Title: Ugrnd Experiments

Speakers:

Collection: TRISEP 2023

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2023/06/27

Underground Science - Day 2

Jodi Cooley
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Last Time:

- Discussed the need for particle dark matter.
- Worked out details of expected event rates, pointing out where uncertainties in calculations could arise.
- Discussed characteristics of a dark matter signal
- Started considering different backgrounds that come into play in underground physics

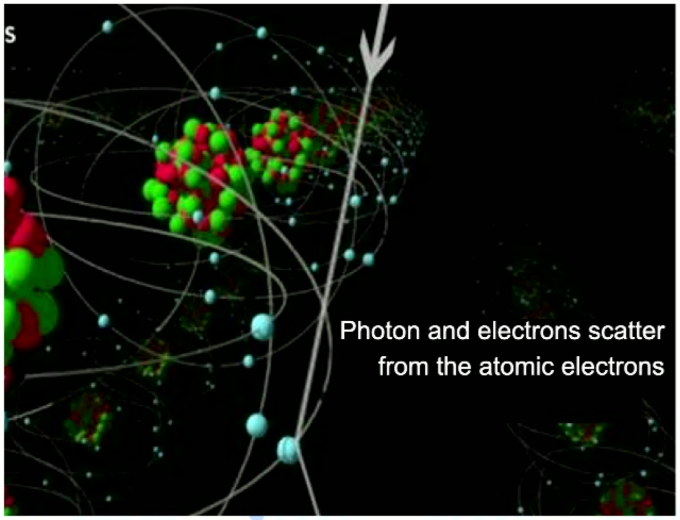
Event Signatures

The most problematic backgrounds are interactions from neutrons that result from (α,n) and fission reactions from ^{238}U and ^{232}Th decays in detector components and in close vicinity of target materials.

Electron Recoils (ER)

Gamma: Most prevalent background

Beta: on surface or in bulk

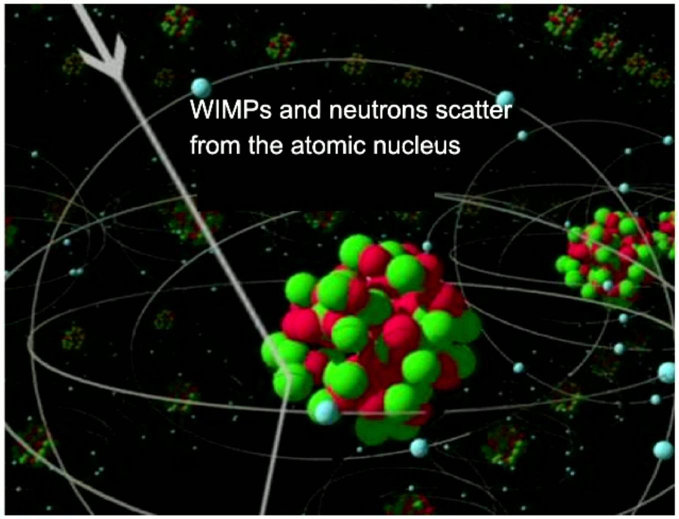


NUCLEAR Recoils (NR)

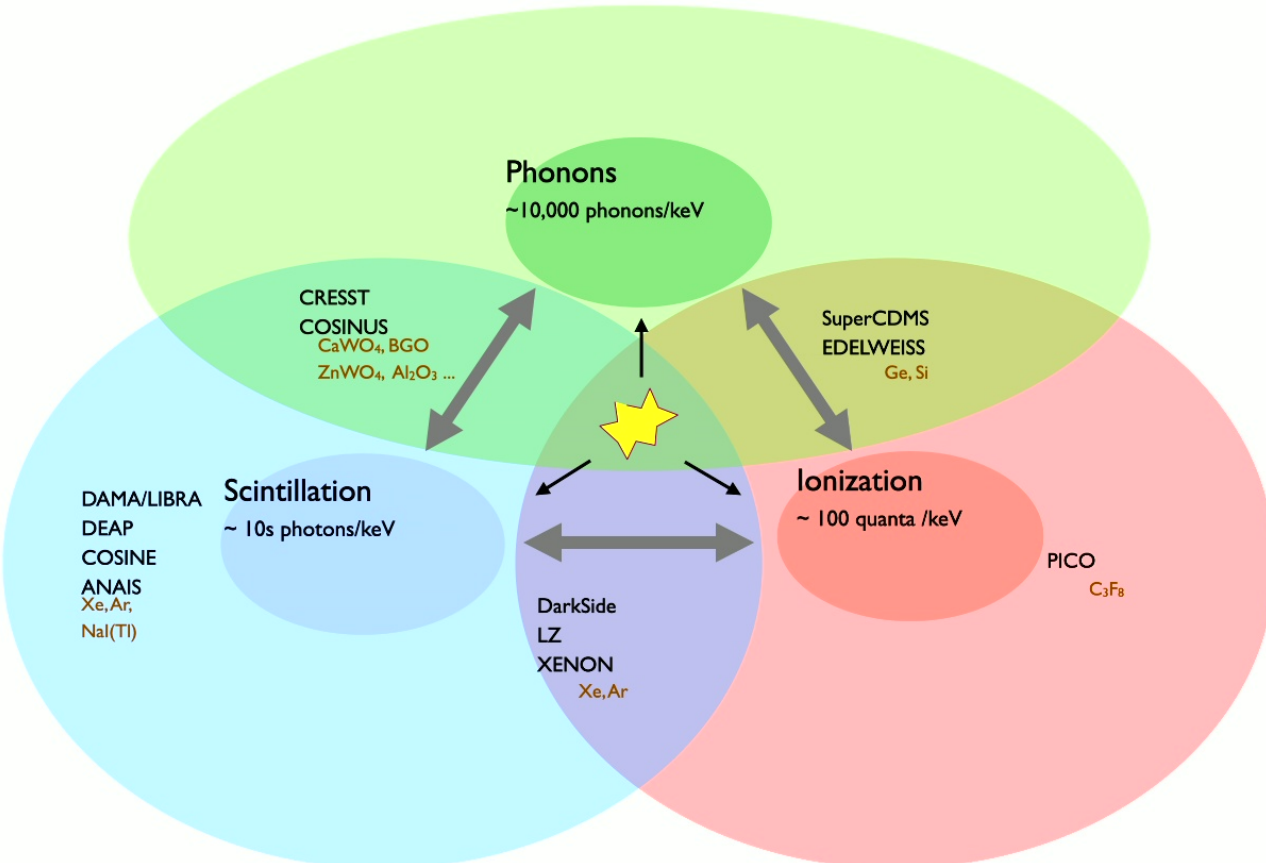
Neutron: NOT distinguishable from WIMP

Alpha: almost always a surface event

Recoiling Parent Nucleus: surface event



Detector Response



Quenching Factor and Discrimination

- WIMPs (and neutrons) scatter off nuclei (NR).
- Most backgrounds scatter off electrons (ER).
- Detectors have different responses to NR then ER.
- Quenching Factor (QF): describes the difference in the amount of visible energy in a detector to these two classes of events.
  - keVee = measured signal from ER
  - keVnr = measured signal from NR
- For NR events

$$E_{visible}(keVee) = QF \times E_{recoil} keV_{nr}$$

- Calibration sources (gamma and neutron) are used to calibrate the two energy scales.

Particle Dependent Response

- Simultaneous measurement of energy in two channels allows discrimination of ER from NR

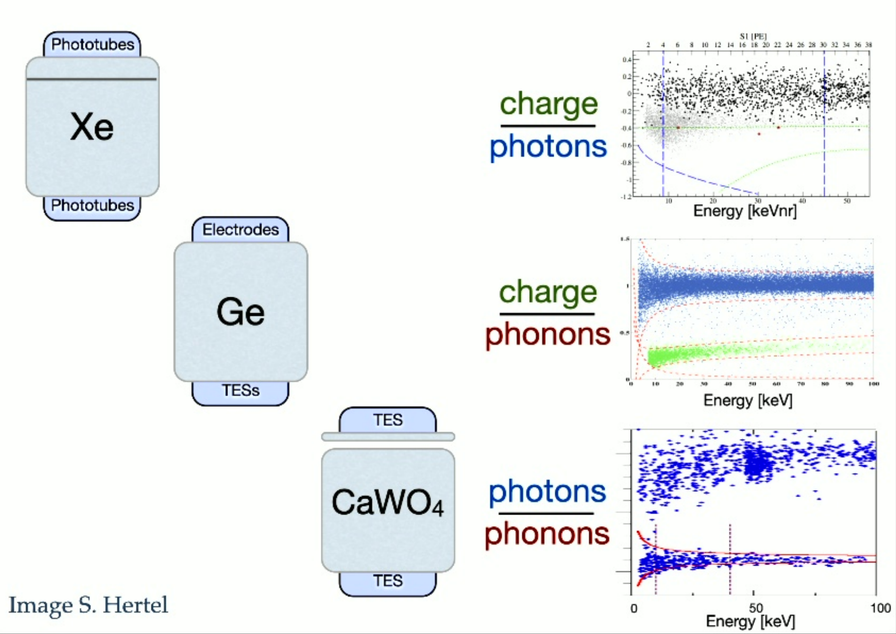


Image S. Hertel

Particle Dependent Response

- Simultaneous measurement of energy in two channels allows discrimination of ER from NR

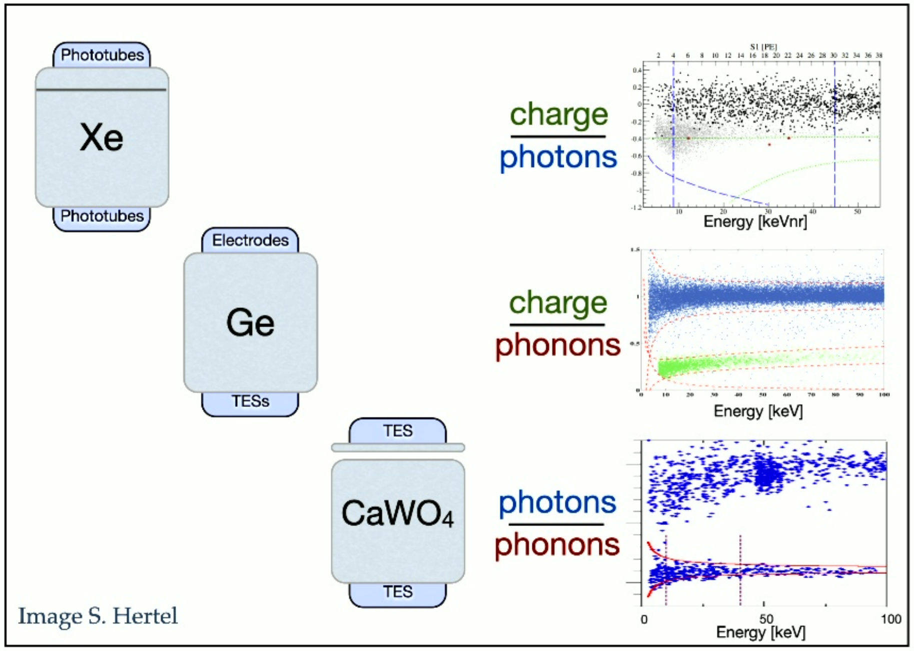
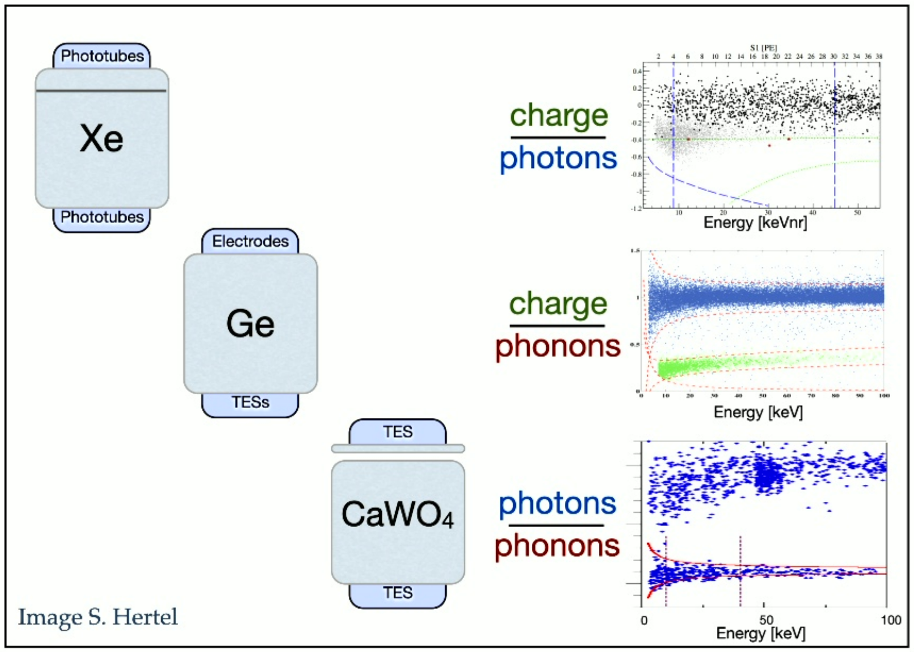


