2023/06/27

Underground Science - Day 2

Jodi Cooley
Executive Director I SNOLAB
Professor of Physics I Queen's University
Adjunct Research Professor I SMU

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

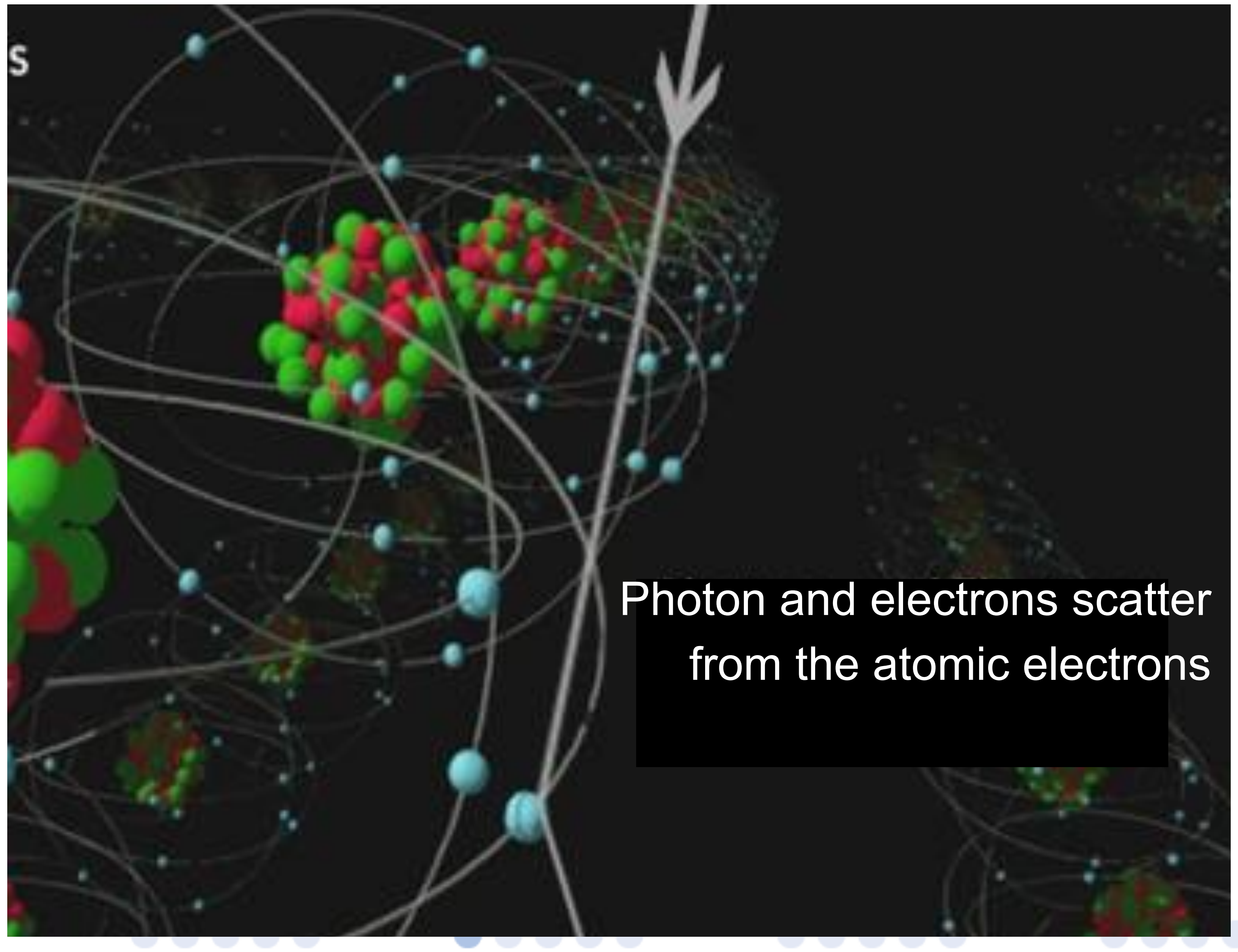
Event Signatures

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

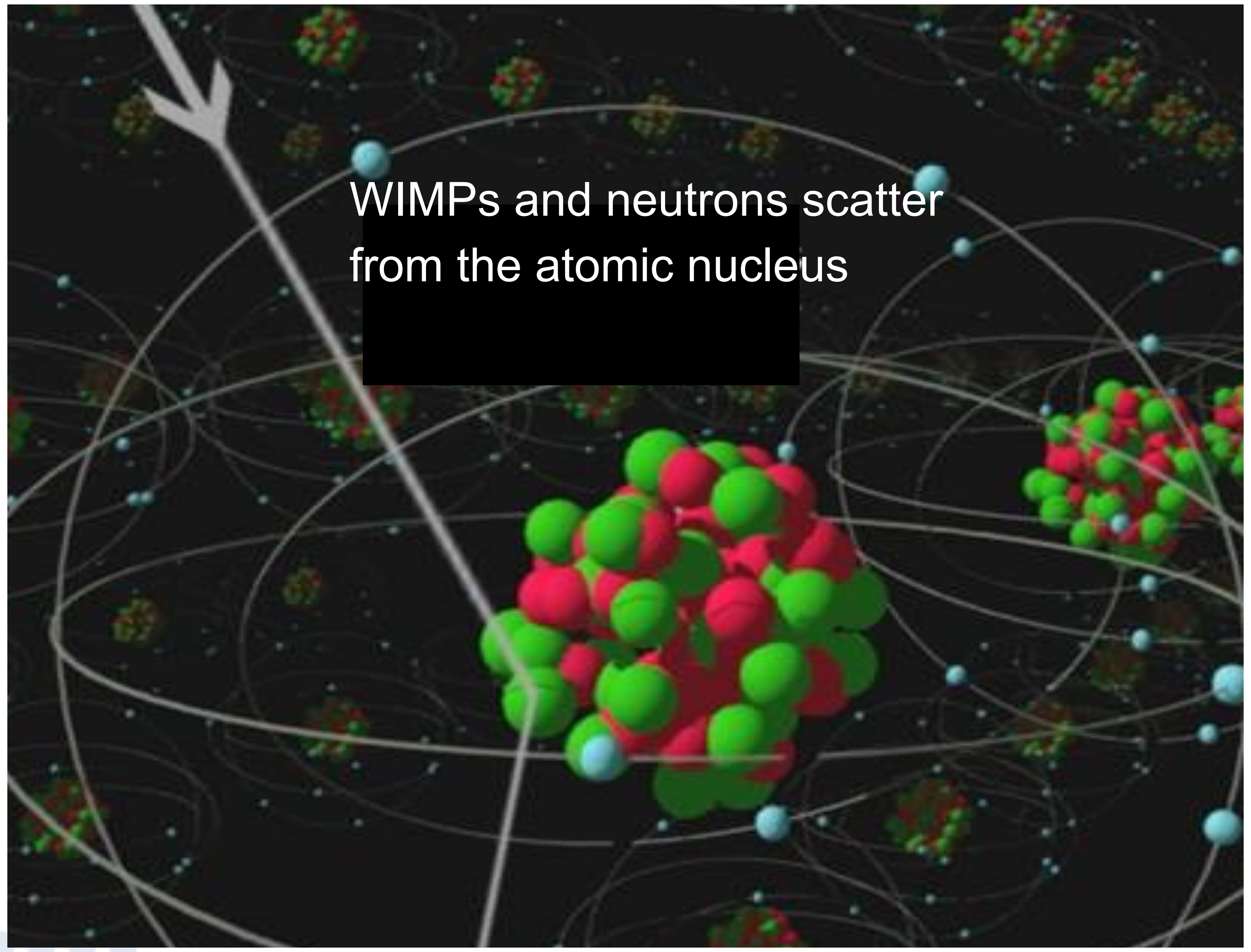


NUCLEAR Recoils (NR)

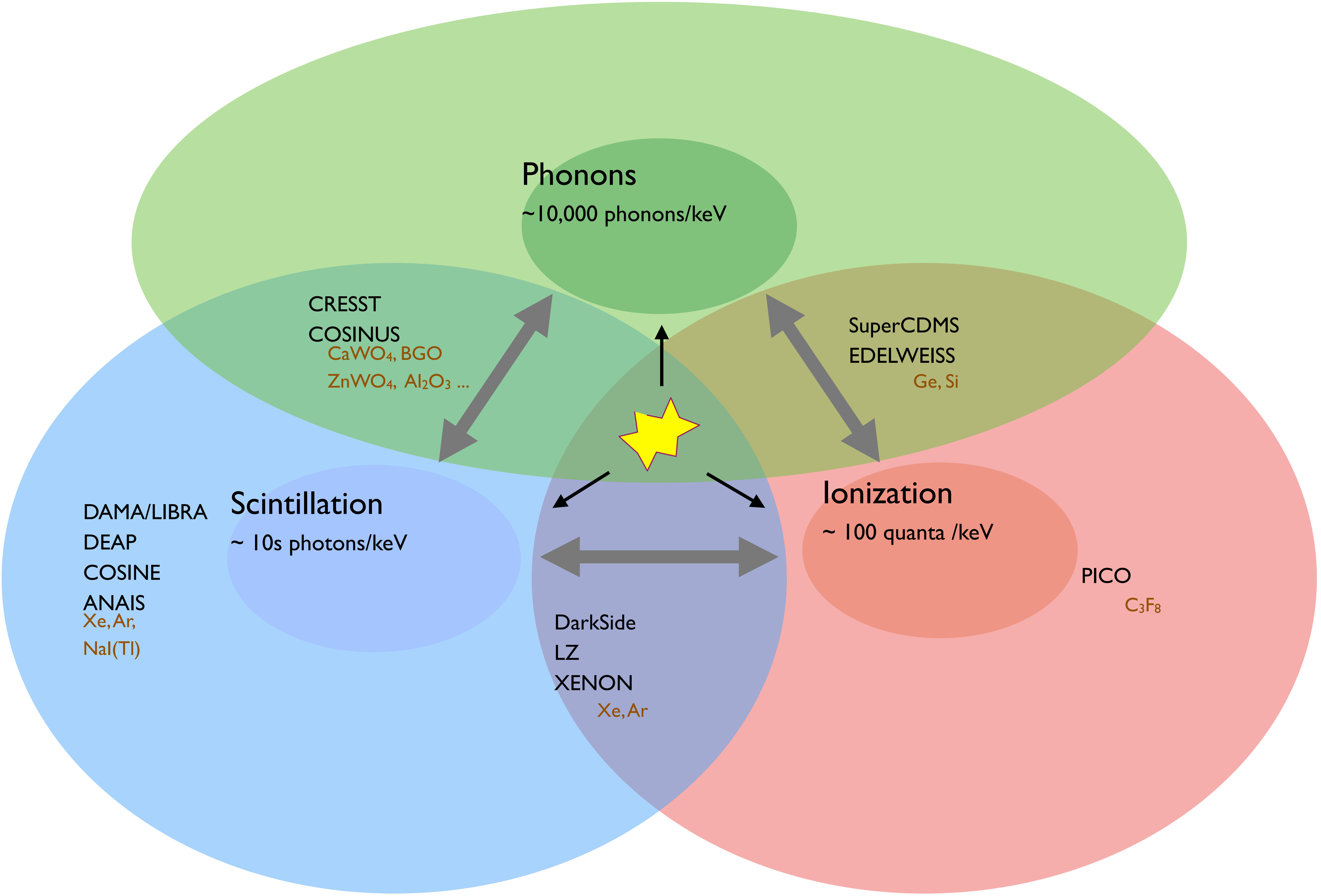
Neutron: NOT distinguishable from WIMP

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

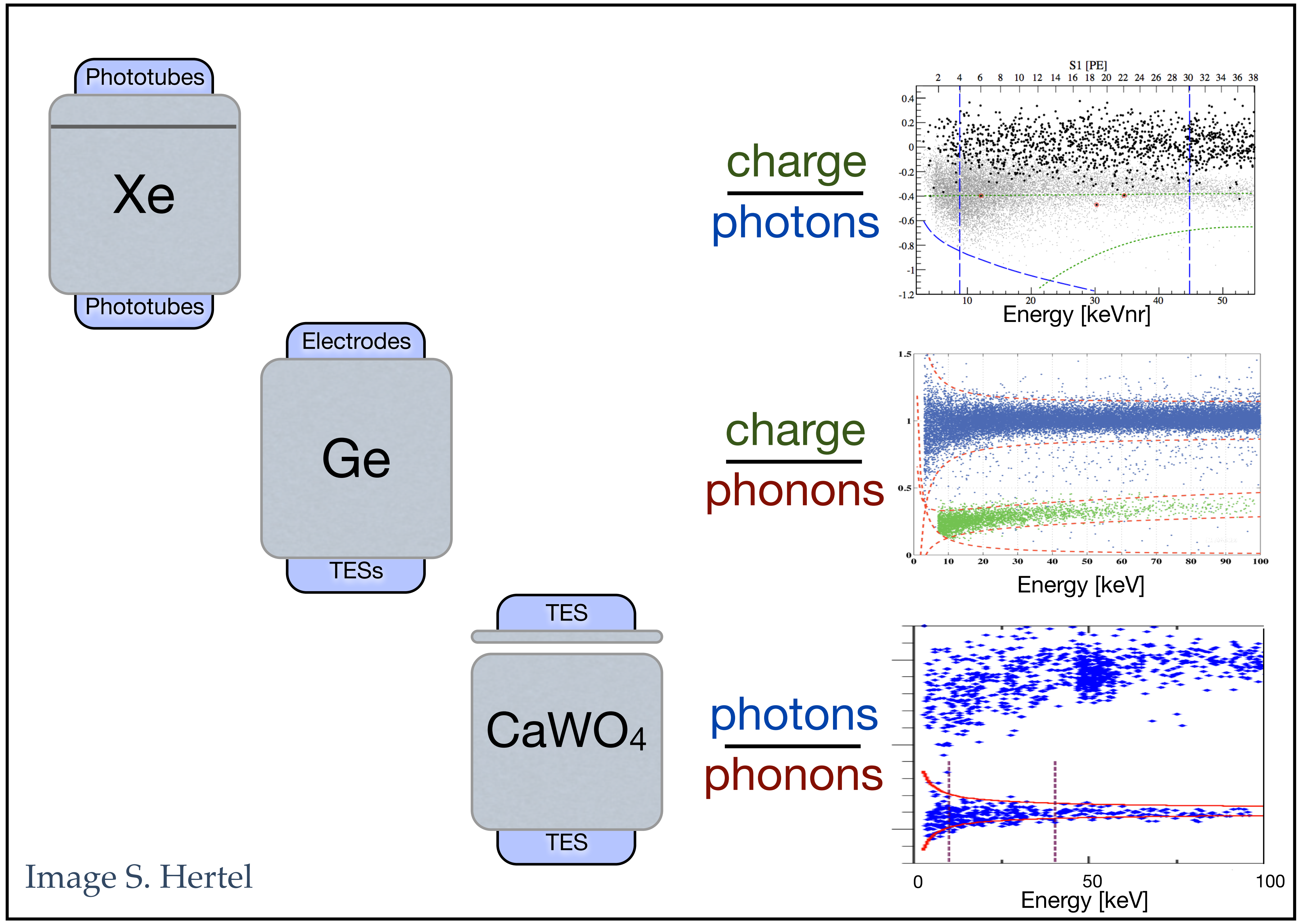


Image S. Hertel

- 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

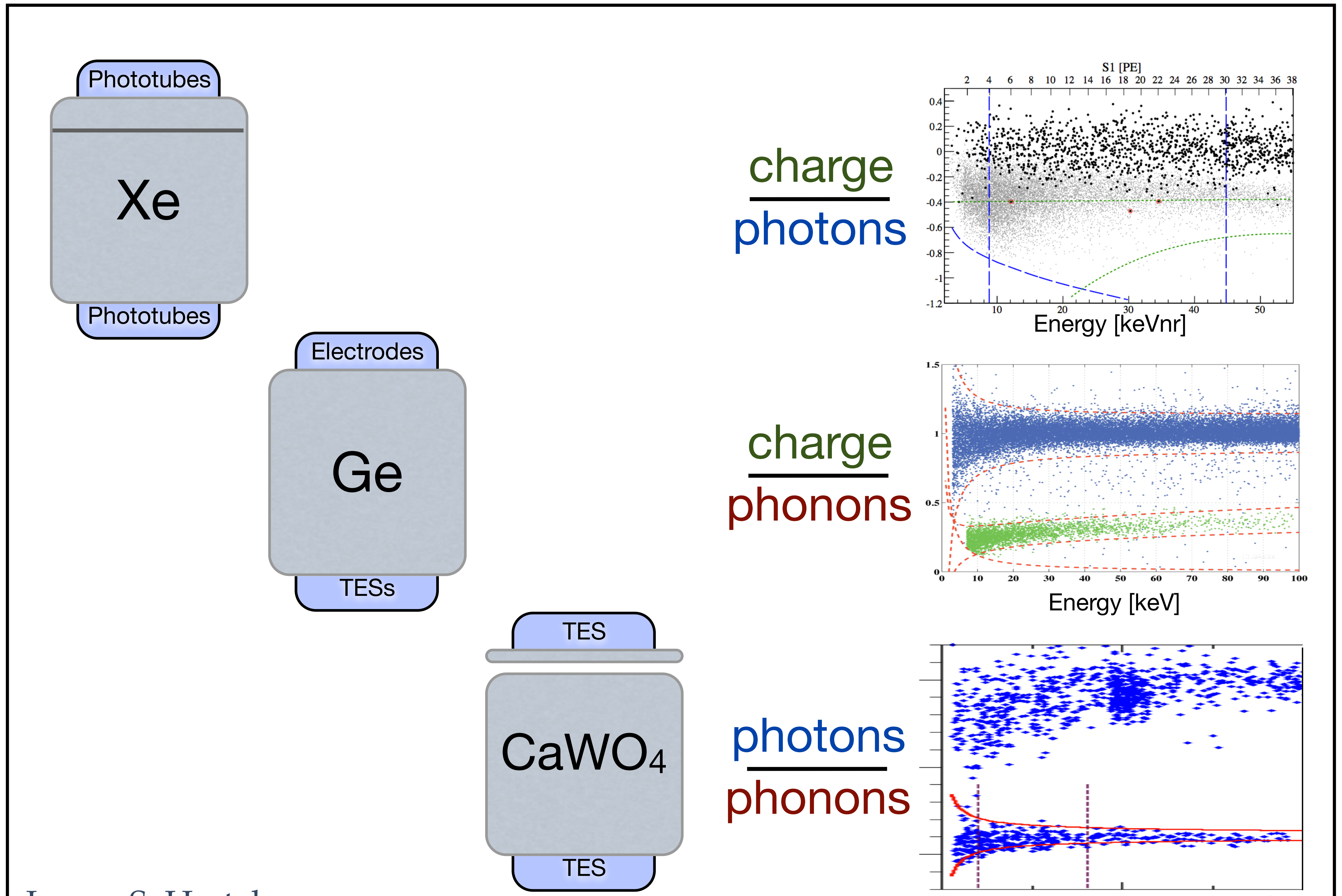
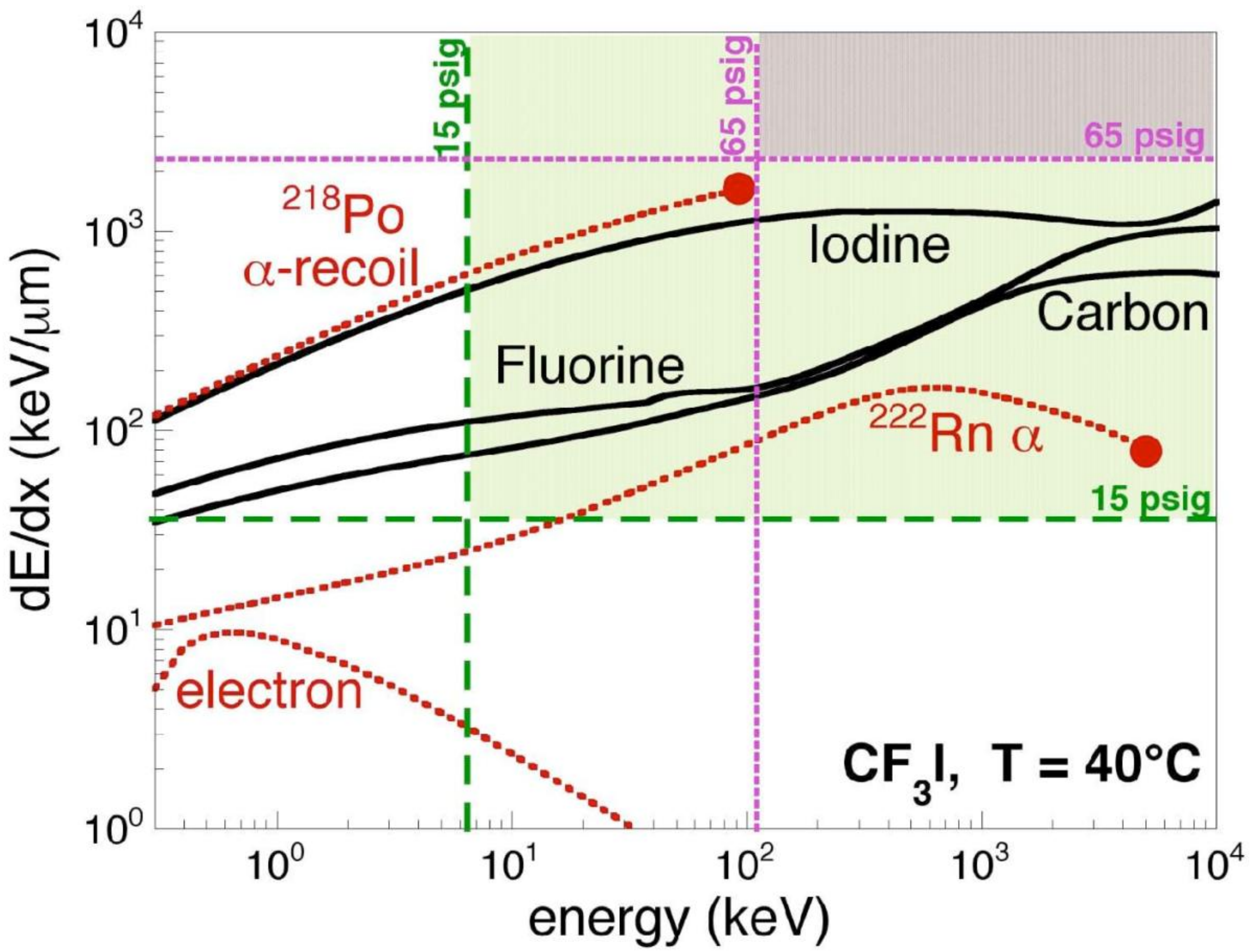


