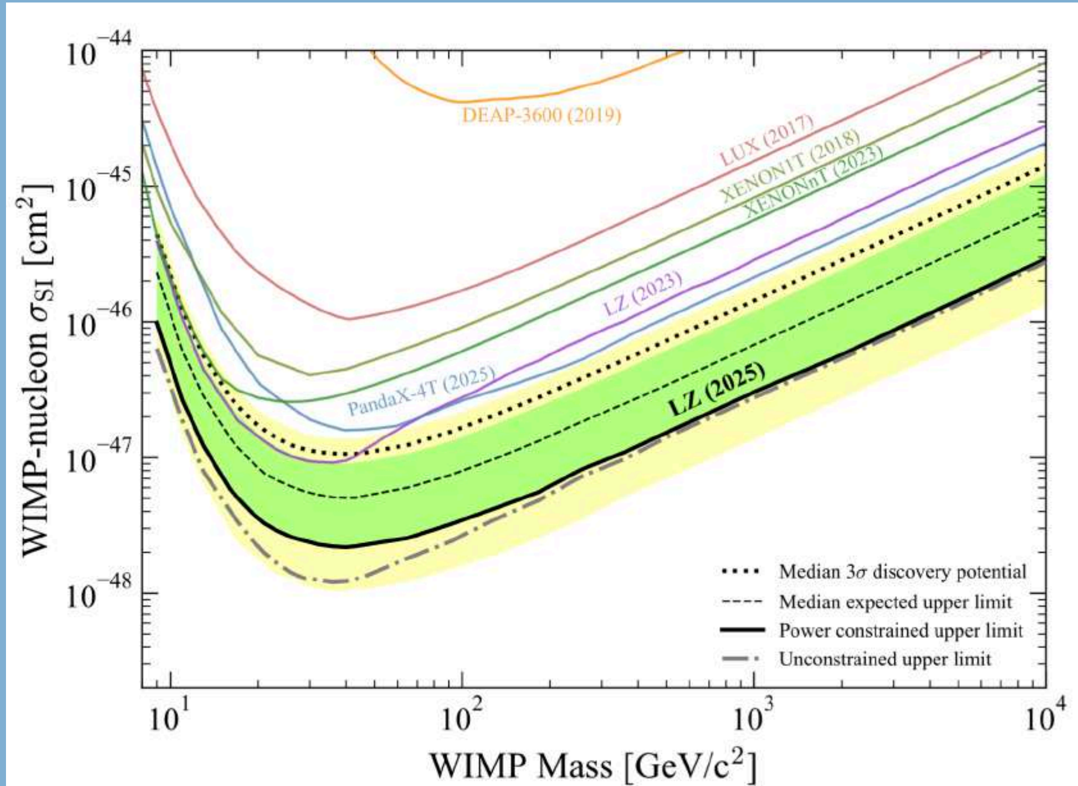
LIQUID XENON TPCS

Introduction

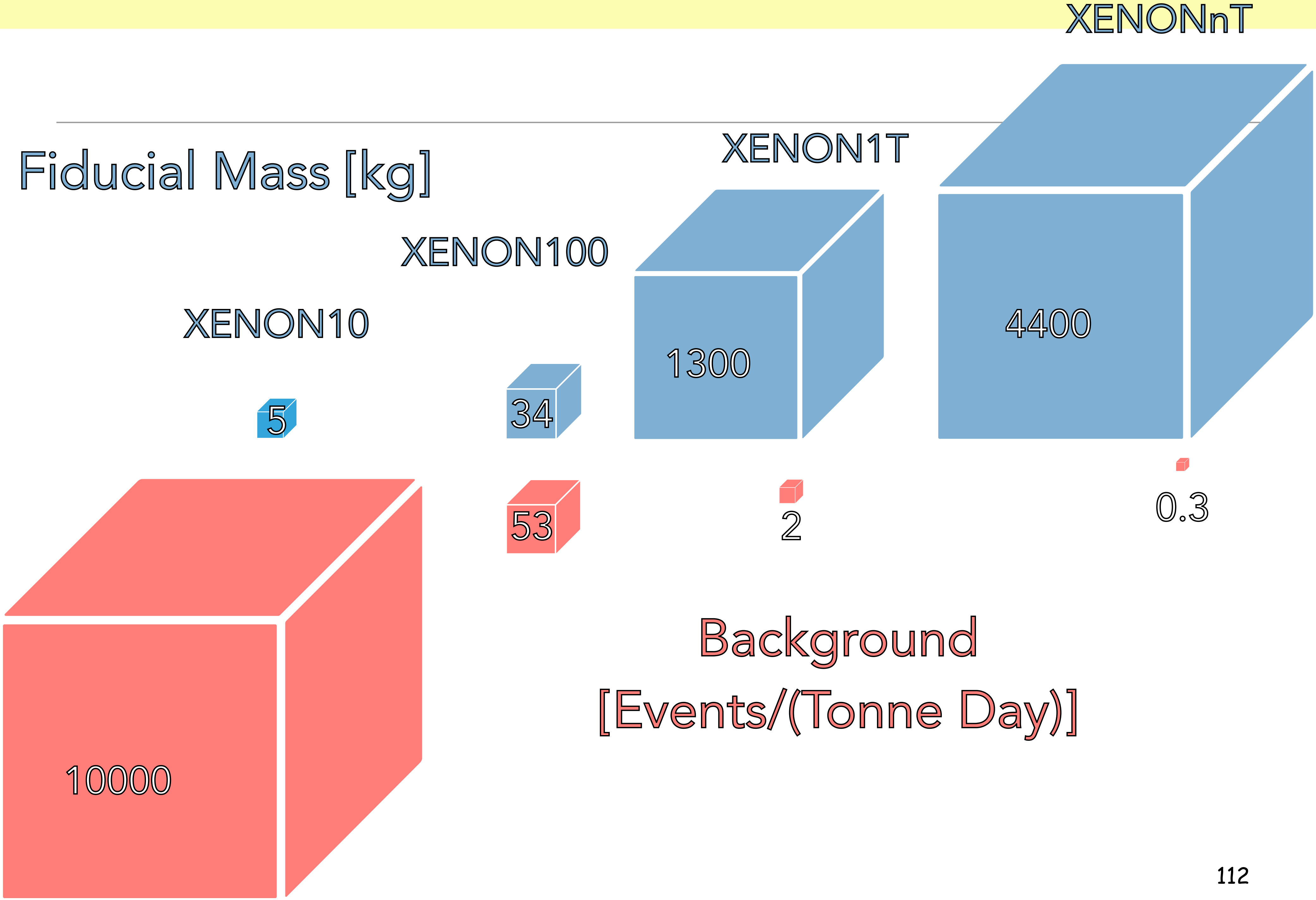
RECAP:

- lXe TPCs give the best performance for WIMP masses above ~ 6 GeV/c^2
- Reached masses 3-7 tonnes,
- XENONnT and LZ currently running
- Very pure self-shielding targets, with additional background reduction due to
  - Fiducialisation (choosing an analysis volume)
  - and the separation of electronic and nuclear recoils

Dark Matter Search Results from 4.2 Tonne-Years of Exposure of LUX-ZEPLIN (LZ) Experiment
https://arxiv.org/abs/2410.17036

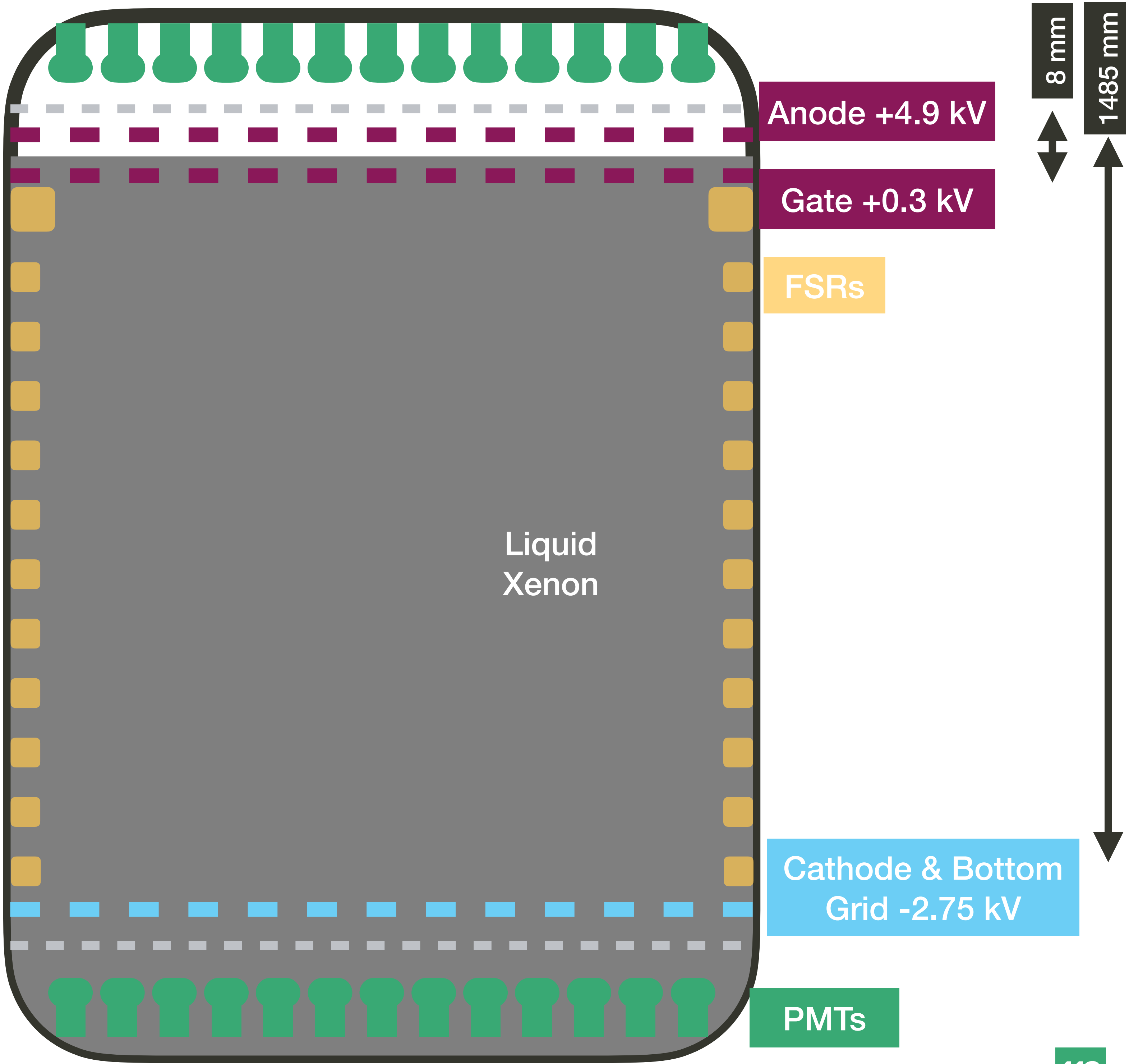


DETECTOR MASS AND BACKGROUND



TWO-PHASE TPC

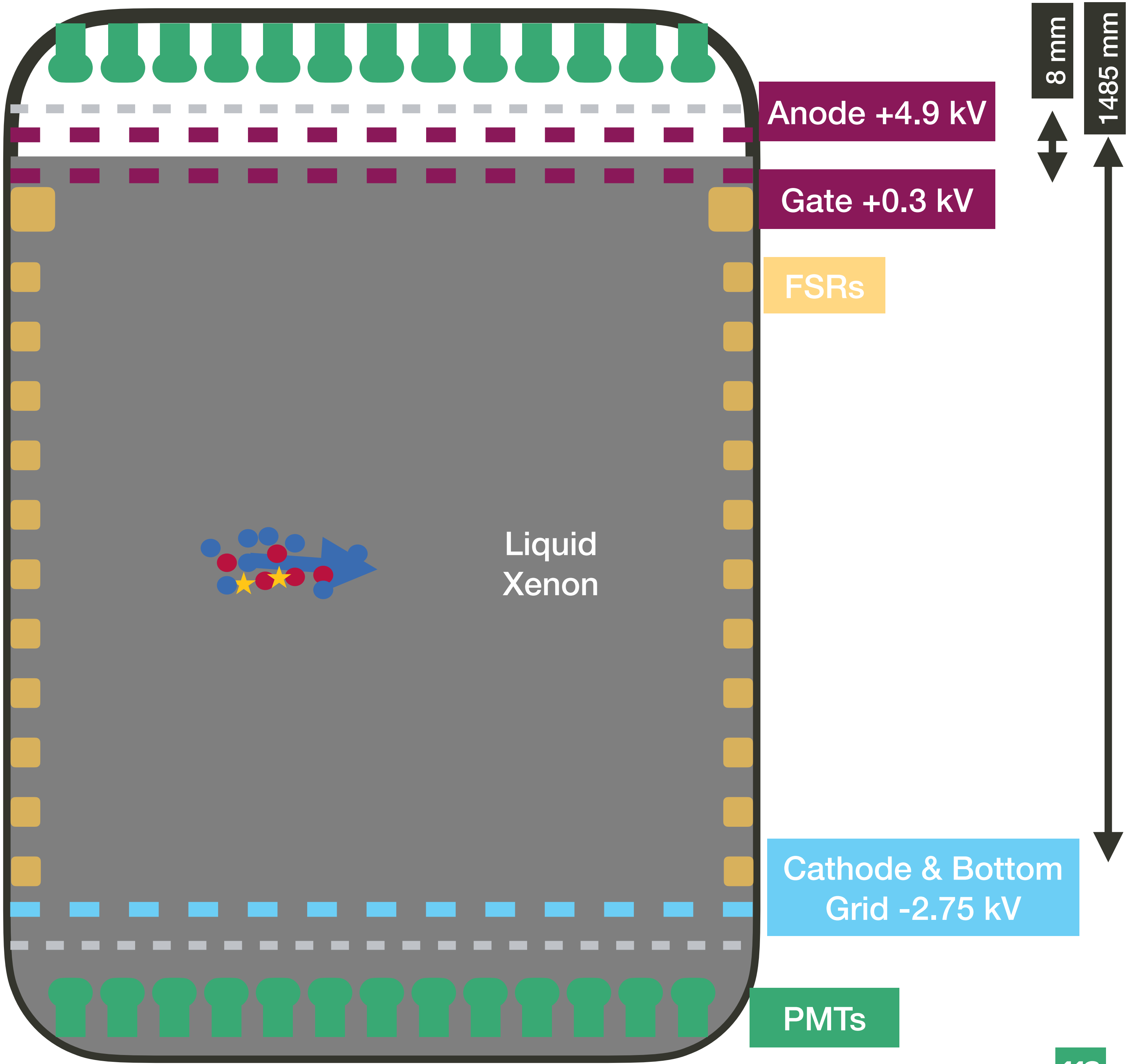
With XENONnT SR0 numbers



TWO-PHASE TPC

With XENONnT SR0 numbers

An Interaction deposits energy, scintillation light and charge is liberated



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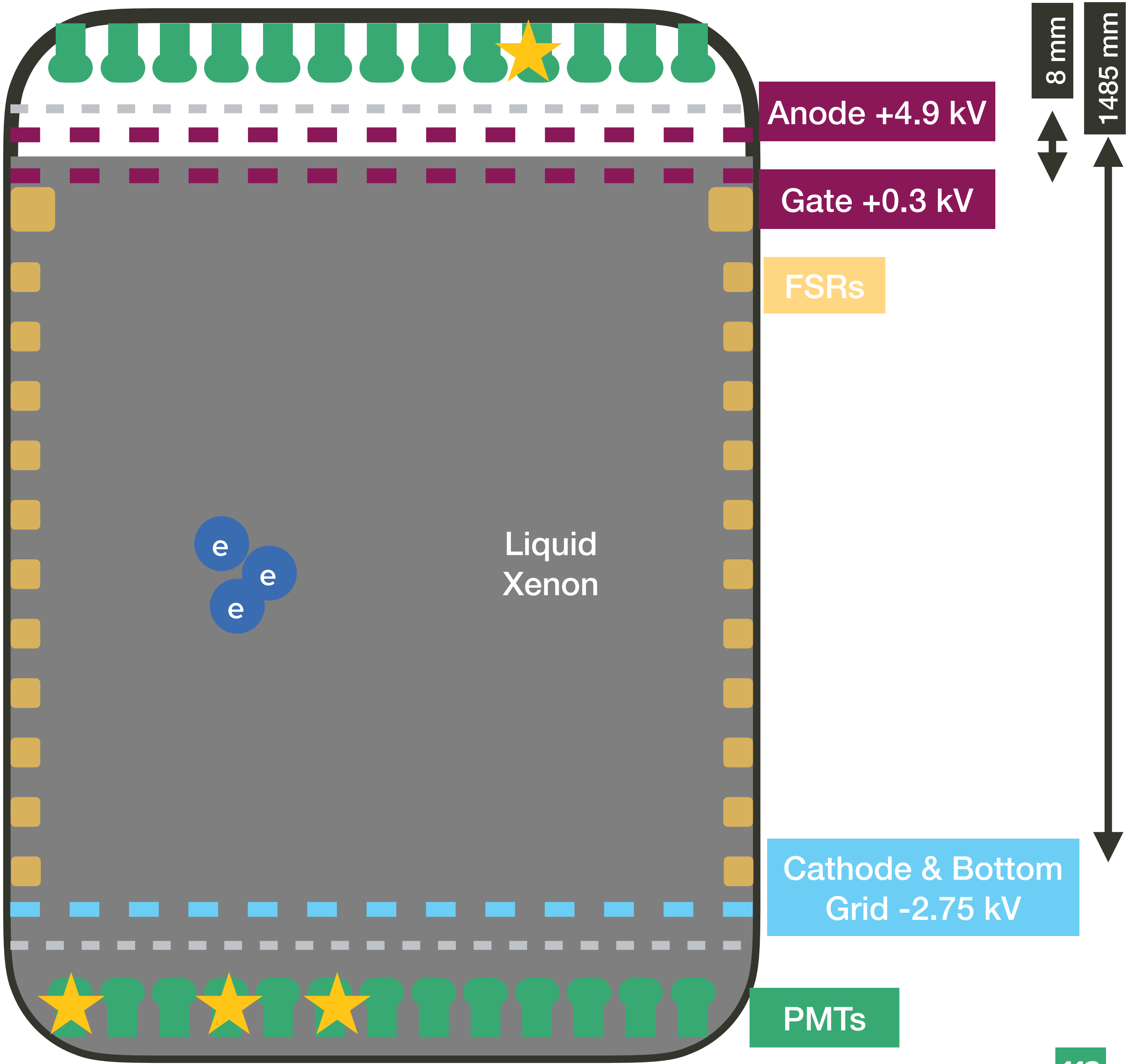

TWO-PHASE TPC

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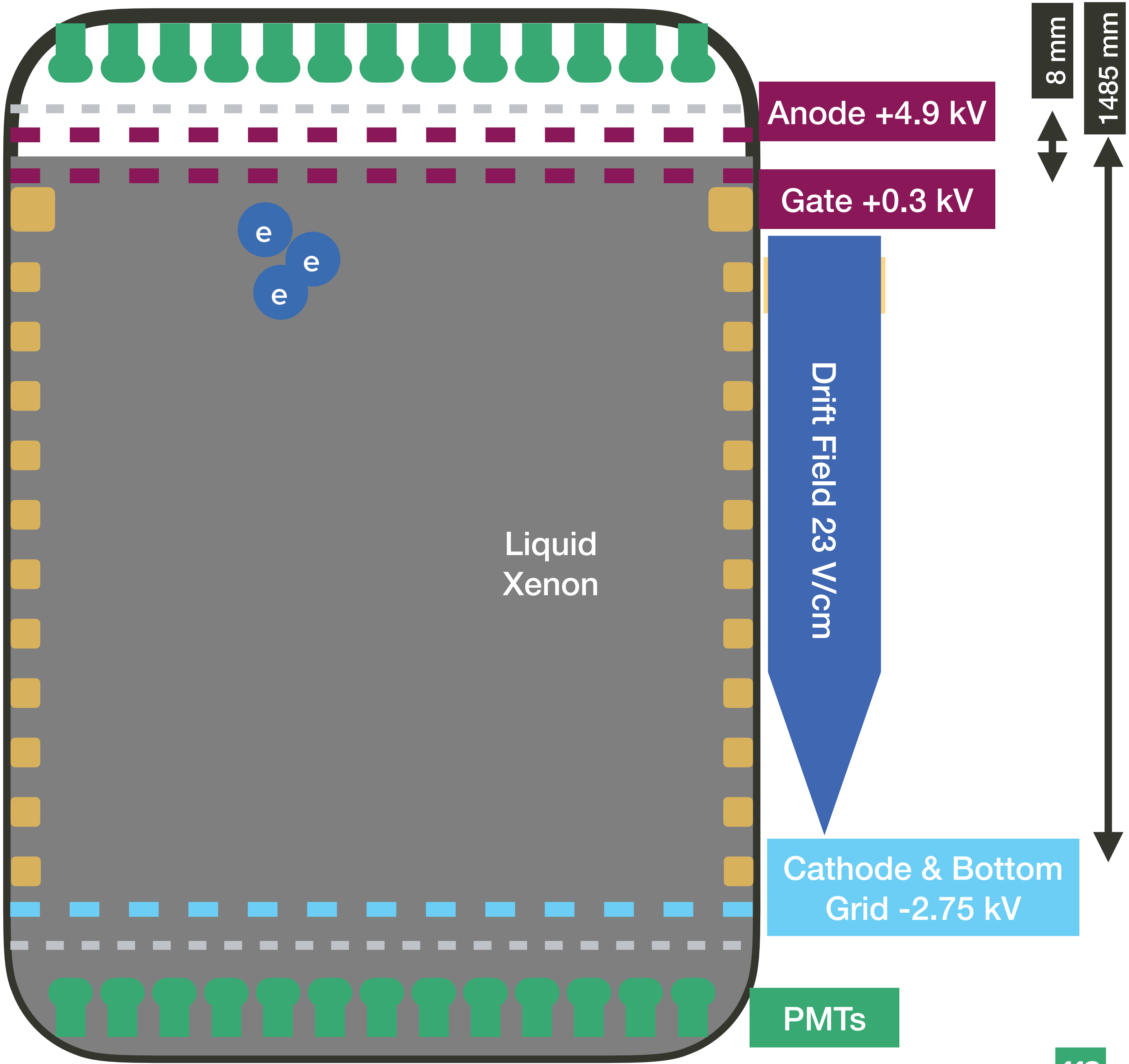
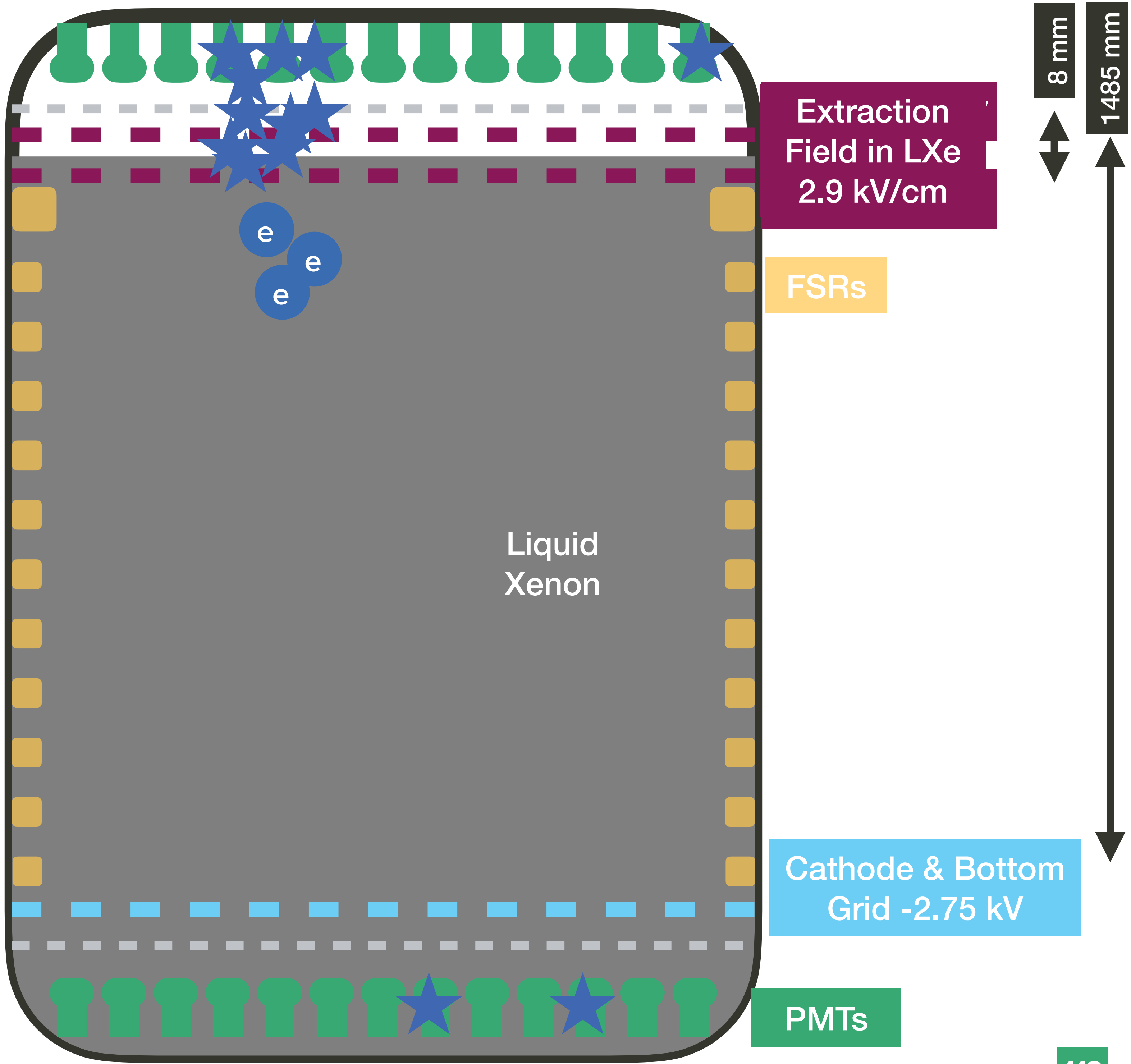


