Canadian Association
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SUPER CDMS
Cryogenic Dark Matter Search

Background modelling at SuperCDMS

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CAP Congress - 2026/08/25

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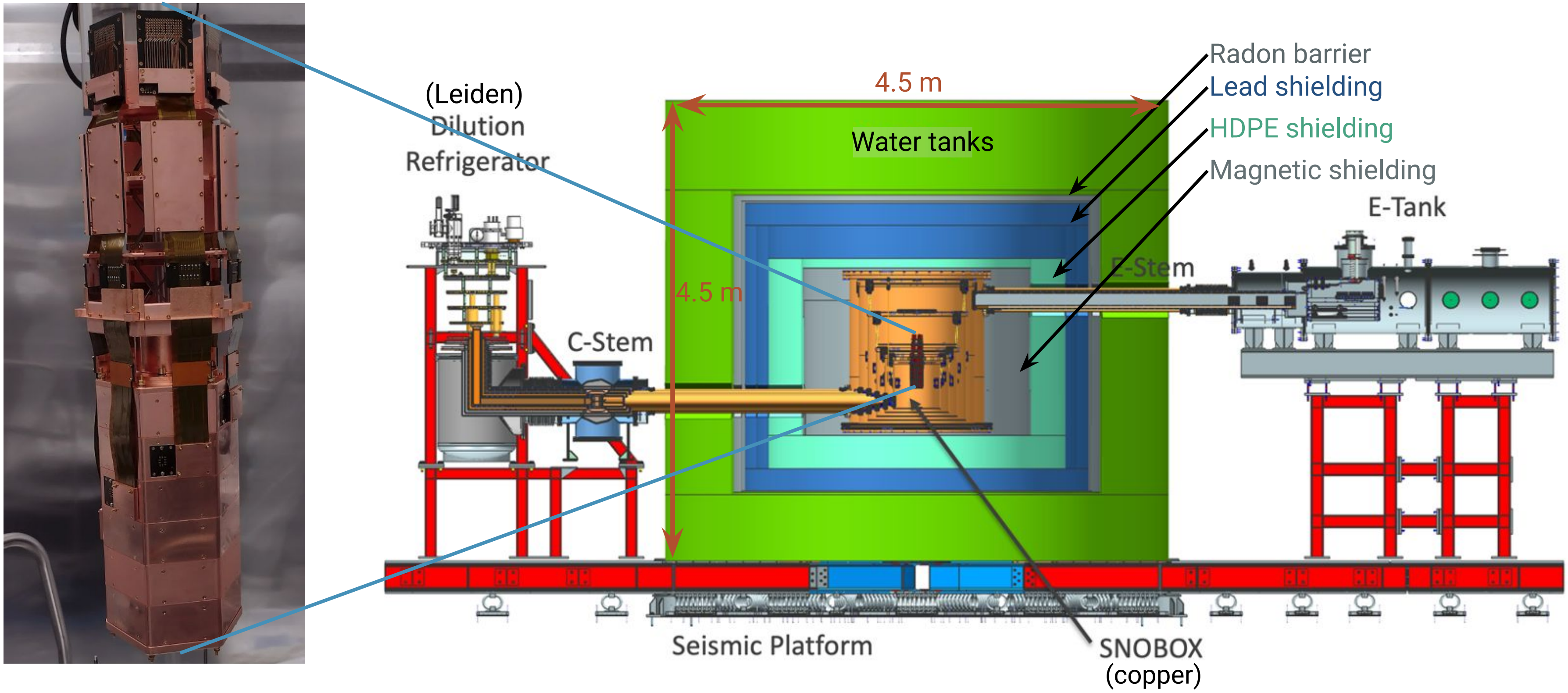
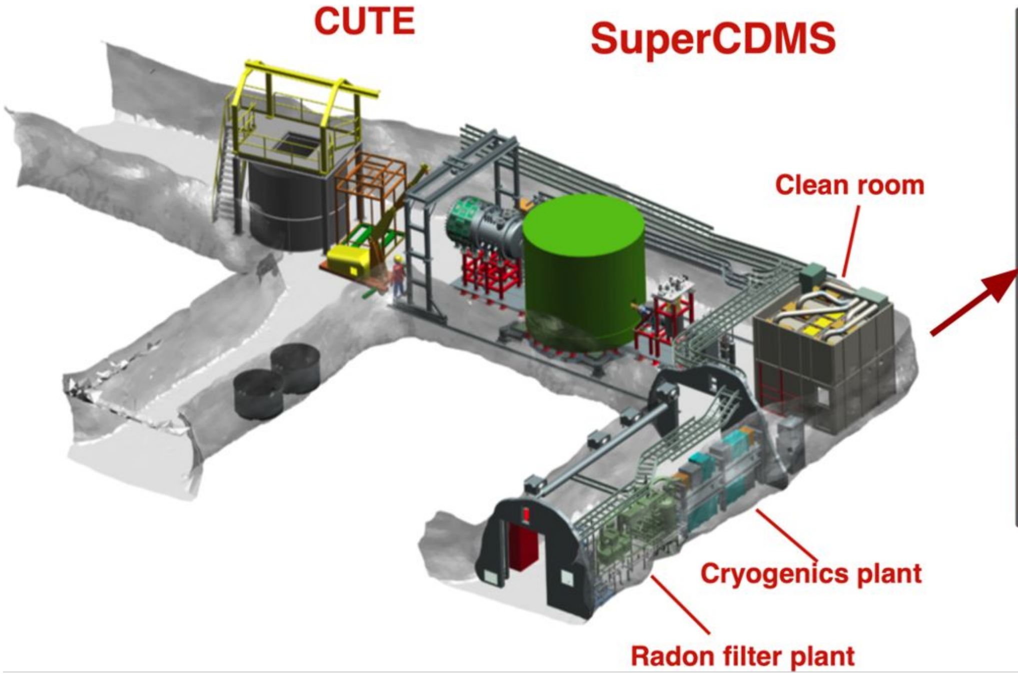
SuperCDMS - a search for dark matter

