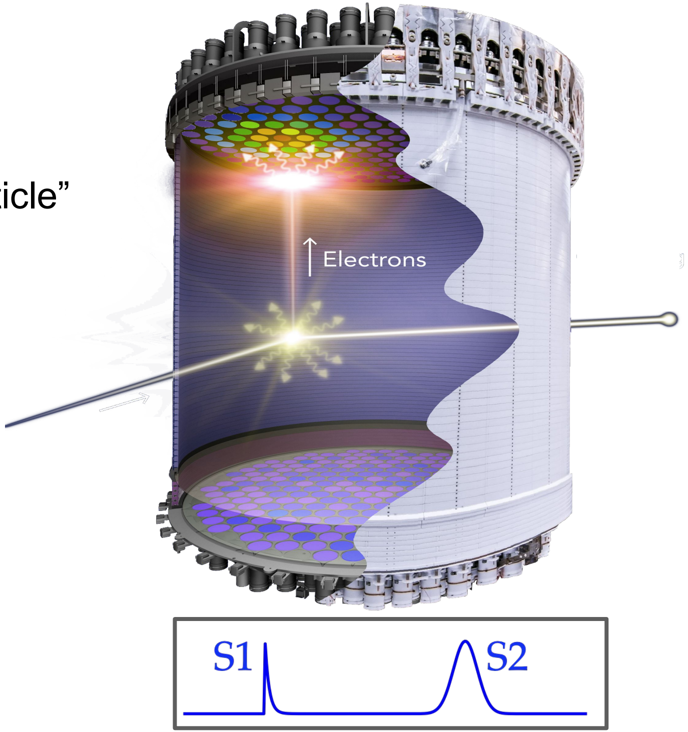
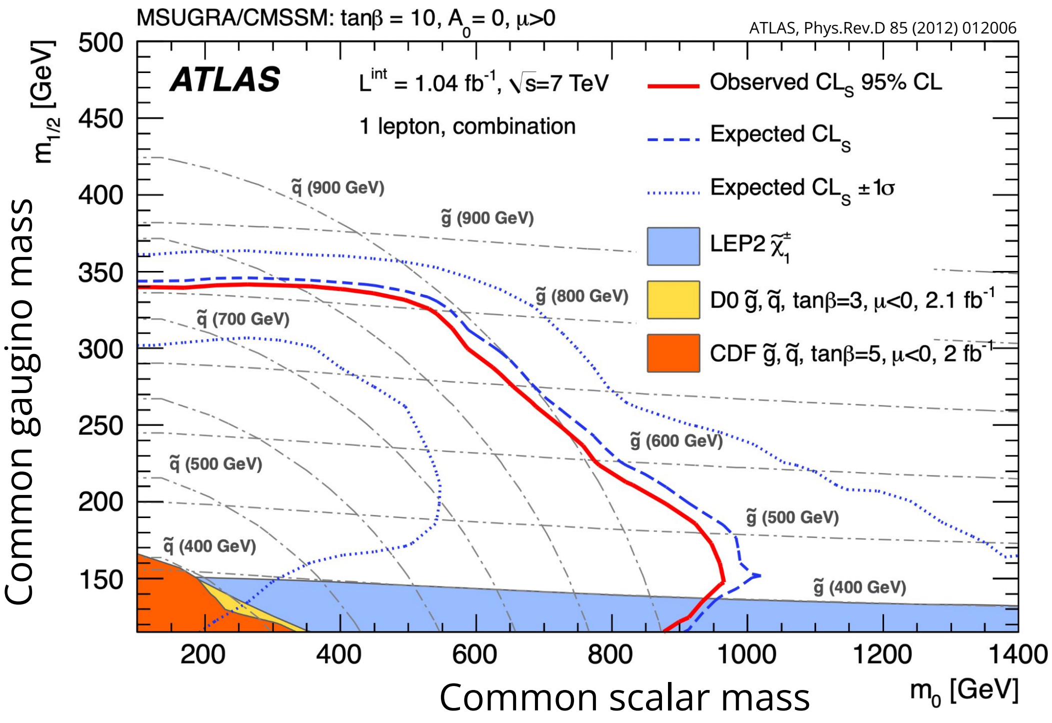
What are we looking for with LZ and LZ-like instruments?

a. “A specific model! e.g. a new weak scale particle”
b. “A surprise”

