SOLID XENON AS THE PATH TO THE NEUTRINO FLOOR

SCOTT KRAVITZ, PETER SORENSEN,
SCOTT HASELSCHWARDT, MATTHEW FORMAN
LAWRENCE BERKELEY NATIONAL LAB

*CPAD WORKSHOP,
DEC 8 2019*

Where will dark matter direct detection be in 2025?

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- Either:
  - no evidence for WIMPs
  - a hint of WIMPs
  - a handful of WIMPs

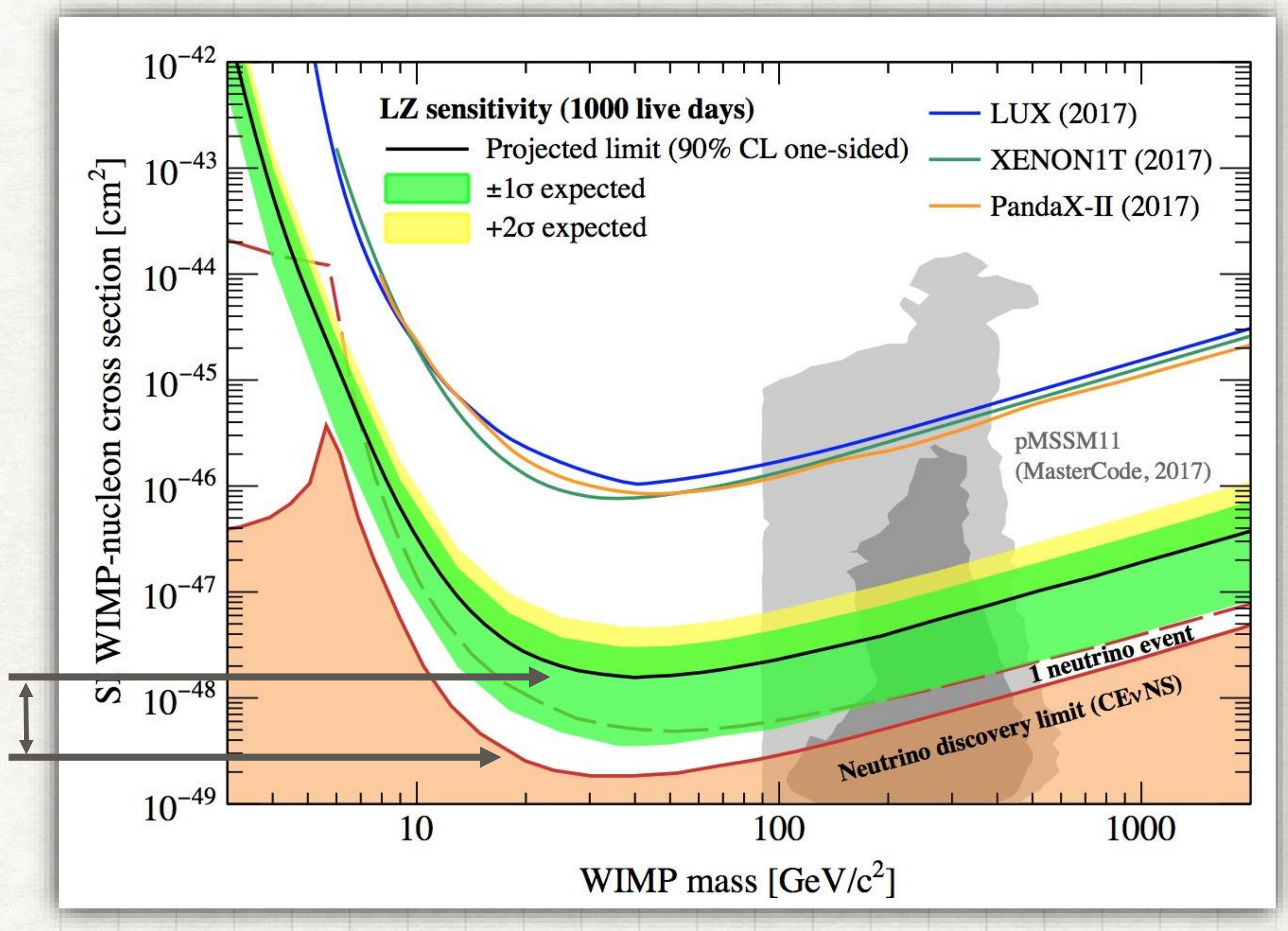

Figure from LZ: arXiv:1802.06039

- But must reach the neutrino floor:

- A G3 (i.e. 20+ tonne) xenon TPC would require a lot of:
  - time (10+ years)
  - money ($200+ M)
- Not obvious this is the best path

Limitations from LZ backgrounds

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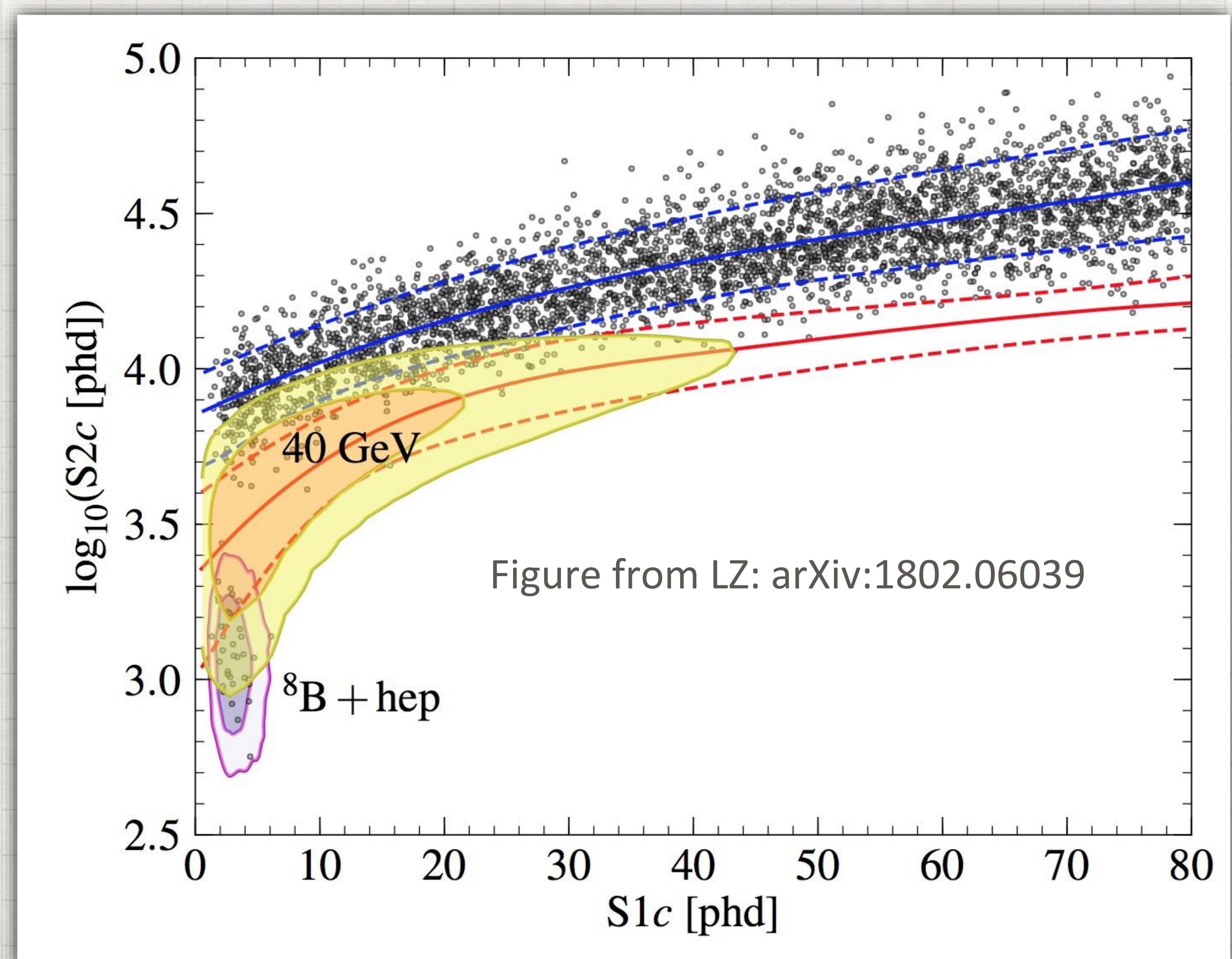

1100 BG events
- 800 from Rn
- 200 from solar nu
- <1 atm. nu
- 40 8B nu

w/ 99.5% ER/NR discrimination, 4 of 6 bkg events from Rn

Internal backgrounds !!

Run LZ for longer?

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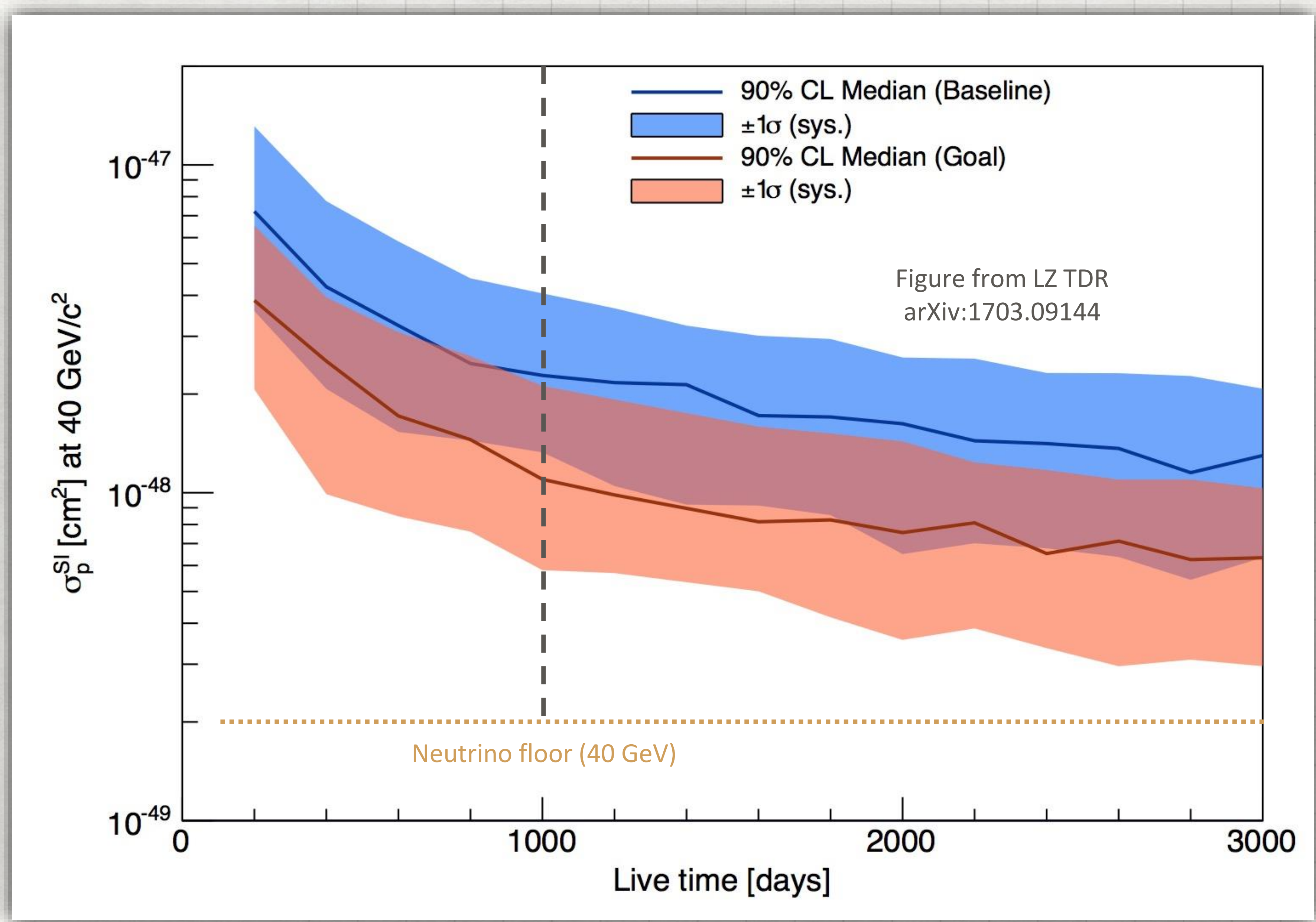
Doesn't work.
Backgrounds win,
mostly radon



Get better at radon reduction?