Image S. Hertel



Particle Dependent Response

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

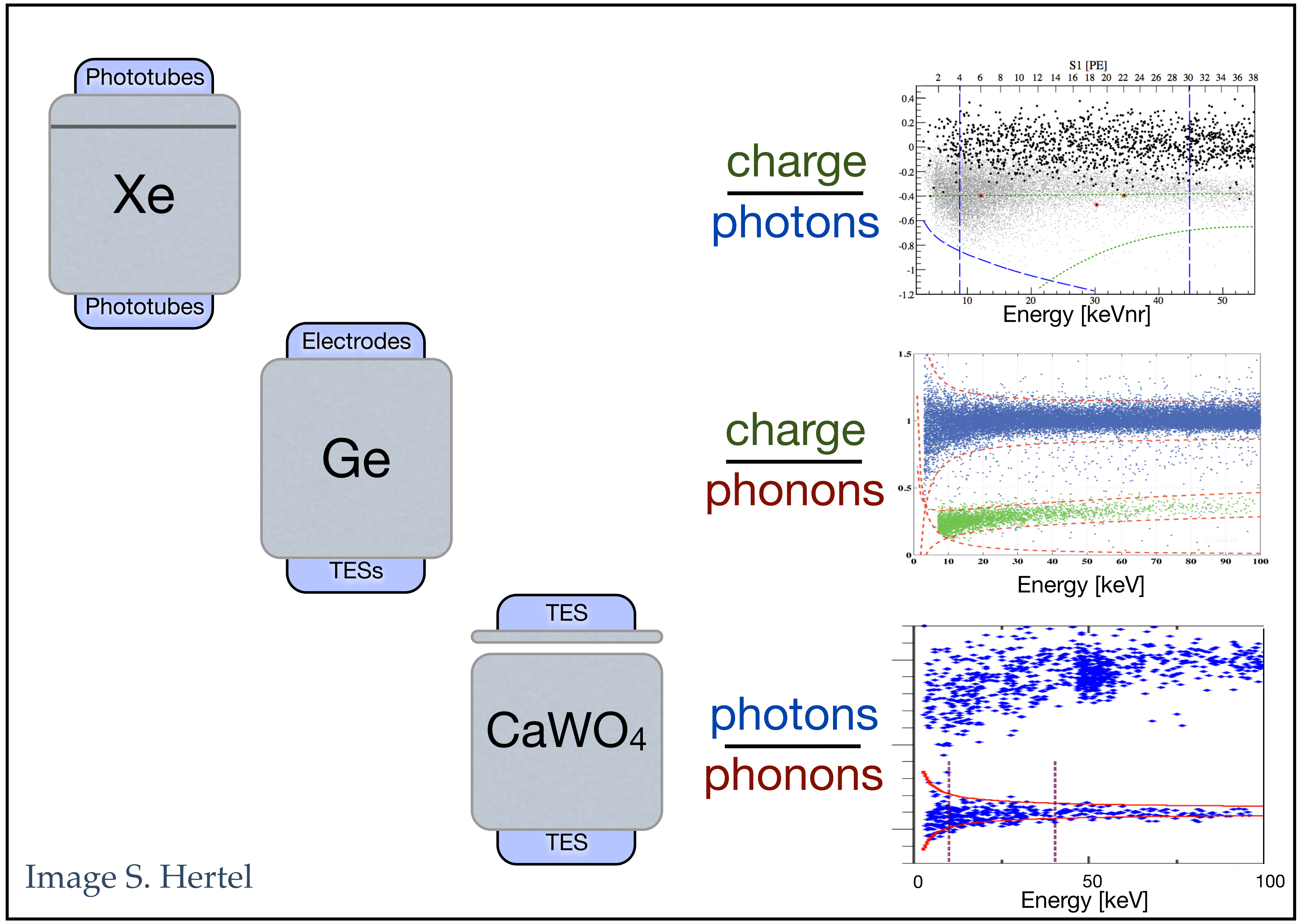
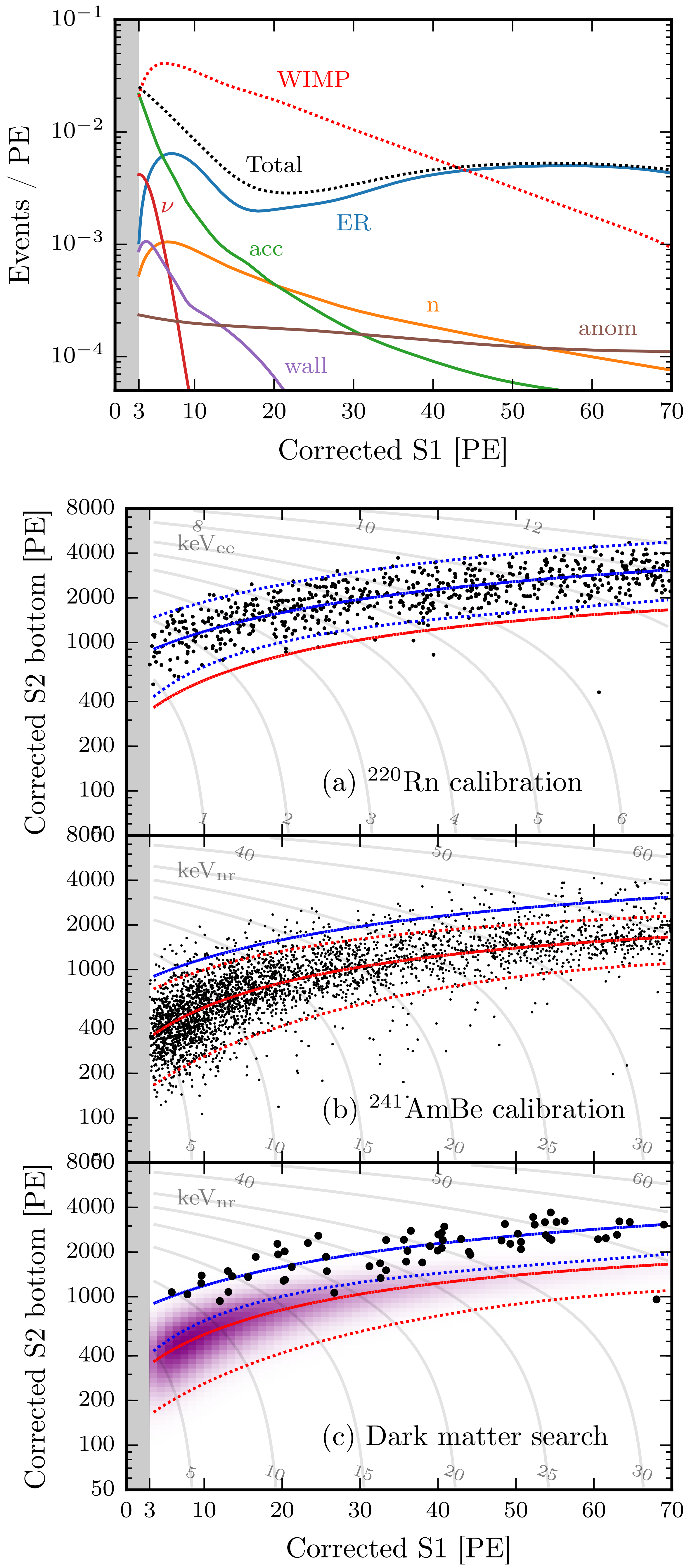


Image S. Hertel

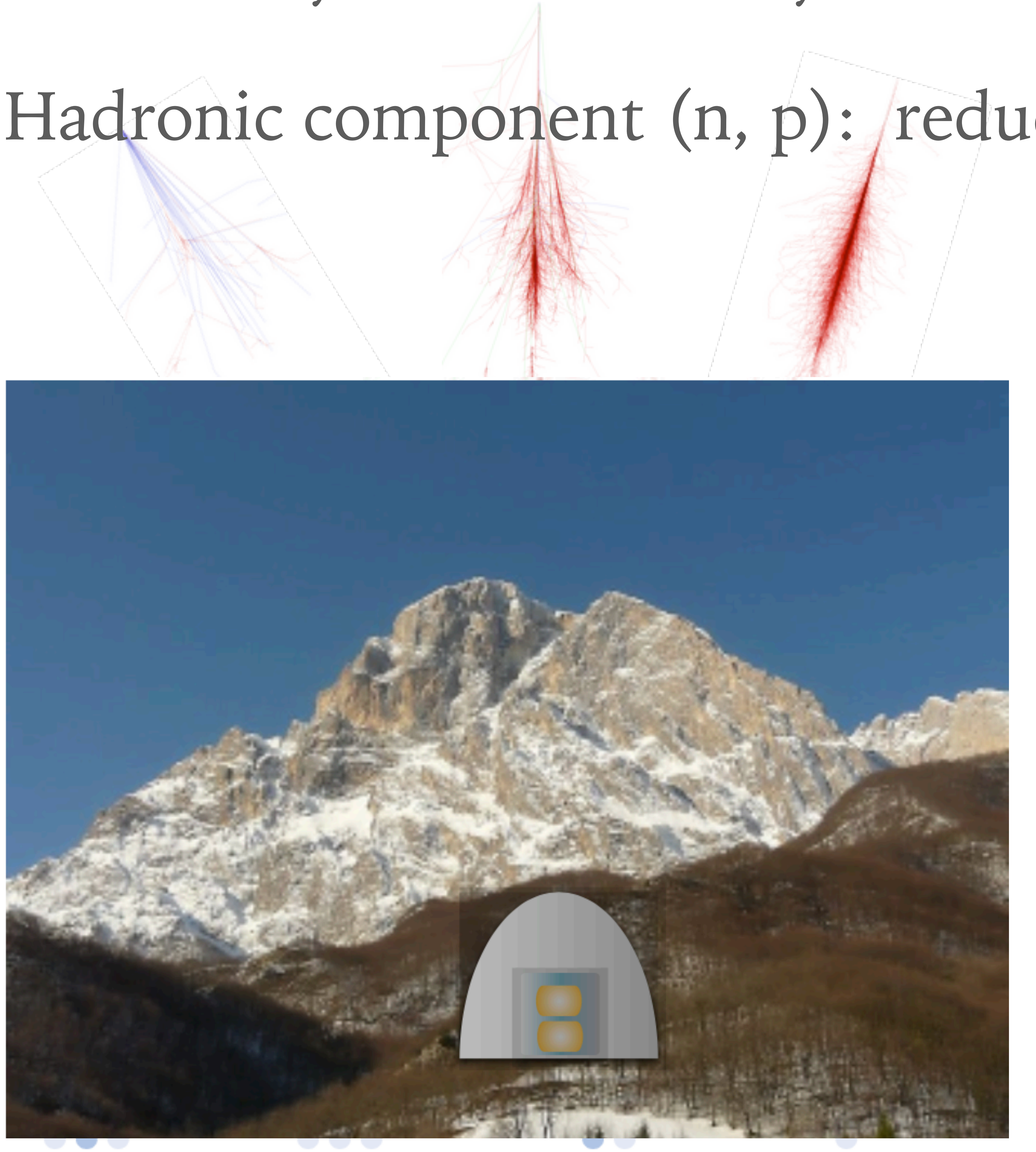
- ➤ Cut-and-count analysis methods no longer deliver required sensitivity.
- ➤ Profile likelihood and other multivariate analysis techniques that rely on accurate background models are now standard.



