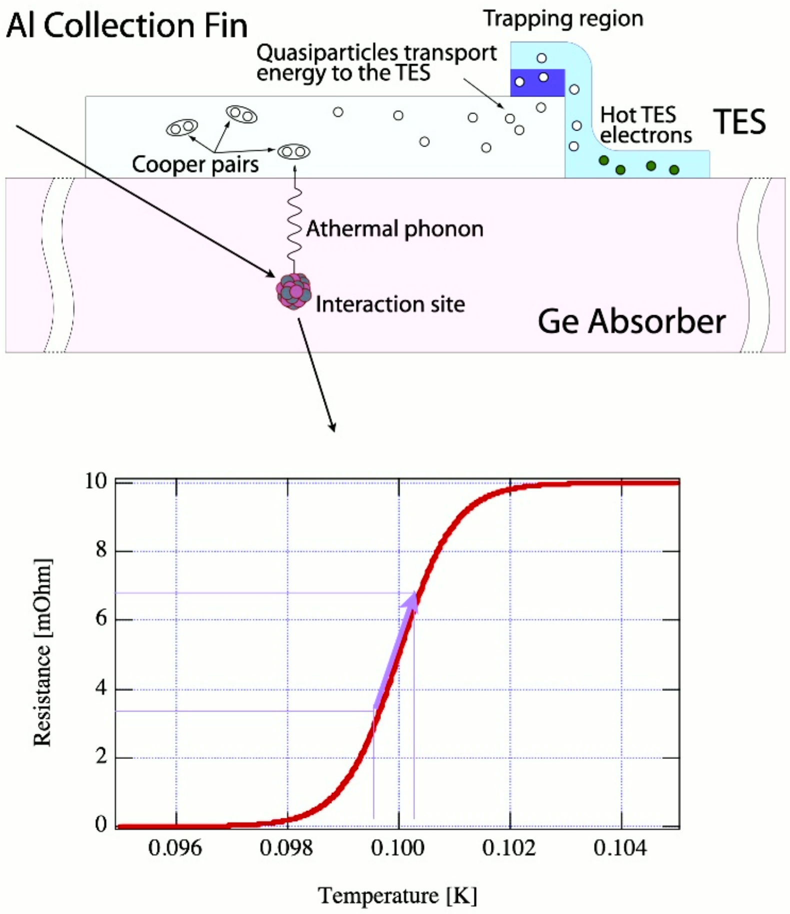
NTDs



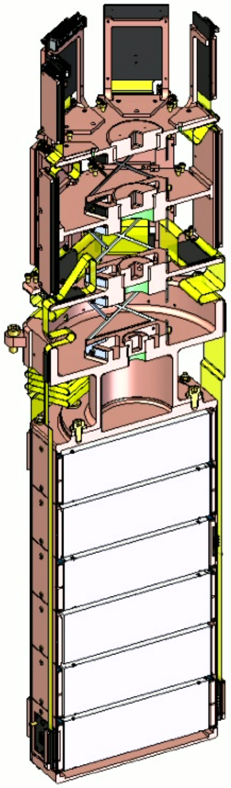
Schematic “Ge-NTD”
EDELWEISS detector

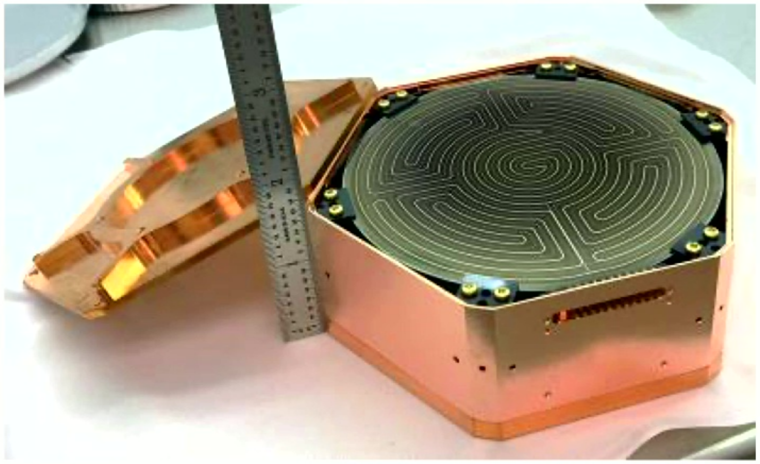
- ➤ NTDs are small Ge semiconductor crystals that have been exposed to a neutron flux to make a large, controlled density of impurity.
- ➤ NTD measures small temperature variations relative to $T_{0,}$ which is set to be on the transition from superconducting and resistance regime with dependence of the resistance with temperature T
- ➤ Resistance is continuously measured by flowing current through it and measuring the resulting voltage.
- ➤ Sensors are glued onto detector.

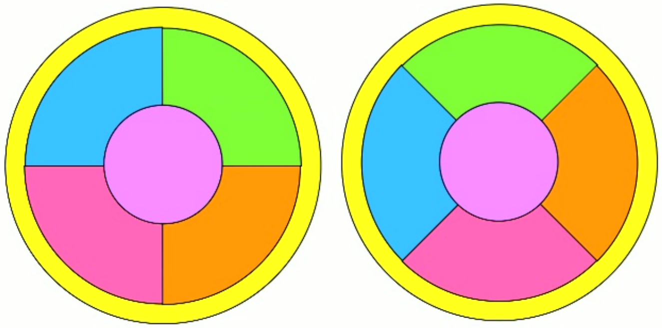
Transition Edge Sensors



- TES is a thin superconducting film operated near its T_c.
- Refrigerator temperature needs to be close to absolute zero.
- A heater with an electothermal feedback system maintains temperature at superconducting edge.
- Temperature changes are detected by a change in the feedback current, collected by a SQUID.



