# A CRYSTALLINE XENON TPC TO REACH THE NEUTRINO DETECTION LIMIT

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On behalf of

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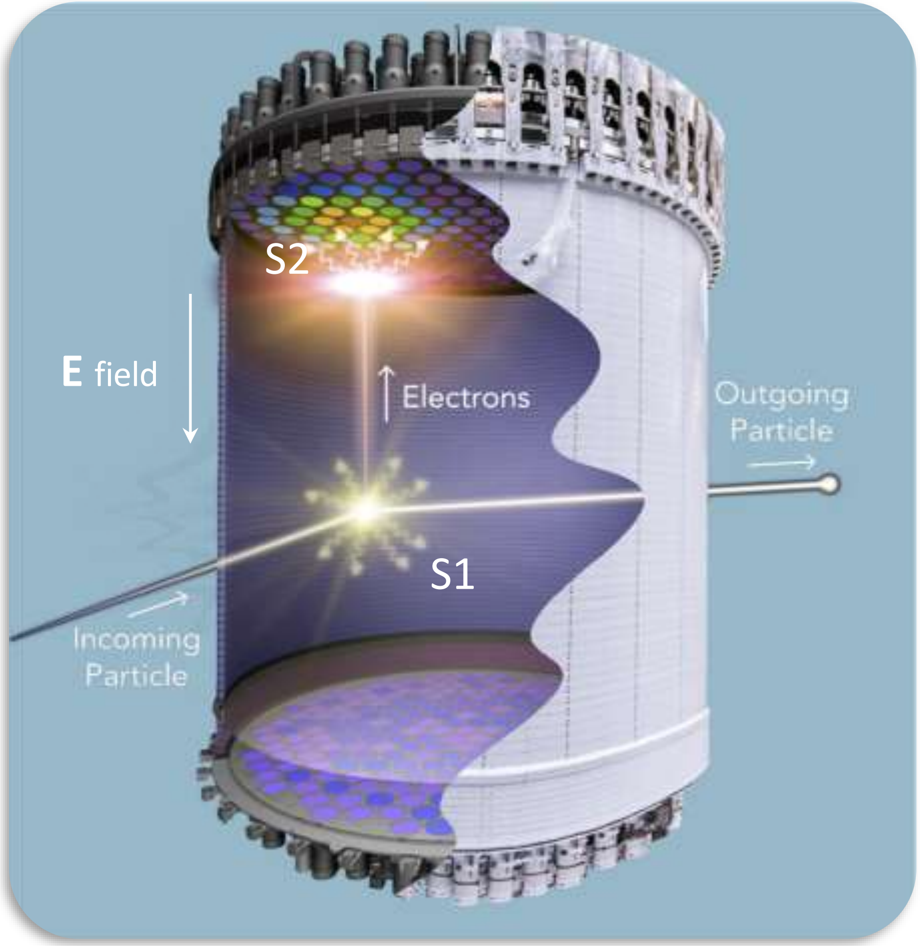
**@XeSAT 2024**

# DIRECT DARK MATTER SEARCH WITH LIQUID XENON TPC




Lux-zeplin experiment. Picture credit to: Matt Kapust and SLAC LZ GROUP.

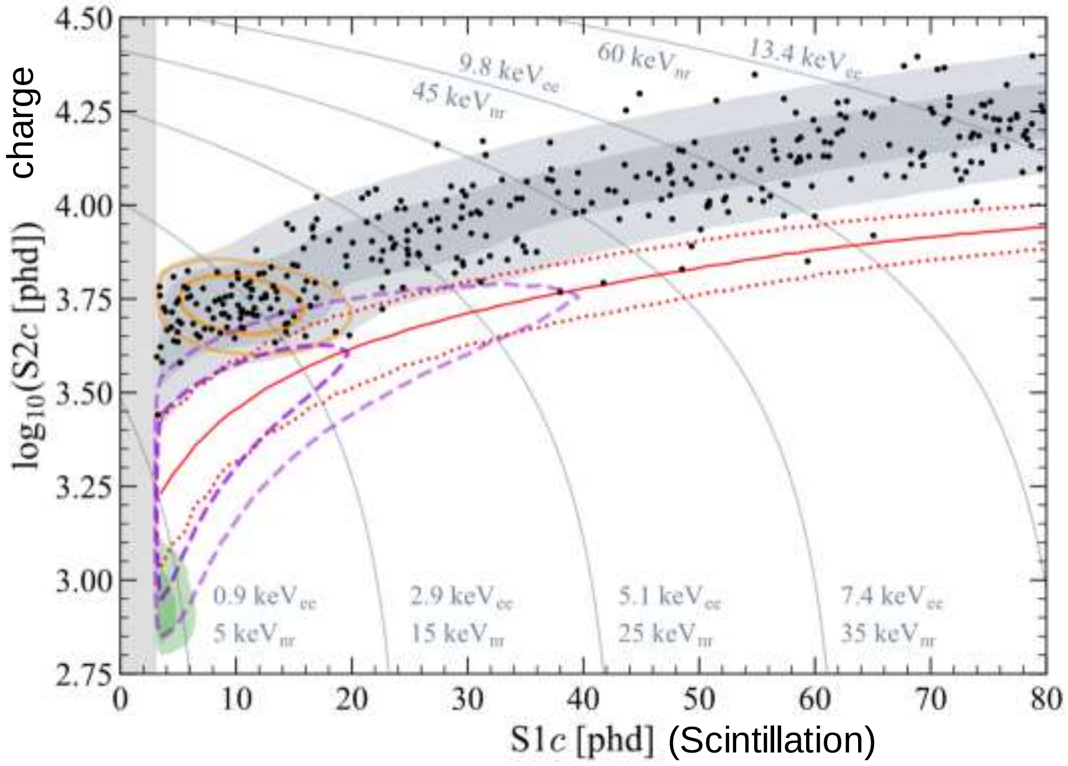
Liquid/vapor dual phase xenon time projection chamber (LZ, PandaX, XenonNt) plays a significant role in dark matter search, especially in WIMP search.

Advantages of xenon TPC

- Xenon is a good target: pure, low radioactivity, high atomic mass number, etc.)
- Event location reconstruction
- Signal(nuclear recoil)/background(electron recoil) discrimination

# BACKGROND IN LZ

LZ SR1




Aalbers, et al. Phys. Rev. Lett. 131, 041002

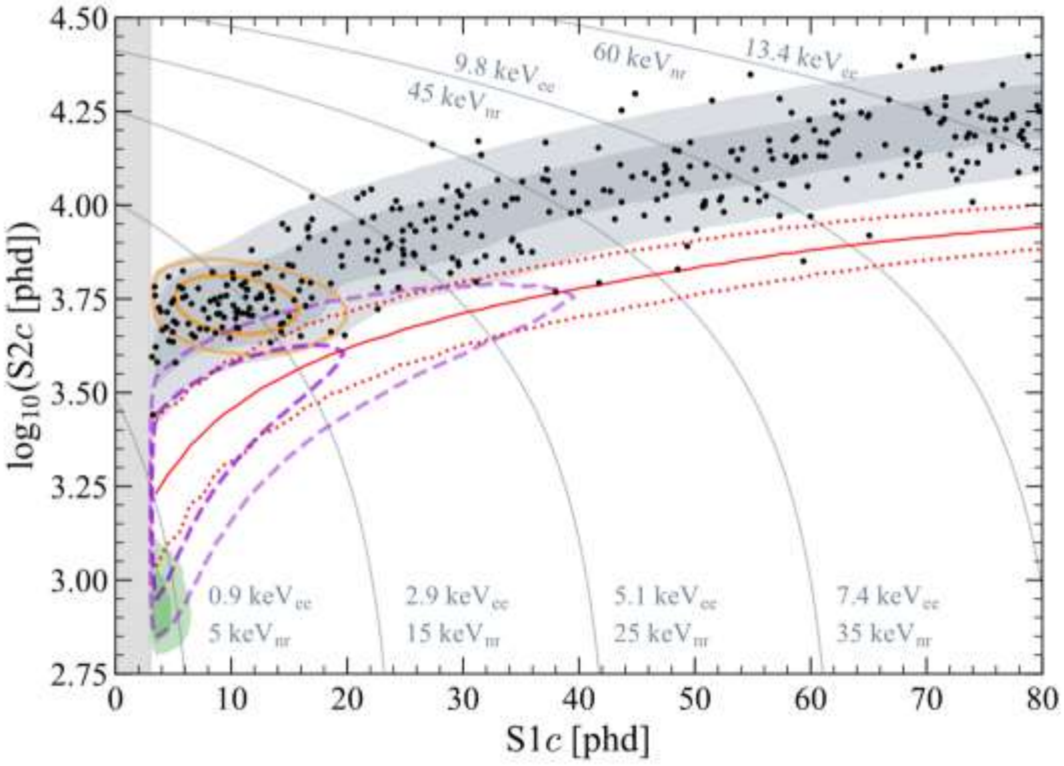
| Source | Expected Events | Fit Result |
|---|---|---|
| $^{214}$Pb | 164 ± 35 | - |
| $^{212}$Pb | 18 ± 5 | - |
| $^{85}$Kr | 32 ± 5 | - |
| Det. ER | 1.4 ± 0.4 | - |
| $\beta$ decays + Det. ER | 215 ± 36 | 222 ± 16 |
| $\nu$ ER | 27.1 ± 1.6 | 27.2 ± 1.6 |
| $^{127}$Xe | 9.2 ± 0.8 | 9.3 ± 0.8 |
| $^{124}$Xe | 5.0 ± 1.4 | 5.2 ± 1.4 |
| $^{136}$Xe | 15.1 ± 2.4 | 15.2 ± 2.4 |
| $^{8}$B CE$\nu$NS | 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 progeny atoms

