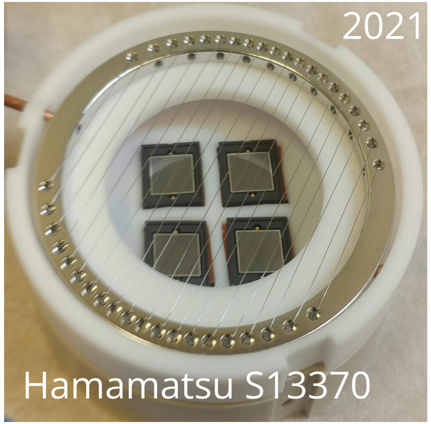
R&D towards a crystalline/vapor xenon TPC

On behalf of the crew

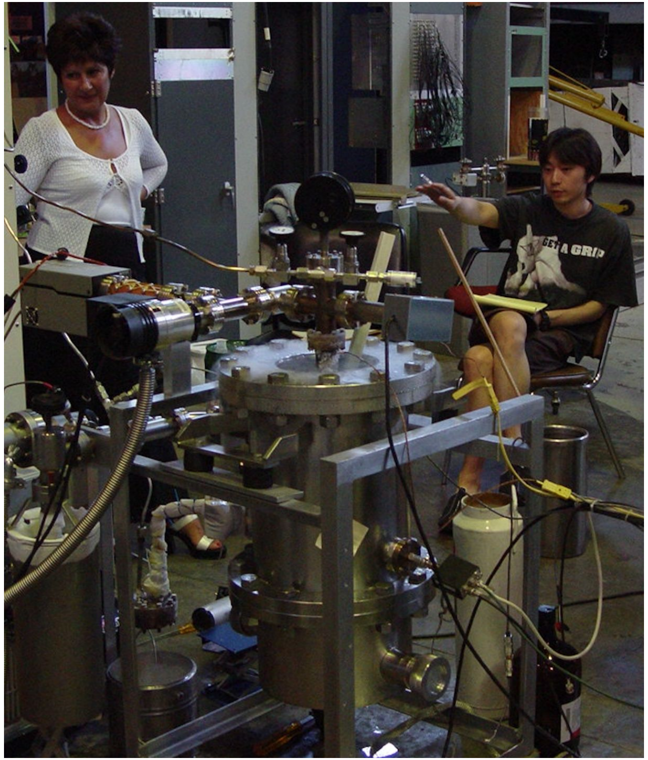
Recent R&D publications:

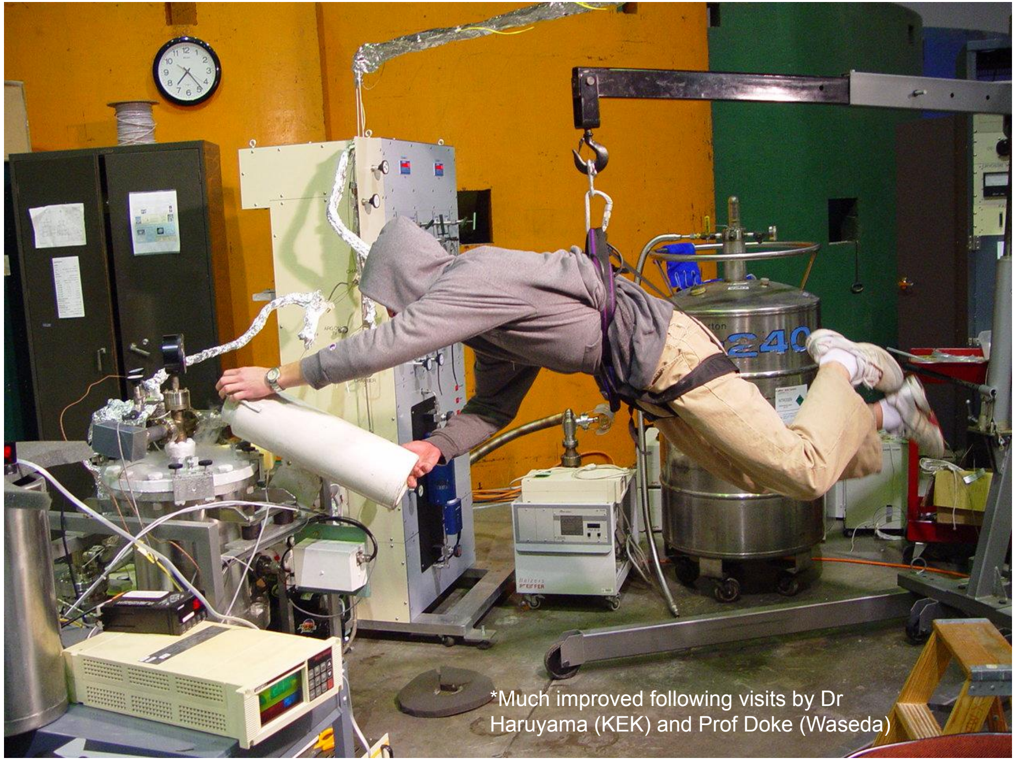
- **arXiv:2312.15082** “Towards a neutrino-limited dark matter search with crystalline xenon”
- **arXiv:2309.07913** “Why would you put a flashlight in a dark matter detector?”
- **arXiv:2308.02430** “First measurement of discrimination between helium and electron recoils in liquid xenon for low-mass dark matter searches”
- **arXiv:2201.05740** “Operation and performance of a dual-phase crystalline/vapor xenon time projection chamber”



Early (2003) inspiration:

A liquid xenon test stand with no PTR and old-fashion thermal control*





*Much improved following visits by Dr Haruyama (KEK) and Prof Doke (Waseda)

Liquid and solid xenon have essentially the same E_G

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

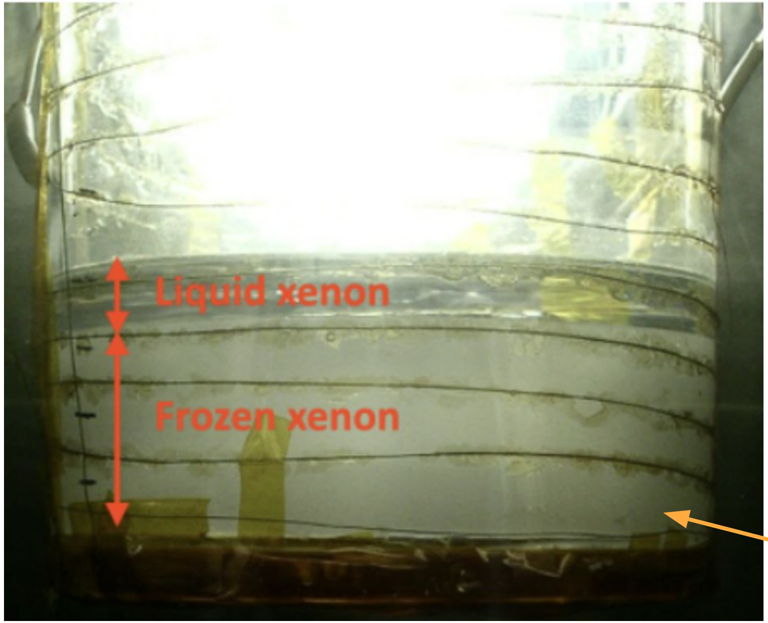
Thus “same” response to ionizing radiation

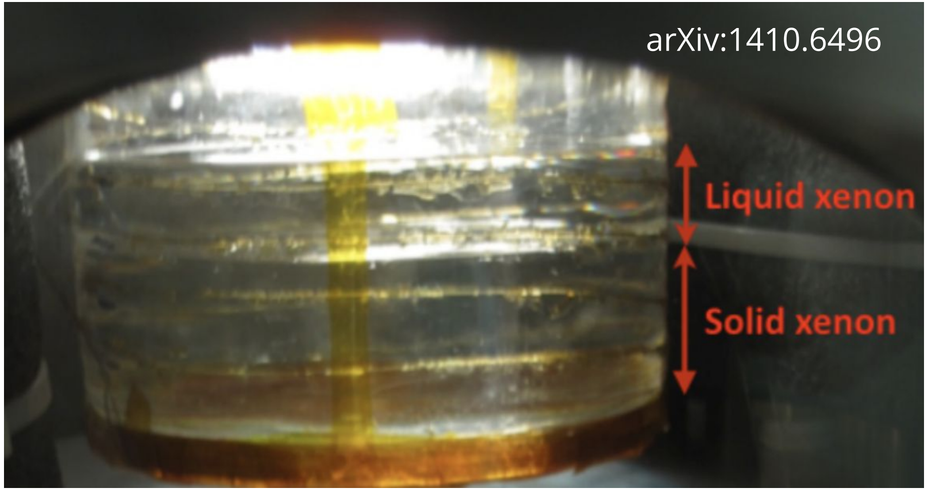
Also:

- x2 higher e- mobility
- 17% higher density

Investigated by Yoo et al (Fermilab) 2010–2015

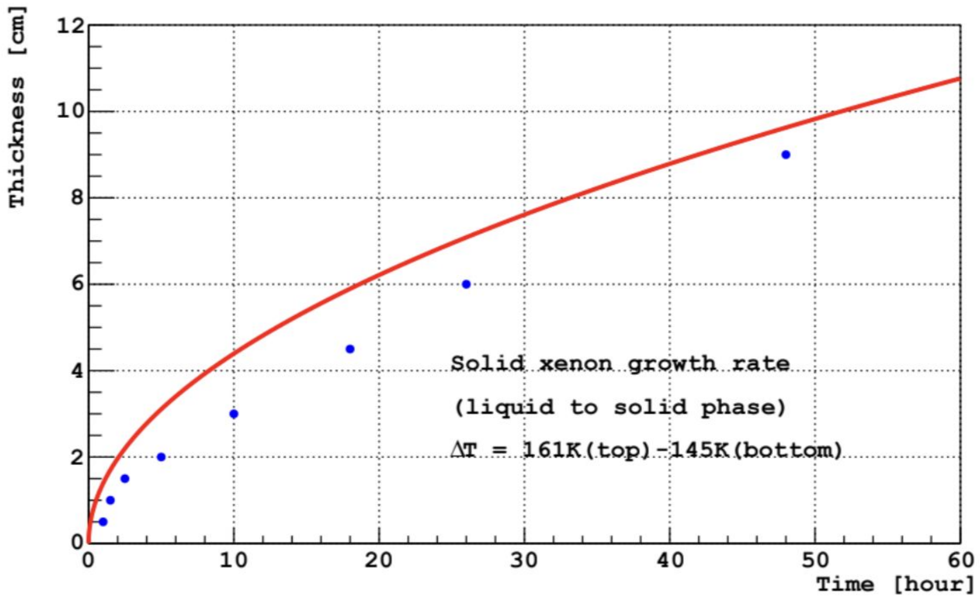
–but why?





