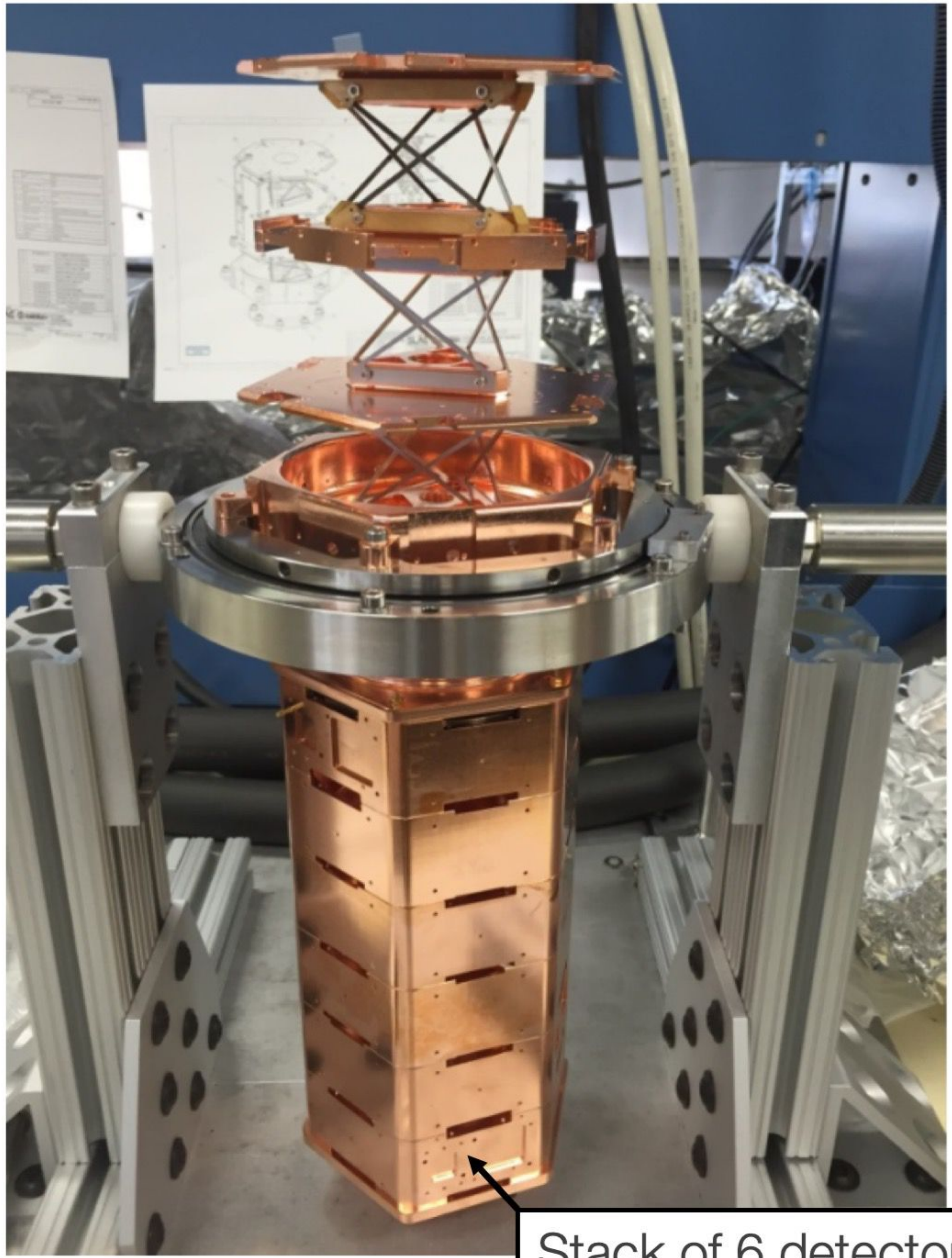
Radon Background Control for the SuperCDMS SNOLAB Dark Matter Experiment

Joseph Street
South Dakota School of Mines & Technology

July 17th, 2019

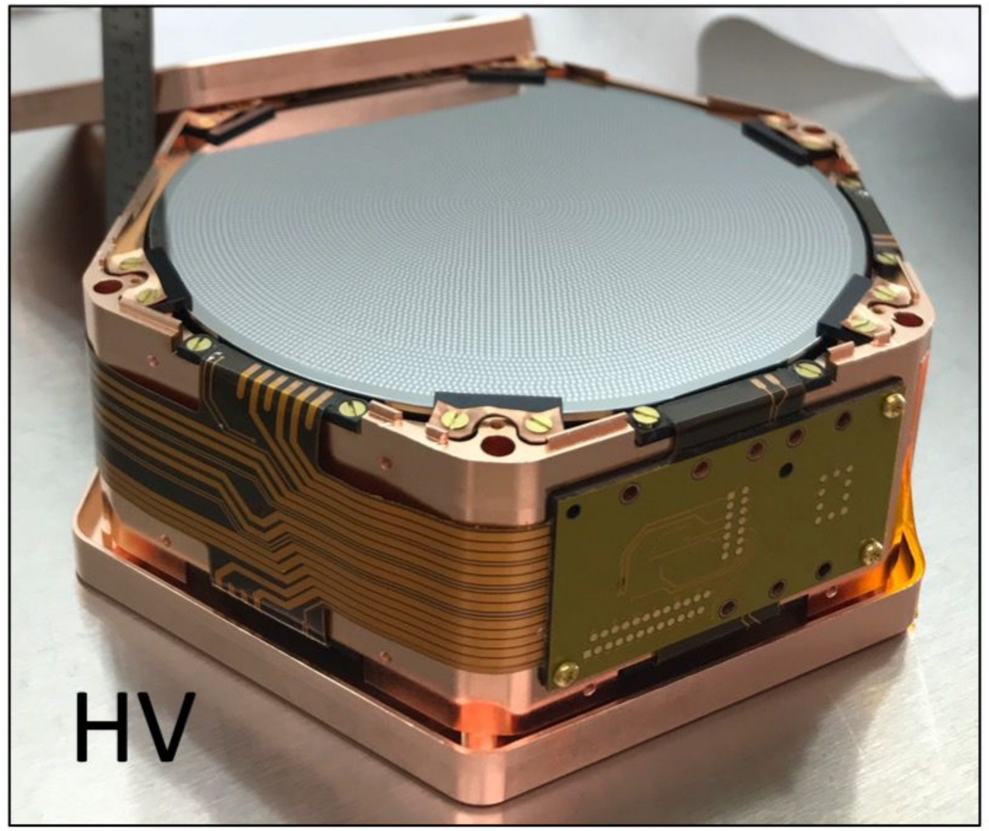
SNOLAB Future Projects Workshop

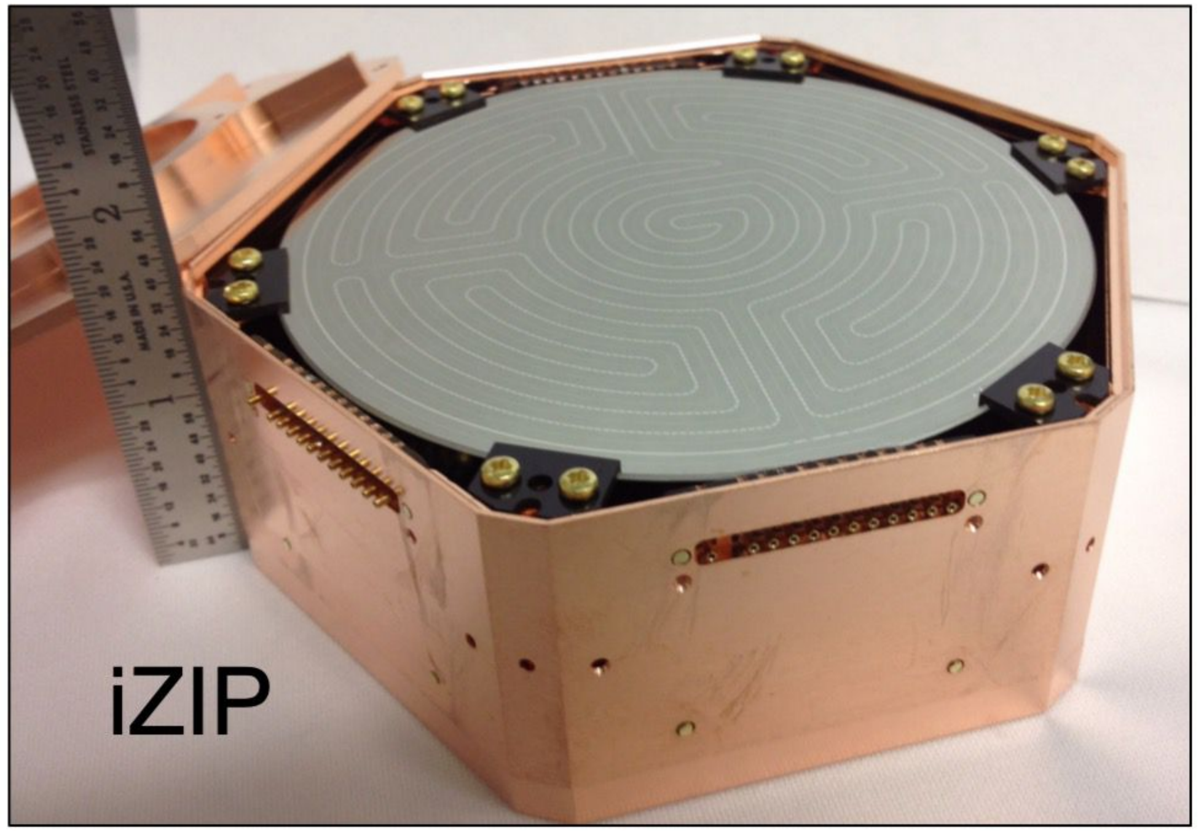
Super **C**ryogenic **D**ark **M**atter **S**earch



SuperCDMS SNOLAB is an experiment being built to detect dark matter

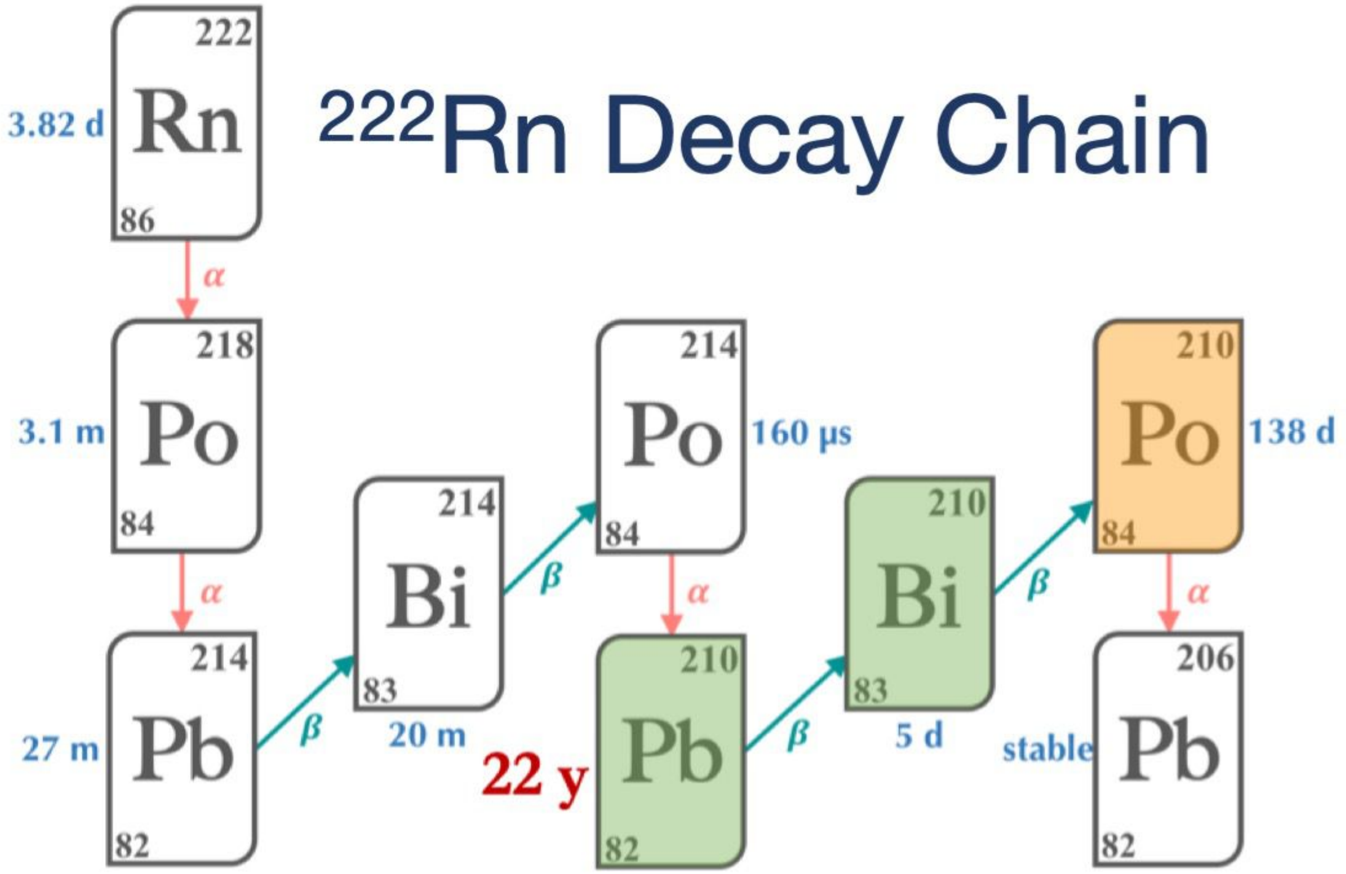
- Detectors are made from high-purity germanium or silicon
- Detectors measure electron-hole pairs (charge) and heat (phonons)
- Most sensitive to dark matter with mass 0.5–10 $\mathrm{GeV/c^2}$

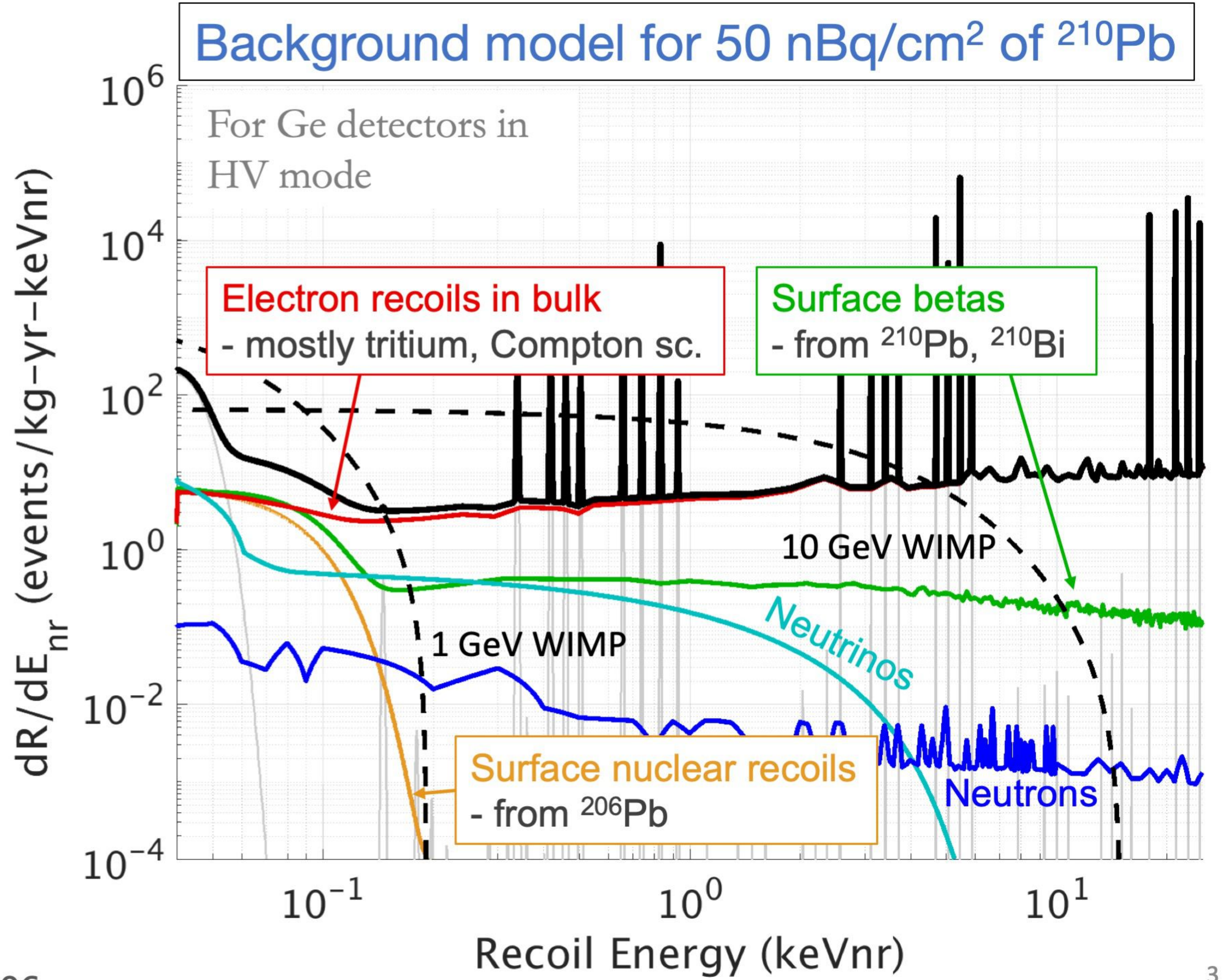




Stack of 6 detectors with no material between them

SuperCDMS SNOLAB : Line-of-Sight Backgrounds

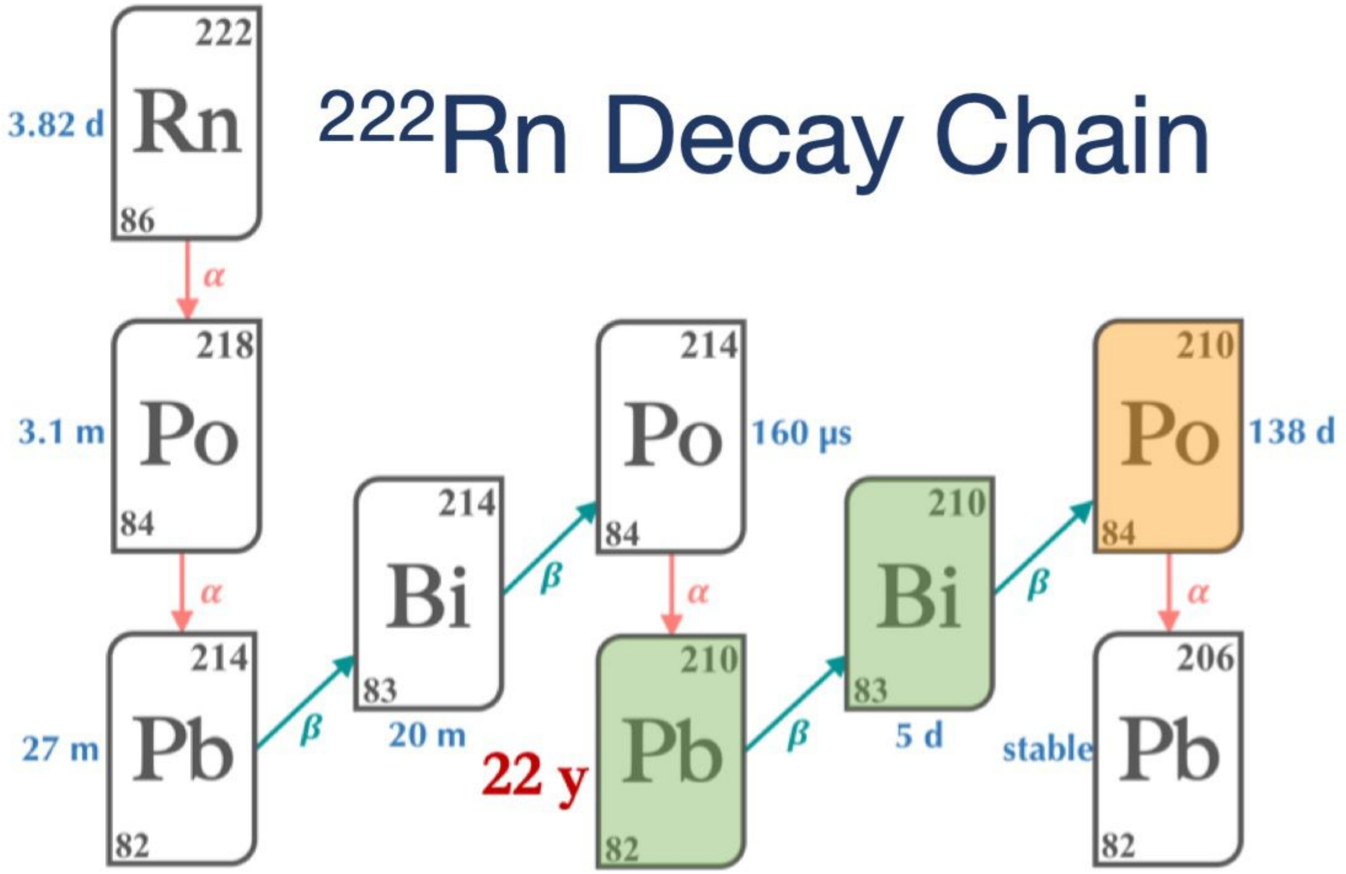




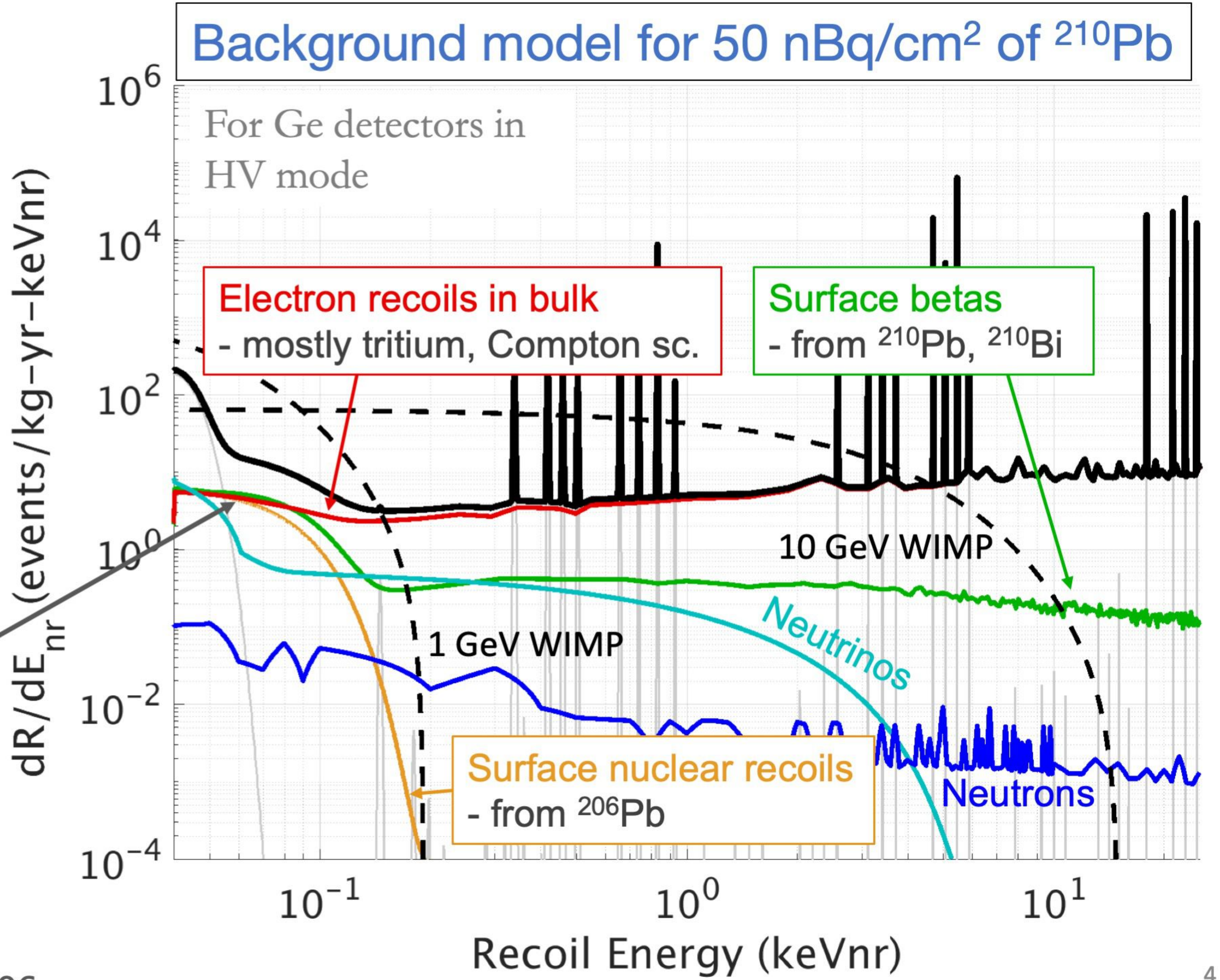
Phys Rev D 95 082002 or arXiv:1610.00006

