A CRYSTALLINE XENON TPC TO REACH THE NEUTRINO DETECTION LIMIT

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On behalf of

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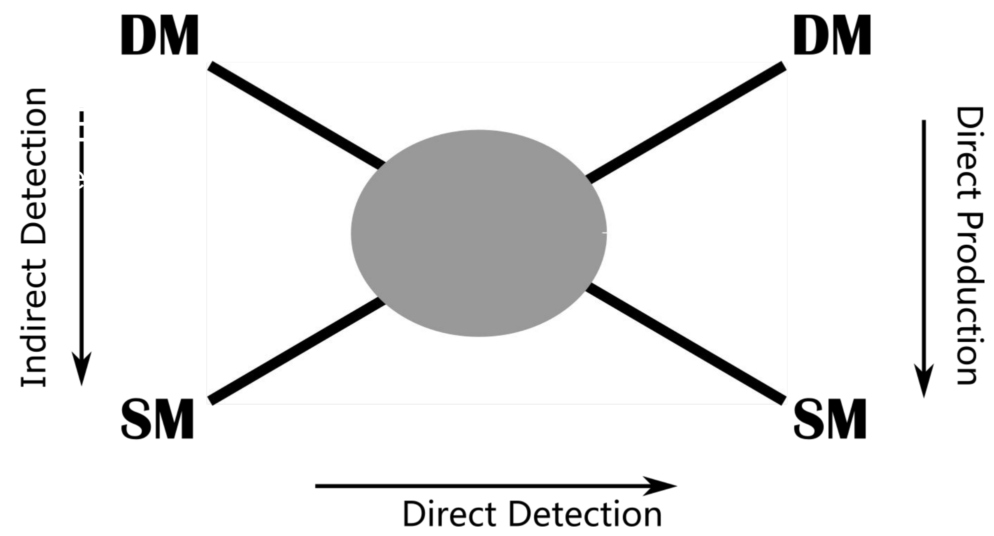
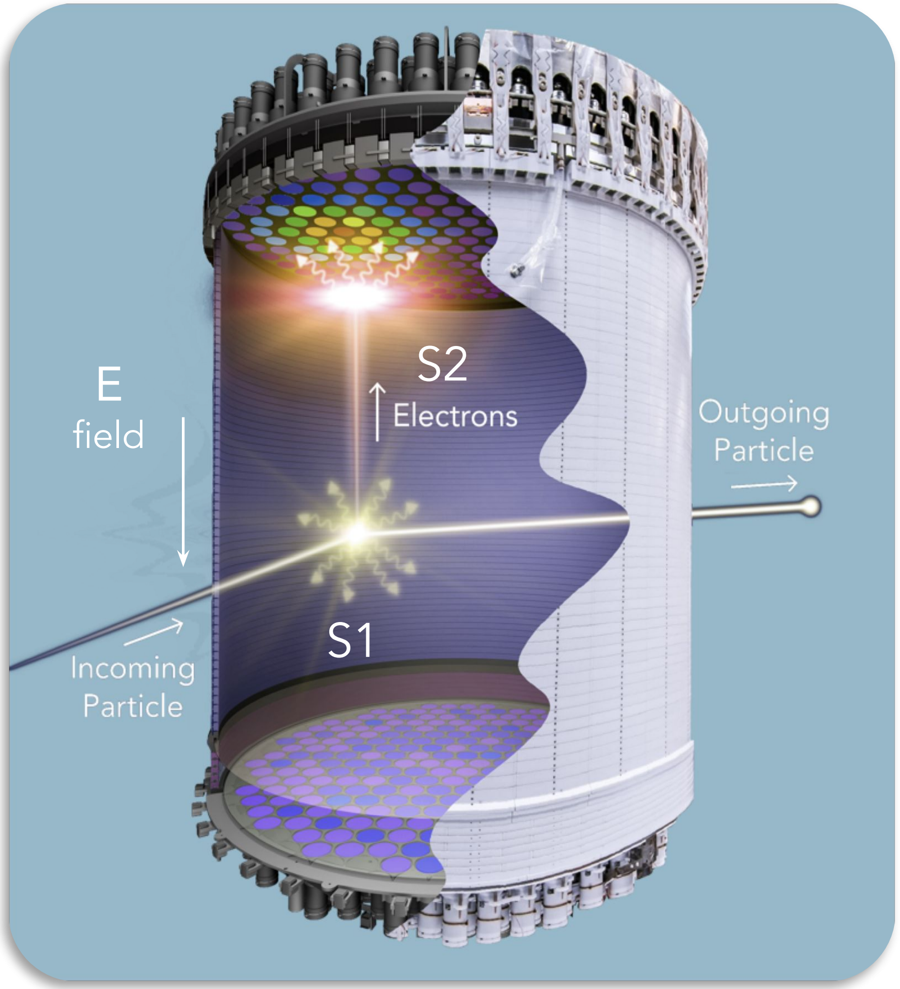
@UCLA Dark Matter 2023

DIRECT DARK MATTER SEARCH





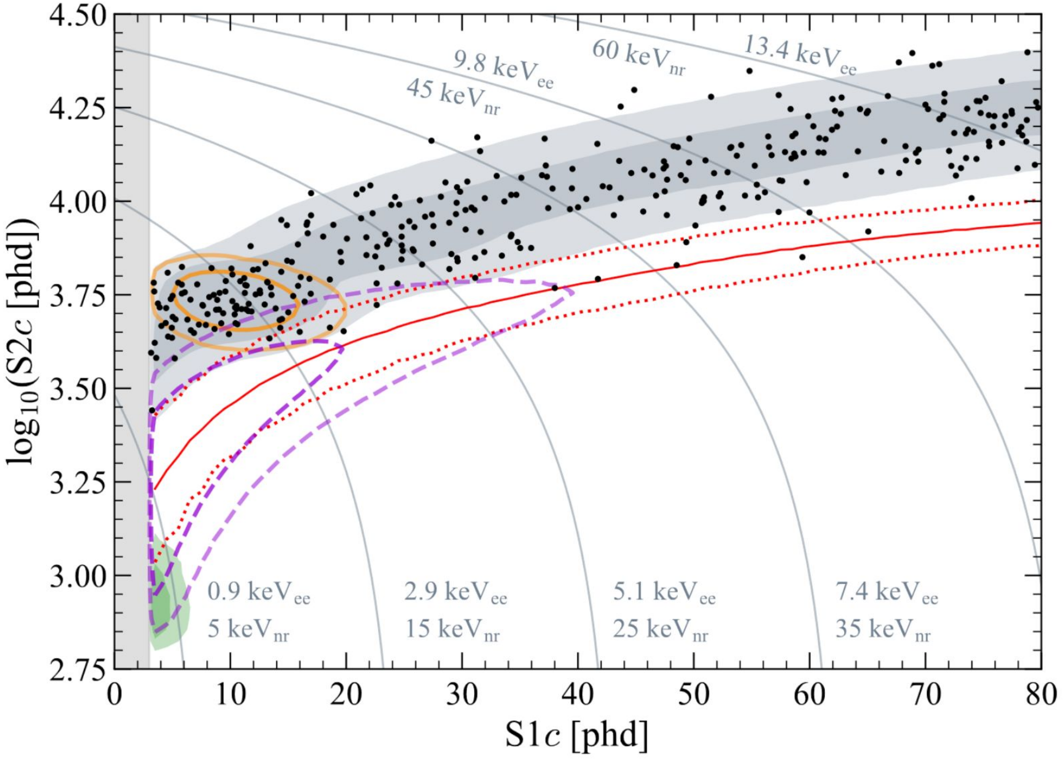
Weak interaction → Rare events search

LZ. Picture credit to: Matt Kapust and SLAC LZ GROUP.

See Maria Elena Monzani, Ibles Olcina, Amy Cottle and Jeanne Bang's talks about LZ

FIRST DARK MATTER SEARCH RESULTS FROM LZ

LZ SR1



Aalbers, et al. “First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment.” arXiv:2207.03764 [hep-ex]

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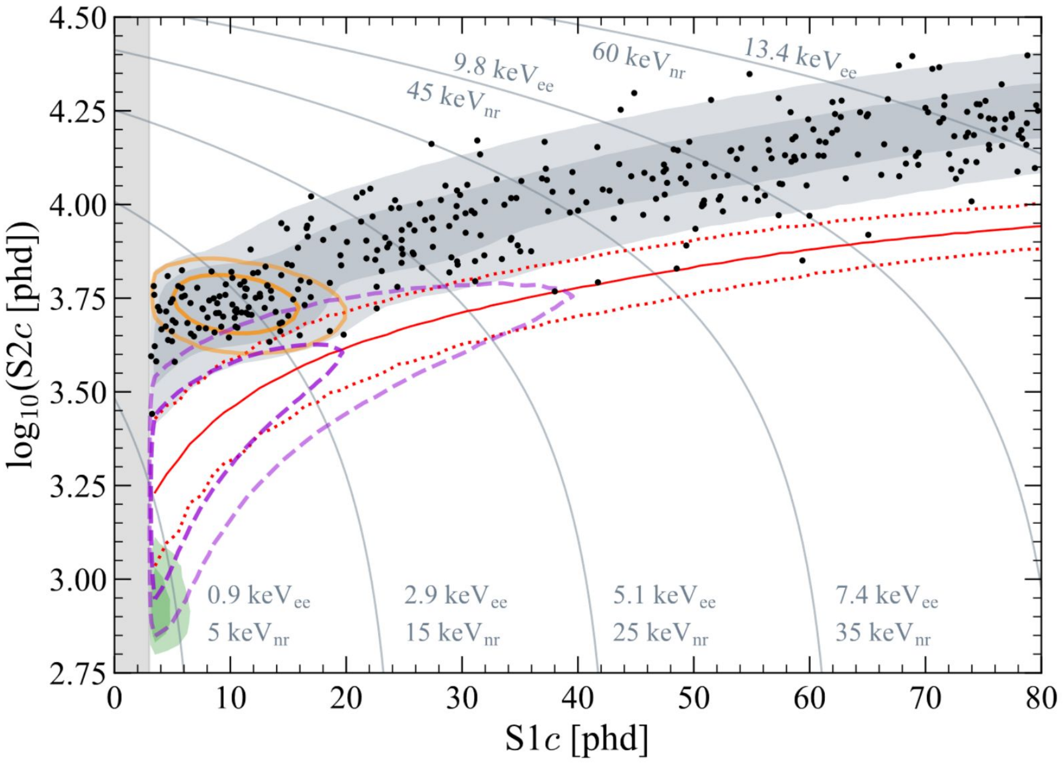

Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	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

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Aalbers, et al. "Background Determination for the LUX-ZEPLIN (LZ) Dark Matter Experiment ." arXiv:2211.17120 [hep-ex]

FIRST DARK MATTER SEARCH RESULTS FROM LZ

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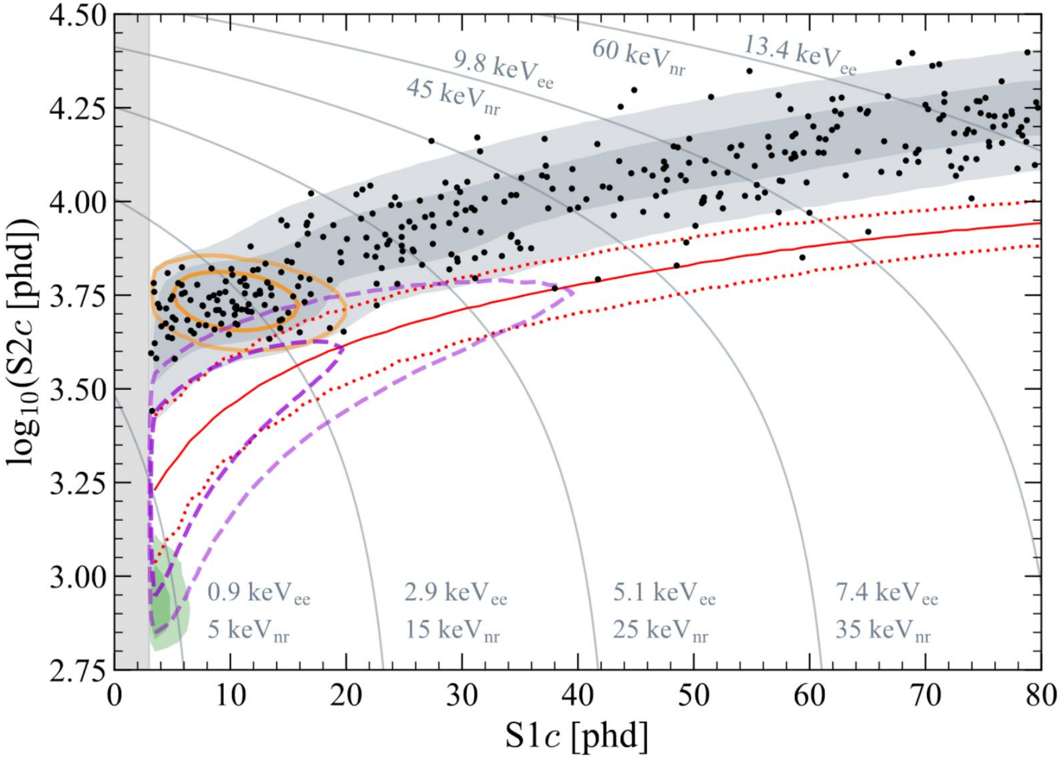

