CRYSTALIZE:
A SOLID FUTURE FOR LZ

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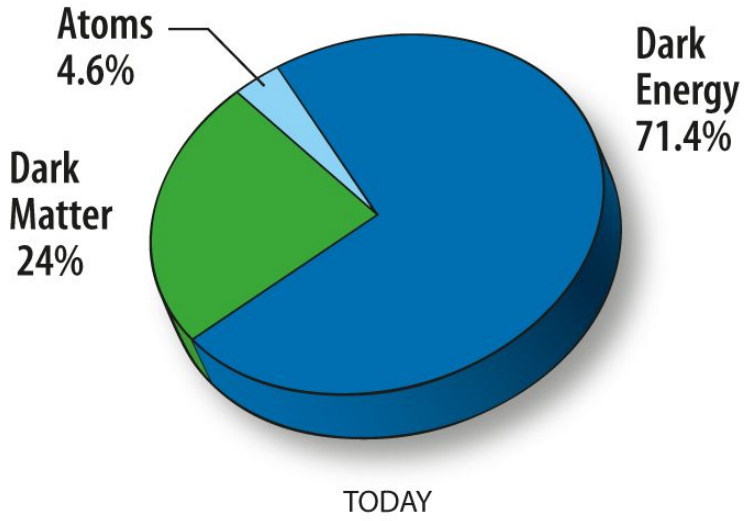
DIRECT DARK MATTER SEARCH

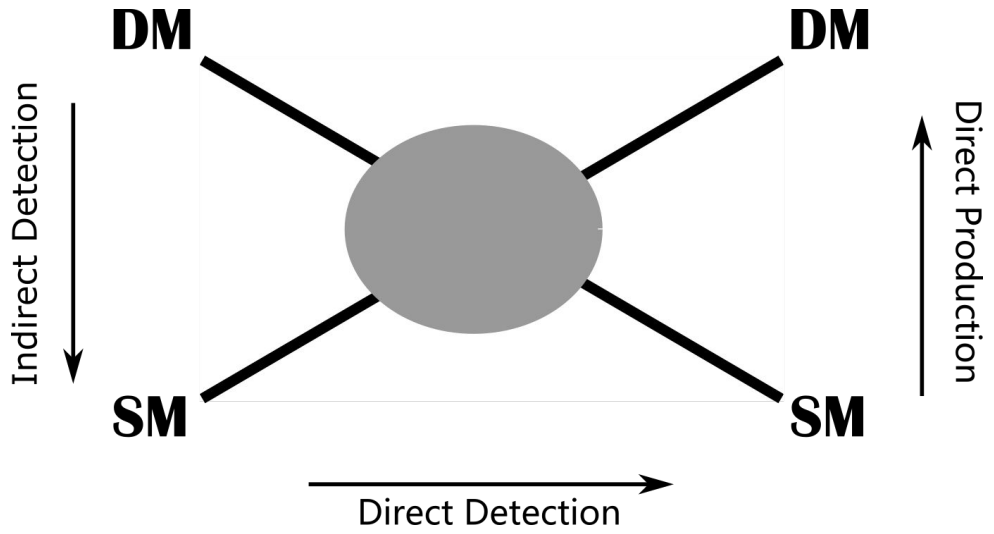


Credit: NASA / WMAP Science Team

Evidences from cosmic scale:

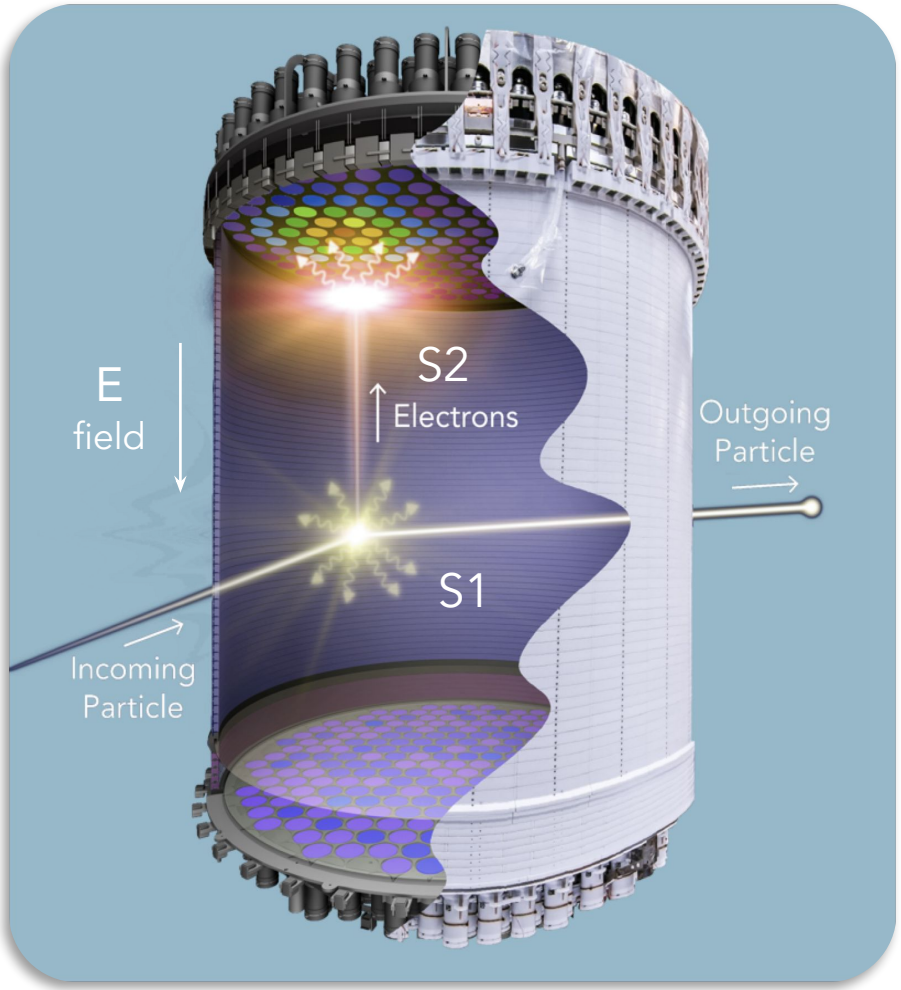
- rotation curves of galaxies
- bullet cluster collision
- Cosmic microwave background
- Only gravitational and collective effects

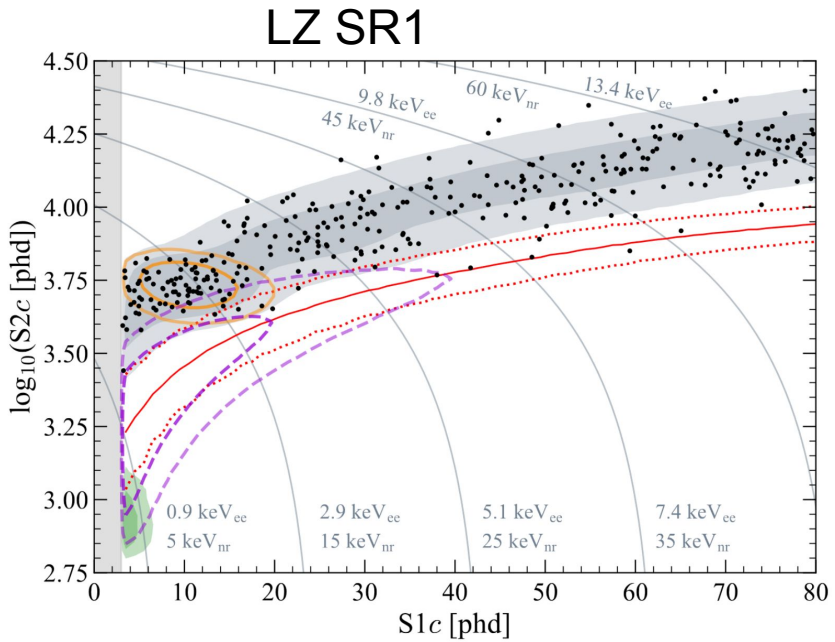
In particle scale:



Weak interaction → Rare events search

LZ EXPERIMENT



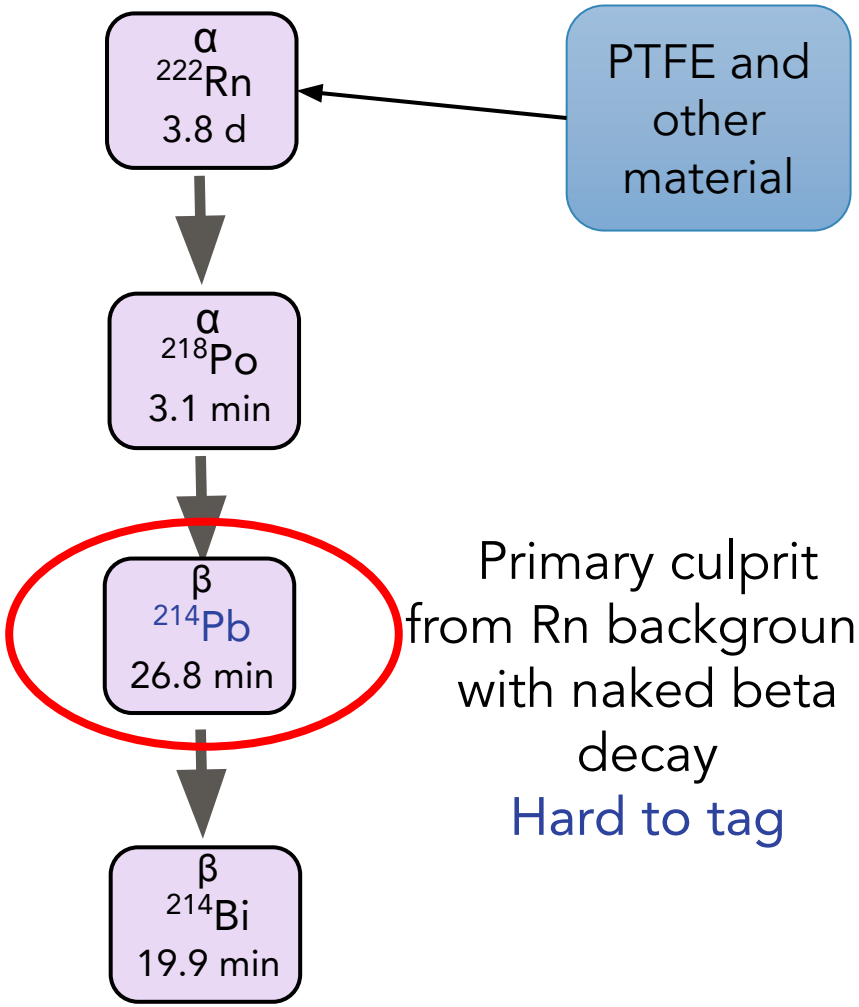


Source	Expected Events	Fit Result
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Radon is the primary culprit

Aalbers, et al. “First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment.” arXiv, October 27, 2022. https://doi.org/10.48550/arXiv.2207.03764.

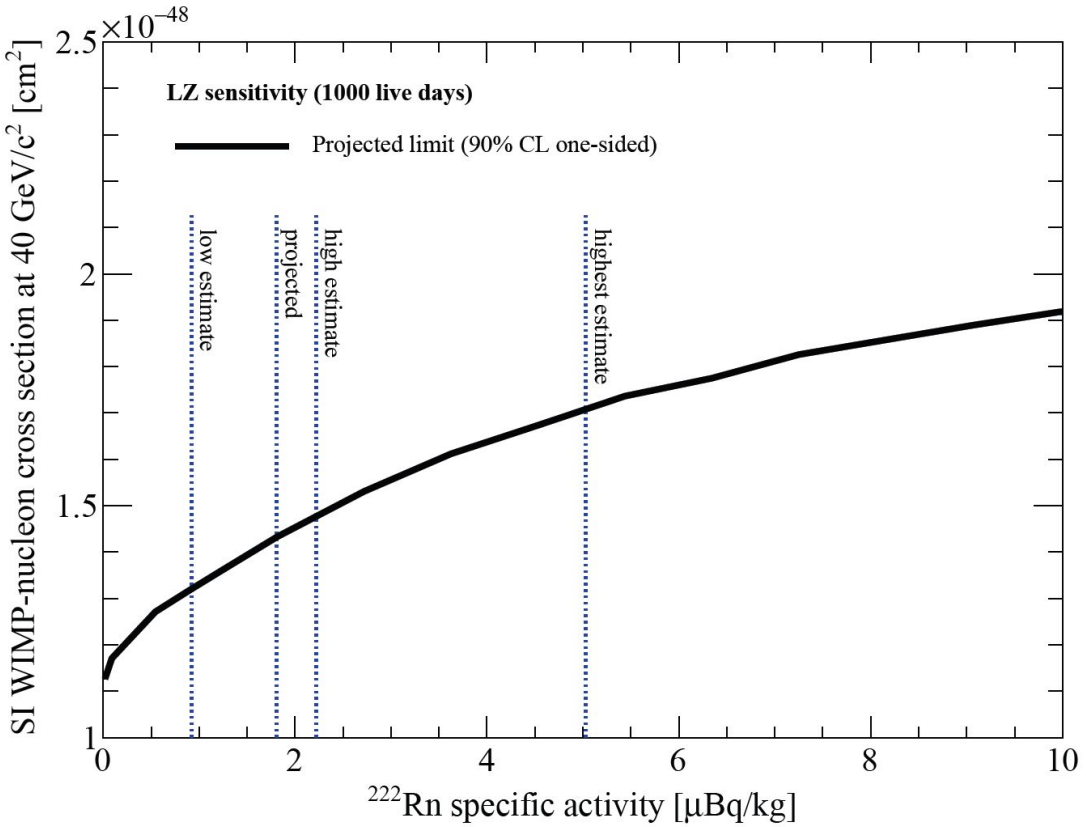
RADON BACKGROUND



Primary culprit from Rn background with naked beta decay

Hard to tag

How much do we care?



Phys. Rev. D **101**, 052002

Reduce the time to reach the neutrino fog significantly.