cool too quickly, obtain an opaque crystal

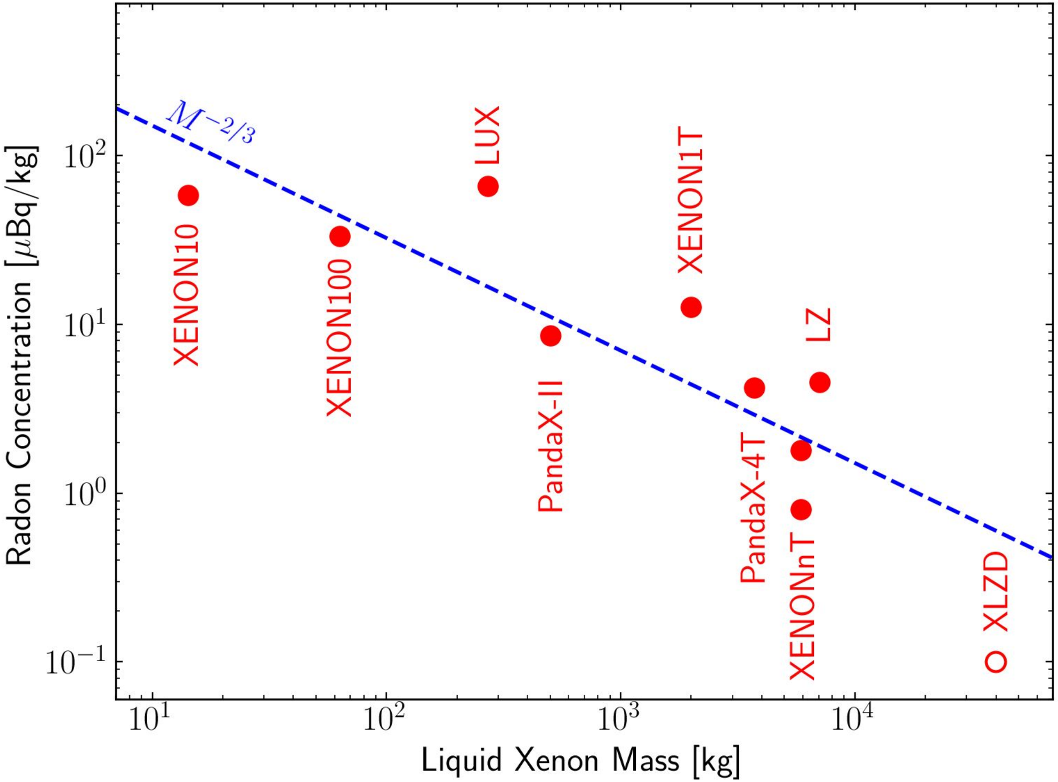
They developed a recipe to grow a 2 kg crystal in 2 days



Extrapolate to XENONnT or LZ: about a year to crystallize

Crystalline xenon: primary motivation

(missing attribution)



To have a data point that is waaaay off this plot

Crystal should exclude radon ingress; does it?

Goal: background-free dark matter search

LZ Backgrounds paper arXiv:2211.17120, Table VI

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

Rn-removal w infinite flow rate can solve

$, time and chromatography can solve

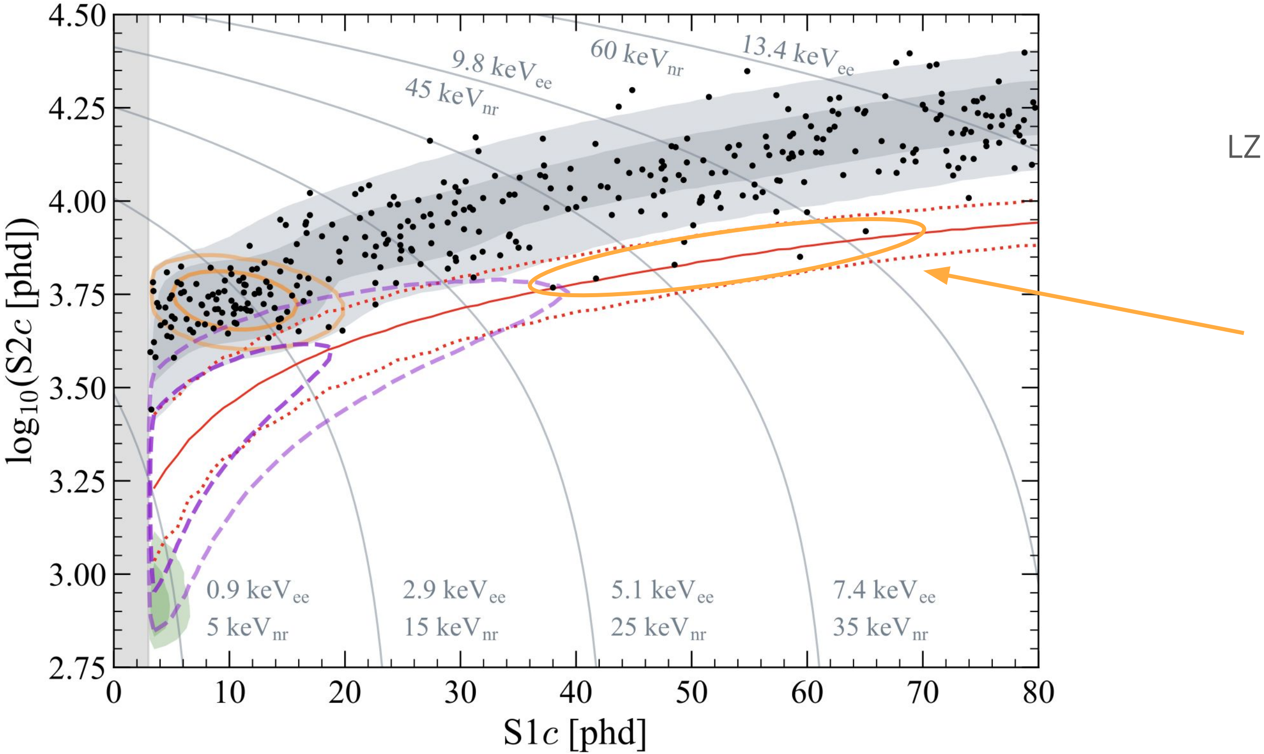
Interesting + others can measure

time can solve

$ can solve (give it to nEXO :)

Detector design, clever selection can solve

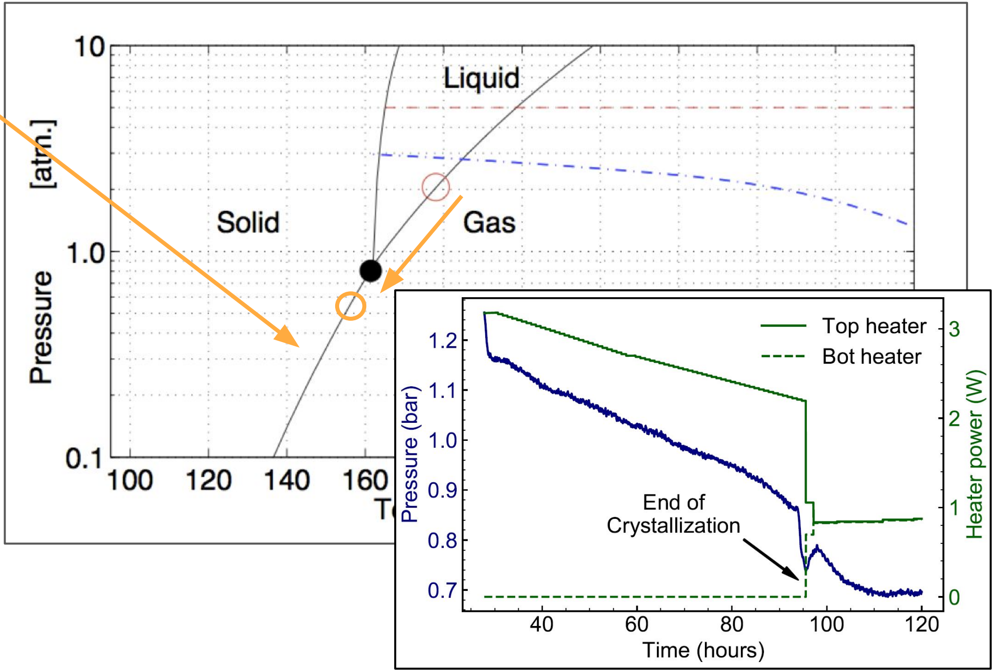
Extra important due to 5-10 keV fluctuation maximum



LZ Collaboration, arXiv:2207.03764

Crystal/vapor xenon TPC

- **Walk down phase boundary ~20 K**
- Similar electron and photon yields (photon verified)
- Easier e- emission into vapor
- Mobility increase x2
- Density increase x1.17
- Radon exclusion



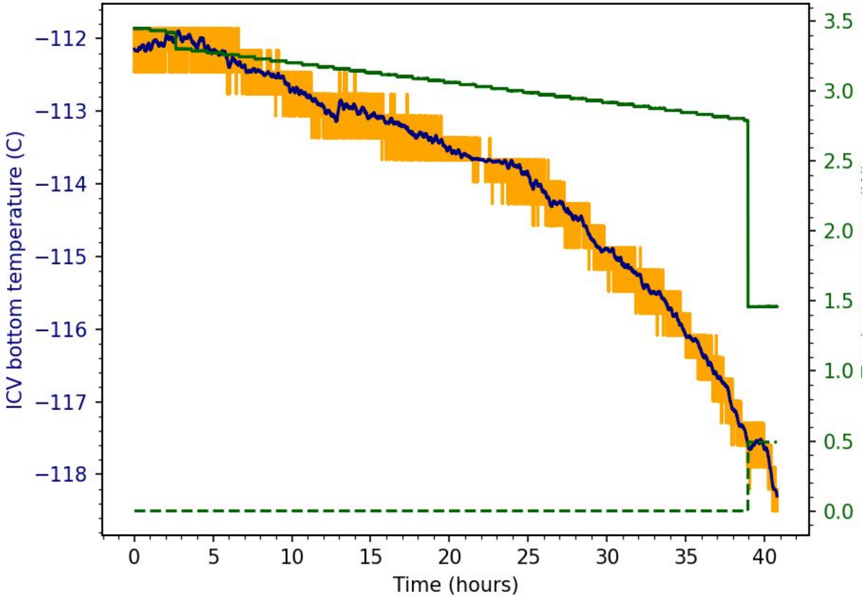
Freezing from bottom to top

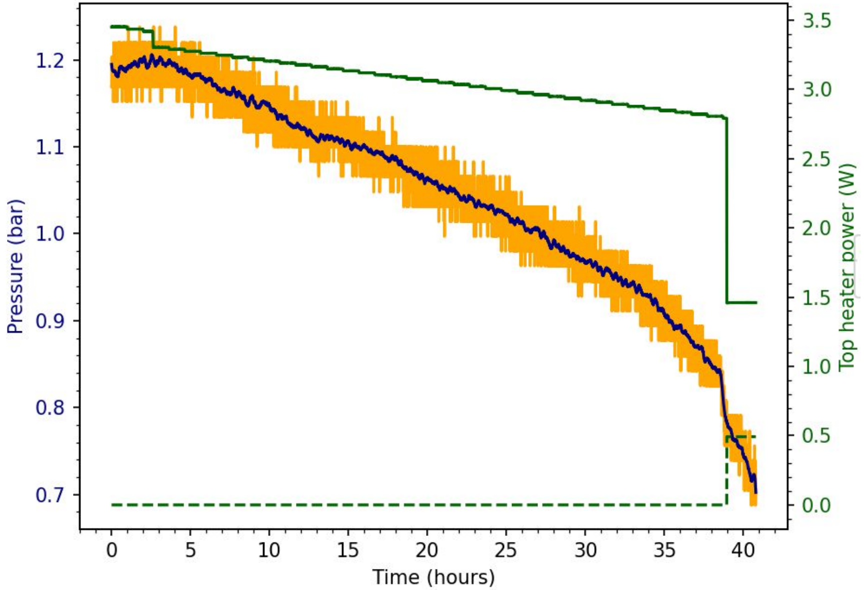
Crystal growth via “modified-Bridgman” technique