SuperCDMS SNOLAB : Line-of-Sight Backgrounds

^{222}Rn Decay Chain



^{210}Pb surface backgrounds expected to dominate at lowest energies



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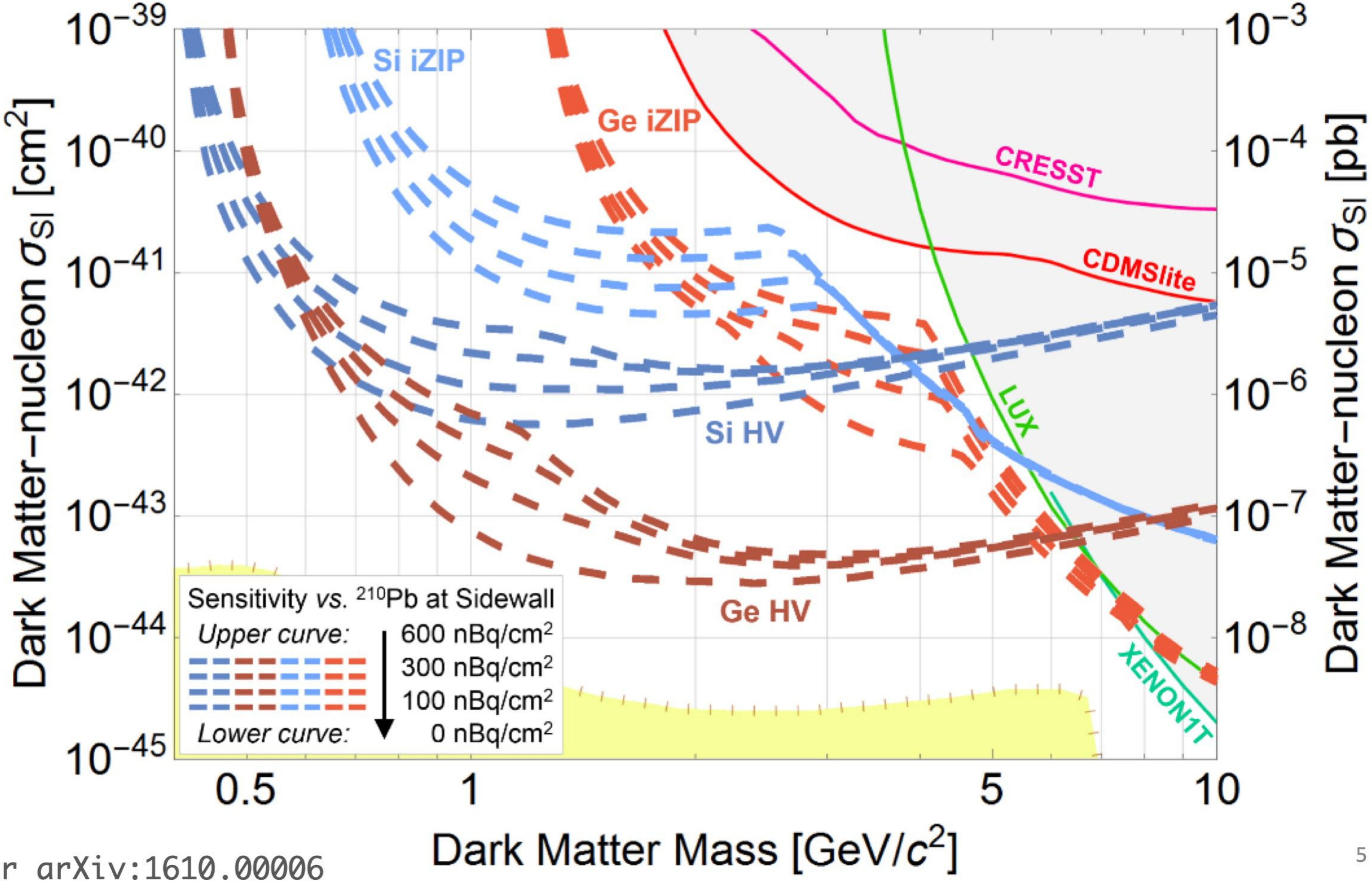
SuperCDMS SNOLAB : Impact on Sensitivity

Dashed curves represent

0×, 2×, 6×, and 12× the 50 nBq/cm² ^{210}Pb goal



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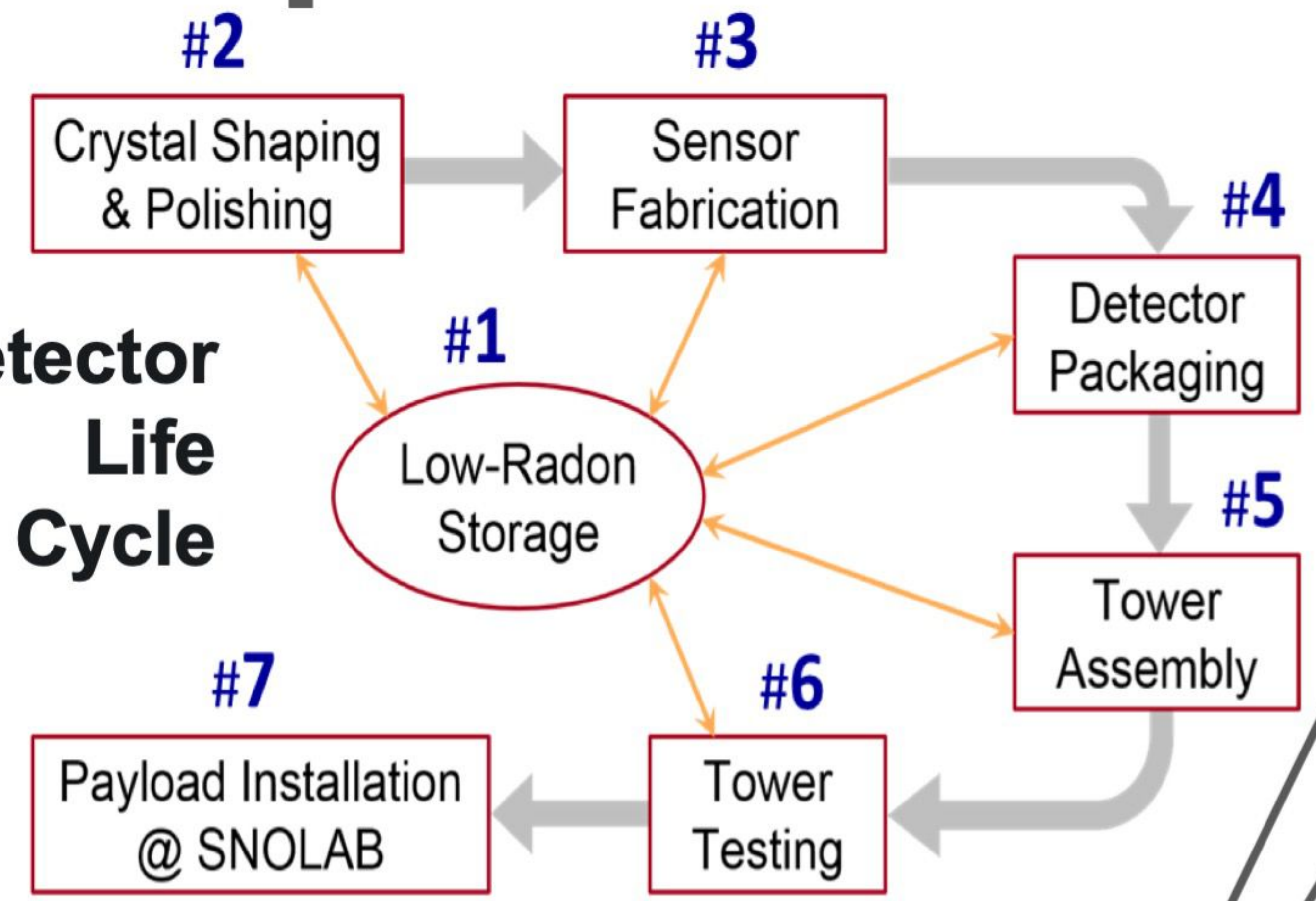
SuperCDMS SNOLAB : Detector Life Cycle

Detector Life Cycle



Sources of Surface Bkgd (nBq/cm^2 ^{210}Pb)

#1 - storage	**< 0.1**
#2 - polishing	**12-45**
#3 - fabrication	**28**
#4 - packaging	**4.8**
#5 – tower assembly	**0.9**
#6 - testing	**1.1**
#7 - installation	**<0.1**

[nBq/cm^2]

Total: w/ Rn mitigation: 48, w/o Rn mitigation: 118

Topics covered in this presentation…

- Storage (slide 8)
- ^{210}Pb plate-out during polishing (slide 9-10)
- Environmental radon (slide 11)
- SuperCDMS copper cleaning and assays (slides 12-16)
- Radon mitigation during detector assembly (slides 17-19)
- Simulation of the radon-mitigation system (slides 20-29)

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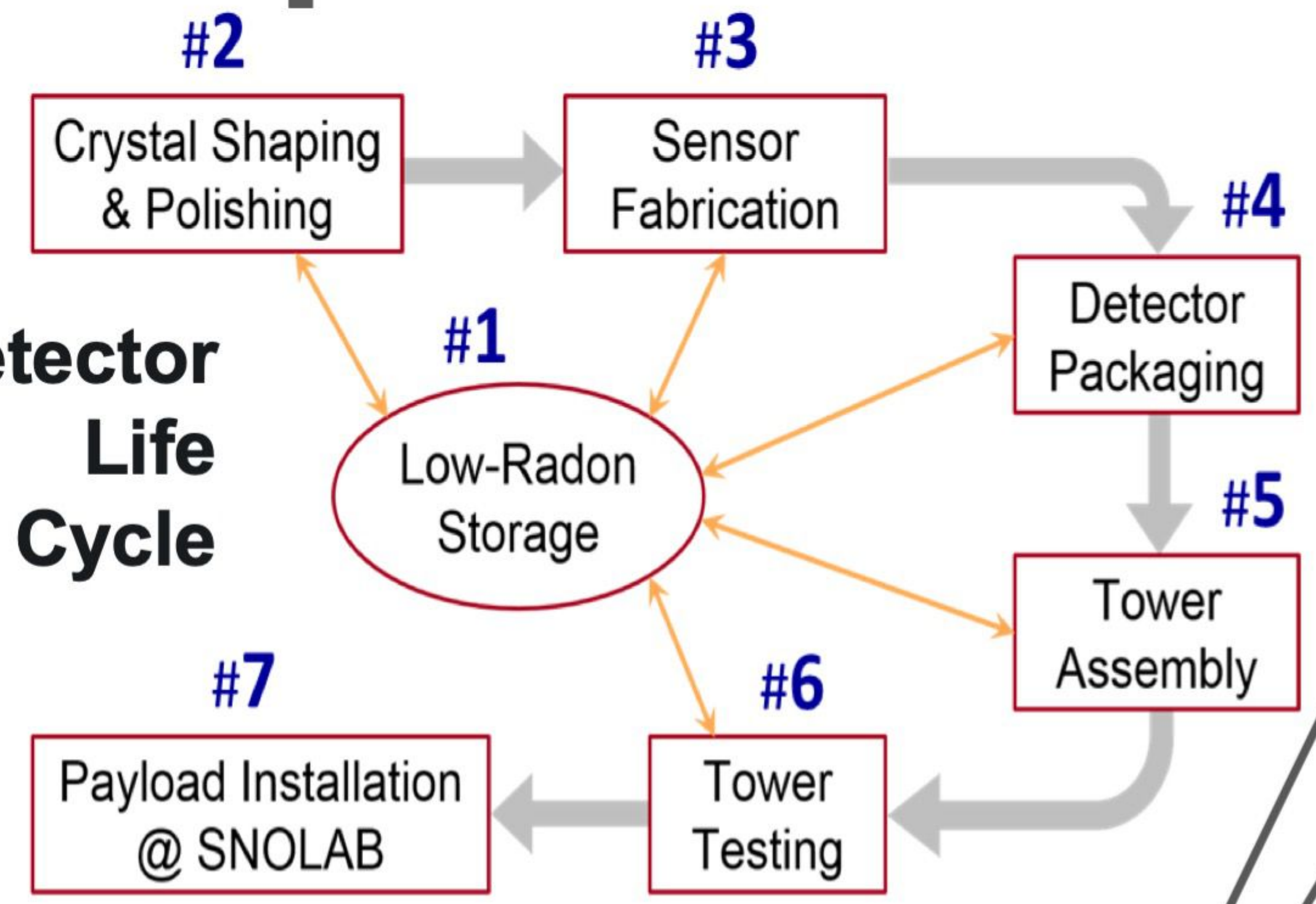

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- Simulation of the radon-mitigation system (slides 20-29)
- Future radon-daughter contamination removal (slides 31-34)

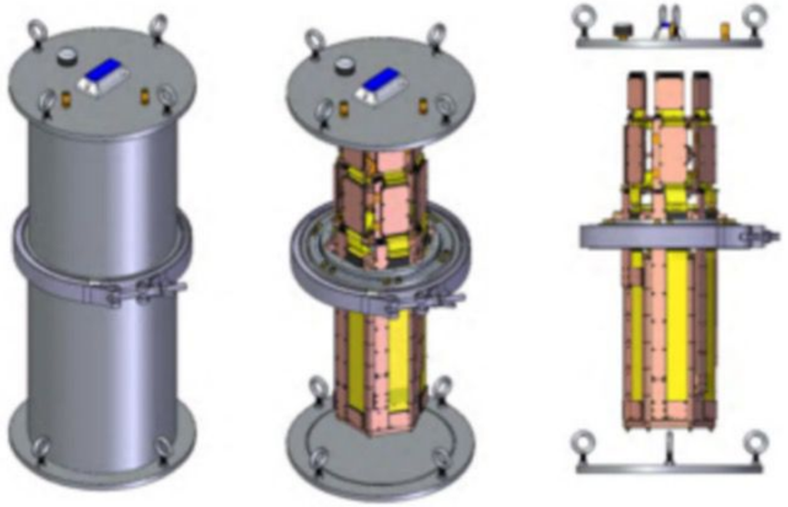
SuperCDMS SNOLAB : Storage

Detectors and line-of-sight materials accrue a negligible ^{210}Pb contribution < 0.1 nBq/cm^2 during low-radon storage.

LN_2 boil-off dry boxes with digital monitoring

Vacuum canister for detector tower shipment

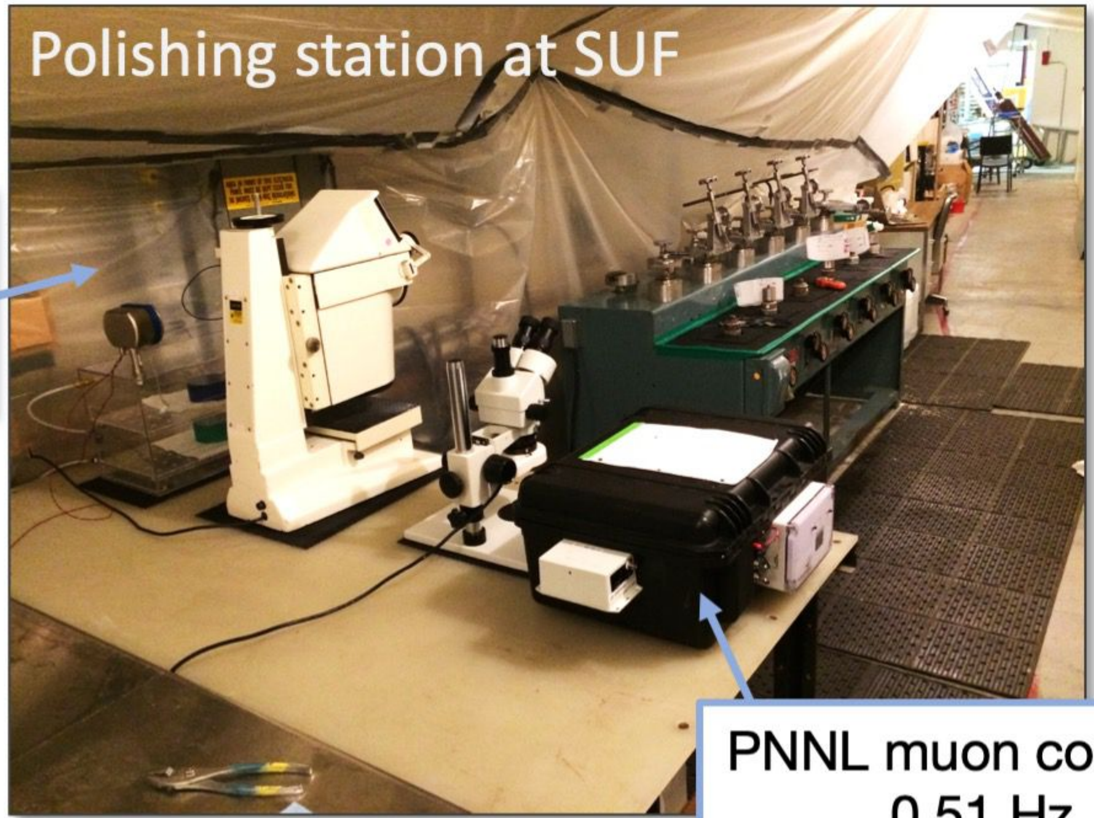
vacuum canister cartoon



SuperCDMS SNOLAB : Polishing

Polishing is being done underground at the Stanford Underground Facility (SUF)

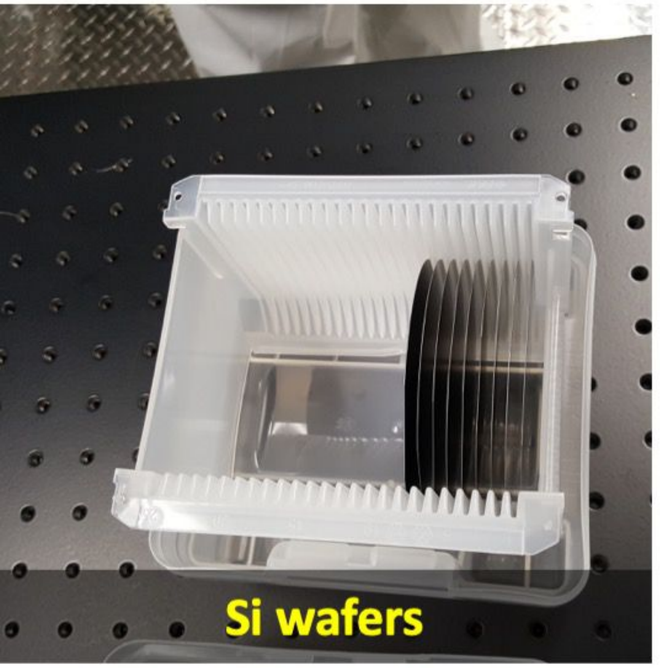
- Cosmogenic activation reduced by ~100×
  → SUF: 17 mwe, 0.5 neutrons/day/kg
- Assumed environmental radon increased by ~10× (to 100 Bq/m^3)
  → is measured in real time (before and during polishing)
  → currently measured to be ~20 Bq/m^3

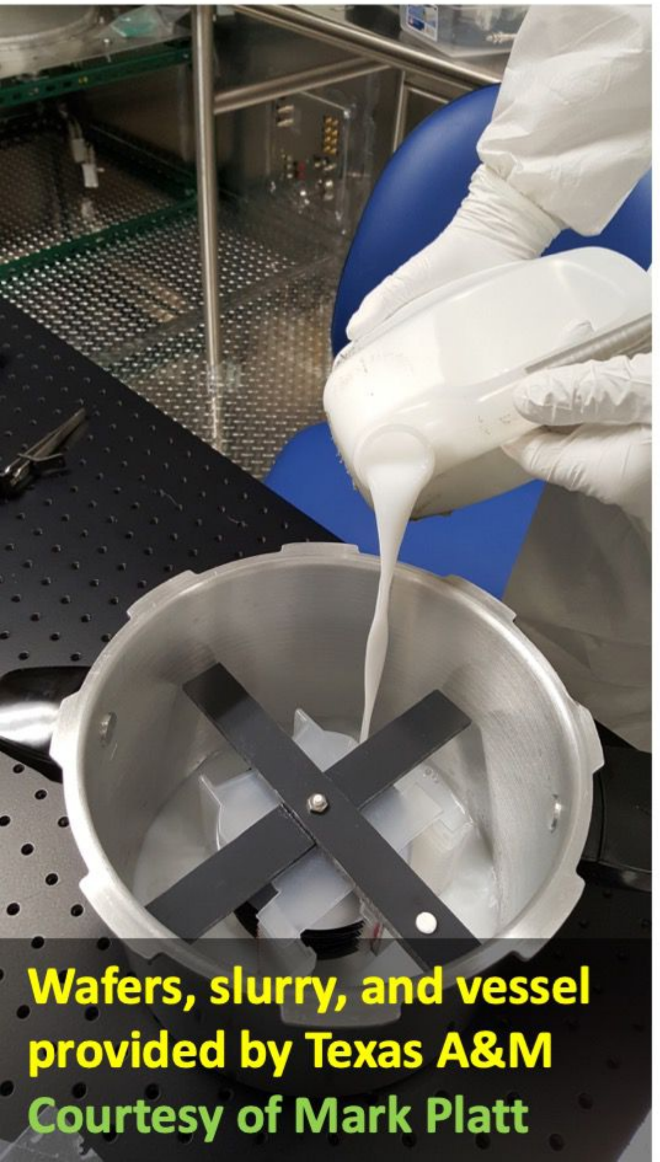


^{210}Pb contamination during polishing can come from:

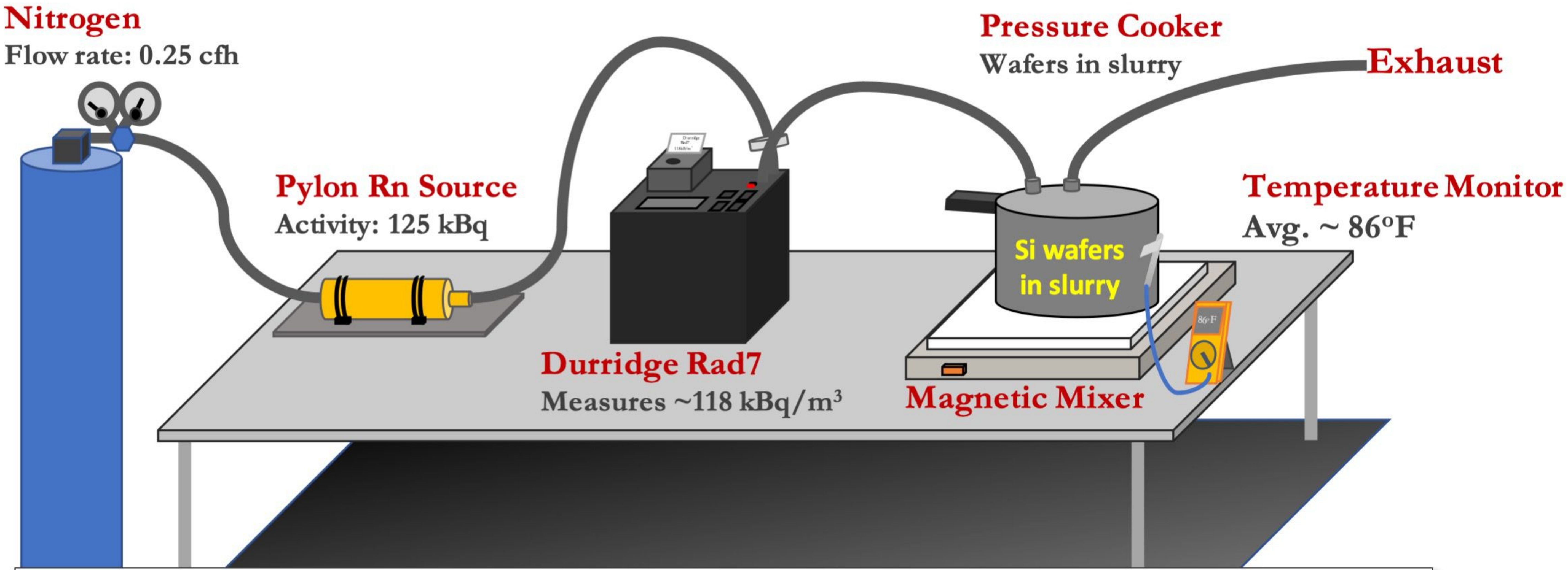
1. **Exposure to environmental radon**
   → When detectors are exposed to air (≤5% of total time)
2. **Radon in or diffusing through polishing slurry**
   → measured to be negligible (as shown on next slide)