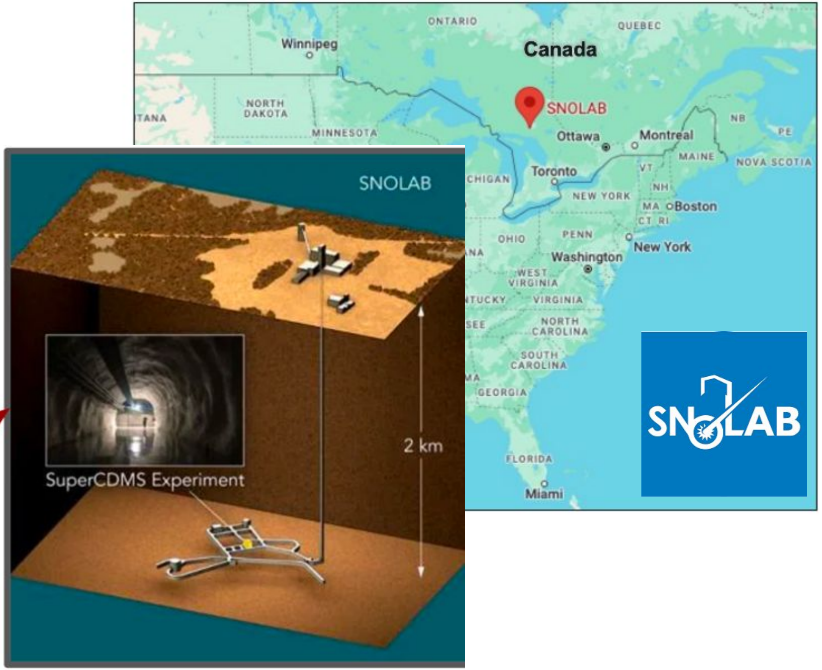
24 detector module of Si and Ge targets for dark matter scattering



SuperCDMS - a search for dark matter

2 km underground in Sudbury





Expected background sources

Expected # DM events: **<5 hits every year** in each detector!
Need to **reduce and model interactions from non-DM** particles for conclusive observation

Material contamination

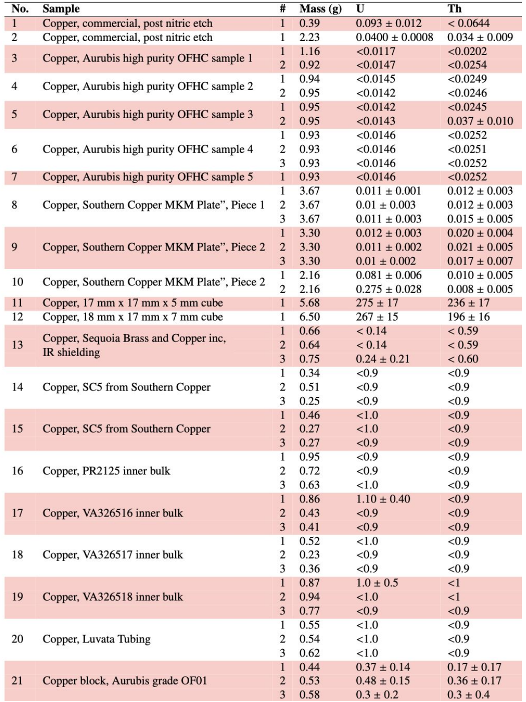
Material activation

Environmental backgrounds

Material contamination: ~40% of background

All materials have low levels of **^{238}U**, **^{232}Th**, and **^{40}K**

Measure many (many!) samples and **select lowest radioactivity** then **clean carefully** before install



