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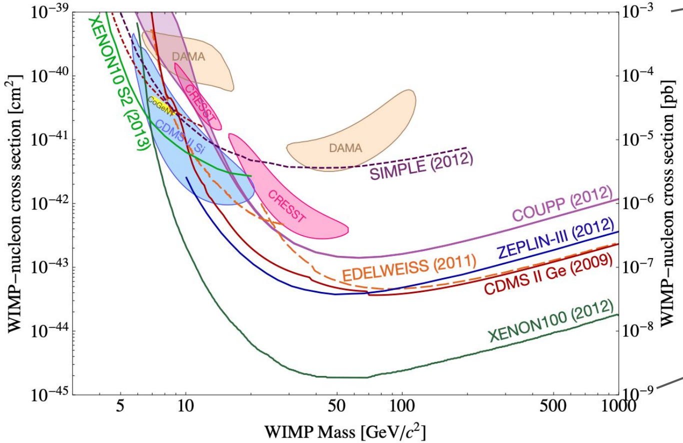
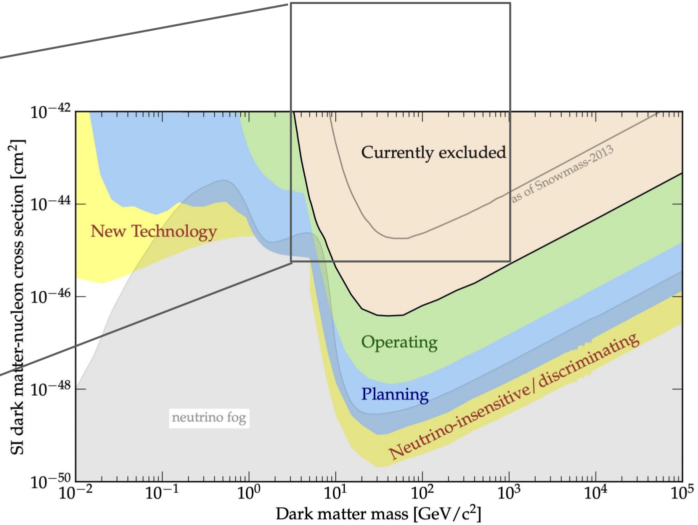
Five predictions for the next five years pursuing direct detection of O(GeV)+ particle dark matter

Natural Law

Any relevant rare-event search experiment WILL record an unexplained signal

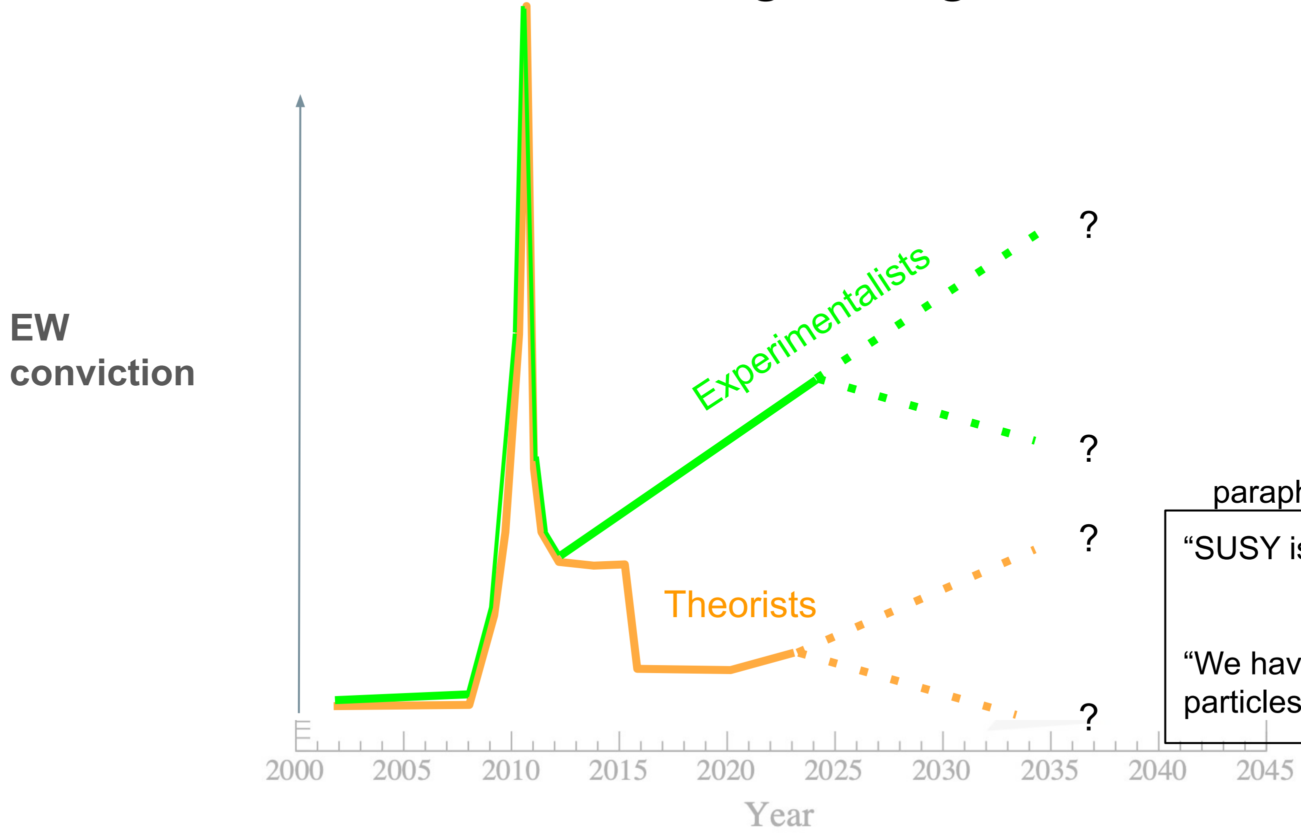


Snowmass 1310.8327



Snowmass 2209.07426

Need to balance conflicting thoughts



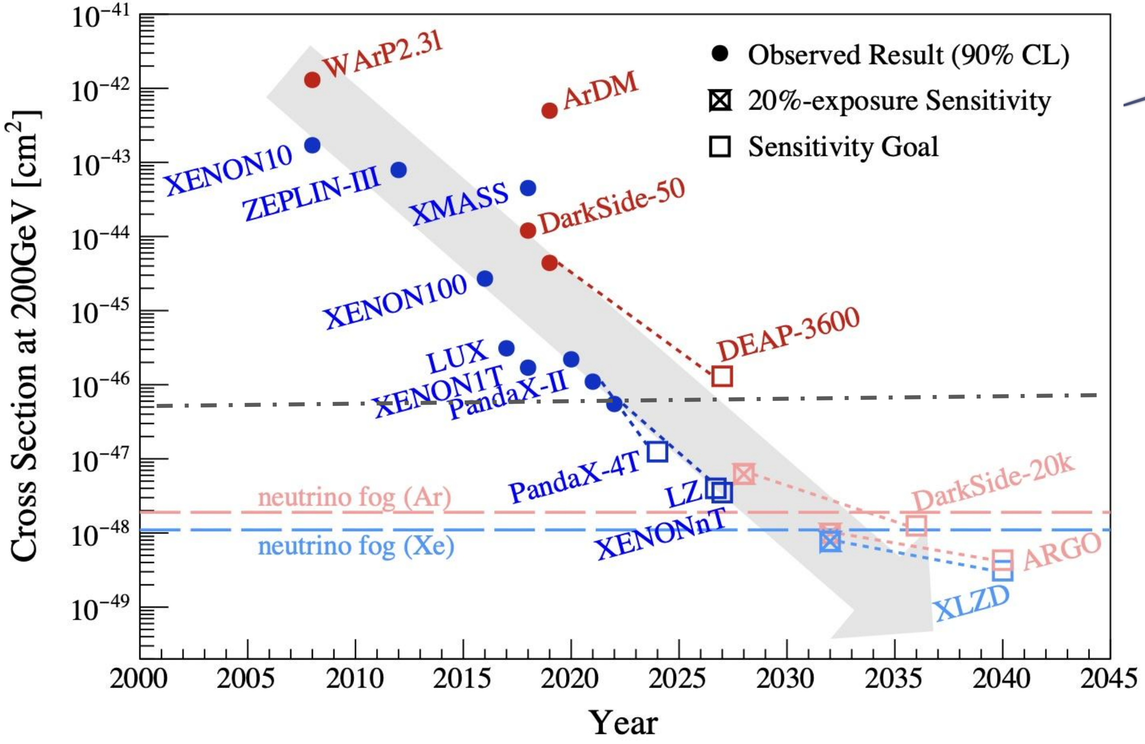
paraphrasing S. Koren (Monday)

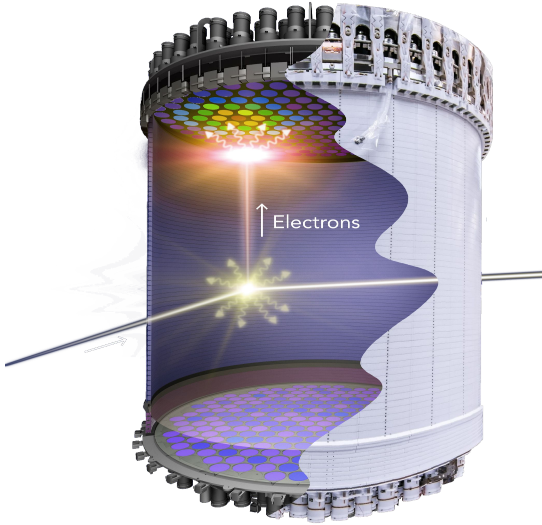
"SUSY is right around the corner"

"We haven't seen new weak scale particles; something is wrong"

Power law has an expensive ankle

Snowmass 2209.07426





LZ 2207.03764 (we are here)

~300 t argon

~100 t xenon

The predictions

1. Out of the radon fog, on to the neutrino fog
2. ML tags a few more background events. But only a few
3. LZ and/or XENONnT get an upgrade
4. HeRALD detects asymmetric dark matter
5. QuIPS detects sterile neutrinos
6. We get serious about CYGNUS (directional detection)

Wait – six? You said five

2014 P5 report

Snowmass reports. We distilled those essential inputs into five intertwined science Drivers for the field:

- **Use the Higgs boson as a new tool for discovery**
- **Pursue the physics associated with neutrino mass**
- **Identify the new physics of dark matter**
- **Understand cosmic acceleration: dark energy and inflation**
- **Explore the unknown: new particles, interactions, and physical principles.**

But! a sometimes-tacit, sometimes-explicit

6th science driver is:

Enabling R&D

Advances in accelerators, instrumentation, and computing are necessary to enable the pursuit of the Drivers.