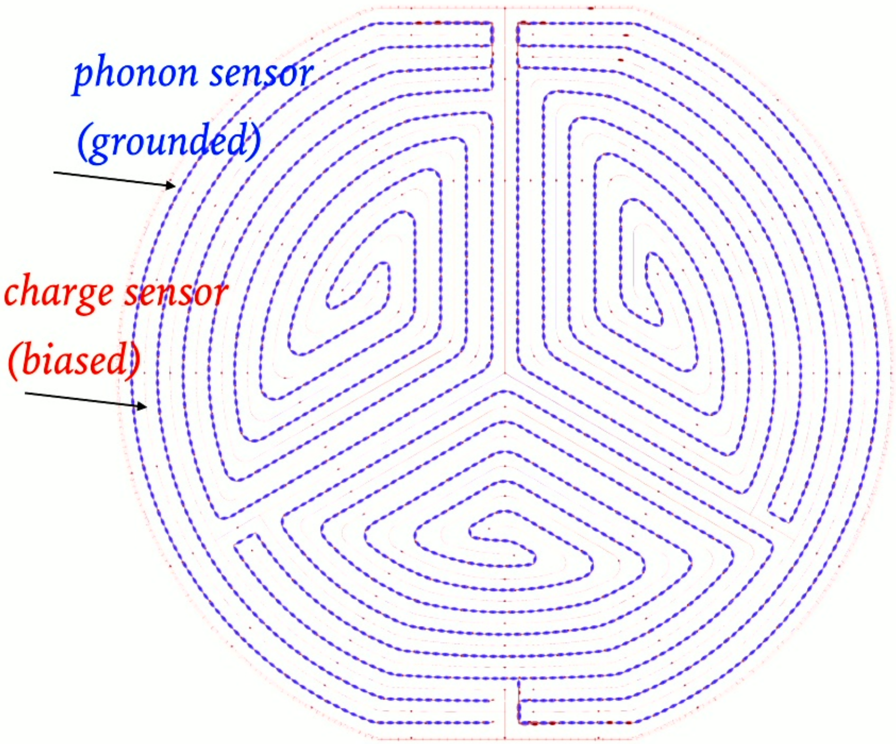




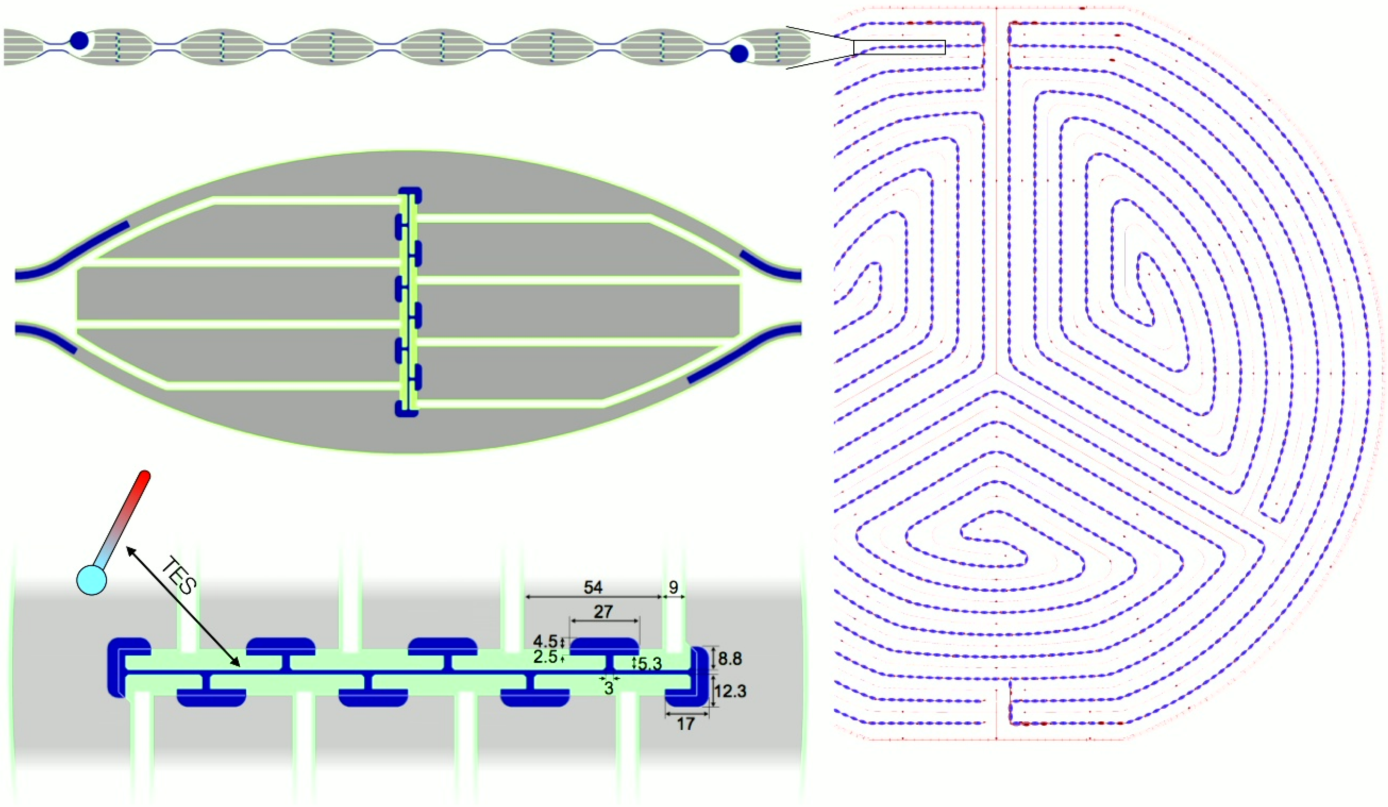
SuperCDMS SNOLAB Detectors

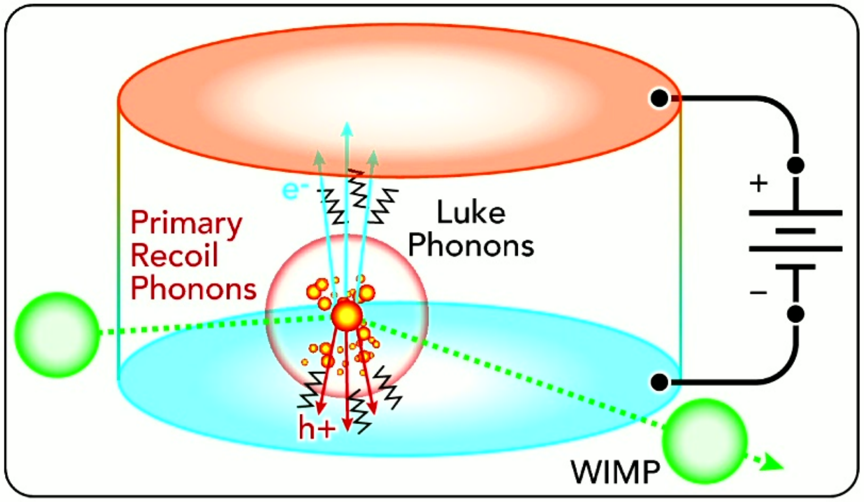
- Initial payload 4 towers, each w/6 detectors (1.39 kg Ge crystals, 0.61 kg Is crystals) each 100 mm diameter, 33.3 mm thick:
  - 2 HV (4 Ge + 2 Si)
  - 2 iZIP (6 Ge & 4 Ge + 2 Si)
- iZIP detectors
  - 8 phonon channels + 2 charge sensors each side
- HV detectors
  - 6 phonon channels on each side