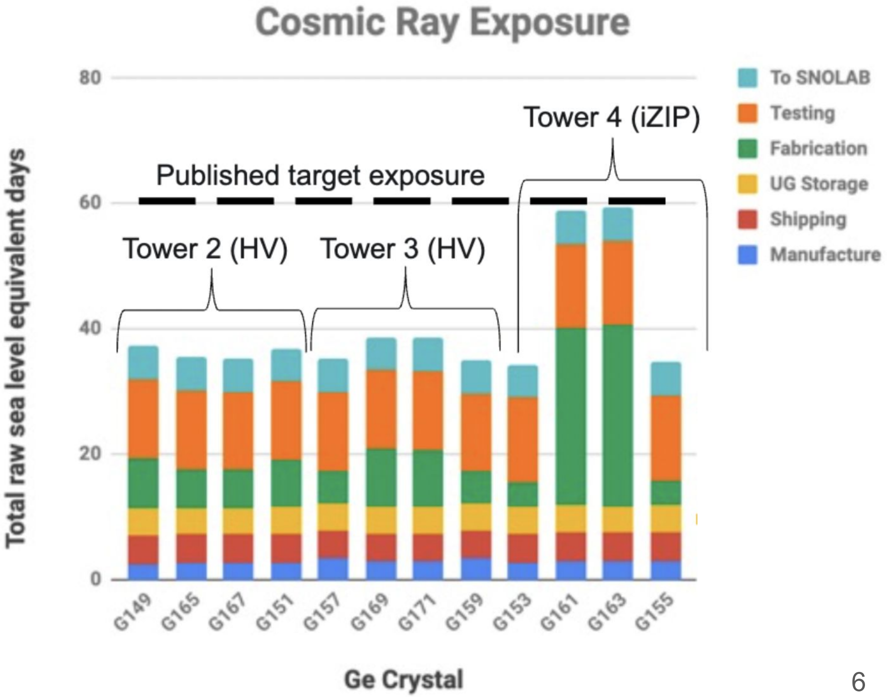
No.	Sample	#	Mass (g)	U	Th
1	Copper, commercial, post nitric etch	1	0.39	0.093 ± 0.012	< 0.0644
2	Copper, commercial, post nitric etch	1	2.23	0.0400 ± 0.0008	0.034 ± 0.009
3	Copper, Aurubis high purity OFHC sample 1	1	1.16	<0.0117	<0.0202
		2	0.92	<0.0147	<0.0254
4	Copper, Aurubis high purity OFHC sample 2	1	0.94	<0.0145	<0.0249
		2	0.95	<0.0142	<0.0246
5	Copper, Aurubis high purity OFHC sample 3	1	0.95	<0.0142	<0.0245
		2	0.95	<0.0143	0.037 ± 0.010
6	Copper, Aurubis high purity OFHC sample 4	1	0.93	<0.0146	<0.0252
		2	0.93	<0.0146	<0.0251
		3	0.93	<0.0146	<0.0252
7	Copper, Aurubis high purity OFHC sample 5	1	0.93	<0.0146	<0.0252
8	Copper, Southern Copper MKM Plate", Piece 1	1	3.67	0.011 ± 0.001	0.012 ± 0.003
		2	3.67	0.01 ± 0.003	0.012 ± 0.003
		3	3.67	0.011 ± 0.003	0.015 ± 0.005
9	Copper, Southern Copper MKM Plate", Piece 2	1	3.30	0.012 ± 0.003	0.020 ± 0.004
		2	3.30	0.011 ± 0.002	0.021 ± 0.005
		3	3.30	0.01 ± 0.002	0.017 ± 0.007
10	Copper, Southern Copper MKM Plate", Piece 2	1	2.16	0.081 ± 0.006	0.010 ± 0.005
		2	2.16	0.275 ± 0.028	0.008 ± 0.005
11	Copper, 17 mm x 17 mm x 5 mm cube	1	5.68	275 ± 17	236 ± 17
12	Copper, 18 mm x 17 mm x 7 mm cube	1	6.50	267 ± 15	196 ± 16
13	Copper, Sequoia Brass and Copper inc, IR shielding	1	0.66	< 0.14	< 0.59
		2	0.64	< 0.14	< 0.59
		3	0.75	0.24 ± 0.21	< 0.60
14	Copper, SC5 from Southern Copper	1	0.34	<0.9	<0.9
		2	0.51	<0.9	<0.9
		3	0.25	<0.9	<0.9
15	Copper, SC5 from Southern Copper	1	0.46	<1.0	<0.9
		2	0.27	<1.0	<0.9
		3	0.27	<0.9	<0.9
16	Copper, PR2125 inner bulk	1	0.95	<0.9	<0.9
		2	0.72	<0.9	<0.9
		3	0.63	<1.0	<0.9
17	Copper, VA326516 inner bulk	1	0.86	1.10 ± 0.40	<0.9
		2	0.43	<0.9	<0.9
		3	0.41	<0.9	<0.9
18	Copper, VA326517 inner bulk	1	0.52	<1.0	<0.9
		2	0.23	<0.9	<0.9
		3	0.36	<0.9	<0.9
19	Copper, VA326518 inner bulk	1	0.87	1.0 ± 0.5	<1
		2	0.94	<1.0	<1
		3	0.77	<0.9	<0.9
20	Copper, Luvata Tubing	1	0.55	<1.0	<0.9
		2	0.54	<1.0	<0.9
		3	0.62	<1.0	<0.9
21	Copper block, Aurubis grade OF01	1	0.44	0.37 ± 0.14	0.17 ± 0.17
		2	0.53	0.48 ± 0.15	0.36 ± 0.17
		3	0.58	0.3 ± 0.2	0.3 ± 0.4

Clean + etch for surface contamination removal

Material activation: ~40% of background

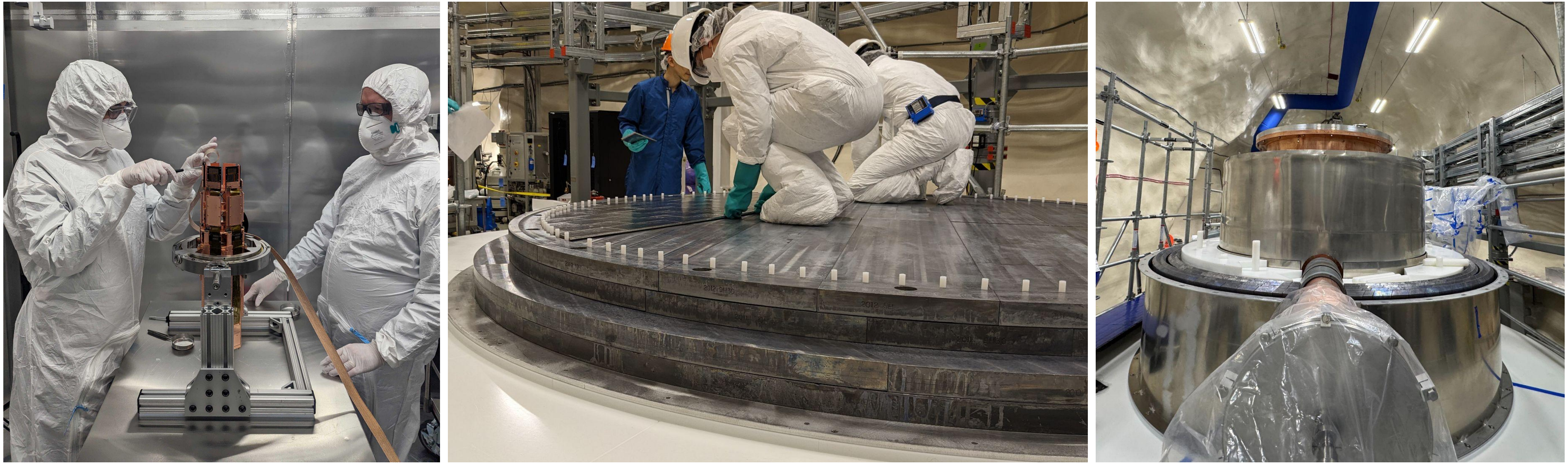
Exposure to cosmic rays produces radioactive isotopes in copper, germanium, and silicon
Carefully **track exposure at sea level**, and **use shielding** where needed for shipping


Packaging for international shipping



Environmental sources: ~20% of background

Dust, rock in lab walls and human activity carry trace amounts of **^{238}U**, **^{232}Th**, and **^{40}K**
Radon gas underground produces **^{210}Pb**
Can’t prevent any of these from occuring, so **protect and shield** as best we can



Building a background rate

Rate = (number of expected events) x (normalised energy spectrum)

~420 individual material assays

+

Exposure tracking of every component

+

~2,500 unique simulations

(See Birgit Zatschler's talk later for more info)

Use full suite of simulation results to build projections, then categorise and construct downsampled templates to use in fitting

More info on how we do downsampling in backups

What do we want from a background model?