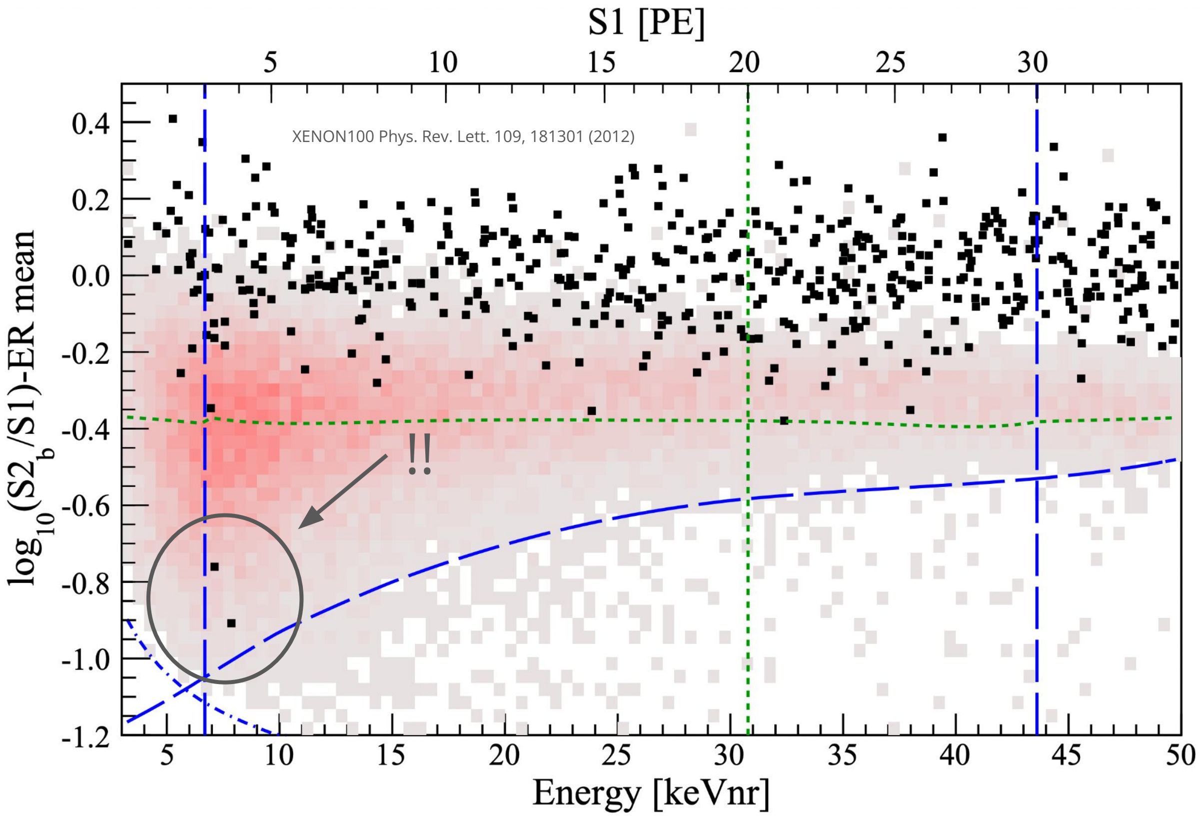


Summer of 2012, dark matter direct detection malaise

WIMPs excluded
up to ~100 GeV

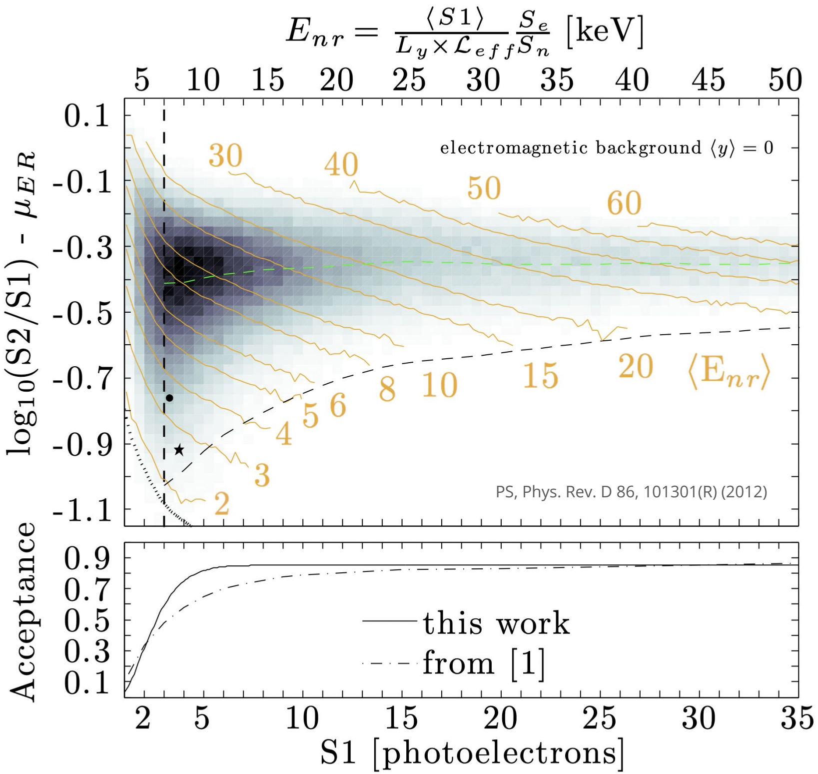


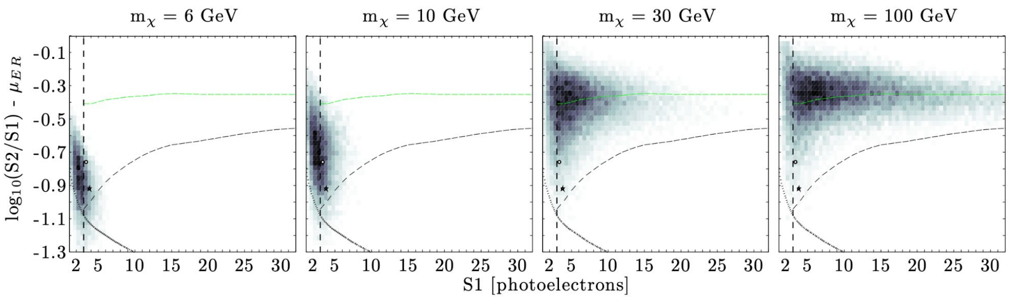
2012, Surprise!

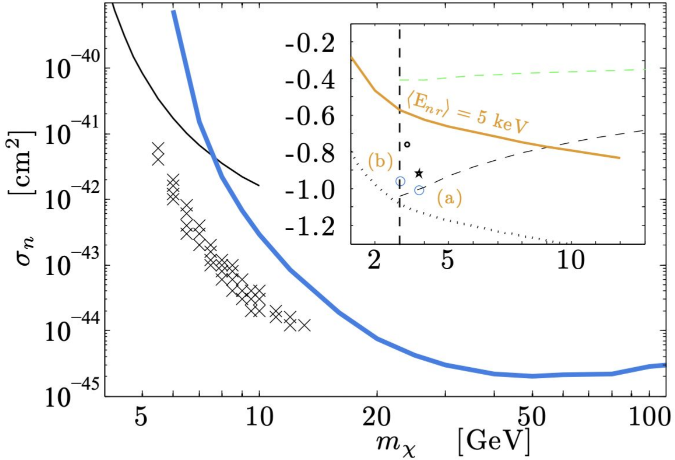


"The PL analysis yields a p-value of ≥ 5% for all WIMP masses for the background-only hypothesis