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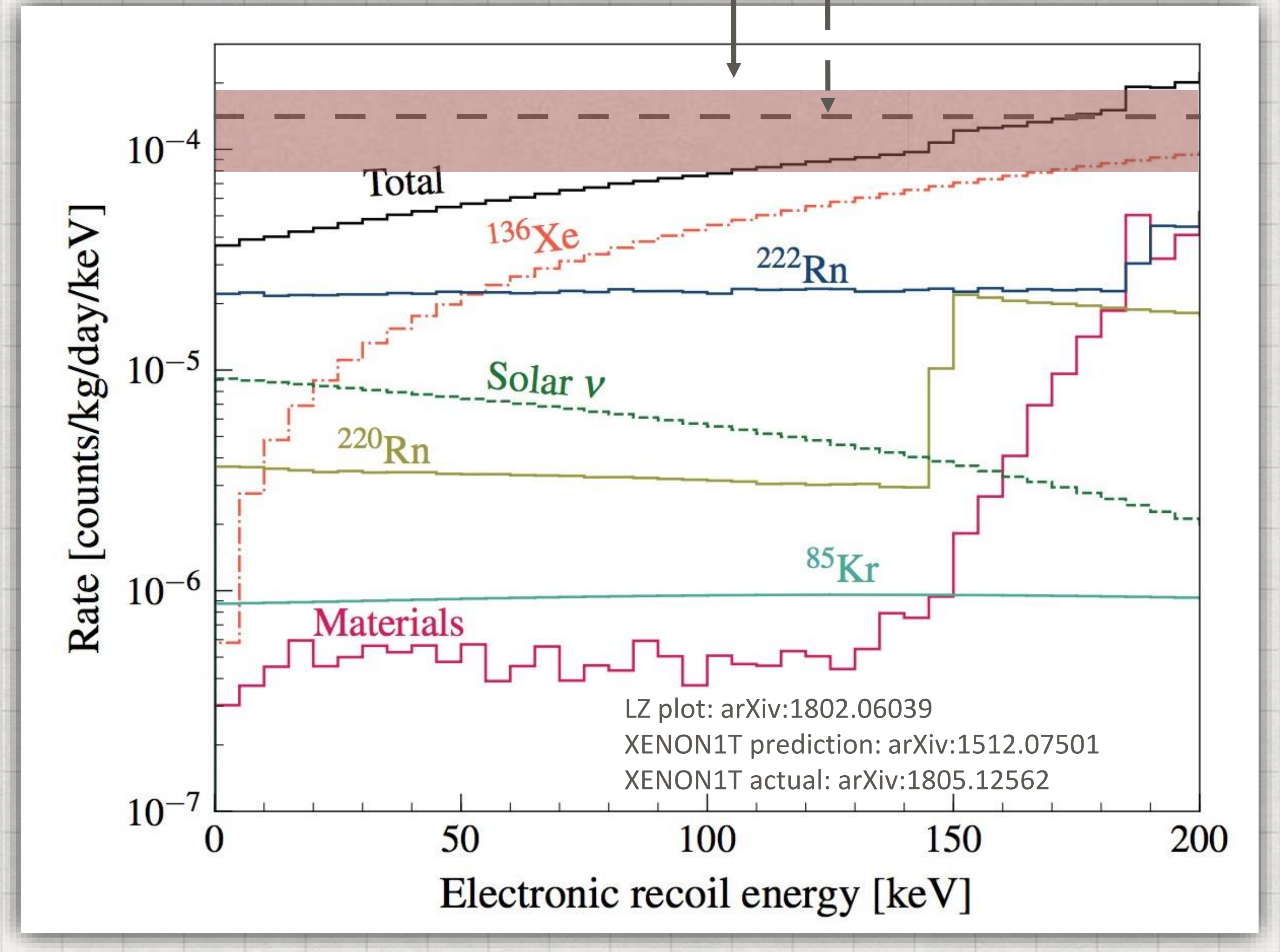
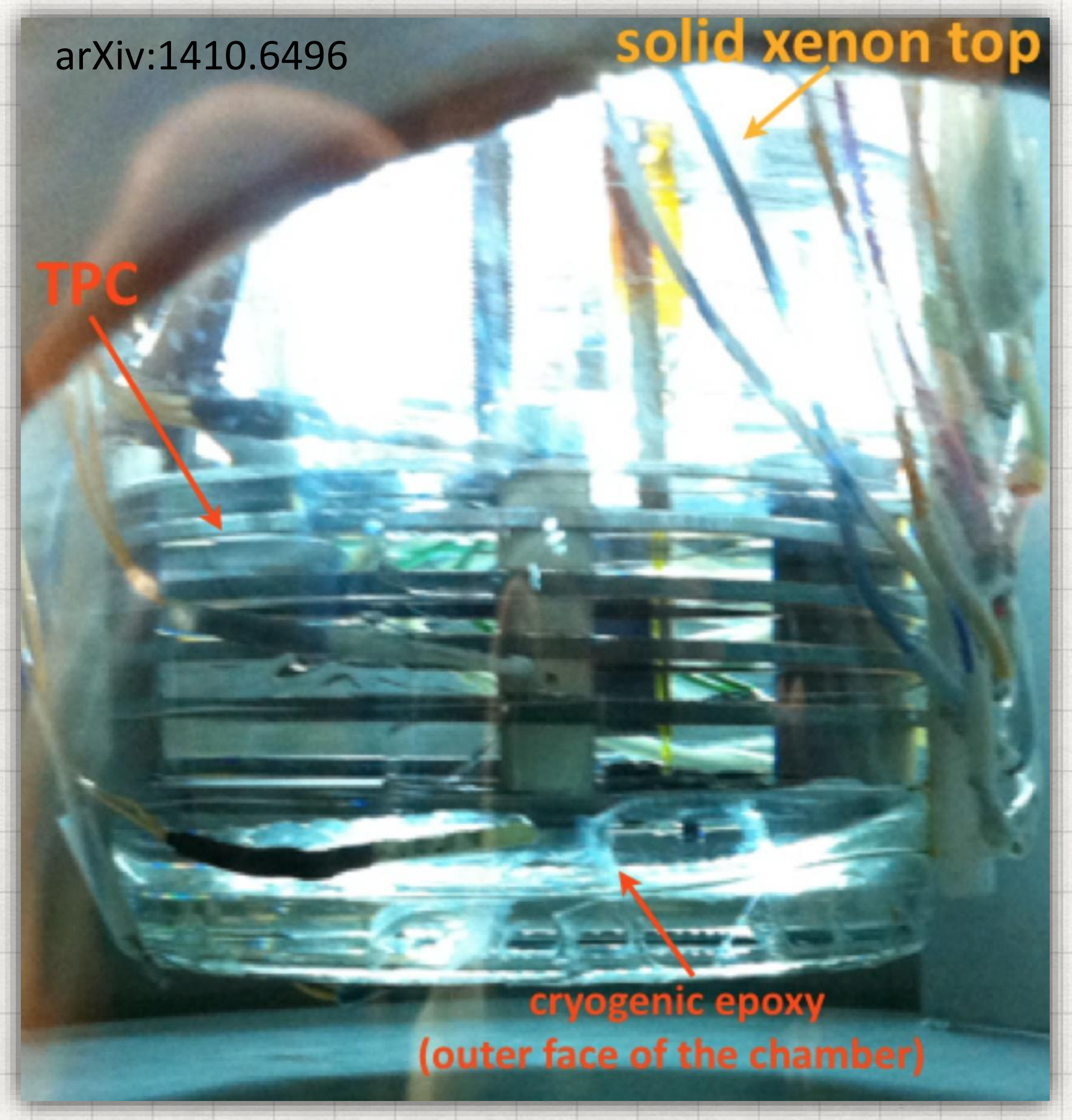
Active area of R&D. HARD.

XENON1T prediction w/o cryogenic distillation (dash) and measured w/ cryogenic distillation (shaded)



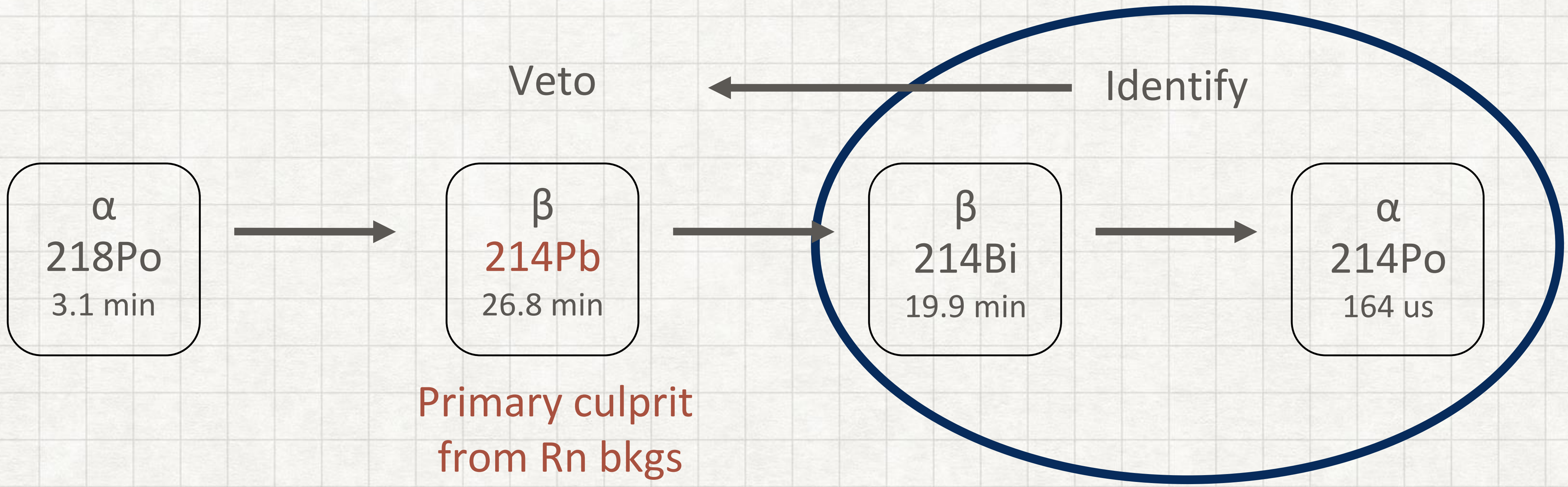
Solution: Crysta**LiZ**e

- **Freeze LZ**:
  Radon emanated from surfaces now **excluded** from solid bulk
- In a crystal, radon decay daughters would stay at the same (x,y,z) as the parent, **enabling tagging/veto**
- DAMIC has used this trick in Si arXiv:1506.02562