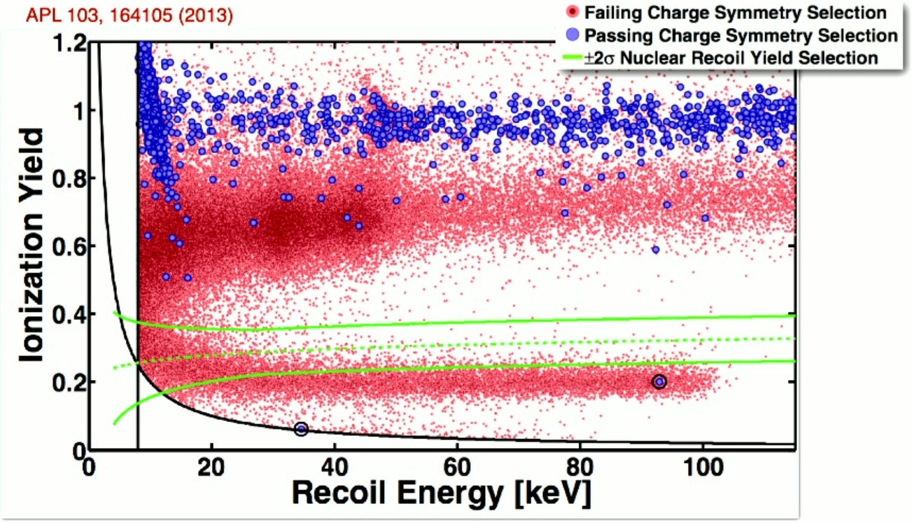
iZIP Detector



iZIP Detector

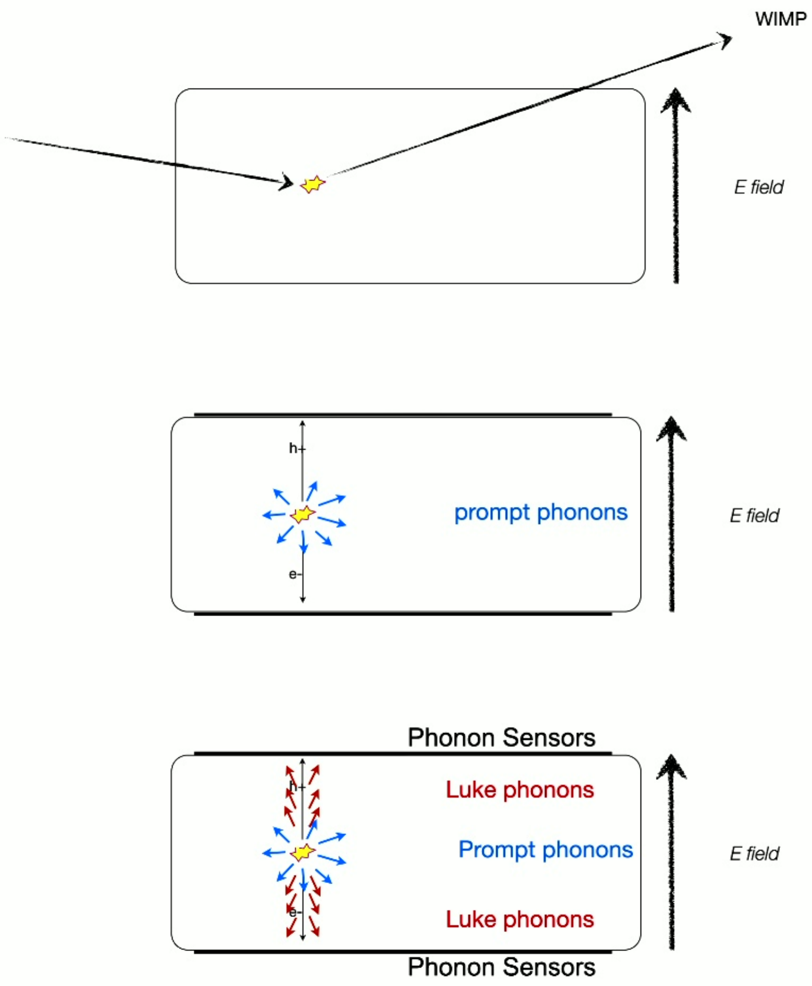





APL 103, 164105 (2013)

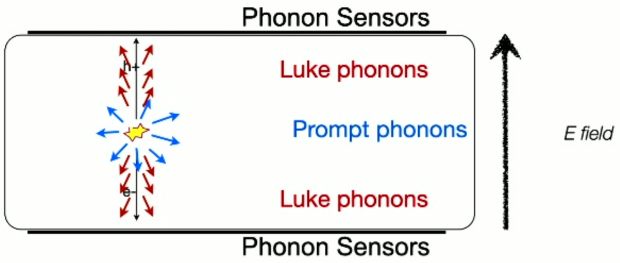
SuperCDMS - iZIP Mode

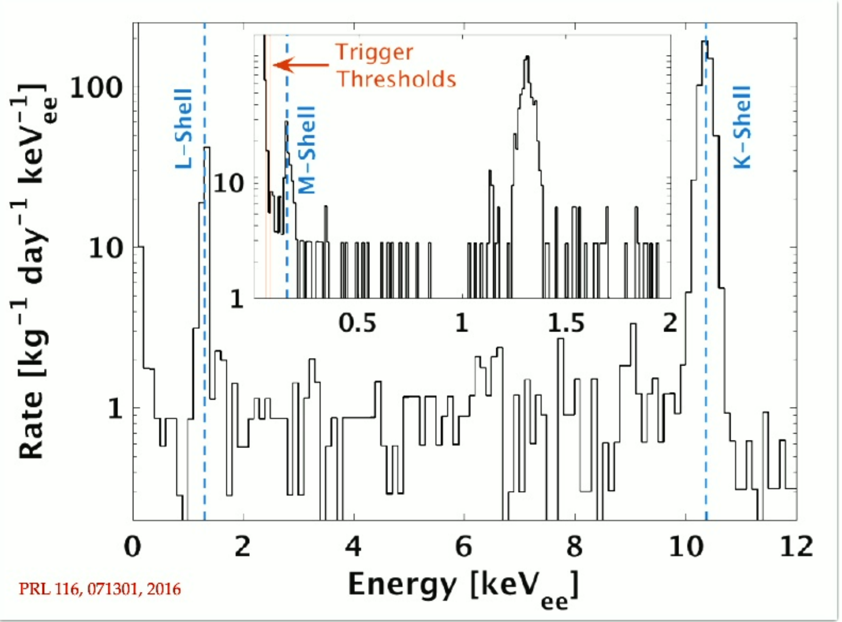
- Primary (prompt) phonon and ionization signals allow for discrimination between NR and ER events
- High resolution phonon and charge readout
- All surface and ER backgrounds above a few keV can be easily removed with selection criteria.