(temperature differential, random seed)

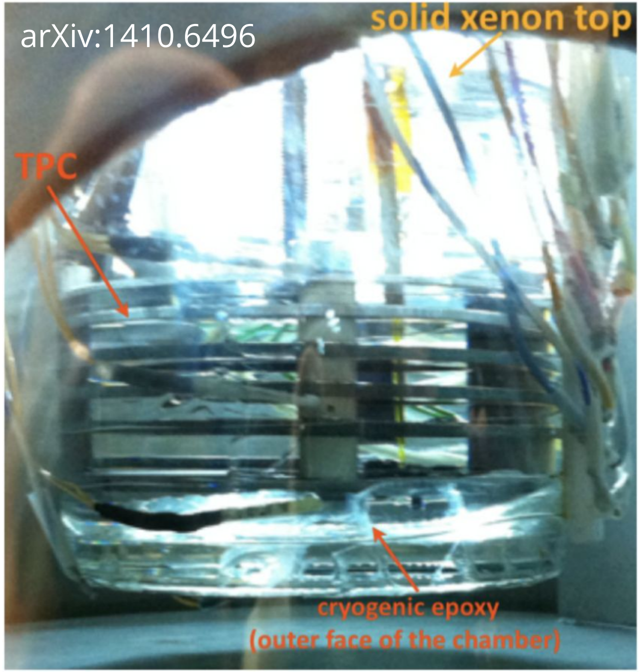
Supercooling precedes crystallization (jump in T)

Crystallization complete (crash in p)



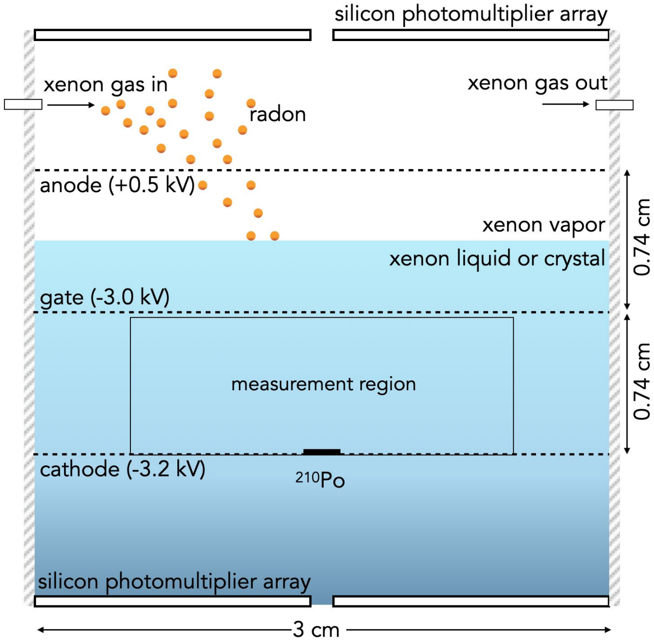


Practical detail of dual-phase operation: **precise** crystal height



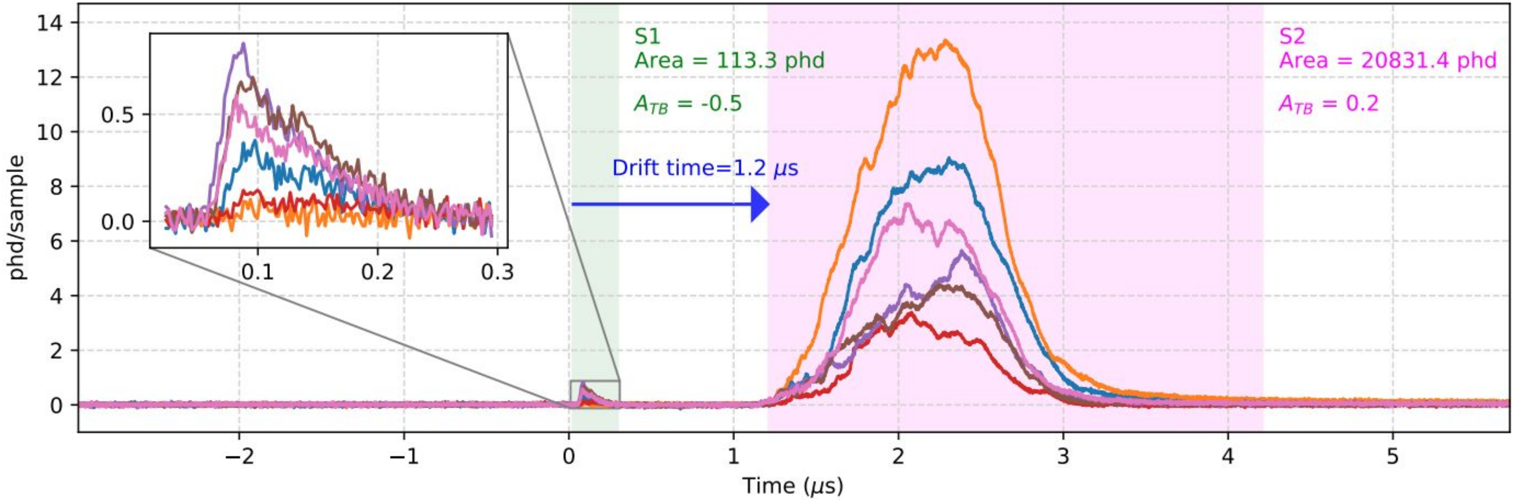
(left) single-phase TPC
crystal height arbitrary

(right) dual-phase TPC
start from liquid emission TPC,
overfill liquid above anode
(~17% mass)
crystallize



Crystal/vapor xenon TPC – works

observe S1 and S2 in crystal/vapor TPC, just as in liquid/vapor TPC



arXiv:2201.05740 also in JINST

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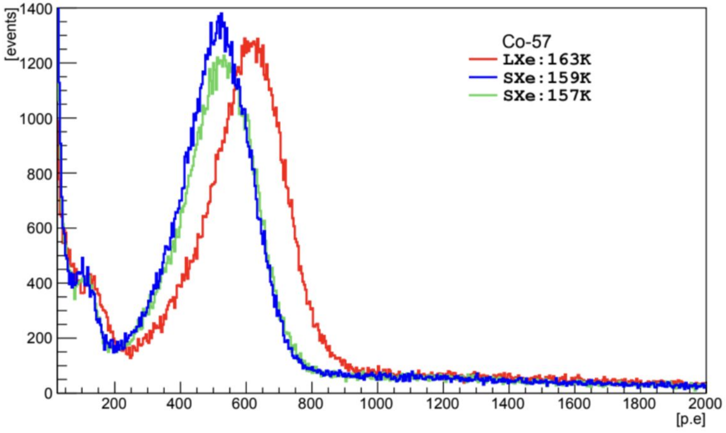
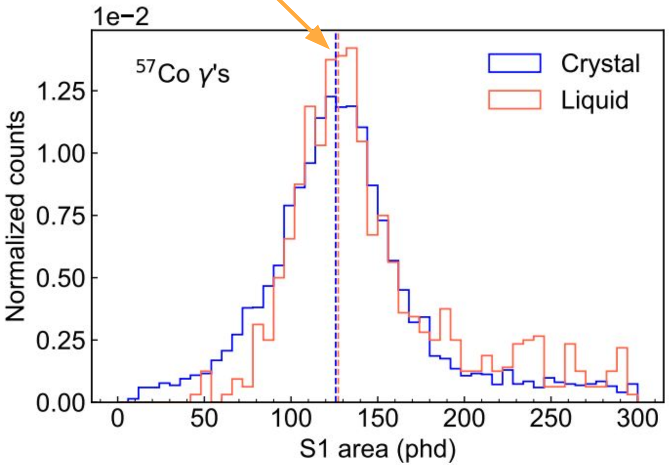


Yoo et al. arXiv:1410.6496



Our result arXiv:2201.05740

20% decrease in scintillation from gammas – wavelength shift?

Varding et al. phys. stat. sol. (b) 185, 301 (1994)

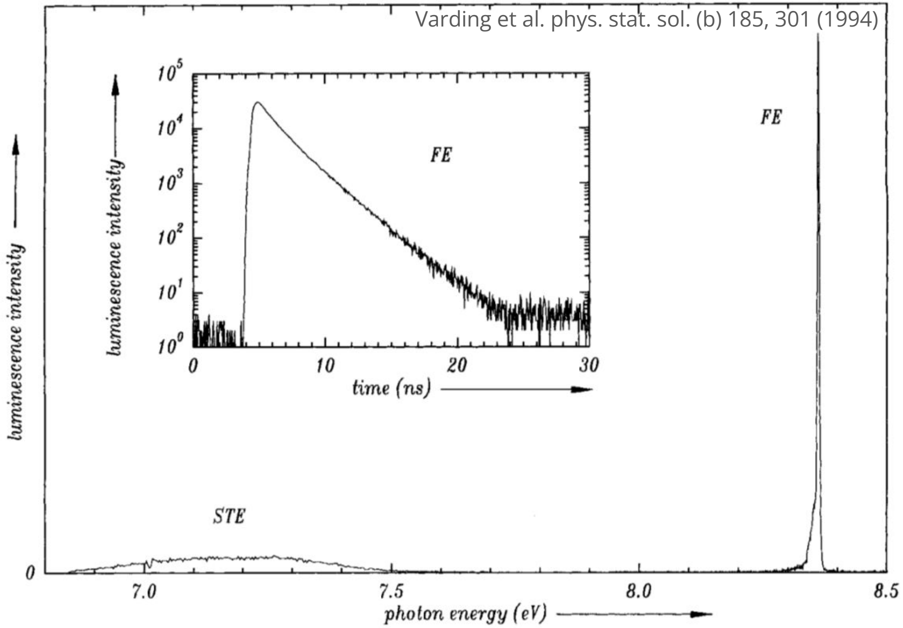


Fig. 1. Luminescence of solid Xe at $T = 4.7$ K, excited with synchrotron radiation (photon energy 8.86 eV). The inset shows a time-resolved spectrum of the FE line at 8.359 eV. The spectral resolution intervals are given in the text

Below 60 K crystalline xenon has been found to scintillate at λ=147 nm (“FE”) in addition to the usual λ=174 nm (“STE”)

Our result (previous slide) used Hamamatsu S13370-6050 SiPM (no quartz window), thus sensitive to photons with λ<160 nm