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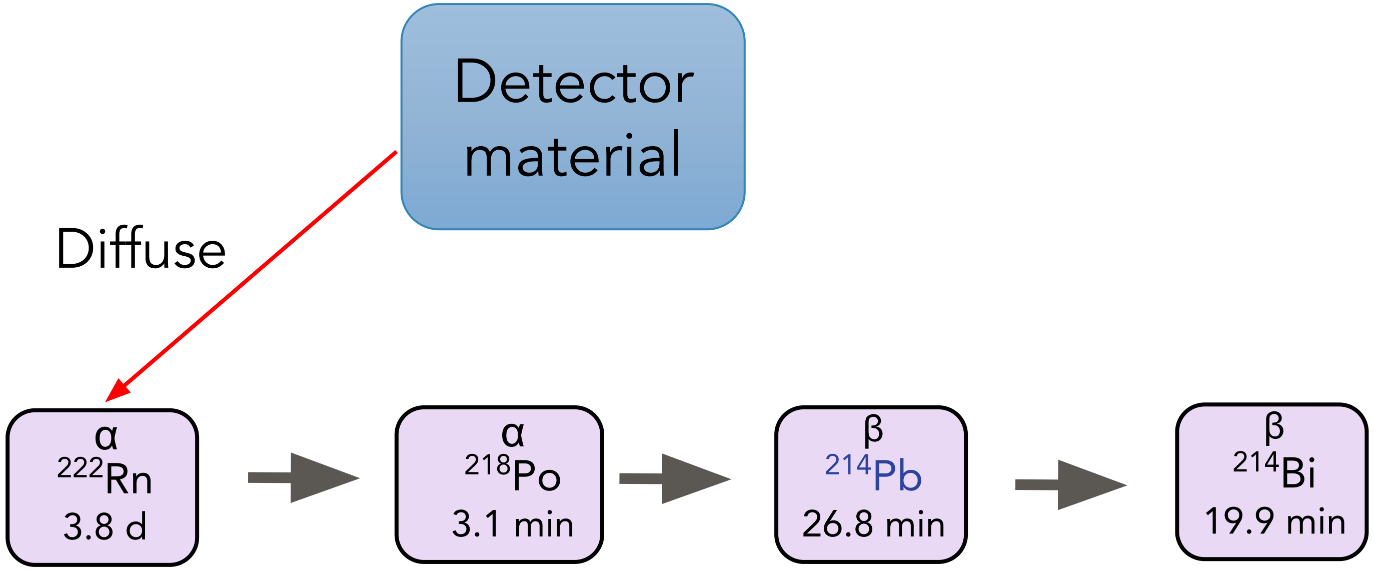
Can we remove this?

Aalbers, et al. "Background Determination for the LUX-ZEPLIN (LZ) Dark Matter Experiment." arXiv:2211.17120 [hep-ex]

RADON BACKGROUND



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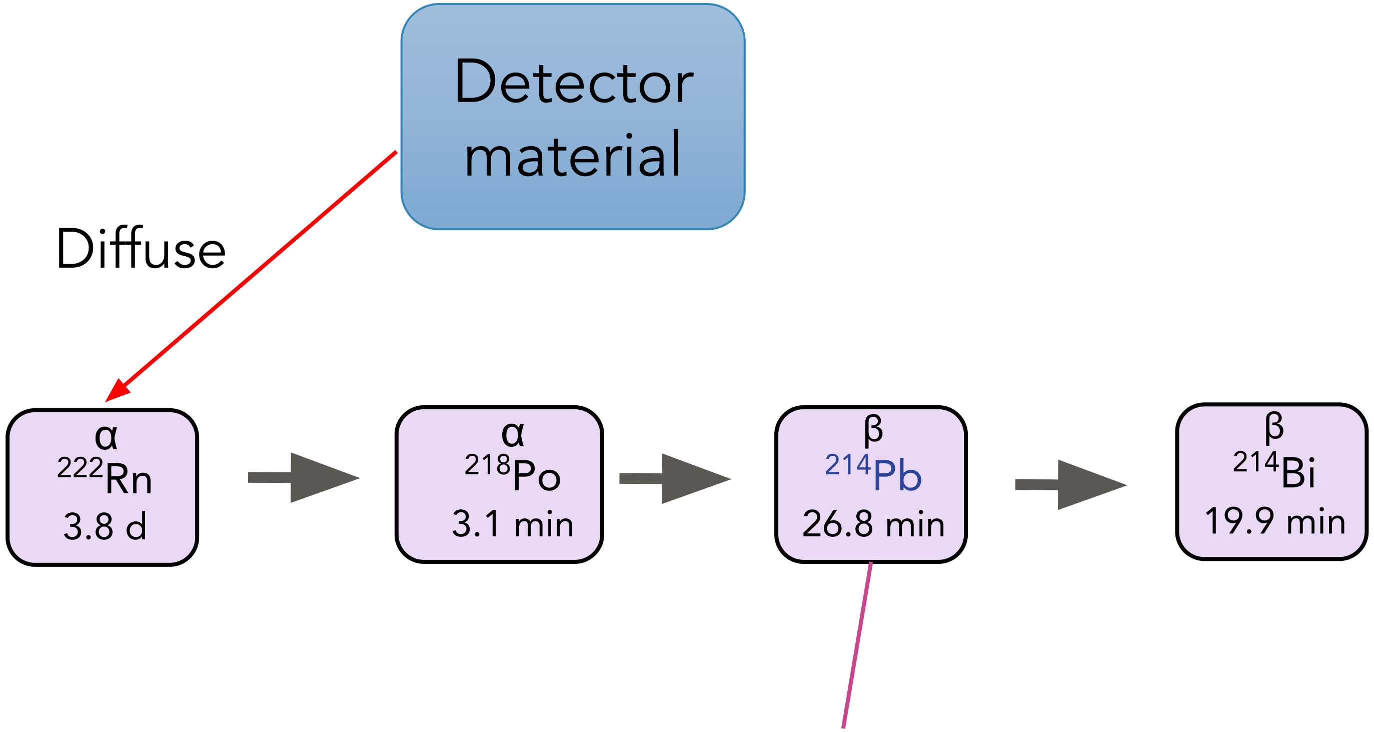
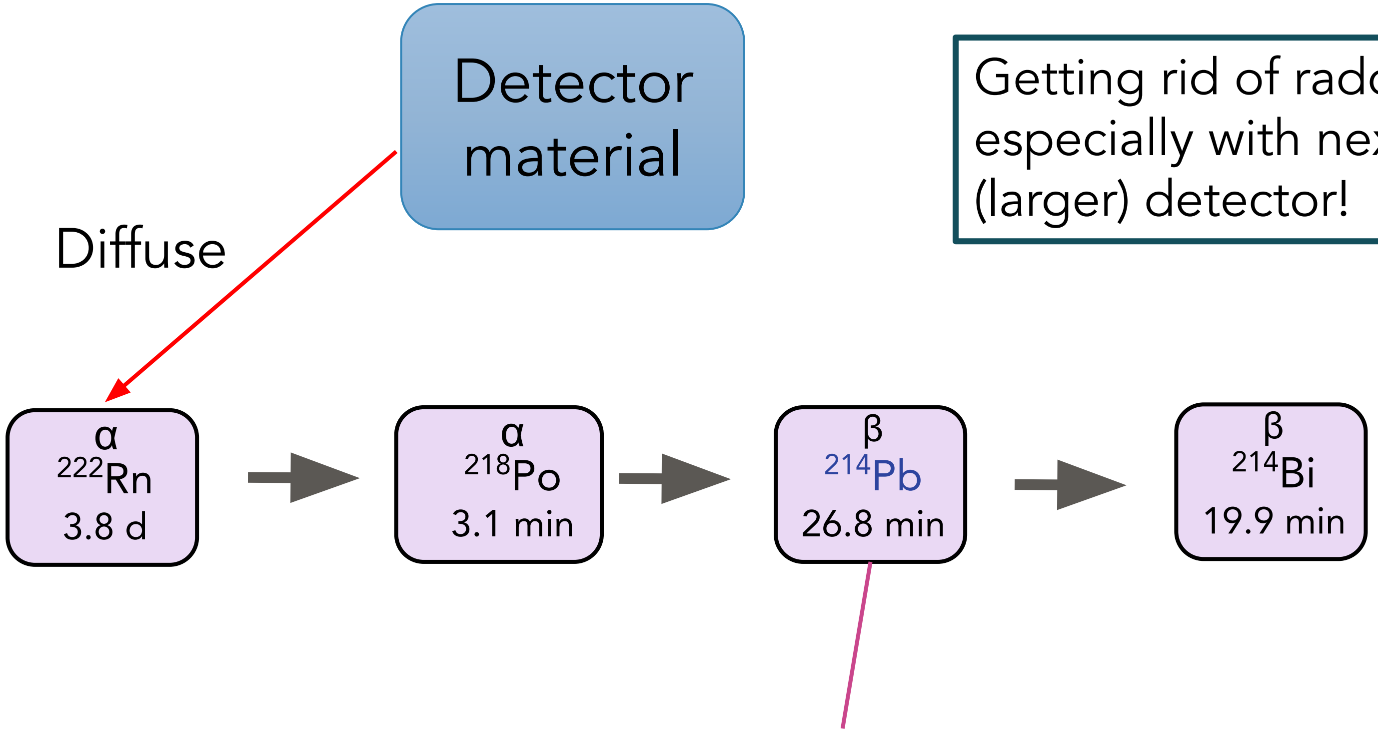


Primary culprit

with~10% beta decay to the ground state

~20min is too long to tag in liquid Xenon

RADON BACKGROUND



Getting rid of radon is hard, especially with next generation (larger) detector!