Rn daughter tagging

…

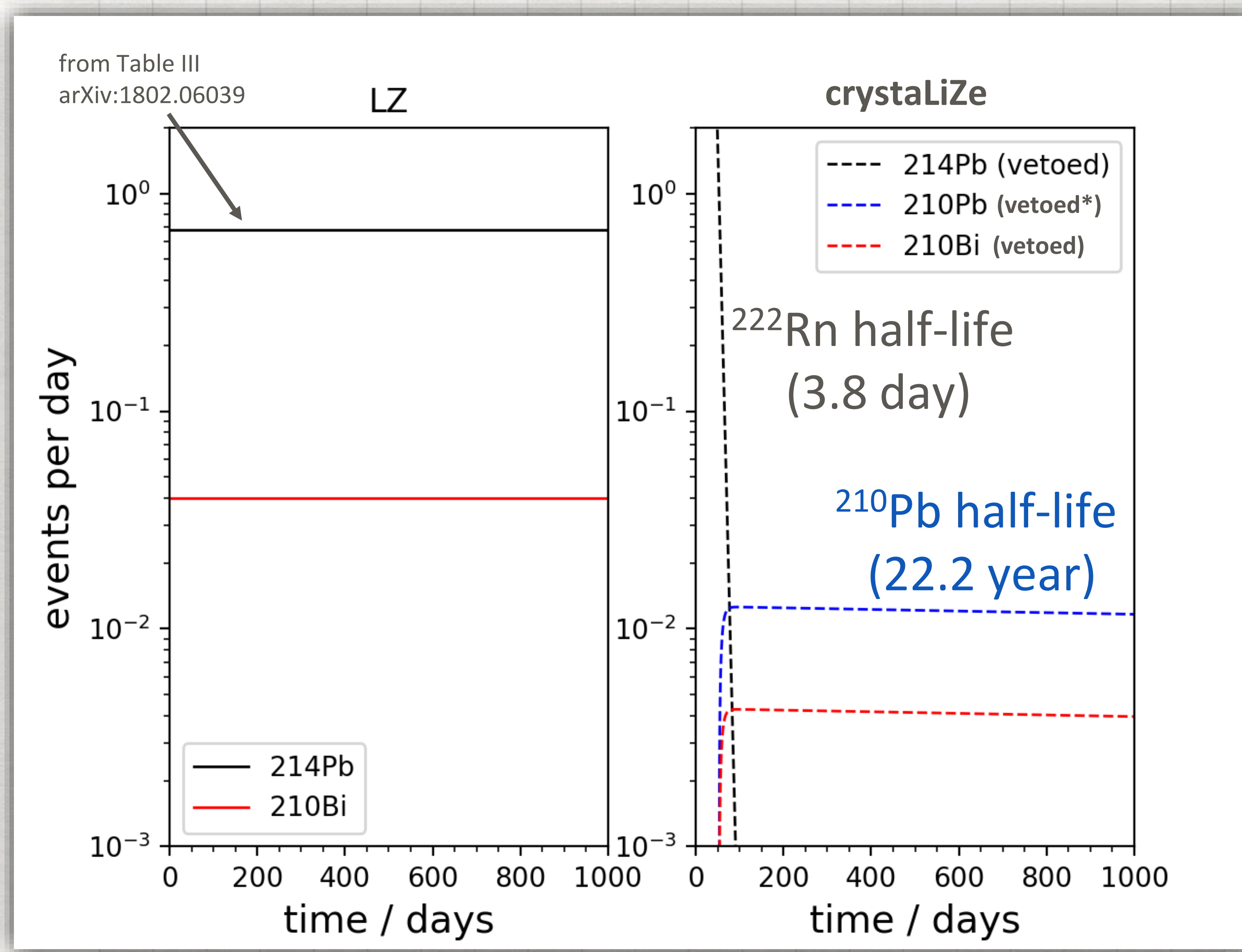


This is an easy sequence to tag if all the decays happen in exactly the same spot in a low-background instrument

(similar situation for 220Rn chain)

Radon tagging by the numbers

- In LZ, Rn emanates into the liquid and flows in to the bulk
- In crystaLiZe, Rn would emanate into the bulk for O(100) days while the crystal is growing; then, Rn in bulk target would be fixed and decay away



same LZ emanation and dust assumptions

Two slopes towards discovery

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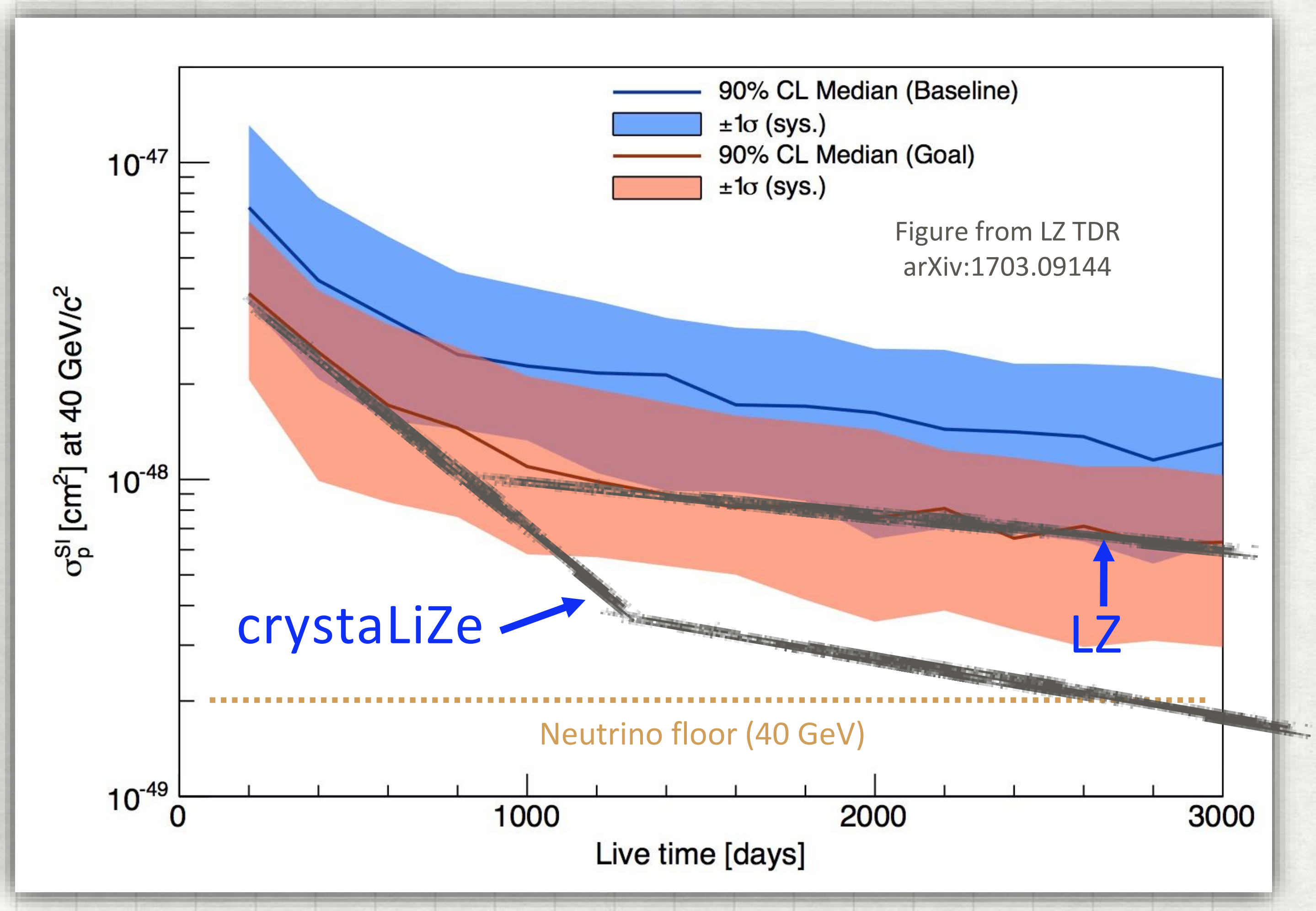
- a crystalline xenon TPC ("crystaLiZe") would progress along the first slope for longer



crystaLiZe looks technically feasible

…

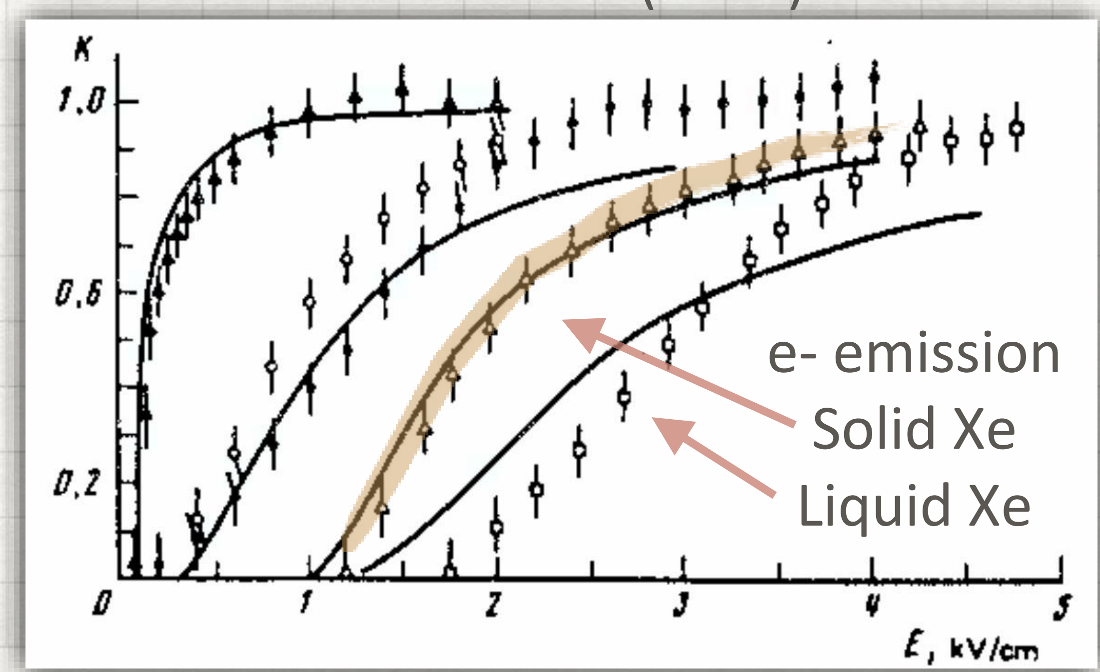
- Solid and liquid xenon have similar physical properties
- Solid xenon emission TPC is expected to perform as well as a liquid xenon emission TPC
  - **band gap (hence W-value)**
  - **electron mobility (doubled)**
  - electron emission
  - density (20% bonus!)
  - high voltage **
- **Similar scintillation signal observed in solid and liquid**
- cf. arXiv:1410.6496 and arXiv:1508.05903

Phys Rev B 10 4464 (1974)

TABLE II. Comparison of transport parameters in solid and liquid xenon. Values of other data used in the calculations are also quoted.

	Solid $T=161.2$ °K	Liquid $T=163$ °K	Unit
E_G	9.272	9.22	eV
G	1.063	1.084	eV
ϵ_∞	2.00 [a]	1.85 [b]	⋯
m^*	0.31 [c]	0.27	electron mass
μ	4.5×10^3 [d]	2.2×10^3 [e]	$cm^2\ V^{-1}\ sec^{-1}$
τ_p	8.0×10^{-13}	3.4×10^{-13}	sec
L	7.1×10^{-6}	3.3×10^{-6}	cm
β	1.36×10^{10} [f]	0.58×10^{10} [g]	dyn/cm^2
$\lvert a \rvert$	3.8×10^{-9}	4.2×10^{-9}	cm
$\lvert E_{1CB} \rvert$	0.93	1.01	eV

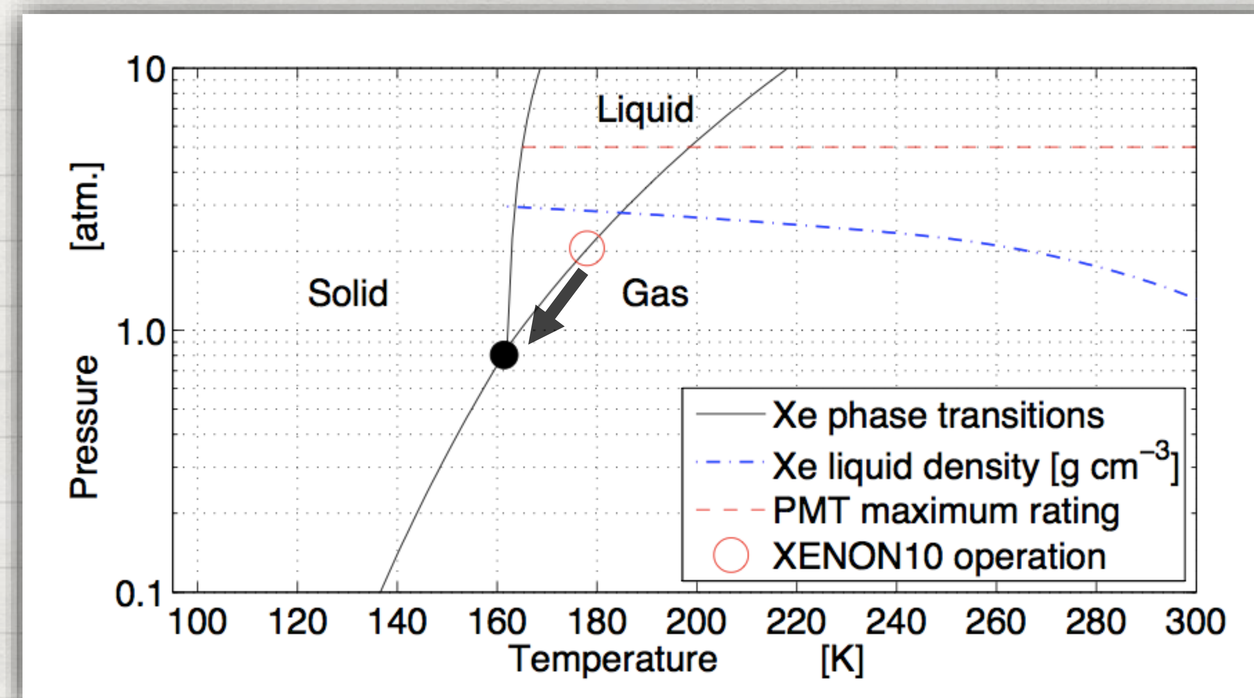
JETP 55 860 (1982)