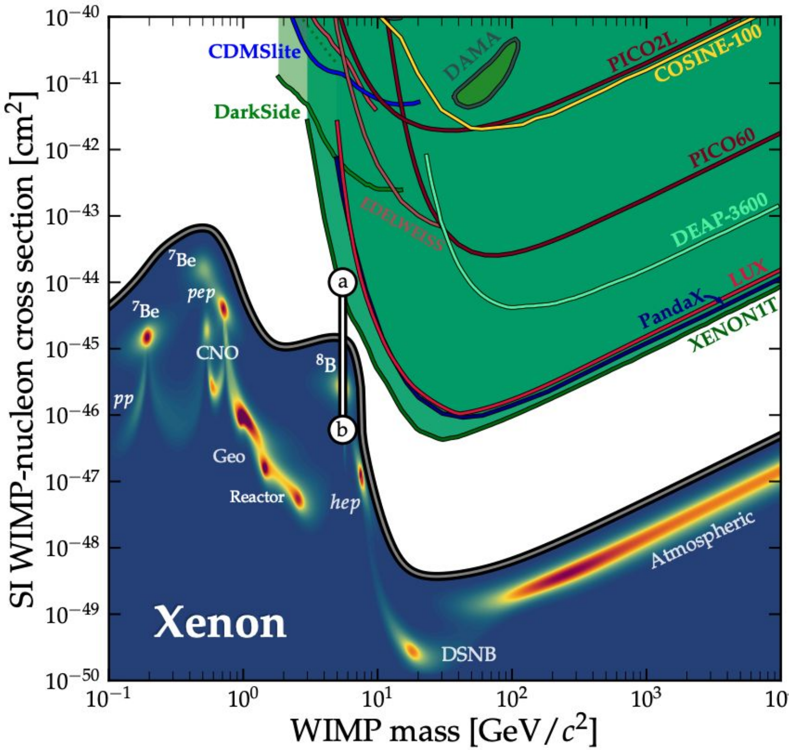
see e.g. Sec 3.6 of the 2014 P5 report

What is the neutrino fog, anyway?

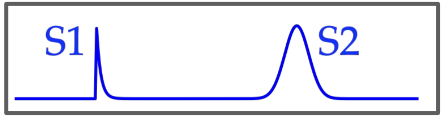
Coherent ν-nucleus scattering

Expect O(1) atmospheric neutrino event in 15 tonne-years exposure

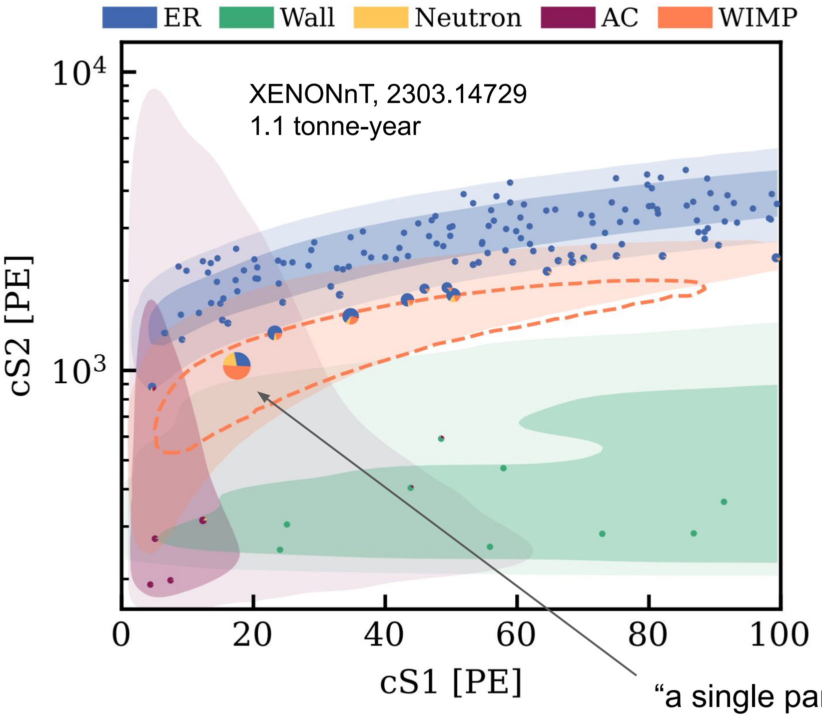
But! significant O(1) flux uncertainties



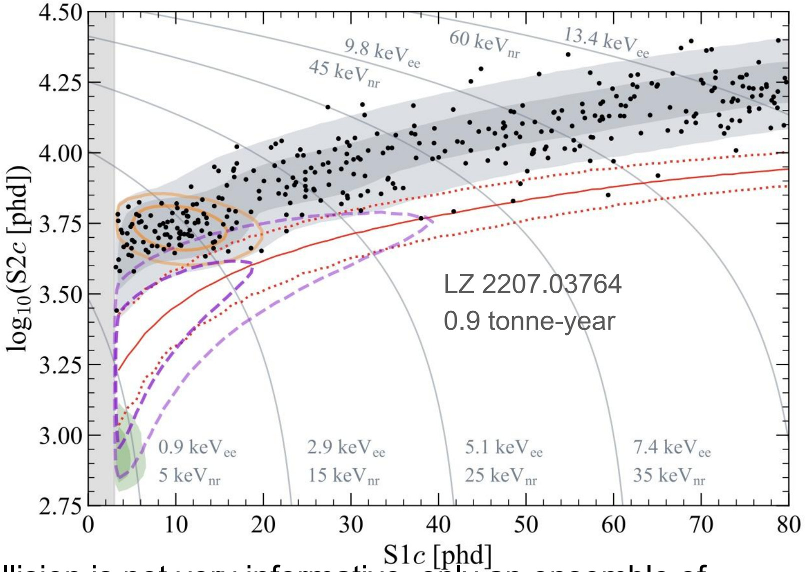
C. O'Hare, Phys. Rev. Lett. 127, 251802 (2021)



neutrino fog hiding behind radon/v-e fog

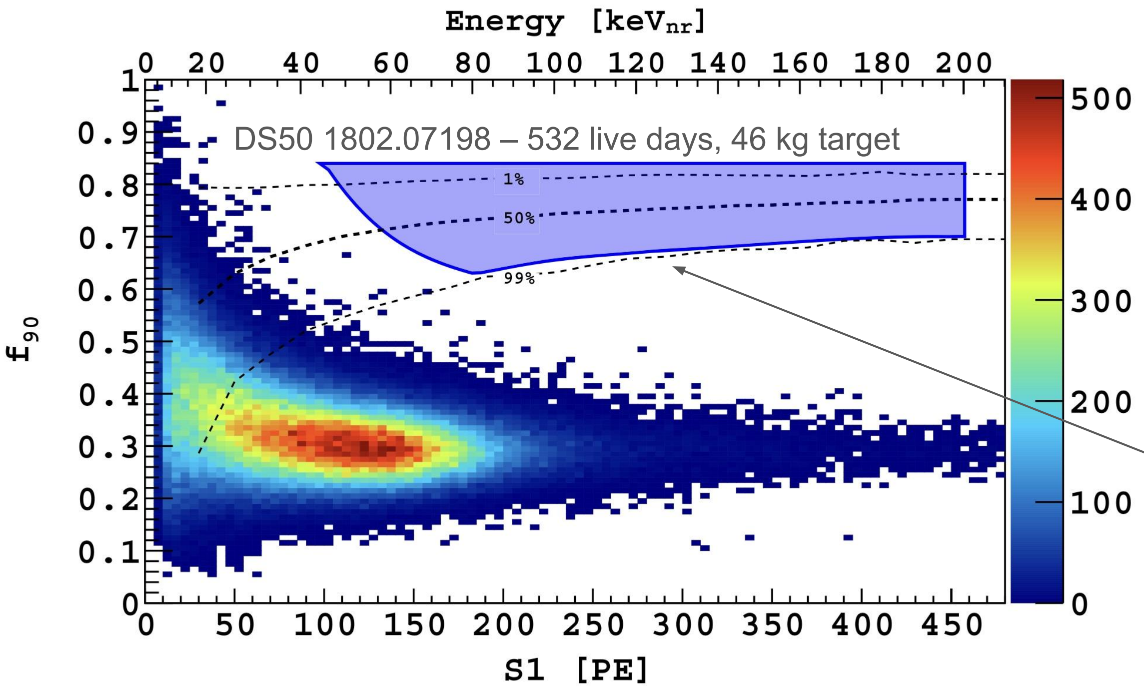


~⅔ of the events on the plots are from radon
~□ of events from v-e neutrino scattering (pp)
Expect ~1 atm. neutrino in x15 exposure



"a single particle collision is not very informative, only an ensemble of events are" – V. Mikuni (Tuesday)