indicating that there is no excess due to a dark matter signal. The probability that the expected background in the benchmark region fluctuates to 2 events is 26.4% and confirms this conclusion." – XENON100

I disagreed – the excess 2 events look like ~10 GeV dark matter!







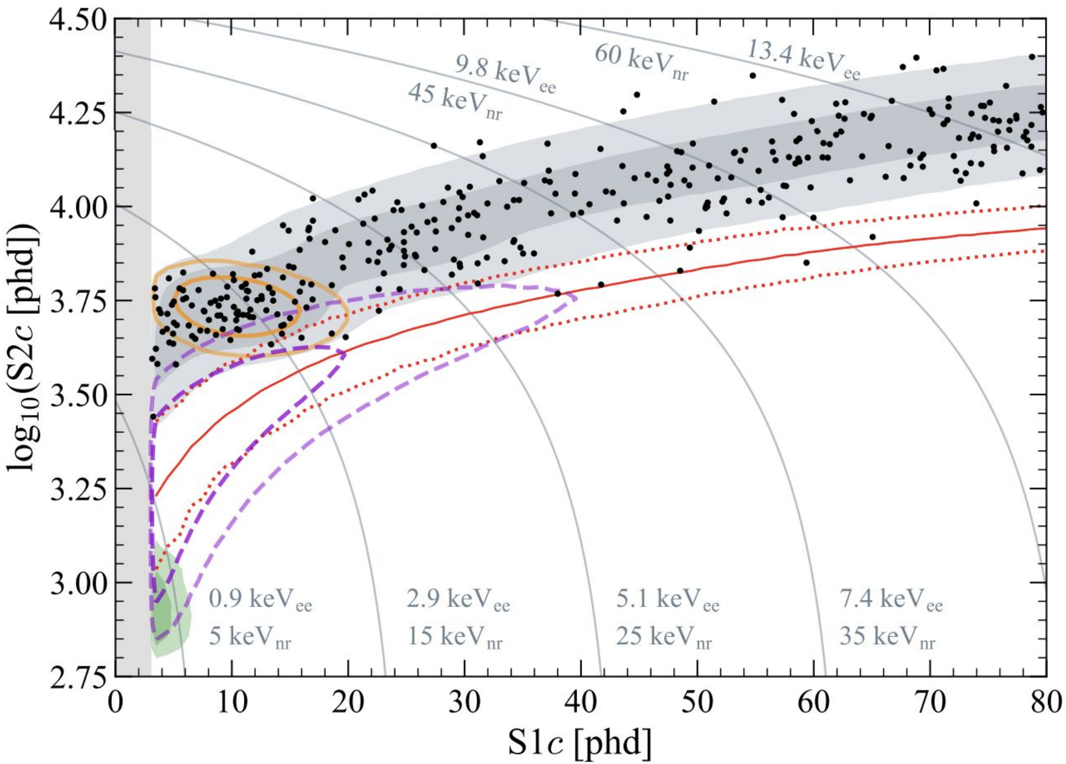
Background obscures possibility of surprise