TWO-PHASE TPC

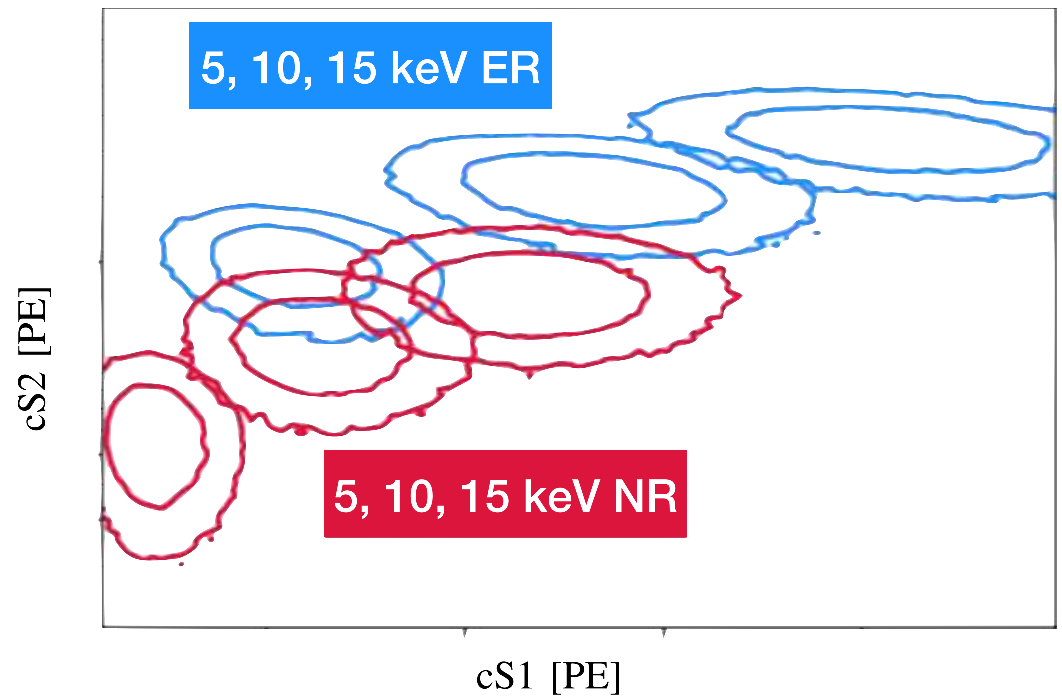
With XENONnT SR0 numbers

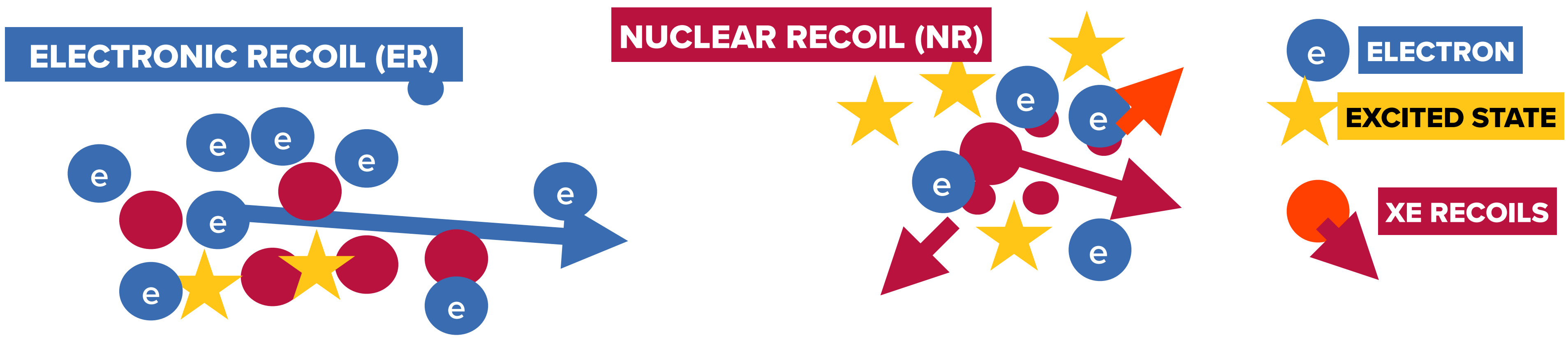
- An Interaction deposits energy, scintillation light and charge is liberated
- S1 signal reaches photomultipliers
- Electrons drift to the surface
- The extraction field pulls the electrons to the gas phase where they make more scintillation light



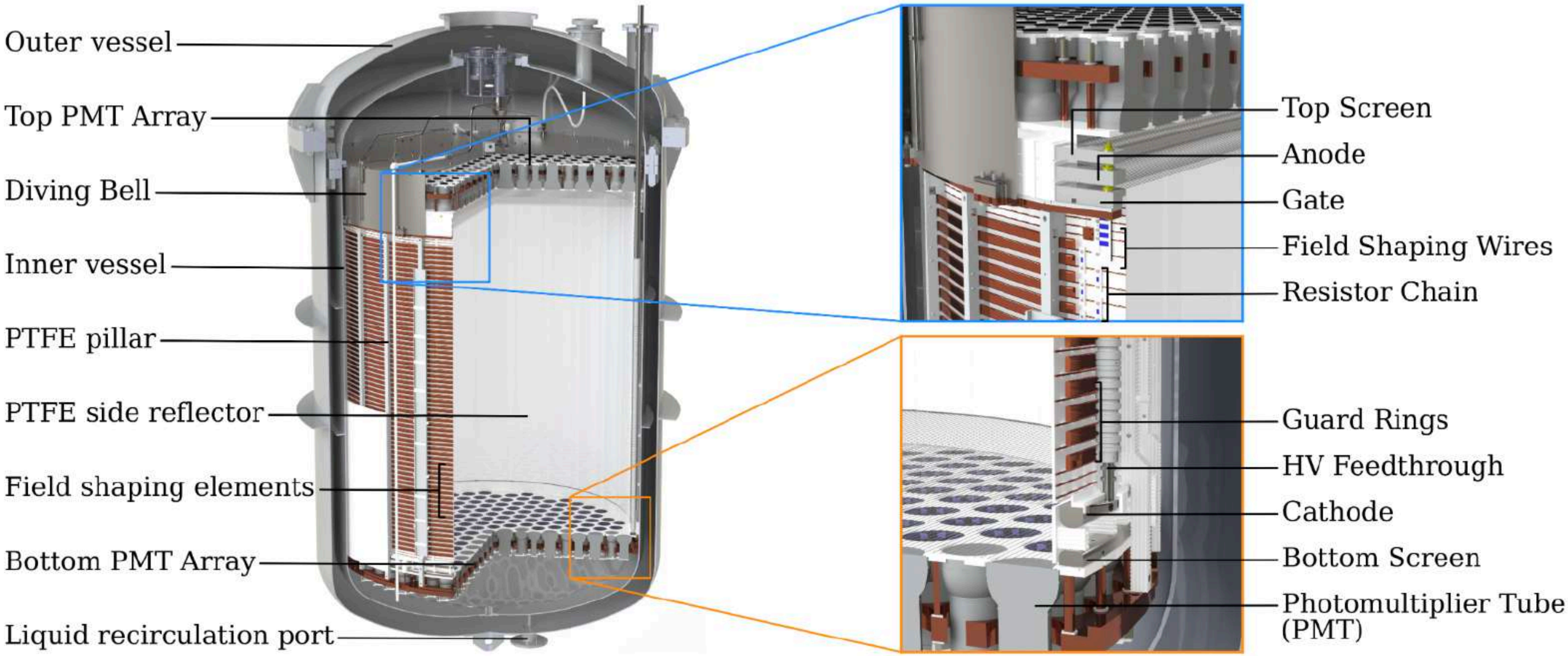
OBSERVABLE SIGNALS IN LIQUID XENON

- Recoiling xenon atoms or electrons in the liquid cause ionization and excites xenon atoms, which will yield scintillation light
- Atomic motion, heat, is lost, so that less energy is observed when the nucleus recoils
- The ionization and scintillation signals are observed in two-phase lXe TPCs



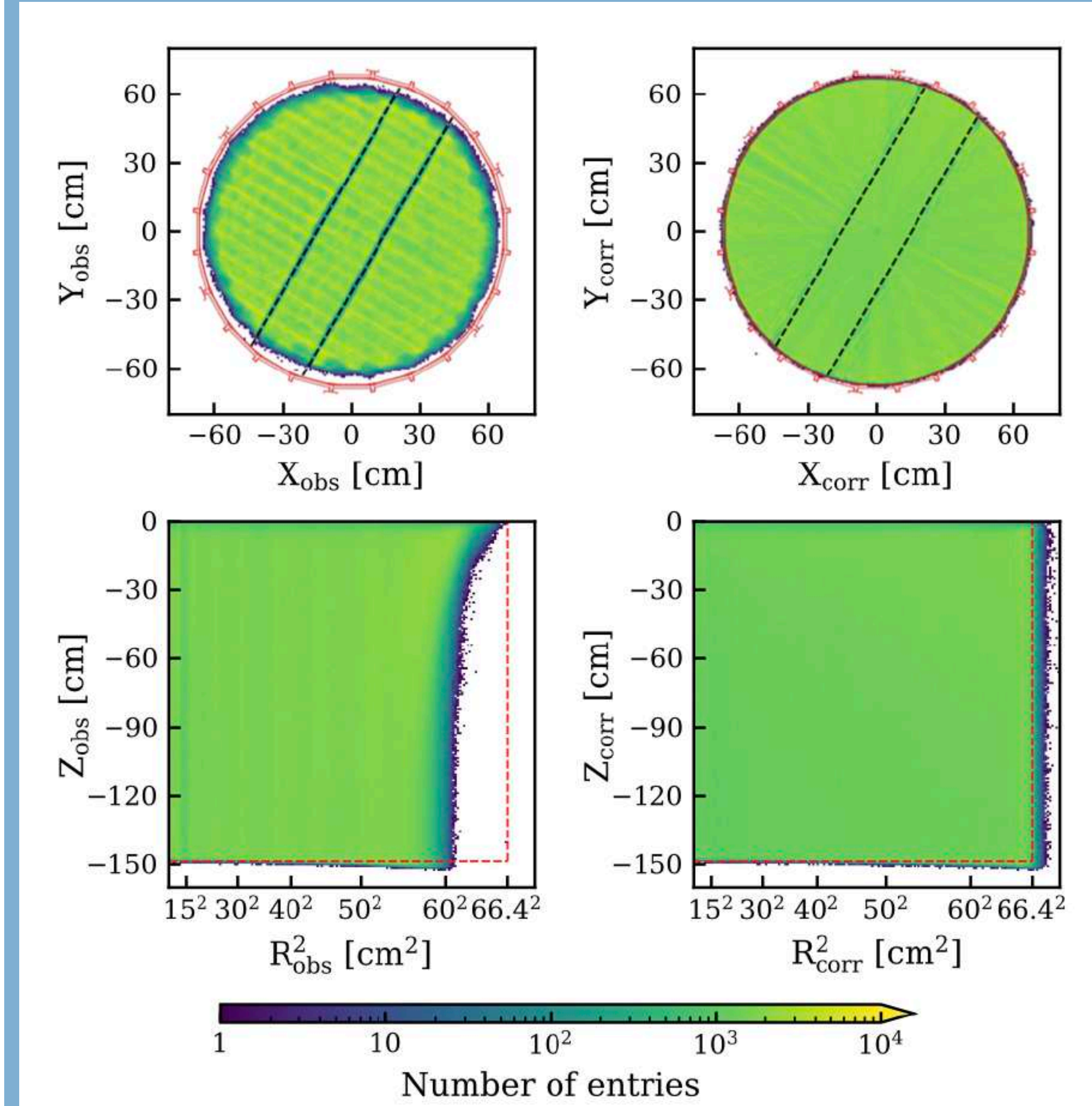


MORE DETAILED LOOK ON THE SCHEMATIC (XENONNT)



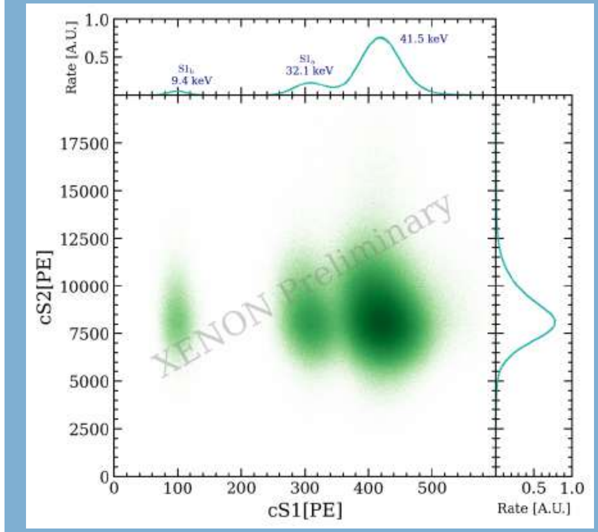
FIELD DISTORTION

- In particular XENONnT, which has to operate at lower fields than designed, but also in LZ and XENONnT, the electrical field is not entirely vertical
- The inner teflon panels may also experience charge-up from ions
- The total effect is that events deep in the detector move inwards as they are drifted up
- Scaling radii outwards recovers a pretty homogenous detector
- But also assumes radial asymmetry—you can see on the top plot that the real patterns caused by the top cathode are smeared out
- Disentangling this from a possibly insensitive volume at the bottom is also challenging

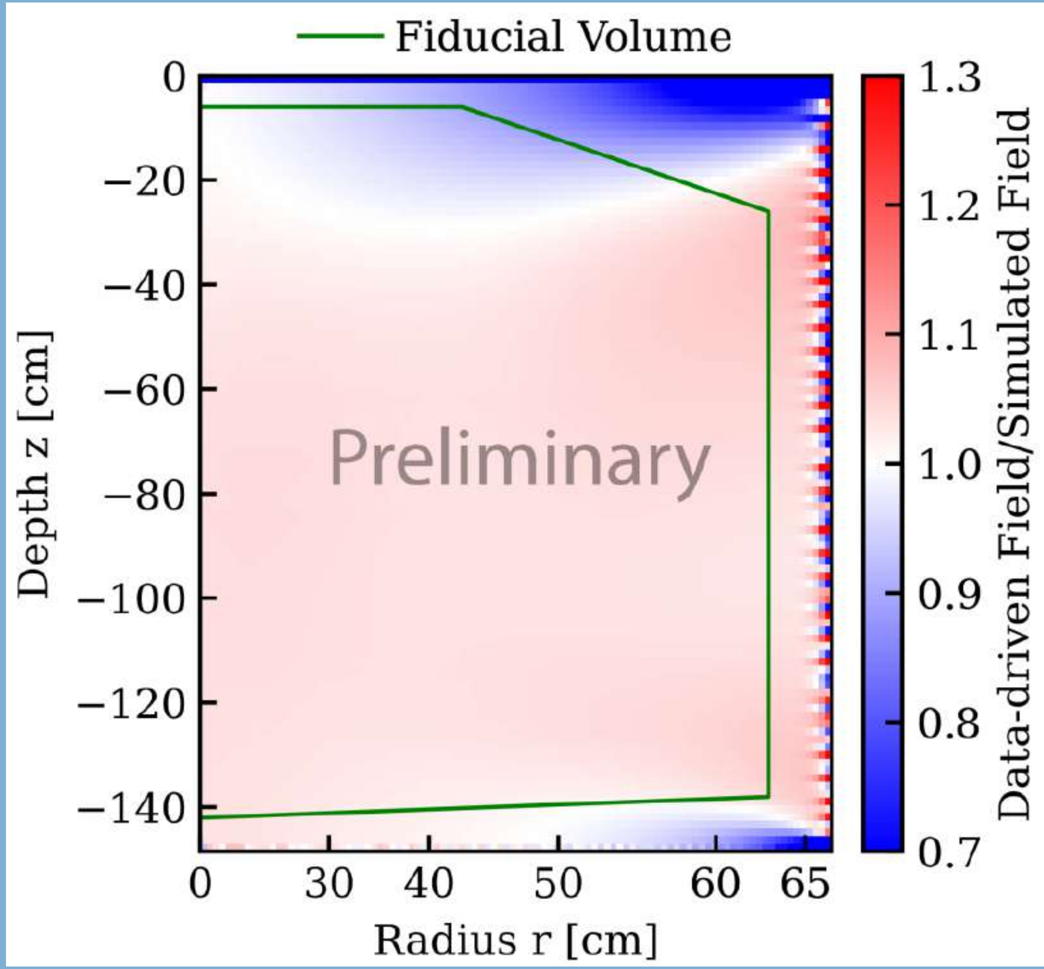


FIELD-DEPENDENCE TO CHARGE/LIGHT YIELD

- ^{83m}Kr **is injected every 14 days**
- **Decays slowly enough** ($T_{1/2} = 1.83$ h) **to distribute uniformly in the detector, used to compute:**
  - **the S1 light collection efficiency as function of position**
  - **The S2 light collection efficiency as function of horizontal position**
  - **The position reconstruction distortion induced by our field**
- **Validated COMSOL field simulation using observed 83mKr signal ratio** $S(32.1\ \mathrm{keV})/S(9.4\ \mathrm{keV})$



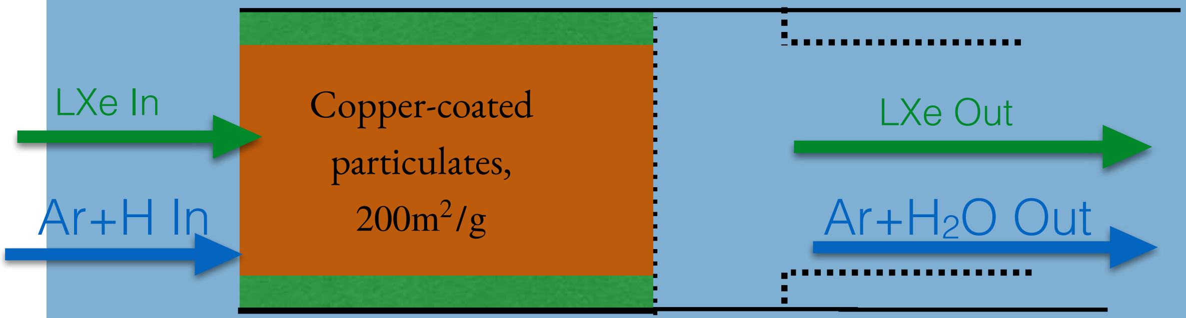
LUX describing the field method: Phys. Rev. D 96, 112009 (2017)



PURIFYING

- Drifting electrons through a meter of liquid Xenon requires a very low amount of electronegative contaminants that would otherwise degrade our ability to detect low-energy S2s and the reconstruction quality of larger S2 signals
- To date, most lXe experiments used gaseous purification, and had to evaporate, filter and then re-liquify the Xenon
- XENONnT pioneered a liquid purification system that passes through a high-surface copper-coated filter
  - Oxygen and electronegative species in the liquid react with the copper surface
  - Extensive R&D to avoid the surface injecting contaminants!