Radon-Daughter Plate-out During Detector Polishing





1. Si wafers are placed in polishing slurry
2. High-radon nitrogen fills the gas volume above the slurry
3. Radon diffuses through the slurry and its daughters plate out onto the Si wafers
4. The Si wafers are assayed (using an XIA, courtesy of Rob Calkins at SMU)



Assay indicates:

→ **Plate-out rate during polishing is $<10^{-5}$ (nBq/cm^2)/day/(Bq/m^3)**

→ **Under expected Rn concentration, plate-out will be negligible!**

Environmental Radon : Model Assumption and Measurement

- We model exposure during the full life cycle of detector fabrication
- Detailed measurements are made before and during procedures
- Originally assumed radon concentrations tend to be conservative
- Plate-out is found from environmental radon concentrations and exposure time

Site	**Measurement date**	**Measurement Rad7 [Bq/m³]**	**Plate-out model assumption [Bq/m³]**
Stanford Underground (SUF) Tunnel C (storage)	20th Nov 2017	36 +/- 1	-
Stanford Underground (SUF) Tunnel A (lot-B polishing)	29th Oct 2017	33 +/- 1	100
TAMU polishing – general (during Ge lot-A for Tower 1)	July-Sep 2017	19 +/- 7	26
TAMU polishing – LN purge	23rd Feb 2016	< 0.7	0.001
TAMU photolithography	20th Oct 2017	5.6 +/- 0.2	12
Stanford thin-films (B04)	1st Nov 2017	9.42 +/- 0.035	20
Stanford Nanofabrication Facility (SNF)	27th Jan 2010	11 +/- 4	12
Stanford Detector Packaging (RSF)	1st Nov 2018	11.7 +/- 0.4	5
SLAC Tower assembly (B33)	24th Feb 2014	8 +/- 5	15
SLAC B33 LN purge	April 25, 2018	0.053 ± 0.016	0.001

SuperCDMS SNOLAB : Tower and Detector Copper

Tower Materials

→ comprise the dominant line-of-sight backgrounds for the experiment (other than the detectors themselves)

→ are the largest mass near detectors

  → background due to ^{238}U, ^{232}Th, ^{60}Co and ^{210}Pb contaminants

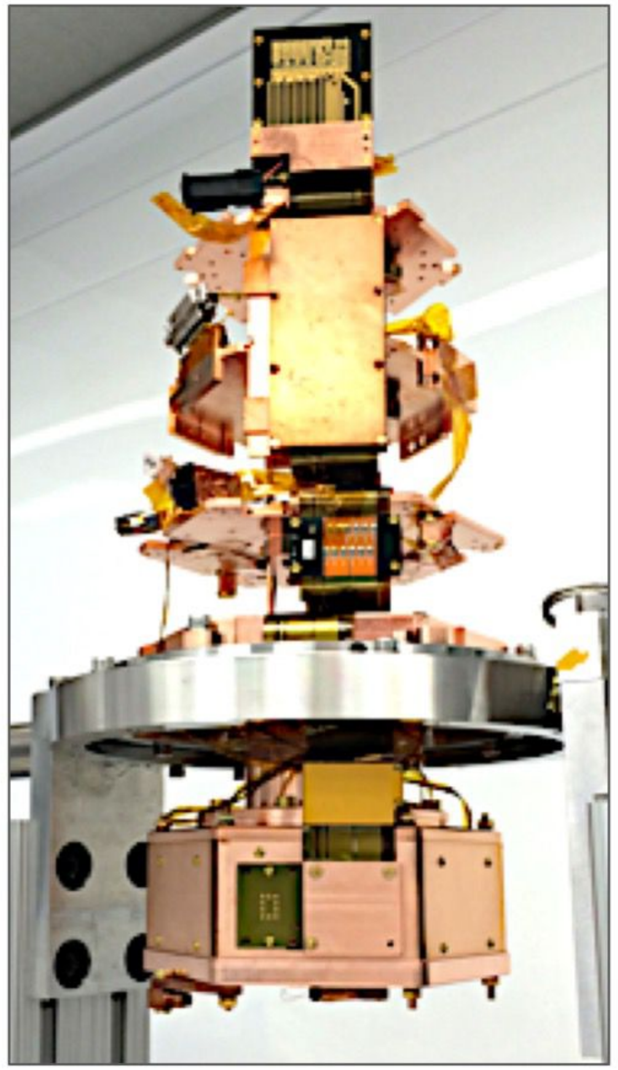
→ must meet mechanical, electrical, and thermal specifications

Commercial OFHC copper is a practical solution:

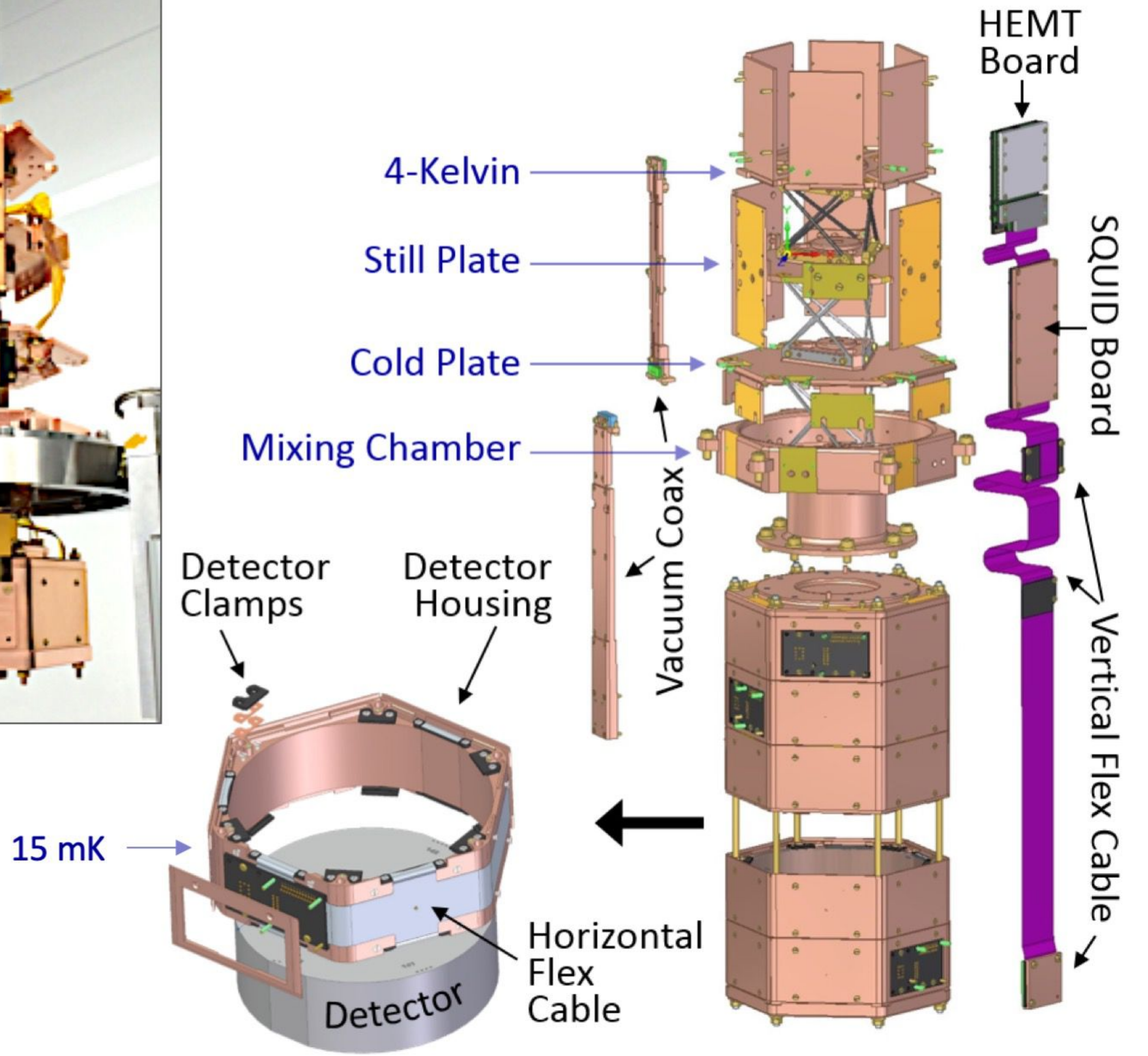
→ High chemical purity (99.99%)

→ Aurubis copper selected

Pathfinder Tower



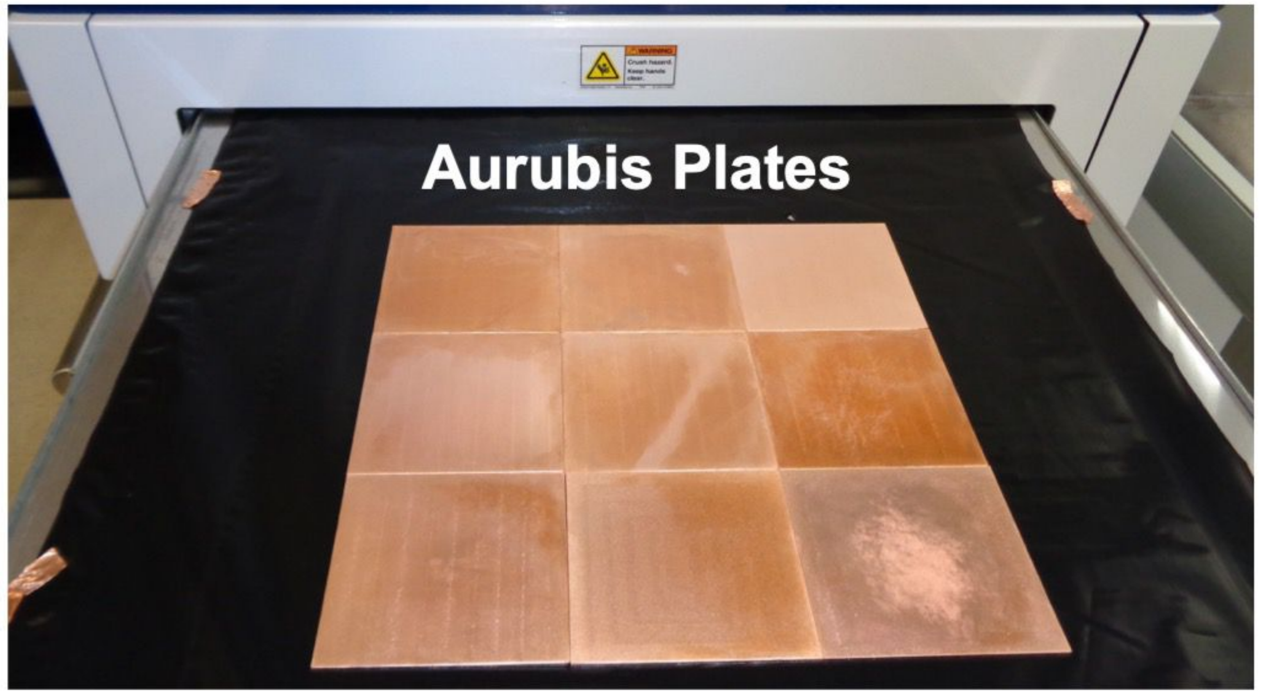
Detector Tower



OFHC = **O**xygen **F**ree **H**igh **C**onductivity

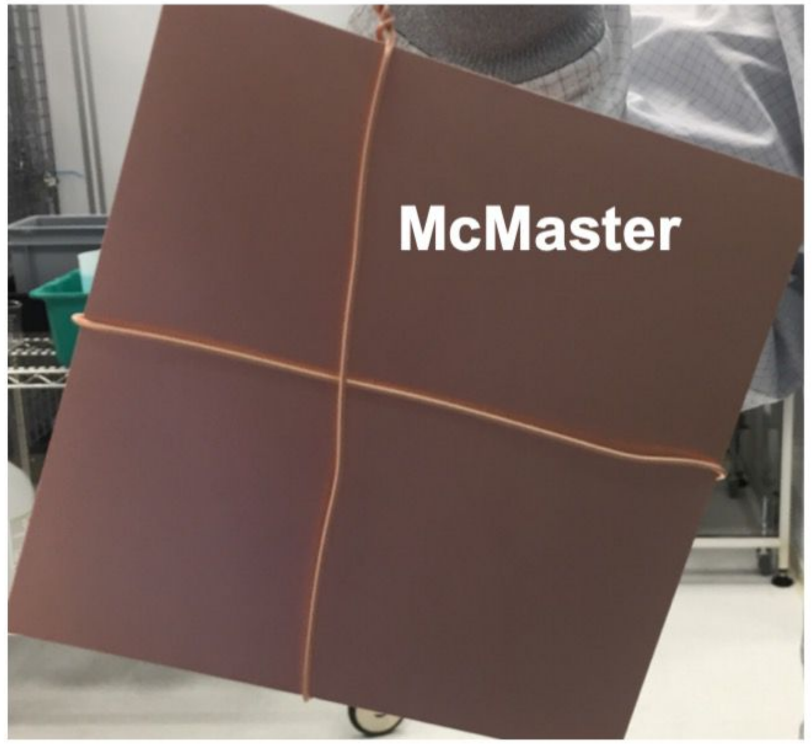
Copper Cleaning Tests

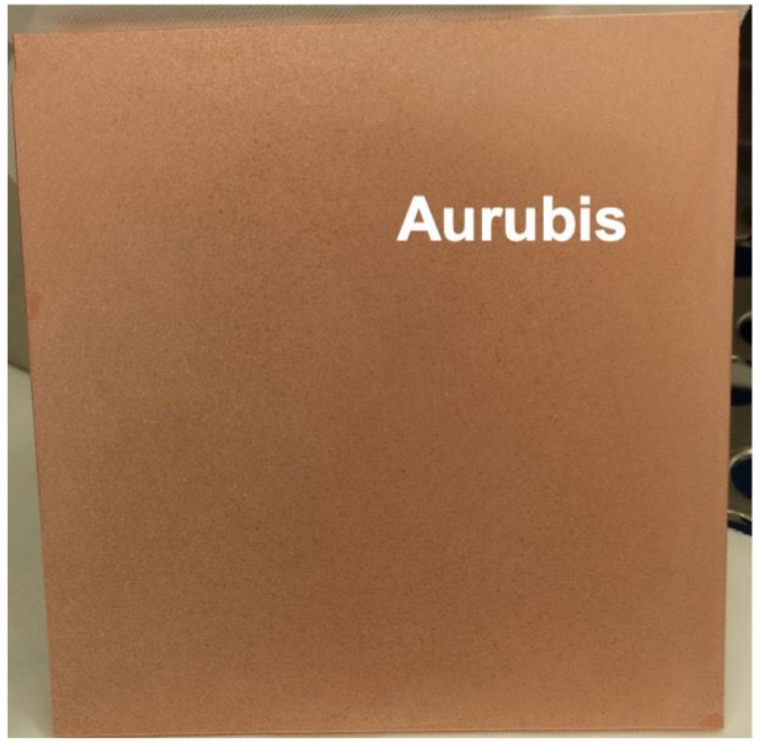
Count ^{210}Po alphas with XIA UltraLo-1800 at SMU



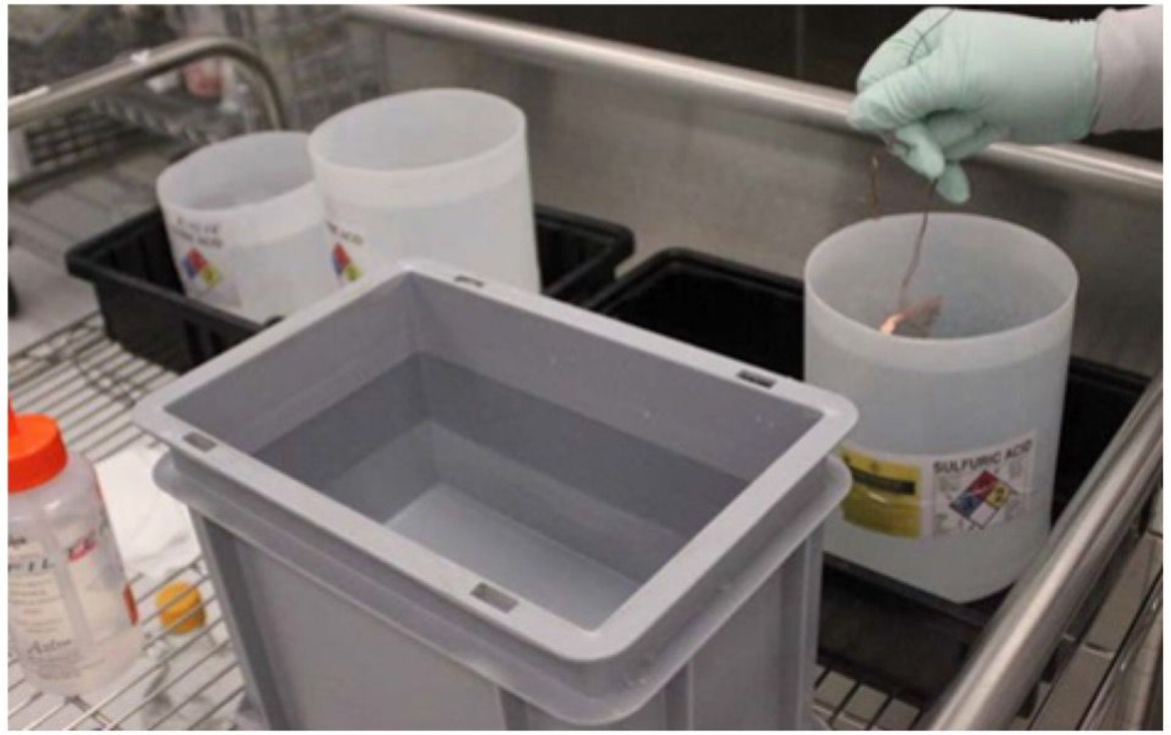
Two Samples of OFHC Copper Tested

1. Plate stock from McMaster
   - Four 6”x6” plates
2. Aurubis copper rod stock
   - Nine 4”x4” plates
   - Same stock used for first two detector towers





Etch with PNNL acidified peroxide recipe, passivate with citric acid, dry & bag in nylon



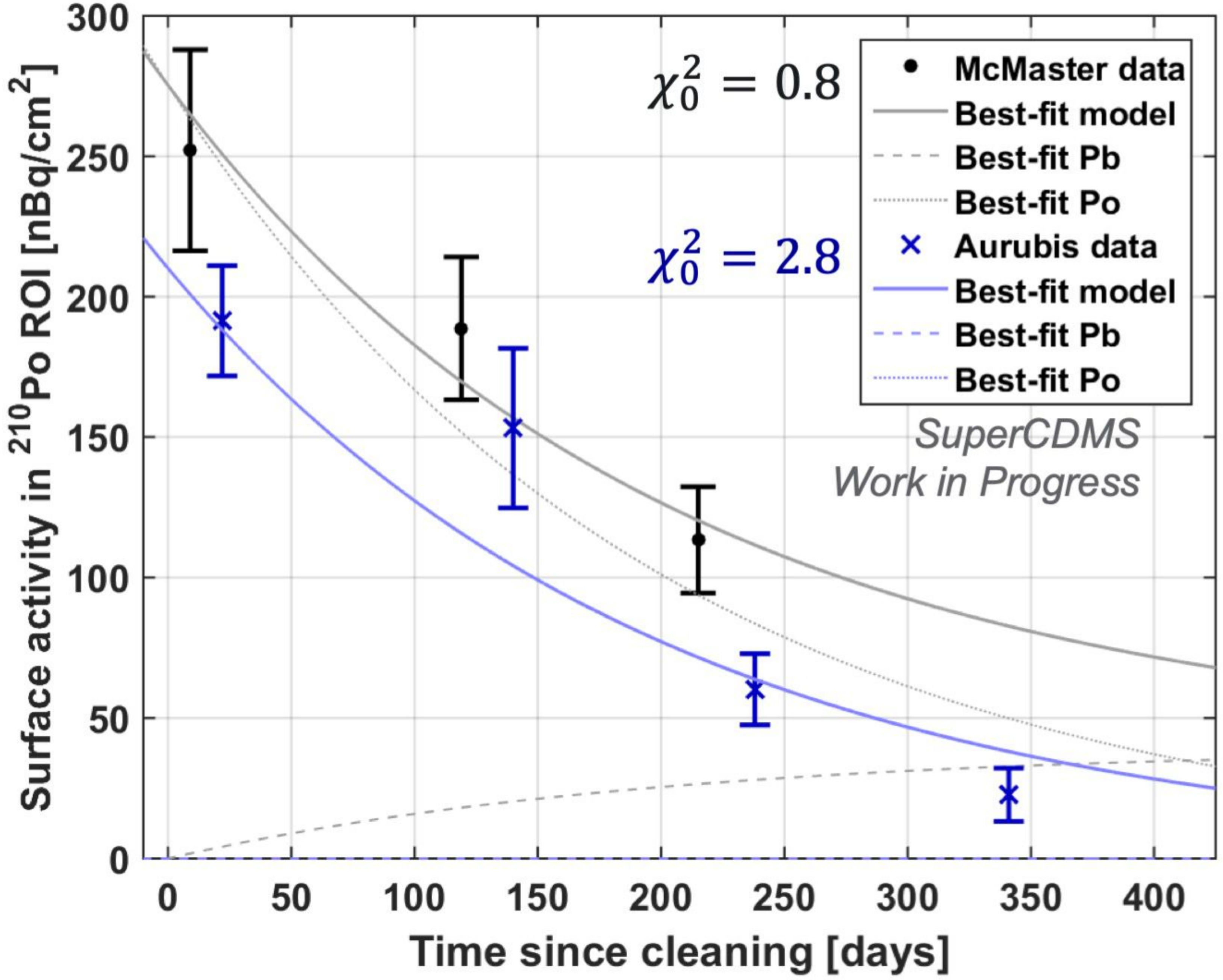
Large-area plates to optimize alpha-counting sensitivity
Machined at SLAC using best-effort cleanliness protocols:
→ *clean mill, new tools, fresh cutting fluids, minimal contact*