LZ Backgrounds paper arXiv:2211.17120, Table VI

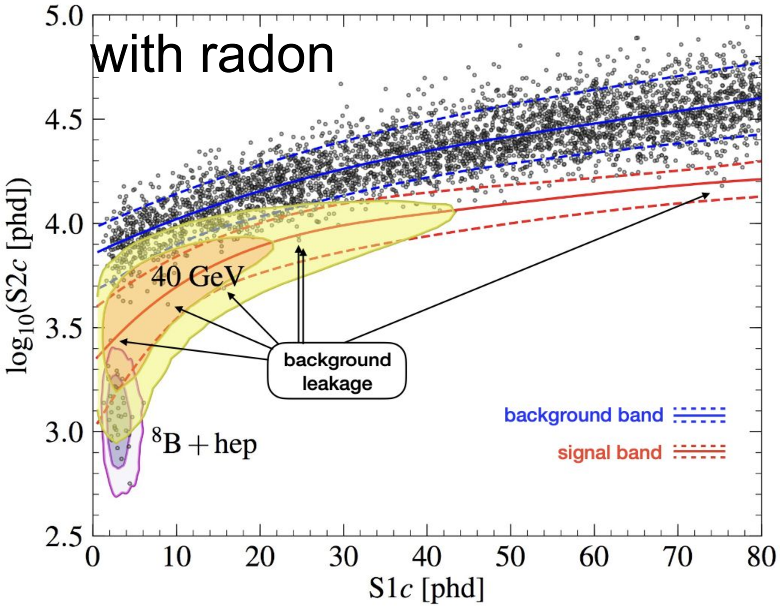
Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals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

- ^{214}Pb, ^{212}Pb: Tagging can help, crystaLiZe can solve
- ^{85}Kr: $, time and SLAC can solve
- ν ER: Interesting + others can measure
- ^{127}Xe: time can solve
- ^{136}Xe: $ can solve (give it to nEXO :)
- Accidentals: Detector design, clever selection can solve

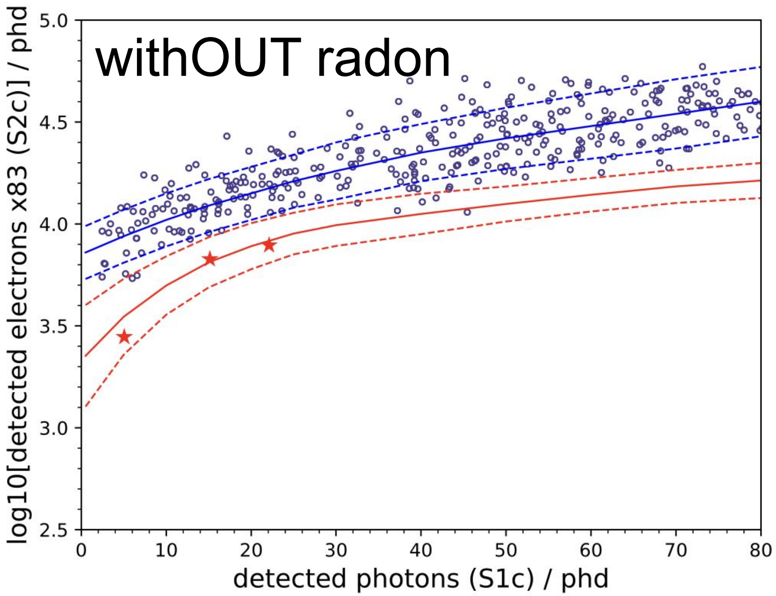
LZ First Results



LZ full exposure 1000 days x 5.6 tonnes PROJECTIONS



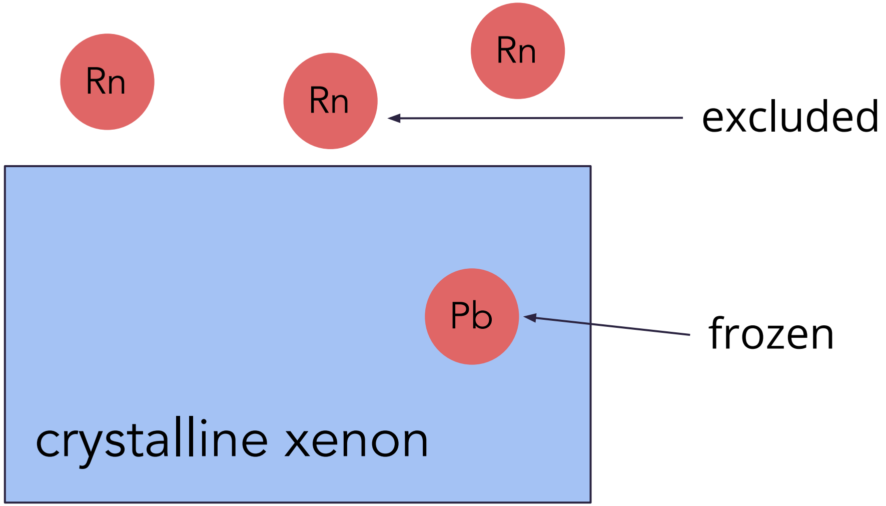
Annotated from LZ Collab arxiv:1802.06039