Purification system installed in nT service building



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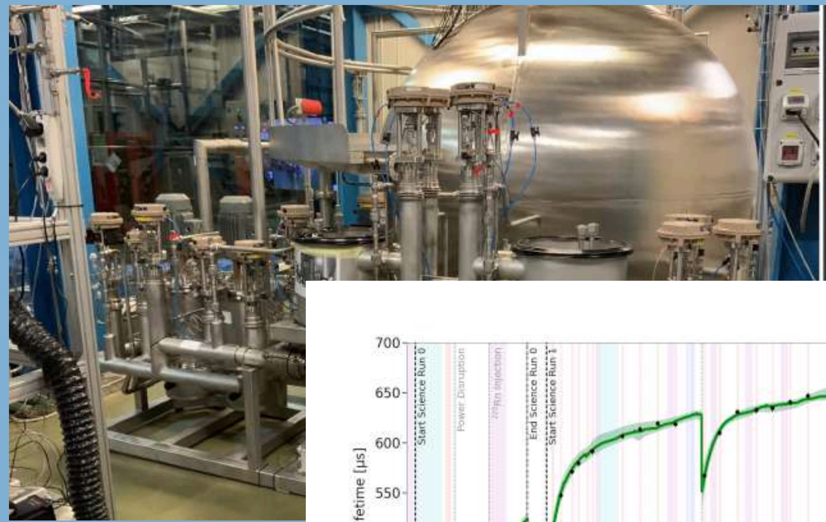
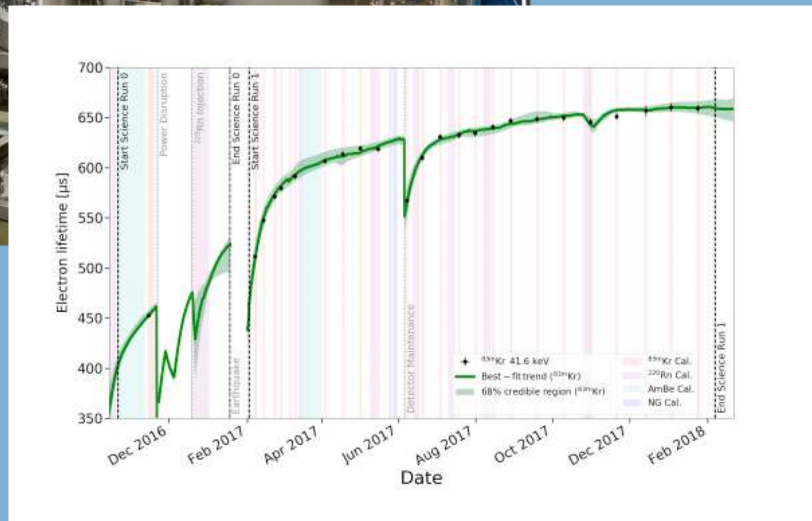
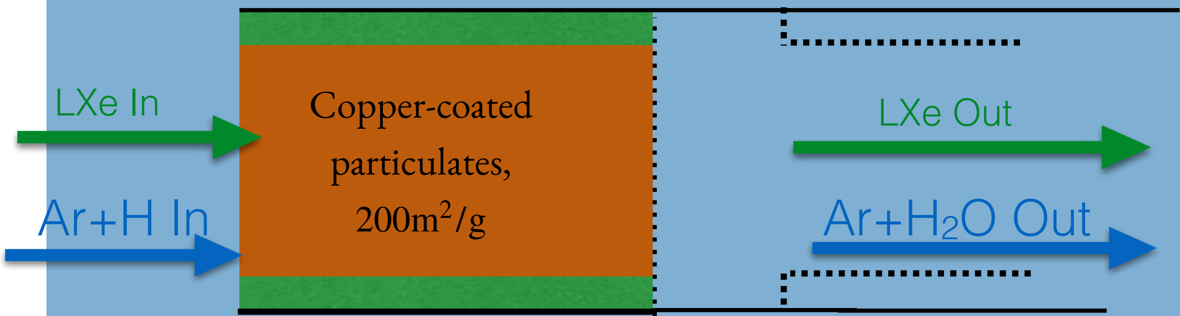
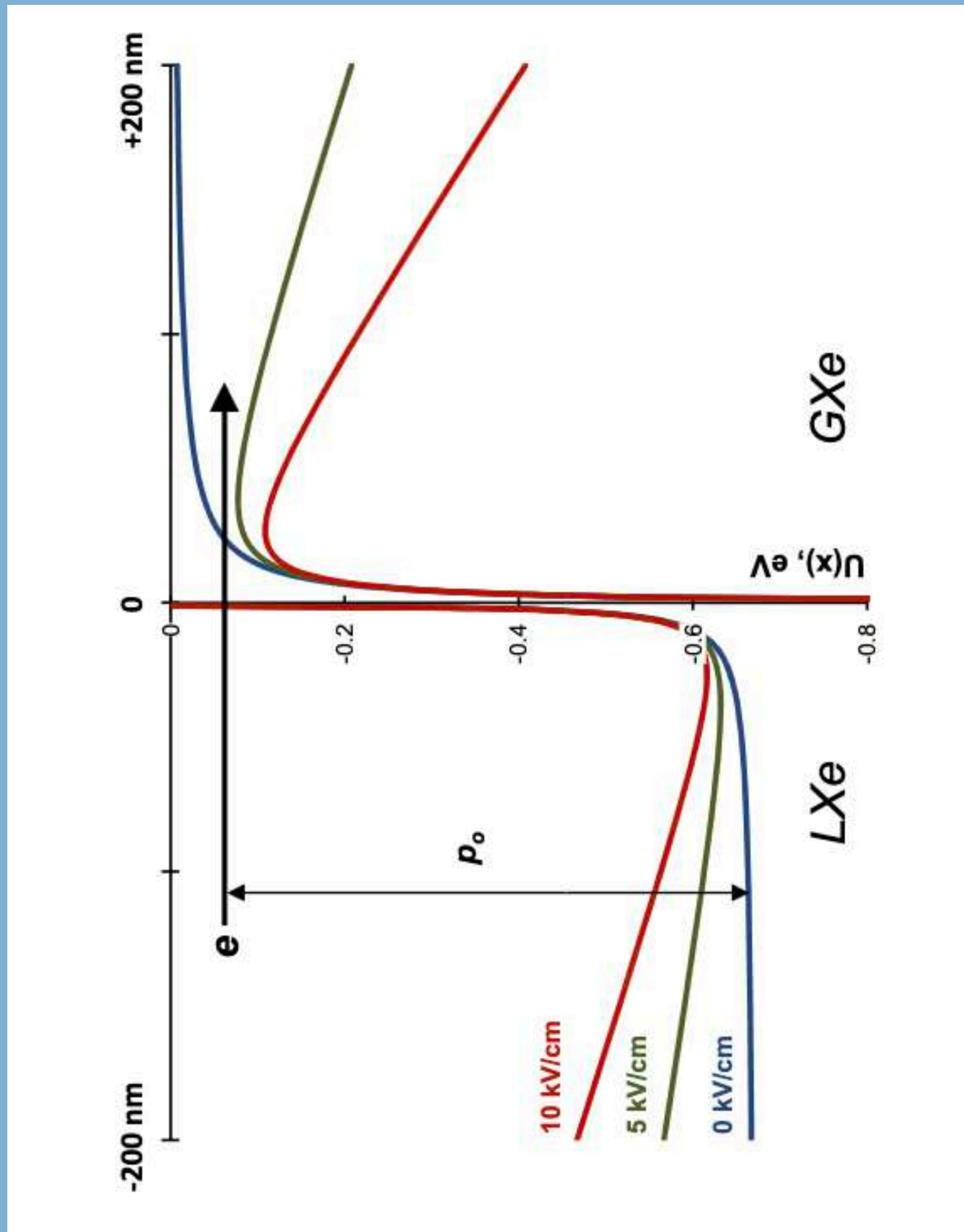






PROPORTIONAL SCINTILLATION

- The central point of lXe two-phase TPCs is that they are able to convert the ionization into more light, simplifying readout _and_ getting an amplification at the same time
- This is done by proportional scintillation— the light emitted by the electrons is proportional to the number of electrons
  - Rather than a geiger-like avalanche that erase the energy information
- First step: need high enough field to overcome the trapping of the electrons at the surface
- Electrons typically have slowed down with drift— they tunnel through instead of having inertia

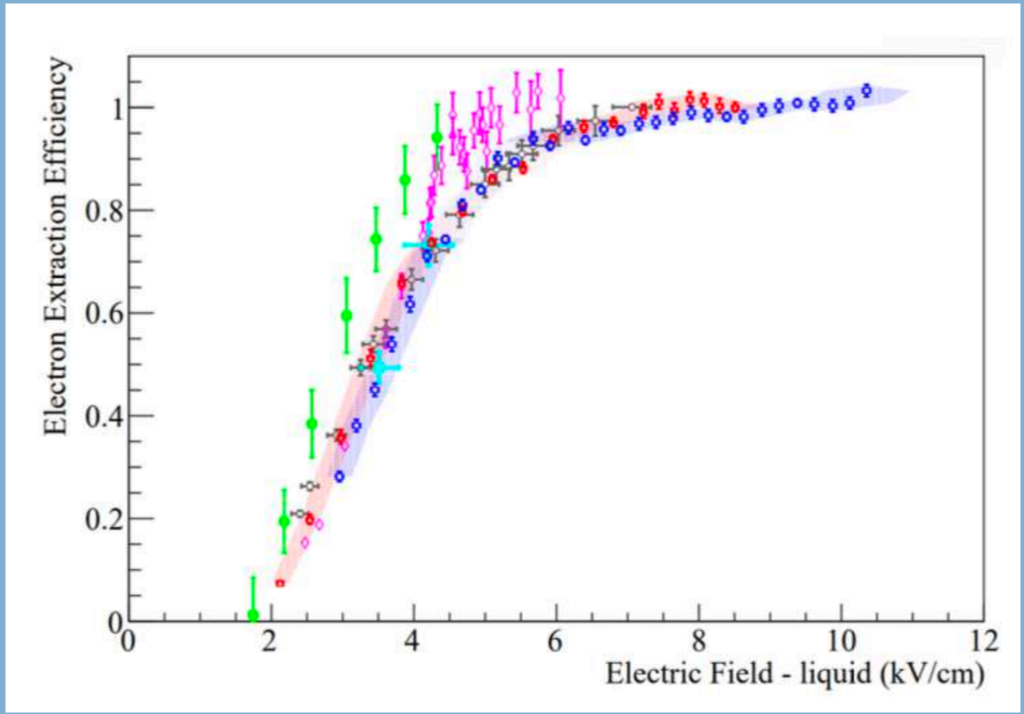


Liquid noble gas detectors for low energy particle physics

https://arxiv.org/abs/1207.2292

WHAT IS HIGH ENOUGH TO EXTRACT?

- **Extraction efficiency says how many electrons will be extracted**
- **Plateau above** $\sim$ 6kV/cm



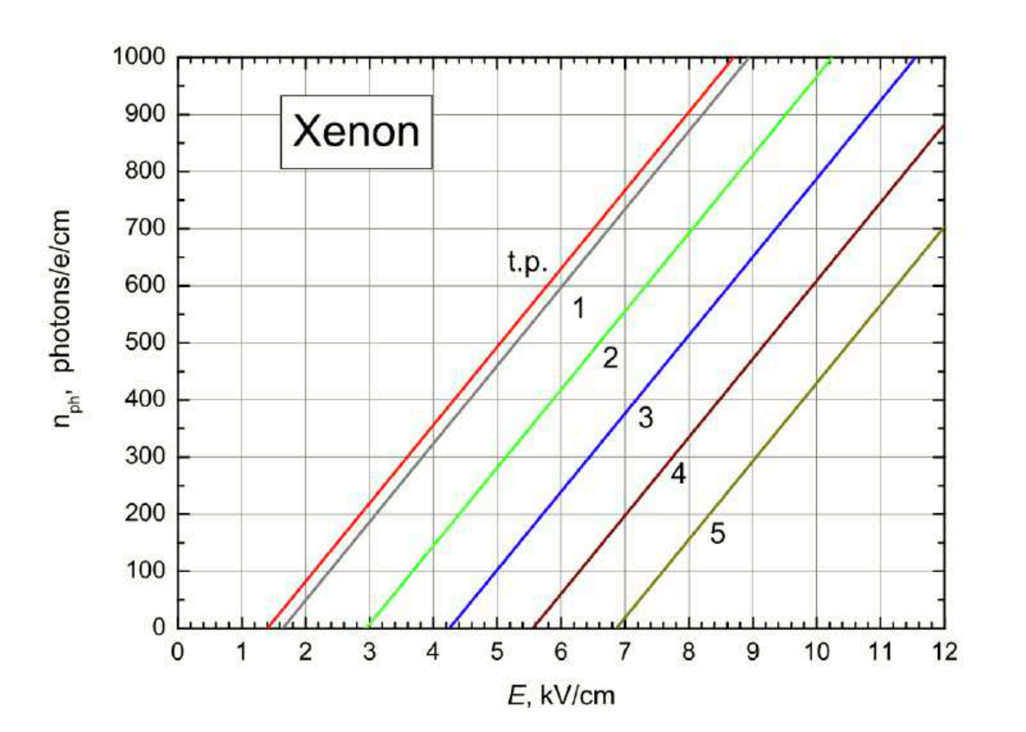
Electron extraction efficiency study for dual-phase xenon dark matter experiments. Phys. Rev. D, 99(10):103024, 2019.

PROPORTIONAL SCINTILLATION

$$\frac{1}{\eta}\frac{dN_\gamma}{dx} = a\frac{E}{\eta} - b[\text{photons}\cdot\text{cm}^2/\text{e}]$$

- **η is number density of gas, E the field.**

- **The light emitted in the gas phase is proportional to the drift length and linear in the electric field**
- **Emission similar in mechanism to the liquid— excimers are formed etc.**
- **Minimum field to emit;** $E/P \sim 1\text{keV/cm/bar}$
- **Plot shows emitted photons in a 1cm distance with pressures in bar.**



Liquid noble gas detectors for low energy particle physics

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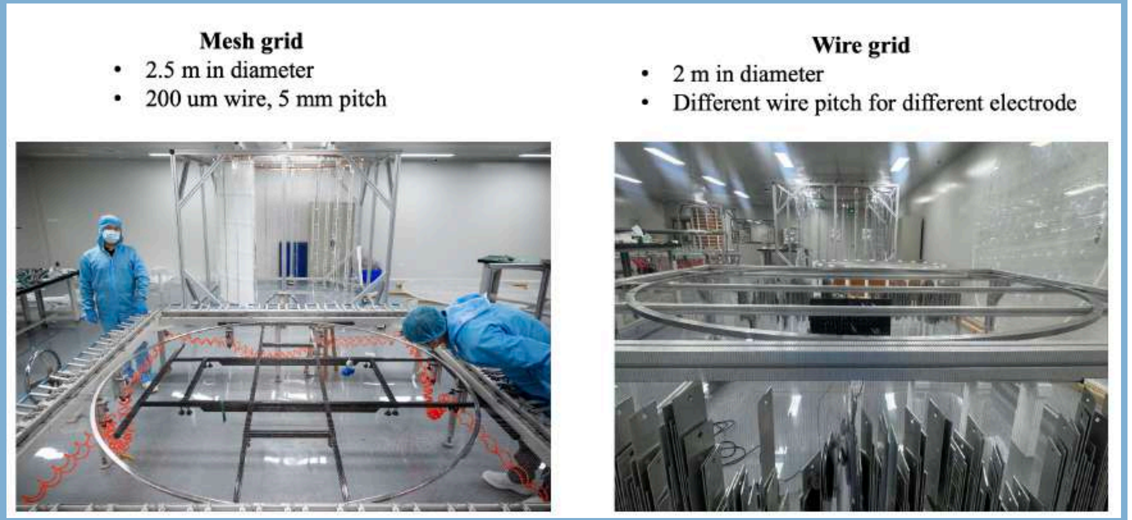
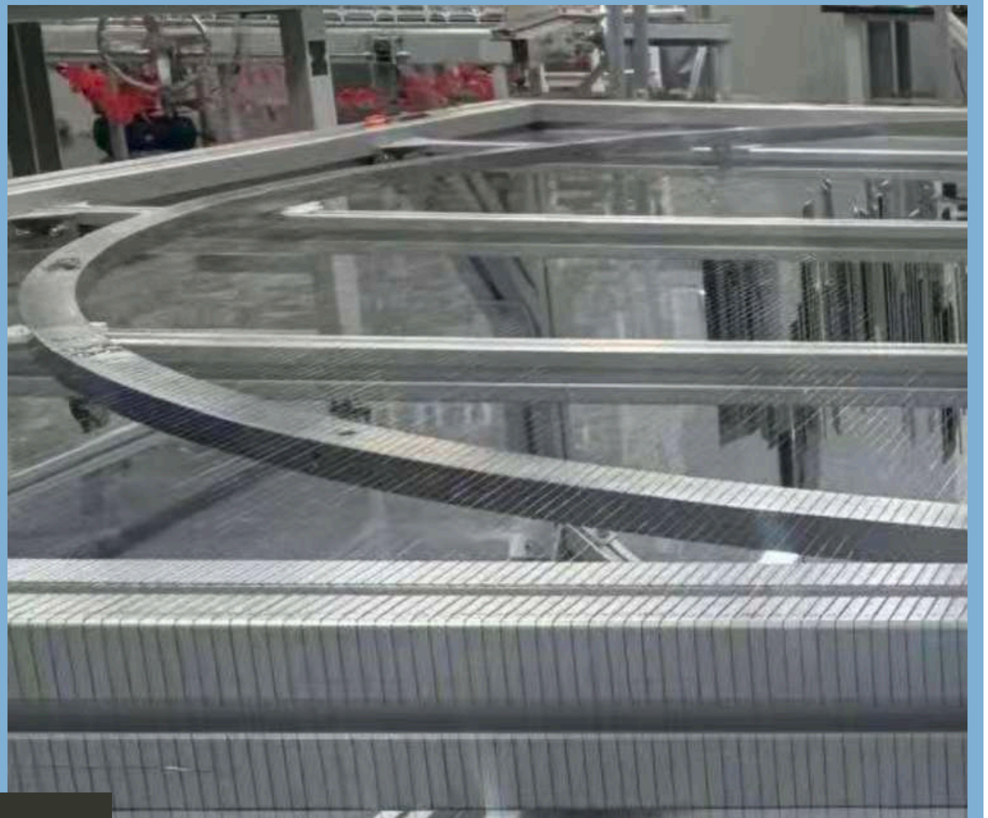
ELECTRODES

- One of the critical components of the TPC is the electrodes required to set up the electric fields, and to shield the PMTs from the same fields.
- From both a radiopurity and light collection standpoint, they should be as whispy thin as possible
- However, they are also under very high electromechanical stress, and too much sagging will distort the experiment, or limit operating voltage
- XENONnT and LZ have also had issues with “hot spots”, regions of localised emission associated with the grids
- and XENONnT had a short between the bottom cathode and shielding electrodes, severely restricting performance

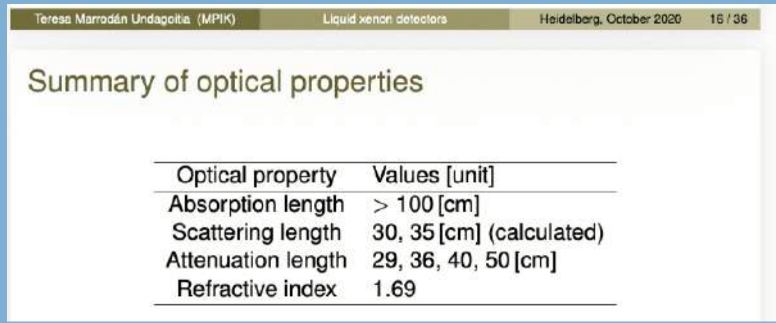




PandaX-20T: the next generation xenon detector for dark matter and neutrino searches, Xiang Xiao, presentation at IDM2026

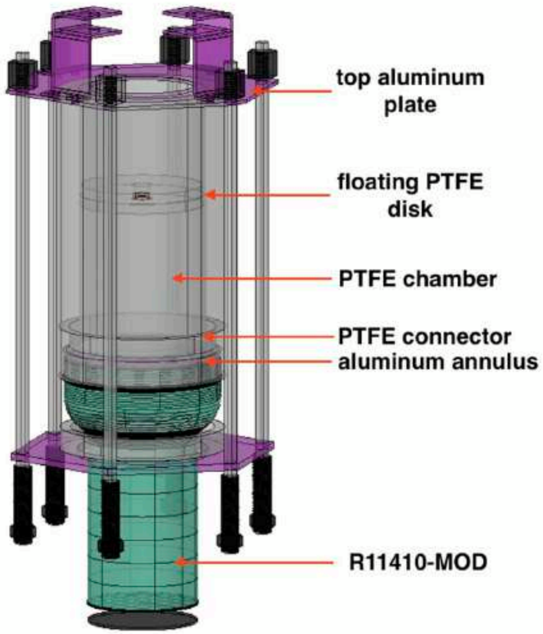
LIGHT COLLECTION OPTIMISATION

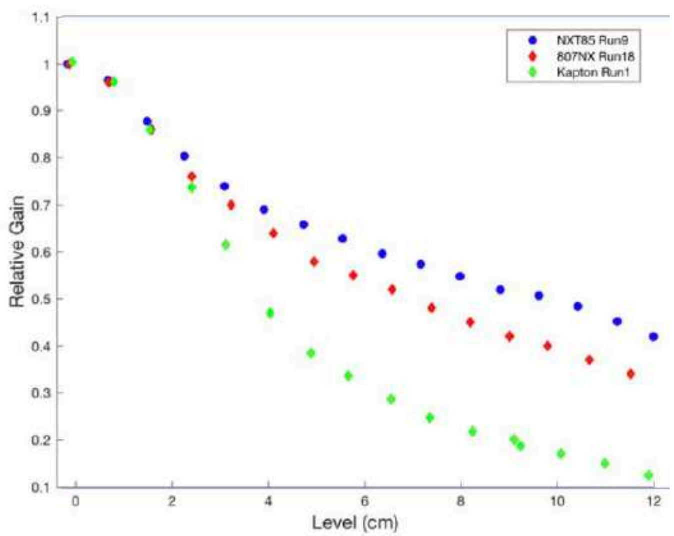
- **Since the S1 light is sparse, we wish to collect all of it**
- **The sides of the TPC are covered in PTFE (teflon) to reflect the scintillation light, reflectivity** $\sim 99\,\%$
- **Tuning the reflectivity and the optical absorbtion length is a main focus of the simulations of the observables for the detector**
- **For high reflectivity, you need a thick PTFE layer but this introduces unwanted material (and thus radioactivity)— need to optimise!**


Teresa Marrodán Undagoitia (MPIK) Liquid xenon detectors Heidelberg, October 2020 16 / 36

Summary of optical properties

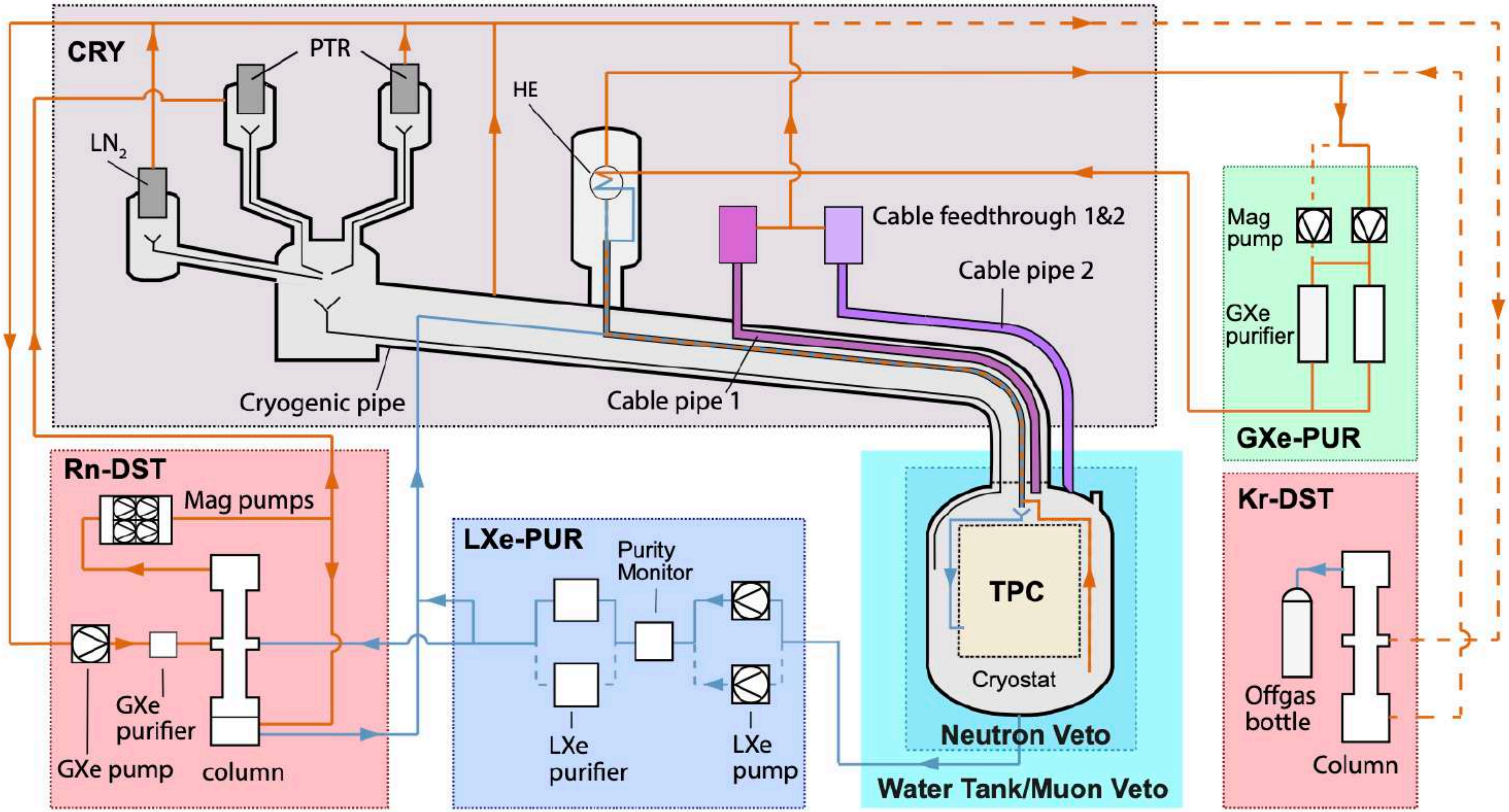
Optical property	Values [unit]
Absorption length	> 100 [cm]
Scattering length	30, 35 [cm] (calculated)
Attenuation length	29, 36, 40, 50 [cm]
Refractive index	1.69