Primary culprit

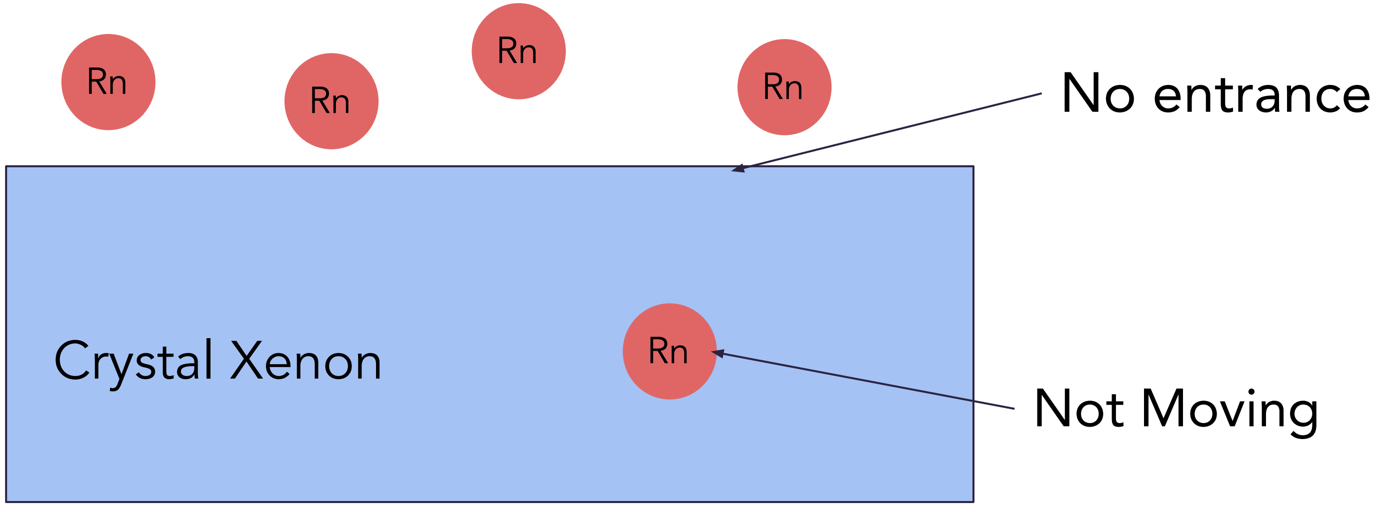
with~10% beta decay to the ground state

~20min is too long to tag in liquid Xenon

Solution: CrystaLiZe, an LZ-upgrade idea

Freeze the liquid xenon into a ***CRYSTAL***

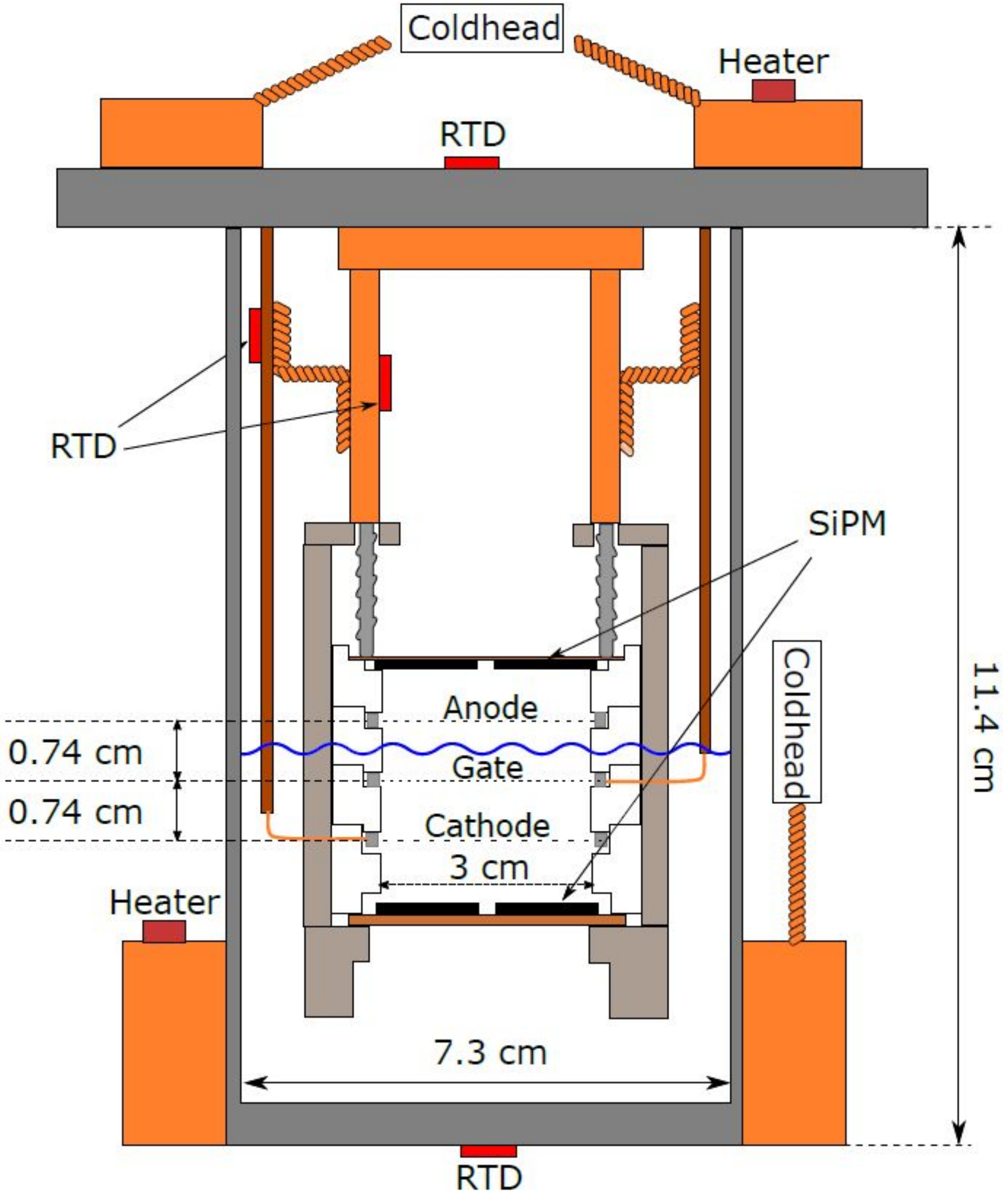
- Radon emanated from other materials now **excluded** from solid bulk
- Radon decay daughters stay at same (x,y,z) as parent -> tagging/veto



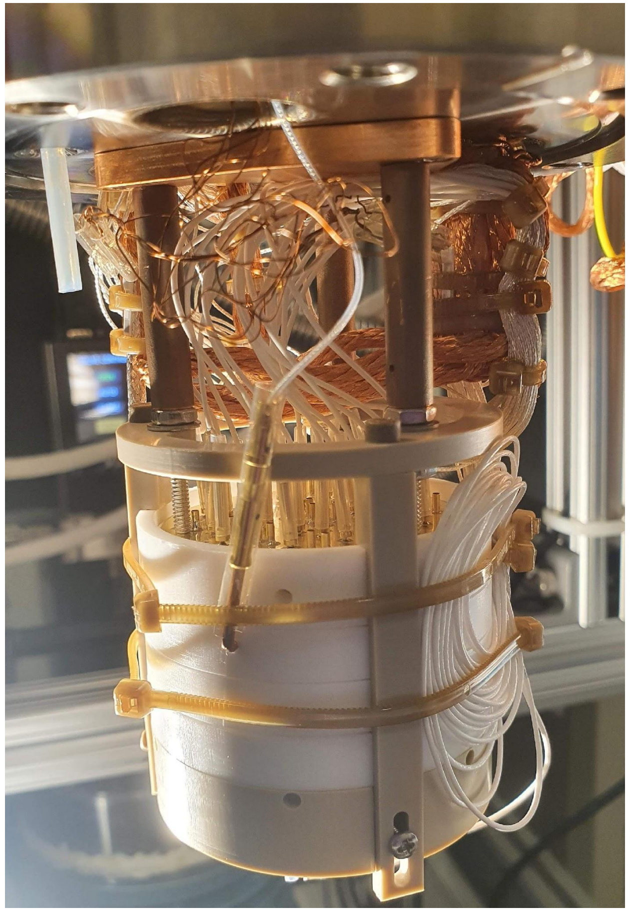
TEST BED DESIGN

- Two phase Xe mini-TPC at LBL
  - Liquid/vapor
  - Crystal/vapor
- Two separate coldheads for freezing process.
- ~20-25 g Xe when full
- Signal readout:
  32 SiPMs (16 top, 16 bottom; Hamamatsu S13371)
- ^{210}Po plated on a small stainless steel plate on the cathode

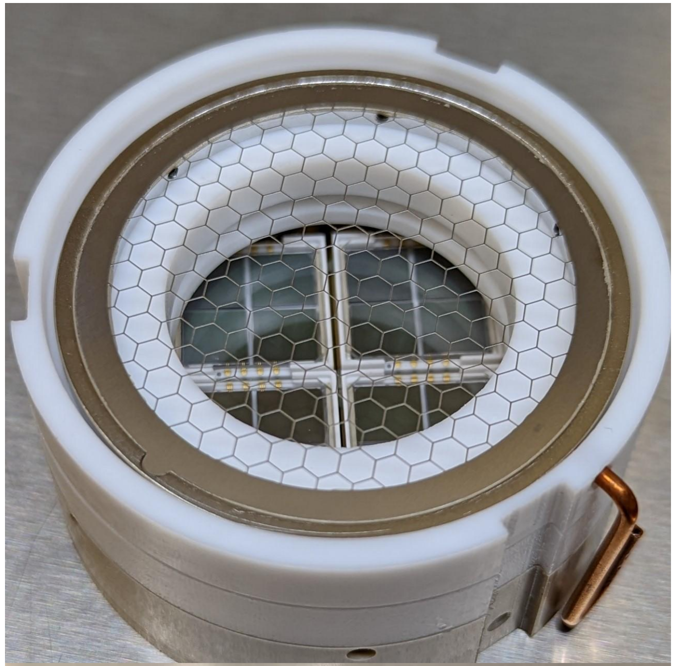
Note: The same TPC in Scott Haselschwardt's previous talk



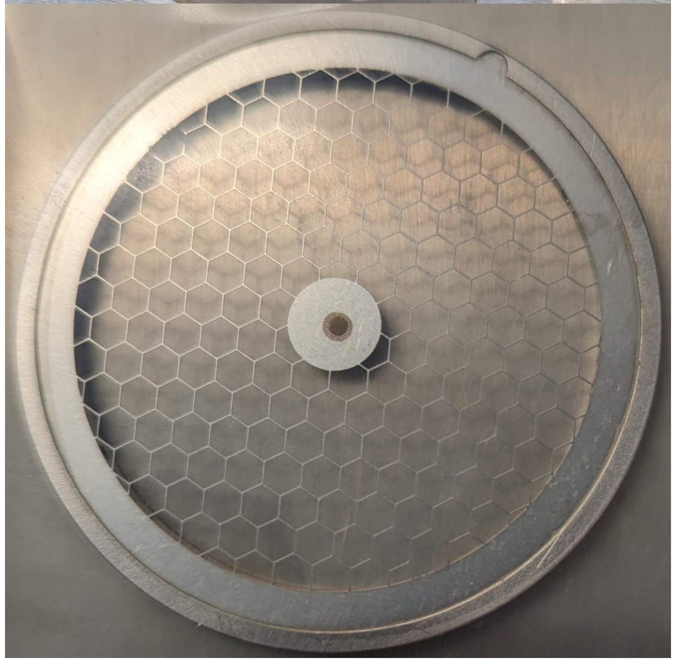
CRYSTALIZE TESTBED



TPC



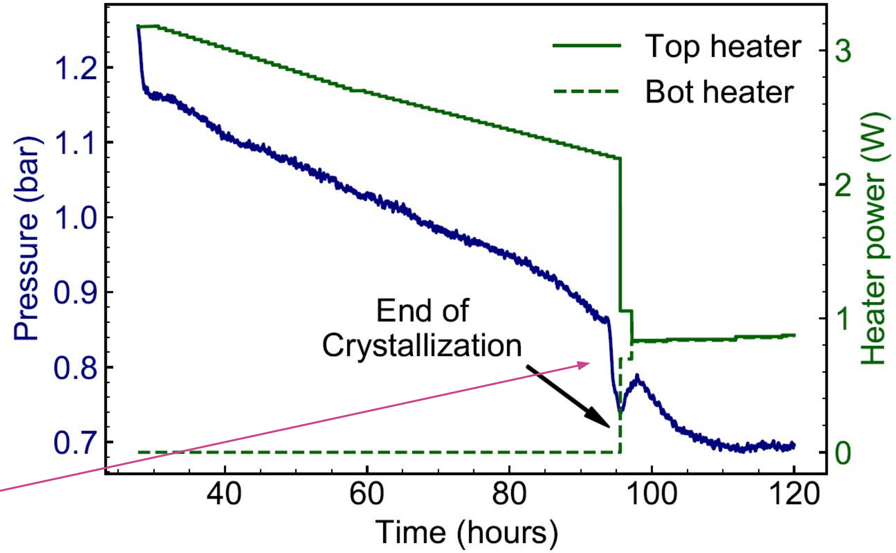
Gate grids and SiPMs



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

CRYSTALLIZATION

- Stable, repeatable crystallization procedure. Crystal grows from **bottom to top** (Bridgeman's technique)
- Realistic / scalable cryogenics for ton-scale experiment.
- Clear indications of freezing:
  - Vapor pressure below triple point
  - Drift time reduced (~1.6x)