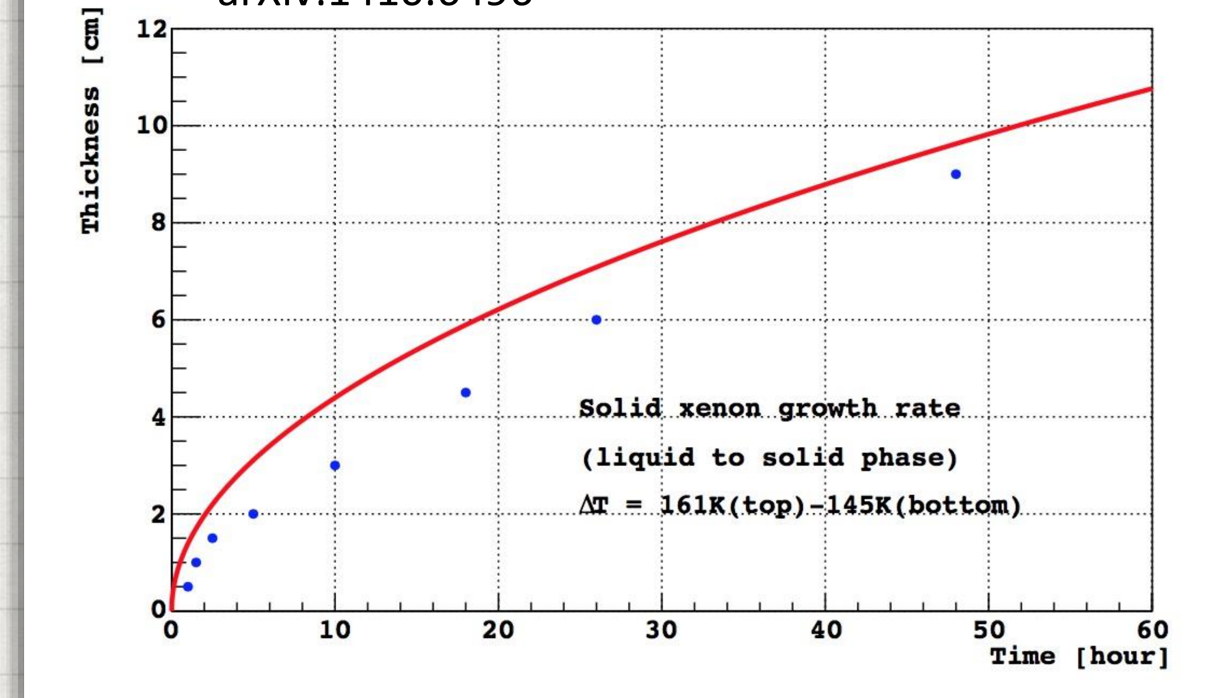
Technical Challenges

- Single e- sensitivity?
- Retaining high purity while crystallizing
  - likely requiring elevated temperature bakeout
  - would take multiple months to crystallize LZ w/o defects
- Precise temperature gradients require more elaborate control/measurement of T
- **R&D:** use small scale crystalline Xe TPC test bed to gauge performance

…



arXiv:1410.6496



Test Bed Design

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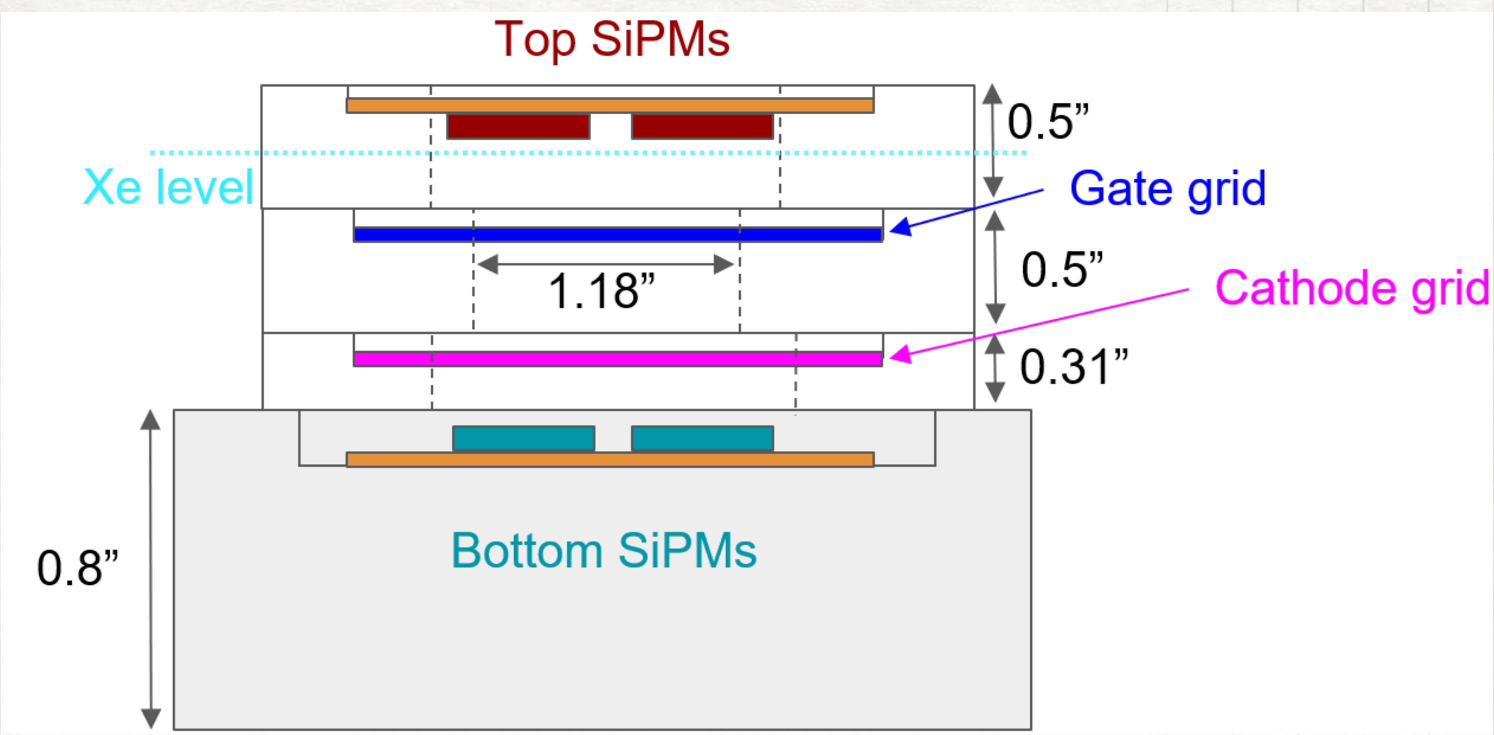
- Two phase Xe mini-TPC
- ~500 g Xe when full
- S1 and S2 readout:
  SiPM arrays (4 top, 4 bottom)



Why SiPMs?