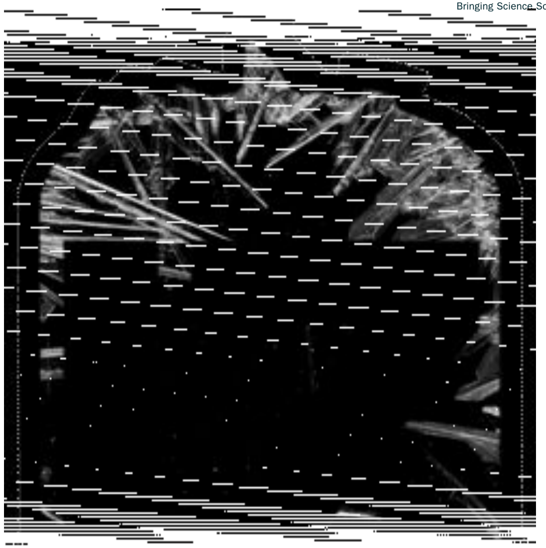


non-LZ simulation, excluding 8B neutrinos

Towards radon-free: “crystaLiZe” R&D @LBL

- liquid/vapor xenon TPC
  - ⇒ crystal/vapor xenon TPC

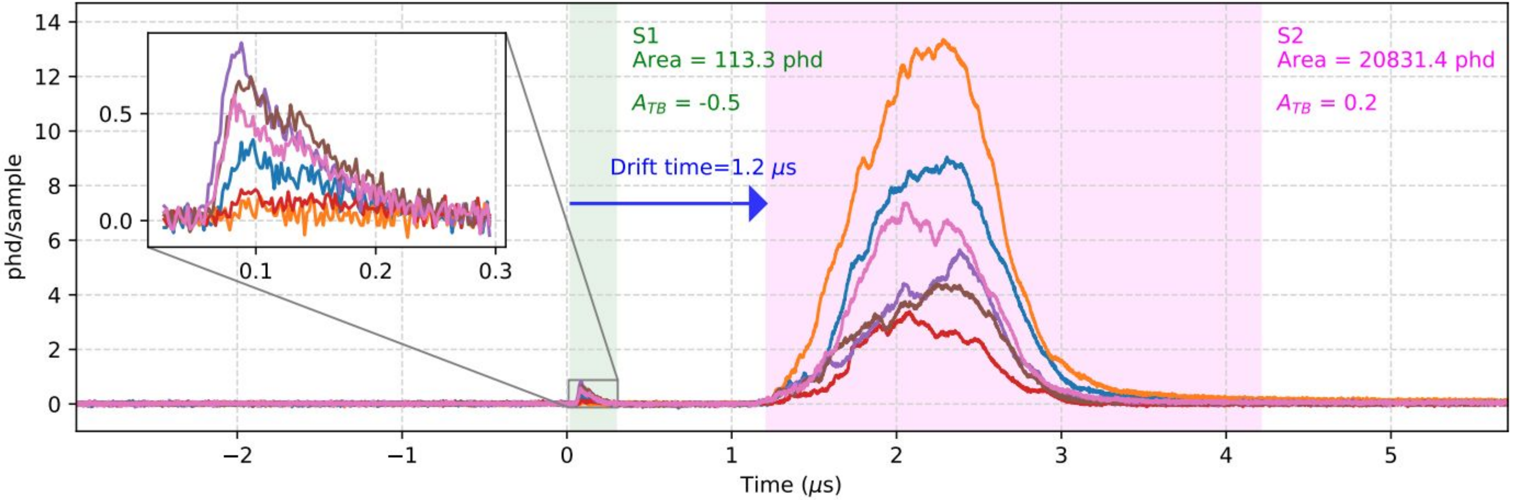




“crystaLiZe”
LZ upgrade concept

Crystalline xenon as particle detector – it works!

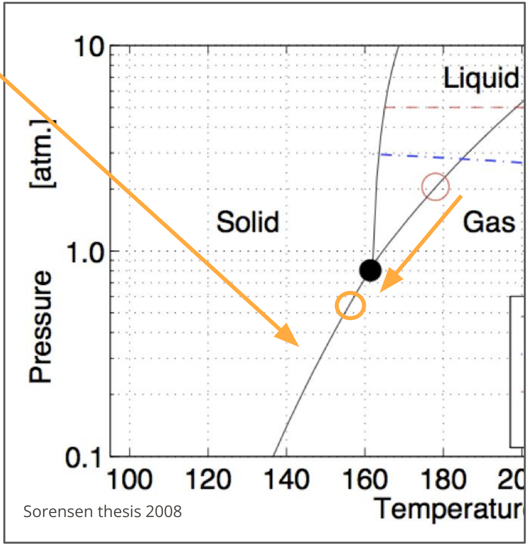
observe S1 and S2 in crystal/vapor TPC, just as in liquid/vapor TPC