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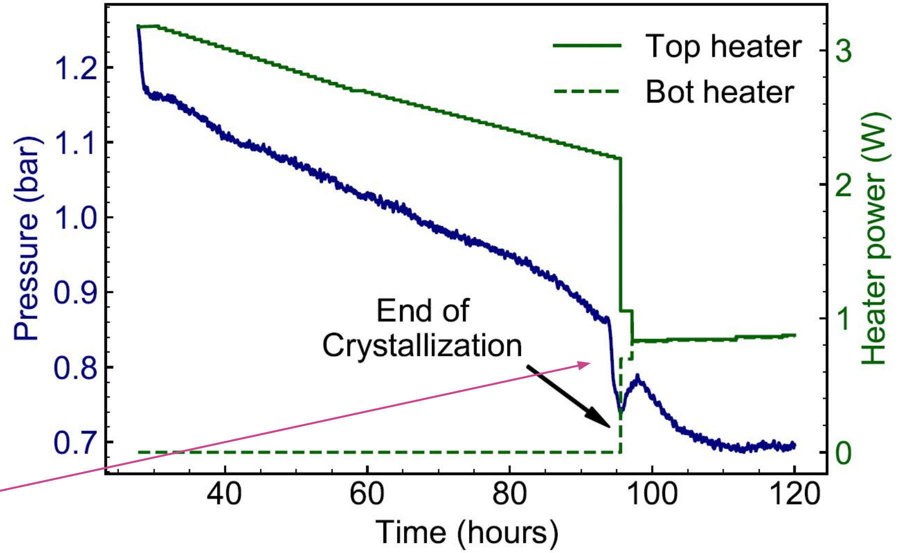

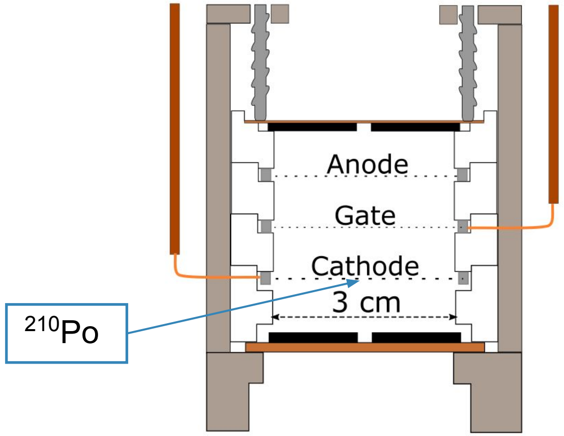

2022 *JINST* 17 P04014

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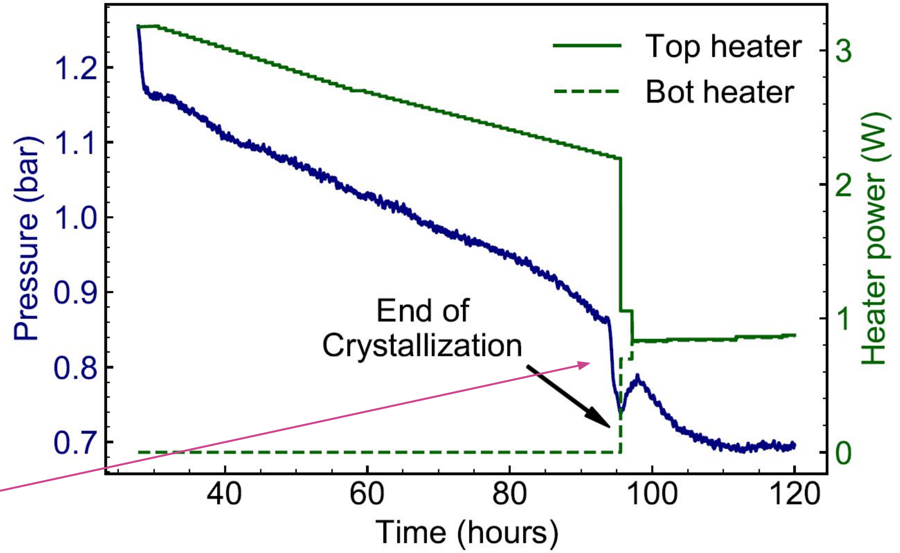

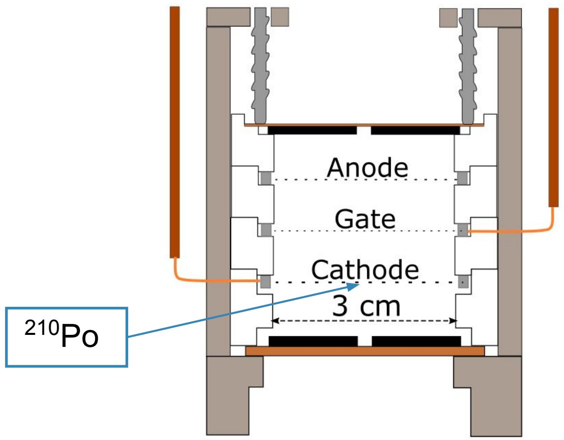

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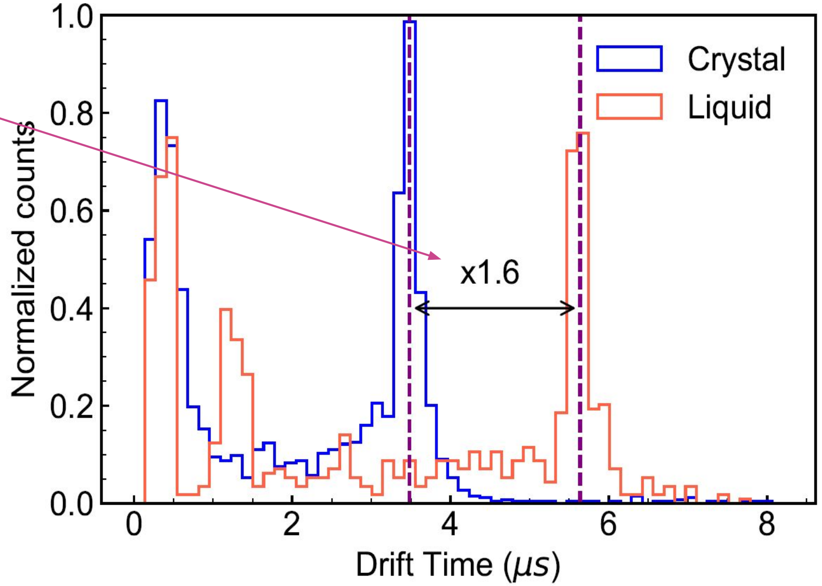
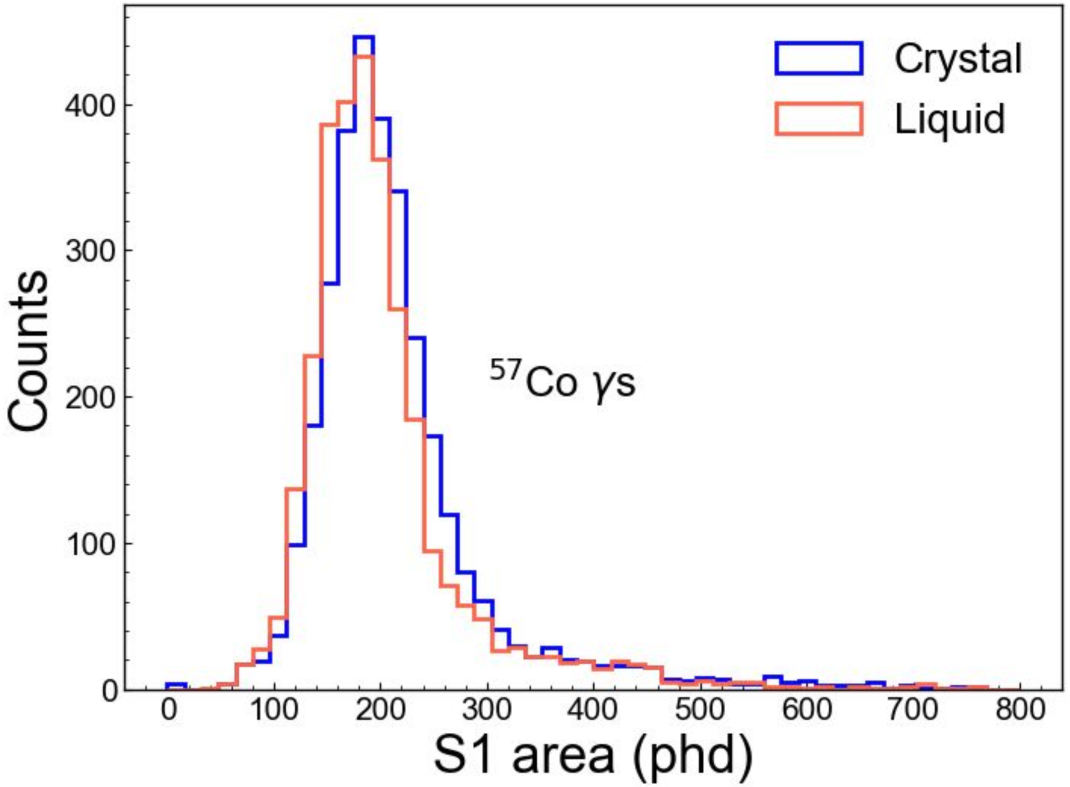
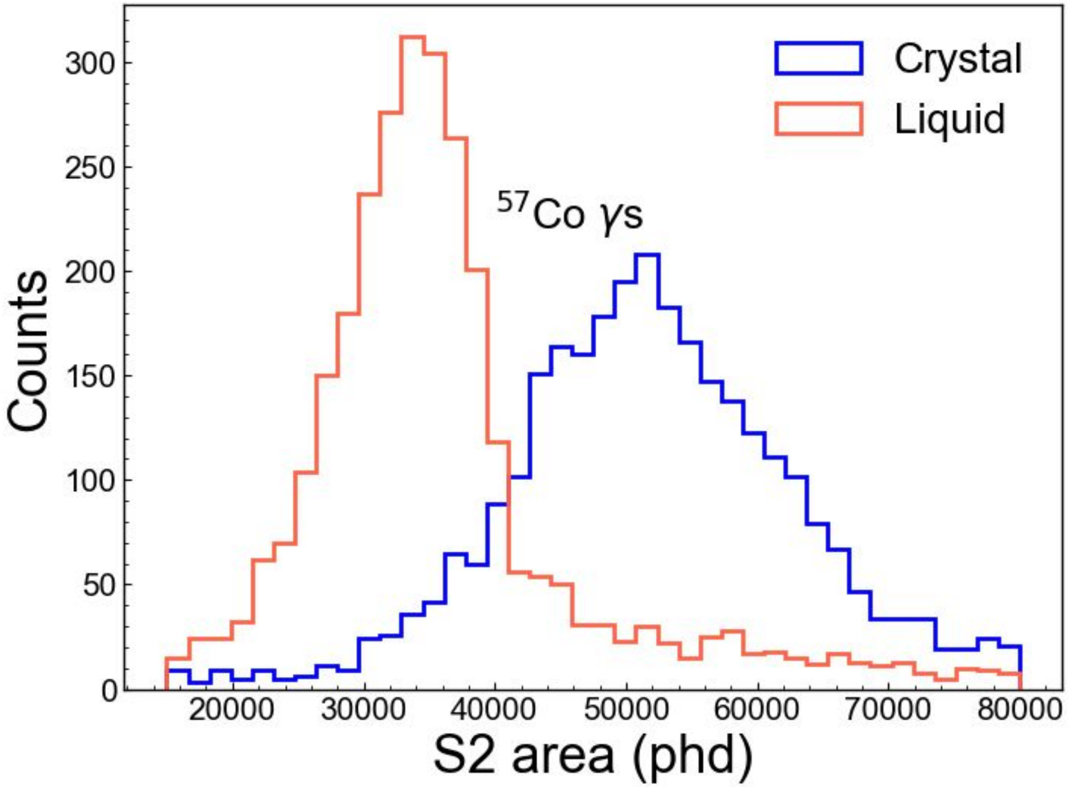