Aalbers, et al. Phys. Rev. D 108, 012010

# BACKGROUND FROM RADON PROGENY LIMITS DETECTION SENSITIVITY

LZ SR1




**For WIMP:**

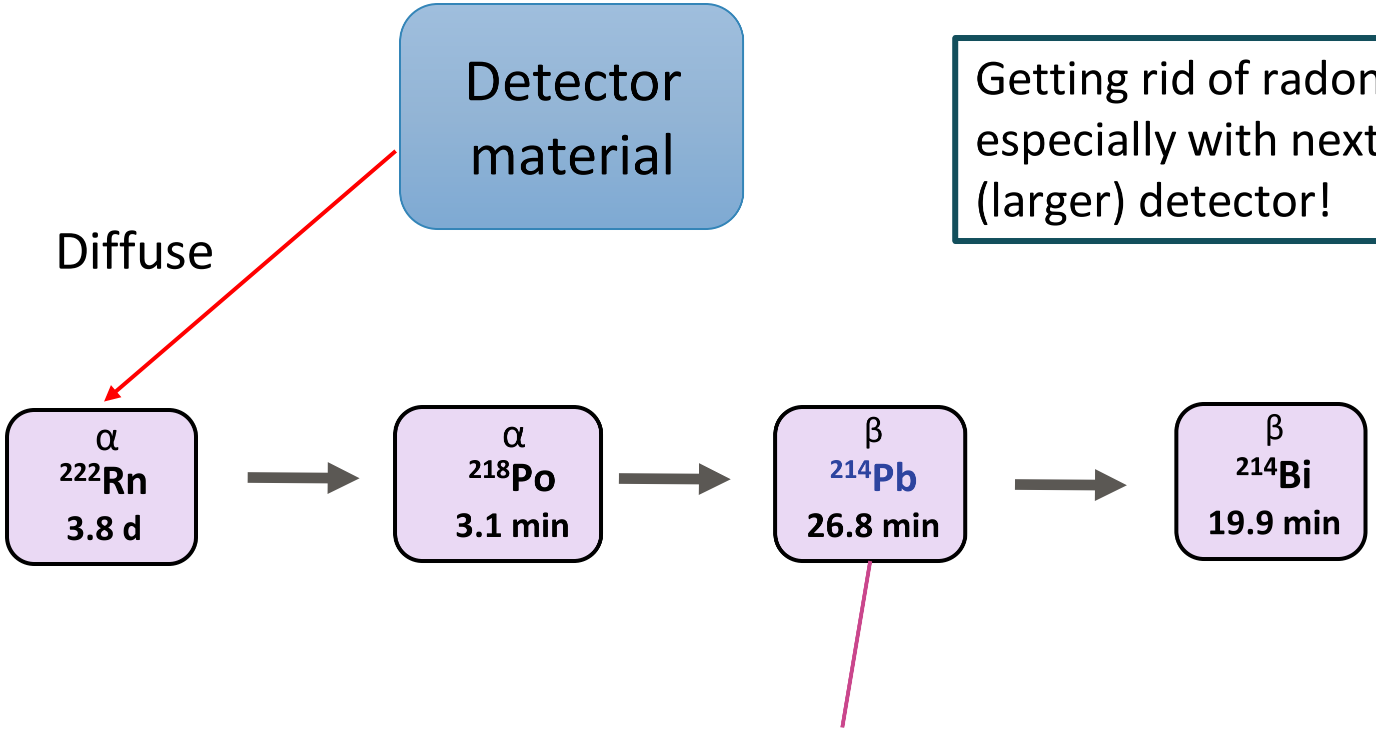
0.5% of electron recoil background leaks into the signal region in spite of the discrimination.

**For other physics goals produce electron recoil:**

Electron recoil background is a much bigger problem.

# SOURCE OF RADON BACKGROUND

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




Primary culprit

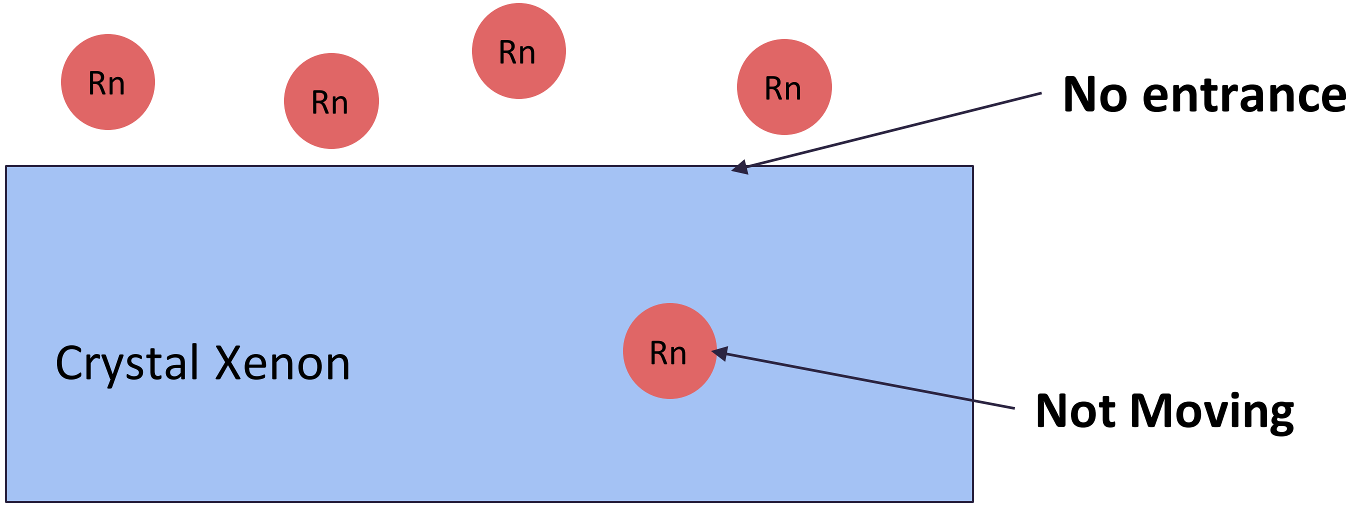
with~10% beta decay to the ground state

**~20min is too long to tag in liquid Xenon**

# Solution: crystalline xenon

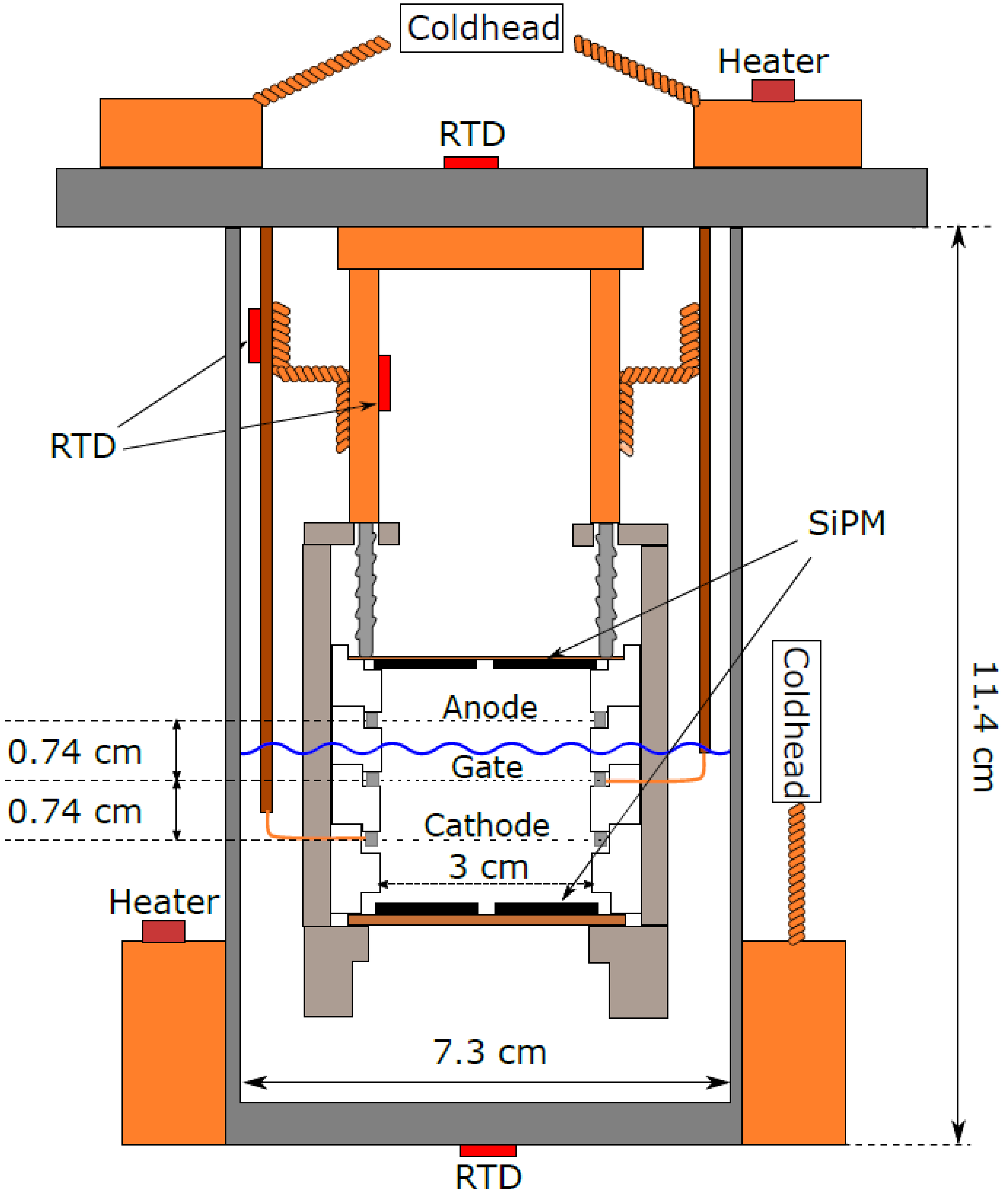
Freeze the liquid xenon into a ***CRYSTAL***