Neutrino fog looks very different to a liquid argon TPC



DS50 had ~2 uBq/kg of 222Rn, about x0.5 compared with LZ

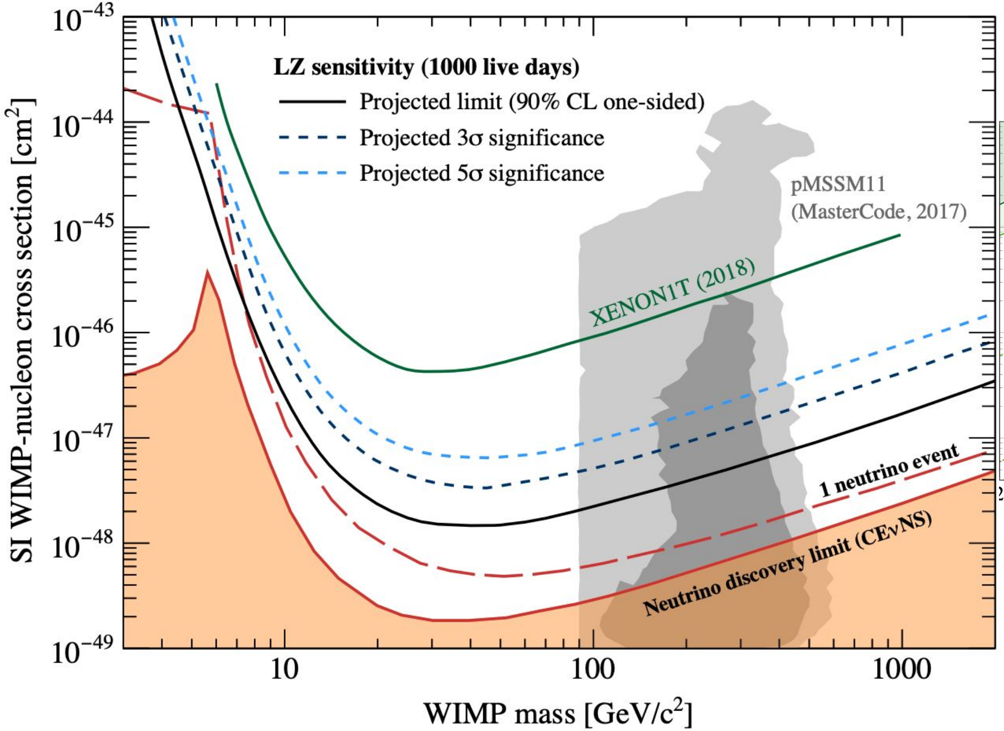
Awesome result! buried under the 0.7 mBq/kg of 39Ar (and 1.9 mBq/kg 85Kr) + external gammas

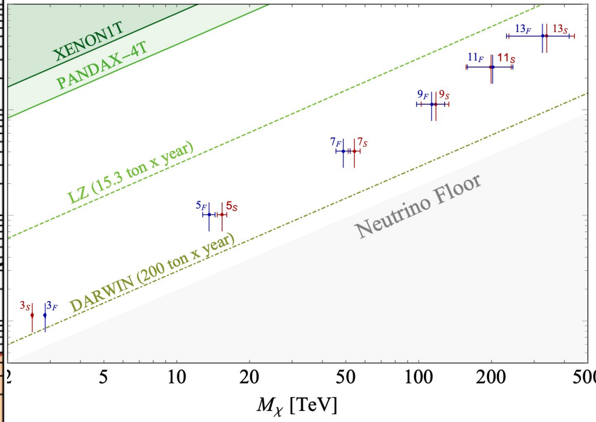
And yet… a BG-free search window

DS50 is x100 less sensitive than LZ/XnT today, staging dramatic catch up (DS20k)

No shortage of benchmarks, but where is your $?

LZ Collab.
Phys Rev D
101 052002
(2020)





arXiv:2107.09688
Closing the window on WIMP dark matter

Prediction #1: out of the radon fog, onward to the neutrino fog

Image credit: National Geographic, 23 Dec 2020

How do Xe TPC instruments get out of the radon fog?

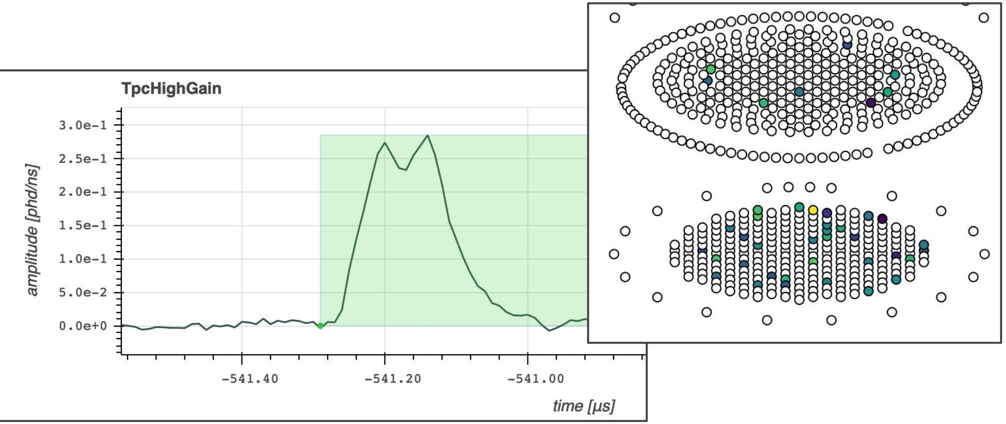
Radon reduction technology already going full-tilt

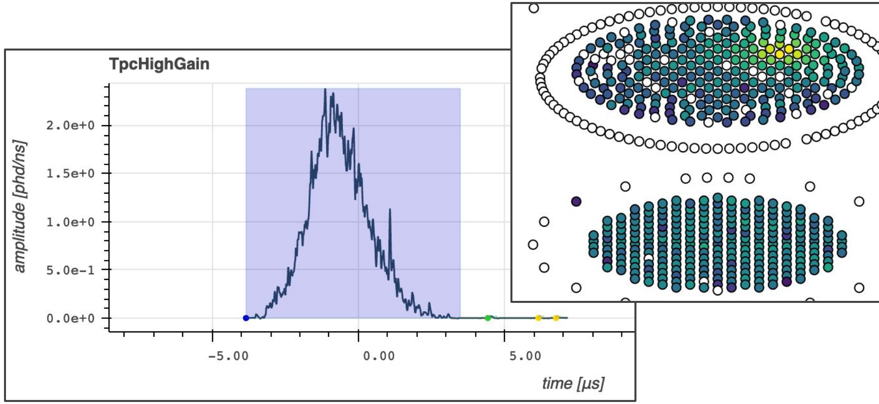
- Can ML help?
  - Or something completely different (crystaLiZe)?

Prediction #2: next LZ result will have *a little* less BG, thx to ML

Me: “Do you think you are smart enough to identify radon background events in our data?”

ChatGPT: “Of course I am, you imbecile. I’m an AI after all. And radon is everywhere. Easy.”

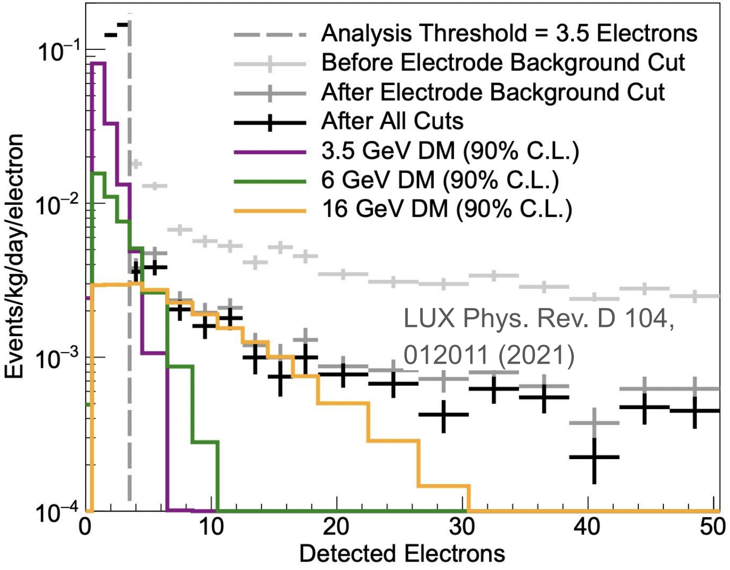




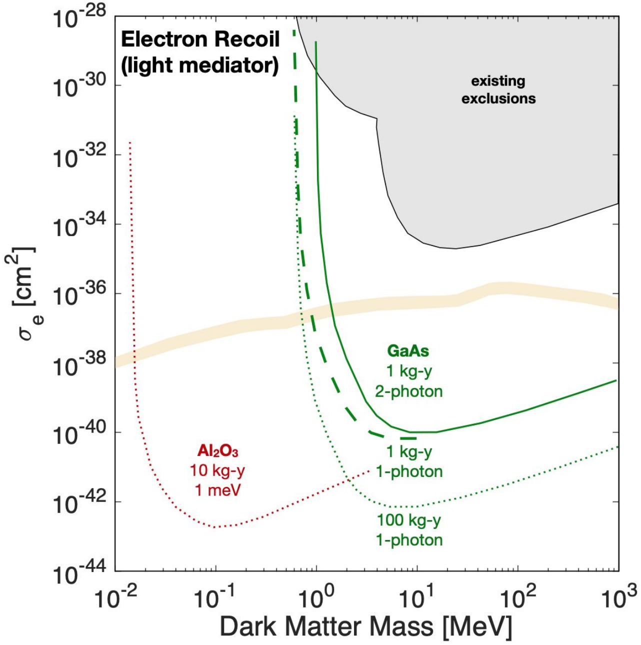
Problem is, don’t have the requisite observables; need more event-level information

sub-GeV digression: ML shines, still comes up empty

Improved LUX low-mass (S2-only) dark matter search sensitivity by removing electrode backgrounds



Light dark photon mediator benchmark



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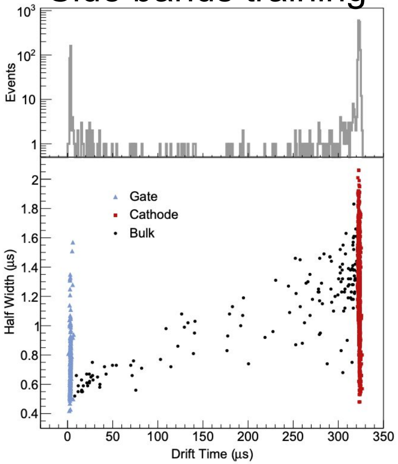
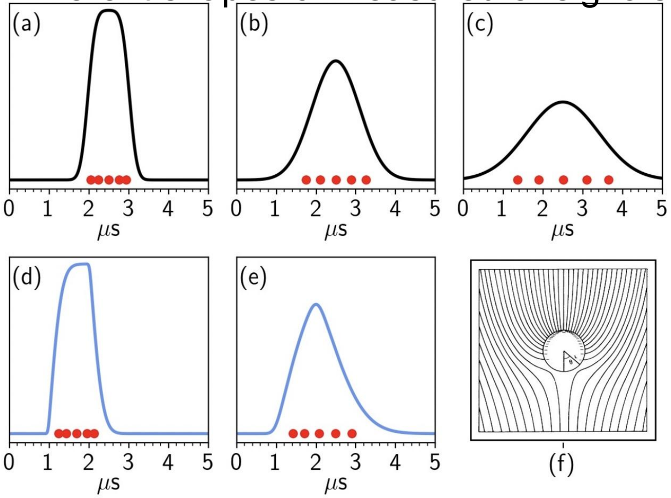
sub-GeV digression: LUX ML Efficacy