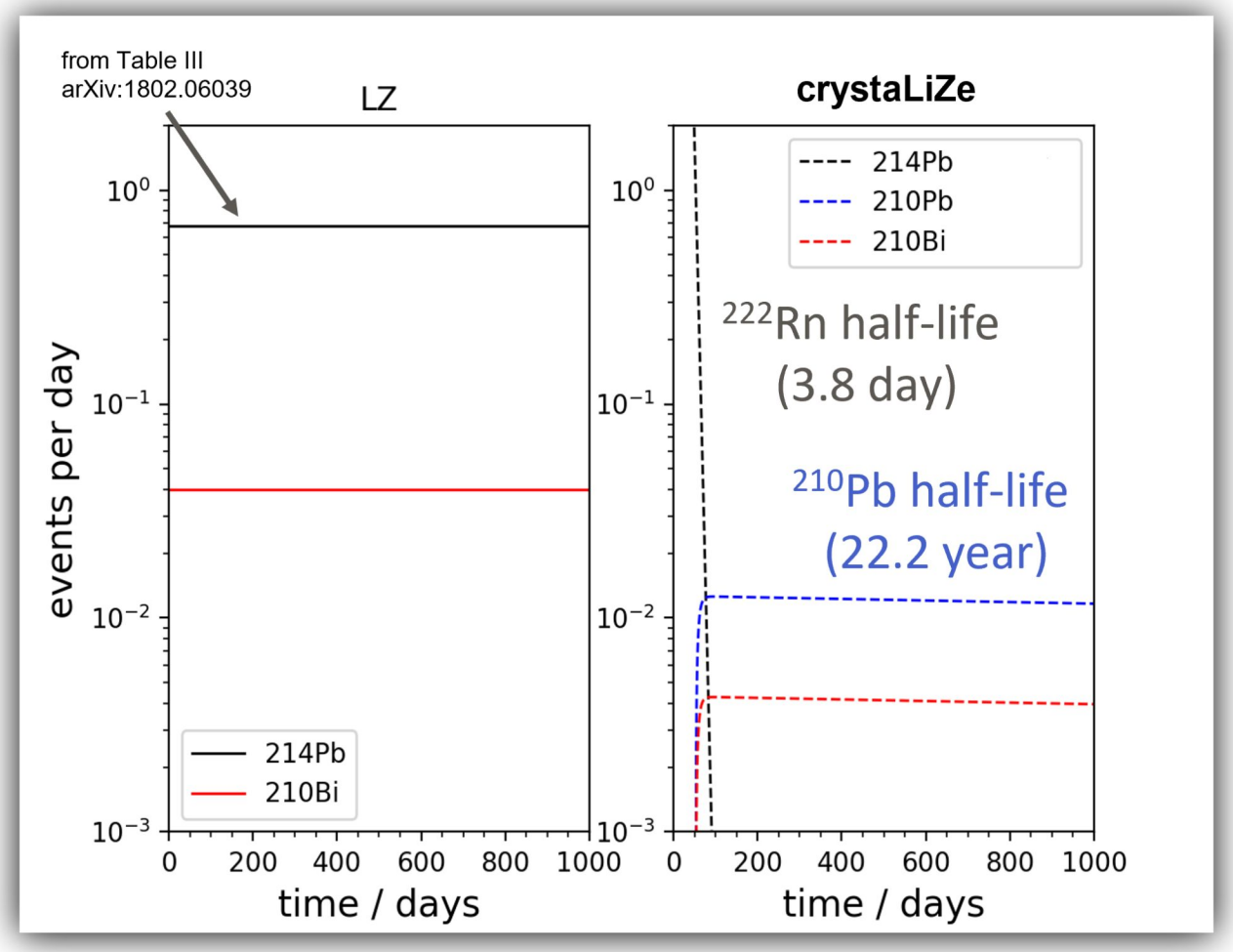
Solution: CrystaLiZe

we propose to freeze the liquid xenon into a ***CRYSTAL***

- Radon emanated from surfaces now **excluded** from solid bulk*
- Radon in bulk target from LXe phase would be fixed, decay away in O(100) days
- Radon decay daughters stay at same (x,y,z) as parent* -> **tagging/veto**
- **Reduction in Rn chain daughters of nearly 1%**

*Diffusion of Rn in solid Xe needs to be studied, but even if diffusion is not negligible

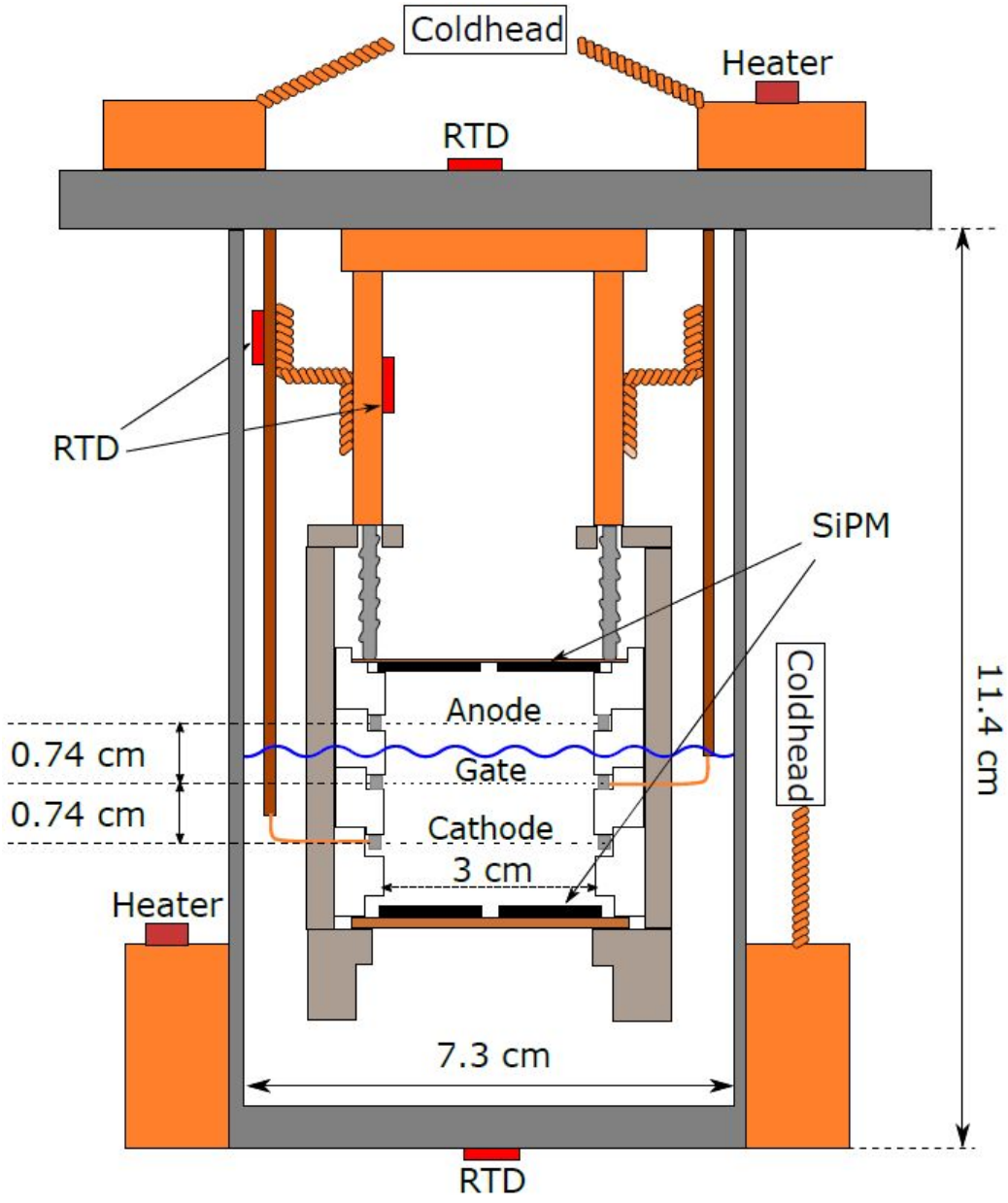
Tagging



same LZ emanation and dust assumptions

TEST BED DESIGN

- Two phase Xe mini-TPC at LBL
  - Liquid/vapor
  - Crystal/vapor
- ~500 g Xe when full
- Signal readout:
  - 8 SiPMs (4 top, 4 bottom) before 2022
  - 32 SiPMs since 2022 (16 top, 16 bottom; Hamamatsu S13371)
- ^{210}Po plated on a small stainless steel plate on the cathode
- Two separate coldheads for freezing process.



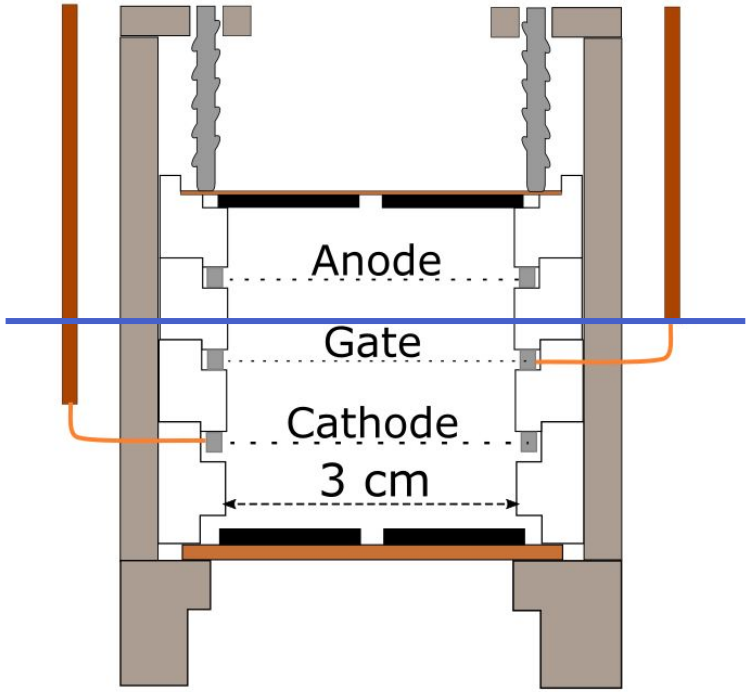
XENON LEVEL

The level of condensed phase needs to be between the gate and anode for electroluminescence to work.

liquid/vapor mode:
the level is set by observing detector response. Set the cathode/gate voltage to 2.6/2.4 kV, when the level is between the gate and anode, we see events with S1/S2 pairs.

Crystal/vapor mode:

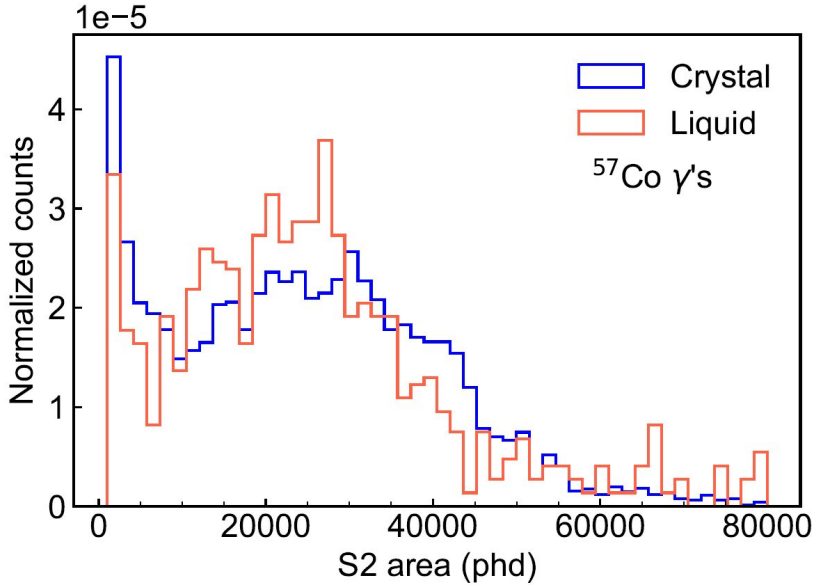
1. Record the total mass of liquid xenon (from flow meter)
2. Extra xenon is needed in crystal/gas mode, the extra amount is calculated by the density of two phases.

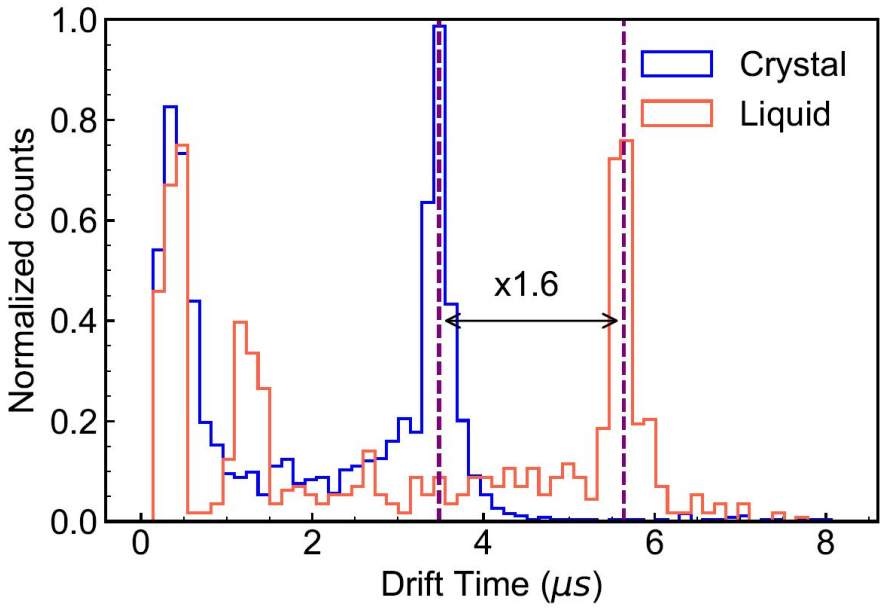


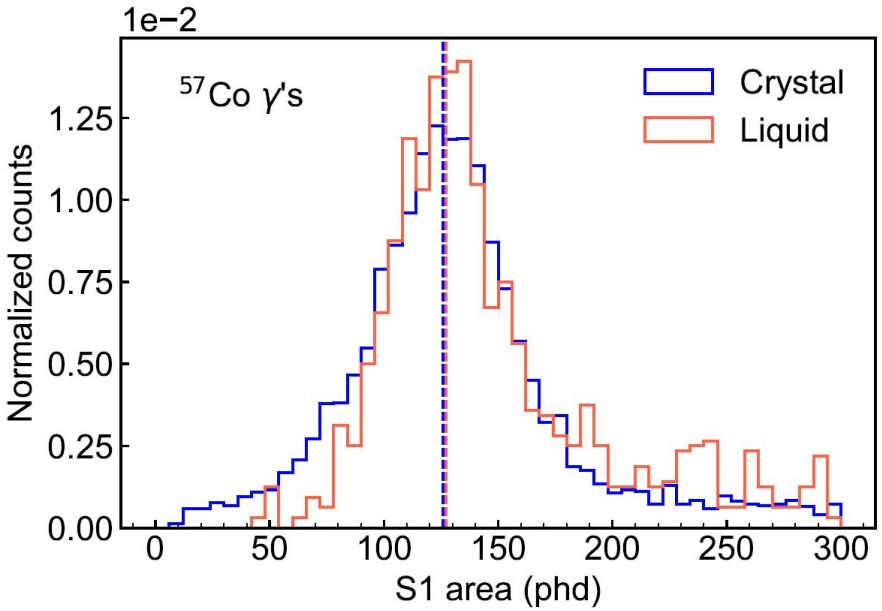
Detector performance

Brief review of our previous work (**S. Kravitz *et al* 2022 *JINST* 17 P04014**):

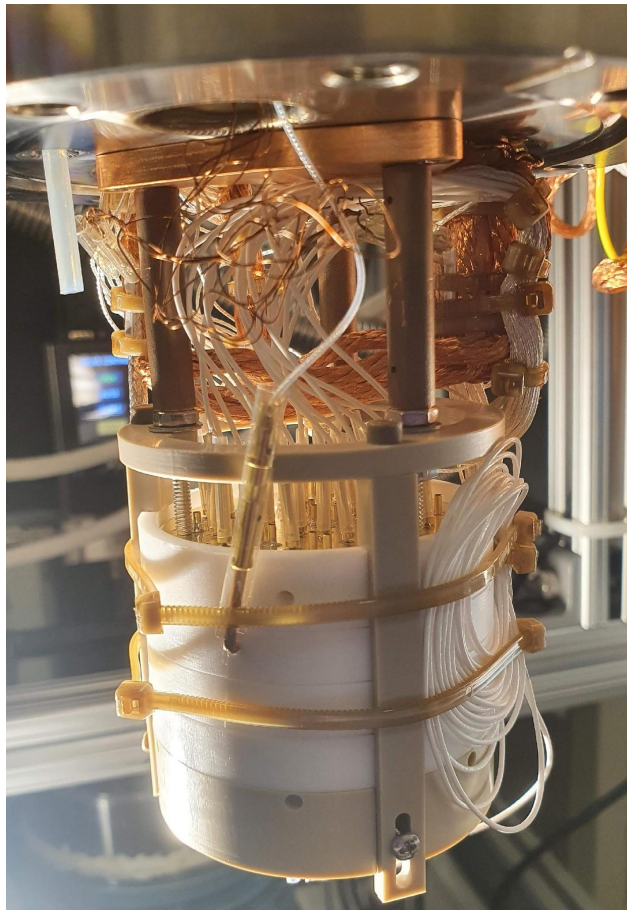
- No apparent charge or photon loss in crystal compared to liquid
- Electron drift velocity is bigger in crystal xenon



