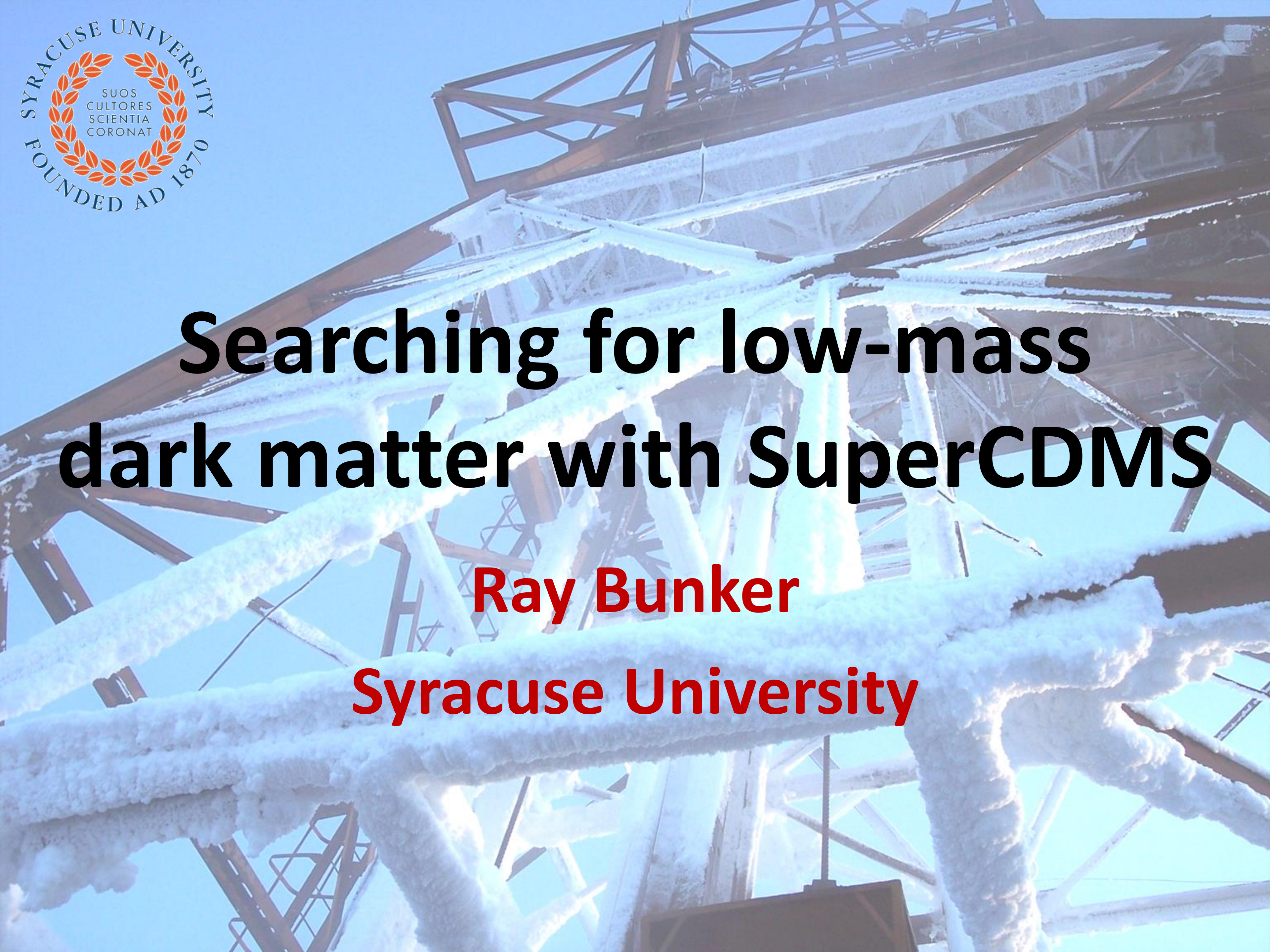


# Searching for low-mass dark matter with SuperCDMS

**Ray Bunker**

**Syracuse University**

Syracuse University

# The SuperCDMS Collaboration

California Inst. of Tech.

CNRS-LPN

FNAL

Mass. Inst. of Tech.

U. Evansville

NIST Inst. of Tech.

PNNL

Queen's University

Santa Clara University

U. Florida

SLAC

Southern Methodist U.

Stanford University

U. California, Berkeley

U. Minnesota

Texas A&M University

U. Autónoma de Madrid

U. British Columbia

U. Colorado Denver

U. South Dakota

# Outline

## I. Introduction

a) SuperCDMS direct-detection technique
b) Demonstrated background discrimination

## II. SuperCDMS Soudan

a) Run description
b) High-voltage-bias operation (CDMSlite)
c) Low-threshold analysis

## III. SuperCDMS SNOLAB

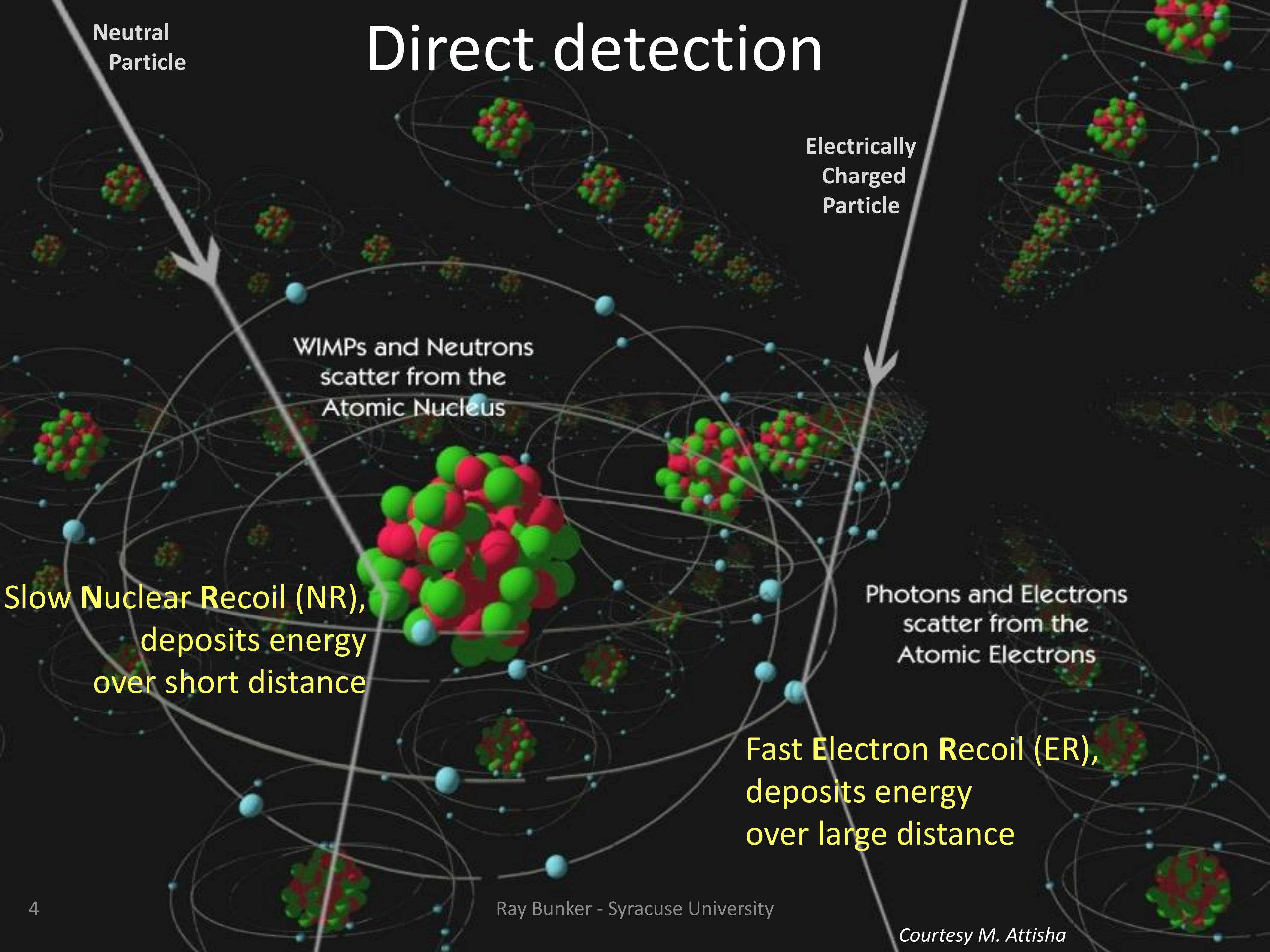
a) Improvements *vs.* Soudan
b) Projected reach

## IV. Radon Mitigation & Assay

a) Vacuum-swing absorption filtering
b) Emanation assay & the BetaCage

## V. Conclusions

# Direct detection



**Neutral** **Particle**

**Electrically Charged Particle**

Slow **N**uclear **R**ecoil (NR), deposits energy over short distance

Fast **E**lectron **R**ecoil (ER), deposits energy over large distance

*Courtesy M. Attisha*

# CDMS technique — ionization & phonons

Inner & outer electrodes for radial fiducialization

Channel partitioning enables xy-position reconstruction

Recoil energy

Extra energy: Neganov-Luke phonon amplification → CDMSlite

Nuclear recoil (NR)

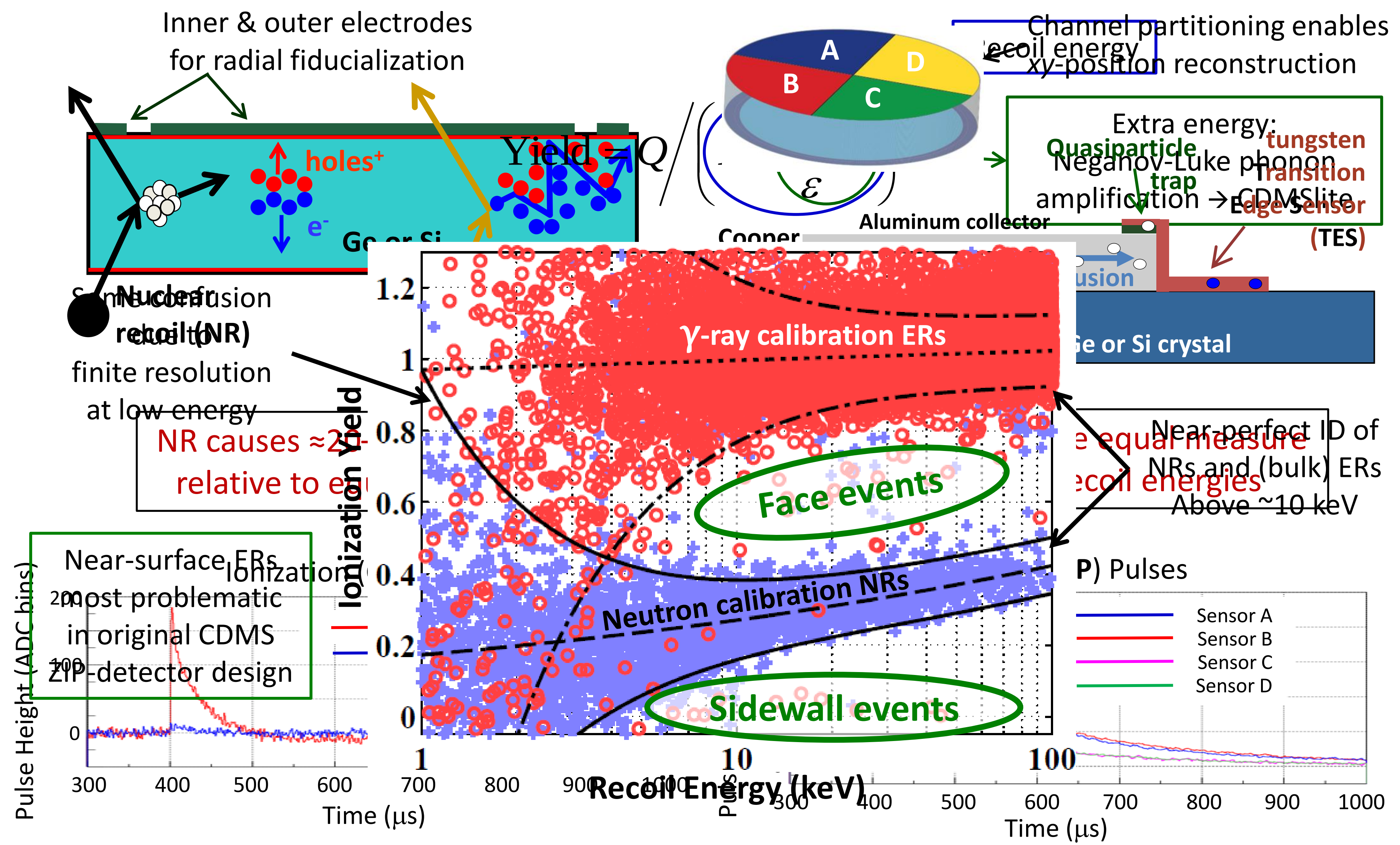
Some confusion due to finite resolution at low energy

NR causes ≈2… relative to e…

Near-surface ERs most problematic in original CDMS ZIP-detector design

Near-perfect ID of NRs and (bulk) ERs Above ~10 keV

…e equal measure …ecoil energies



# SuperCDMS technique — the iZIP

Interleaved ionization & phonon sensors

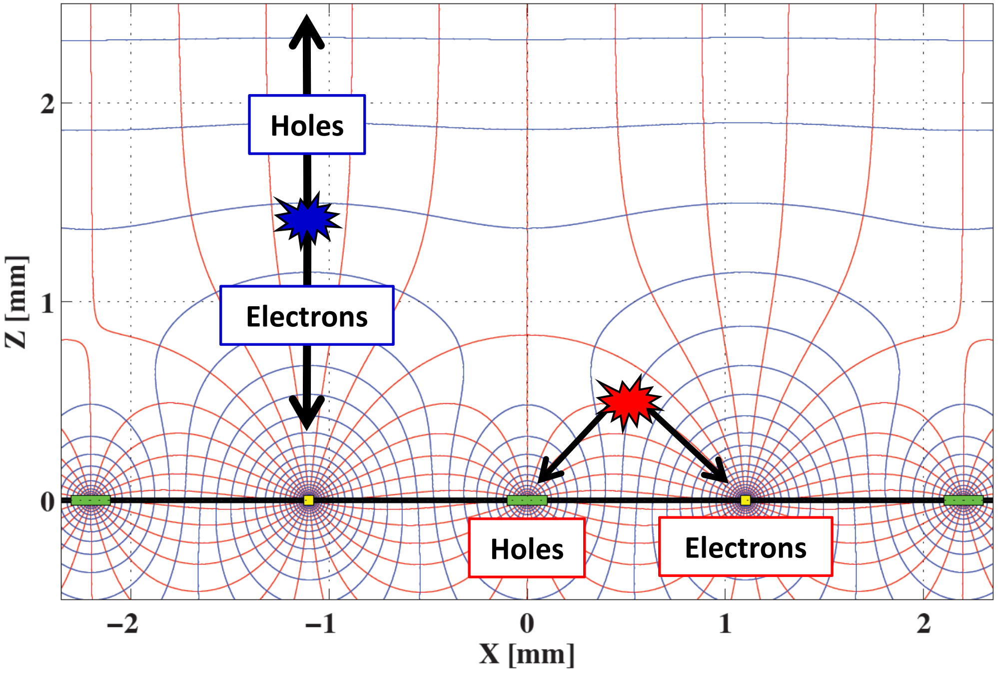
**Bulk event** → Side-symmetric Ionization signal

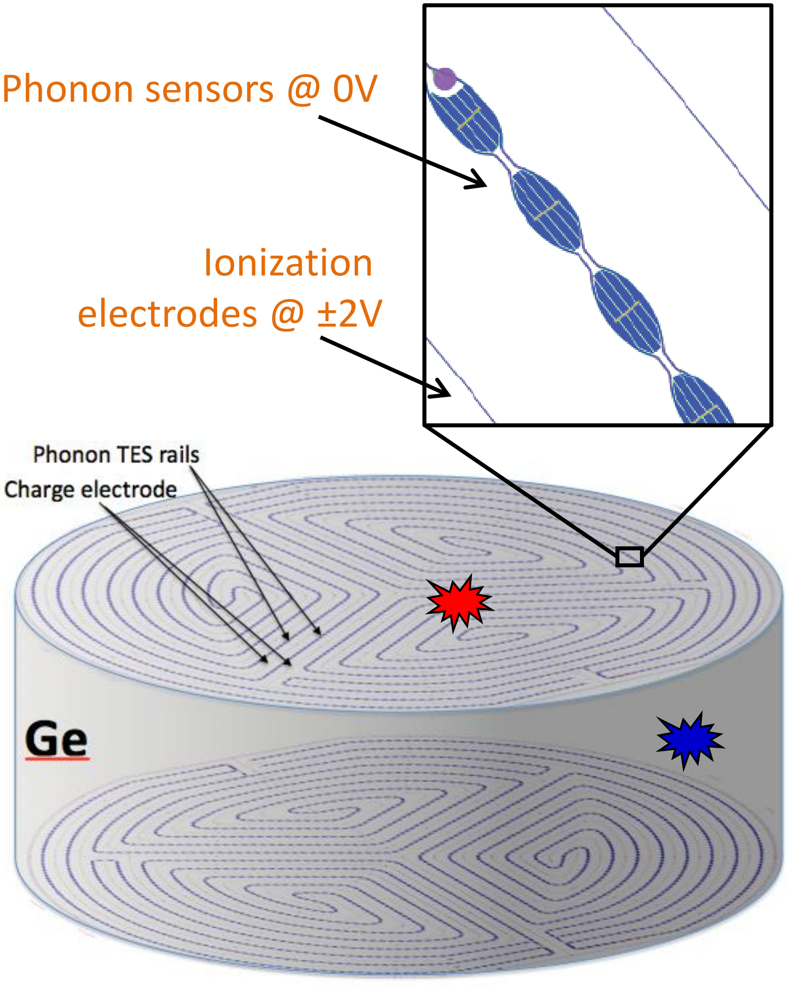
+

**Surface event** → Asymmetric ionization signal

=

**Significantly improved face-event rejection**




Phonon sensors @ 0V

Ionization electrodes @ ±2V

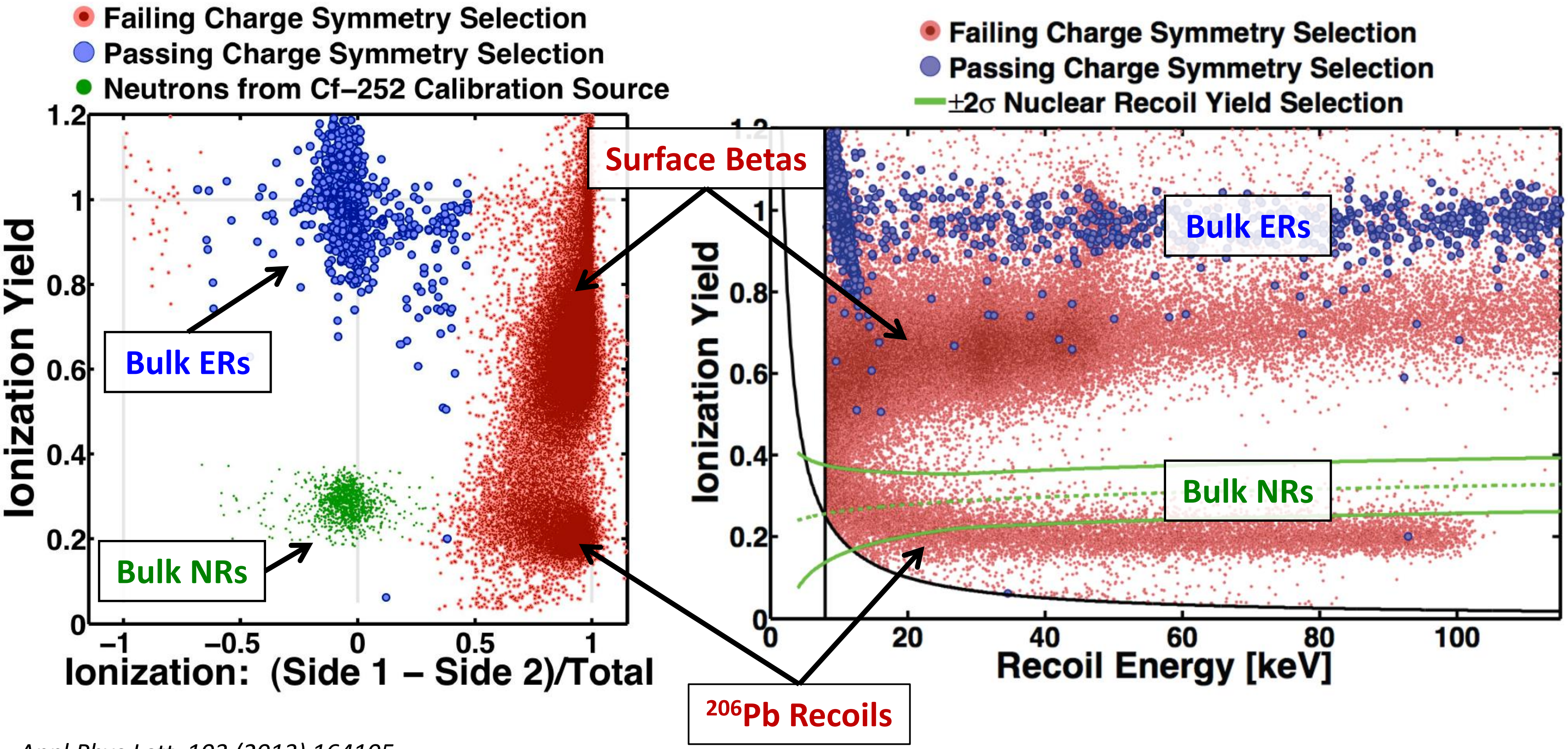
# SuperCDMS background rejection

Surface-event Rn-daughter sources placed above and below 2 detectors (*in situ* @ Soudan)

50 live days → 0 of 132,968 leaked surface events in (symmetric) NR signal region

→ Good enough rejection for proposed SuperCDMS SNOLAB

(100 kg, $\sigma_{\chi\text{-N}} < 8 \times 10^{-47}$ cm$^2$ for 60 GeV/$c^2$ dark matter)



*Appl.Phys.Lett. 103 (2013) 164105*
*[arXiv:1305.2405]*

# SuperCDMS Soudan

## 5 Super Towers of Ge iZIPs

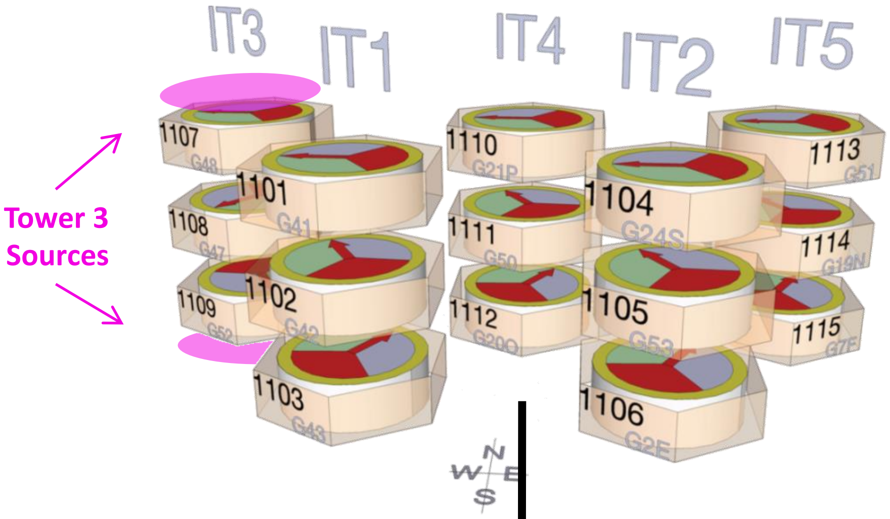
3 iZIPs per tower, 0.6 kg each

→ total mass of 9 kg

Installed in CDMS II shielding end of 2011

Fully operational since early 2012

Science run ends this summer.



## Low-mass Search Strategies

*Ge is a relatively heavy nucleus*

*→ Go as low in threshold as possible*

CDMSlite →

Special bias configuration & readout

Extra-low threshold: < 1 $\text{keV}_{nr}$

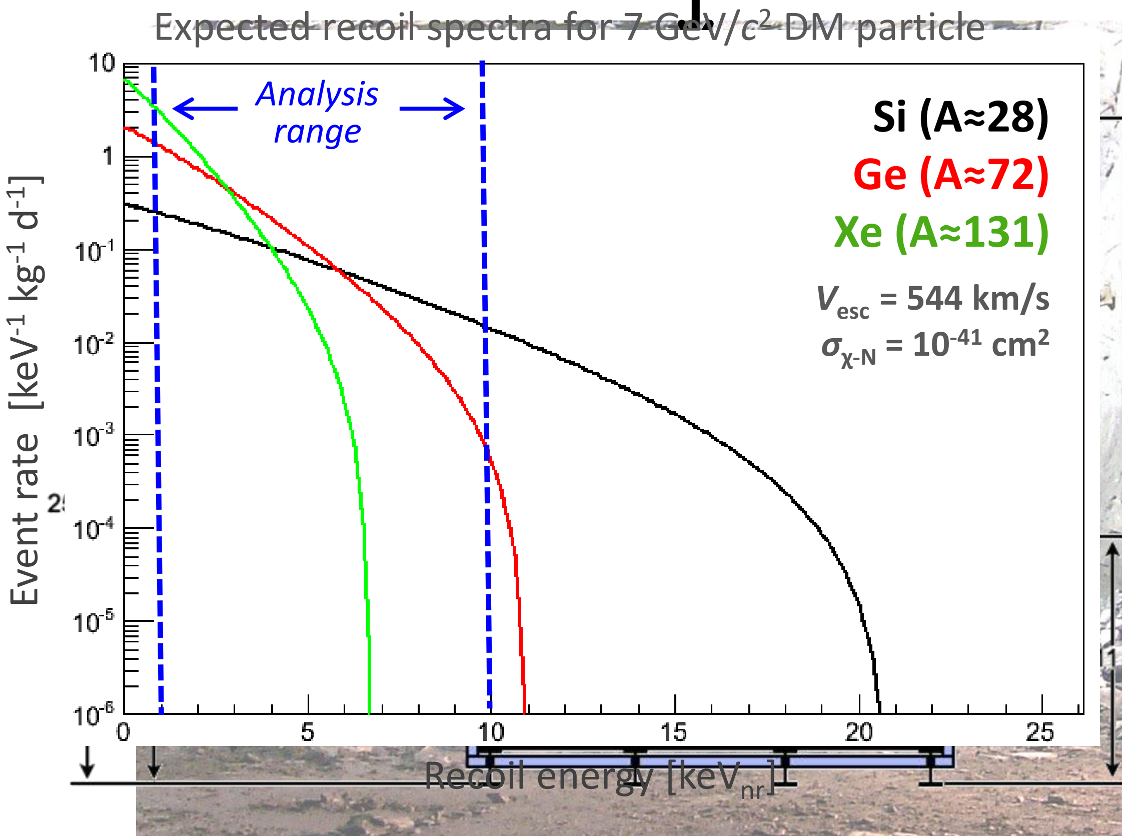
Target masses: < 10 GeV/$c^2$

Low-threshold (LT) analysis →

Low threshold: ≈1.6 $\text{keV}_{nr}$

Use improved iZIP fiducial volume

Target masses: < 20 GeV/$c^2$

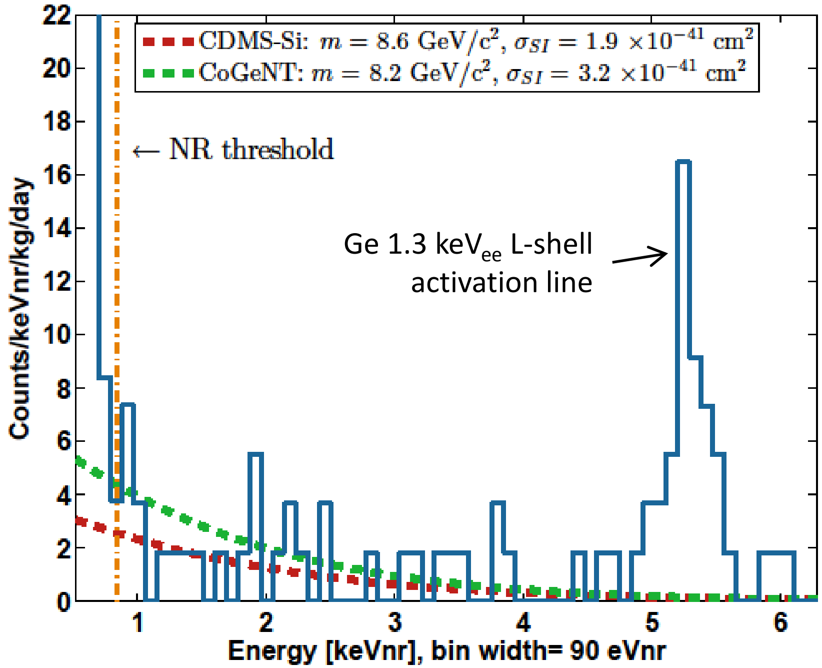


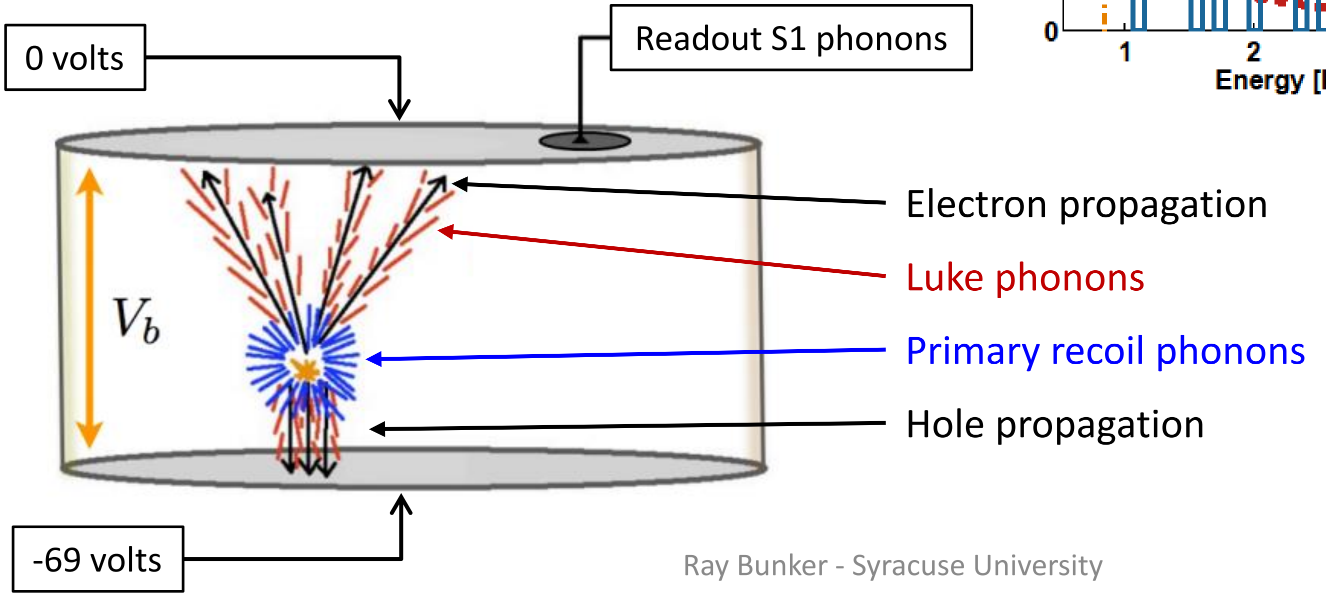
# SuperCDMS Soudan — CDMSlite

Luke-amplified ionization-energy measurement

- 24x amplification of ionization energy via phonons
  - → 10x lower threshold for ERs
  - → ≈ equal noise performance

  ***vs.* normal ±2V mode**
- No event-by-event ER-NR discrimination
  - → But near perfect signal efficiency
- Fall 2012 search for light WIMPs
  - → Single-detector 10-day exposure (5.9 kg-days)
  - → Observed rate → 1.2±0.2 events /$\mathrm{keV_{nr}}$ /kg-d





0 volts

Readout S1 phonons

Electron propagation

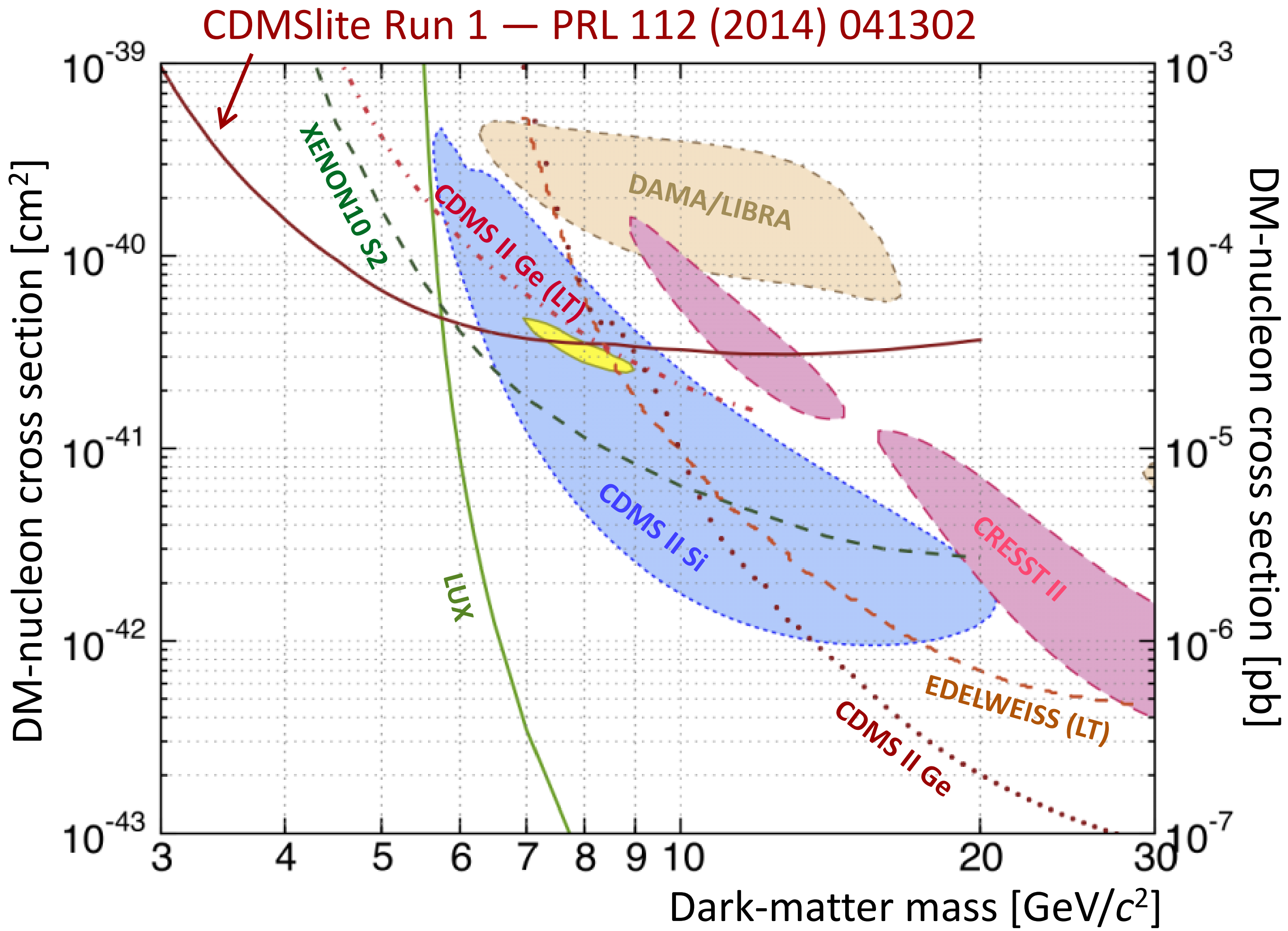
Luke phonons

Primary recoil phonons

Hole propagation

-69 volts

# CDMSlite result



~6-month CDMSlite Run 2 with electronics upgrade now complete!

