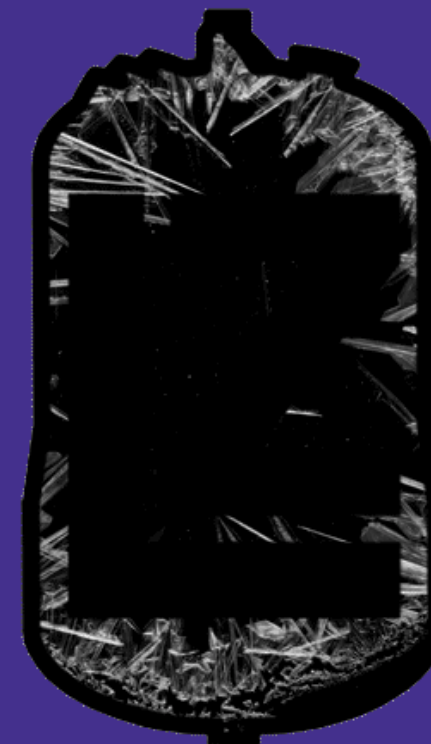


CRYSTALIZE: DARK MATTER DETECTION AND BEYOND WITH CRYSTAL XENON



SCOTT KRAVITZ, CHLOE O'BRIEN, GREGORY SEHR
UNIVERSITY OF TEXAS AT AUSTIN

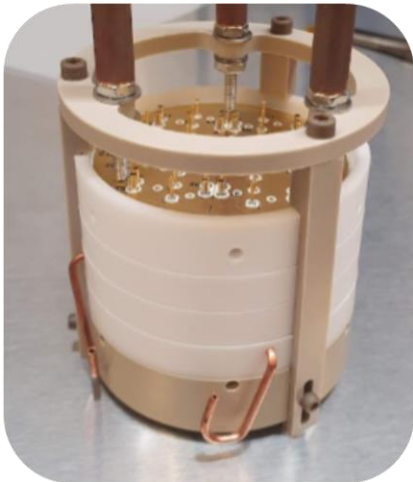
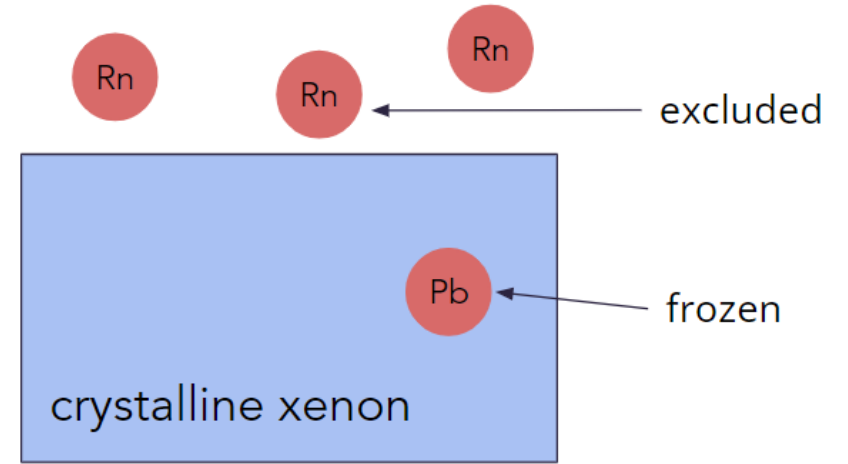
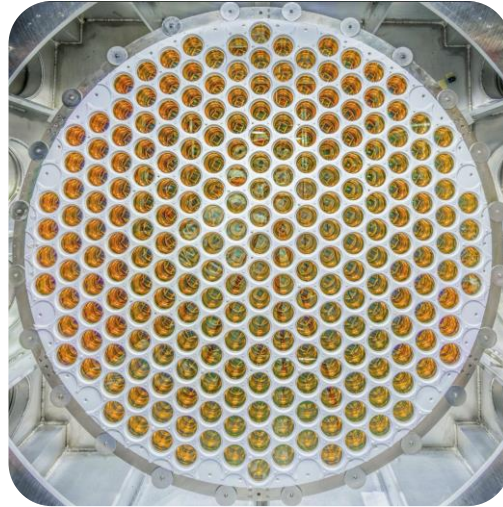
HAO CHEN, RYAN GIBBONS, SCOTT HASELSCHWARDT,
SHILO XIA, PETER SORENSEN
LBNL



CPAD 2024, UNIVERSITY OF TENNESSEE, KNOXVILLE
NOV 20, 2024

OUTLINE

- LZ's search for dark matter
- The problem of radon
- The solution: crystal xenon
- Demonstration of the crystal xenon TPC (< kg scale)
- Plans for exploring the crystal xenon TPC technology



THE LUX-ZEPLIN EXPERIMENT (LZ)

7 tonnes of Xe in active volume

Located 4850 ft. underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA

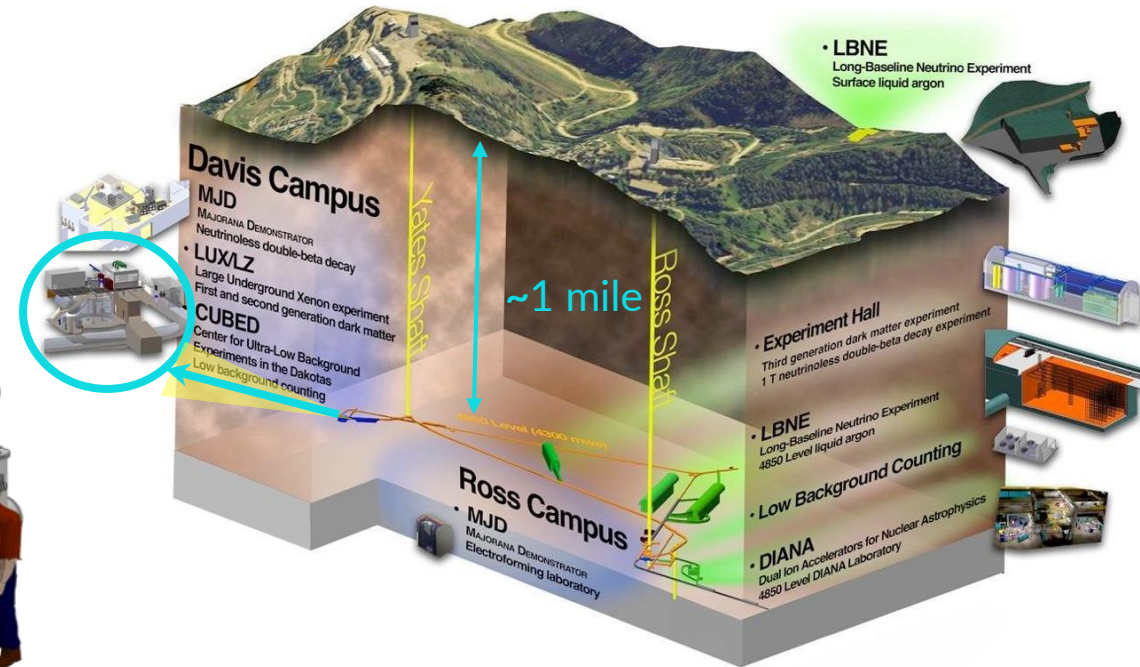
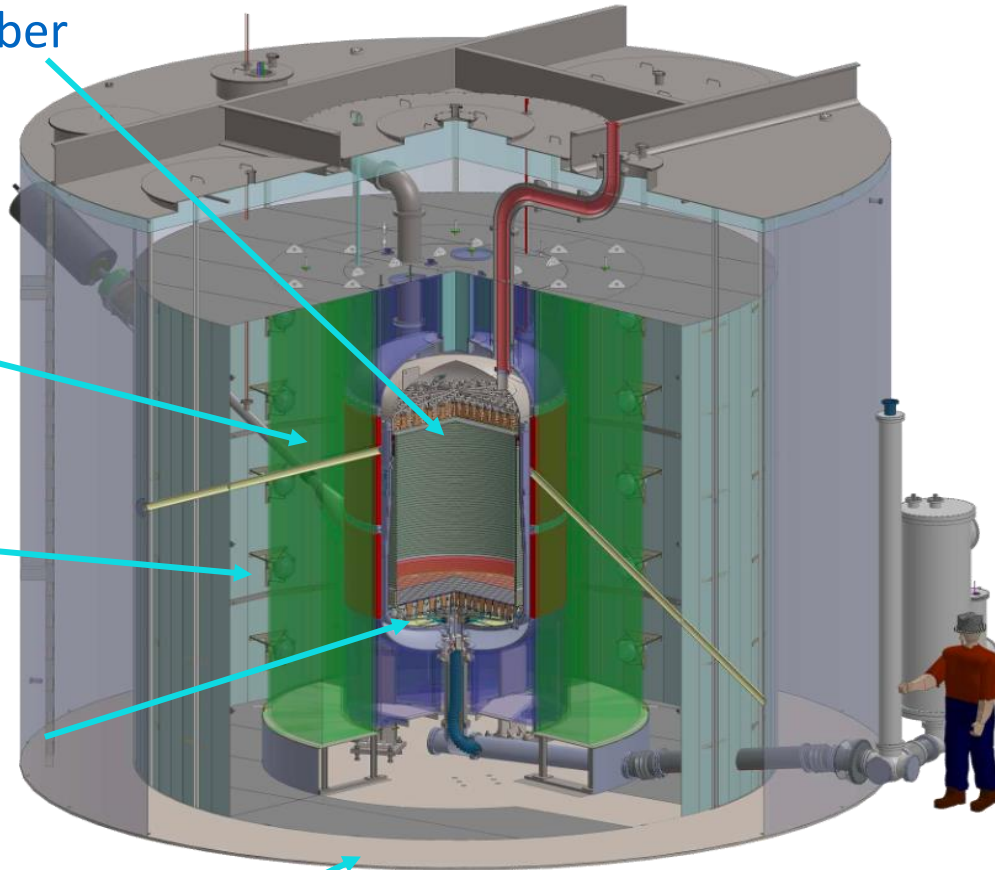
Liquid Xenon (LXe) Time projection chamber (TPC)

Outer detector (veto)

Outer detector PMTs

LXe Skin (veto)

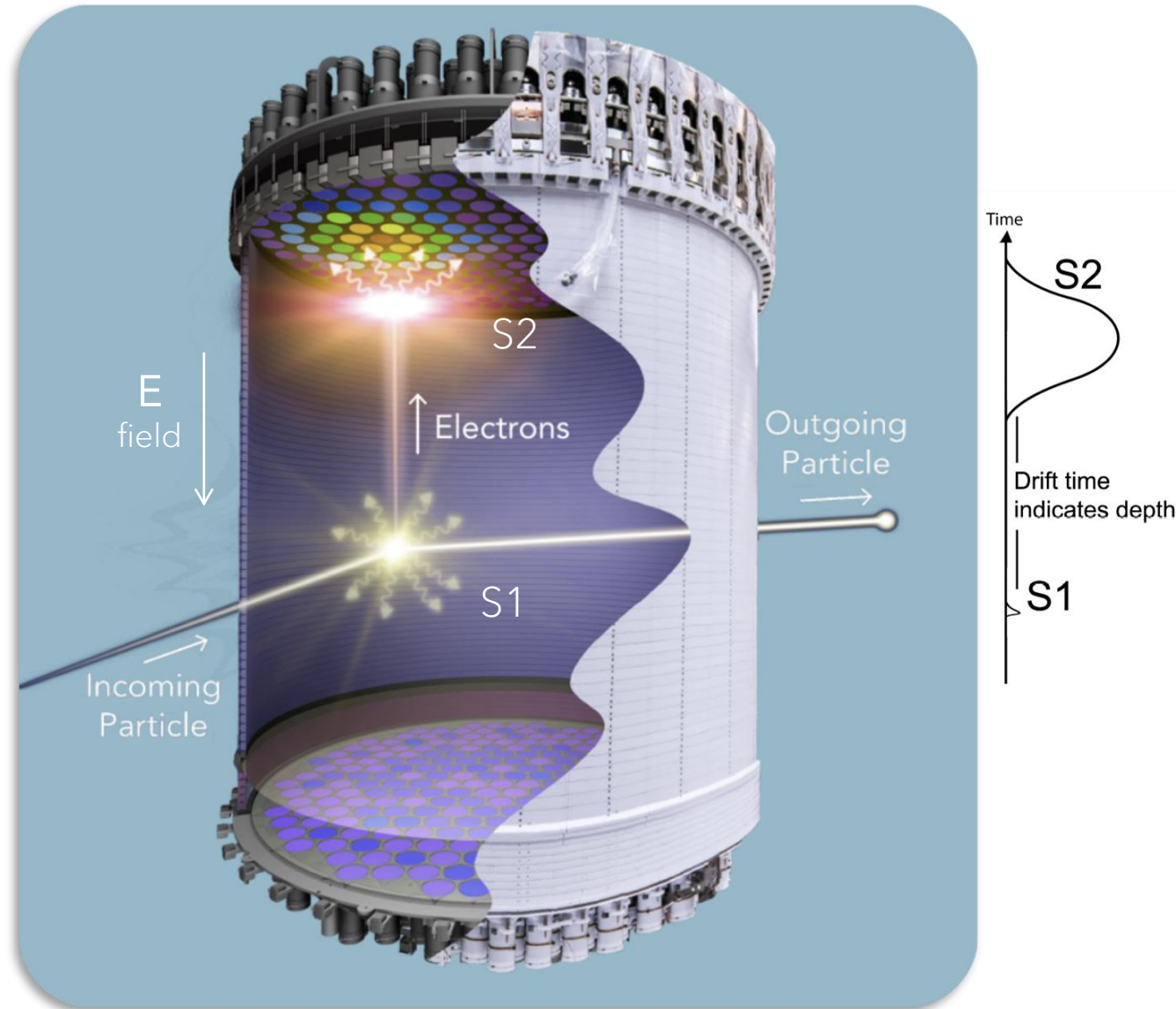
Water tank



LZ detector design:
[NIM A, 163047 \(2020\)](#)

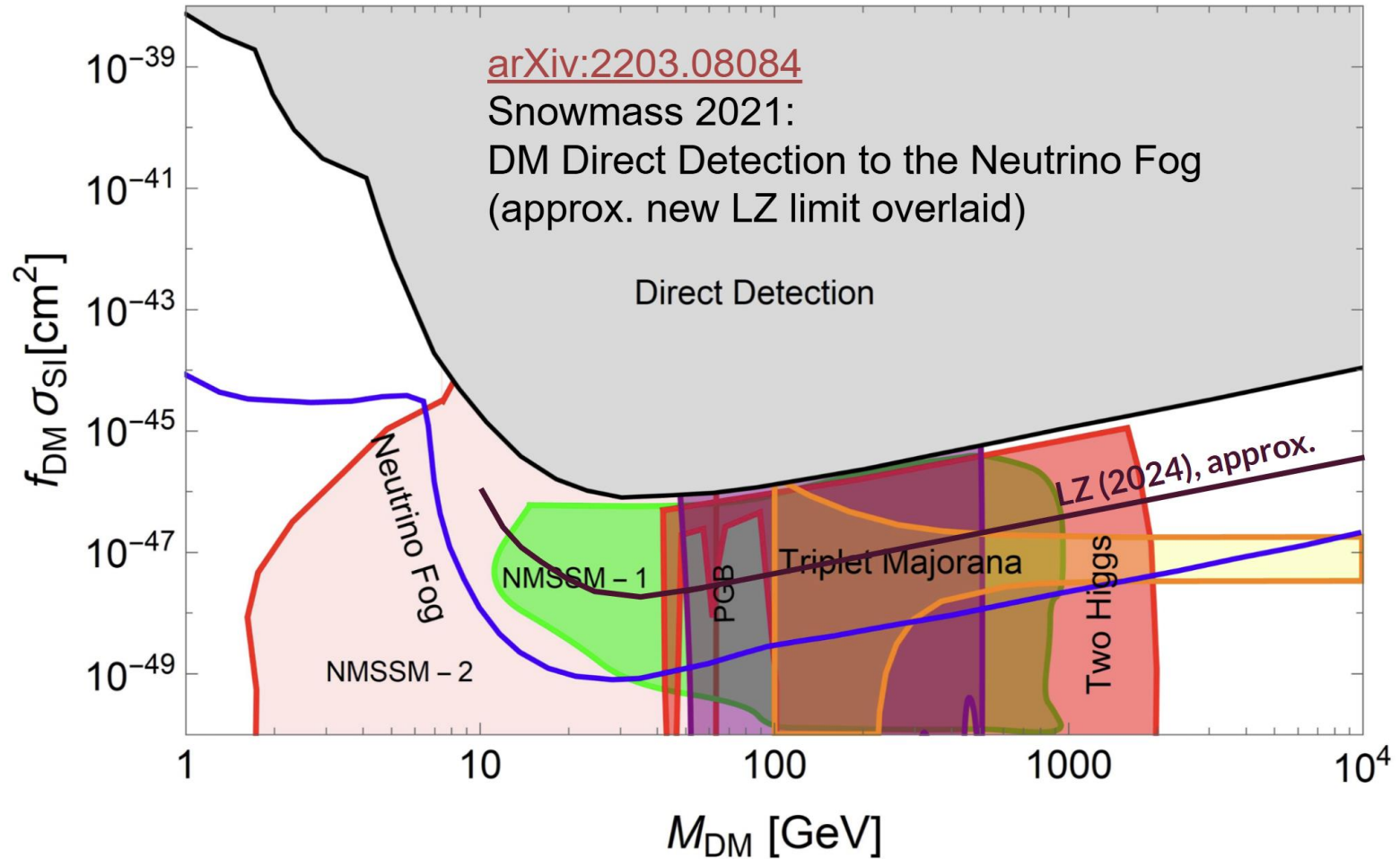
DATA IN LZ

- Typical reconstructed info (for each scatter):
 - S1 (prompt scintillation) total area
 - S2 (ionization signal) total area
 - X, Y position (S2 PMT hit pattern)
 - Z (from Δt between S1 and S2)
- Weighted sum of S1, S2 gives **energy**
- S1/S2 ratio implies **recoil type**
 - Dominant backgrounds are electron recoils (ER)
 - WIMP interactions are nuclear recoils (NR)