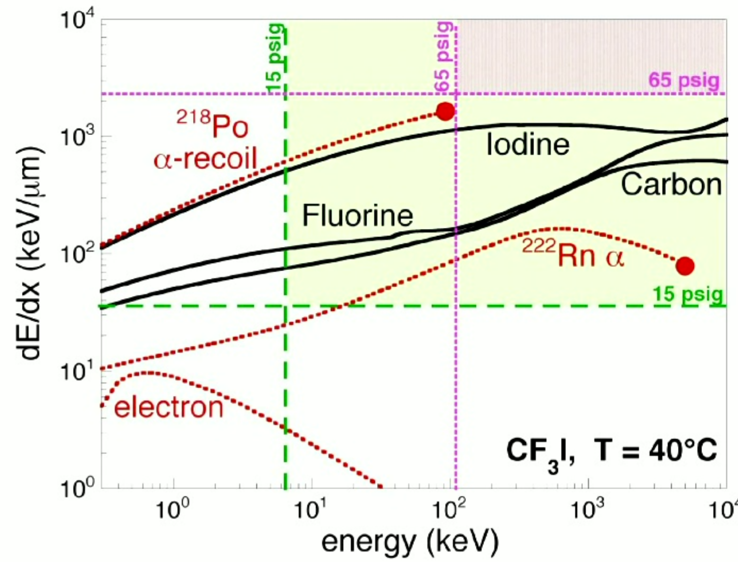
Image S. Hertel

- Example: Charge and phonons in Ge
  - $E_{visible} \sim 1/3\ E_{recoil}$ for NR
  - QF ~ 30% in Ge

Particle Dependent Response

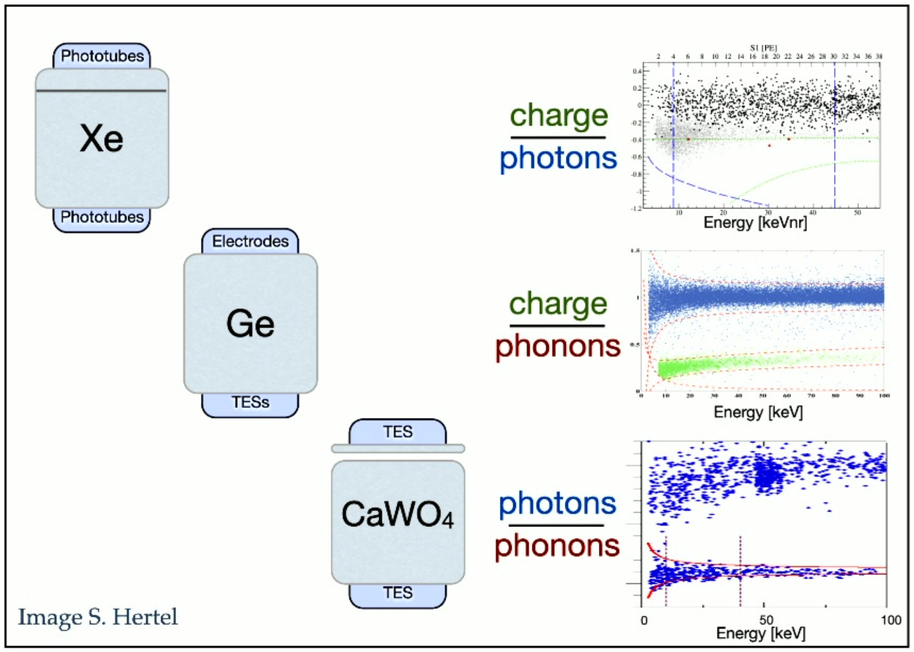
➤ Simultaneous measurement of energy in two channels allows discrimination of ER from NR



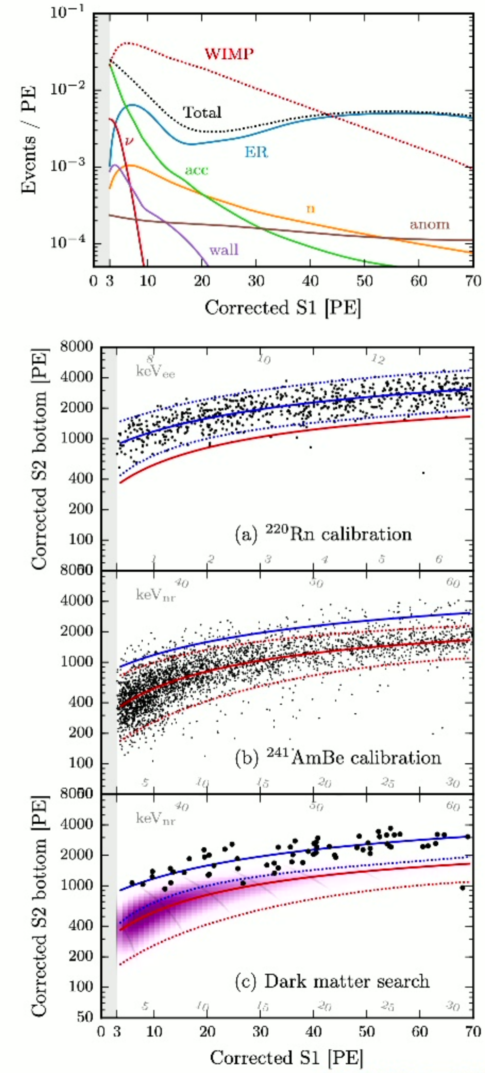


Particle Dependent Response

- Simultaneous measurement of energy in two channels allows discrimination of ER from NR



- Cut-and-count analysis methods no longer deliver required sensitivity.
- Profile likelihood and other multivariate analysis techniques that rely on accurate background models are now standard.

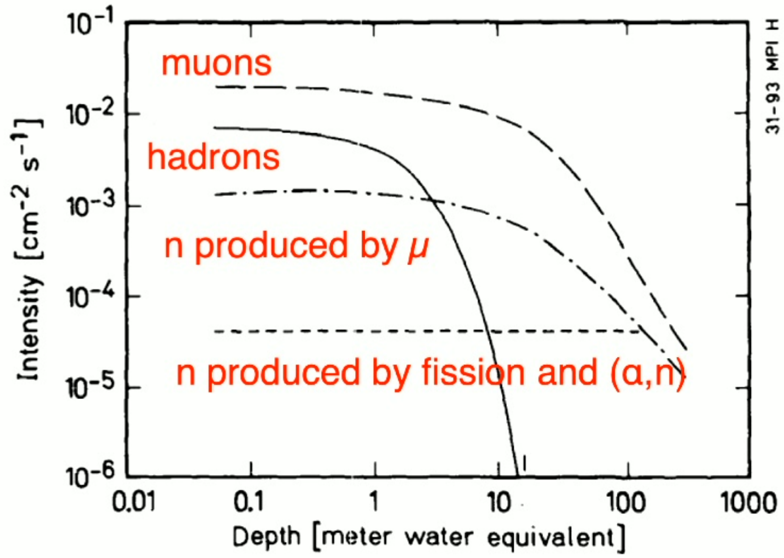


PRL 119.181301

Cosmic Ray Induced Backgrounds

- Cosmic rays and secondary/tertiary particles can be problematic!
- Hadronic component (n, p): reduced by a few meters water equivalent (mew)

Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth
Gerd Heusser, 1995



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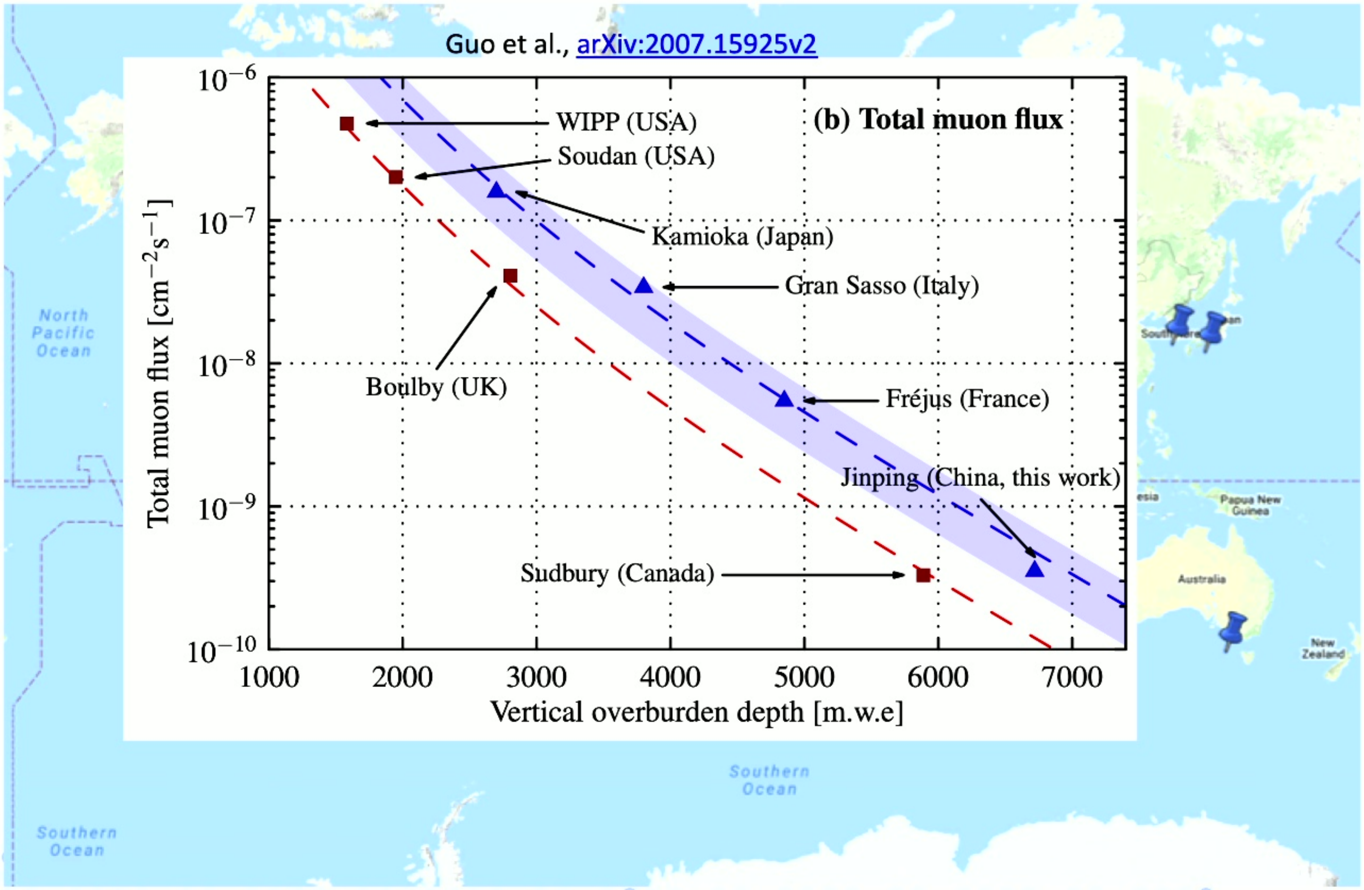
Underground Facilities