SuperCDMS - HV Mode

- Drifting electrons across a potential (V) generates a large number of phonons (NLT phonons)





PRL 116, 071301, 2016

- Drifting electrons across a potential (V) generates a large number of phonons (N phonons)

$$E_t = E_r + N_{eh} e V_b$$

total phonon energy

primary recoil energy

Luke phonon energy

- Ultra high resolution indirect charge measurement
- Thresholds 75 eVee and 56 eVee
- No yield or detector face discrimination

On Units

We know that NTL phonon energy is given by

$$E_{NTL} = N_{eh} V_b$$

The number of electron hole pairs generated in an interaction is given by

$$N_{eh} = \frac{E_r}{\epsilon}$$

$\epsilon_{Ge} = 3.0\ \mathrm{eV}$

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NR produce eh-pairs less efficiently than ER. Take this into account, define $Y \equiv 1$ for ER.

$$N_{eh} = Y(E_r)\frac{E_r}{\epsilon}$$

The total energy can then be written

$$E_{tot} = E_r\left(1 + Y(E_r)\frac{eV_b}{\epsilon}\right)$$

If we calibrate detectors using ER, the resulting energy scale is keV_{ee} to convert to keV_{nr} equate for NR and ER.

$$E_{nr}\left(1 + Y(E_{nr})\frac{eV_b}{\epsilon}\right) = E_{ee}\left(1 + \underbrace{Y(E_{ee})}_{\text{recall } Y = 1 \text{ for ER}}\frac{eV_b}{\epsilon}\right)$$

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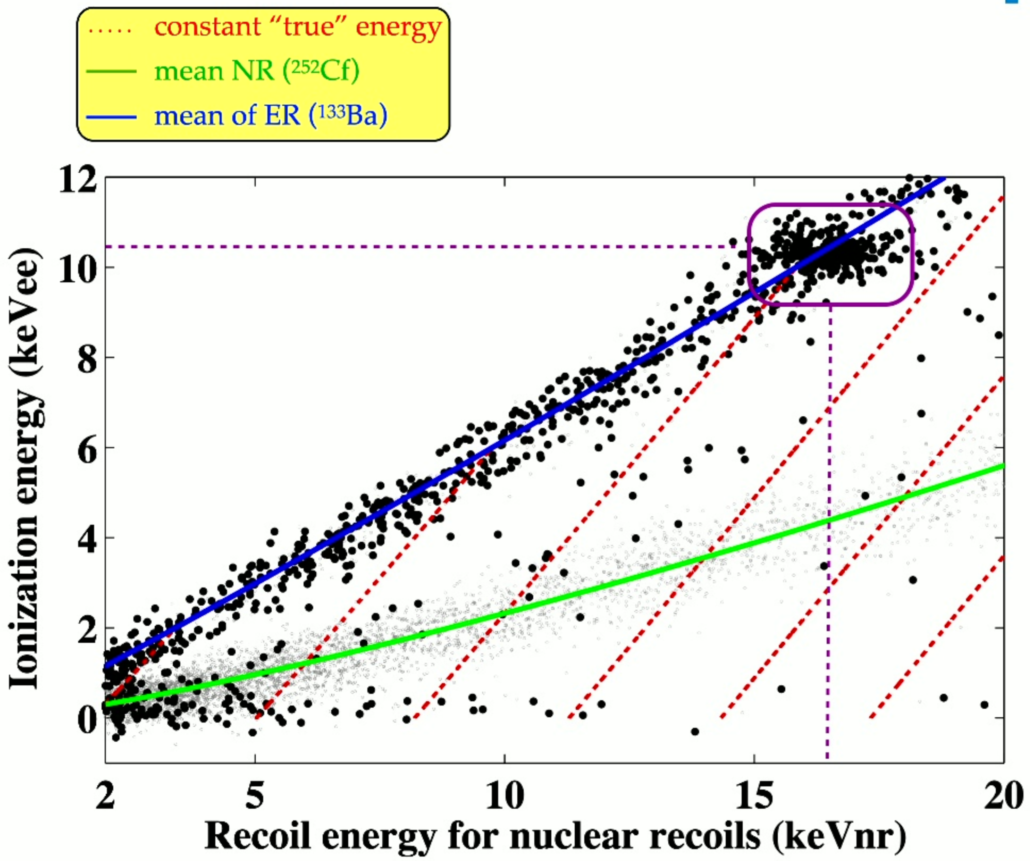
recall $Y = 1$ for ER

$$E_{nr} = E_{ee}\left(\frac{1 + eV_b/\epsilon}{1 + Y(E_{nr})eV_b/\epsilon}\right)$$

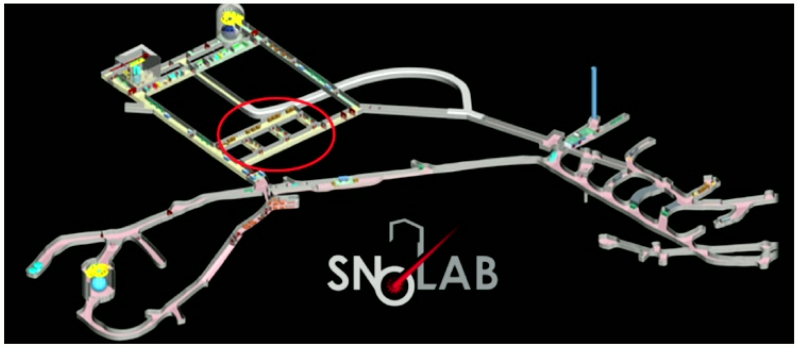
KeV$_{ee}$ vs KeV$_{nr}$

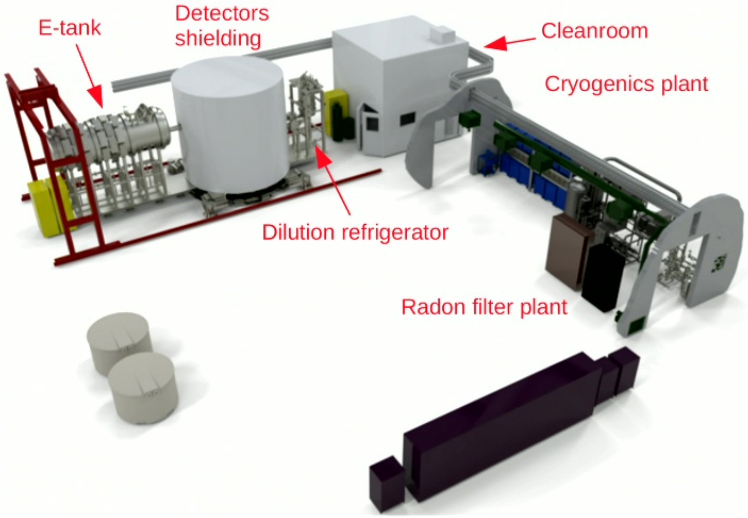


- Ionization energy vs recoil energy assuming NR scale consistent with Luke phonon contributions for NR.
  - ER recoils are pushed to higher energies using the NR scale.
  - Example - 10.4 keV$_{ee}$ ER line appears at ~16 keV$_{nr}$

*A good reference is David Moore's thesis, Chapters 3 and 4
http://thesis.library.caltech.edu/7043/