T = -117 C, p = 0.74 Bar
T = -111 C, p = 1.20 Bar

Note: triple point
T = -111.8 C,
p = 0.82 Bar

PERFORMANCE OF CRYSTAL/VAPOR TPC



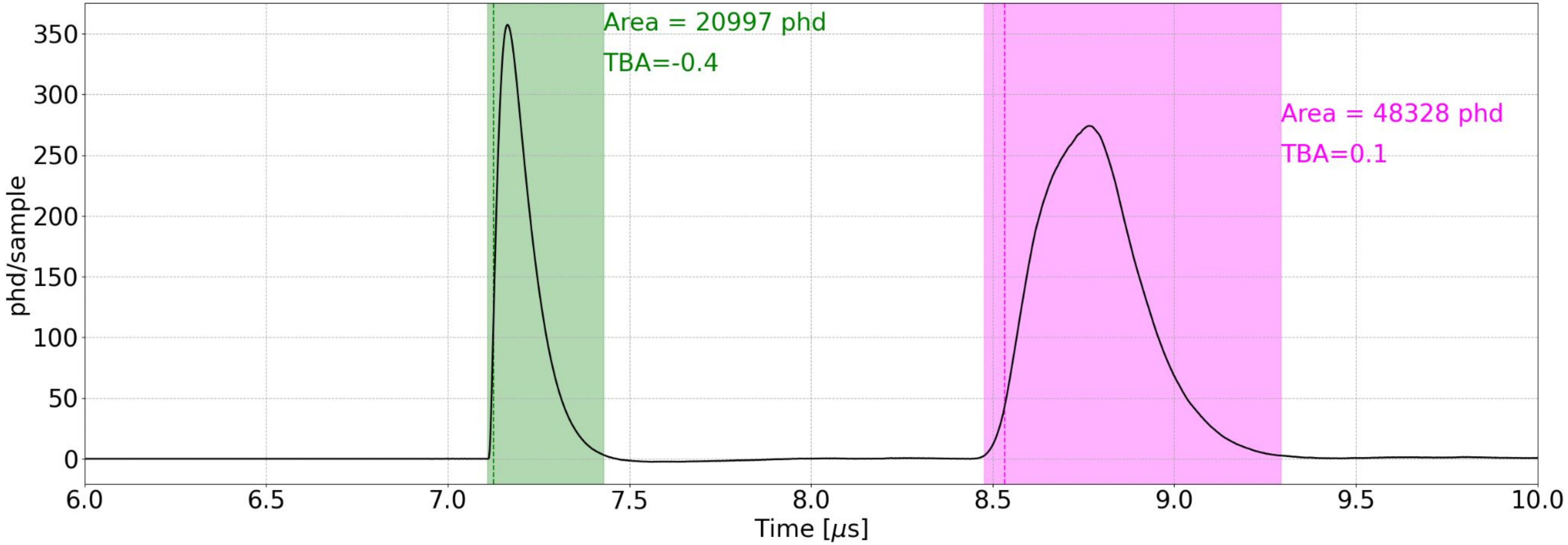


Note: the S2 size is much bigger in crystal, but it is likely affected by gas gap, field, we are still exploring, but at least it indicates the yield from crystal is reasonably good.

RADON EXCLUSION TEST

We used two flow radon source to test the exclusion power of crystal xenon:

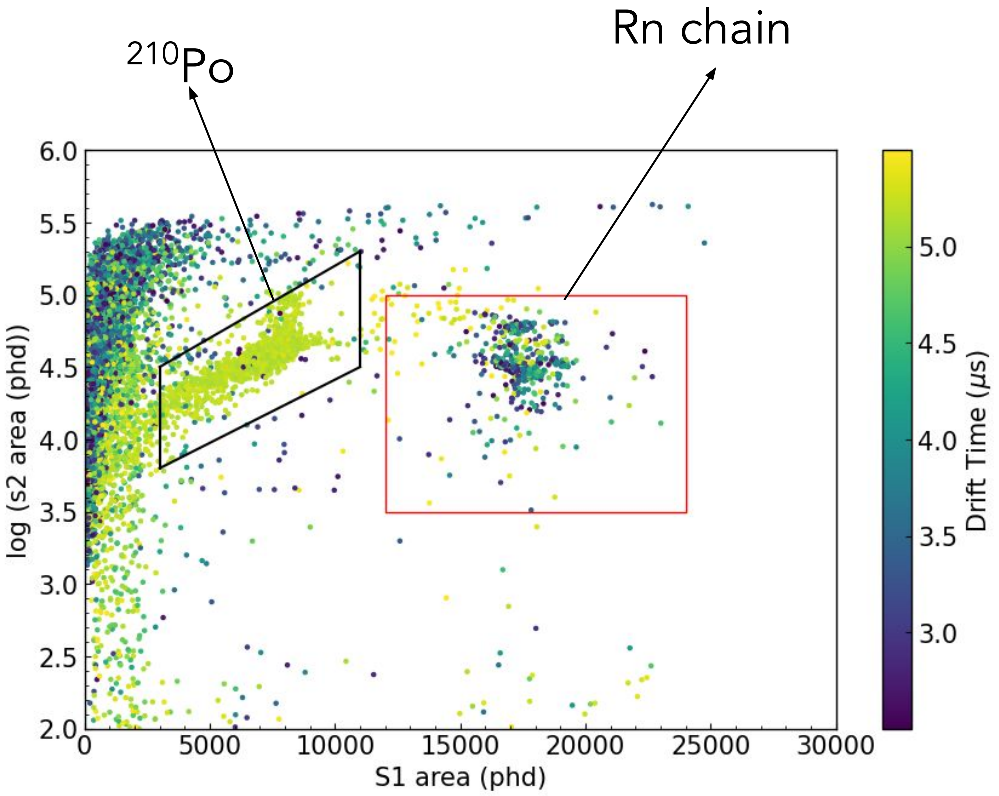
- ^{222}Rn source (low activity)
- ^{220}Rn source (high activity)



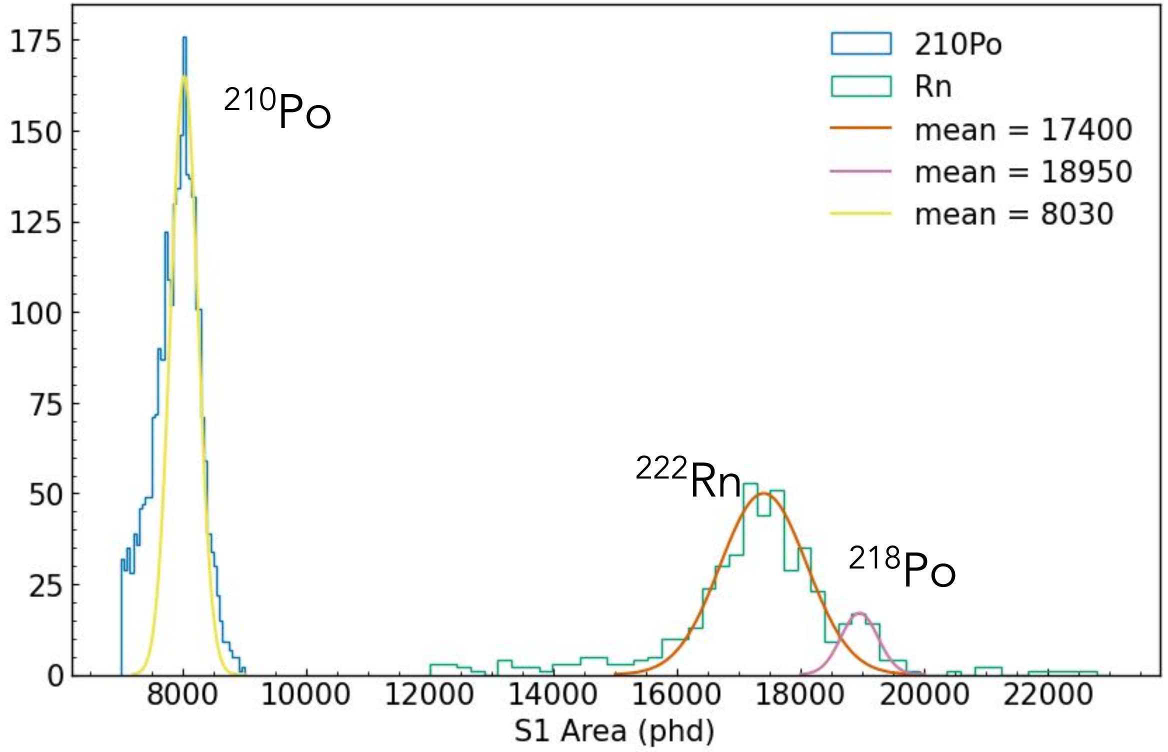
One alpha event from Rn chain.

We can tag these events easily, since both their S1 and S2 are huge.

^{222}Rn EVENTS IN LIQUID XENON

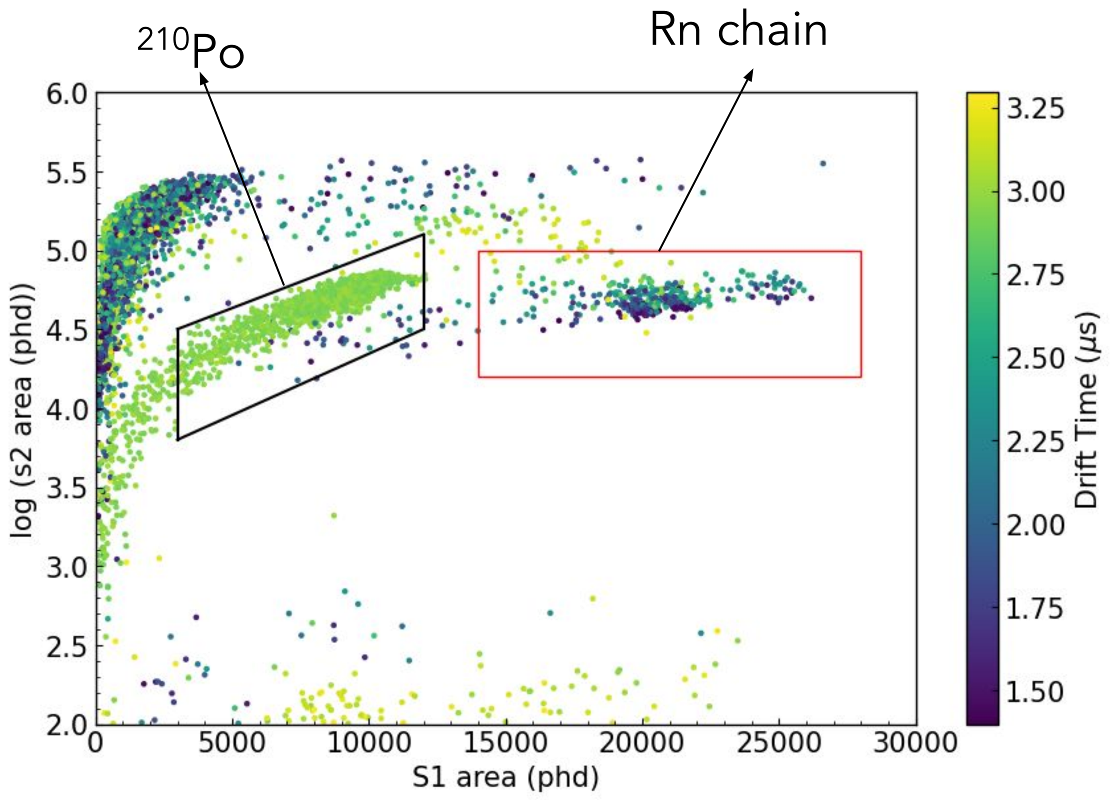


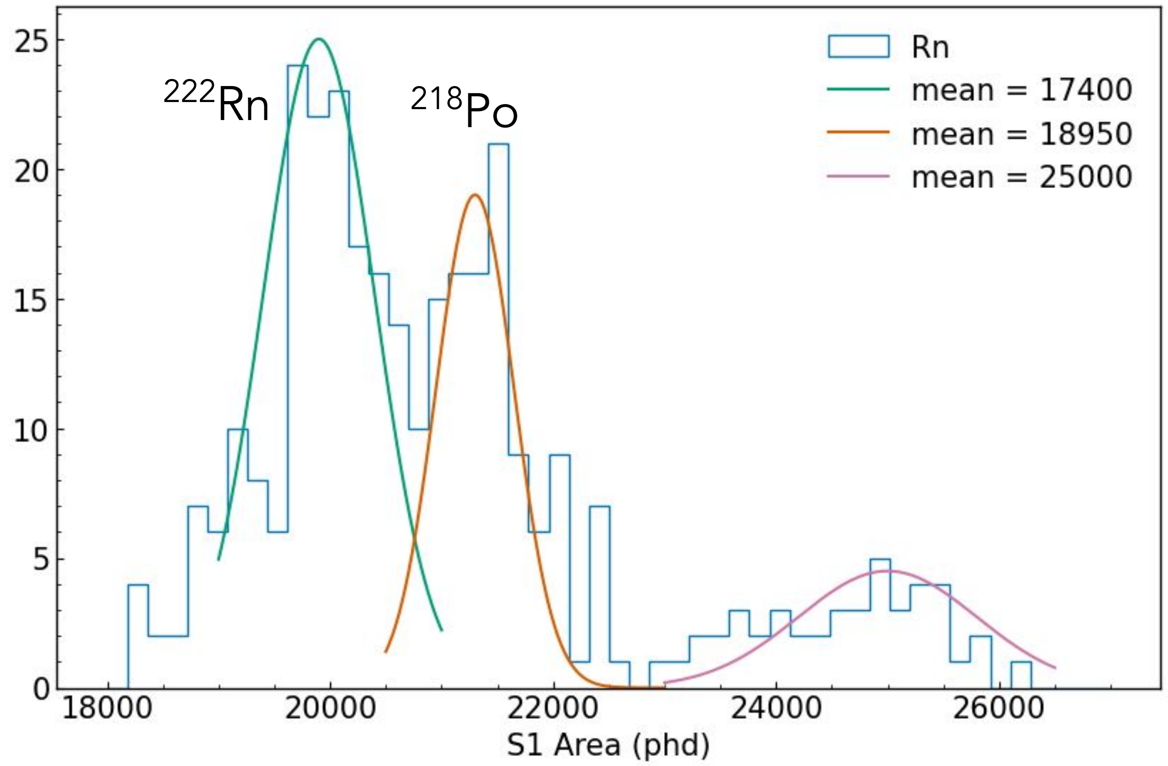
Here is how we select Rn events.
Note: these are events within a small fiducial volume of several grams of xenon.