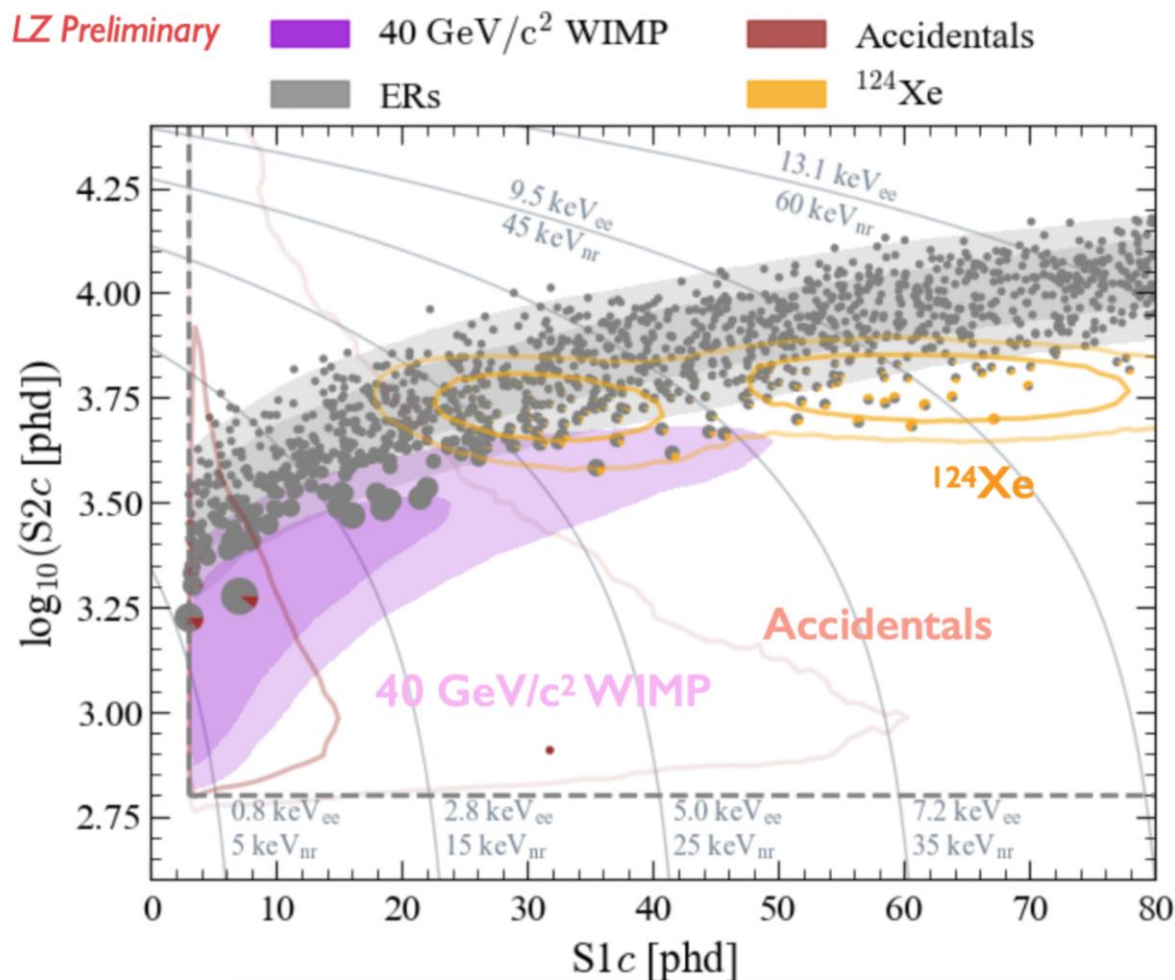
THE STATUS OF DIRECT DETECTION

- LZ's latest results (280 days livetime): world-leading sensitivity to WIMPs*
- WIMPs remain strongly motivated, e.g. EW multiplets live above neutrino floor
- Ultimate goal: detect DM or reach neutrino floor/fog
- What are the key limitations to probing another 1+ order of magnitude?



*arXiv:2410:17036

LZ LIMITATIONS FROM BACKGROUNDS



LZ WS 2024 fit result: [arXiv:2410:17036](https://arxiv.org/abs/2410.17036)

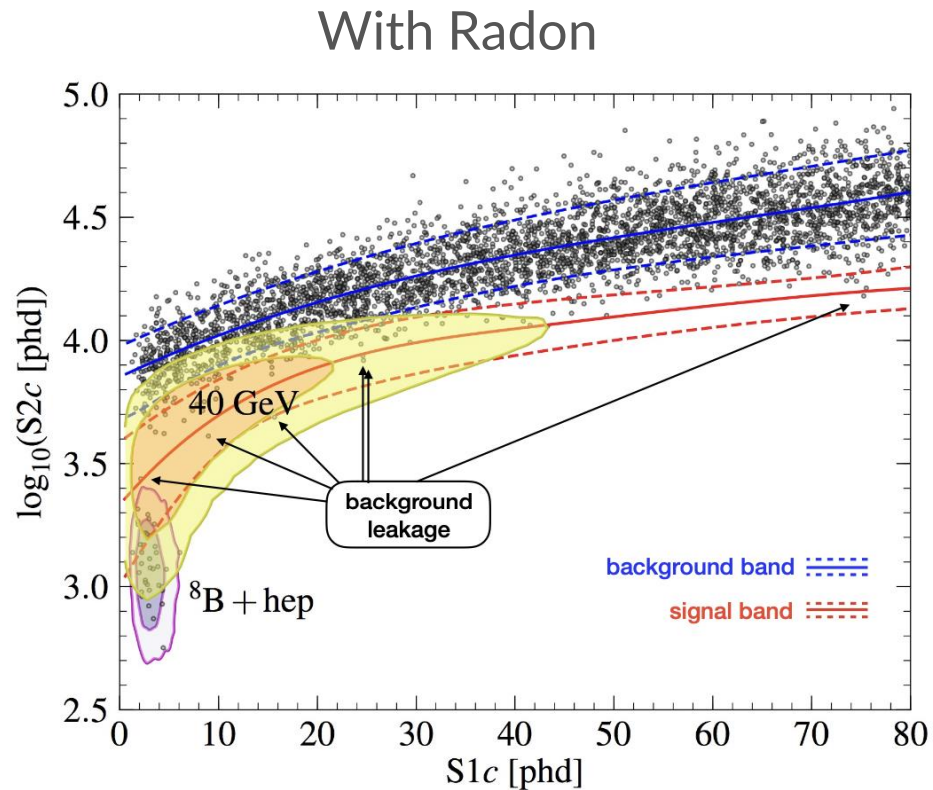
Source	Pre-fit Constraint	Fit Result
²¹⁴ Pb βs	743 ± 88	733 ± 34
²¹² Pb + ²¹⁸ Po βs	62.7 ± 7.5	63.7 ± 7.4
⁸⁵ Kr* + ³⁹ Ar βs + det. γs	162 ± 22	161 ± 21
Tritium + ¹⁴ C βs**	58.3 ± 3.3	59.7 ± 3.3
Solar ν ER	102 ± 6	102 ± 6
¹²⁷ Xe + ¹²⁵ Xe EC**	3.2 ± 0.6	2.7 ± 0.6
¹²⁴ Xe DEC	19.4 ± 3.9	21.4 ± 3.6
¹³⁶ Xe 2νββ	55.6 ± 8.3	55.8 ± 8.2
⁸ B + hep ν NR	0.06 ± 0.01	0.06 ± 0.01
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Detector neutrons	–	0.0 ^{+0.2}
40 GeV/c ² WIMP	–	0.0 ^{+0.6}
Total	1210 ± 91	1203 ± 42

Dominant!

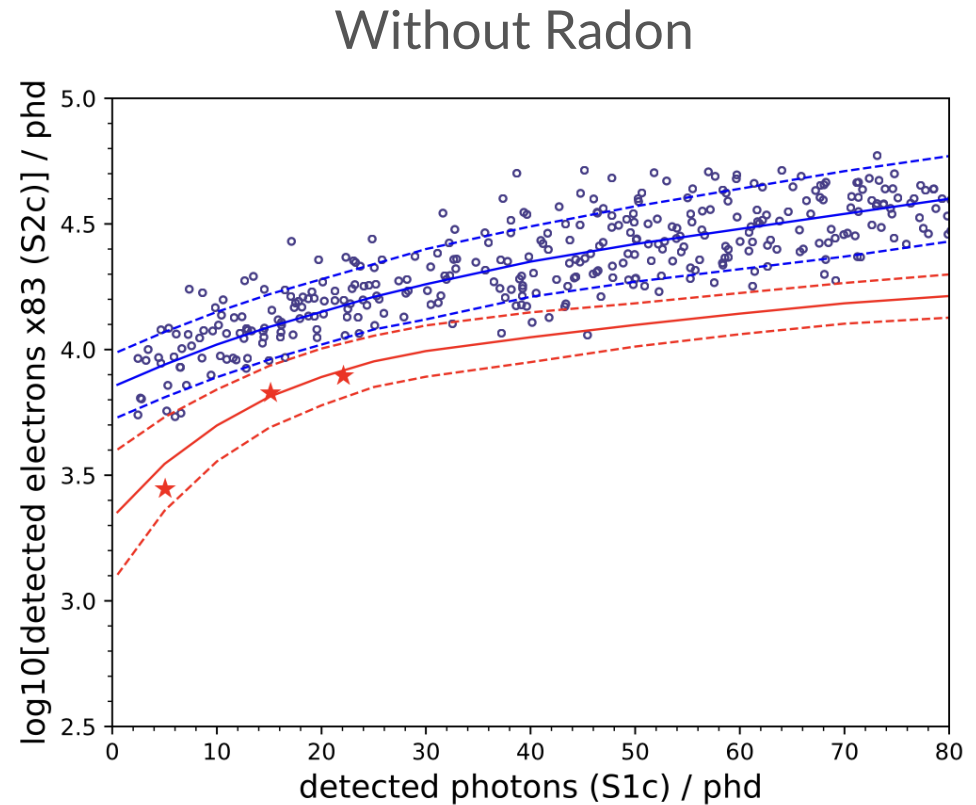
* Permanently removable w/ distillation

** Residual from calibrations; transient

LZ PROJECTIONS: RADON IMPACT



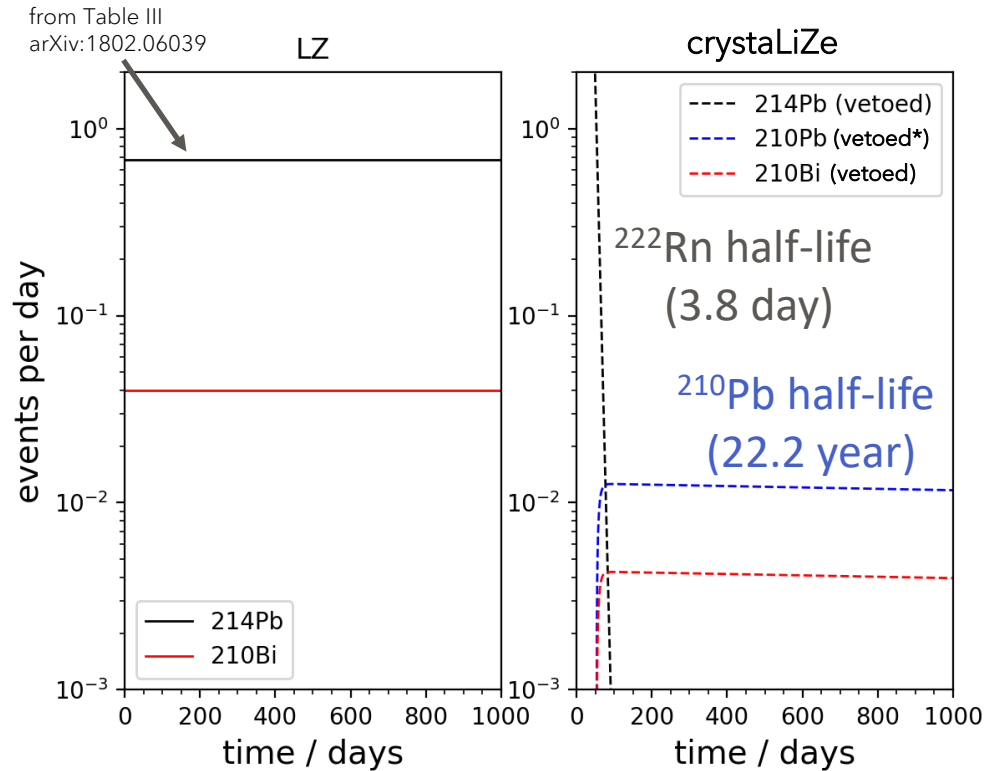
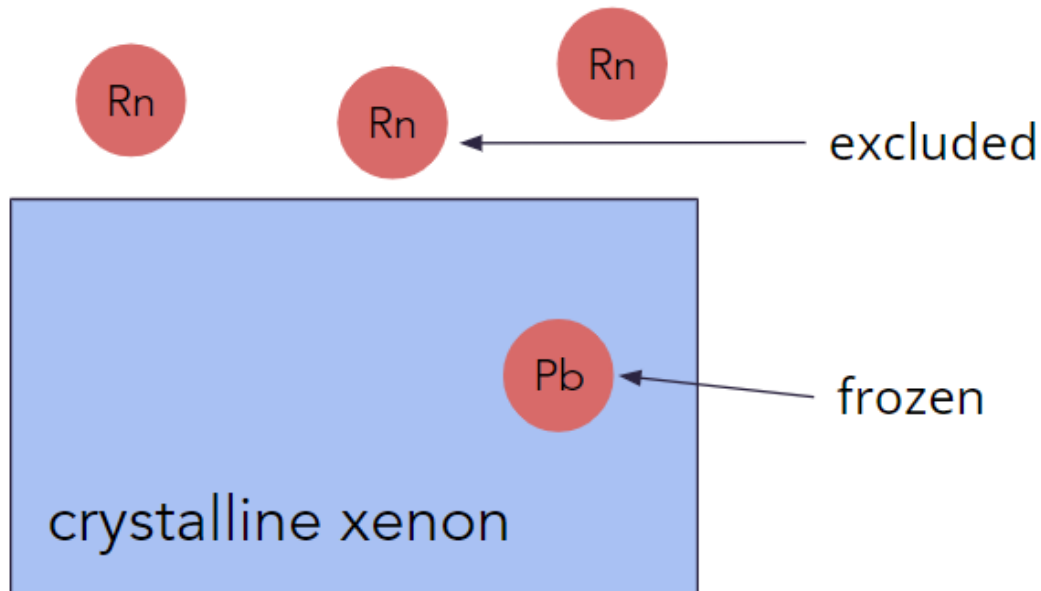
Annotated from LZ projected sensitivity:
[Phys. Rev. D 101, 052002 \(2020\)](#)



Non-LZ simulation, excluding $8B$ neutrinos

Solution: CrystaLiZe

- Freeze LZ (solid/vapor two-phase TPC):
Radon emanated from surfaces now **excluded** from solid bulk*
- In **crystaLiZe**, Rn in bulk target from LXe phase would be fixed, decay away in $O(100)$ days



same LZ emanation and dust assumptions

- In crystal, radon decay daughters stay at same (x,y,z) as parent* -> **tagging/veto**
- Reduction in Rn chain daughters of nearly 100x