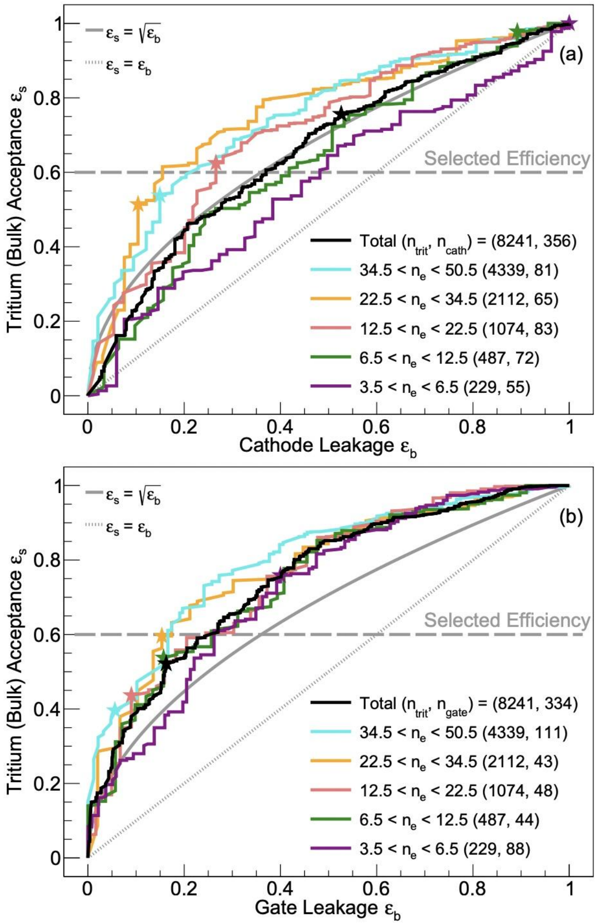
Use S2 (electron signal) timing parameters (red dots) to characterize origin of signal.

Side bands training

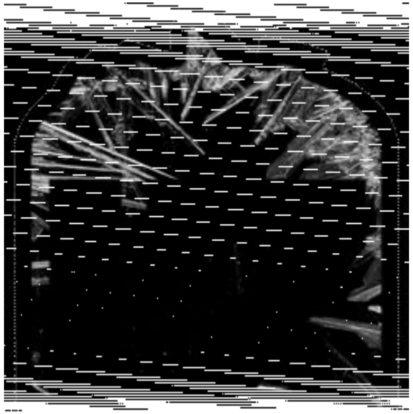


Different shapes of measured e- signals





Back to the weak scale… LZ upgrade concept: crystaLiZe

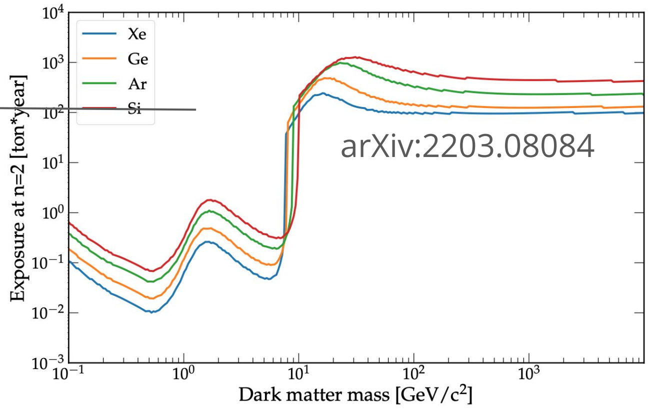


Premise: LZ could reach neutrino discovery limit if not for radon backgrounds

Solution: <u>crystalize the liquid xenon</u>, exclude the radon backgrounds

Tacit: do we need a G3 experiment? What's the rush? Cf. slide 3

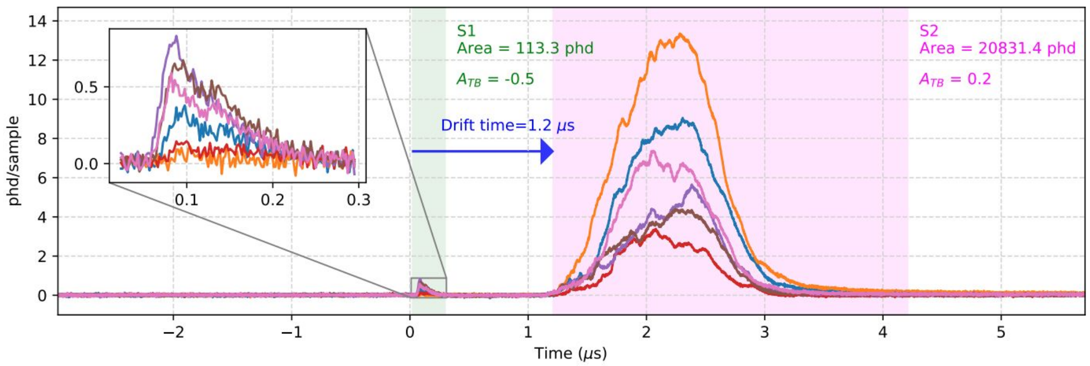
15 years of crystaLiZe with no radon (optimistically)



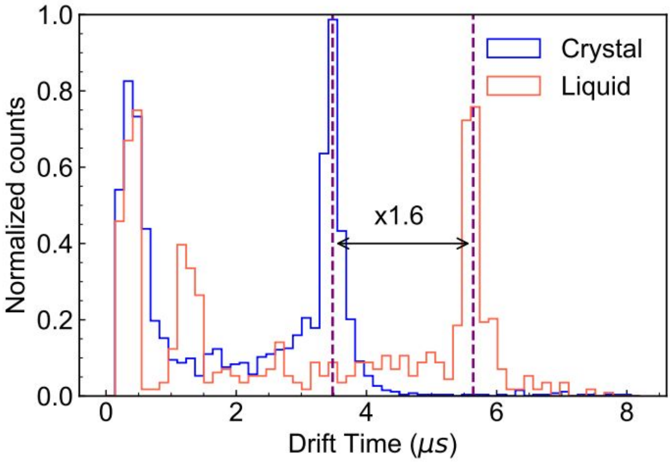
arXiv:2203.08084

Status of crystaLiZe R&D: it 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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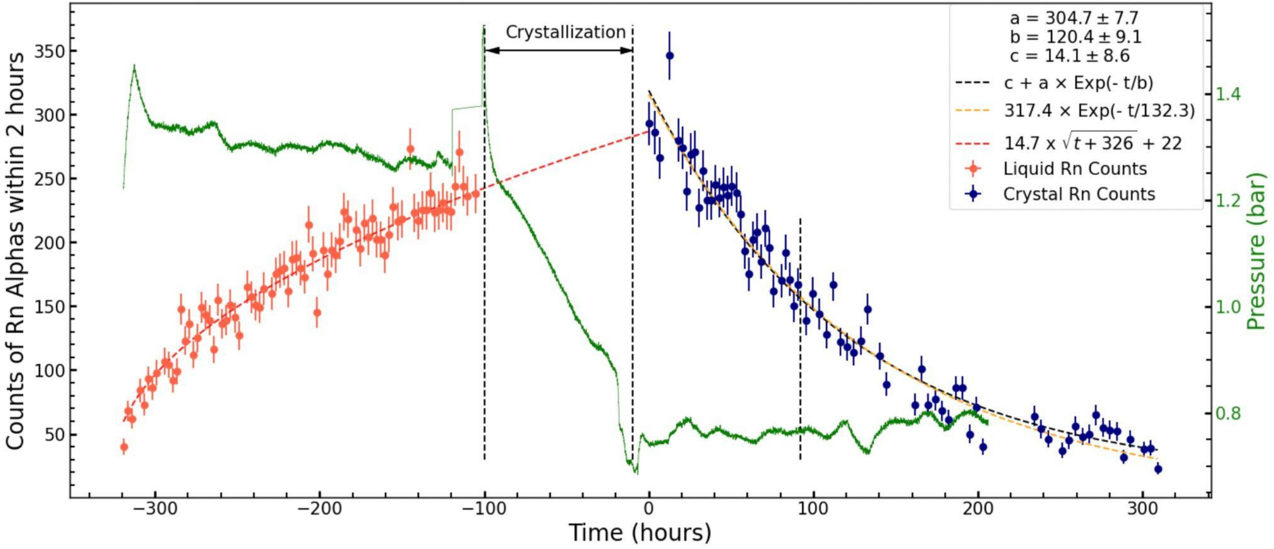
See Hao Chen talk at UCLA DM for details

Status of crystaLiZe R&D: it works! And it excludes radon

Alpha rate grows in due to flow-through radon source. Flow rate is CONSTANT for the entire time period shown in this plot.