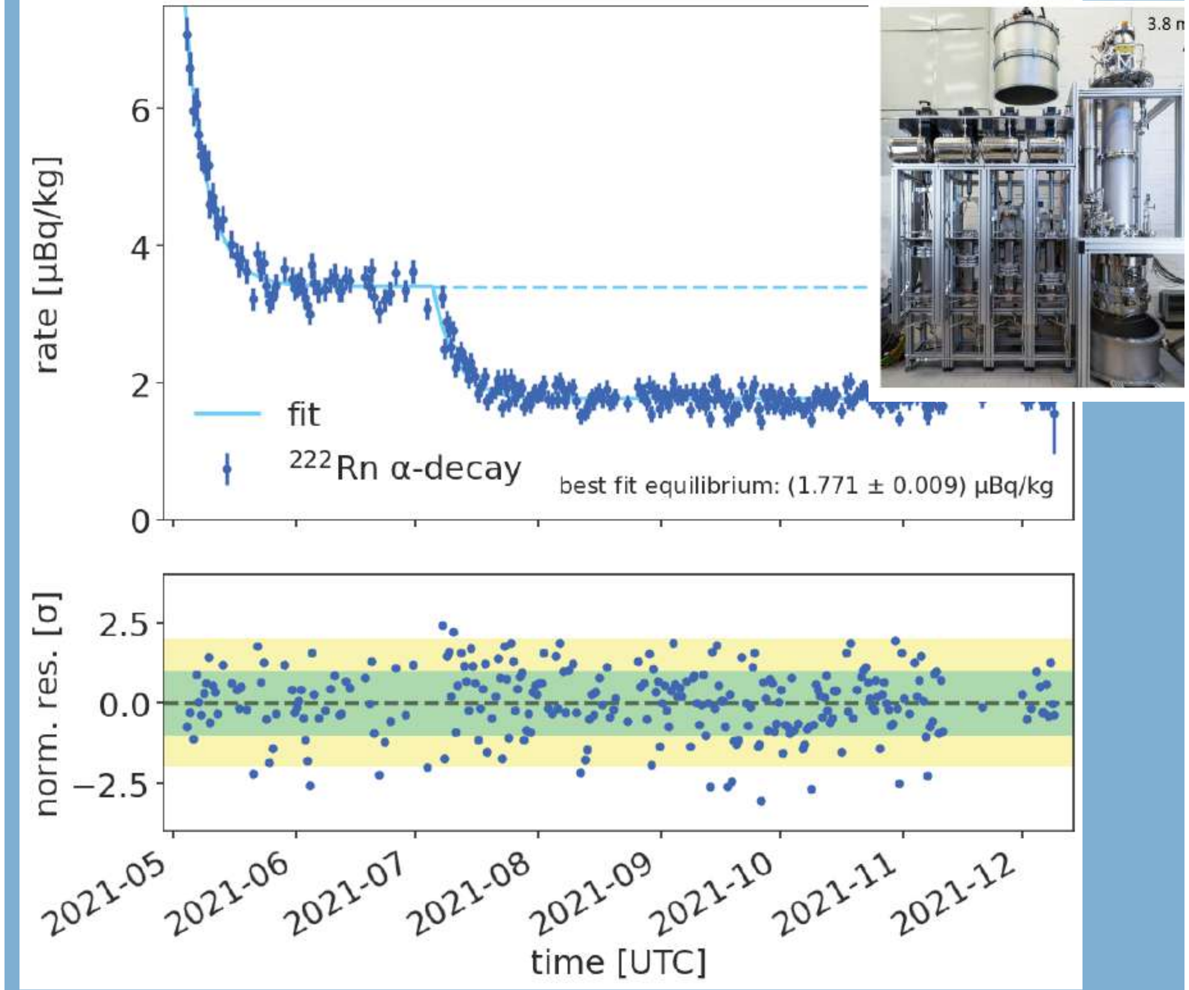
Teresa Marrodan Liquid Xenon detectors,
PTFE Reflectance for Xenon
Scintillation Light Wolfgang Lorenzon, slides for LIDINE 2017, SLAC National Accelerator Laboratory

CRYOGENIC PURIFICATION AND HANDLING



REMOVING RADON

- ^{222}Rn is the primary source of background events in both XENON1T and XENONnT.
- The newly developed Rn column can handle large xenon flows using radon-free compressors and heat exchangers
- For the first science run, the column operated in gas-only mode
- Reached $< 1\ \mu Bq/kg$ in stable operation
- LZ cleans a Rn-rich subset of the cryogenics flow with a charcoal trap where Rn will decay before passing through



M. Murra, D. Schulte, C. Huhmann, C. Weinheimer
e-print: arXiv:2205.11492 [physics.ins-det]

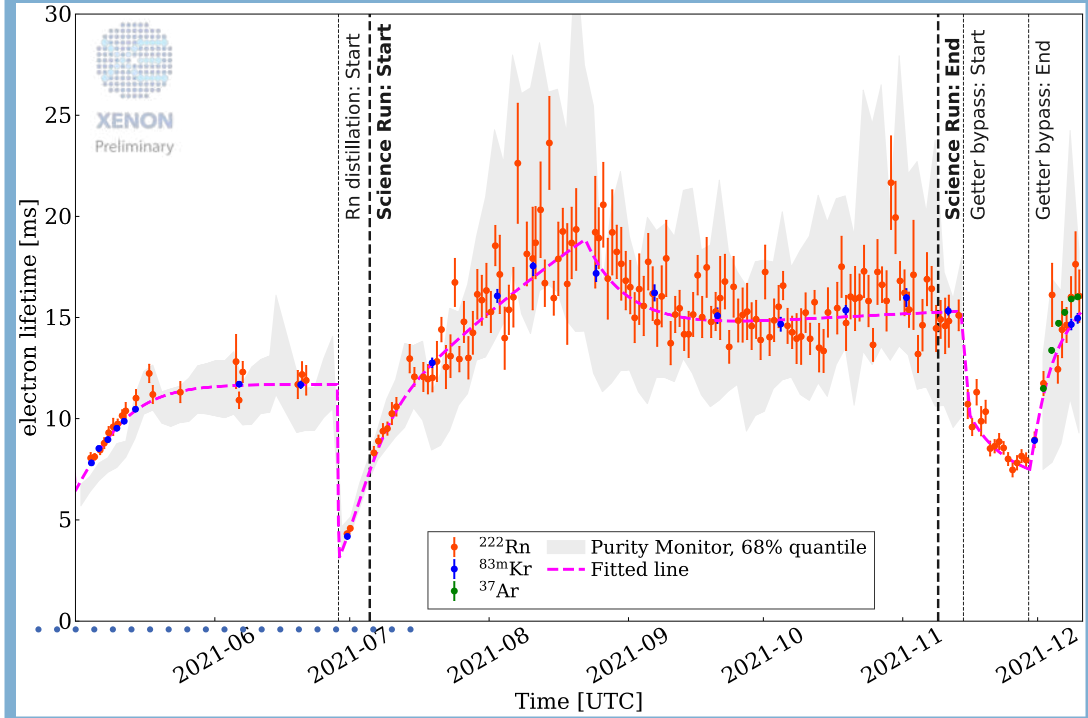
LIQUID XENON PURIFICATION

- Drift lengths O(m) demands improvements in removing electronegative impurities that dampen the S2 signal
- XENONnT uses a new liquid purification technique with replaceable filter units with extremely low radon emanation (in the science run mode).
- High flow of 2 liters liquid xenon / minute— reach very high purity in less than a week— 18 h to exchange the entire volume

	Full TPC drift time	electron lifetime	electrons surviving a full drift length
XENON1T	0.67 ms	0.65 ms	30 %
XENONnT	2.2 ms	10+ ms	86 % @ 15 ms

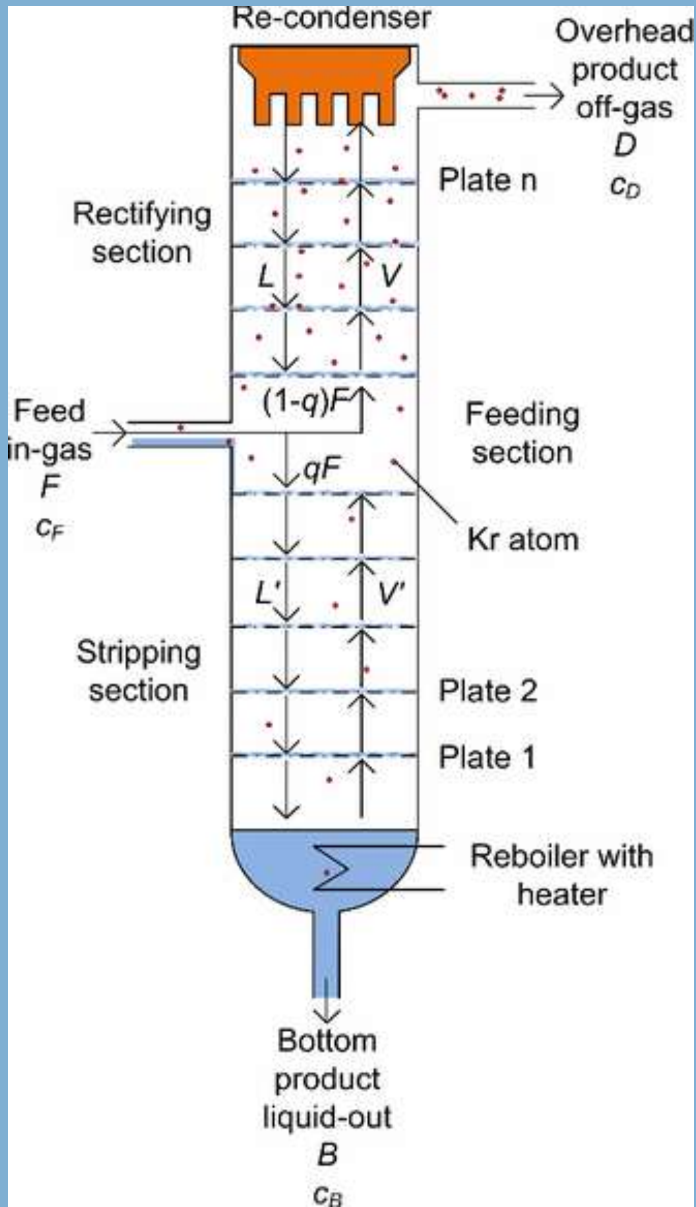
G. Plante E. Aprile, J. Howlett, Y. Zhang

e-Print: 2205.07336 [physics.ins-det]



REMOVING KRYPTON

- ^{85}Kr originates from nuclear testing, and contaminates commercial xenon at the 10^{-6} level
- 85Kr for XENON is removed with an ongoing cryogenic distillation, reducing the concentration by more than a factor 105
- 222Rn (emanating from detector materials) is the source of most background events in the WIMP search region. XENONnT will feature an online radon distillation column to reduce the rate of 222Rn events by a factor ~4
- LZ purified their xenon offline, 10 tonnes over 16 months, and measures 0.186 ppt



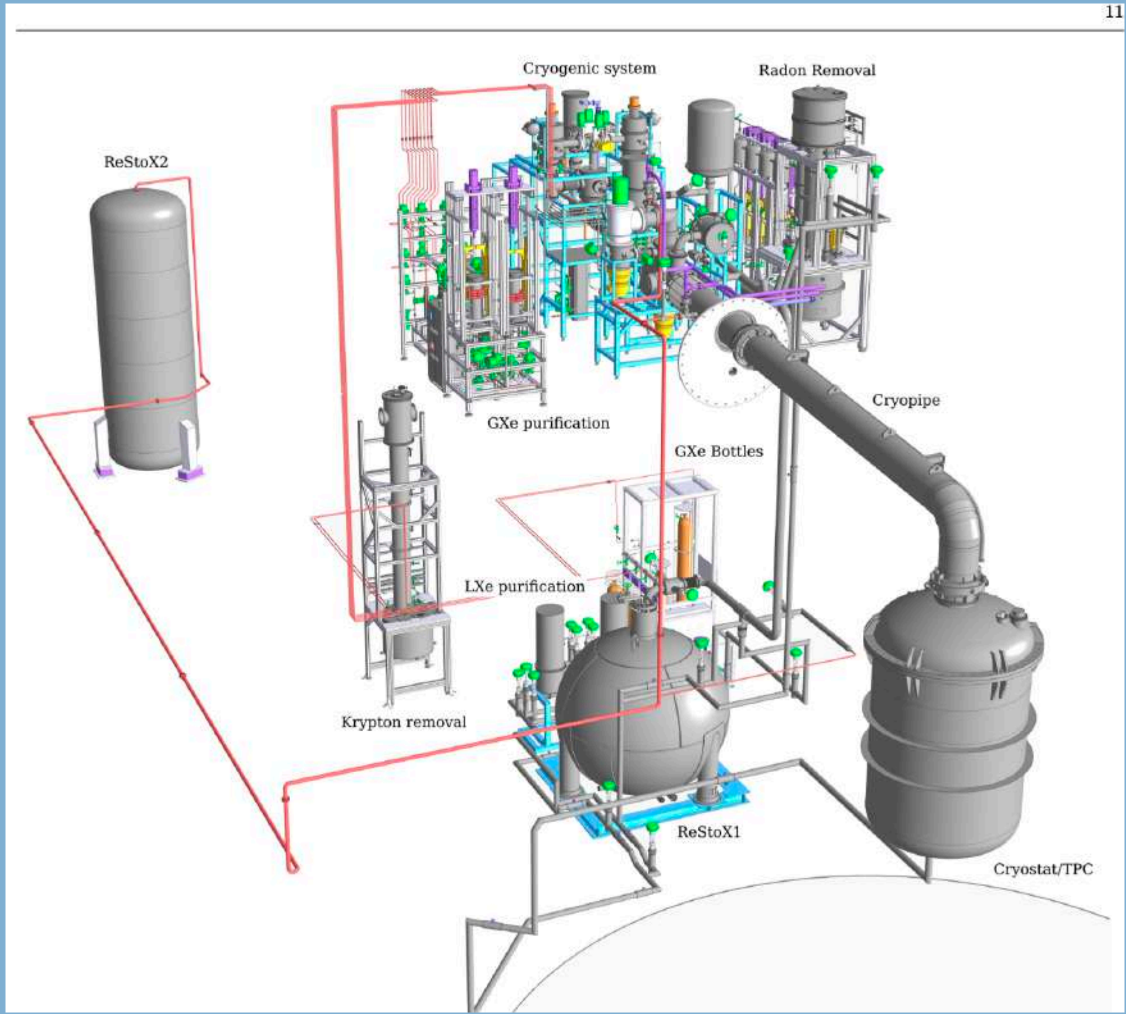
Removing krypton from xenon by cryogenic distillation to the ppq level

XENON Collaboration • E. Aprile (Columbia U.) et al. (Dec 13, 2016)

Published in: *Eur.Phys.J.C* 77 (2017) 5, 275 • e-Print: 1612.04284 [physics.ins-det]

RESTOX

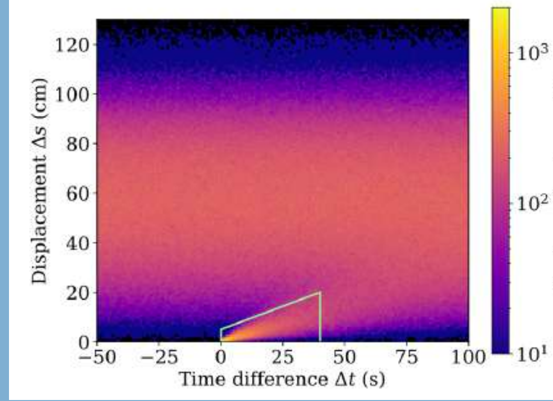
- XENON has pioneered liquid xenon storage units— large pressure-safe dewars
- In an emergency these systems can rapidly extract the xenon from the TPC by moving it in liquid form to RESTOX1
  - RESTOX1 can contain the pressure of 7.6 tonne of xenon in supercritical state at room temperature
- RESTOX2 has a large cooling capacity (1 tonne xe liquified/h) to take xenon from RESTOX1
- The alternative, standard method is to "cryopump"— connect the TPC to gas bottles cooled by liquid nitrogen to take gas from the TPC and condense it there.

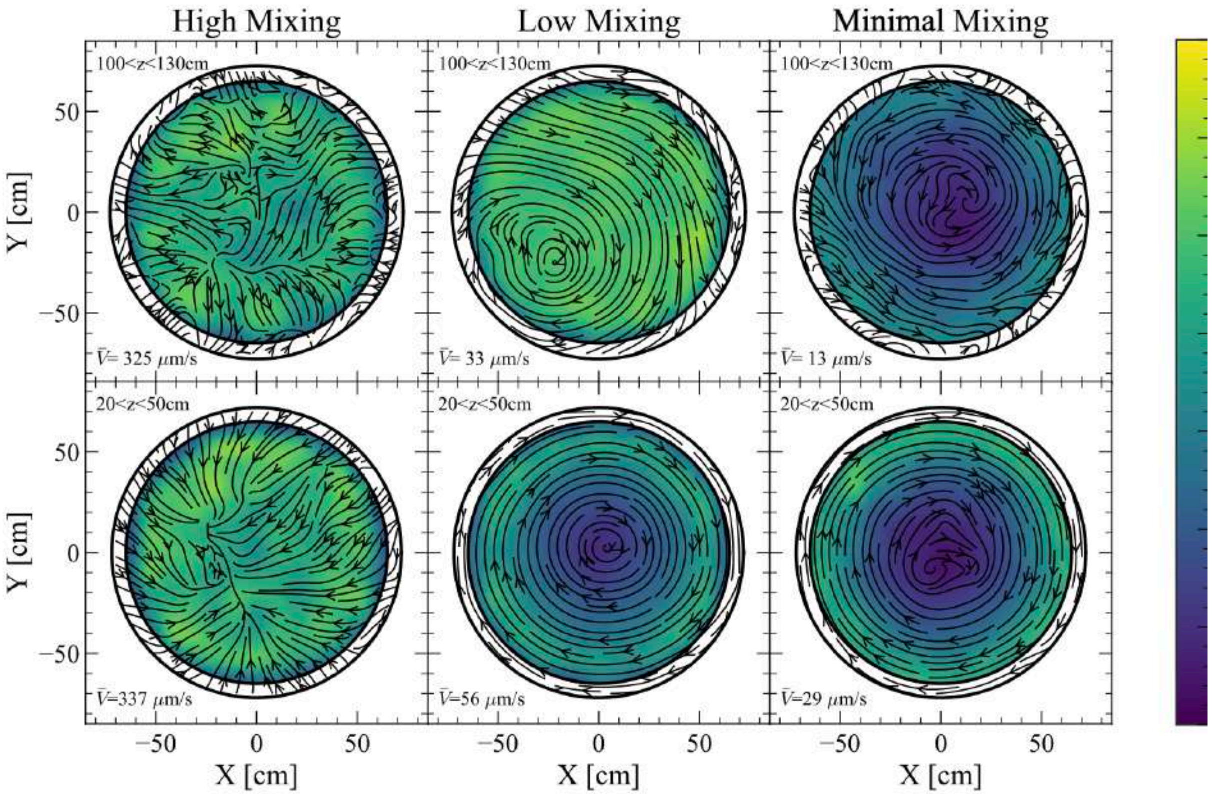


ONLINE RN VETO

- **The main background in lXe TPCs is β-decays of ^{214}Pb, which is a daughter of ^{222}Rn, emanating from detector surfaces.**
- **The preceding steps in the decay take up to hours, and so a time cut would not work**
- **However, if you can characterise your xenon flow pattern accurately enough, and it moves slowly enough, it is possible to trace the streamlines over time (LZ managed 81 minutes) and tag events**
- **LZ was able to significantly reduce their backgrounds, due to their slow convection speed and careful mapping of the flow**
  - **60% tagging efficiency using 10% of the livetime**

Offline tagging of radon-induced backgrounds in XENON1T and applicability to other liquid xenon time projection chambers
Flow-dependent tagging of 214Pb decays in the LZ dark matter detector
https://arxiv.org/pdf/2508.19117





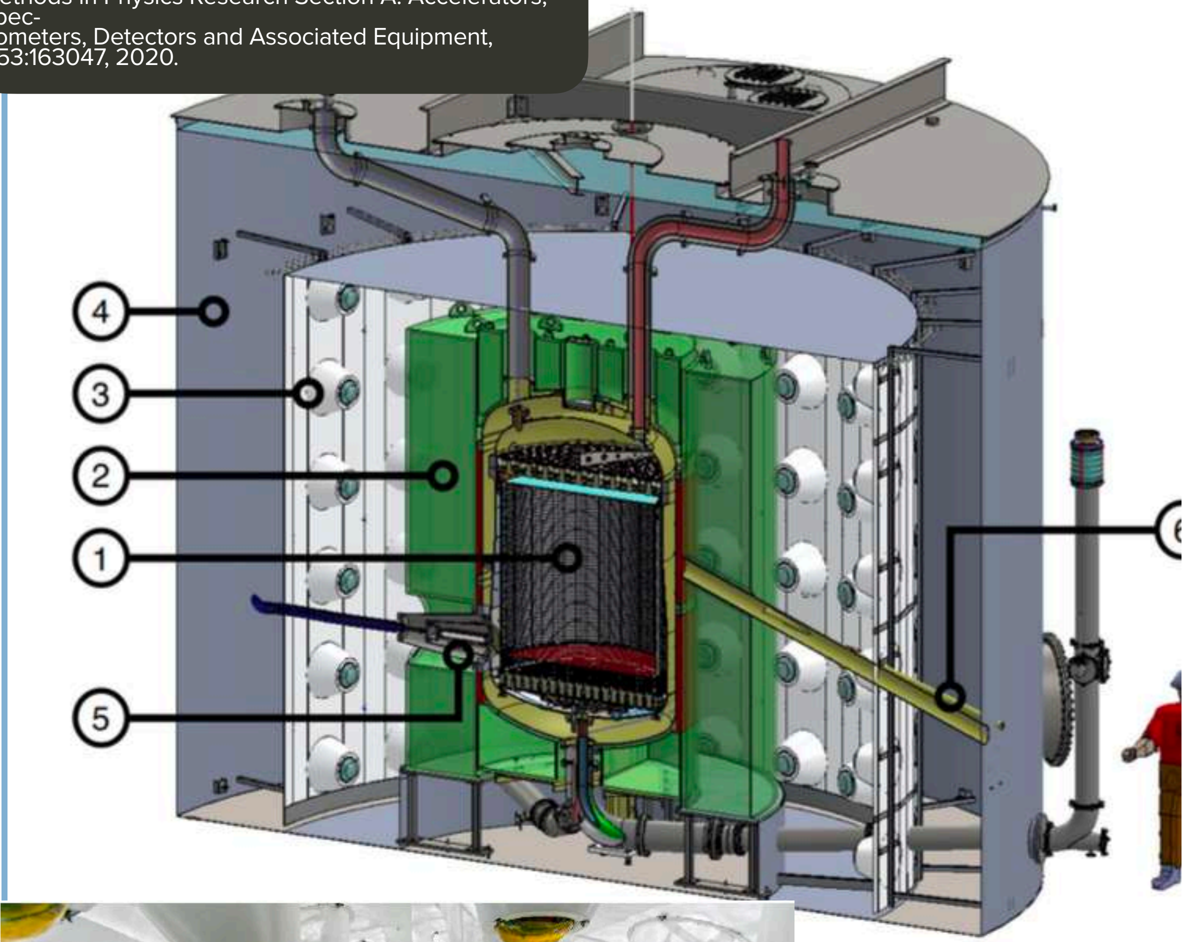
SHIELDING

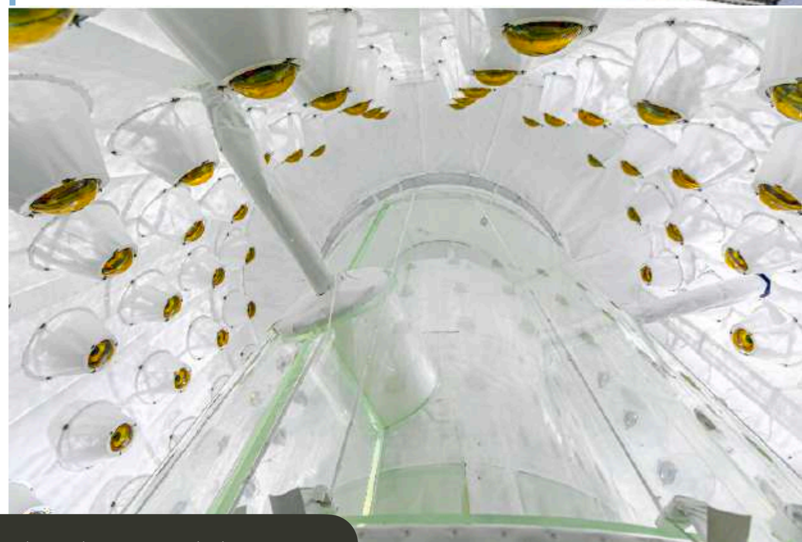
- Even underground, there is enough radioactivity
- Layers of lead, copper, or large water tank provide shielding against external gamma-rays
- while polyethylene or water, again can reduce the neutron flux
- Not only a benefit by removing background; at some level of sensitivity, your detector would simply be lost in deadtime if you don't shield it.

NEUTRON VETO SYSTEMS

- Neutrons are weakly interacting massive particles, and the self-shielding length is too long to completely eliminate them
- instead, tag them either looking for multiple scatters in the TPC, or using active vetos
- As an example, LZ uses a liquid scintillator loaded with gadolinium (green) which emits a characteristic $\sim 8\mathrm{MeV}$ gamma-ray when capturing a neutron with their very high capture cross-sections
- Neutron vetos reach efficiencies of 95%, which are also invaluable to provide tagged samples to validate analysis

The lux-zeplin (lz) experiment. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spec-
trometers, Detectors and Associated Equipment, 953:163047, 2020.