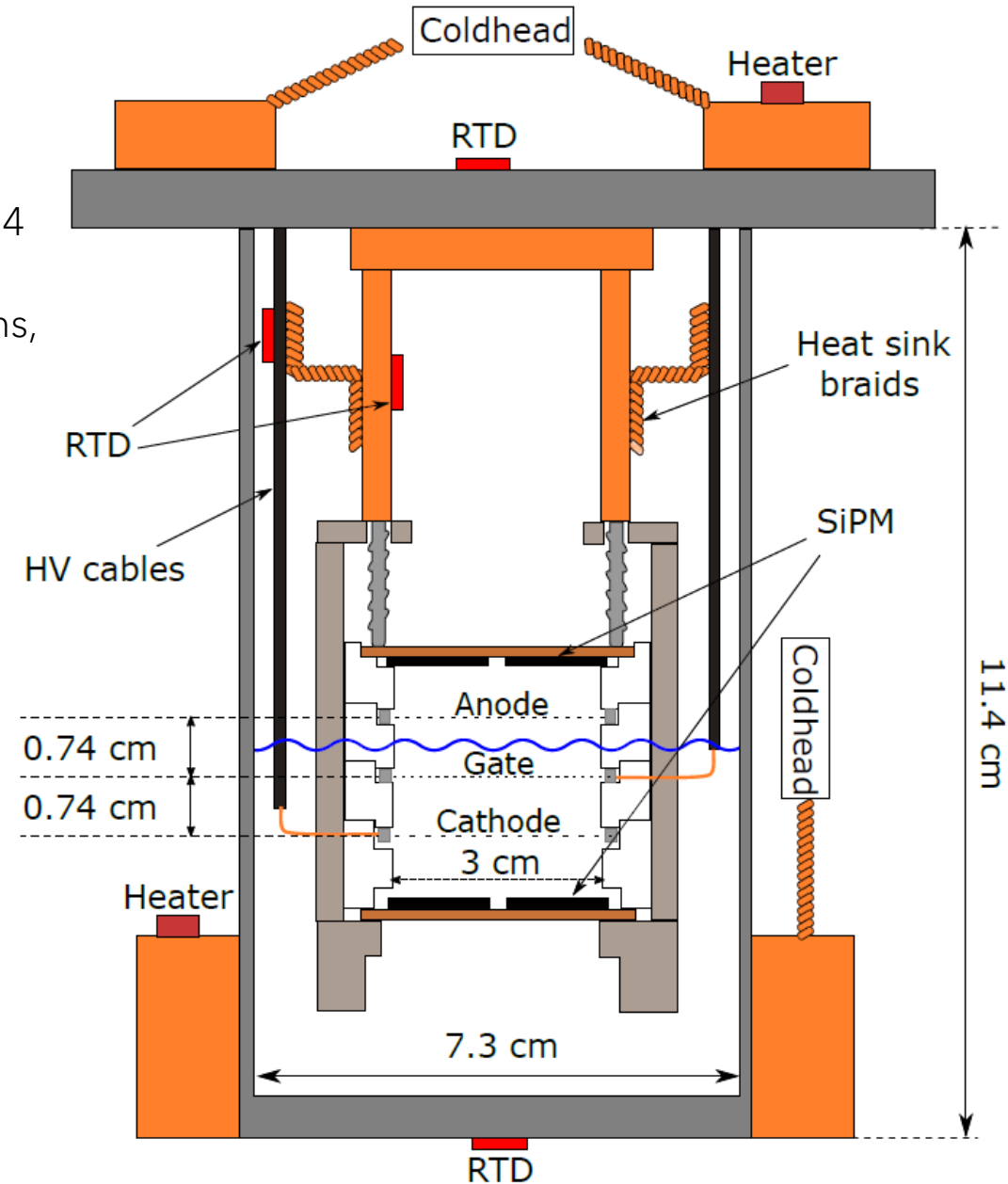
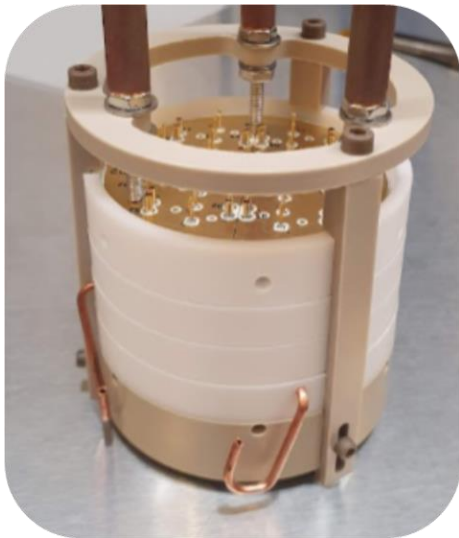
*Diffusion of Rn in solid Xe to be studied to verify

THE CRYSTAL XE TPC

- Two phase Xe mini-TPC at LBL
- ~700 g Xe when full
- S1 and S2 readout:
SiPMs (Hamamatsu VUV4 S13371)

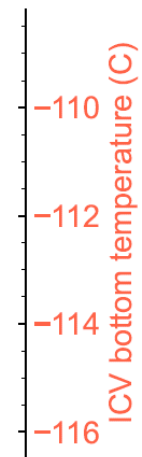
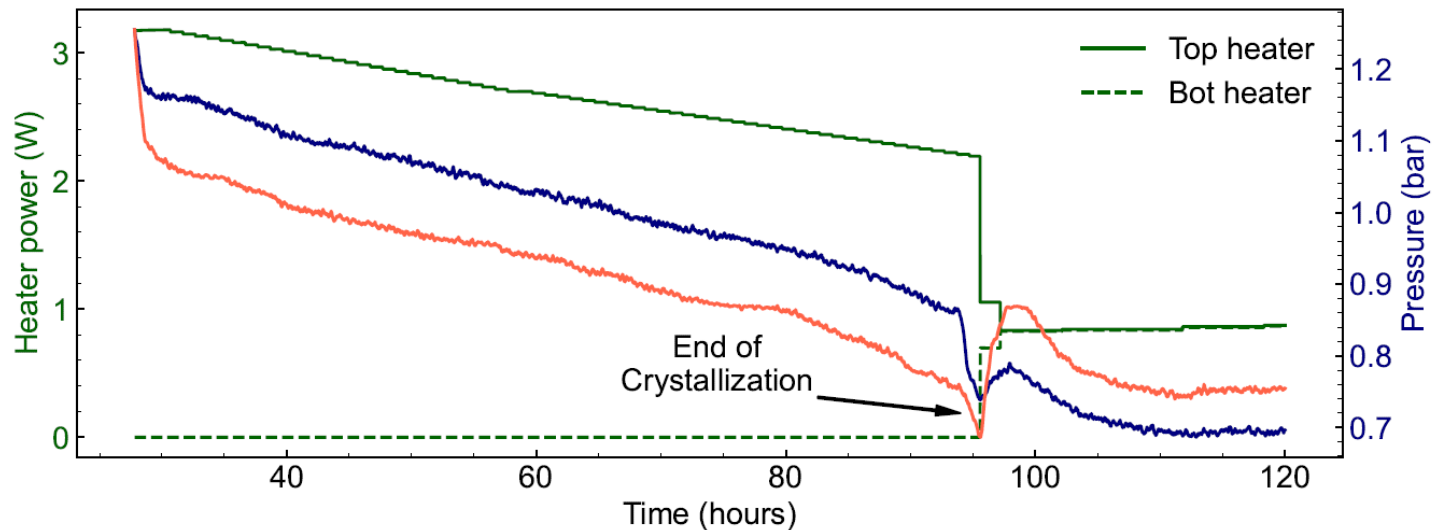
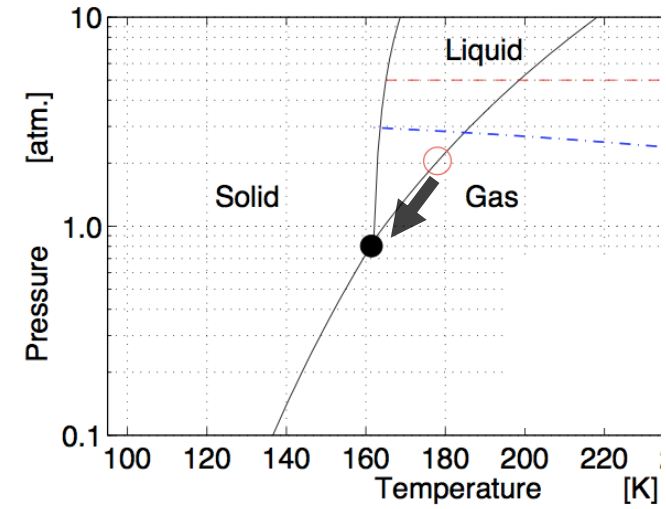
JINST 17 (2022) P04014
[arXiv 2201.05740]

S.K., H. Chen, R. Gibbons,
S.J. Haselschwardt,
Q. Xia, P. Sorensen

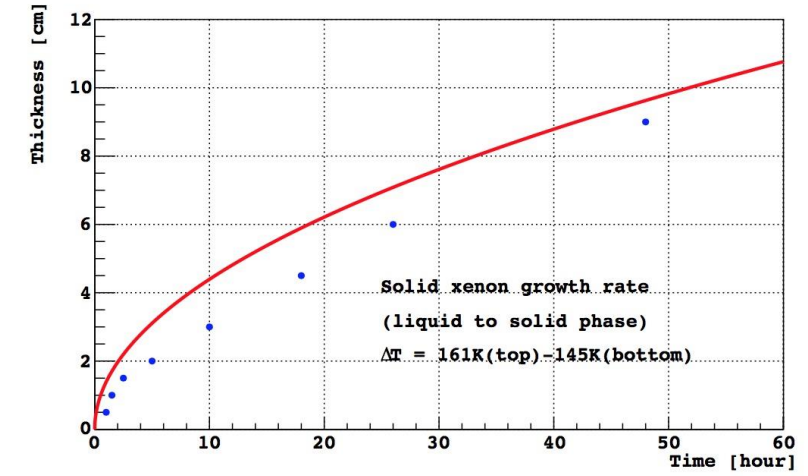


CRYOGENICS

- ~20 K colder than typical LXe operation
- Key challenge is careful crystal growth: Bridgeman method w/ constant gradient*
- Realistic / scalable cryogenics for tonne-scale
- Bonus: expect ~17% higher density (contraction = less risk of damage to components)

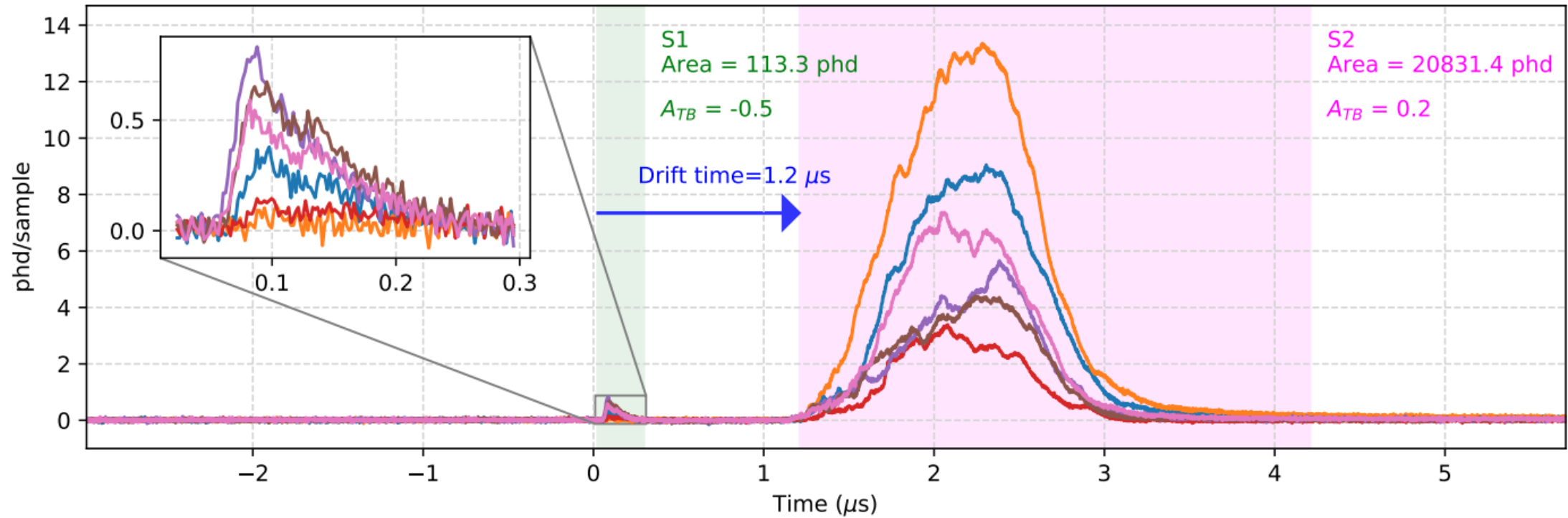


*Method/plot from Fermilab, arXiv:1410.6496



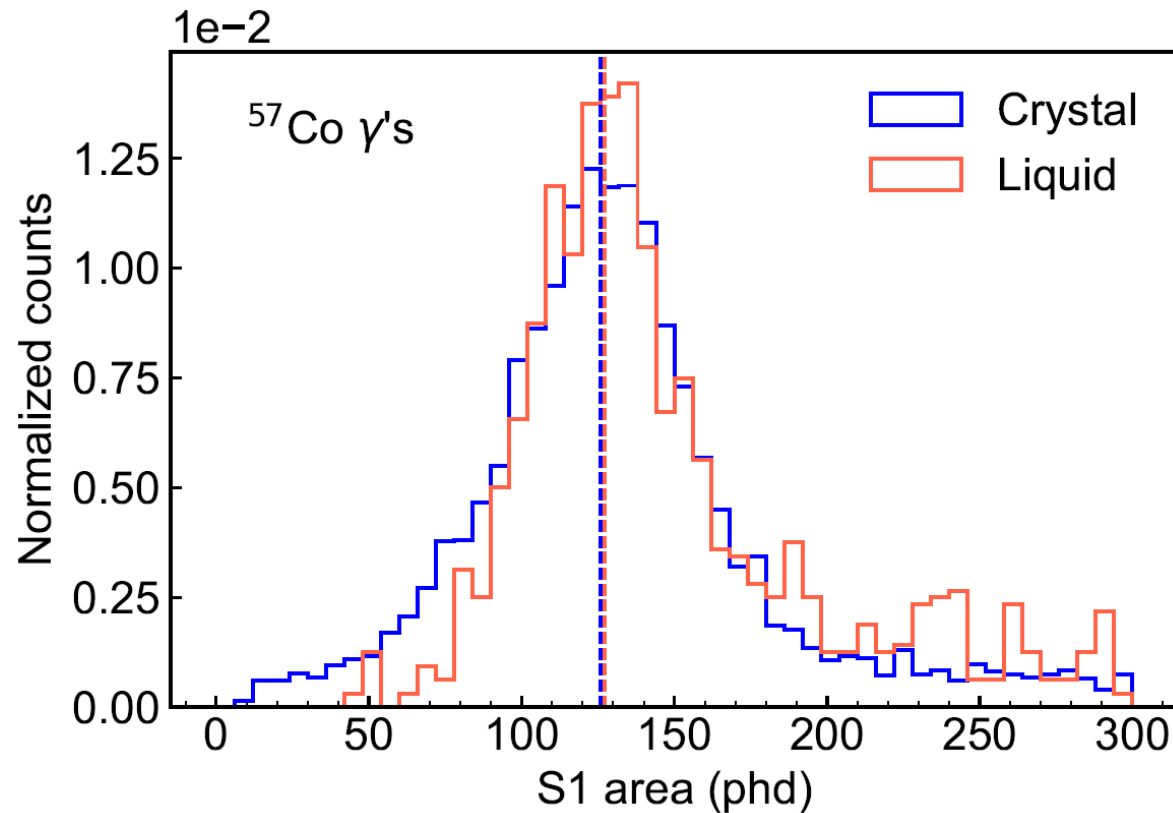
THE CRYSTAL XE TPC - DATA

Functions just like its LXe cousin!