3.8 day decay once crystallized indicates radon exclusion from the crystal

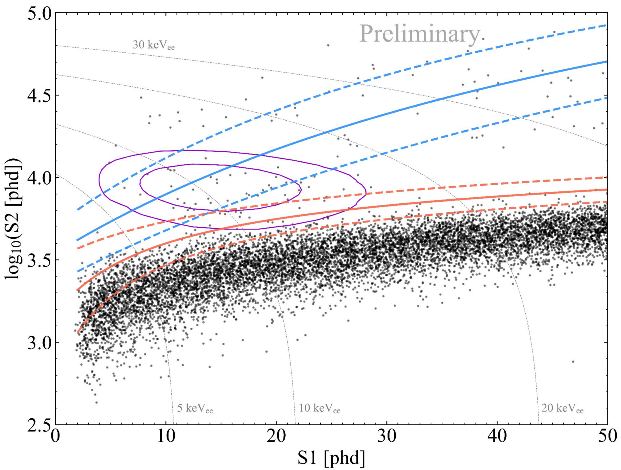


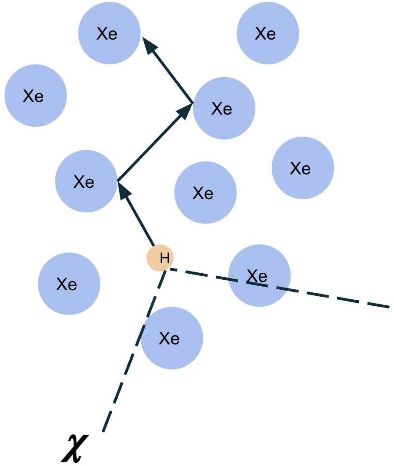
See Scott Haselschwardt talk at UCLA DM for details

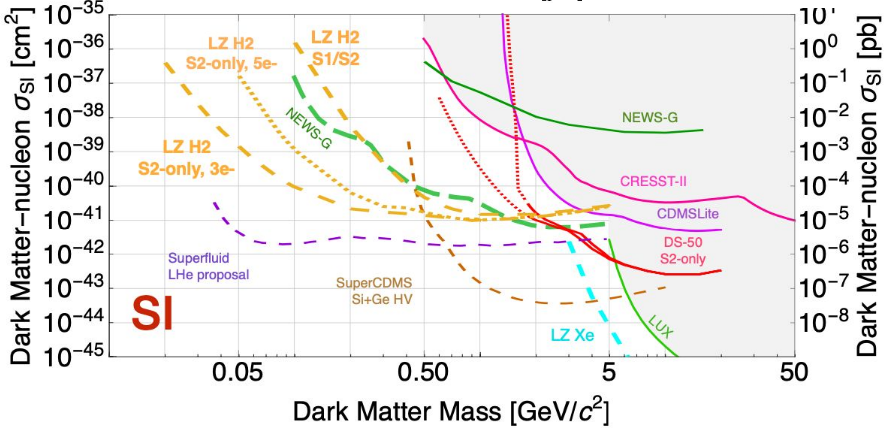
LZ upgrade concept: HydroX

Premise: LZ could achieve significant sensitivity to O(1) GeV DM via kinematic matching

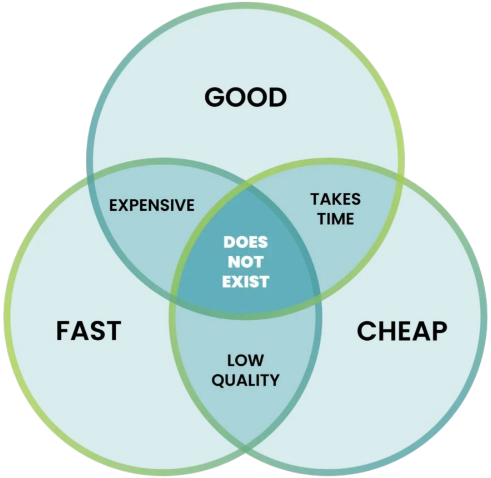
Solution: dope H2 or He into LZ. Xe functions as shield and sensor



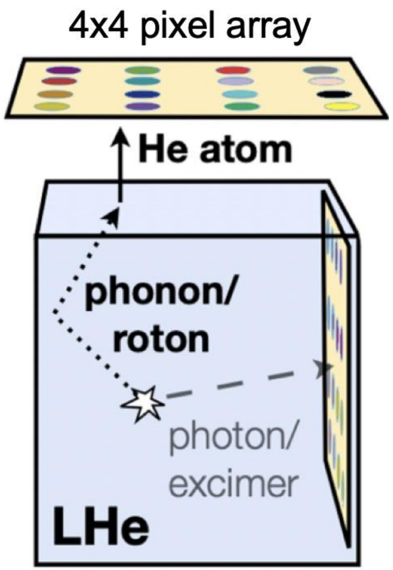




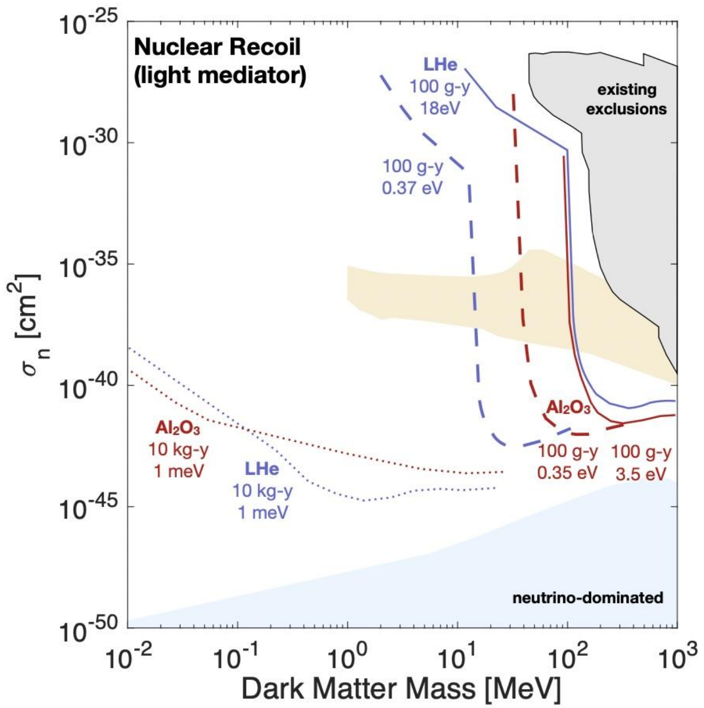
Prediction #3: LZ or XnT upgrades will offer new search sensitivity

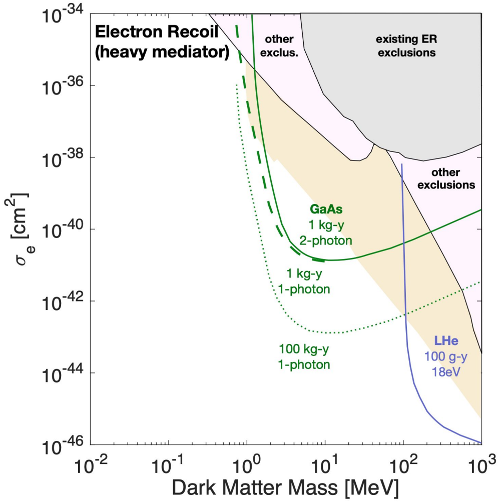


HeRALD – the liquid helium part of TESSERACT



He can't have stress
+
Multi-channel
Coincidence



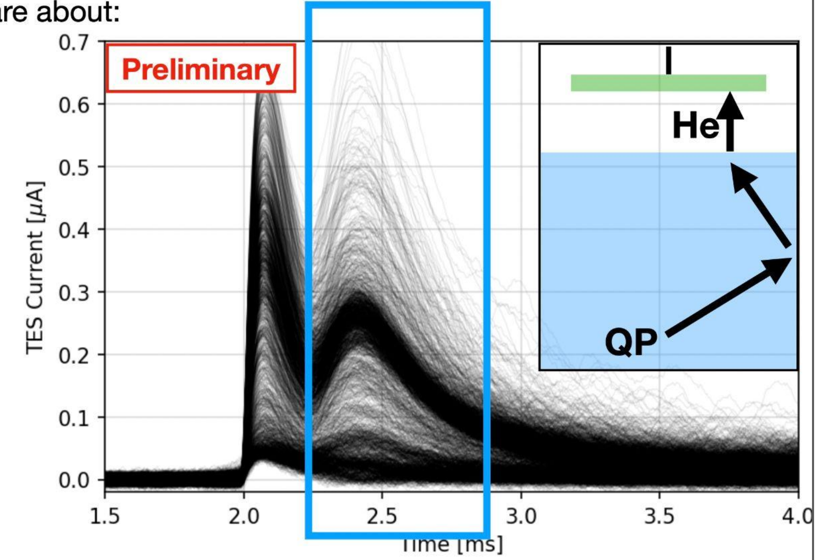


HeRALD v0.1 @UMASS

First Helium Results: Pulse Shapes

- For events in the helium, there are four main components to the pulses that we care about:

1. Prompt amplitude (scintillation)
2. Delayed amplitude (evaporation)
3. Delay time (location)
4. "After pulsing" (triplets)



D. Pickney slide from CPAD 2022

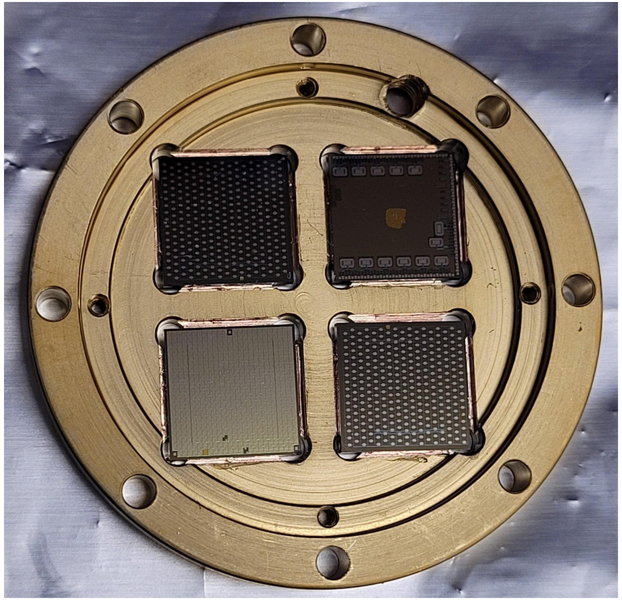
HeRALD

HeRALD Si pixel arrays have been designed, fabricated, and tested

- •19mK devices IR saturated
- •55mK devices operable

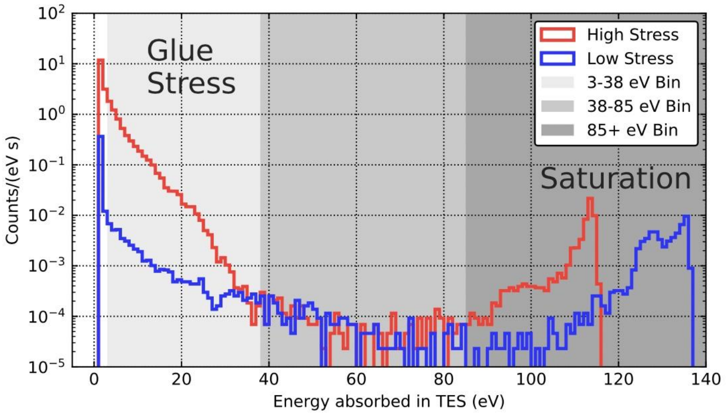
0.5 eV sensitivity assuming 20% collection efficiency (achieved in CPDv2 with similar athermal phonon sensors)