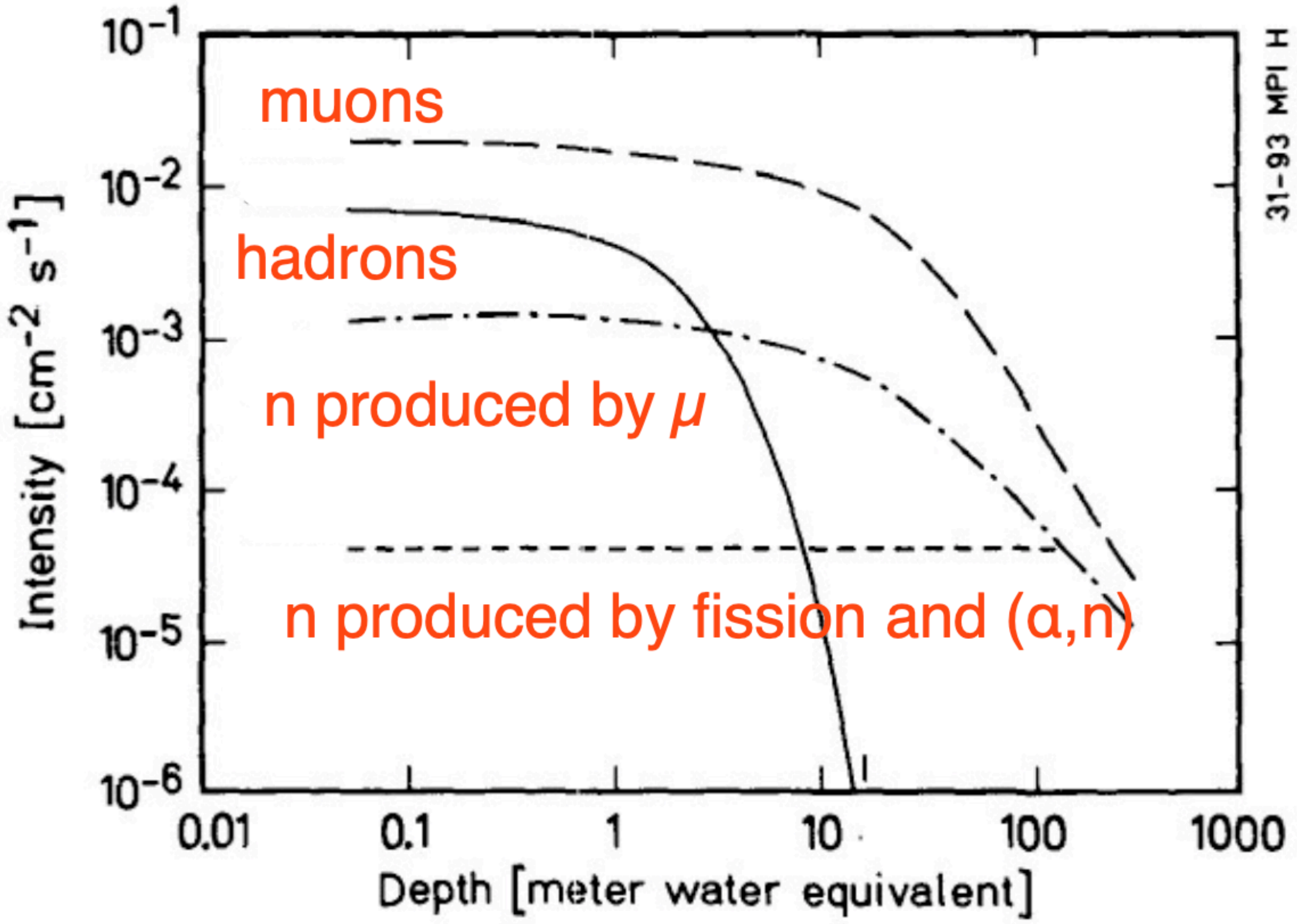
PRL 119.181301

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

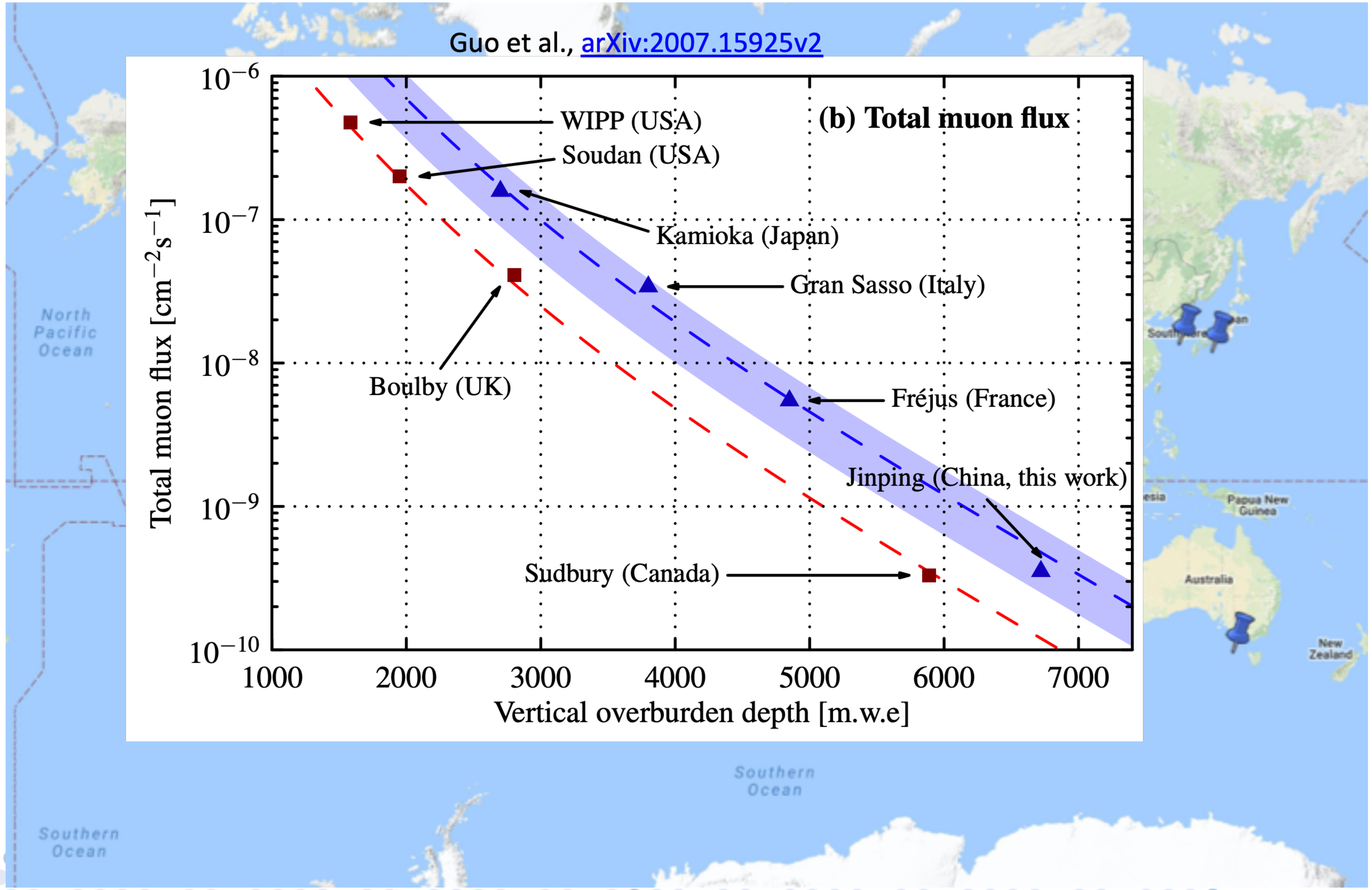


Underground Facilities

- Worldwide 17 underground sites for physics research

Underground Facilities

Guo et al., arXiv:2007.15925v2



- ➤ 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

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

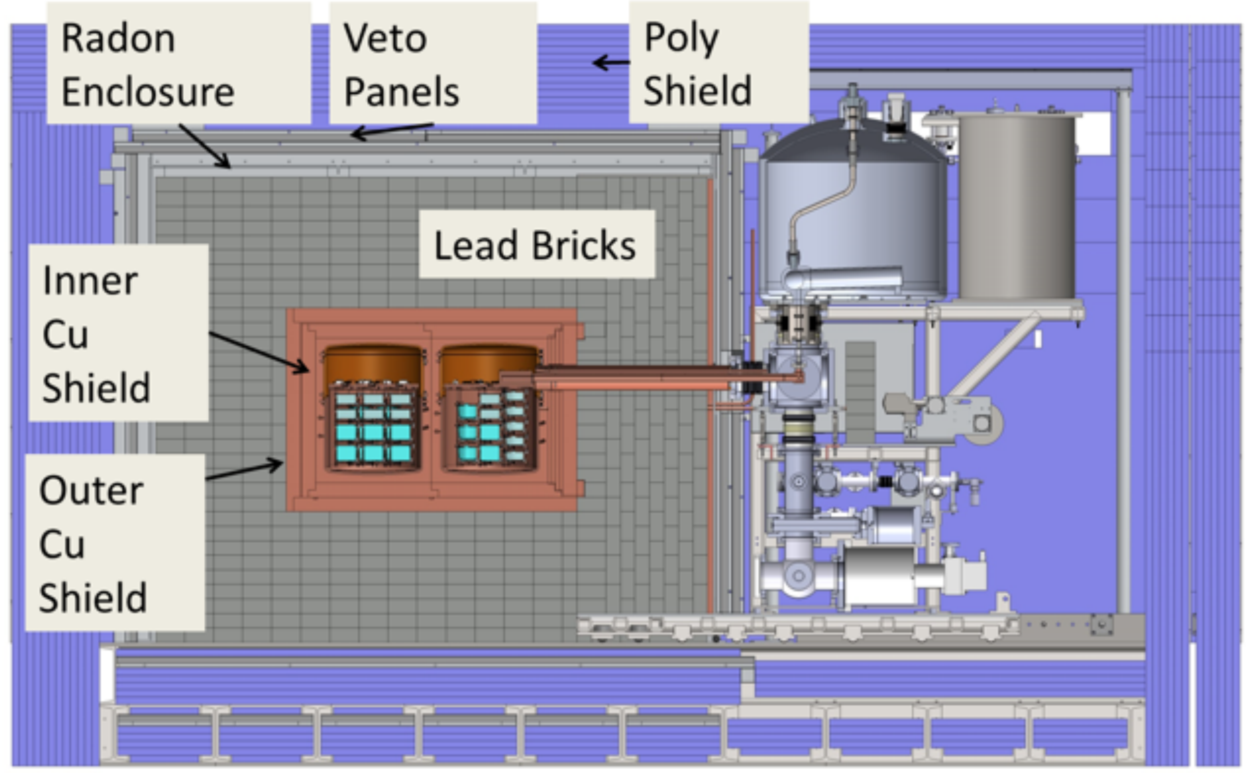
Isotope	Decay	Half life	Energy in Ge [keV]	Activity [μBq/kg]
^{3}H	β^-	12.33 yr	$E_{max(\beta-)}$=18.6	2
^{49}V	EC	330 d	$E_{K(Ti)}$ = 5	1.6
^{54}Mn	EC, β^+	312 d	$E_{K(Cr)}$ = 5.4, E_γ=841	0.95
^{55}Fe	EC	2.7 yr	$E_{K(Mn)}$ = 6	0.66
^{57}Co	EC	272 d	$E_{K(Fe)}$=6.4, E_γ=128	1.3
^{60}Co	β^-	5.3 yr	$E_{max(\beta-)}$=318, 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

SNOLAB

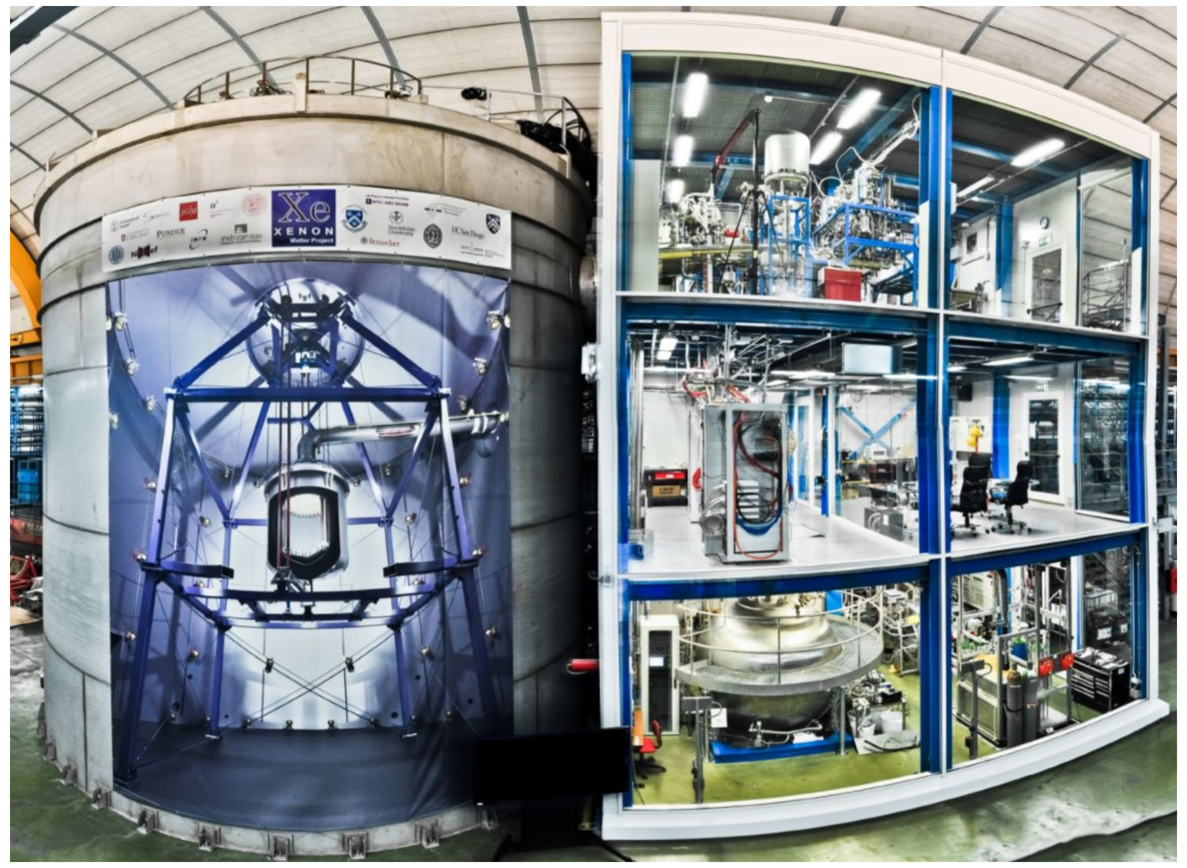
Environmental Backgrounds

LUX/LZ Muon Veto

SuperCDMS Soudan Passive Shield



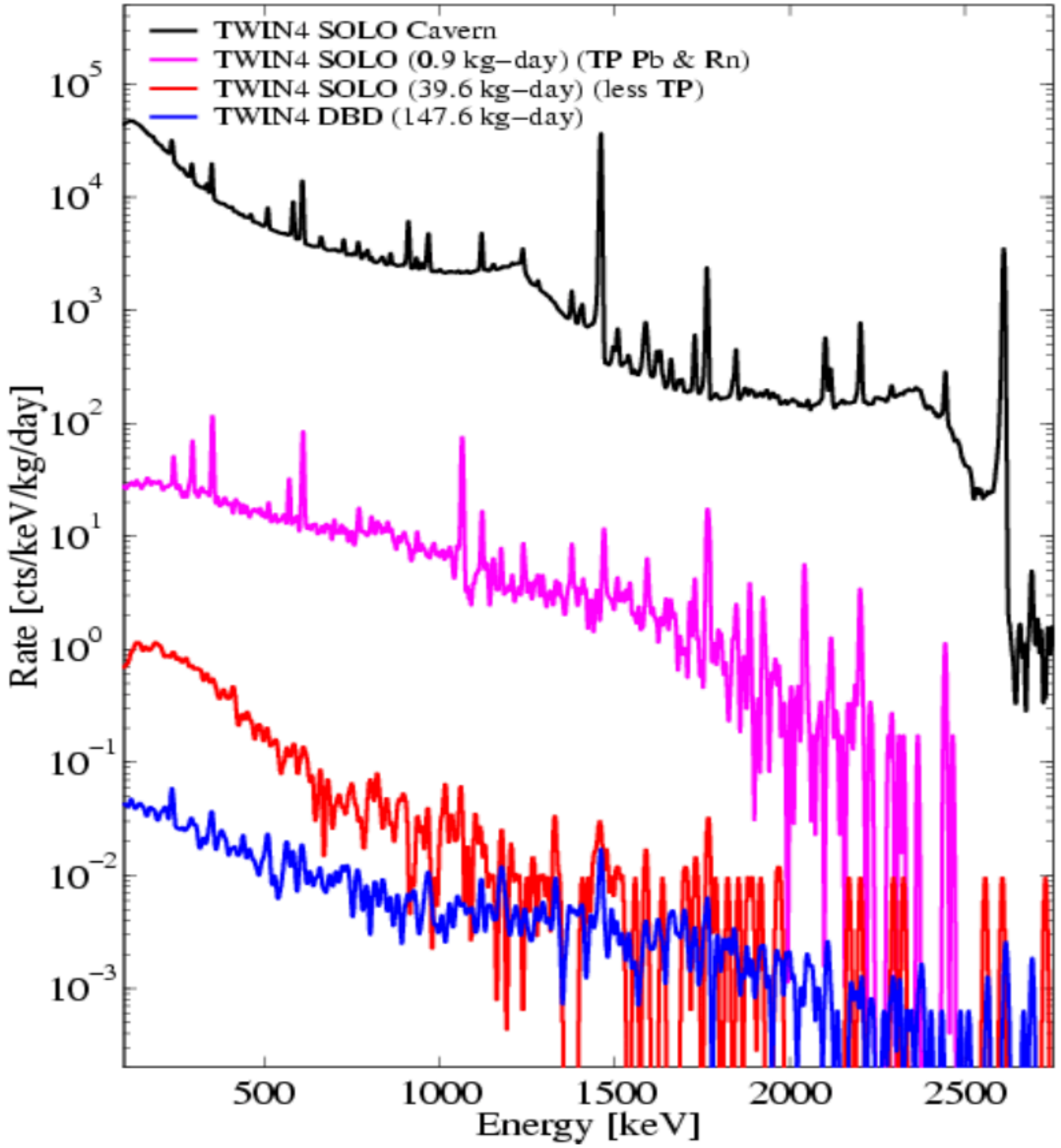
MAJORANA Demonstrator Passive Shield



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.

Environmental Backgrounds



Ge detector underground, no shield

Ge detector underground, Pb shield and purge for Rn

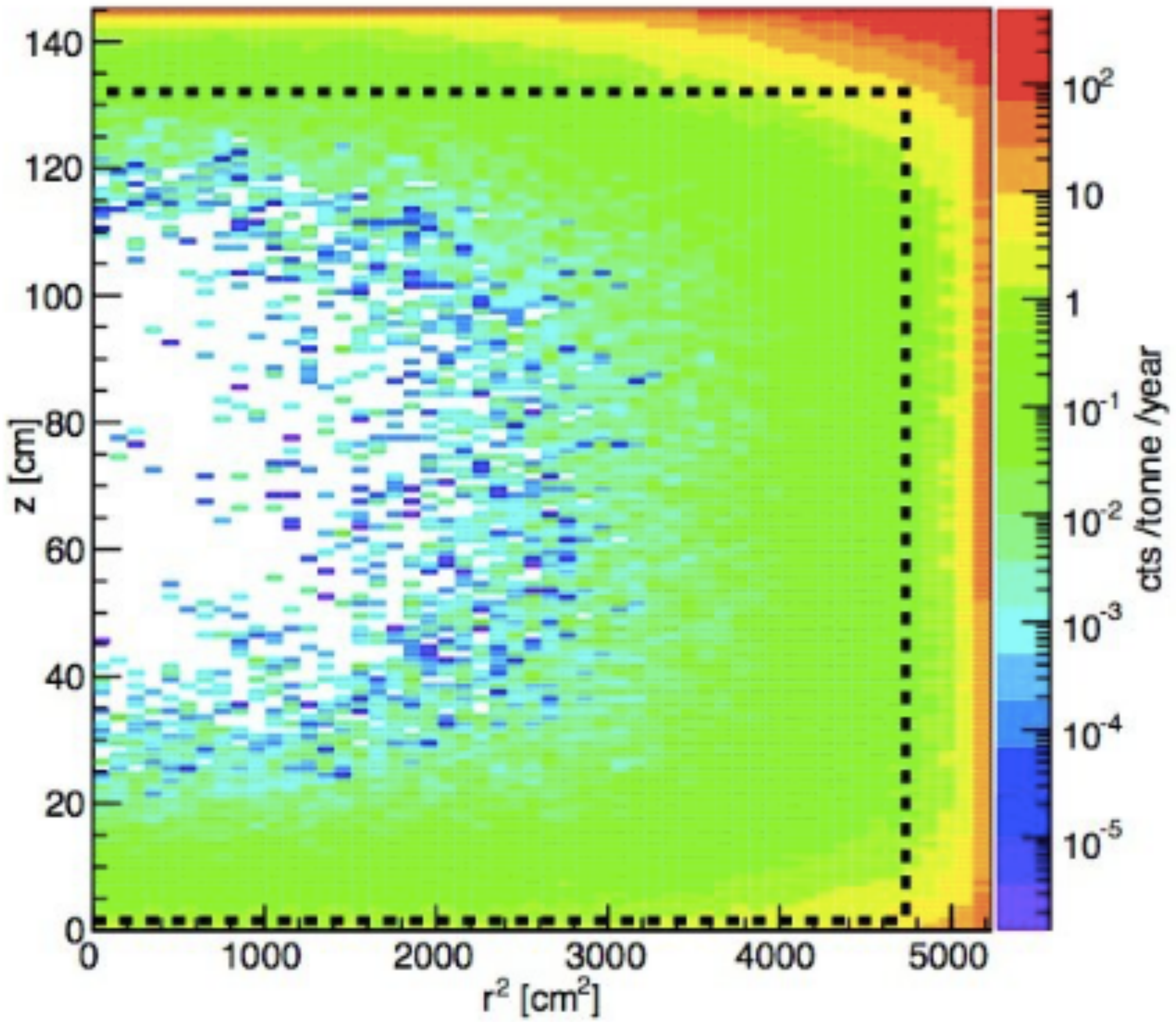
- A combination of high-Z and low-Z materials are employed to diminish the neutron and gamma fluxes.
  - Lead, polyethelyne, copper
- Nitrogen purge of shield structors to reduce backgrounds induced by airborne radon decays
- Large water shields
  - passively reduce environmental radioactivity and muon-induced 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.