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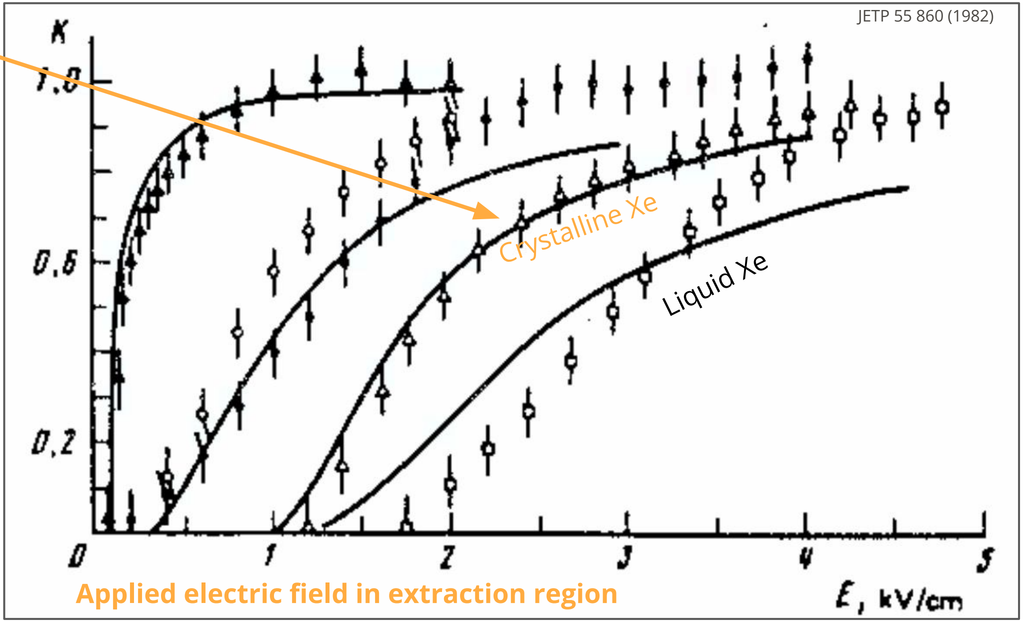
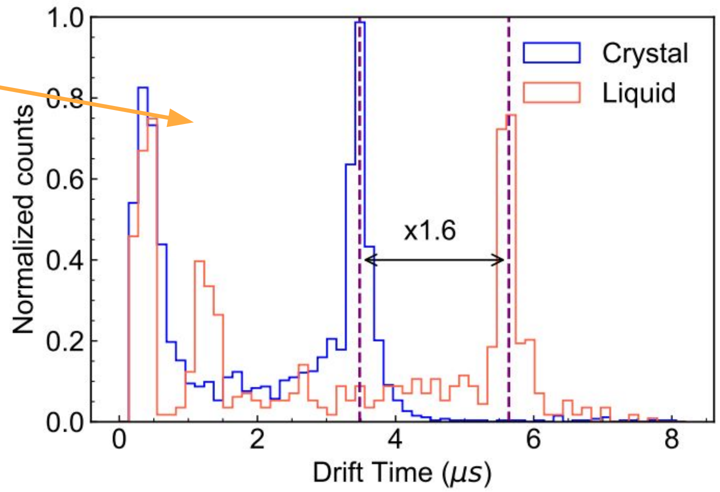
- **Easier e- emission into vapor**
- Mobility increase x2
- Density increase x1.17
- Radon exclusion



Crystal/vapor xenon TPC

- Walk down phase boundary ~20 K
- Similar electron and photon yields (photon verified)
- Easier e- emission into vapor
- **Mobility increase x2 (ish)**
- Density increase x1.17
- Radon exclusion

Surprising? Maybe not: crystal structure leads to reduced electron-phonon scattering



consistent with x2 due to uncertainty in crystal surface height above gate

Crystal/vapor xenon TPC

- Walk down phase boundary ~20 K
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- Easier e- emission into vapor
- Mobility increase x2
- **Density increase x1.17**
- Radon exclusion

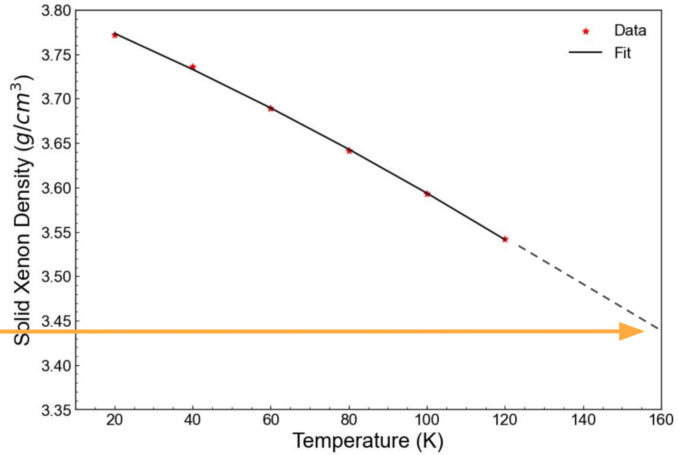
A. J. Eatwell & B. L. Smith (1961) Density and expansivity of solid xenon, Philosophical Magazine, 6:63, 461-46

Correspondence 463

Table 1. Density (g cm^{-3})

T (°K)	20	40	60	80	100	120
Argon	1·764	1·737	1·691	1·636	—	—
Krypton	3·078	3·040	2·988	2·926	—	—
Xenon	3·772	3·736	3·689	3·642	3·593	3·542

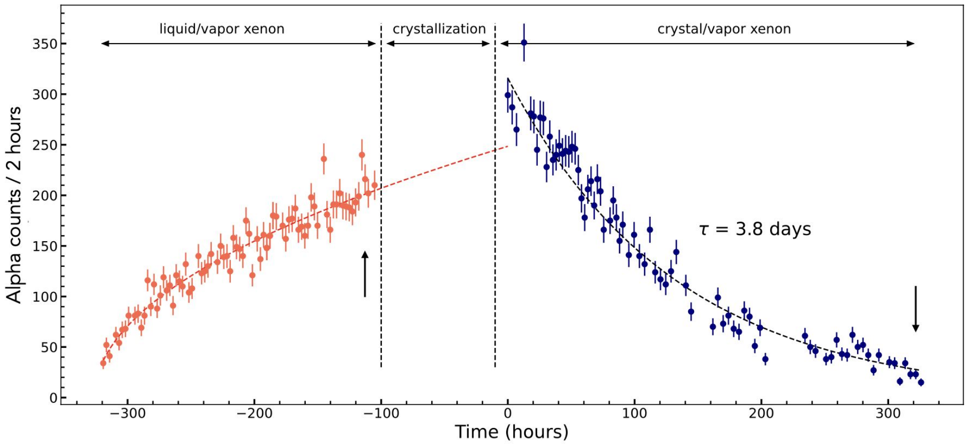
Extrapolate to 3.44 g/cm^3 at triple point



Crystal/vapor xenon TPC

- Walk down phase boundary ~20 K
- Similar electron and photon yields (photon verified)
- Easier e- emission into vapor
- Mobility increase x2
- Density increase x1.17
- **Radon exclusion**

Measured alpha rate with CONTINUOUS radon source flow



x17 exclusion from ^{222}Rn

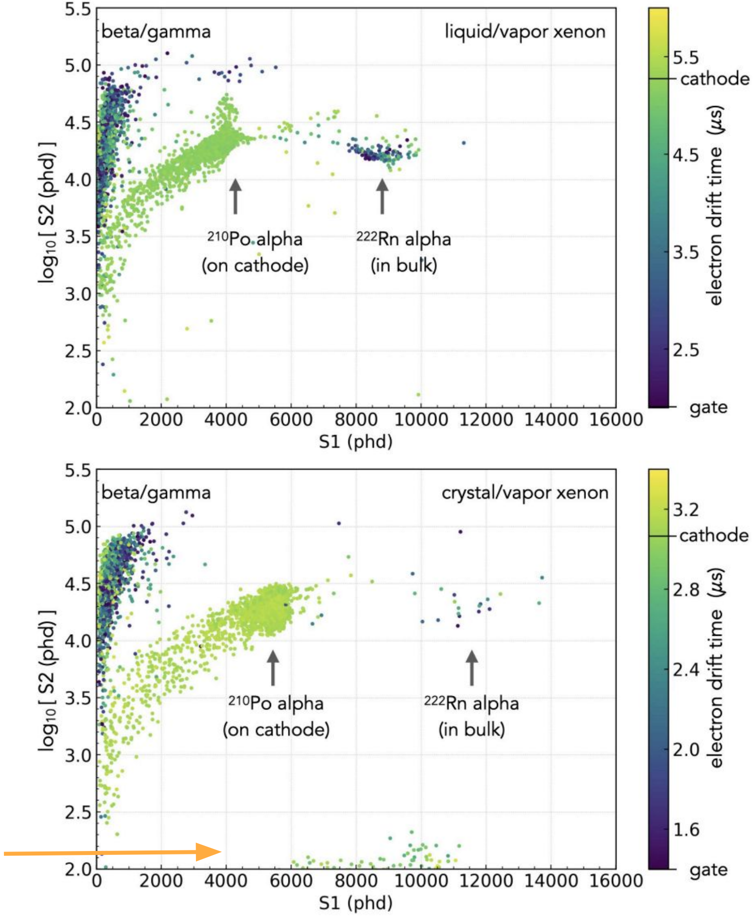
arxiv:2312.15082

Crystalline xenon radon exclusion

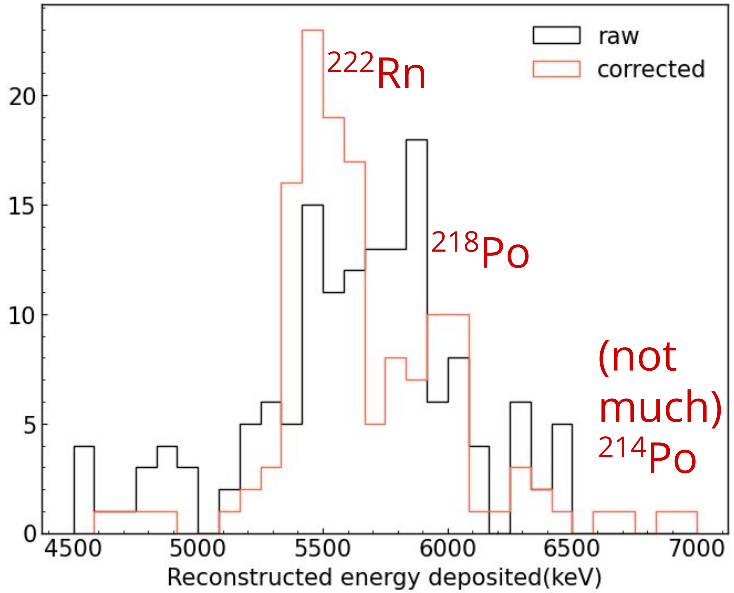
measuring the decay of ^{222}Rn

- Note 20-30% increase in crystal S1
  - Pressure-dependence? (depends on thermal history)
  - IR scintillation?
- Note also population of low-S2 alphas
  - ^{210}Po alphas on side of cathode