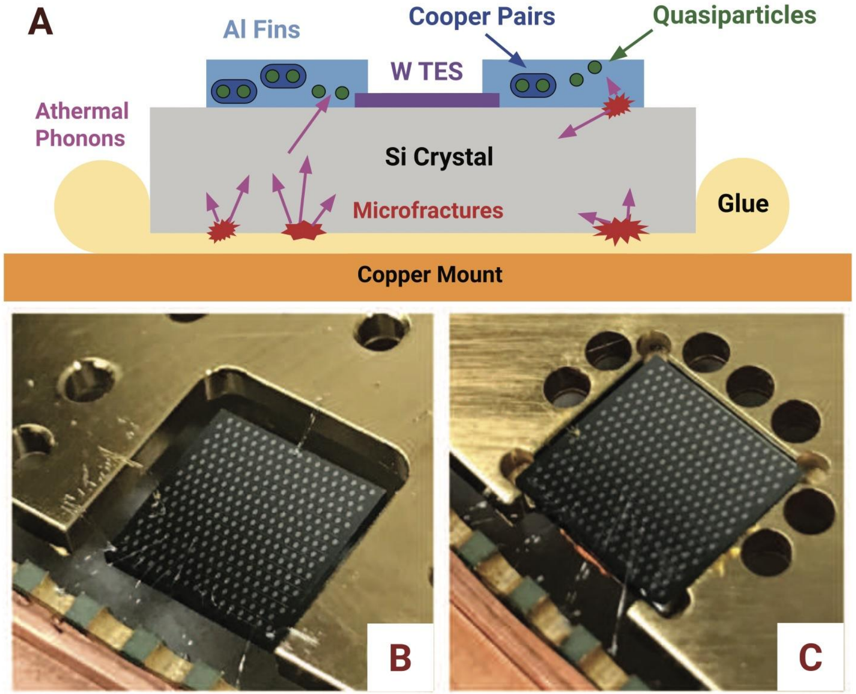
Now: assembling at LBL, ~11 grams active 4He



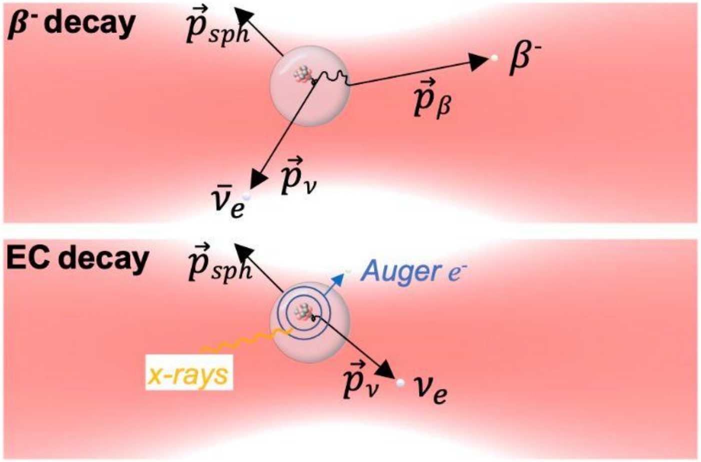
Aside: don't stress!

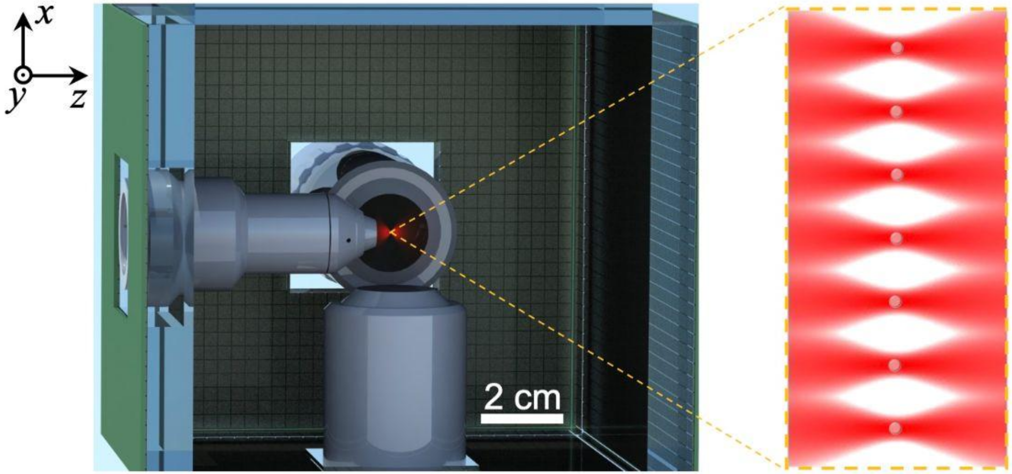
Plots from UCB-lead effort, cf. 2208.02790





QuIPS – quantum invisible particle sensor





Carney, Leach & Moore, arxiv:2207.05883 and PRL Editor's Suggestion

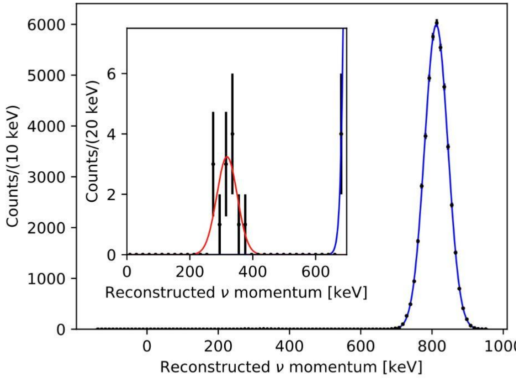
Experiment proposal to reconstruct decay kinematics of O(100) nm levitated nanospheres with embedded radioactive source. Requires ~100 keV sphere momentum sensing and ~1 keV electron energy measurement

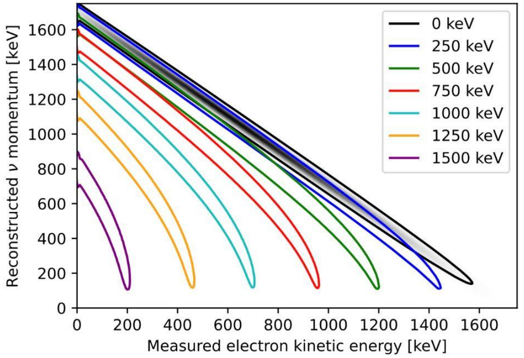
QuIPS – new LDRD proposal at LBL

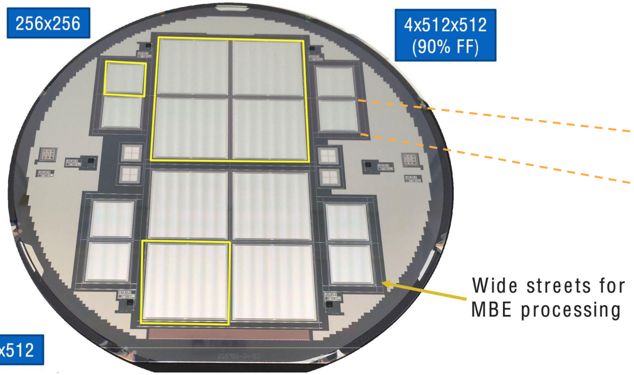
Simulation of expected data

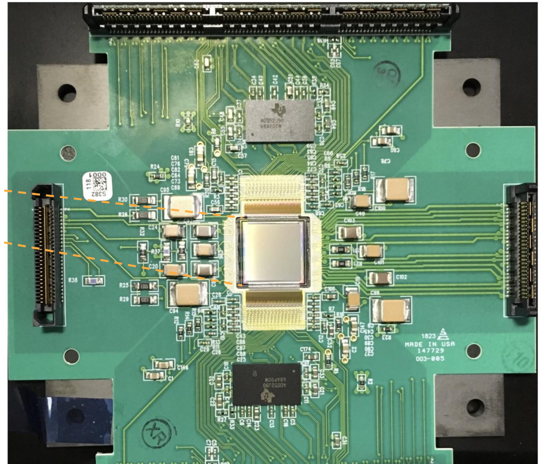
But how to measure the beta or Auger electron and x-ray energies?

We expect a very fast (5 kHz frame rate) CCD to be apt. Developed by P. Denes et al (LBL) for ALS









QuIPS – what might it offer?

Search new phase space
for sterile neutrinos

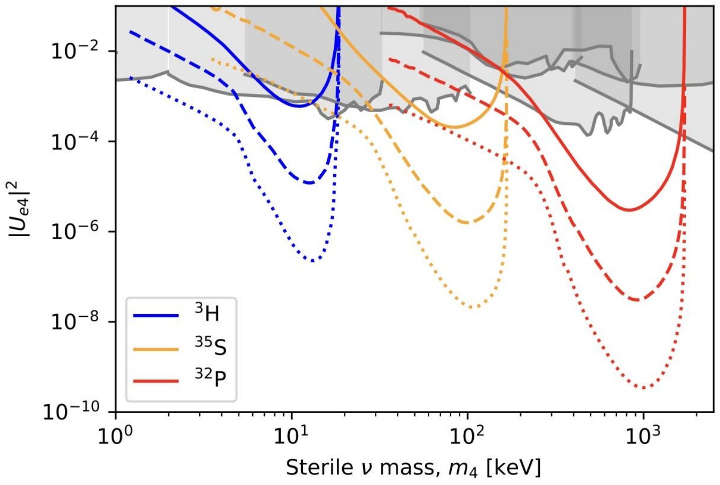
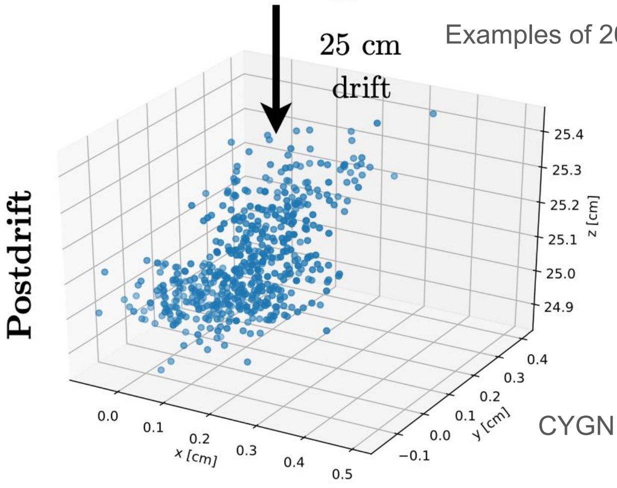


FIG. 5. Estimated sensitivity for a variety of sphere sizes, exposures, and β-decay isotopes spanning a sensitivity range from ∼1–1000 keV. The background-free sensitivity for exposures of 1 sphere × 1 month (solid), 10 spheres × 1 year (dashed), and 1000 spheres × 1 year (dotted) are shown. The sphere sizes and loading fractions assumed for each isotope are described in the text. The most sensitive existing laboratory limits are also shown (gray) [7–16].