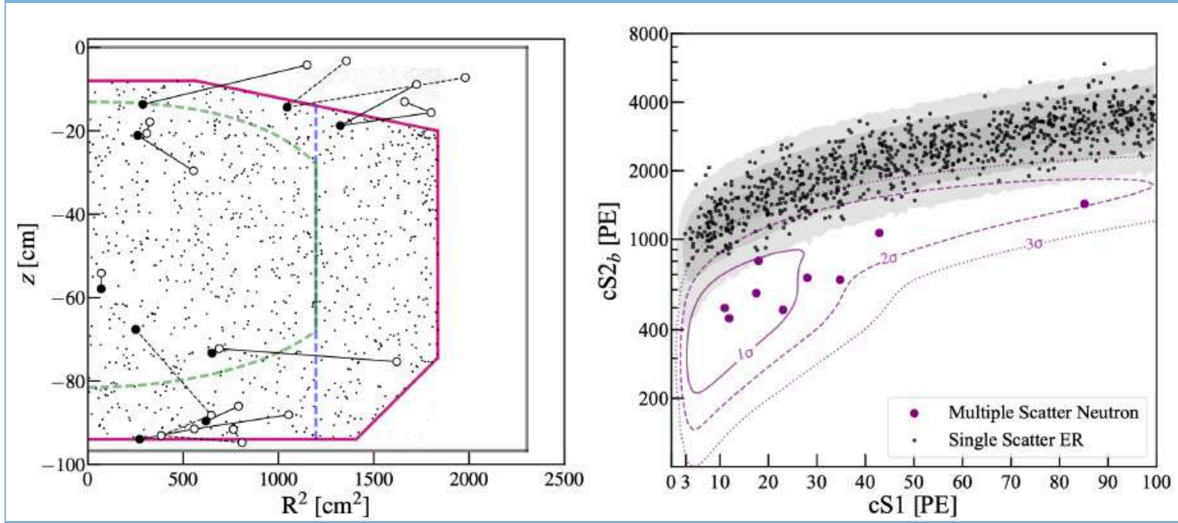




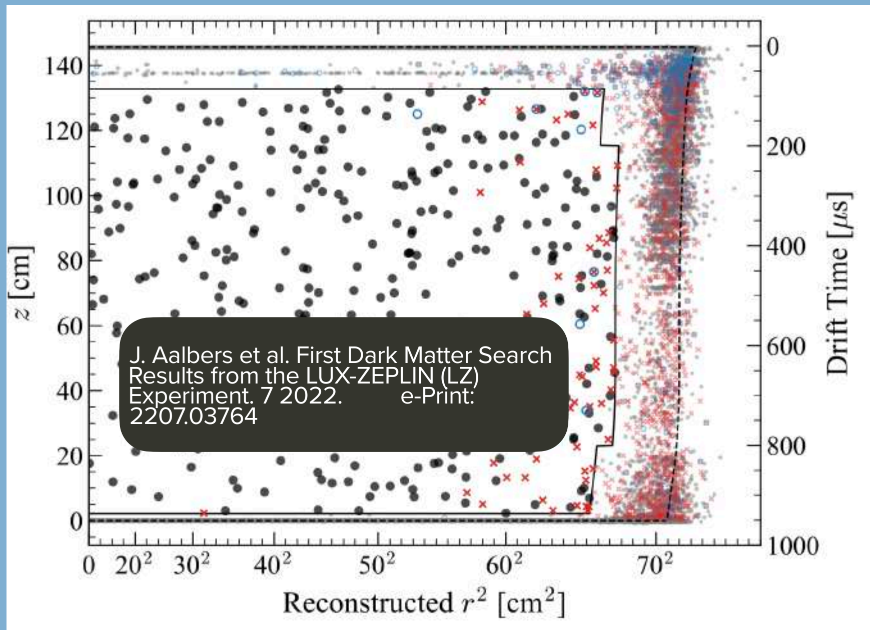
Far and Wide: Searches for Particle Dark Matter with the LZ and TESSERACT Experiments
Michael Williams, PhD thesis

REJECTING NEUTRONS

- **Neutrons are distinguishable from WIMPs statistically via their spatial distribution, and directly either when they scatter multiple times or via neutron vetos:**
- **XENONnT uses a denser instrumented TPC array in its muon water tank, and plans to dope the water with Gd**
  - **Current tagging efficiency: 0.68, with Gd projected 0.87**
- **LZ surrounds the detector with blocks filled with 17 tonnes liquid scintillator + Gd (blue circles are vetoed events)**
  - **Tagging efficiency 0.88 in calibration**



E. Aprile et al. XENON1T dark matter data analysis: Signal and background models and statistical inference. Phys. Rev. D, 99(11):112009, 2019. doi: 10.1103/PhysRevD.99.112009.

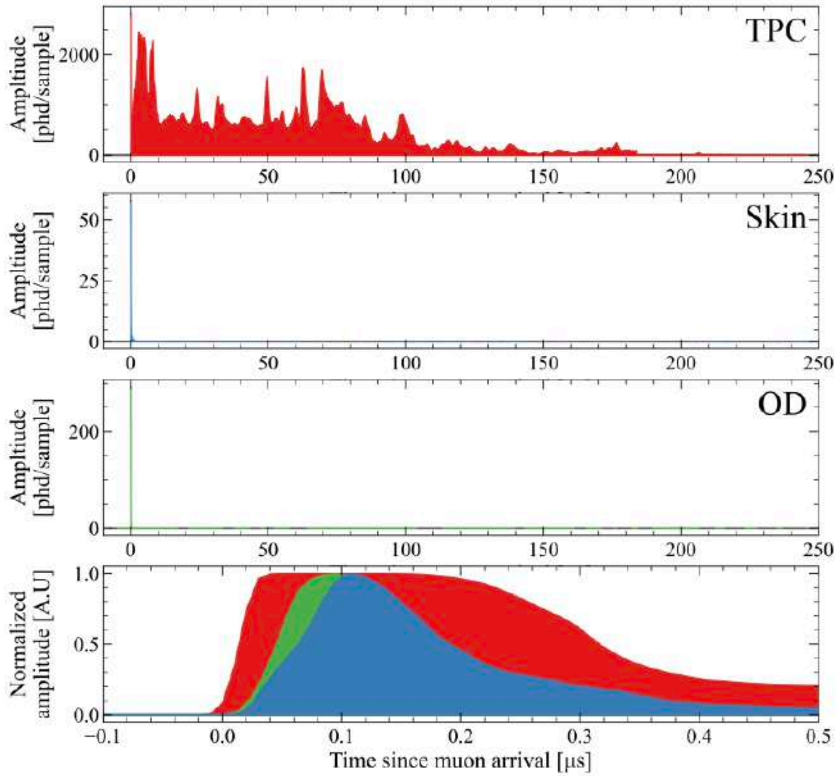


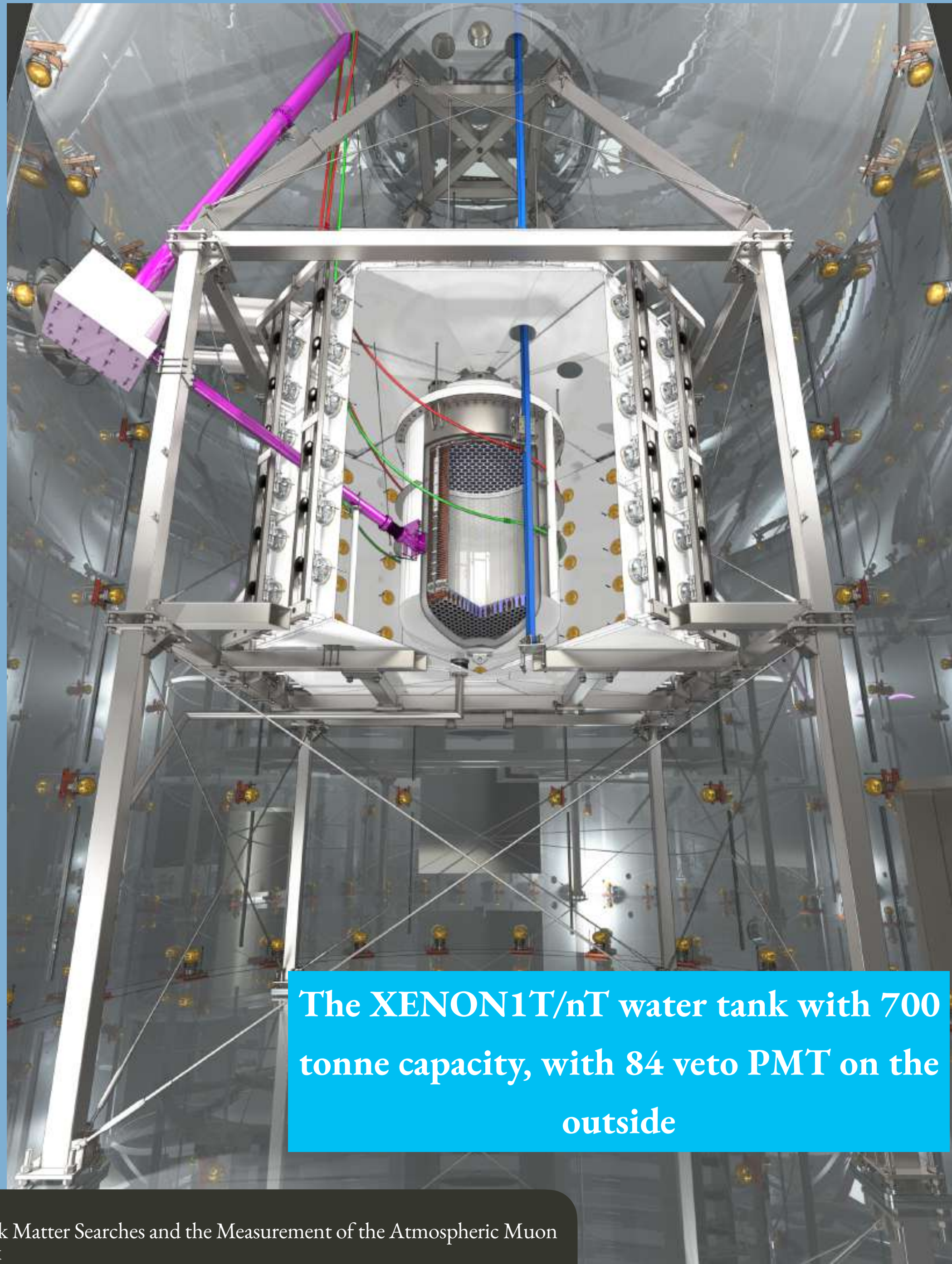
J. Aalbers et al. First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment. 7 2022. e-Print: 2207.03764

MUON VETO SYSTEMS

- **Muons can be tagged from their cherenkov light passing through the outer water tank of the detector,**

- **Muons also cause longer-time noise in the TPC**





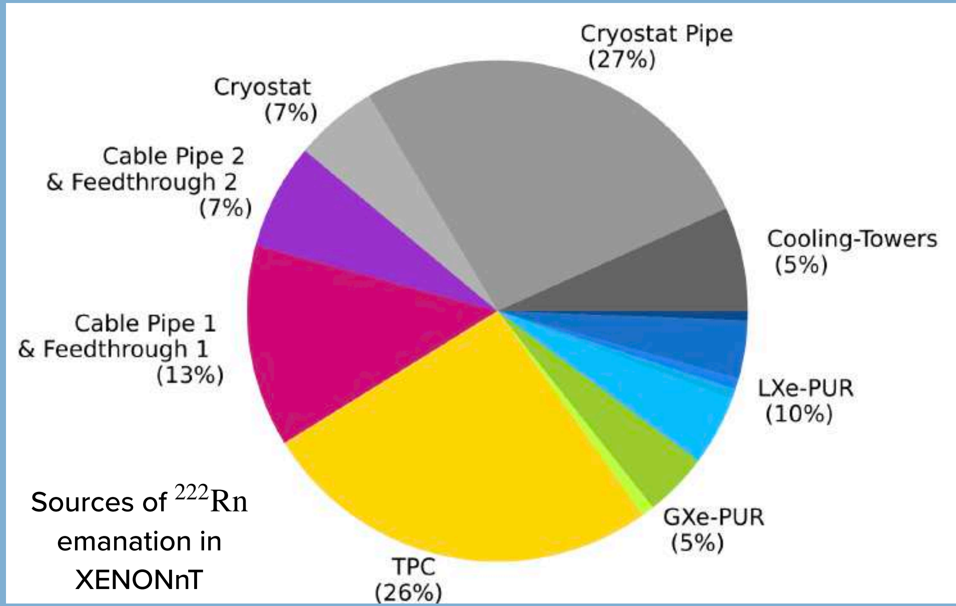
The XENON1T/nT water tank with 700 tonne capacity, with 84 veto PMT on the outside

Dark Matter Searches and the Measurement of the Atmospheric Muon Flux
with the LUX-ZEPLIN Experiment
PhD thesis, Harvey Birch

MATERIAL SCREENING, SELECTION

- Every piece of the detector is assayed; e.g. LZ had a 6 year campaign
- ^{226}Rn present in most materials (part of the ^{238}U chain) decays and produces ^{222}Rn as one of its daughter, which can emanate into the LXe
  - Etching, diamond shaving and cleaning steps used to reduce emanation
- Radioactive isotopes contribute both to ER background from surfaces, and to signal-like neutron signals
  - O(80) samples assayed at several detectors
- Detectors are assembled in cleanrooms, but the operations do introduce dust— LZ estimates (0.64 ± 0.05)g in their TPC

E. Aprile et al. Material radiopurity control in the XENONnT experiment. Eur. Phys. J. C, 82(7):599, 2022. doi: 10.1140/epjc/s10052-022-10345-6.



D. S. Akerib et al. The LUX-ZEPLIN (LZ) radioactivity and cleanliness control pro- grams. Eur. Phys. J. C, 80(11):1044, 2020. doi: 10.1140/epjc/s10052-020-8420-x.

MATERIAL SCREENING, SELECTION

- As another example, the above is the result of the LZ radon emanation screening
- Note how large the dust contribution is!

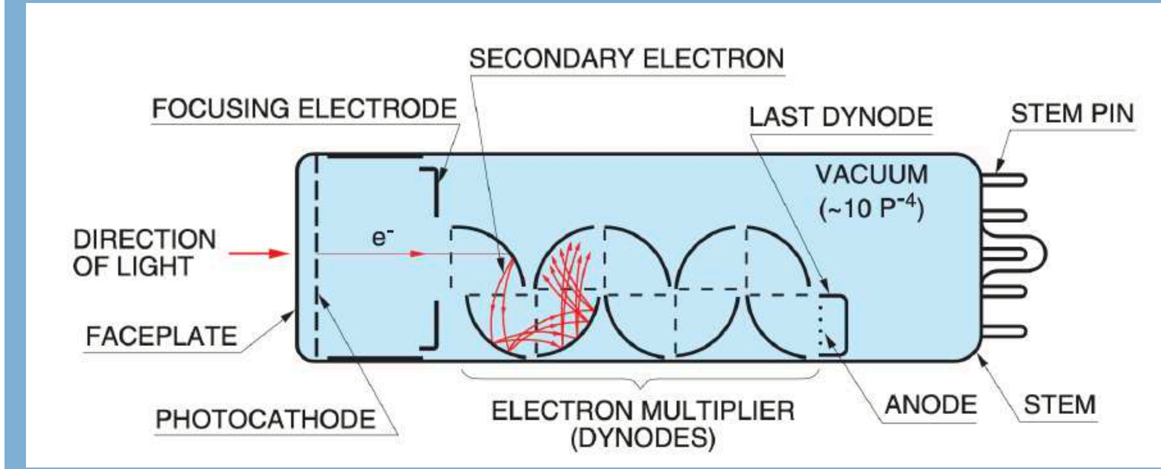
Material	Component(s)	Quantity	Unit	Estimate (mBq)
Al_2O_3 resistor	PMT Bases	9790	#	**0.58***
$BaTiO_3$ capacitor	PMT Bases	3010	#	**0.016***
Cirlex	PMT Bases	6000	cm^2	**0.37***
Titanium	Cryostat, PMT Mounts, Field Rings, Grid Supports	412,000	cm^2	0.41
PTFE	Reflectors, Field Cage	840,000	cm^2	**<1.3***
PMT cabling†	PMT Cabling	17,000	m	**0.8**
PMT feedthrough†	PMT Feedthrough	88	#	**<0.24**
Steel conduit†	Cabling Conduit	100,000	cm^2	0.055
R11410 PMT	R11410 PMT	488	#	1.26
R8520 PMT	R8520 PMT	90	#	0.15
R8778 PMT	R8778 PMT	38	#	0.09
Polyethylene	HV Umbilical	4200	cm^2	0.10*
Tin-coated copper	HV Umbilical	11,000	cm^2	0.002
Tivar	HV Umbilical	3894	cm^2	0.004*
Acetal	HV Umbilical	195	cm^2	0.0002*
Copper	HV Umbilical	39	cm^2	0.000007
Epoxy	HV Umbilical, Feedthroughs	1000	cm^2	0.0001*
Steel	Cryostat Seals, Xe Recirculation	135,000	cm^2	0.104
Recirculation pump	Xe Recirculation	1	#	0.1
Purification getter	Xe Recirculation	2.5	kg	1.34
Transducers & Valves	Xe Recirculation	30	#	0.17
Welds	Recirculation System, Cryostat	32.3	m	**0.11**
Dust		1	g	10.0
Total				< 17.3

Constraining Radon Backgrounds in LZ
https://arxiv.org/pdf/1708.08533

PHOTODETECTORS: PMTS

- Photomultipliers are the standard for single-photon detection
- A vacuum-filled vessel contains a (glass) window, a photocathode and a number of dynodes
- A single photon may liberate an electron from the photocathode via the photoelectric effect
  - Choice of cathode material determines frequency + quantum sensitivity
- The electron is focused and accelerated onto the dynode where it liberates more electrons in an avalanche, ending up with a detectable charge signal at the anode end of the amplification chain

PHOTOMULTIPLIER TUBES: Basics and Applications by Hamamatsu is an amazing resource; link



PMT voltage signals are normalised to calibrations to give physics-units;

- Photoelectrons (PE); normalise the signal to the voltage when a single electron is liberated from the photocathode
- - Photons detected (PhD); normalise to the signal of one photon hit

PHOTODETECTORS: PMTS

- **PMTs may feature amplification factors of 10^6 or more, and good timing resolution and low dark counts**
- **LZ, Panda-X and XENON all have used Hamamatsu PMTs of the R11410 model**
  - **Good performance at low power,**
  - **well-matched for xenon scintillation light**
- **A custom-made variant uses selected material sources to achieve very low radioactivity— 13mBq,0.4mBq, respectively for ^{238}U and ^{228}Th**

Property	Unit	Result	
		Mean	Spread
Quantum efficiency	%	34.0	2.8
Gain at 1.5 kV	10^6	8.4	2.3
HV for gain of 5×10^6	kV	1.41	0.04
SPE resolution (median)	%	25.1	1.5
Peak-to-valley ratio (median)	-	4.3	0.4
Transit time spread	ns	9.2	0.5

PHOTOMULTIPLIER TUBES: Basics and Applications by Hamamatsu is an amazing resource; link

Improved quality tests of R11410-21 photomultiplier tubes

for the XENONnT experiment

https://arxiv.org/pdf/2104.15051

PMT FAILURES :(

- PMTs are made in low quantities and sometimes by hand, and show significant variability
  - They can essentially become tiny linear particle accelerators
- For example, flashing PMTs
- The vacuum may also leak after cool-down, which can be identified by the characteristic time of each atom, causing “afterpulsing”
  - In some cases, this also causes light emission from the PMT
- During running, experiments see some PMTs degrading and turn them off, this must be taken into account in reconstruction

Improved quality tests of R11410-21 photomultiplier tubes

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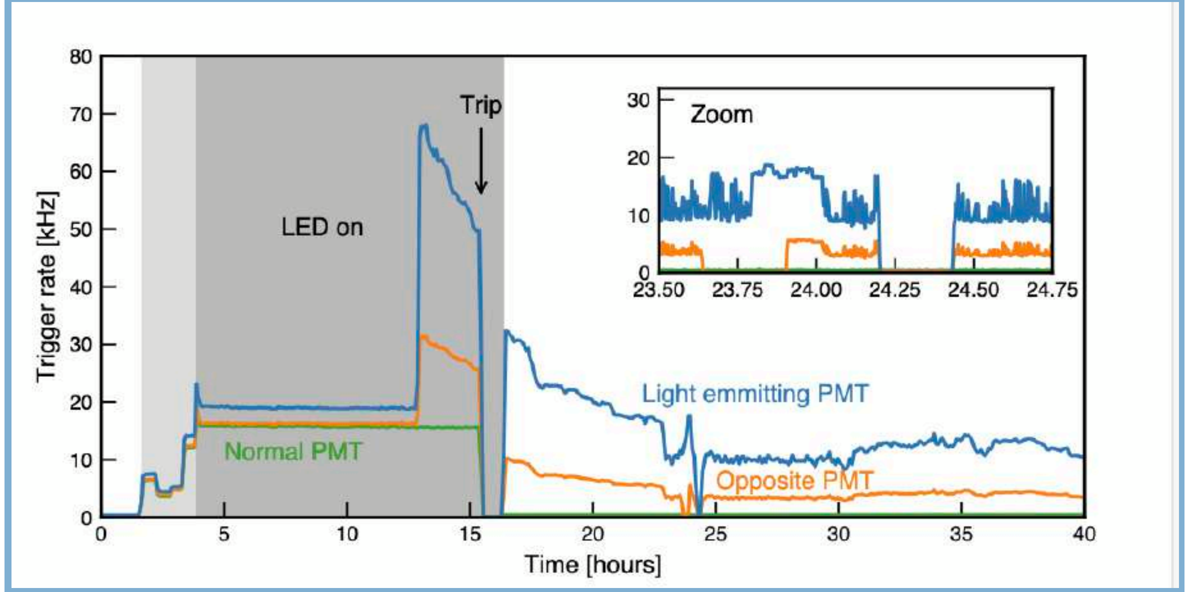
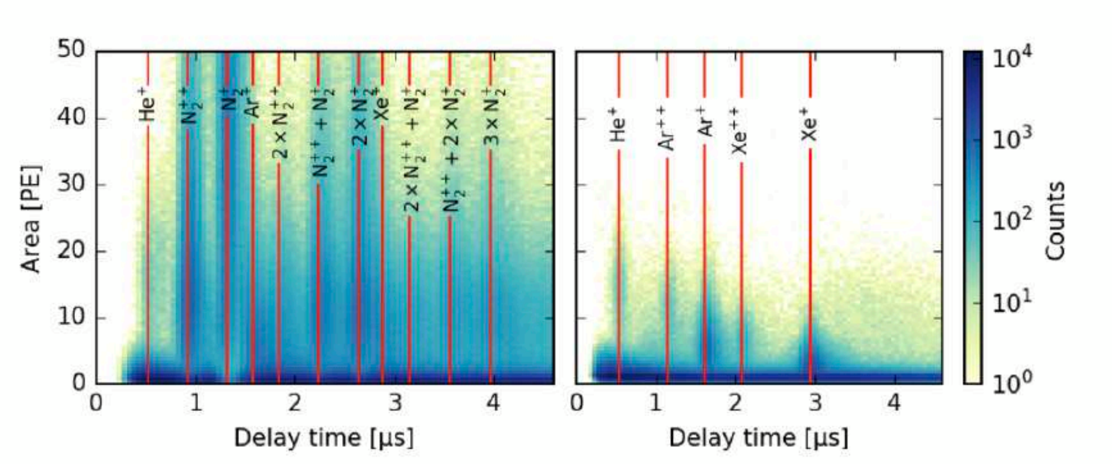
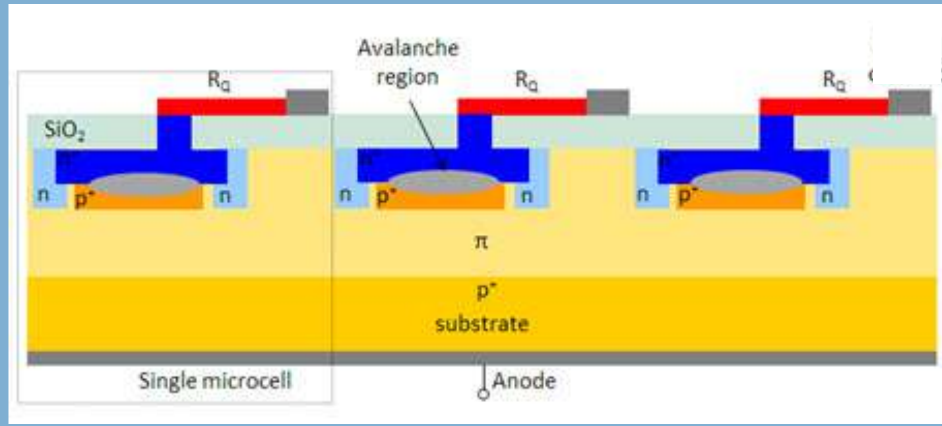
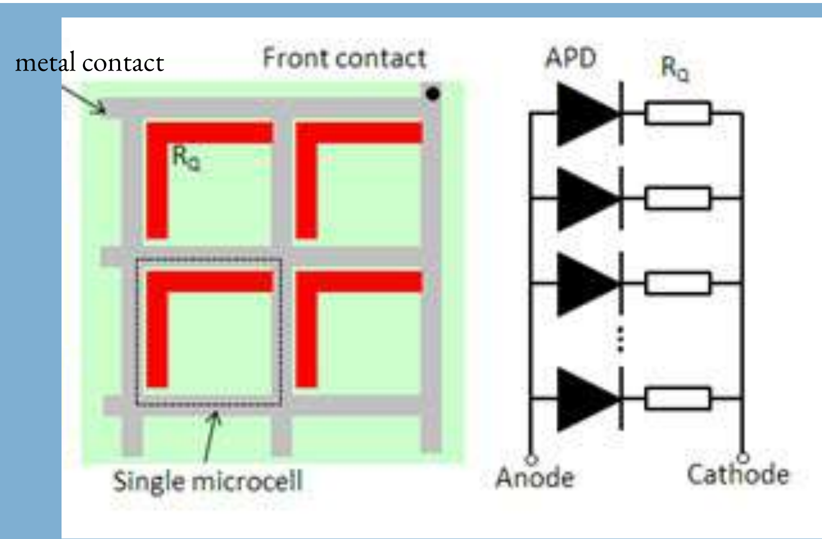