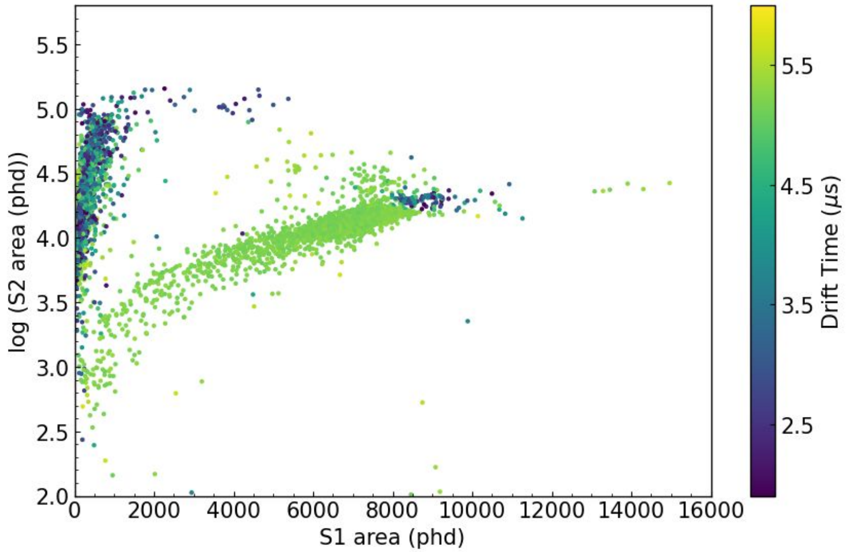
arxiv:2312.15082



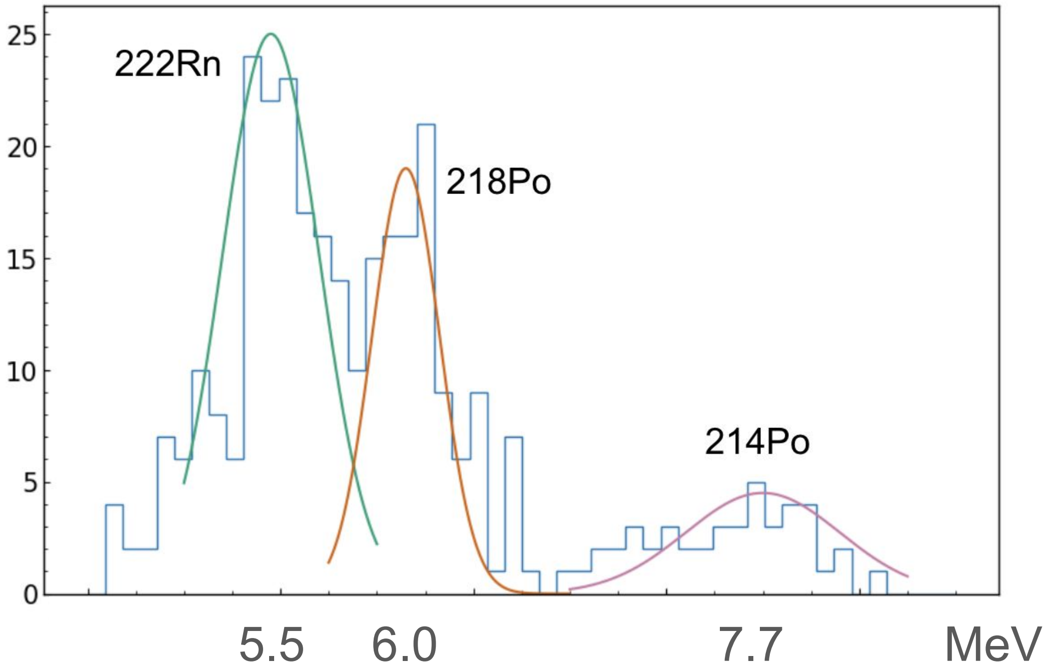
Not in publication: (x,y,z) corrected spectra (liquid)



Leads to calibration/data overlap

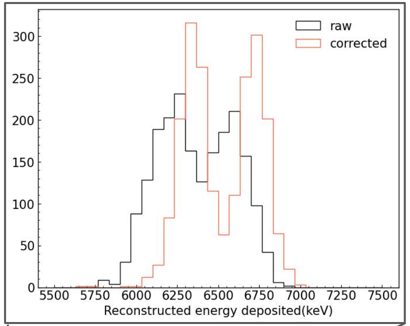


Although we do see the ^{214}Po in crystal Xe **(it can't drift to the cathode!)**



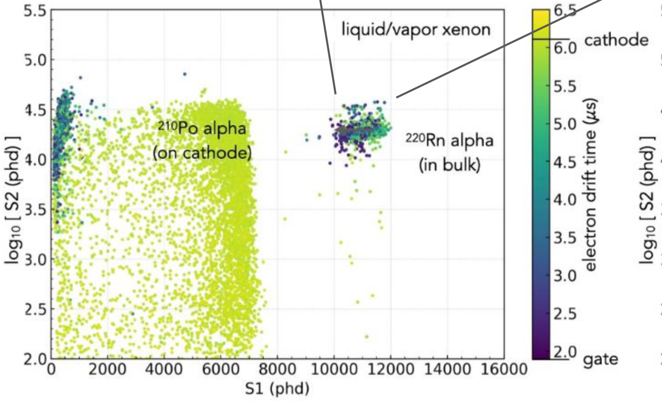
NB: mild saturation (due to photon occupancy per SiPM pixel) causes mild deviation from linearity

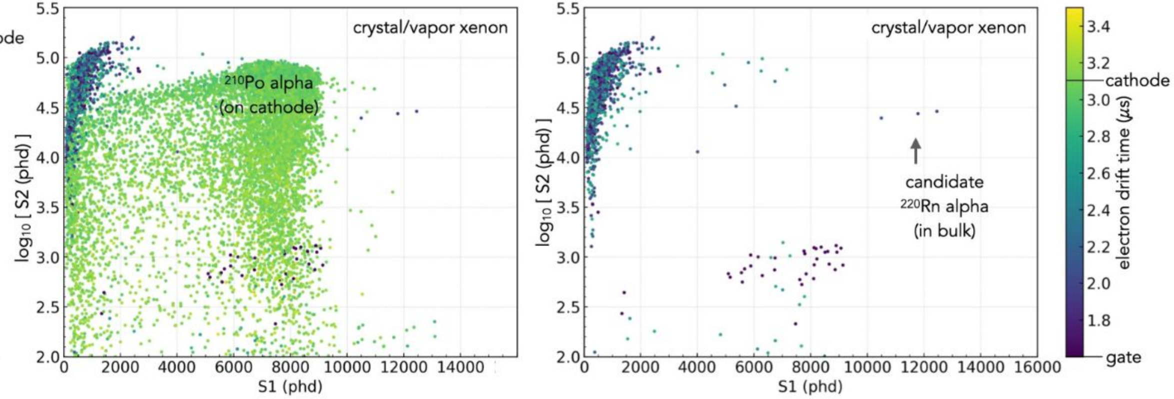
Crystalline xenon radon exclusion: x500 compared w liquid from ^{220}Rn



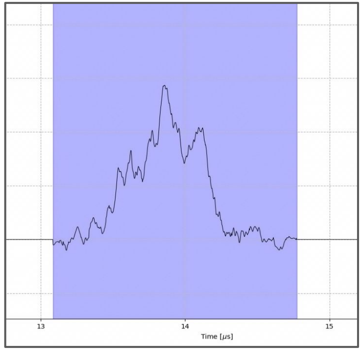
arxiv:2312.15082

Same plot, with/without cathode events

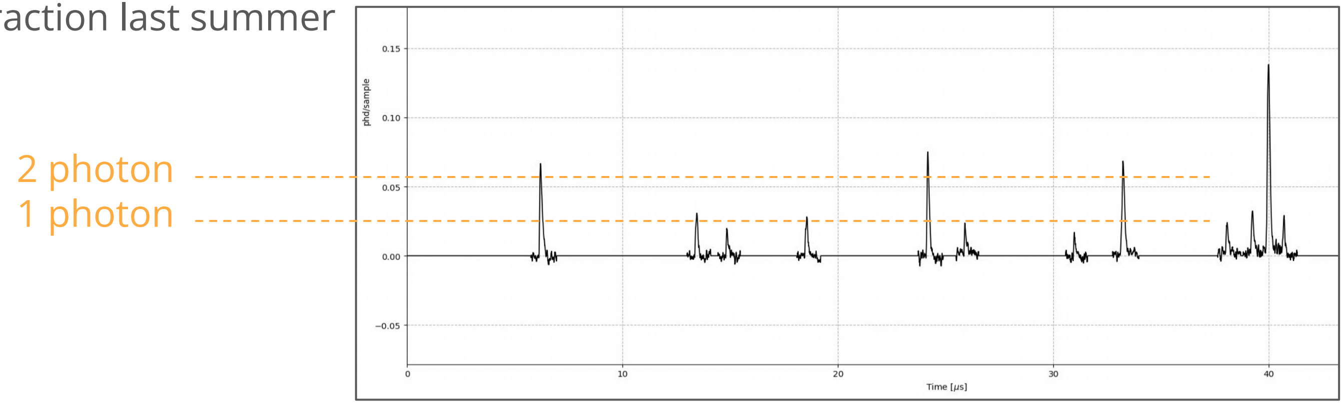




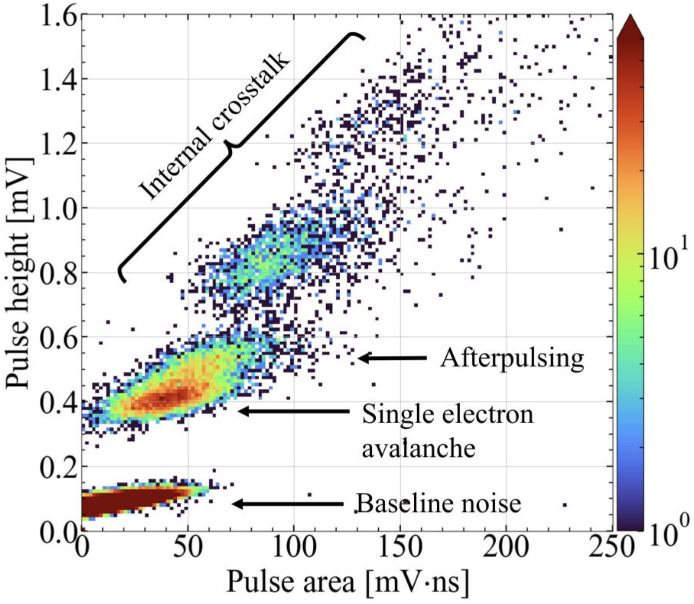
Digression: electron (S2) yields in crystal