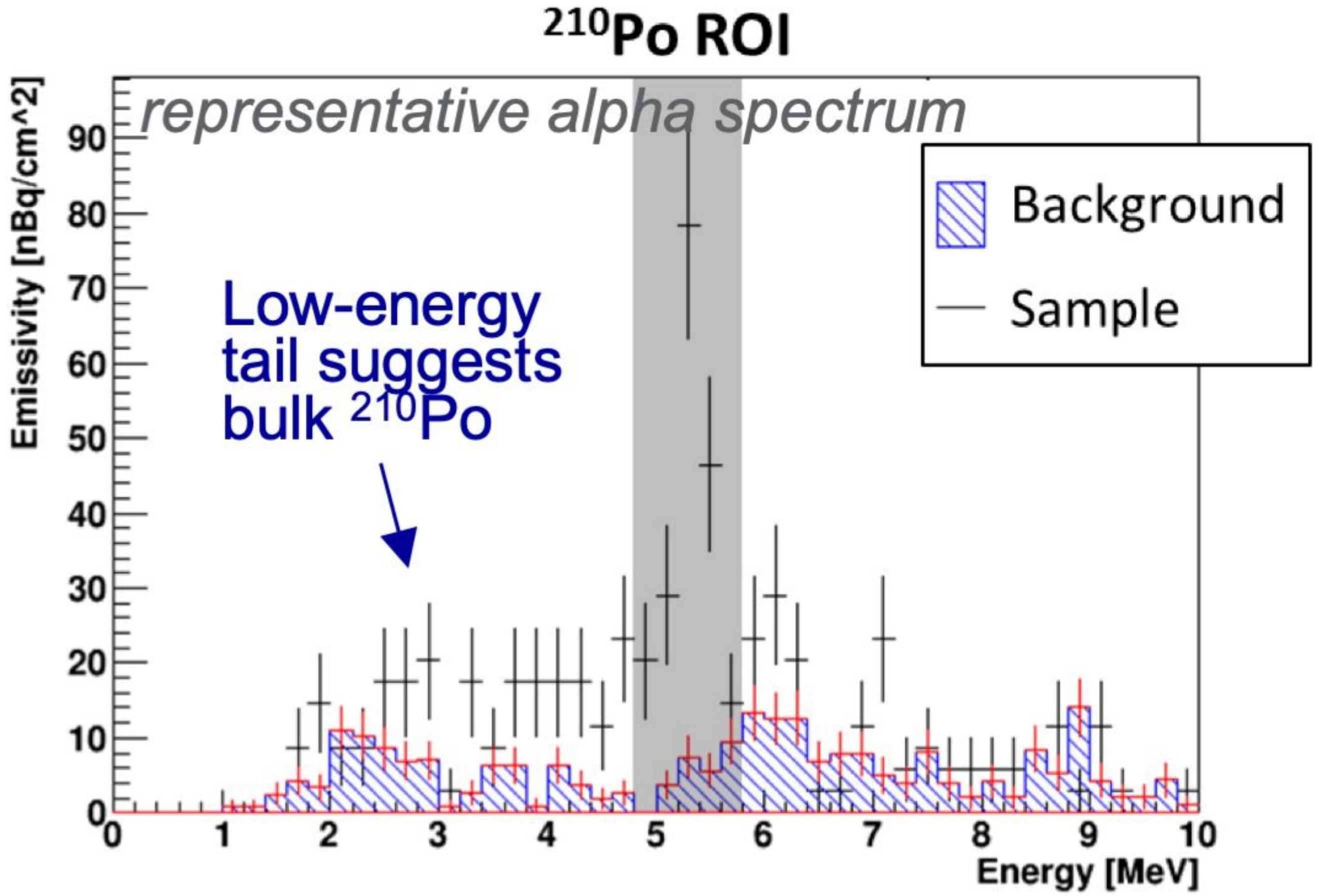
PNNL Recipe → Hoppe et al. NIM A ***579*** *(2007) 486*

slide courtesy of Ray Bunker

Copper Cleaning Tests Results

^{210}Po surface activity decreases vs. time:
→ suggests near-zero ^{210}Pb on surface





Best-fit post-cleaning activities

McMaster plates:
^{210}Po = 275 ± 35 nBq/cm^2
^{210}Pb = 42 ± 37 nBq/cm^2

Aurubis plates:
^{210}Po = 210 ± 21 nBq/cm^2
^{210}Pb = 0 ± 12 nBq/cm^2

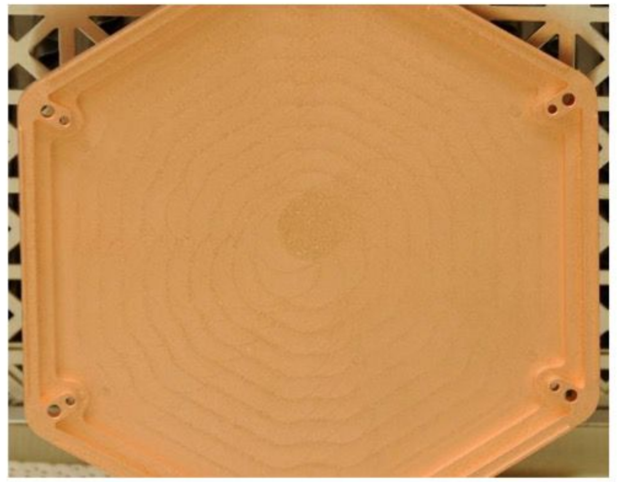
^{210}Po likely etched from copper bulk & redepositing on surface

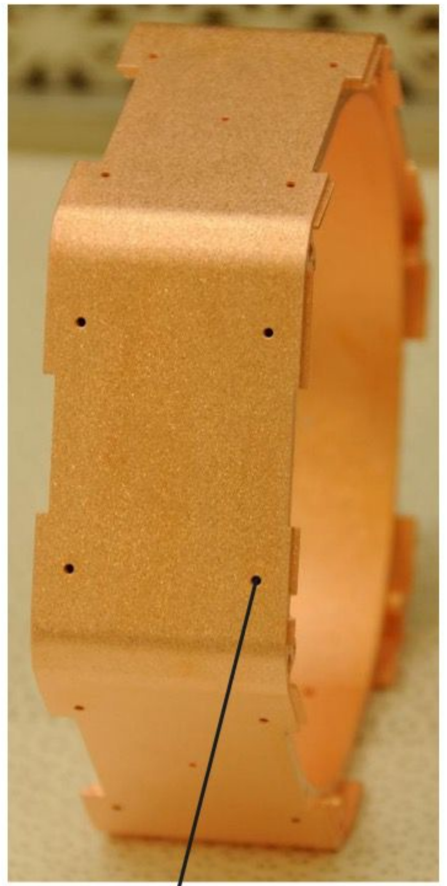
Demonstrated ^{210}Pb background level meets SuperCDMS goal for copper surface

slide courtesy of Ray Bunker

Pacific Northwest NATIONAL LABORATORY

Mitigation of Surface Pb/Po





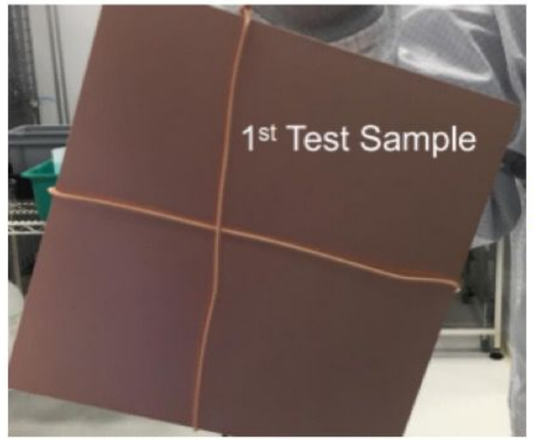
PNL electroformed copper is the most radiopure in the world

→Expect significantly lower bulk ^{210}Pb and ^{210}Po

→*Strategy:* electroform thin layer onto parts fabricated from commercial OFHC copper (*e.g.* detector housing)

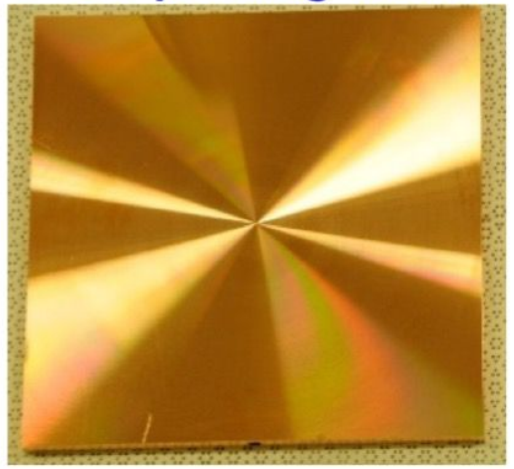
→Used McMaster plates with well-characterized ^{210}Po surface activity

Original OFHC plate



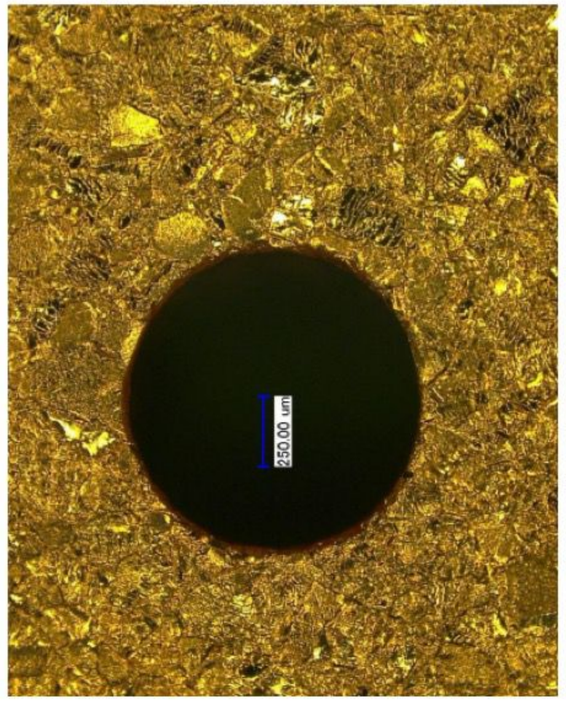
Pre-plating treatment

Post-plating finish



Bare OFHC copper

+40 µm PNNL copper

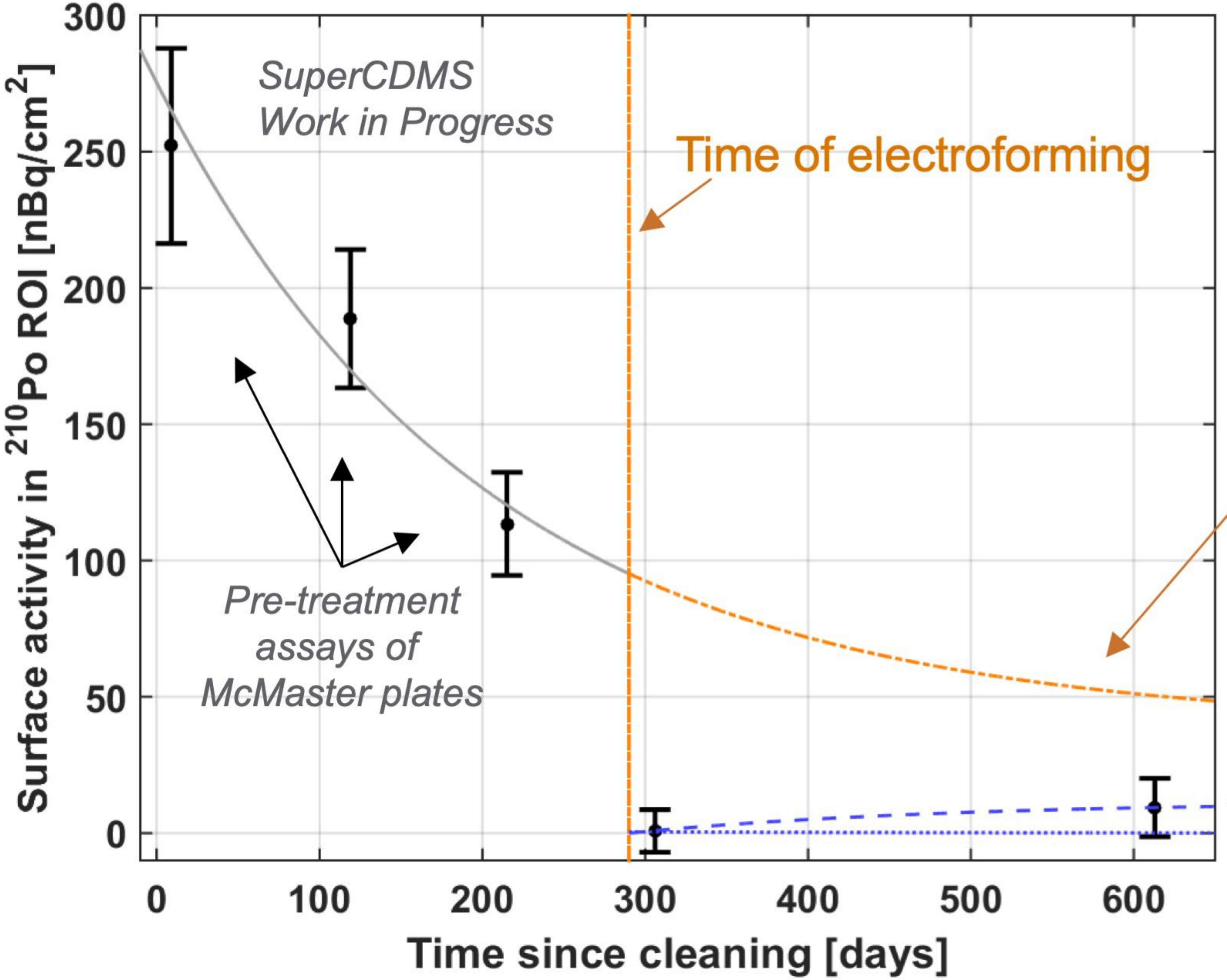


→ Re-assay following plating

→ Also apply to detector housing to demonstrate ability to apply uniform coating for actual (more complicated) geometry

slide courtesy of Ray Bunker

Surface Mitigation Results



High-purity electroformed copper acts as a shield against underlying ^{210}Po contamination

Expected ^{210}Po activity without treatment

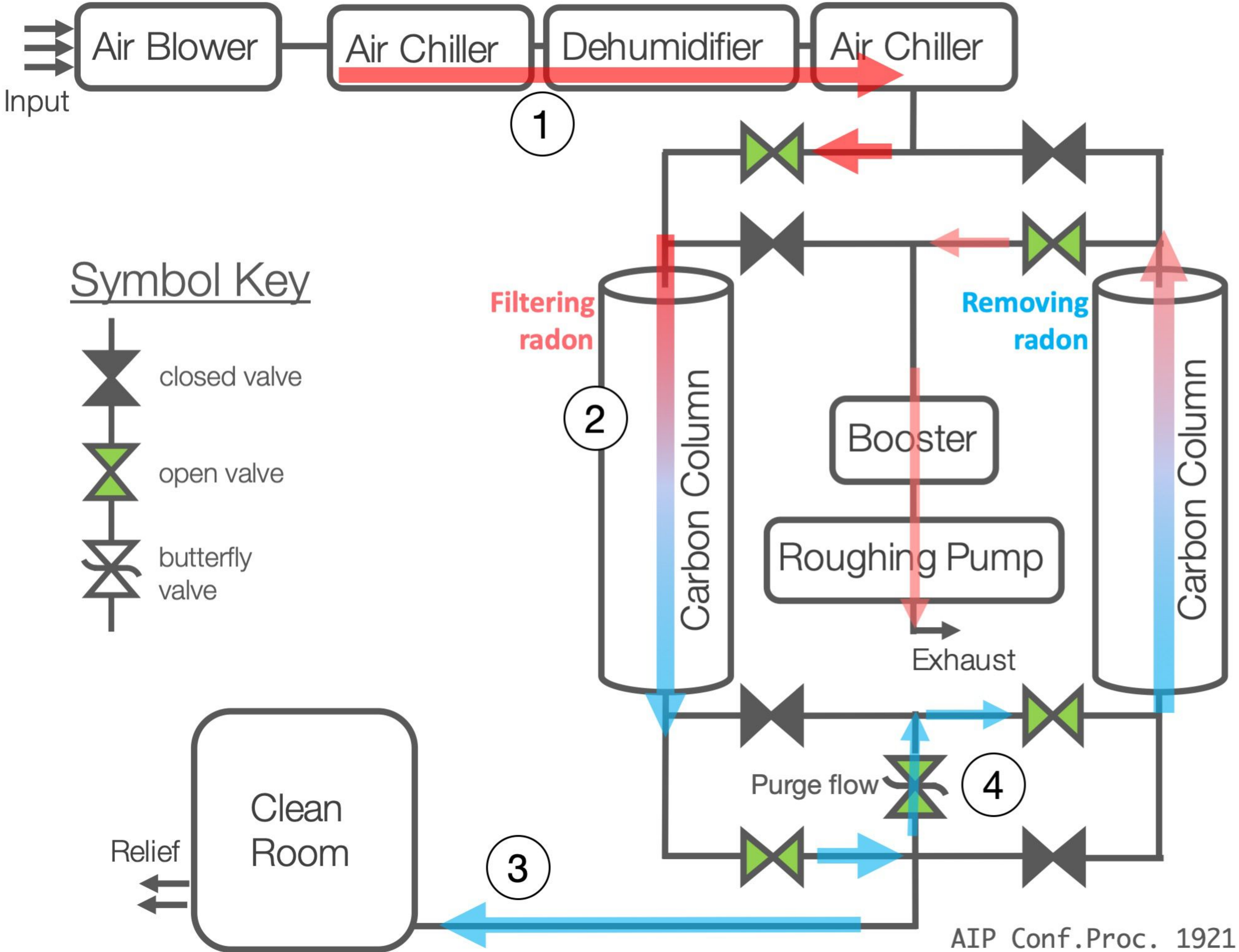
Post-treatment analysis

Best-fit Pb-only hypothesis:
^{210}Pb = 12 ± 14 nBq/cm^2

Best-fit Po-only hypothesis:
^{210}Po = 1.4 ± 8.3 nBq/cm^2

slide courtesy of Ray Bunker

Radon-Mitigation System : “Swing” Operation



① **High-radon air** (~130 Bq/m³) is dehumidified, but not heated

② Dehumidified air passes through a carbon column and radon in the air adsorbs to sites on the activated carbon

③ Most of the **radon-mitigated air** is supplied to a cleanroom

④ Some **radon-mitigated air** is pumped (at low pressure) through the 2nd carbon column removing radon from it

❖ The system “swings”—radon in the 1st column is removed while the 2nd begins filtering radon.

AIP Conf.Proc. 1921 (2018) no.1, 050002or arXiv:1708.08535

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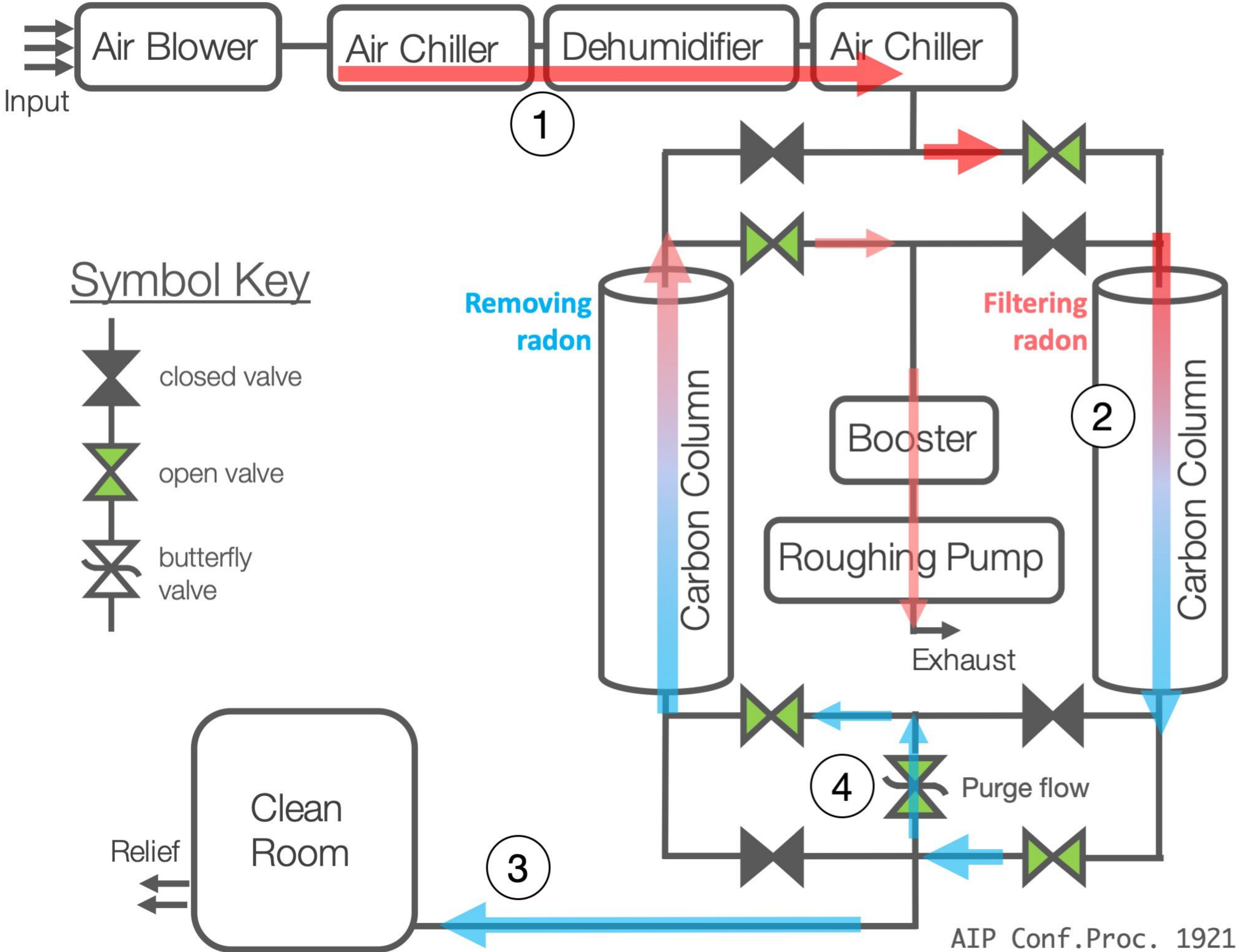

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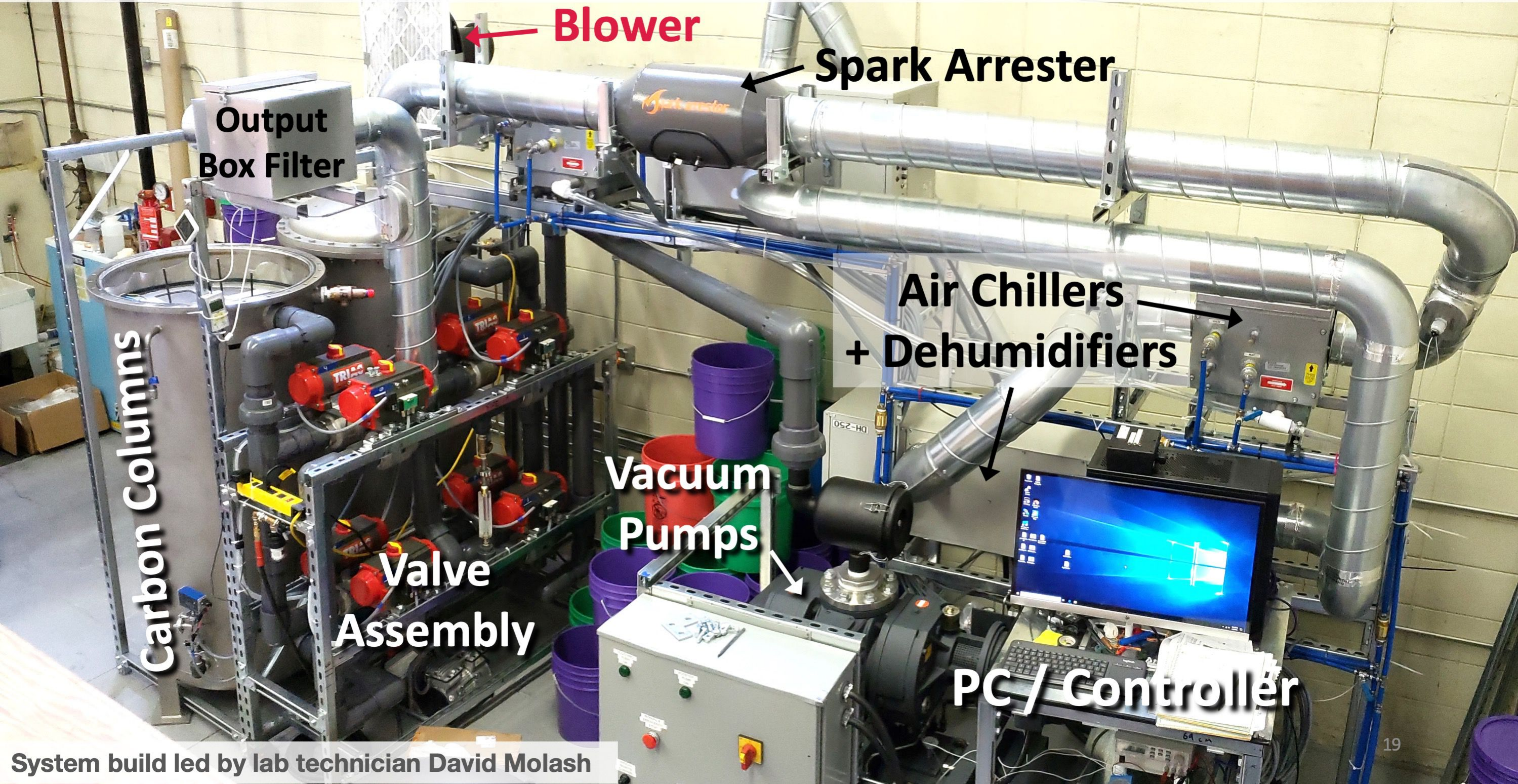
Radon-Mitigation System : Built at SDSM&T



System build led by lab technician David Molash

Radon-Mitigation System : Simulation

Uses for a simulation

- Better understanding vacuum-swing adsorption
- Troubleshooting and optimizing the physical system
- Inform designs of future systems

Simulation Basics

$\boldsymbol{c}(x,t)$ = radon concentration in a column, as a function of distance x and time t.