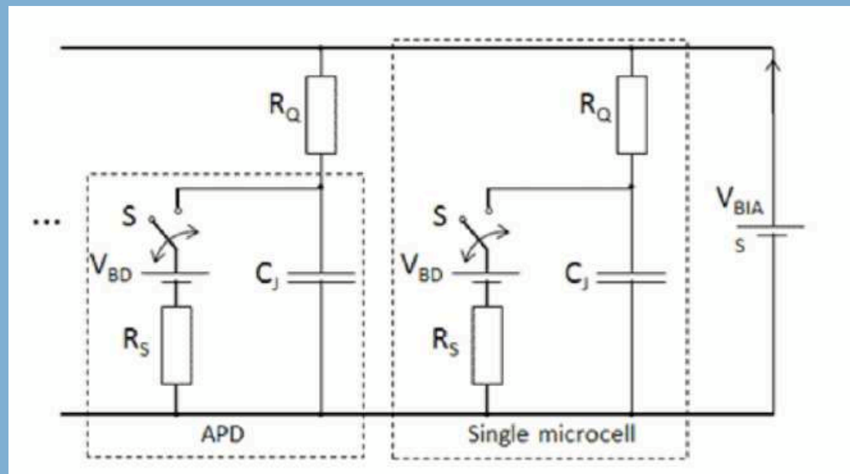


PHOTODETECTORS: SIPMS

- **Silicon photomultipliers are a solid-state alternative to PMTs fabricated directly onto silicon wafers**
- **Placing each avalanche photodiode above breakdown voltage will allow an incoming photon to trip the diode into breakdown, amplifying the signal by** $10^5 - 10^6$
  - **much lower (** ~ 50V **voltage than PMT)**
  - **Very good timing resolution,** 50ps **possible**
  - **Each microcell is a geiger-like device, double-photon hits don't give a higher signal**
- **The SiPMs can also be very robust against electrical and magnetic fields due to their compact design**



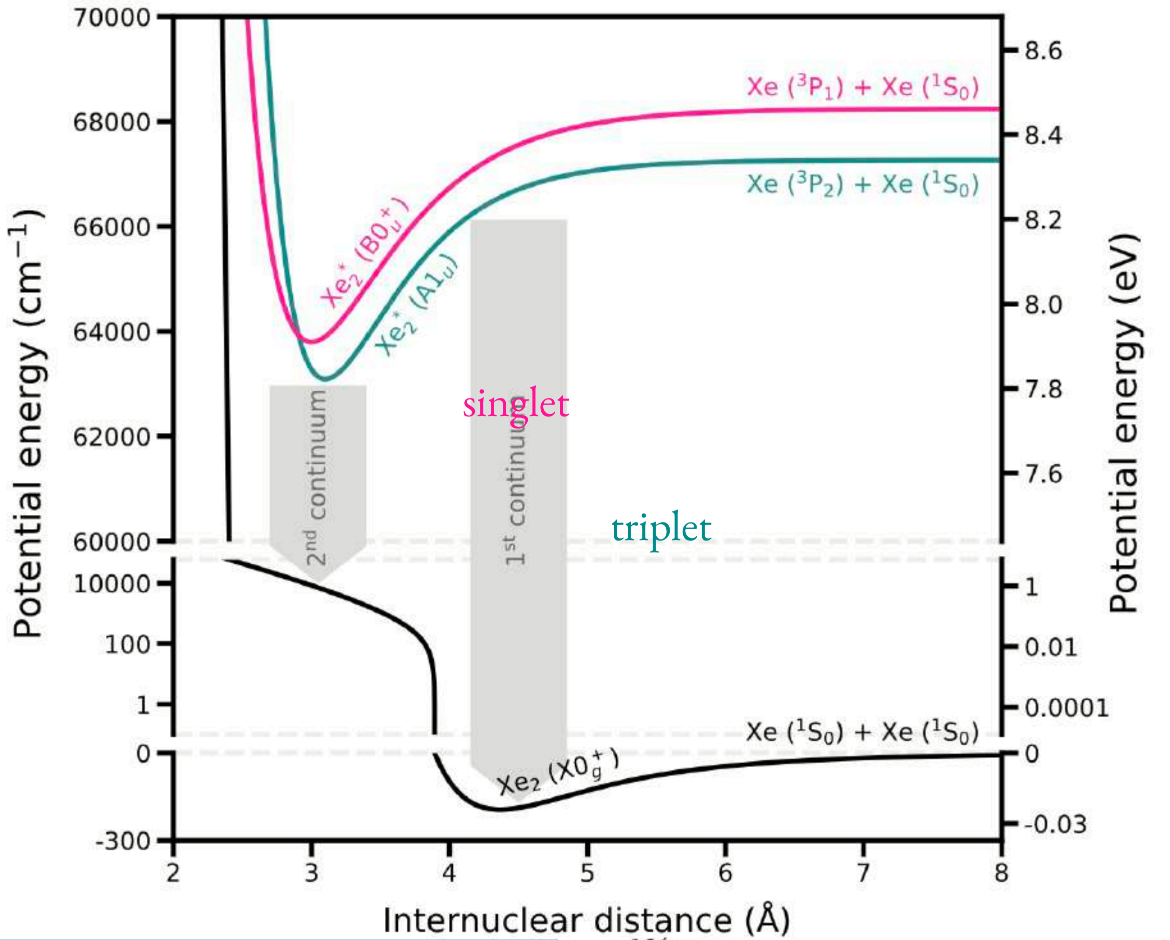


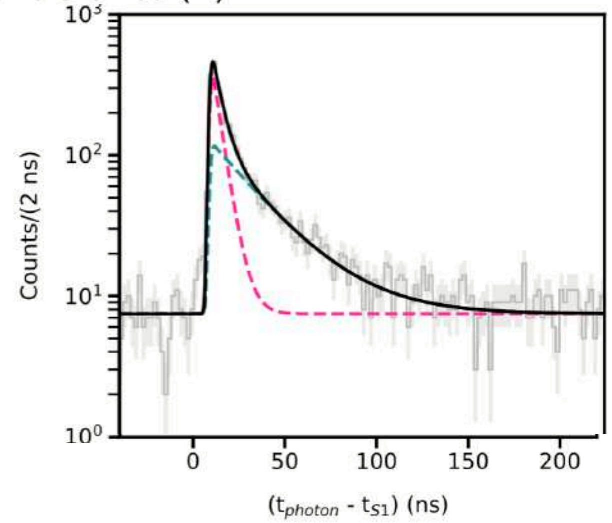


https://hub.hamamatsu.com/us/en/technical-notes/mppc-sipms/what-is-an-SiPM-and-how-does-it-work.html

LXE SCINTILLATION DETAILS

- **Xenon is a scintillator— it emits light when ionizing radiation excites it**
- **Main interest for us:** 175nm **"vacuum UV" light (this is being pedantic, IMO, but it is trying to remind us that this is not the wavelength of the light in the liquid xenon with a 1.6 refractive index)**
- **Excited xenon atoms,** Xe* **combine with a neighbour to create dimers,** Xe_2^* **that emit scintillation light**
- **Ionized atoms first need to grab an electron, and then create a dimer.**
- **Two dimer species: singlet and triplets have different decay times**





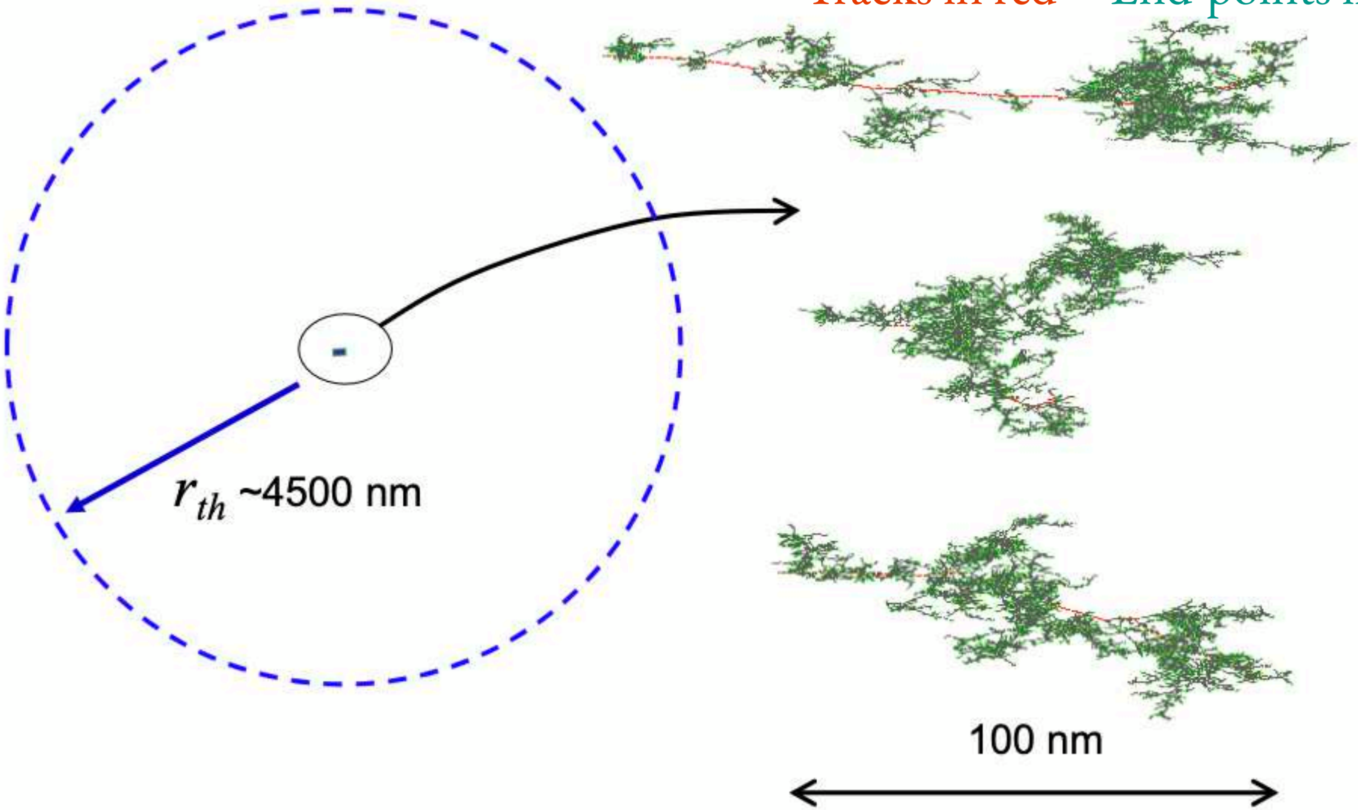
Spectroscopy of VUV luminescence in dual-phase xenon detectors
https://arxiv.org/pdf/2512.20935v1

MENTAL IMAGE OF ENERGY DEPOSITS

Only atoms and ion tracks:

Electrons are kicked out in a much wider cloud

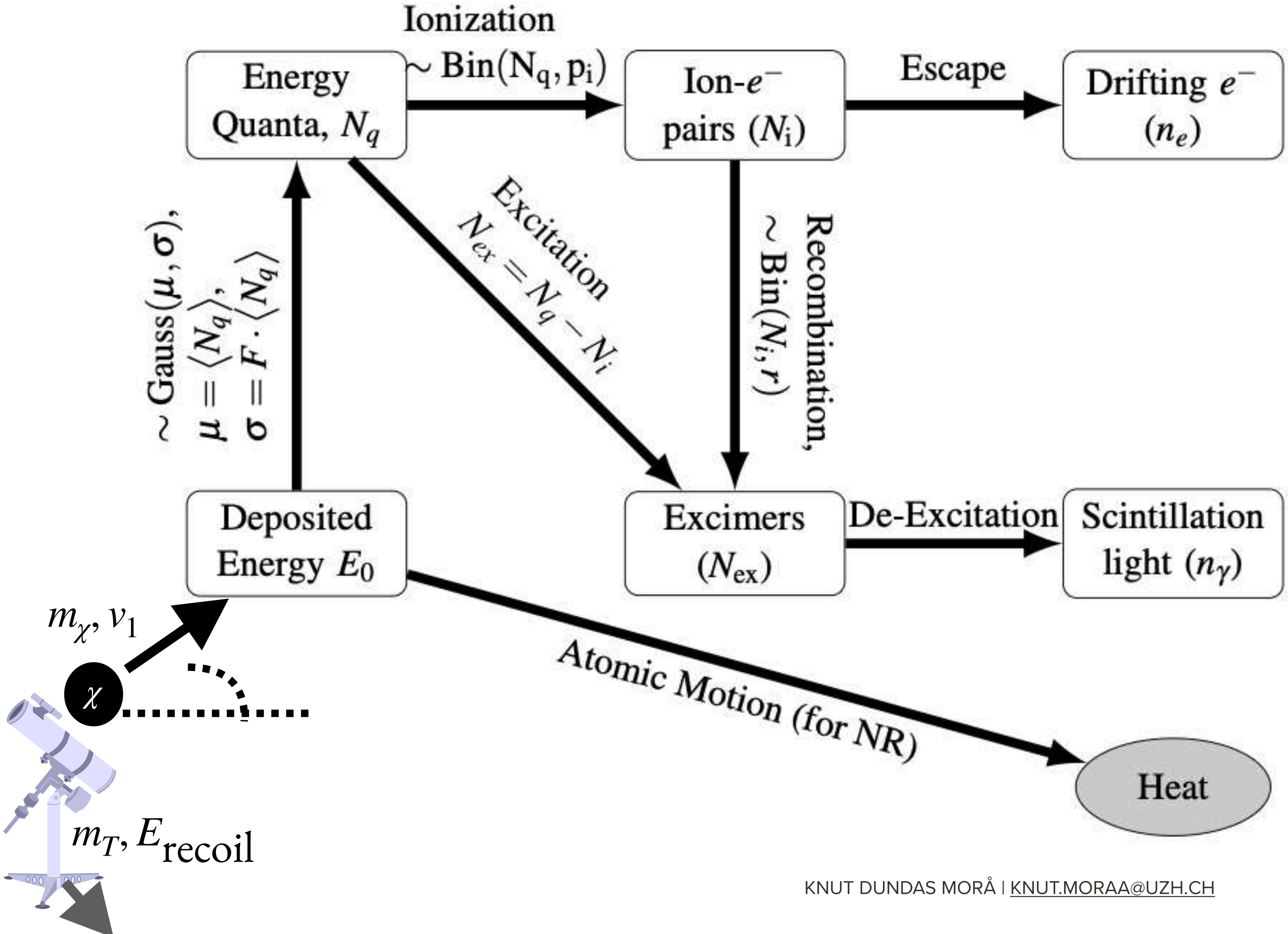
Tracks in red   End-points in green



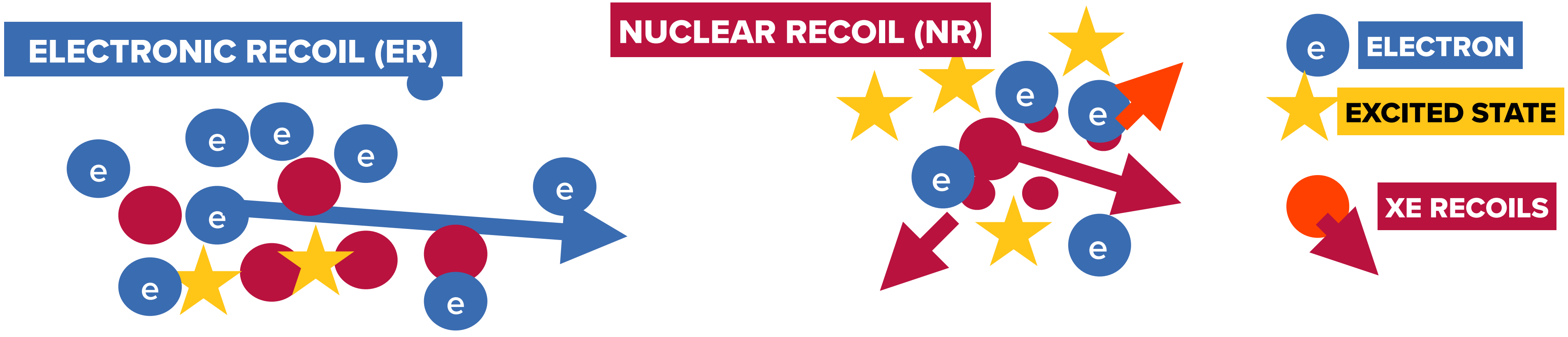
Liquid noble gas detectors for low energy particle physics

https://arxiv.org/abs/1207.2292

WHERE DOES THE ENERGY GO?



DIVYING UP THE SPOILS



- After the dark matter particle (or some radioactive interaction) has given the initial particle some recoil energy E_0, it recoils through the liquid.
- The average energy needed to create an excimer or liberate an electron is $W = (13.7 \pm 0.2)\mathrm{eV}$
- The Lindhard factor L expresses how much of the energy is deposited in excited states and ionization
- The rest goes to heat— $L \sim 1$ for electronic recoils, and $L \sim 0.2$ for nuclear recoils

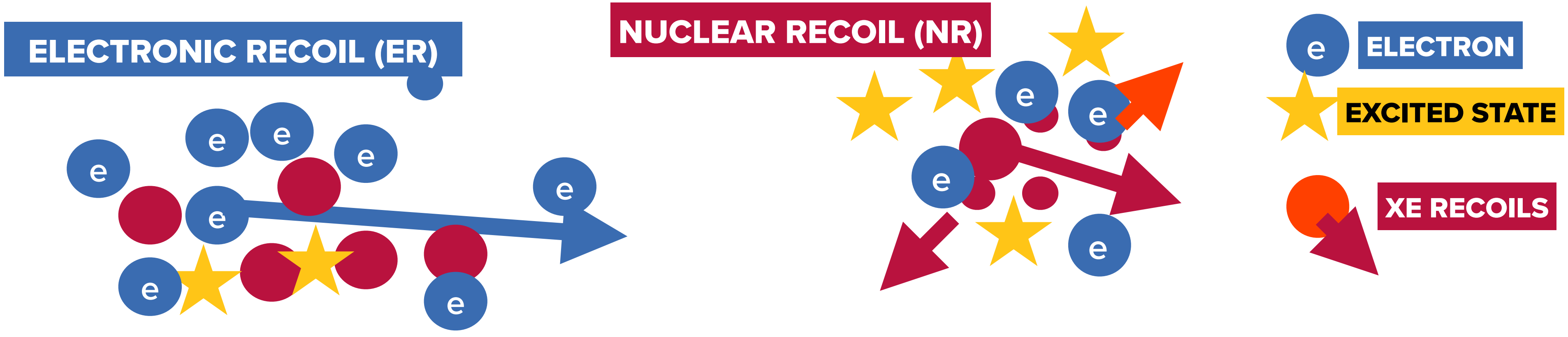
$$E_0 \times \frac{L}{W} = \langle N_{\mathrm{ex}} + N_{\mathrm{i}} \rangle$$

Parameterisation for ERs:

$$\left\langle \frac{N_{ex}}{N_i} \right\rangle = \alpha |\boldsymbol{E}|^{-\zeta} \left(1 - e^{-\beta E_0}\right)$$

DIVYING UP THE SPOILS

$$E_0 \times \frac{L}{W} = \langle N_{ex} + N_i \rangle$$

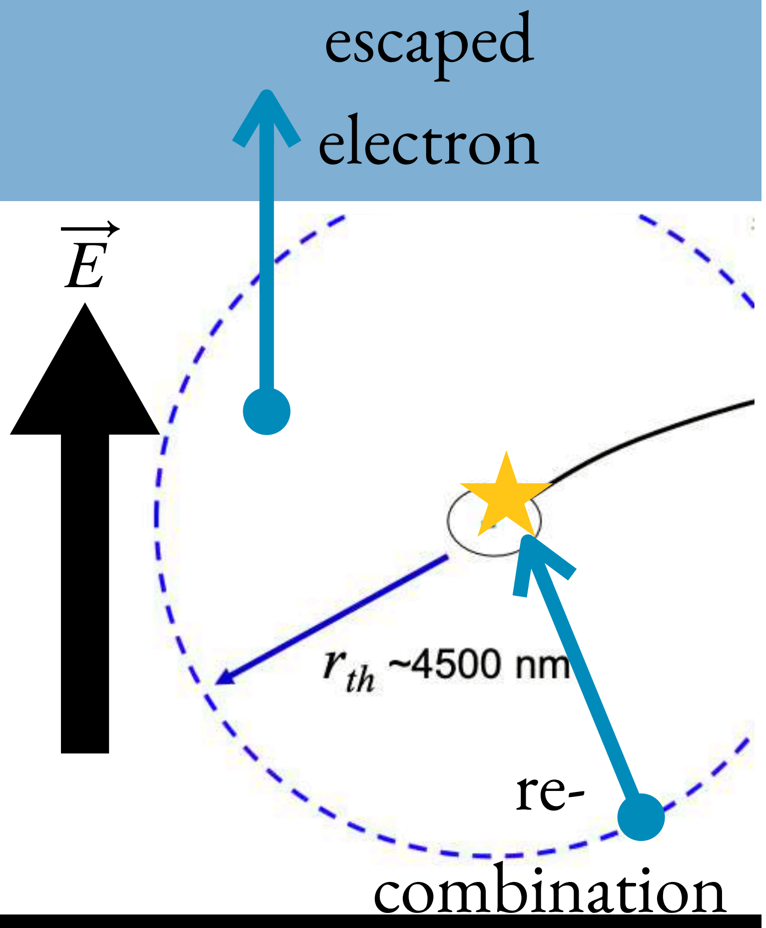


- The expected exciton-to-ion ratio is a free parameter, and part of the fit to data
- Measured with gamma-ray depositions and other calibrations
- Higher for NRs than ERs
- The variation of the total number of quanta, $N_{ex} + N_i$ shows less variation than you'd expect if they were Poisson distributed
  - This is a sign that there is correlations at play
  - Expressed with a Fano factor ~ 0.06

$$F = \frac{\text{Variance}(N)}{\text{Expectation}(N)}$$

TAKESIES-BACKSIES

- Electrons from the ionization cloud will return to the ions in the absence of an applied electric field
- When the electrons recombine with the ions, they create more excimers, which add to the scintillation light signal
- The probability for an electron to recombine increases with the density of electrons
  - For higher-energy multiple-scatters, the overlap of several tracks increases this density
- The probability decreases with the applied electric field
- Parameterisation; the Thomas-Imel box model, which considers electrons drifting and diffusing in a box with scale size a , and power-law of the field $\zeta(\vec{E})$
- This gives the mean recombination probability, the probability for each track is modeled as a Gaussian distribution around this mean
  - Expresses individual track topology etc.