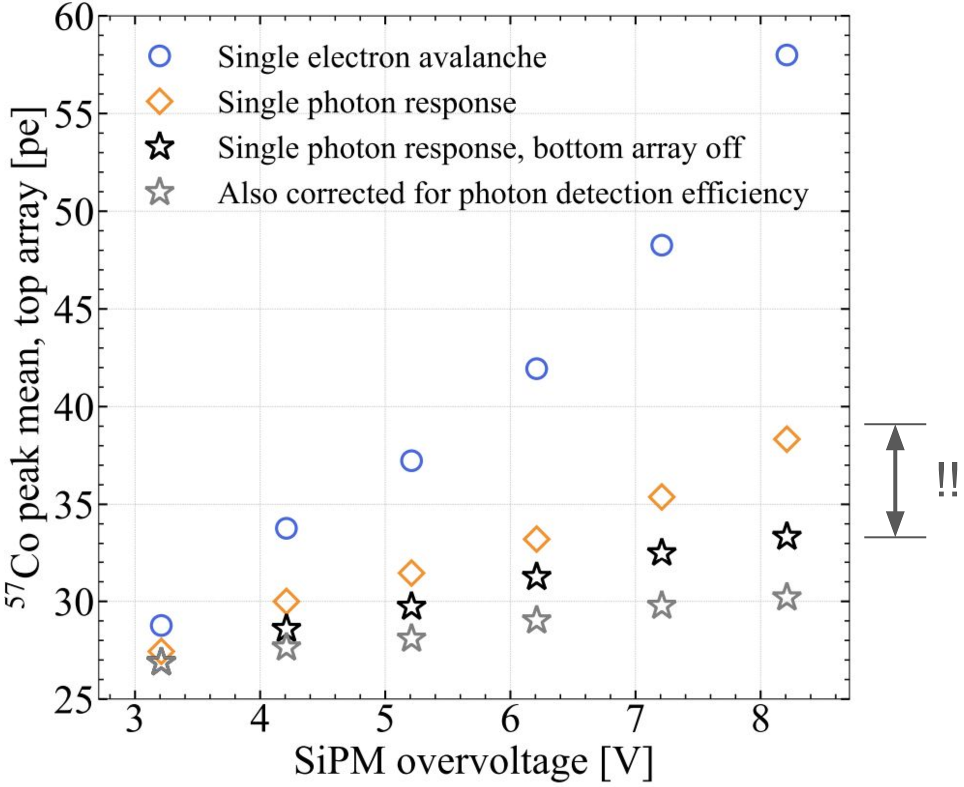


- In liquid we can operate at higher voltages ~5 kV on gate
  - single e- ~20-30 phd
- Single e- sensitivity not yet established in crystal
  - (limited to about 3.0–3.5 kV on gate)
- Estimate about 5 phd/single e-
  - While looking for single e-, noticed "too many" double phd pulses
  - Big distraction last summer



“Flashlight Effect” or external crosstalk (eCT) from SiPM





Effect of Flashlight on DM search

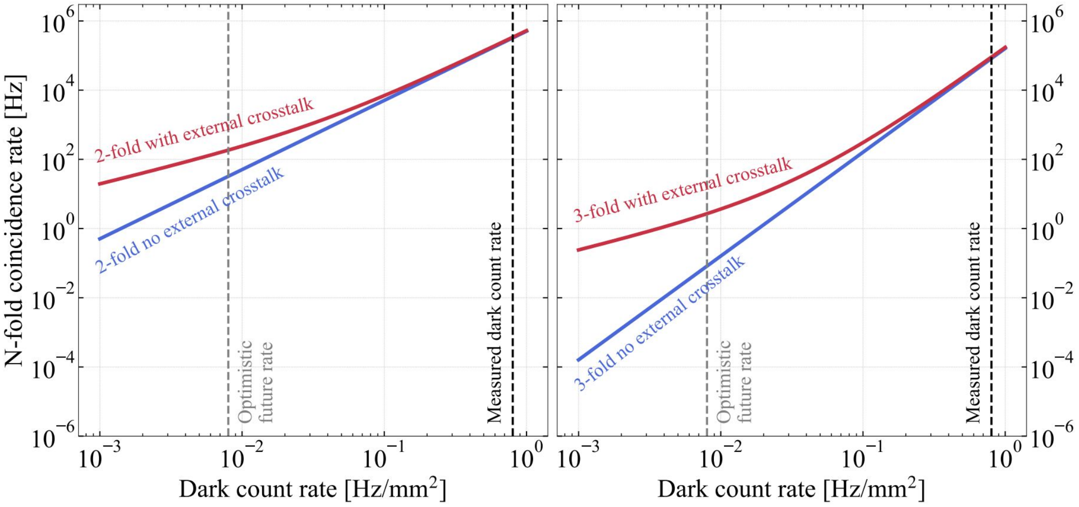
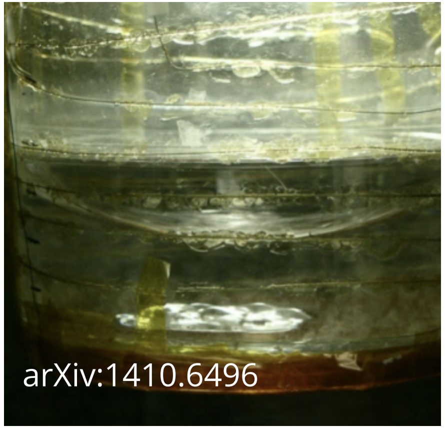


Figure 6. *Left:* the 2-fold coincidence values for a range of dark count rates using a fixed number of SiPM channels equivalent to the photosensor coverage in the LZ detector [24]. Two vertical dashed lines are shown: the measured dark count rate from ref. [11] and a dark count rate two orders of magnitude lower, as suggested in ref. [25]. *Right:* the same as the left panel, but for 3-fold coincidence.

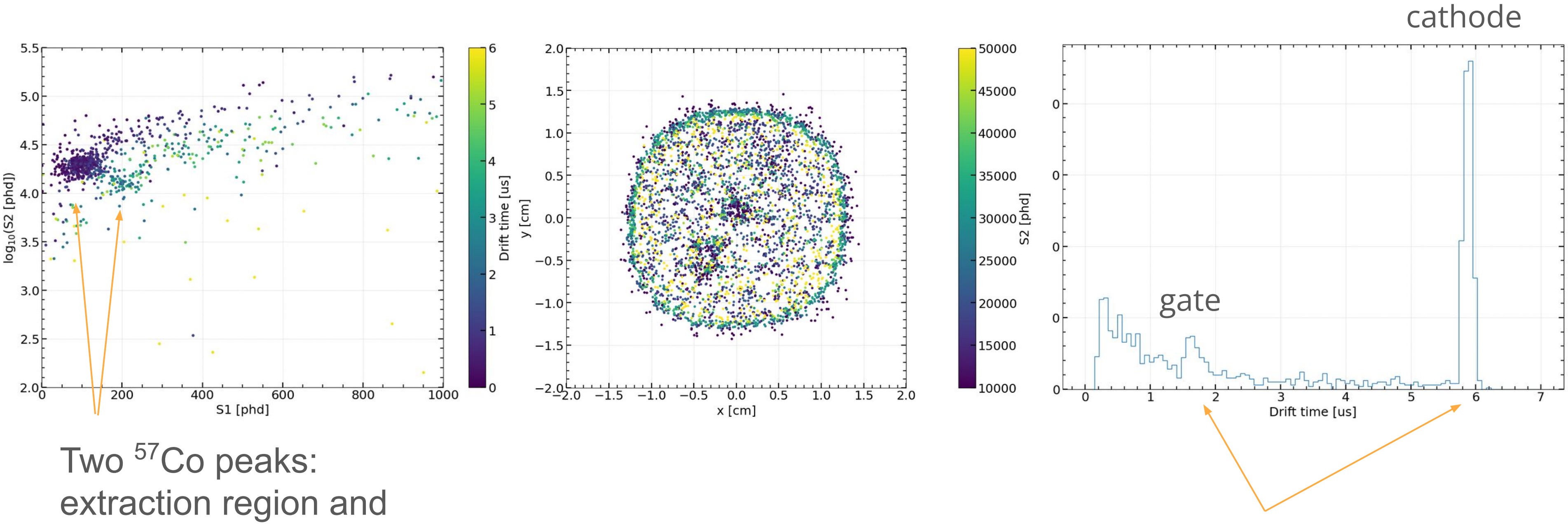
Crystal surface quality is a function of freeze conditions

source



Each freeze, we wonder: is it smooth? Level? Transparent?

Liquid data – ^{57}Co source

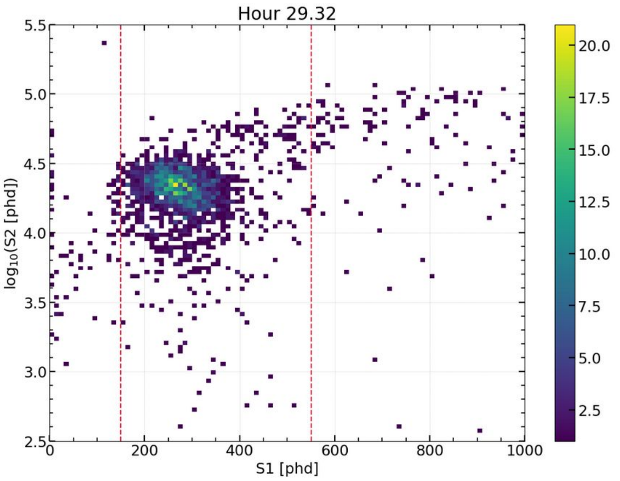


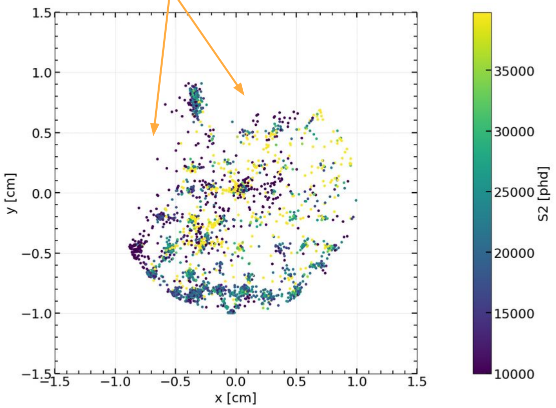
Two ^{57}Co peaks: extraction region and drift region

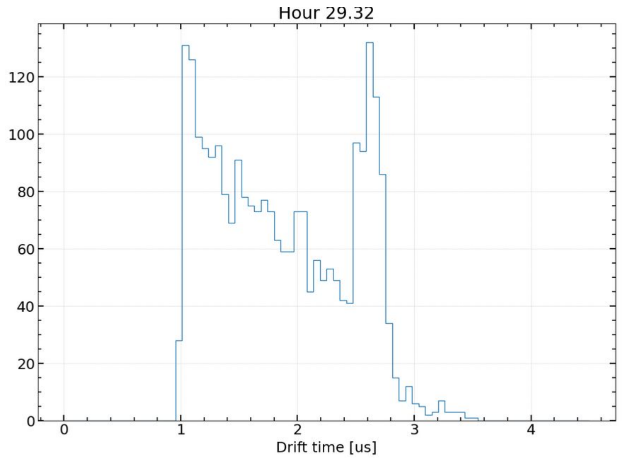
210Po source(s)