- Worldwide 17 underground sites for physics research

Underground Facilities



- Worldwide 17 underground sites for physics research
- Hadronic component of the cosmic ray flux is negligible with a few 10 mwe overburden.
- Muons that penetrate deep and produce high energy neutrons (fast neutrons) can produce keV recoils in detectors when attenuated by rock or shields.
- Processes to produce fast neutrons include:
  - negative muon capture
  - photo-nuclear reactions in associated EM showers
  - deep-inelastic muon-nucleus scatters
  - hadronic interactions of nucleons, pions and kaons

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Activation of Detector Materials

- Activation of a detector or materials close to the detector during production or transportation at Earth's surface is another concern.
  - CR spectrum varies with geomagnetic latitude and the flux varies with height above Earth.
  - Cross section for production of isotopes — not all are measured
- Production is dominated by (n, x) reactions (95%) and (p, x) reactions (5%)

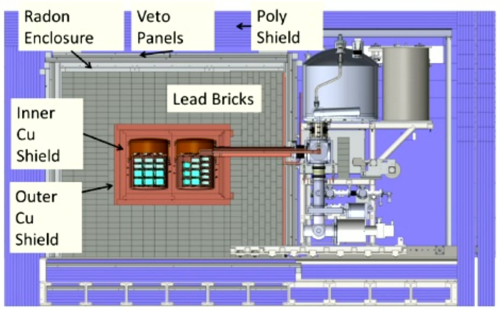
production in Ge after 30d exposure at the Earth's surface and 1 yr storage below ground

Isotope	Decay	Half life	Energy in Ge [keV]	Activity [μBq/kg]
^{3}H	β^-	12.33 yr	$E_{max(\beta-)}$=18.6	2
^{49}V	EC	330 d	$E_{K(Ti)}$ = 5	1.6
^{54}Mn	EC, β^+	312 d	$E_{K(Cr)}$ = 5.4, E_γ=841	0.95
^{55}Fe	EC	2.7 yr	$E_{K(Mn)}$ = 6	0.66
^{57}Co	EC	272 d	$E_{K(Fe)}$=6.4, E_γ=128	1.3
^{60}Co	β^-	5.3 yr	$E_{max(\beta-)}$=318, E_γ=1173,1333	0.2
^{63}Ni	β-	100 yr	$E_{max(\beta-)}$=67	0.009
^{65}Zn	EC, β^+	244 d	$E^{K(Cu)}$ = 9, E_γ=1125	9.2
^{68}Ge	EC	271 d	$E_{K(Ga)}$ = 10.4	172

Environmental Backgrounds

LUX/LZ Muon Veto

SuperCDMS Soudan Passive Shield



MAJORANA Demonstrator Passive Shield

XENON1T water shield & infrastructure

Environmental Backgrounds

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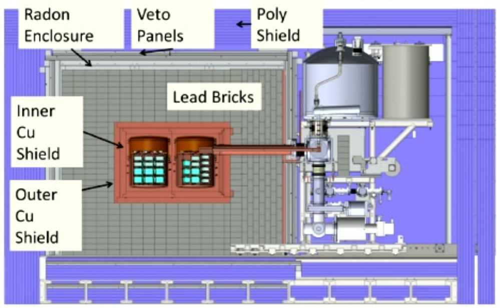

MAJORANA Demonstrator Passive Shield

XENON1T water shield & infrastructure

- A combination of high-Z and low-Z materials are employed to diminish the neutron and gamma fluxes.
  - Lead, polyethelyne, copper
- Nitrogen purge of shield structors to reduce backgrounds induced by airborne radon decays
- Large water shields
  - passively reduce environmental radioactivity and muon-induced neutrons
  - can reduce underground fluxes of gamma and radiogenic fluxes by a factor of $\sim 10^6$ by employing a 1 - 3 m water shield
- Active muon vetos using doped scintillator (ie boron) can be used to identify events related to both cosmogenic and radiogenic neutrons.

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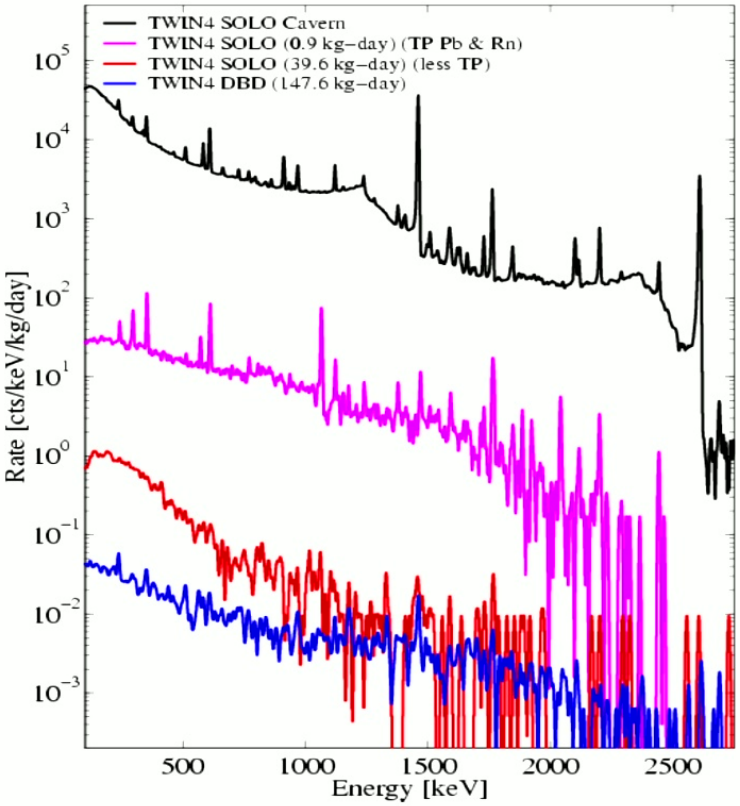
Environmental Backgrounds



Ge detector underground, no shield

Ge detector underground, Pb shield and purge for Rn

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eld & infrastructure

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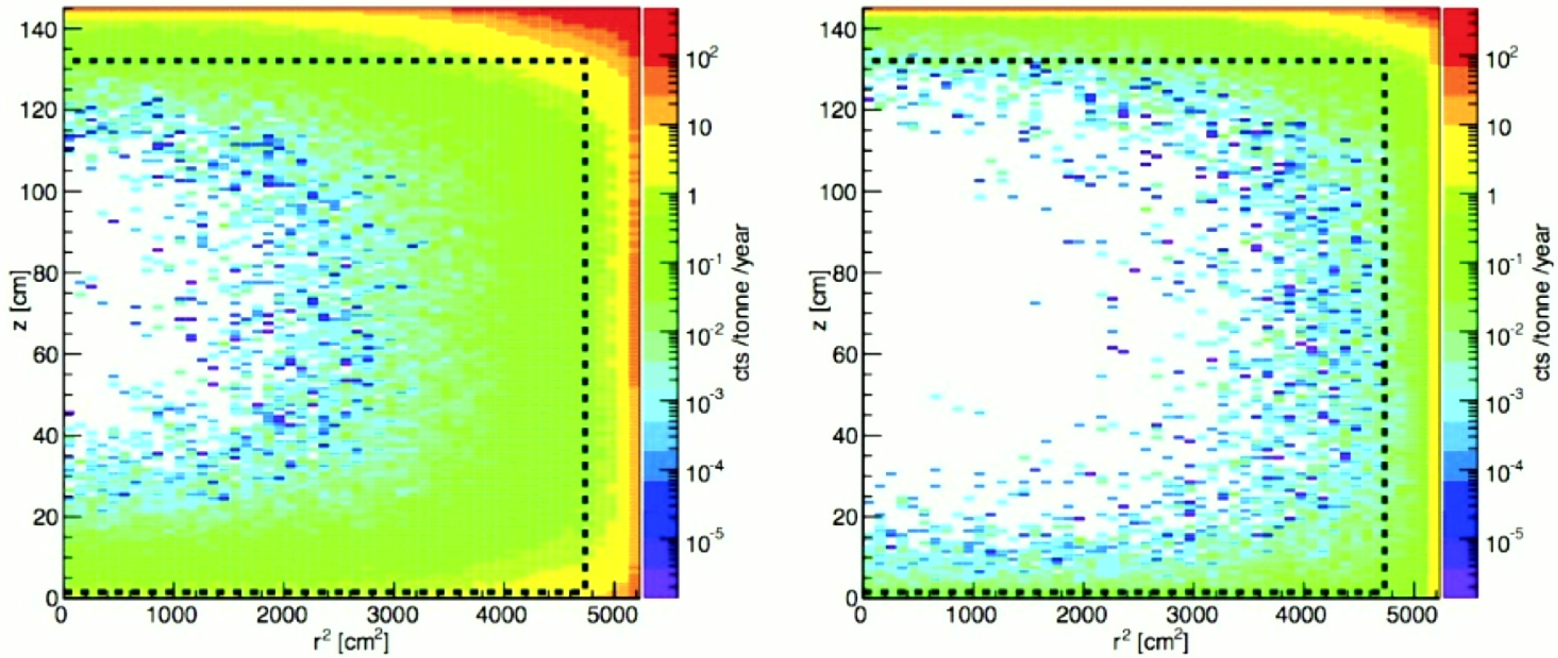
Self Shielding Properties