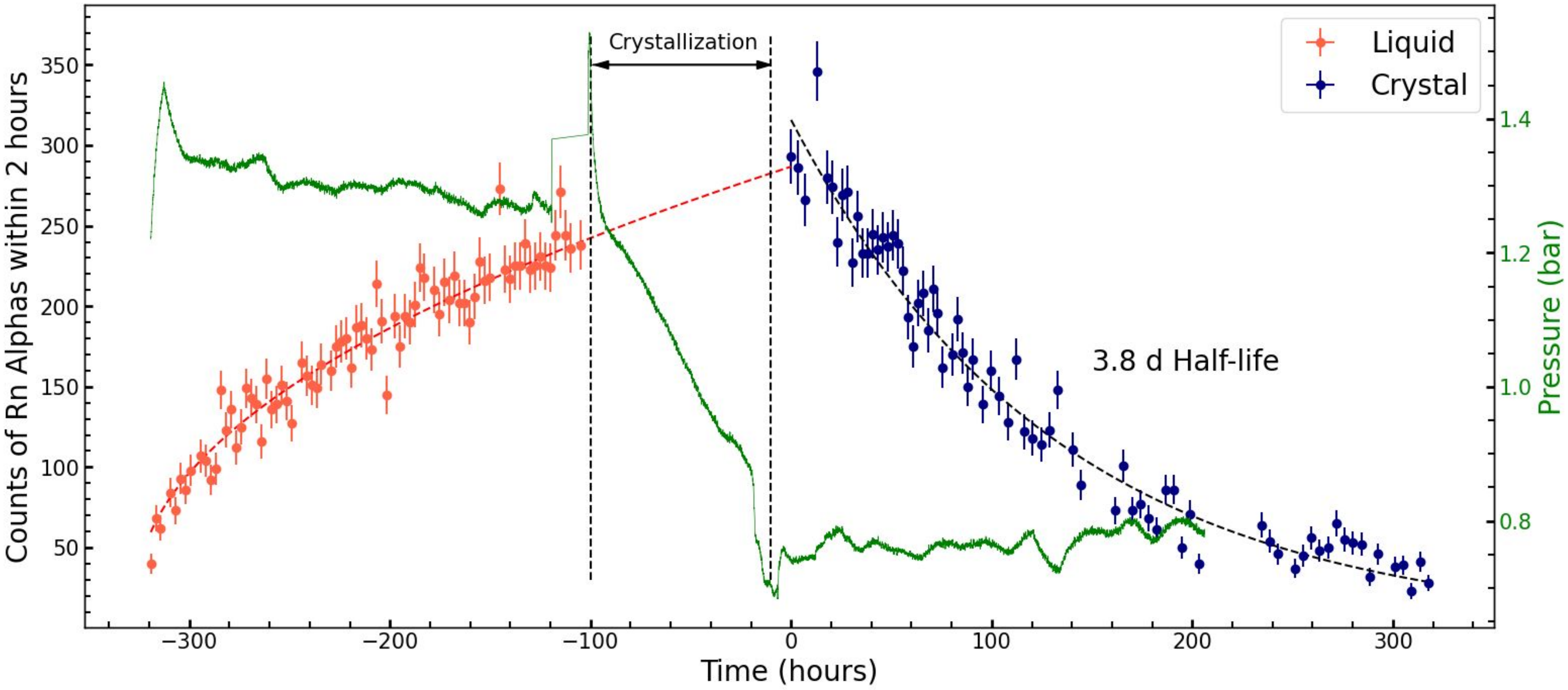
The S1 from ^{210}Po is much smaller than those from Rn chain, even their energy is similar. That is because of the light collection suppression from the center plate holding the ^{210}Po source

^{222}Rn EVENTS IN CRYSTAL XENON





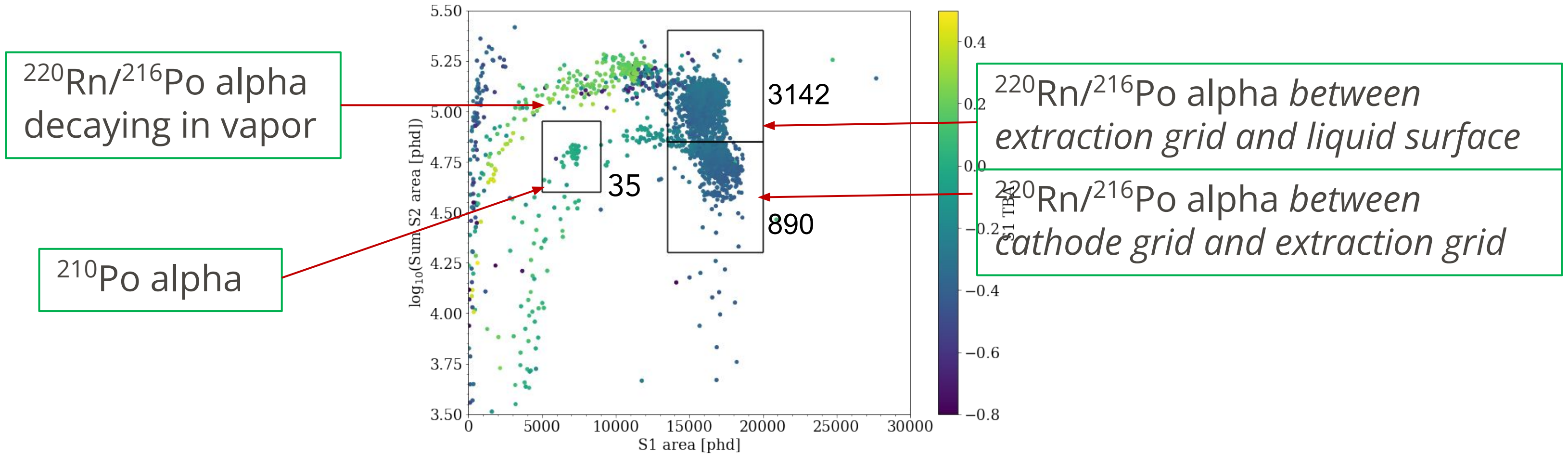
Alpha rate with continuous ^{222}Rn source flow



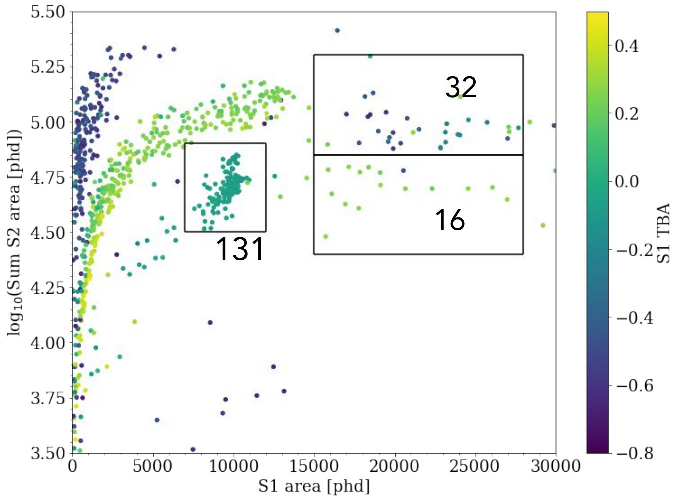
We **continuously** circulate gas xenon with a **steady flow rate** of 0.3 slpm.

- In liquid/vapor mode, the Rn rate increase 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.

^{220}Rn (higher activity) TEST to investigate radon suppression factor



Liquid



Crystal

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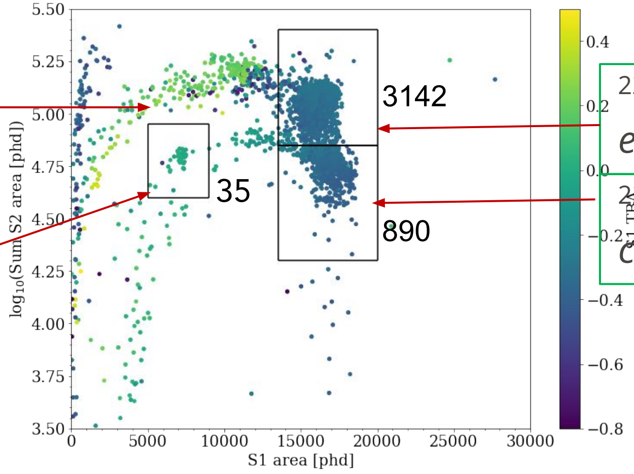

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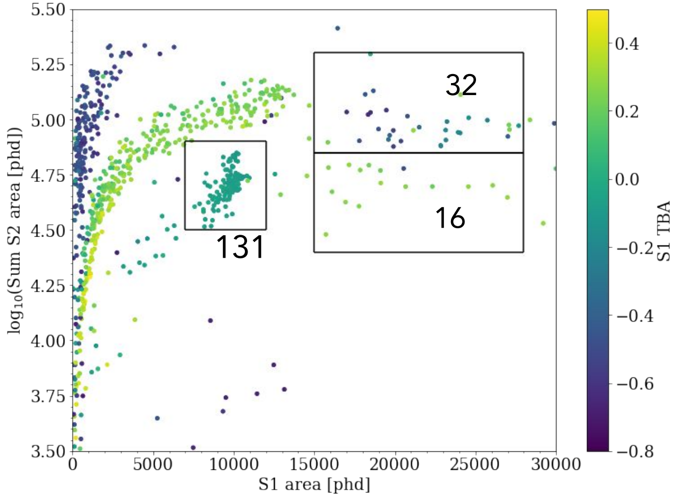


Crystal

Preliminary

Rn exclusion factor:	Crystalline Xe relative to liquid Xe
Conservative (Counts for S1 TBA < -0.25)	**x932**

SUMMARY

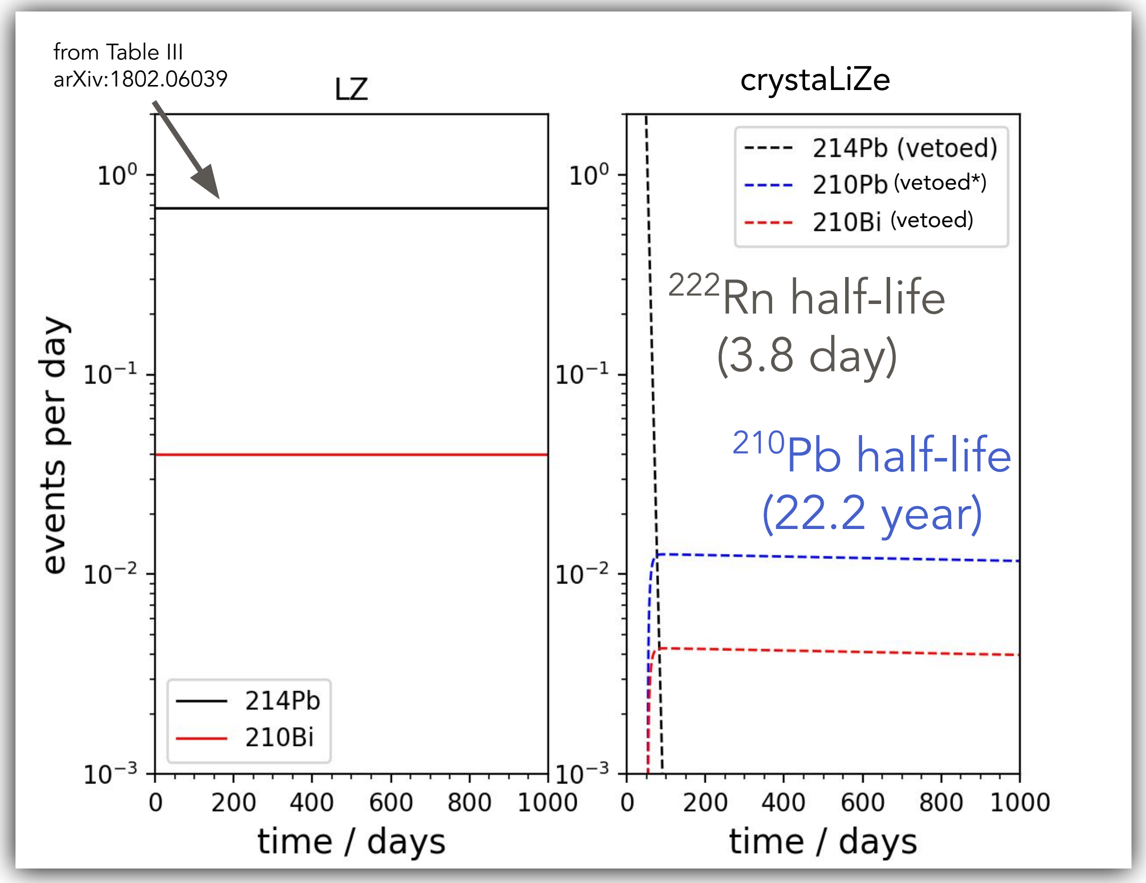
- Removing the radon background in xenon detector is necessary but challenging. We propose crystalline TPC as a LZ-upgrade idea.