(analysis in progress)

SuperCDMS SNOLAB CDMSlite → even lower threshold via:

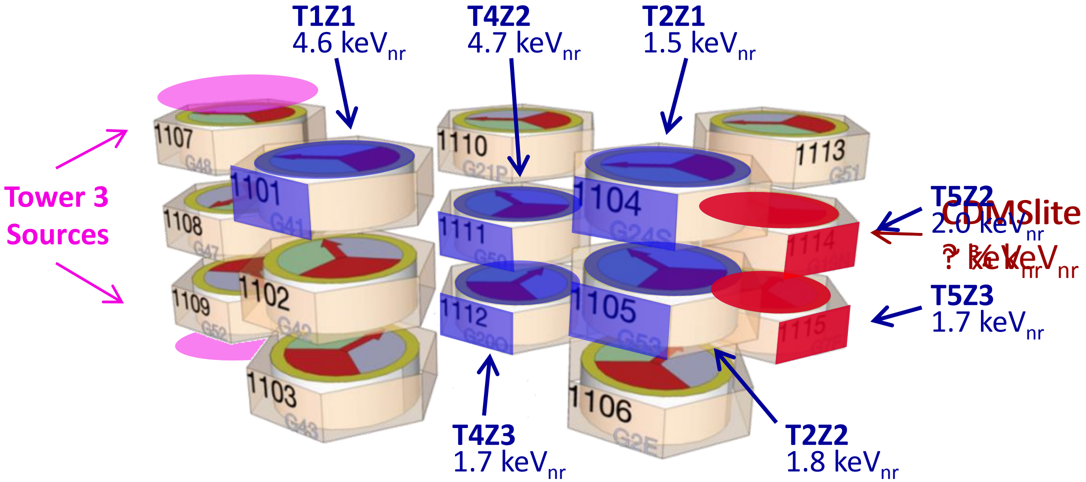
Lower backgrounds, improved electronics, higher voltage & superior resolution

# SuperCDMS Soudan — LT analysis

Normal ±2V bias configuration

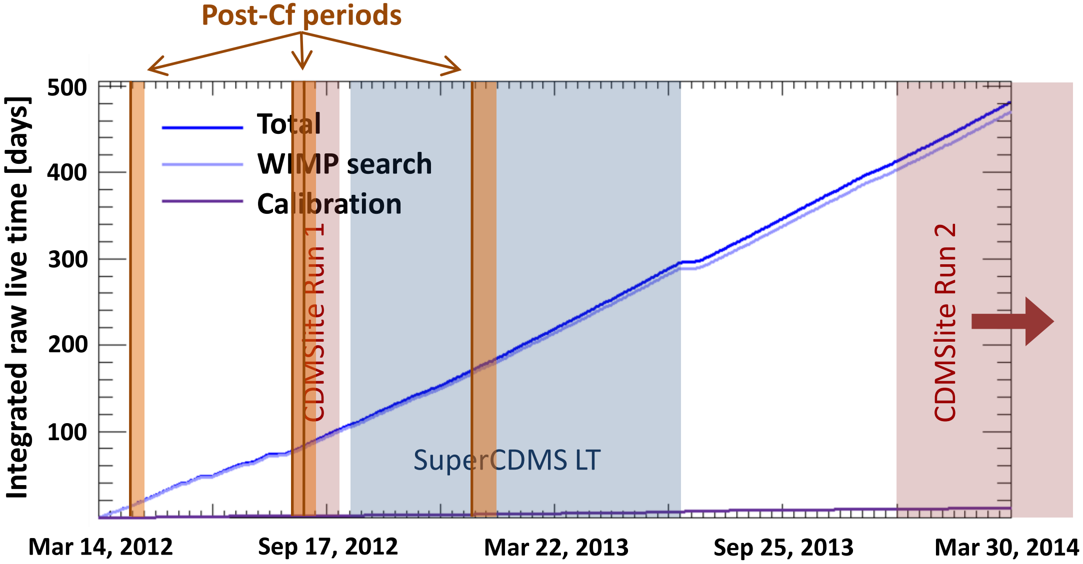
WIMP search → Oct 2012 – July 2013

- 577 kg-day ***blinded*** exposure
- ER calibration throughout via $^{133}$Ba
- NR calibrations via $^{252}$Cf
  - → 97 kg-day open dataset



7 detectors w/ lowest trigger thresholds

- → ~1.6 to 5 $\text{keV}_{nr}$ (detector & time dependence)

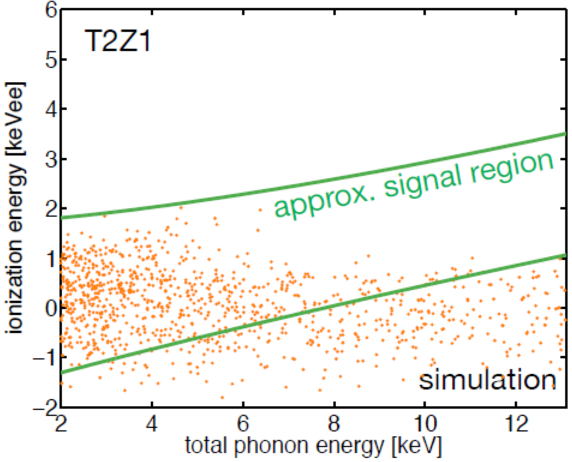


Note: 2 special-case detectors

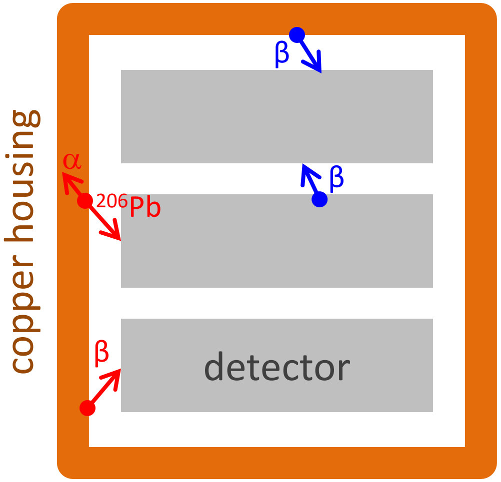
- → T5Z2 in 2013 had noisy S1 Q guard
- → T5Z3 has S1 Q guard not biased

# LT-analysis backgrounds

**$^{210}$Pb decay chain**

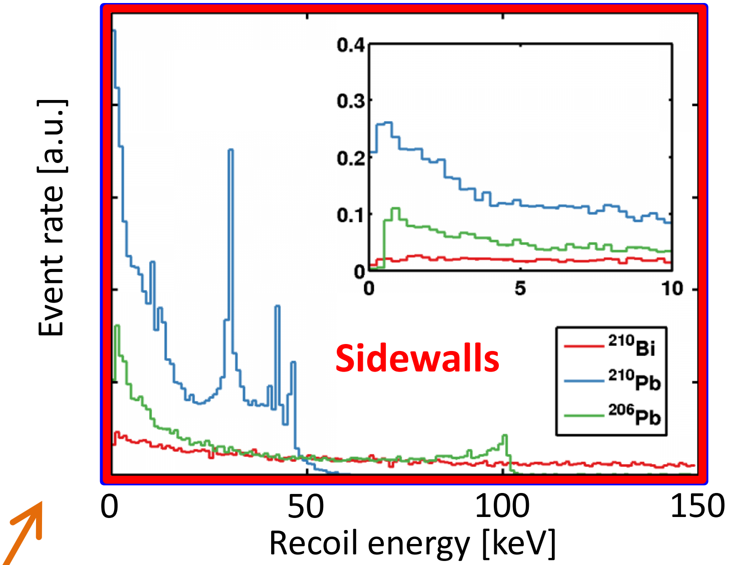


- $^{210}$Pb, $^{210}$Bi → β's & X-rays
- $^{210}$Po decays → $^{206}$Pb recoils
- Divide by location:
  - → detector **faces**
  - → detector **sidewalls**

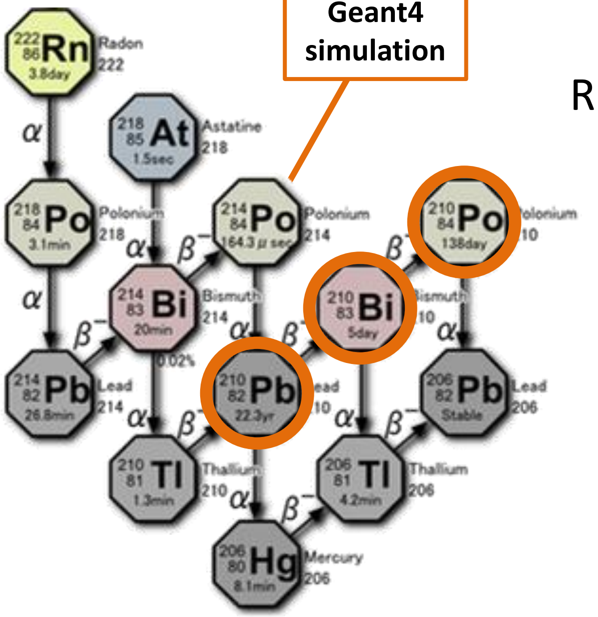


**"Pulse Simulation"**

Simulate low-energy detector response by combining noise traces w/ template pulses taken from higher-energy sidebands & scaled to give MC energy spectrum



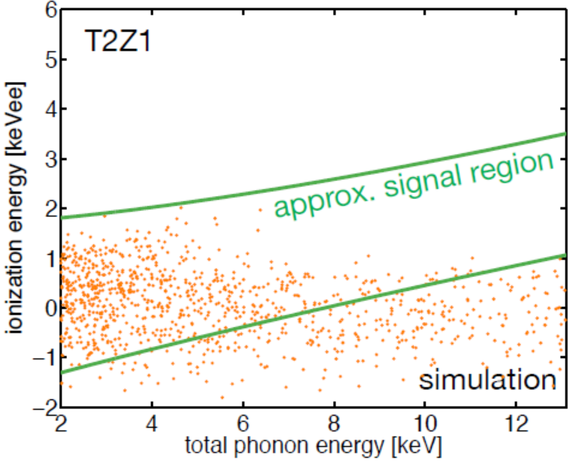
**Geant4 simulation**



Rn progeny plate-out onto detector & copper surfaces, creating long-lived $^{210}$Pb source

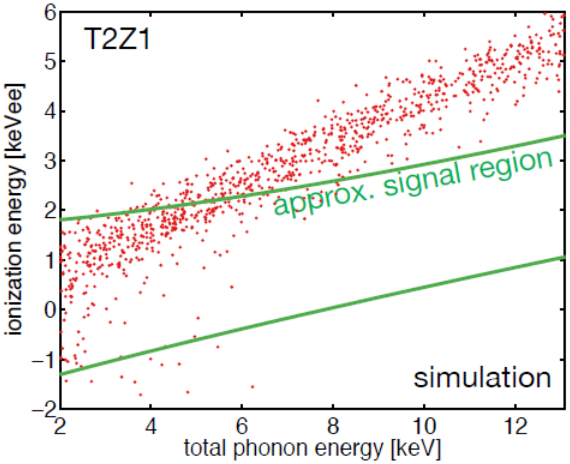
# LT-analysis backgrounds

**$^{210}$Pb decay chain**

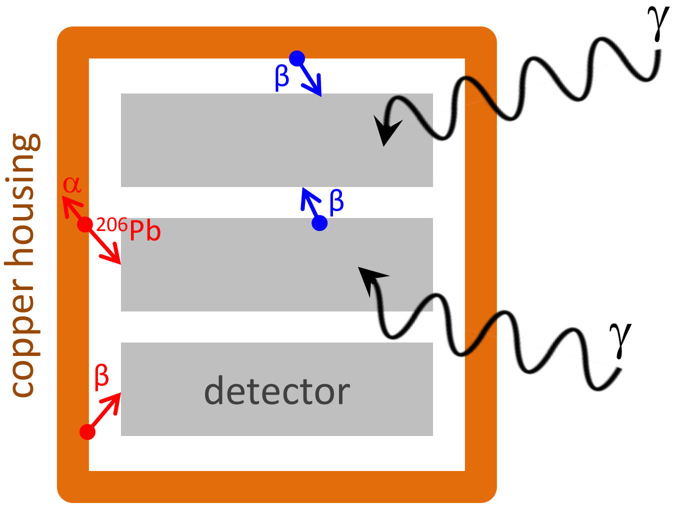


- $^{210}$Pb, $^{210}$Bi → β's & X-rays
- $^{210}$Po decays → $^{206}$Pb recoils
- Divide by location:
  - → detector **faces**
  - → detector **sidewalls**

**External Gammas**

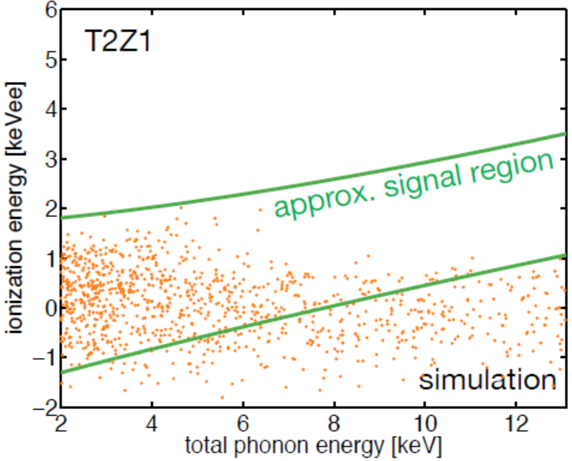


- External gammas from radioactivity in shielding & cryostat
- Detector response via pulse simulation



# LT-analysis backgrounds

**$^{210}$Pb decay chain**



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  - → detector **faces**
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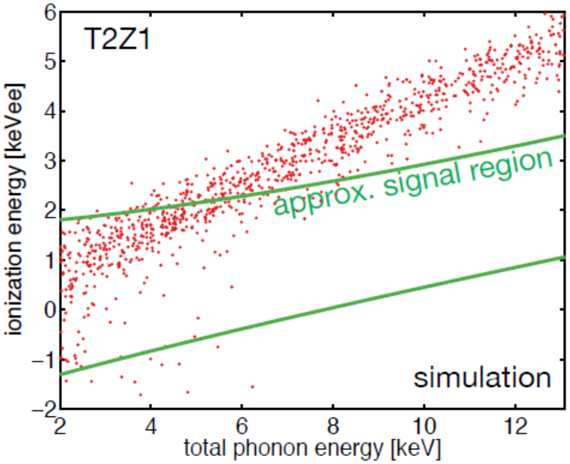
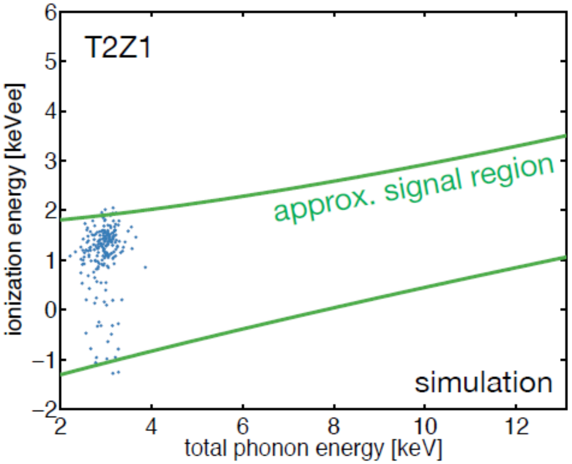
**External Gammas**

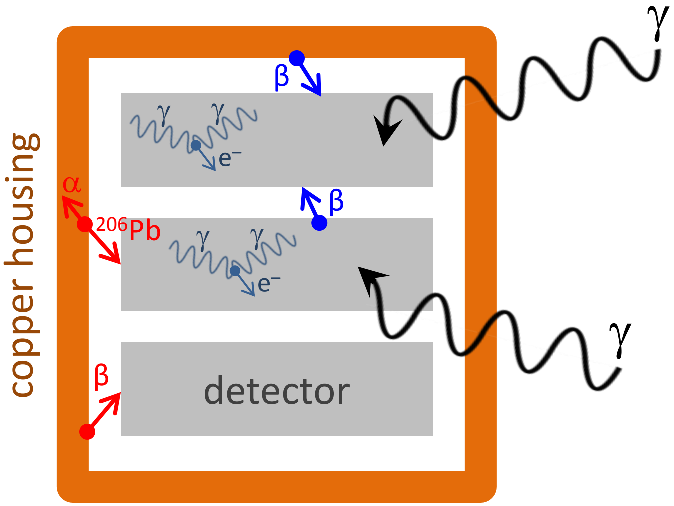


- External gammas from radioactivity in shielding & cryostat
- Detector response via pulse simulation

**Internal Activation Lines**



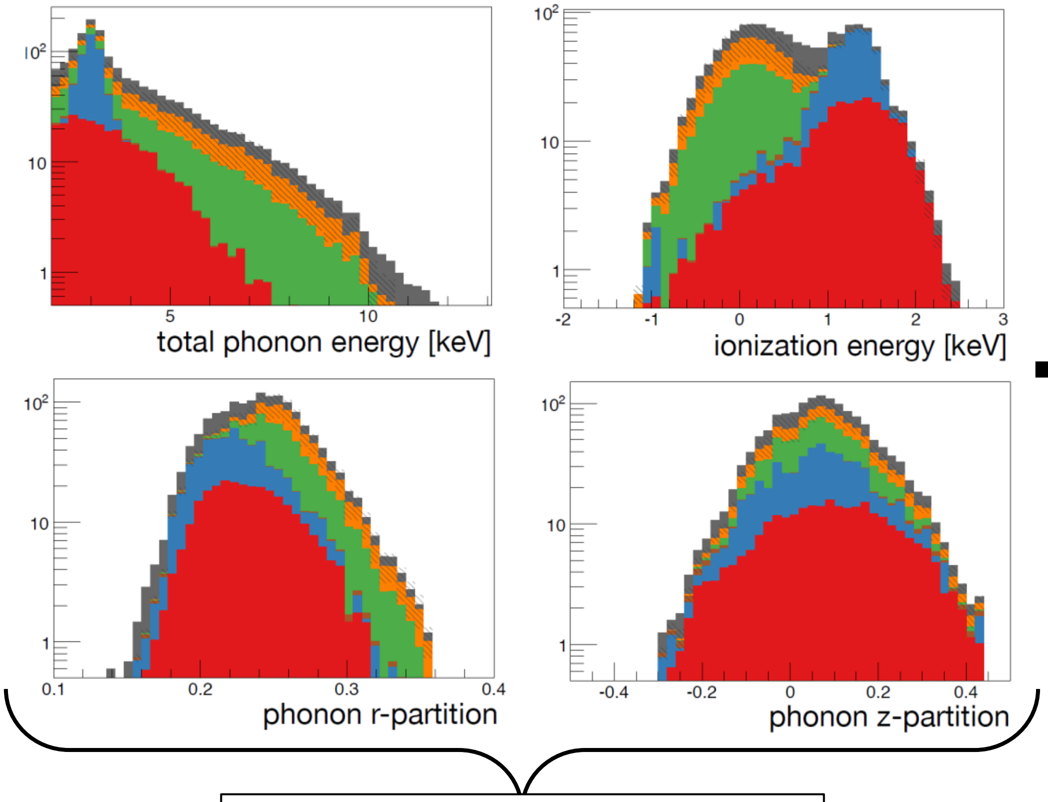
- Detector activation from cosmics & thermal-neutron capture
- X-rays & Auger electrons from $^{68,71}$Ge, $^{65}$Zn, $^{68}$Ga L-shell e⁻ capture
- Detector response via pulse simulation



- Also, radiogenic & cosmogenic neutron backgrounds
  - → but irreducible & rate is very low

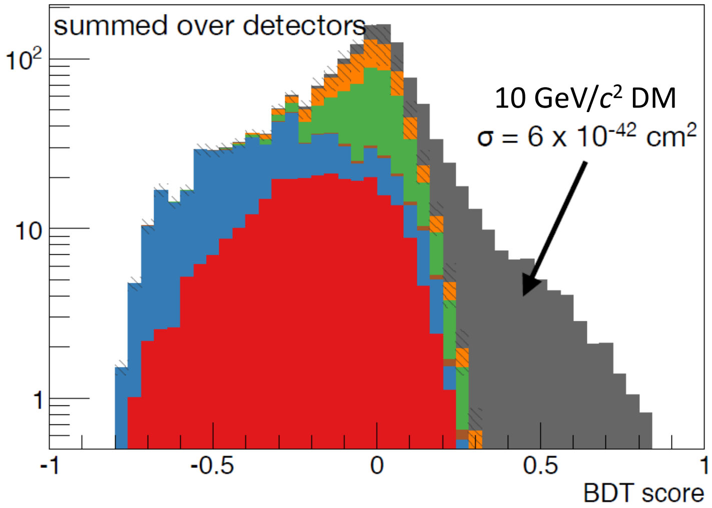
- Signal region blinded & no calibration for $^{210}$Pb-sourced sidewall events
  - → $^{210}$Pb decay-chain simulation systematics not yet understood in detail
  - → Before unblinding, chose to set upper limit based on any candidates

# LT-analysis BDT



Boosted Decision Tree — inputs

Boosted Decision Tree — Output



- ⬛ → Expected signal (10 GeV/$c^2$ shown here)
- 🟧 → **Sidewall $^{206}$Pb recoils**
- 🟩 → **Sidewall β's & X-rays**
- 🟫 → **Face β's & X-rays**
- 🟦 → **1.1–1.3 keV L-shell activation lines**
- 🟥 → **External gammas ("Comptons")**

Sidewall $^{206}$Pb recoils, Sidewall β's & X-rays, Face β's & X-rays → $^{210}$Pb-sourced

Train BDT with:

- Background events from pulse simulation
- Signal from $^{252}$Cf NRs reweighted to expected energy spectra for 5, 7, 10 & 15 GeV/$c^2$ DM particles

Create 1 BDT per detector per DM-particle mass

Optimize BDT-score cuts simultaneously across detectors to minimize expected 90% C.L. upper limit separately for each mass

OR across 4 DM-particle masses to accept events that pass one or more of 4 BDT cuts

# LT-analysis detection efficiency

Remove:

→ bad data periods (*e.g.* noise)
→ incorrect pulse shapes (*e.g.* glitches)

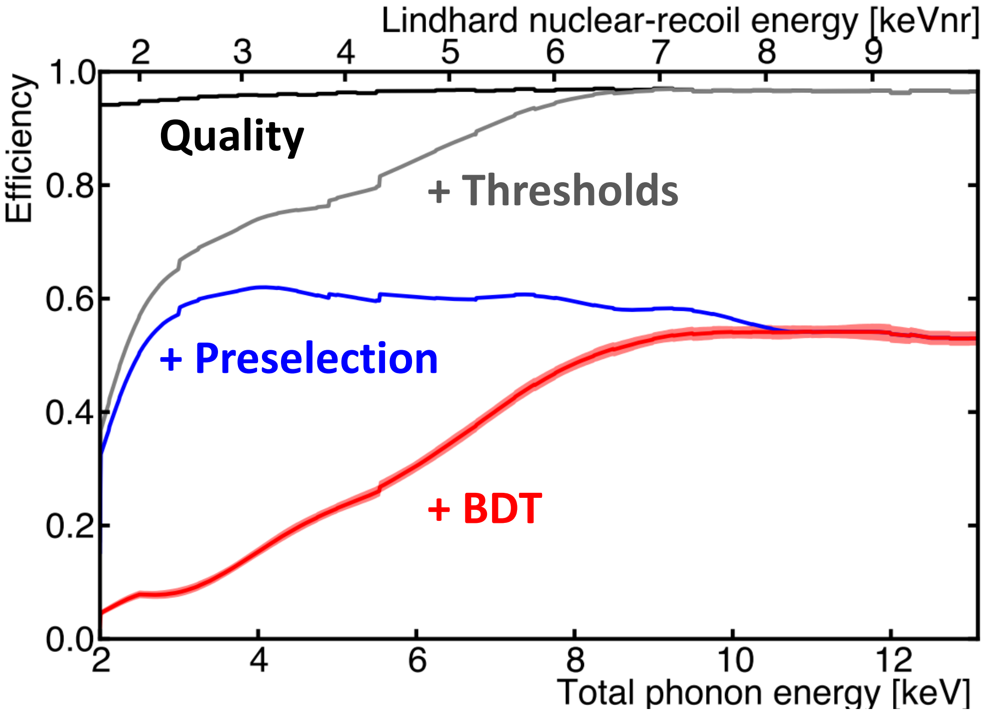
Efficiency via pulse-shape simulation

Apply trigger & analysis thresholds
→ ≈ 1.5–5 $\mathrm{keV_{nr}}$

Efficiency measured from $^{133}$Ba calibration ERs

Single-detector events only
No activity in muon veto
Loose ionization-based 3D fiducial volume
NR-consistent ionization energy

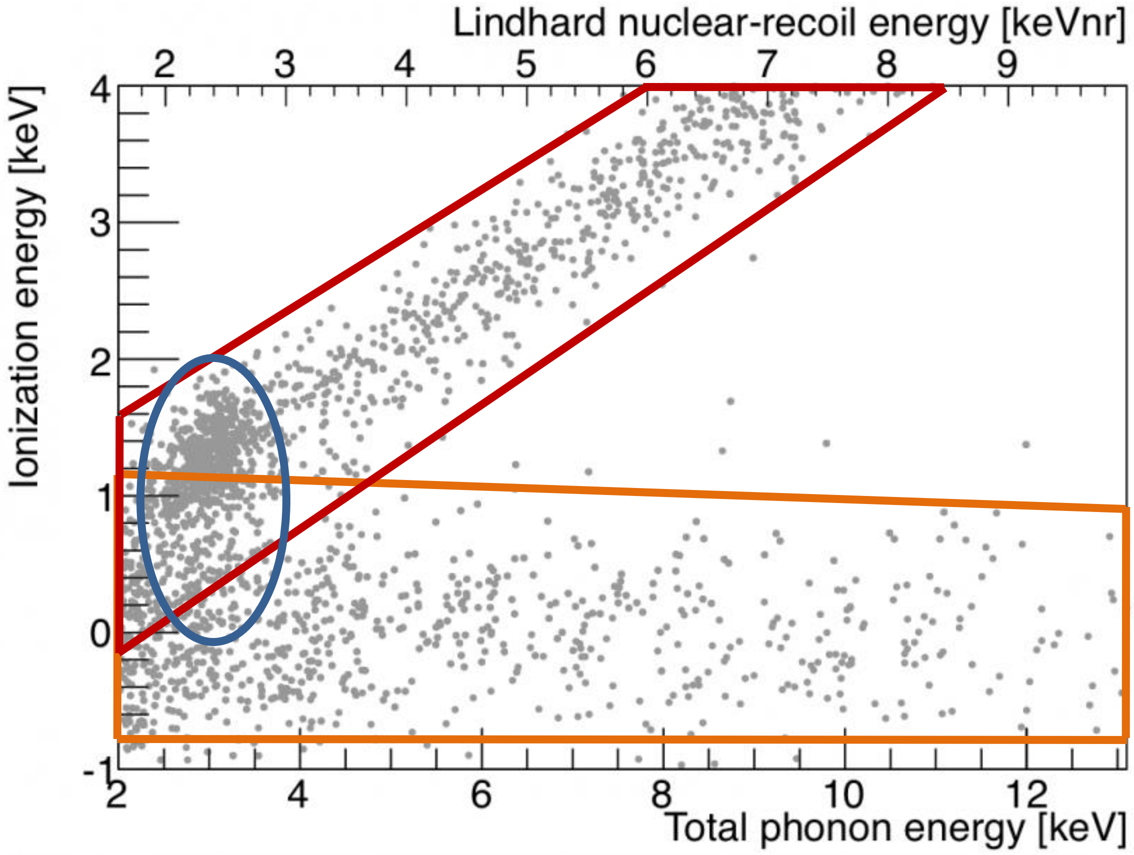
Final selection optimized on energy & phonon position estimators
Efficiency measured together with preselection using $^{252}$Cf passage fraction & Geant4 sim to correct fiducial volume for differences between neutrons & DM particles



1σ band includes uncertainties in:

- Trigger efficiency
- Fiducial volume (stat. & syst.)
- NR energy scale

# LT-analysis unblinding (before BDT)



All events passing:

- Quality &
- Thresholds &
- Preselection (except NR ionization)

3 background components evident:

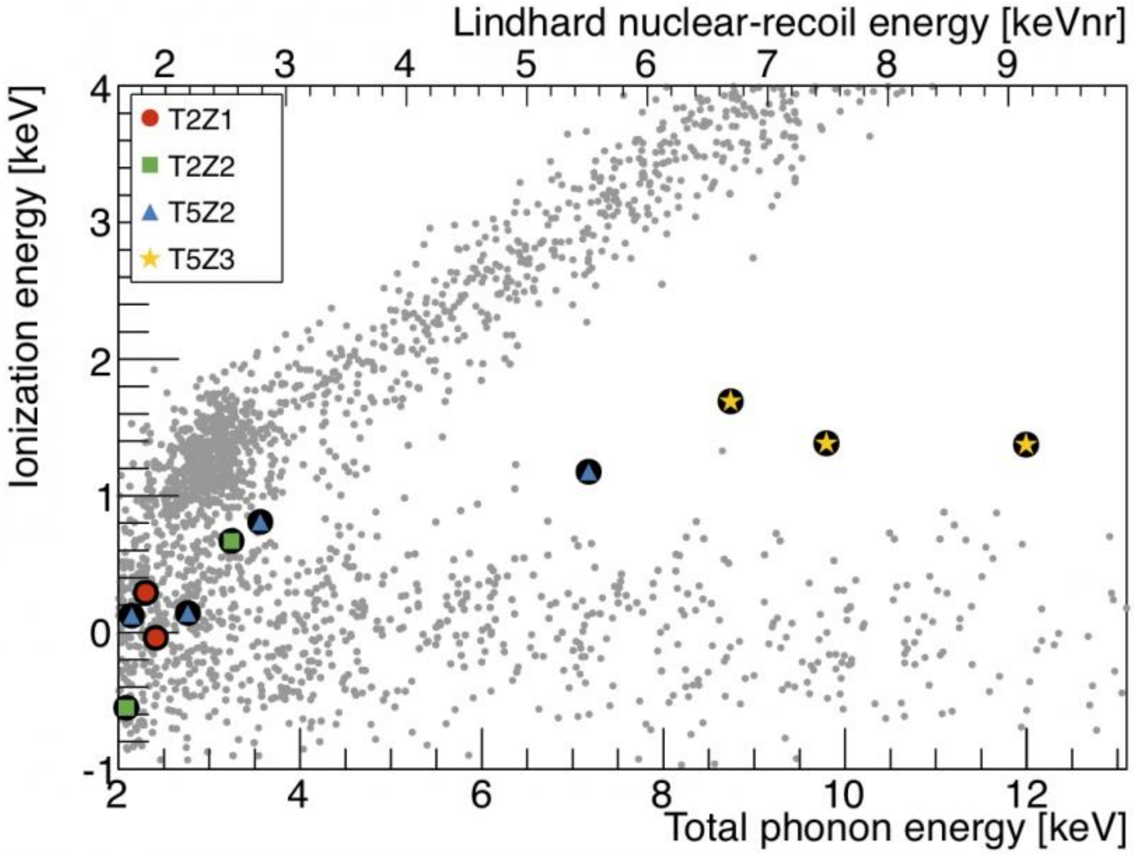
- $^{210}$Pb-sourced surface events
- External gammas ("Comptons")
- Internal activation lines

Expected background after BDT:

$6.1^{+1.1}_{-0.8}$ (stat. & syst.)