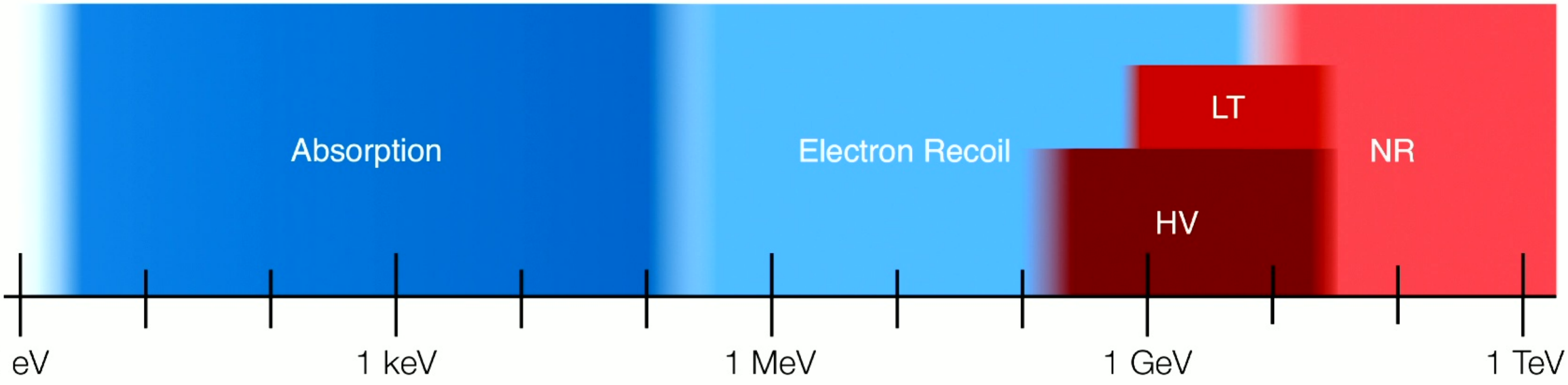
SuperCDMS SNOLAB





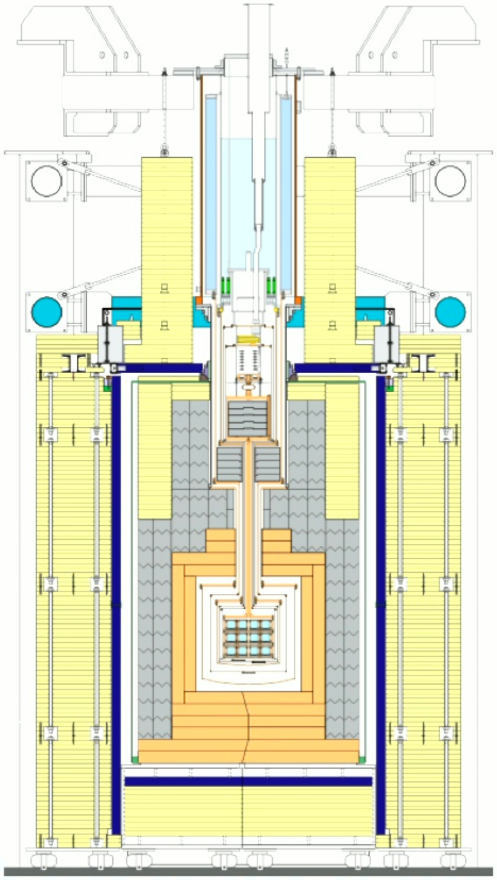
- Generation-2 dark matter experiment under construction at SNOLAB
- Infrastructure:
  - depth ~6900 mwe (results in a factor 100 reduction in muon flux from cosmic rays as compared to Soudan)
  - class 2000 or better cleanroom
  - Cryostat will be able to accommodate up to 7 towers
  - (0.1) dru gamma background
  - 15 mK base temperature
  - vibration isolation
- Initial payload: ~ 30 kg total, 4 towers with 6 detectors per tower (12 iZIP, 12 HV)

SuperCDMS Dark Matter Sensitivity

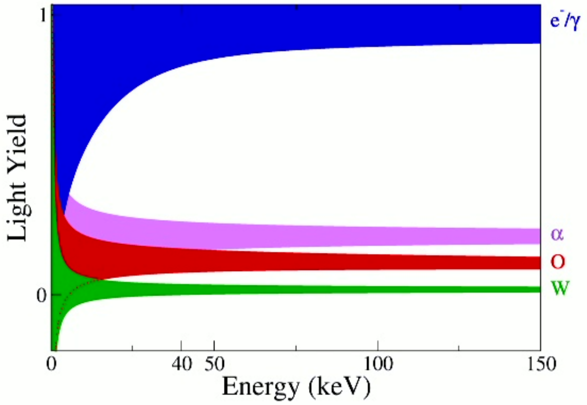


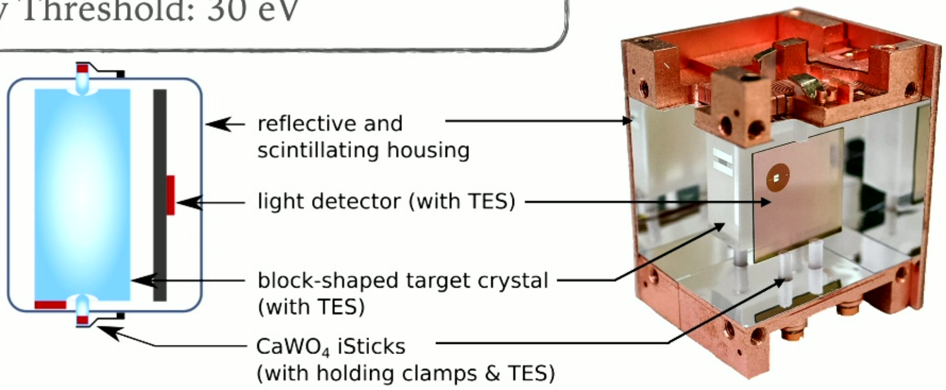
Traditional NR:	iZIP, Background free	>5 GeV
Low Threshold NR:	iZIP, limited discrimination	>1 GeV
HV Mode:	HV, no discrimination	~0.3 - 10 GeV
Electron Recoil:	HV, no discrimination	~0.5 MeV - 10 GeV
Absorption (Dark Photons, ALPs)	HV, no discrimintion	~1 eV - 500 keV (peak search)