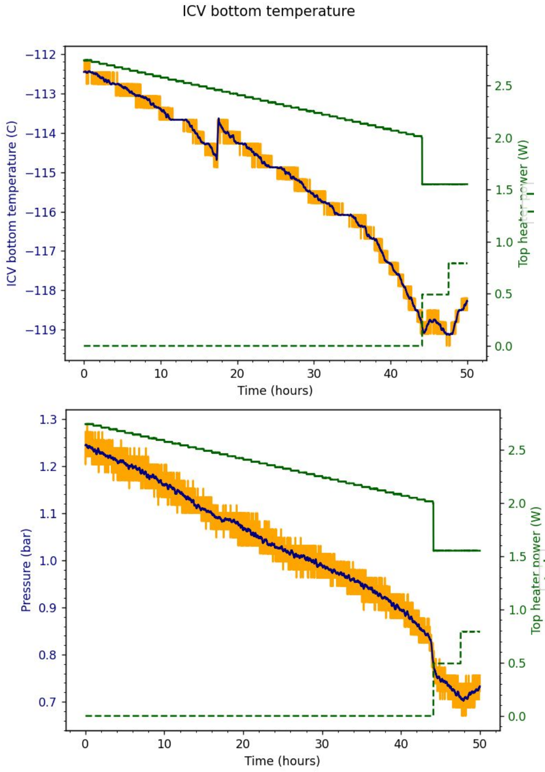
arXiv: 2201.05740 also in [JINST]

Crystalline xenon as particle detector

- **Walk down phase boundary ~20 K**
- Same electron and photon yields (photon verified)
- Easier e- emission into vapor
- Mobility increase x2
- Density increase x1.17
- Radon exclusion (> x1000)



Sorensen thesis 2008



Freezing from bottom to top

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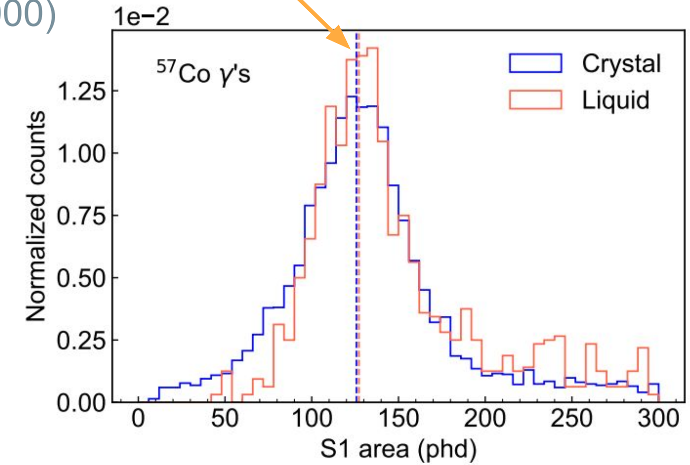
Phys Rev B 10 4464 (1974)

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
$\|a\|$	3.8×10^{-9}	4.2×10^{-9}	cm
$\|E_{1CB}\|$	0.93	1.01	eV



Also expected theoretically based on nearly identical E_G in liquid/solid

Our result arXiv:2201.05740

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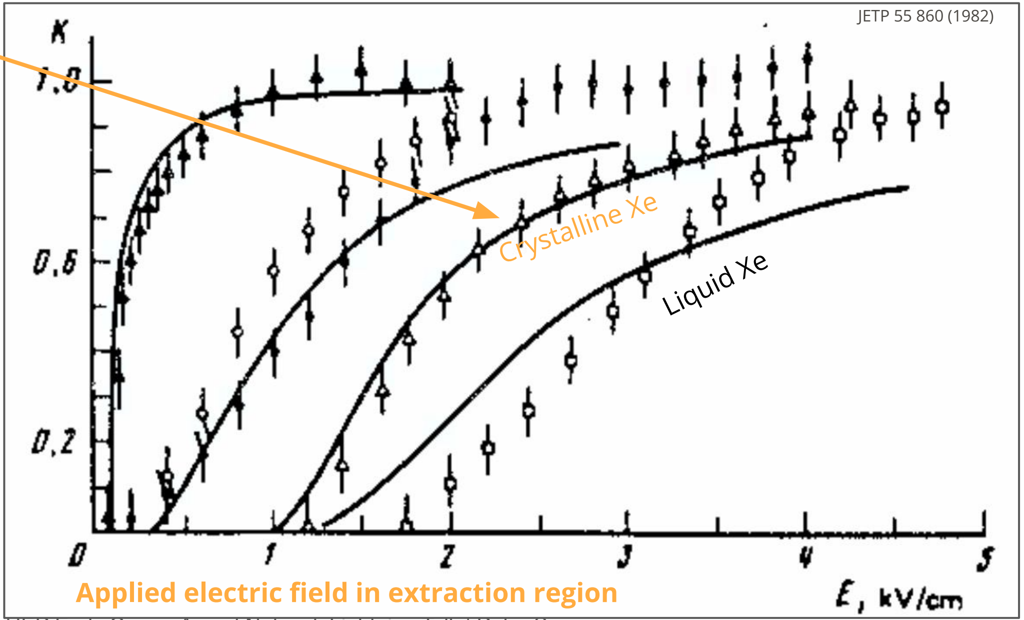