Example: LZ Dark Matter Experiment

K. Palladino, TAUP 2017



LXe TPC only

3.8 T fiducial mass

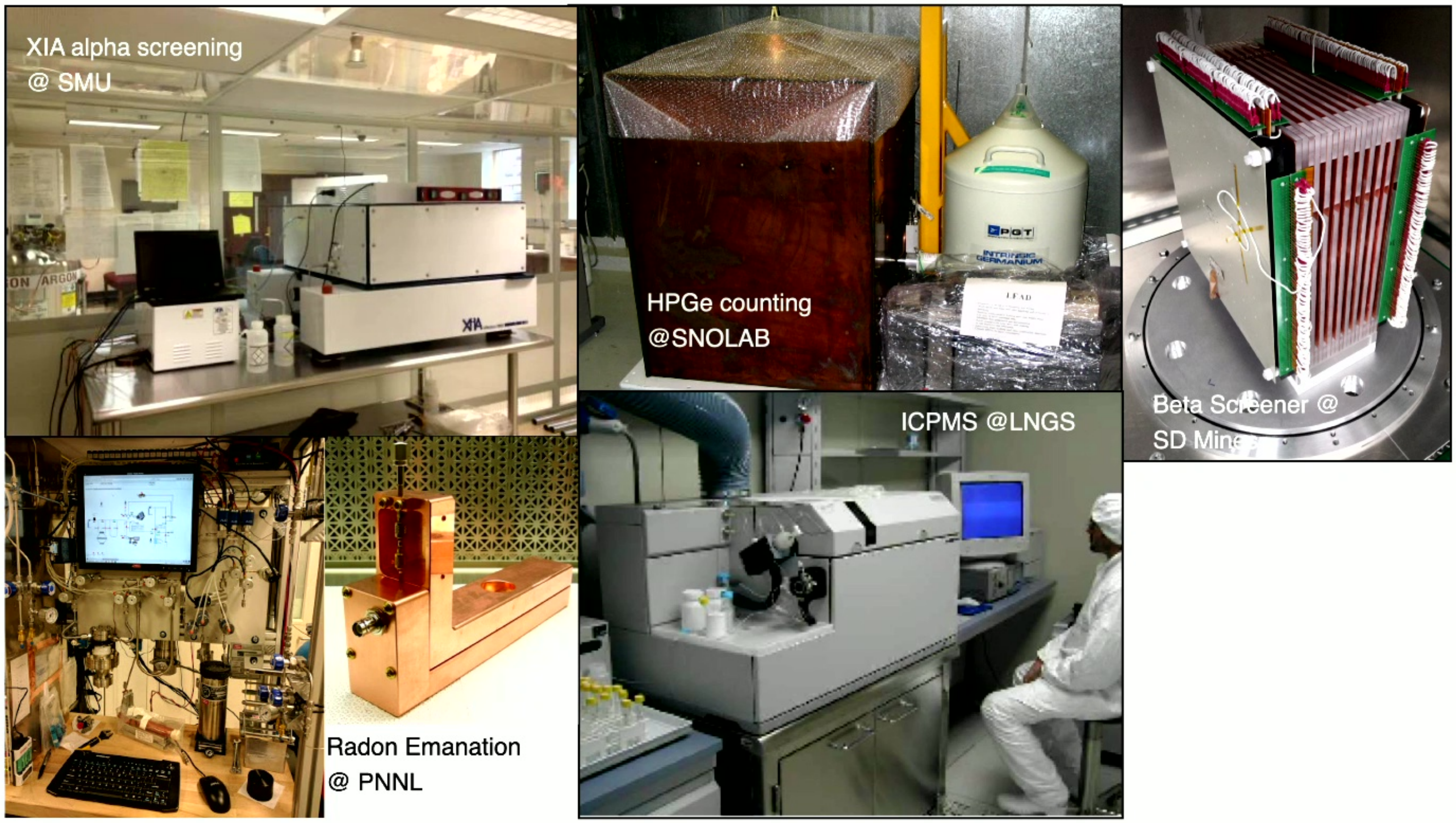
LXe TPC + Skin + OD

5.6 T fiducial mass

Internal Radioactivity

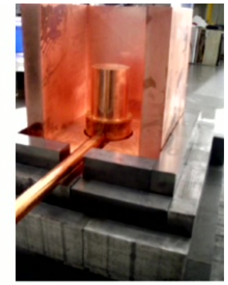
- ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, …. decays in the detector target, materials surrounding the target medium and shield
- A number of methods are employed to characterize materials before using them as detector components.
- In most cases, looking for materials at levels of < 1 ppb.

Internal Radioactivity



In most cases, looking for materials at levels of < 1 ppb.

How Well Can We Do?



HPGe Counting:

Augmented Commercial Systems:
Commercially purchased High-Purity Ge detector is placed in a custom designed shield (Pb, copper, neutron moderation and capture materials, active cosmic ray veto, underground location)

Fully Custom Systems:
In addition to a custom shield, a custom cryostat design with attention to design of and placement of electronics to minimize background sources (U/Th/K).

Isotope/ Chain	Standard Size (ppb)	(mBq/kg)	Large Size & Long Count (ppb)
^{238}U	~0.1	~1.0	0.009
^{232}Th	~0.3	~1.5	0.02
^{40}K	~700	~21	87
^{238}U	0.001	0.12	
^{232}Th	0.001	0.004	
^{40}K	1	0.031	

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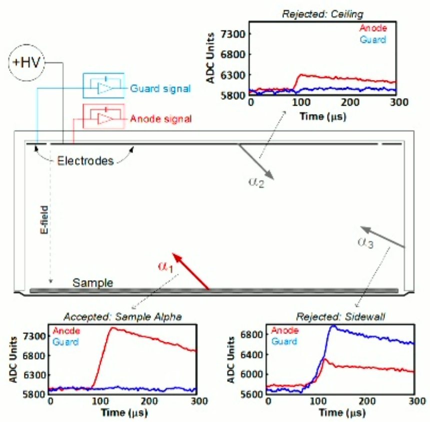
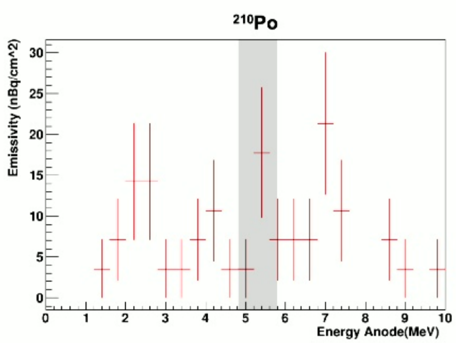
Surface Alpha Screening:



XIA uses uses pulse shape to reject events not originating from sample tray.



Ultra-pure PNNL Copper

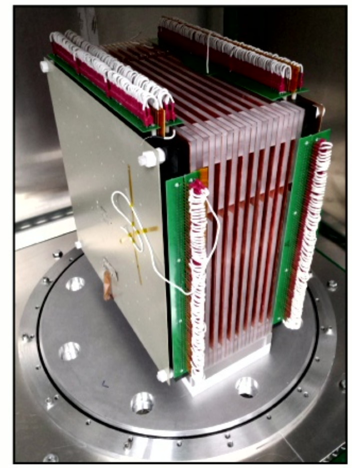
- *~25 nBq/cm^2 in ^{210}Po ROI*

indicative of instrument background

Surface Beta Screening:

BetaCage:

South Dakota Mines, Caltech, PNNL U Alberta



Expected Sensitivity:

- *0.1 β keV^{-1} m^{-2} day^{-1}*
- *0.1 a m^{-2} day*
- *(0.1 a nBq/cm^2)*

Modeling Backgrounds

- Three software frameworks exist to calculate the spectra of neutrons produced by (α-n) interactions.
  - SOURCES - (EMPIRE2.19 libraries for cross section inputs)
  - USD WebTool (TENDL 2012 libraries which are validated by TALYS for cross section inputs)
  - NeuCBOT (TALYS for cross section inputs)

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  - SOURCES - (EMPIRE2.19 libraries for cross section inputs)
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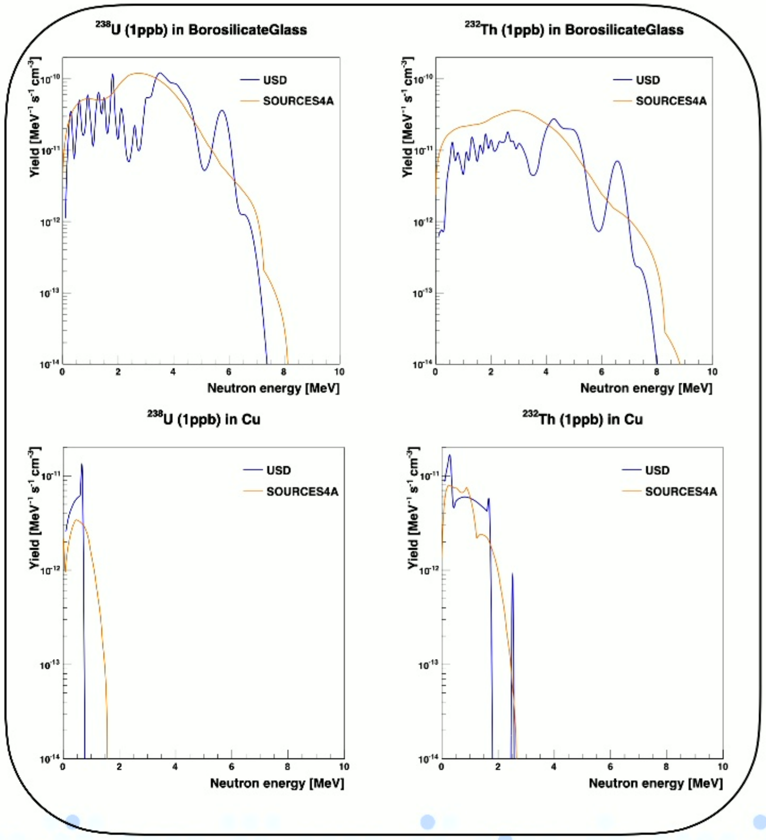
  - NeuCBOT (TALYS for cross section inputs)
- TENDL is a validated library and EMPIRE is recommended by the International Atomic Energy Agency, but neither can properly calculate all resonant behavior that is experimentally observed.
- Those spectra can be used in simulation to predict the number of background events from neutrons in an experiment.

NIM A. 888 (2018) 110-118

Framework Comparisons: USD Webtool vs Sources-4C

Calculated Radiogenic Neutron Spectra



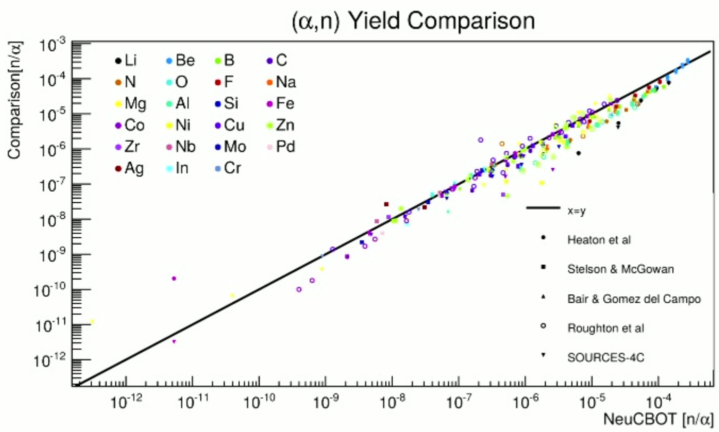
Material	Chain	Neutron Yield $(n{\cdot}s^{-1}{\cdot}cm^{-3})$ SOURCES-4A	USD	Diff %
Cu	^{238}U	$2.84\ 10^{-12}$	$3.46\ 10^{-12}$	20
	^{232}Th	$9.49\ 10^{-12}$	$1.11\ 10^{-11}$	16
PE (CH_2)	^{238}U	$1.26\ 10^{-11}$	$9.56\ 10^{-12}$	-27
	^{232}Th	$5.28\ 10^{-12}$	$2.87\ 10^{-12}$	-59
Titanium	^{238}U	$1.04\ 10^{-10}$	$1.99\ 10^{-10}$	-63
	^{232}Th	$9.29\ 10^{-11}$	$1.24\ 10^{-10}$	-28
Stainless Steel	^{238}U	$3.10\ 10^{-11}$	$5.95\ 10^{-11}$	-63
	^{232}Th	$4.05\ 10^{-11}$	$6.80\ 10^{-11}$	-51
Pyrex	^{238}U	$2.30\ 10^{-10}$	$1.61\ 10^{-10}$	36
	^{232}Th	$8.66\ 10^{-11}$	$4.59\ 10^{-11}$	61
Borosilicate Glass	^{238}U	$3.48\ 10^{-10}$	$2.45\ 10^{-10}$	35
	^{232}Th	$1.27\ 10^{-10}$	$6.98\ 10^{-11}$	58
PTFE (CF_2)	^{238}U	$1.81\ 10^{-9}$	$1.60\ 10^{-9}$	12
	^{232}Th	$7.76\ 10^{-10}$	$5.42\ 10^{-10}$	36