CRESST Experiment Operation Principles



- Search of light DM direct interactions with $CaWO_4$ cryogenic detectors
- Operating temperature ~15 mK
- Second cryogenic detector to collect emitted scintillation light: particle identification
- Single detector mass ~24 g
- Energy Threshold: 30 eV





reflective and scintillating housing

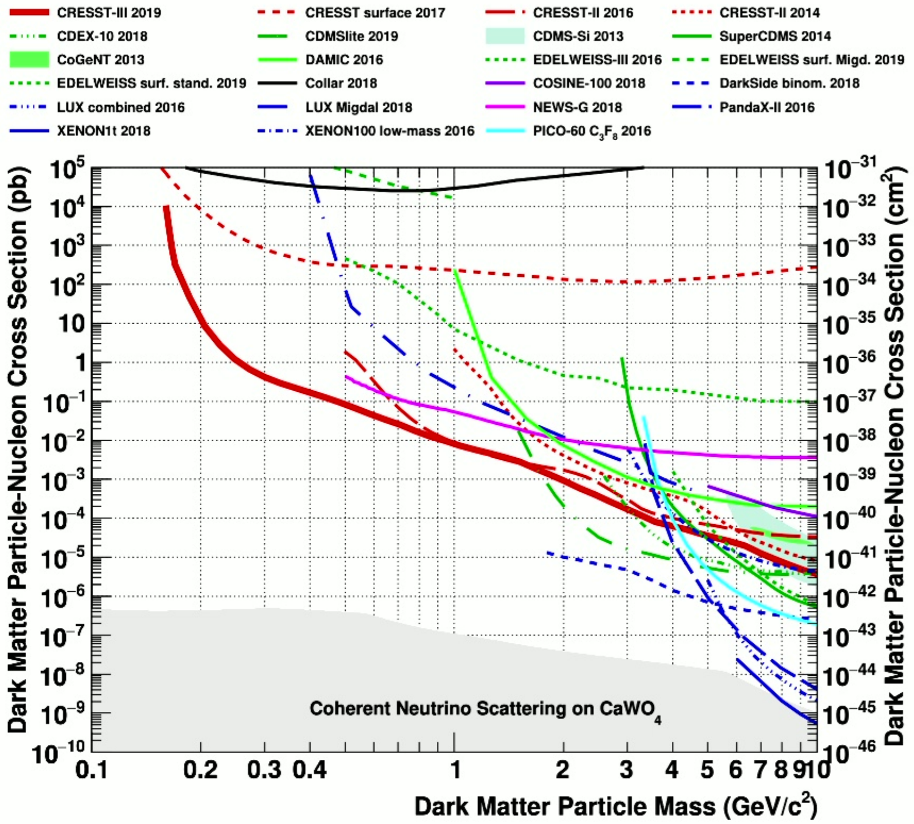
light detector (with TES)

block-shaped target crystal (with TES)

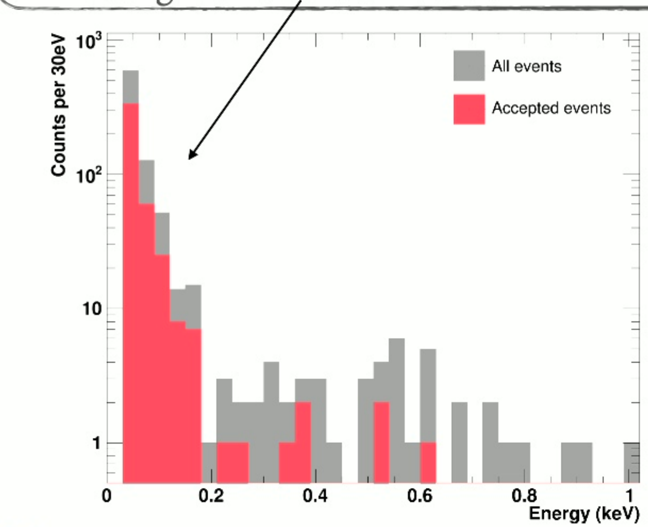
$CaWO_4$ iSticks (with holding clamps & TES)

Phys. Rev. D 100, 102002 (2019)

Limitations: CRESST-III Recent Results



- ➤ More than one order of magnitude improvement at 0.5 GeV/c2
- ➤ Extended reach from 0.5 GeV/c2 to 0.16 GeV/c2
- ➤ Sensitivity limited by unknown background below 200 eV



CRESST Future Plans

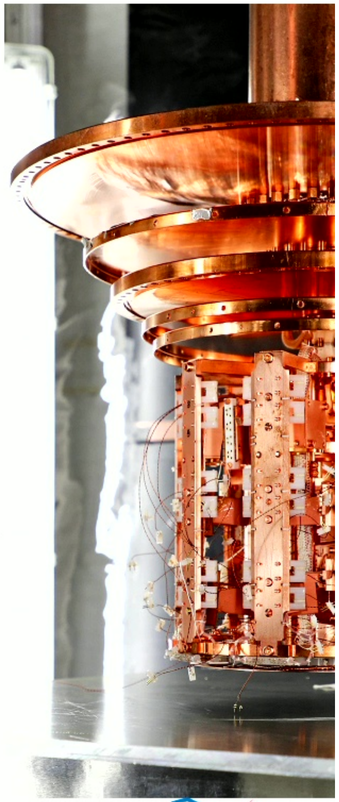
CRESST Upgrade

- Upgrade to 288 readout channels to accommodate 100 modules for O(2 kg) target mass
- Final planning, prototyping and testing of SQUID read-out electronics, biasing system and DAQ
- Sensor development to further push detector threshold (10 eV)
- Complementary detector materials ($LiAlO_2$,) which also yield sensitivity for spin-dependent interactions

Run3

2020 - 2021

- 2nd round with additional modifications.
- Successful cool-down in 03/2020, but stopped due to Corona virus pandemic
- Cool-down started July 20, 2020
- Detetor commissioning Aug - Oct 2020
- November 2020 - August 2021 science data!
- Following science run, dedicated neutron calibration runs to study low energy event excess.



SNOLAB

Phys. Rev. D 100, 102002 (2019)

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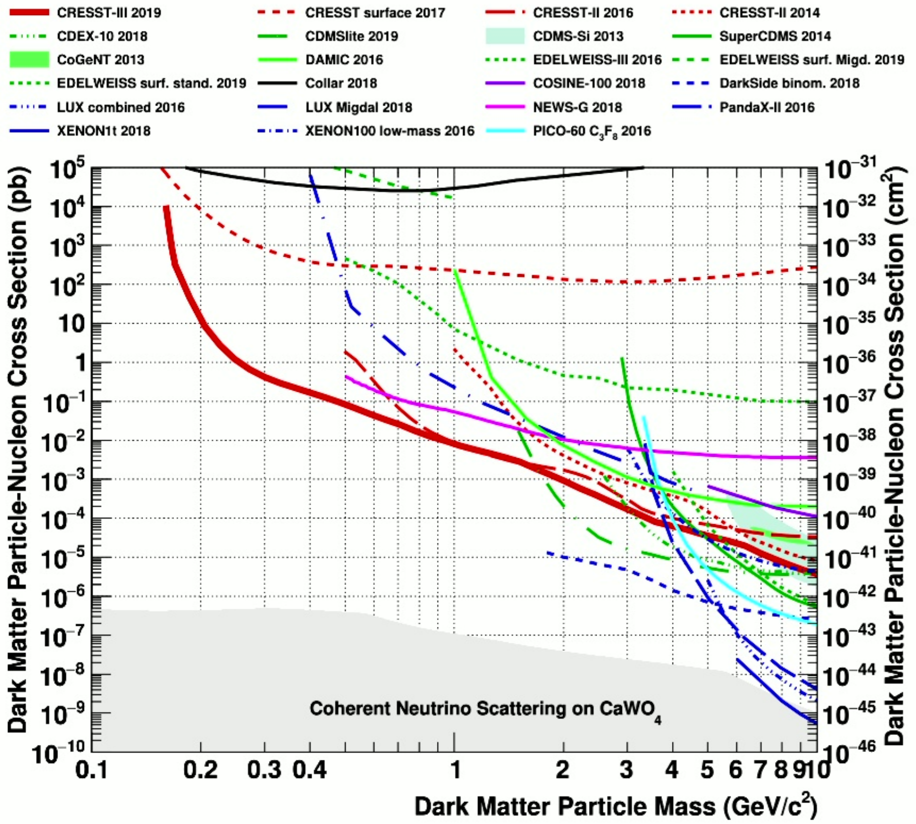