Also, 0.10 ± 0.02 neutrons

# LT-analysis unblinding (after BDT)



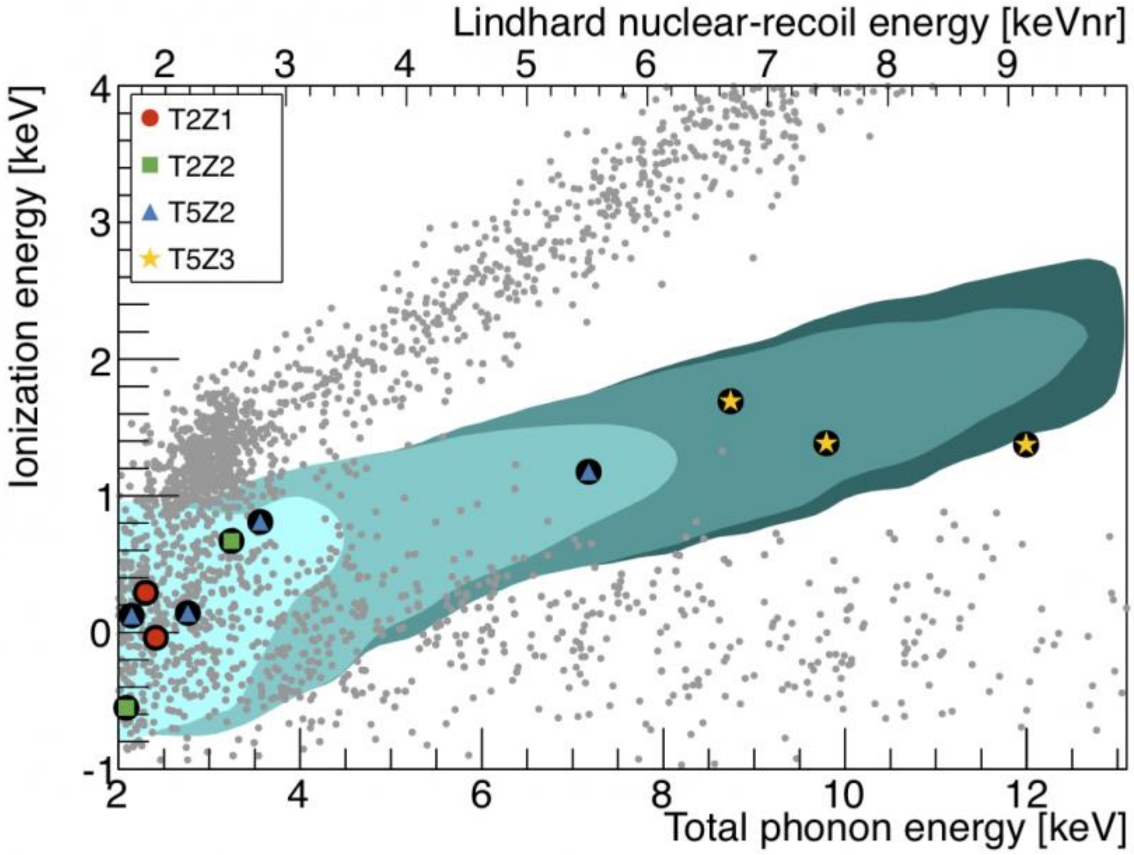
11 candidate events pass all cuts!

($6.1^{+1.1}_{-0.8}$ expected)

3 with unexpectedly high energies

→ all in T5Z3 w/ altered E-field

# LT-analysis unblinding (after BDT)



11 candidate events pass all cuts!
($6.1^{+1.1}_{-0.8}$ expected)

3 with unexpectedly high energies
→ all in T5Z3 w/ altered E-field

95% confidence contours for expected signal from **5**, **7**, **10** & **15** GeV/$c^2$ DM

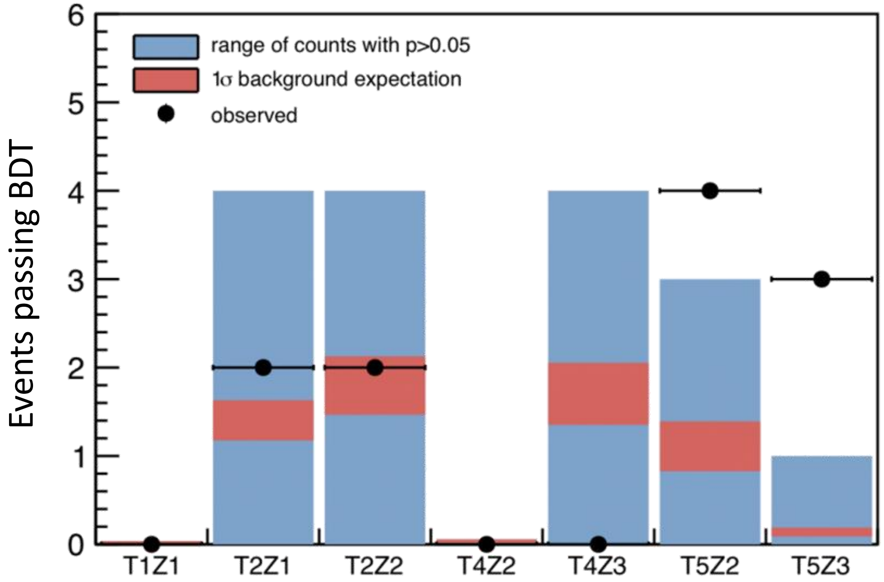
# LT-analysis post-unblinding comparison

Overall, 11 candidate events are consistent w/ background expectation & most individual detectors agree w/ model

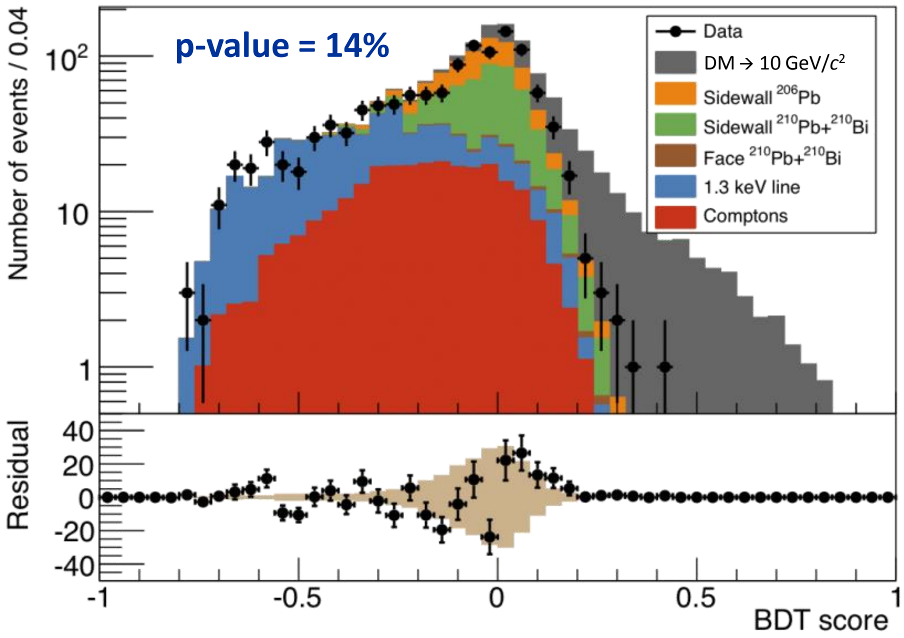
Altered electric field on T5Z3 may have affected background-model performance
→ *further investigation in progress*

Average thresholds (keV$_{nr}$):

| | | | | | | |
|---|---|---|---|---|---|---|
| 4.6 | 1.5 | 1.8 | 4.7 | 1.7 | 2.0 | 1.7 |



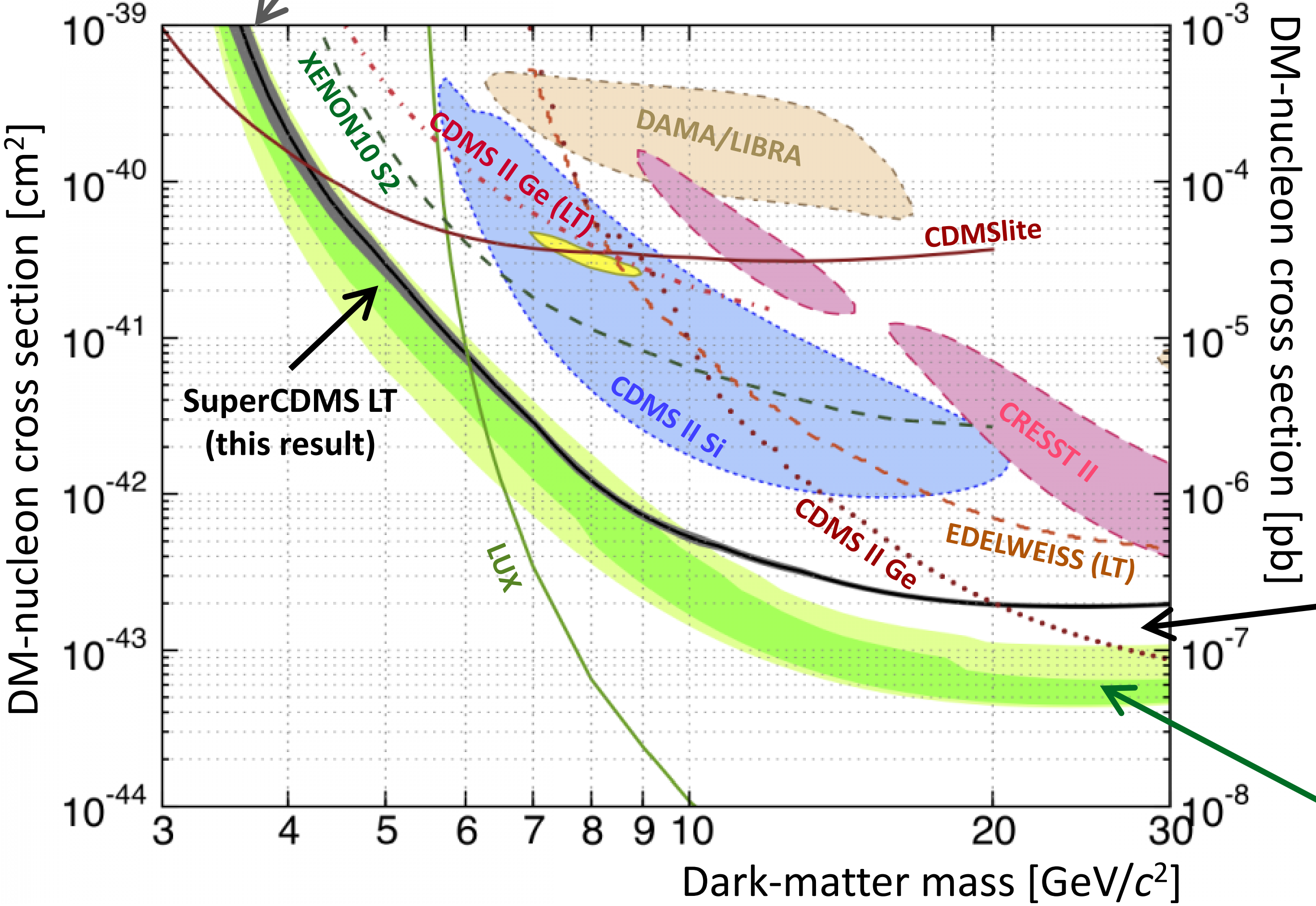
**Quality** + Thresholds + **Preselection**



Background model agrees well with events observed in preselection region
→ p-values = 8–26% for 4 DM masses

# LT-analysis result

95% C.L. uncertainty band
(trigger, energy scale, fiducial volume)



**SuperCDMS LT**
**(this result)**

difference due to T5Z3
high-energy events

Expected sensitivity
at 68 and 95% C.L.

*PRL 112 (2014) 241302 — Editor's suggestion!*

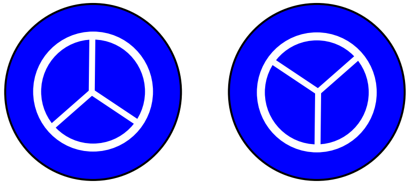
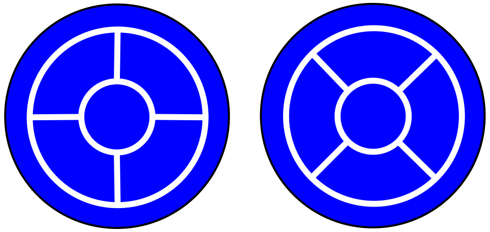
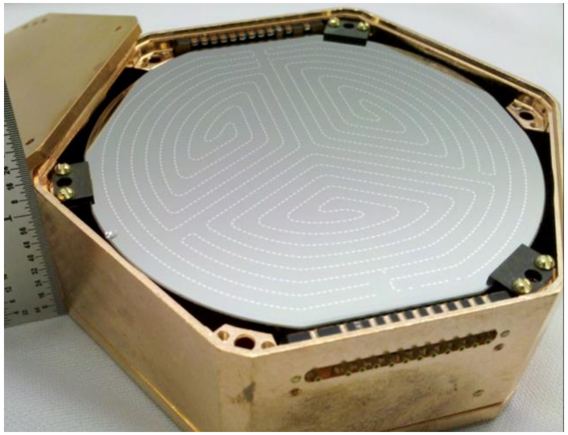
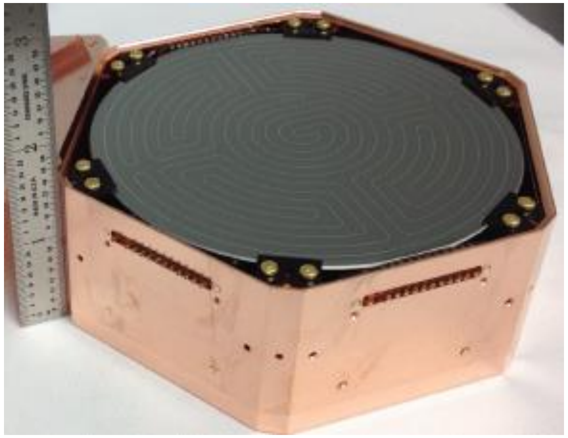
# Next generation → SuperCDMS SNOLAB

Larger target mass:
- More & larger iZIPs
- Cryostat large enough for 400 kg
- **Si & Ge crystals**
- 1 tower in CDMSlite configuration
  - → also with Si & Ge

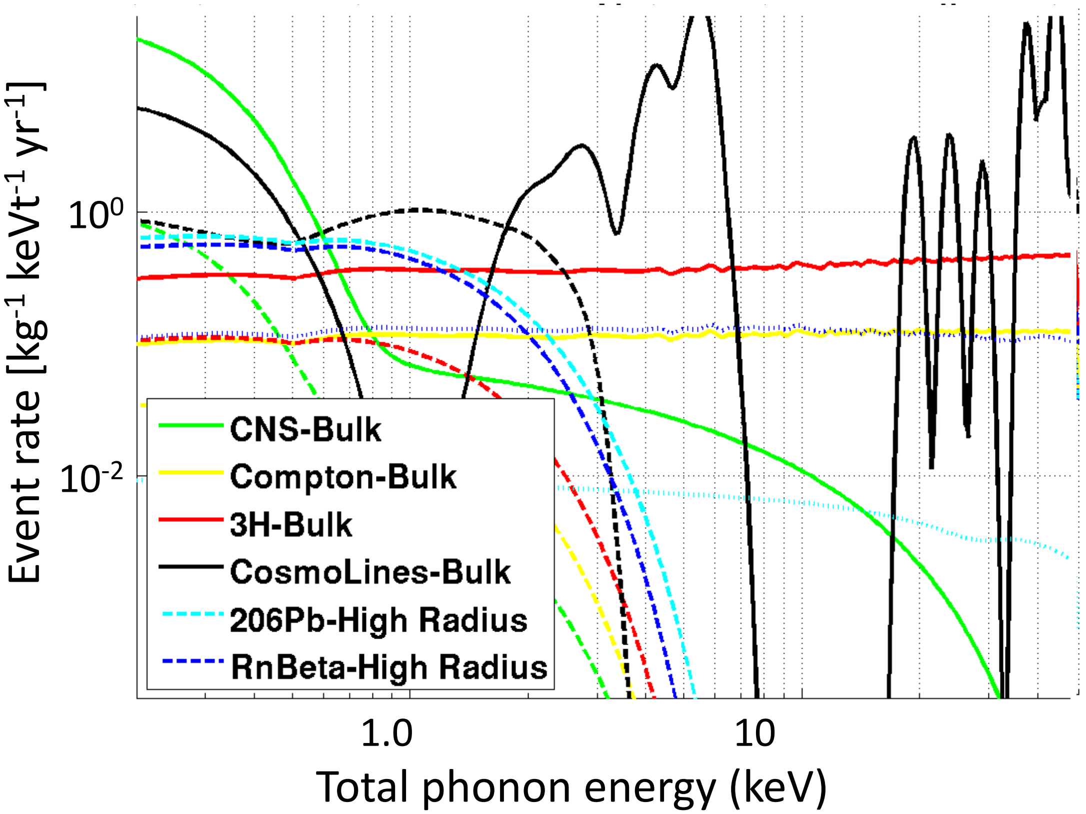
Lower background:
- New facility at deeper site
- Cleaner materials selection
- Active neutron veto

Improved signal readout:
- Phonons → new SQUID arrays
- Ionization → switch to HEMTs
- Improved tower design

Improved resolution:
- $\sigma_{\text{phonon}} \propto T_c^3$ →lower operating temp
- 42 eV demonstrated (>4x better)
- Improved cryogenics could give
  - >100x improvement!

| **SuperCDMS Soudan** | **SuperCDMS SNOLAB** |
|---|---|
| 2.5 cm thick<br>3"diameter<br>600 g Ge | 3.3 cm thick<br>4"diameter<br>1.4 kg Ge / 615 g Si |
| 2 ionization + 2 ionization<br>4 phonon + 4 phonon | 2 ionization + 2 ionization<br>6 phonon + 6 phonon |
|  |  |
| 5 towers of 3 iZIPs each | 7 towers of 6 iZIPs each |
|  |  |

# Beyond SuperCDMS Soudan


CDMSlite mode w/ modest radial fiducialization

## Background Reduction

Step 1 → Bulk gamma background via cleaner copper … 220x lower

→ Based on levels achieved by DEAP/CLEAN and XENON100

Step 2 → Rn-sourced backgrounds, primarily at high radius

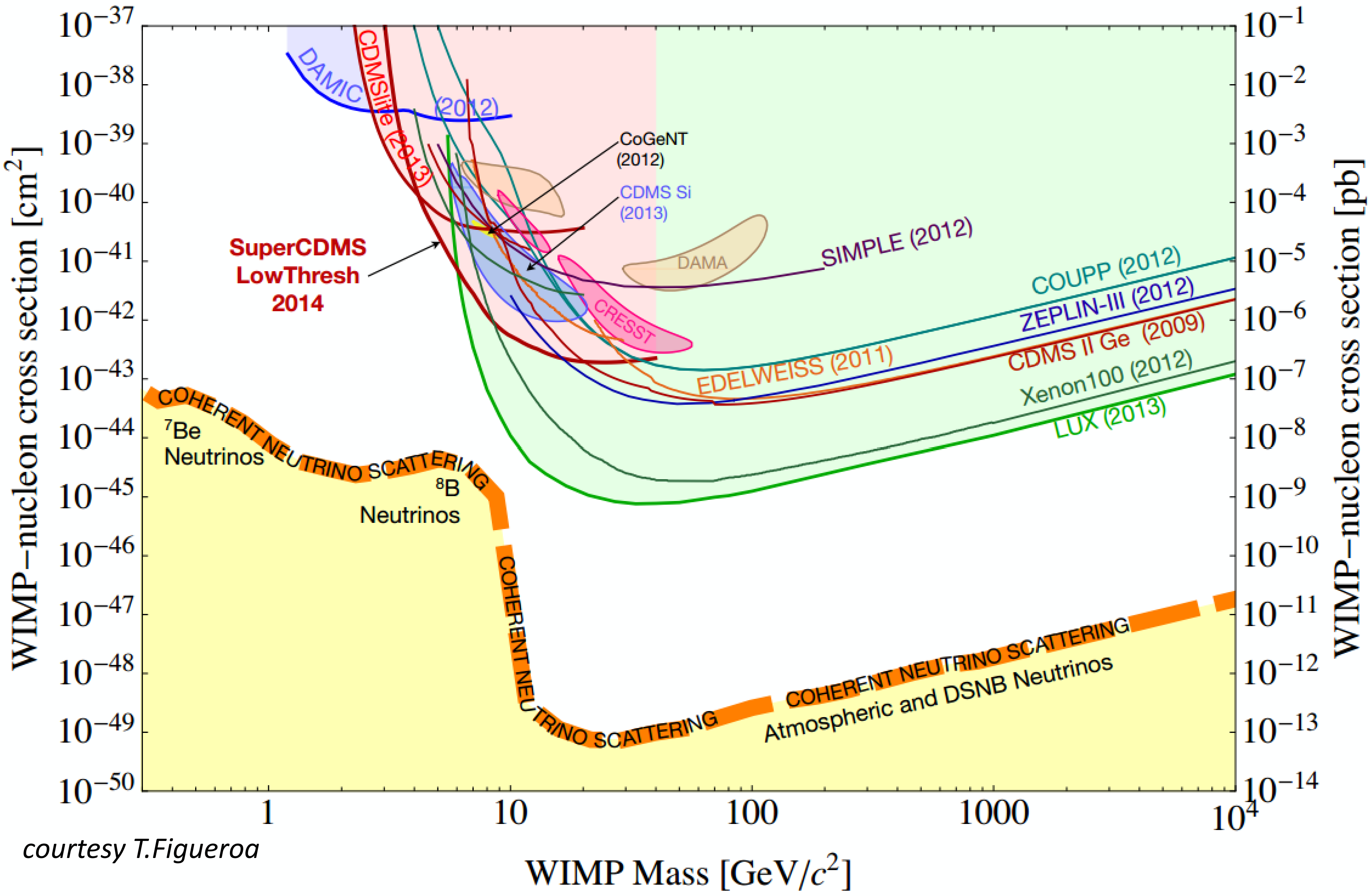
→ copper housings … 22x lower via cleaner handling & storage

Further improvement →

- Superior resolution via lower Tc’s
- Fiducialization
- Lower energy thresholds

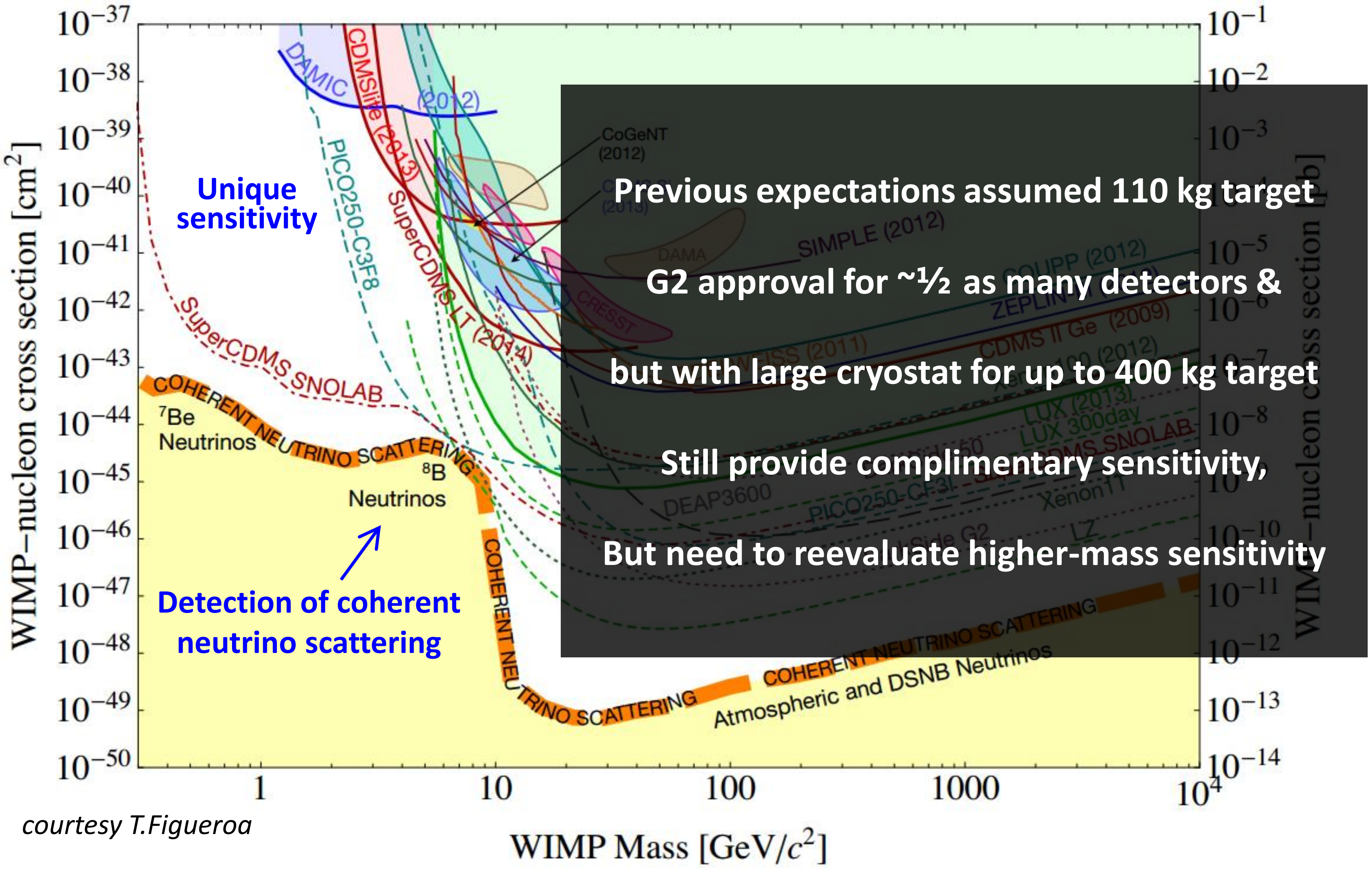
Dependent on detector mode!

# SuperCDMS SNOLAB expected sensitivity



*courtesy T.Figueroa*

# SuperCDMS SNOLAB expected sensitivity



**Unique sensitivity**

**Detection of coherent neutrino scattering**

*courtesy T.Figueroa*

**Previous expectations assumed 110 kg target**

**G2 approval for ~½ as many detectors &**

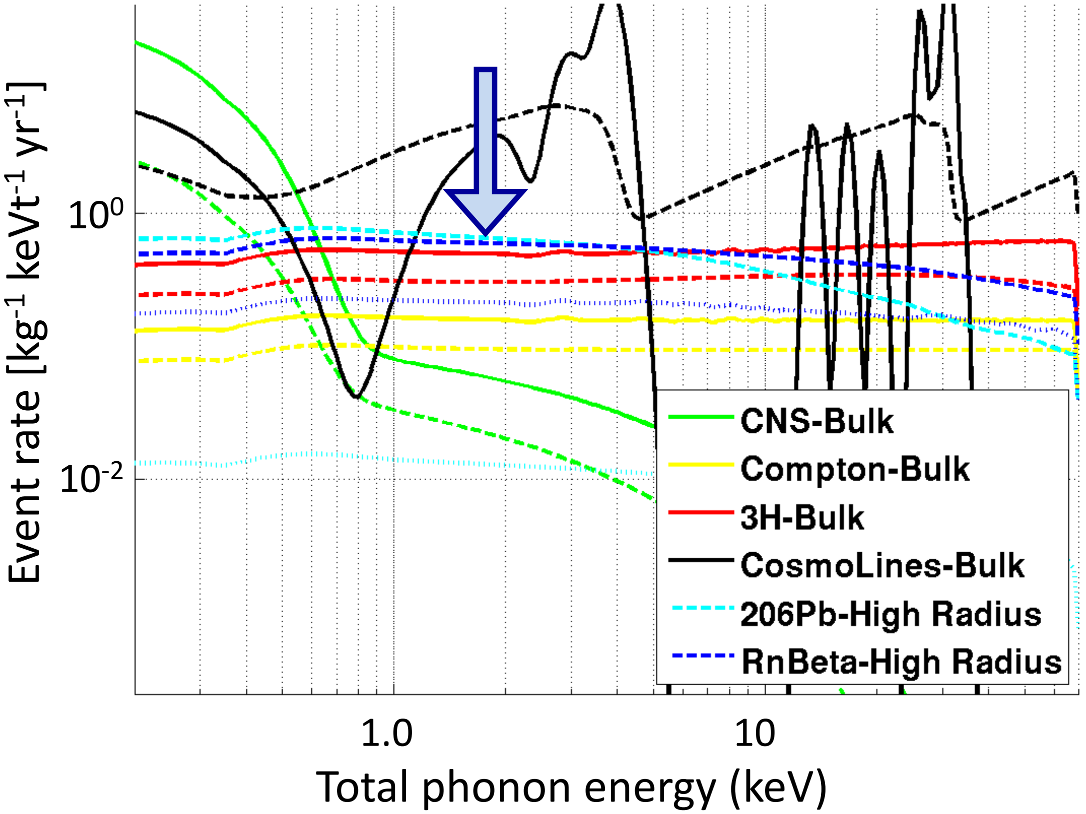
**but with large cryostat for up to 400 kg target**

**Still provide complimentary sensitivity,**

**But need to reevaluate higher-mass sensitivity**

# Beyond SuperCDMS Soudan

Simulation of current background levels



## Background Reduction

Step 1 → Bulk gamma background via cleaner copper … 220x lower
→ Based on levels achieved by DEAP/CLEAN and XENON100

Step 2 → Rn-sourced backgrounds, primarily at high radius
→ copper housings … 22x lower via cleaner handling & storage

Further improvement →

- Superior resolution via lower Tc's
- Fiducialization
- Lower energy thresholds

# Plans for Radon Exclusion

## Protect detector and nearby copper surfaces from exposure to Rn!

- Use standard etching techniques to clean copper surfaces
- Radiopurity of Ge & Si substrates already sufficient for SNOLAB sensitivity
- Improved procedures to limit exposure during payload assembly
- Radon-mitigated clean room underground at SNOLAB
  - → To prevent contamination during detector installation

## Looking toward the future and G3:

- More robust protection while in storage
  - → Use radon emanation measurements to study storage cabinets & purge packaging
  - → Commission & operate Rn-emanation system
- Development of BetaCage detector
  - → More sensitive screening of $\alpha$- & $\beta$-emitting surface contaminants (*i.e.*, Rn daughters)

# Radon Mitigation Systems

## Continuous flow:

- Most Rn decays before exiting carbon
- $C_{final} = C_{initial} \exp[-t/t_{Rn}]$ breakthrough time Rn lifetime
  → *Assuming ideal column*
- Relatively simple & robust
- Need to cool carbon to be effective
  → *Ateko commercial system effective for NEMO*

## Swing flow:

- Stop gas flow well before breakthrough
  - *Use at least 2 columns:*
    → Regenerate column #1
    → Flow through column #2
- $C_{final} = 0$
  → *Assuming ideal column*
- More complicated
- Vacuum-swing:
  → *Potentially better performance than continuous system at lower cost*
  → *A. Pocar, LRT2004 (Borexino)*
- Temperature-swing:
  → *Expect best performance at highest cost*
  → *A. Hallin, LRT2010*

# Radon Mitigation Systems

Continuous system commercially available from Ateko

Syracuse Vacuum-swing

| Average air flow | Reduction factor | Budgetary price (EUR) |
|---:|---:|---:|
| 300 m³/h | 1000 | 365 000,- |
| 220 m³/h | 1000 | 280 000,- |
| 150 m³/h | 1000 | 230 000,- |
| 120 m³/h | 1000 | 215 000,- |
| 20 m³/h | 1000 | 68 000,- |
| **90 m³/h** | **>50** | **40 000,-** |

*Hardware only*

# Vacuum-Swing Absorption (VSA)

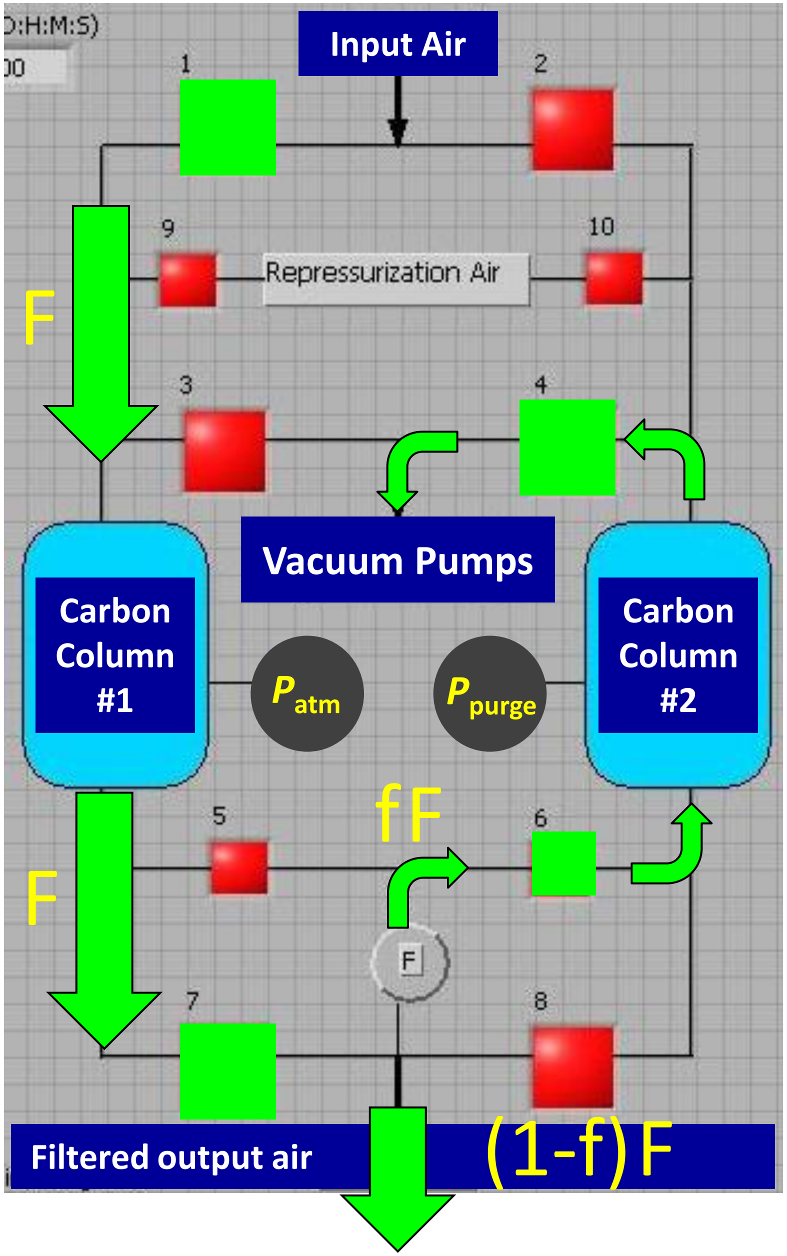
- Takes advantage of greater adsorption capacity at high pressures:
  - Regenerate carbon by flowing small fraction f of gas mass flow F back through tank at low purge pressure
  - Volume purge flow $\phi_{purge}$

$$\phi_{purge} = \frac{P_{atm}}{P_{purge}} f \cdot F = \frac{f \cdot P_{atm}}{P_{purge}} \phi_{feed}$$