Crystal data with surface just at gate electrode

absence of events

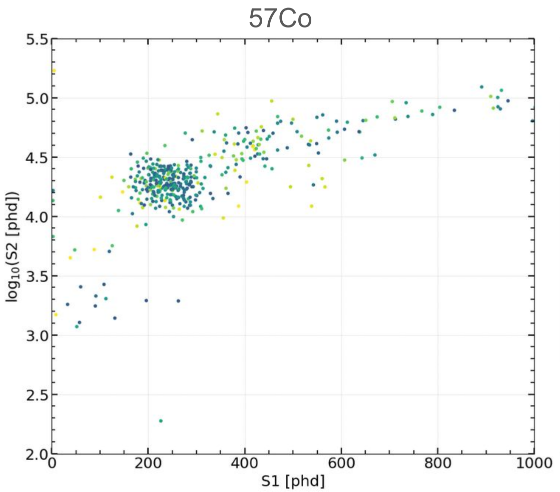


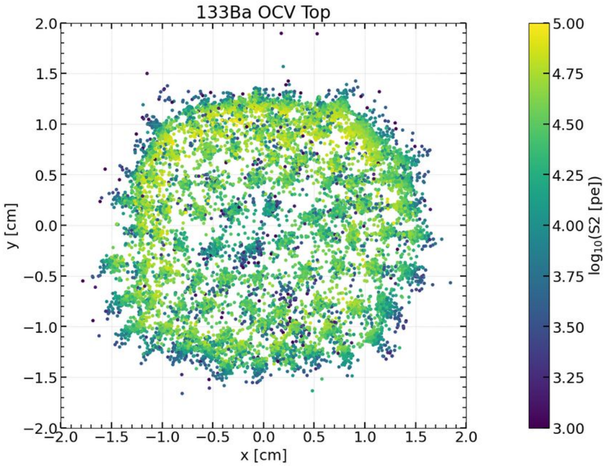


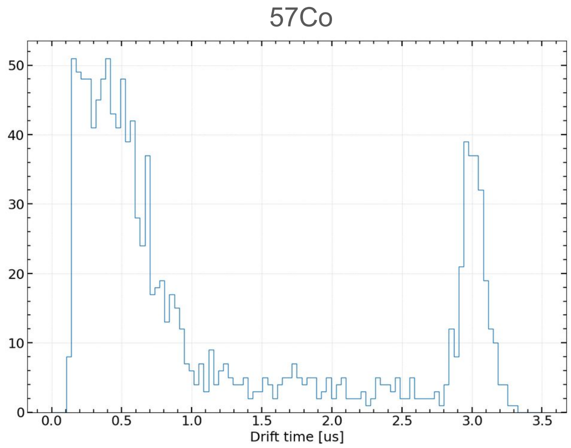


^{57}Co in drift region

Added 9 g more xenon and let it crystalize

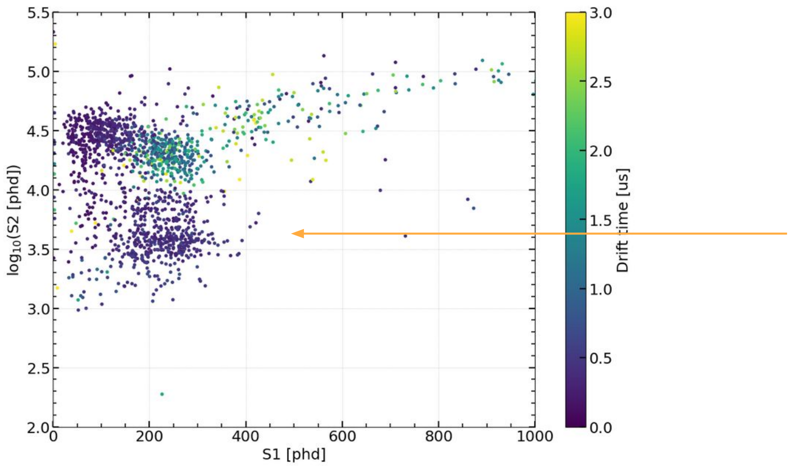






^{57}Co in drift region

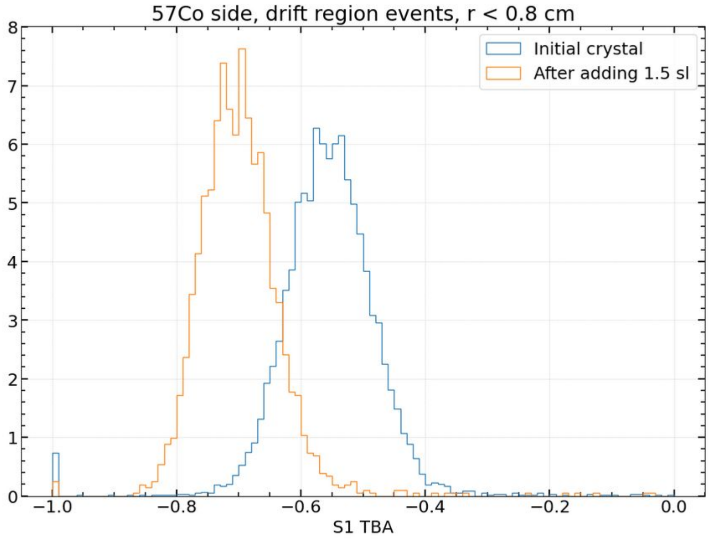
Same plot, but also showing extraction region events



A few hours later, a new blob appeared for short-drift time events (somehow related to sublimated crystal layer)

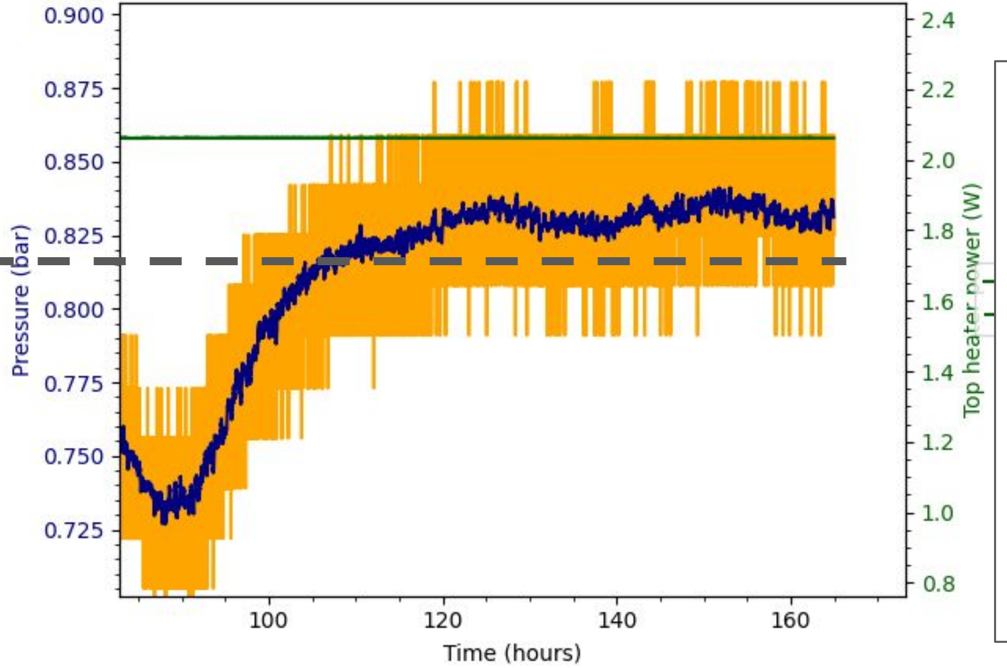
Surface transparency decreased, electron emission (locally) decreased

∴ avoid crystal growth via sublimation

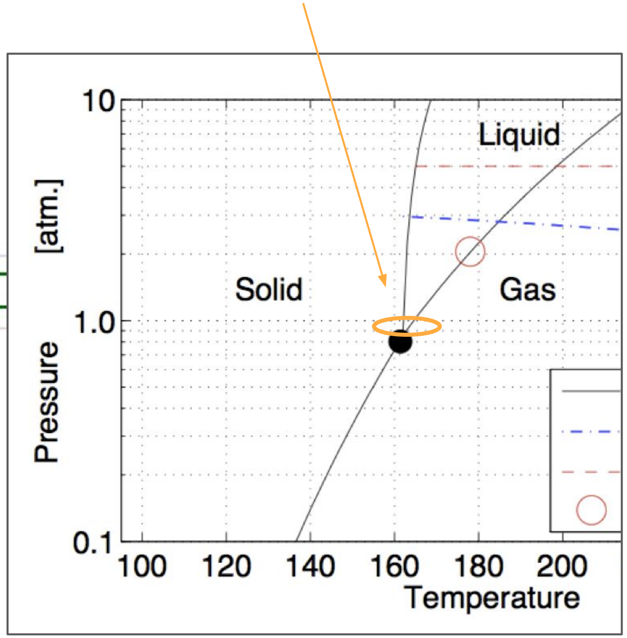


A possible solution to the surface problem: triple phase

Triple point

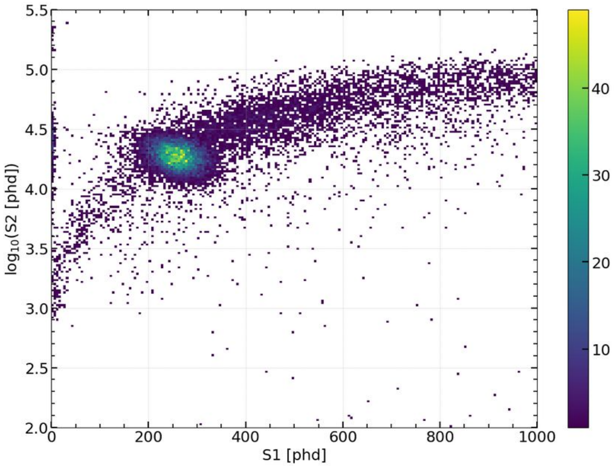


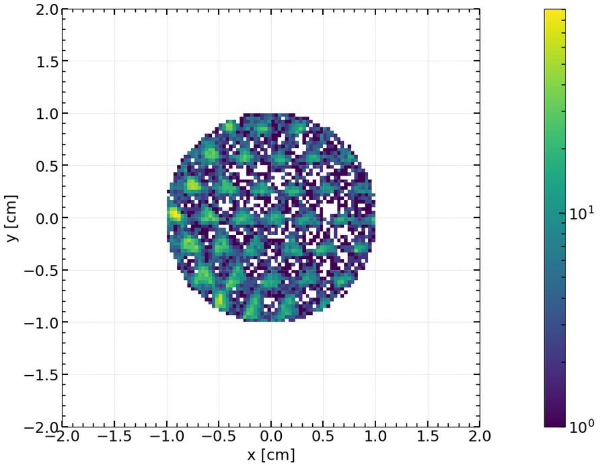
(offset exaggerated)

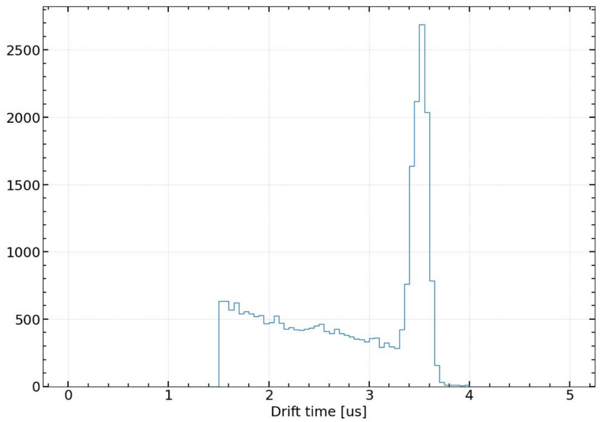


Triple phase! Wow.