eld & infrastructure

Self Shielding Properties

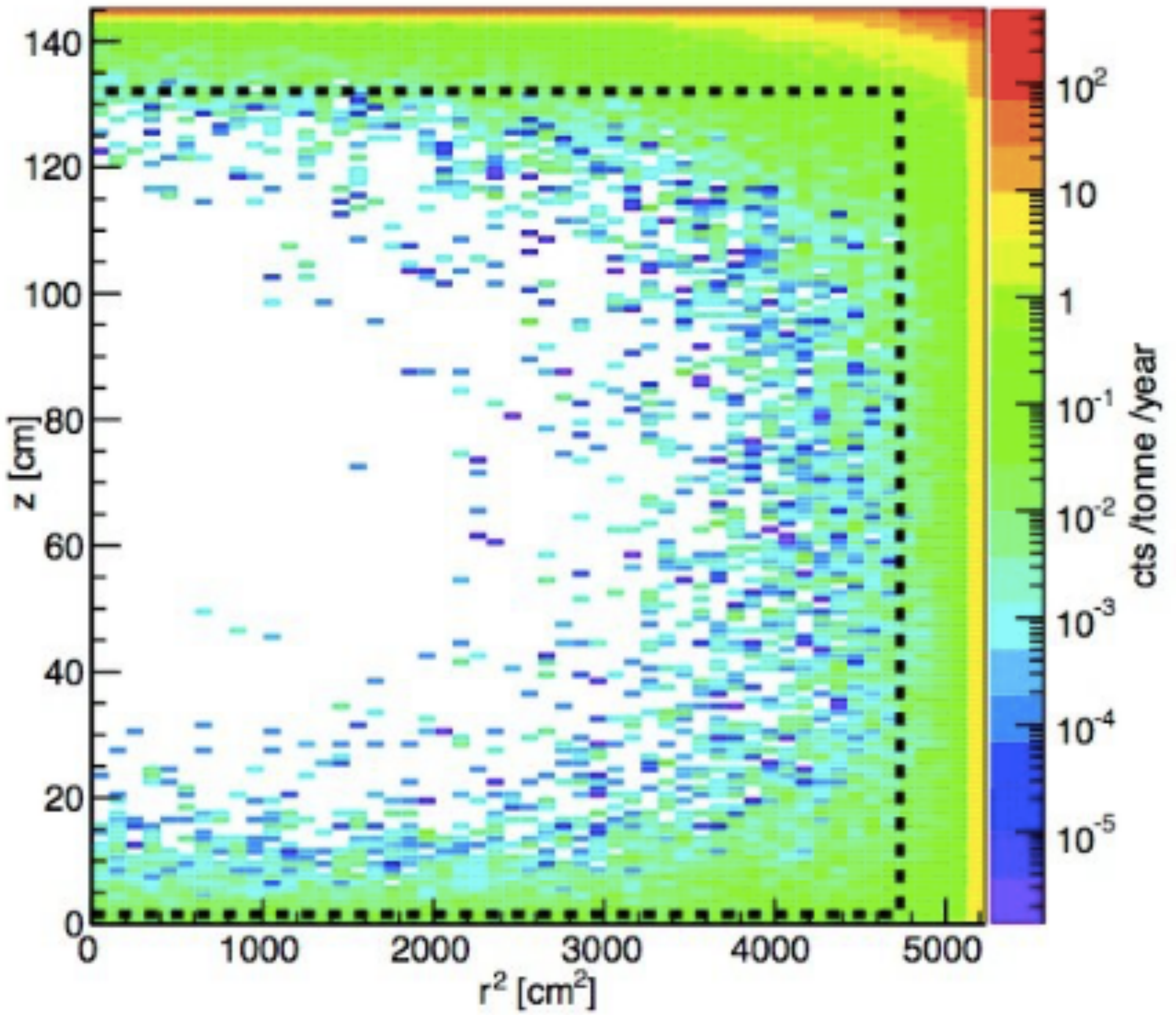
Example: LZ Dark Matter Experiment

K. Palladino, TAUP 2017



LXe TPC only

3.8 T fiducial mass



LXe TPC + Skin + OD

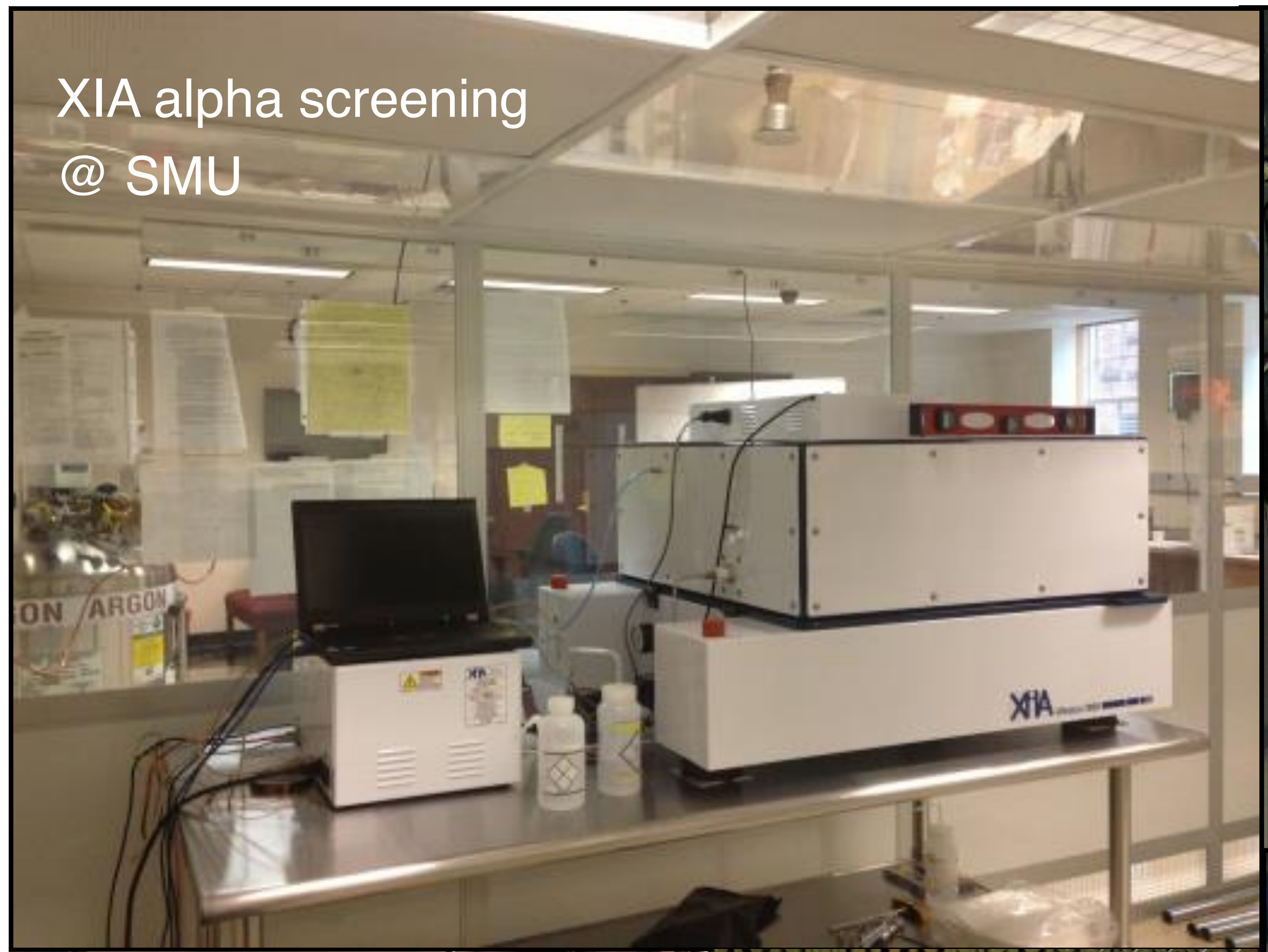
5.6 T fiducial mass

SNOLAB

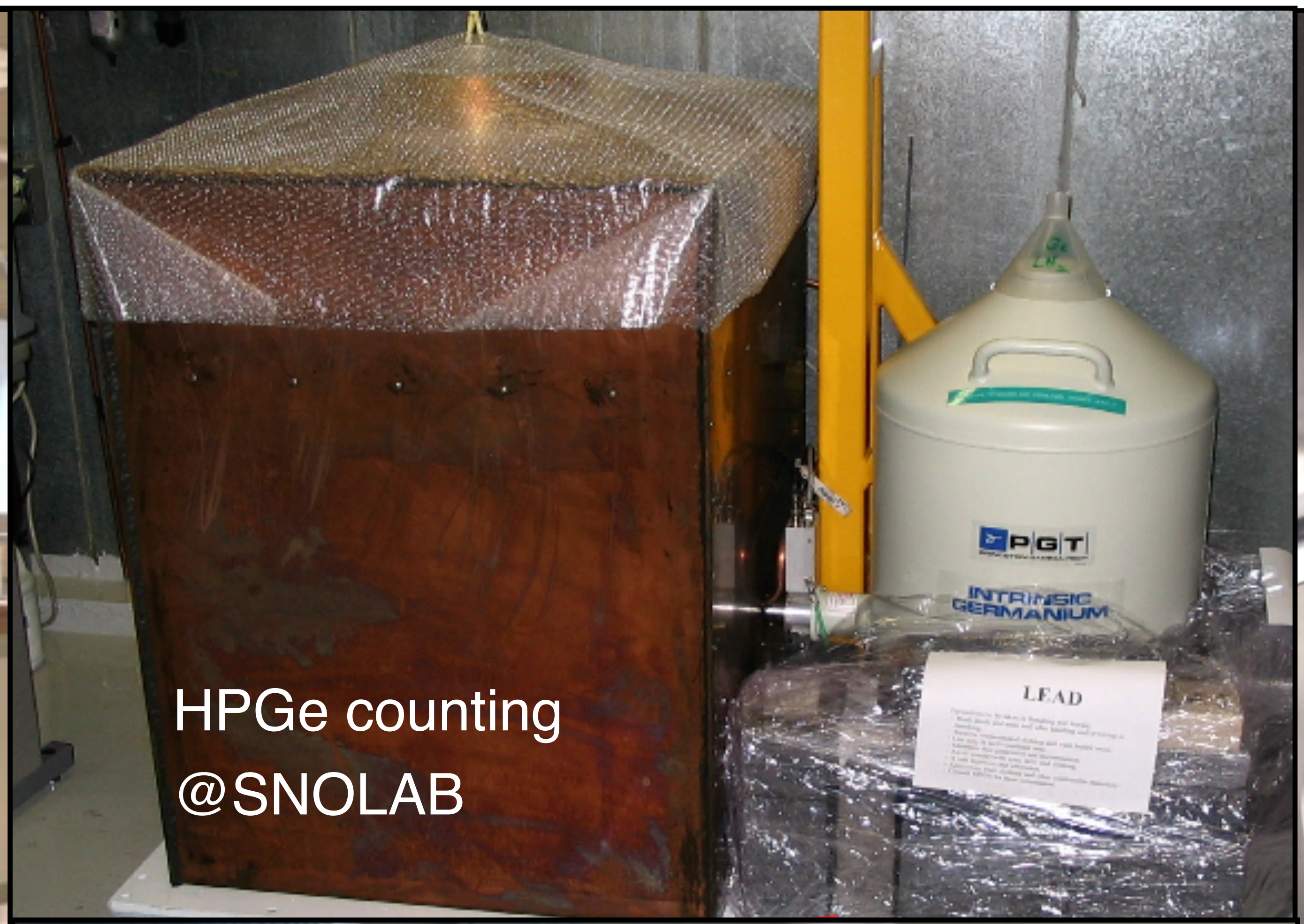
Internal Radioactivity

- ^{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.

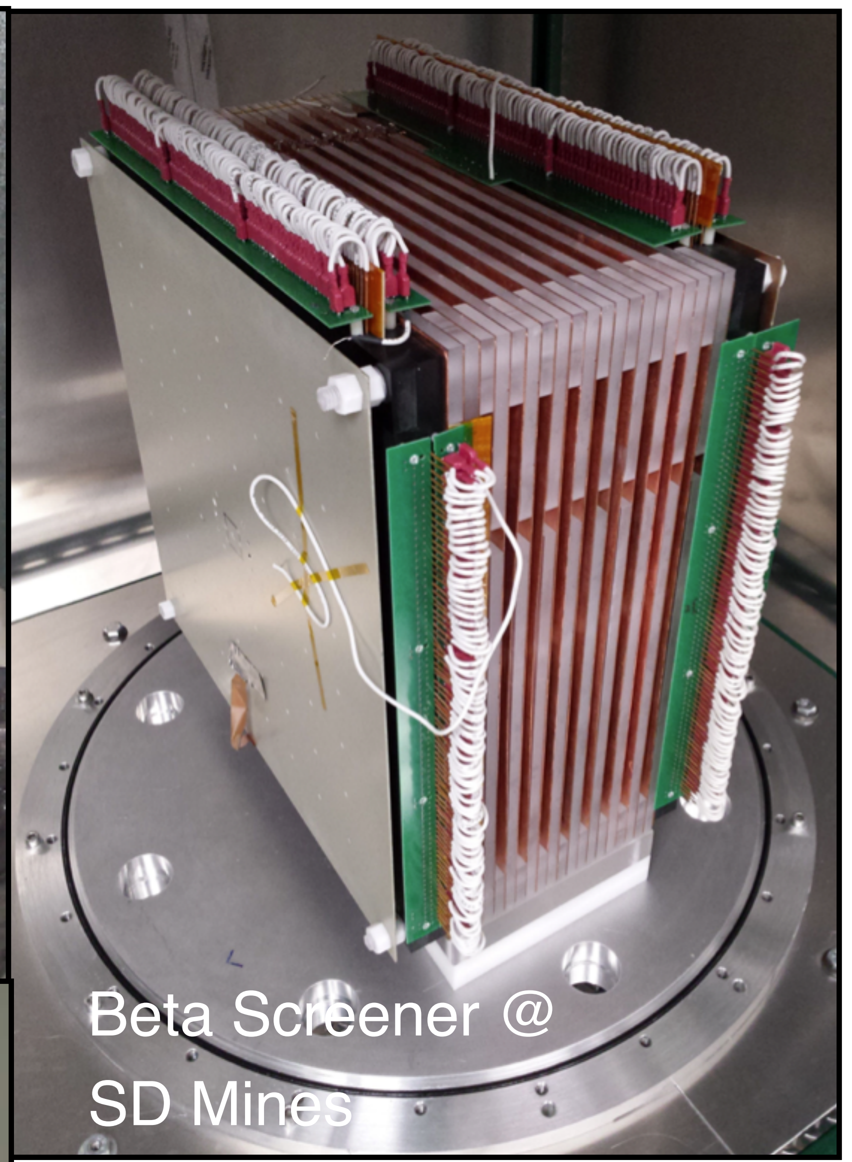
Internal Radioactivity



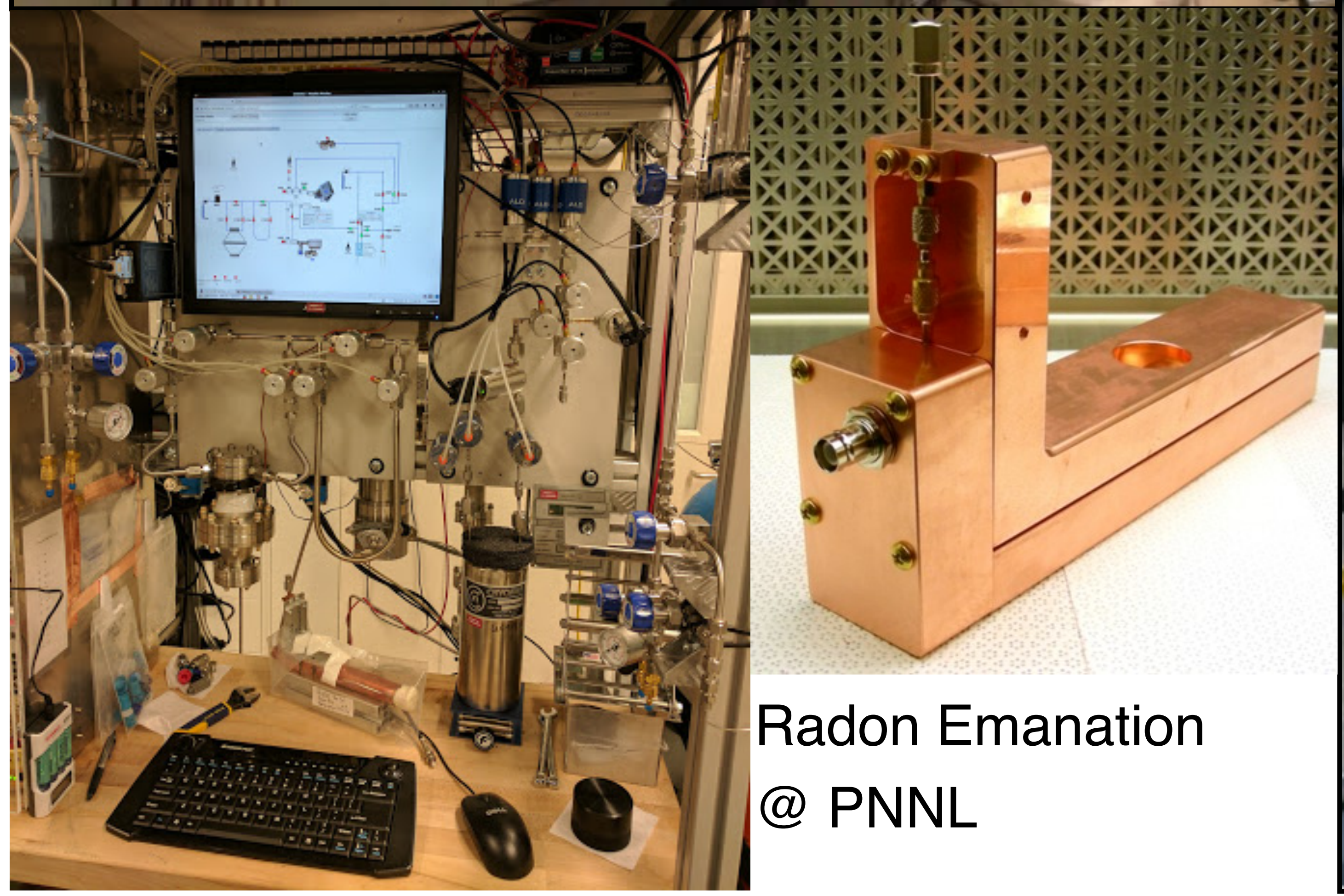
XIA alpha screening
@ SMU



HPGe counting
@SNOLAB



Beta Screener @
SD Mines

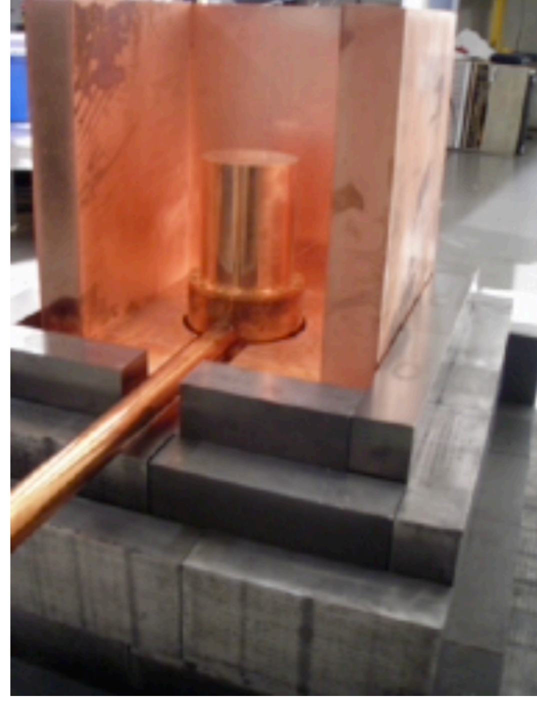


Radon Emanation
@ PNNL

ICPMS @LNGS

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

How Well Can We Do?



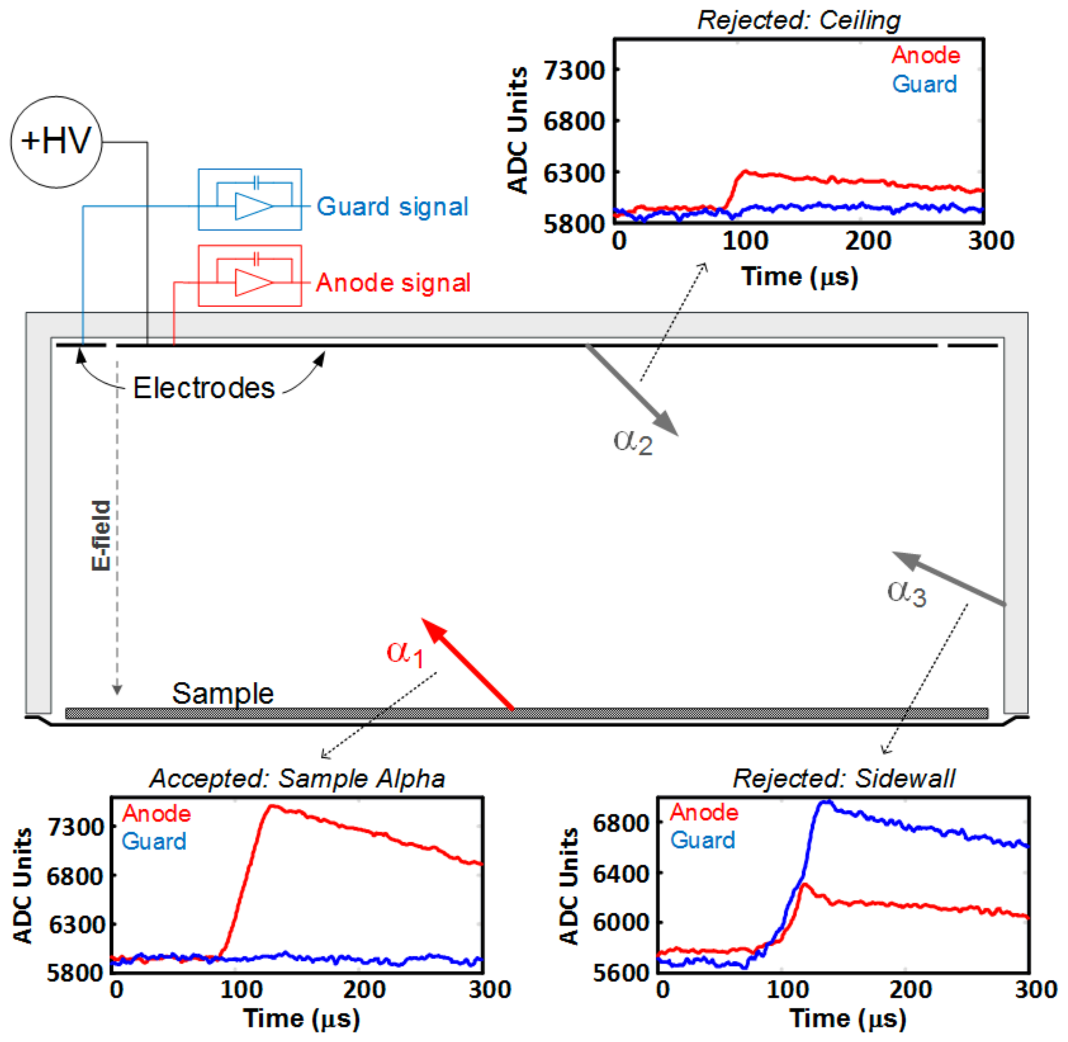
Augmented Commercial Systems:
Commercially purchased High-Purity Ge detector is placed in a custom designed shield (Pb, copper, neutron moderation and capture materials, active cosmic ray veto, underground location)

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).