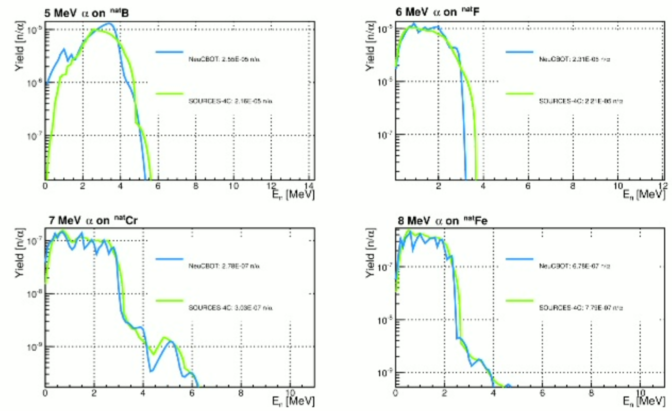
$$\text{Diff }\% = \frac{\text{SOURCES} - \text{USD}}{(\text{SOURCES} + \text{USD})/2}$$

- Study found no major systematic differences between the two in terms input spectra, output spectra and yield.
- Both have errors in cross sections and outputs that may require a human eye to catch.

arXiv:1702.02465
S. Westerdale, TAUP 2017

Framework Comparisons: NeuCBOT vs SOURCES-4C





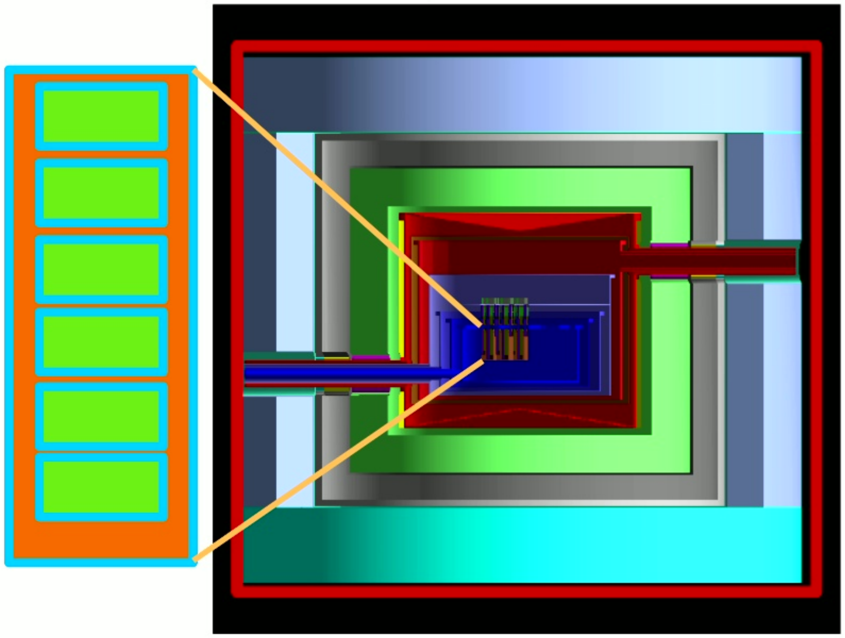
NeuCBOT used by DEAP to predict Neutrons in materials of interest.

NeuCBOT	n/s/Bq			
Material	U238 upper	U238 lower	U235	Th232
Borosilicate Glass	3.93E-06	1.76E-05	2.56E-05	2.43E-05
Acrylic	.19E-0	[illegible]	[illegible]	1.33E-06
Invar	.06E-1	[illegible]	[illegible]	1.08E-06
TPB	.15E-0	[illegible]	[illegible]	1.84E-06
Polyethylene	.52E-0	[illegible]	[illegible]	1.49E-06
Polystyrene	.01E-0	[illegible]	[illegible]	1.77E-06
Stainless Steel	1.31E-0	[illegible]	[illegible]	1.96E-06
Argon	8.82E-08	1.41E-05	1.72E-05	2.64E-05

NeuCBOT:
- 15 n/year from PMT glass
- 1 n/year from PMT ceramic
- 3 n/year from polystyrene filler foam

SOURCES-4C:
- 13 n/year from PMT glass
- 2 n/year from PMT ceramic
- 2 n/year from polystyrene filler foam

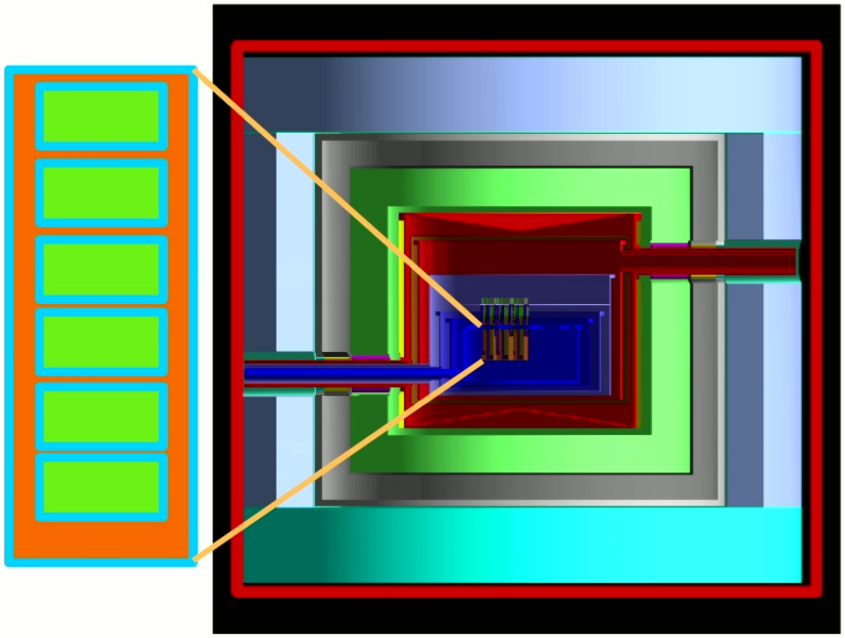
Simulation Tools



SuperCDMS Geometry in Geant4

➤ Geant4 simulations of backgrounds based on assay information

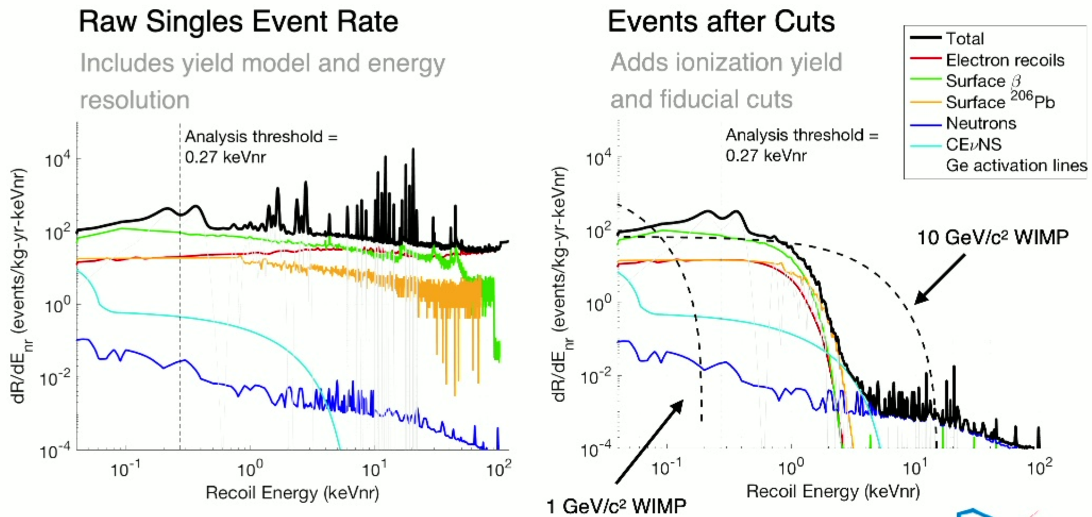
Simulation Tools



SuperCDMS Geometry in Geant4

- ➤ Geant4 simulations of backgrounds based on assay information
- ➤ Produce anticipated background spectra

SuperCDMS anticipated background spectra (Ge iZIPs)



Background Inventory

SuperCDMS Background Inventory

Predicted rates in counts / kg*keVr*year

Category	Ge HV ERsingles	Si HV ERsingles	Ge iZIP ERsingles	Si iZIP ERsingles	Ge iZIP NRsingles ($x10^{-6}$)	Si iZIP NRsingles ($x10^{-6}$)
-Total	48.	360.	50.	400.	3200.	2300.
Coherent Neutrinos					2300.	1600.
-Detector Internal Contamination	24.	280.	4.7	250.	0	0
Tritium	24.	33.	4.7	6.6	0	0
Silicon-32	0	250.	0	250.	0	0
Other						
-Material Internal Contamination	17.	66.	36.	120.	370.	460.
+Housing and Towers	6.5	34.	19.	65.	51.	66.
+Readout Cables	0.31	0.46	0.39	0.80	11.	15.
+SNOBOX Cans	4.0	13.	6.5	22.	68.	75.
Kevlar Ropes	2.1	5.1	2.7	8.3	3.6	4.0
+Calibration	0.92	3.0	1.2	3.6	0.05	0.05
+Shield Materials	3.5	10.	5.3	17.	240.	300.
Bulk Pb-210 in Lead	0.07	0	0.22	0.75		
-Material Internal Activation	2.3	8.4	3.9	13.		
Housing and Towers	0.64	2.5	1.0	4.1		
+SNOBOX	1.5	5.6	2.8	8.9		
Shield	0.07	0.28	0.14	0.41		
Other						
+Non-line-of-sight Surfaces	1.6	5.0	2.9	9.3	35.	41.
Prompt Interstitial Radon	0.61	1.8	0.87	2.7		
+Cavern Environment	2.3	3.5	2.0	9.6	330.	160.
Cosmic Ray Flux	0.00	0.00	0.00	0.00	85.	99.

LZ Background Inventory

Detector components from assays

Xenon contaminants

External backgrounds

Physics: Neutrinos!