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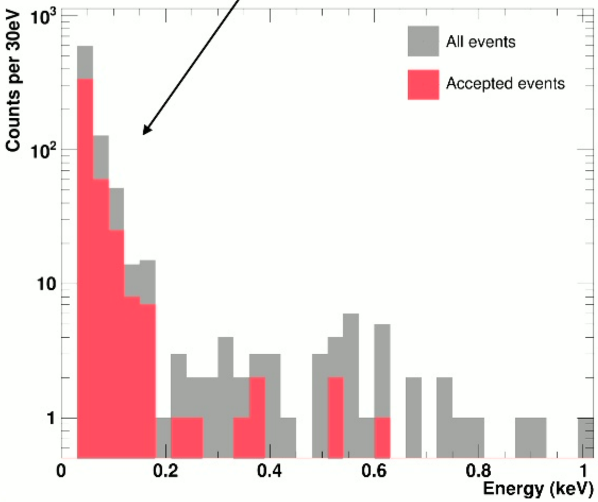
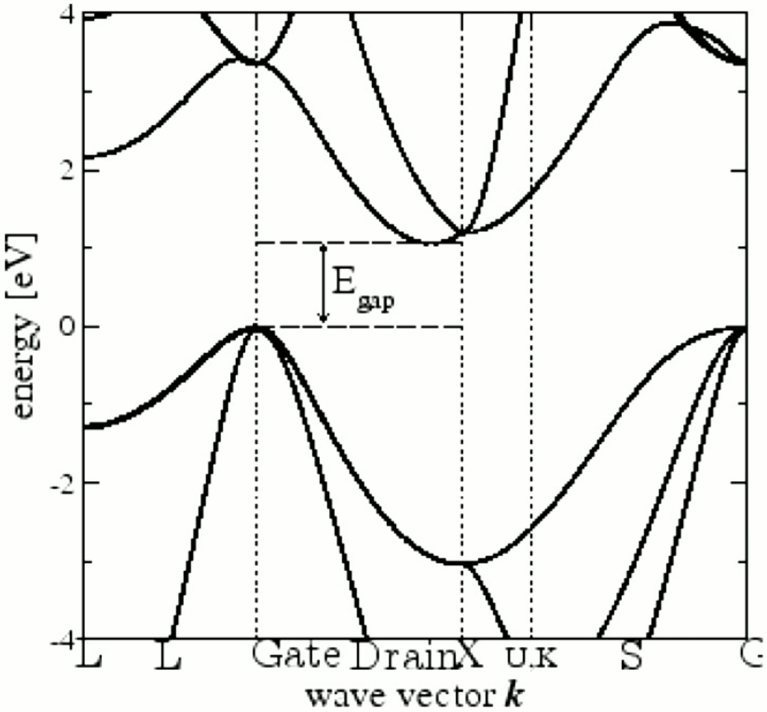


Single e-/h+ Pair Sensitivity

Energy Scale in Semiconductors

Band Diagram for Si



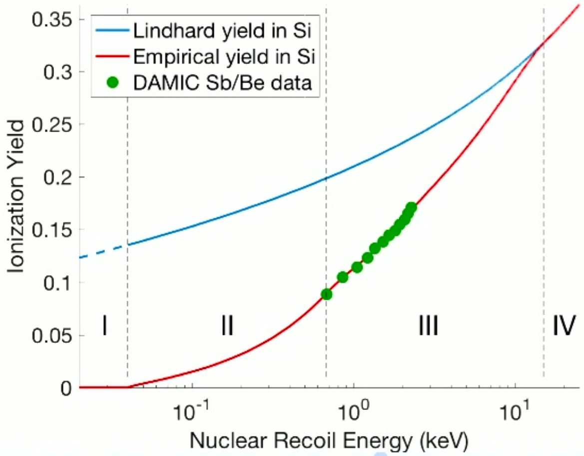
- e- excitation momentum and energy scales in semiconductors can be exploited to search for light mass dark matter
- Si $E_{gap} \sim 1.2$ eV
  - Indirect band gap requires phonon for transition to happen.
  - Temperature dependent
- $\varepsilon_{Si} \sim 3.6$ eV
  - Average energy to produce e/h pair
  - Temperature dependent
- Sensitive to energy deposits of $\mathcal{O}(\mathrm{eV})$ (electron scattering) to $\mathcal{O}(10\ \mathrm{eV})$ (nuclear scattering)

Realm of Solid State Physics

Solid state physics	Particle physics
E < 30 eV	E > keV
Multi-body system	Free particles
Allowed energies/momenta given by dispersion relation	$E = p^2/2m$
Particles may have effective masses	Particle masses well defined

Challenges

- **Detector Response**
  - Details of the band structure become increasingly important
  - PDF to get the numbers of e/h pairs given an energy deposition required, $P(n_{eh}|E_{dep})$
    - Fano statistics (dispersion probabilities)
    - For NR: quenching (ionization yield < 1)



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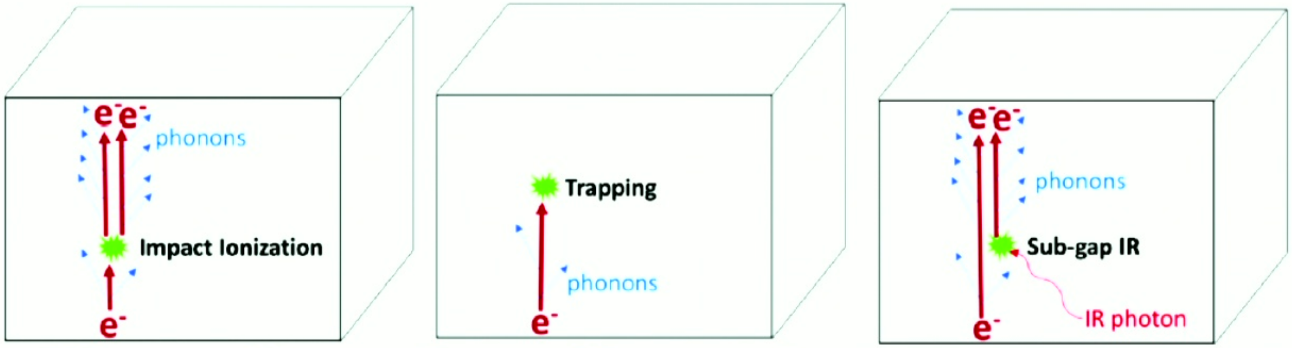

Figure: R.K. Romani

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  - Spectral information about radioactive decays at eV scale required.
    - Relevance is exposure dependent
  - IR and optical photons become significant backgrounds at lowest energies.