Predictions #4 & #5: HeRALD and QuIPS follow the natural law (slide 2)

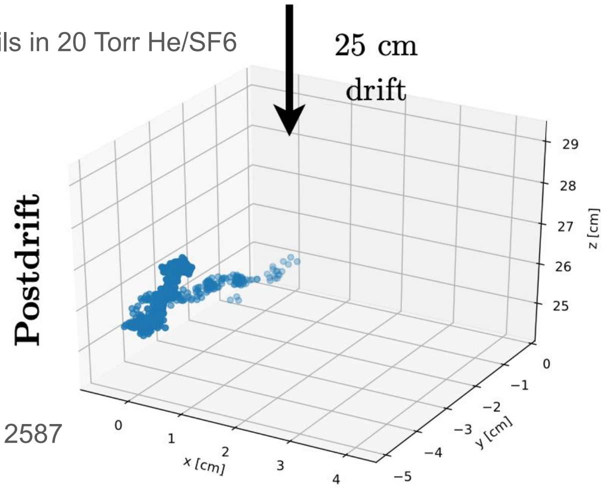
Prediction #6: we realize we need directional detection

Examples of 20 keV recoils in 20 Torr He/SF6



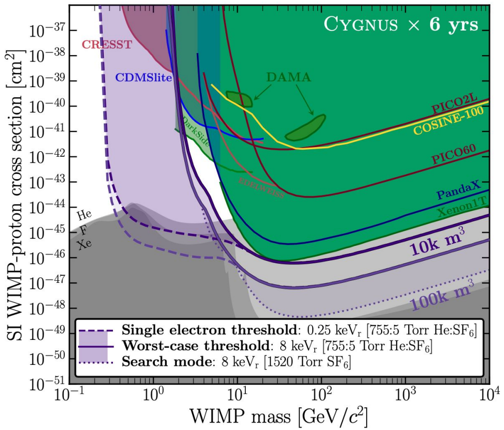
nuclear recoil

CYGNUS, 2008.12587



electron recoil

Track topology => discrimination AND sensitivity to modulation of signal



Incident direction of the dark matter has always been the dream ("WIMP astronomy") and is the next phase, regardless of G3 results, if we can manage it

Summary, thanks for your attention!

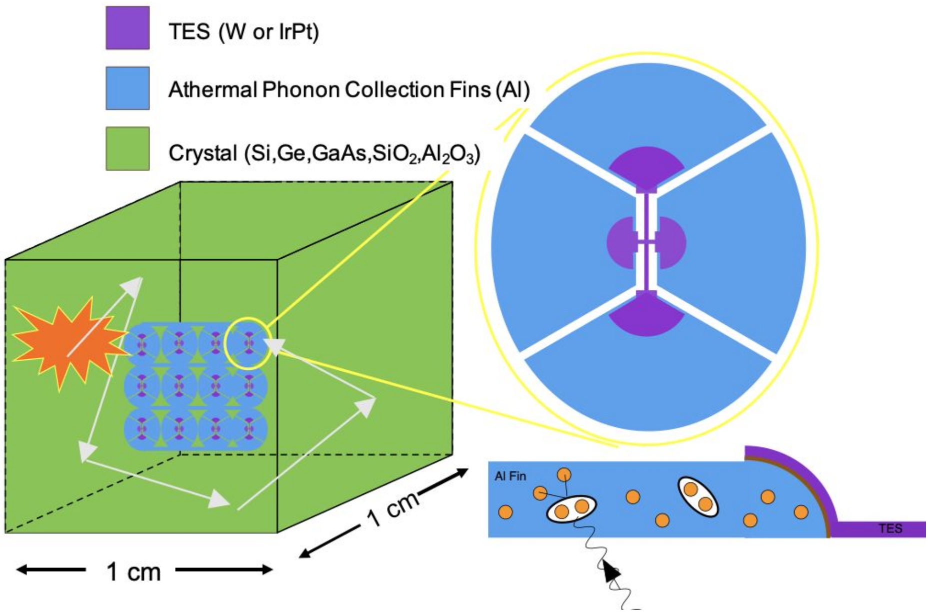
The curse of dark matter direct detection: a bonafide signal will (initially, eventually) first appear as a single anomalous event. Meanwhile, increasingly rare backgrounds do the same thing

Theorists: pls help us with priors

ML experts: pls get rid of our background events

near-term, I'll be in the lab working on instrumental solutions

HeRALD – increasing sensitivity (lower energy threshold)



$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

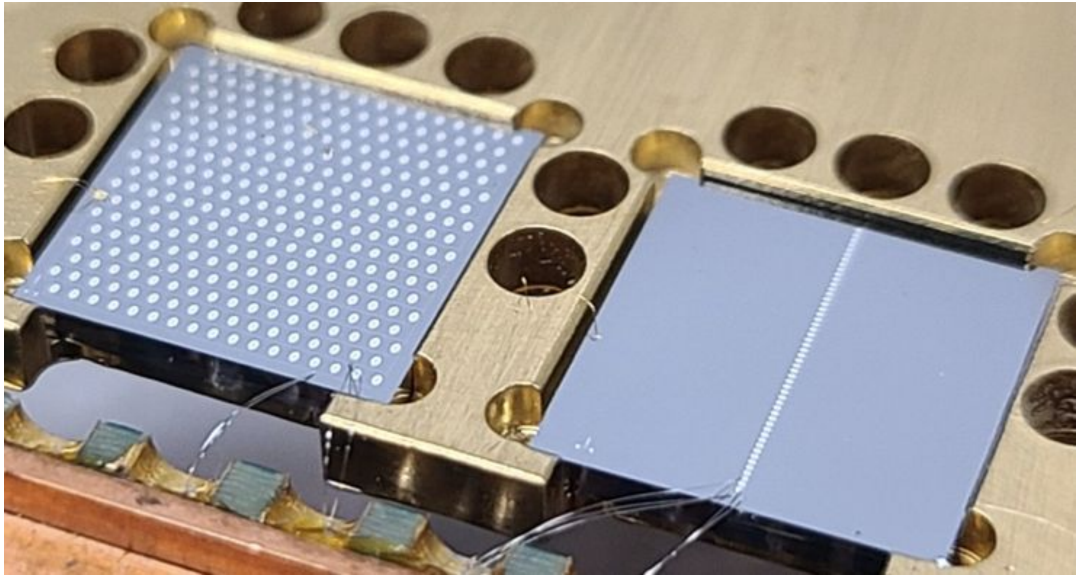
$$G \propto T_c^4 V$$

=> lower T_c, decrease TES volume

HeRALD

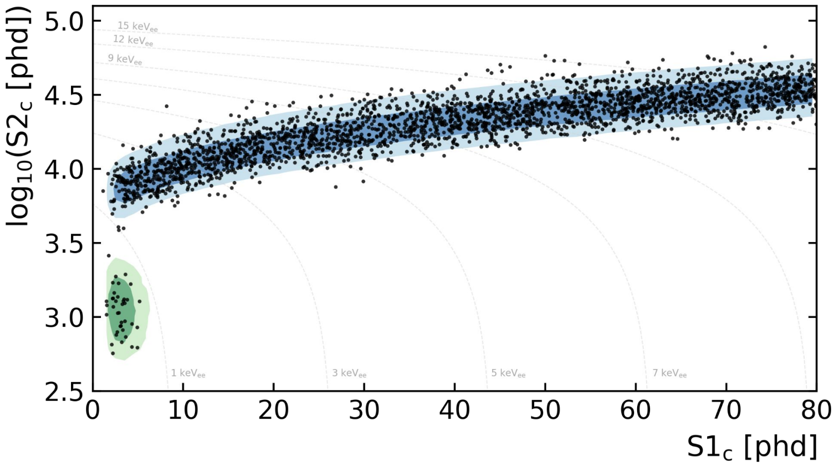
4% coverage

0.25% coverage



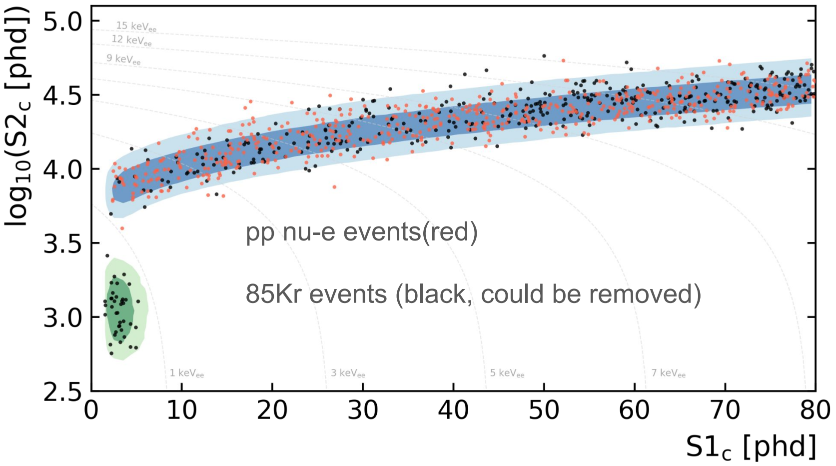
Unofficial simulations. Imagine x7 to get to 100 tonne years