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



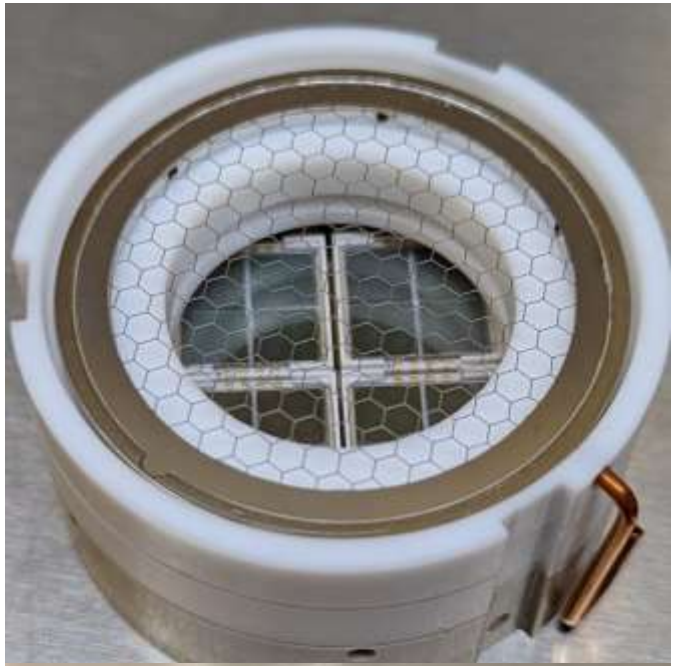
# TEST BED DESIGN

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

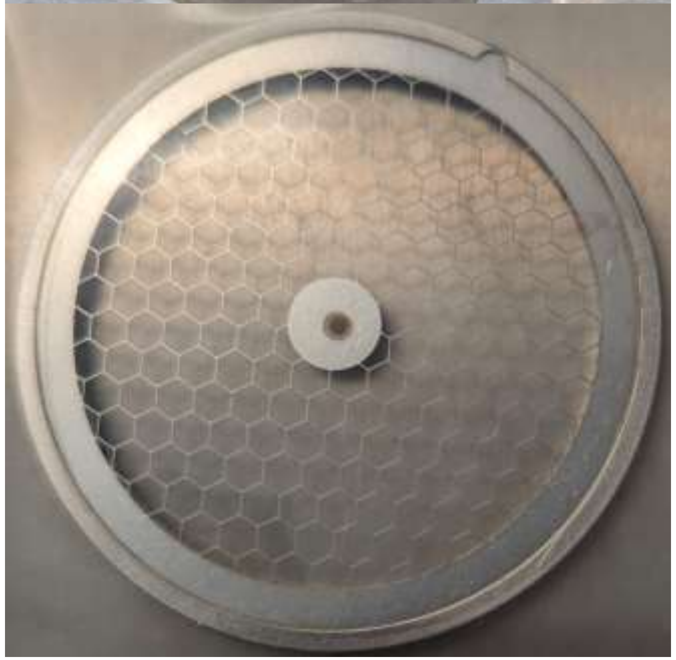


# CRYSTALIZE TESTBED

TPC



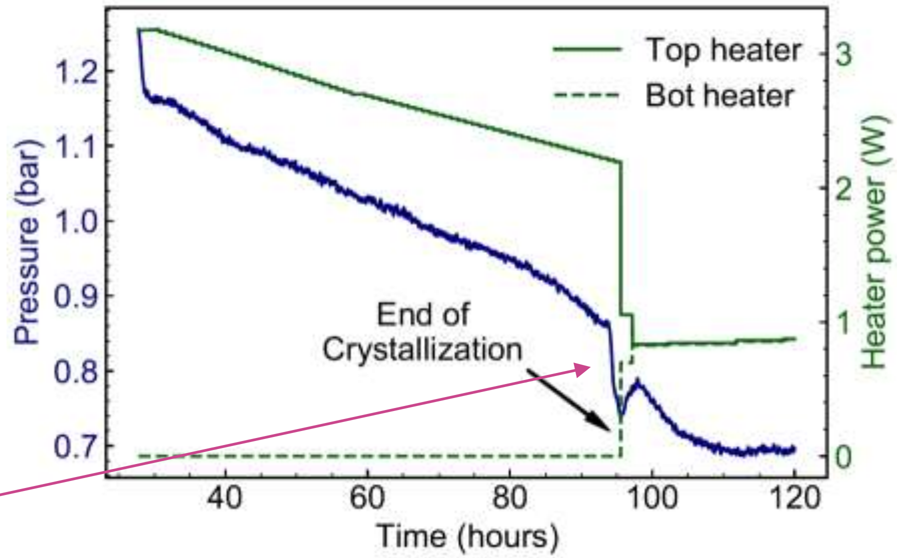
Gate grids
and SiPMs

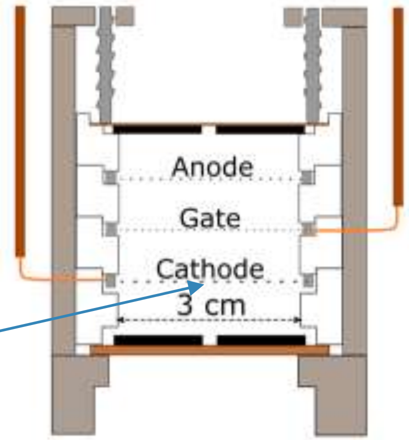


Cathode grids with center plate to hold $^{210}Po$ source, this structure suppress the S1 size of $^{210}Po$.

# 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)




$^{210}$Po

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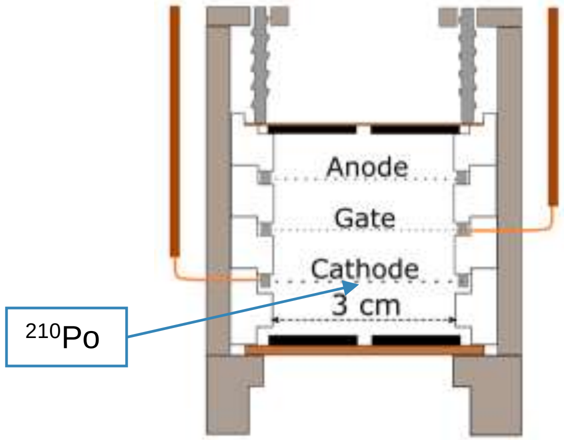
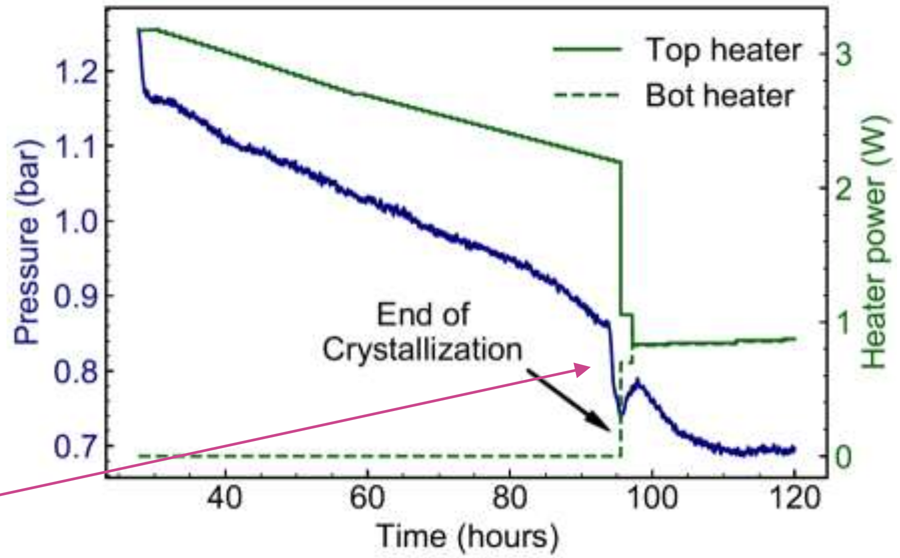
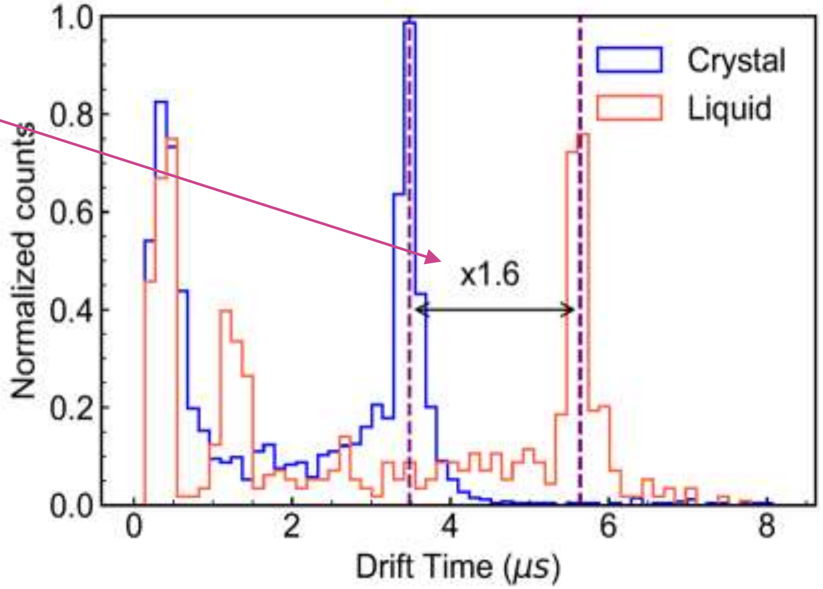