Intrinsic Contamination Backgrounds	Mass (kg)	Composite	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr (inc. S.F. rej.)	ER (cts)	NR (cts) (w/ SF rej.)
Upper PMT Structure	46.7	Y	5.32	0.80	1.08	0.72	0.03	3.81	5.23	0.14	0.001
Lower PMT Structure	71.7	Y	2.62	0.24	0.41	0.30	0.00	1.33	6.57	0.08	0.001
R11410 3" PMTs	91.9	Y	71.63	3.20	3.12	2.99	2.91	15.41	[illegible]	1.47	0.013
R11410 PMT Bases *	2.8	Y	369.62	75.87	38.91	33.07	0.97	50.58	[illegible]	0.37	0.003
R8778 2" PMTs	6.1	Y	138.02	59.39	16.93	16.90	16.25	412.67	[illegible]	0.13	0.008
R8520 Skin 1" PMTs	2.1	Y	62.17	5.29	4.91	4.85	24.44	[illegible]	53.71	0.02	0.006
R8520 Skin PMT Bases *	0.2	Y	212.95	108.46	42.19	37.62	2.23	[illegible]	3.62	0.00	0.000
PMT Cabling	62.5	Y	5.81	7.05	1.24	1.62	[illegible]	6.30	0.75	0.68	0.000
TPC PTFE	184.0	N	0.02	0.02	0.03	0.03	[illegible]	0.12	22.54	0.06	0.008
Grid Wires	0.18	N	1.20	0.27	0.33	[illegible]	1.60	0.40	0.00	0.00	0.000
Grid Holders	92.3	Y	2.86	0.83	0.94	[illegible]	1.42	2.82	20.71	0.97	0.008
Field Shaping Rings	92.5	Y	5.49	1.14	0.72	[illegible]	0.00	2.00	41.04	0.98	0.016
TPC Sensors	4.45	Y	21.17	5.04	[illegible]	1.56	1.36	9.36	4.96	0.02	0.000
TPC Thermometers	0.57	Y	26.57	11.84	[illegible]	4.31	0.99	462.60	1.79	0.06	0.000
Xe Recirculation Tubing	15.1	Y	0.79	[illegible]	0.23	0.33	1.05	0.30	0.64	0.00	0.000
HV Conduits and Cables	137.7	Y	3.6	[illegible]	0.6	0.8	1.4	2.5	26.5	0.05	0.006
HX and PMT Conduits	199.6	Y	3.36	[illegible]	0.48	0.58	1.24	1.47	5.23	0.05	0.001
Cryostat Vessel	2705.0	Y	[illegible]	0.11	0.40	0.40	0.18	0.54	159.44	0.94	0.017
Cryostat Seals	33.7	Y	[illegible]	27.56	3.50	5.93	9.76	140.80	127.08	0.54	0.006
Cryostat Insulation	13.8	[illegible]	85.84	36.55	11.44	9.15	3.40	78.87	35.33	0.48	0.004
Cryostat Teflon Liner	26.0	[illegible]	0.02	0.02	0.03	0.03	0.00	0.12	3.18	0.00	0.000
Outer Detector Tanks	4299.3	[illegible]	3.28	0.60	0.54	0.57	0.03	4.78	200.65	0.96	0.002
Liquid Scintillator	17640.3	Y	0.01	0.01	0.01	0.01	0.00	0.00	14.28	0.03	0.000
Outer Detector PMTs	204.7	Y	570	470	395	388	0.00	534	7 587	0.01	0.000
Outer Detector PMT Supports	770.0	N	12.35	12.35	4.07	4.07	9.62	9.29	258.83	0.00	0.000
Subtotal (Detector Components)										8.01	0.101
222Rn (1.83 μBq/kg)										588	-
220Rn (0.08 μBq/kg)										99	-
natKr (0.015 ppt g/g)										24.5	-
natAr (0.45 ppb g/g)										2.47	-
210Bi (0.1 μBq/kg)										40.0	-
Laboratory and Cosmogenics										4.3	0.06
Fixed Surface Contamination										0.19	0.39
Subtotal (Non-ν counts)										767	0.55
Physics Backgrounds											
136Xe 2νββ										67	0
Astrophysical ν counts (pp+7Be+13N)										255	0
Astrophysical ν counts (8B)										0	0**
Astrophysical ν counts (Hep)										0	0.21
Astrophysical ν counts (diffuse supernova)										0	0.05
Astrophysical ν counts (atmospheric)										0	0.46
Subtotal (Physics backgrounds)										322	0.72
Total										1 090	1.27
Total (with 99.5% ER discrimination, 50% NR efficiency)										5.44	0.63
										6.08	

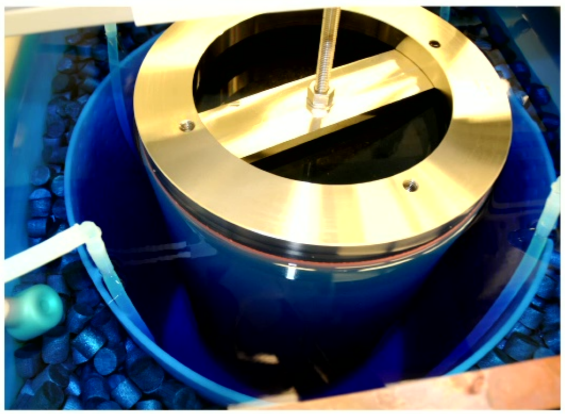
- Background inventories of components and their required purity can be made.
- Provides a tool that can be used for material and vendor selection.

Background Inventory

Electroformed copper at PNNL

Th decay chain (ave) ≤ 0.1 μBq/kg

U decay chain (ave) ≤ 0.1 μBq/kg



XENON1T Gas Purification System and Distillation Column

- *Commercial Xe: 1 ppm - 10 ppb of Kr*
- *XENON1T sensitivity demands: 0.2 ppt*
- *5.5 m distillation column, 6.5 kg/h throughput*

Aprile, UCLA 2018

DarkSide Cryogenic distillation column for purification of ^{39}Ar

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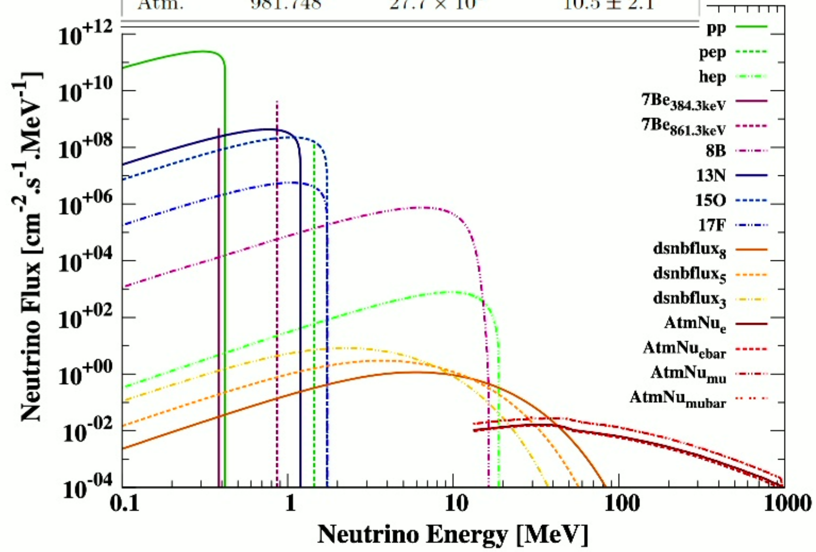
Neutrino Backgrounds

- Solar pp-neutrinos
  - low energies, high fluxes
  - contribute to the ER background via ν-e scattering at a level of 10 - 25 event per(ton x year)at low energies
- Neutrino-induced NR can not be distinguished from WIMP signals (8B solar neutrinos)
  - $\sim 10^3$ events per(ton x year) for heavy targets
  - Atmospheric Neutrinos and Diffuse Supernovae Neutrinos
    - $\sim$1-5 events per (100 ton x year)

ν type	E_ν^{max} (MeV)	$E_{r_{Ge}}^{max}$ (keV)	ν flux ($cm^{-2}.s^{-1}$)
pp	0.42341	5.30×10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
^{7}Be	0.861	0.0219	$4.84 \pm 0.48 \times 10^{9}$
pep	1.440	0.0613	$1.42 \pm 0.04 \times 10^{8}$
^{15}O	1.732	0.0887	$2.33 \pm 0.72 \times 10^{8}$
^{8}B	16.360	7.91	$5.69 \pm 0.91 \times 10^{6}$
hep	18.784	10.42	$7.93 \pm 1.27 \times 10^{3}$
DSNB	91.201	245	85.5 ± 42.7
Atm.	981.748	27.7×10^3	10.5 ± 2.1



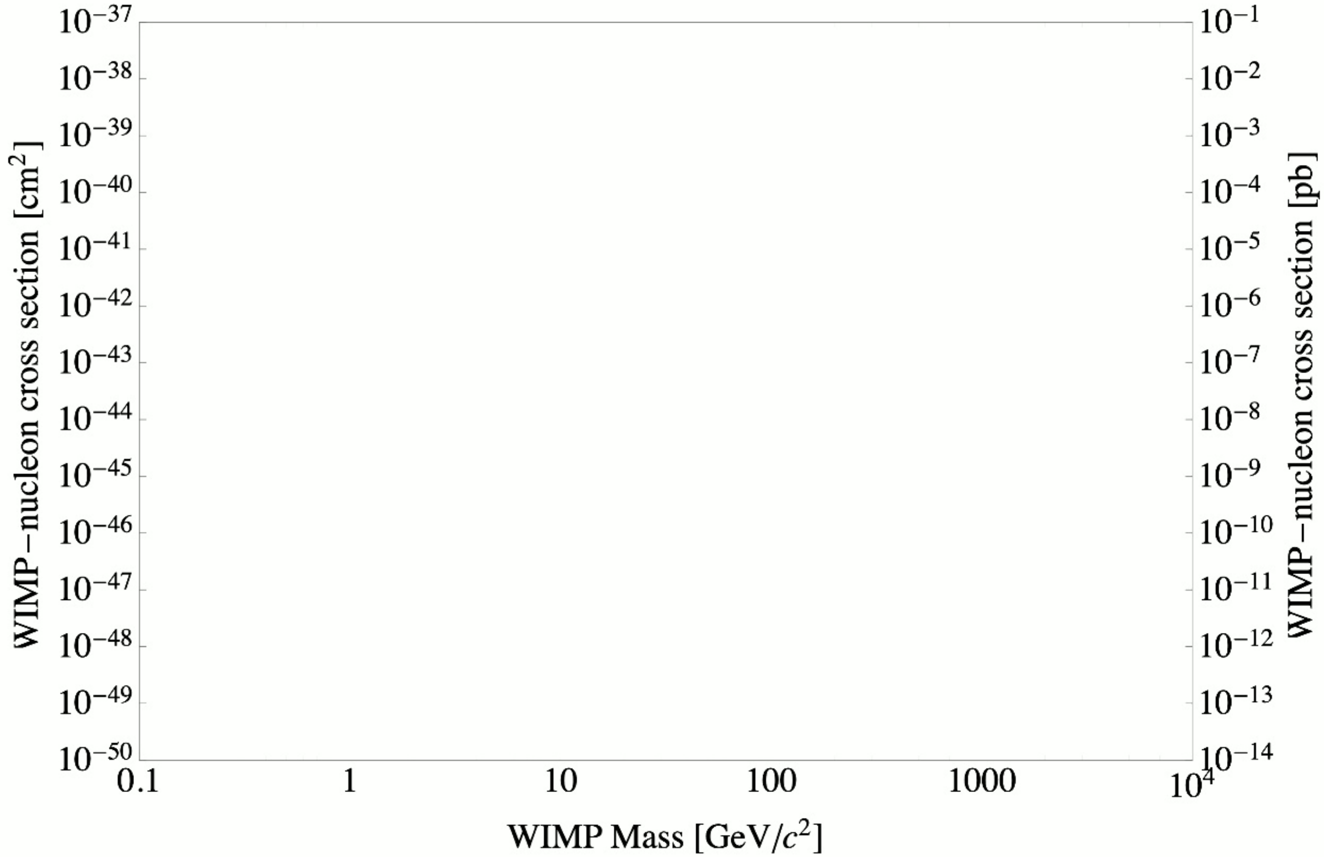
Direct Detection Needs

- Ability to see low energy WIMP induced recoils (>10 keV - 10s keV)
  - Radiogenically pure
  - Low threshold
- Ability to distinguish nuclear recoils
  - Difference between electronic recoils & nuclear recoils
  - Difference between alphas and nuclear recoils