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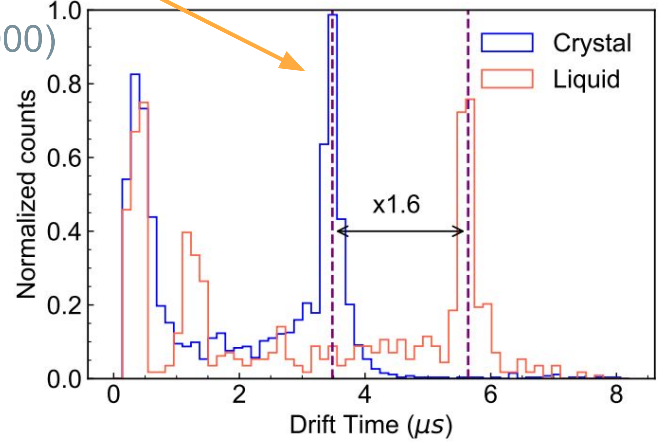

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$\lvert E_{1CB} \rvert$	0.93	1.01	eV

Our result arXiv:2201.05740 from 210Po alphas on the cathode shows x1.6, but is consistent with x2 (uncertainty in crystal surface z position)

Crystalline xenon as particle detector

- Walk down phase boundary ~20 K
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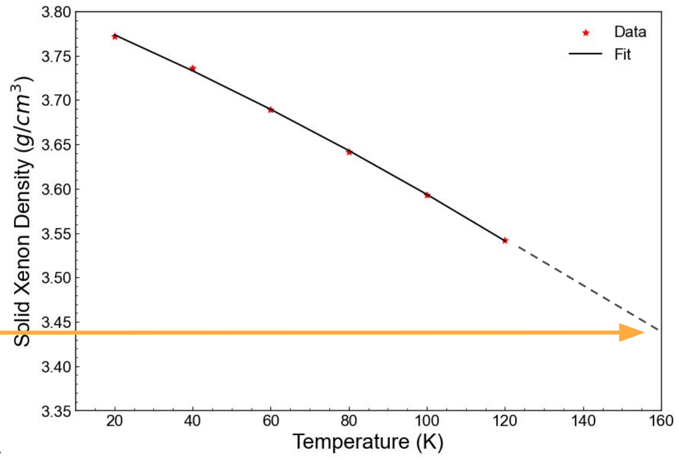
- Easier e- emission into vapor
- Mobility increase x2
- **Density increase x1.17**
- Radon exclusion (> x1000)

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

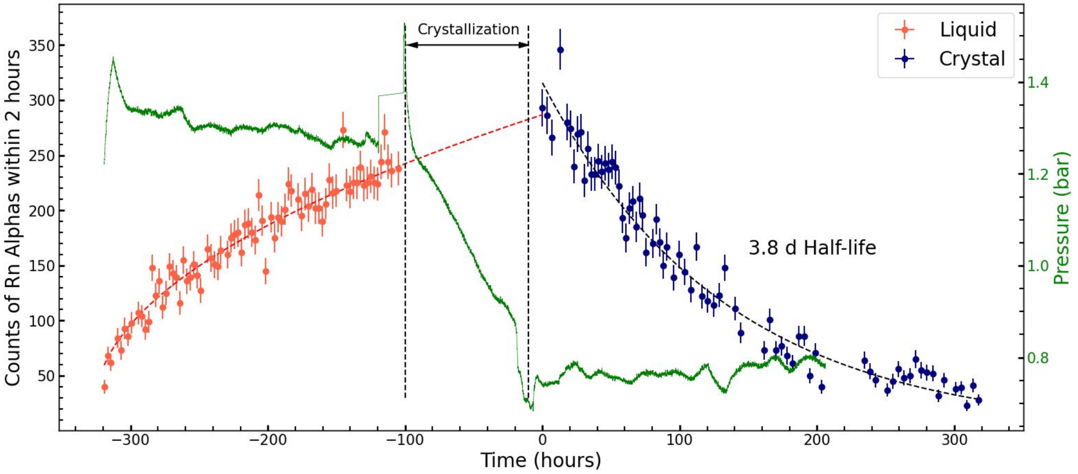


Extrapolate to 3.44 g/cm^3 at triple point

Crystalline xenon as particle detector

- Walk down phase boundary ~20 K
- Same 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



Not shown: x1000 exclusion of radon tested with 220Rn source
cf. H. Chen talk at UCLA

Next: ER/NR discrimination improvement? TBD!