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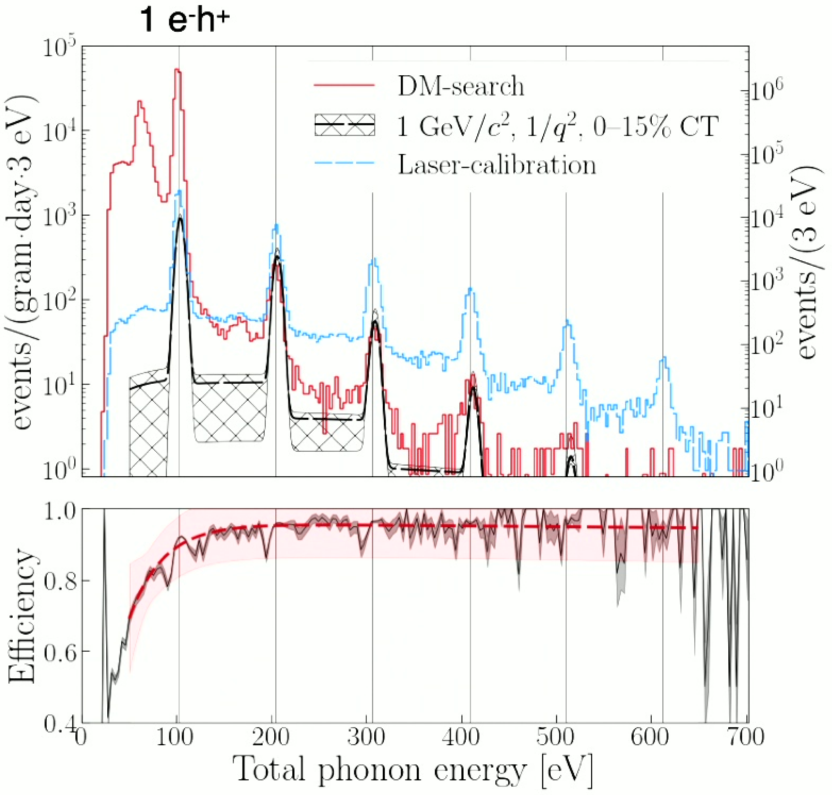
  - Crystal impurities can lead to partial energy deposits —> gives events between quantization peaks
- **Backgrounds**
  - Spectral information about radioactive decays at eV scale required.
    - Relevance is exposure dependent
  - IR and optical photons become significant backgrounds at lowest energies.
  - Dark/leakage current can be significant, dominant background at lowest energies.

HVeV Detectors

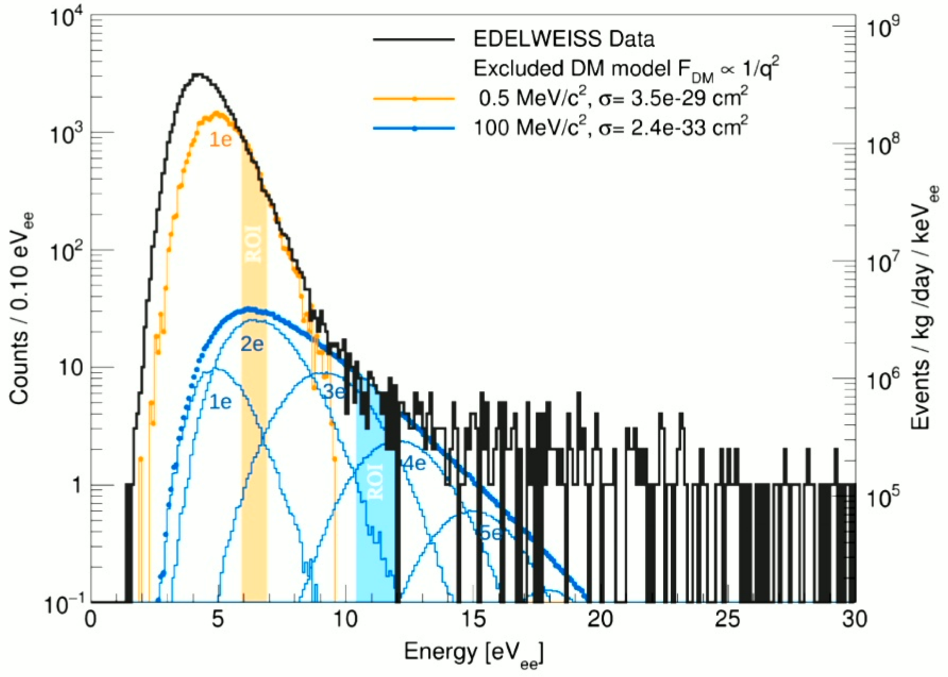
arXiv:2005.14067
PRL 121, 051301 (2018)
APL 112, 043501 (2018)
NIM A 963, 163757 (2020)

- Single-hole e/h-pair resolution devices will have sensitivity to a variety of sub-GeV DM models with g*d exposures
- 0.93 g Si crystal (1 x 1x 0.4 cm^3) operated at 50-52 mK at a surface test facility.
- Exposure: 3.0 gram-days (collected over 3 days)
    - operation voltage: 100 V
    - energy resolution: $\sigma_{ph} = 3$ eV
    - charge resolution: $\sigma_{eh} = 0.03$ e^-h^+
- Calibrations with in-run monochromatic 635 nm laser fiber-coupled to room temperature.
- Data selection criteria were applied to remove leakage and surface events.



Edelweiss RED 30 Detector: HV Operation

- Heat only events (those not affected by NTL amplification) are the main source of backgrounds.
  - 10^6 DRU @ 10 eVee
  - 1.5 x 10^5 DRU @ 25 eVee
- Dominant limitation for >3 e- signals
- May hypothesis have been studied as to the origin. No single contributor has been found
  - These events are probably multiple sources.



(dru = event/day/keV/kg)

Conclusions - Dark Matter

- The next decade will be very exciting for dark matter direct detection. Various G2 Experiments will come online, covering a lot of new parameter space.
- Although WIMPs remain a very interesting dark matter candidate, other scenarios are gaining traction in the theoretical community, while new ideas for direct searches have been proposed and are gaining momentum.
- Given the wealth of theoretical possibilities, a diversity of experimental designs and targets will be discovered signal.