Supports standard statistical inference

- Profile likelihood ratio approach
- Ancillary measurements to constrain:
  - Material activity
  - Resolution parameters
  - Ionisation yield parameters
  - Cut efficiencies
  - Detector live time

Ease of use

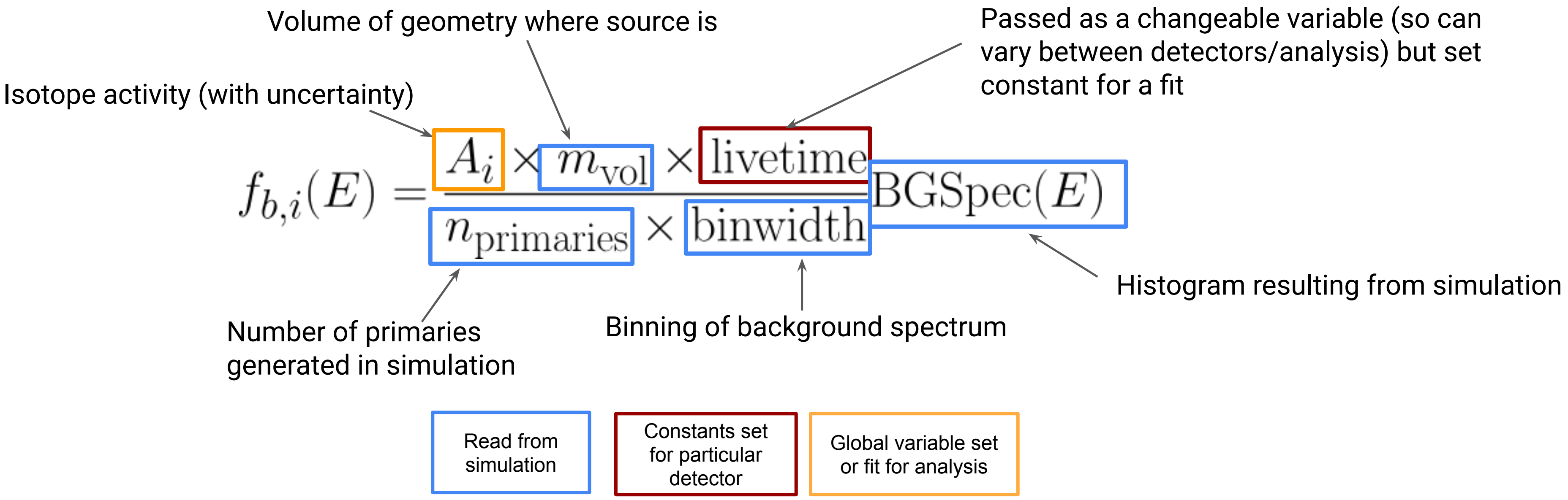
- Centrally accessible and reproducible
- Adjustable priors
- No technical understanding needed for use
- Flexible coding language

One option: **RooWorkspaces** - A persistable container for RooFit objects**

** more info in backups

Constructing a model: background shape + normalisation

Construct a function that gives you the expected counts/eV (recoil energy) for a background (or signal) source. Summed to create a function of the form $f_b(E_R) = \sum_i f_{b,i}(E_r)$



$$f_{b,i}(E) = \frac{\boxed{A_i} \times \boxed{m_{\text{vol}}} \times \boxed{\text{livetime}}}{\boxed{n_{\text{primaries}}} \times \boxed{\text{binwidth}}} \boxed{\text{BGSpec}(E)}$$

Volume of geometry where source is

Passed as a changeable variable (so can vary between detectors/analysis) but set constant for a fit

Isotope activity (with uncertainty)

Histogram resulting from simulation

Number of primaries generated in simulation

Binning of background spectrum

Read from simulation

Constants set for particular detector

Global variable set or fit for analysis

Constructing a model: apply detector response

Apply detector response terms to get the energy in units of keV$_{ee}$ - what we observe: ionisation effect

Yield makes this non-trivial

Transform recoil to phonon energy

$$E_t = E_R \left(1 + Y(E_R)\frac{eV}{\varepsilon}\right)$$

Transform phonon to reconstructed energy

$$E_{ee} = E_t \times \left(1 + \frac{eV}{\epsilon}\right)^{-1}$$

Theoretical reconstruction - better to use calibration!

Use these to transform full spectrum

$$f_{\text{ion}}(E_{ee}) = \frac{dE_R}{dE_{ee}} f(E_R(E_{ee}))$$

Constructing a model: apply detector response

Apply detector response terms to get the energy in units of keV$_{ee}$ - what we observe: resolution smearing and efficiencies