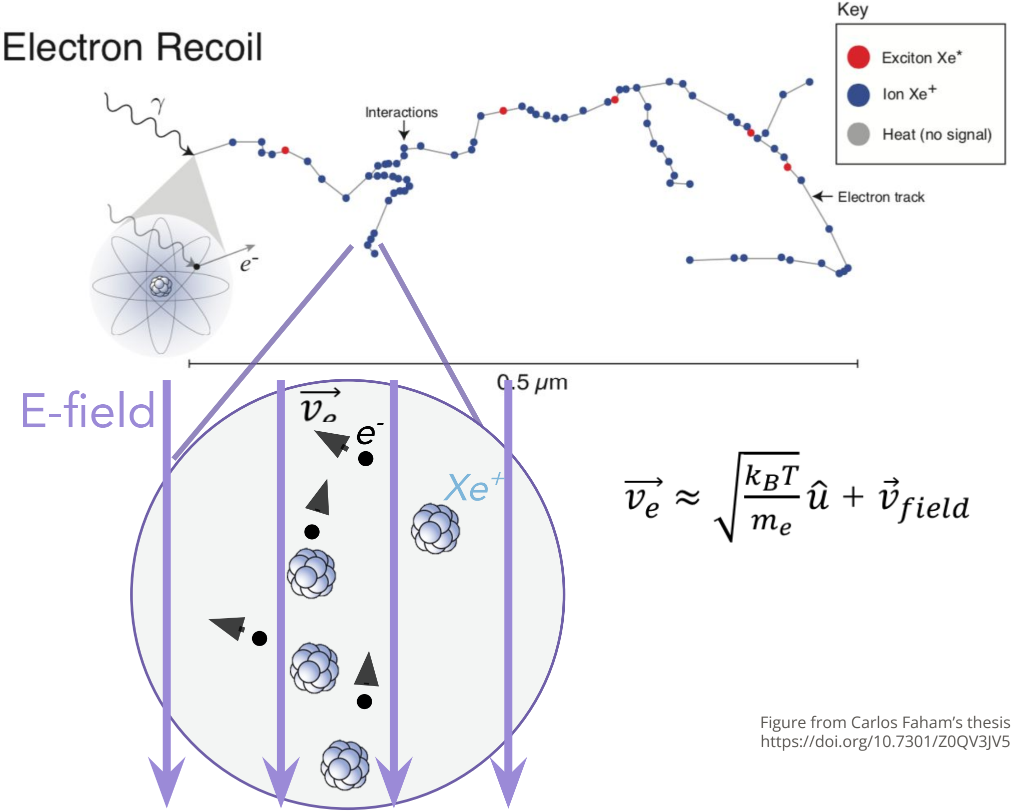
x2 e- mobility in crystal Xe

?

Less recombination of thermal electrons?

Smaller fluctuations from recombination, narrower bands in S2 vs S?

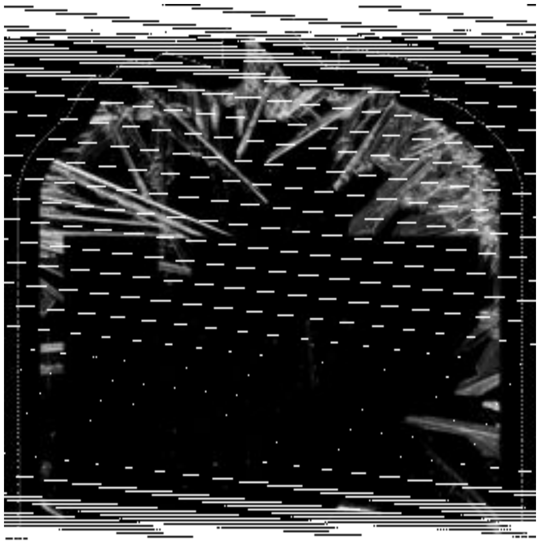
Better ER/NR discrimination from S1/S2 ratio?



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

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

Crystalline xenon TPC – open questions



1. Does it scale gracefully from grams to tonnes?
   a. Need: a bigger test bed. UT Austin planning ~10 kg (Kravitz)
2. Are crystalline defects an issue?
   a. Preliminarily, no
   b. Need: bigger test bed to explore 3D response.
3. How can the thermal model/implementation be improved?
   a. Example: does the cathode connection cable locally melt the ice? Do asymmetries in phi affect the surface?
4. What does the ice surface look like? Does it matter?
   a. Need: camera, boroscope, light source
   b. S2 response (not at the same time)
5. What about overall crystal neutrality or “charging up” ?
   a. Super-interesting question. We see some preliminary evidence that the S2 response can degrade over time. Yet the e- and h+ mobility are larger in crystal than in liquid. Mystery!
6. Can one operate crystalline xenon at mK temperatures with TES readout?
7. Is the discrimination the same or better in crystal xenon?
   a. We hope to address this in the final year of ECA
8. Do PMTs work in crystal? We have been using SiPMs…
9. Is crystaLiZe compatible with HydroX (hydrogen doping of xenon)?
   a. UCSB working on HydroX, LBL (Manalaysay) has a new LDRD on this topic
10. Would we really freeze LZ or XENONnT?