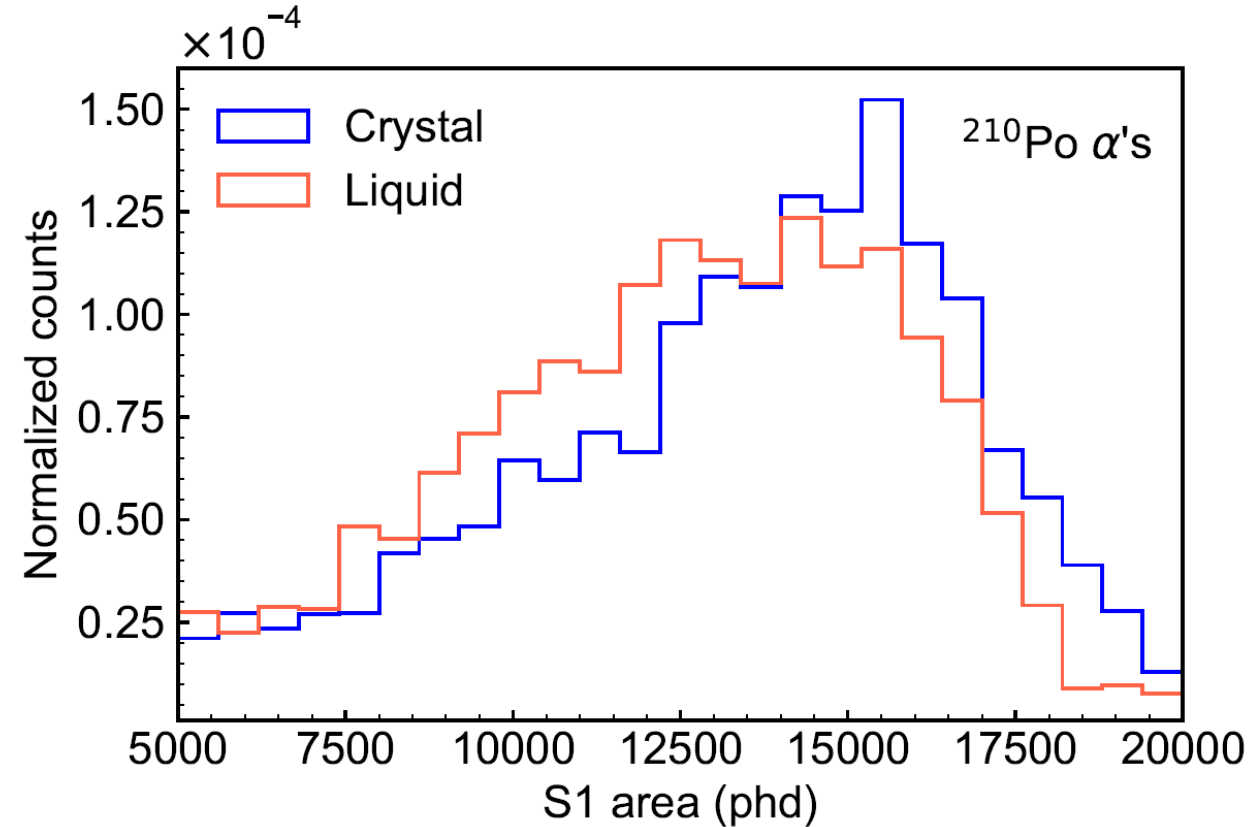


SCINTILLATION - MATCHES LXE

- Co S1 size equal for drift field ~ 270 V/cm

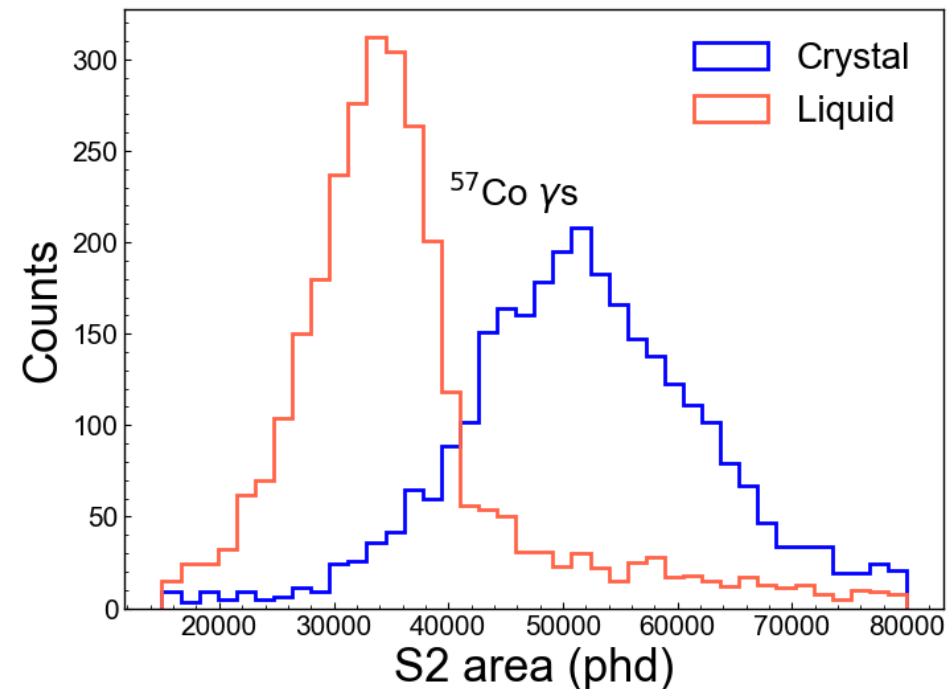


- Po S1 size equal or slightly larger at 0 field

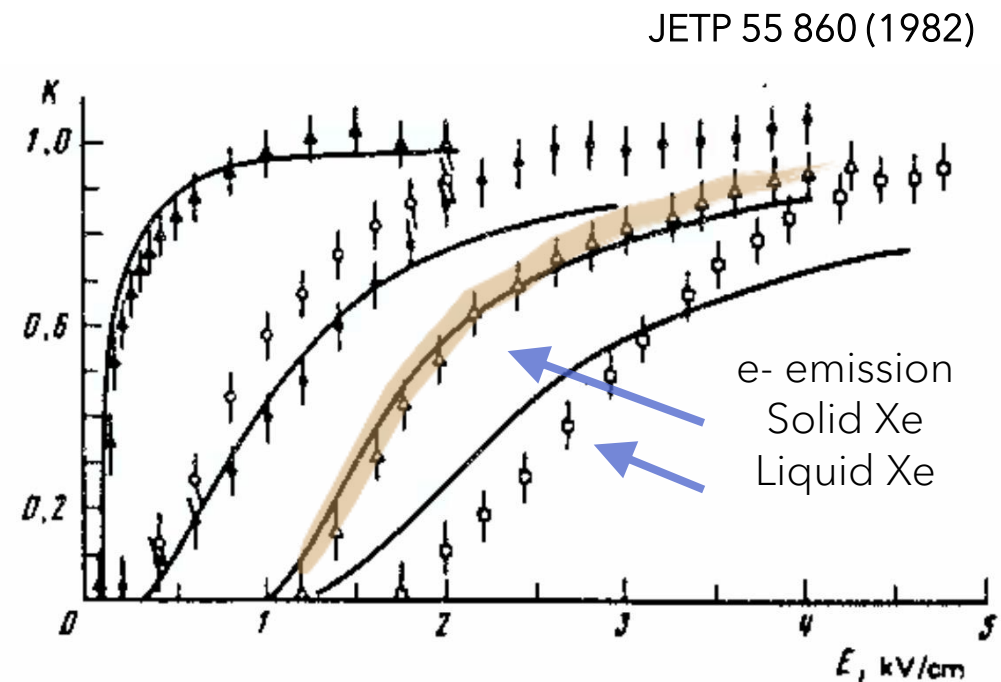


IONIZATION - READILY DETECTED

- No issues seeing S2s in crystal
- Raw yield measurement pending: gas gap may differ

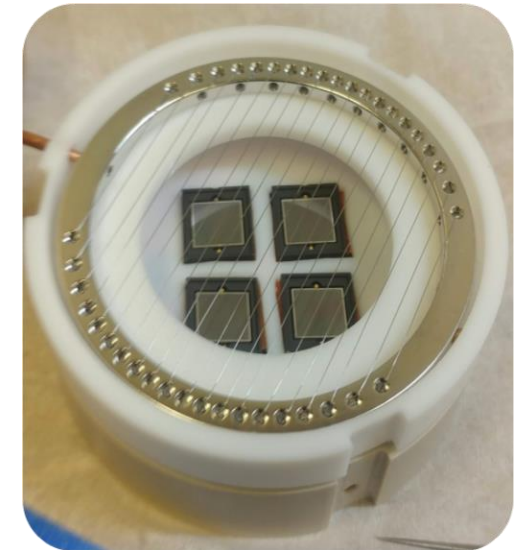
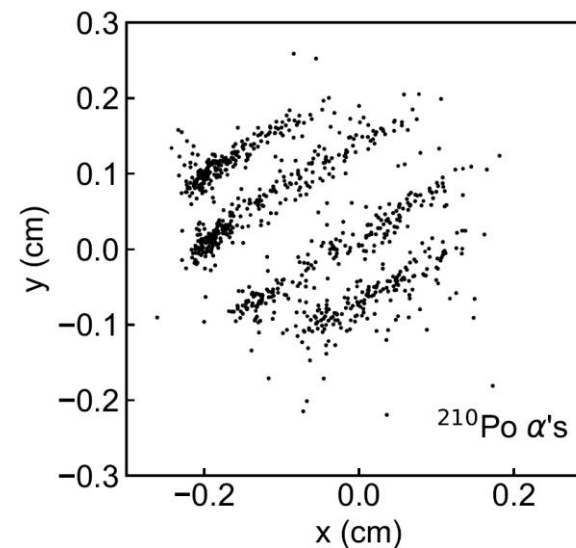
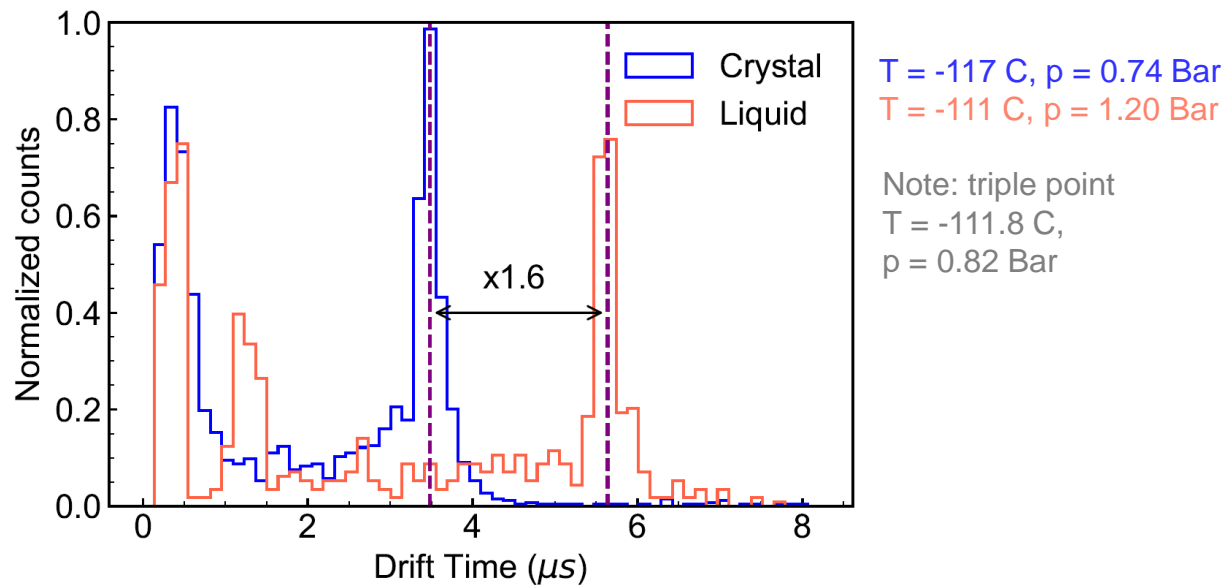


- Higher e- extraction for same field
- Bonus: smaller few-electron background due to less trapping at surface?



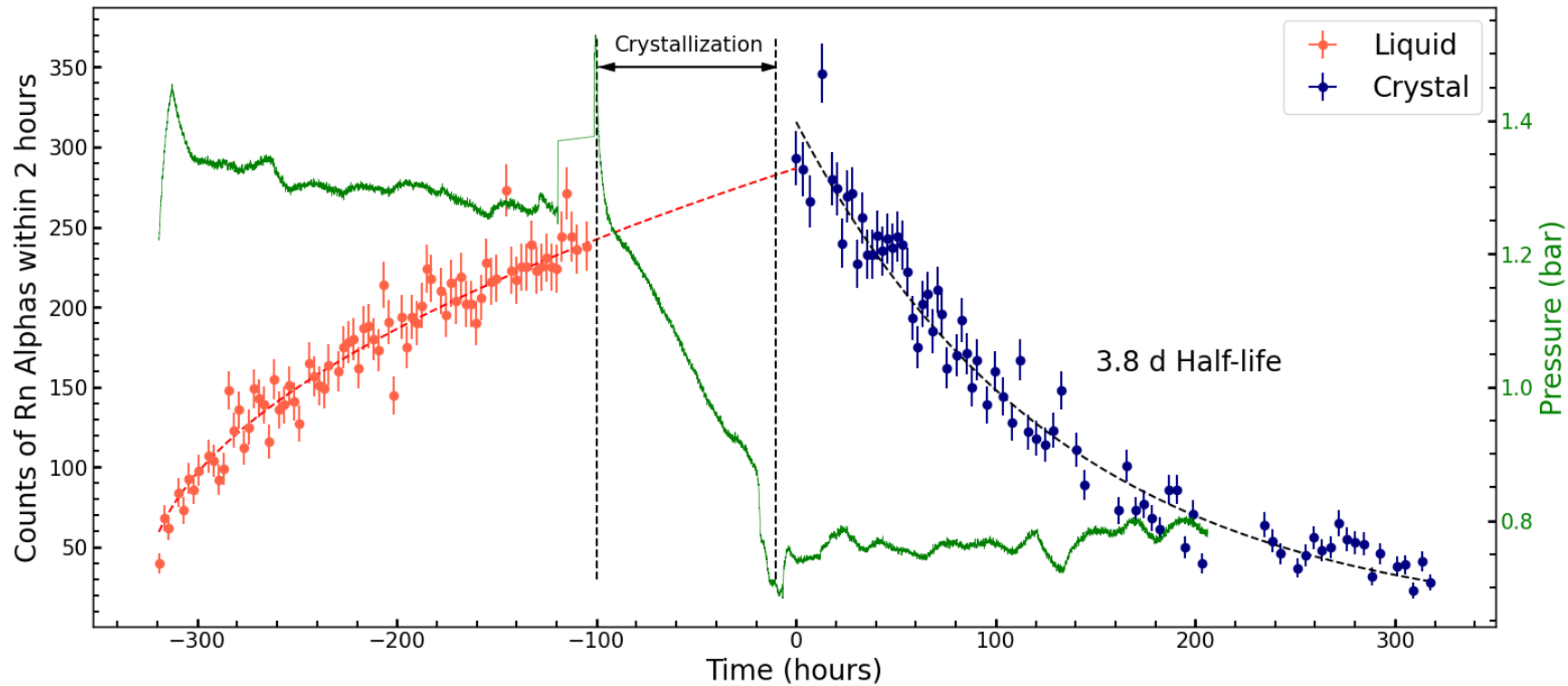
ELECTRON MOBILITY - HIGHER

- ^{210}Po plated on cathode wires defines max drift
- Drift speed $\sim 1.6\text{-}2\text{x}$ faster in crystal
(consistent w/ Fermilab arXiv:1410.6496 and Phys Rev B 10 4464 (1974))
- Bonus: less pileup, fewer accidental coincidences