T = -117 C, p = 0.74 Bar

T = -111 C, p = 1.20 Bar

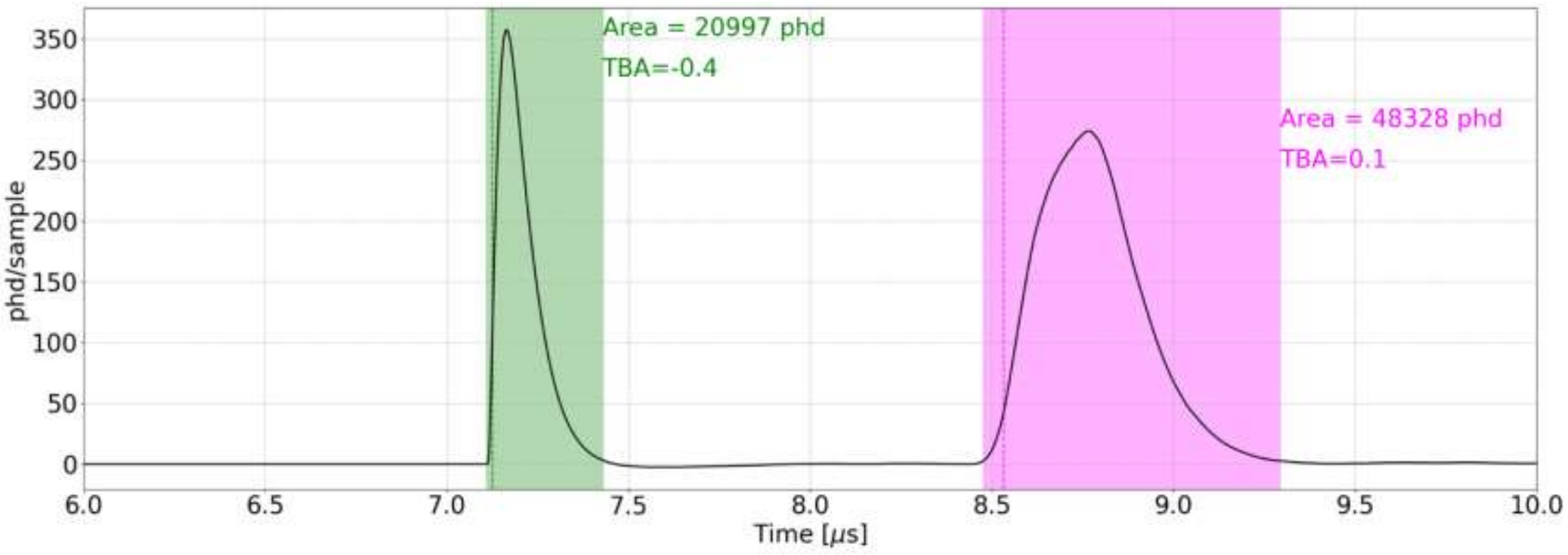
Note: triple point
T = -111.8 C,
p = 0.82 Bar

**S. Kravitz et al 2022 JINST 17 P04014**

# RADON EXCLUSION TEST

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

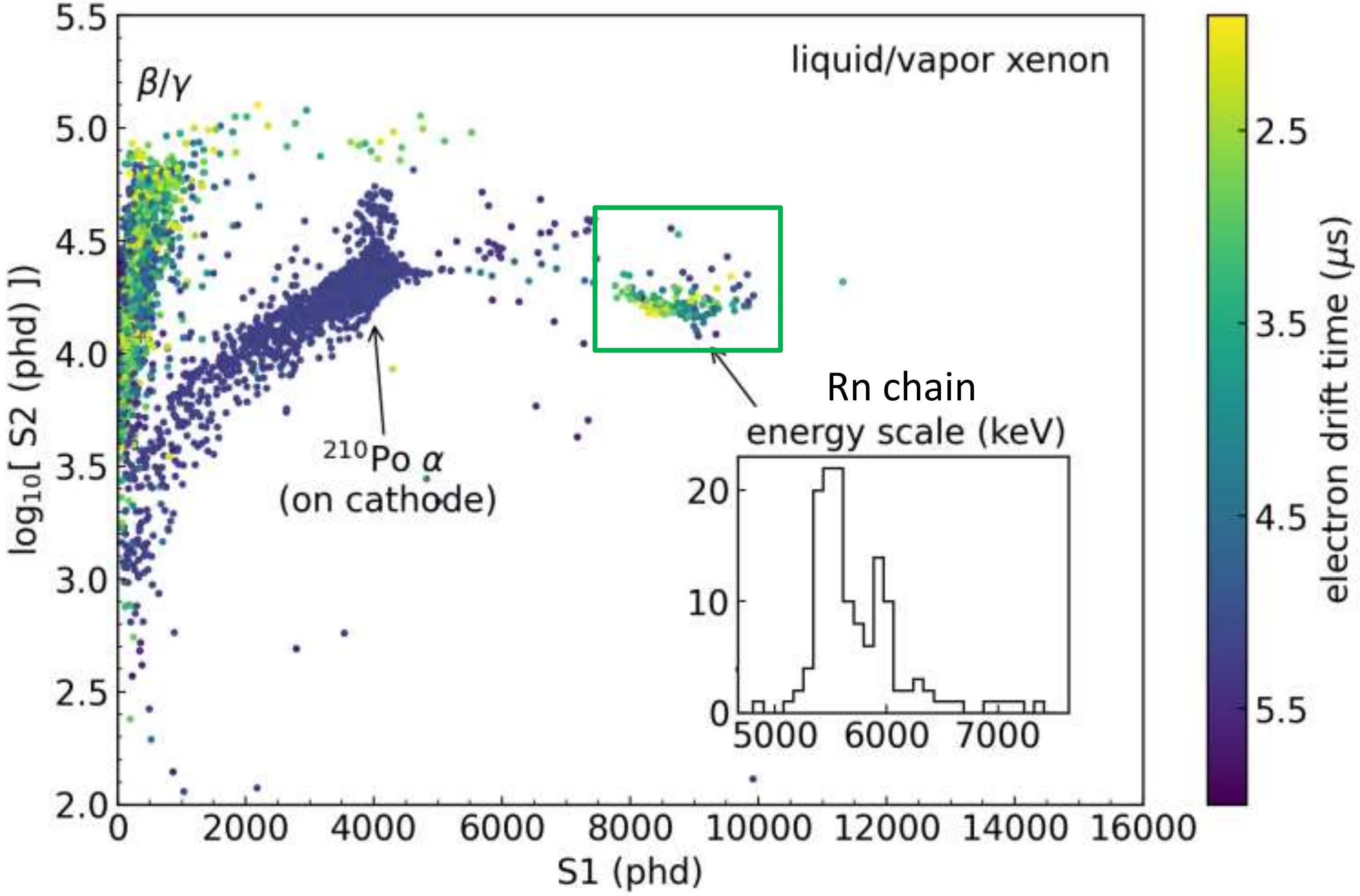
- $^{222}Rn$ source (low activity, half life = 3.8 days)
- $^{220}Rn$ source (high activity, half life < 1 min)




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

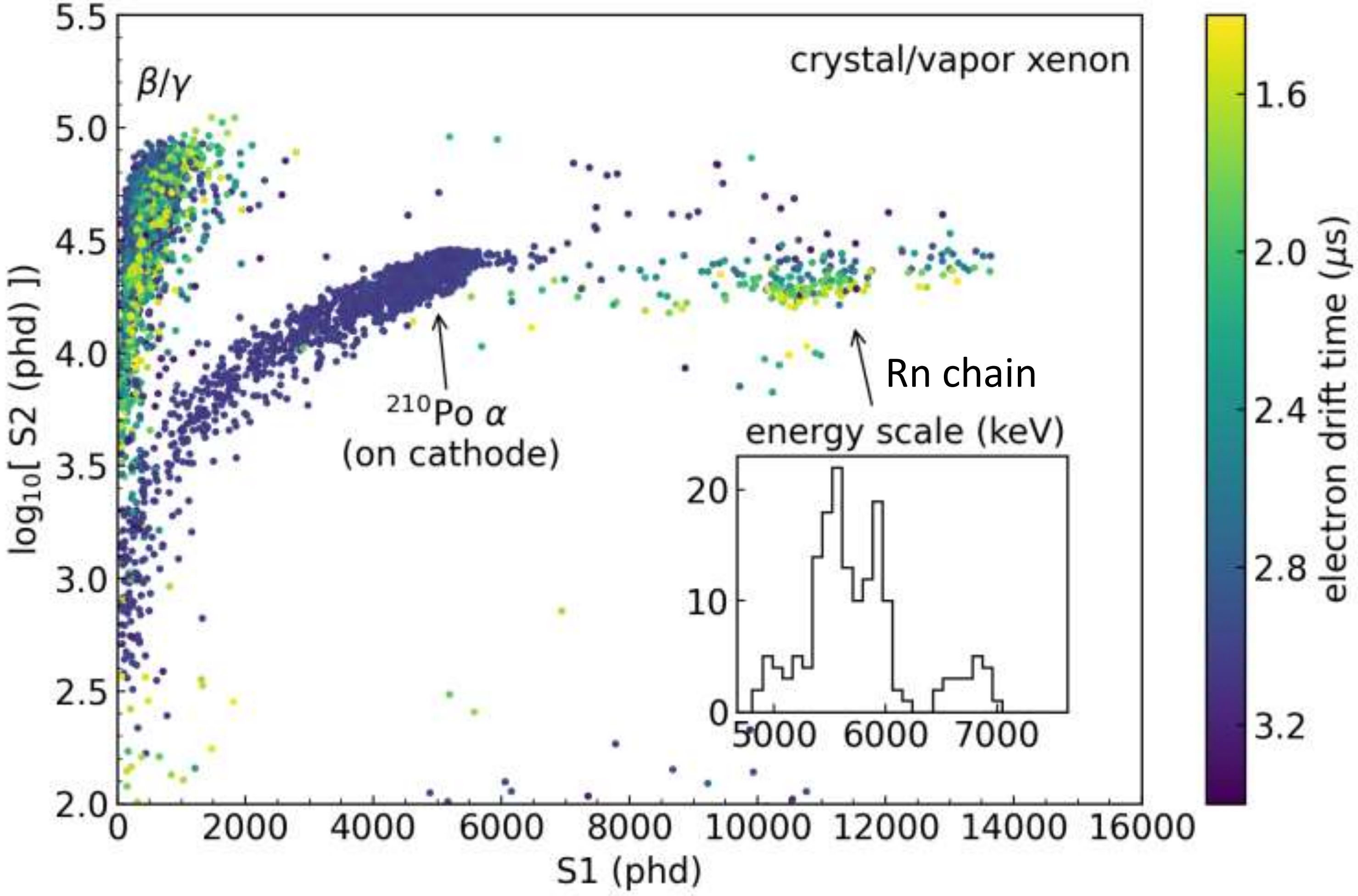



**How we select Rn events.**

Note: these are events within a small fiducial volume of several grams of xenon.