  - R&D at LBNL has established that a crystal/vapor TPC has similar performance as a Liquid/vapor TPCs (possibly better!)
  - A crystal/vapor TPC can remove the primary DM background, leading to neutrinos as the primary limiting background

Future:

- S1/S2 discrimination
- Scale up (Dr. Kravitz's group @UT Austin)

BACKUP SLIDES



same LZ emanation and dust assumptions

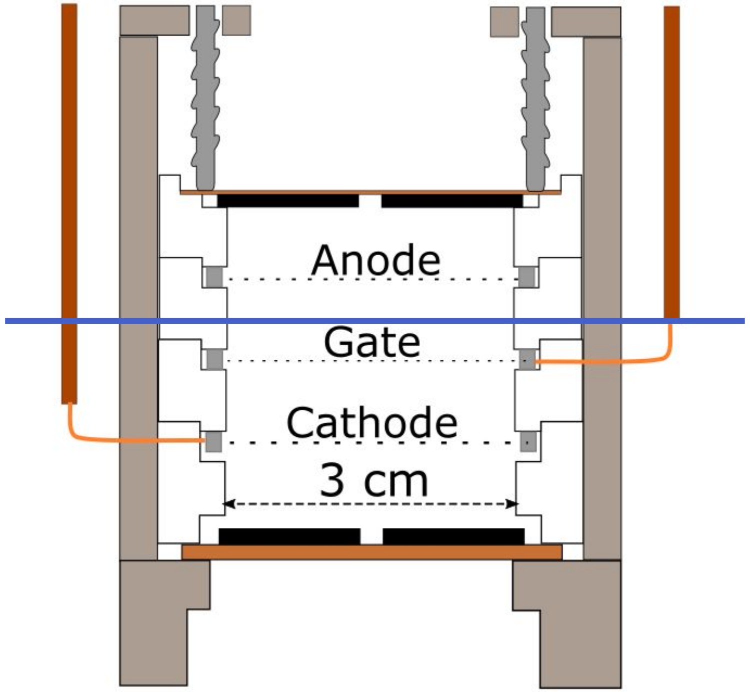
XENON LEVEL

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

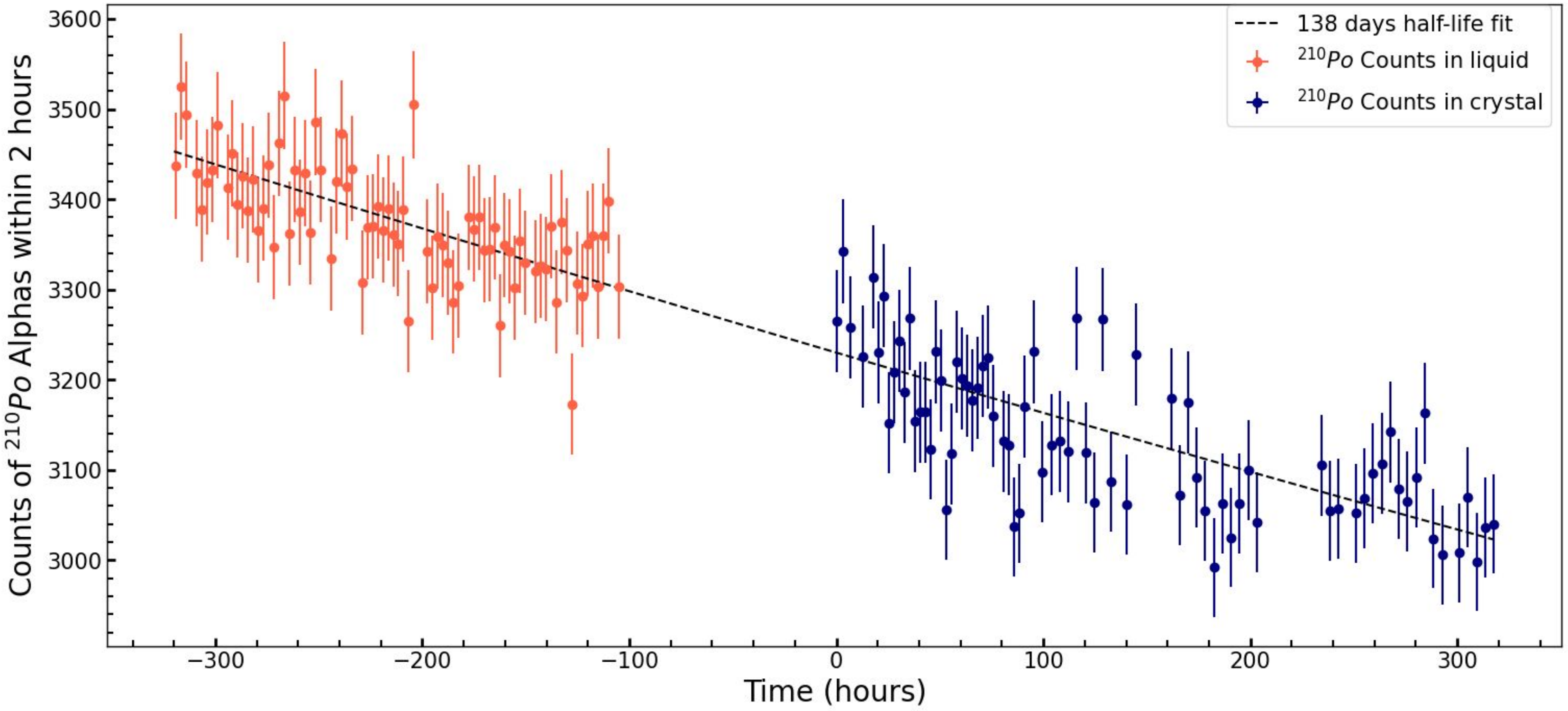
liquid/gas mode:
the level is set by observing detector response. Set the cathode/gate voltage to 2.6/2.4 kV, when the level is between the gate and anode, we see events with S1/S2 pairs.

Crystal/gas mode:

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



HEARBEAT (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.

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:

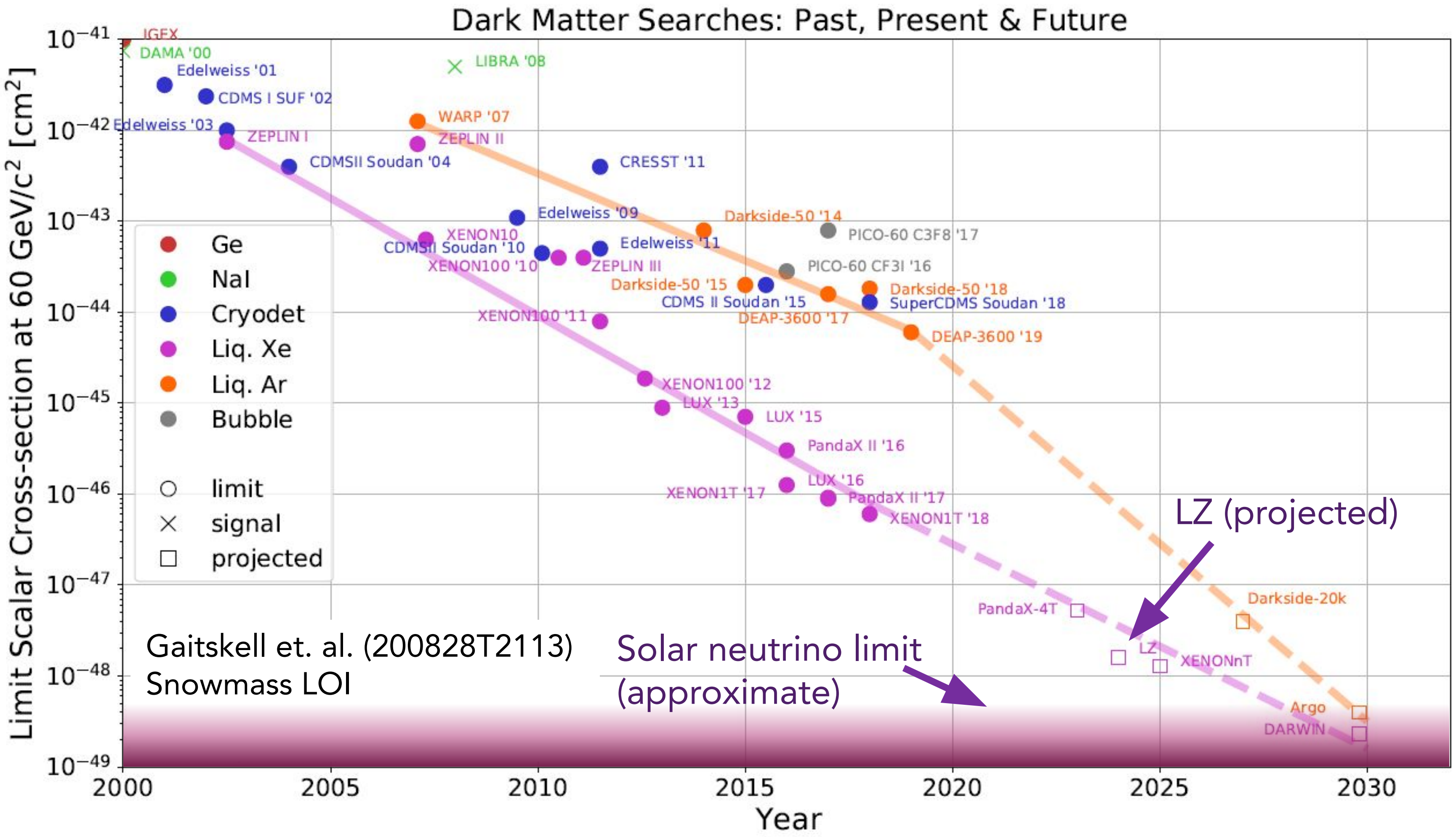
"…The 222Rn concentration was reduced by ~20% relative to the equilibrium value using the krypton distillation column in inverse mode…