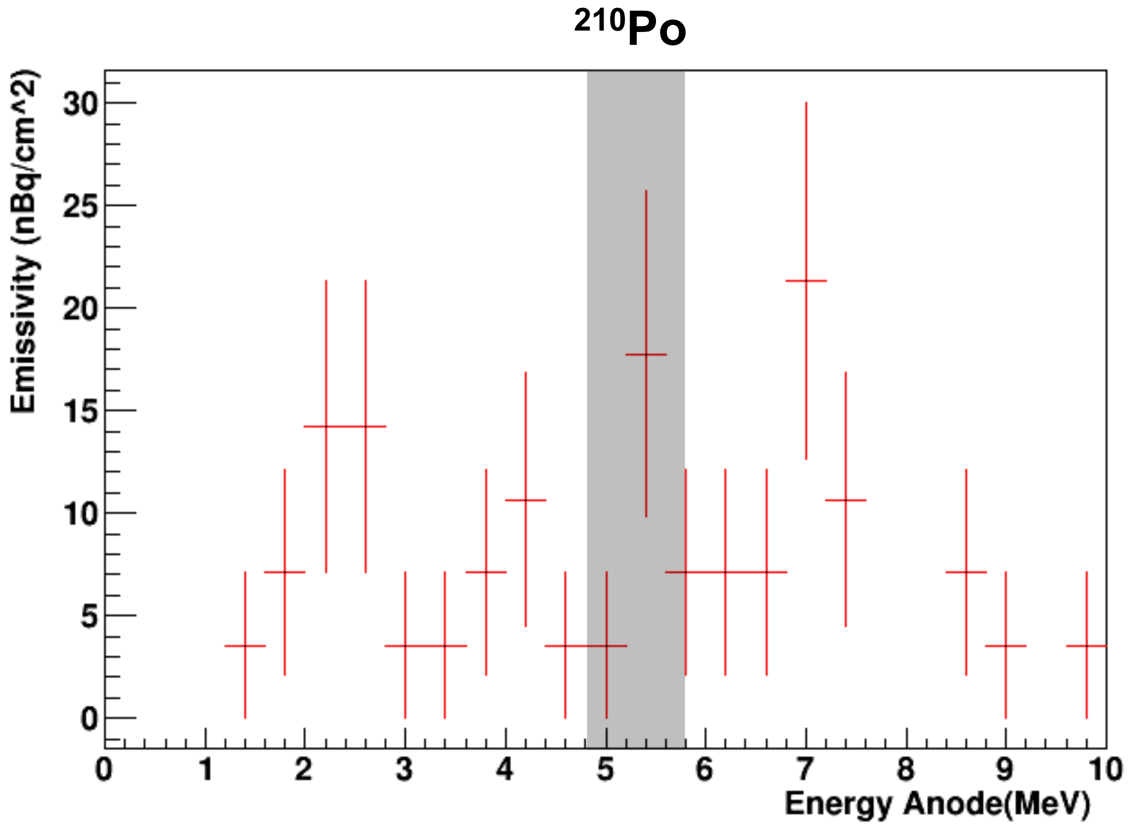
HPGe Counting:

Isotope/ Chain	Standard Size (ppb) I (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	

Surface Alpha Screening:



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



Ultra-pure PNNL Copper

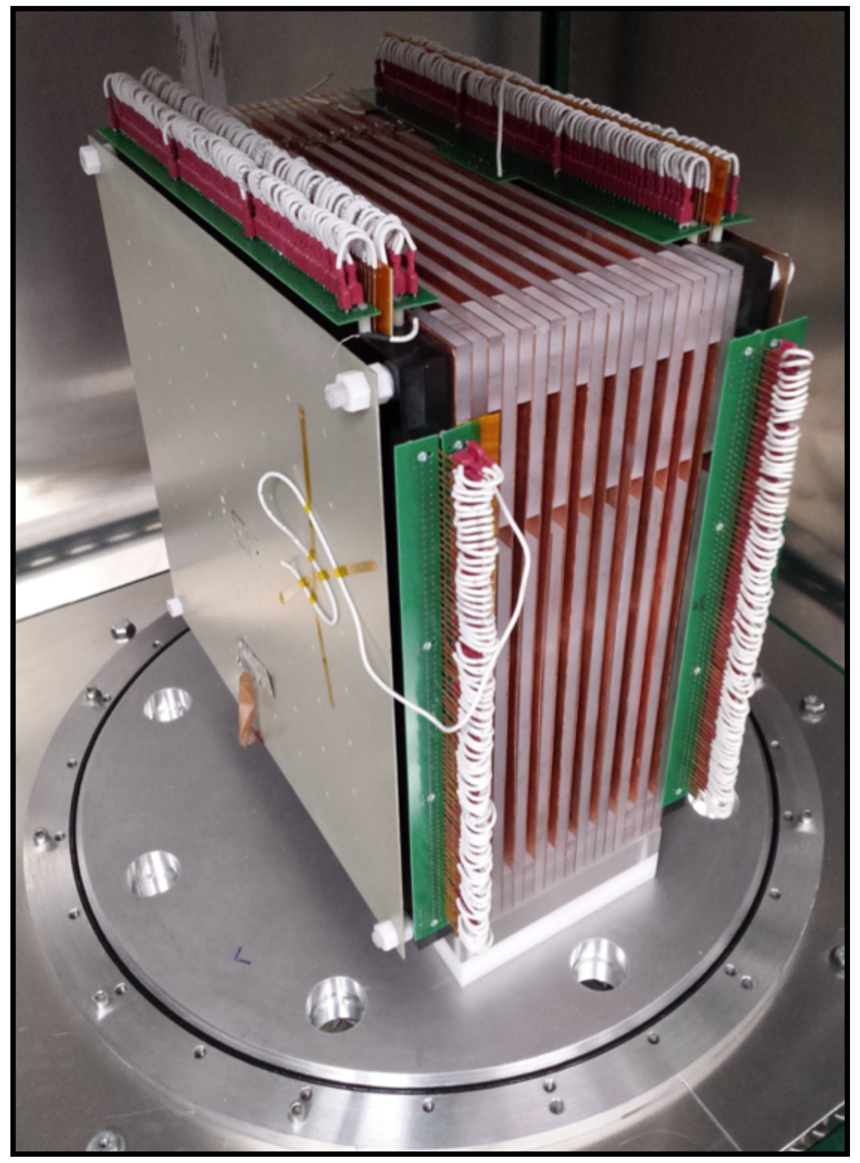
- *~25 nBq/cm^2 in ^{210}Po ROI*

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)*

Many other Options

Technique	Sensitivity
Radon Emanation	0.1-10 µBq/kg (Ra)
Immersion Whole Body Counters	10^{-13}-10^{-14} g/g (U/Th)
ICPMS (Inductively Coupled Plasma Mass Spectrometry)	ppt to ppt (U/Th/K)
SIMS/GDMS (Secondary Ion & Glow Discharge Mass Spectroscopy)	1 ppb (SIMS) 10-100ppt (GDMS)
AMS (Accelerator Mass Sepctroscopy)	< 1 ppt
Neutron Activation Analysis	100 pg (U), 10 ng (K)

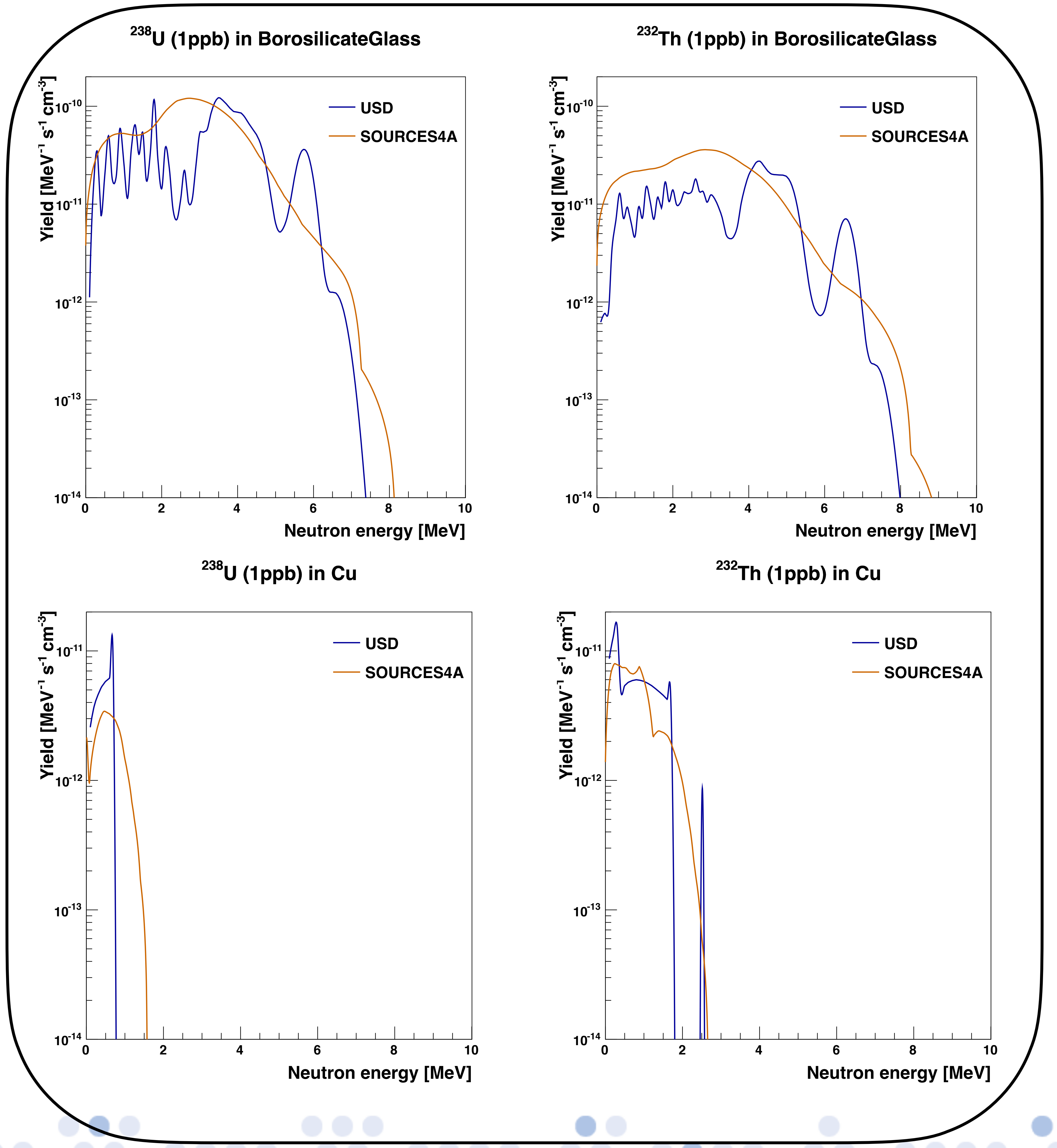
Modeling Backgrounds

- 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)
- 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

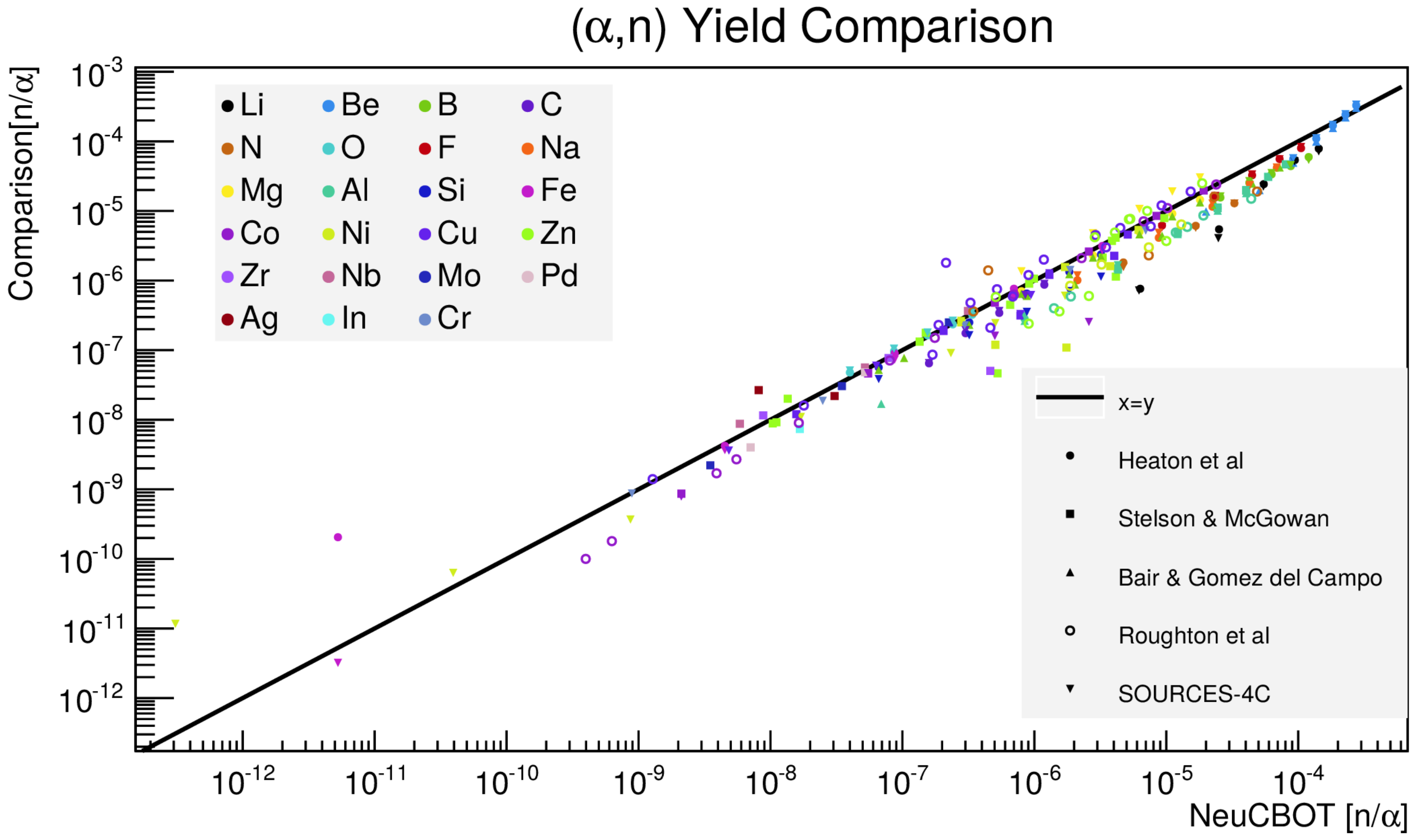


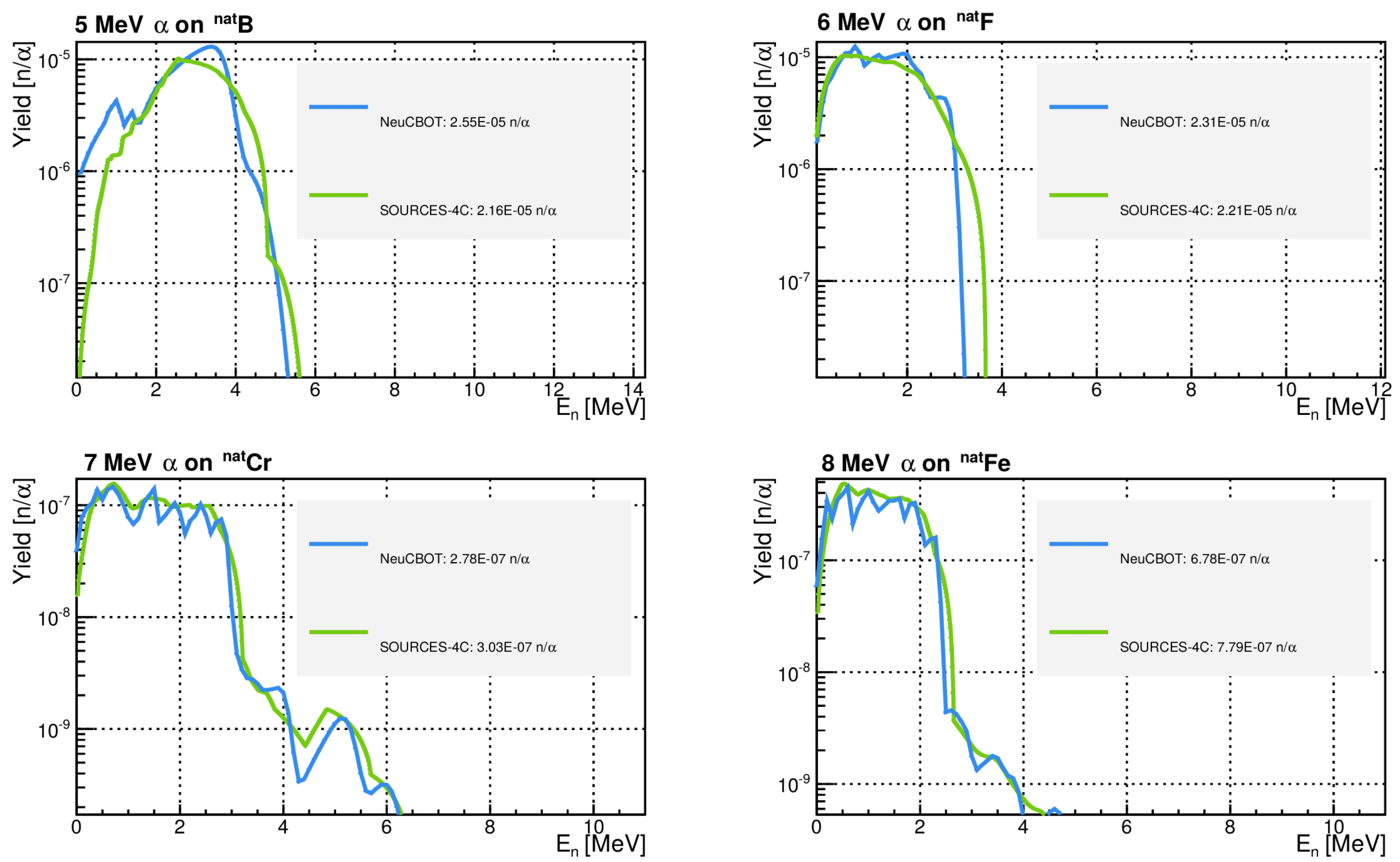
Material	Chain	Neutron Yield ($n \cdot s^{-1} \cdot cm^{-3}$) SOURCES-4A	USD	Diff %
Cu	^{238}U	$2.84\ 10^{-12}$	$3.46\ 10^{-12}$	20
	^{232}Th	$9.49\ 10^{-12}$	$1.11\ 10^{-11}$	16
PE (CH_2)	^{238}U	$1.26\ 10^{-11}$	$9.56\ 10^{-12}$	-27
	^{232}Th	$5.28\ 10^{-12}$	$2.87\ 10^{-12}$	-59
Titanium	^{238}U	$1.04\ 10^{-10}$	$1.99\ 10^{-10}$	-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.