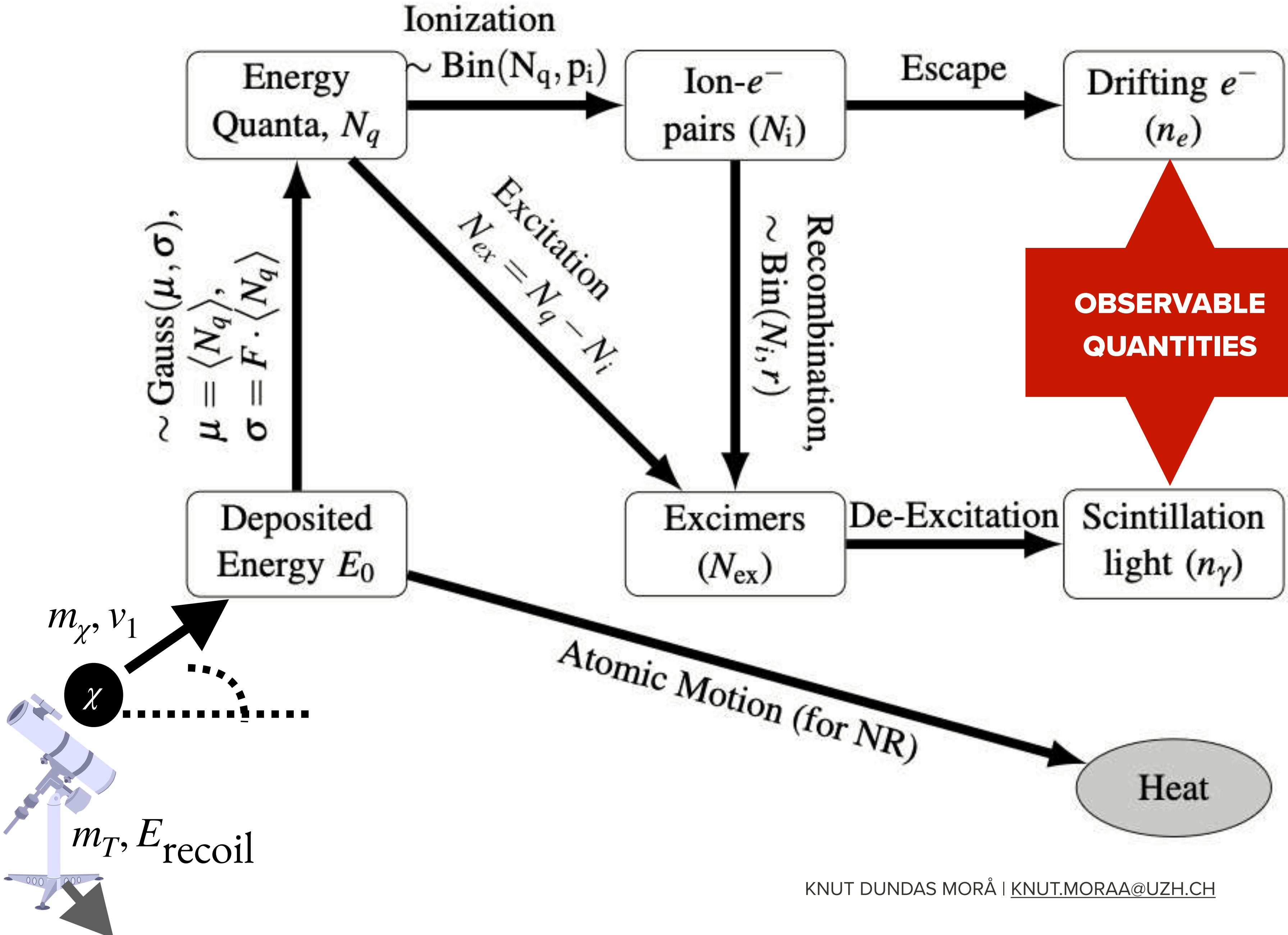
$$1 - \langle r \rangle = \frac{\ln(1 + N_i\zeta)}{N_i\zeta}$$

$$r \propto \text{Gaus}(\langle r \rangle, \Delta r)$$

$$N_{ex} = N_{ex}^0 + \text{binom}(N_i, r)$$

$$N_{e\,free} = N - N_{ex}$$

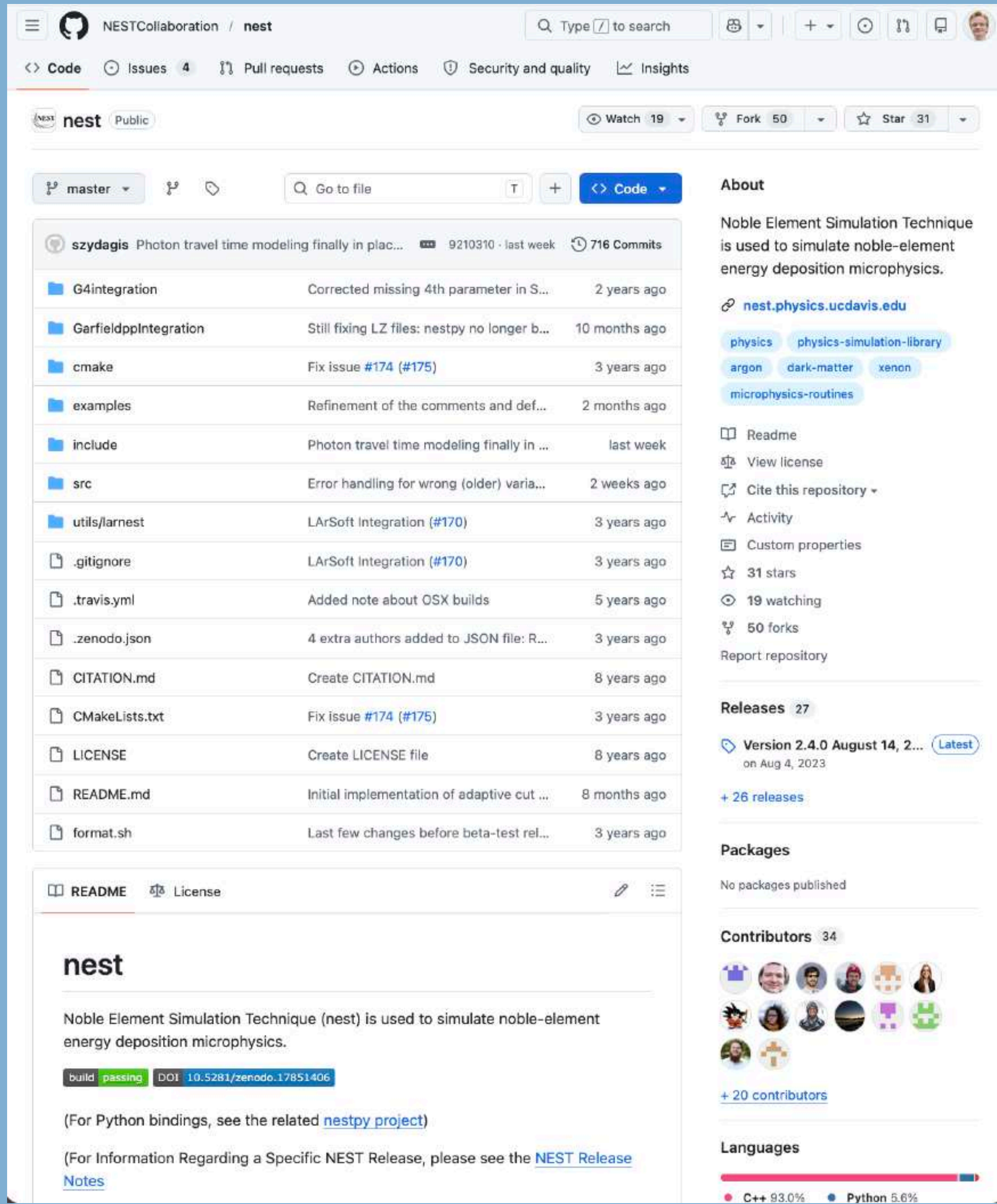
WHERE DOES THE ENERGY GO?



NEST

- It has so far not been possible to construct a first-principles-only model of how a nuclear or electronic recoil yields observable quanta
- Many of the quantities above can be computed for gaseous Xe, but the collective behaviour of the liquid means you have to measure
- However, experiments have been able to collect a large collection of data on charge and light yield
- NEST is a software package that aims to provide an empirical parameterisation tuned to these outputs

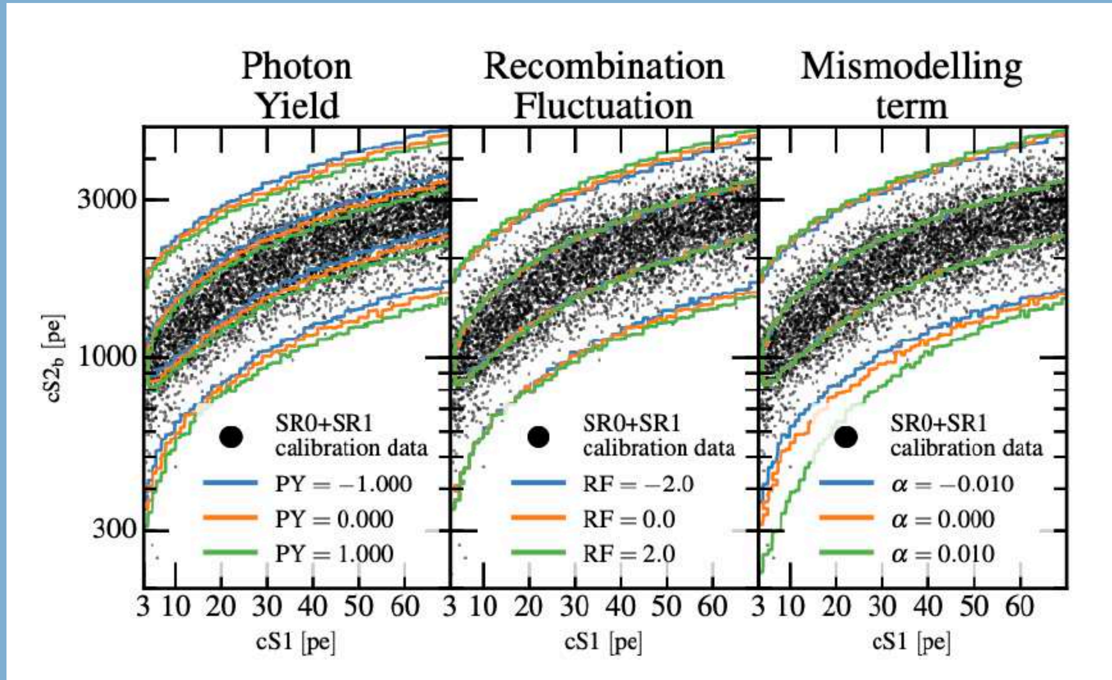
https://nest.physics.ucdavis.edu/

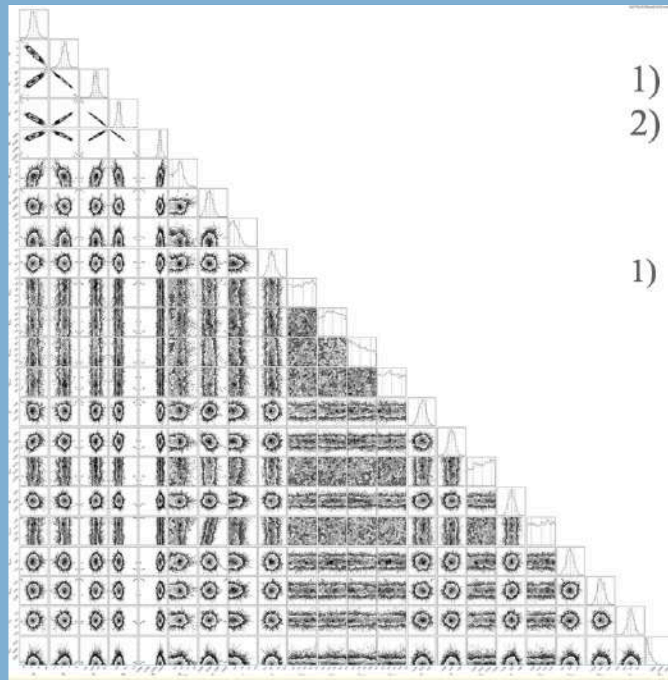


FITTING/ TUNING NEST

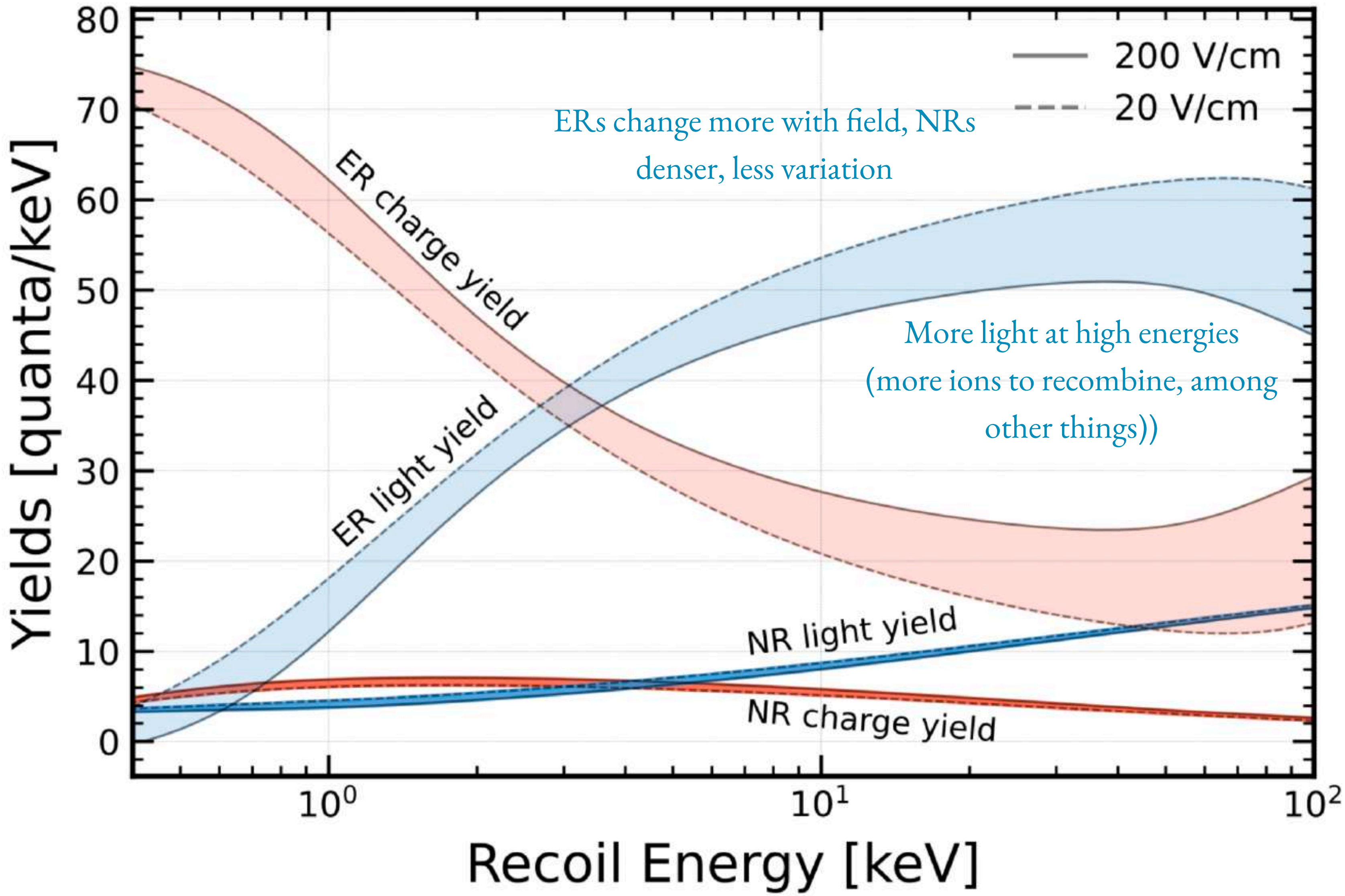
- NEST includes a large number (20-30) fit parameters,
  - Plus the freedom of choice of parameterisation to start with!
- Fitting these can be challenging, and the developers introduce new parmeterizations as the data sets become more precise
- Most correct approach I know of uses Markov-Chain Monte Carlo to be able to fit many parameters alongside each other
- Warning: Since NEST tries to include all relevant data, there are datasets with clear systematic differences included in the tuning. This will reduce the uncertainty band more than it should

FIRST AND FOREMOST: CHECK THAT YOUR MODEL FITS YOUR CALIBRATION DATA WELL



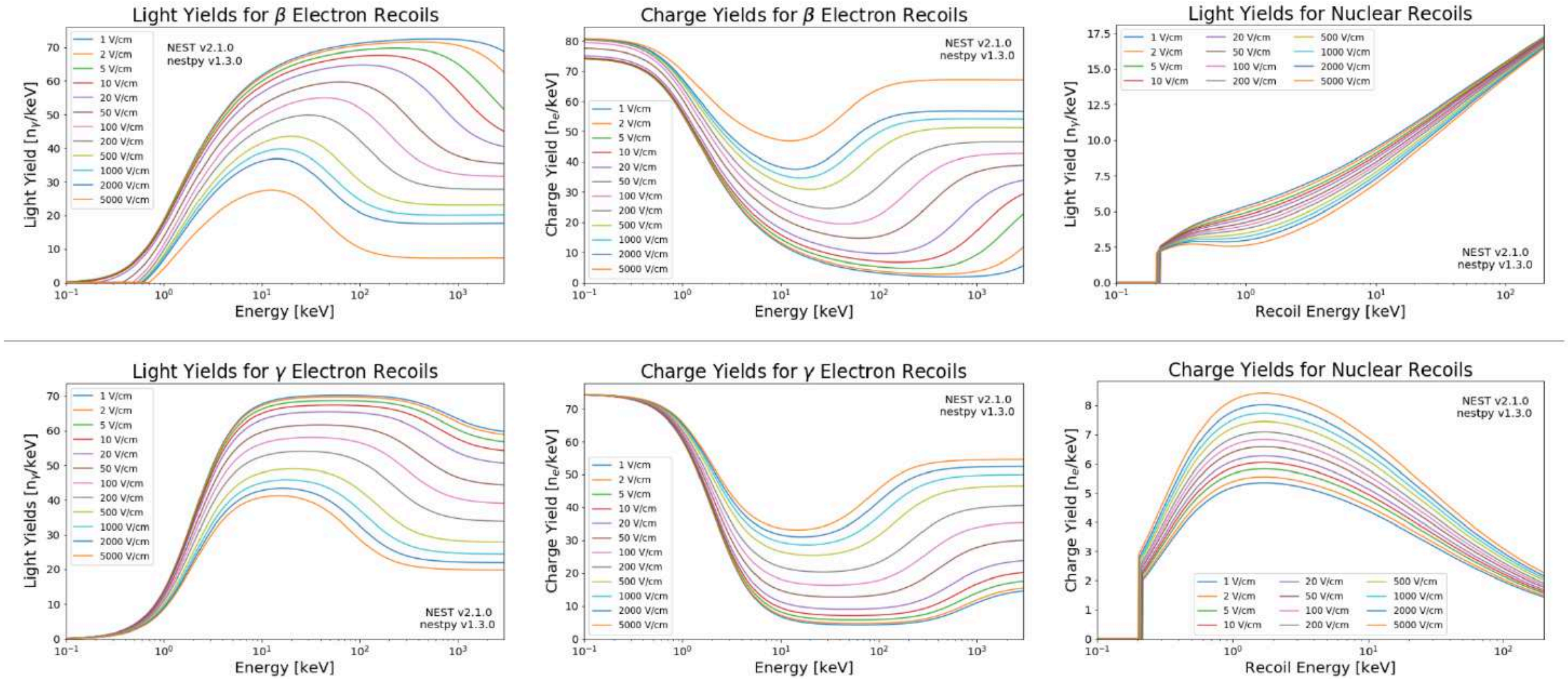


CHARGE AND LIGHT YIELD



Plot from Giovanna Volta, NEST curves

DEPENDENCE ON DEPOSIT

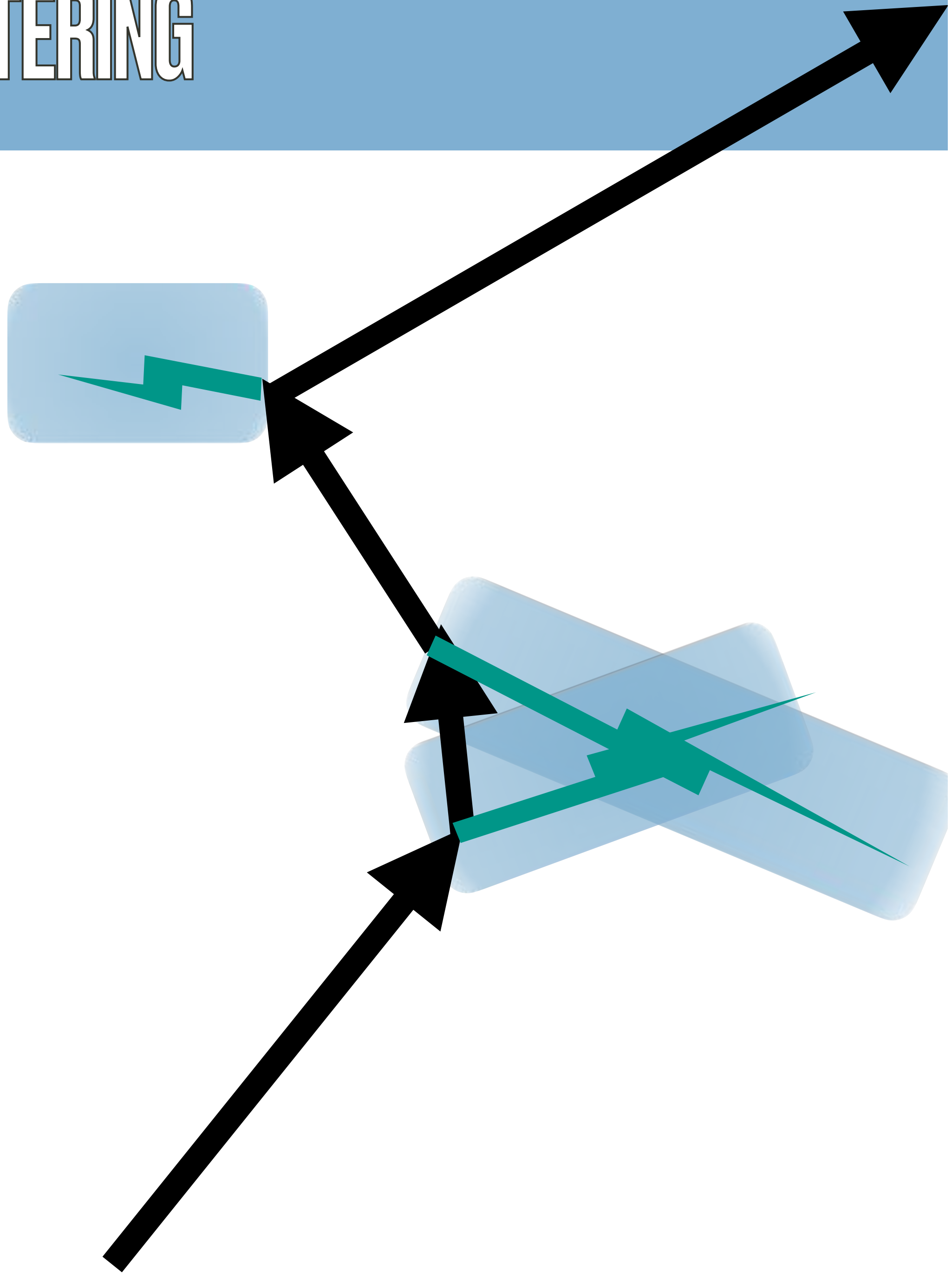


- The difference in track density and topology, as well as whether there was an electron or nucleon recoiling affects the exciton-to-ion ratio and the recombination probability
- You can either compensate for this by computing how different the track density etc. is,
- or refer to the yield separately for gammas, betas, alphas, nuclear recoils