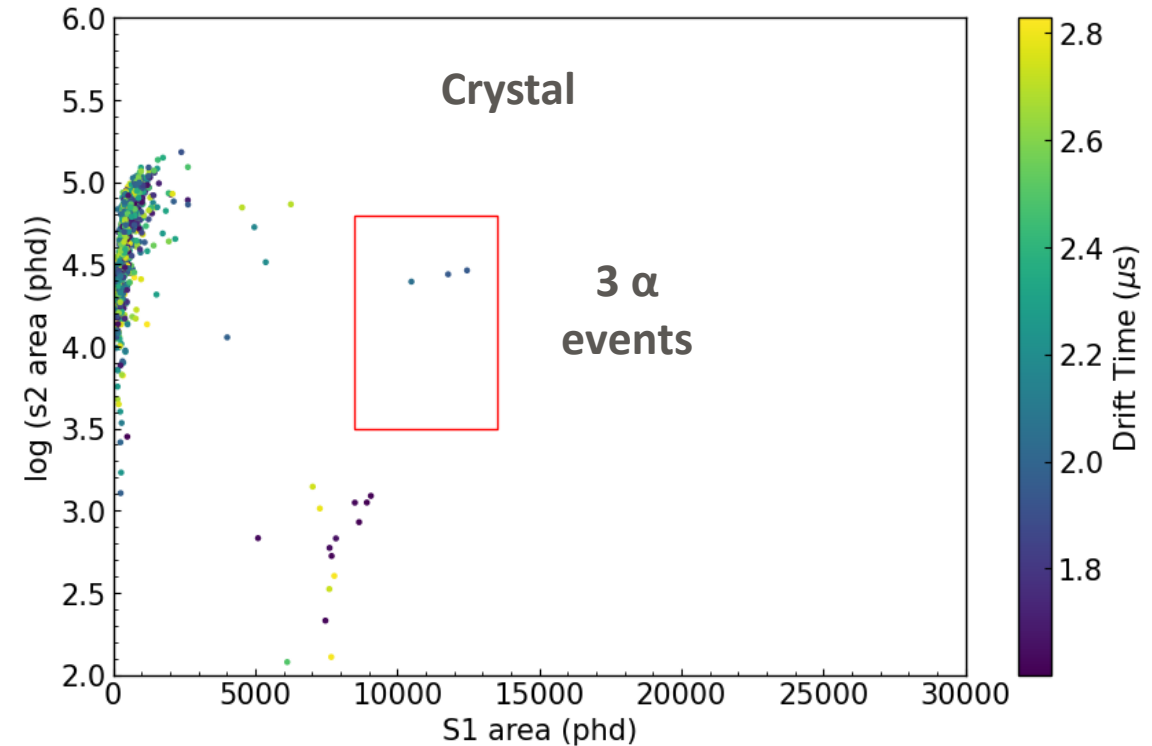
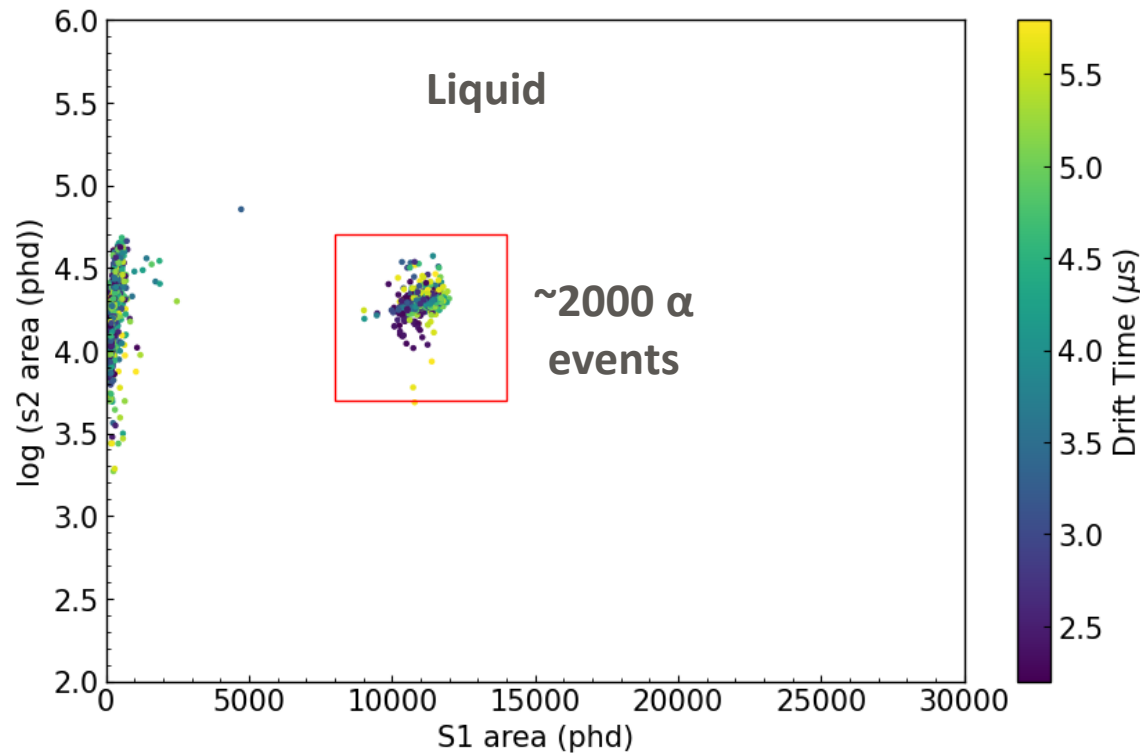
RADON EXCLUSION

- Steady decay in crystal despite continuous flow past ^{222}Rn source



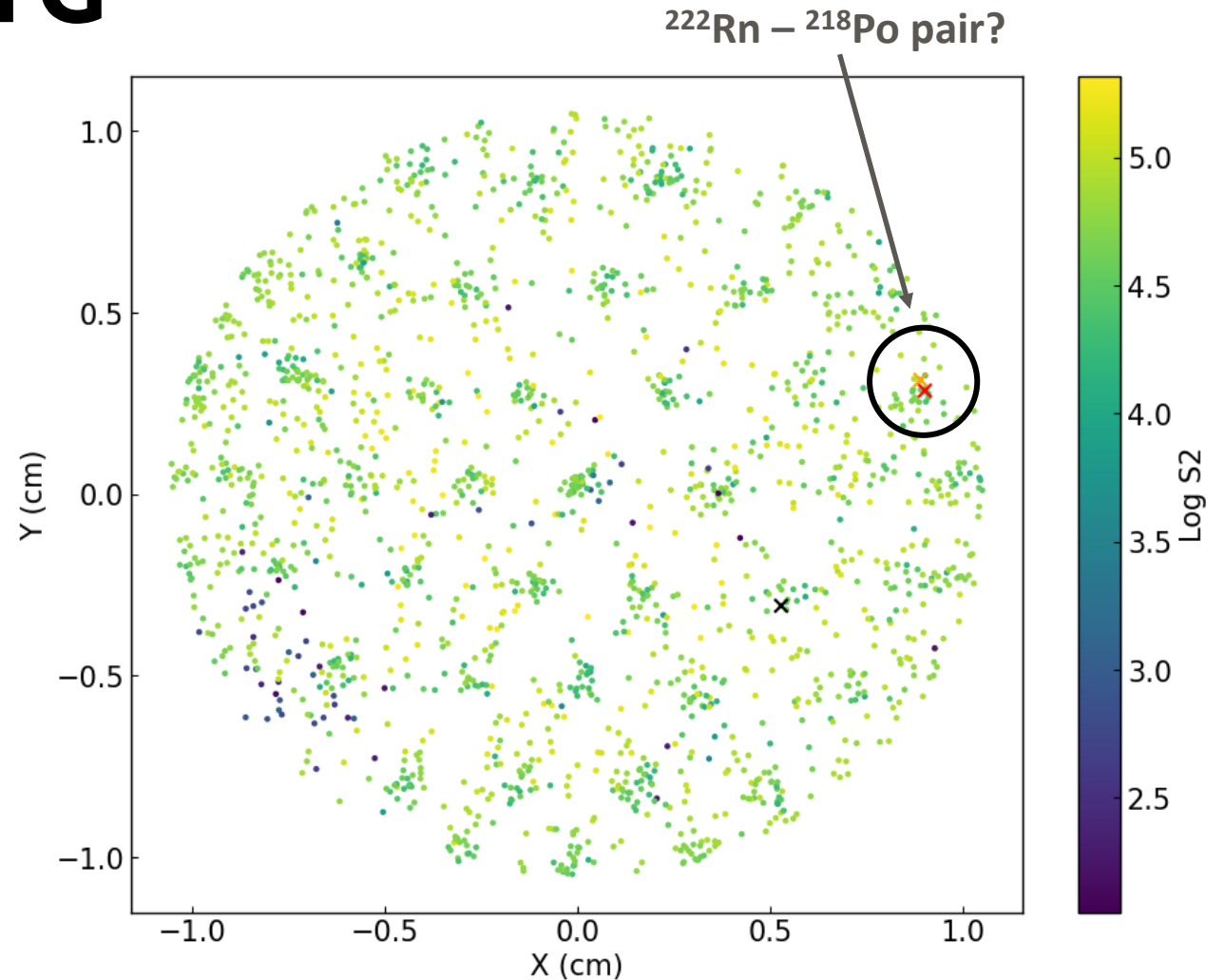
RADON EXCLUSION FACTOR

- Test: flow ^{220}Rn for hours in liquid (left) or after crystallization (right)
- ~2000 Rn chain alphas in liquid, only 3 in crystal
- Exclusion factor of >600x
- Crystal alphas are unlikely to be from diffusion through crystal:
 - In center (vertically)
 - Rate consistent w/ pre-existing ^{222}Rn background



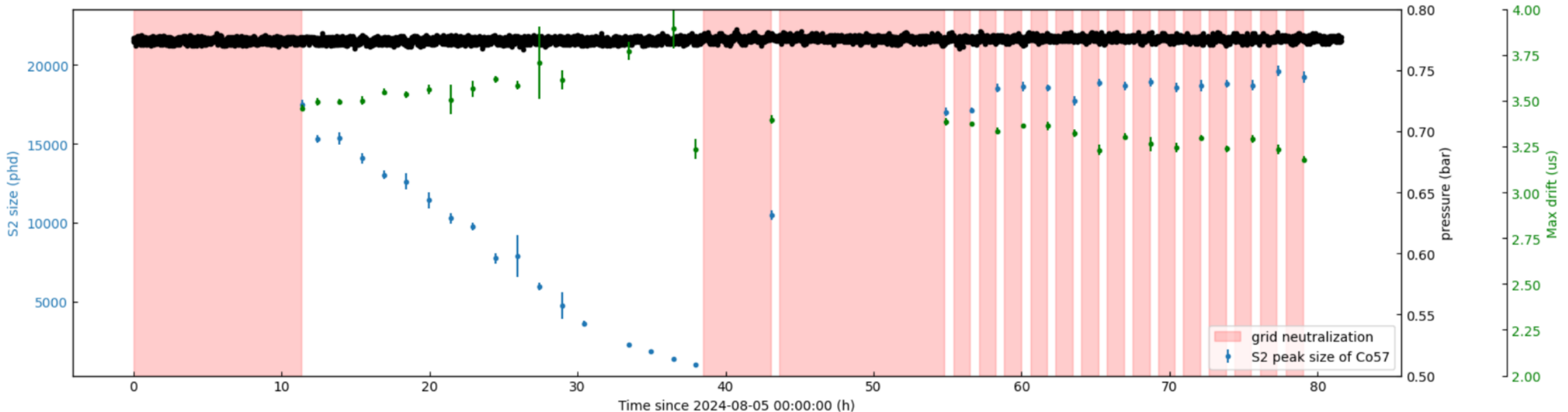
RADON TAGGING

- Two of three candidate events share nearly identical (x, y, z)
- Time between events is ~3 min (consistent with 3.1 min ^{218}Po half-life)
- <1 mm shift in 3 min
- Implies <1 cm shift in ~20 min half-life of ^{214}Bi (comparable to LZ position resolution)
- Hints at successful Rn tagging w/ minimal loss of livetime



CRYSTAL STABILITY

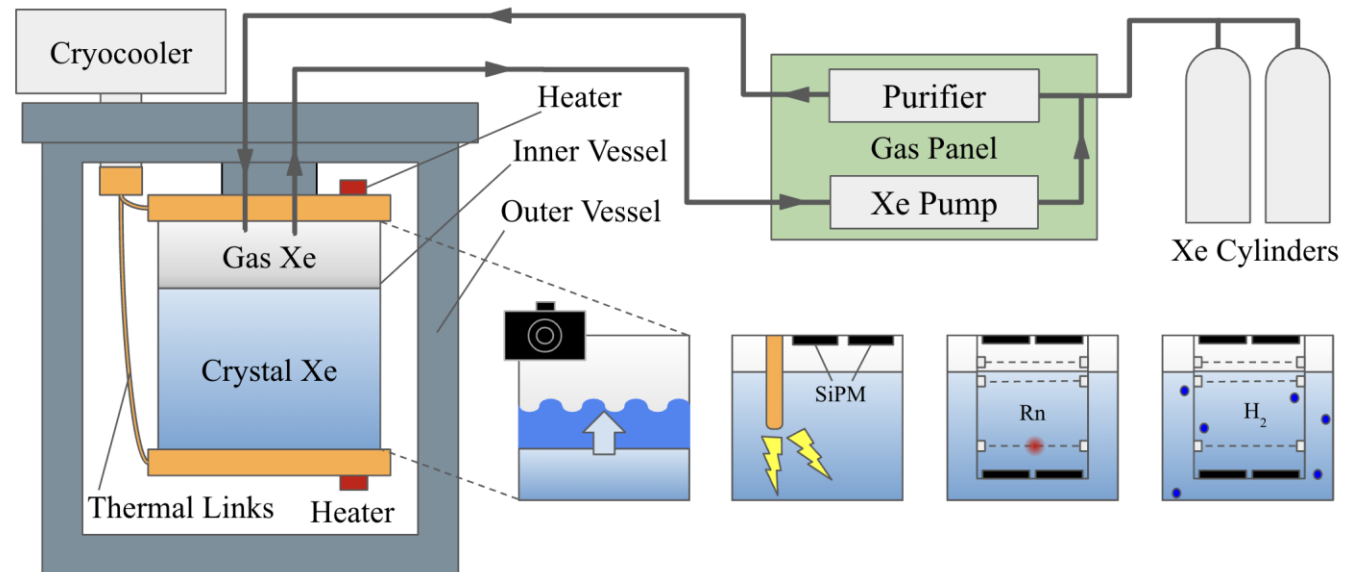
- With ^{57}Co calibration source continuously near detector, S2 size degrades over time
- Recovered by periodic grid neutralization (hypothesis: charge build-up)
- Future tests planned for crystal neutralization w/ reverse field



CHALLENGES AND OPPORTUNITIES

- Crystal stability and neutralization
- Do PMTs work in crystal (vs SiPMs)?
- Can we scale up from 700 g to 7 tonnes?
 - UT Austin setup to study scale-up to ~25 kg
- How does crystallization rate affect yields?
- What is the crystal surface shape?
- Can we achieve the needed HV?
 - Quantify S2 response
 - Possible application: single phase, charge msmt. in crystal

LBNL
UT Austin



CHALLENGES AND OPPORTUNITIES

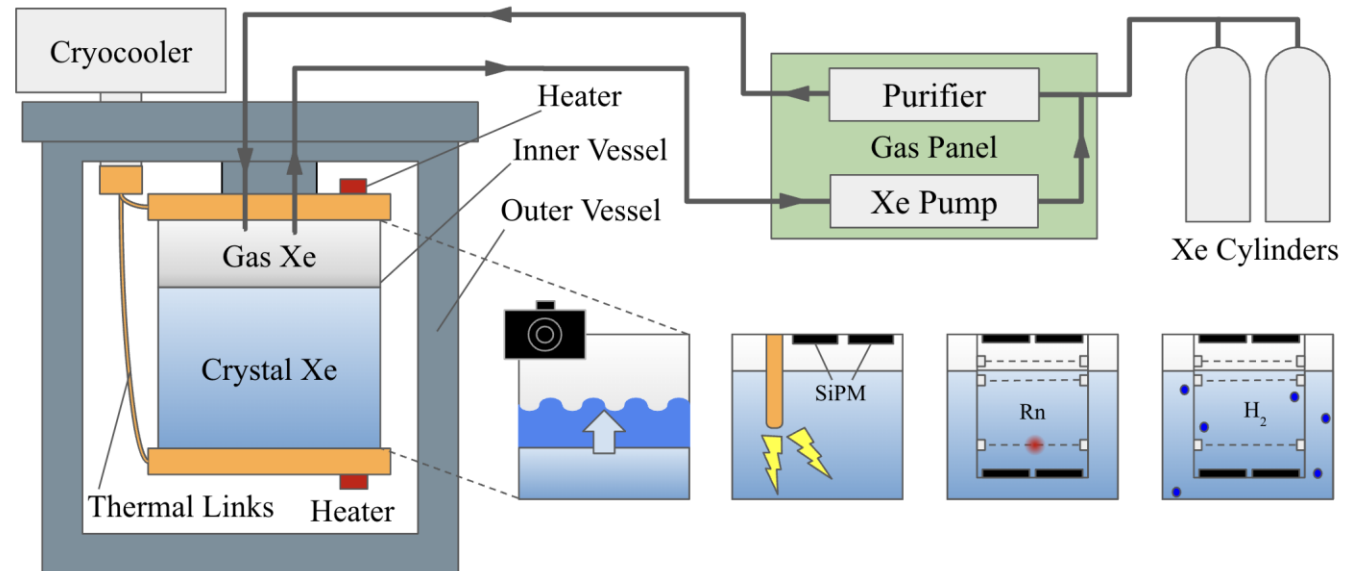
- What are the diffusion rates in crystal?

LBNL
UT Austin

- Radon and electrons
- Possible application: neutrinoless DBD
largest bkg in LXe is cathode plate-out of Rn daughters; less diffusion = better position and energy resolution

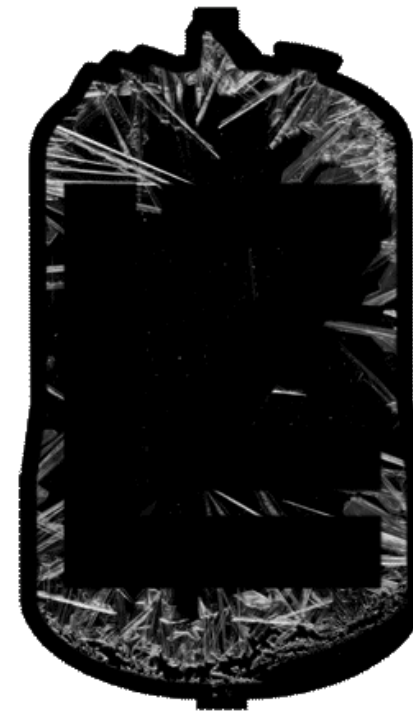
- Is *crystalize* compatible with HydroX (hydrogen doping of xenon)?