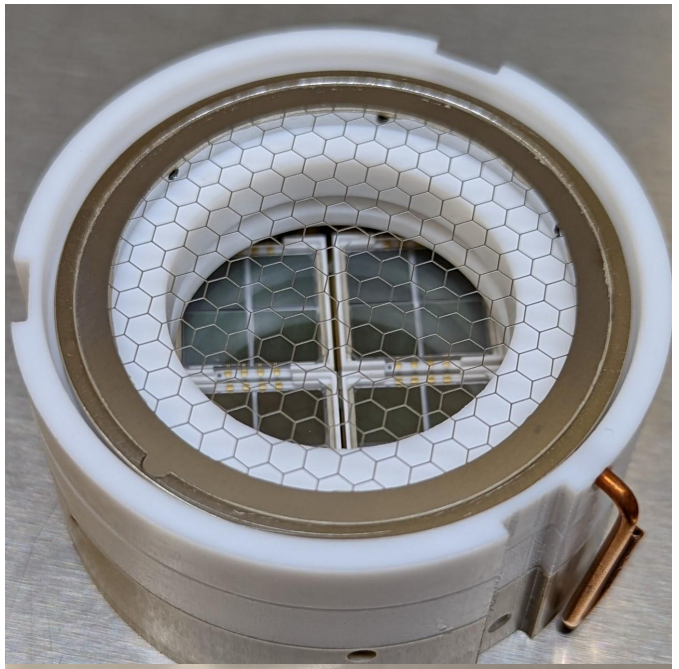




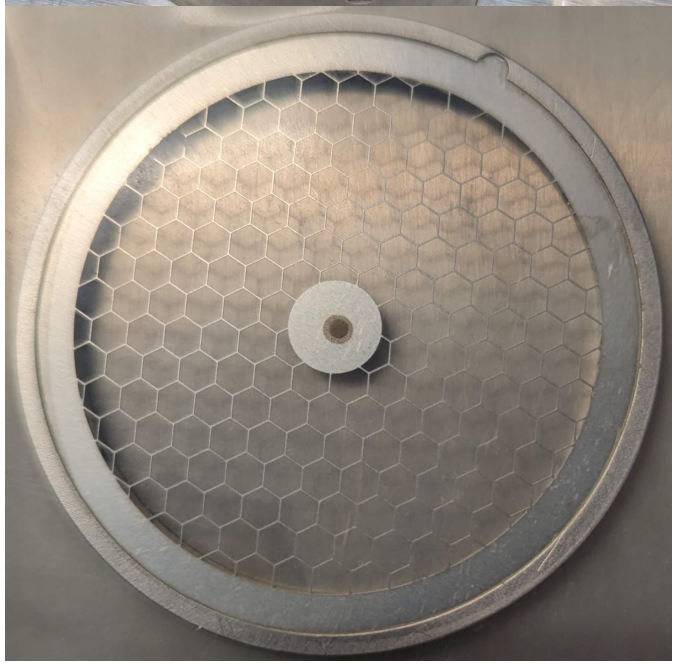
CRYSTALIZE TESTBED



TPC



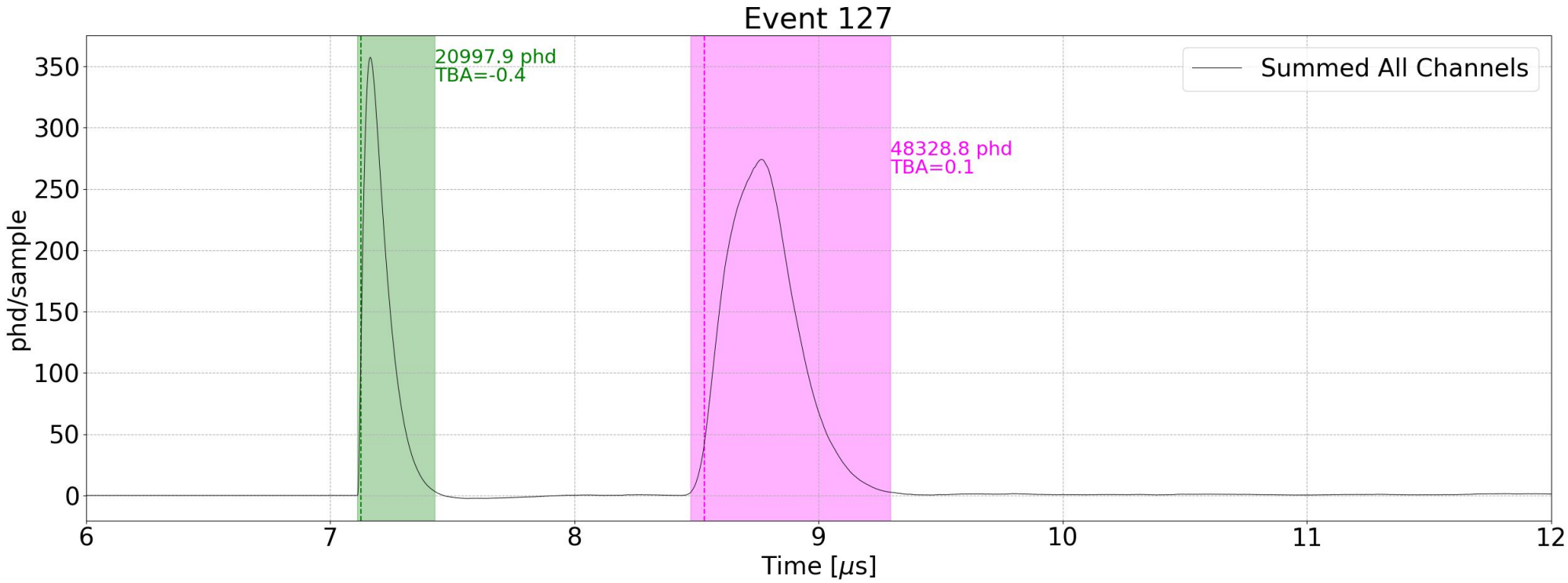
Gate grid
and SiPMs



Cathode grids with center plate to hold ^{210}Po source, this structure suppress the S1 size of ^{210}Po.

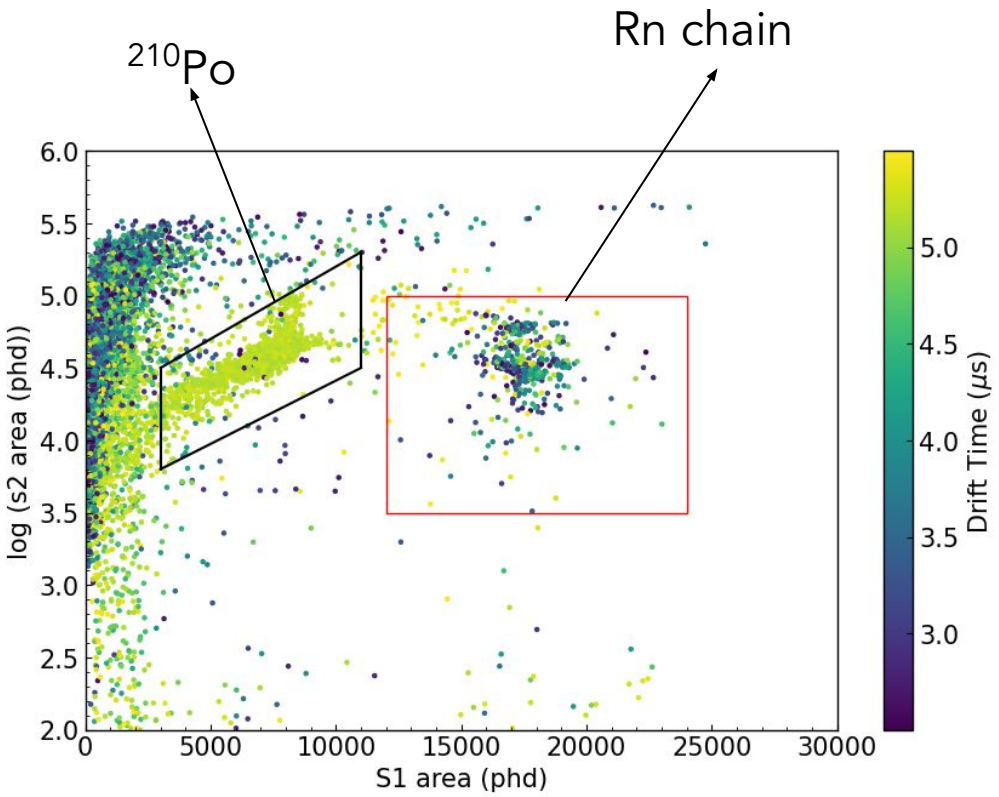
RADON EXCLUSION TEST

Some ^{222}Rn were introduced to the TPC from the circulation line, most from a gas purifier. We use it to demonstrate the radon exclusion power of crystal xenon.

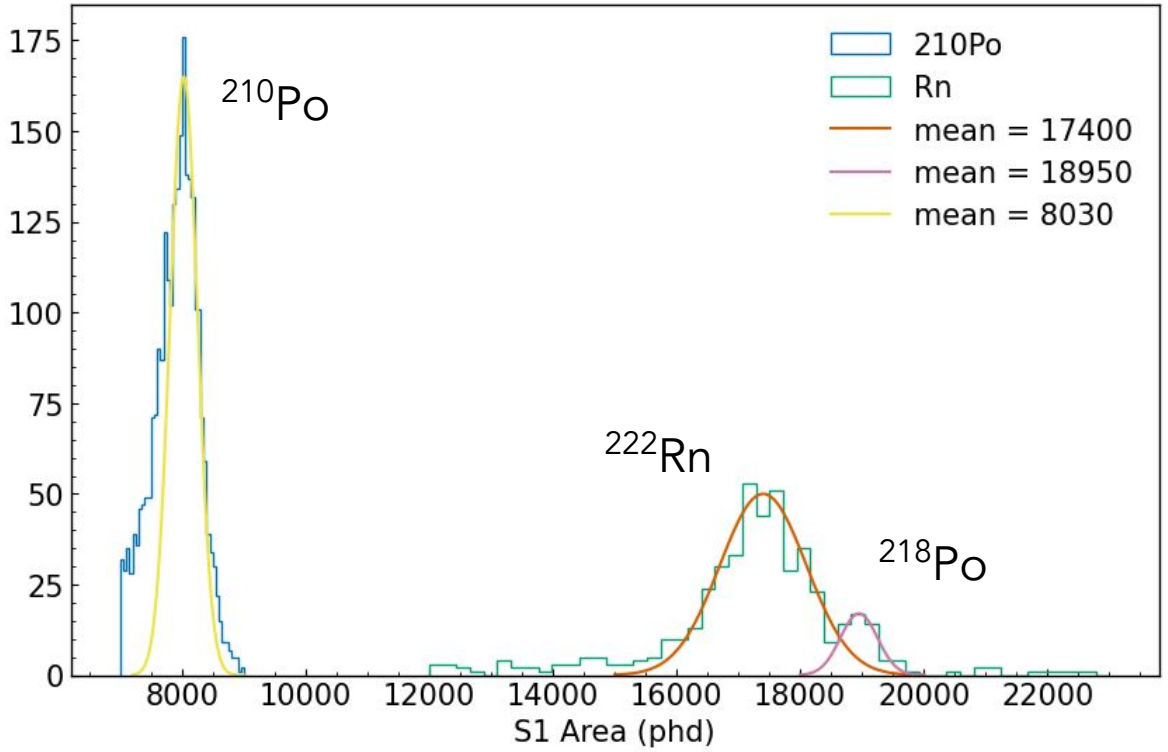


One alpha event from Rn chain.
We can tag these events fairly easily, since both their S1 and S2 are huge.

RN EVENTS IN LIQUID/VAPOR XENON



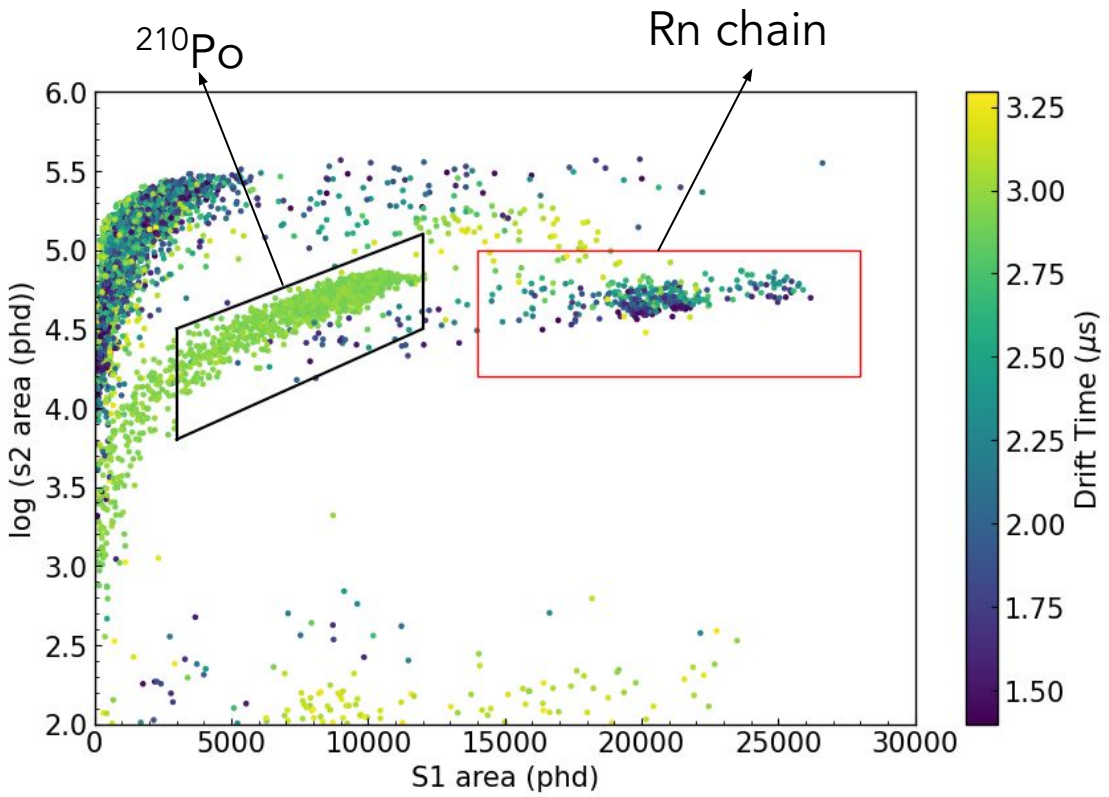
Rn events selection. Within a fiducial volume of several grams of xenon.