Note 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



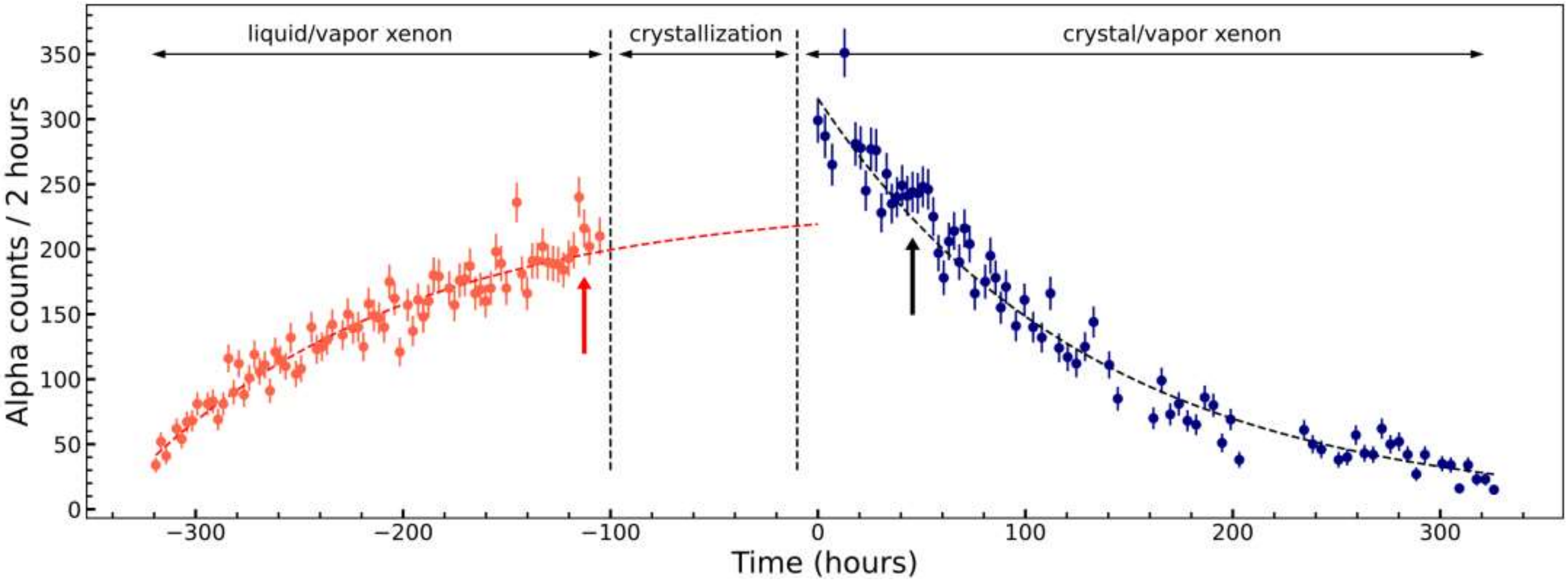

Good:
The response of the crystalline xenon is similar with that of liquid xenon.

But:
Hmm, still a lot of events from radon chain, but lets come back to this point later.

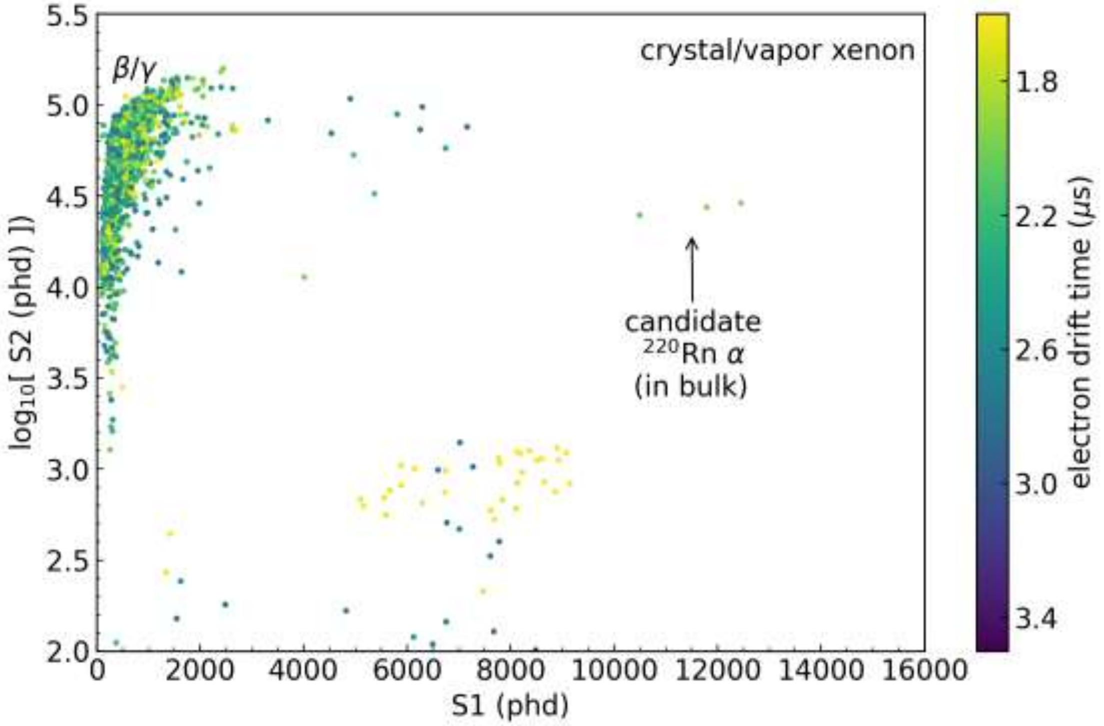
# Alpha rate with continuous $^{222}$Rn source flow

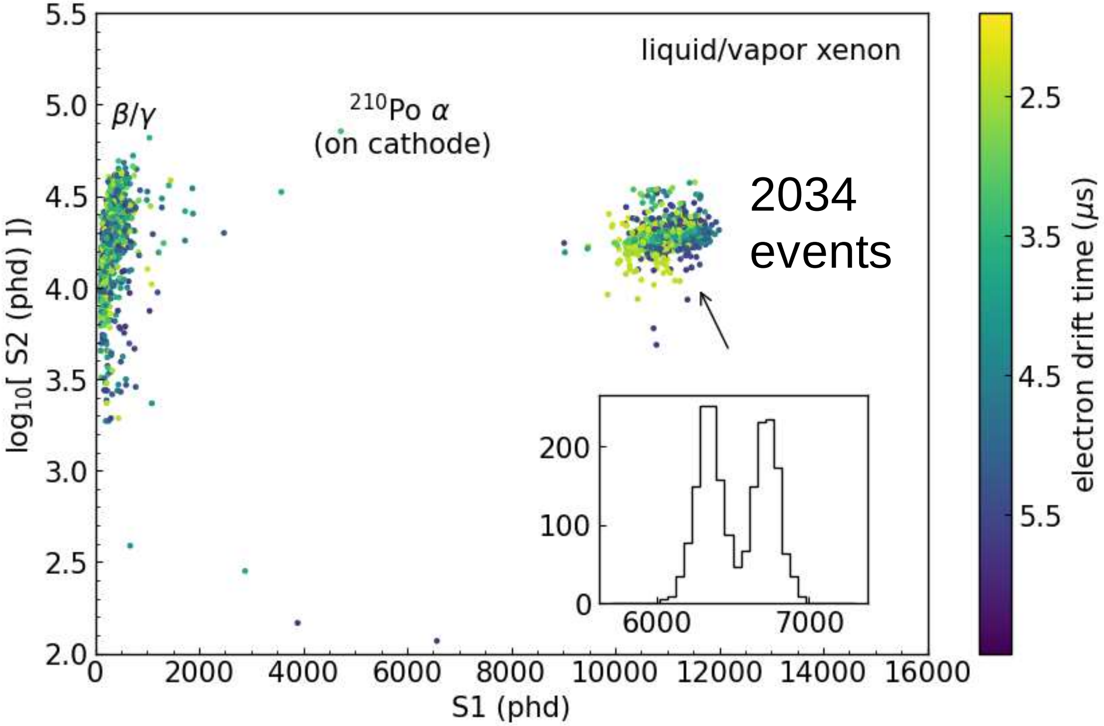
We **continuously** circulate gas xenon with a **steady flow rate** of 0.3 slpm.

- 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.



# $^{220}Rn$ EVENTS IN LIQUID VS CRYSTAL XENON




Two of the three events appear to be due to $^{222}Rn$ followed by $^{218}Po$, because they are at same location and separated by several mins (close to $^{218}Po$'s half life)