$$\sigma_T(E_t) = \sqrt{\sigma_E^2 + B_E E_t + (A_E E_t)^2}$$

This energy dependence is annoying…

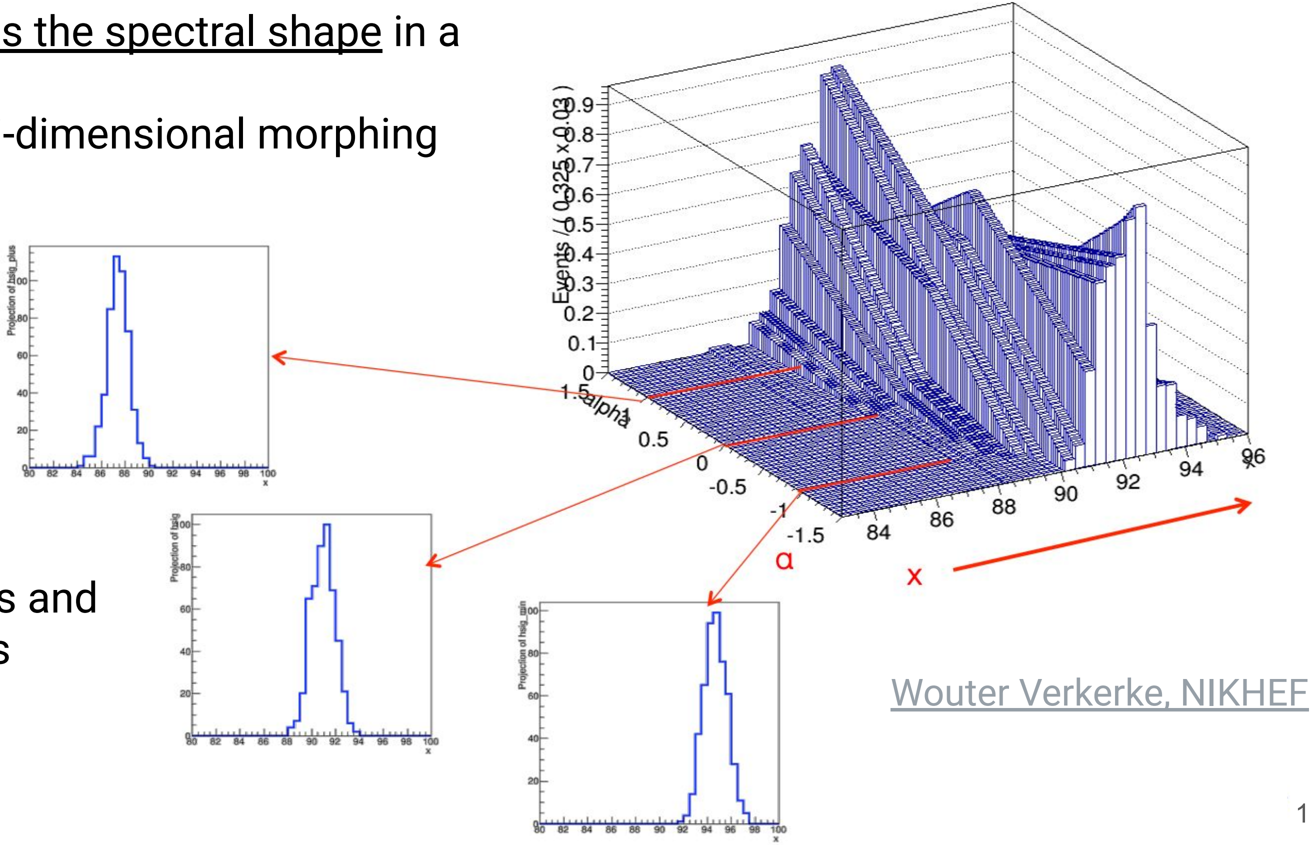
$$\frac{dR}{dE_{\text{obs}}} = \int f_{\text{ion}}(E_t) \frac{1}{\sigma_T(E_t)\sqrt{2\pi}} \exp\left[\frac{-(E_t - E_{\text{obs}})^2}{2\sigma_T(E_t)}\right] dE_t$$

$$f_{\text{obs}}(E_{\text{obs}}) = \epsilon(E_{\text{obs}}) \frac{dR}{dE_{\text{obs}}}$$

Use this as our PDF of observed energy

Nuisance parameters and morphing

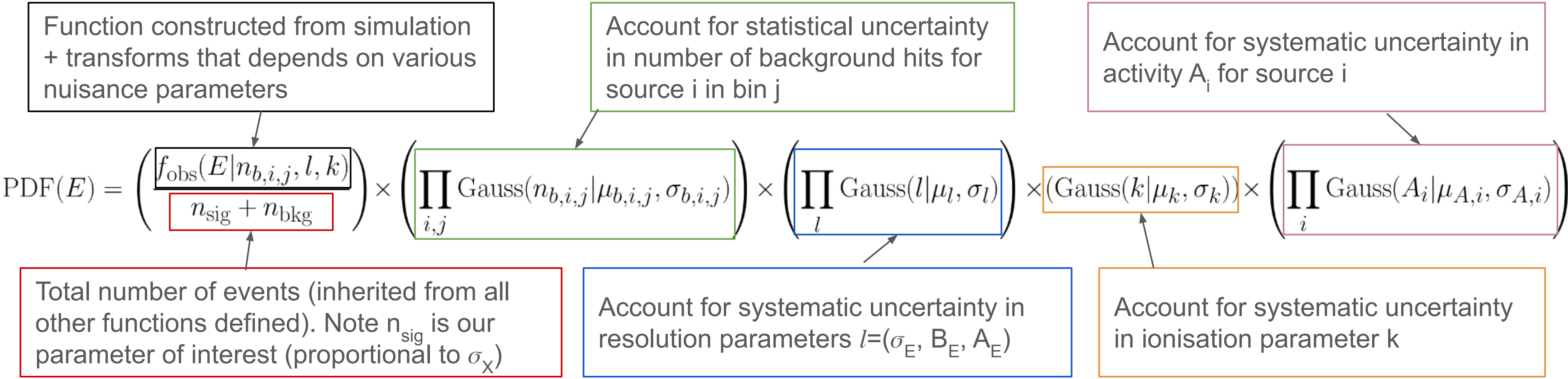
Detector response <u>changes the spectral shape</u> in a <u>non-analytic way</u>
Account for this with multi-dimensional morphing
⇒ interpolation of shapes



RooFit designed to do this and save outputs as functions

Wouter Verkerke, NIKHEF

Constructing a model: full PDF



Function constructed from simulation + transforms that depends on various nuisance parameters

Account for statistical uncertainty in number of background hits for source i in bin j

Account for systematic uncertainty in activity A_i for source i

$$\mathrm{PDF}(E) = \left(\frac{\boxed{f_{\mathrm{obs}}(E|n_{b,i,j}, l, k)}}{\boxed{n_{\mathrm{sig}} + n_{\mathrm{bkg}}}}\right) \times \left(\boxed{\prod_{i,j} \mathrm{Gauss}(n_{b,i,j}|\mu_{b,i,j}, \sigma_{b,i,j})}\right) \times \left(\boxed{\prod_{l} \mathrm{Gauss}(l|\mu_l, \sigma_l)}\right) \times \boxed{(\mathrm{Gauss}(k|\mu_k, \sigma_k))} \times \left(\boxed{\prod_{i} \mathrm{Gauss}(A_i|\mu_{A,i}, \sigma_{A,i})}\right)$$

Total number of events (inherited from all other functions defined). Note n_{sig} is our parameter of interest (proportional to σ_X)

Account for systematic uncertainty in resolution parameters l=(σ_E, B_E, A_E)

Account for systematic uncertainty in ionisation parameter k

Once constructed, these objects are combined as above to make a PDF that can then be used in various likelihood minimisation strategies.