  - Push back radon front if:

$$G \equiv \frac{\phi_{purge}}{\phi_{feed}} = \frac{f \cdot P_{atm}}{P_{purge}} > 1$$

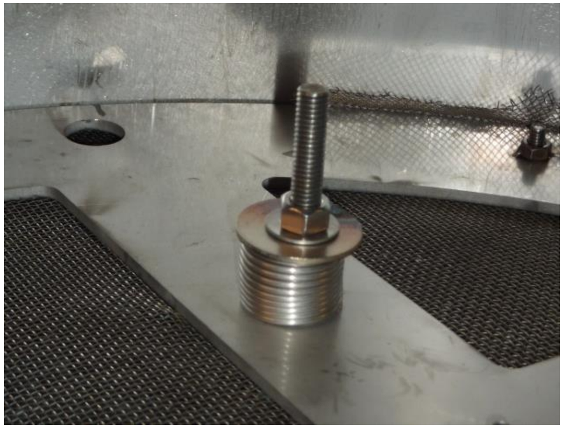
  - Syracuse system, f ≈ 10% with $P_{purge}$ ≈ 2.5 Torr → $G$ ≈ 30 (ideally)

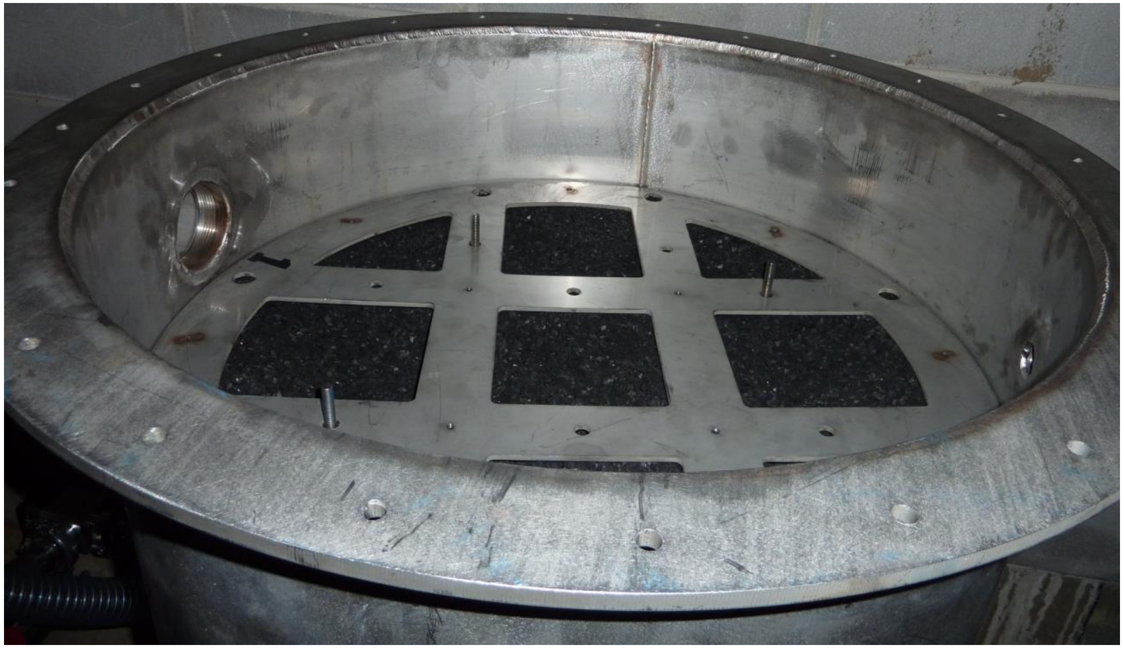


# Activated-Carbon Columns

**Calgon Coconut Activated Carbon Product OVC Plus 4x8 (mesh) Multiply rinsed, then dried under high-flow fume hoods**

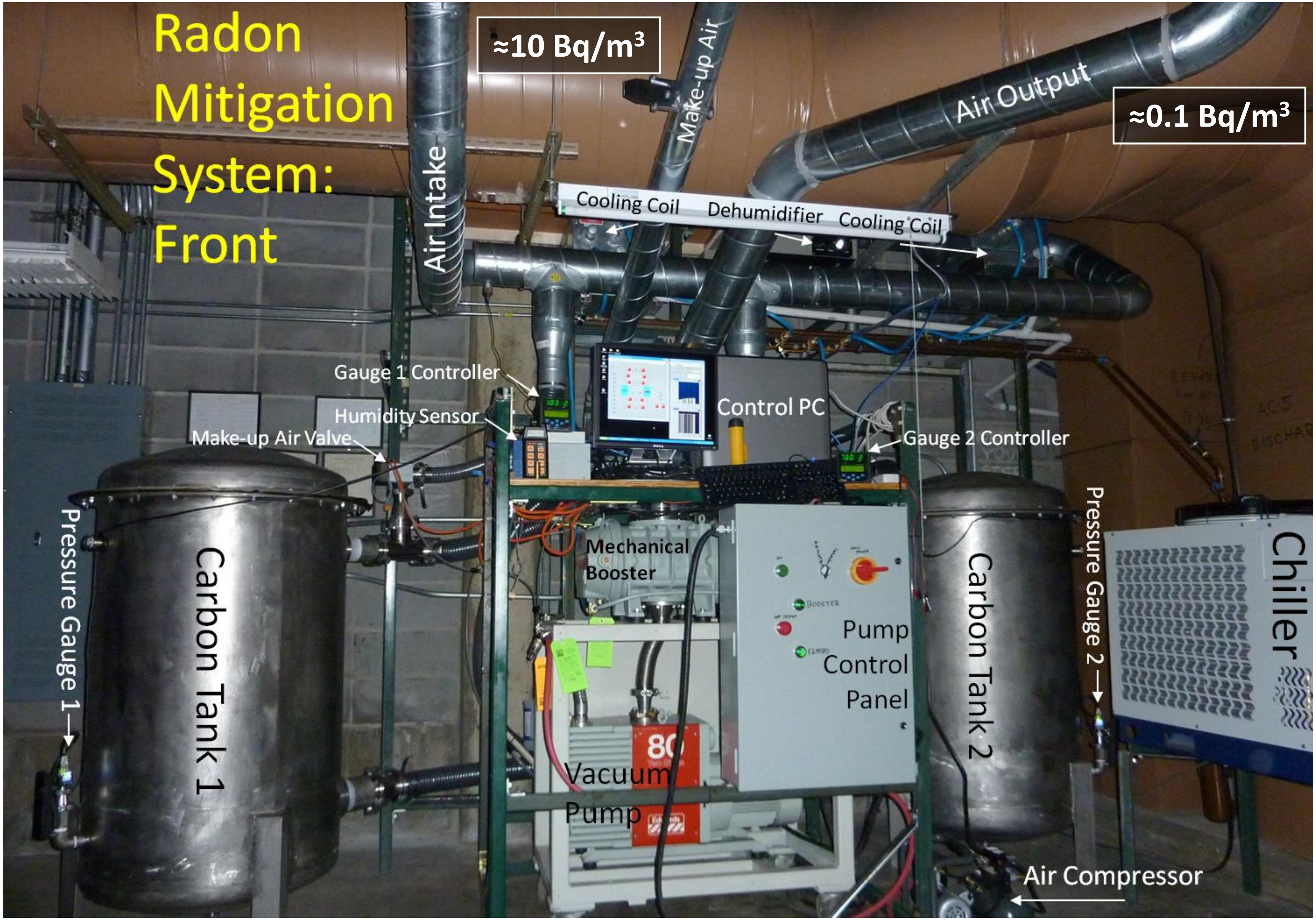
**Two Identical Stainless-steel Vacuum Vessels Filled with ~150 kg each & Spring Loaded**



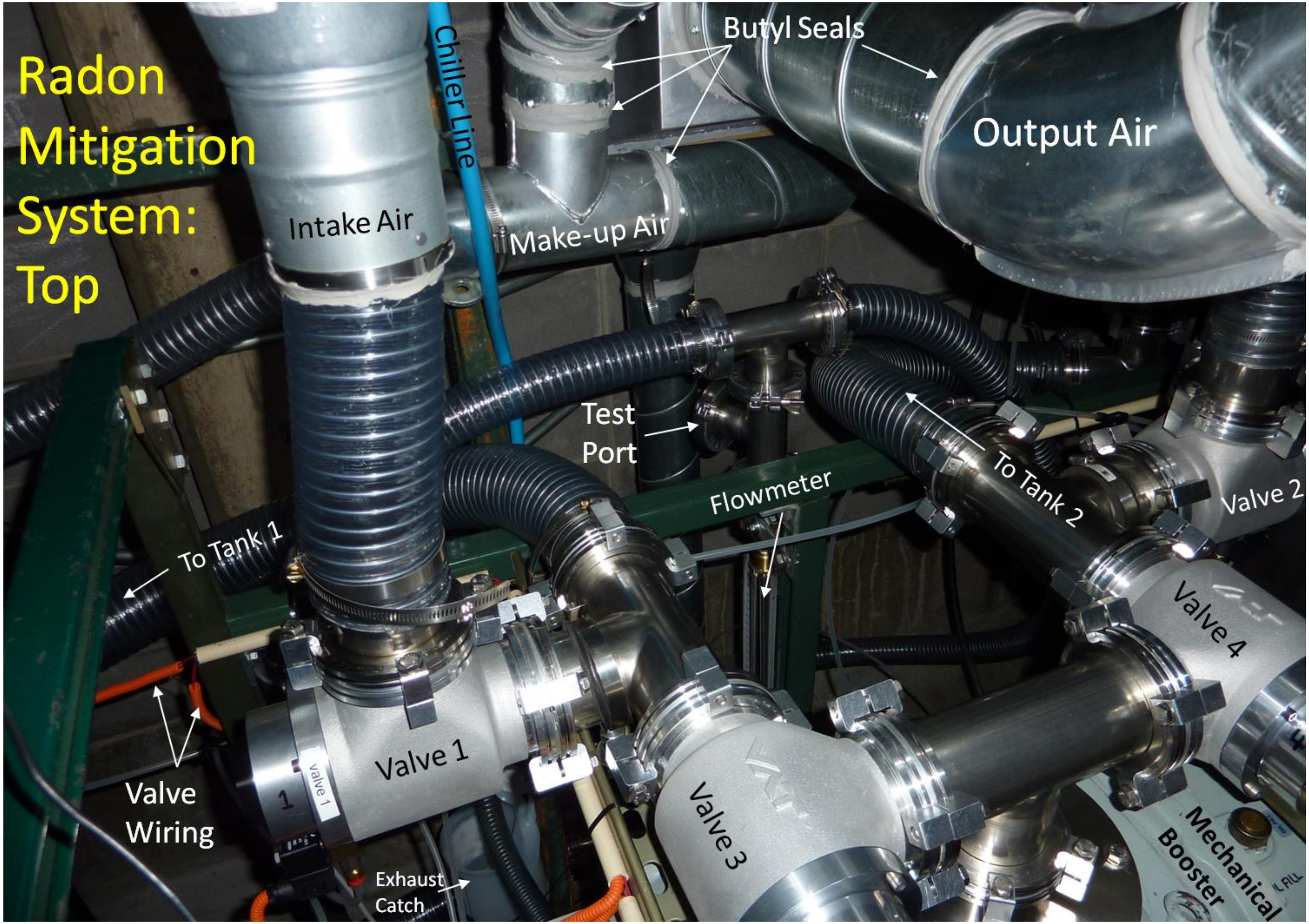


**Opened up tank after first month commissioning, found carbon still in good shape & well packed.**

# The VSA Radon Filter



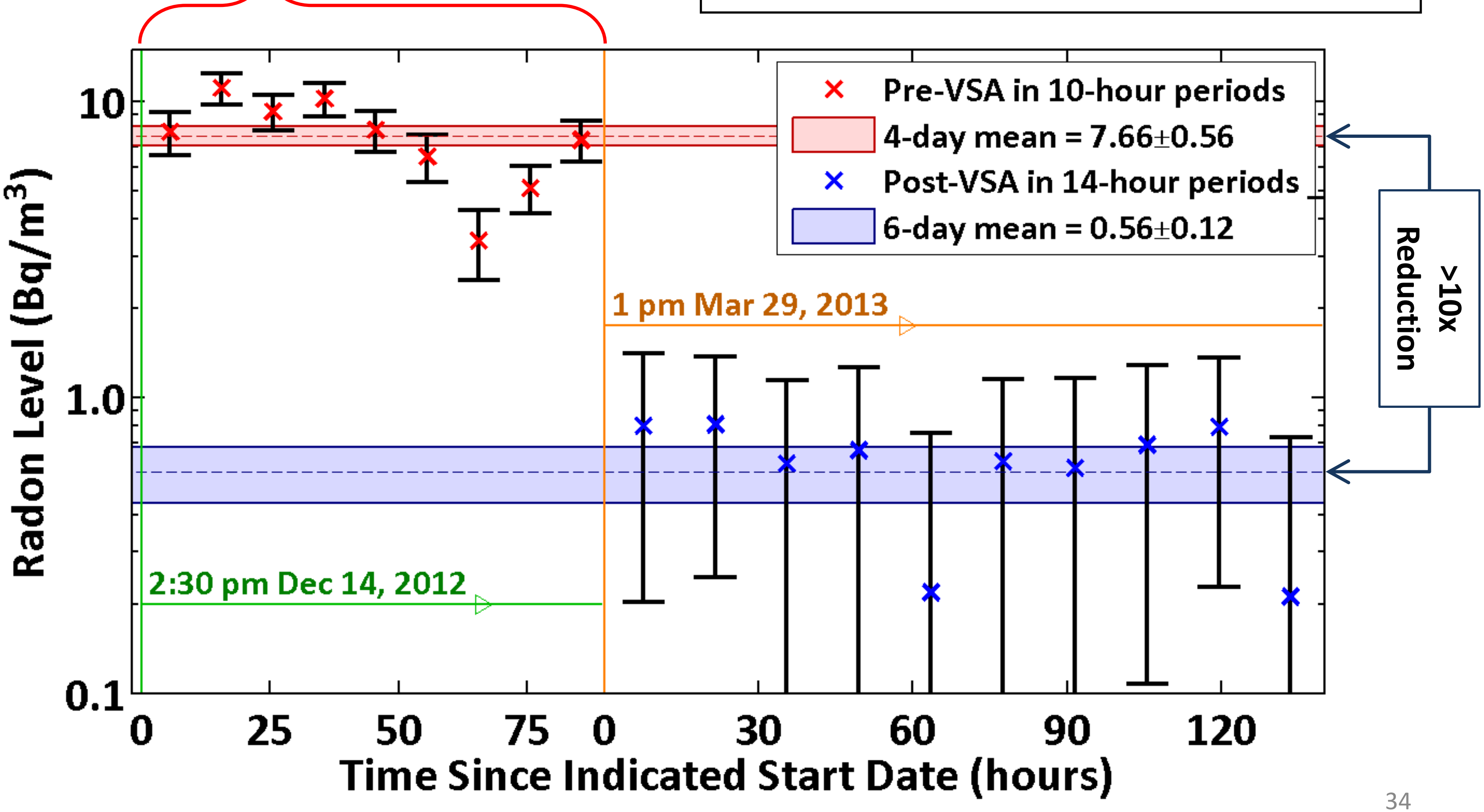
# The VSA Radon Filter



# Initial Performance at Filter Output

Unfiltered, but conditioned air from building HVAC, first collected by vent at roof level

Re-binned RAD7 measurements, derived from $^{214}$Po & $^{218}$Po alphas & originally taken in 1-hour intervals



# Optimizations in 2013-2014

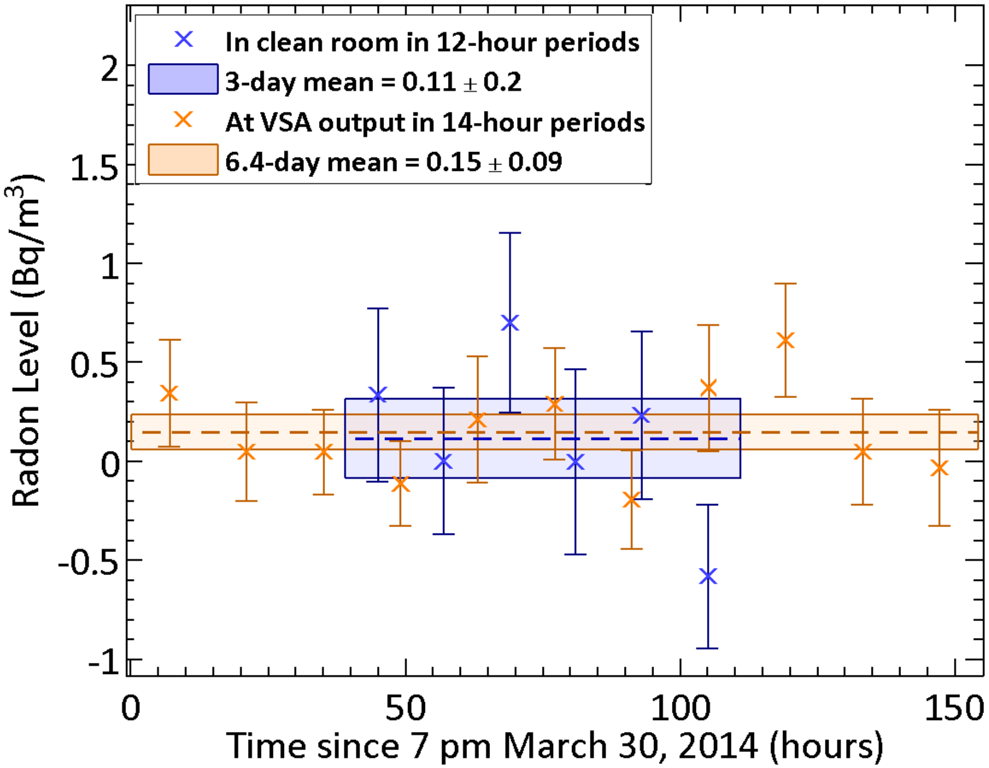
Increased robustness of system:

- Overcame difficulty of roughing pump to handle high humidity of upstate NY in summer

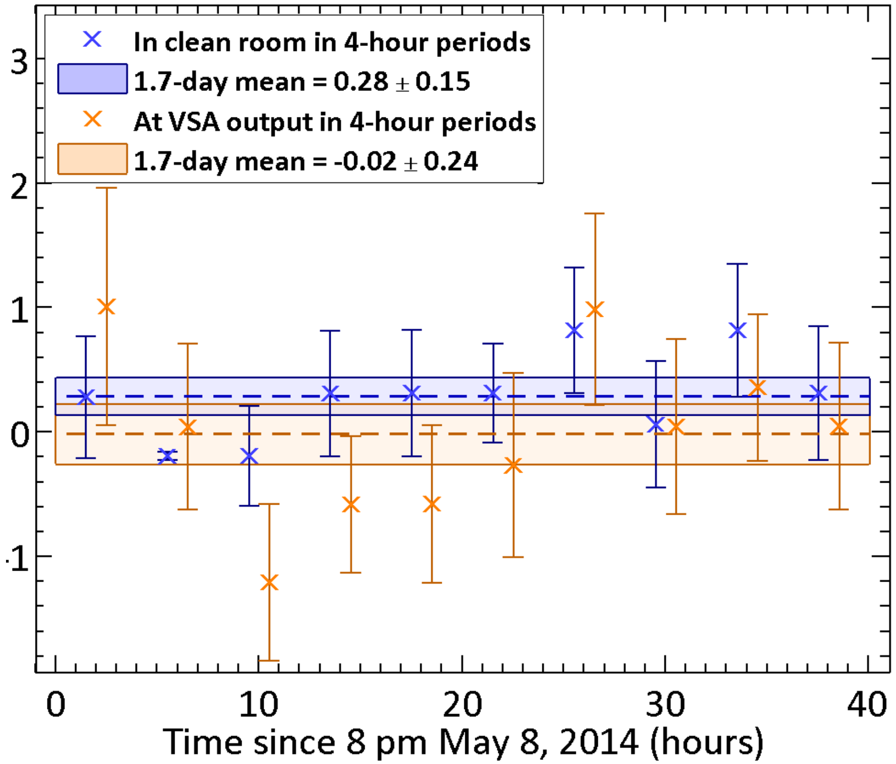
Identified & reduced leaks all along system:

- Still limited by leaks in clean-room HVAC when HVAC circulation is on

Clean-room HVAC Off → >50x reduction



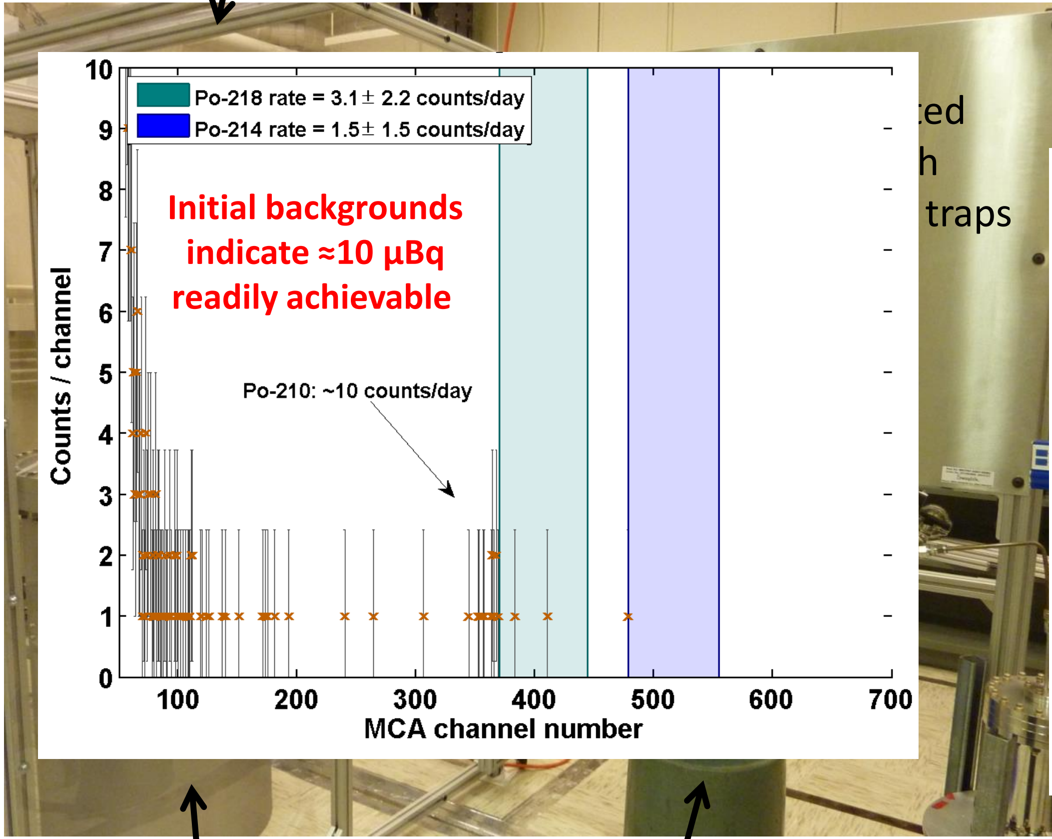
Clean-room HVAC On → >25x reduction



Further recent optimizations → 0.1 Bq/$m^3$ in clean room with HVAC circulation on!

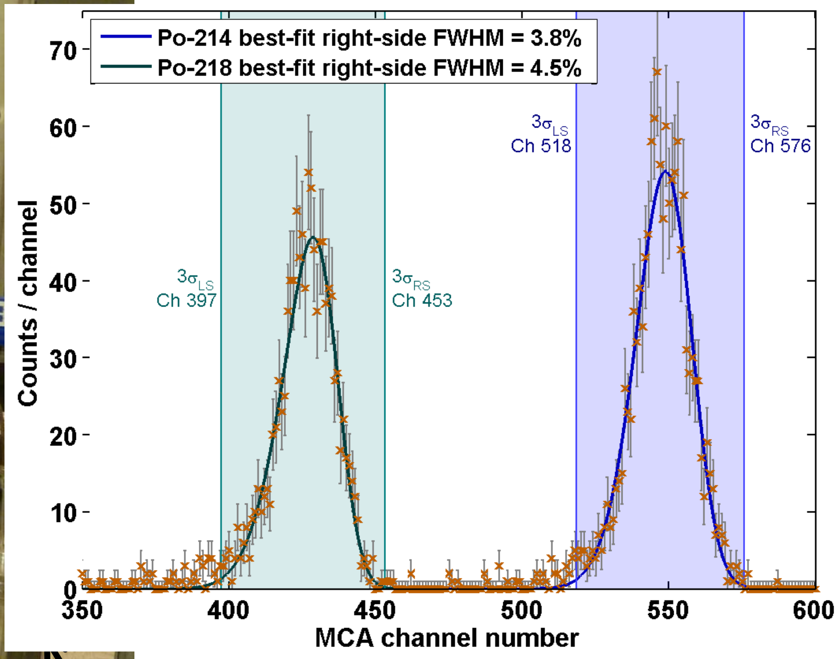
# Radon Emanation System

HEPA-filtered acrylic enclosure … class ≈100



Currently commissioning

→ Demonstrated sensitivity to Po peaks



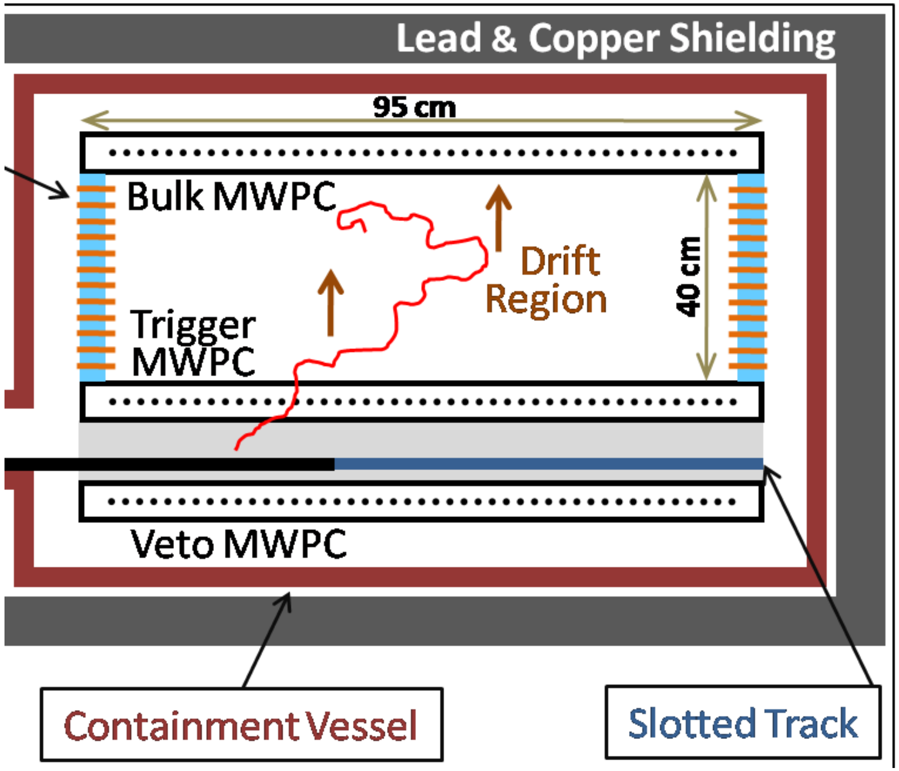
Electropolished chamber for emanating radon from samples

Small liquid-nitrogen dewar for freezing radon onto brass wool

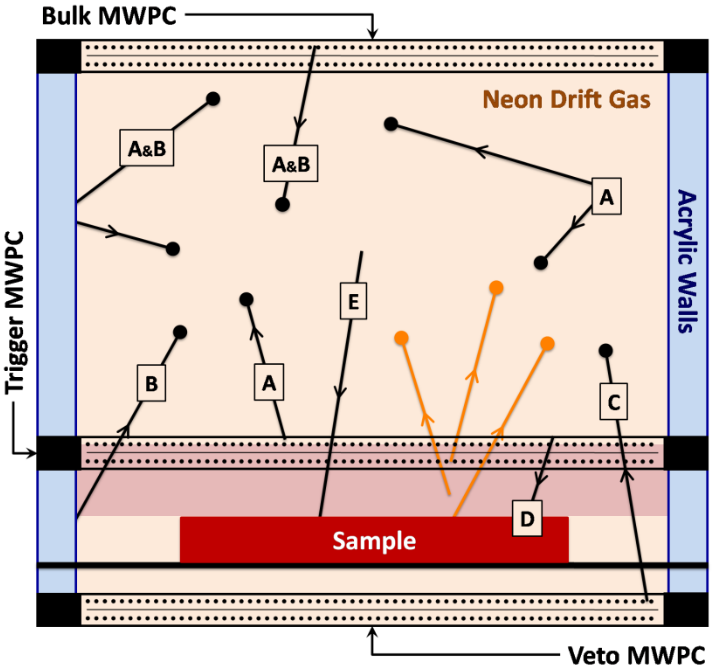
Electrostatic detector: Ortec Si alpha detector held at large negative voltage

# The BetaCage Concept

- Goal is for 100x more sensitive surface β screening
- Radiopure time projection chamber
- Wires provide minimum surface area for emissions
- Crossed grids → ≈mm *xy* position information



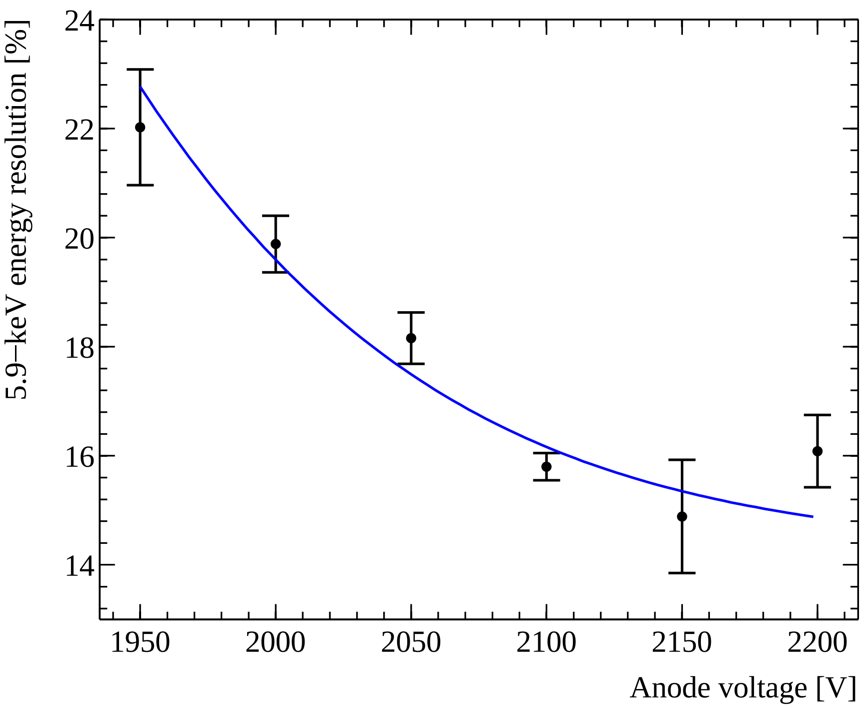
- Can screen for $^{210}$Pb β's promptly, without waiting for $^{210}$Po grow-in
- Sensitivity goals are: (Bunker LRT2013)
  - → 0.1 β /keV/m$^2$/day
  - → 0.1 α/m$^2$/day
- Smaller-sized prototype should have essentially zero background for α's



# The BetaCage Prototype

- 2 40x40-cm$^2$ MWPCs around 20-cm field-cage
  → Trigger MWPC & imaging “bulk” MWPC

- Characterized with $^{55}$Fe X-rays
  → Achieved intrinsic resolution of ≈14% *vs* ideal 12-13% from Fano & avalanche statistics
  →JINST **9** (2014) P01009
- Stability to voltage & pressure variations consistent with Diethorn formalism



# Conclusions

## SuperCDMS Soudan

CDMSlite demonstrates utility of Luke-amplified phonons for low-mass DM

→ *PRL 112 (2014) 041302 with 170 eVee threshold*

→ Better measure of backgrounds with 2nd run

577 kg-day low-threshold analysis sets 90% C.L. limit of 1.2x10$^{-42}$ at 8 GeV/$c^2$

→ Rules out DM interpretation of CoGeNT excess, also for standard-halo spin-independent interpretations of CDMS II Si, DAMA/LIBRA & CRESST

→ Rules out new parameter space for masses < 6 GeV/$c^2$; *PRL 112 (2014) 241302*

## SuperCDMS SNOLAB

Lower backgrounds, improved resolution, lower energy thresholds:

→ unique discovery potential for WIMP masses 1–10 GeV/$c^2$

CDMSlite tower with high-gain, low-noise operation:

→ extremely low thresholds for world leading light-WIMP sensitivity from 0.3–5 GeV/$c^2$

Radon exclusion critical to achieve background goals:

→ VSA technique is viable alternative to more expensive continuous-flow filter

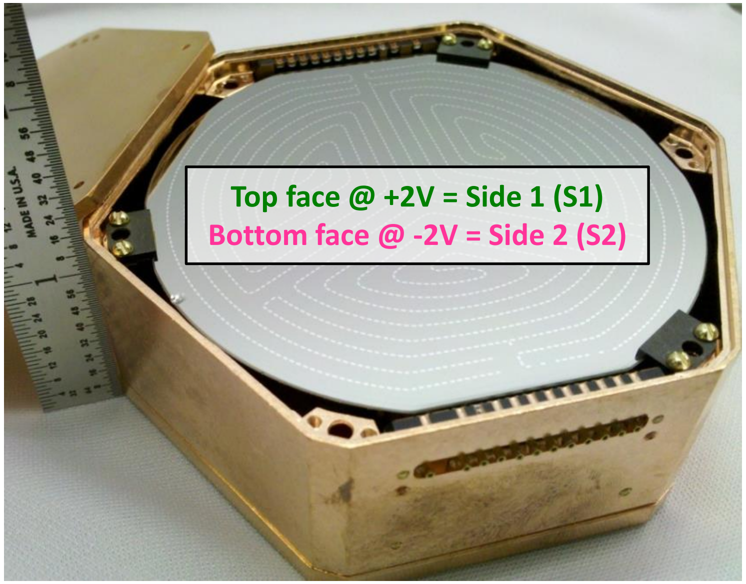
# Backup slides

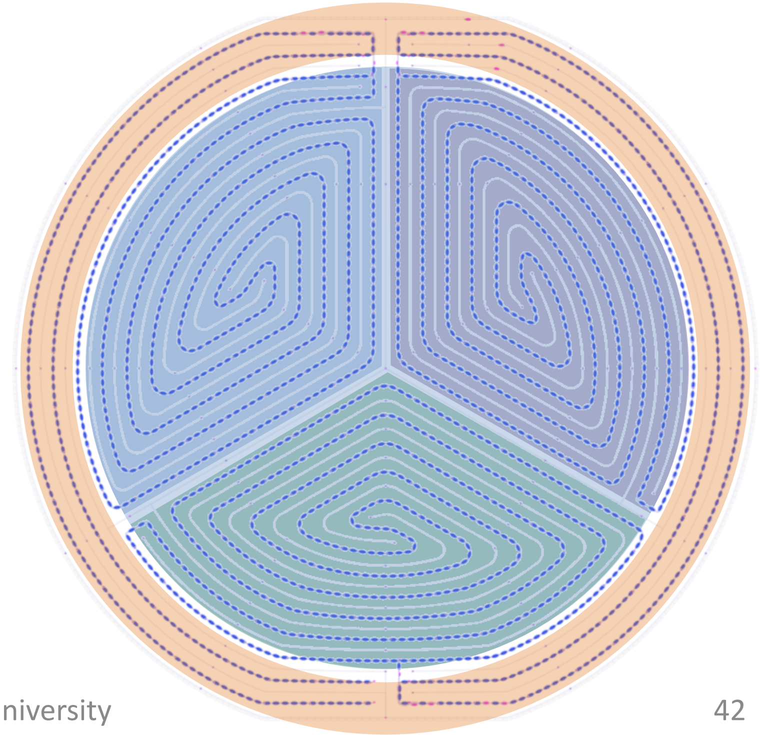
# 2) Asymmetric Dark Matter

- Kaplan et al
  - 0901.4117
  - Rooted in Technicolor
- Relic Density Determined by Asymmetry Magnitude (NOT Freeze Out)
- No Power Injection at low Z-> No distortion of CMB
- "ADM Miracle"
  - $\Omega_{DM} \sim 5\ \Omega_B \rightarrow M_{DM} \sim 5\ M_B$
  - $M_{DM}$ ~5GeV

*Courtesy M. Pyle*

# SuperCDMS iZIP





Detector upgrade to CDMS II

2.5x thicker → 600 gram Ge crystals with interleaved phonon & ionization sensors

Doubled channel count:

**Ionization Sensors (on both sides)**

Inner & Outer-guard electrodes
Radial partitioning: Outer / (Inner + Outer)
*z*-direction partitioning: (S1 – S2) / (S1 + S2)
3D fiducialization with ionization signals alone
Near-perfect rejection of surface events for >8 keVr

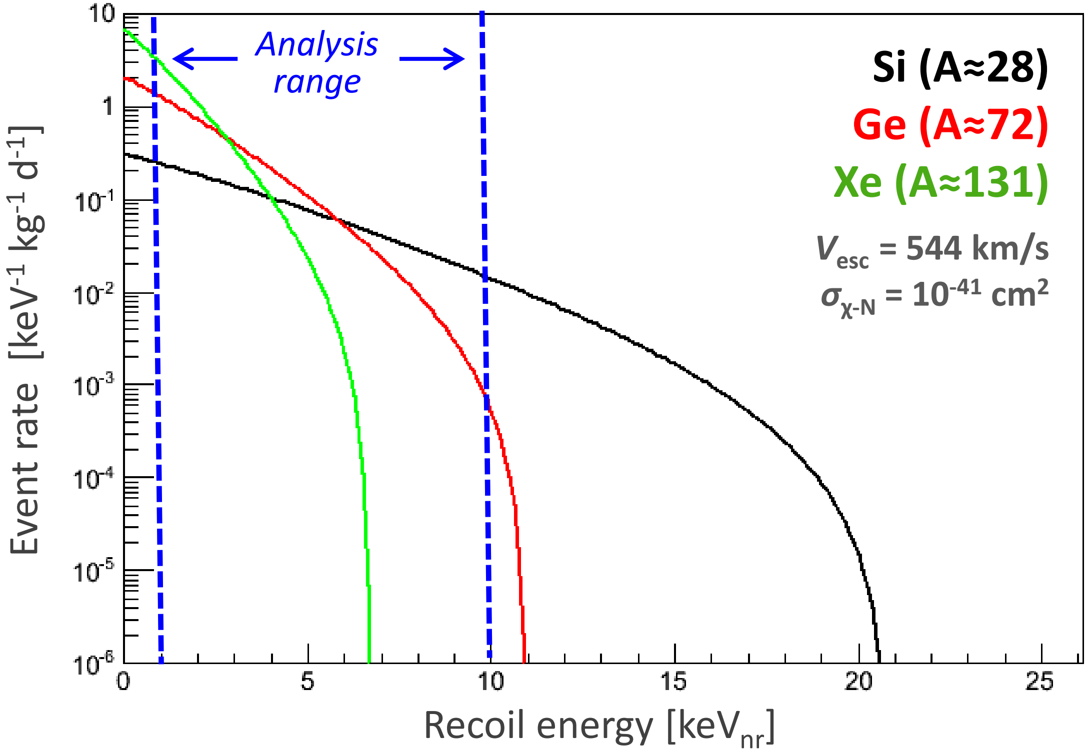
**Phonons Sensors (on both sides)**

3 Inner channels + Outer-guard channel
Radial partitioning: Outer/(Outer + Σ Inner)
z-direction partitioning: (S1 – S2)/(S1 + S2)
Better signal to noise for lowest-energy triggers
→ Extend 3D fiducialization to low energy!

# Searching for low-mass dark matter

Experiments with lighter targets and lower thresholds have the advantage when looking for dark-matter (DM) particles with mass < 10 GeV/$c^2$

Expected recoil spectra for 7 GeV/$c^2$ DM particle



**Our strategy**

Ge is a relatively heavy target, so go as low in threshold as possible

- CDMSlite search → < 1 keV$_{nr}$
- LT analysis → ≈1.6 keV$_{nr}$

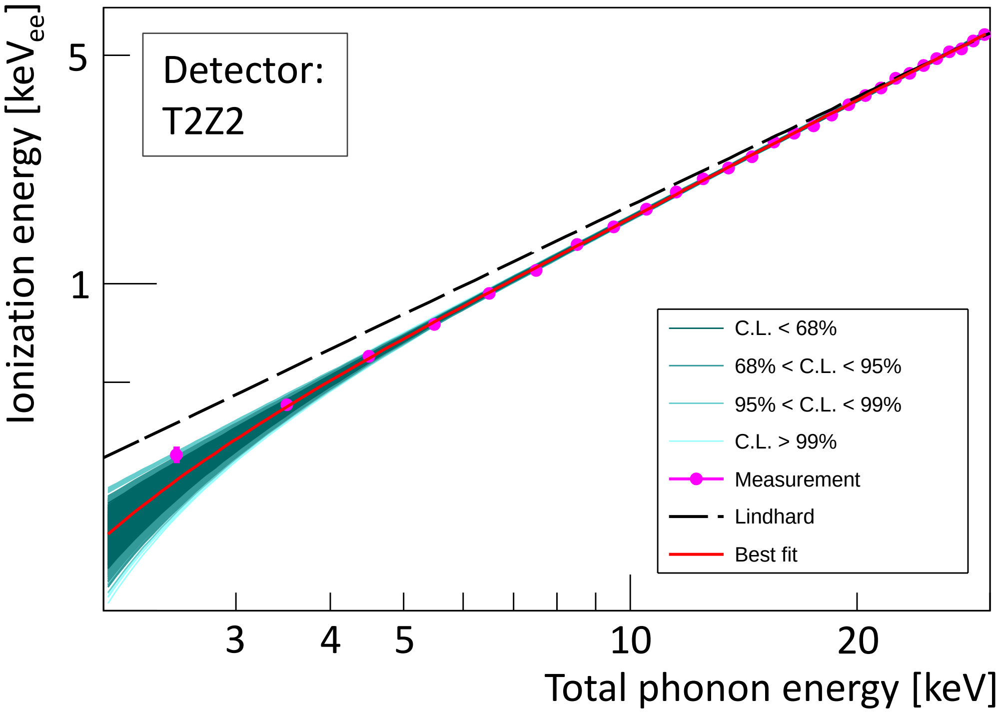
Backgrounds more difficult to reject below 10 keV$_{nr}$

- CDMSlite → extra-low threshold
- LT analysis → use improved iZIP fiducialization capability to reject as much background as possible

We expect background events in the signal region…
tradeoff is greater sensitivity to low masses

# LT-analysis energy scale

Ionization for nuclear recoils measured from $^{252}$Cf data



Total phonon energy =

$$E_{total} = E_{Luke} + E_{recoil}$$

$E_{total}$ is measured with phonons

NR equivalent energy =

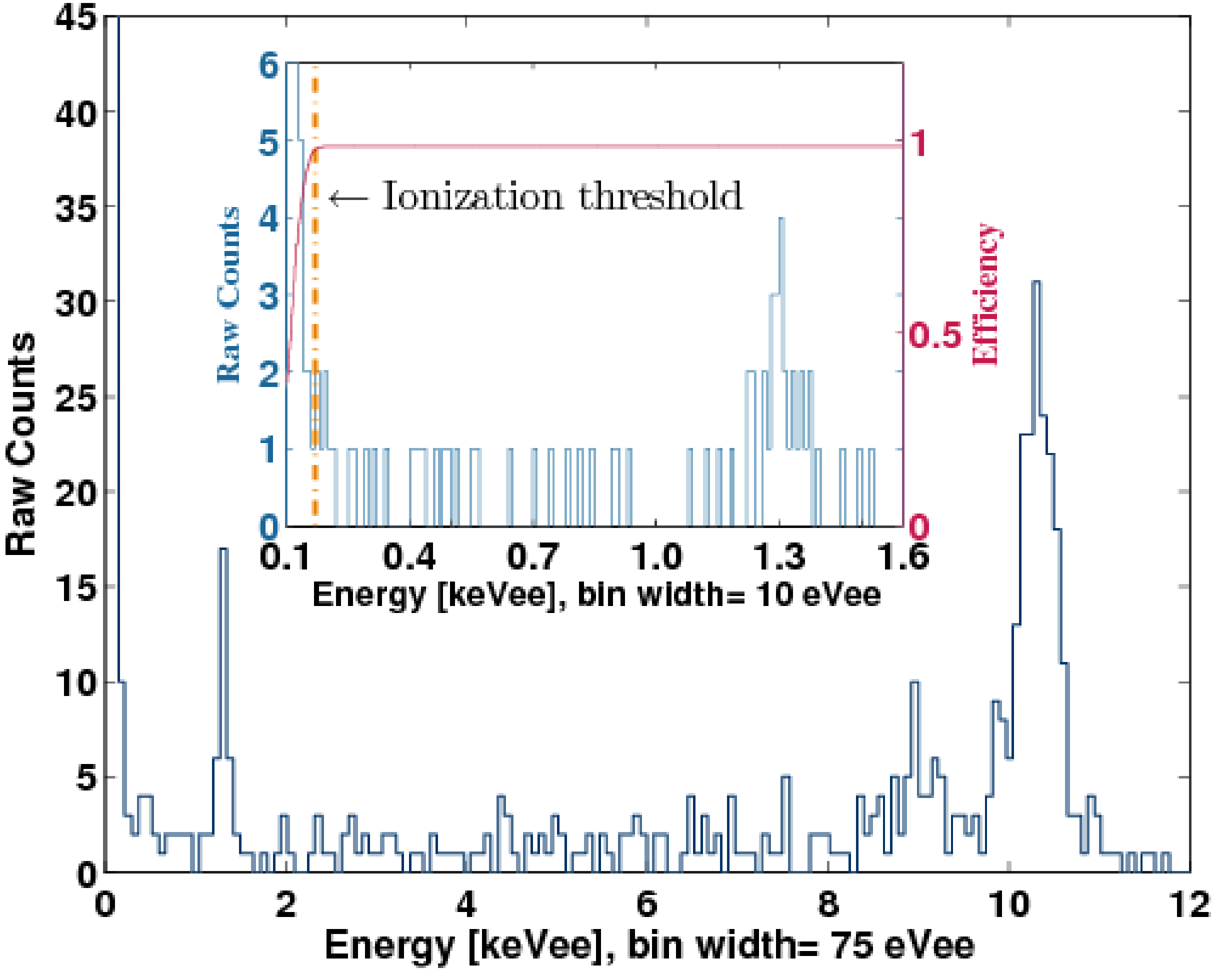
$$E_{total} – E_{Luke,NR}$$

$E_{Luke,NR}$ estimated from mean NR ionization, varies with $E_{total}$

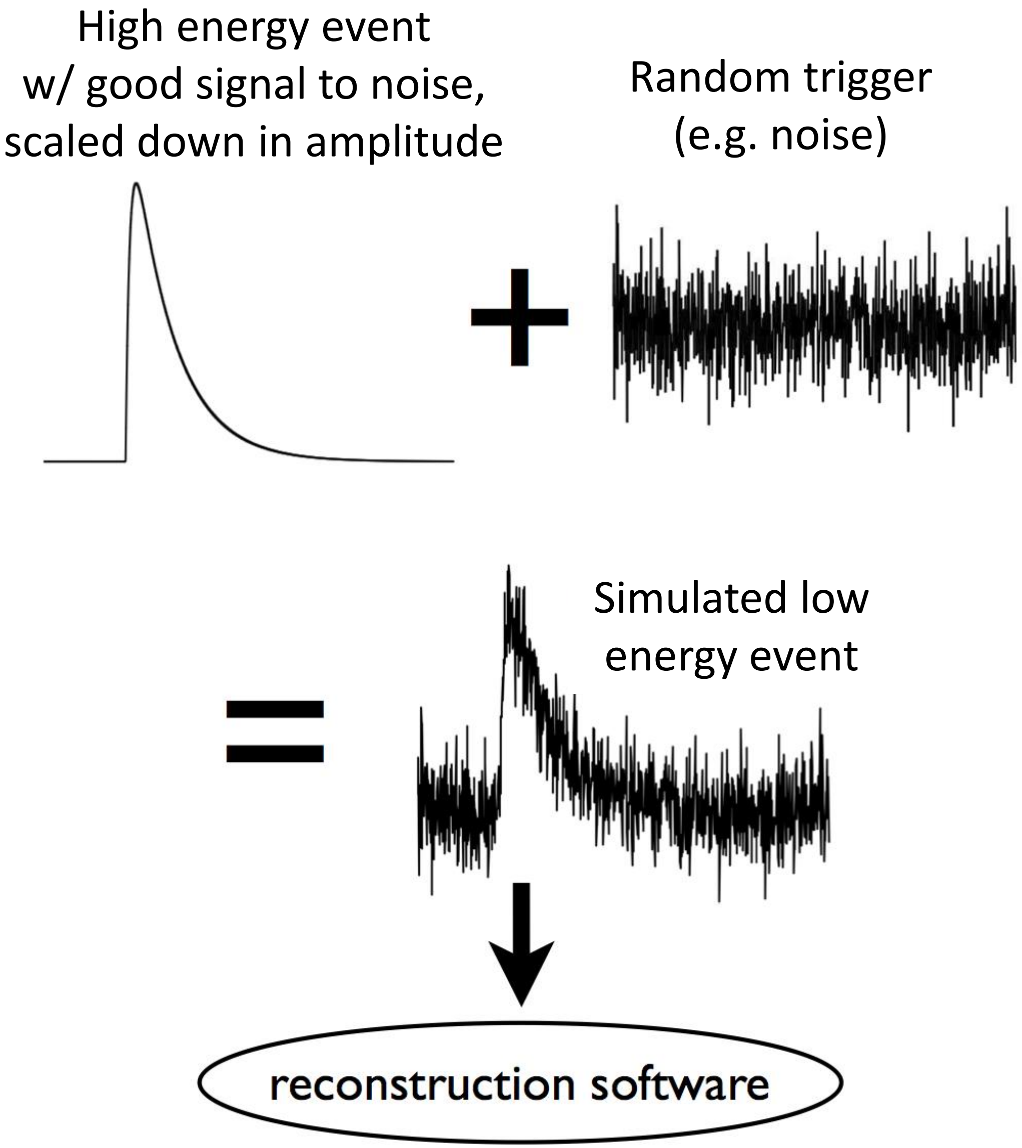
(same as CDMS II low-energy analysis)

Note: we sometimes approximate mean ionization with Lindhard theory because measured values are detector-dependent. This is labeled “Lindhard nuclear recoil energy”; difference is a few %.

# CDMSlite Run 1 raw spectrum



# LT-analysis pulse simulation



High energy event
w/ good signal to noise,
scaled down in amplitude

Random trigger
(e.g. noise)

Simulated low
energy event

reconstruction software

Backgrounds at low energy are more difficult to separate from signal region due to poor signal to noise

Study directly with a pulse simulation, using high energy events in sidebands and calibration data

weight events as a function of energy to match low energy spectrum

# LT-analysis backgrounds

## $^{210}$Pb-sourced templates:

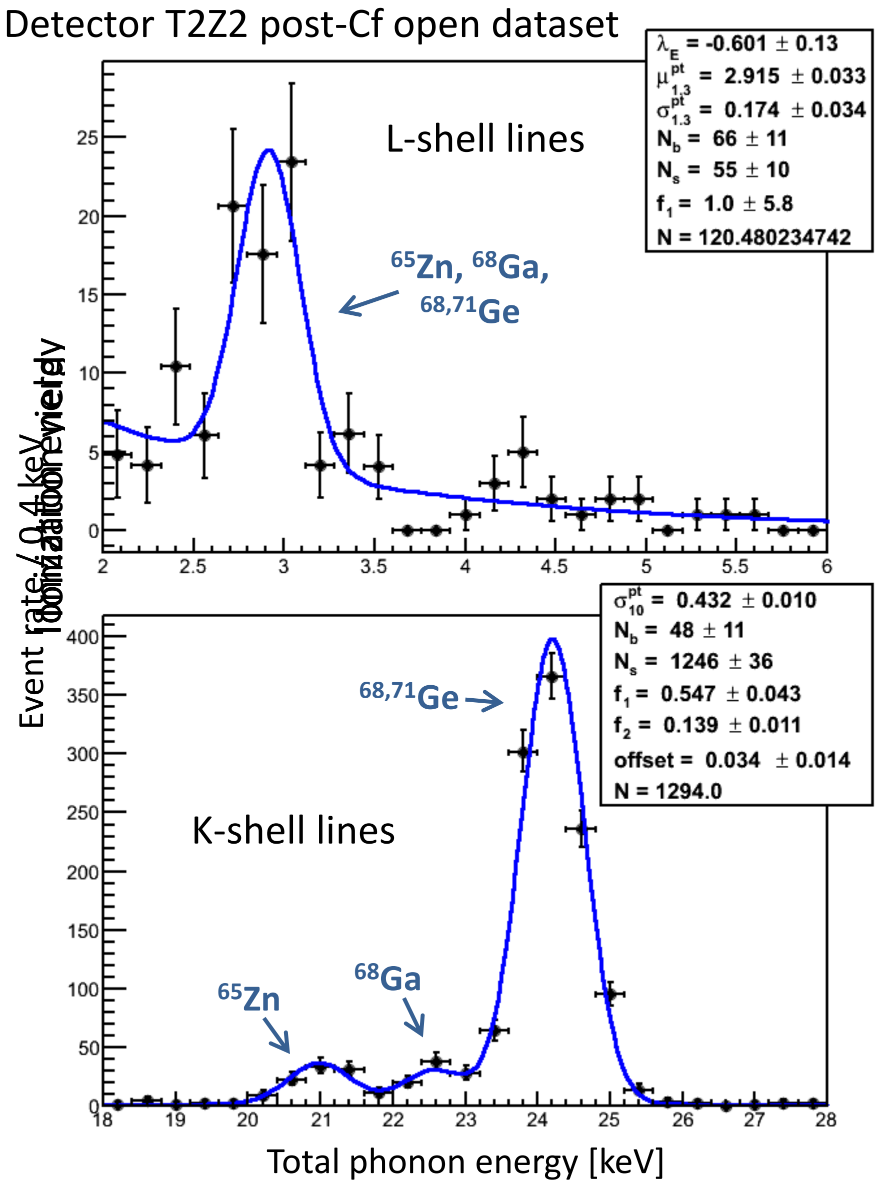
From WIMP-search sidebands
Sidewalls → high radius, **mid** & **low** yield
Faces → inner radius, asymmetric, **mid** & **low** yield
Dominant systematic uncertainty:
→ yield naively extrapolated to low energy
Normalized to $^{206}$Pb rates at higher energy
→ checked with $^{210}$Po $\alpha$ rates
→ difference assigned as systematic uncertainty

## External-gamma templates:

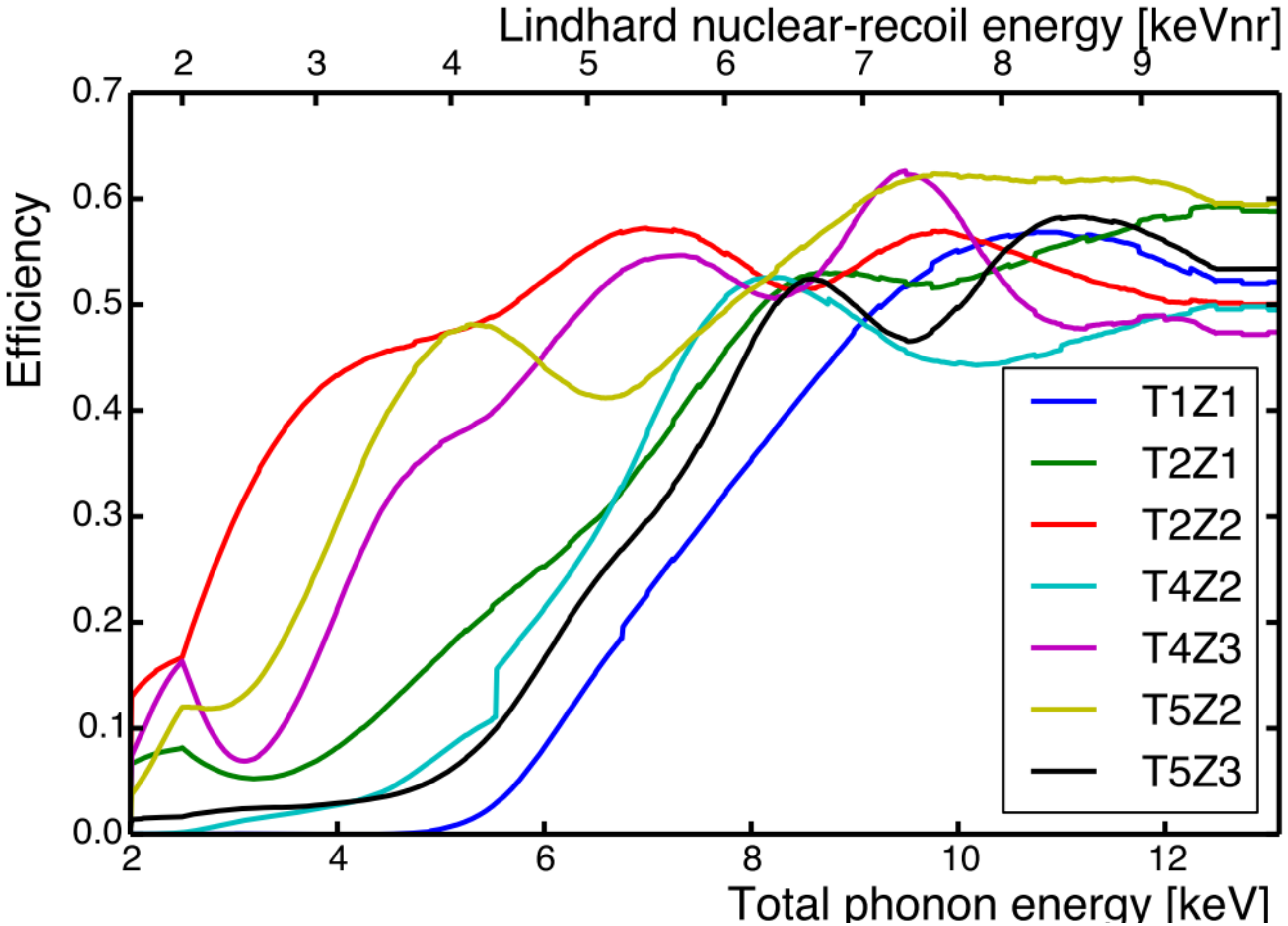
From ≈100 keV$_{ee}$ $^{133}$Ba calibration events
Randomly chosen from WIMP-search period
Normalized to WIMP-search sideband:
→ 2.6–5.1 keV$_{ee}$ bulk ER rate

## Internal activation-line templates:

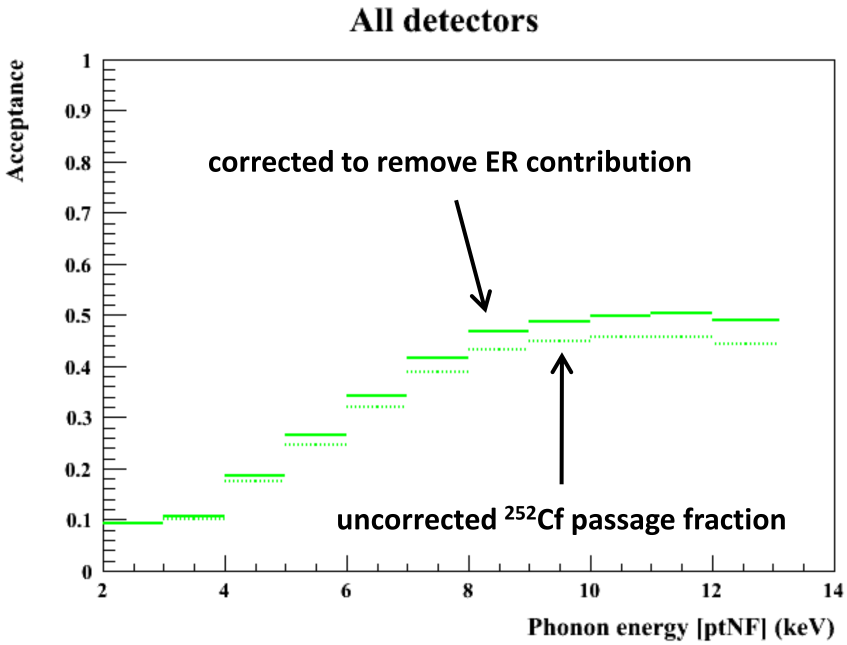
From WIMP-search sideband
K-shell e$^{-}$ captures at ≈10.4 keV$_{ee}$
→ same distribution in crystal as L-shell captures
Normalize using K-shell rate in sidebands & ratio
of L- to K-shell captures in post-Cf open dataset



# LT-analysis by-detector efficiencies

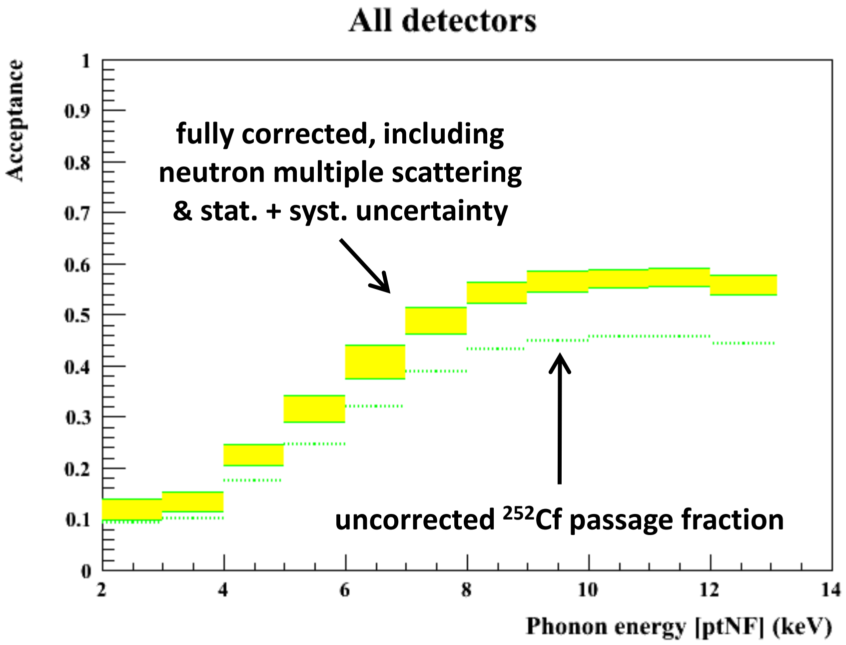


# LT-analysis fiducial-volume correction



corrected to remove ER contribution

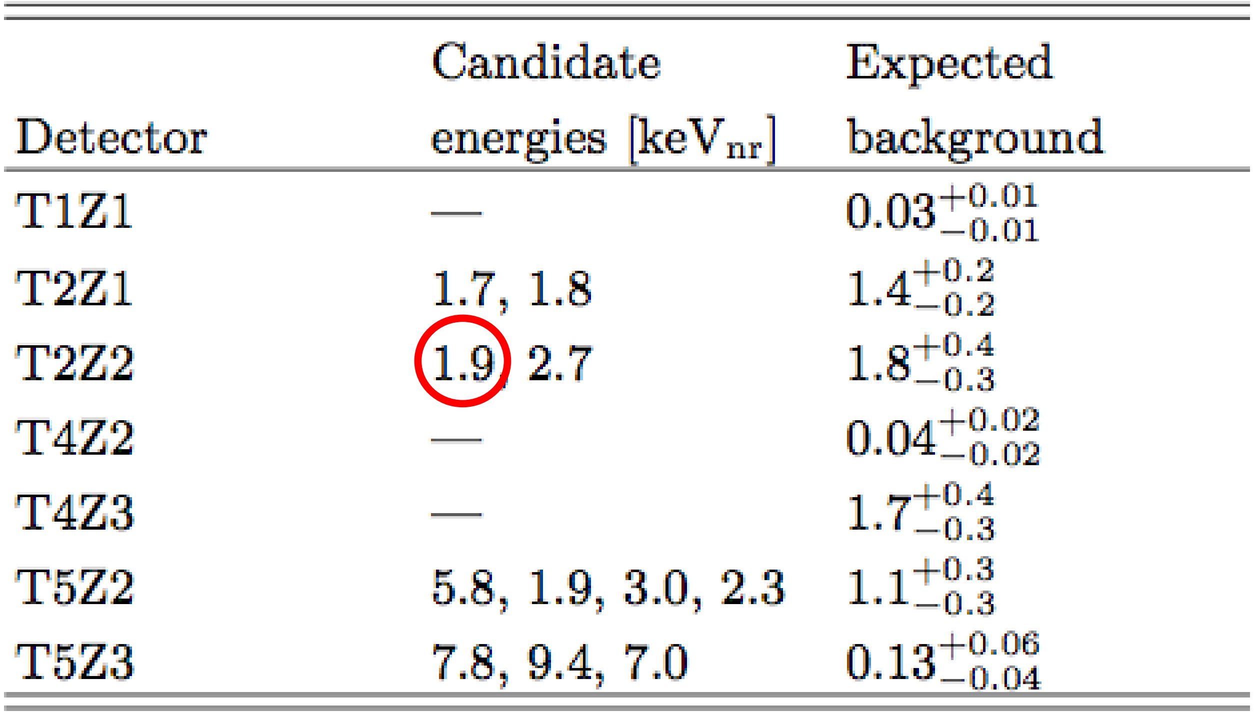
uncorrected $^{252}$Cf passage fraction



fully corrected, including neutron multiple scattering & stat. + syst. uncertainty