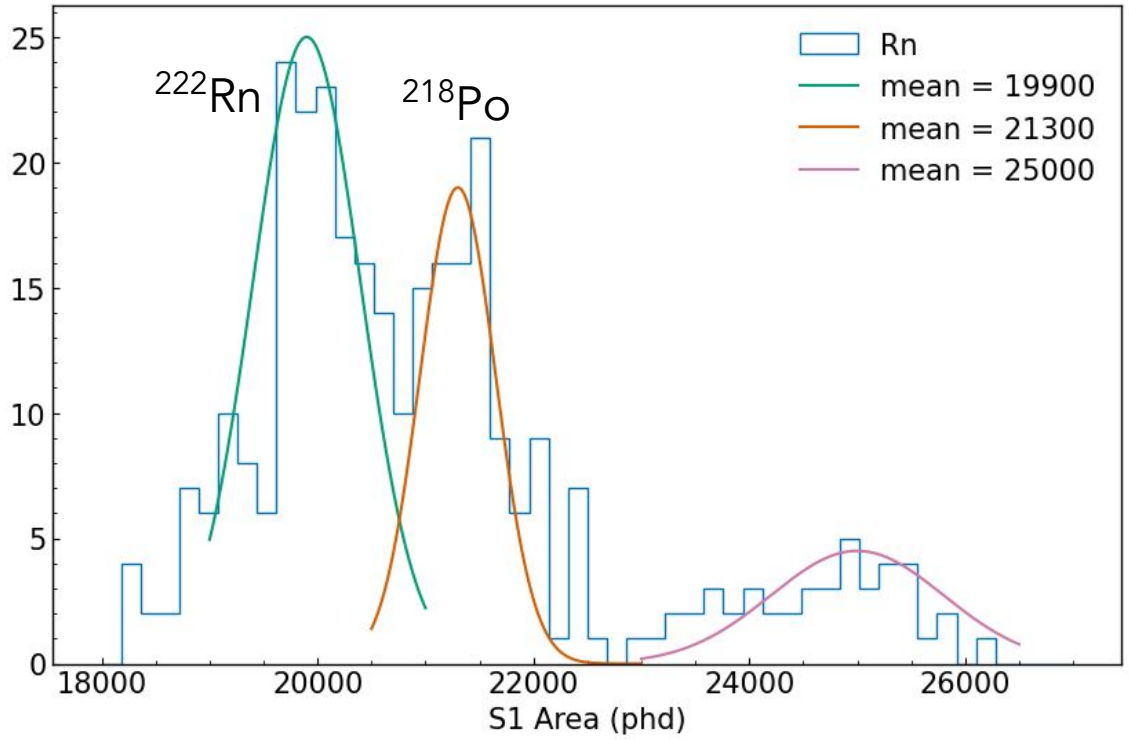


The S1 from ^{210}Po is much smaller than those from Rn chain, even though their energy is similar. That is because of the light collection suppression from the center plate.

RN EVENTS IN CRYSTAL XENON

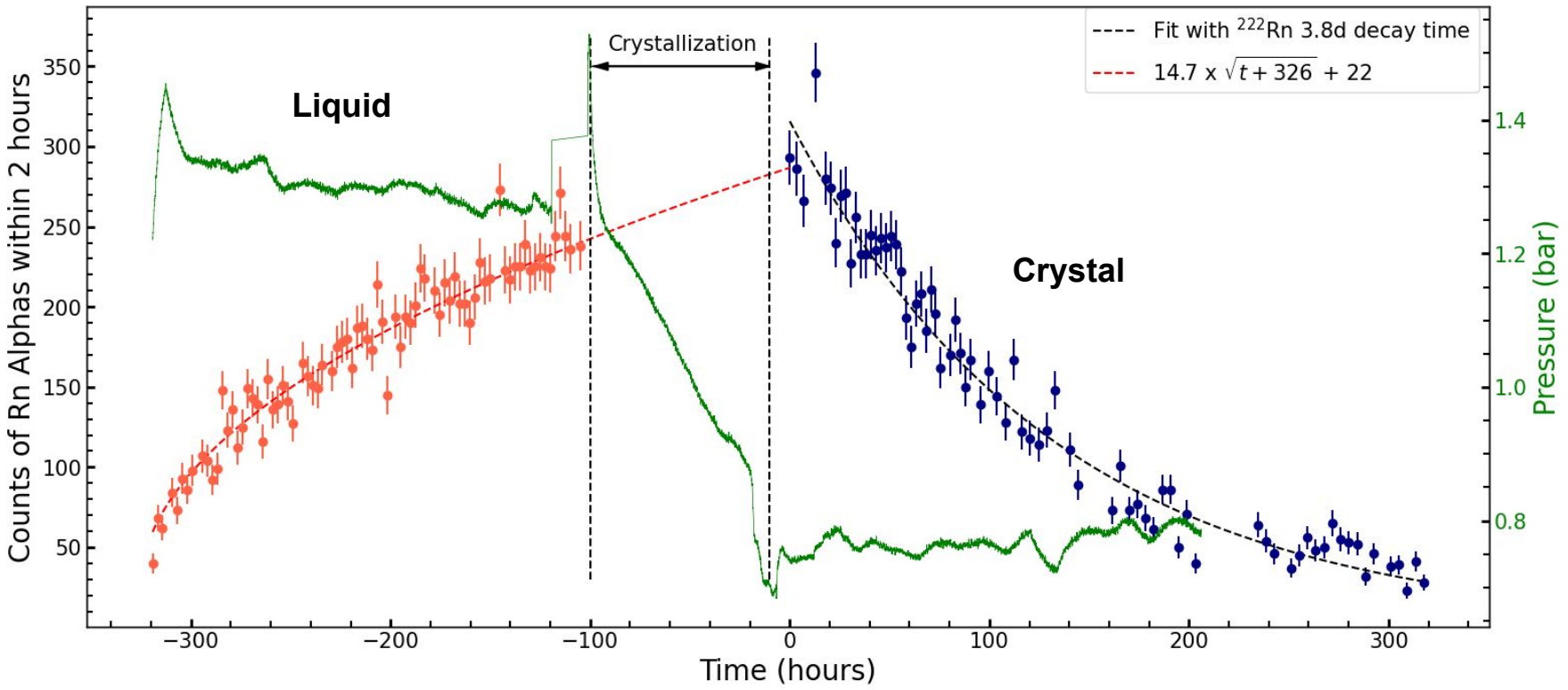
Both liquid and crystal data are taken with +0.5 kV on the anode, -3.0 kV on the gate and -3.2 kV on the cathode.





A simple approach: count the number of alphas from Rn chain, observe its change over time.

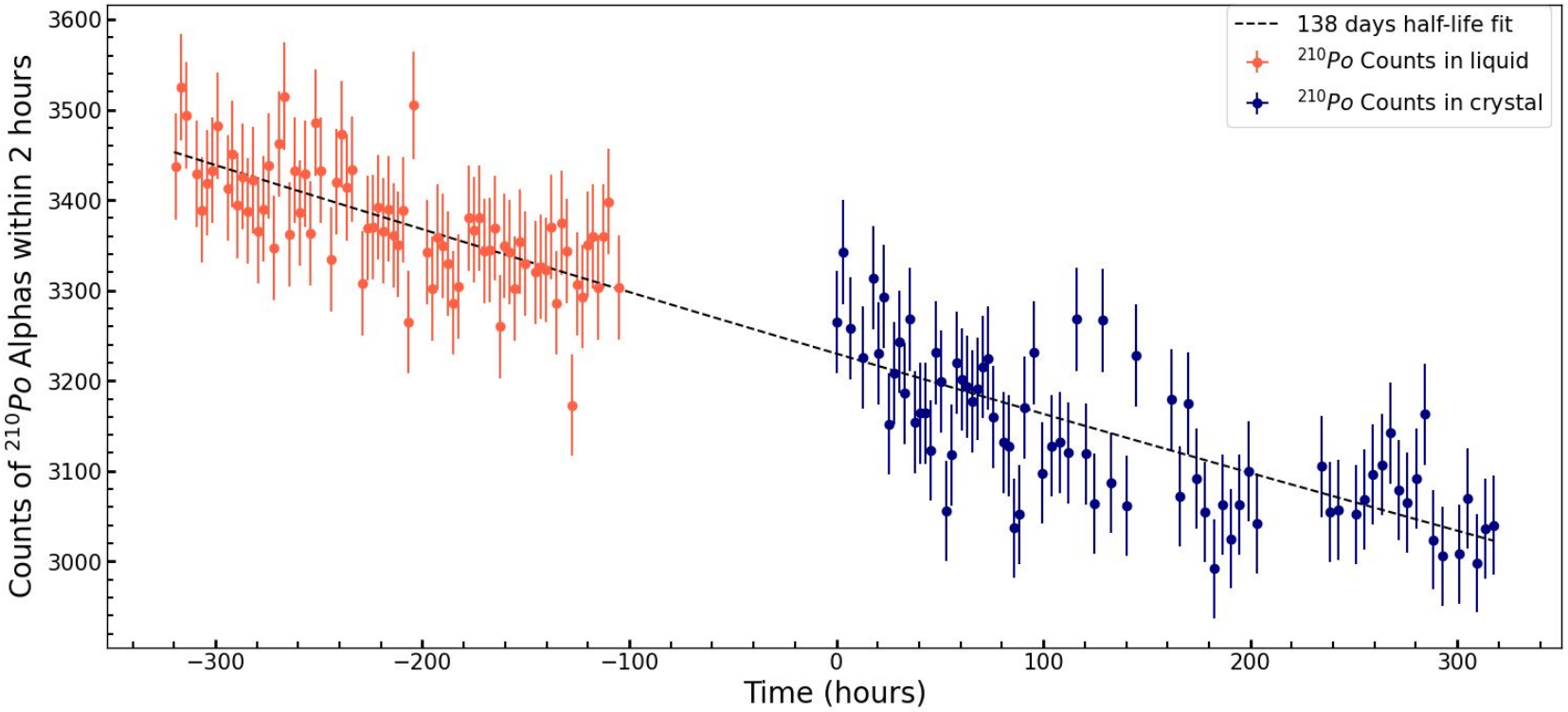
CONTINUOUS RADON SOURCE



We **continuously circulate** gas xenon through the gas purifier (Rn source) with a steady flow rate of 0.3 slpm.

- In liquid/vapor mode, the Rn rate increases overtime, indicating Radon is added to the liquid bulk.
- In crystal/vapor mode, the Rn rate drops with a half-life of ^{222}Rn, indicating no or very few of Radon leaking into the crystal bulk.

HEARTBEAT (LIVE TIME) FROM ^{210}PO



We use the rate of ^{210}Po as heartbeat, to demonstrate there is no livetime issue.

As shown in the plot, the rate of ^{210}Po follows its half life (138 days) pretty well.

SUMMARY

- Improving the detector sensitivity for DM direct detection requires innovation in detector design to minimize the background.
- The crystal/vapor dual-phase xenon TPC is a promising new particle detector technology as it can exclude radon from the detector bulk.

Next step:

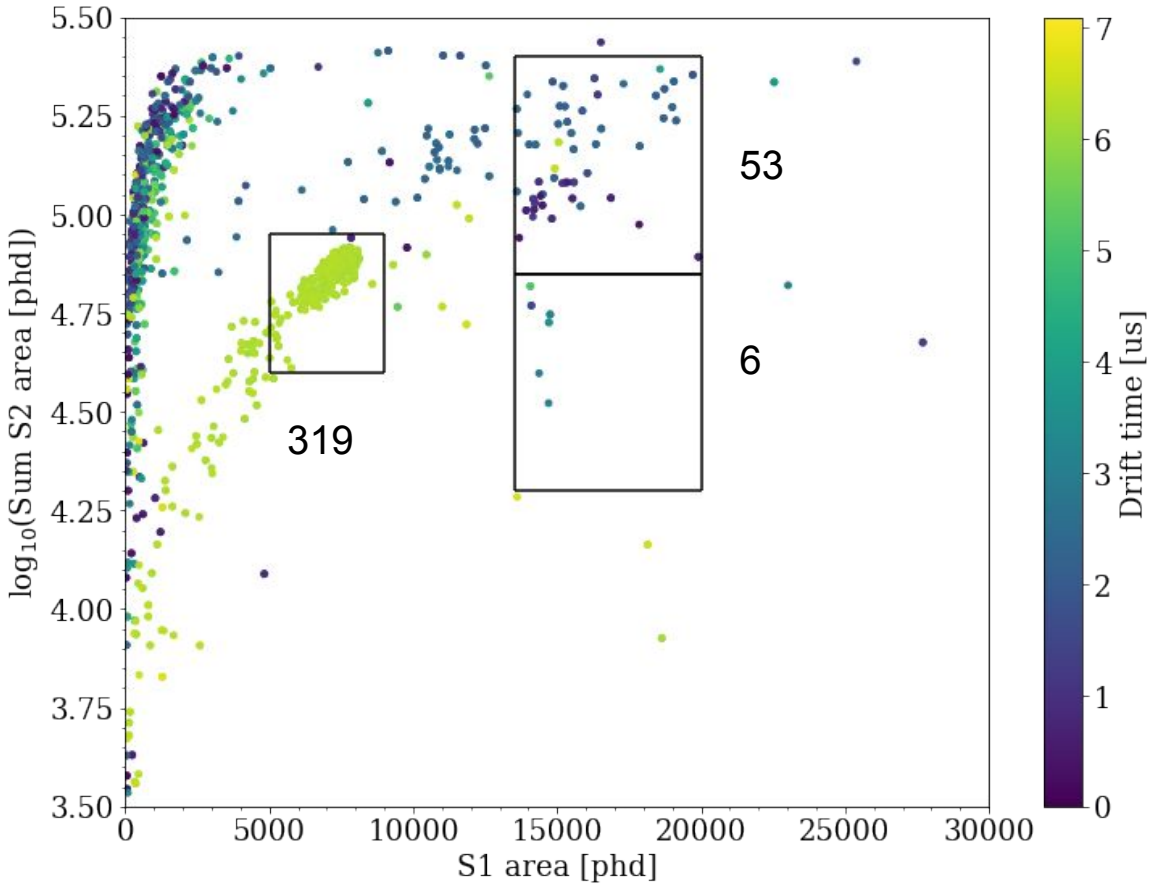
- ❑ Reach single electron sensitivity
- ❑ Rn tagging in crystal xenon
- ❑ Overcome technical challenges of scaling up and long-term stability of the crystal xenon

BACKUP SLIDES

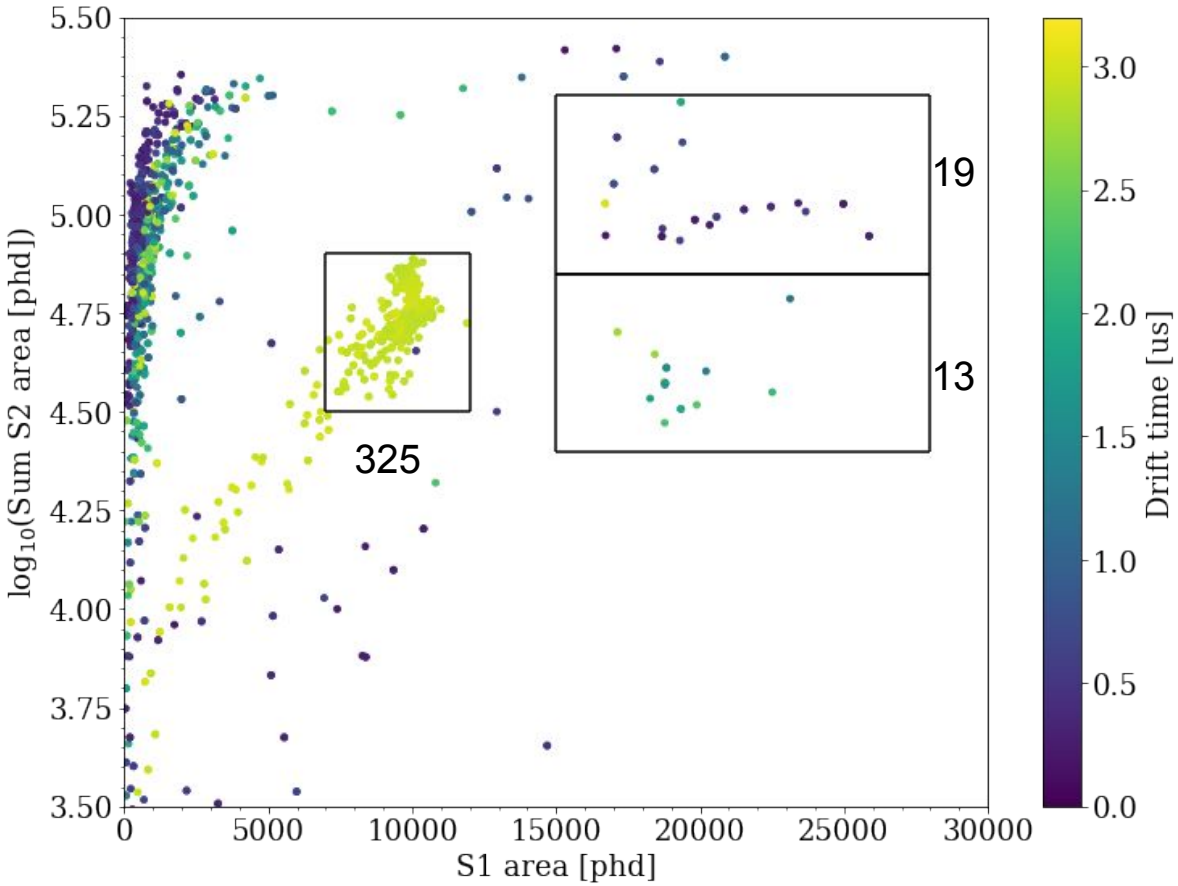
Flow Rn test

Background (no flowing Rn)