Framework Comparisons: NeuCBOT vs SOURCES-4C

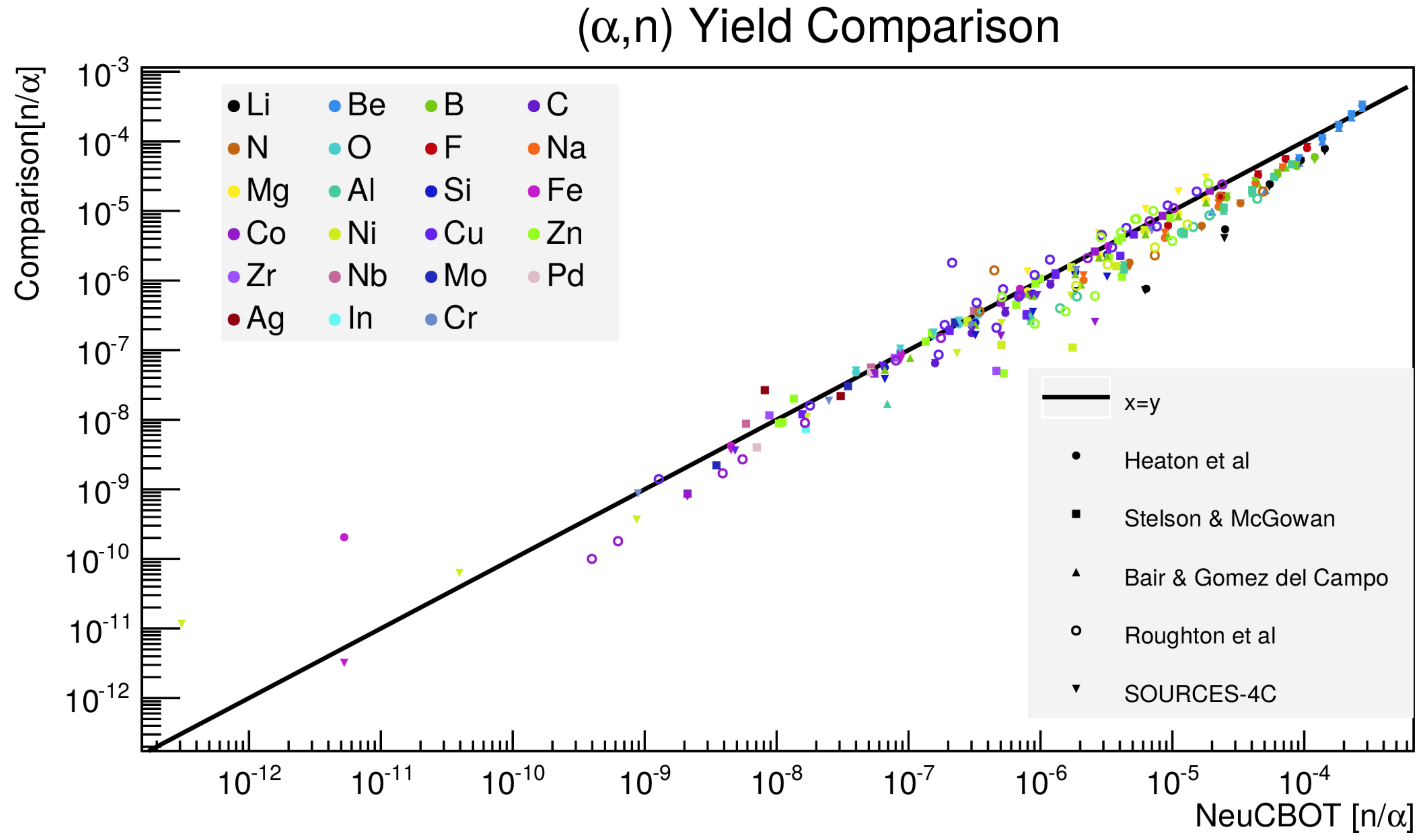


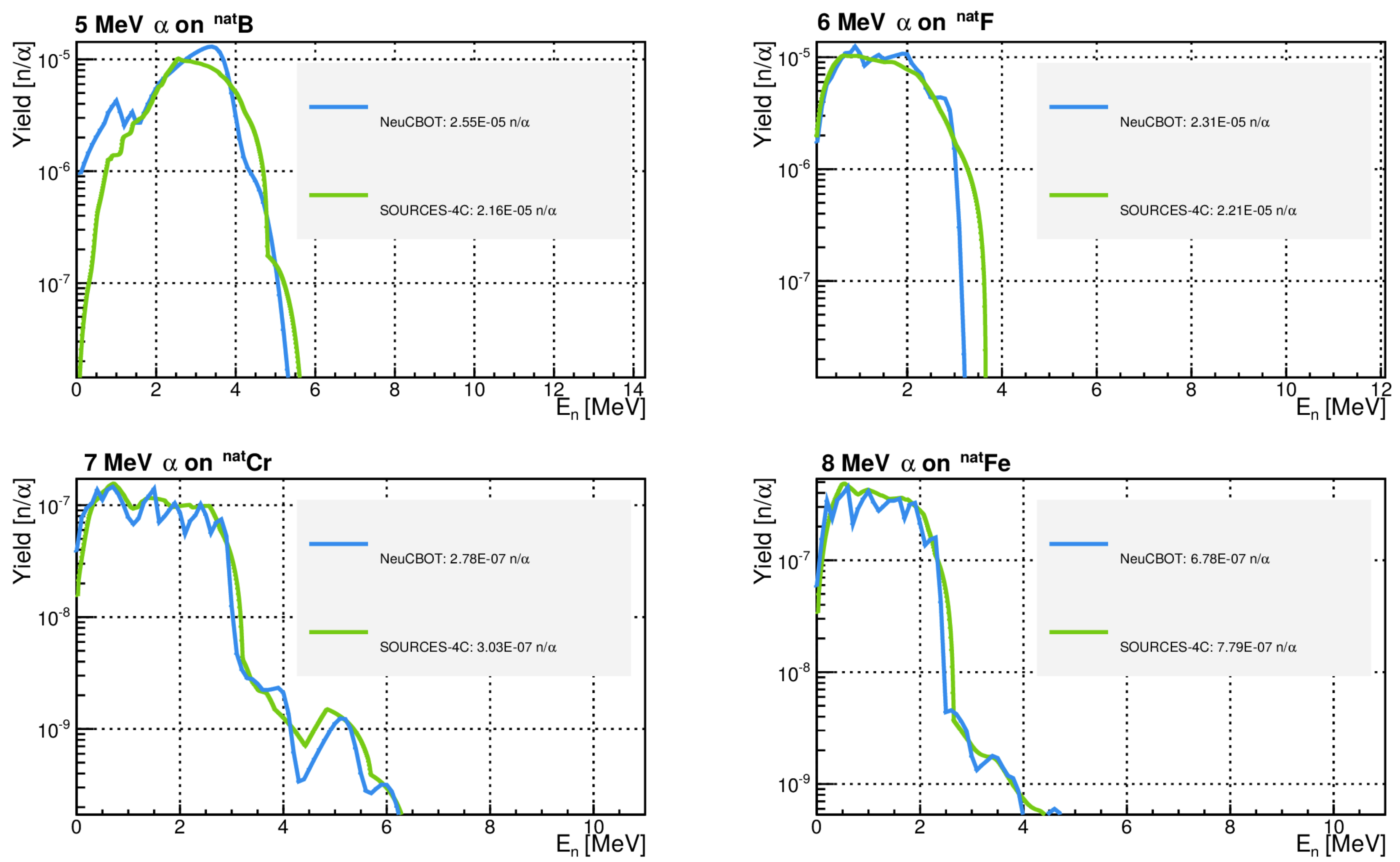


NeuCBOT used by DEAP to predict Neutrons in materials of interest.

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	2.19E-07	9.72E-07	1.42E-06	1.33E-06
Invar	2.06E-12	2.58E-07	1.84E-07	1.08E-06
TPB	3.15E-07	1.35E-06	1.96E-06	1.84E-06
Polyethylene	2.52E-07	1.09E-06	1.58E-06	1.49E-06
Polystyrene	3.01E-07	1.29E-06	1.88E-06	1.77E-06
Stainless Steel	1.31E-09	5.52E-07	4.42E-07	1.96E-06
Argon	8.82E-08	1.41E-05	1.72E-05	2.64E-05

Framework Comparisons: NeuCBOT vs SOURCES-4C





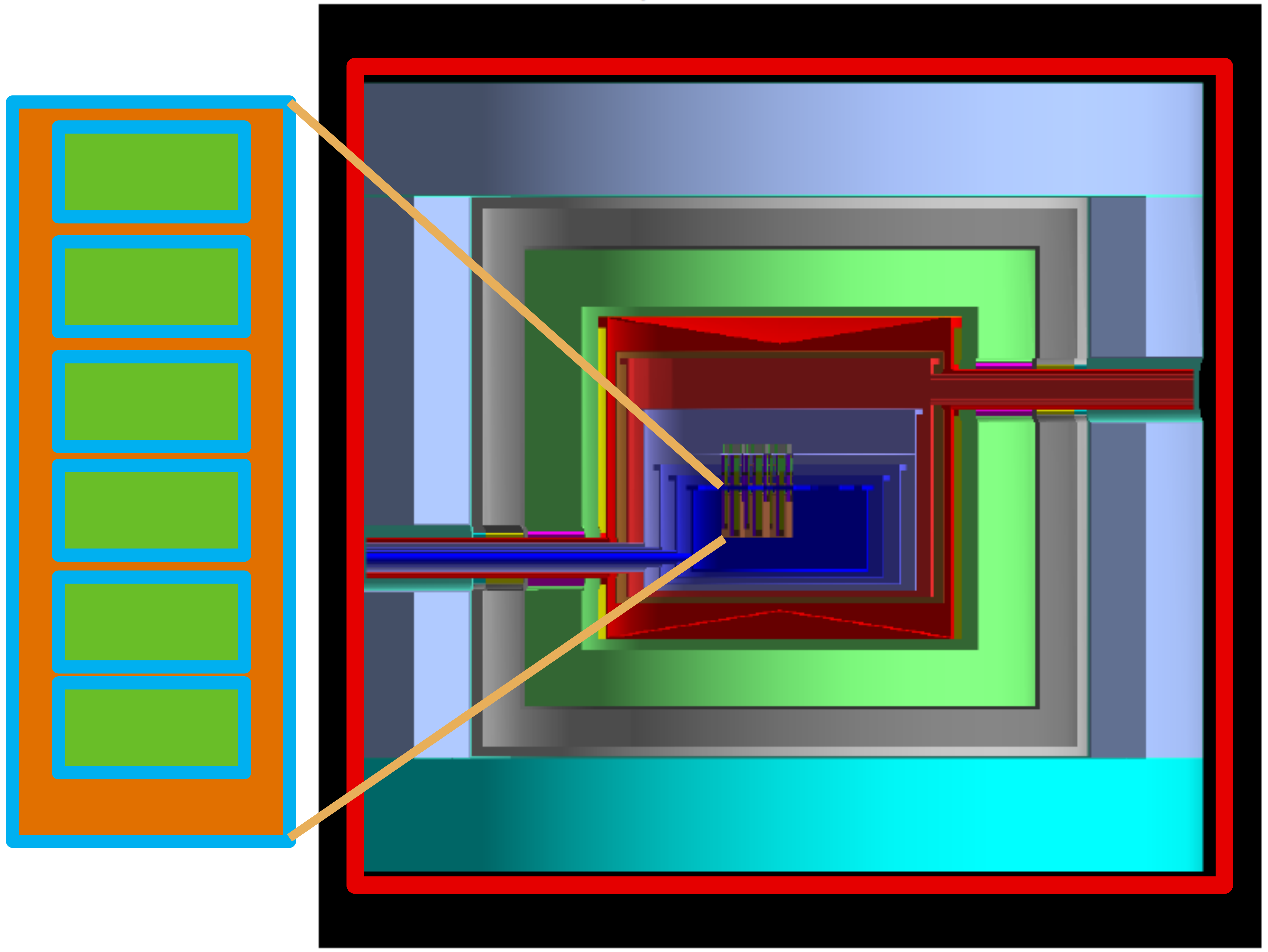
NeuCBOT used by DEAP to predict Neutrons in materials of interest.

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			1.33E-06
Invar	.06E-1			1.08E-06
TPB	.15E-0			1.84E-06
Polyethylene	.52E-0			1.49E-06
Polystyrene	.01E-0			1.77E-06
Stainless Ste	1.31E-0			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

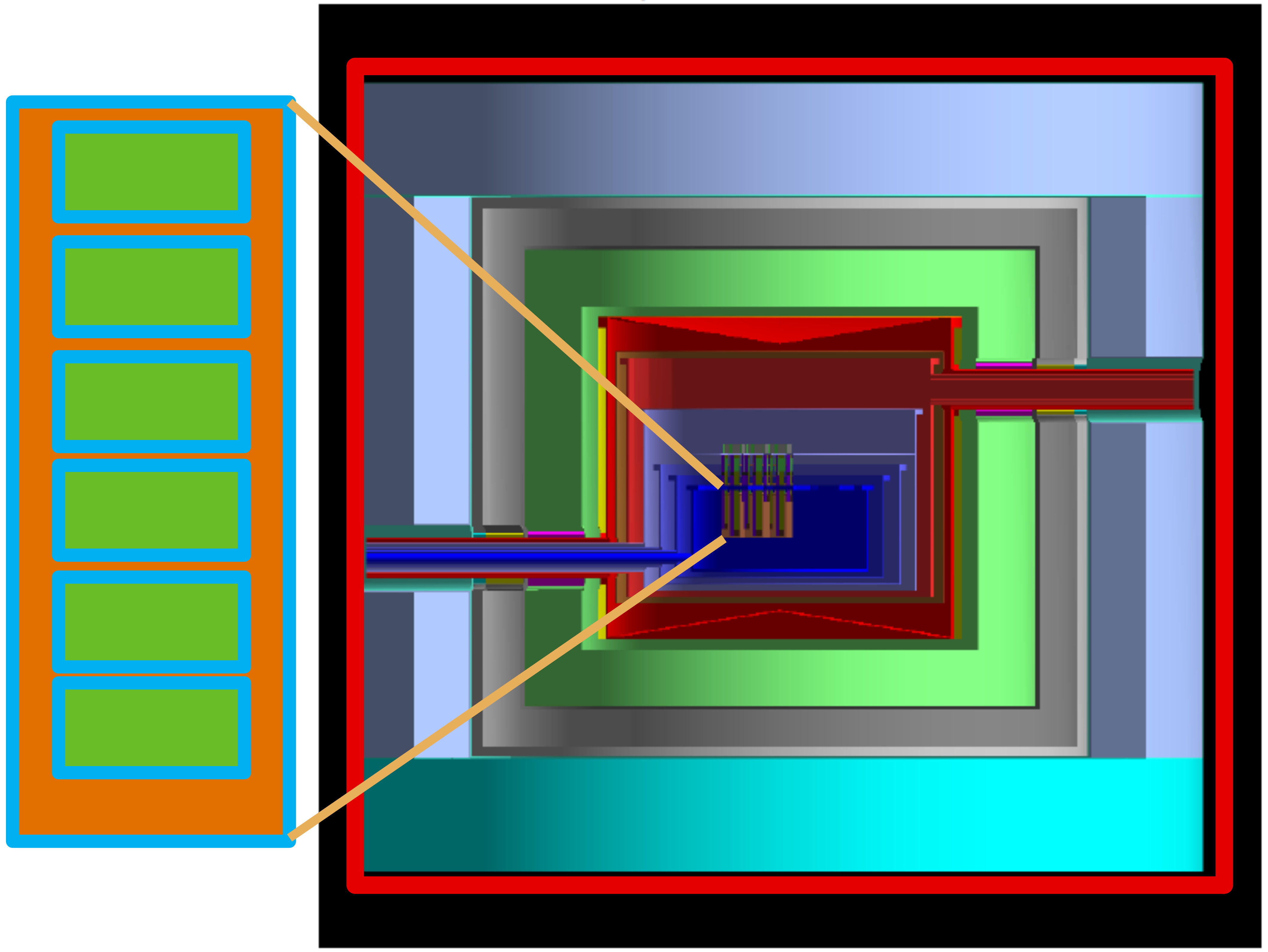
Simulation Tools



SuperCDMS Geometry in Geant4

- Geant4 simulations of backgrounds based on assay information

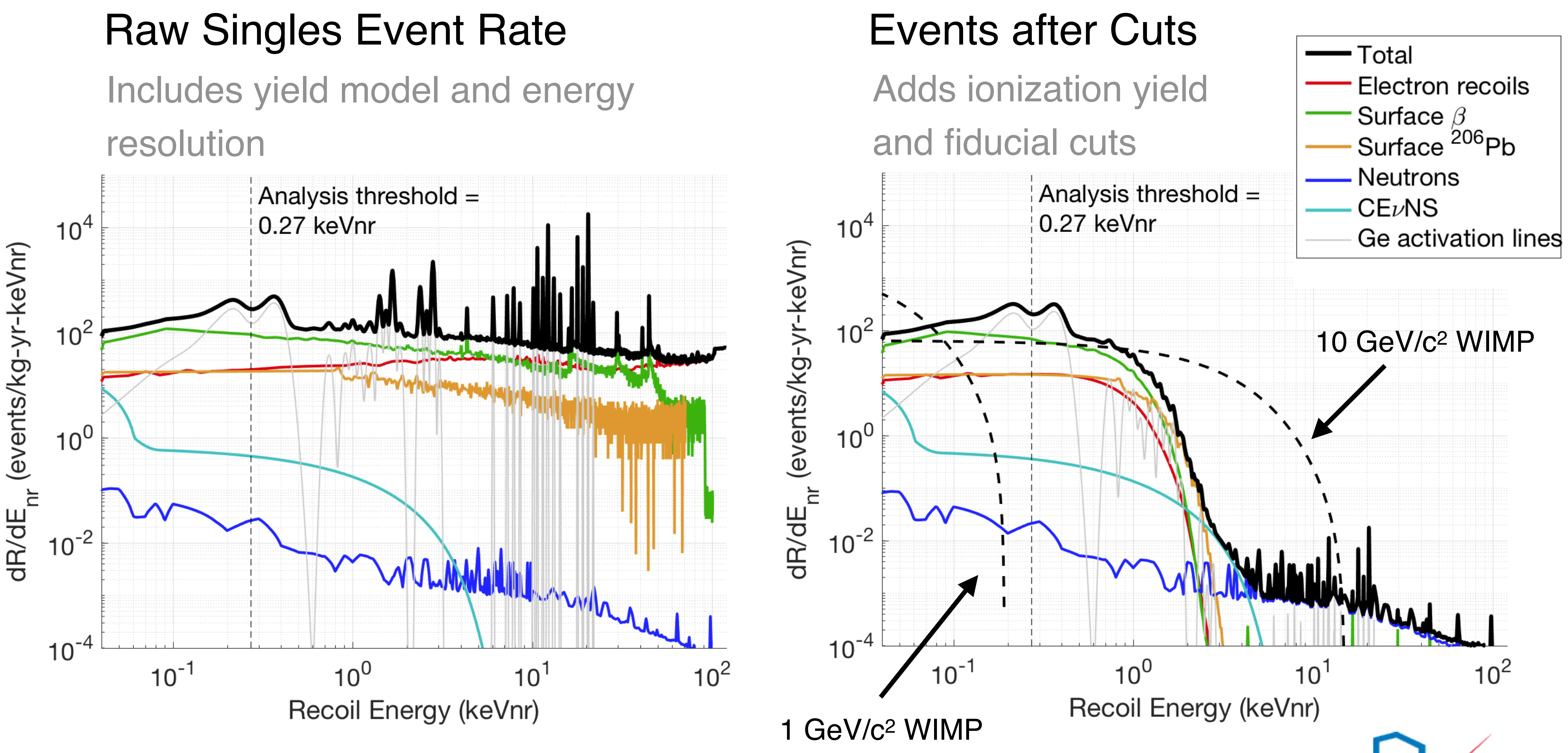
Simulation Tools



SuperCDMS Geometry in Geant4

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

SuperCDMS anticipated background spectra (Ge iZIPs)



SNOLAB

Background Inventory

SNOLAB

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

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	0.49	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	0.18	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	Y	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	Y	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 (1.63 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	

Detector components from assays

Xenon contaminants

External backgrounds

Physics: Neutrinos!