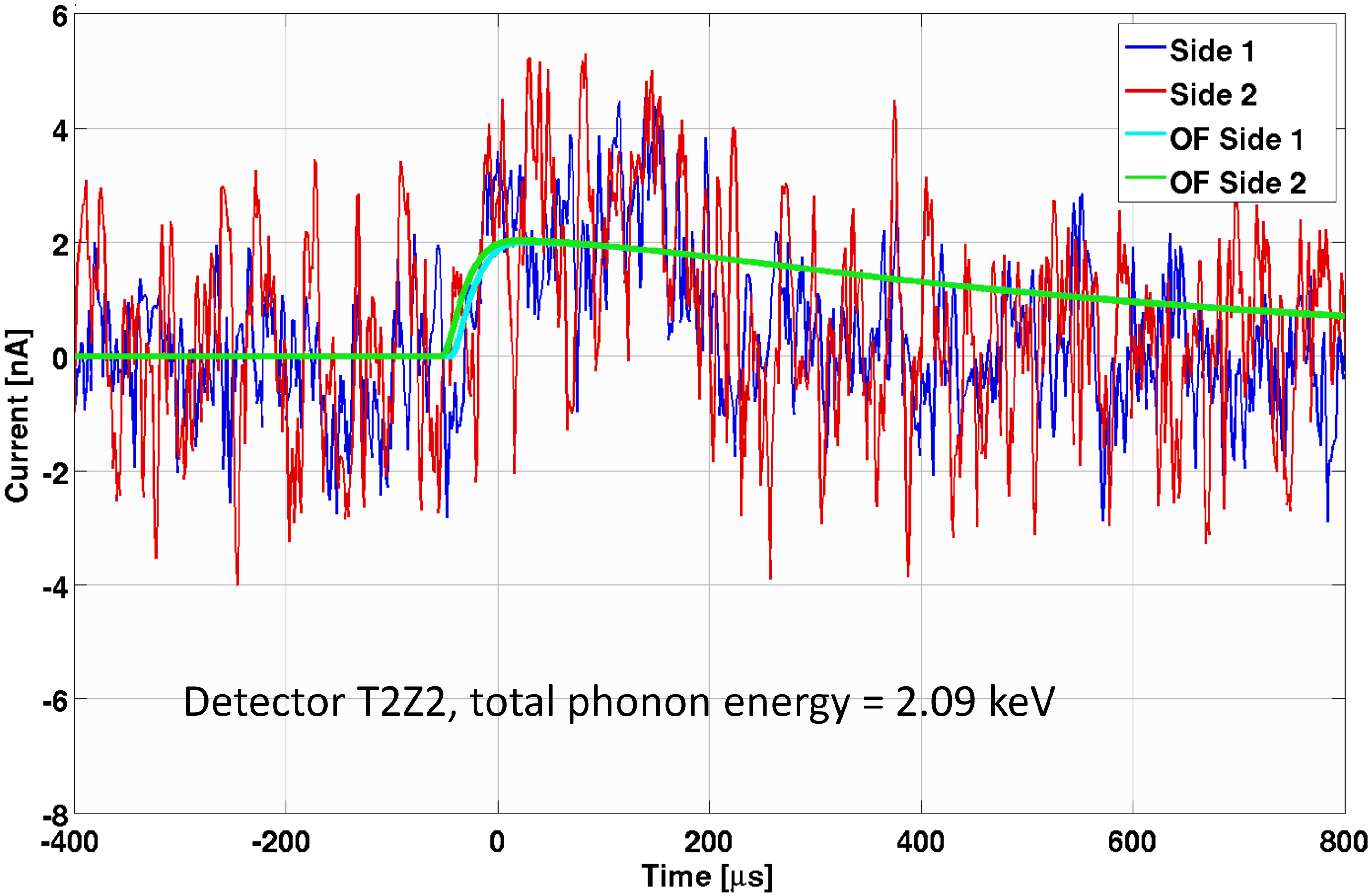
uncorrected $^{252}$Cf passage fraction

# LT-analysis candidate summary



| Detector | Candidate energies [$\mathrm{keV_{nr}}$] | Expected background |
|---|---|---|
| T1Z1 | — | $0.03^{+0.01}_{-0.01}$ |
| T2Z1 | 1.7, 1.8 | $1.4^{+0.2}_{-0.2}$ |
| T2Z2 | 1.9, 2.7 | $1.8^{+0.4}_{-0.3}$ |
| T4Z2 | — | $0.04^{+0.02}_{-0.02}$ |
| T4Z3 | — | $1.7^{+0.4}_{-0.3}$ |
| T5Z2 | 5.8, 1.9, 3.0, 2.3 | $1.1^{+0.3}_{-0.3}$ |
| T5Z3 | 7.8, 9.4, 7.0 | $0.13^{+0.06}_{-0.04}$ |

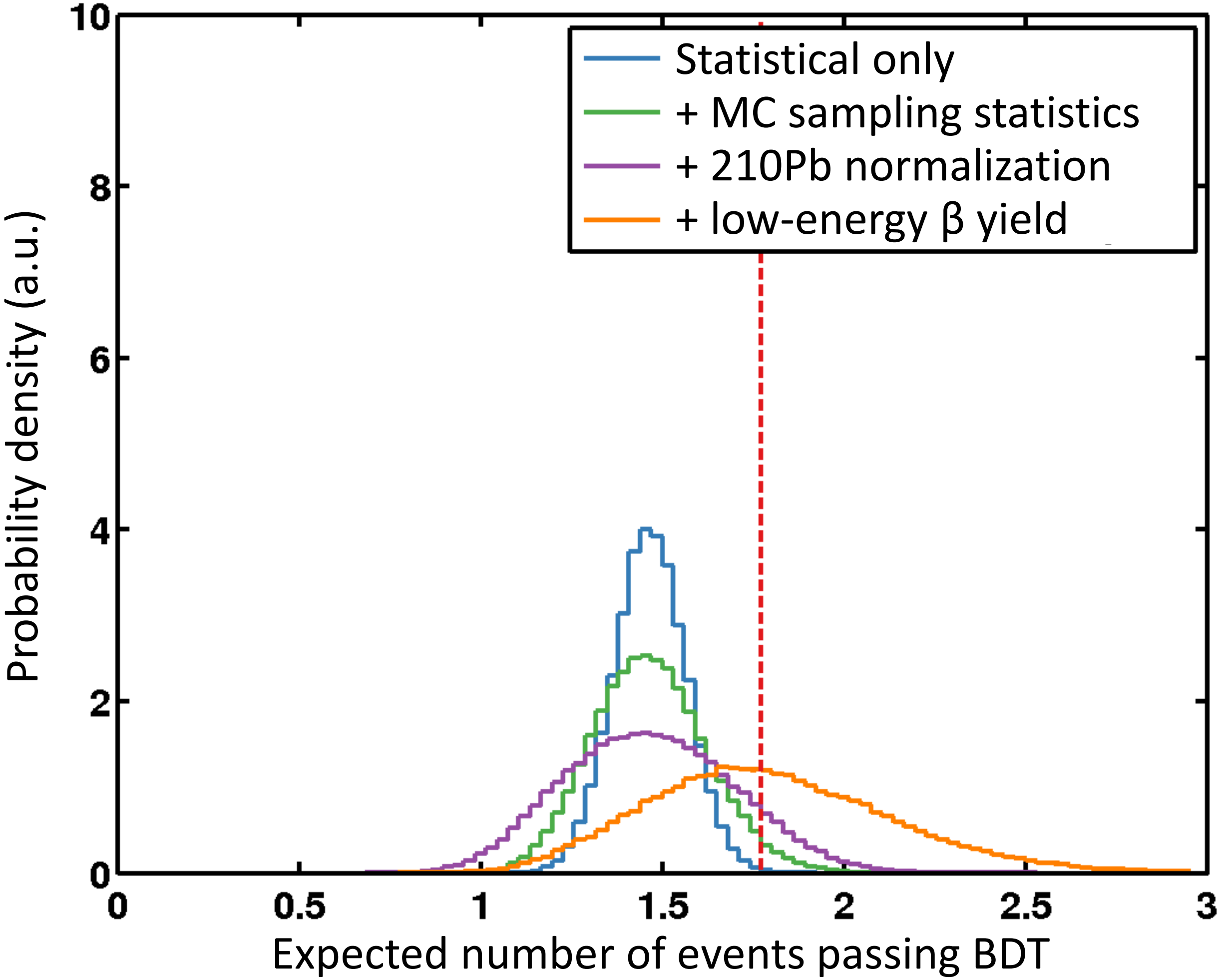
# LT-analysis lowest-energy candidate



Detector T2Z2, total phonon energy = 2.09 keV

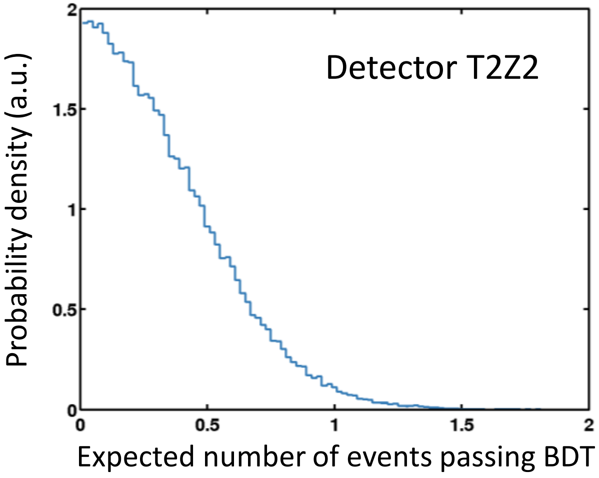
# LT-analysis background-model uncertainty

Detector T2Z2 → 1.77 +0.36 -0.31 events

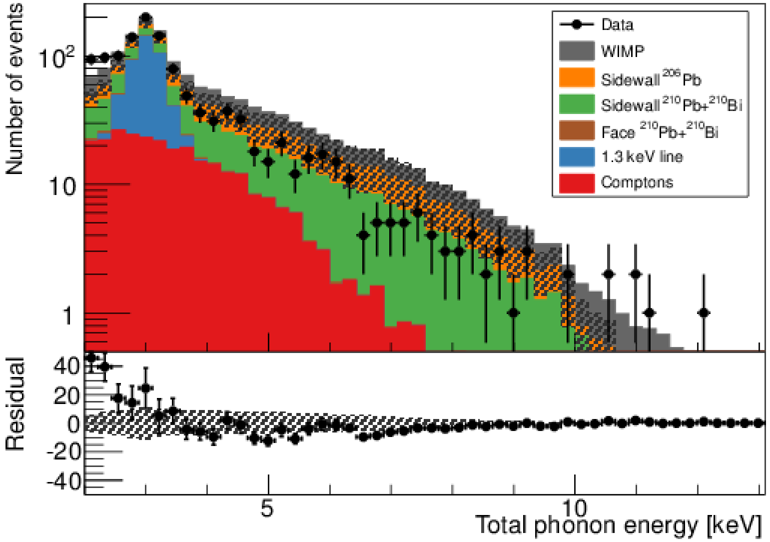


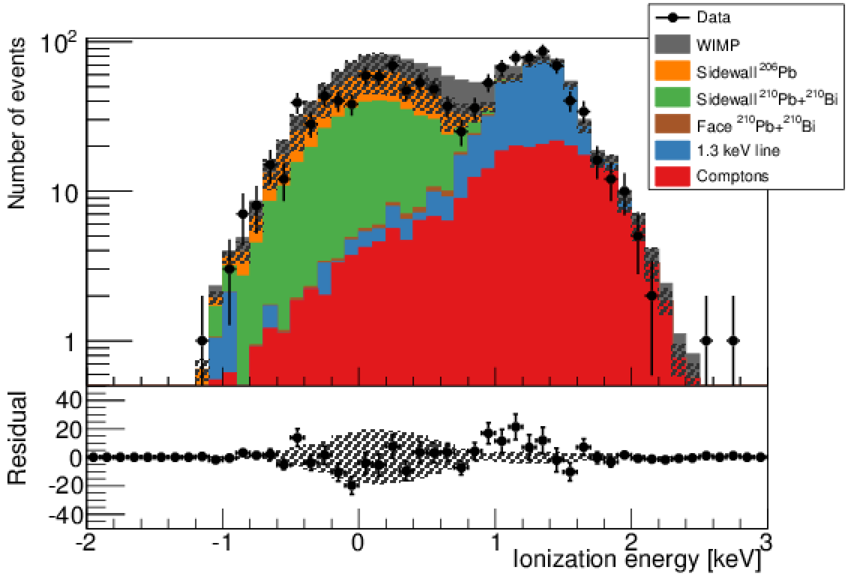
Statistical & systematic uncertainties combined via Monte Carlo simulation

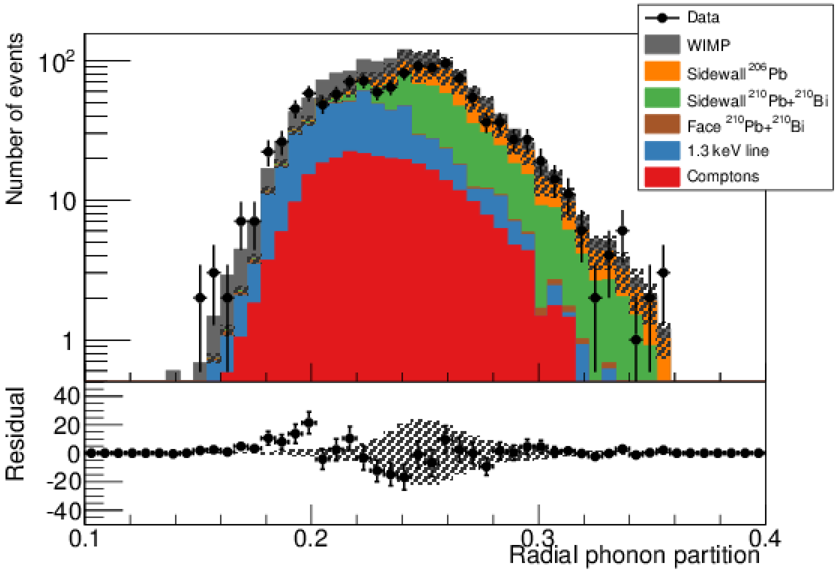
Low-energy β yield uncertainty
→ highly asymmetric