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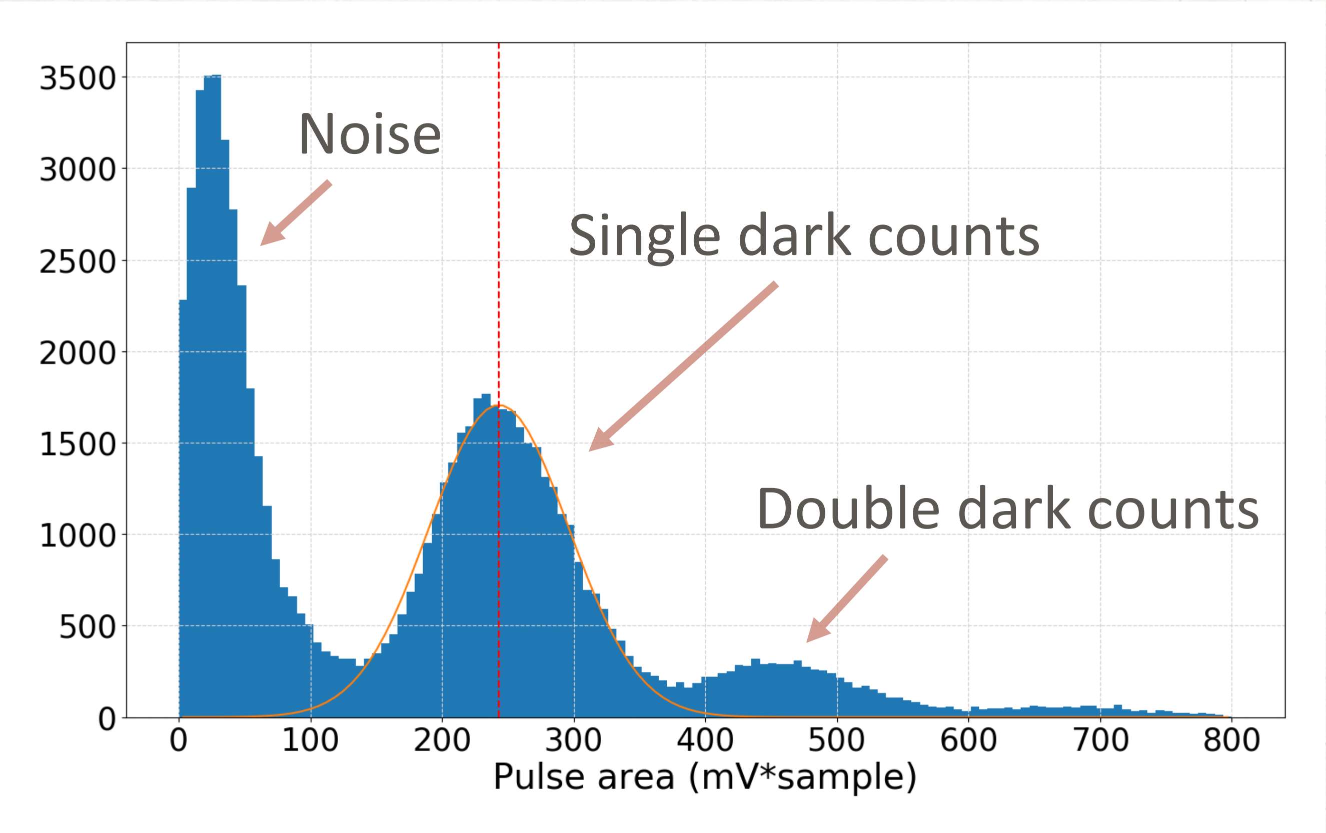
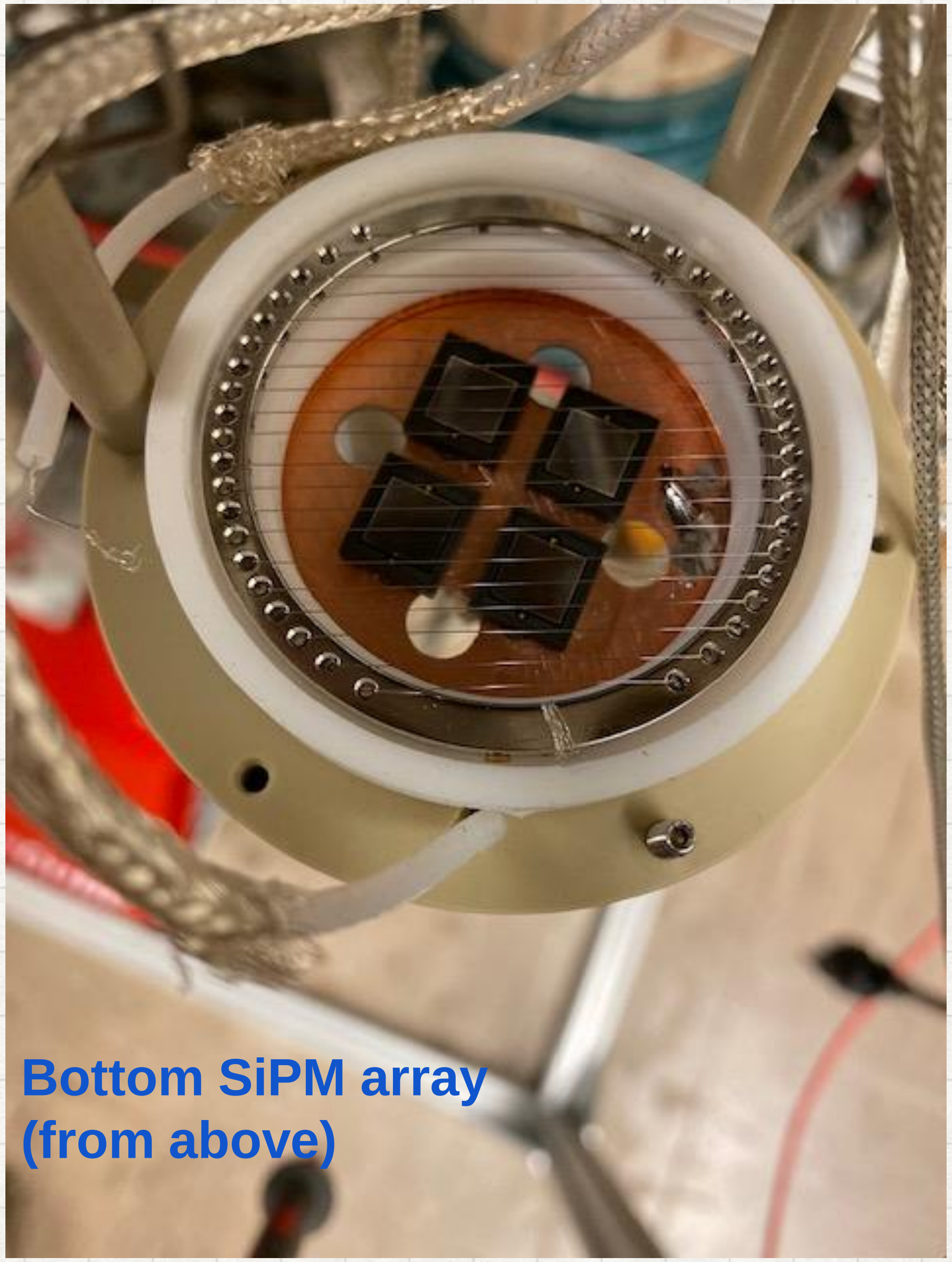
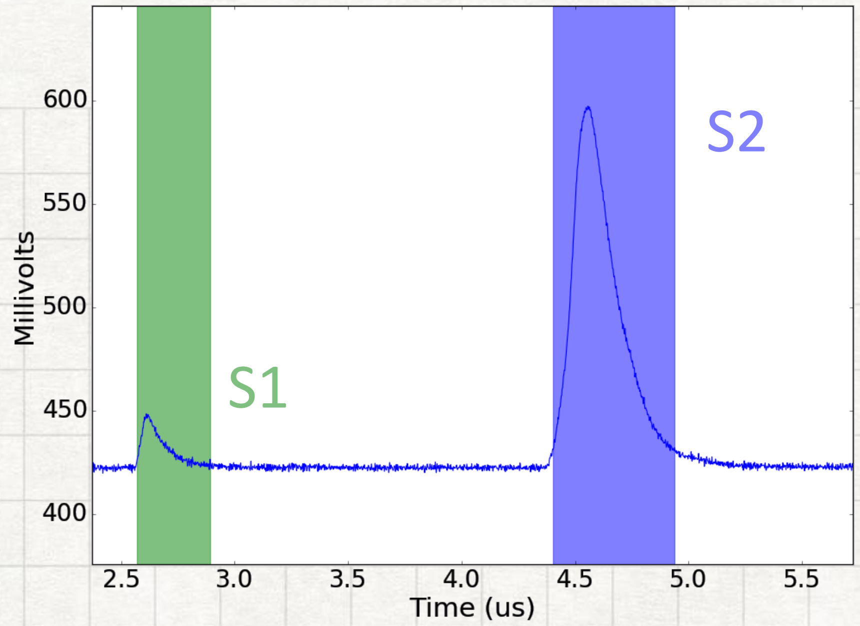
- Compact – less Xe needed
- No vacuum space – no structural concerns, esp. during freezing
- QE extends to deeper-UV light that may be present in ice

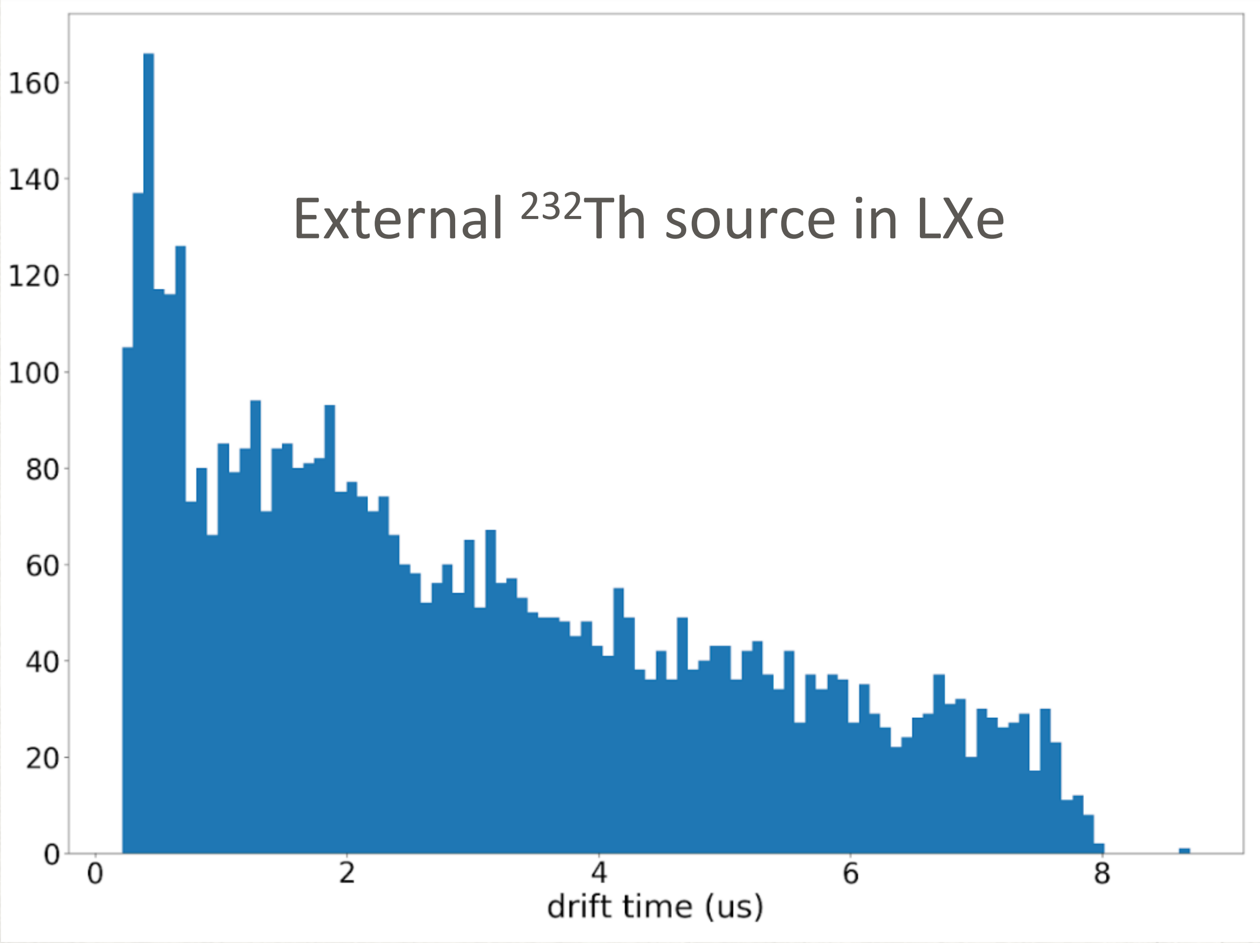


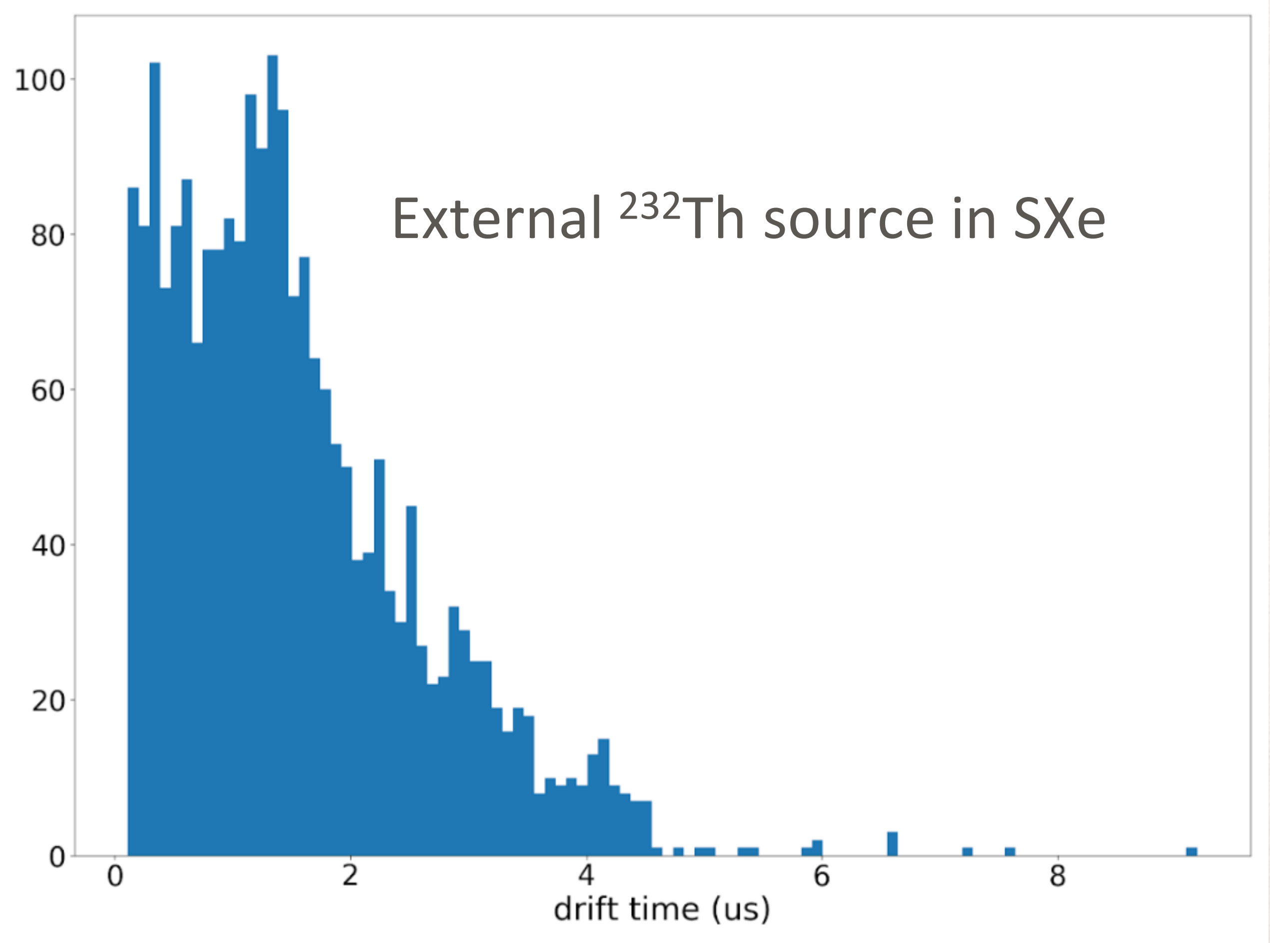


TPC Tests

- Observe S1s and S2s in Xe
- Clear indications of freezing:
  - Vapor pressure below triple point
  - Drift time halves