RooWorkspace example

WIP

<u>1 Detector</u>
1 Ge HV 100V

+

<u>4 backgrounds</u>

1. Neutrons from externals (NR)
2. ^{210}Pb in housing (NR + ER)
3. ^{3}H in detector (ER)
4. ^{71}Ge in detector (ER)

+

<u>4 morphing parameters</u>

1x ionisation yield (NR only)
- 2 morphing steps

3x resolution
- 5 morphing steps

=

750 histograms

Parseable as <u>4 background PDFs with normalisation factors</u>
Resulting RooWorkspace saves in file of ~200 MB

<u>Next steps</u>: optimising morphing set up, scaling up to more detectors…

Outlook

- We have a solid understanding of our radioactive background sources
- Set of priors based on updated simulations and assays
  - Significant work on matching simulation to reality
  - Paper on 10+ years of assay results in preparation
- Task now is turning this understanding into a form that can be used in a statistical framework
  - All steps in framework are working
  - Now optimising how they fit together


2025 collaboration photo

Still have questions?
Scan QR code for my details

Backup

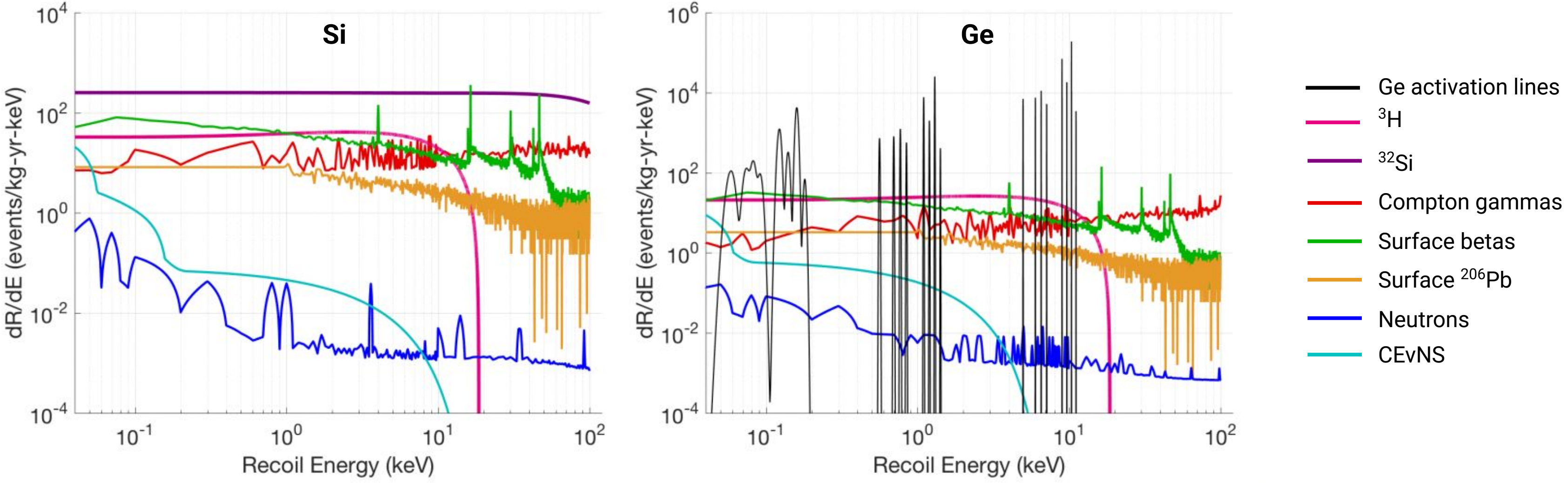
R. Agnese *et al.* Phys. Rev. D **95**, 082002

Background downsampling

Detailed bookkeeping done using eTraveller and BGExplorer:

- 329 components catalogued
- 32 sources considered
- Tracking of location for cosmogenic and radon exposure

Challenge now is to turn this information into a background model suitable for analysis