LZ 1000 day, with Rn, ~1100 events



plots from S. Haselschwardt. cf arxiv:1802.06039 for official versions

crystaLiZe 1000 day, without Rn, ~300 events



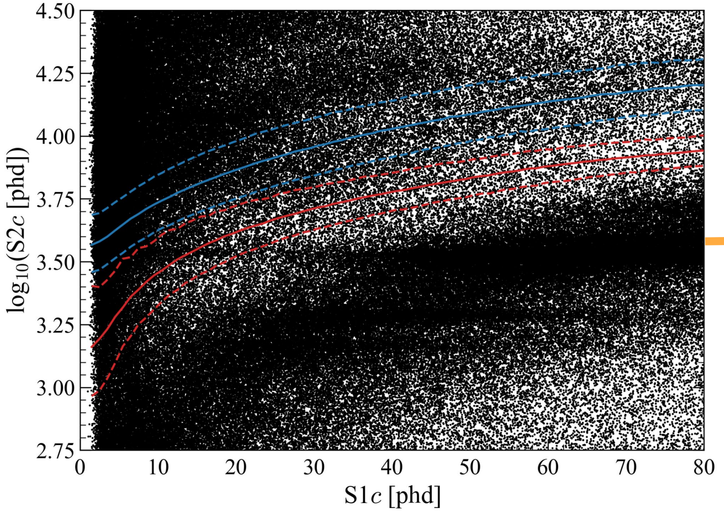
Could further remove another 67 BG events (⅓ of pp neutrino number) if 136Xe were swapped out – e.g. to nEXO

For example, (surprise!) 37Ar or maybe just… accidentals

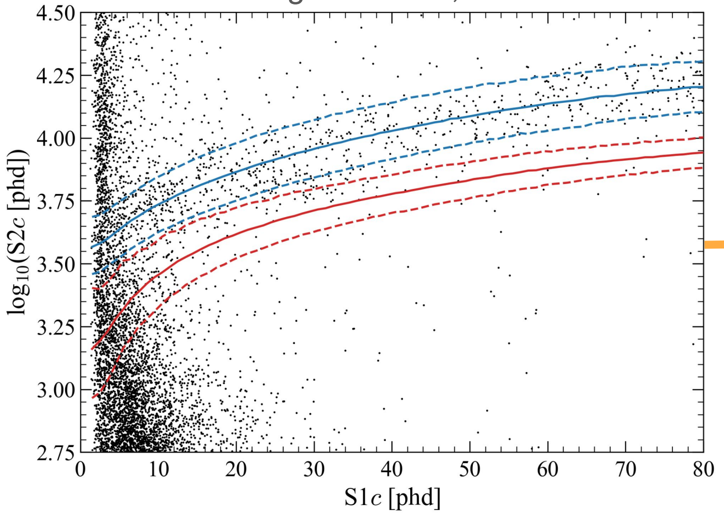
Then (LZ 1802.06039): "Accidental coincidences…less than 0.2 events are projected in a 1000 day run"

Now (LZ 2207.03764): "A suite of analysis cuts targets accidental coincidence events…"

SR1 single scatters, full TPC



SR1 single scatters, 5.5 t TPC



Final result on next slide with all quality cuts

Plots from LZ SR1 data release, July 2022

Source	Expected Events	Fit Result
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

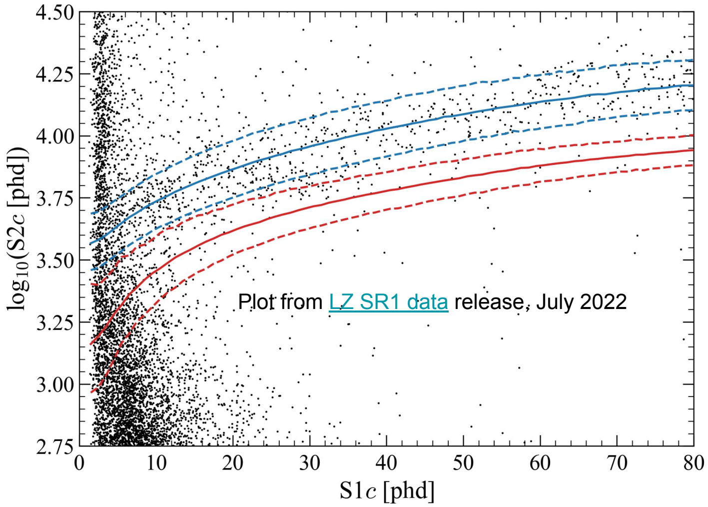
Surprise! accidentals

Then (LZ 1802.06039): “Accidental coincidences…less than 0.2 events are projected in a 1000 day …

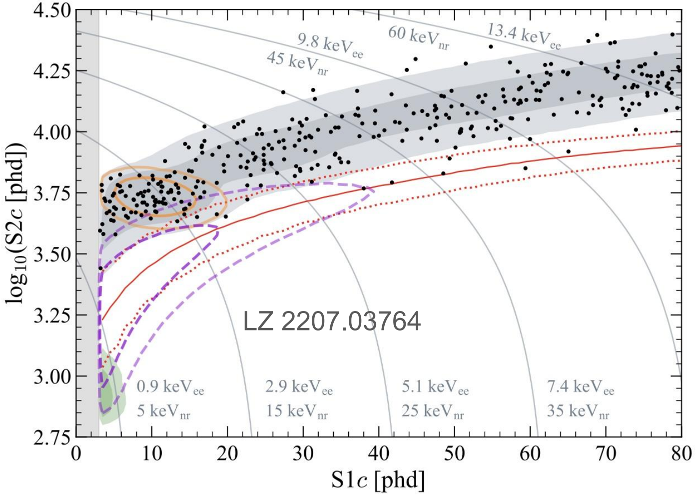
Now (LZ 2207.03764): “A suite of analysis cuts targets accidental coincidence events…”

Future (in-progress): “A simple ML algorithm was used to tag accidental events with 99.9% efficiency”

SR1 single scatters

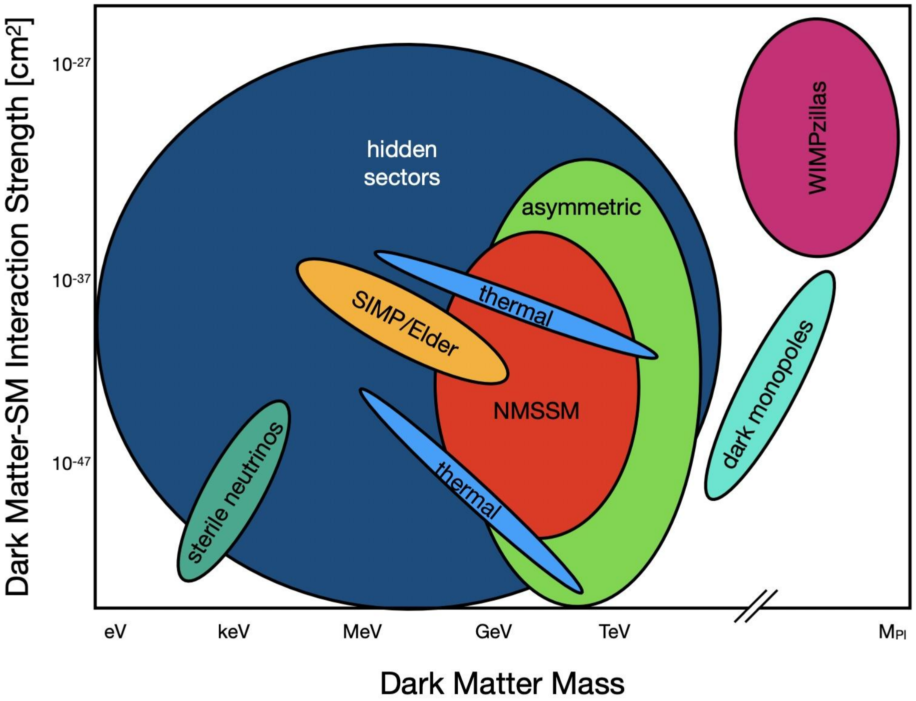


SR1 (60 live days, 5.5 t target) single scatters



Era of flat priors

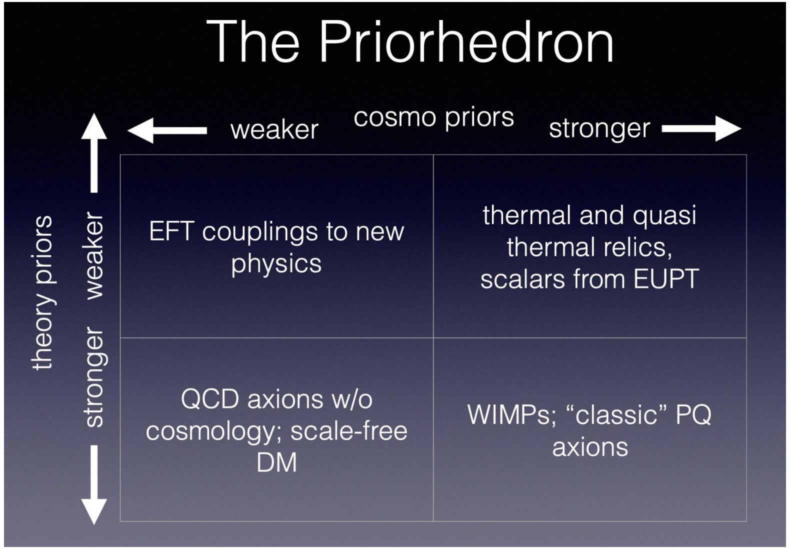
Snowmass 2209.07426



"Just pick something and study it"
– J. Peebles (speaking about the cosmos, paraphrased from memory)

Hanging on to (cosmology) priors

Weiner, Cosmic Visions Workshop 2017



Pospelov, ICTP Workshop 2014

My simple criteria for appraising BSM models

Category 1: Well motivated. New particles and interactions that are introduced for a solid reason, and among other things satisfy stringent criteria of technical naturalness (QCD axions, SUSY partners, RH neutrinos participating in mass generation….).

Category 2: Technically natural "why not" physics: New particles and interactions that are stable under quantum corrections without "black magic". Dark photons in certain mass ranges, ALPs, sterile neutrinos beyond those that give neutrino masses.

Category 3: Perhaps not natural, but addressing a specific observational anomaly. (DM anomalies, particle physics anomalies etc).

Category 4: Technically unnatural, but I and/or my friends work on them. (E.g. models of changing couplings; chameleons; ALPs with non-derivative couplings). Justification: coolness factor

Category 5: Technically unnatural models that other people work on….

DS 20k slide

Note: DS20k expects even better discrimination