Liquid Xenon

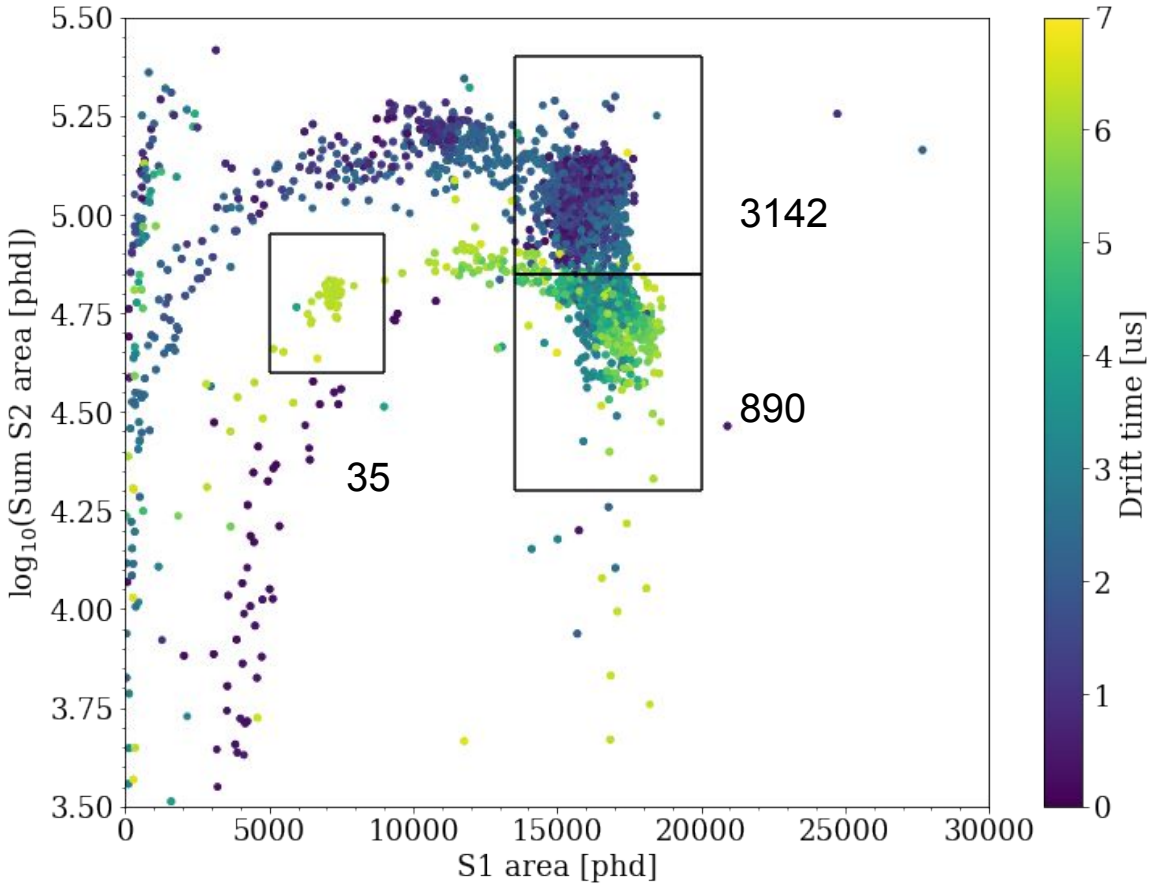


Crystal Xenon

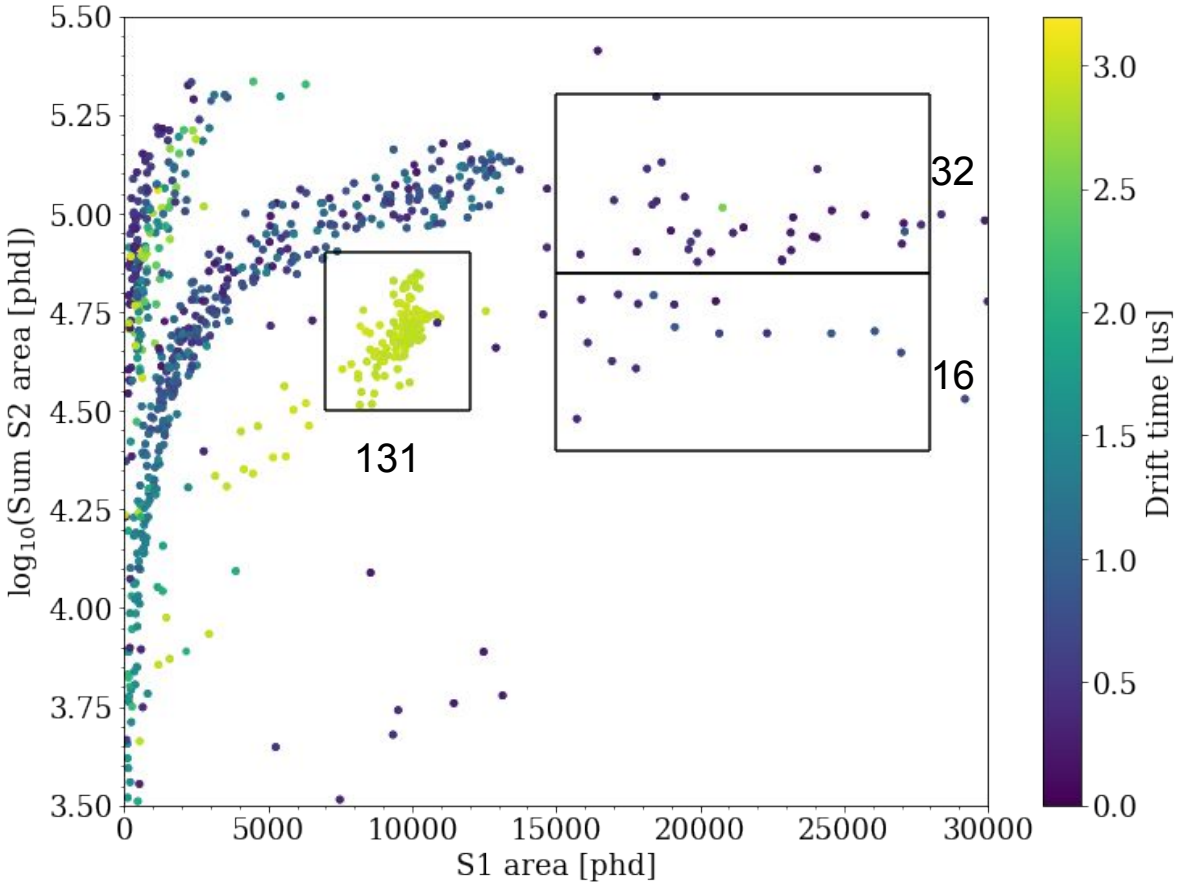


Flowing Rn

Liquid Xenon



Crystal Xenon



RADON BACKGROUND MITIGATION

Radon reduction BY Absorption

- Active area of R&D. HARD.
- Conclusions from a paper on radon reduction [arXiv:2009.06069]:

  "…even for perfect radon traps, circulation speeds of 2,000 SLPM are needed to reduce radon concentration in a 10 ton detector by 90%. This is faster by a factor of four than the highest circulation speeds currently achieved in dark matter detectors... The effectiveness of vacuum swing adsorption systems… is limited by the intrinsic radon activity of the charcoal adsorbent in ultra-low radon environments. Adsorbents with significantly lower intrinsic radon activity than in currently available activated charcoals would be necessary…"

Radon reduction BY Distillation

Xenon1T use this technique:

"…The 222Rn concentration was reduced by ~20% relative to the equilibrium value using the krypton distillation column in inverse mode…

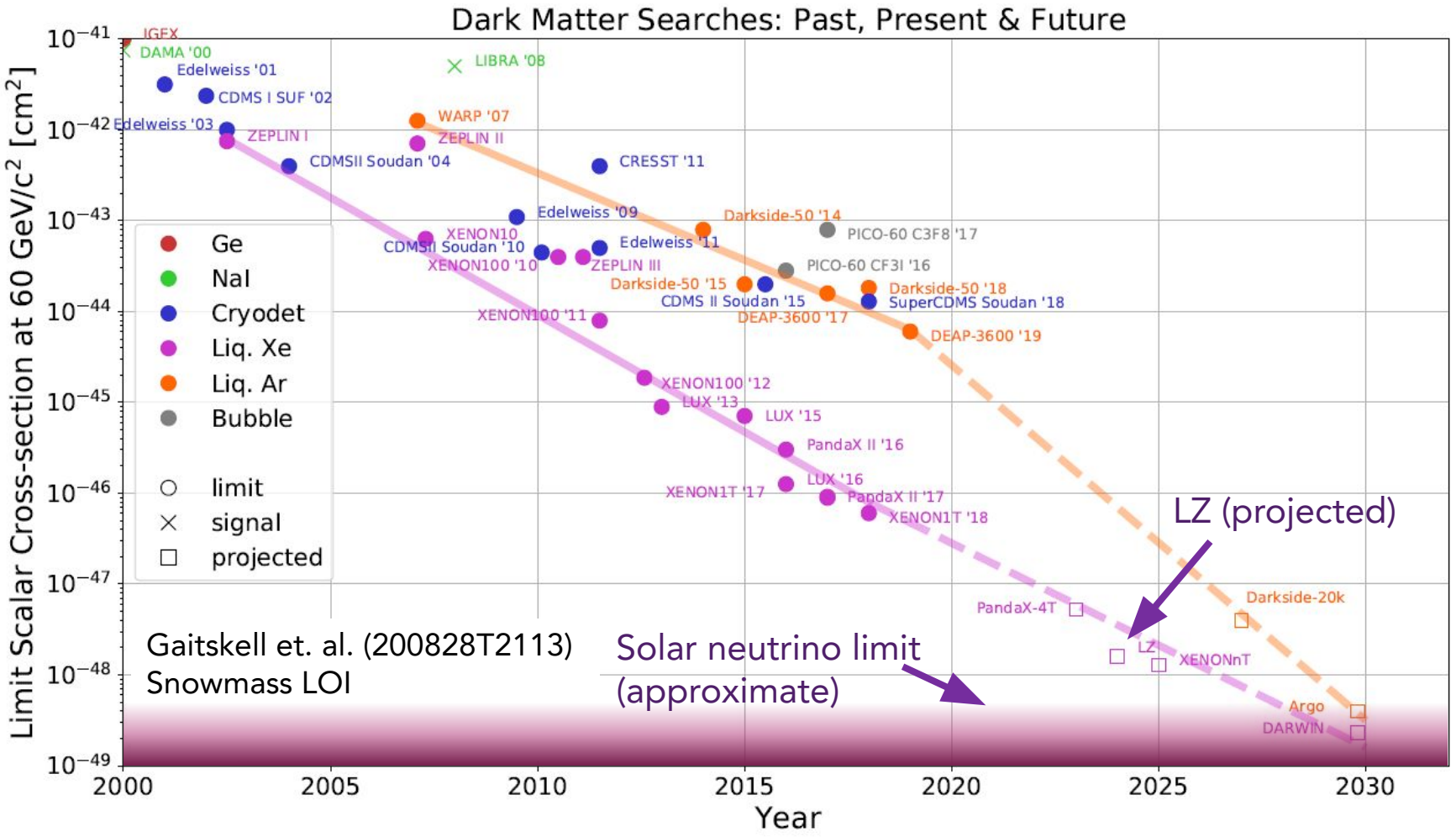
Problem only gets harder for larger detectors (e.g. G3 Xe experiment)

Let's kill the source

TIMING IN THE DECAY CHAIN

THE FUTURE OF DIRECT DETECTION

- Ultimate goal: detect DM or reach neutrino floor/fog
- Xe detectors leading the way for WIMP dark matter
- Simply increasing detector size likely insufficient!
- Must continue innovating from both detector design and data analysis angles

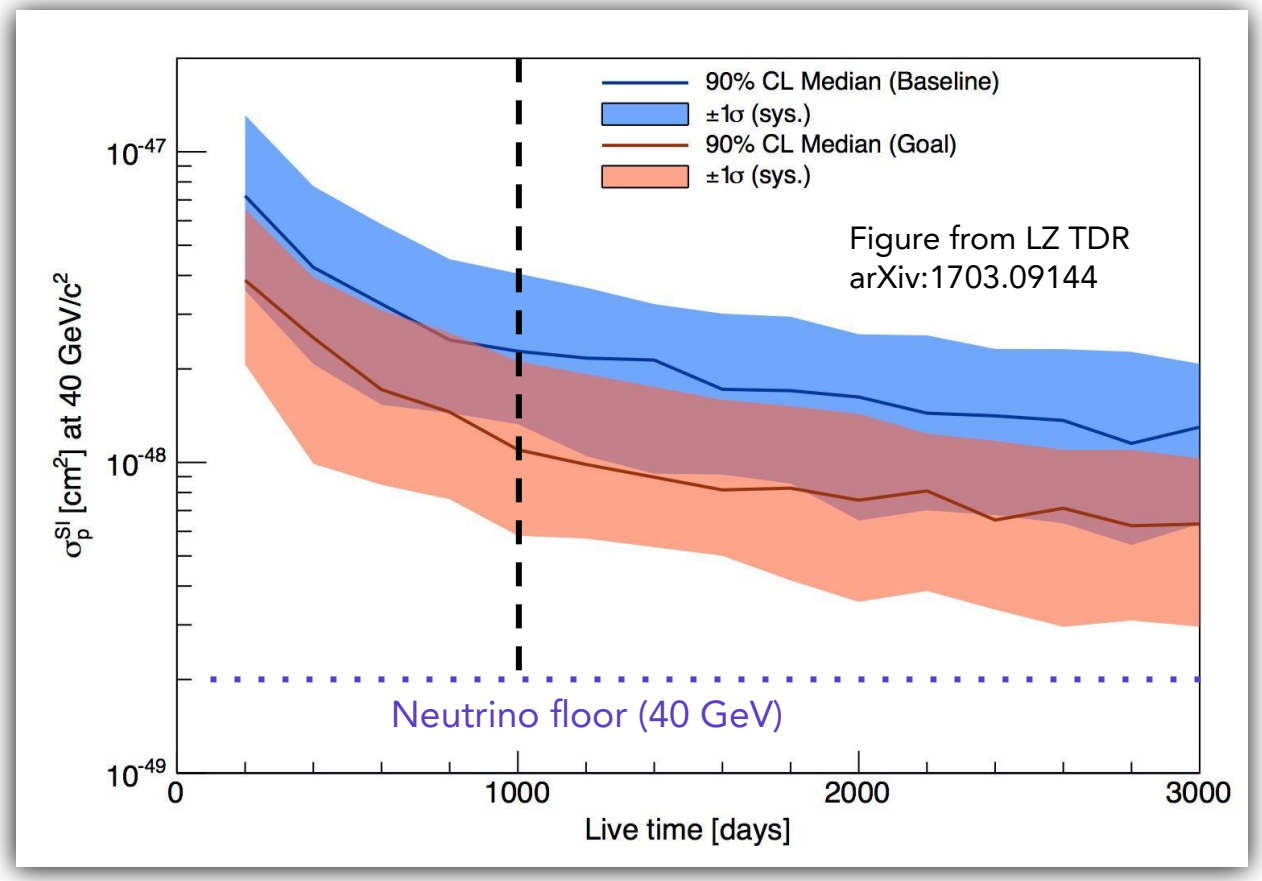


RUN LZ FOR LONGER?