- Better resolution than we obtained in liquid!
- Challenging to keep thermodynamics stable
- Still investigating







On deck: ER/NR discrimination improvement (hypothesis)

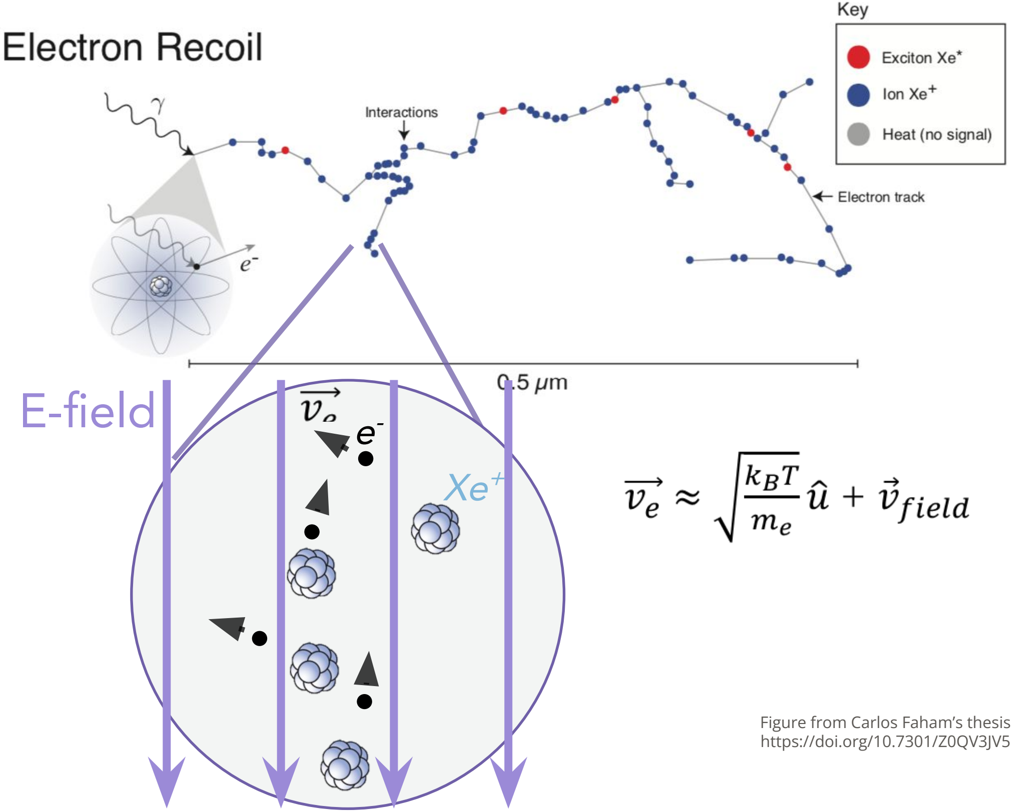
higher e- mobility in crystal Xe

↓

reduced recombination of thermal electrons?

↓

better ER/NR discrimination?



$$\vec{v_e} \approx \sqrt{\frac{k_B T}{m_e}}\,\hat{u} + \vec{v}_{field}$$

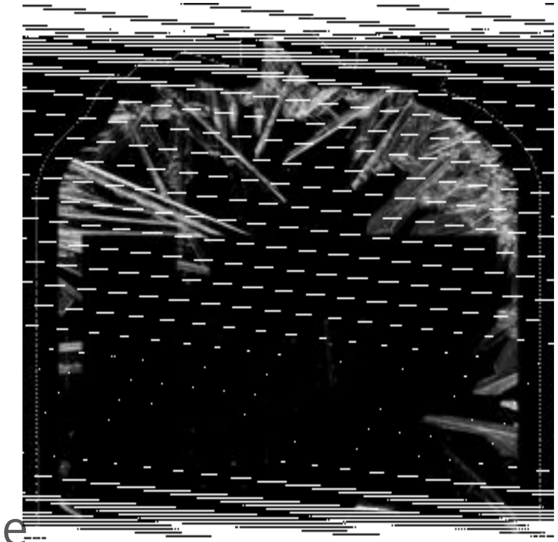
Figure from Carlos Faham's thesis
https://doi.org/10.7301/Z0QV3JV5

Crystal/vapor xenon TPC: preliminary conclusions

1. Still early days! Similar to liquid xenon TPCs last century (or maybe 2003 ish)
2. It works, but it needs work
3. It has a “killer app” (radon exclusion) and strong supporting properties (mobility, density), but it isn’t ballistic (yet?)

Crystal/vapor xenon TPC: open questions

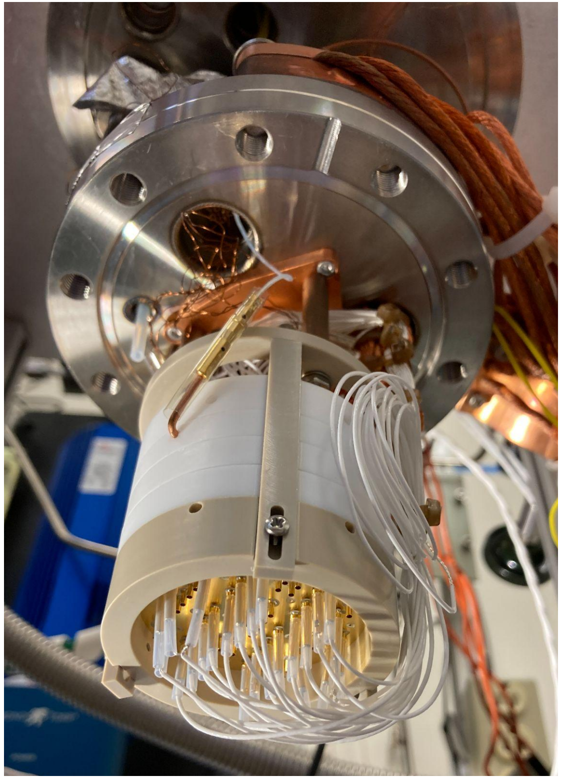
1. Demonstrate scaling to O(100) kg +
    a. without crystalline defect issues?
    b. with ms e- lifetimes
2. Control of surface and evolution
    a. does triple phase work?
3. Demonstrate single e- sensitivity
4. Investigate overall neutrality or “charging up” due to impurities
5. Is crystaLiZe compatible with H2/He doping? (HydroX) ?
6. Would we really freeze LZ or XENONnT (or beyond)?



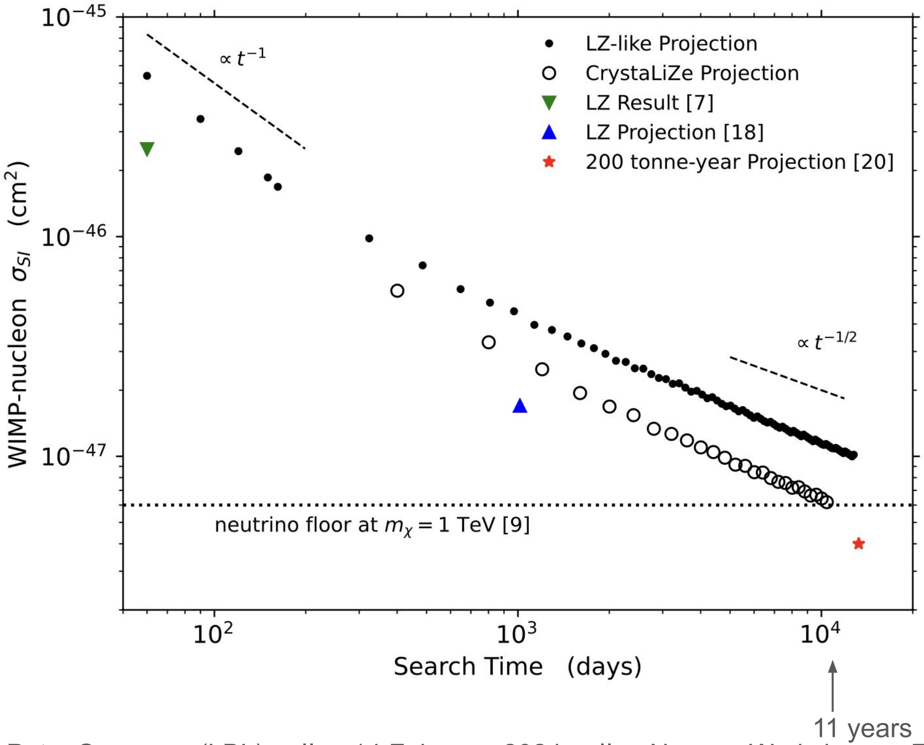
(gif does not imply LZ endorsement)

Extra slides follow

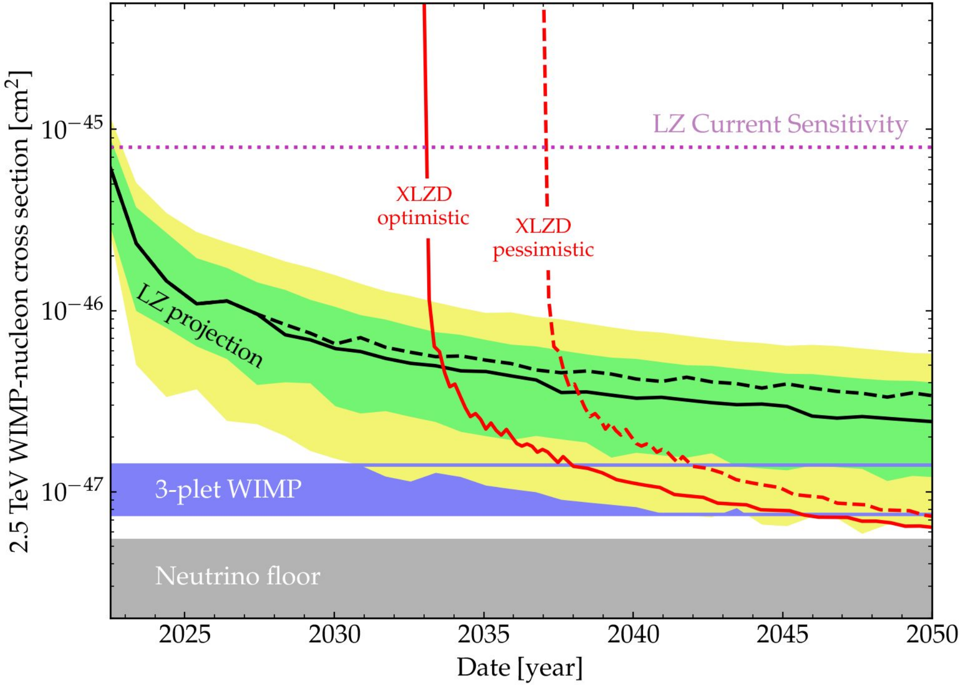
Test bed



Simple sensitivity projection w and wo radon



arxiv:2312.15082



LZ Current Sensitivity
XLZD optimistic
XLZD pessimistic
LZ projection
3-plet WIMP
Neutrino floor
2.5 TeV WIMP-nucleon cross section [cm^2]
10^{-45}
10^{-46}
10^{-47}
2025
2030
2035
2040
2045
2050
Date [year]