**Radon suppression factor:**

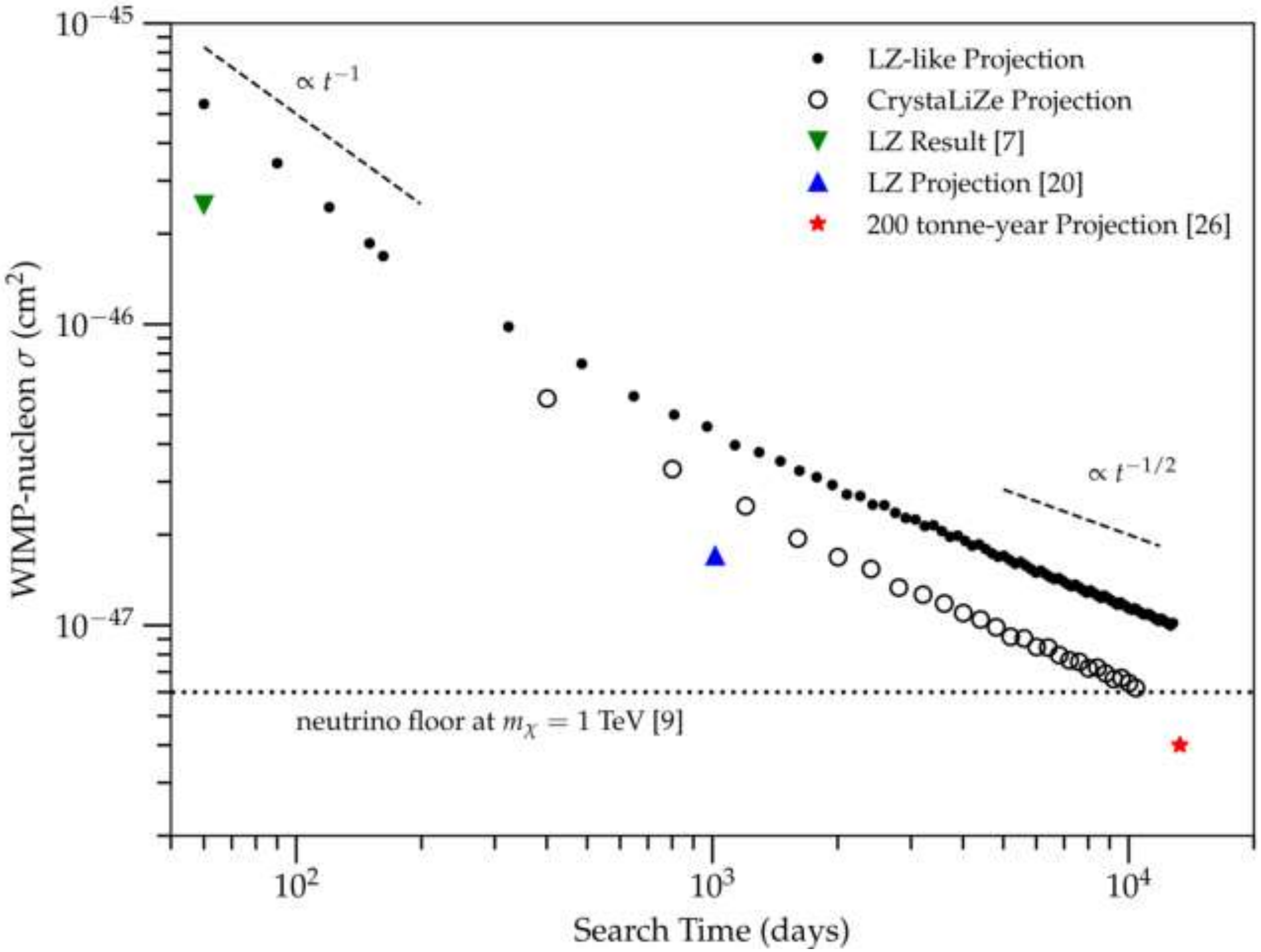
**x500 or conservatively x300, if we consider the 90% confidence level Poisson upper limit**

# PROJECTED SENSITIVITY of SPIN-INDEPENDENT WIMP-NUCLEON CROSS SECTION

Assumptions:

- Same discrimination power as liquid xenon (not tested yet)
- Background rate of 6.2/1000 days for LZ, see Phys. Rev. D 101, 052002 (2020)
- Background rate of 2/1000 days for crystallin xenon detector with same volume as LZ (assume all radon and krypton background were removed)

- A simple Feldman-Cousins "cut-and-count" method




More details in H. Chen et al Phys. Rev. D **109**, L071102 (2024)

# SUMMARY

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

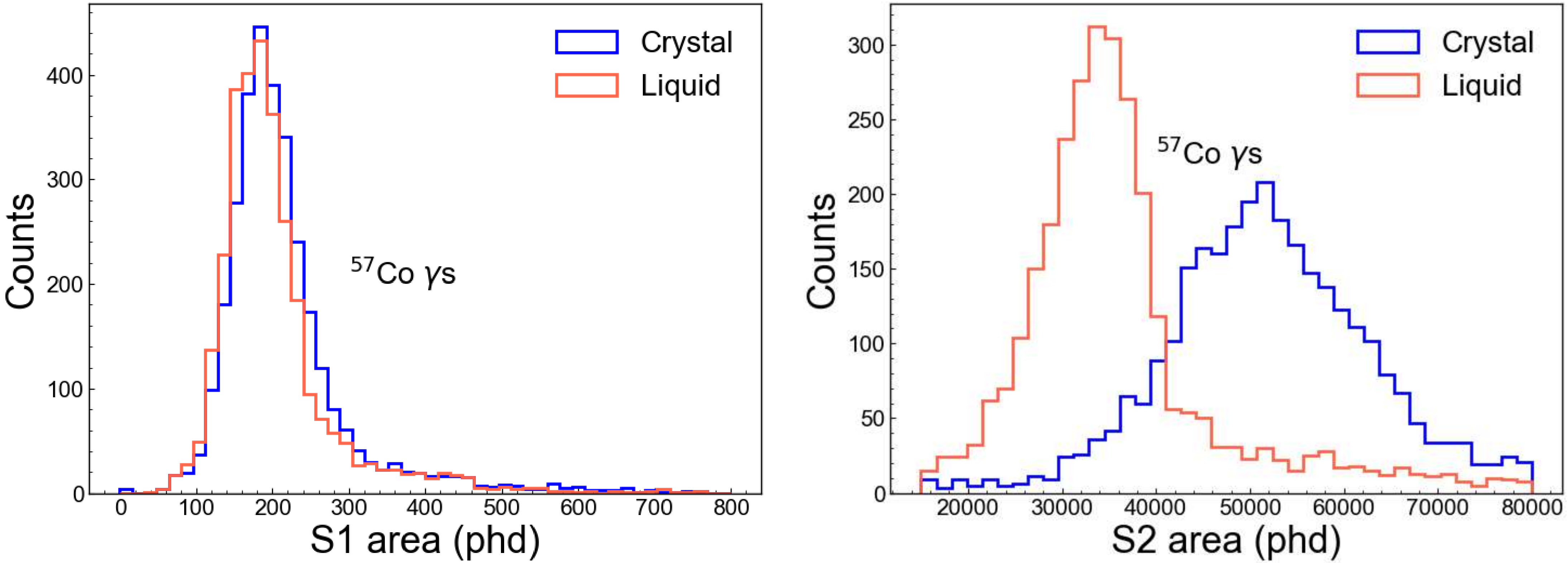
    - R&D at LBNL has established that a crystal/vapor TPC has similar performance as a Liquid/vapor TPCs (possibly better!)
    - A crystal/vapor TPC can remove the primary DM background, leading to neutrinos as the primary limiting background

Future:

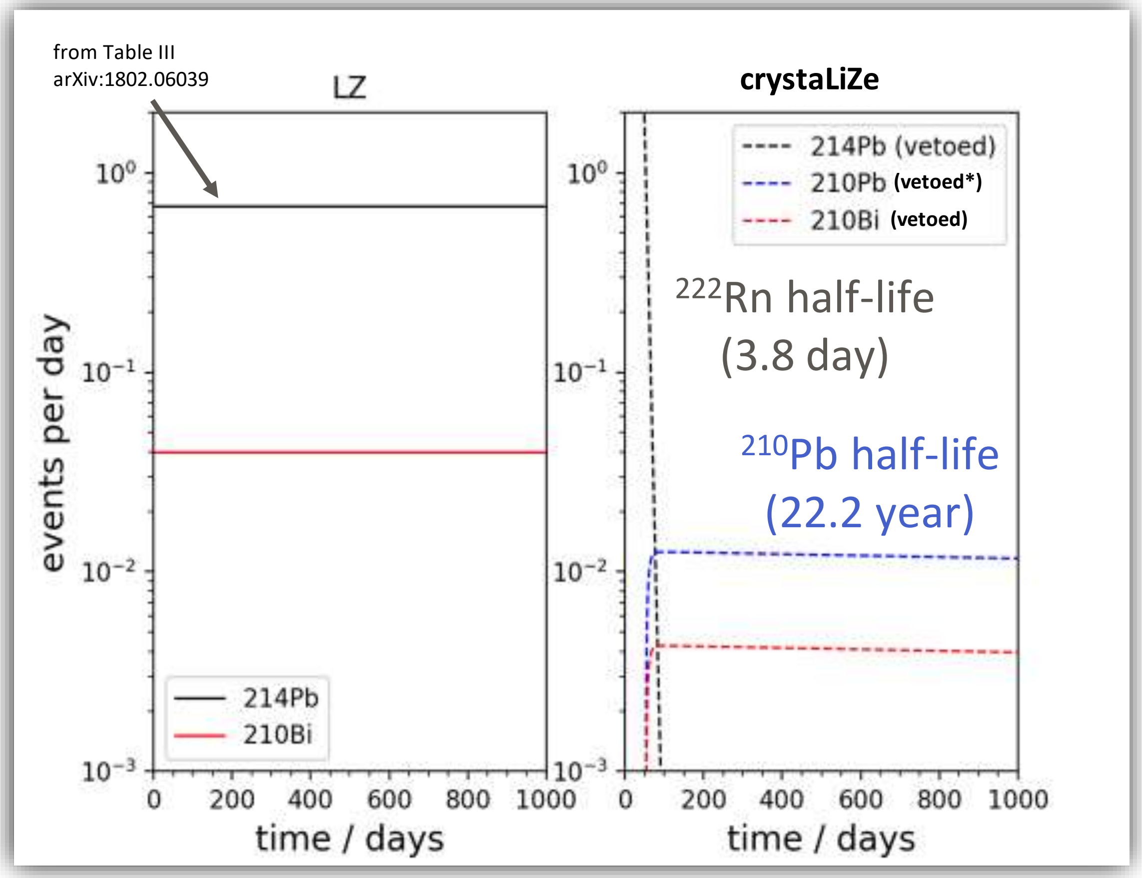
- ➢ Stability and resolution study
- ➢ Contamination study
- ➢ Scale up (Dr. Kravitz's group @UT Austin)