Matrix operators evolve the elements of $\boldsymbol{c}(x,t)$ by Δt for

- Filtering – flowing forward
- Regenerating – flowing backward
- Slow-filling – flowing backward while raising the column to atmosphere

arXiv:1708.08535 (or talk to me)

Radon-Mitig… System : Simulation

What is “slow-fill” ?

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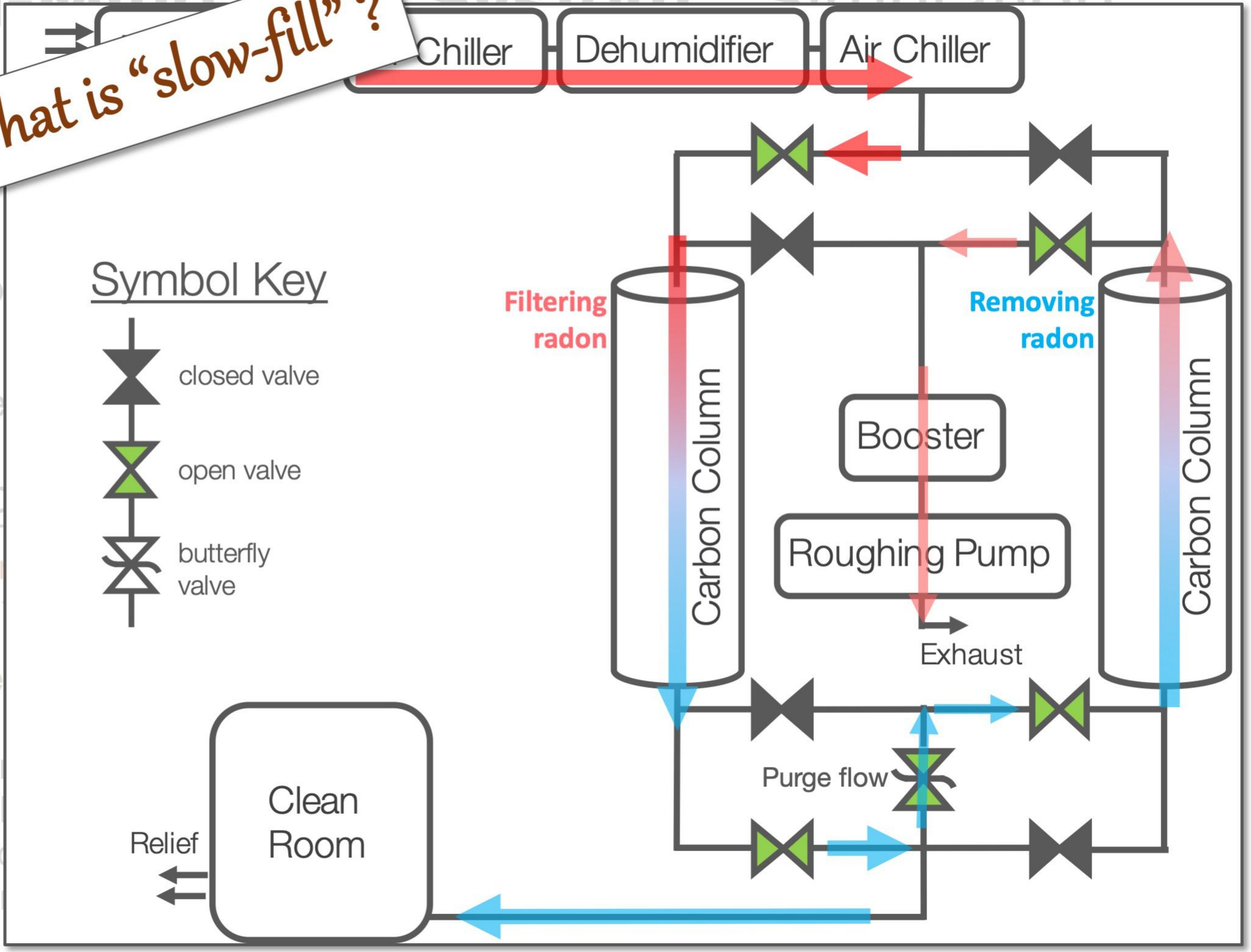

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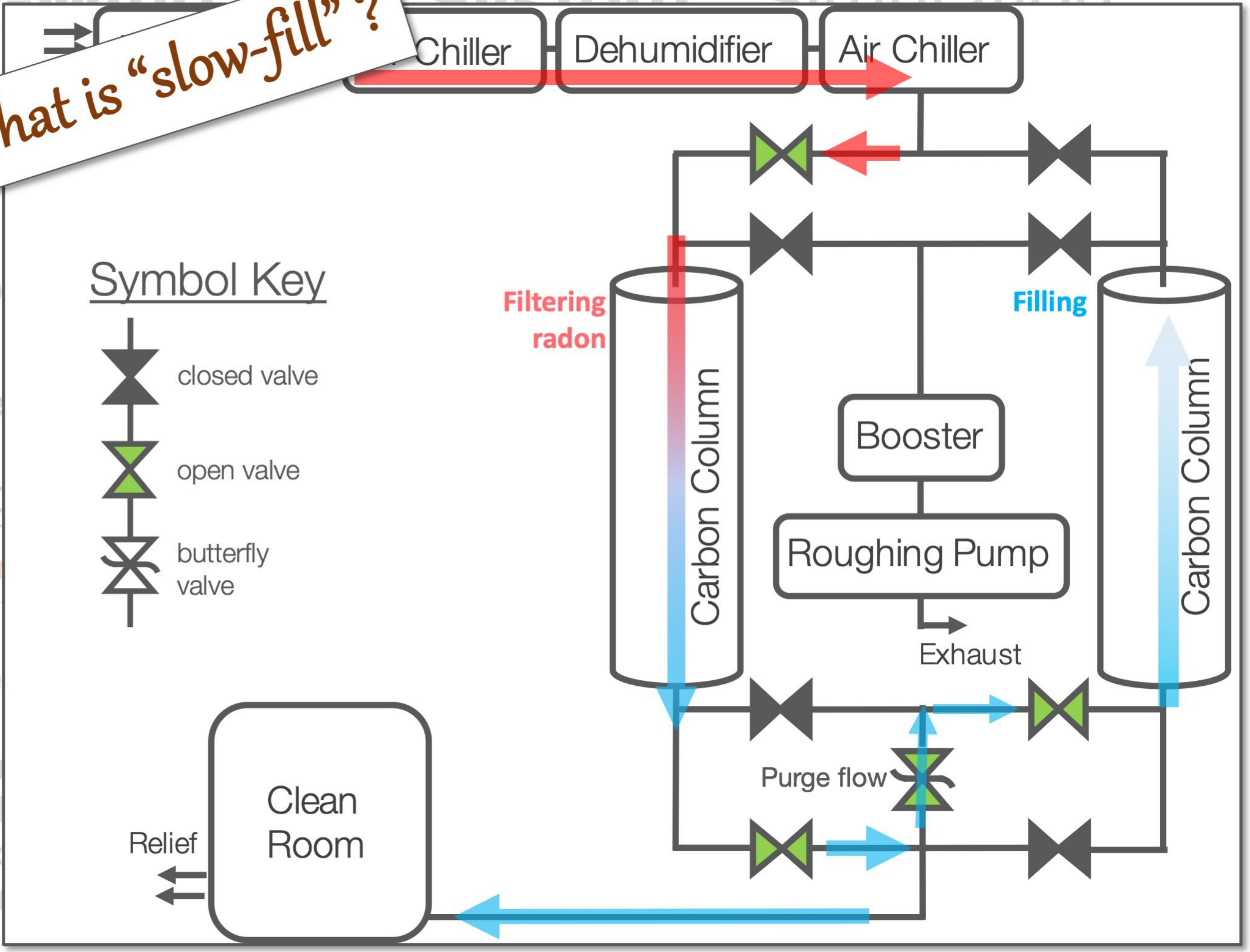

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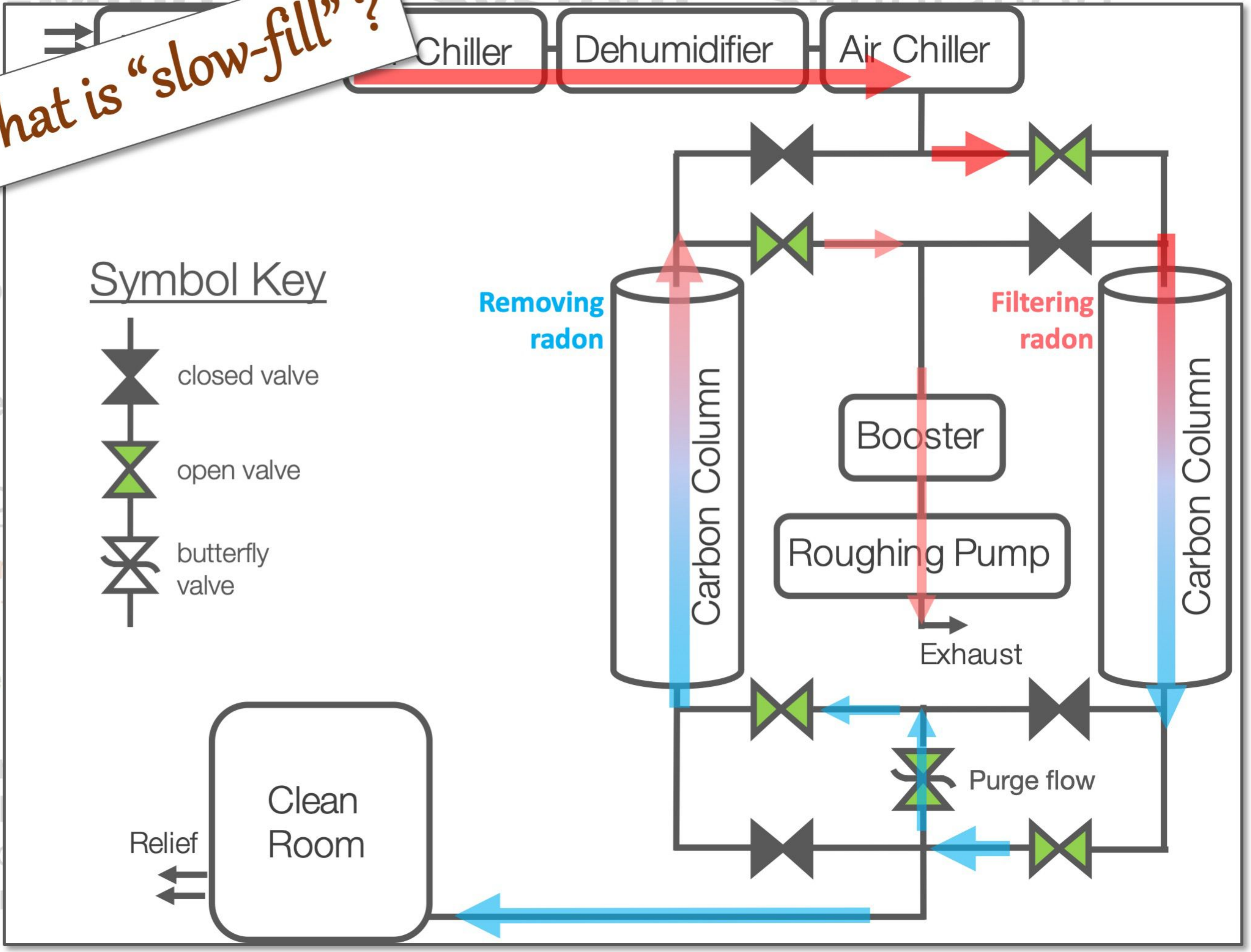

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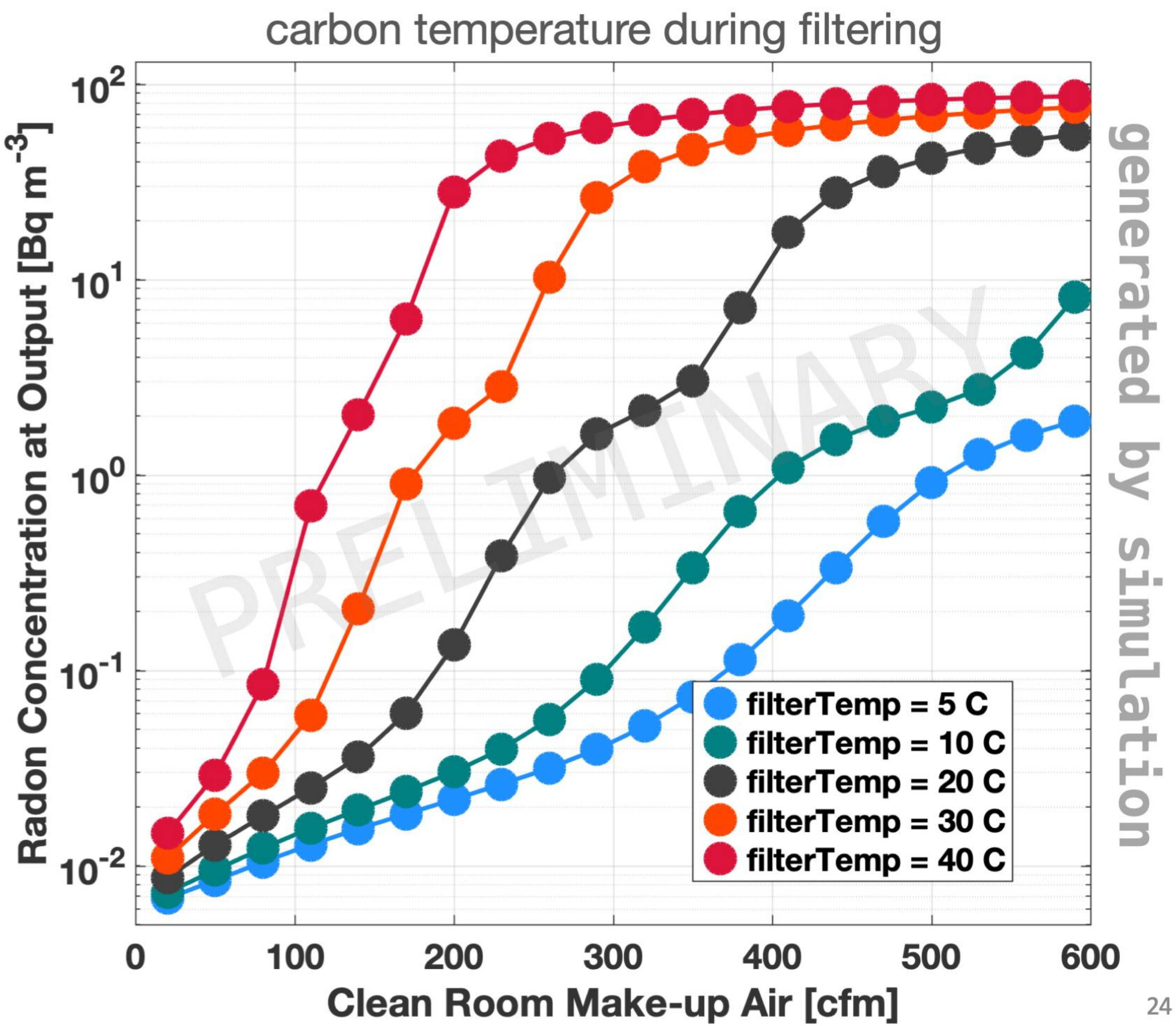

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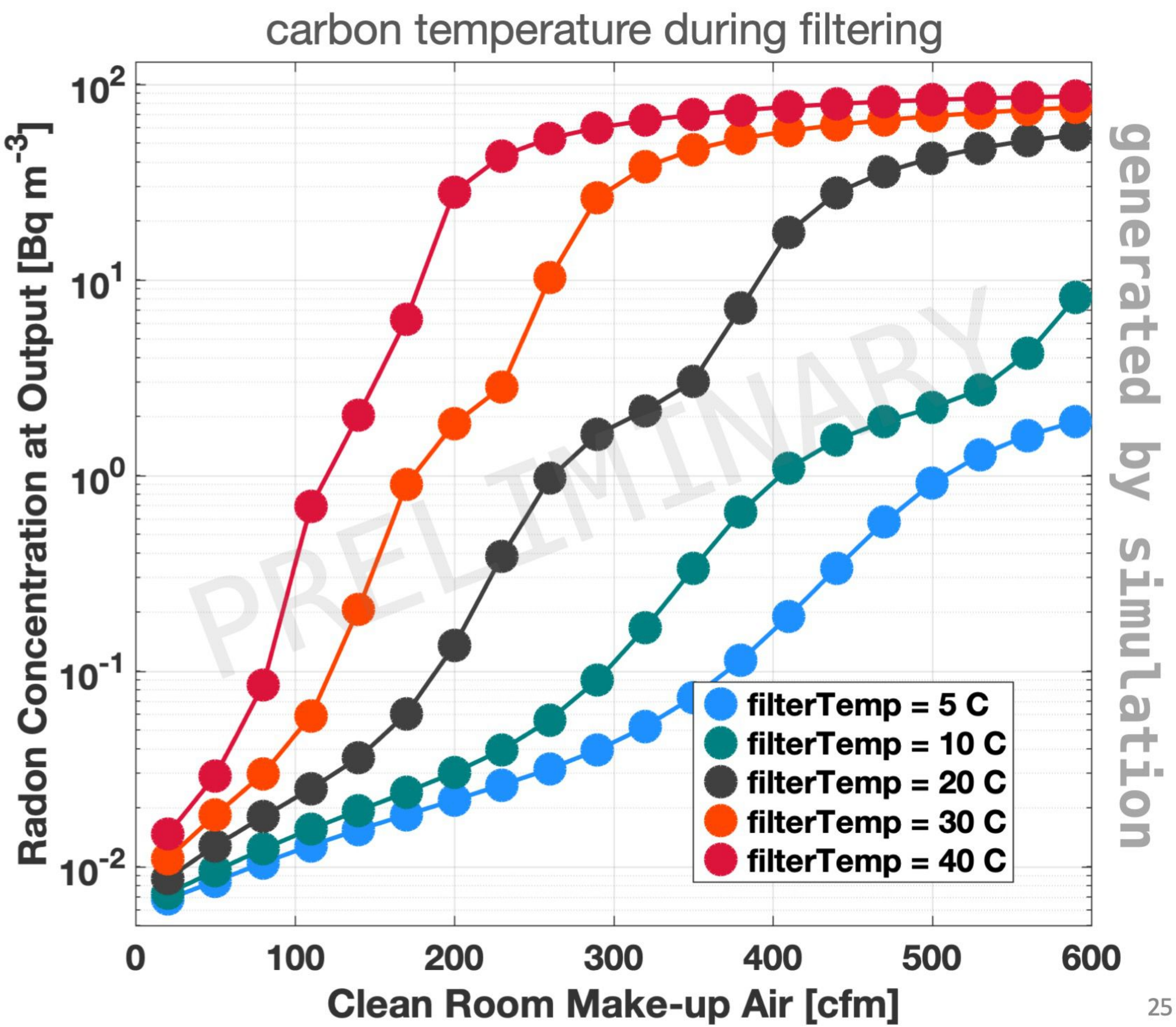
Radon-Mitigation System : Simulation

Some observations...

- **Further cooling input air could improve reduction at higher flows**



Radon-Mitigation System : Simulation

Some observations...

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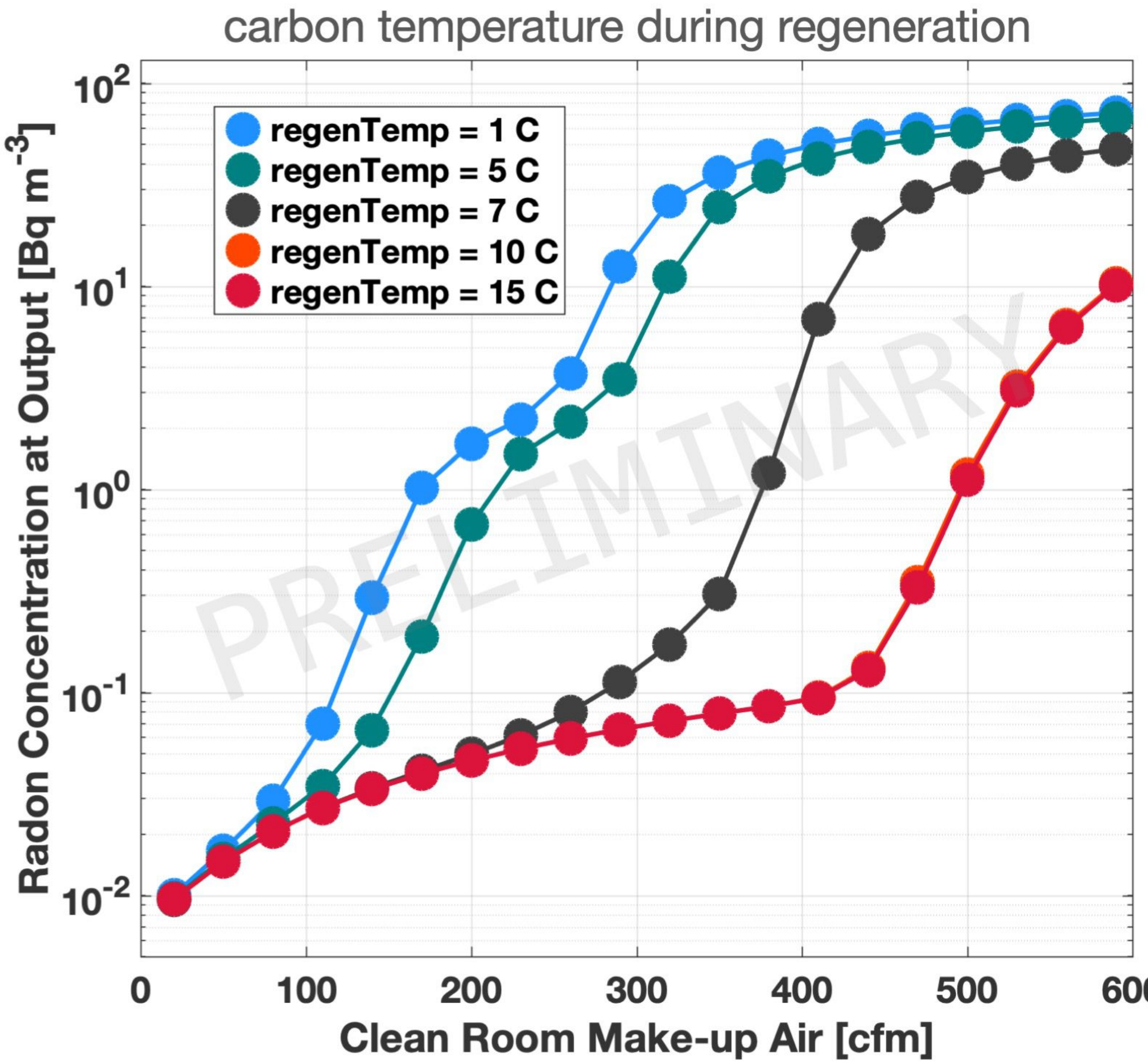

generated by simulation

Radon-Mitigation System : Simulation

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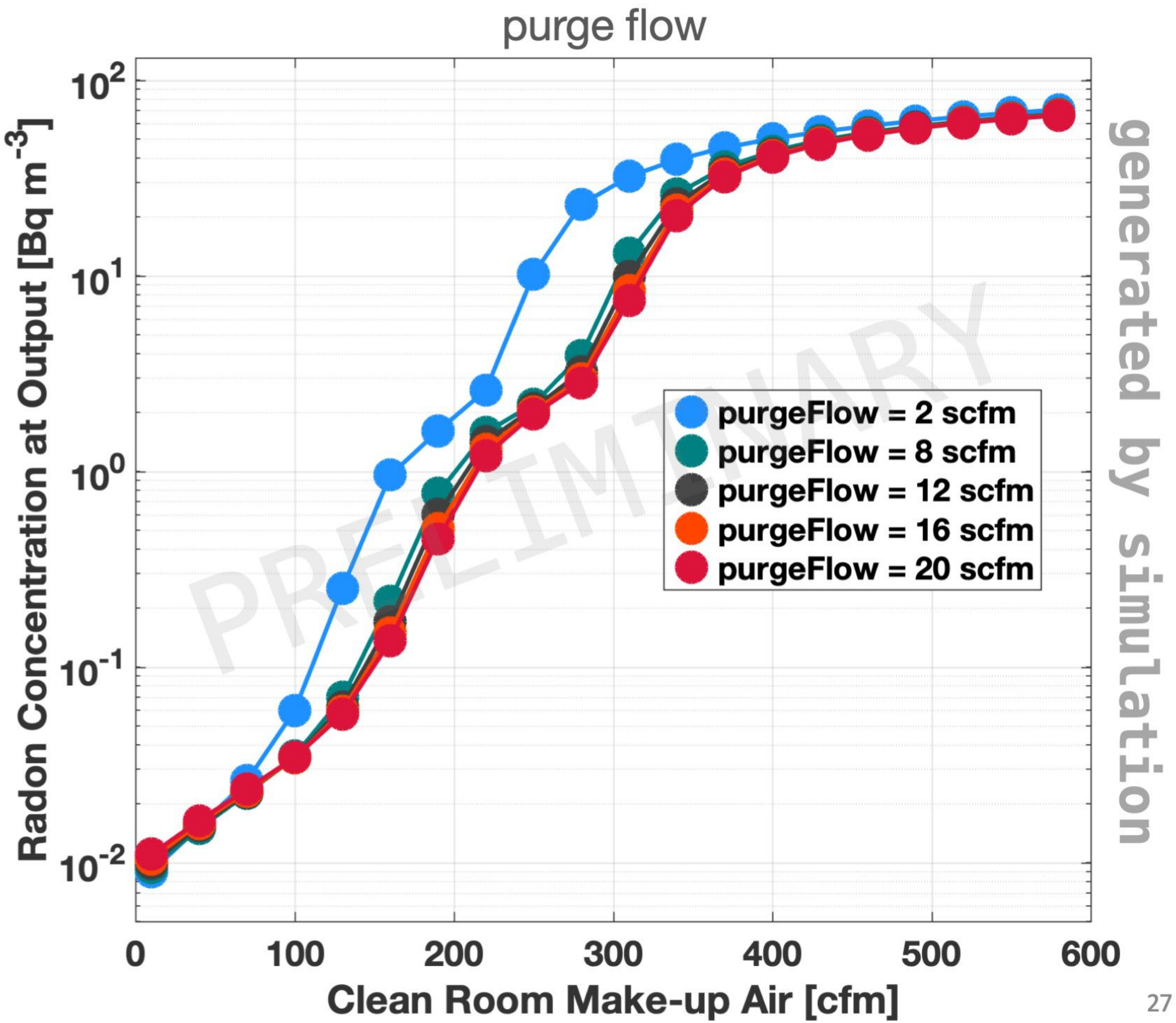
- **Increasing the purge flow rate doesn't really improve performance**