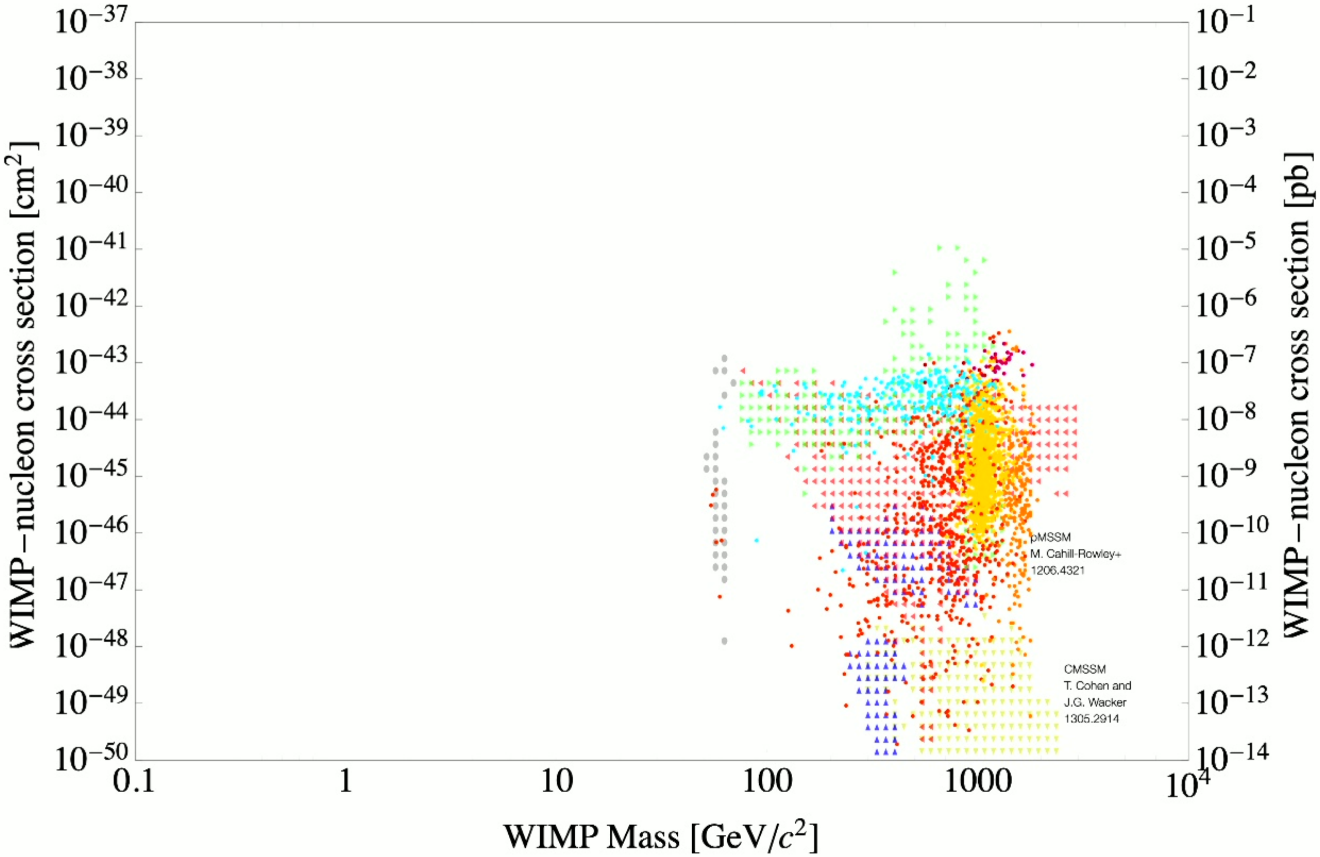
Direct Detection Needs

- Ability to see low energy WIMP induced recoils (>10 keV - 10s keV)
  - Radiogenically pure
  - Low threshold
- Ability to distinguish nuclear recoils
  - Difference between electronic recoils & nuclear recoils
  - Difference between alphas and nuclear recoils
- Radiogenic and cosmogenic backgrounds mitigation
  - Passive and/or Active shielding from these backgrounds
  - Position reconstruction and fiducialization
  - Characterization of these backgrounds