# BACKUP SLIDES

# 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.



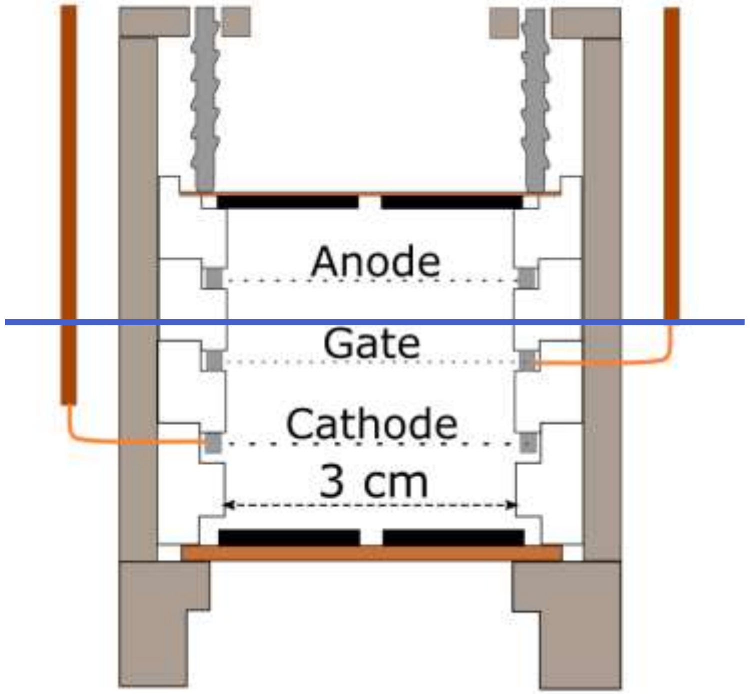

same LZ emanation and dust assumptions

# XENON LEVEL

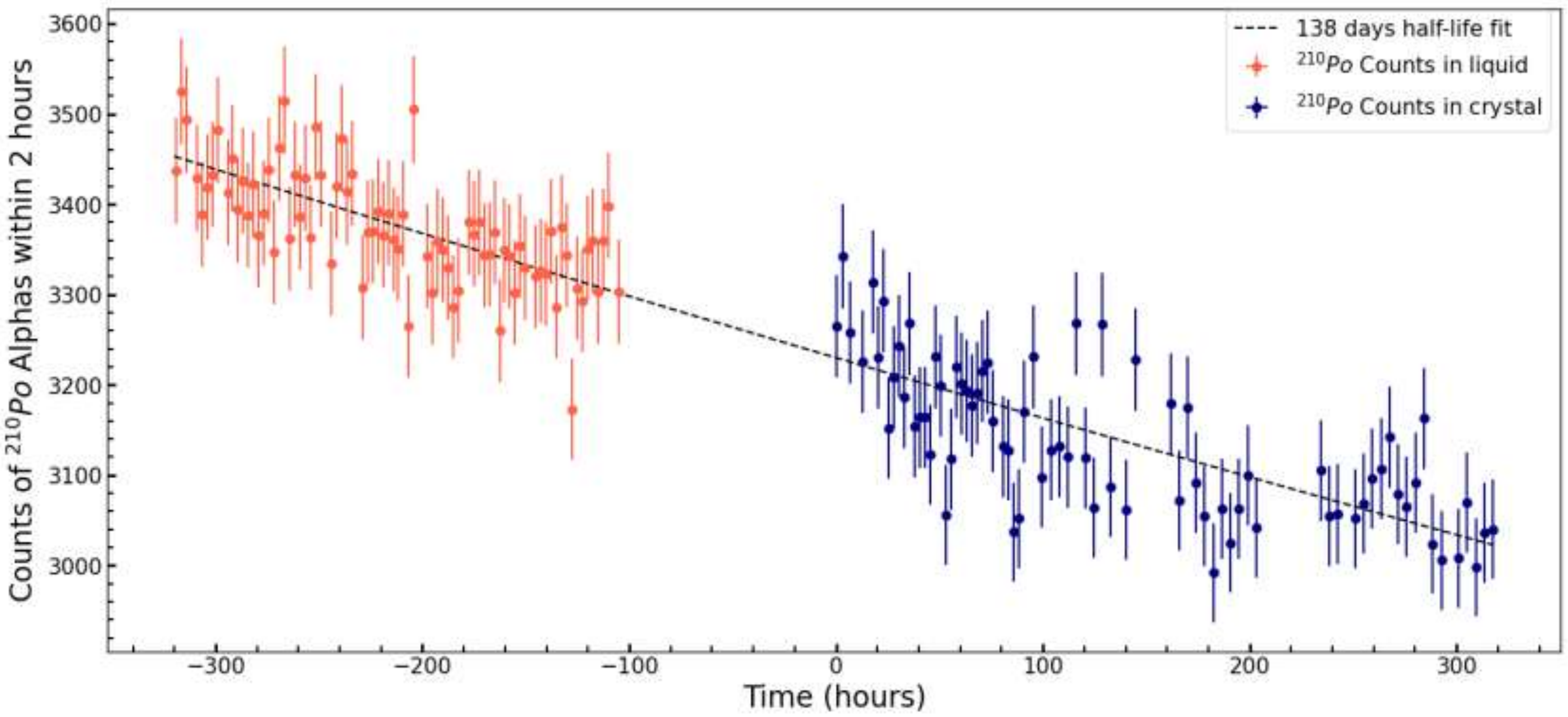
The level of condensed phase needs to be between the gate and anode for electroluminescence to work.

***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:

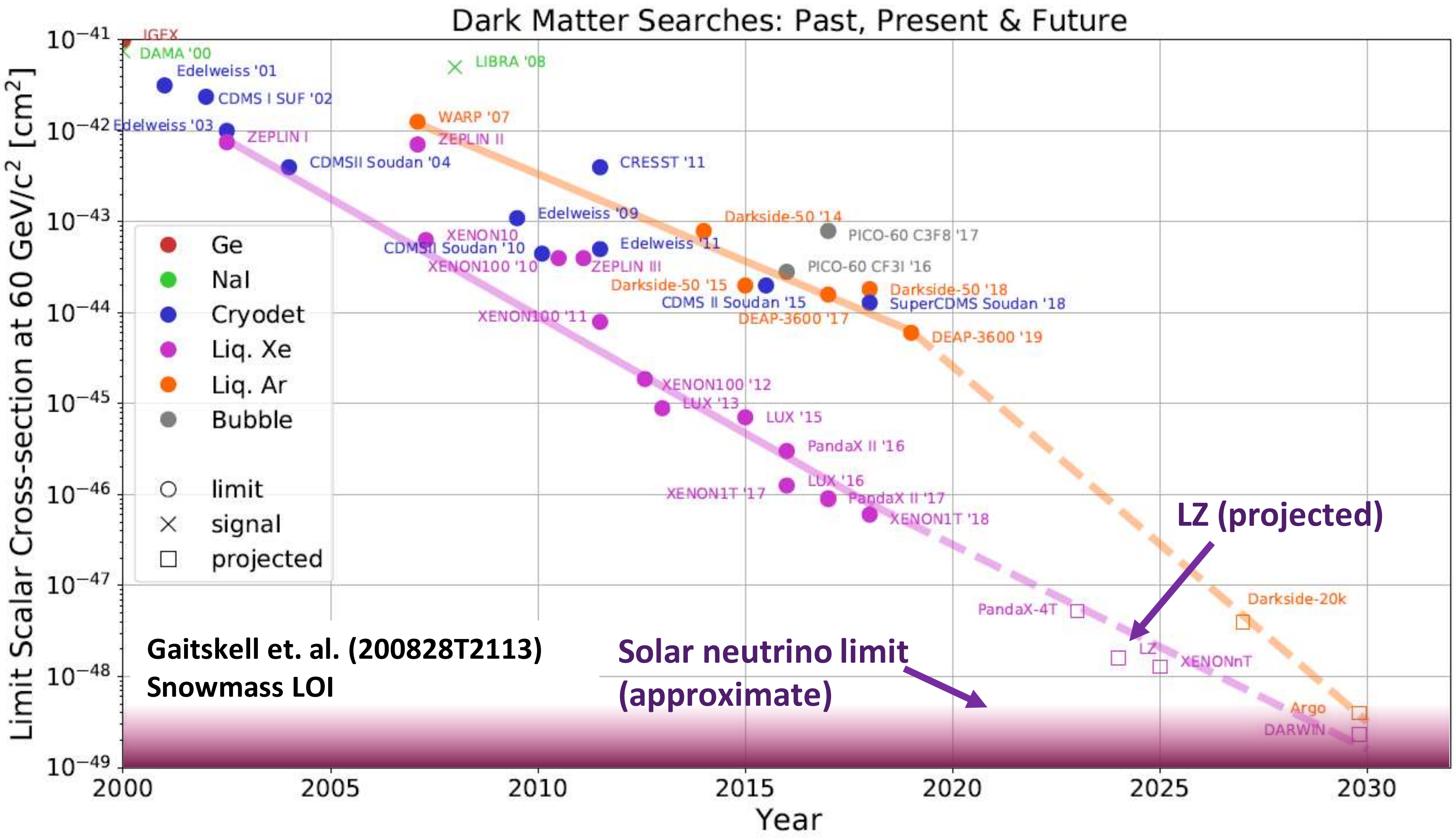
"…The 222Rn concentration was reduced by ~20% relative to the equilibrium value using the krypton distillation column in inverse mode…