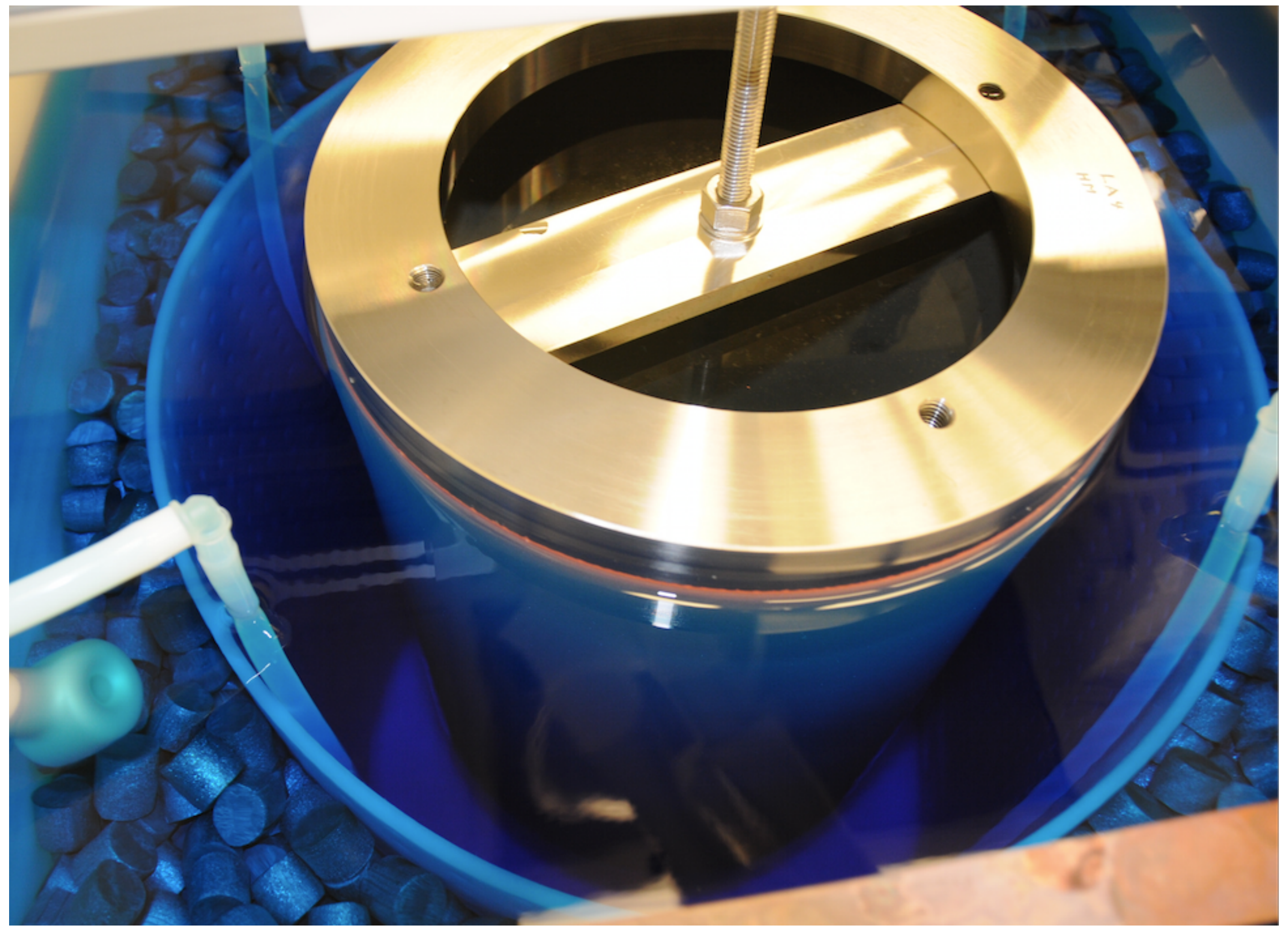
- Background inventories of components and their required purity can be made.
- Provides a tool that can be used for material and vendor selection.

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

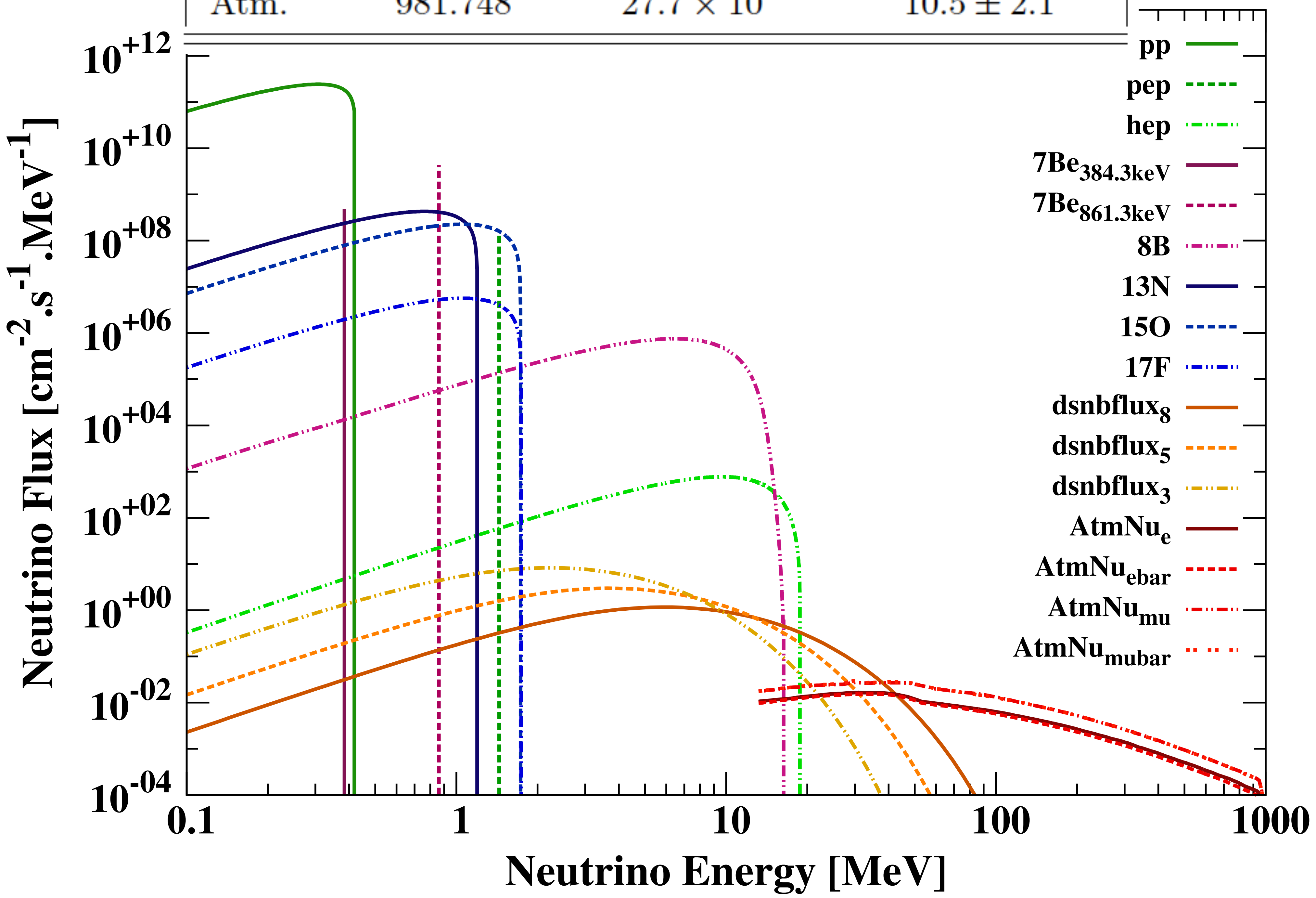
DarkSide Cryogenic distillation column for purification of ^{39}Ar

SNOLAB

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
    - ~1-5 events per (100 ton x year)

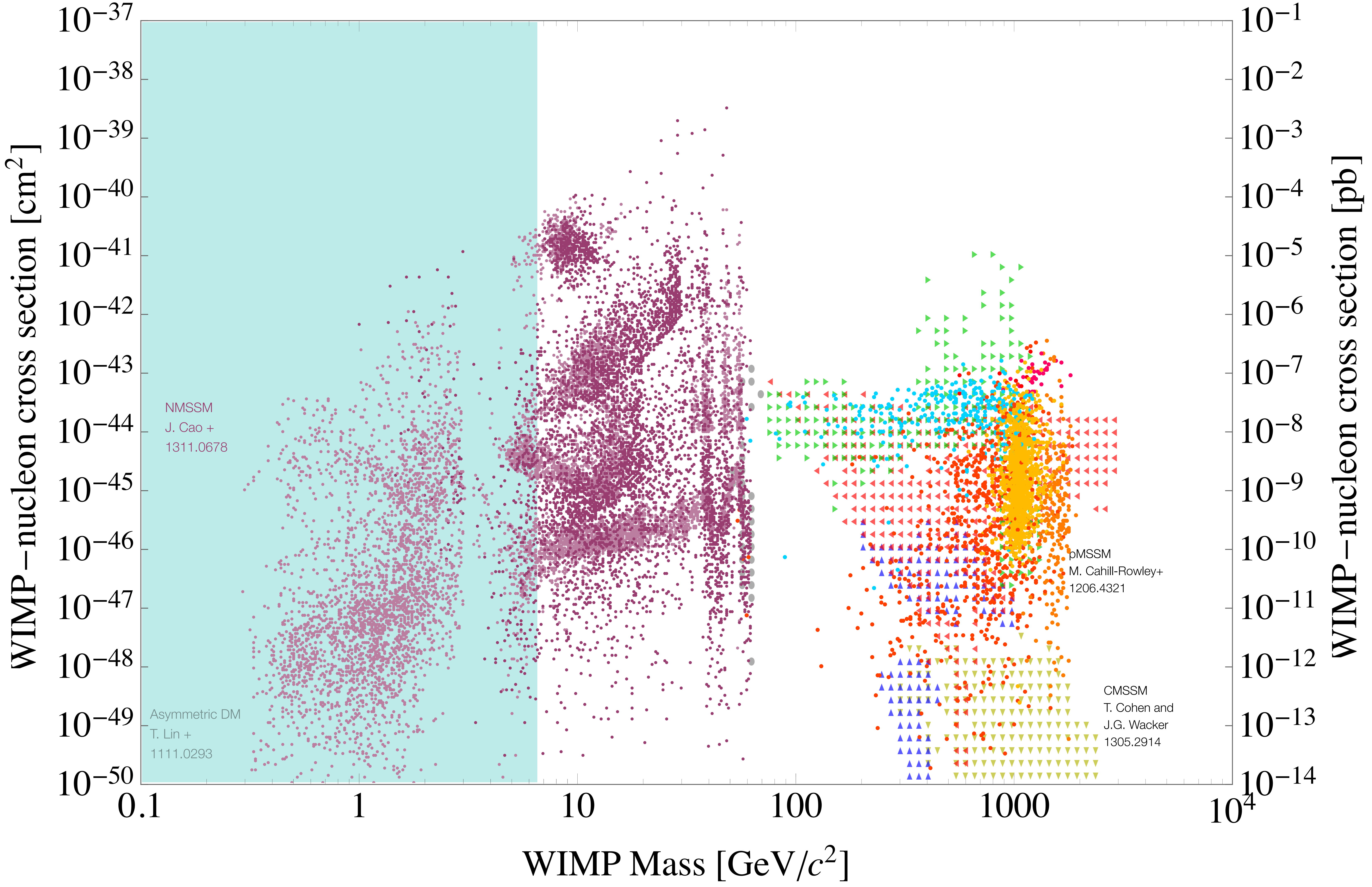
ν type	E_ν^{max} (MeV)	$E_{r_{Ge}}^{max}$ (keV)	ν flux ($cm^{-2}.s^{-1}$)
pp	0.42341	5.30×10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
^{7}Be	0.861	0.0219	$4.84 \pm 0.48 \times 10^9$
pep	1.440	0.0613	$1.42 \pm 0.04 \times 10^8$
^{15}O	1.732	0.0887	$2.33 \pm 0.72 \times 10^8$
^{8}B	16.360	7.91	$5.69 \pm 0.91 \times 10^6$
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



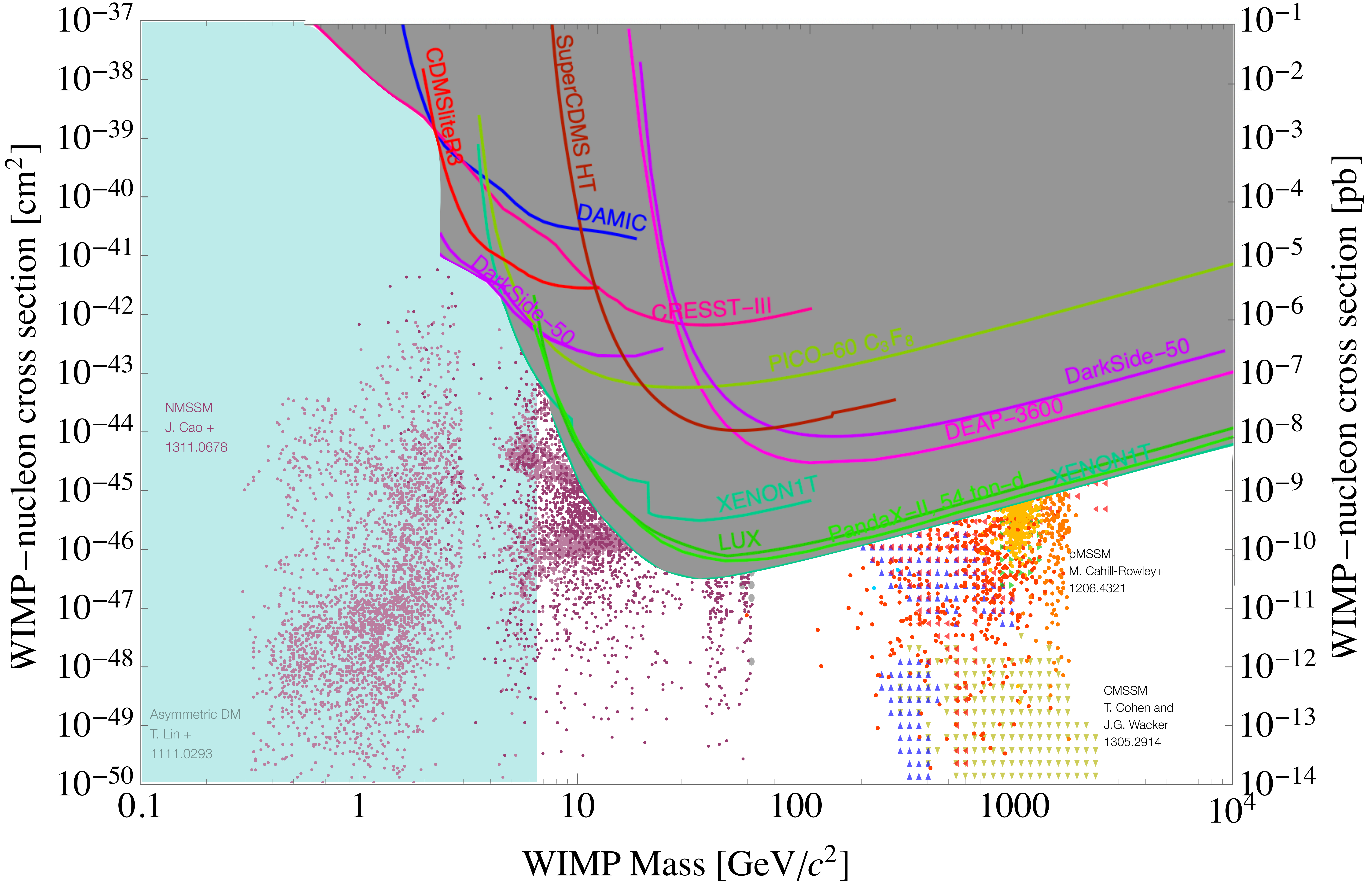
Direct Detection Needs

- 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
- Radiogenic and cosmogenic backgrounds mitigation
  - Passive and/or Active shielding from these backgrounds
  - Position reconstruction and fiducialization
  - Characterization of these backgrounds
- Long exposures with long term stability
  - Especially for annual and diurnal modulation

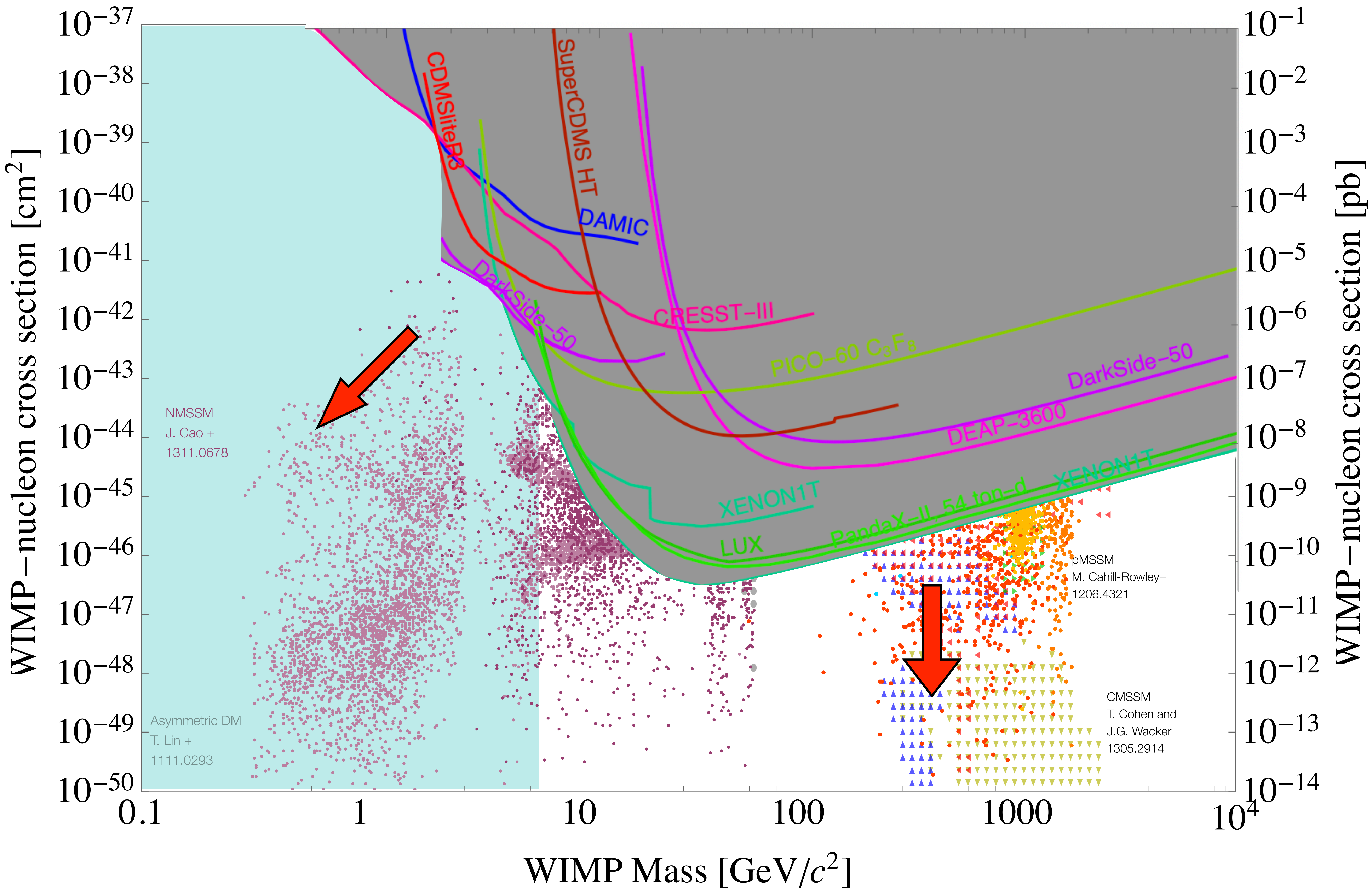
The Search Space



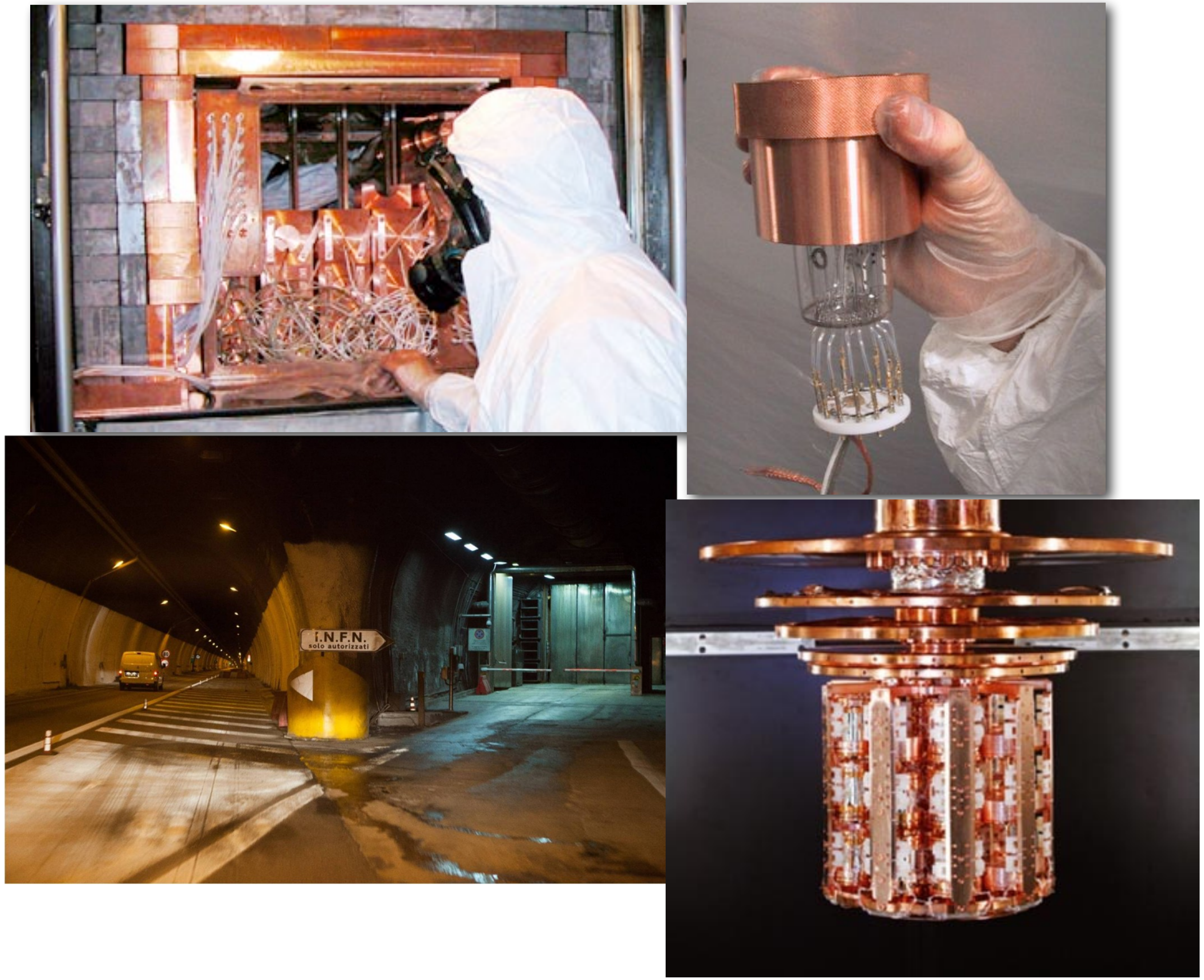
The Search Space



The Search Space



Have We Already Seen a Dark Matter Signal?