Doesn't work.
Backgrounds win,
mostly radon

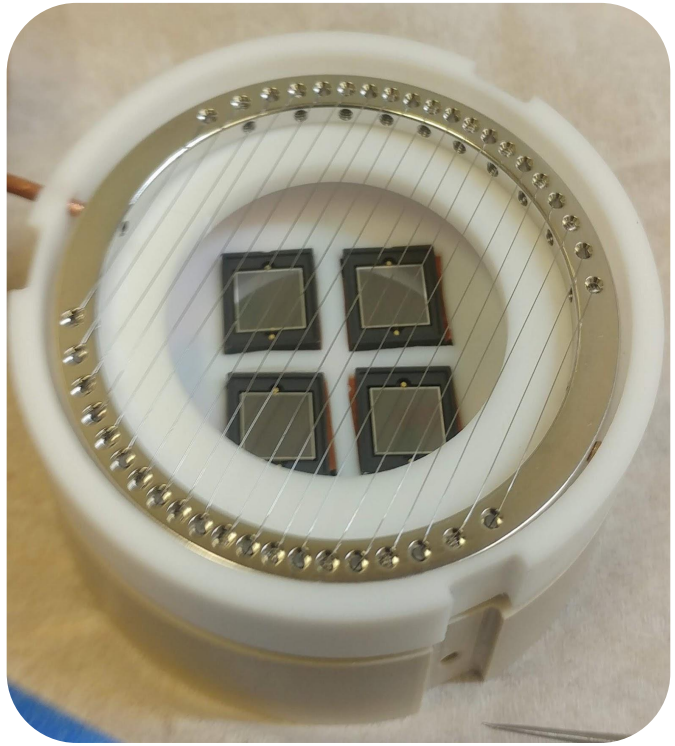
Sensitivity scales poorly
with exposure
when bkg limited

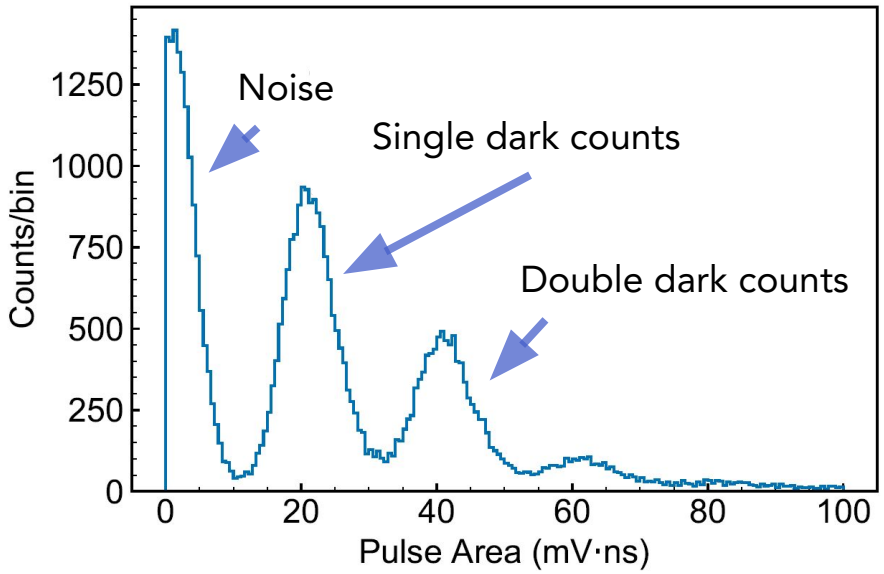
Discovery potential depends
even more strongly on background
level than sensitivity



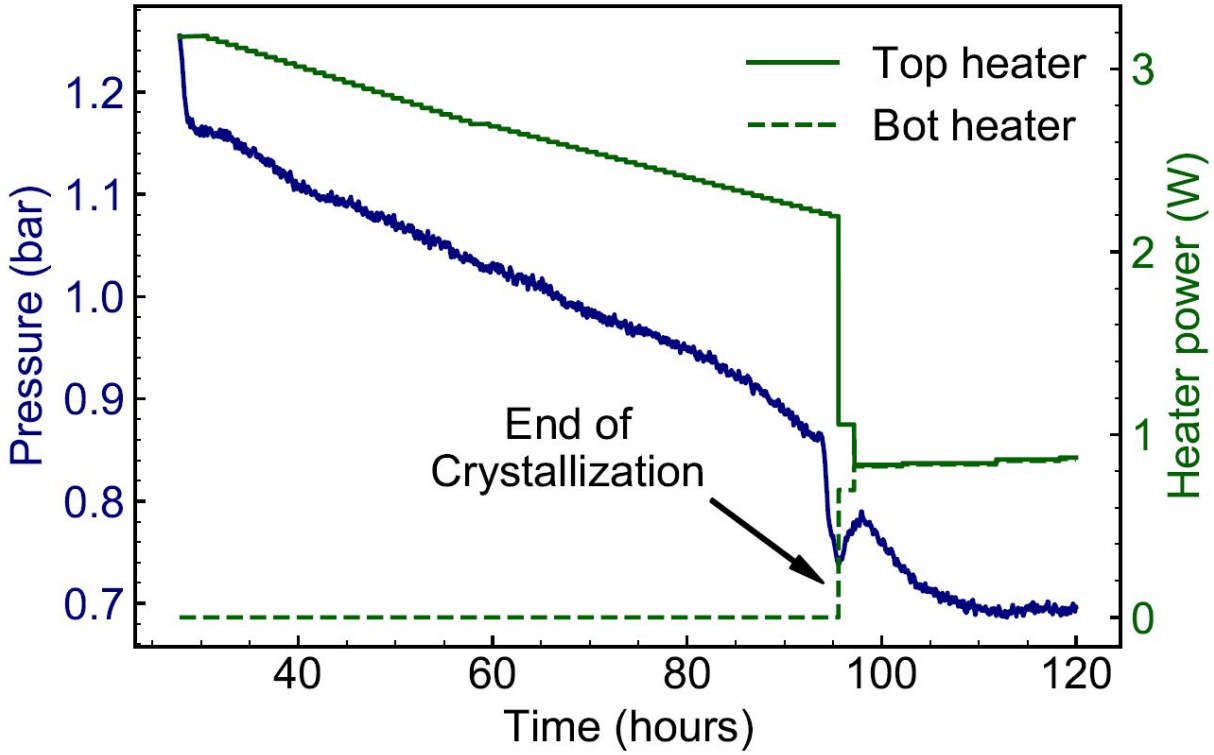
WHY SIPMS?

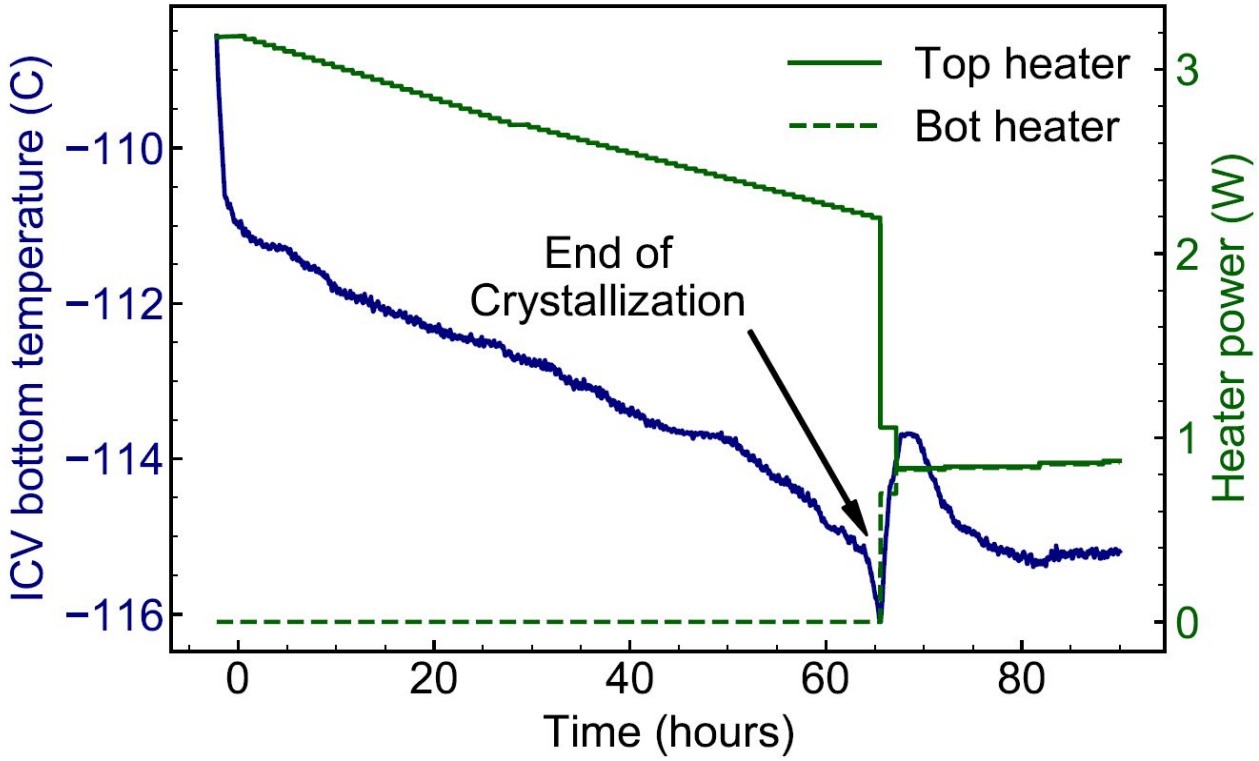
- Compact – less Xe needed
- No vacuum space – no structural concerns, esp. during freezing
- QE extends to deeper-UV (may be present in ice) and IR (possibly observed in EXO-200 APDs, arXiv 1908.04128)