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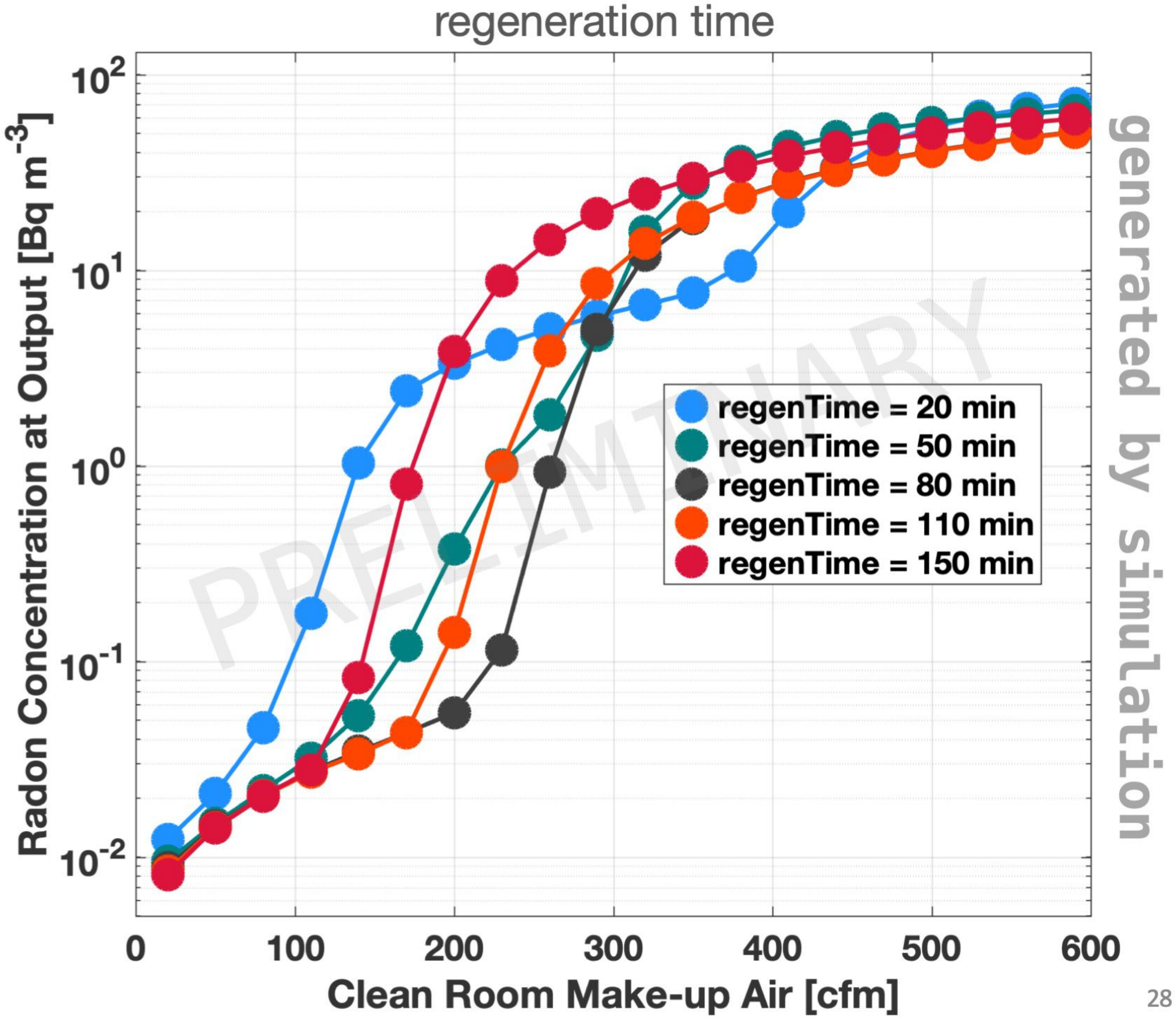
- **For this configuration, there appears to be a best cycle period of ~80 minutes**



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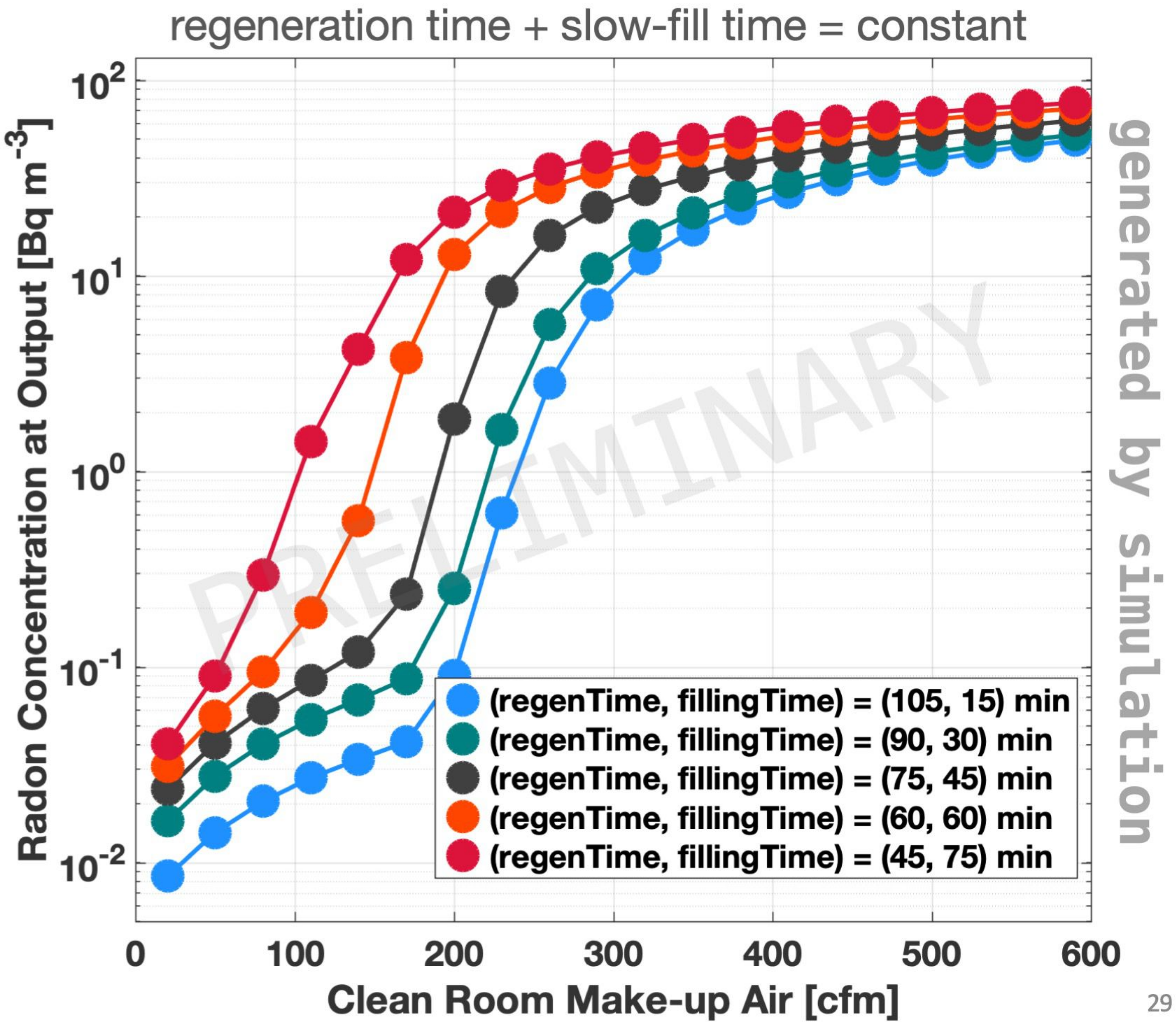
- **As intuition would suggest, time regenerating should be maximized against radon breaking through the column**



Radon-Mitigation System : Simulation

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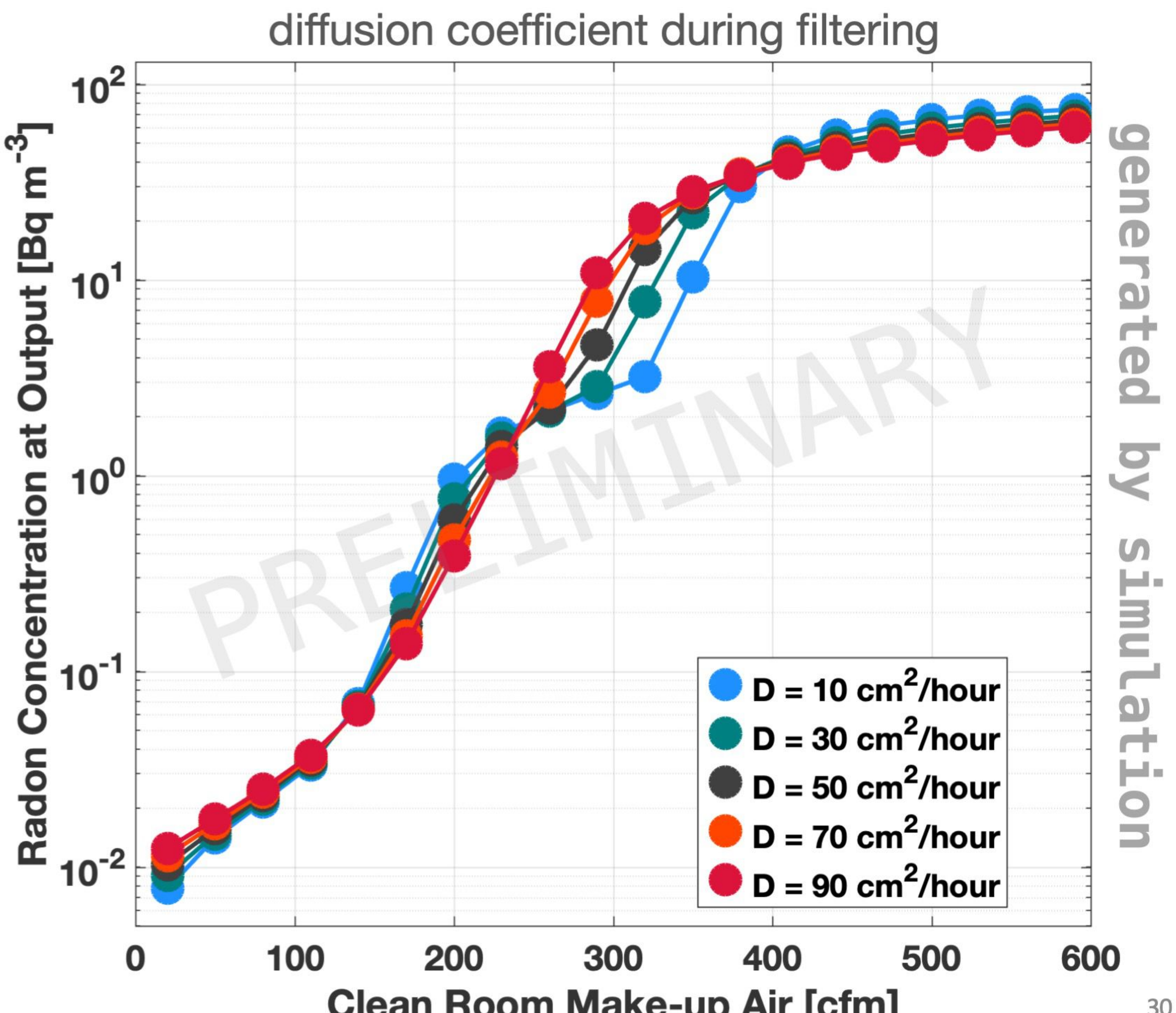
- Further cooling input air could improve reduction at higher flows
- Heating purge-flow air could provide much better regeneration (but with diminishing returns after ~10 C)
- Increasing the purge flow rate doesn't really improve performance
- For this configuration, there appears to be a best cycle period of ~80 minutes
- As intuition would suggest, time regenerating should be maximized against radon breaking through the column
- **Performance does not appear to depend heavily on the diffusion coefficient...**
  - **During filtering**



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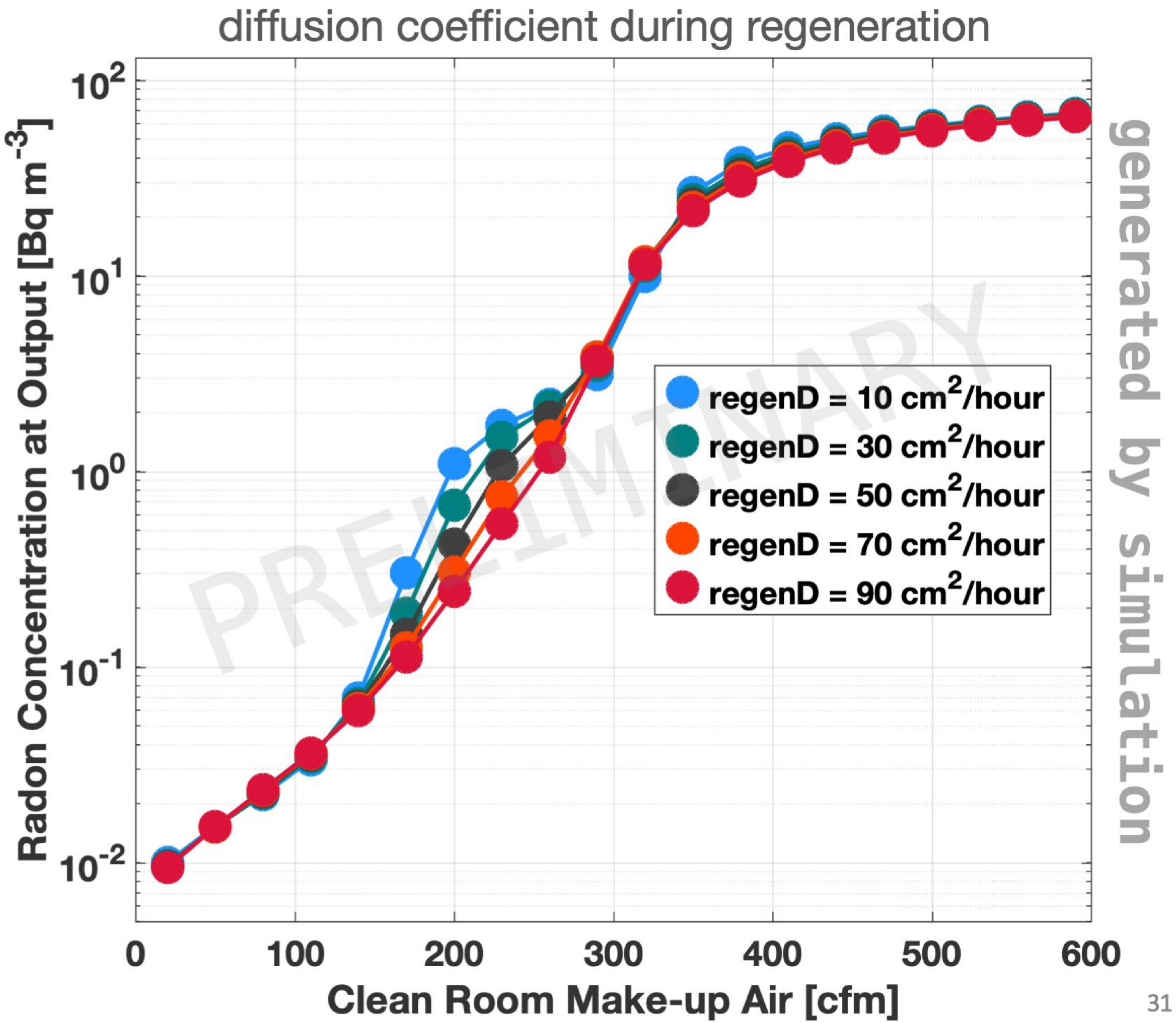

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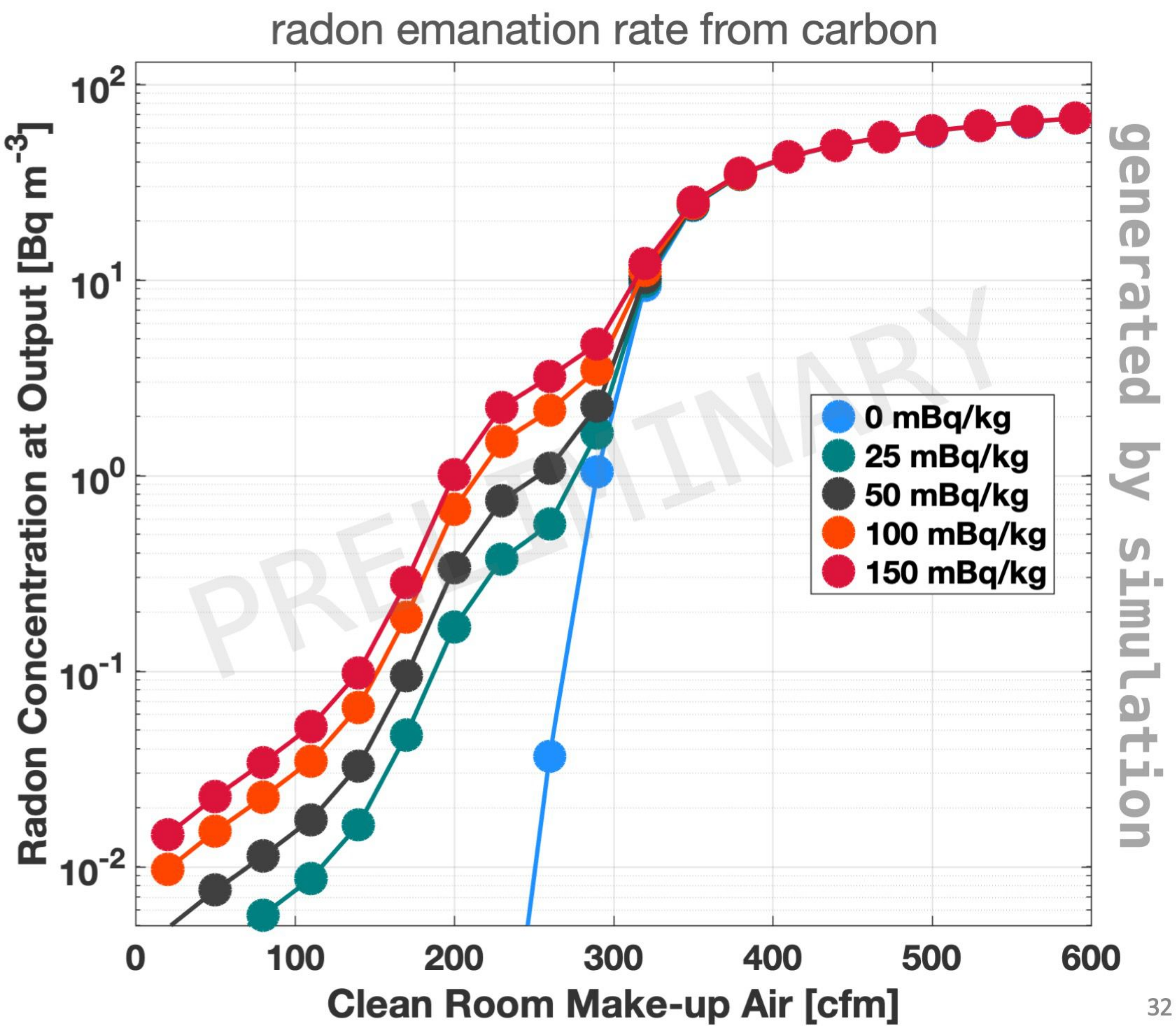
- **Radon emanating from the carbon beds determines ultimate reductions**



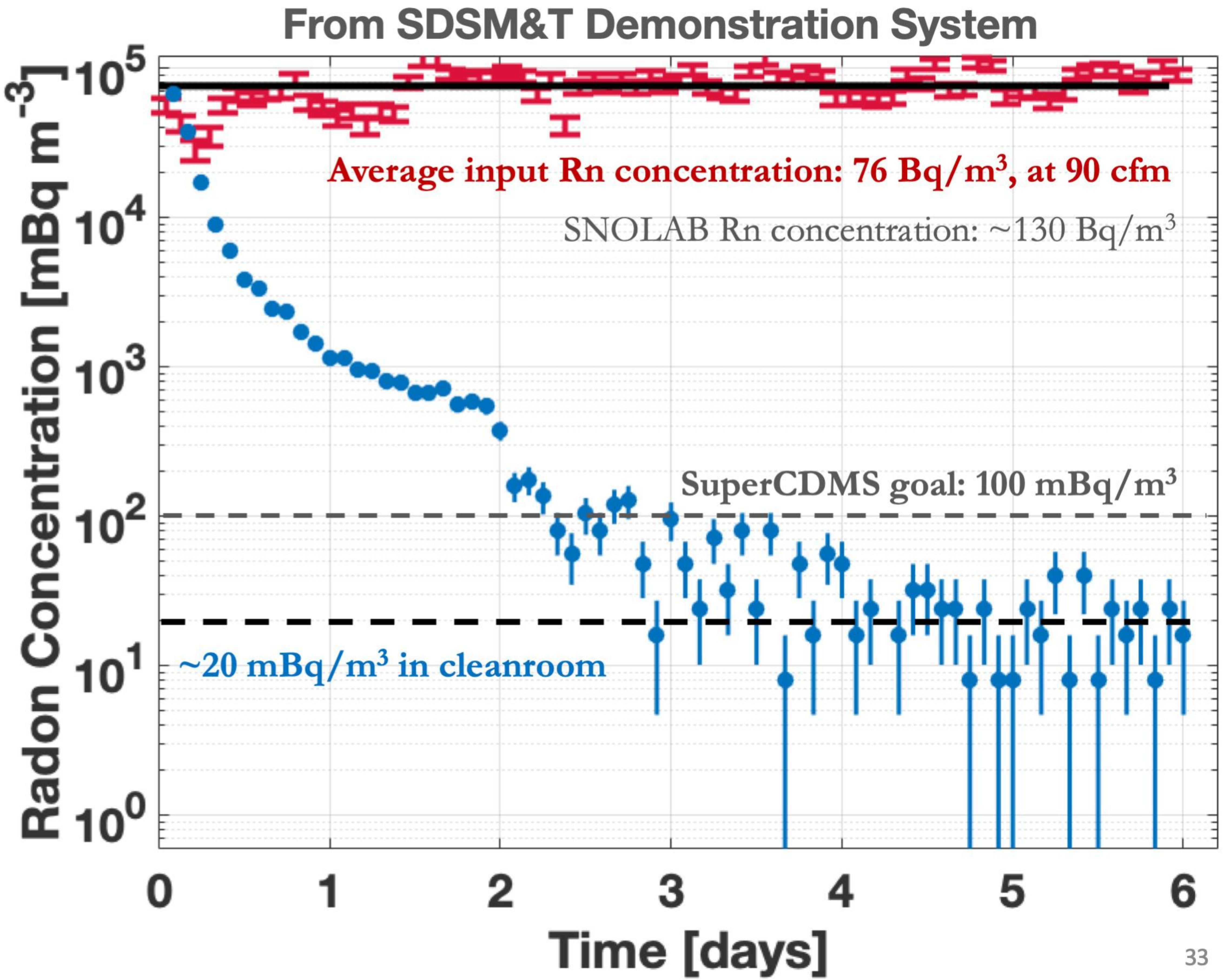
Radon-Mitigation System : Performance

The SDSM&T demonstration radon-mitigation system

- → Shows a radon reduction of about **3,800×**
- → Produces an equilibrium output radon concentration of 20 mBq/m^3