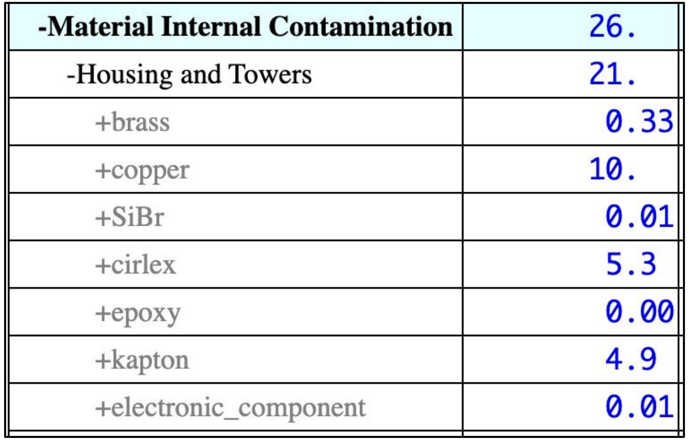


No detector response or analysis cuts applied. Raw spectra only

[1] https://github.com/bloer/bgexplorer-demo

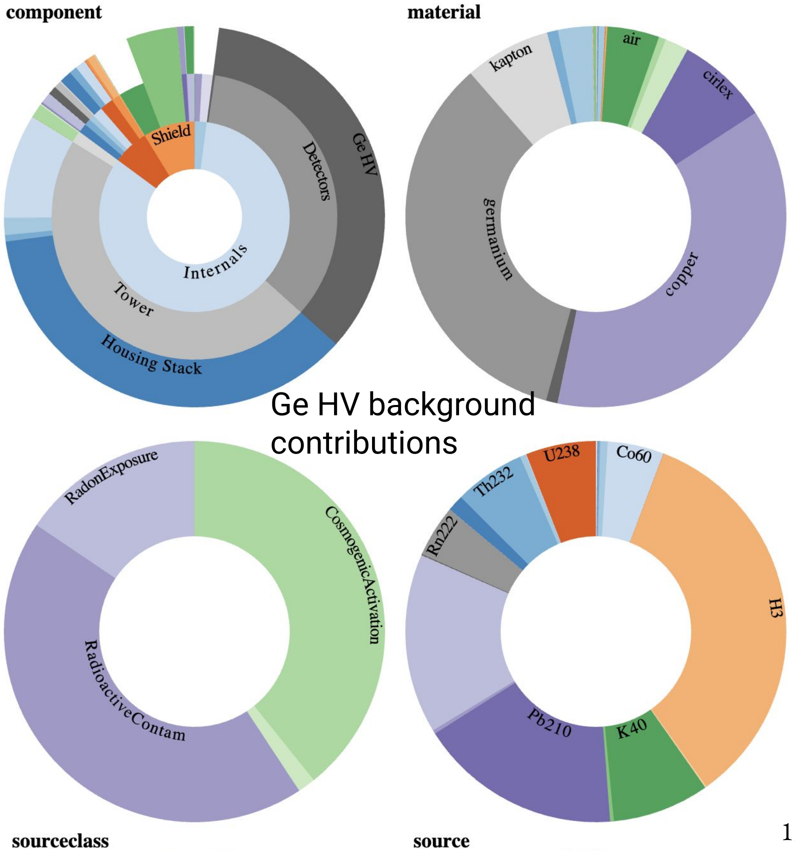
Background downsampling

- Several 1000 background simulations are hard to view at once
- Make use of Background Explorer [1] to assess
  - Understand which sources can be combined, and which need individual modelling



-Material Internal Contamination	26.
-Housing and Towers	21.
+brass	0.33
+copper	10.
+SiBr	0.01
+cirlex	5.3
+epoxy	0.00
+kapton	4.9
+electronic_component	0.01

Counts per kg/keV/year



Ge HV background contributions

Background modelling - detector response

[1] Kelsey et al. NIM A 1055 (2023) 168473
[2] Wilson et al. arxiv: 2403.01259

- Need to account for transformation of energy recoil signal into observable
- Done via simulation (more detailed) or analytic approach (faster)
  - Development of detector effect with G4CMP[1]
  - Analytic approach developed for HVeV detectors[2]

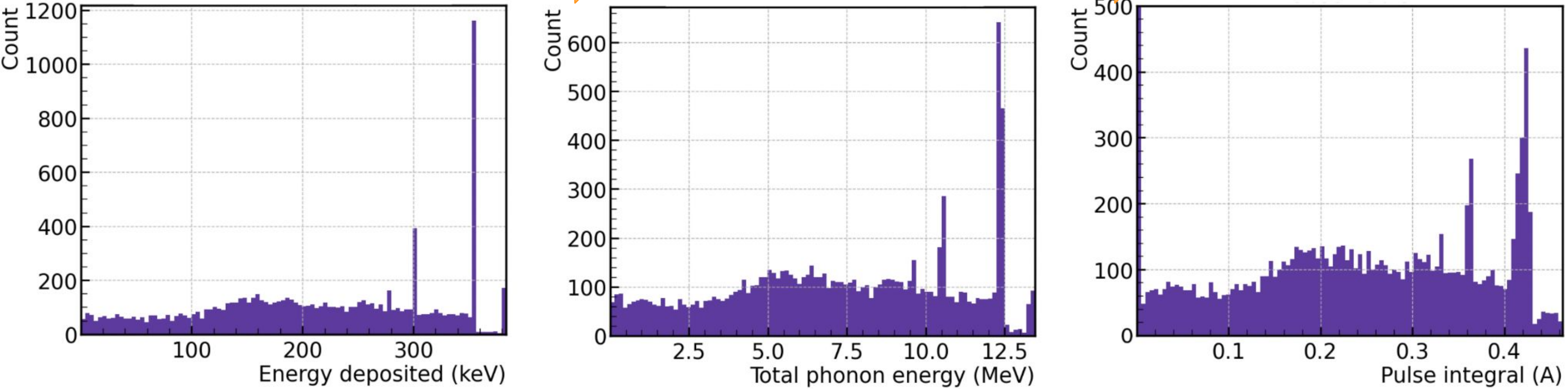
Energy deposition (physics event)

Propagation in detector

Phonon energy detected (intermediate step)

Readout

Change in current (observable)



Sample transformations of ^{133}Ba decay signal in simulation

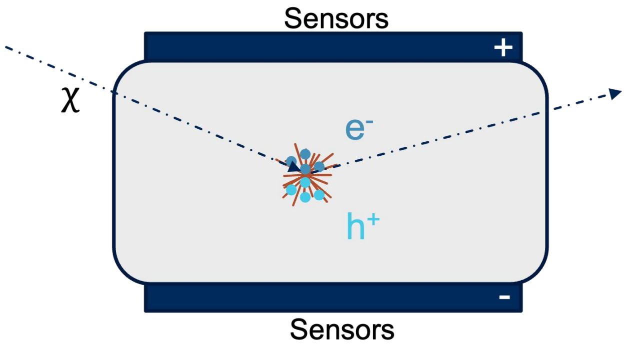
ROOT based strategy

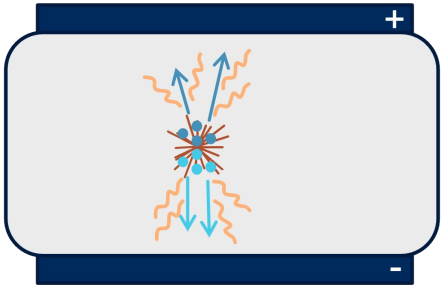
Construct and save background PDF as a RooWorkspace object

"A persistable container for RooFit objects" ⇒ easy to store PDFs, variables, and nuisance parameters in a way that:

1. Allows for analysers to adjust or constrain specific values while maintaining the relationships between objects
2. Saveable as a ROOT file ⇒ consistency across various analysis if everyone is reading the same input
3. Easily accessible for analysis in RooFit or RooStats (in either C++ or python)

Detector Concepts





- DM scatters in crystal and produces recoil in lattice
- Energy deposition produces two observables:
  - Electron-hole pairs
  - Prompt and Neganov-Trofimov-Luke (NTL) phonons
- Charges drifted with electric field to sensors for collection of signals
  - Interleaved electrodes for ionisation
  - QETs for athermal phonons
- Combine these in different ways depending on what we want:
  - Low energy threshold: HV
  - NR/ER and surface/bulk discrimination: iZIP

R. Agnese *et al.* Phys. Rev. D **95**, 082002

HV detectors

Key concept: use NTL effect to reduce energy threshold.