- Crystal solves:
need for re-purifying / re-doping H;
possible concerns about S2 quenching of from H in vapor



SUMMARY

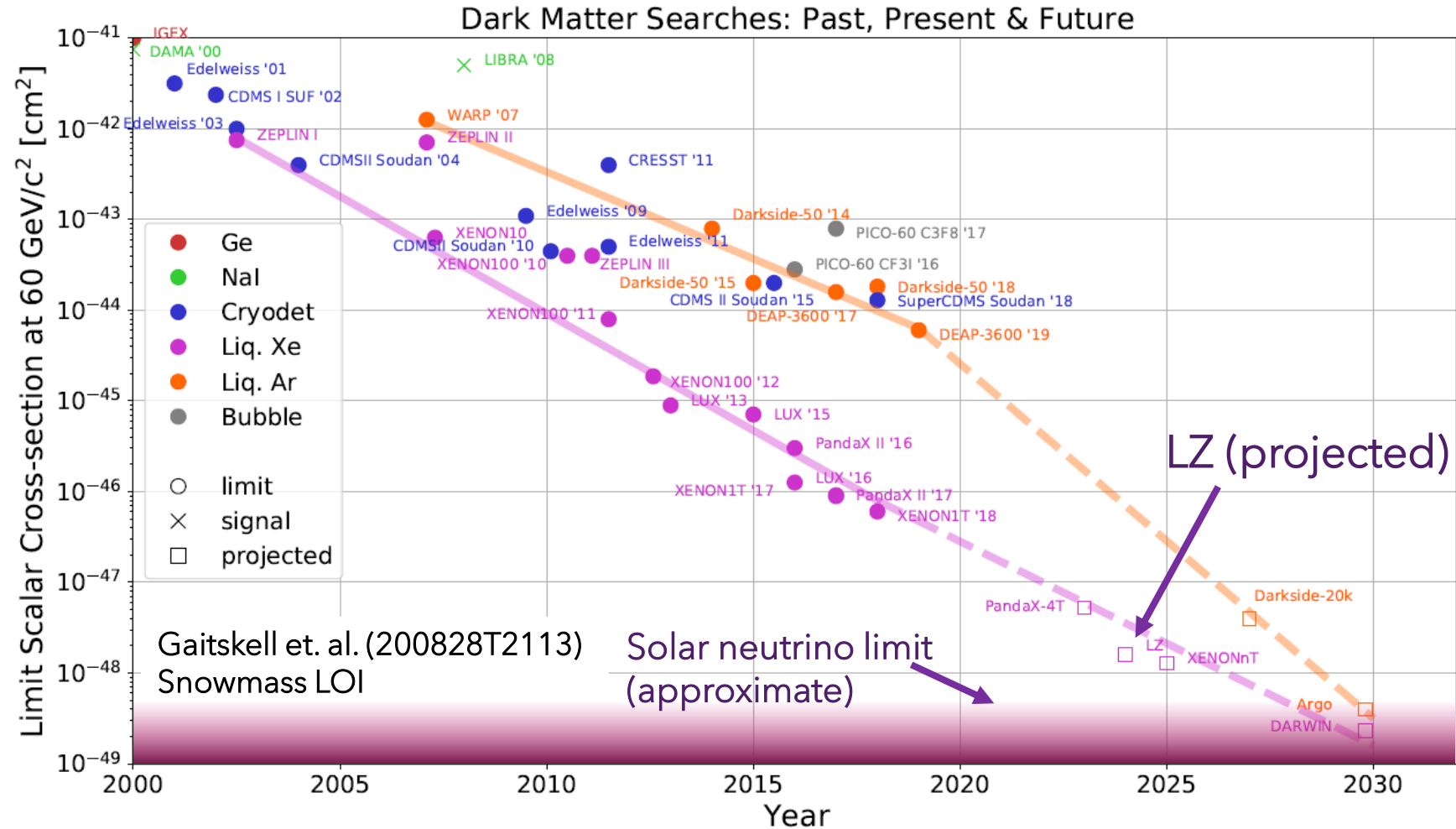
- Reaching the solar neutrino limit for DM direct detection will require innovation in detector design
- The solid xenon TPC is a promising new particle detector technology
 - R&D at LBNL has established almost all of the benefits of LXe TPCs are preserved (more possible!)
 - Removing the primary DM background, internal radon, leads to neutrinos as the only limiting background
 - Future R&D (LBNL + UT Austin) will gauge the feasibility of tonne-scale crystal TPCs, address remaining challenges, and explore new applications such as neutrinoless DBD and combination with H doping



BACKUP SLIDES

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 in detector design



GET BETTER AT RADON REDUCTION?

Active area of R&D. HARD.

Conclusions from a paper on radon reduction [[arXiv:2009.06069](https://arxiv.org/abs/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..."

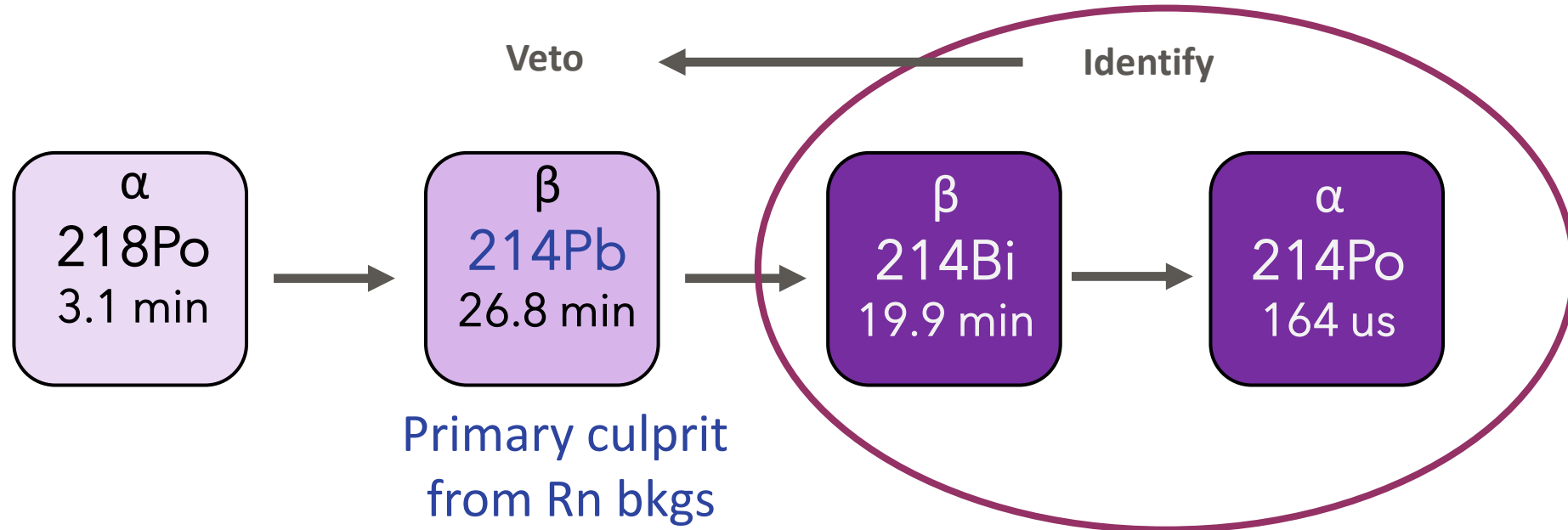
Problem only gets harder for larger detectors (e.g. G3 Xe experiment)

XENON1T cryogenic distillation achieves ~20% Rn reduction

([slides](#))



Rn daughter tagging

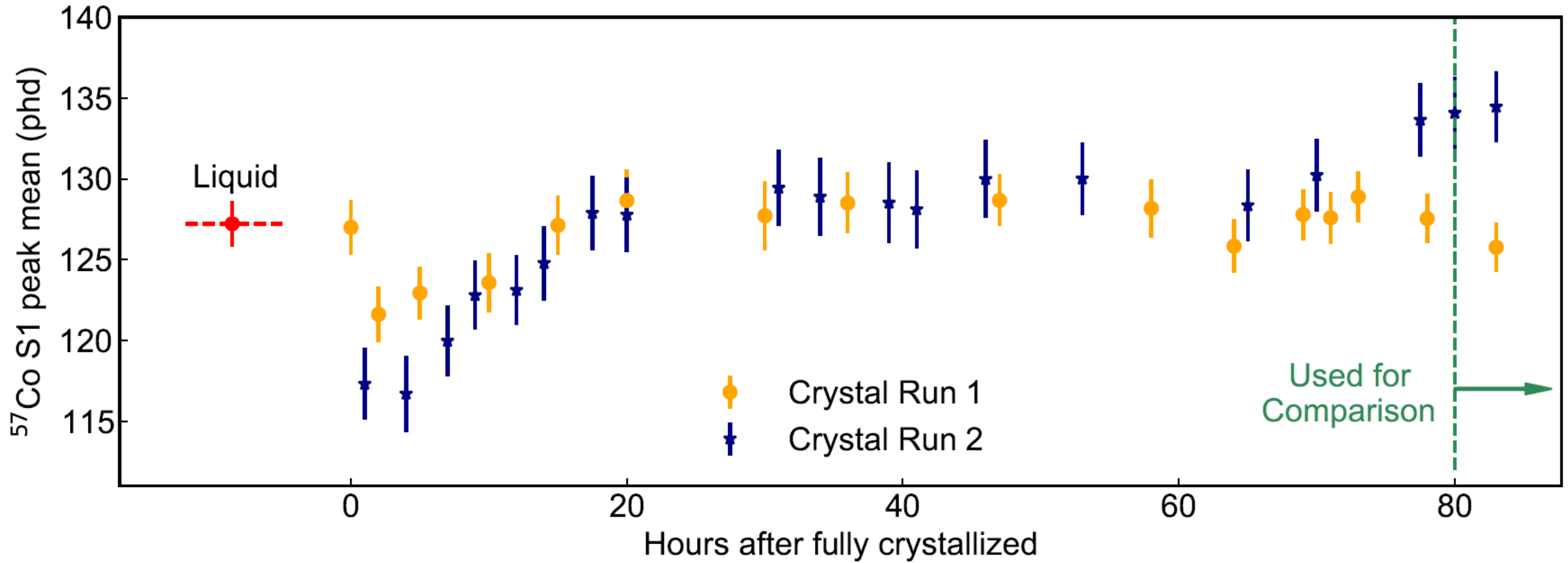


Easy sequence to tag in a low-background instrument
if all decays happen in exactly the same spot

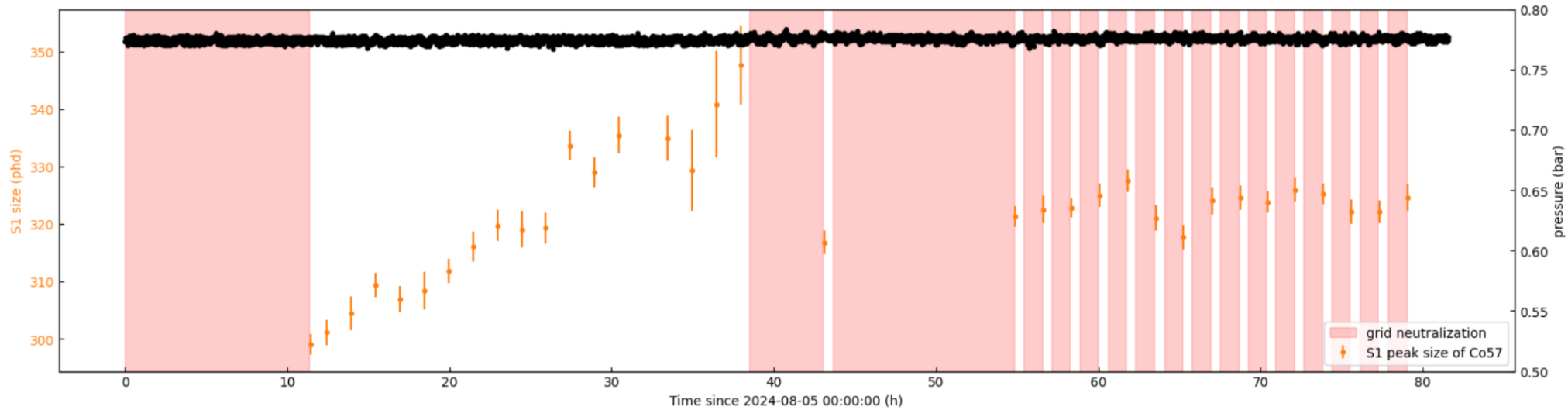
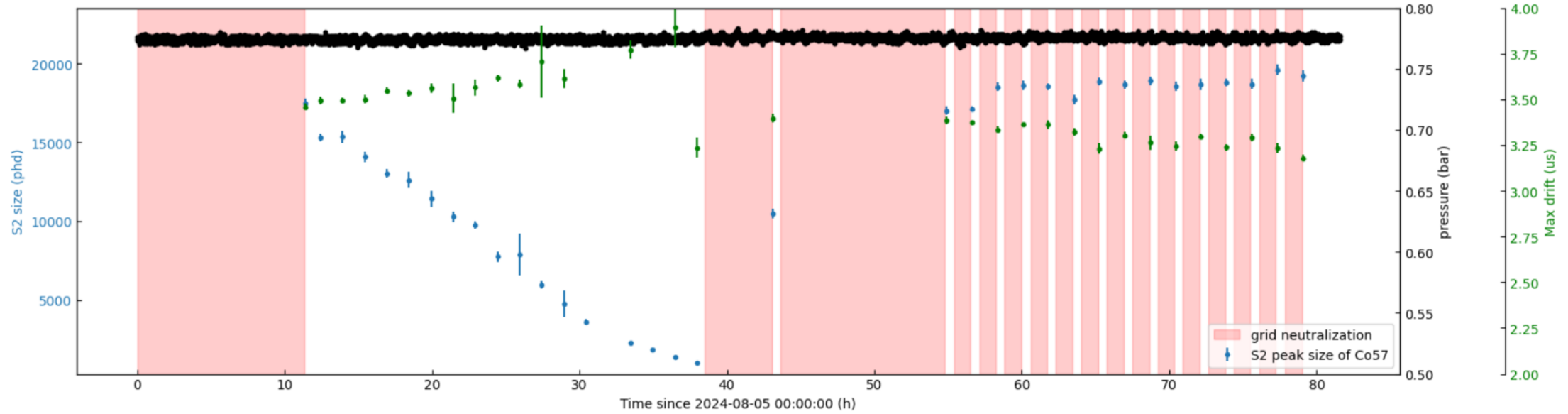
(similar situation for ^{220}Rn chain)

(DAMIC has used this trick in Si [arXiv:1506.02562](https://arxiv.org/abs/1506.02562))