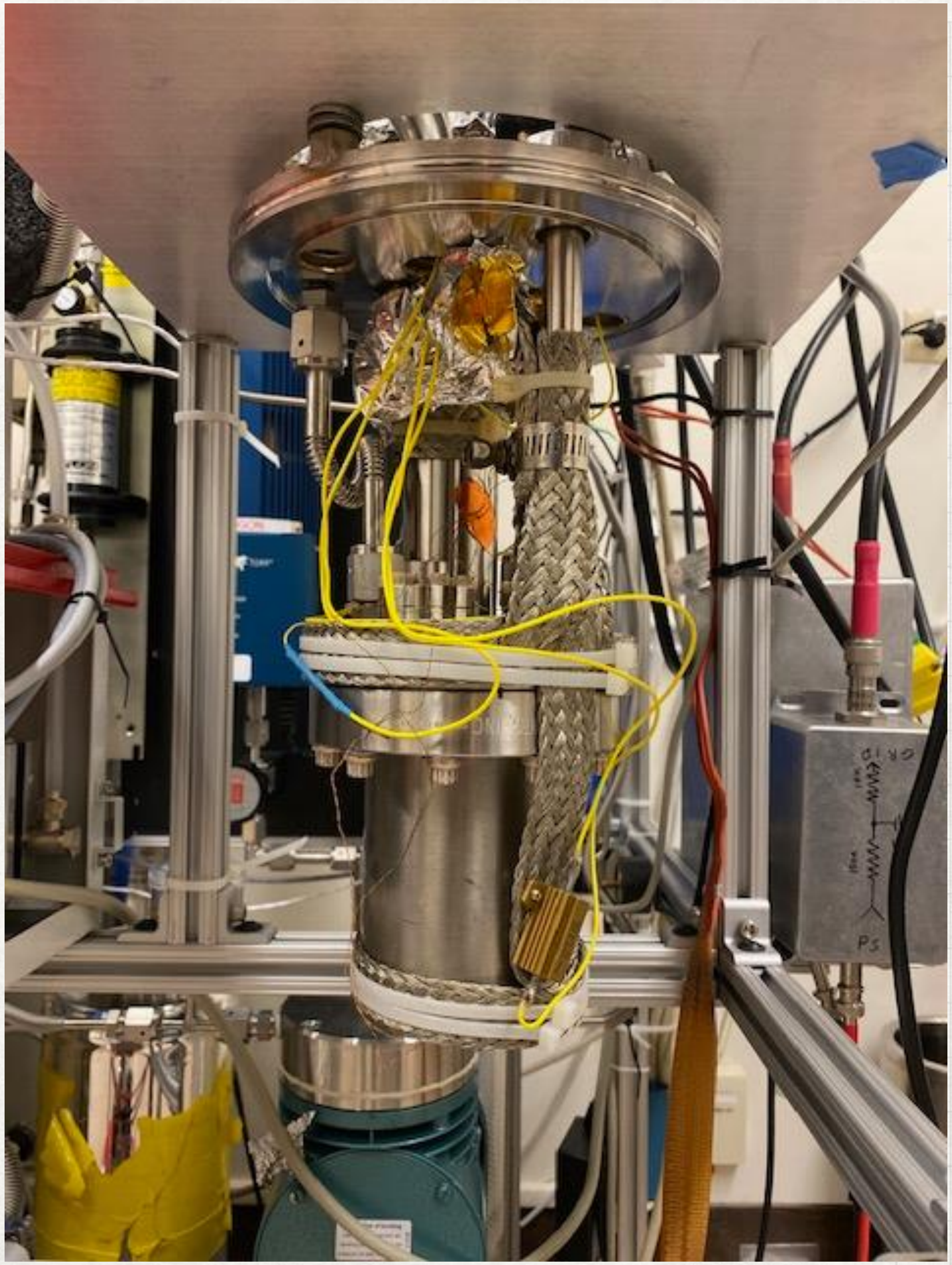
CRYSTALiZE: SUMMARY

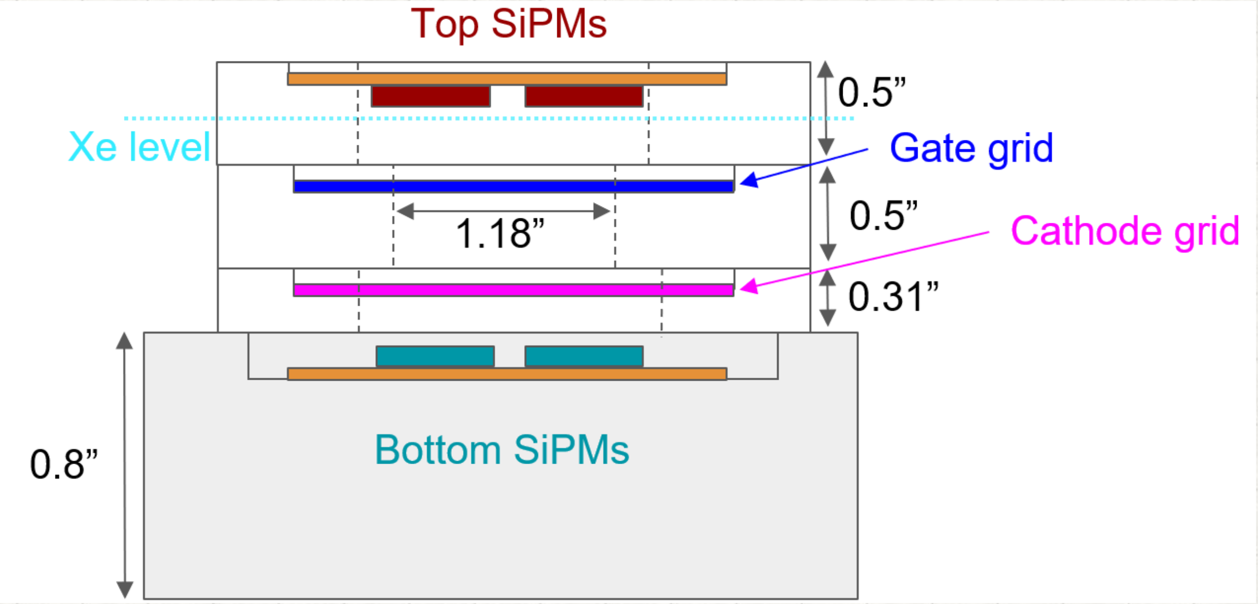
- Performance of large Xe detectors expected to be limited by Rn before reaching the neutrino floor
- CrystaLiZe is a logical upgrade path for LZ to reach the neutrino floor (+solar neutrino science), if it works
- **Near future:** establish if crystalline xenon emission TPC maintains all the benefits of the liquid xenon emission TPC

EXTRA SLIDES FOLLOW

Test Bed Design

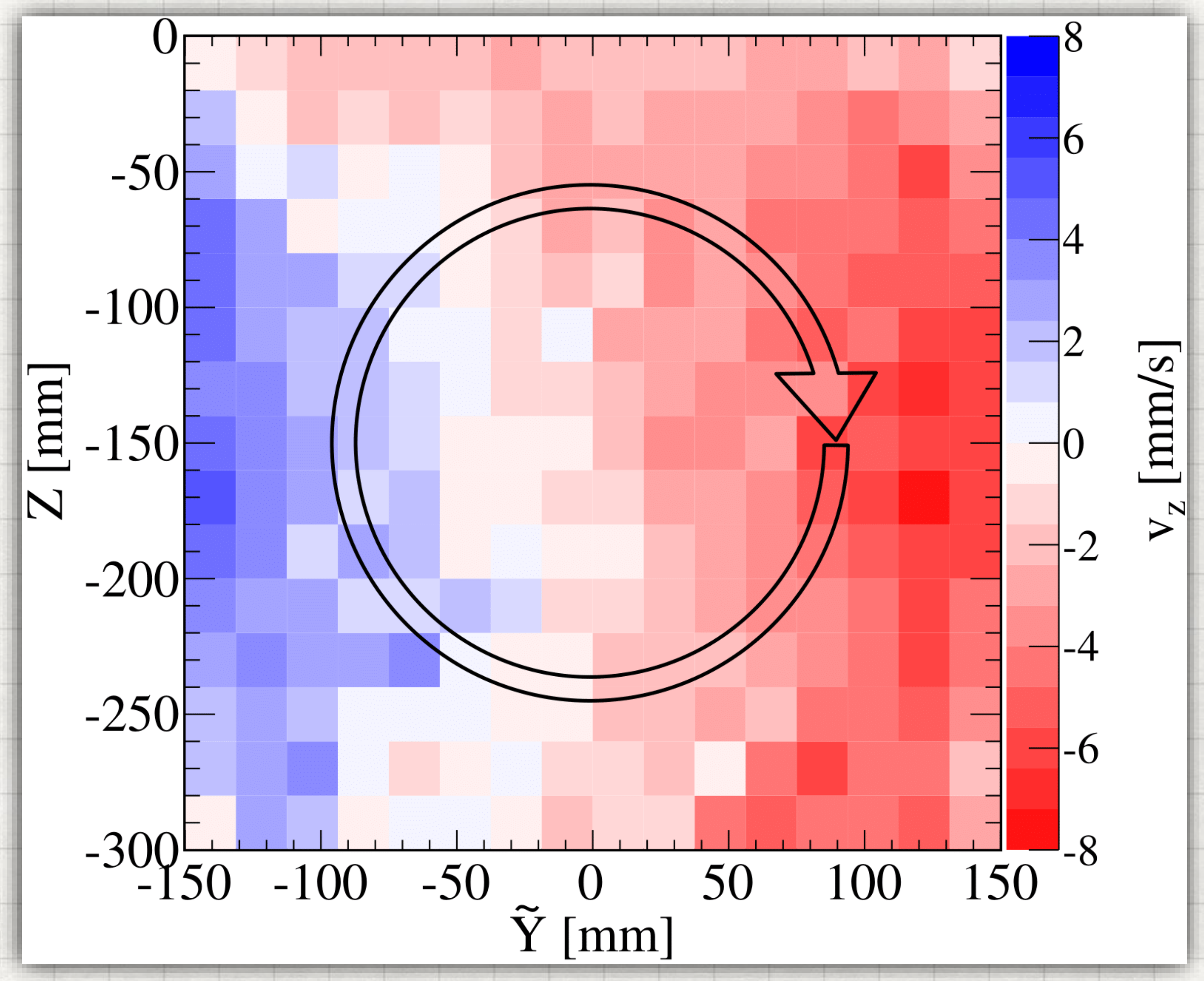
…





LXe convection ~6 cm/min i.e. too fast

…



Phys. Rev. D 95, 072008 (2017)

Operation of a crystalline Xe TPC

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Sorensen, PhD Thesis (2008)