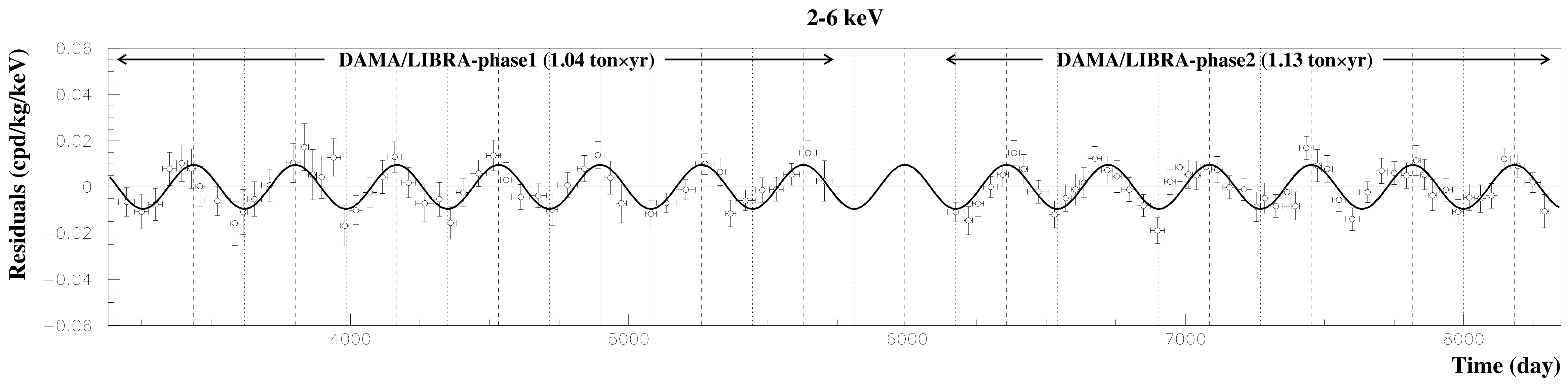


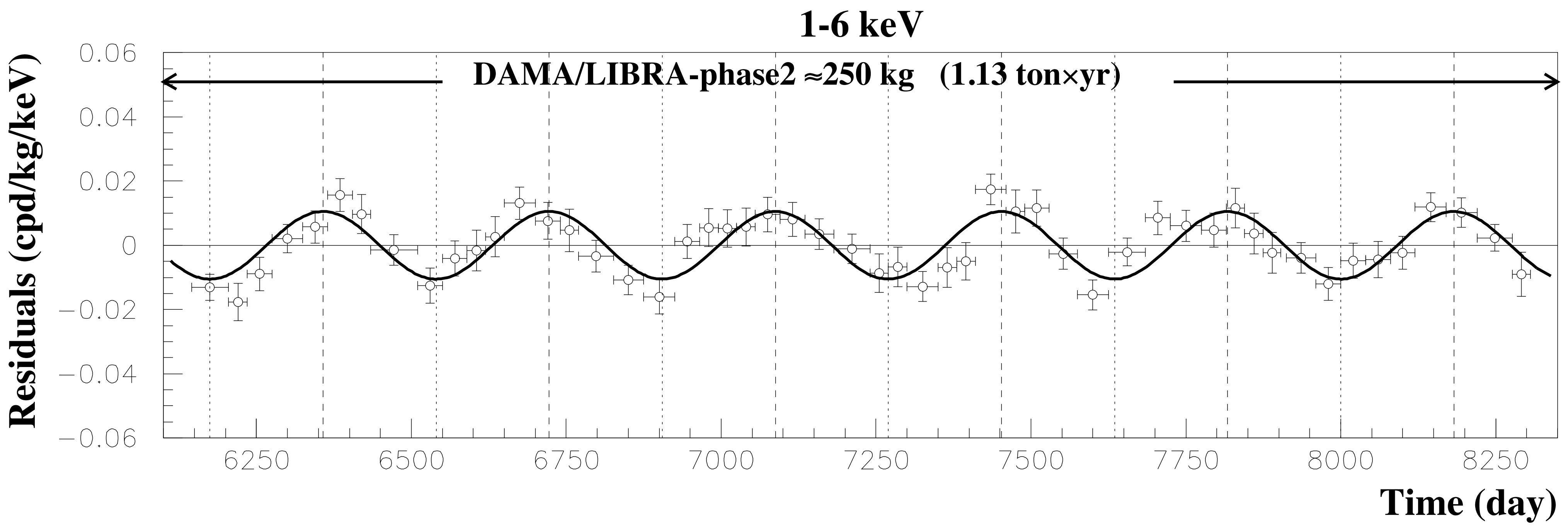
- DAMA/LIBRA have been reporting positive results reported since 1998
- DAMA
  - 100 kg NaI array operated in Laboratori Nazionali del Gran Sasso (1996 - 2002)
- LIBRA
  - 250 kg array operating since 2003 with first results in 2008
- Measures scintillation from particle interactions in detectors.
-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

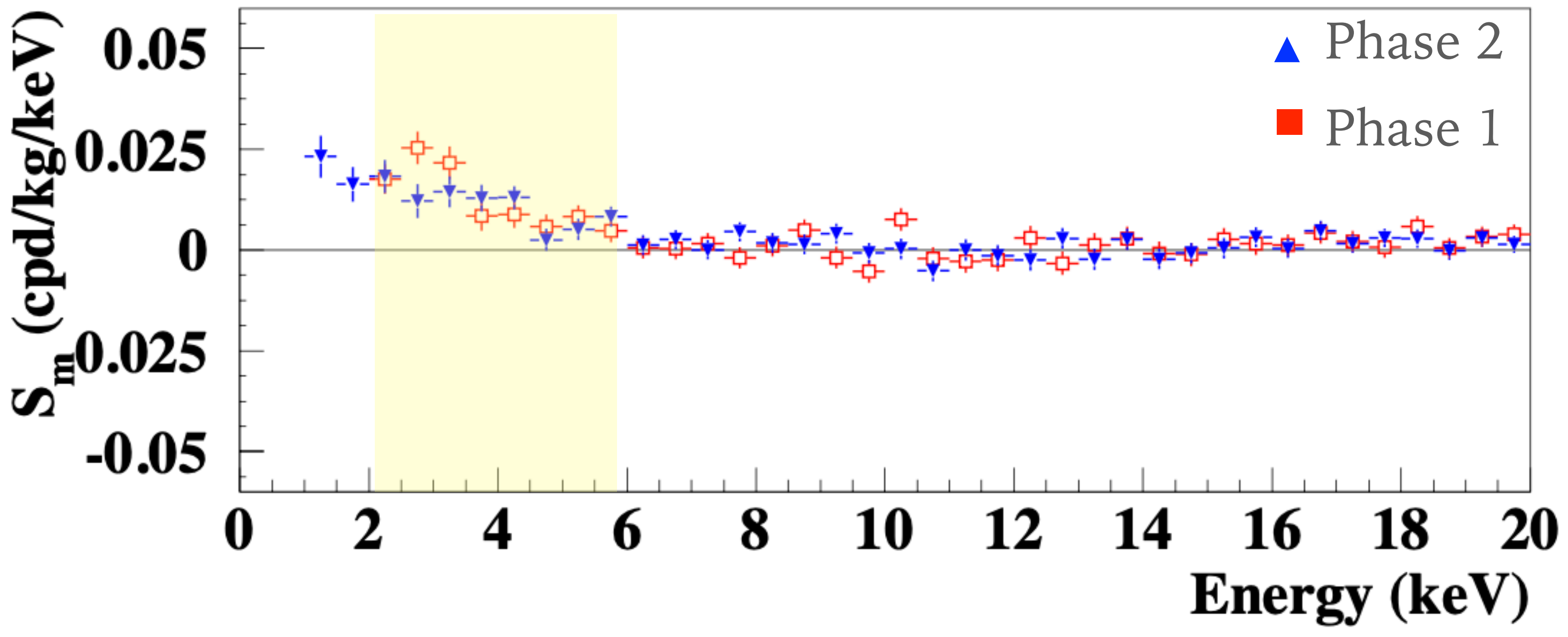
SNOLAB

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

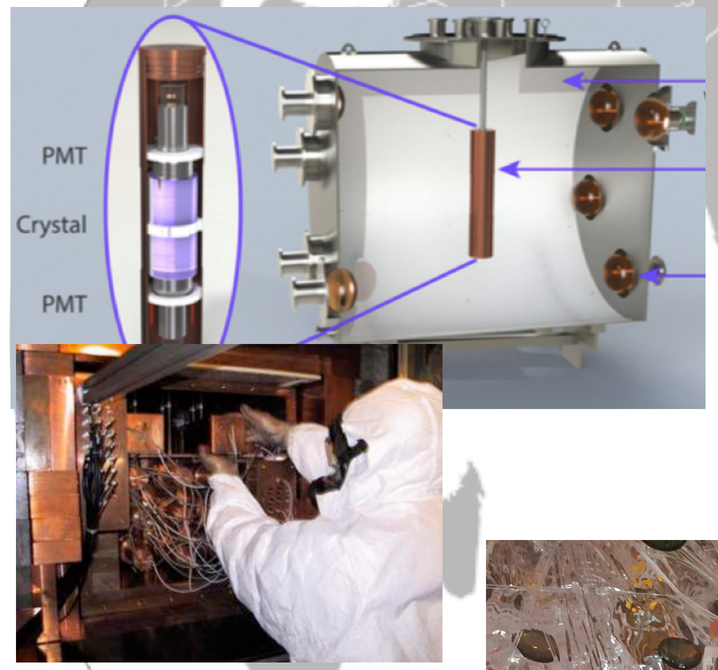
Worldwide Effort to Test DAMA/Libra

SNOLAB

KIMS (+ DM-Ice)

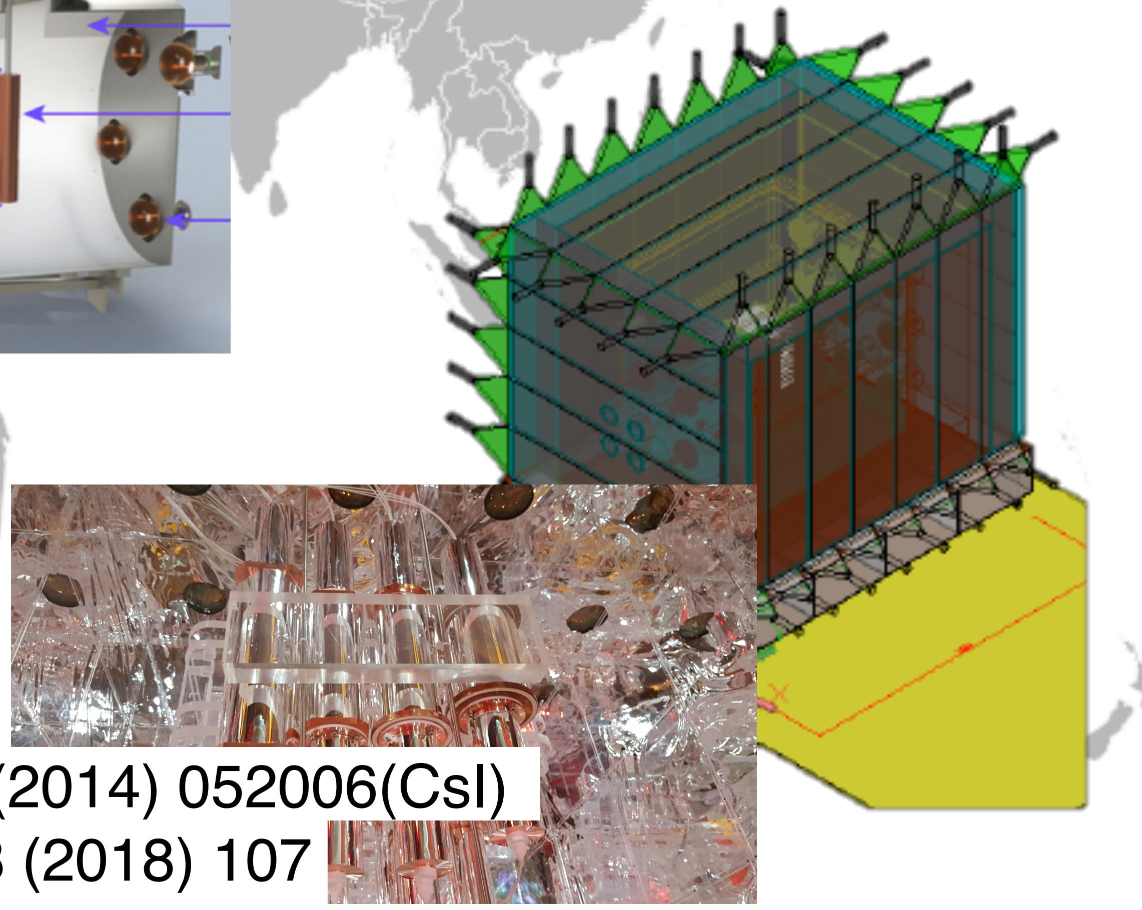
DAMA
SABRE
COSINUS

★ Gran Sasso + Australia



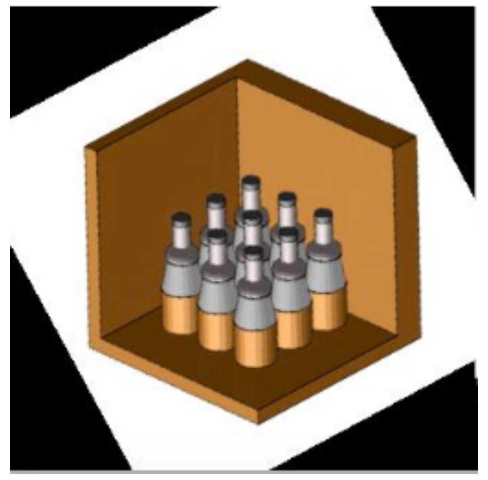
COSINE-100

★ Yangyang ★ Kamioka



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)

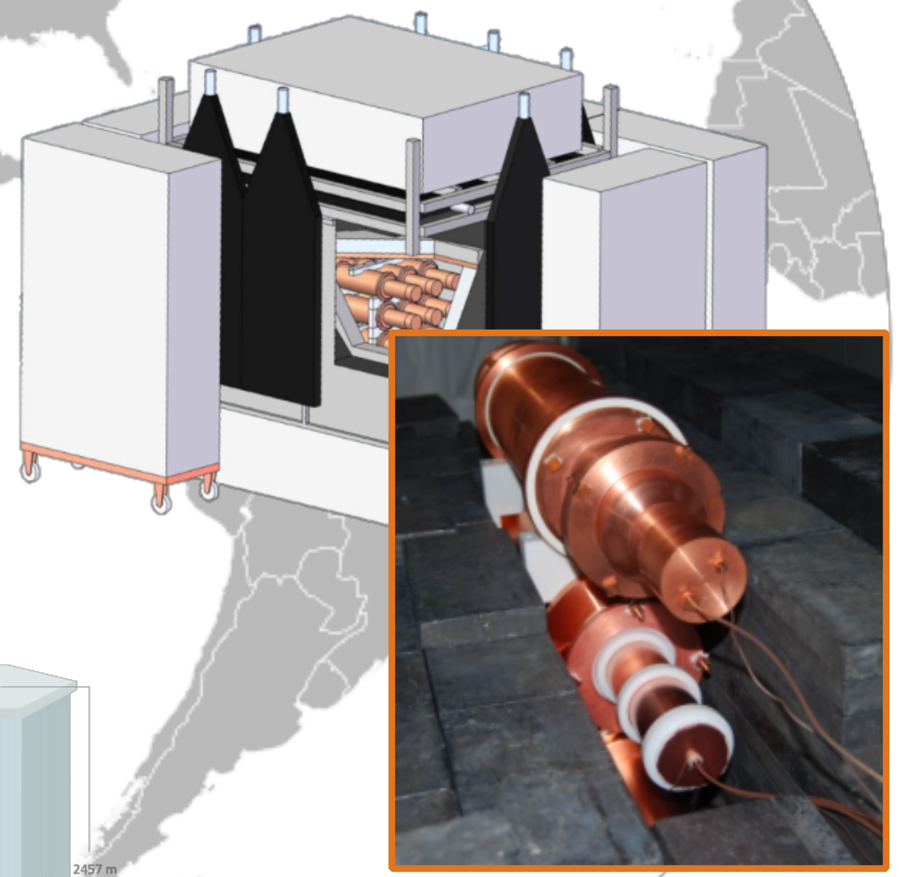
PICOLON

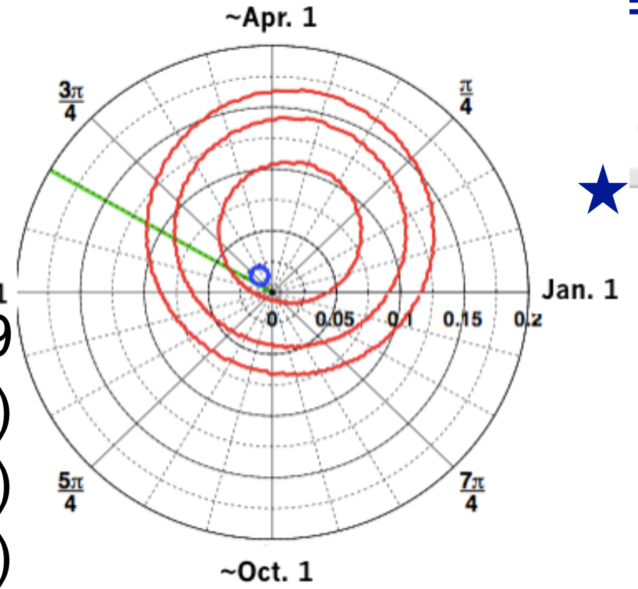


★ Boulby

ANAIS

★ Canfranc





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

DM-Ice17

★ South Pole