STABLE AND REPEATABLE



CRYSTAL STABILITY



ER/NR DISCRIMINATION IMPROVEMENT

Double e- mobility in solid Xe



Less recombination of thermal electrons



Smaller fluctuations from recombination, narrower bands in S2 vs S1



Better ER/NR discrimination from S1/S2 ratio

Electron Recoil

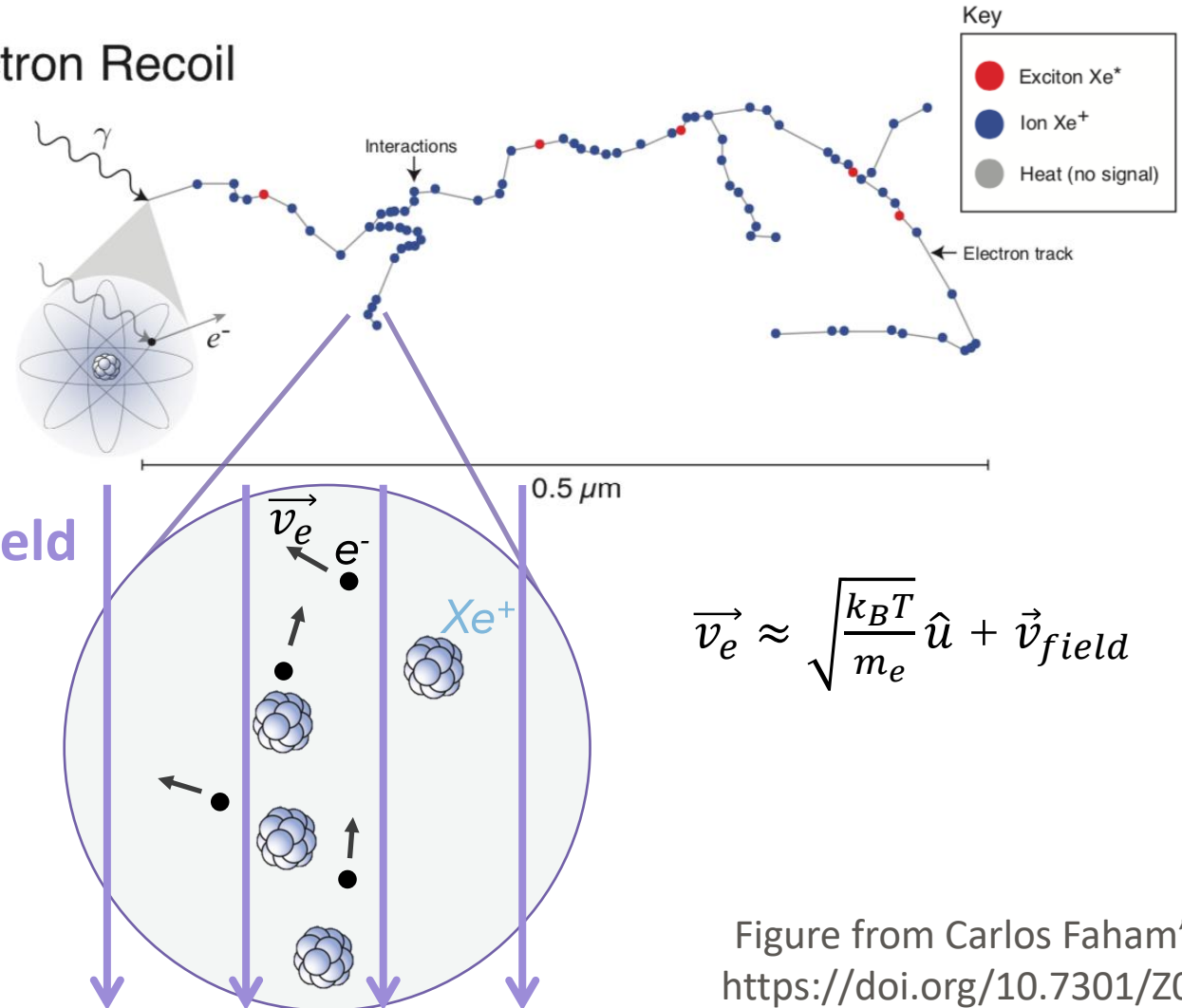
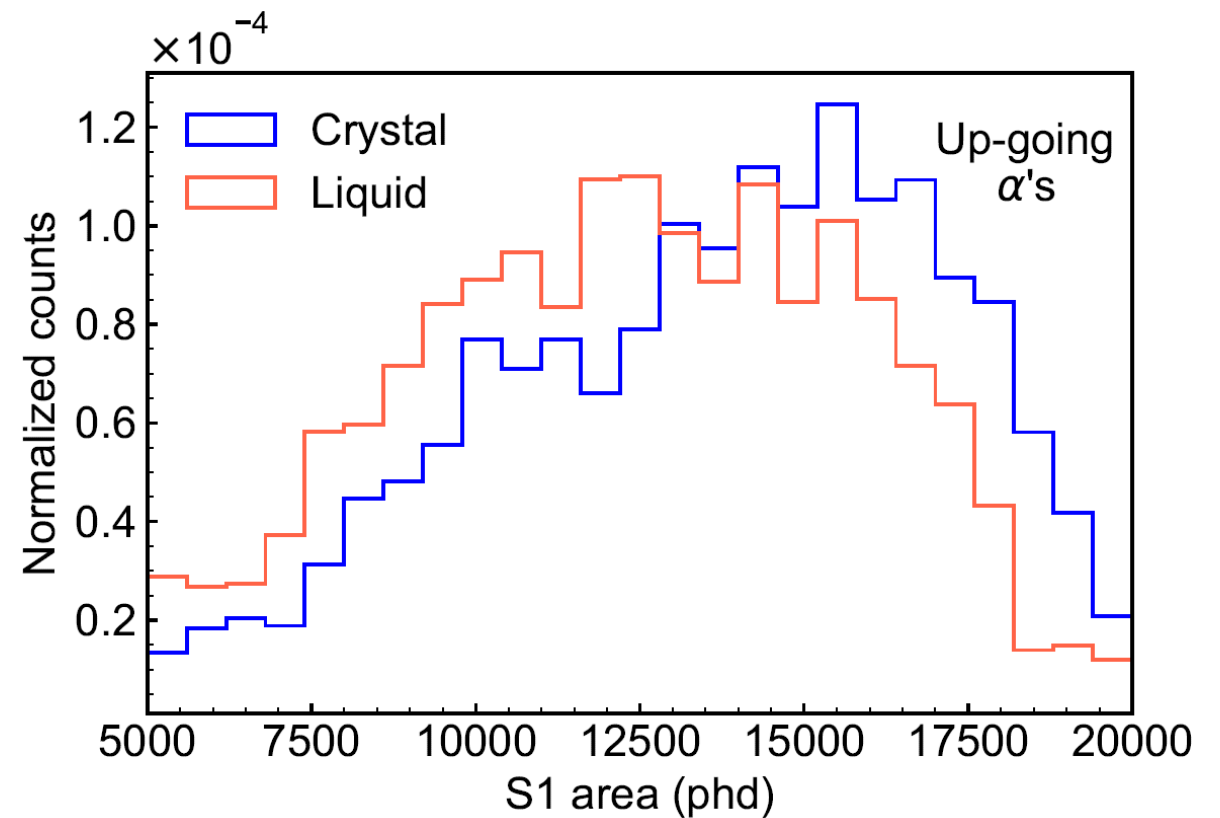
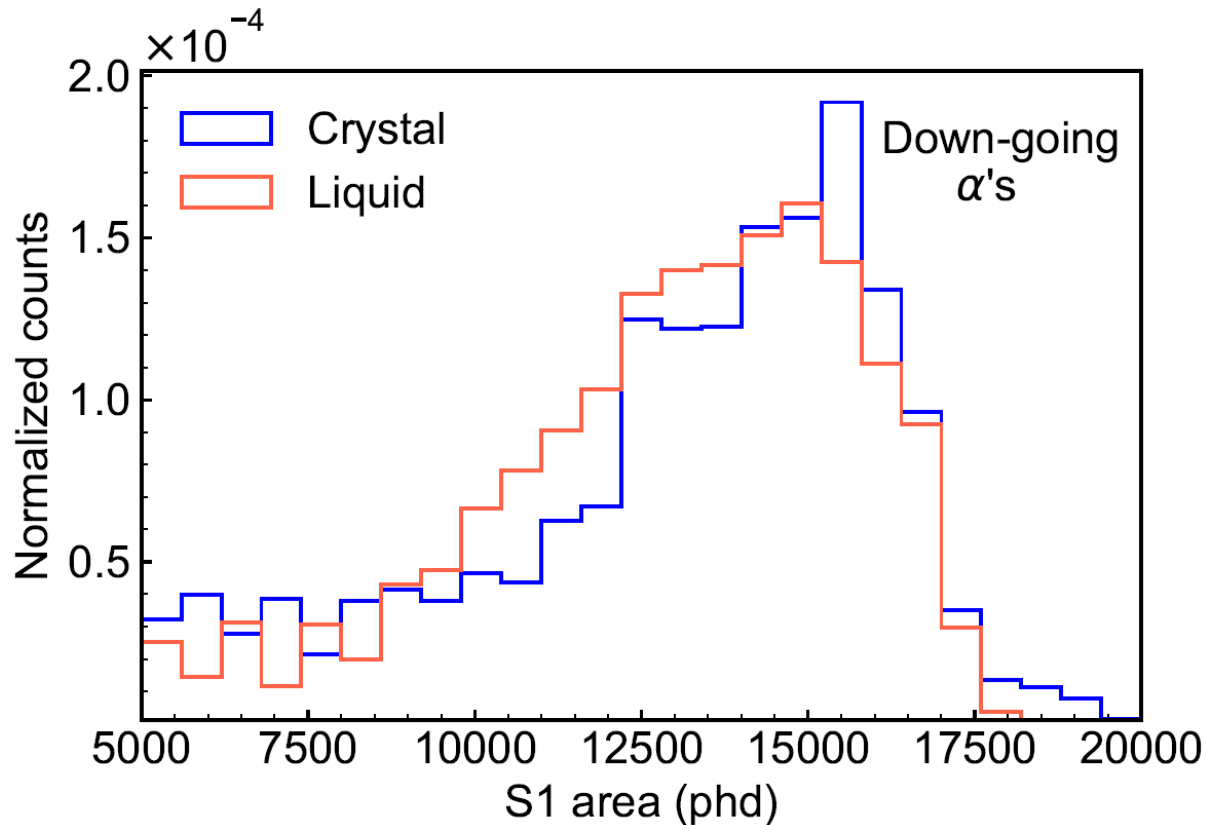
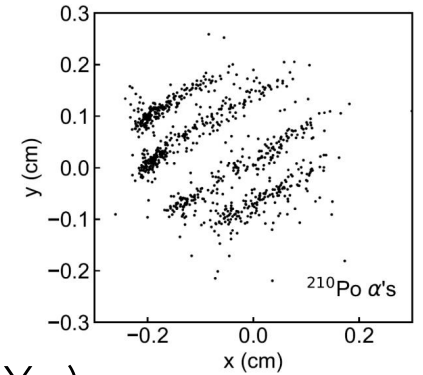


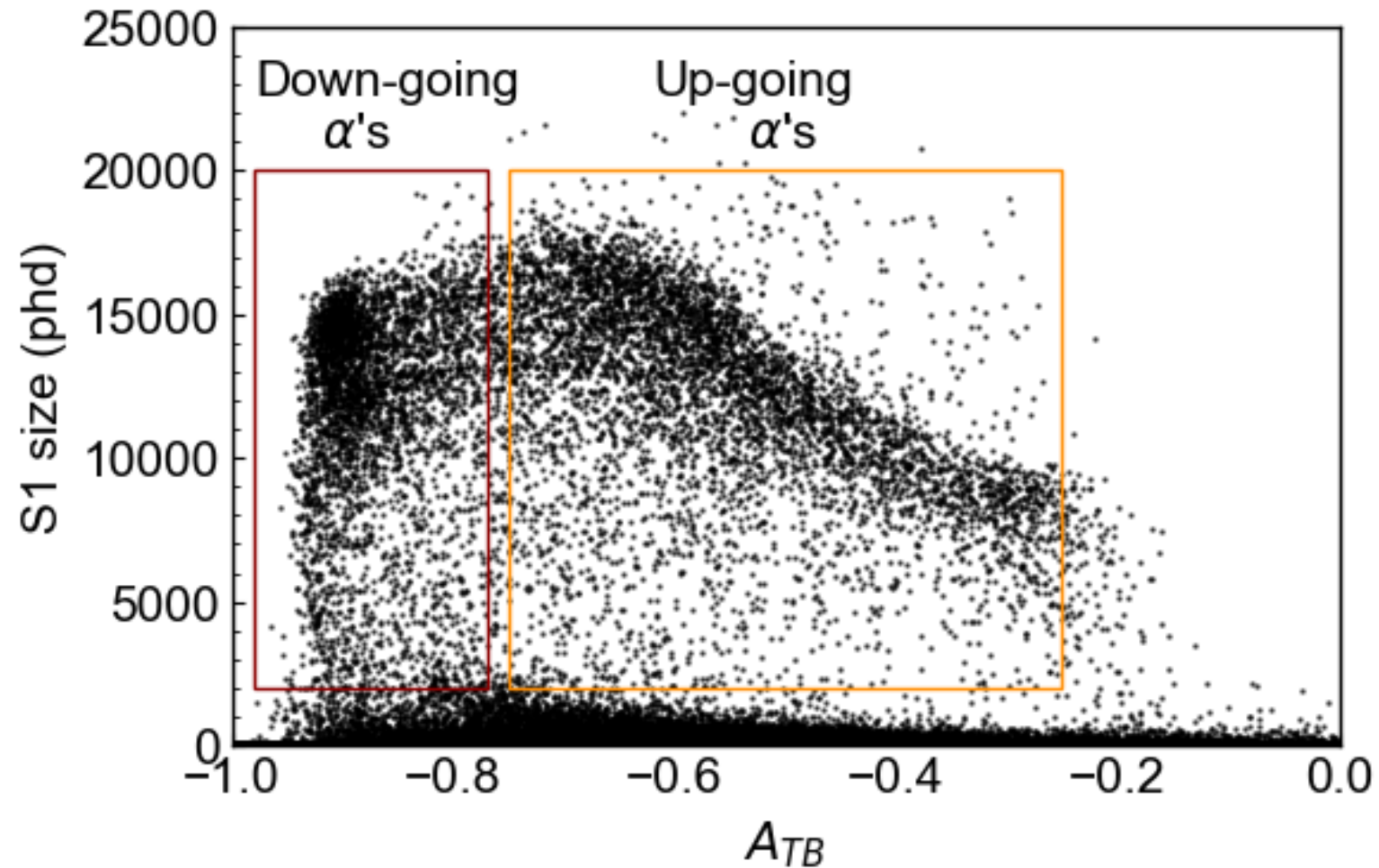
Figure from Carlos Faham's thesis
<https://doi.org/10.7301/Z0QV3JV5>

SXE CRYSTAL TRANSPARENCY

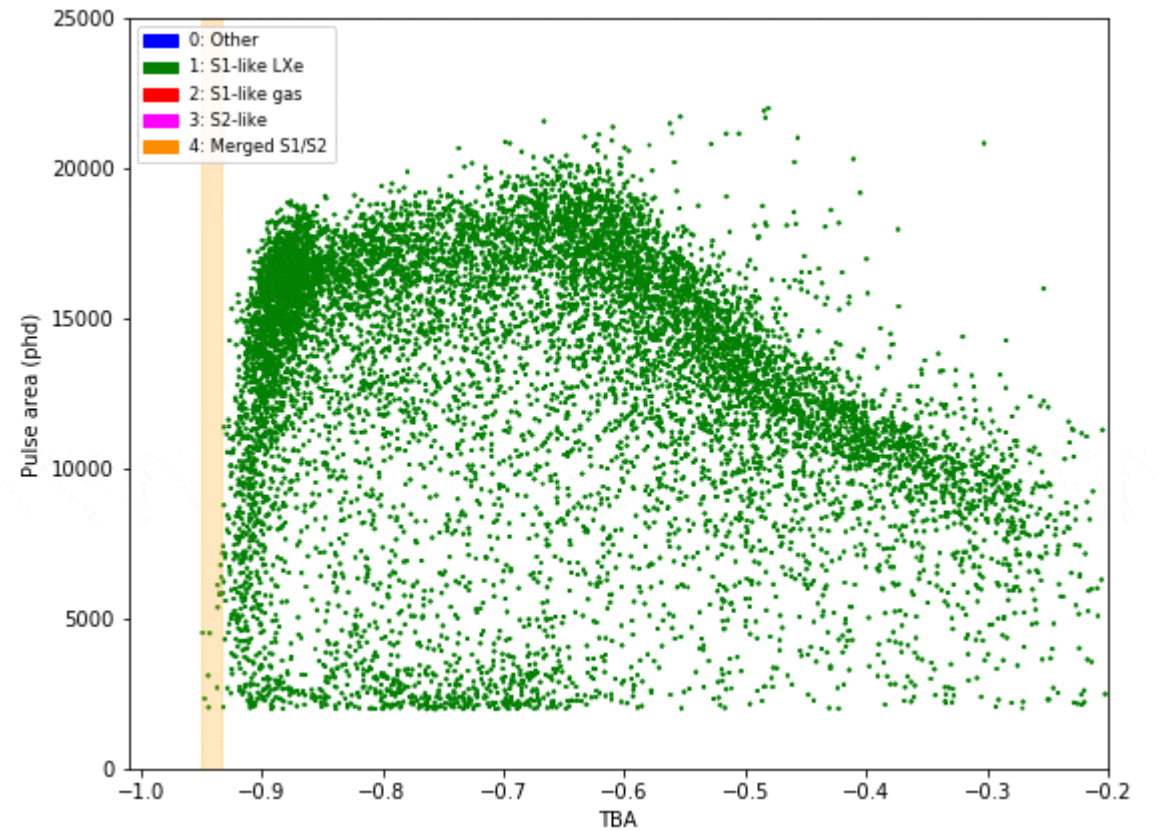
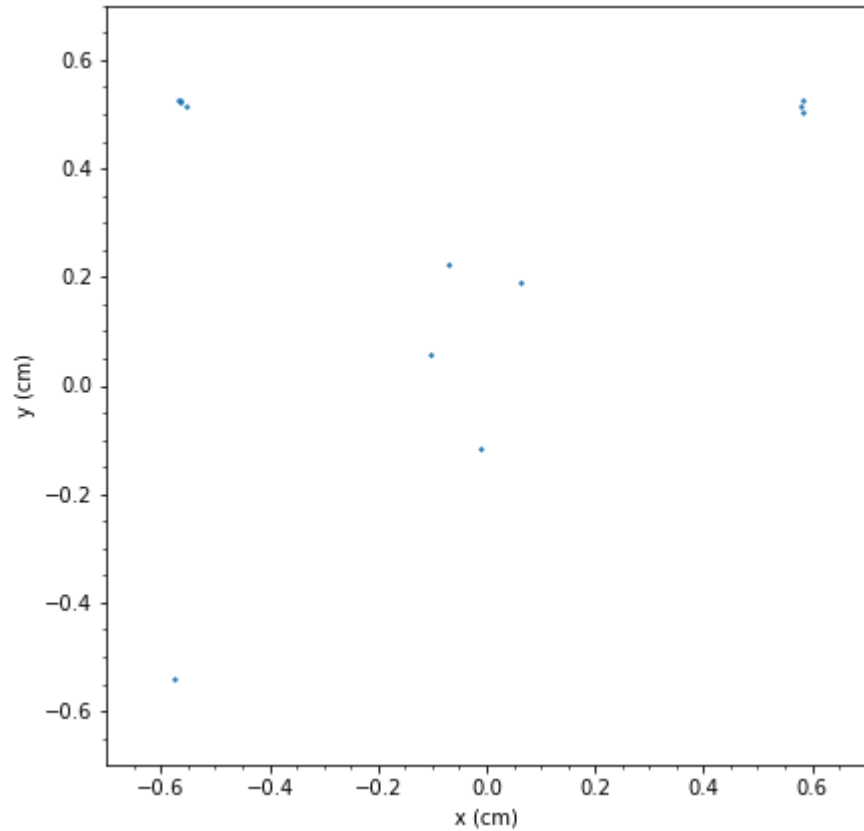
- Can clearly separate out Po from top vs bottom of cathode by TBA
- Slight boost for top - inconsistent w/ opaque Xe (light travels through *more* SXe)