The SuperCDMS SNOLAB Rn-mitigation system should allow installation at SNOLAB with negligible contribution of ^{210}Pb on detectors and housings

Rn-daughter contamination during detector fabrication still needs to be controlled



Reducing Other Radon-daughter Contamination

Previous-generation experiment at Soudan:

→ ***Majority*** of background events from ^{210}Pb on detector sidewalls
→ Some background from detector housing (cleaner Cu for SNOLAB)

^{210}Pb at Soudan [nBq/cm^2]	
Faces	Sidewalls
30	950

Despite improvements, sidewall backgrounds still expected to dominate at SNOLAB:

→ Trenching (read etching) near end of fabrication cleans 65% of HV detector faces
→ Contamination on faces less dangerous since it may be rejected due to coincident scattering in neighboring detectors

Estimated total detector-surface budget [nBq/cm^2]	Surface ^{210}Pb	After face etch (HV) Faces	After face etch (HV) Sidewalls
Detector polishing	45	16	45
Pre-trenching fabrication	25	9	25
Post-trenching fabrication	3	3	3
Post-fabrication exposure	7	7	7
Totals	80	35	80

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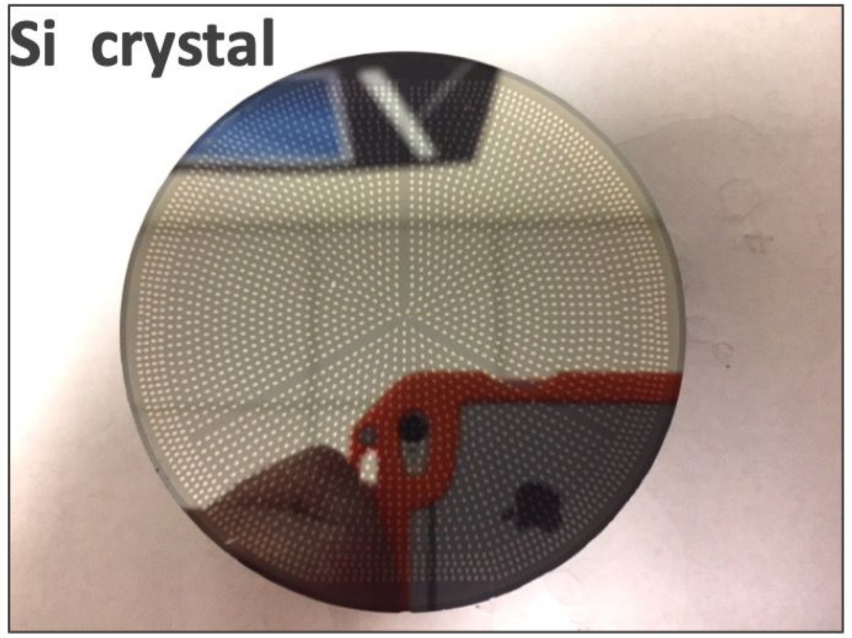
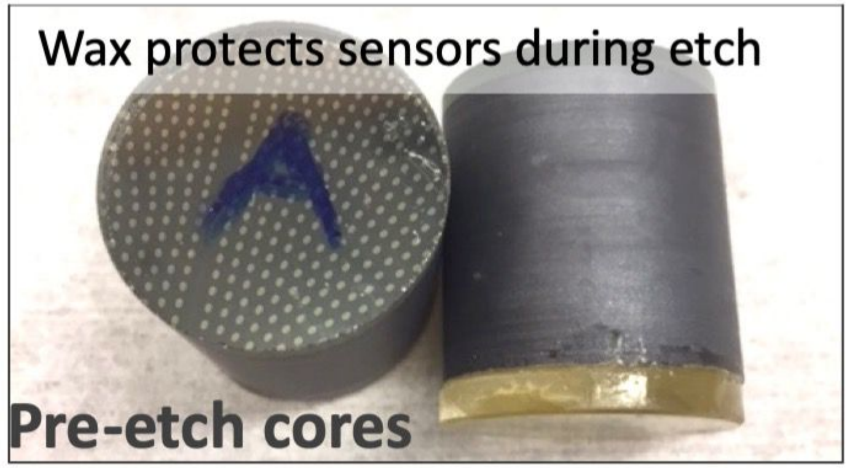
^{210}Pb at Soudan [nBq/cm^2]	
Faces	Sidewalls
30	950

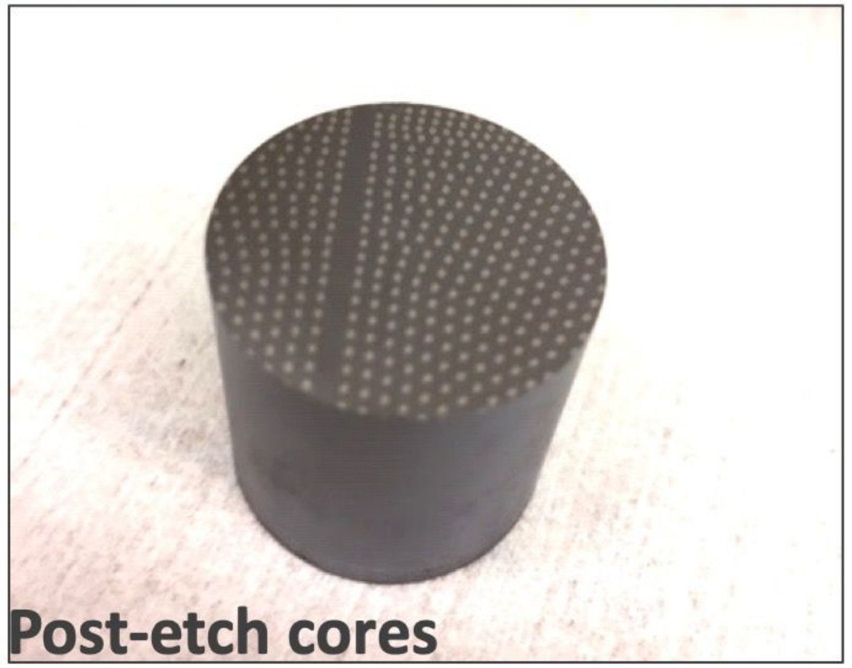
Rupak Mahapatra and Mark Platt at Texas A&M have developed a technique to etch the sidewalls *after* detector fabrication!

Estimated total detector-surface budget [nBq/cm^2]		After face etch (HV)		Sidewall etch
	Surface ^{210}Pb	Faces	Sidewalls	Sidewalls
Detector polishing	45	16	45	0.5
Pre-trenching fabrication	25	9	25	0.3
Post-trenching fabrication	3	3	3	0.03
Post-fabrication exposure	7	7	7	7
Totals	80	35	80	8

Detector Sidewall Etch Test : Procedure







Texas A&M

1. Cores were bored out of a Si crystal with the HV pattern

SDSM&T

2. Cores were exposed to high-radon air (~10^6 Bq/m^3) for about two weeks
3. Exposed cores were assayed for ^{210}Po (**pre-etch assay**)

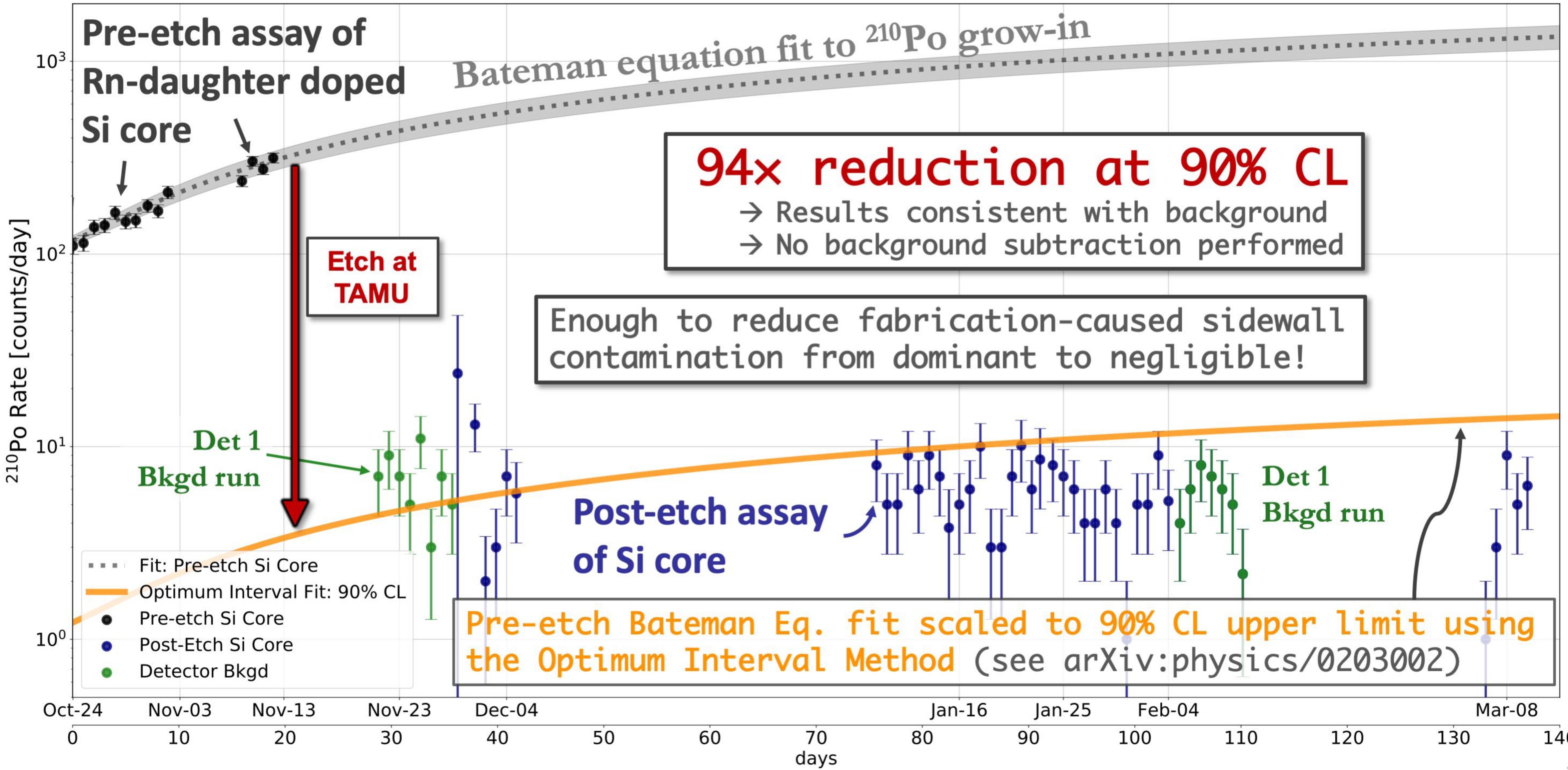
Texas A&M

4. The cores were then etched:
   - Standard heavy etch acid mix
     → 80% Nitric, 16% Hydrofluoric, 4% Acetic
   - 30 second dunk followed by deionized water dunk
   - Material removed from diameter = 0.0006” or 15.2 μm
   - Sensors are protected by wax

SDSM&T

5. Cores were again assayed for ^{210}Po (**post-etch assay**)

Detector Sidewall Etch : Shown to be effective!



Summary

Radon mitigation is critical to reach science goals

→ A radon-mitigation "swing" system will provide radon-reduced air during detector assembly

→ SDSM&T demonstration radon-mitigation system performance exceeds SuperCDMS goal

Copper will be much cleaner than that used previously at Soudan

→ SuperCDMS has demonstrated near-zero ^{210}Pb surface contamination (acidified peroxide etch)

→ Electroforming thin layers of ultra-pure PNNL copper is a viable strategy to further reduce ^{210}Pb and ^{210}Po activities on Cu surfaces

SuperCDMS SNOLAB should achieve ^{210}Pb contamination of ~50 nBq/cm^2

Texas A&M sidewall etch can reduce fabrication-caused sidewall contamination from dominant to negligible!

→ With the sidewall etch, ~10x better than the 50 nBq/cm^2 goal could be achieved by removing contamination from detector fabrication

The SuperCDMS Collaboration

California Inst. of Tech. · CNRS-LPN* · Durham University · FNAL · NISER · NIST*

Northwestern · PNNL · Queen's University · Santa Clara University · SLAC · South Dakota SM&T

SMU · SNOLAB · Stanford University · Texas A&M University · TRIUMF · U. British Columbia

U. California, Berkeley · U. Colorado Denver · U. Evansville · U. Florida

U. Montréal · U. Minnesota · U. South Dakota · U. Toronto

* Associate members

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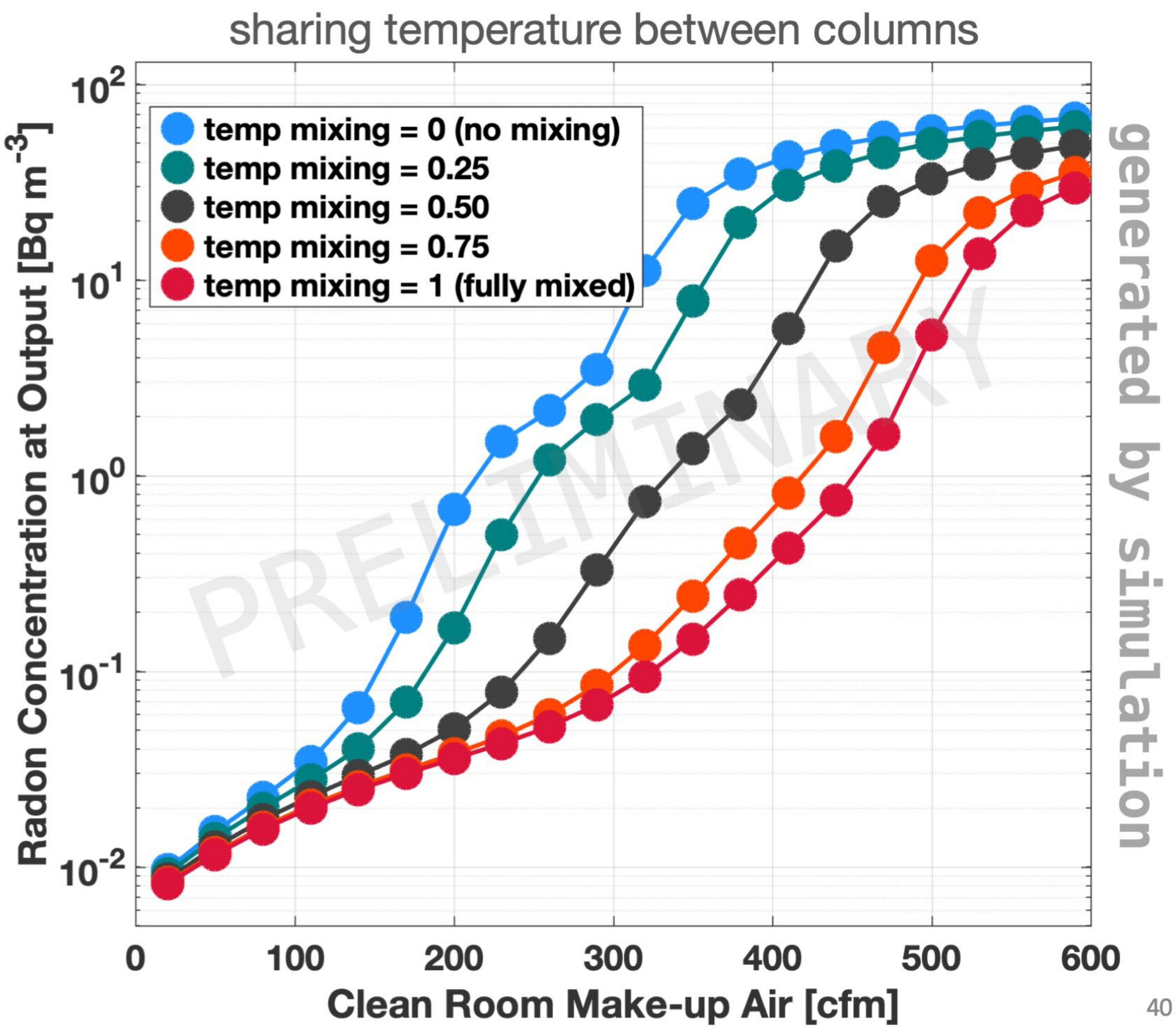
Backup Slides

Radon-Mitigation System : Simulation

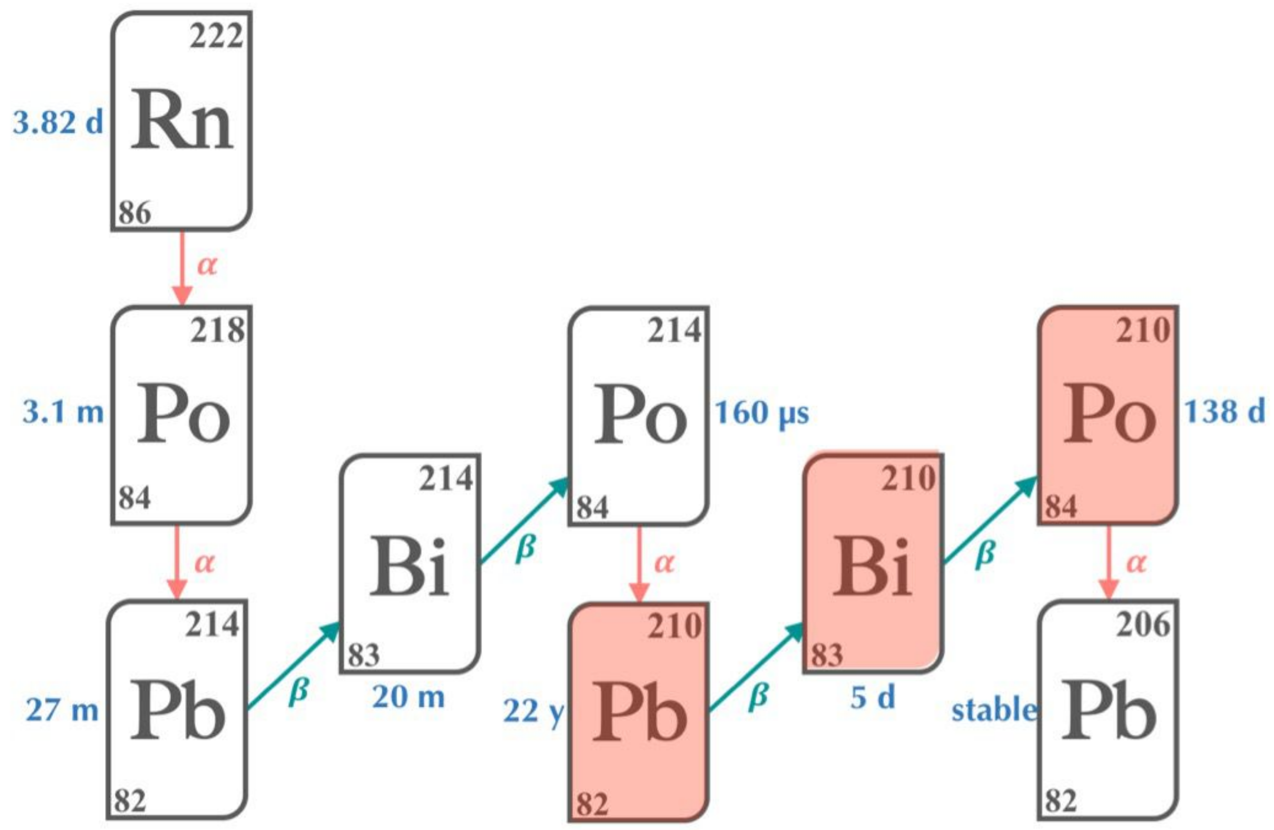
Some more observations...

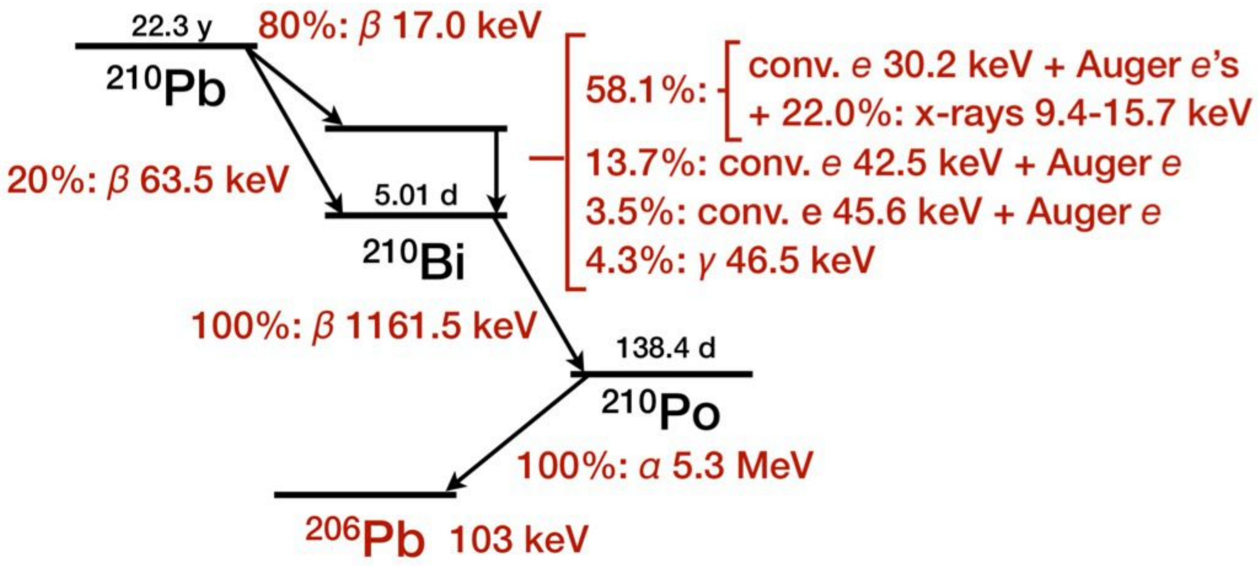
- What if we implemented a **heat sharing** system **between** the filtering and regenerating **columns**?
  - For example, water circulated within lines imbedded in the carbon beds of both columns such that heat can be transferred between them
- Improved performance would be expected with improved temperature sharing.