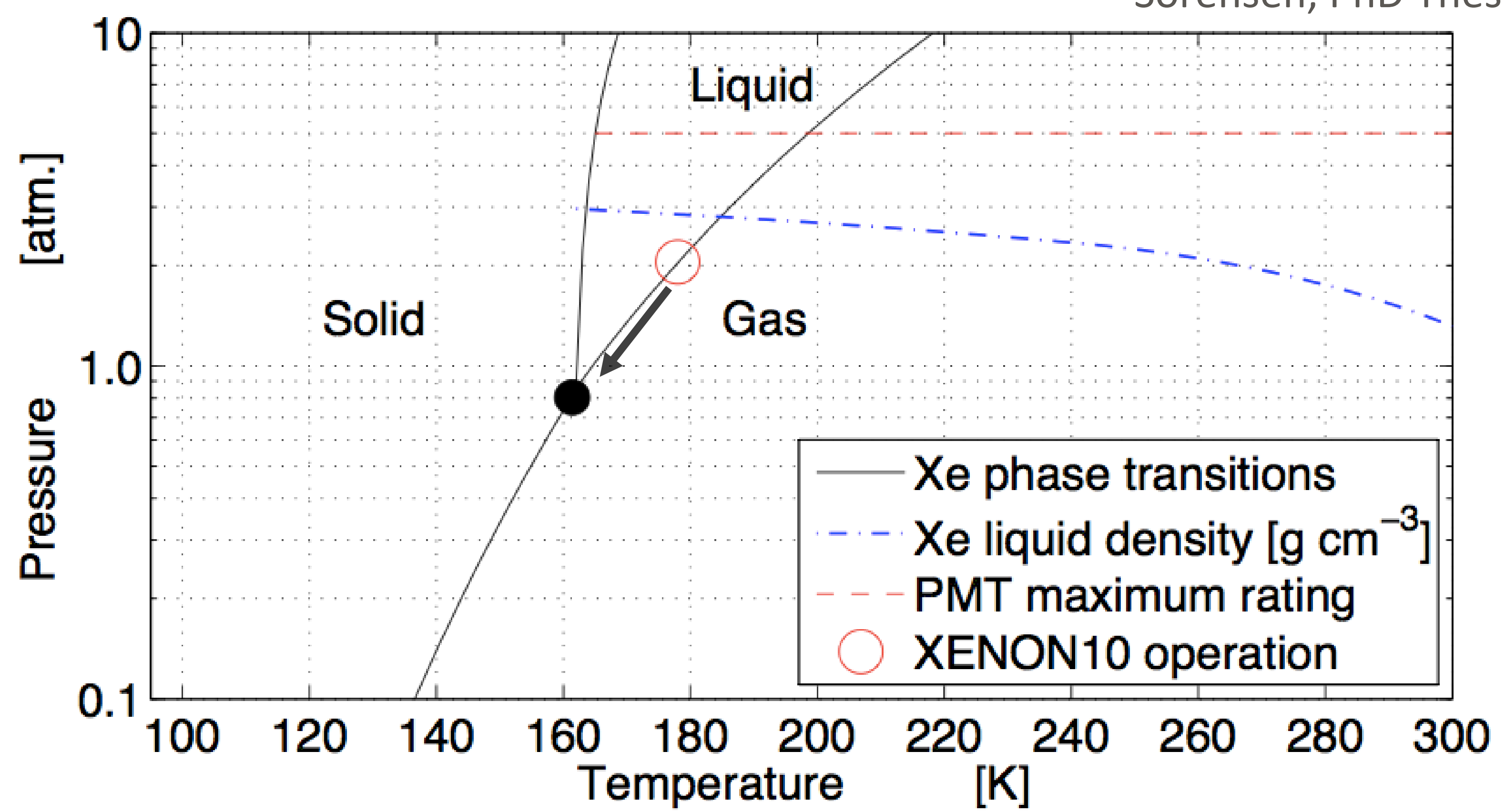


Figure 3.22: Phase Diagram for Xe (data from [127]) and liquid Xe density (data from [123]). For dual-phase operation as in XENON10, the comfortable operating window is indicated by the red circle. Higher pressures are excluded out of consideration for the PMTs (which are rated to a maximum of 5 atm, above which they will crush). Lower temperatures dictate a lower vapor pressure, which reduces the efficiency of the $S2$ proportional scintillation (Sec. 2.2.4). It is also necessary to stay safely above the 161 K, to exclude the possibility of sublimation.

LZ Backgrounds

TABLE III. Estimated backgrounds from all significant sources in the LZ 1000 day WIMP search exposure. Counts are for a region of interest relevant to a 40 GeV/c^2 WIMP: approximately 1.5–6.5 keV for ERs and 6–30 keV for NRs; and after application of the single scatter, skin and OD veto, and 5.6 tonne fiducial volume cuts. Mass-weighted average activities are shown for composite materials and the ^{238}U and ^{232}Th chains are split into contributions from early- and late-chain, with the latter defined as those coming from isotopes below and including ^{226}Ra and ^{224}Ra, respectively.

Background Source	Mass (kg)	^{238}U$_e$ (mBq/kg)	^{238}U$_l$	^{232}Th$_e$	^{232}Th$_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
								subtotal	**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 µBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
								subtotal	**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.8 µBq/kg)									681	-
^{220}Rn (0.09 µBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
								subtotal	**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
								subtotal	**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N, ^{8}B+hep									191	0*
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
								subtotal	**258**	**0.51**
Total									1131	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.66	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									**6.18**	

* Below the 6 keV NR threshold used here.

arxiv:1802.06039

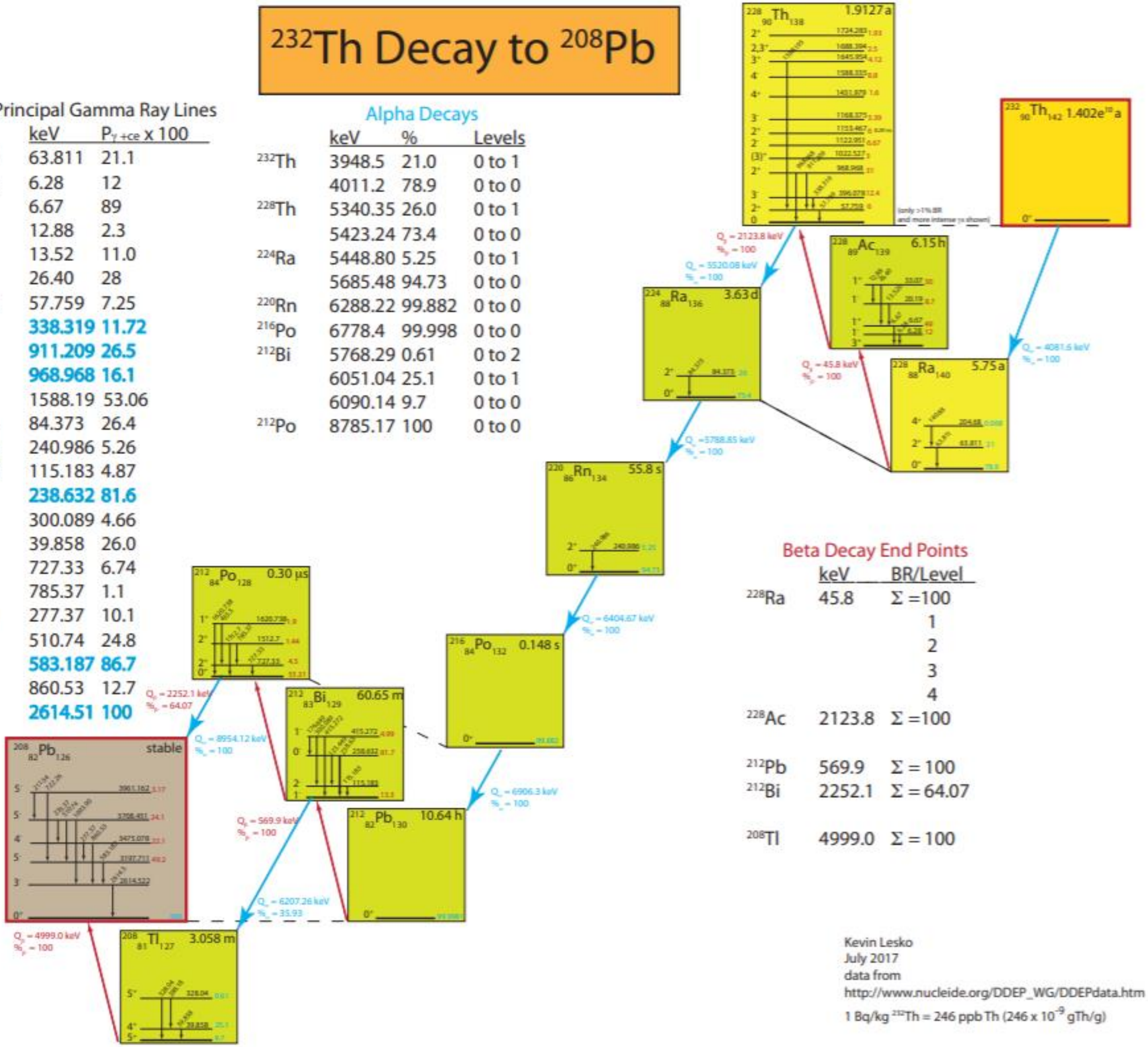
^{232}Th Decay to ^{208}Pb

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

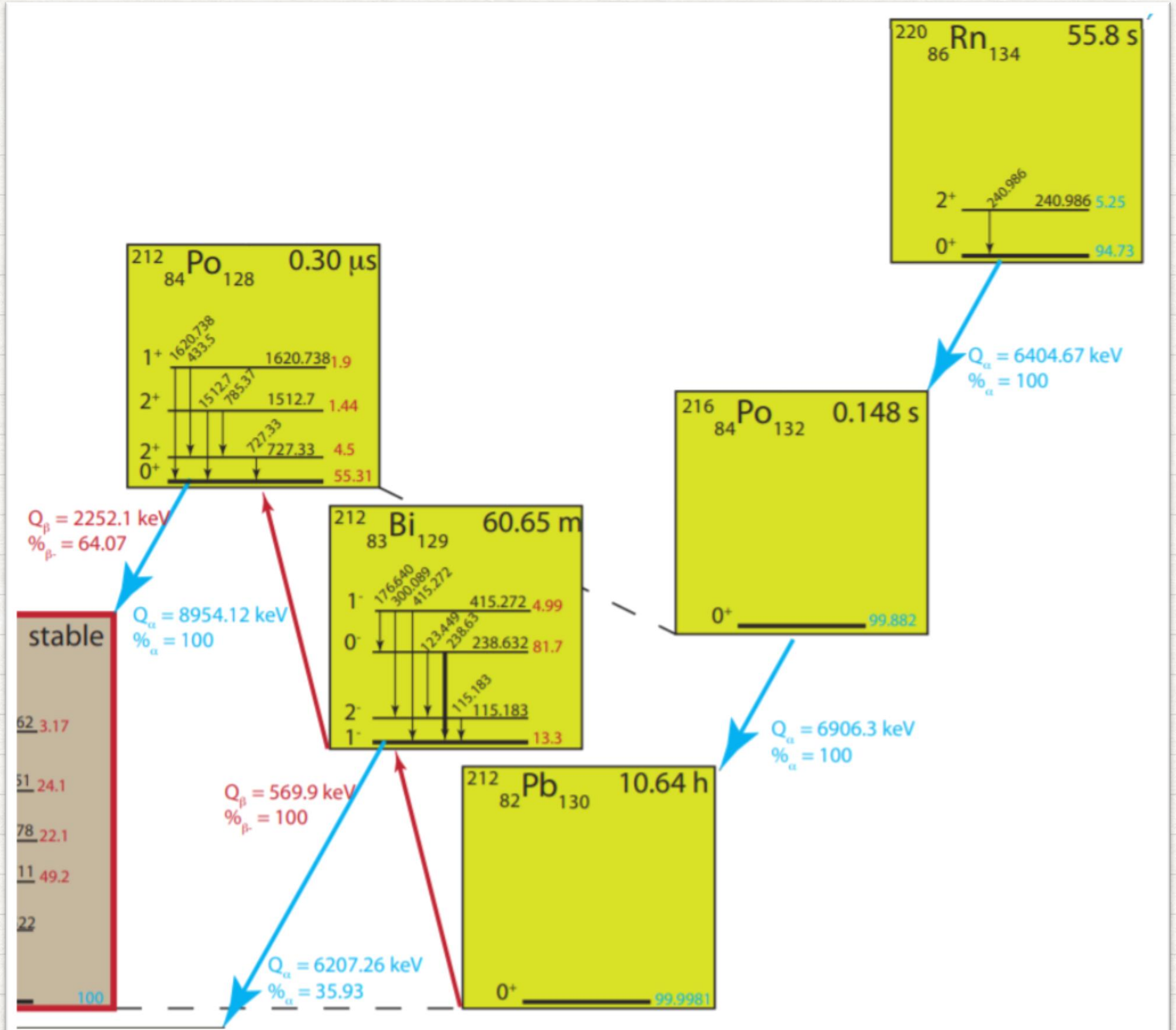
	keV	%	Levels
^{232}Th	3948.5	21.0	0 to 1
	4011.2	78.9	0 to 0
^{228}Th	5340.35	26.0	0 to 1
	5423.24	73.4	0 to 0
^{224}Ra	5448.80	5.25	0 to 1
	5685.48	94.73	0 to 0
^{220}Rn	6288.22	99.882	0 to 0
^{216}Po	6778.4	99.998	0 to 0
^{212}Bi	5768.29	0.61	0 to 2
	6051.04	25.1	0 to 1
	6090.14	9.7	0 to 0
^{212}Po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