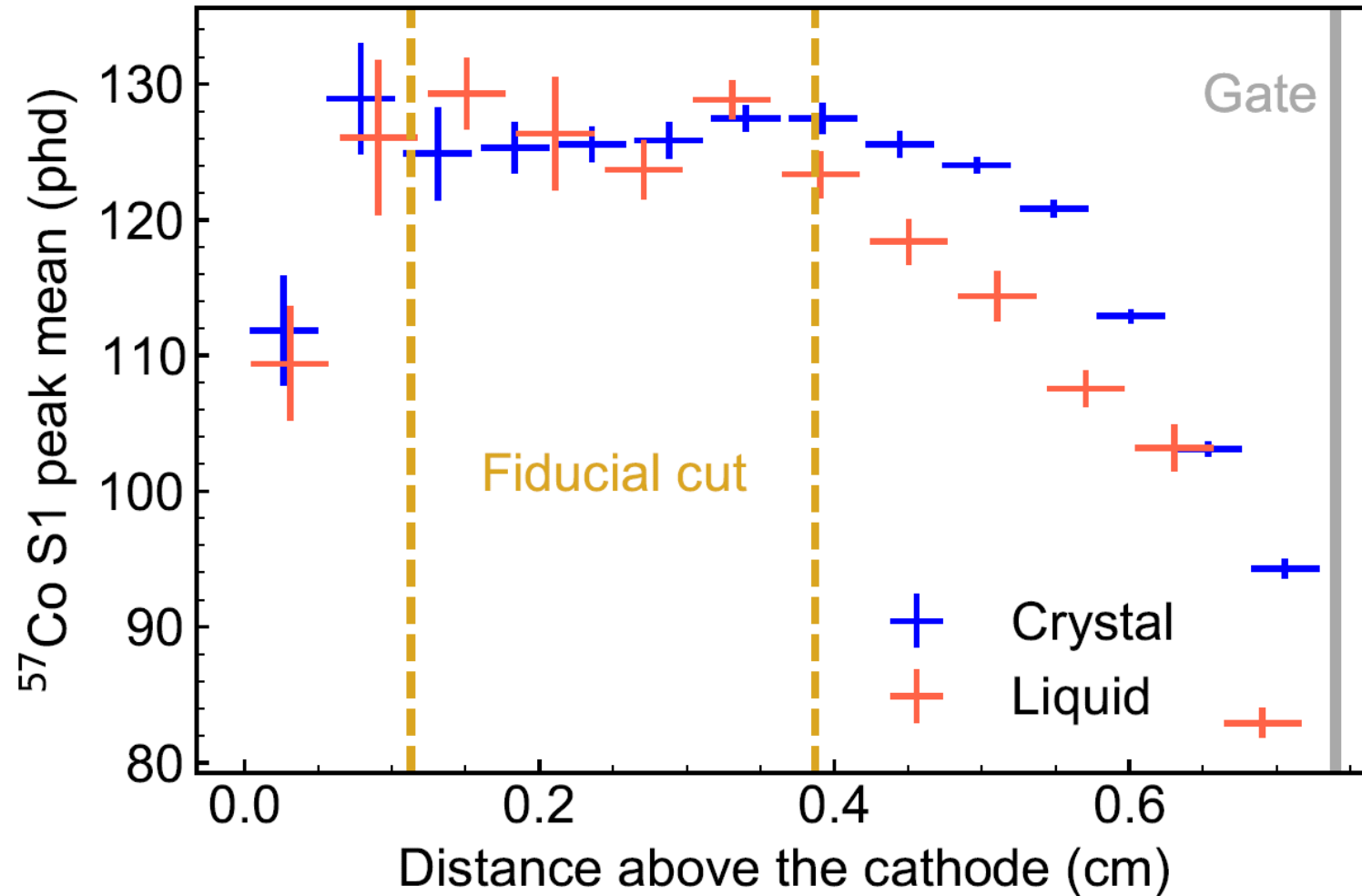
PO S1 POPULATIONS



PO S1 POPULATIONS

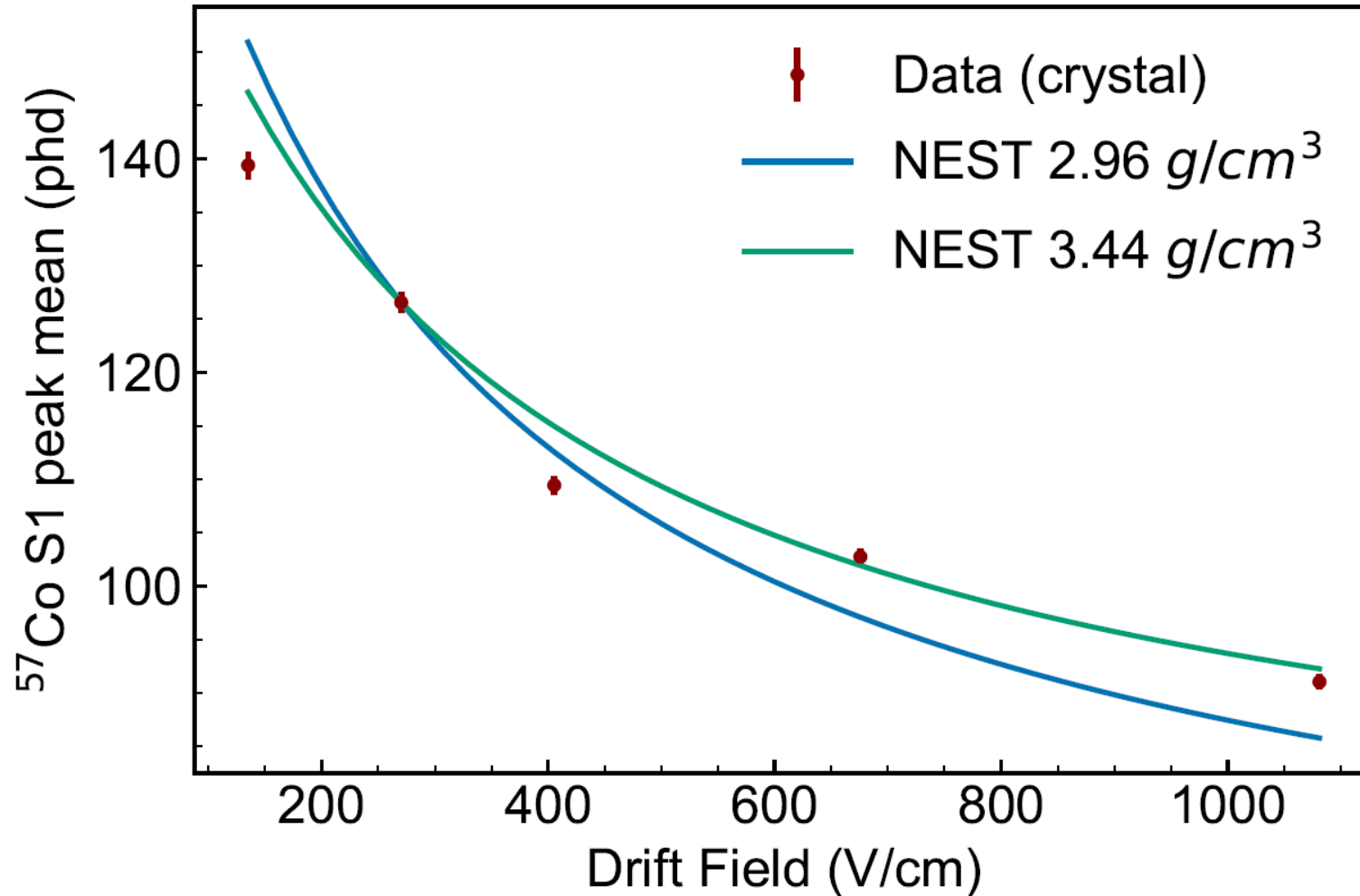


S1 VS Z POSITION



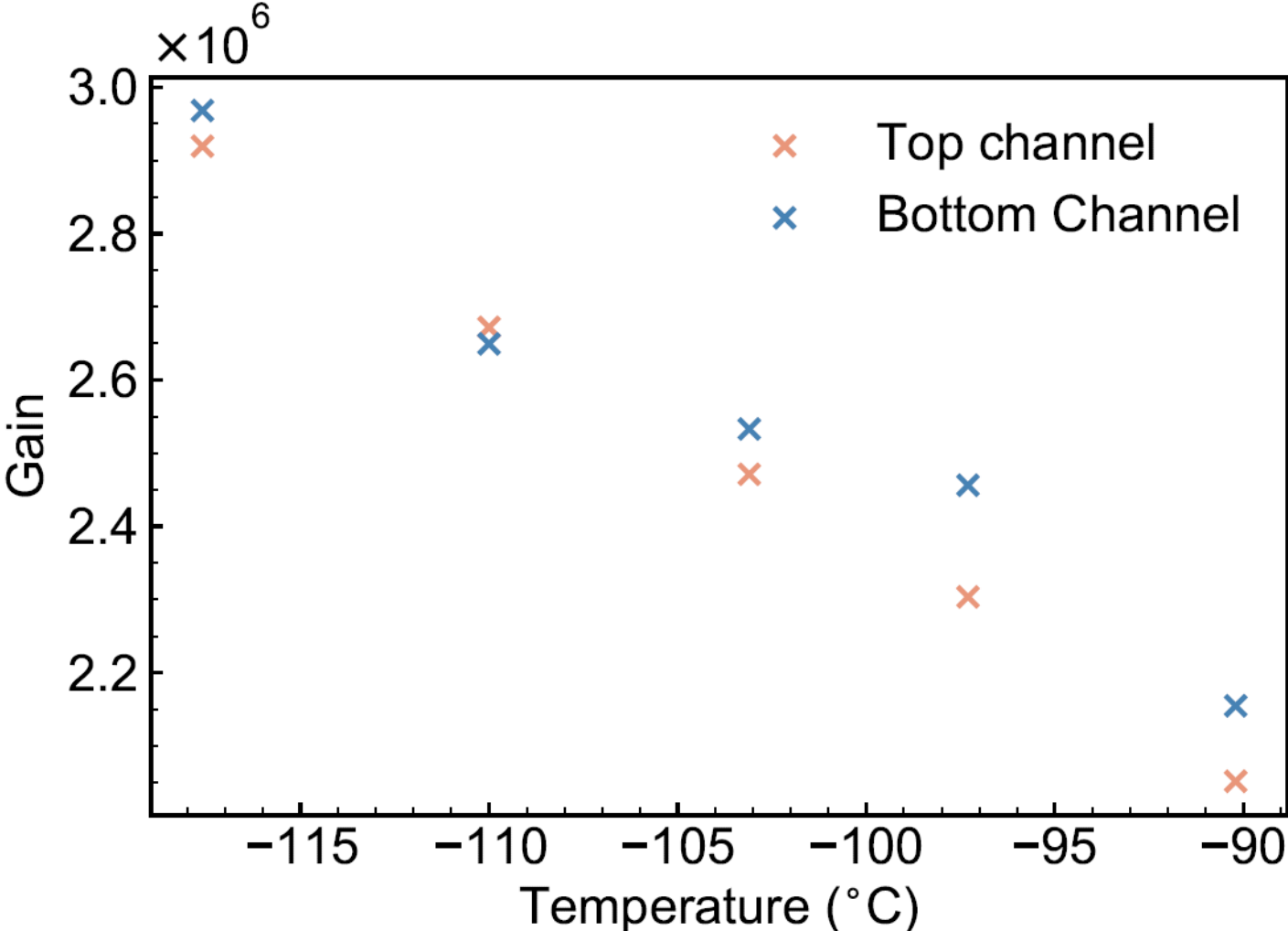
- Avoid field fringing effects by focusing on “flat” region

S1 SIZE VS FIELD IN CRYSTAL



- Consistent with expected field dependence in LXe
- More careful study possible with full ER bands

SIPM GAIN VS TEMPERATURE



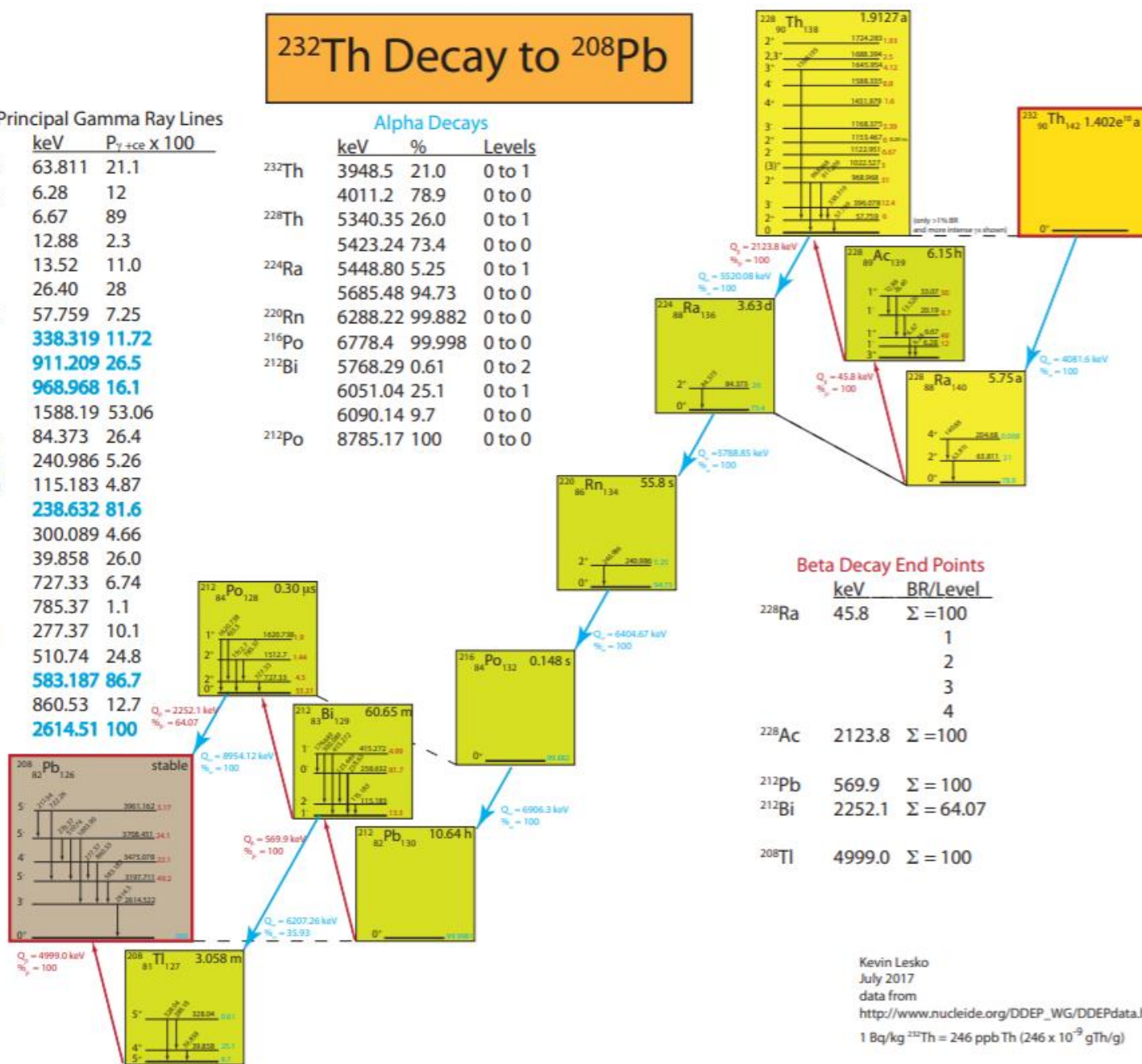
232Th Decay to 208Pb

Principal Gamma Ray Lines

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

Alpha Decays

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



Beta Decay End Points

	keV	BR/Level
228Ra	45.8	$\Sigma = 100$
		1
		2
		3
228Ac	2123.8	$\Sigma = 100$
		4
		4
		4
212Pb	569.9	$\Sigma = 100$
212Bi	2252.1	$\Sigma = 64.07$
208Tl	4999.0	$\Sigma = 100$

Kevin Lesko
 July 2017
 data from
http://www.nucleide.org/DDEP_WG/DDEPdata.htm
 1 Bq/kg ^{232}Th = 246 ppb Th (246×10^{-9} gTh/g)