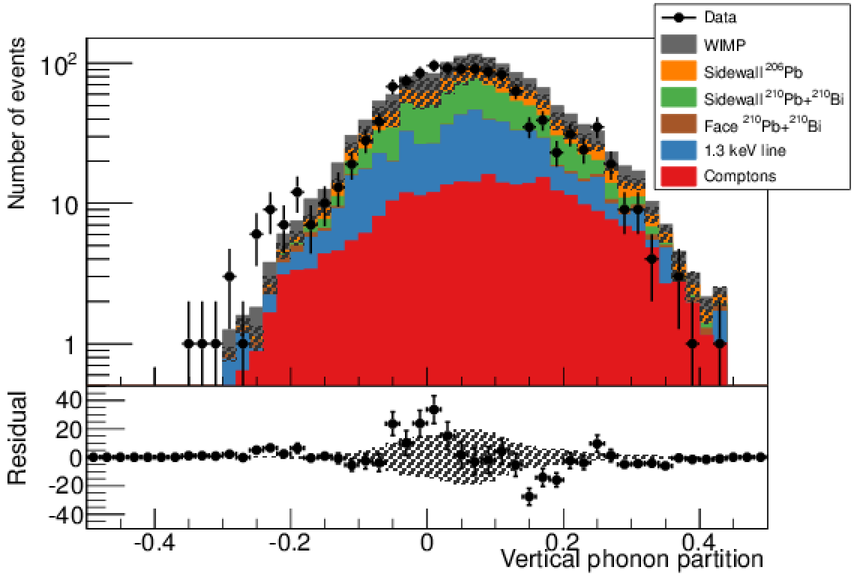


# LT-analysis BDT inputs *vs.* data

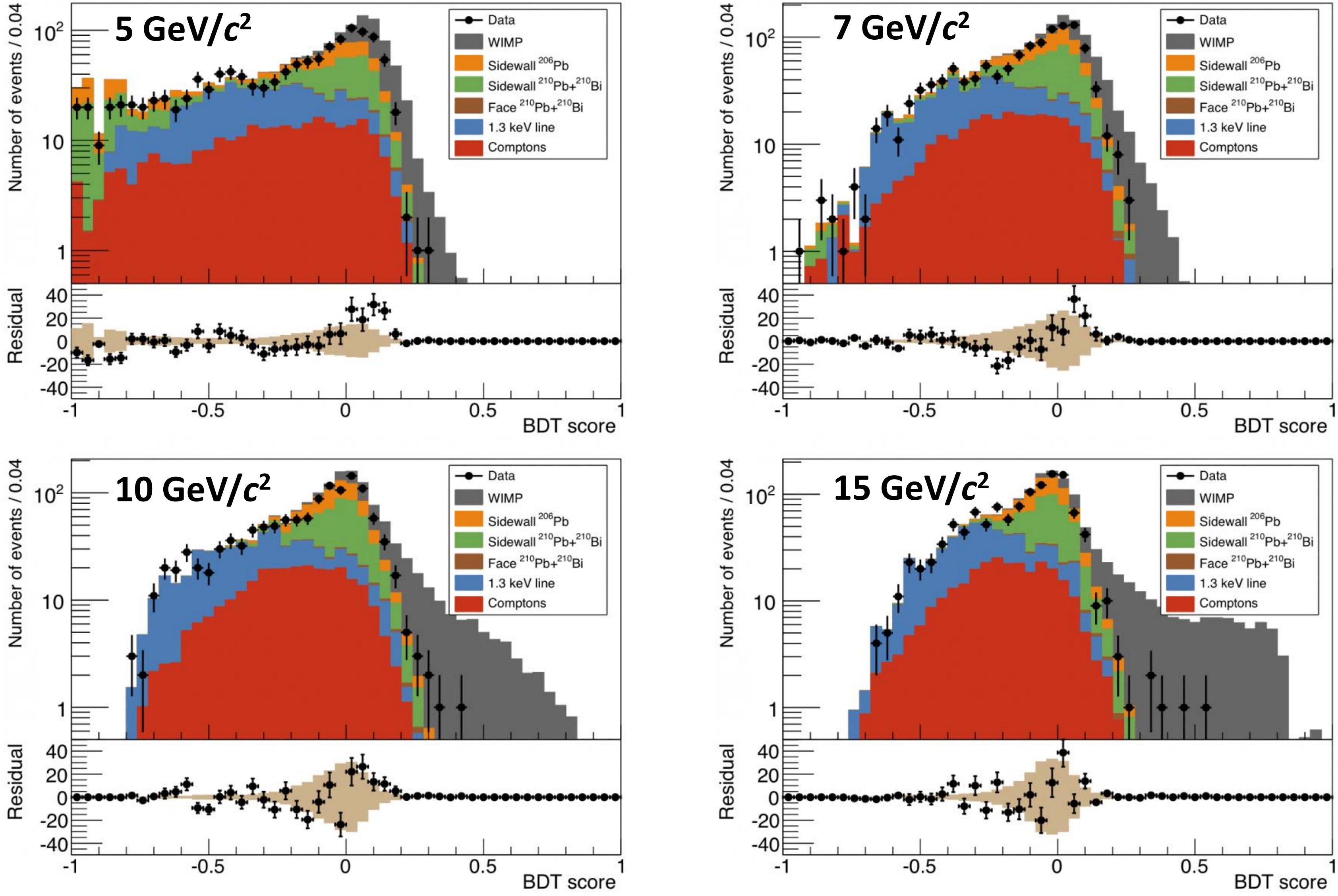




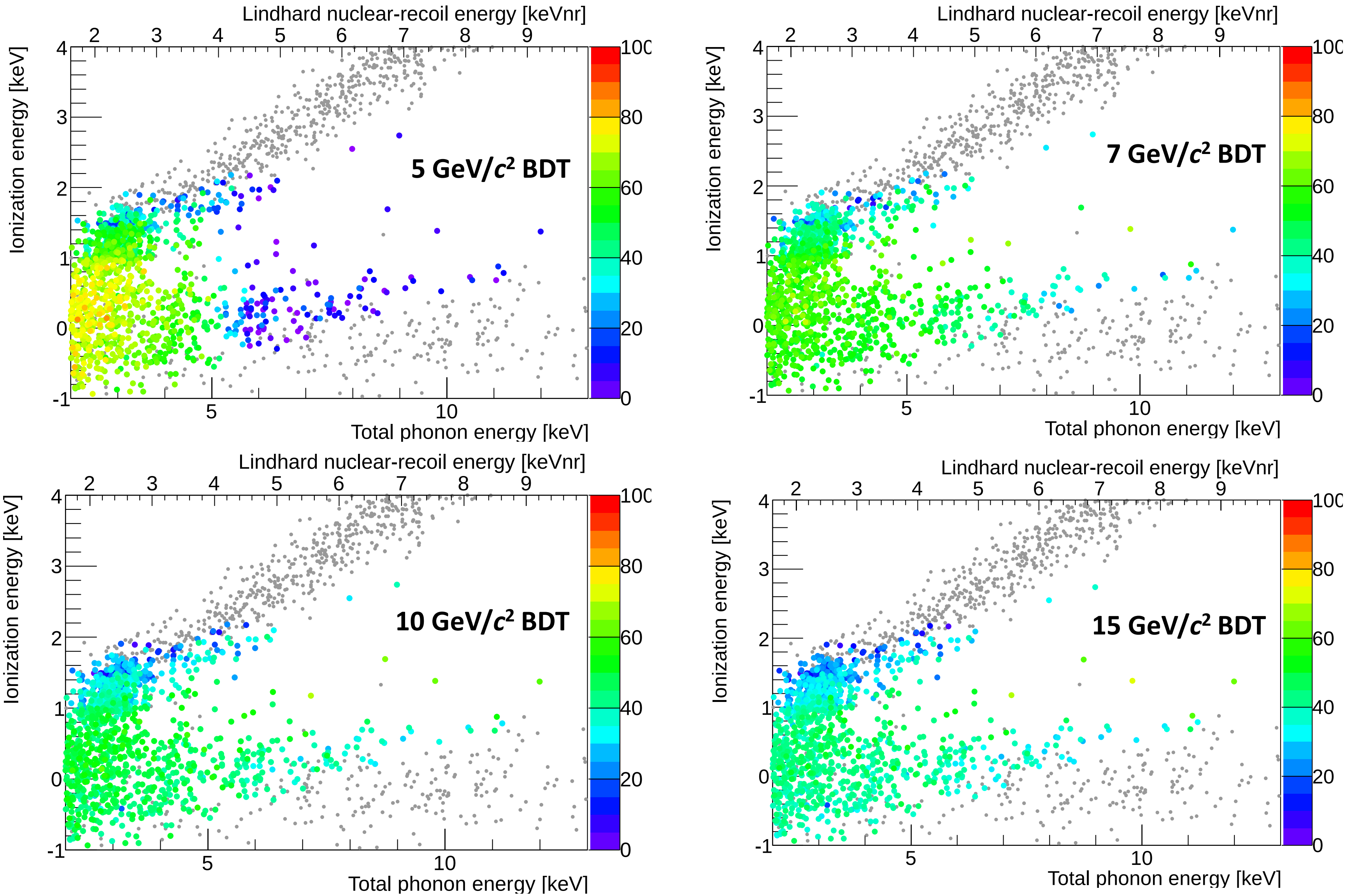




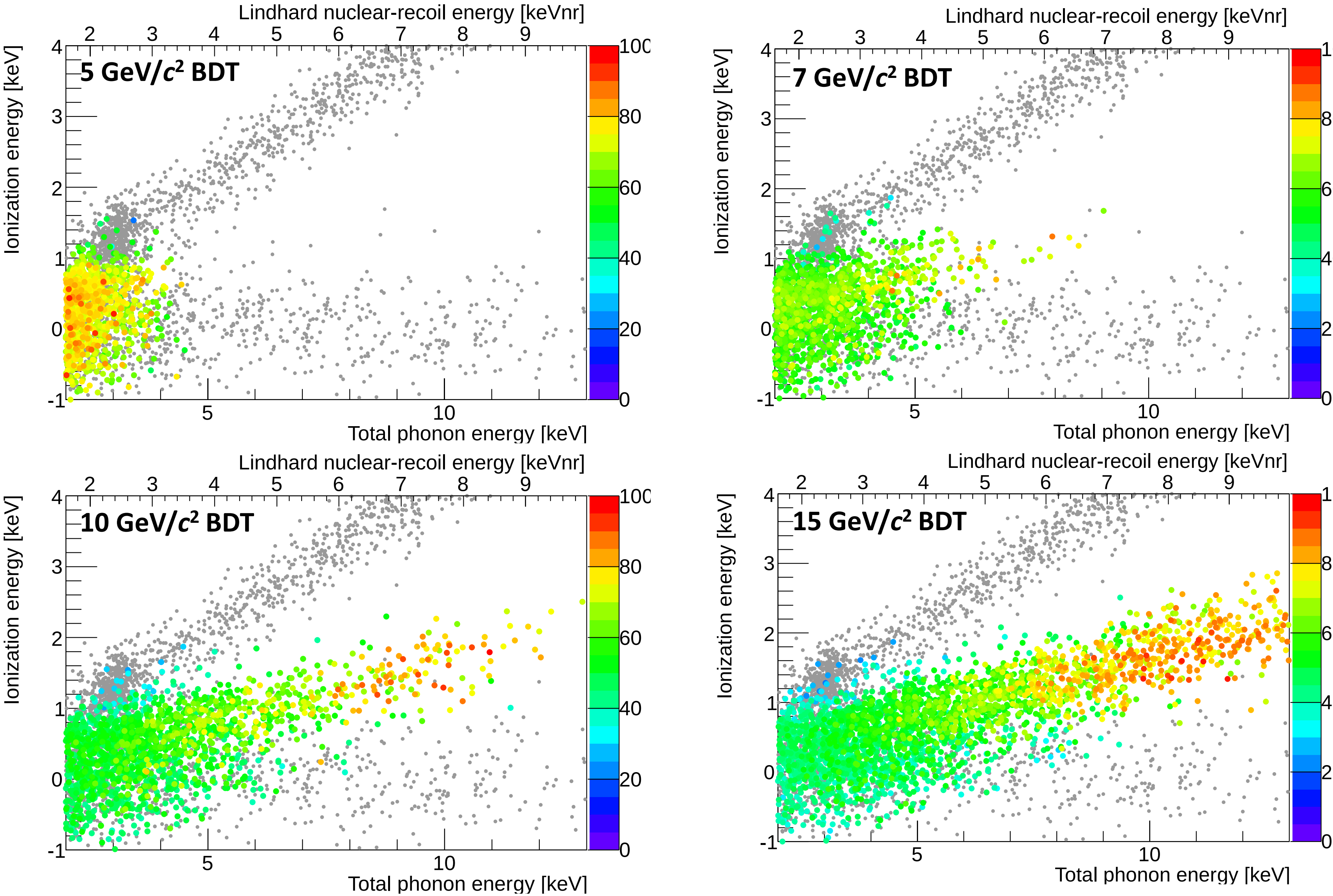
# LT-analysis BDT *vs.* WIMP mass



# LT-analysis BDT scoring of data

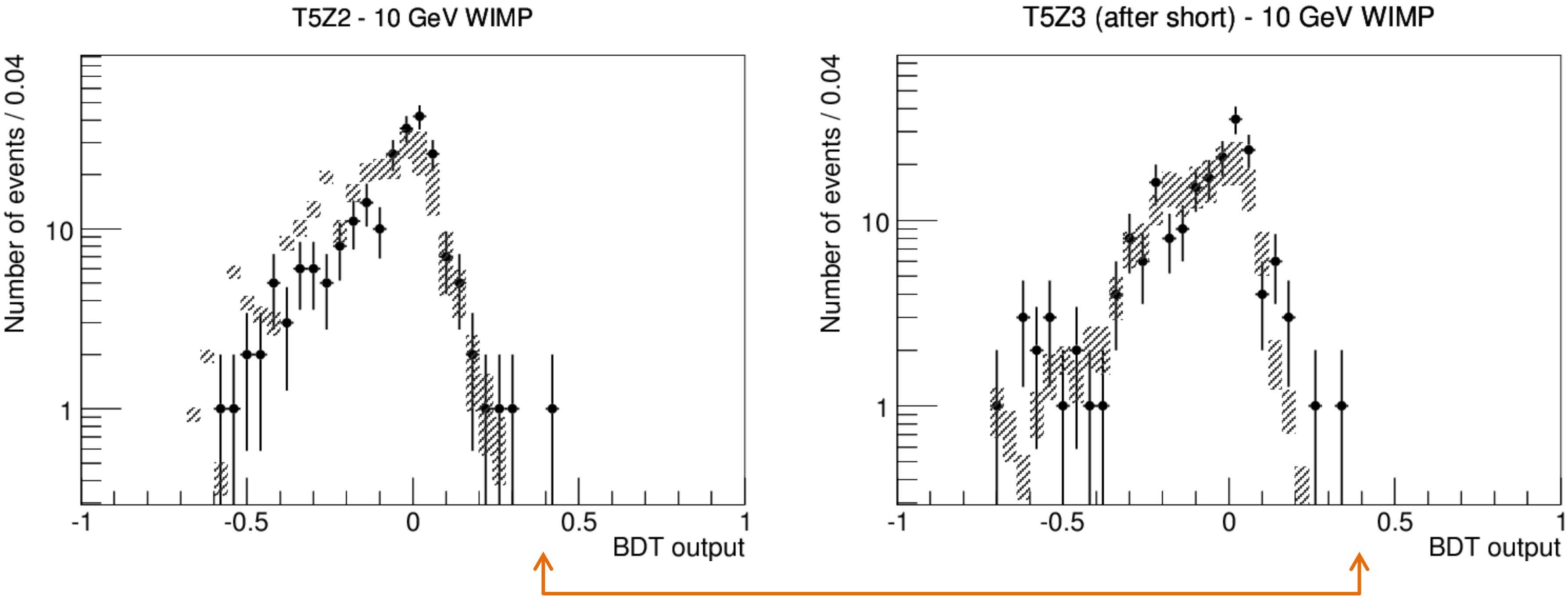


# LT-analysis BDT scoring of signal



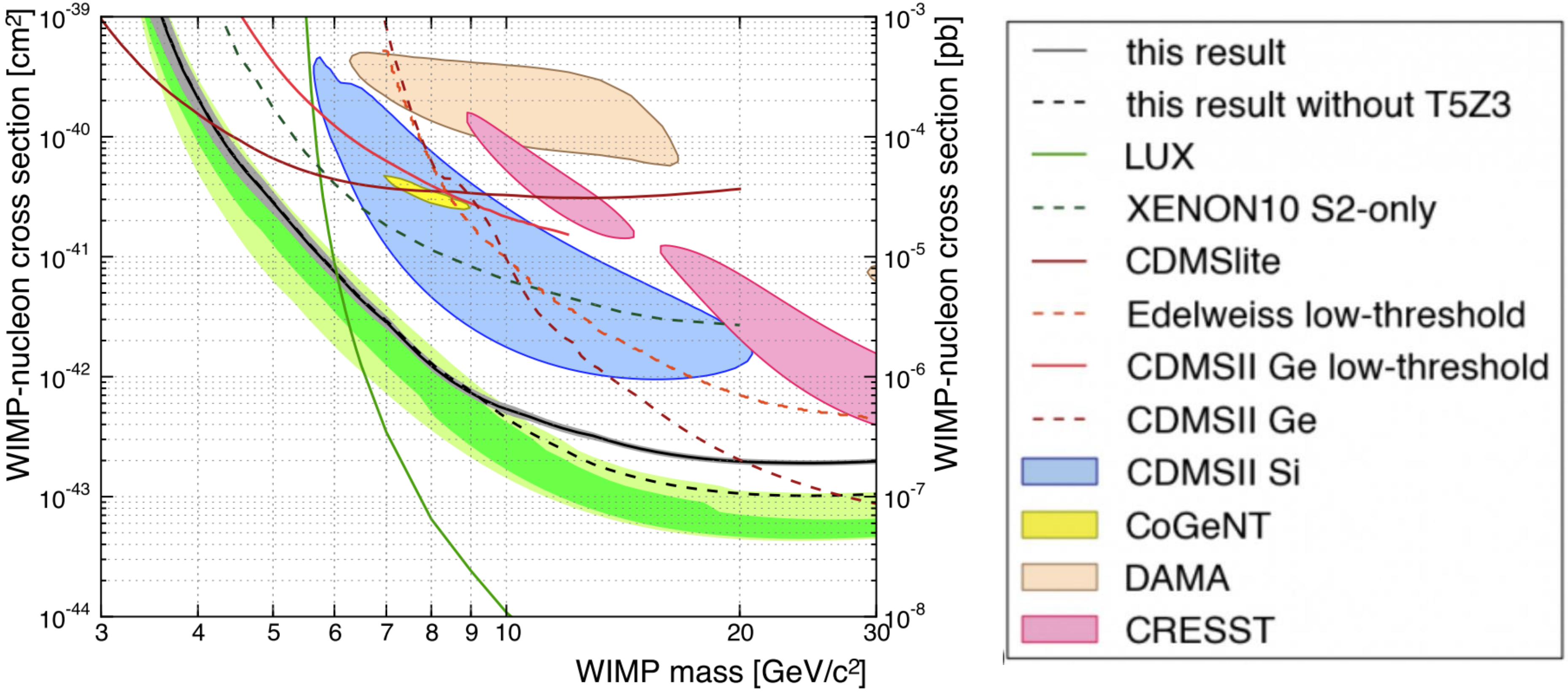
# LT-analysis tower-5 BDTs

Generally good agreement with background model

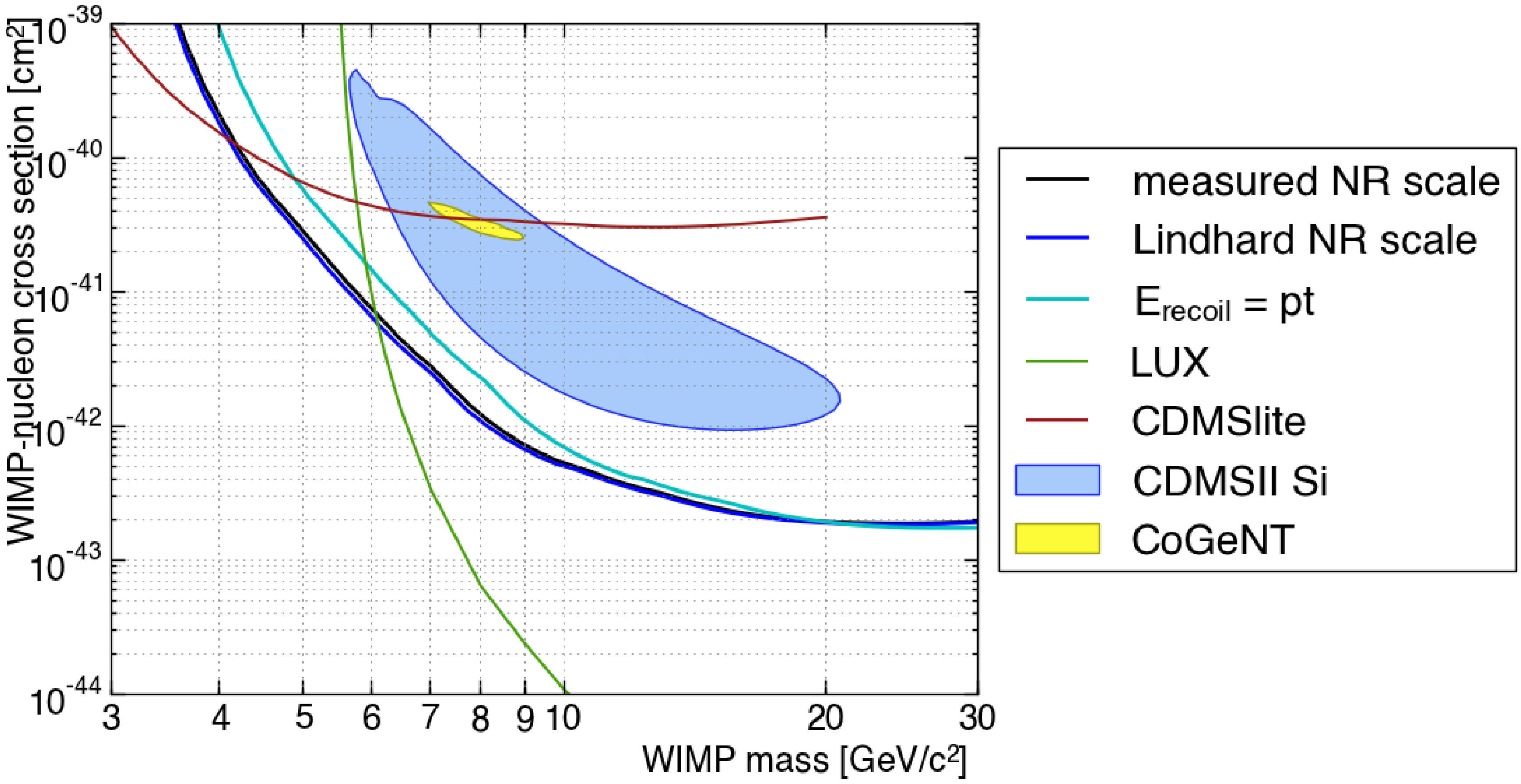


Low-rate BDT tails in data not well-represented by model

# LT-analysis exclusion limit (w/o T5Z3)

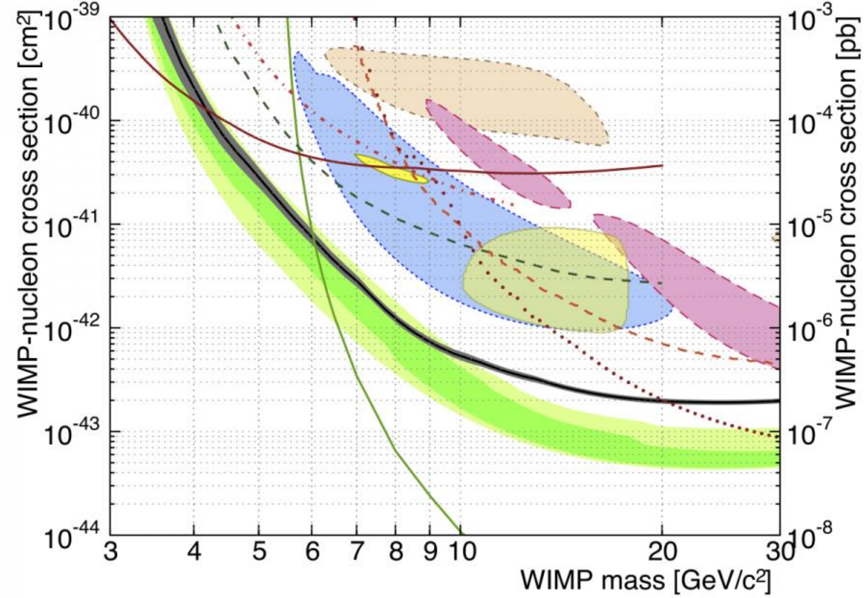


# LT-analysis limit: alternate energy scales



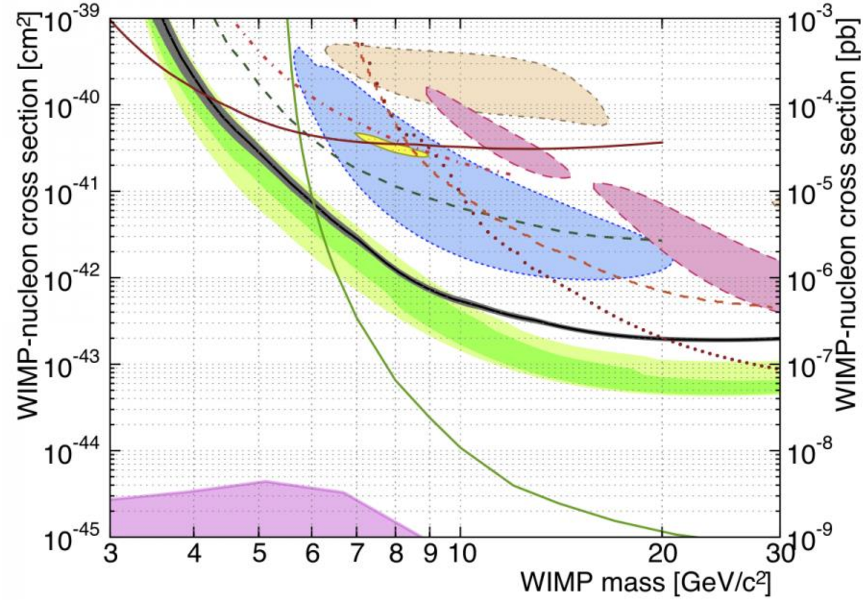
# LT-analysis exclusion limits

with CoGeNT likelihood analysis



*[arXiv:1401.6234]*

with solar-neutrino floor



*[arXiv:1307.5458]*

# SuperCDMS Soudan full exposure

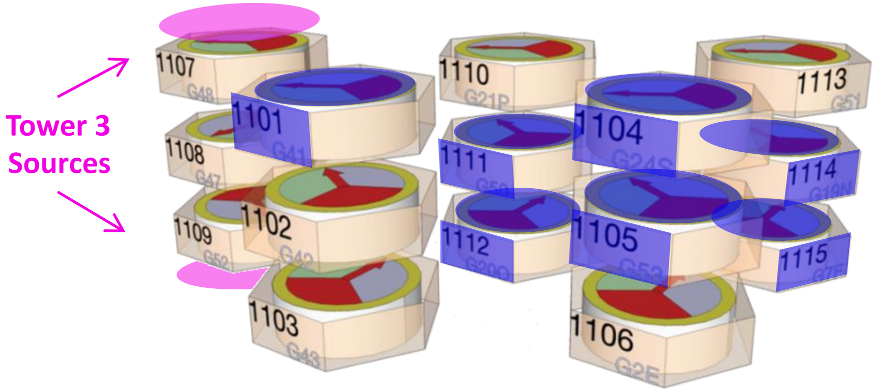
## Near-zero background WIMP-search

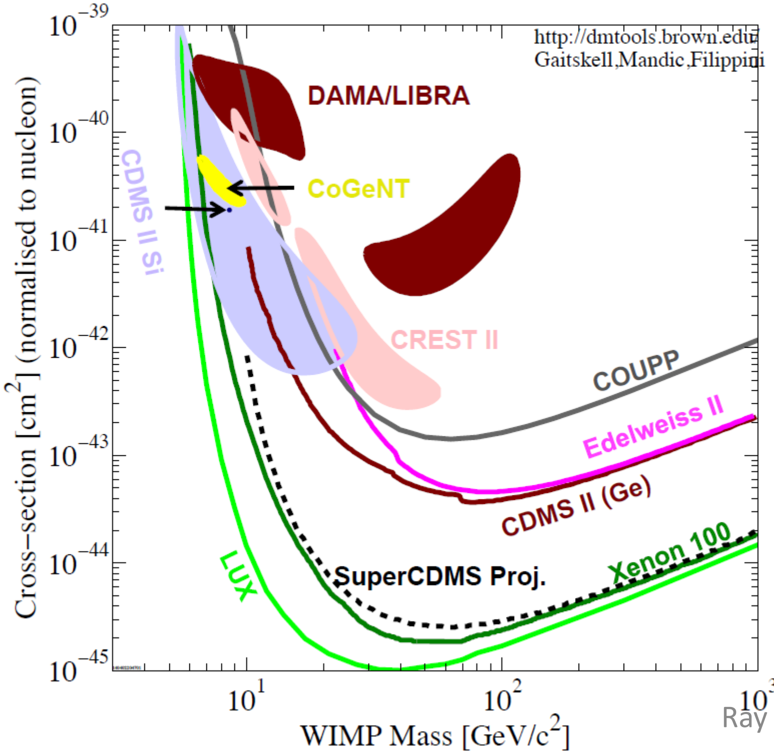
Different strategy:

- → higher thresholds
- → larger exposure (≈3000 kg-days)
- → background from low-rate tails of of surface-event distributions
- → expect larger fiducial volume

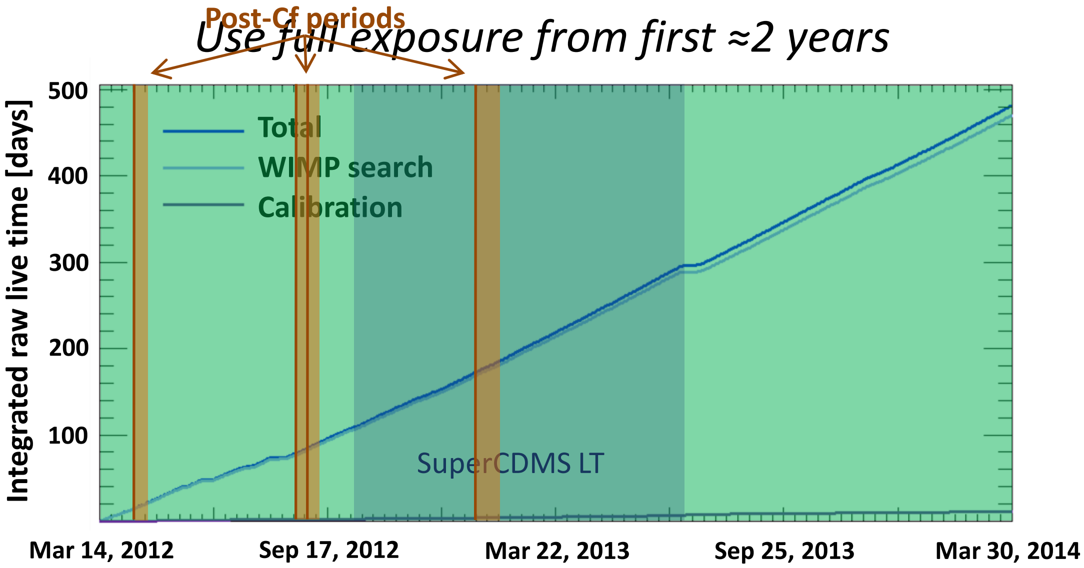
Analysis effort ongoing!

*Use full detector array*

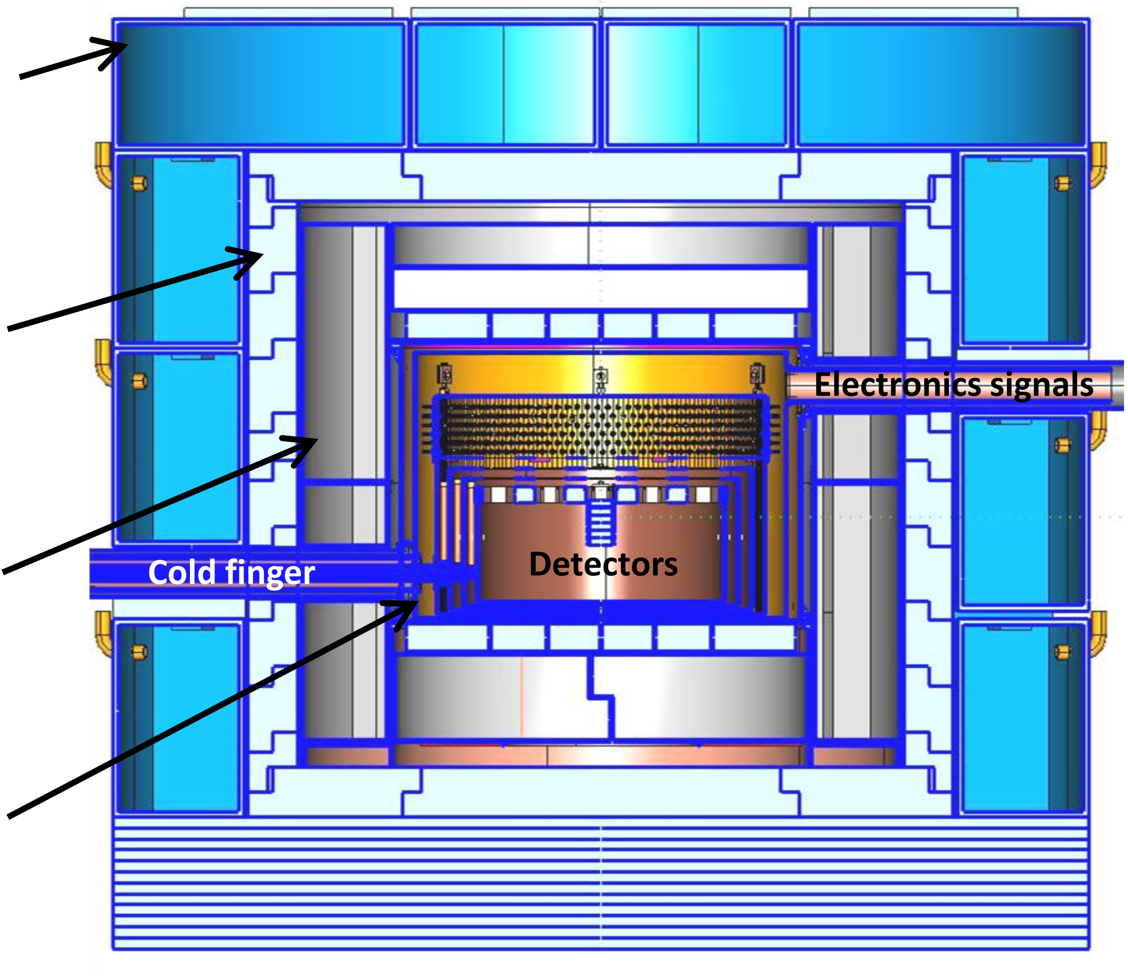




*Use full exposure from first ≈2 years*



# SuperCDMS SNOLAB shielding



Outer shielding (neutrons & gammas):
→ 60 cm water or polyethylene

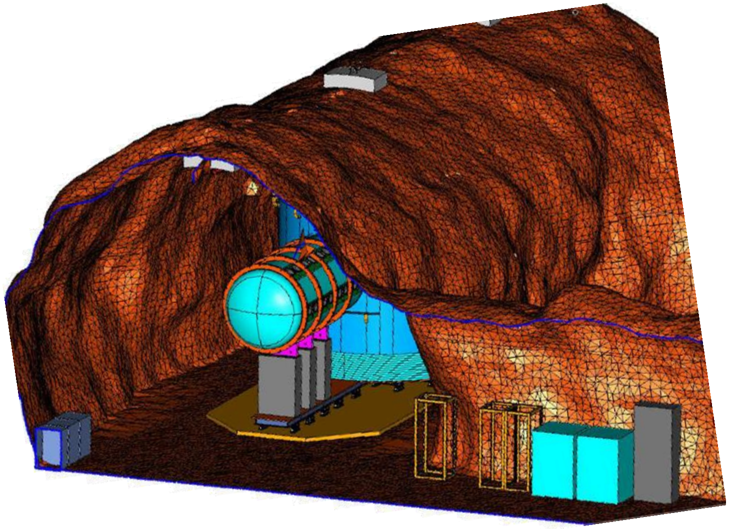
Inner passive shielding (gammas):
→ 23 cm lead with radon purge

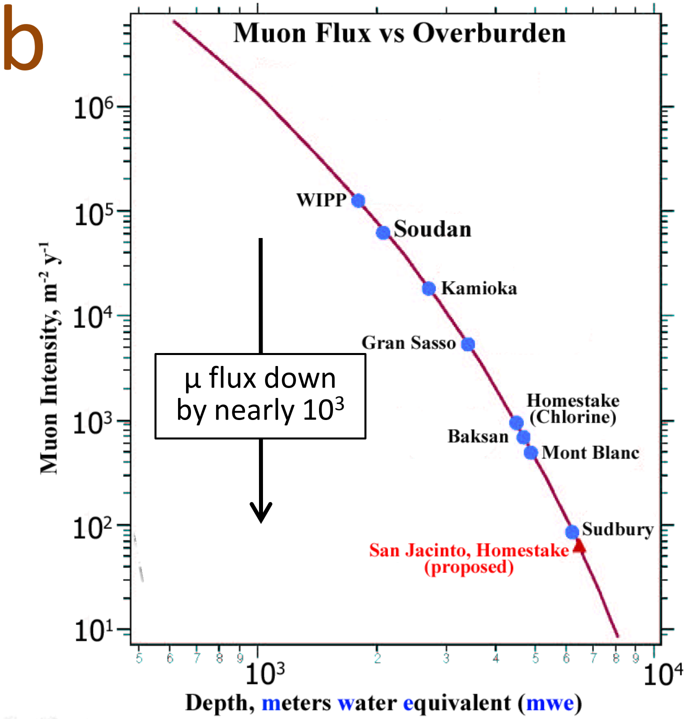
Active shielding (neutrons):
→ 40 cm doped scintillator

Nested cryostat (gammas):
→1/2–3/8” low-activity copper

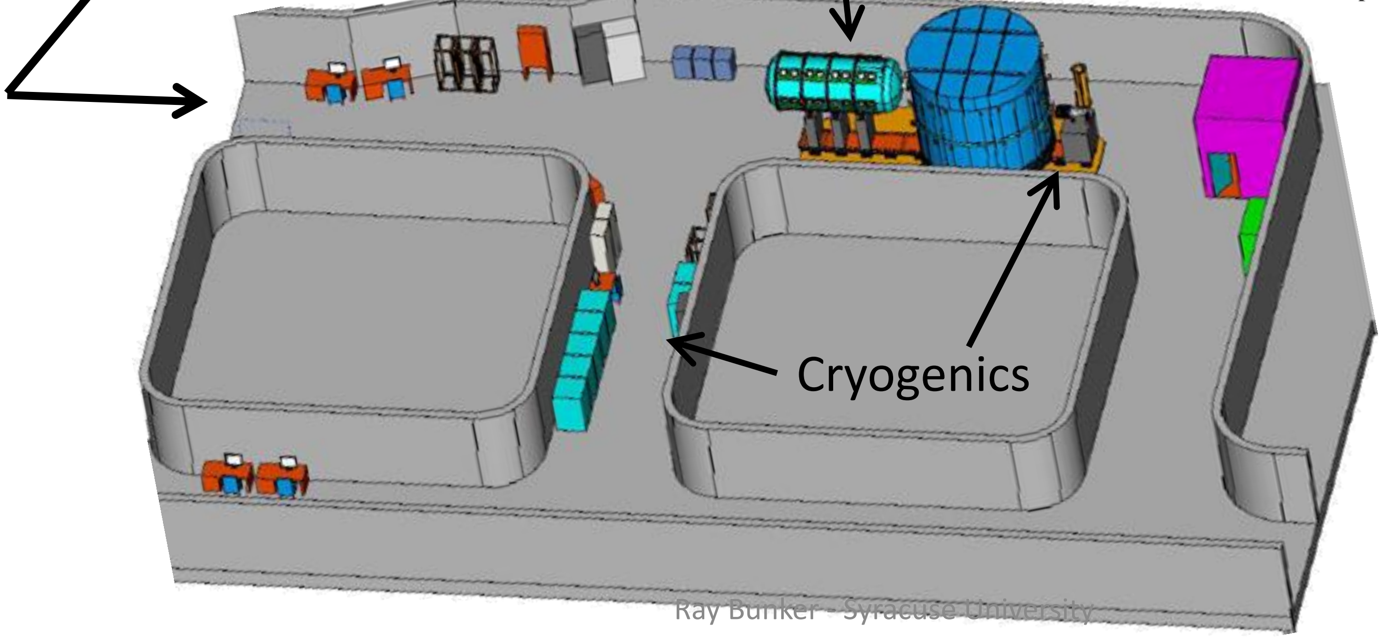
Assumed bulk contaminant levels no lower than measured by other experiments for easily available radiopure materials

# SuperCDMS SNOLAB ladder lab





µ flux down by nearly $10^3$

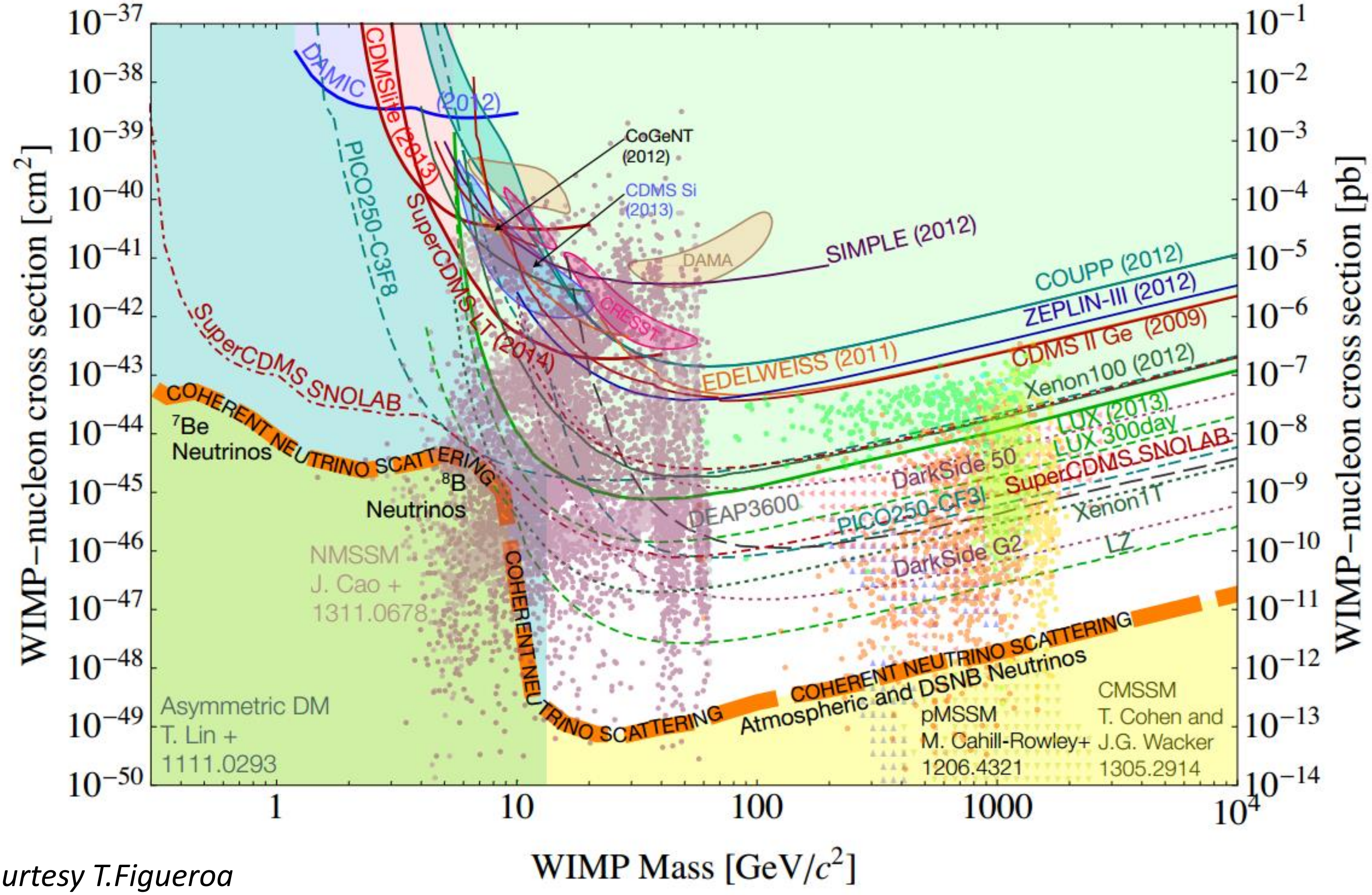


Shielding

Electronics

Cryogenics

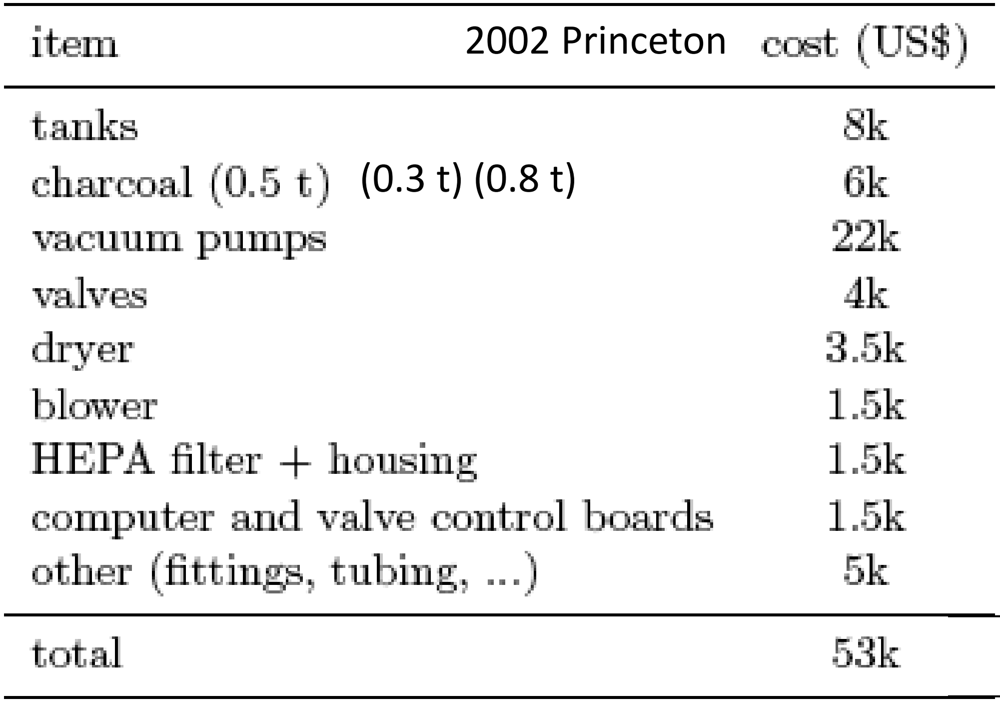
# SuperCDMS SNOLAB reach with theory



*courtesy T.Figueroa*

# VSA Cost Breakdown

- Based closely on Princeton design for Borexino (*described well in Pocar thesis, and thanks to T. Shutt, A. Hallin, A. Pocar for discussions*)

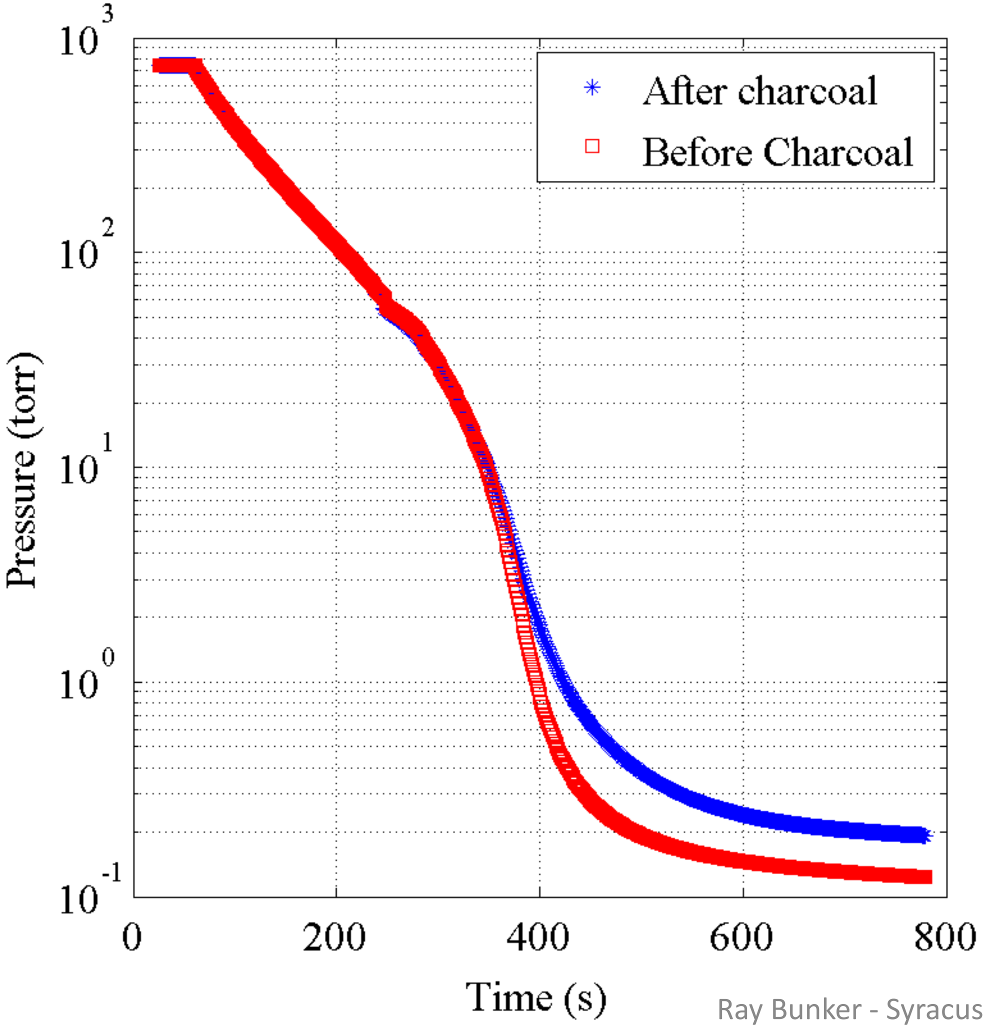


| item | 2002 Princeton cost (US$) | SU cost (10 years later) | SDSMT added cost (now) |
|---|---|---|---|
| tanks | 8k | 9k | 19k |
| charcoal (0.5 t) (0.3 t) (0.8 t) | 6k | 1.5k | 3.3k |
| vacuum pumps | 22k | 10k | 10k |
| valves | 4k | 7k | |
| dryer | 3.5k | 7.5k | |
| blower | 1.5k | (none) | 0.7k |
| HEPA filter + housing | 1.5k | 1k | 0.4k |
| computer and valve control boards | 1.5k | 6k including gauges | |
| other (fittings, tubing, ...) | 5k | 5k + 8k chiller | 3k (later) |
| total | 53k | 55k | + 36k |
| | | **no radon source** | **$8k pylon radon source** |

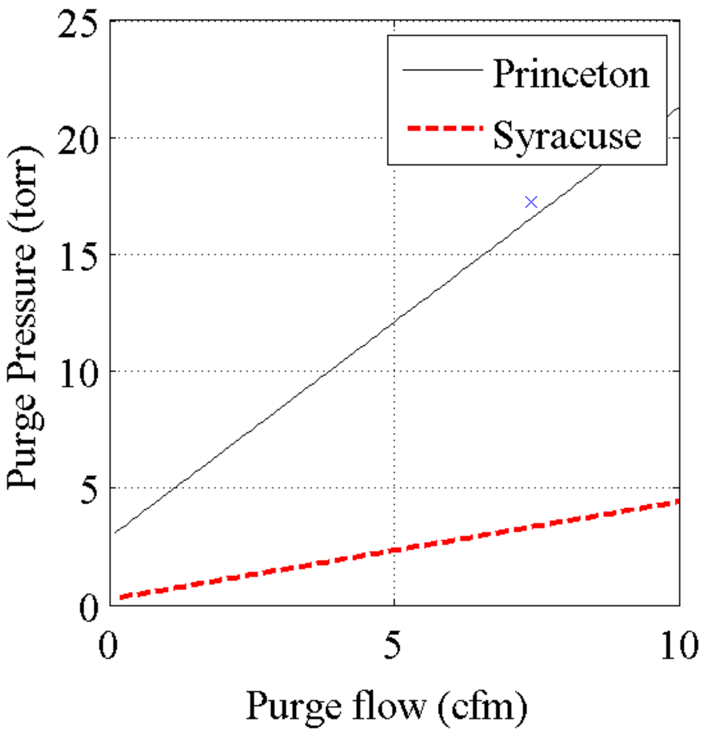
# VSA Comparison: Princeton *vs* Syracuse

Takes 5 minutes to pump down to ≈10 torr (*vs* Princeton ≈1 min)

→ So part of cycle is inefficient



Lower base pressure allows higher volume flow gain



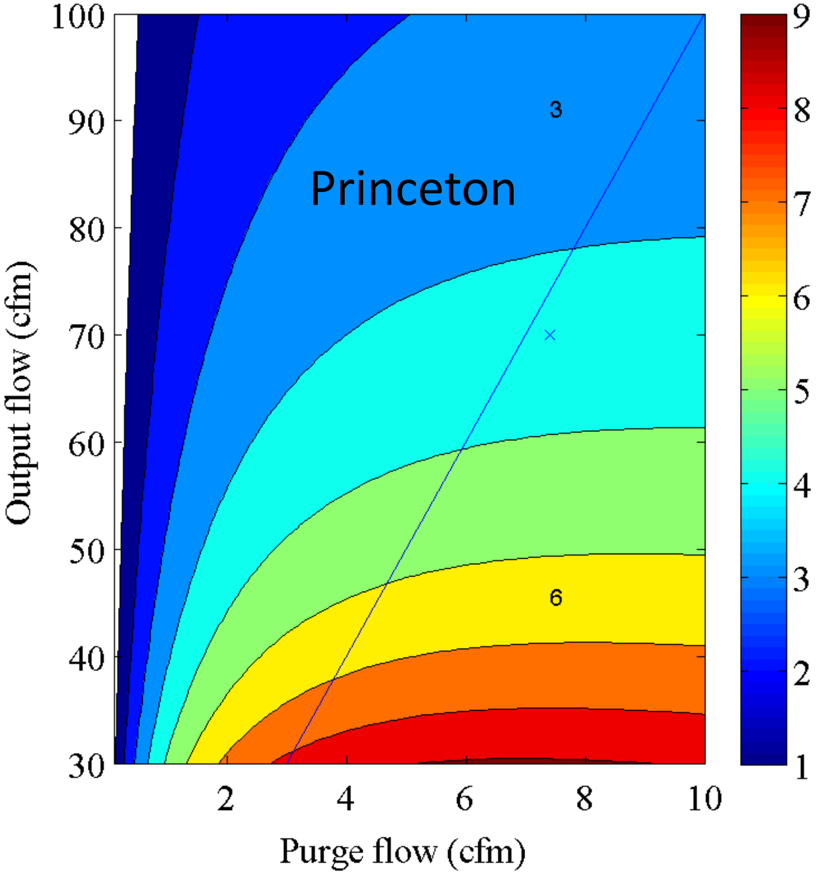
# VSA Comparison: Princeton *vs* Syracuse