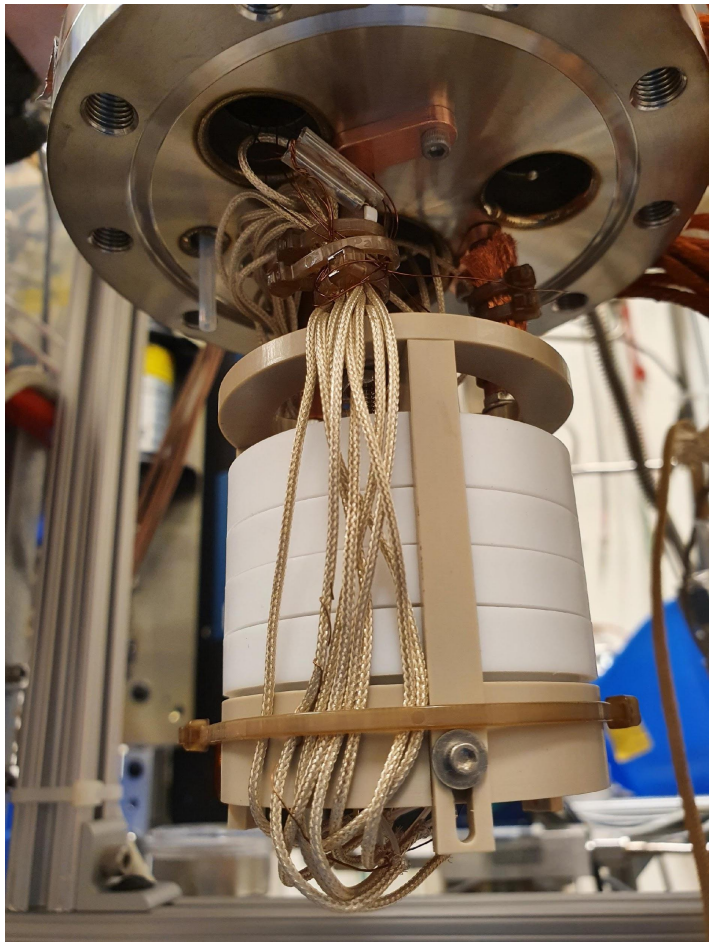


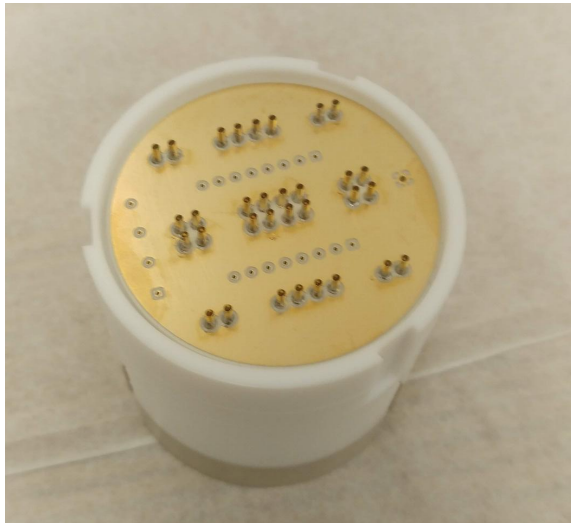
FREEZING PROCEDURE

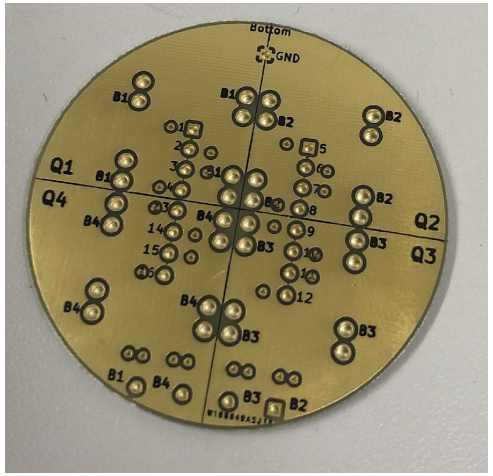


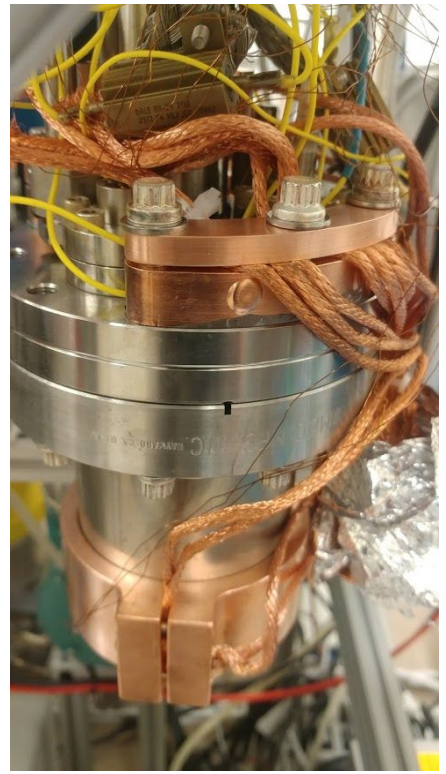


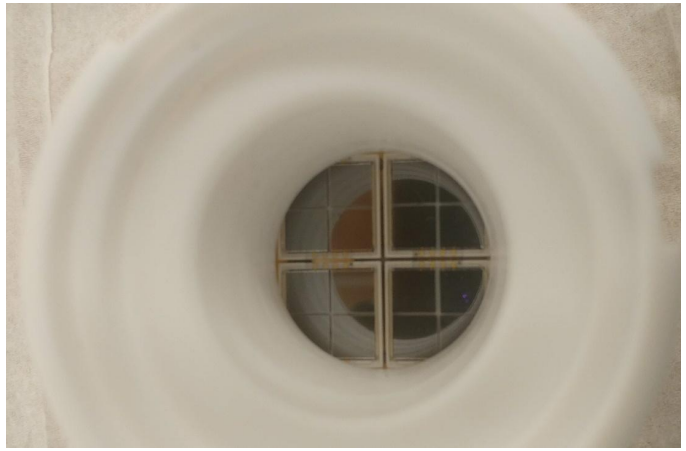
SOLID XENON TEST BED PHOTOS

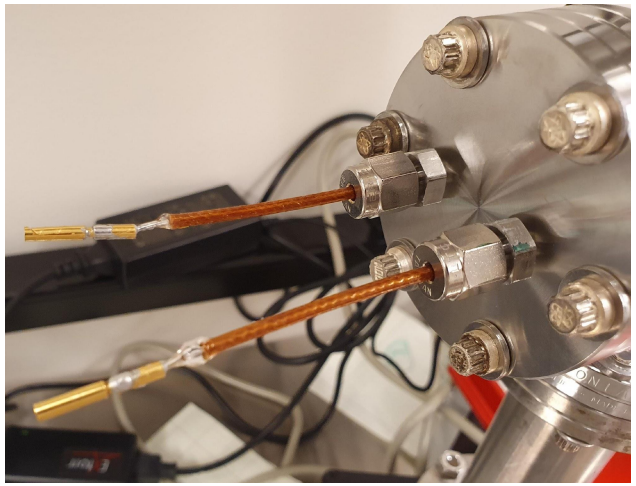




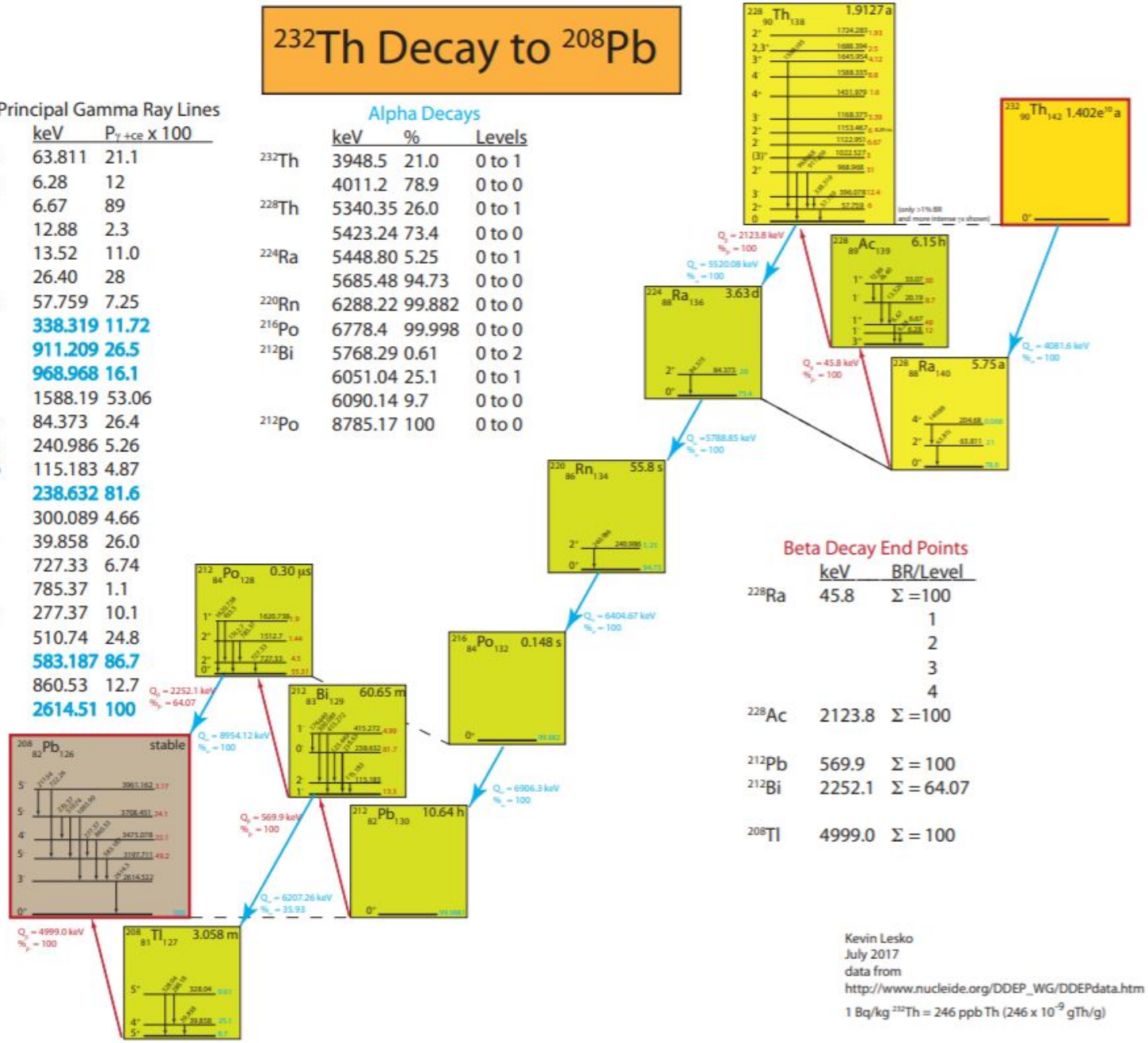








^{232}Th Decay to ^{208}Pb



Principal Gamma Ray Lines

	keV	$P_{\gamma+ce}$ x 100
^{232}Th	63.811	21.1
^{228}Ra	6.28	12
	6.67	89
	12.88	2.3
	13.52	11.0
	26.40	28
^{228}Ac	57.759	7.25
	338.319	**11.72**
	911.209	**26.5**
	968.968	**16.1**
	1588.19	53.06
^{228}Th	84.373	26.4
^{224}Ra	240.986	5.26
^{212}Pb	115.183	4.87
	238.632	**81.6**
	300.089	4.66
^{212}Bi	39.858	26.0
	727.33	6.74
	785.37	1.1
^{208}Tl	277.37	10.1
	510.74	24.8
	583.187	**86.7**
	860.53	12.7
	2614.51	**100**

Alpha Decays

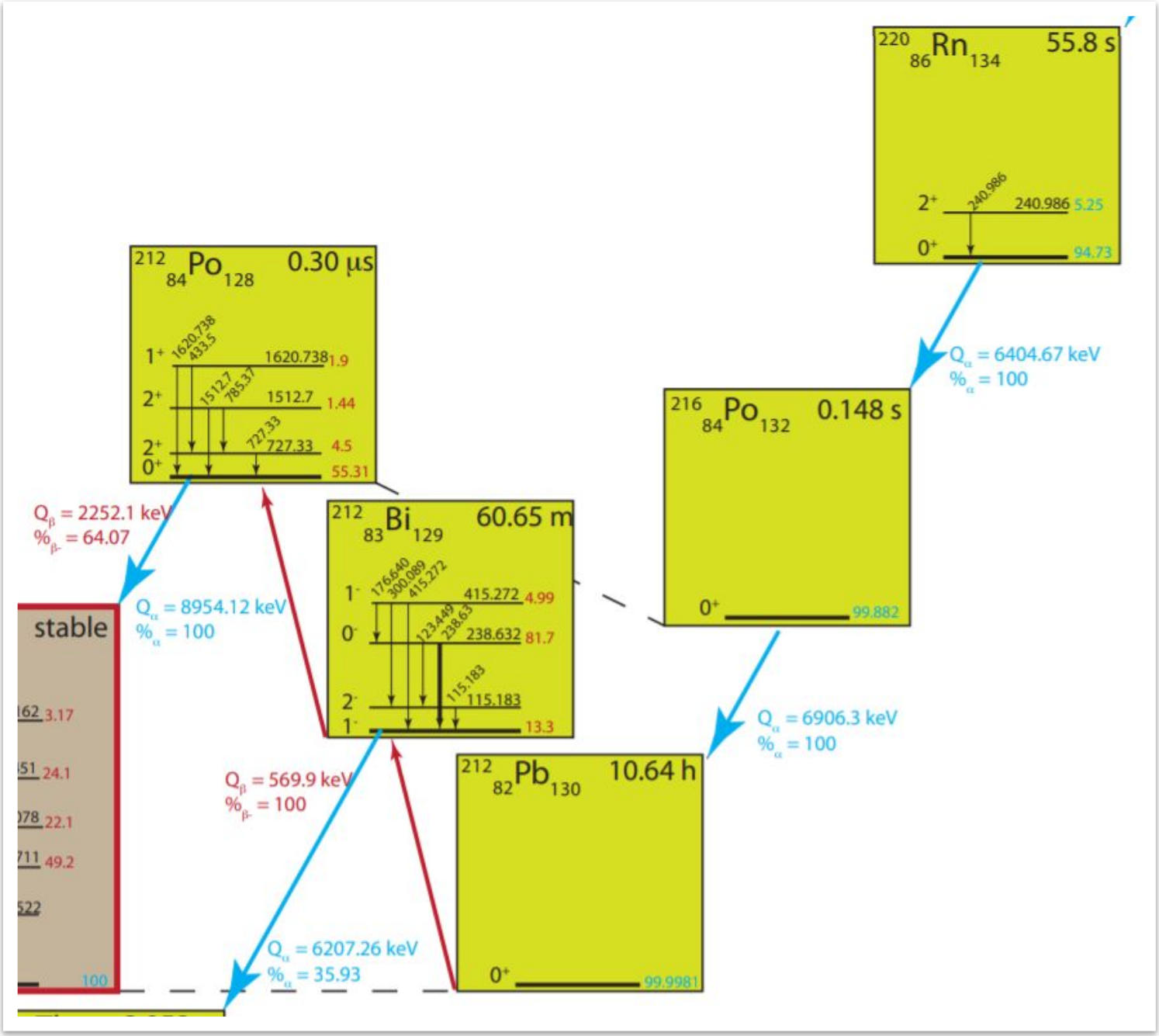
	keV	%	Levels
^{232}Th	3948.5	21.0	0 to 1
	4011.2	78.9	0 to 0
^{228}Th	5340.35	26.0	0 to 1
	5423.24	73.4	0 to 0
^{224}Ra	5448.80	5.25	0 to 1
	5685.48	94.73	0 to 0
^{220}Rn	6288.22	99.882	0 to 0
^{216}Po	6778.4	99.998	0 to 0
^{212}Bi	5768.29	0.61	0 to 2
	6051.04	25.1	0 to 1
	6090.14	9.7	0 to 0
^{212}Po	8785.17	100	0 to 0

Beta Decay End Points

	keV	BR/Level
^{228}Ra	45.8	Σ =100
		1
		2
		3
		4
^{228}Ac	2123.8	Σ =100
^{212}Pb	569.9	Σ = 100
^{212}Bi	2252.1	Σ = 64.07
^{208}Tl	4999.0	Σ = 100

Kevin Lesko
July 2017
data from
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

1 Bq/kg ^{232}Th = 246 ppb Th (246 x 10^{-9} gTh/g)


220 86 Rn 134 55.8 s
2+ 240.986 240.986 5.25
0+ 94.73
Qα = 6404.67 keV
%α = 100
216 84 Po 132 0.148 s
0+ 99.882
Qα = 6906.3 keV
%α = 100
212 84 Po 128 0.30 µs
1+ 1620.738 433.5 1620.738 1.9
2+ 1512.7 151.27 785.37 1512.7 1.44
2+ 727.33 727.33 4.5
0+ 55.31
Qβ = 2252.1 keV
%β- = 64.07
Qα = 8954.12 keV
%α = 100
stable
162 3.17
151 24.1
078 22.1
711 49.2
522
100
212 83 Bi 129 60.65 m
1- 176.640 300.089 415.272 415.272 4.99
0- 123.449 238.63 238.632 81.7
2- 115.183 115.183
1- 13.3
Qβ = 569.9 keV
%β- = 100
212 82 Pb 130 10.64 h
0+ 99.9981
Qα = 6207.26 keV
%α = 35.93

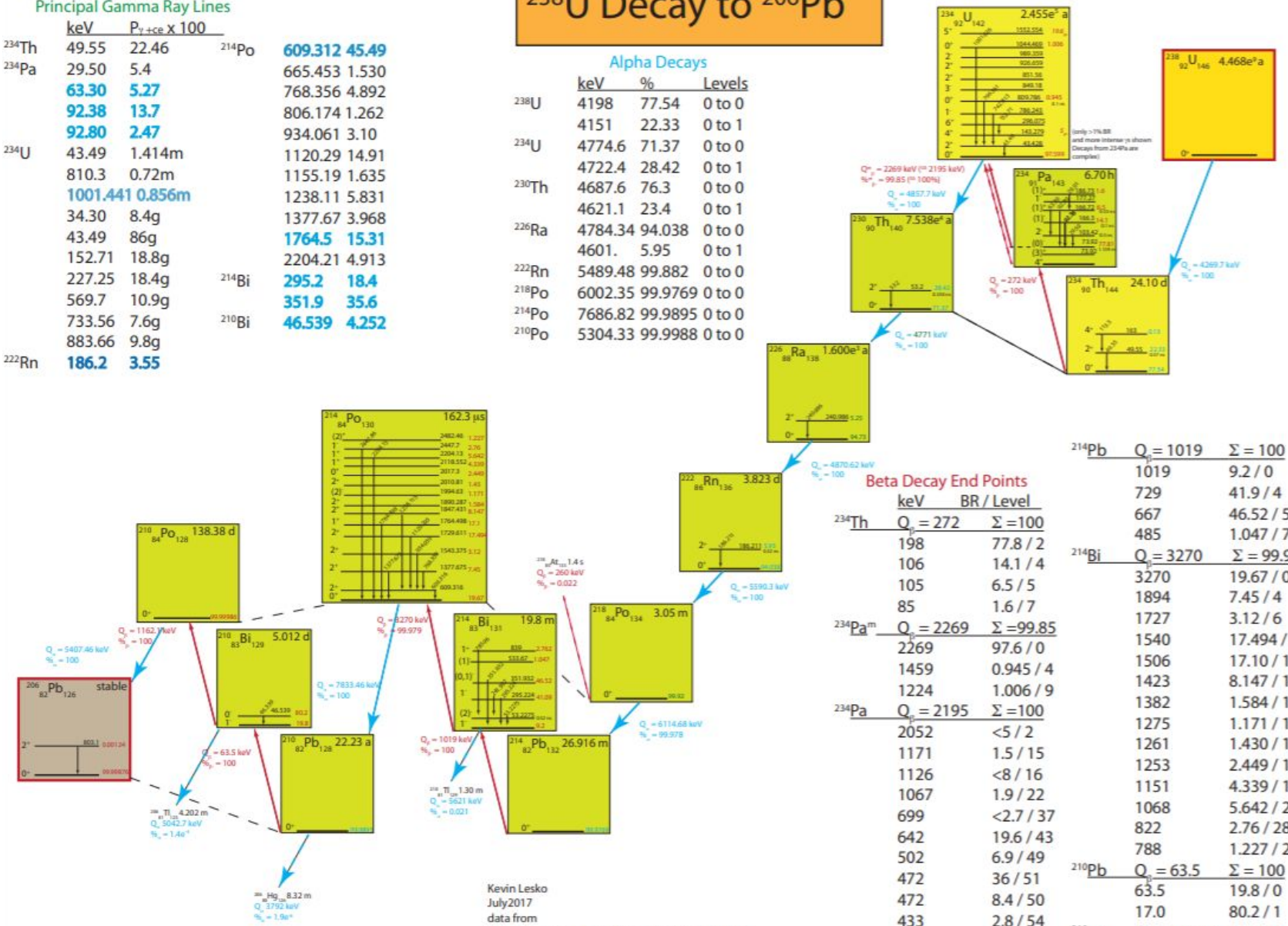
^{238}U Decay to ^{206}Pb

Principal Gamma Ray Lines

	keV	$P_{\gamma+ce}$ x 100
^{234}Th	49.55	22.46
^{234}Pa	29.50	5.4
	63.30	**5.27**
	92.38	**13.7**
	92.80	**2.47**
^{234}U	43.49	1.414m
	810.3	0.72m
	1001.441	**0.856m**
	34.30	8.4g
	43.49	86g
	152.71	18.8g
	227.25	18.4g
	569.7	10.9g
	733.56	7.6g
	883.66	9.8g
^{222}Rn	**186.2**	**3.55**
^{214}Po	**609.312**	**45.49**
	665.453	1.530
	768.356	4.892
	806.174	1.262
	934.061	3.10
	1120.29	14.91
	1155.19	1.635
	1238.11	5.831
	1377.67	3.968
	1764.5	**15.31**
	2204.21	4.913
^{214}Bi	**295.2**	**18.4**
	351.9	**35.6**
^{210}Bi	**46.539**	**4.252**