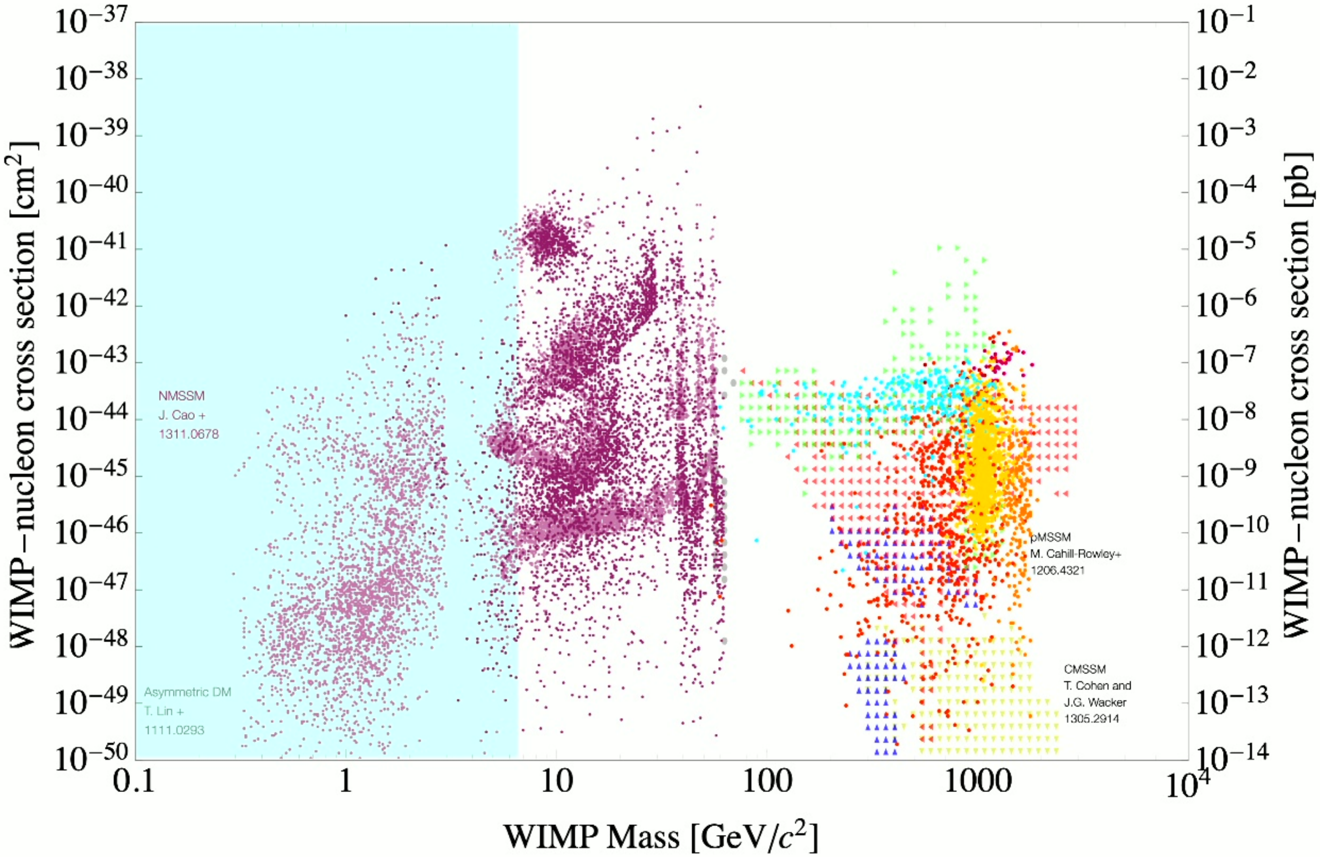
The Search Space



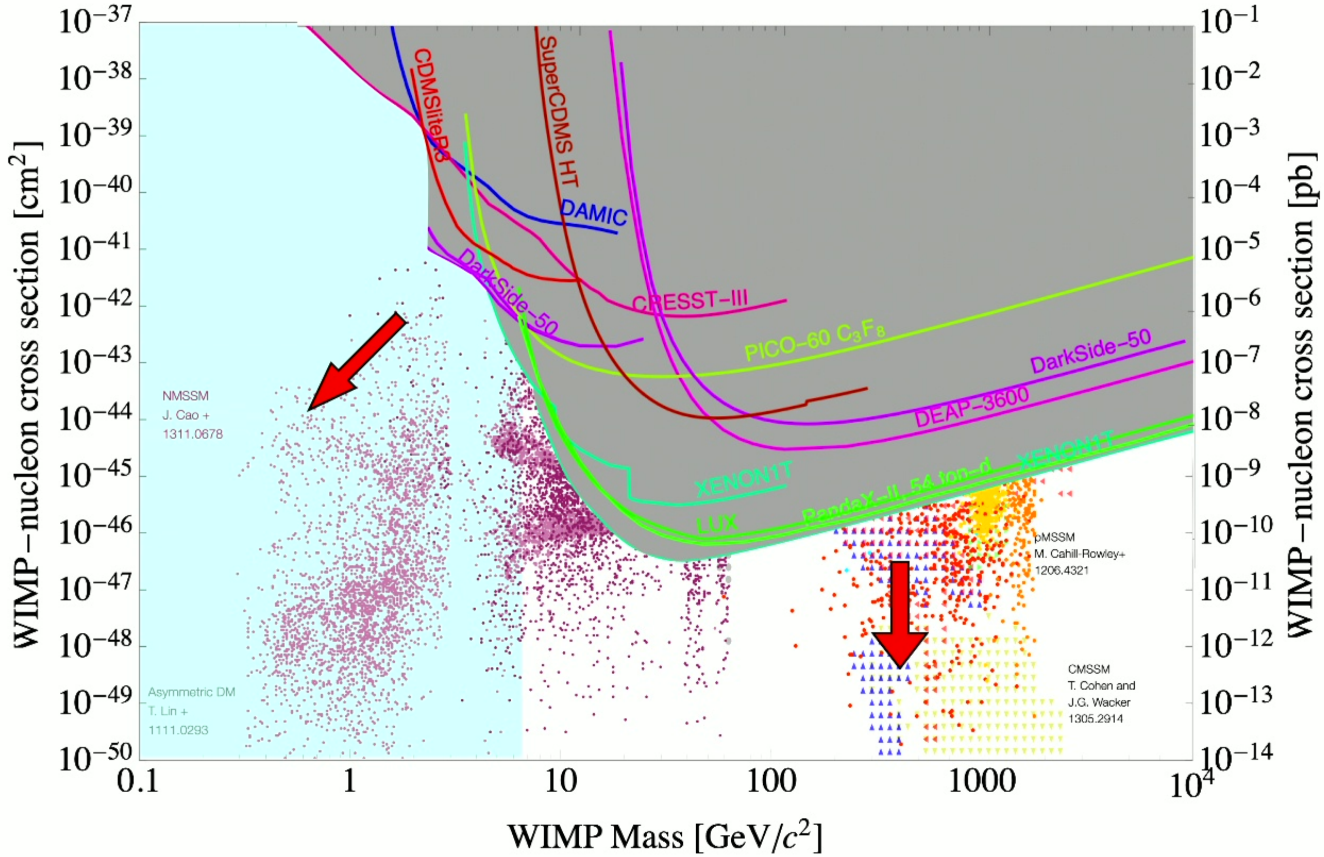
The Search Space



The Search Space



The Search Space



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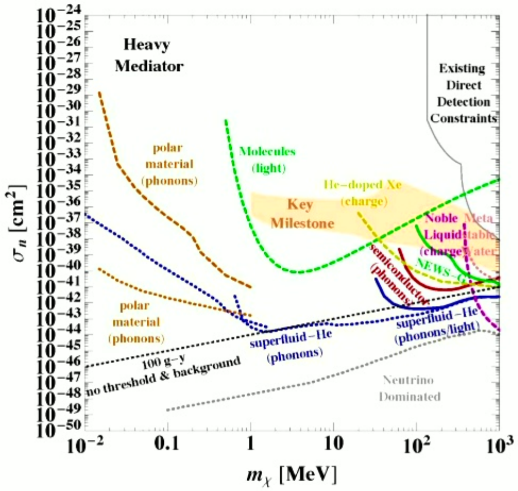
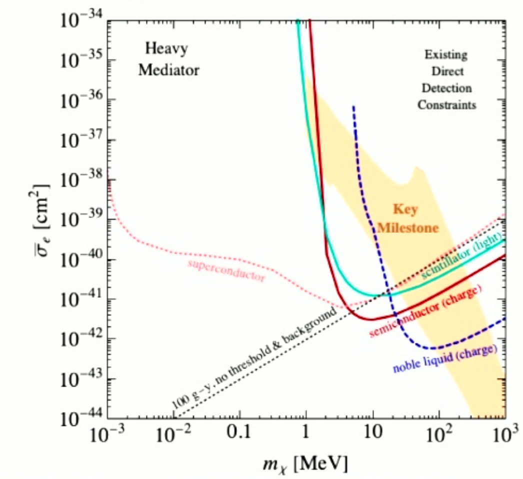
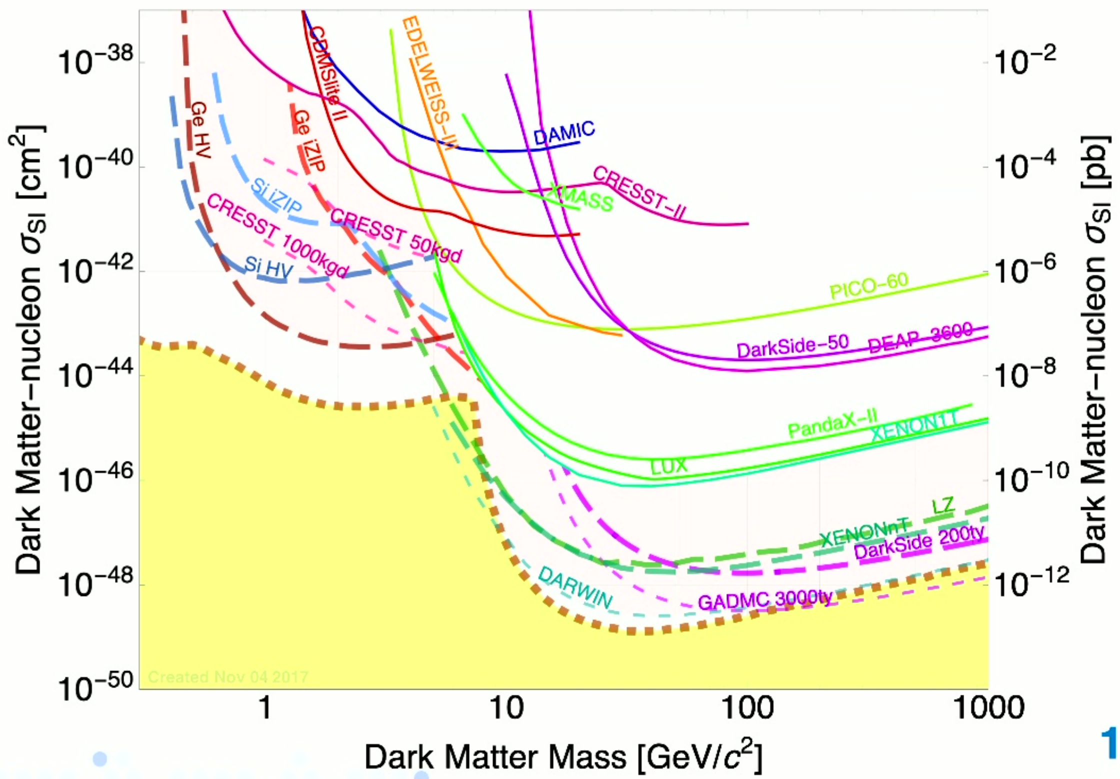
Where Are We Going?

Scattering off nuclei



Scattering off electrons





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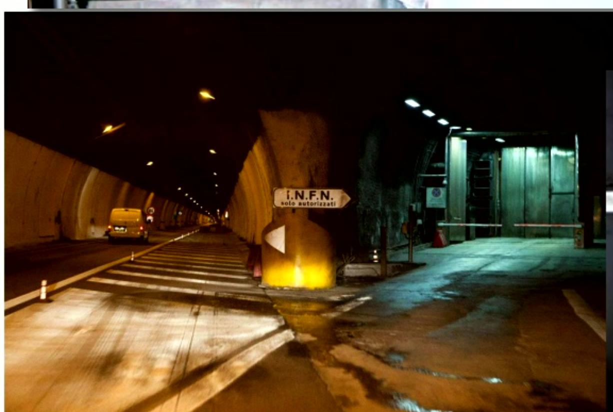
Have We Already Seen a Dark Matter Signal?

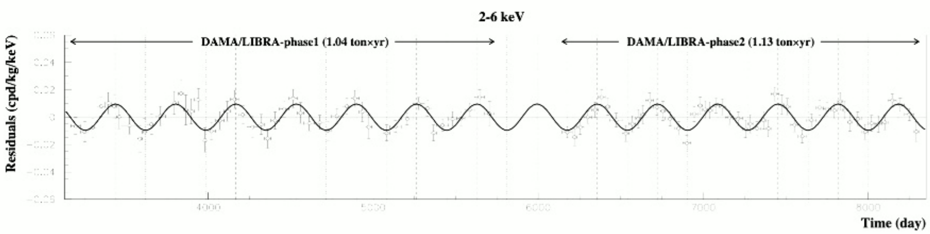


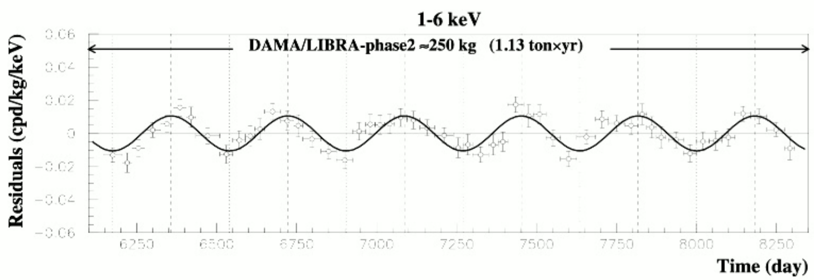


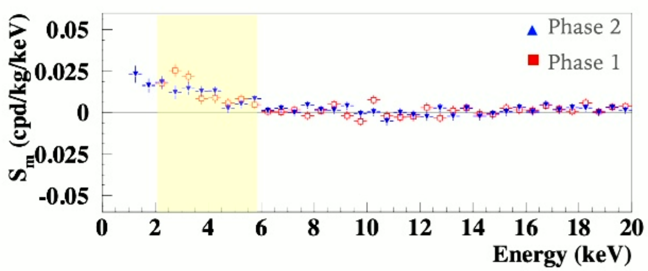
- DAMA/LIBRA have been reporting positive results reported since 1998
- DAMA
  - 100 kg NaI array operated in Laboratori Nazionali del Gran Sasso (1996 - 2002)
- LIBRA
  - 250 kg array operating since 2003 with first results in 2008
- Measures scintillation from particle interactions in detectors.
- No discrimination between nuclear and electron recoils

jnpae2018.94.307
arXiv: 1805.10486
arXiv: 1803.10110

Have We Already Seen a Dark Matter Signal?







10 - 30 keV$_{nr}$ (Na)
30 - 120 keV$_{nr}$ (I)

- Signal observed over 14 cycles at 12.9 σ in the 2-6 keV bin. Phase two signal at 9.5 σ for single scatter events in the 1 - 6 keV energy bin observed over 6 cycles.
- No background/signal discrimination.
- Debate over background or dark matter interpretation
  - DM interpretation is in tension with other experimental results.
  - Disagreements on background models.
    - The release of 3 keV x-rays and Auger electrons associated with the rare EC decay of ^{40}K shows up
    - Radioactive Ar from impurities in Ni purge
    - Radon-included neutron or gamma ray flux from cavern

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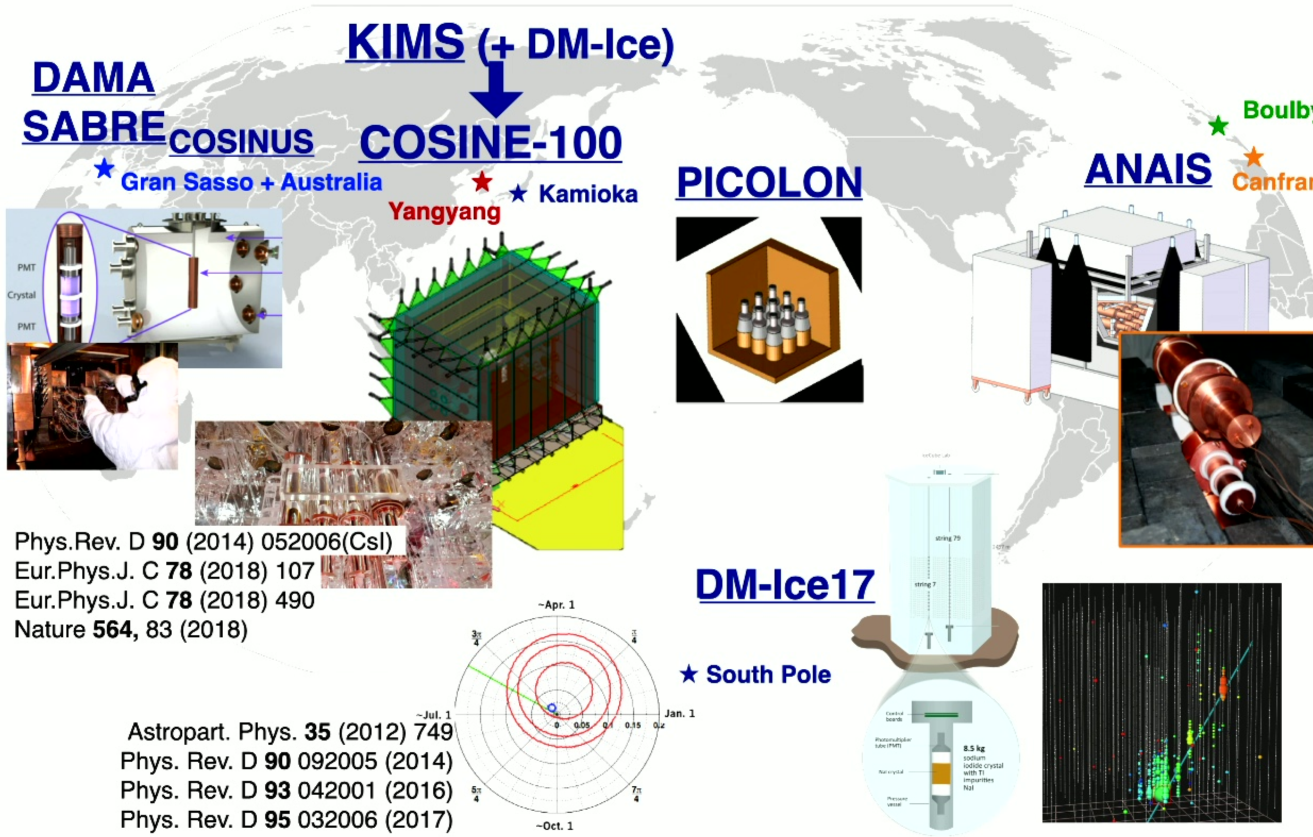
Worldwide Effort to Test DAMA/Libra



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)

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

COSINE-100

- 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