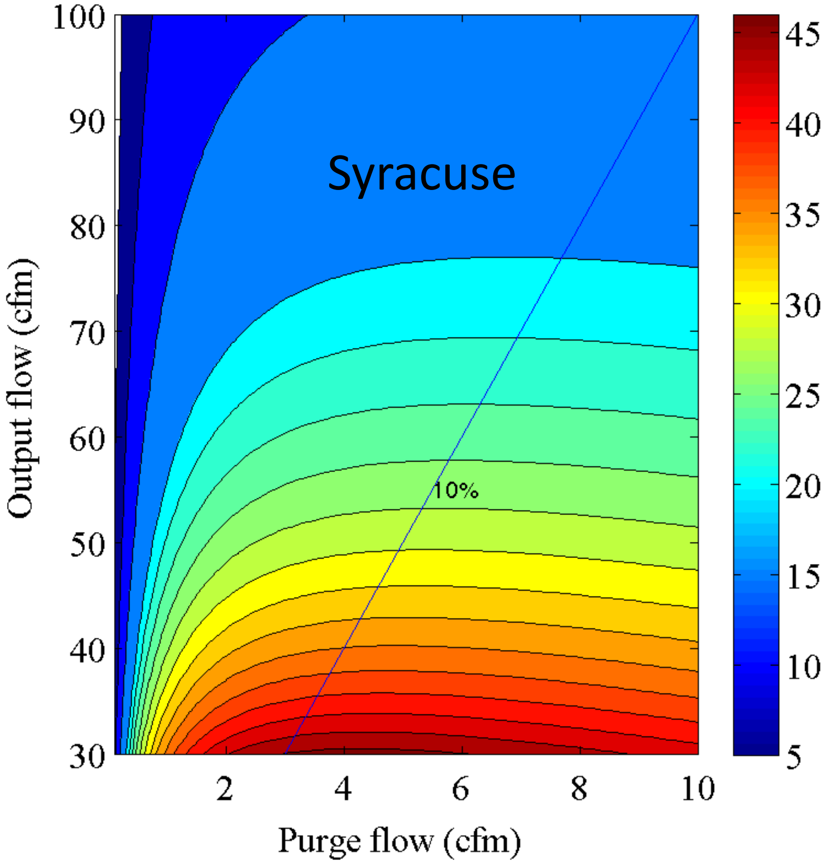
Want large G, big output flow and short cycle times:

Must have G > 1 for system to mitigate at all

Note this is not a valid direct comparison

→ same G in different systems can be different performance





# The Syracuse Clean Room

- Designed for 30 cfm low-Rn makup up (0.04” w.g. in overpressure)

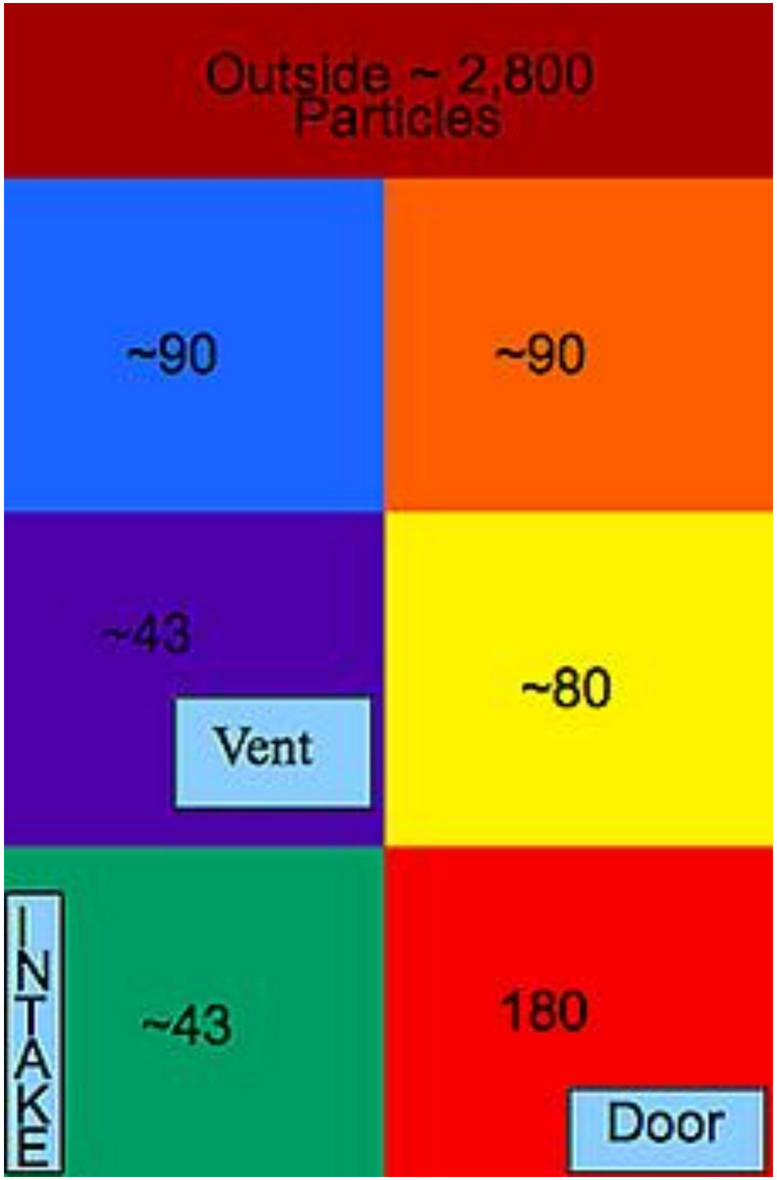
- 8 ft x 12 ft x 8 ft high
  - With 4’ x 8’ anteroom
  - As small as would be practical

- All aluminum panels/extrusions
  - Thick polycarbonate windows
  - Minimize emanation/permeation
  - Very leak tight, eventually (0.25” w.g.)

- HVAC box for re-circulation outside
  - Extensive efforts to make leak tight

- Aged water for humidification

- Fast HEPA filtration: 1 air exchange per 30 s



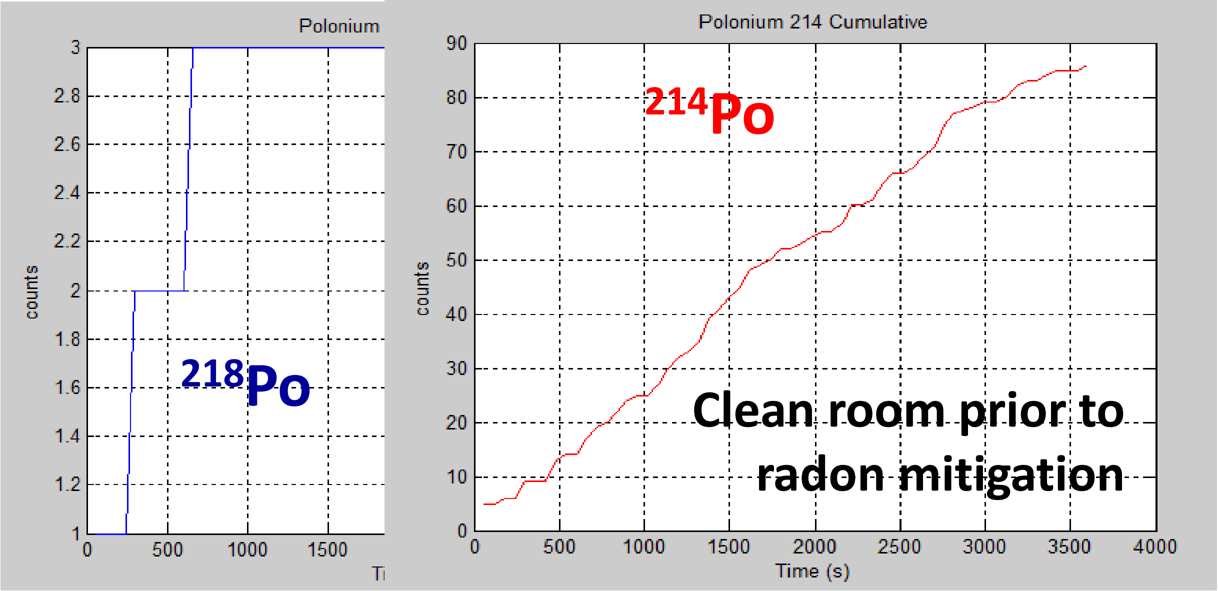
# The Syracuse Clean Room

# Air Sampling of Clean Room

Use high-volume air sampling system with Whatman GF/F glass-fiber filters, transfer to Ortec alpha counter to count $^{218}Po$, $^{214}Po$ decays and infer airborn concentrations of $^{218}Po$, $^{214}Bi$, $^{214}Pb$

→Indicates clean room ≈10x lower radon daughter concentrations than outside lab prior to radon mitigation

HI-Q Environmental Products CF-901
~70 lpm sampling rate



Clean room prior to radon mitigation

# Electrostatic Detector Background

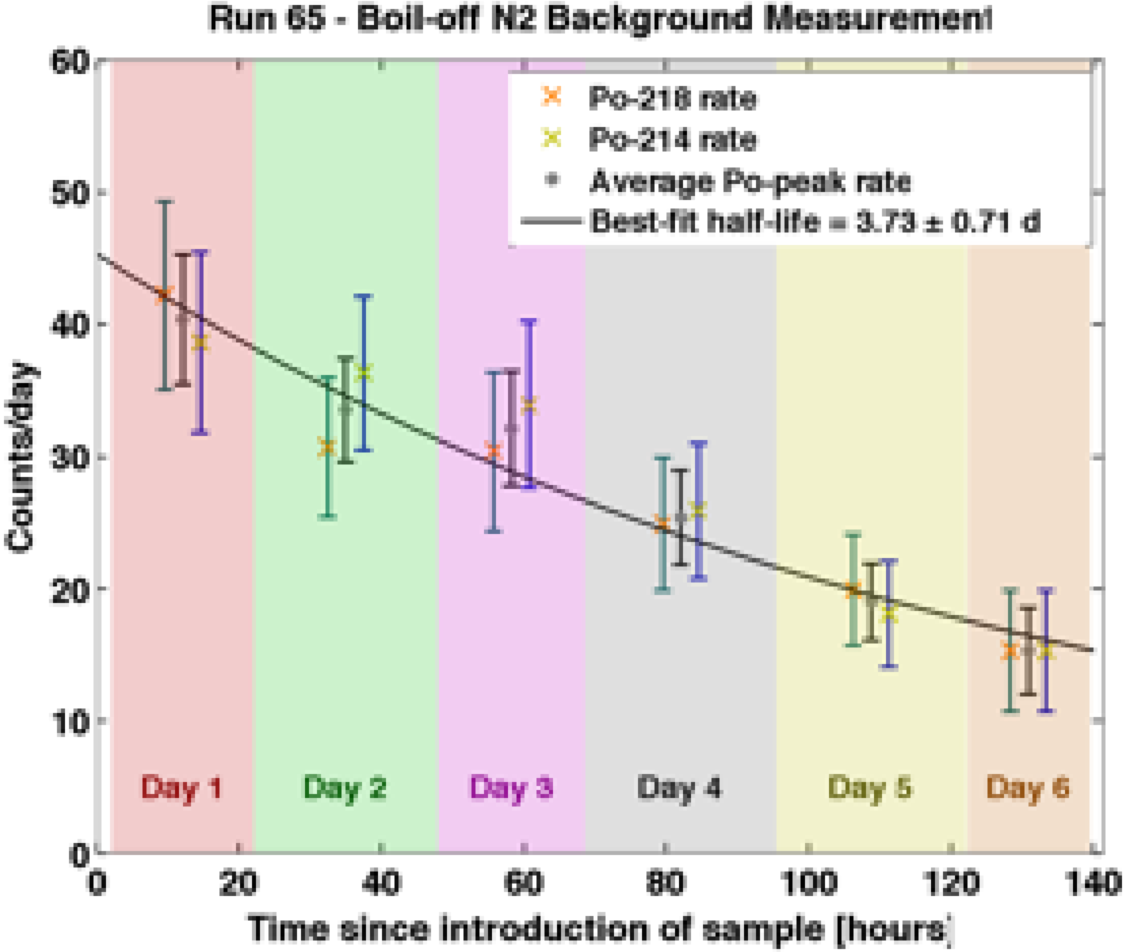
Initial rate from fill 100x too large for $LN_2$ boil-off

→ 300x lower than our room air

Decayed as expected if no source from chamber leaks or emanation

Reduced by factor 4 as expected when lowered pressure from 1000 to 230 Torr:

→ No evidence of chamber leaks/emanation with better sensitivity



# Expected BetaCage Photon Background

| mBq/kg | $^{238}U$ | $^{232}Th$ | $^{40}K$ |
|---|---|---|---|
| **Resistors** [a] | 6,000 | 5,000 | 35,000 |
| **Noryl** [b] | <3 | <1 | 5 |
| **Lead** [c] | 3,000 $^{210}Pb$ | | |
| **Acrylic** [a] | <0.12 | <0.04 | <1.5 |
| **Copper** [d] | 0.08 | 0.12 | 0.04 |
| **Stainless Steel** [a,e] | <1 | <10 | <4 |

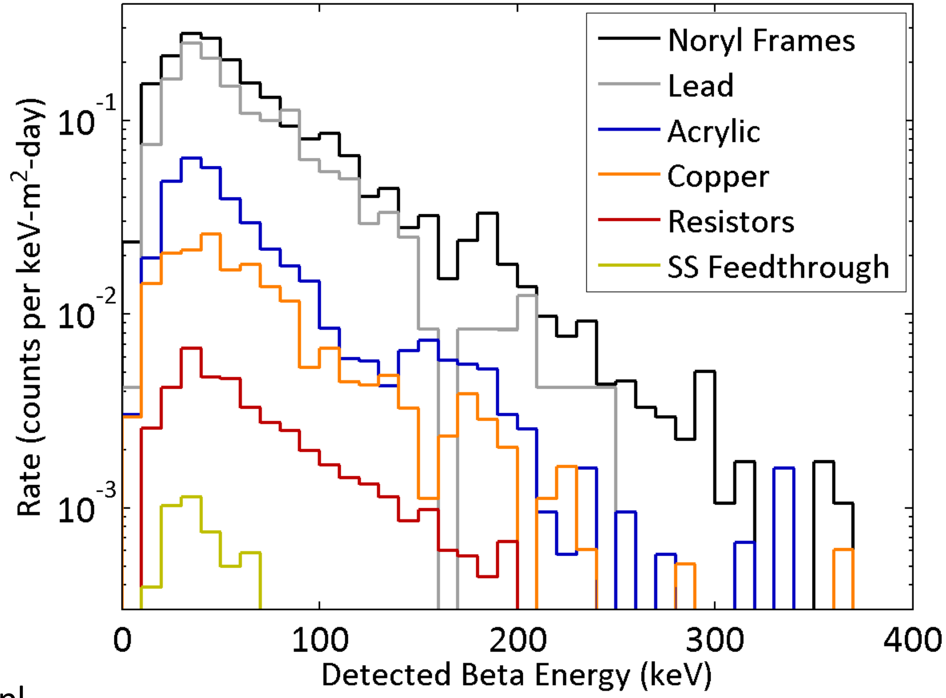
[a] Community Material Assay Database, radiopurity.org

[b] U/Th→UMN Gopher HPGe & Caltech ICP-MS;
K→UC Davis NAA

[c] PLOMBUM low-activity lead, www.plombum.republika.pl

[d] E. Aprile et al., Phys. Rev. D83 (2011) 082001

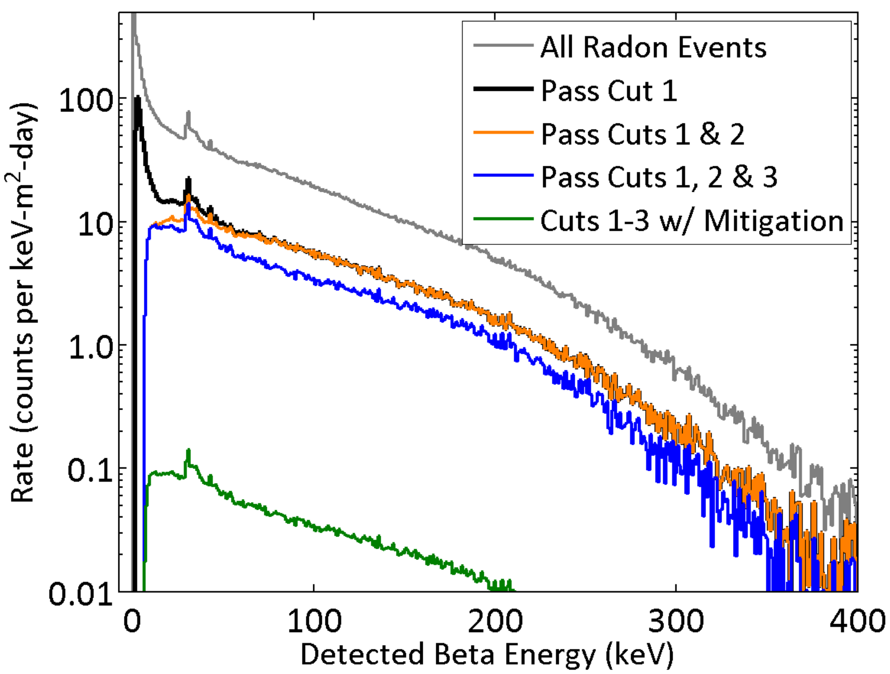
[e] SS feedthrough contributes negligibly to beta background

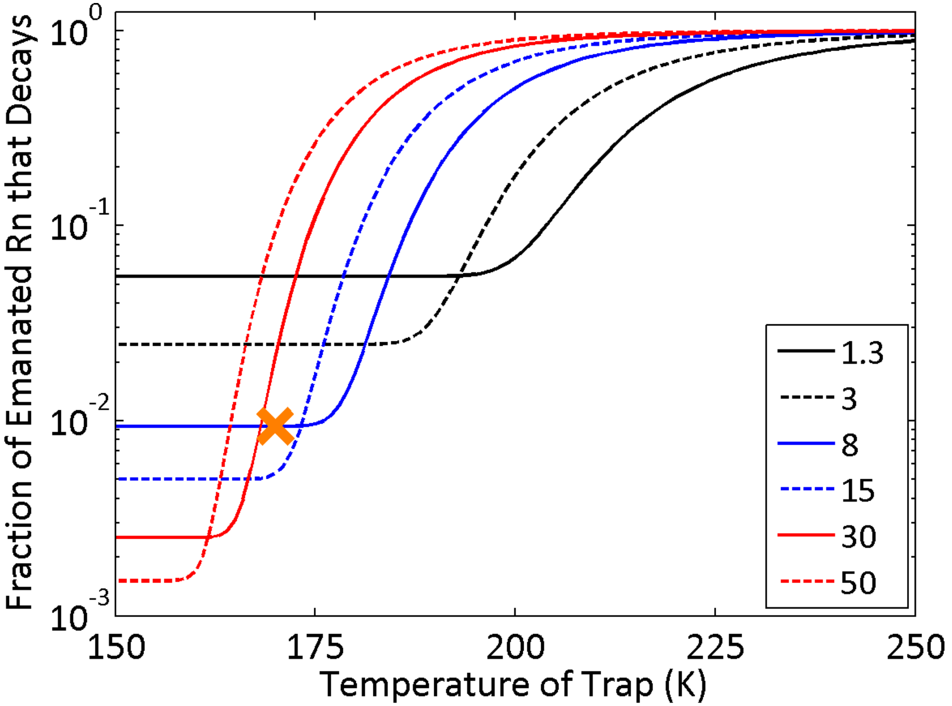


Full background simulation using measured or limited radiopurity of components indicates should be dominated by gammas from Pb shielding:

→ Most challenging component was plastic for wire frames

# Expected BetaCage Radon Background

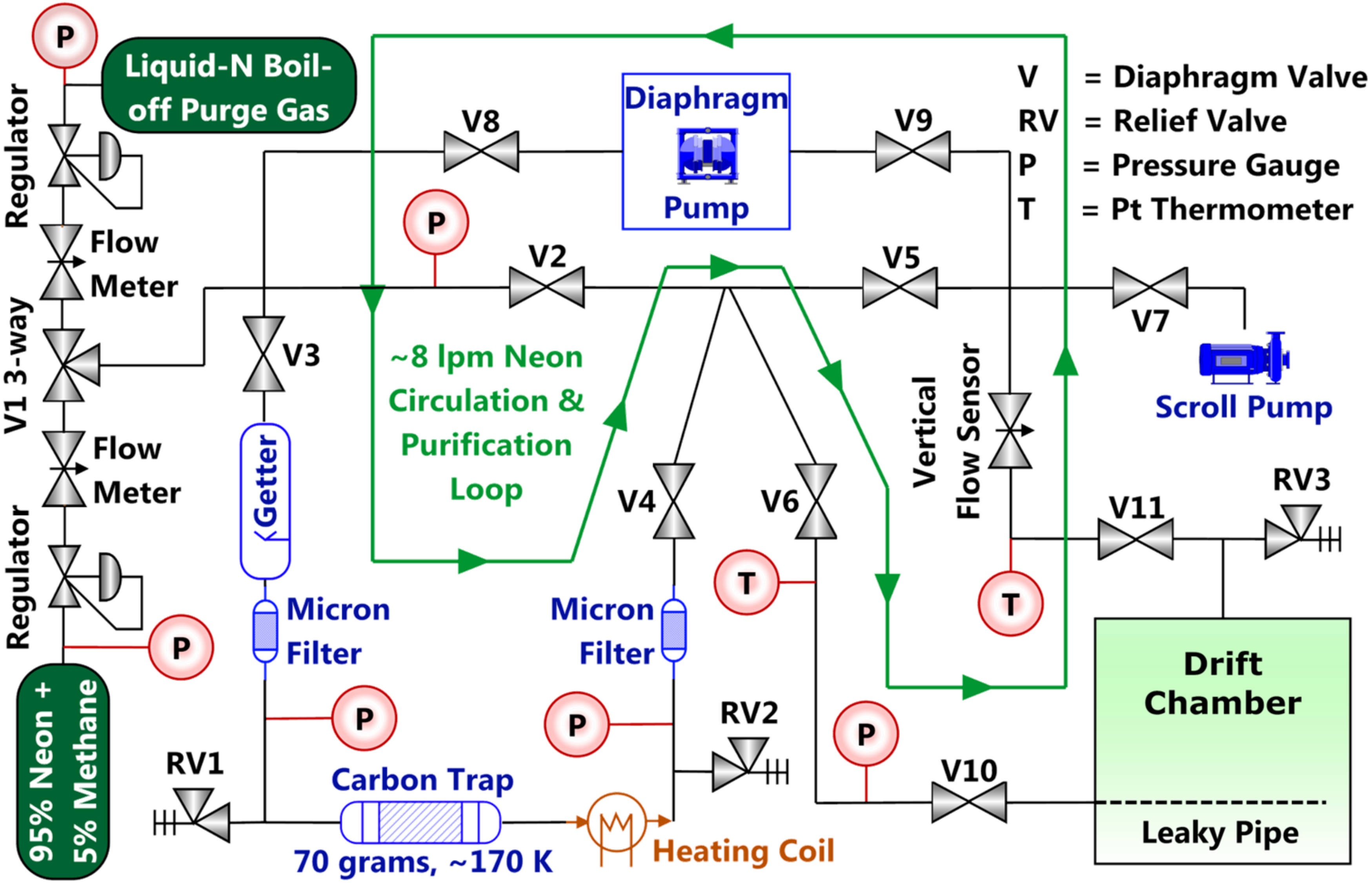




Some radon induced events rejected by requiring energy in trigger and bulk but not edge regions:

- But expected background would still dominate w/o mitigation
- 100x improvement sufficient to make subdominant & achievable w/ 30 lpm flow rate through cooled carbon trap
- Keep wire surfaces clean via stringing in Rn-mitigated clean room

# Mature Design for Gas Handling System



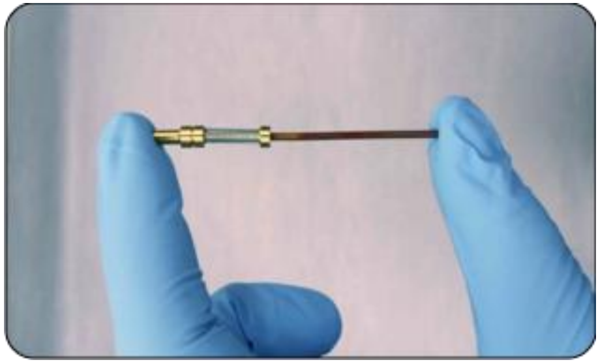
# Fully Strung MWPC Frame

MWPC comprised of 2 cathode layers and a crossed anode layer:  5 mm pitch, 5 mm plane spacing

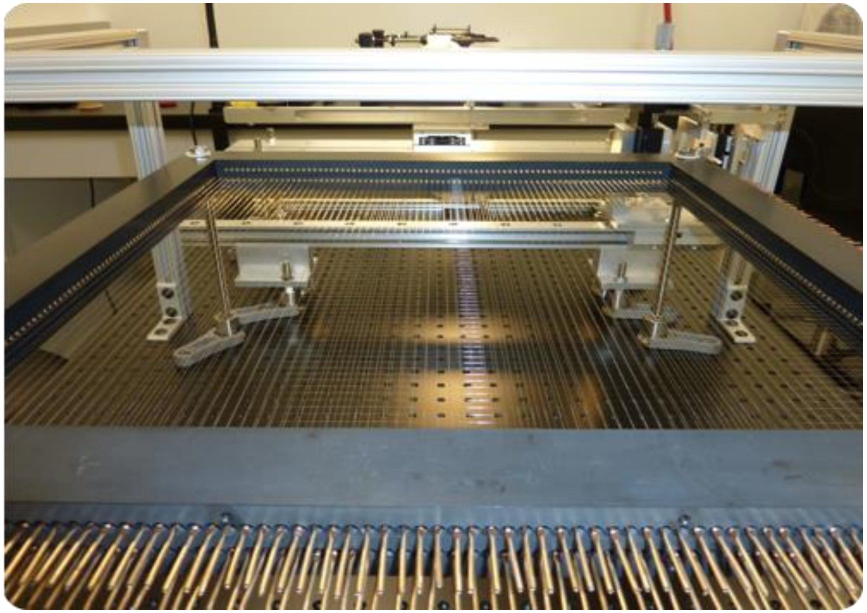
MWPC frame assembly occurred in a class 1000 clean room

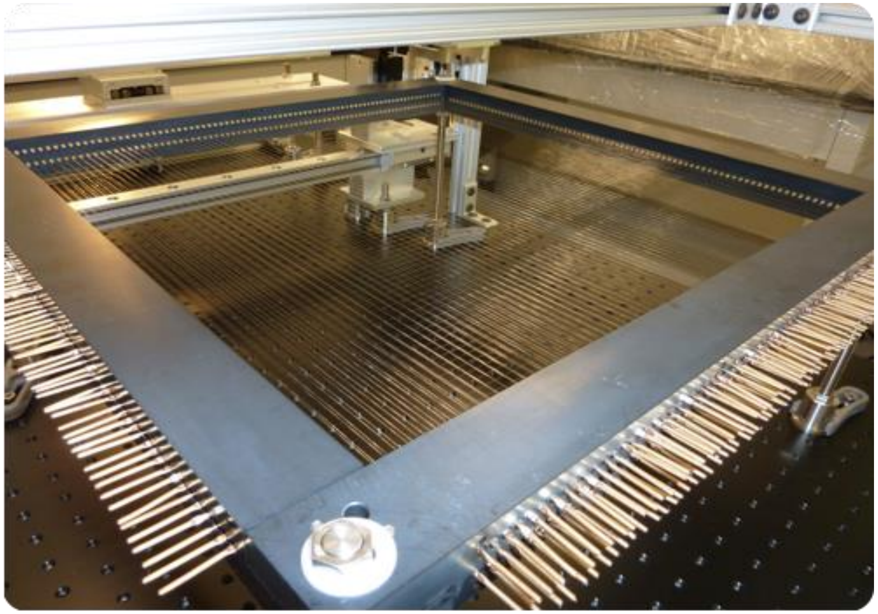
Wires were strung using a custom stringing jig

… roughly 6 minutes per wire.

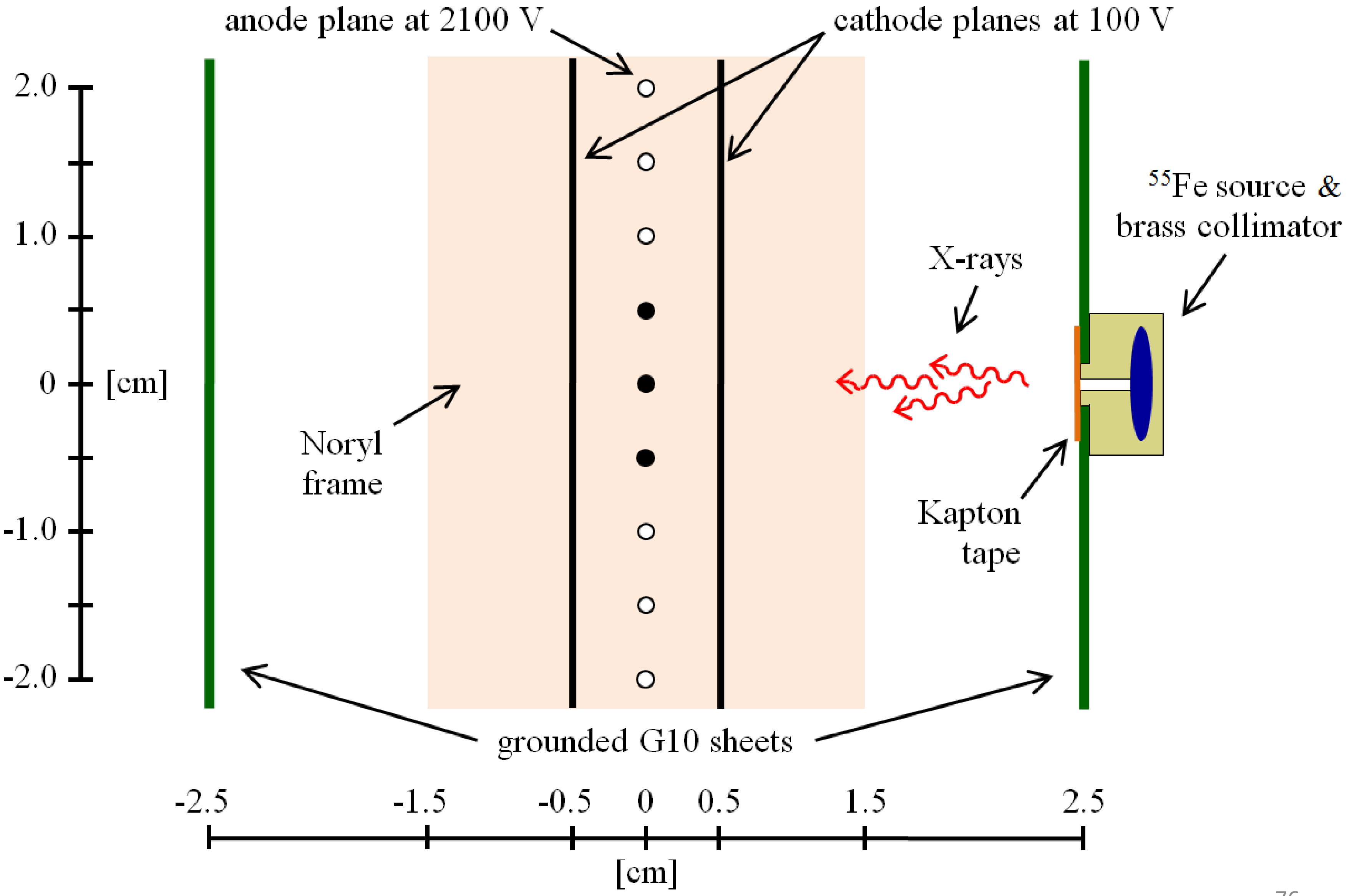


Spring-loaded feedthroughs

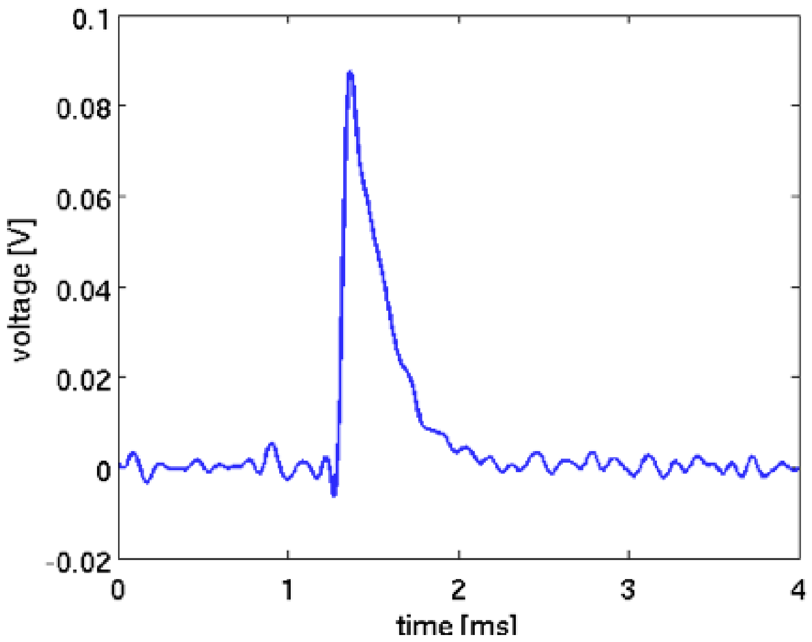




# Prototype Setup for X-ray Characterization



# Prototype $^{55}$Fe Spectrum



Data collected from 55Fe source x-rays
Collimated into the central 3-wire channel.

Read into a charge integrating amp and a
Slow digitizer.

Nearly ideal intrinsic energy resoluiton!

Typical pulse through Cremat amp
With $^{55}$Fe x-ray source.

Gain ~$10^4$ with P10 at STP
Anode 2100 V, Cathode 100 V