Alpha Decays

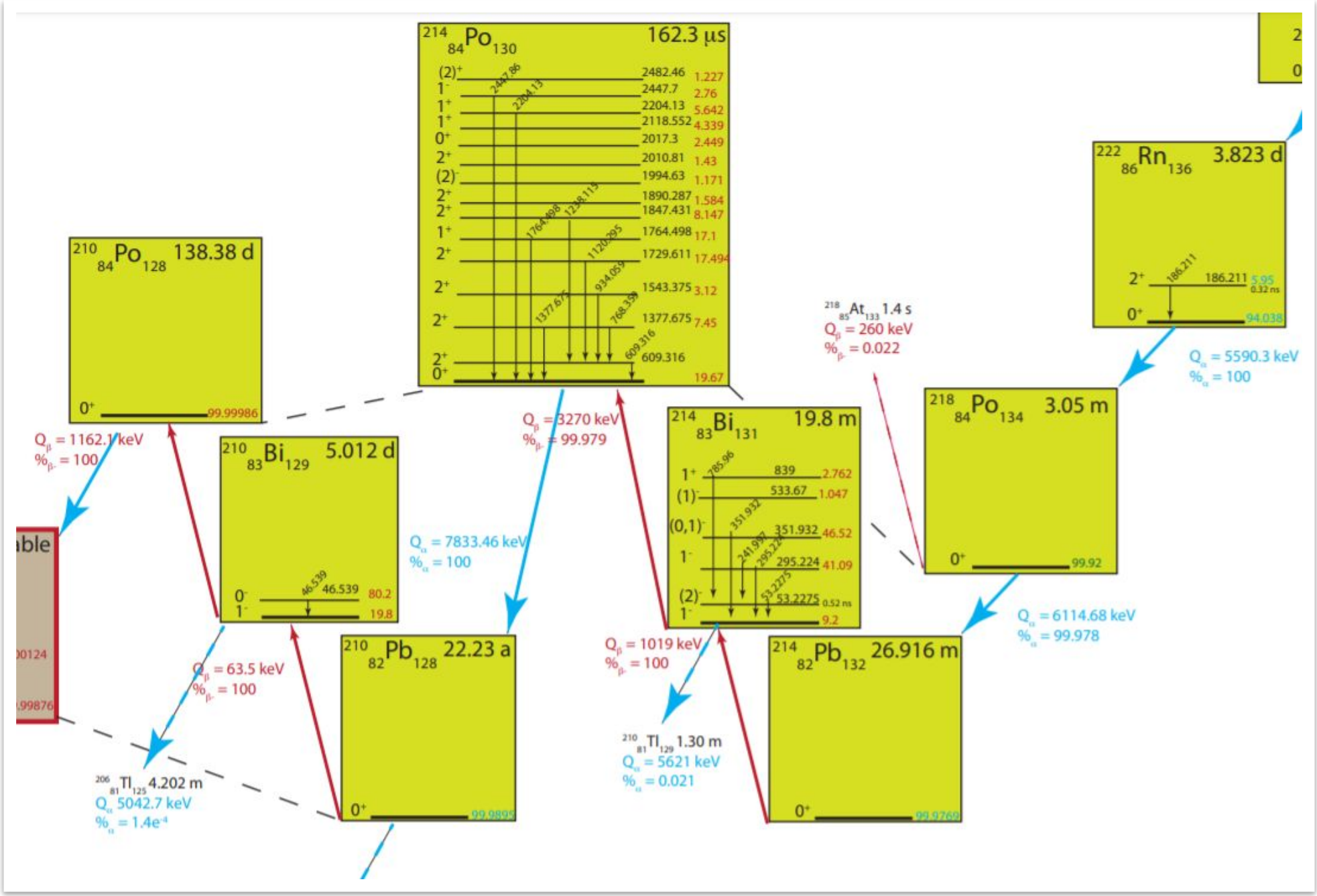
	keV	%	Levels
^{238}U	4198	77.54	0 to 0
	4151	22.33	0 to 1
^{234}U	4774.6	71.37	0 to 0
	4722.4	28.42	0 to 1
^{230}Th	4687.6	76.3	0 to 0
	4621.1	23.4	0 to 1
^{226}Ra	4784.34	94.038	0 to 0
	4601.	5.95	0 to 1
^{222}Rn	5489.48	99.882	0 to 0
^{218}Po	6002.35	99.9769	0 to 0
^{214}Po	7686.82	99.9895	0 to 0
^{210}Po	5304.33	99.9988	0 to 0

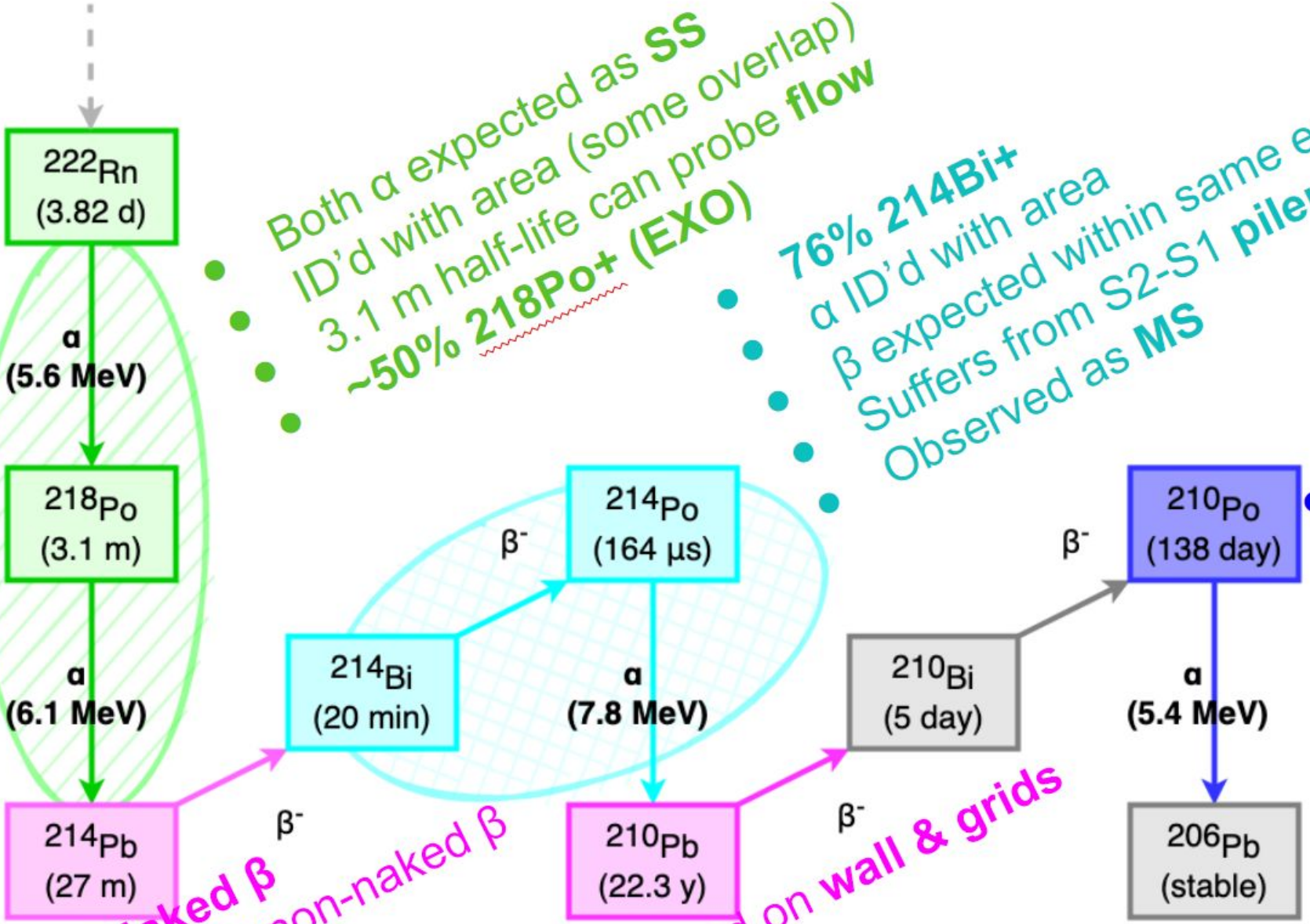


Kevin Lesko
July2017
data from
http://www.nucleide.org/DDEP_WG/DDEPdata.htm
1 Bq/kg ^{238}U = 81 ppb U (81 x 10^{-9} gU/g)

Beta Decay End Points

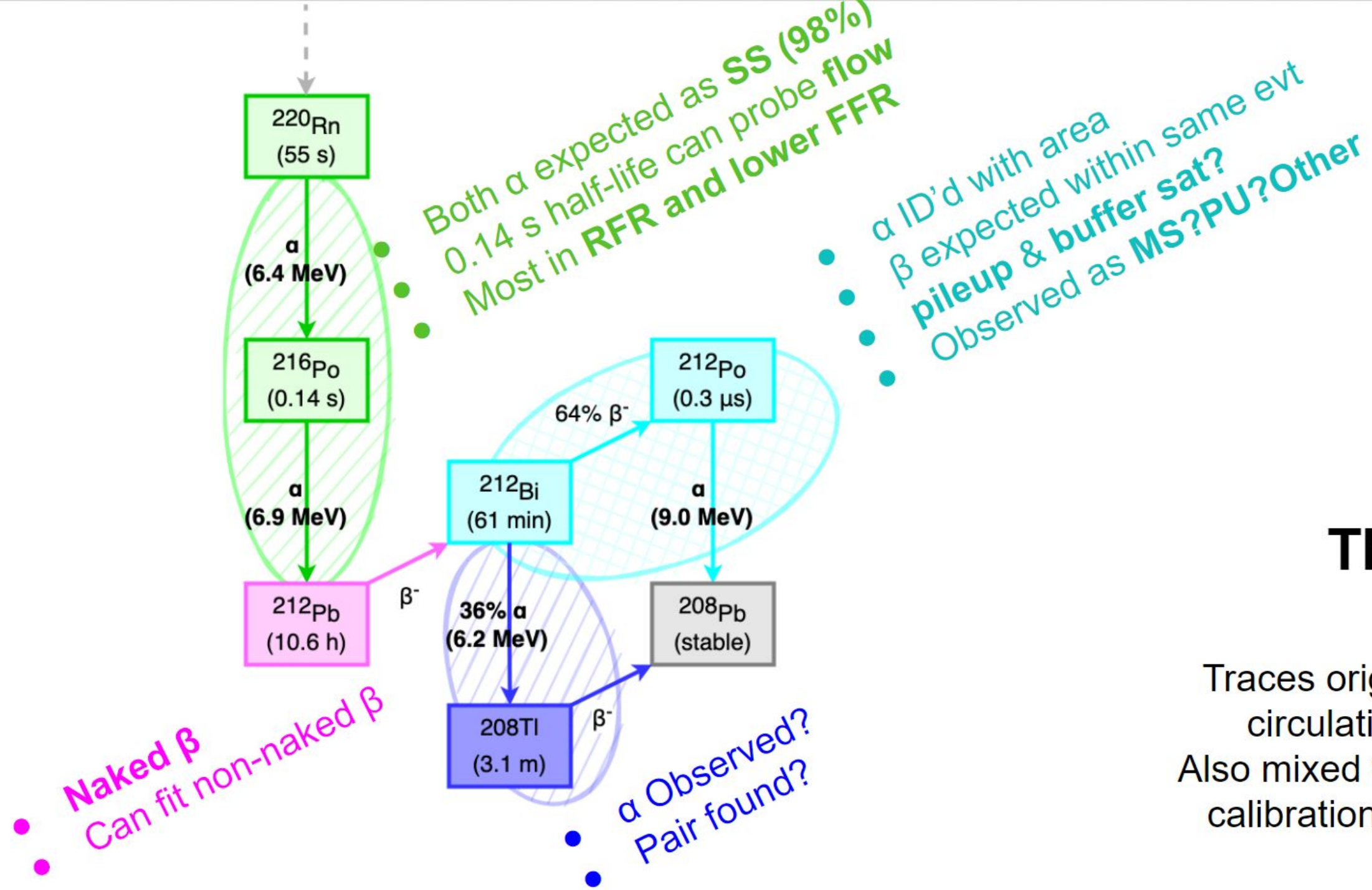
	keV	BR / Level
^{234}Th	Q_β = 272	Σ =100
	198	77.8 / 2
	106	14.1 / 4
	105	6.5 / 5
	85	1.6 / 7
^{234}Pa^m	Q_β = 2269	Σ =99.85
	2269	97.6 / 0
	1459	0.945 / 4
	1224	1.006 / 9
^{234}Pa	Q_β = 2195	Σ =100
	2052	<5 / 2
	1171	1.5 / 15
	1126	<8 / 16
	1067	1.9 / 22
	699	<2.7 / 37
	642	19.6 / 43
	502	6.9 / 49
	472	36 / 51
	472	8.4 / 50
	433	2.8 / 54
	412	8 / 56
^{214}Pb	Q_β = 1019	Σ = 100
	1019	9.2 / 0
	729	41.9 / 4
	667	46.52 / 5
	485	1.047 / 7
^{214}Bi	Q_β = 3270	Σ = 99.976
	3270	19.67 / 0
	1894	7.45 / 4
	1727	3.12 / 6
	1540	17.494 / 9
	1506	17.10 / 11
	1423	8.147 / 12
	1382	1.584 / 13
	1275	1.171 / 14
	1261	1.430 / 15
	1253	2.449 / 16
	1151	4.339 / 18
	1068	5.642 / 21
	822	2.76 / 28
	788	1.227 / 29
^{210}Pb	Q_β = 63.5	Σ = 100
	63.5	19.8 / 0
	17.0	80.2 / 1
^{210}Bi	Q_β = 1162.1	Σ = 100
	1162.1	99.99986 / 0


214 84 Po 130 162.3 µs
210 84 Po 128 138.38 d
210 83 Bi 129 5.012 d
210 82 Pb 128 22.23 a
214 83 Bi 131 19.8 m
214 82 Pb 132 26.916 m
218 85 At 133 1.4 s
Qβ = 260 keV
%β- = 0.022
222 86 Rn 136 3.823 d
Qα = 5590.3 keV
%α = 100
218 84 Po 134 3.05 m
Qα = 6114.68 keV
%α = 99.978
Qβ = 1162.1 keV
%β- = 100
Qβ = 3270 keV
%β- = 99.979
Qα = 7833.46 keV
%α = 100
Qβ = 63.5 keV
%β- = 100
Qβ = 1019 keV
%β- = 100
206 81 Tl 125 4.202 m
Qα 5042.7 keV
%α = 1.4e-4
210 81 Tl 129 1.30 m
Qα = 5621 keV
%α = 0.021



Uranium Series

^{222}Rn emanates from material and mixes with the LXe. Highest contributor to WIMP BG.



Thorium Series

Traces originate from circulation system. Also mixed with LXe in calibration injections.