- NTL effect: drifting electron-hole pairs across potential produces phonons:

$$E_t = E_R + n_{eh}eV$$

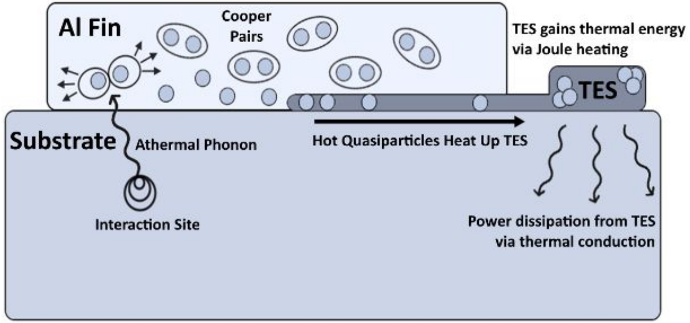
Total phonon energy

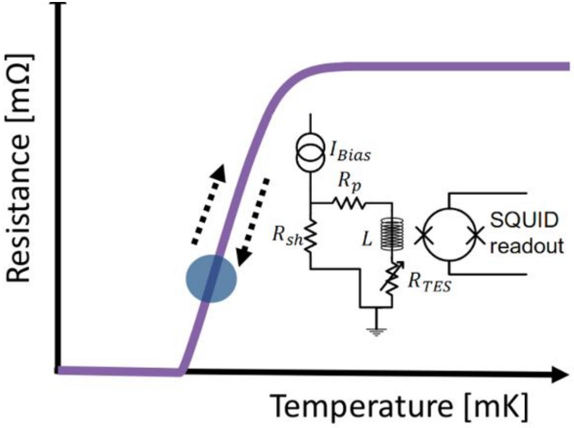
Initial recoil energy

Number of eh pairs

Potential difference

- Increased potential ⇒ increased total energy for the same recoil
- Phonons detected using TES at ~50% bias point
- 12 equal area channels across each HV detector





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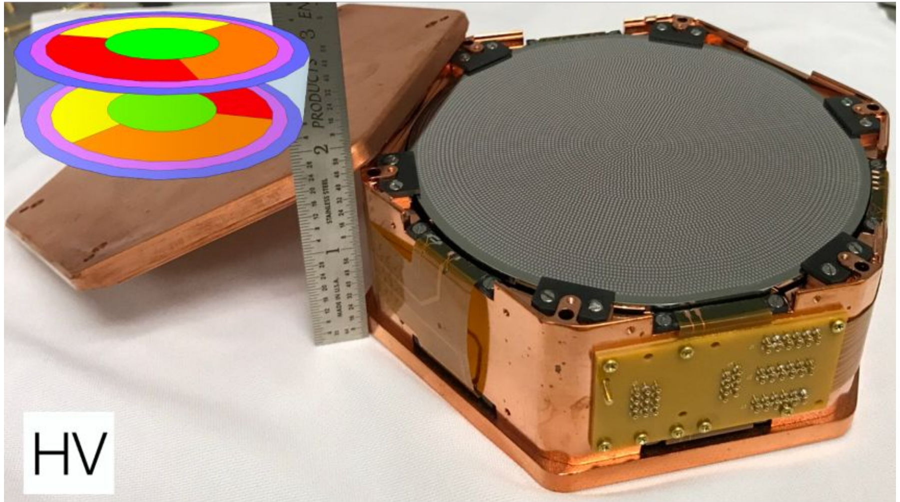

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iZIP detectors

Key concept: use charge and phonon signals for ER/NR discrimination with a higher energy threshold

- Amount of charge generated depends on ionisation yield of interaction:

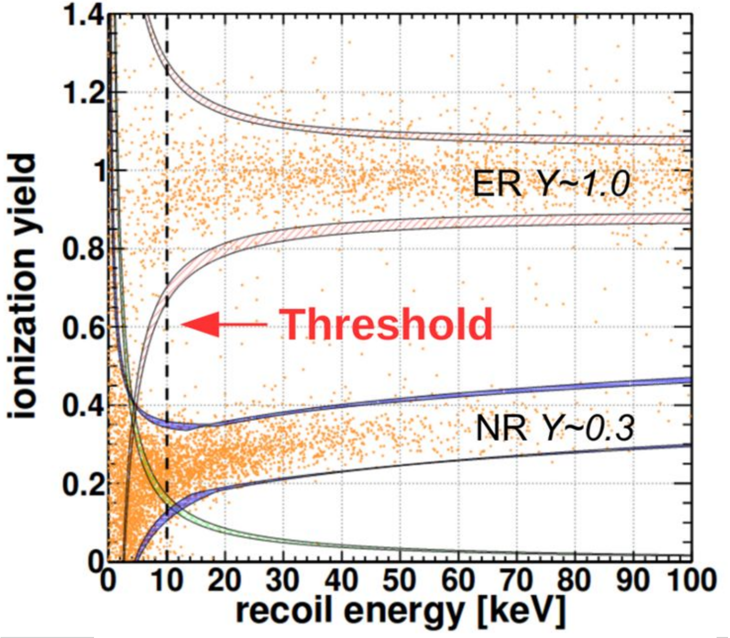
$$n_{eh} = \frac{y(E_R)}{\epsilon_{eh}} E_R$$

Number of charge pairs

Average energy to produce single pair

Initial recoil energy

- Ionisation for ER is 1, for NR<1. Comparing the ratio of this to phonons gives discriminant metric
- Charge detected using electrodes on crystal, amplified with cryogenically operated HEMTs (charge amplifier circuit)
- 4 charge channels, 12 phonon channels for each detector



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