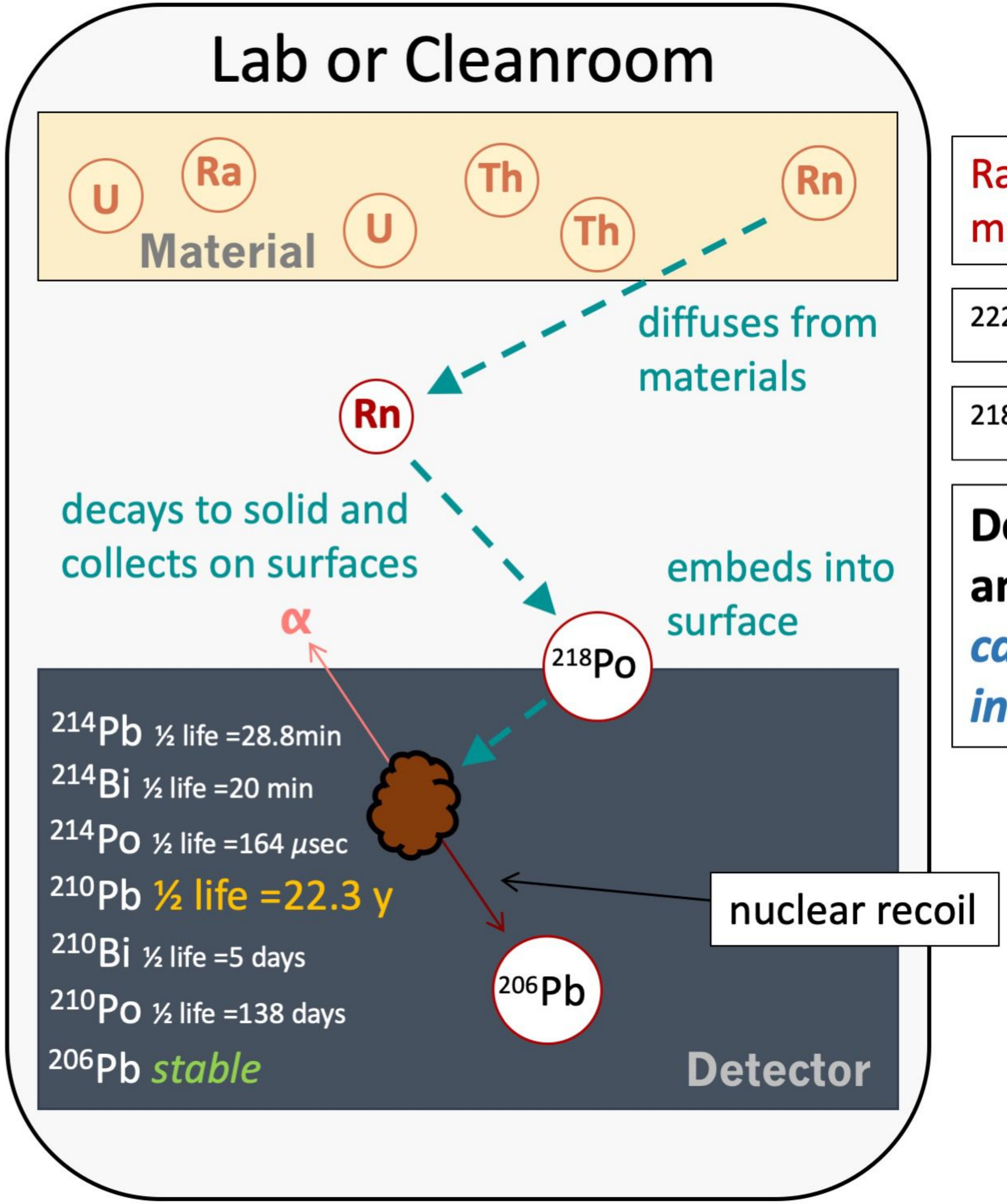


Radon Decay Chain : Radon-daughter Surface Contamination

^{222}Rn Decay Chain







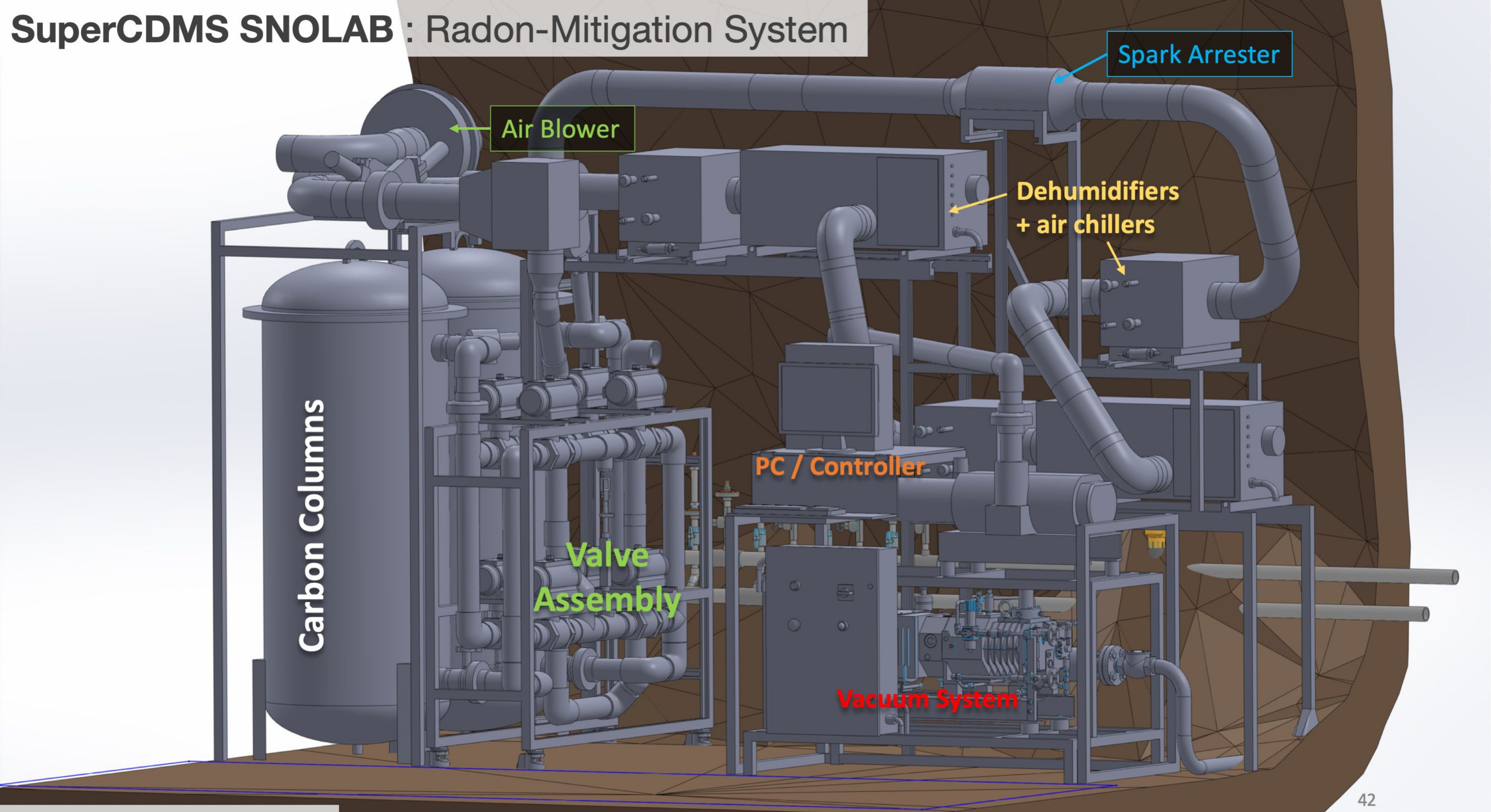
Radon diffuses through most materials

^{222}Rn has ½ life of 3.8 days

^{218}Po has ½ life of 3.1 min

Decays from ^{210}Pb, ^{210}Bi, and ^{210}Po (recoiling ^{206}Pb) ***can look like Dark Matter interactions***

SuperCDMS SNOLAB : Radon-Mitigation System



CAD model courtesy of Chris Hjelmfelt

Detector Sidewall Etch Test: High-Radon Air Exposure

pylon (^{222}Rn) source activity (118 kBq)

exposure time

Radon concentration in vessel

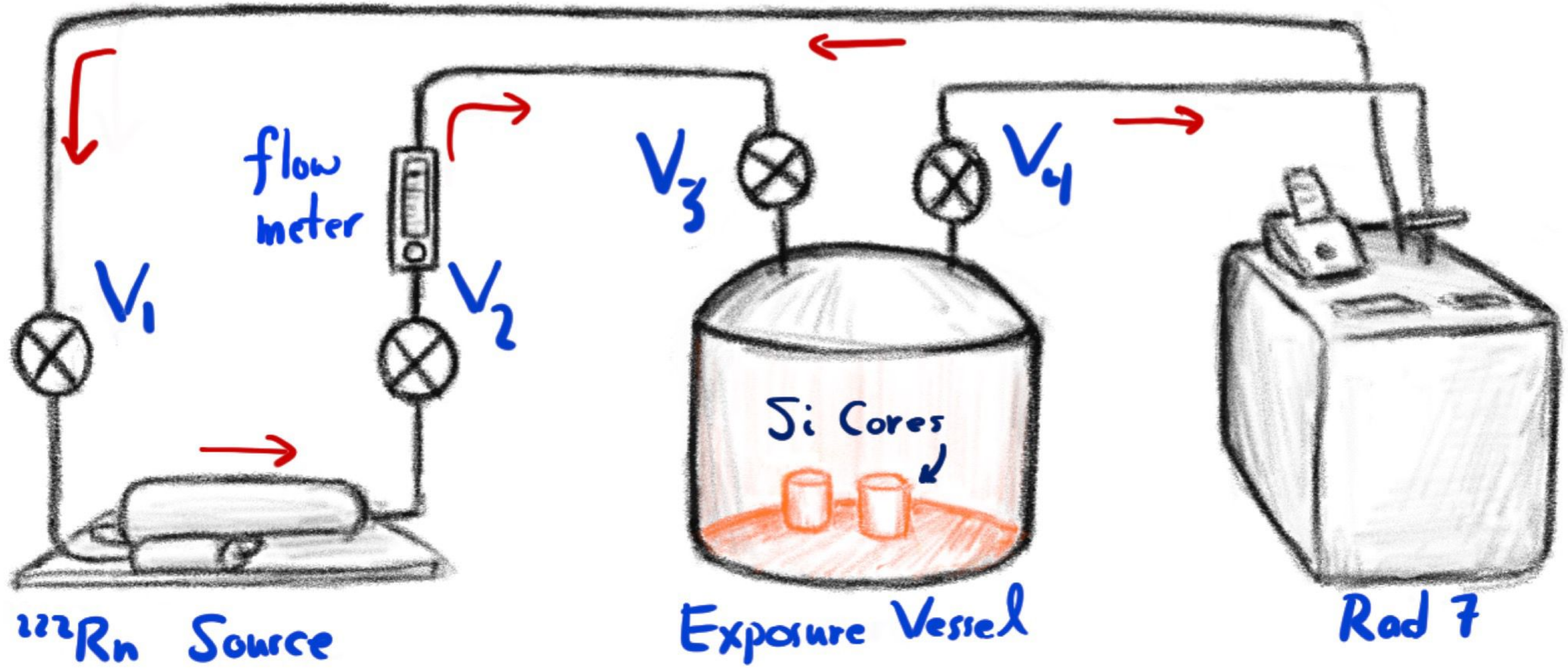
$$C_{\text{Rn}}(t) = \frac{A_{\text{pyl}}}{V_{\text{pyl}} + V_{\text{vess}}}\left[1 - \exp\left(-\frac{t_{\text{e}}}{\tau_{\text{Rn}}}\right)\right] \text{Bq/m}^3$$

pylon source volume (200 cm^2)

vessel volume (3500 cm^2)

^{222}Rn mean life-time

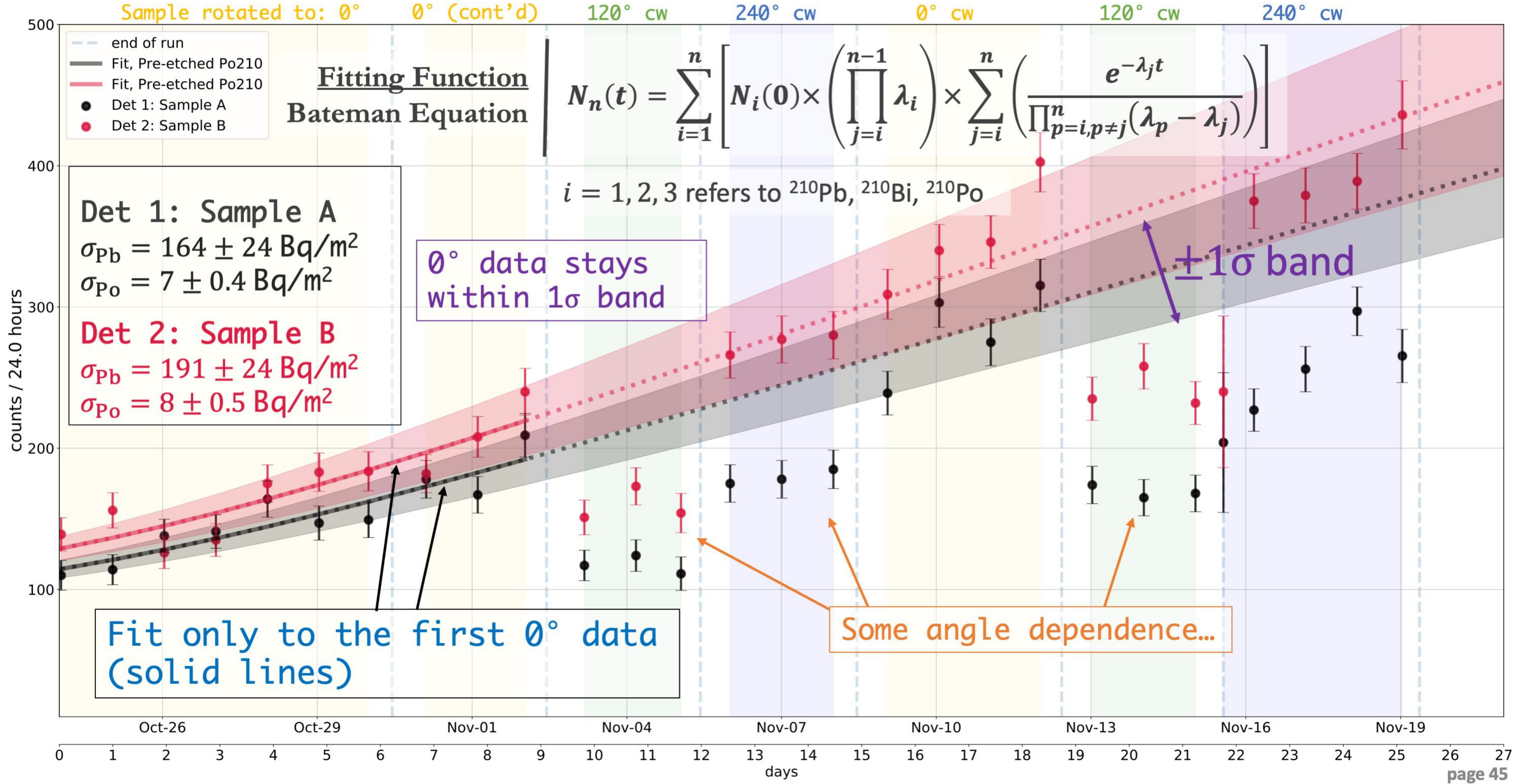
pylon source inline, **closed loop**



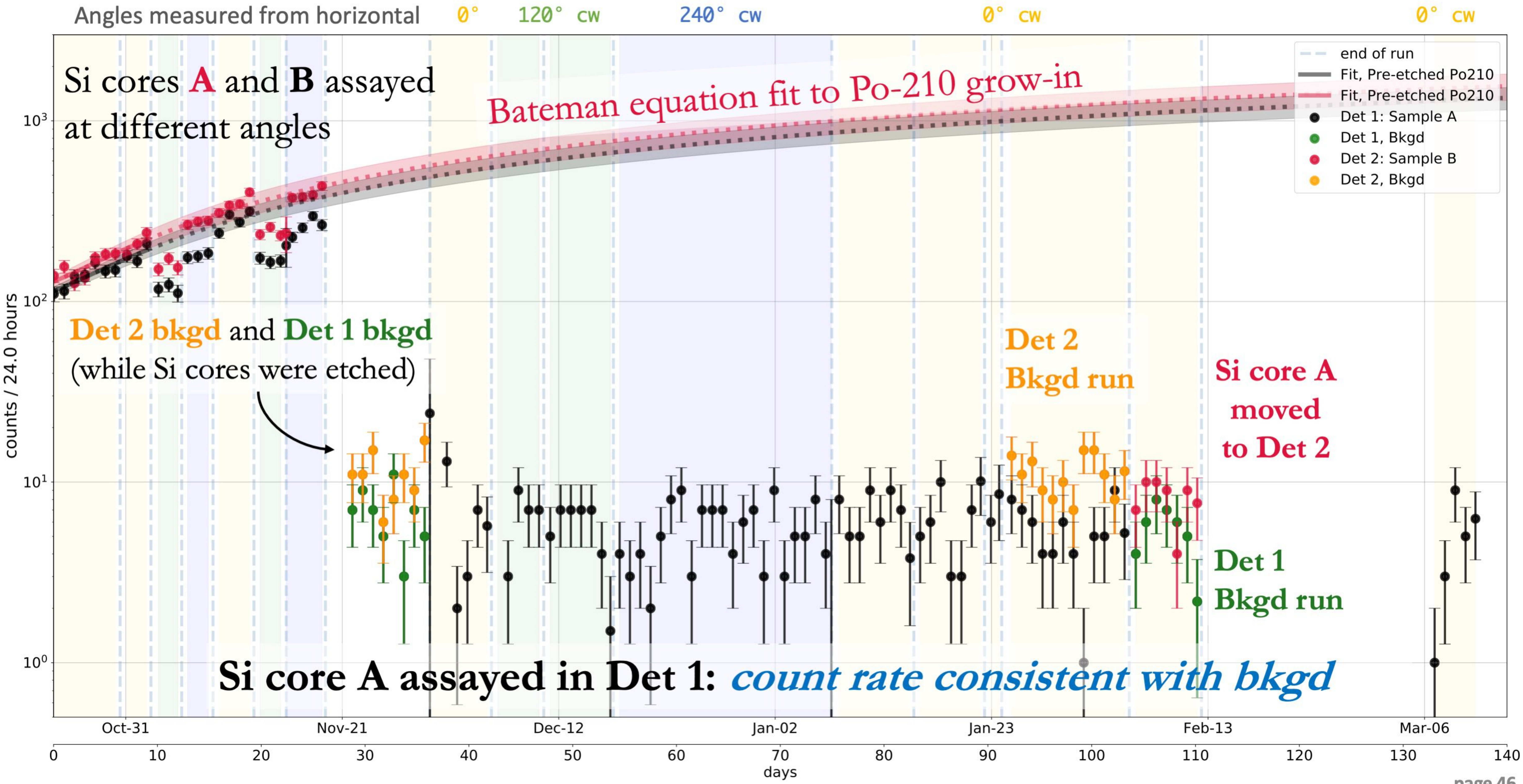
Alpha Duo α – Counter and Si Cores

Detector Sidewall Etch : Pre-etch Assay

Angles measured from horizontal

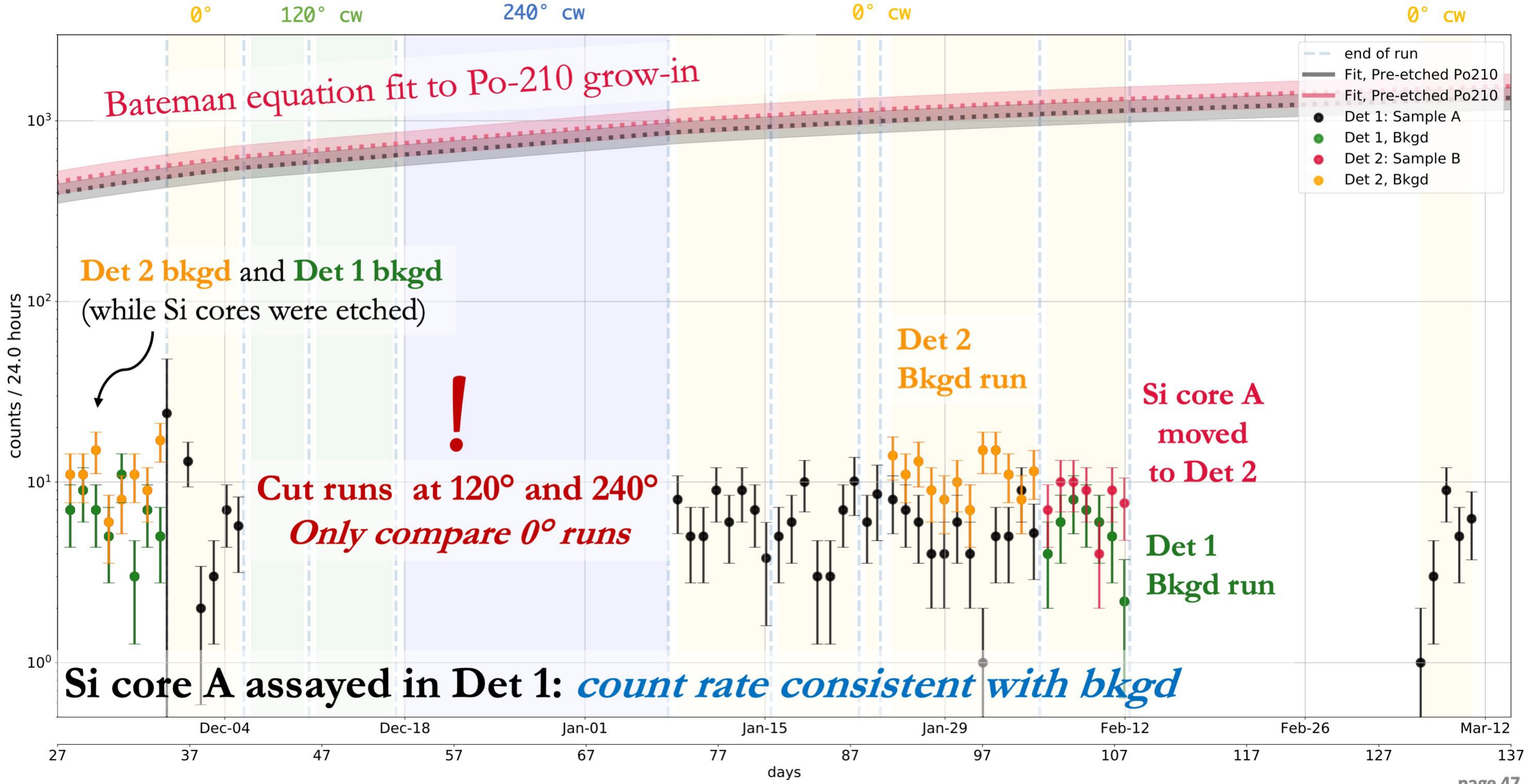


Detector Sidewall Etch : Pre-etch, Background, and Post-etch



Angles measured from horizontal

Detector Sidewall Etch : Post-etch Assay



Optimum Interval Method Used to Set Confidence Limit

How to use the OI method?

1. Get the **timestamp** for each of measured events
2. Use the signal model $f(t)$ (for us, this is the Bateman equation) to create a cumulative density function (CDF):
$$CDF(t_i) = A\int_0^{t_i} f(t)\,\mathrm{d}t\,,$$
where A is a normalization constant
3. For each measured event time t_i, build an array $FC[i] = CDF(t_i)$
   - $CDF(t_i)$ is the probability that a random event would have $t_r \leq t_i$
4. For some given constant C_s, $C_\mathrm{s}\times f(t)$ predicts some number of events μ_N
5. Feed Steve's Optimum Interval (Fortran) code: FC, μ_N, and C_s
6. It then returns: $C_\mathrm{s}^{90\%} = \frac{C_\mathrm{s}}{\mu_\mathrm{N}}\mathrm{UpperLim}(args.)$

Finding an Upper Limit in the Presence of Unknown Background

S. Yellin*
Department of Physics, University of California, Santa Barbara, Santa Barbara, CA 93106, USA

(Dated: October 23, 2018)

Experimenters report an upper limit if the signal they are trying to detect is non-existent or below their experiment's sensitivity. Such experiments may be contaminated with a background too poorly understood to subtract. If the background is distributed differently in some parameter from the expected signal, it is possible to take advantage of this difference to get a stronger limit than would be possible if the difference in distribution were ignored. We discuss the "maximum gap" method, which finds the best gap between events for setting an upper limit, and generalize to the "optimum interval" method, which uses intervals with especially few events. These methods, which apply to the case of relatively small backgrounds, do not use binning, are relatively insensitive to cuts on the range of the parameter, are parameter independent (i.e., do not change when a one-one change of variables is made), and provide true, though possibly conservative, classical one-sided confidence intervals.

PACS numbers: 06.20.Dk, 14.80.-j, 14.80.Ly, 95.35.+d

Method is explained here:
PRD66, 032005 (2002) = **arXiv:physics/0203002** and **arXiv:0709.2701 (2007)**

Code lives online here :
http://titus.stanford.edu/Upperlimit/