Beta Decay End Points

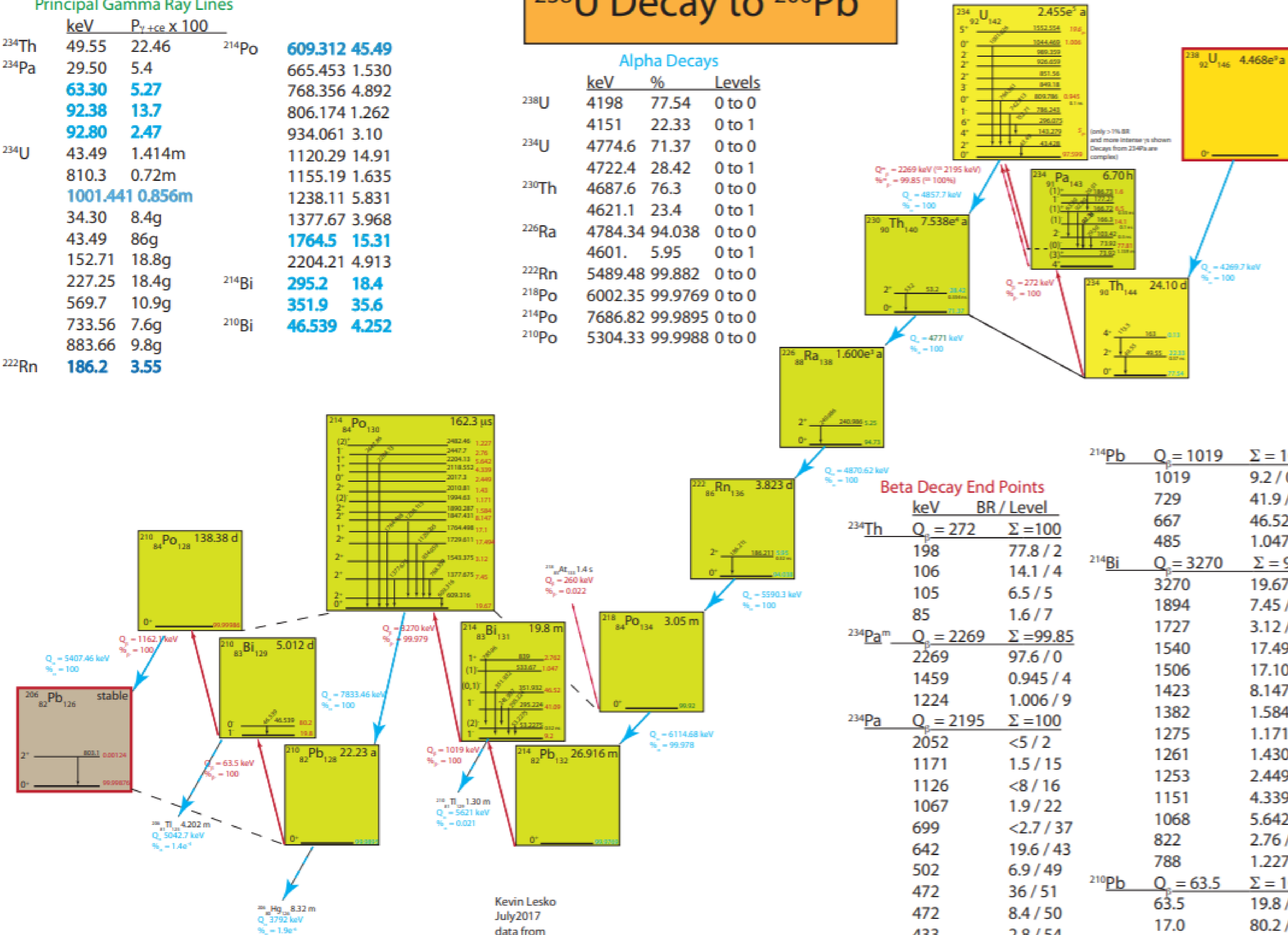
	keV	BR/Level
^{228}Ra	45.8	Σ =100
		1
		2
		3
		4
^{228}Ac	2123.8	Σ =100
^{212}Pb	569.9	Σ = 100
^{212}Bi	2252.1	Σ = 64.07
^{208}Tl	4999.0	Σ = 100

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+ 1512.7 785.37 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
3.17
24.1
22.1
49.2
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
Qα = 6207.26 keV
%α = 35.93
212 82 Pb 130 10.64 h
0+ 99.9981

^{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

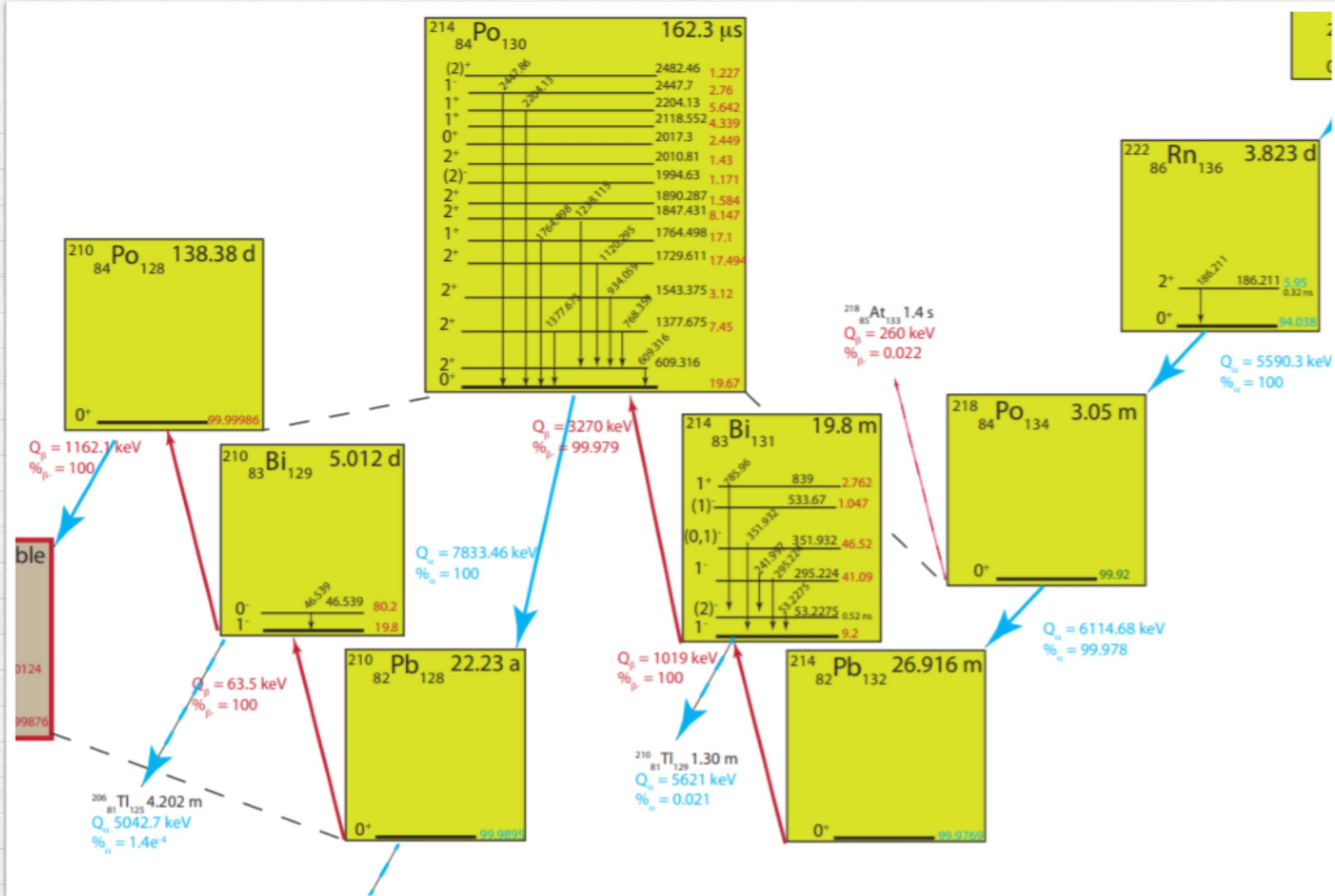
Alpha Decays

	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

Beta Decay End Points

	keV	BR / Level
^{234}Th	$Q_\beta = 272$	$\Sigma = 100$
	198	77.8 / 2
	106	14.1 / 4
	105	6.5 / 5
	85	1.6 / 7
^{234}Pa^m	$Q_\beta = 2269$	$\Sigma = 99.85$
	2269	97.6 / 0
	1459	0.945 / 4
	1224	1.006 / 9
^{234}Pa	$Q_\beta = 2195$	$\Sigma = 100$
	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	$Q_\beta = 1019$	$\Sigma = 100$
	1019	9.2 / 0
	729	41.9 / 4
	667	46.52 / 5
	485	1.047 / 7
^{214}Bi	$Q_\beta = 3270$	$\Sigma = 99.976$
	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	$Q_\beta = 63.5$	$\Sigma = 100$
	63.5	19.8 / 0
	17.0	80.2 / 1
^{210}Bi	$Q_\beta = 1162.1$	$\Sigma = 100$
	1162.1	99.99986 / 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)



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 84 Po 134 3.05 m
222 86 Rn 136 3.823 d
Qβ = 1162.1 keV
%β- = 100
Qβ = 63.5 keV
%β- = 100
Qα = 7833.46 keV
%α = 100
Qβ = 3270 keV
%β- = 99.979
Qβ = 1019 keV
%β- = 100
Qα = 6114.68 keV
%α = 99.978
Qα = 5590.3 keV
%α = 100
218 85 At 133 1.4 s
Qβ = 260 keV
%β- = 0.022
210 81 Tl 129 1.30 m
Qα = 5621 keV
%α = 0.021
206 81 Tl 125 4.202 m
Qα 5042.7 keV
%α = 1.4e-4

PREVIOUS WORK

…

1. arXiv:1410.6496 and arXiv:1508.05903
   - optical photon collection comparison to liquid — mild decrease
   - charge drift comparison to liquid — factor x2 faster
2. solid xenon bolometers (2013, Drexel)

Old Paradigm

…

Phases of the XENON program

	LUX	LZ
XENON10	XENON100	XENON1T / XENONnT

XENON10	XENON100	XENON1T / XENONnT
2005-2007	2008-2016	2013-2018 / 2019-2023
15 cm drift TPC – 25 kg	30 cm drift TPC – 161 kg	100 cm / 144 cm drift TPC - 3200 kg / ~8000 kg
Achieved (2007)	Achieved (2016)	Projected (2018) / Projected (2023)
σ_{SI} = 8.8 x 10^{-44} cm^2	σ_{SI} = 1.1 x 10^{-45} cm^2	σ_{SI} = 1.6 x 10^{-47} cm^2 / σ_{SI} = 1.6 x 10^{-48} cm^2

Elena Aprile (Columbia) XENON1T: First Results @ Andes 2017, June 30, 2017 9

20-50 tonne liquid xenon TPC