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

Let's kill the source

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

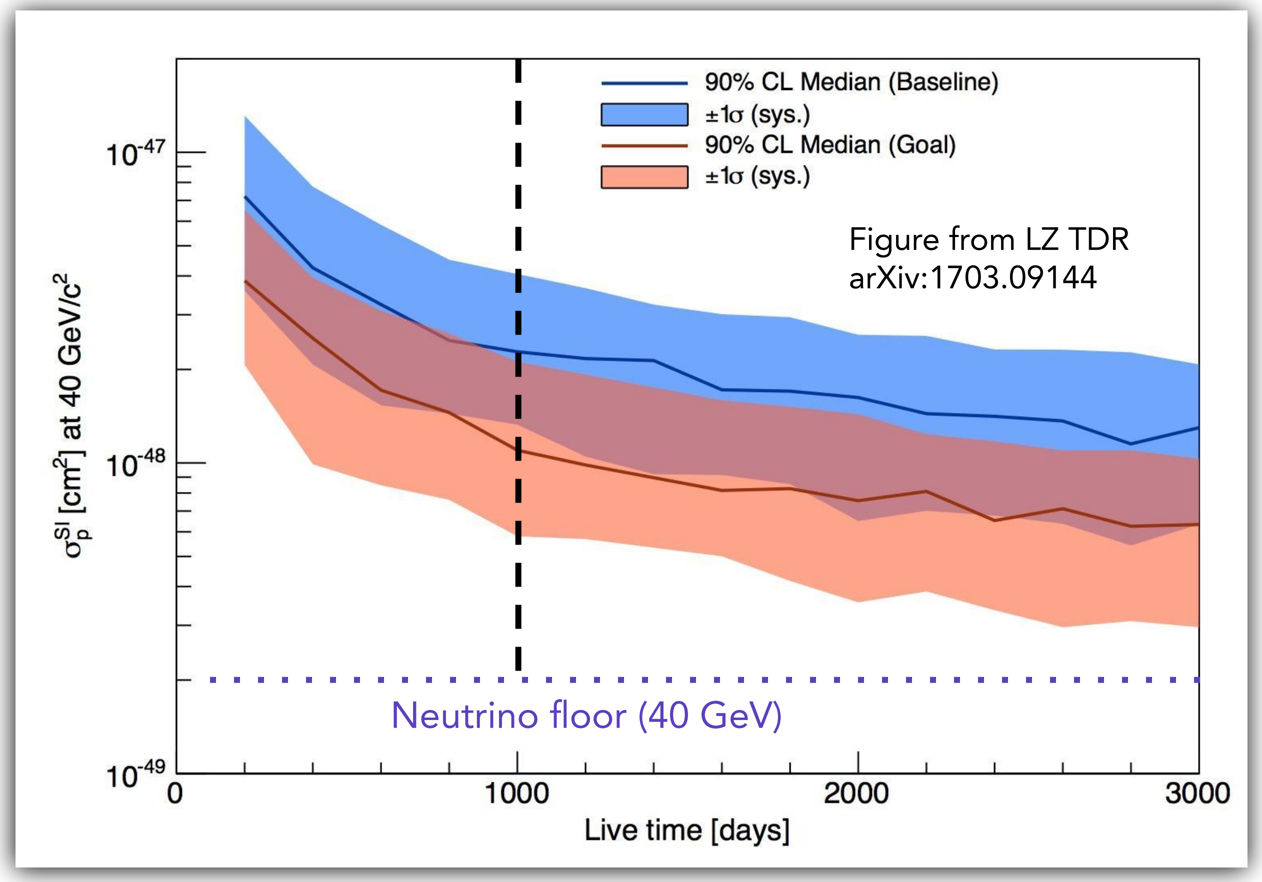


RUN LZ FOR LONGER?

Doesn't work.
Backgrounds win,
mostly radon

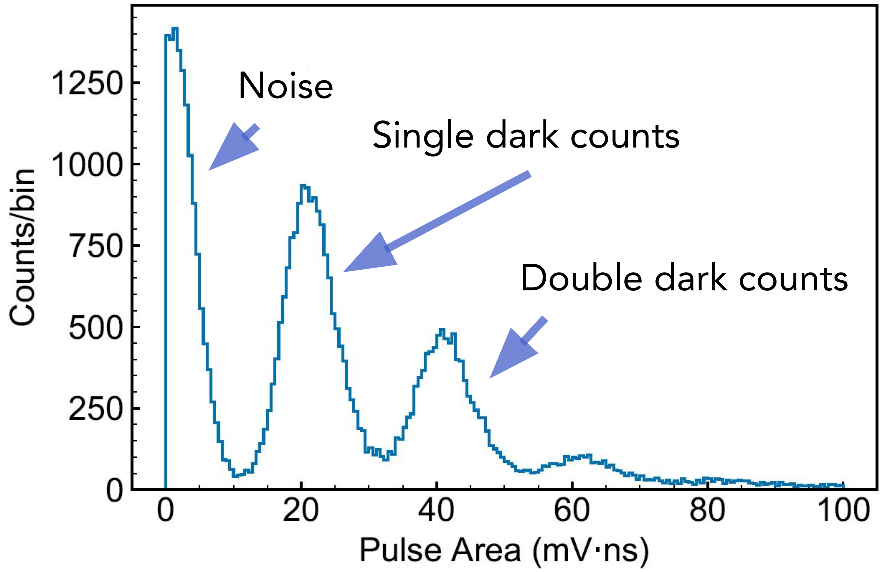
Sensitivity scales poorly
with exposure
when bkg limited

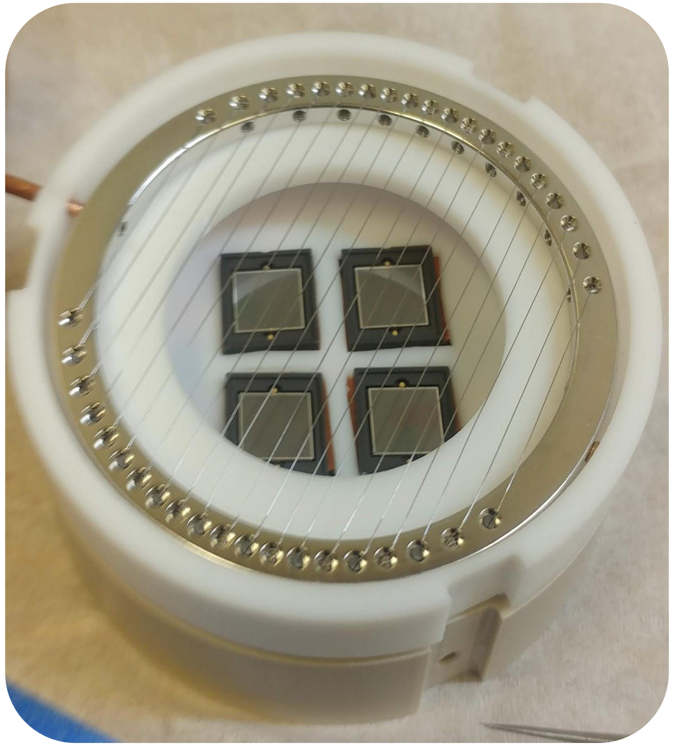
Discovery potential depends even more strongly on background level than sensitivity



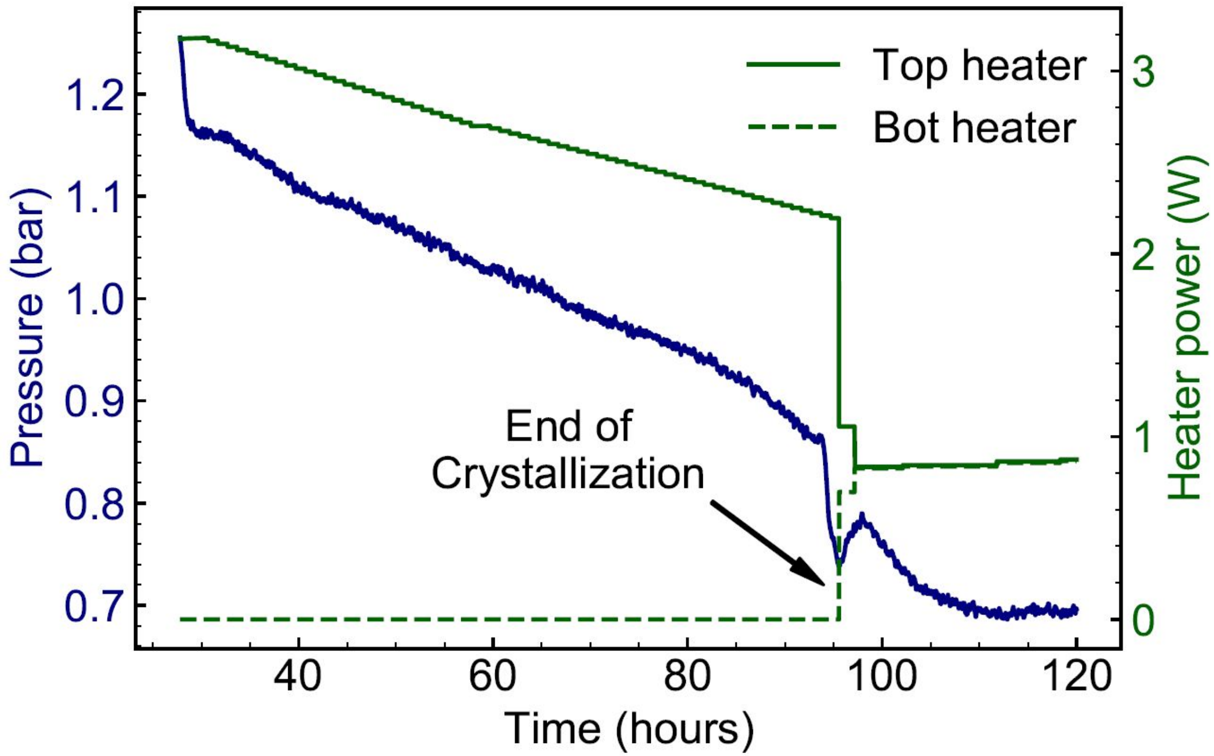
WHY SIPMS?

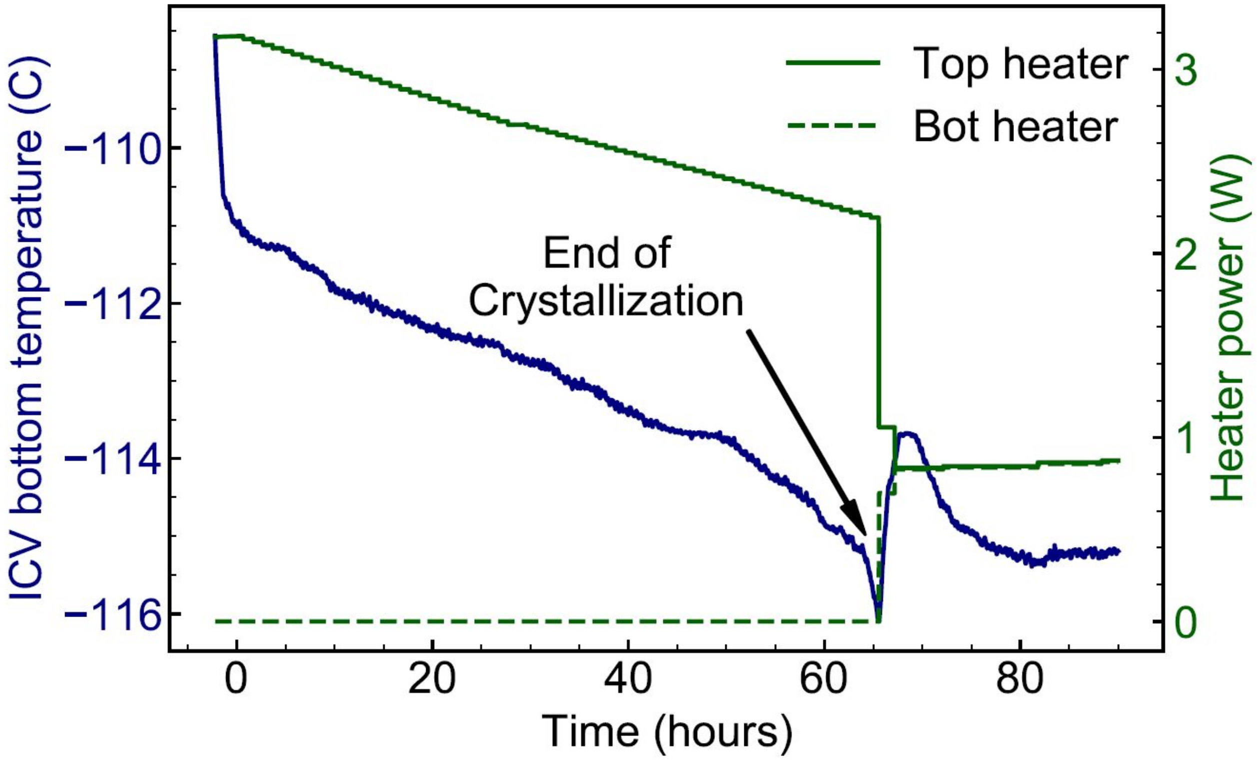
- Compact – less Xe needed
- No vacuum space – no structural concerns, esp. during freezing
- QE extends to deeper-UV (may be present in ice) and IR (possibly observed in EXO-200 APDs, arXiv 1908.04128)





FREEZING PROCEDURE





SOLID XENON TEST BED PHOTOS