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

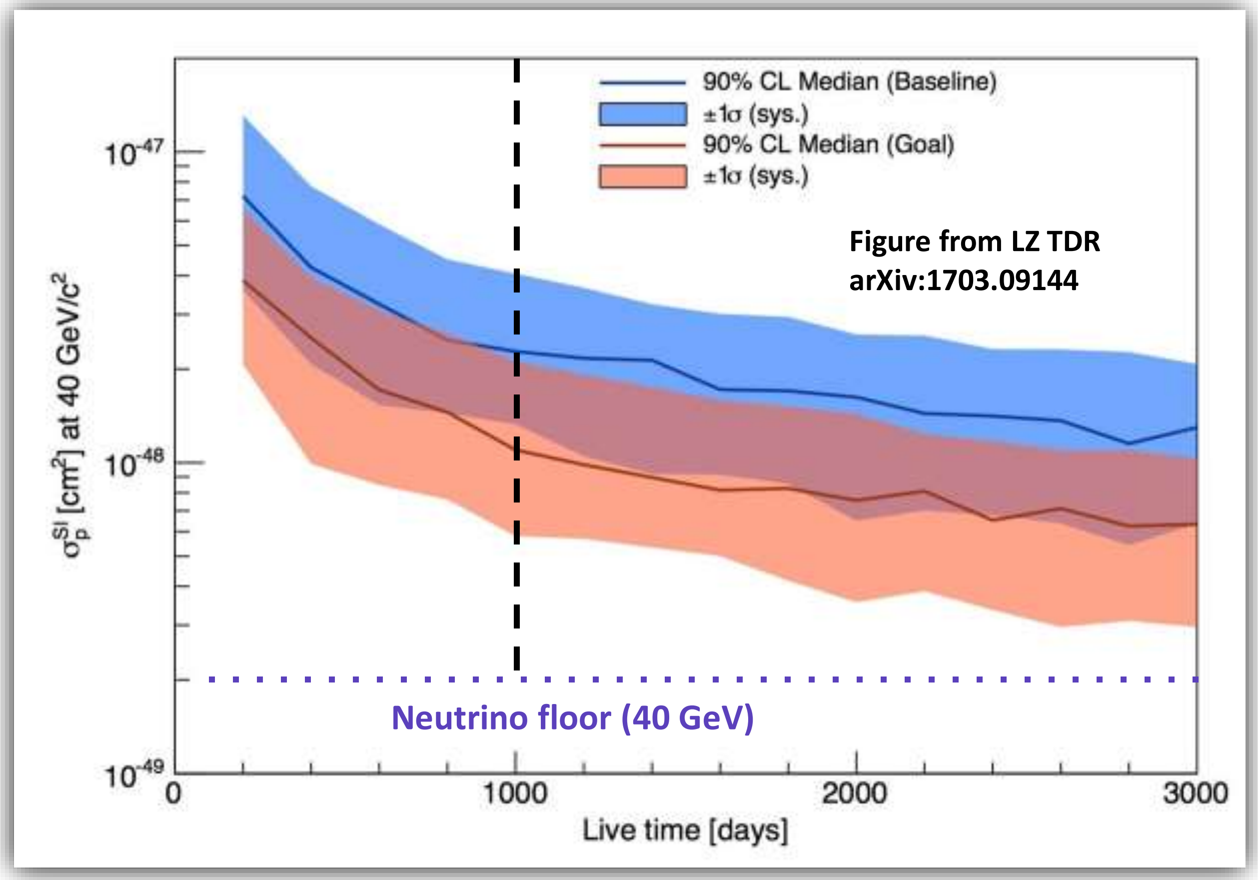
with exposure

when bkg limited

*Discovery potential depends*

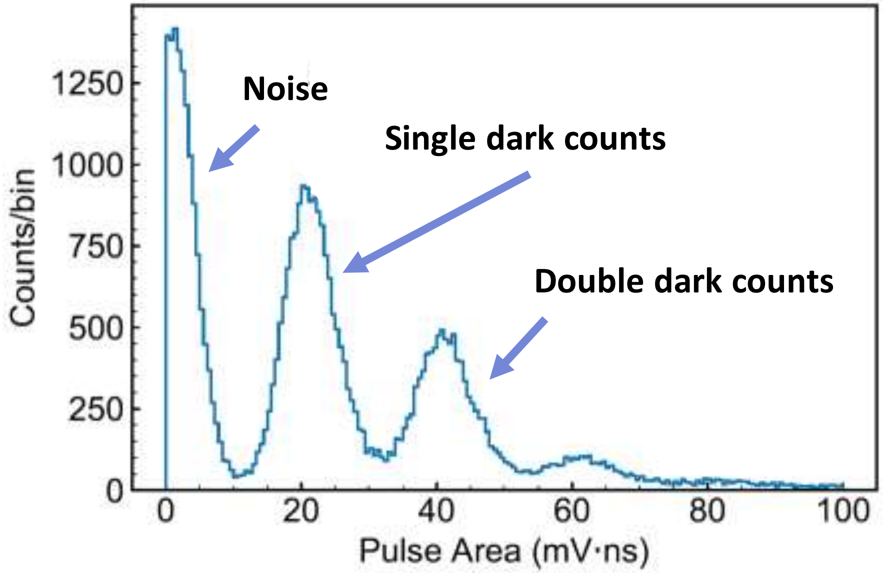
*even more strongly on background level*

*than sensitivity*

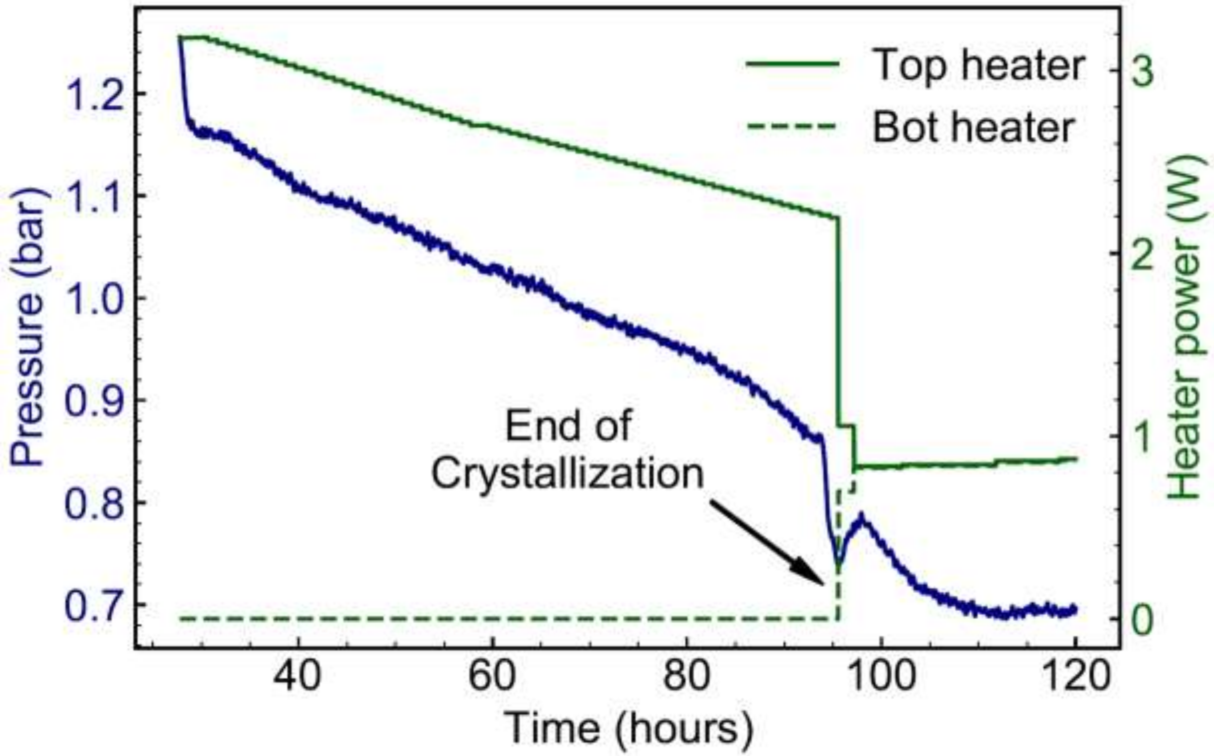


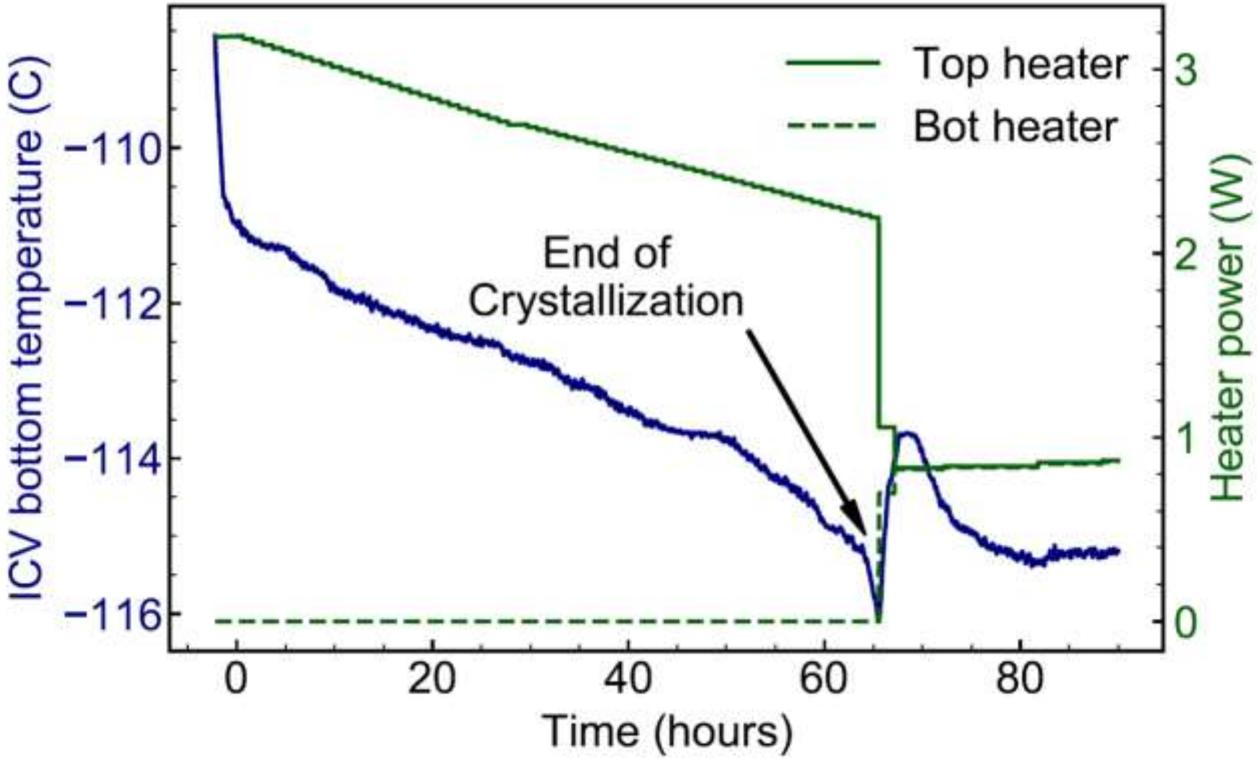
# WHY SIPMS?

- 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