https://nest.physics.ucdavis.edu/

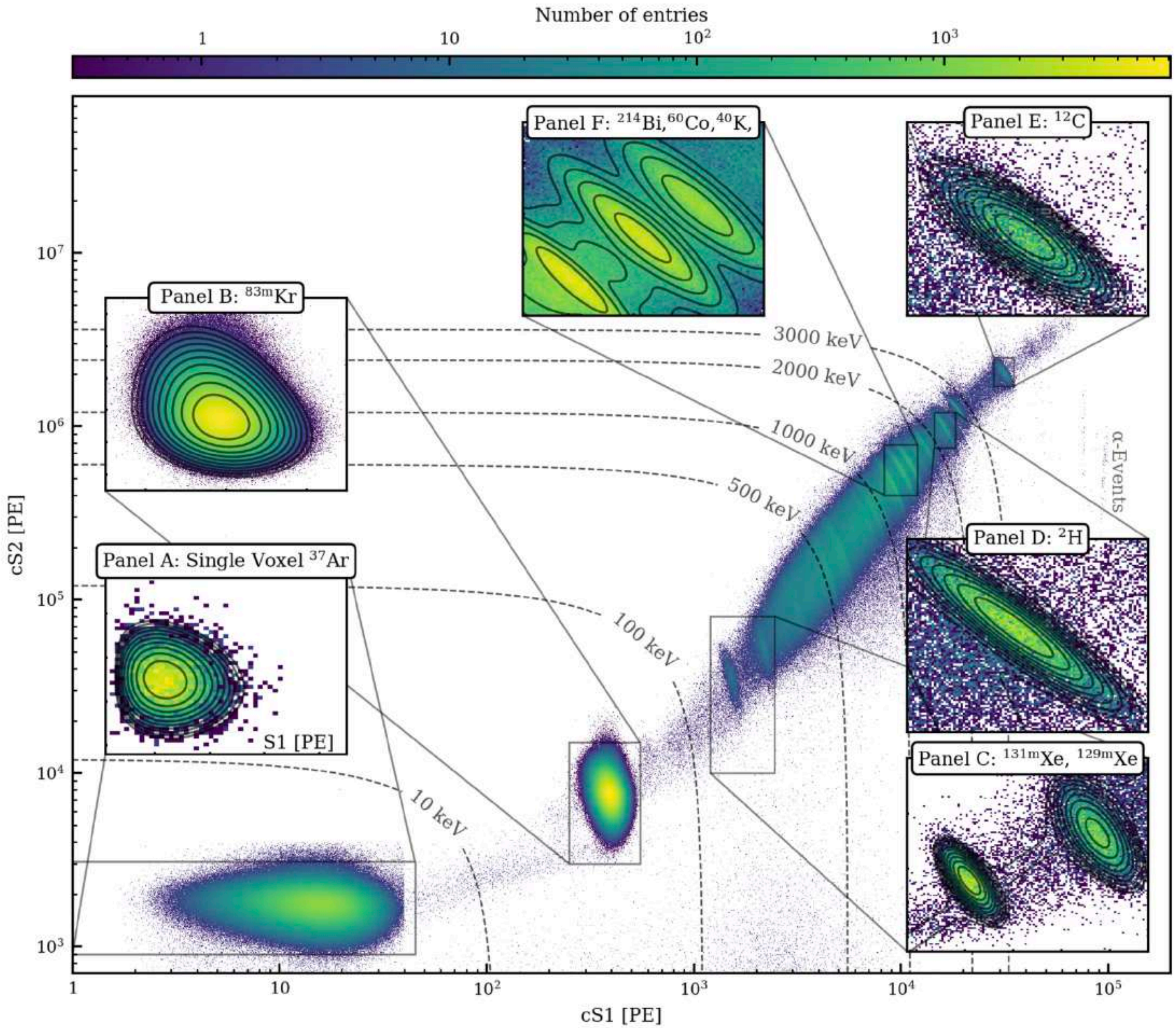
FURTHER MICROPHYSICS: CLUSTERING

- Nature does not know the difference between NRs, ERs, and it does not know what an “interaction” is
- We (humans) introduce this concept knowing that events that are well-separated in time and space can be considered independent
- However, not all cases are clear-cut; particles that scatter multiple times in the target or make little showers have overlapping and potentially interacting energy depositions
    - neutrons,
    - gamma-rays
- The response function for e.g. gamma-rays account for this, but if you want to simulate this in detail, you have to apply a “microclustering” — find which energy depositions should be considered together and apart before applying yields



CALIBRATION LINES

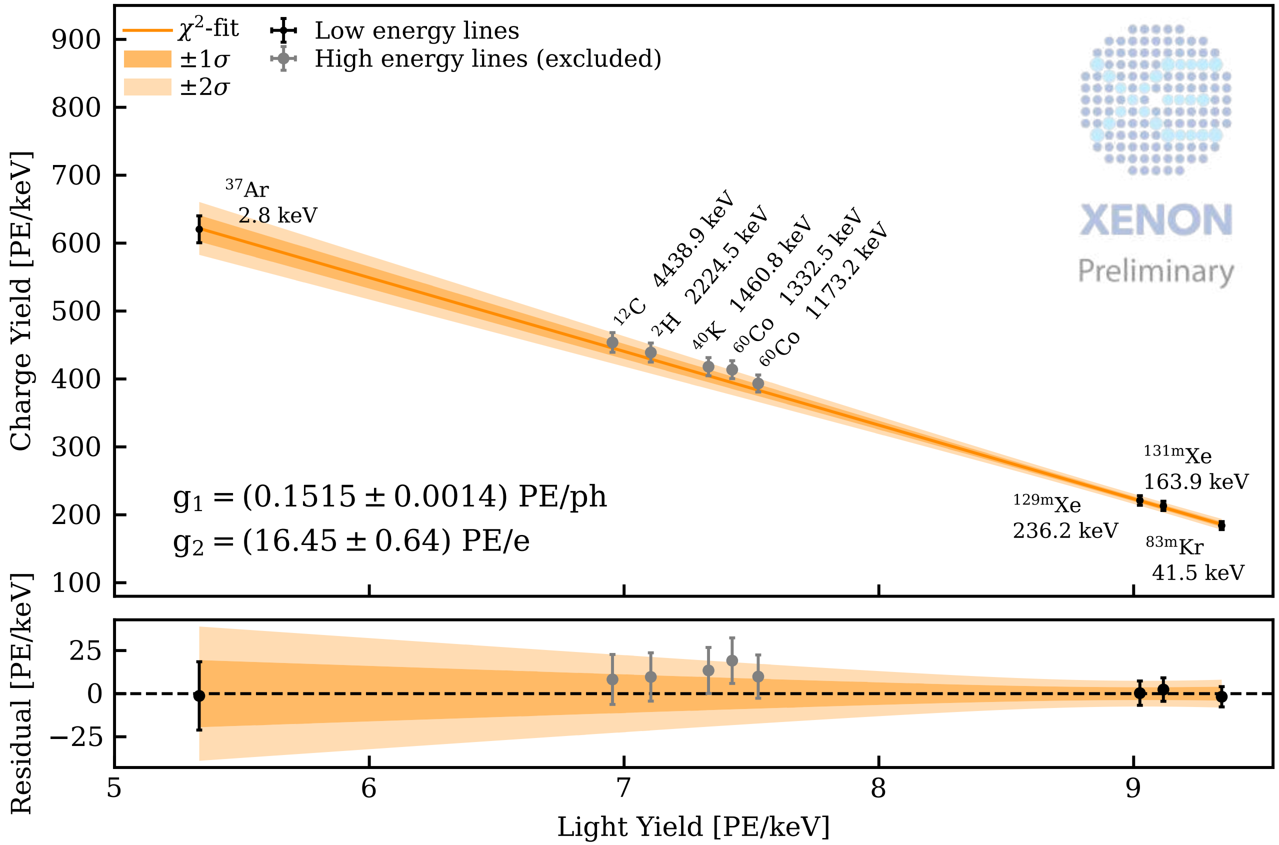
- The plot shows injected and activated gamma-ray lines observed by XENONnT
- 2-3 orders of magnitude
- The “bend” reflects the different charge-to-light yield as function of energy
  - As well as threshold effects for ^{37}Ar
- Each line shows the characteristic anticorrelation expected from the energy being shared between light and charge



ENERGY CALIBRATION

XENONnT analysis: Signal reconstruction, calibration, and event selection

- Rewriting the energy partition function and fitting the centre of each calibration line gives us the "Doke plot"
- Combines charge and light yield with the detector efficiency for both to give the average number of detected light quanta
- Note that different energies, and thus different charge/light yields only move points along the line.
- Very high statistics for many lines mean high precision— this plot is a good way to find deficiencies in your reconstruction
- W is degenerate here— needs dedicated calibration with absolute measurement of collection efficiency

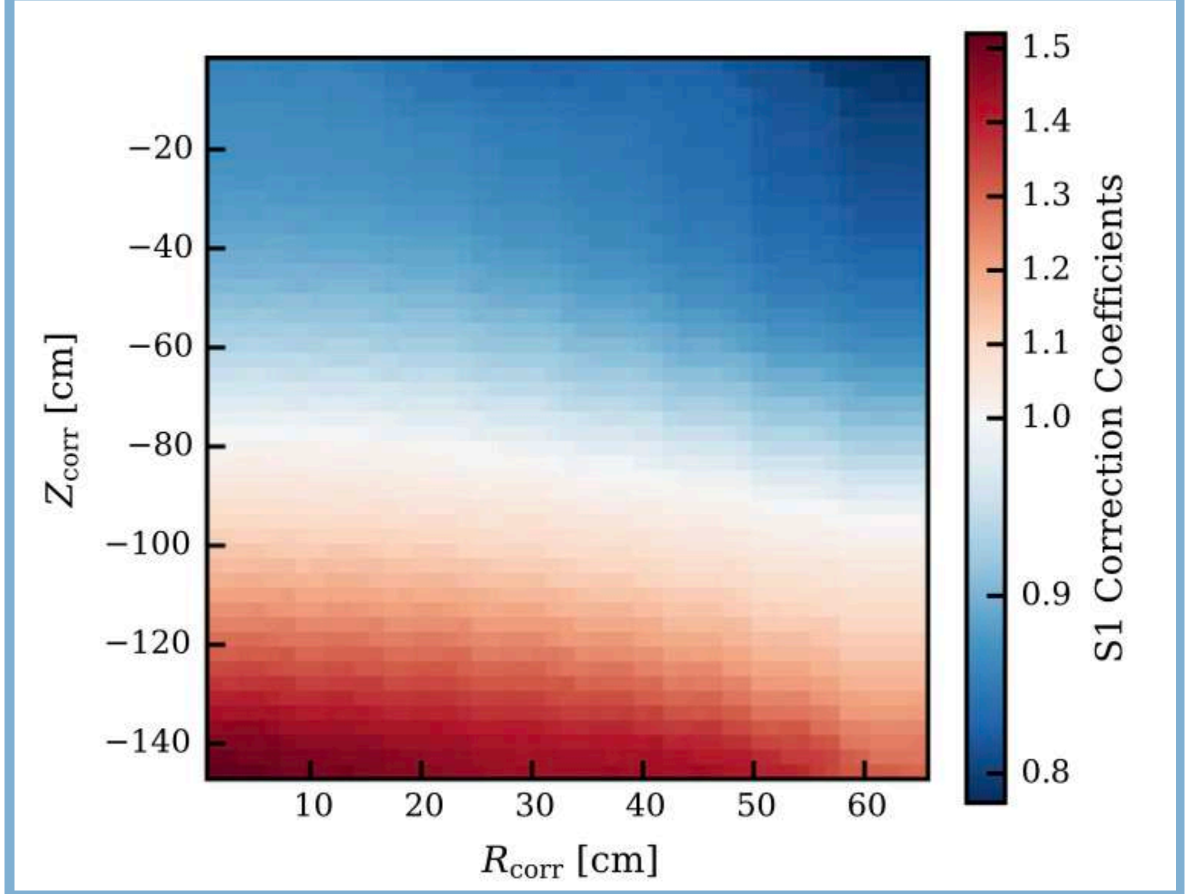


$$E = \frac{W}{L}\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

$$(L = 1) \rightarrow S2 \cdot \frac{W}{E} = g_2 - \frac{g_2}{g_1} S1 \cdot \frac{W}{E}$$

S1 CORRECTION

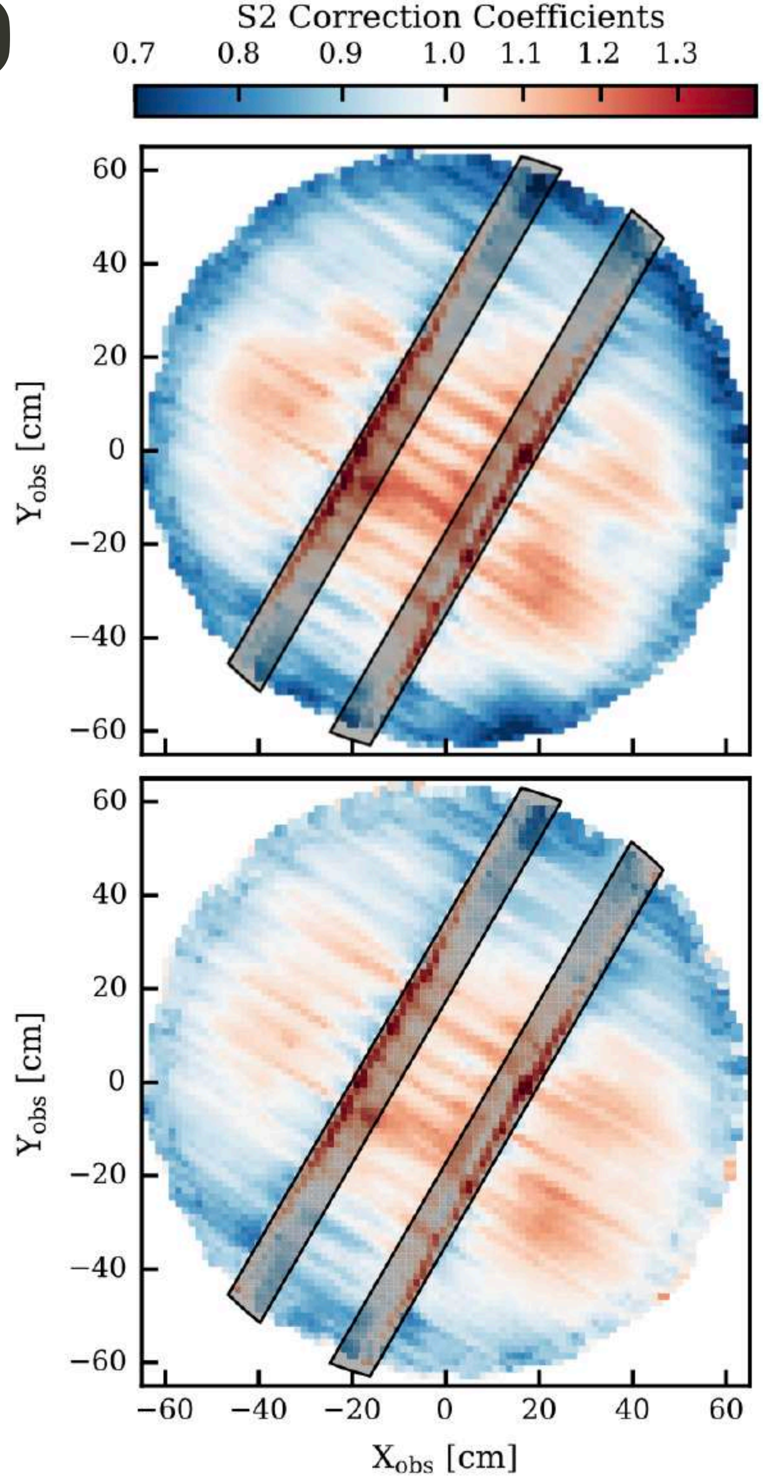
- **Events deeper in the detector are closer to the lower PMT array, and will be brighter (internal reflection reduces this effect at the top)**
- **^{83m}Kr injected into the detector provides an evenly distributed source of S1 light, which is voxellised to yield a map in radius and X,Y**
- **This also compensates for spatial variation in photosensor resposne**
- **Photosensor gains vary over time, and is also compensated for**
- **The corrected S1— cS1, is normalised to have the same response as the central region of the detector**



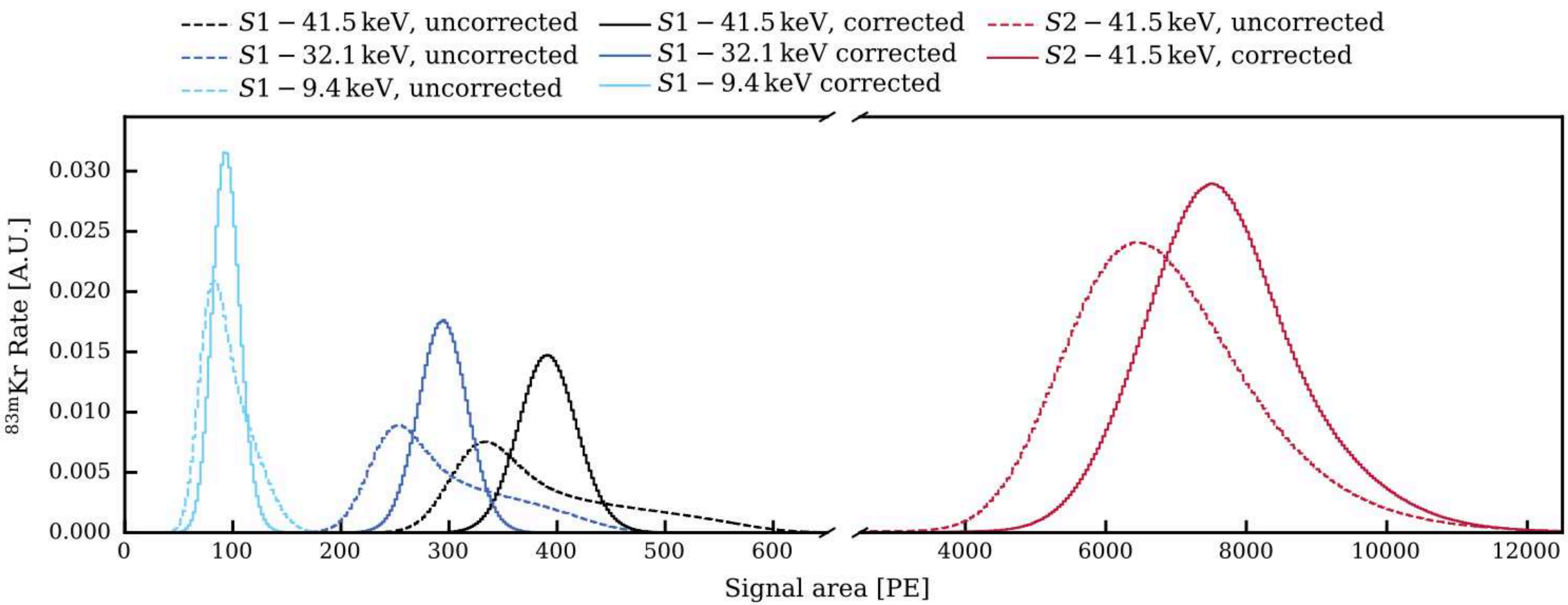
S2 CORRECTION

- All S2s are produced at the surface, so that effects only depend on X,Y and time-dependent features.
- The single-electron gain can be monitored from background lone-electron events, and are used to create correction maps
- If the field is low, the extraction efficiency is also lower than unity
- Variations in the height of the gas gap is due to electrode sagging, wire shadowing and focusing, and in XENONnTs case, stiffening wires
- Lastly, the electron livetime is corrected for by the drift time

$$S2 = S2_0 e^{-\Delta t/\tau_e}$$



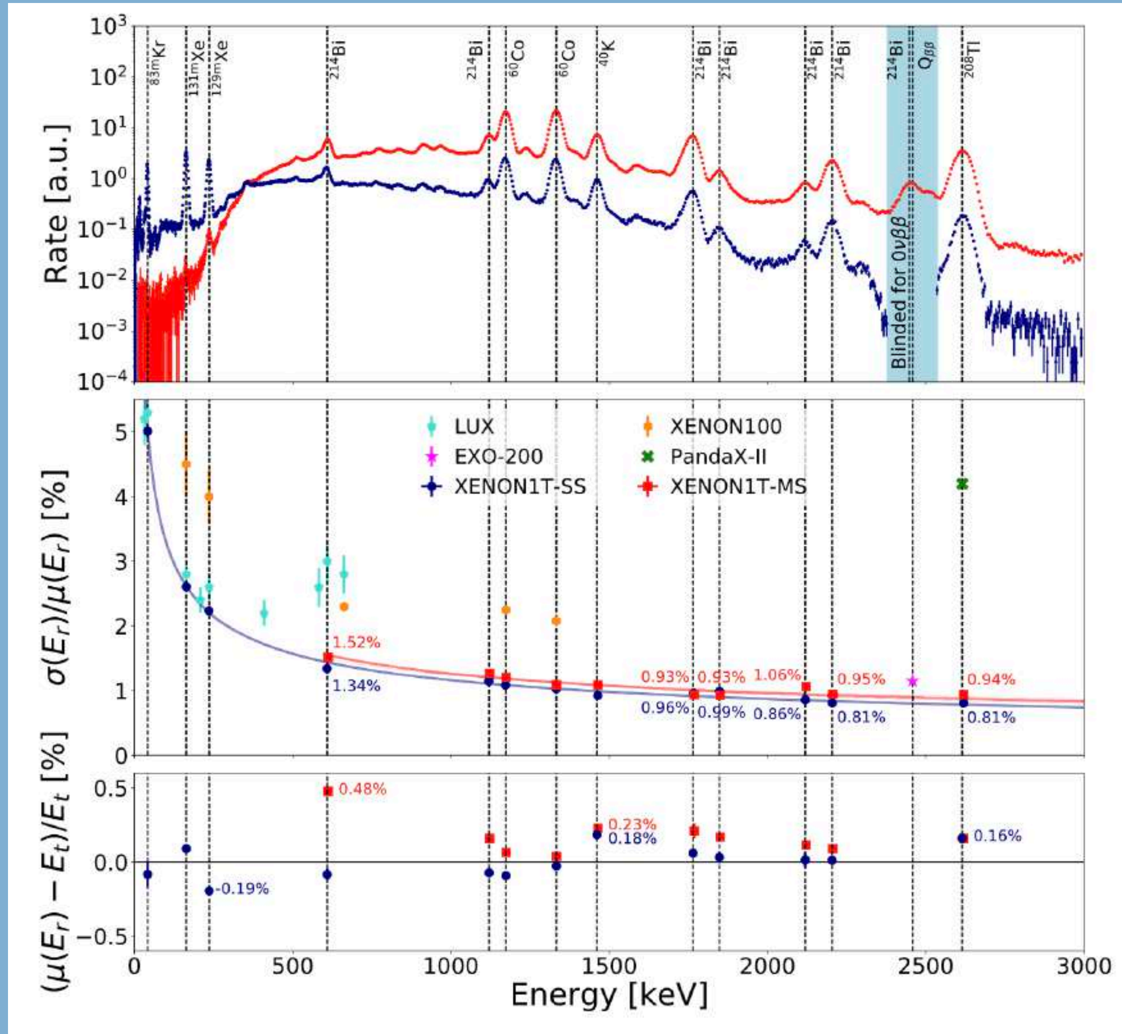
EFFECT OF CORRECTIONS

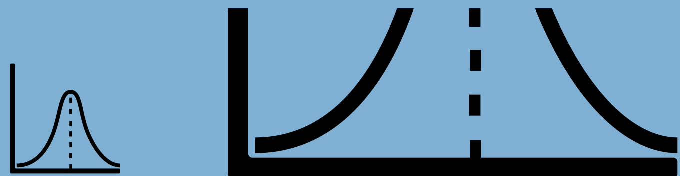


- **With corrections applied, each signal area tightens up**
- **This is krypton which has a characteristic double-S1 emission**

ENERGY RESOLUTION

- **At high energy, saturation of PMTs becomes a challenge,**
- **Experiments sometimes resort to using only the S2-signal from the bottom of the detector,**
- **or fit the saturated waveform outside the saturated region**
- **In total, this has allowed them to reach around 1% energy resolution in the MeV energy range**

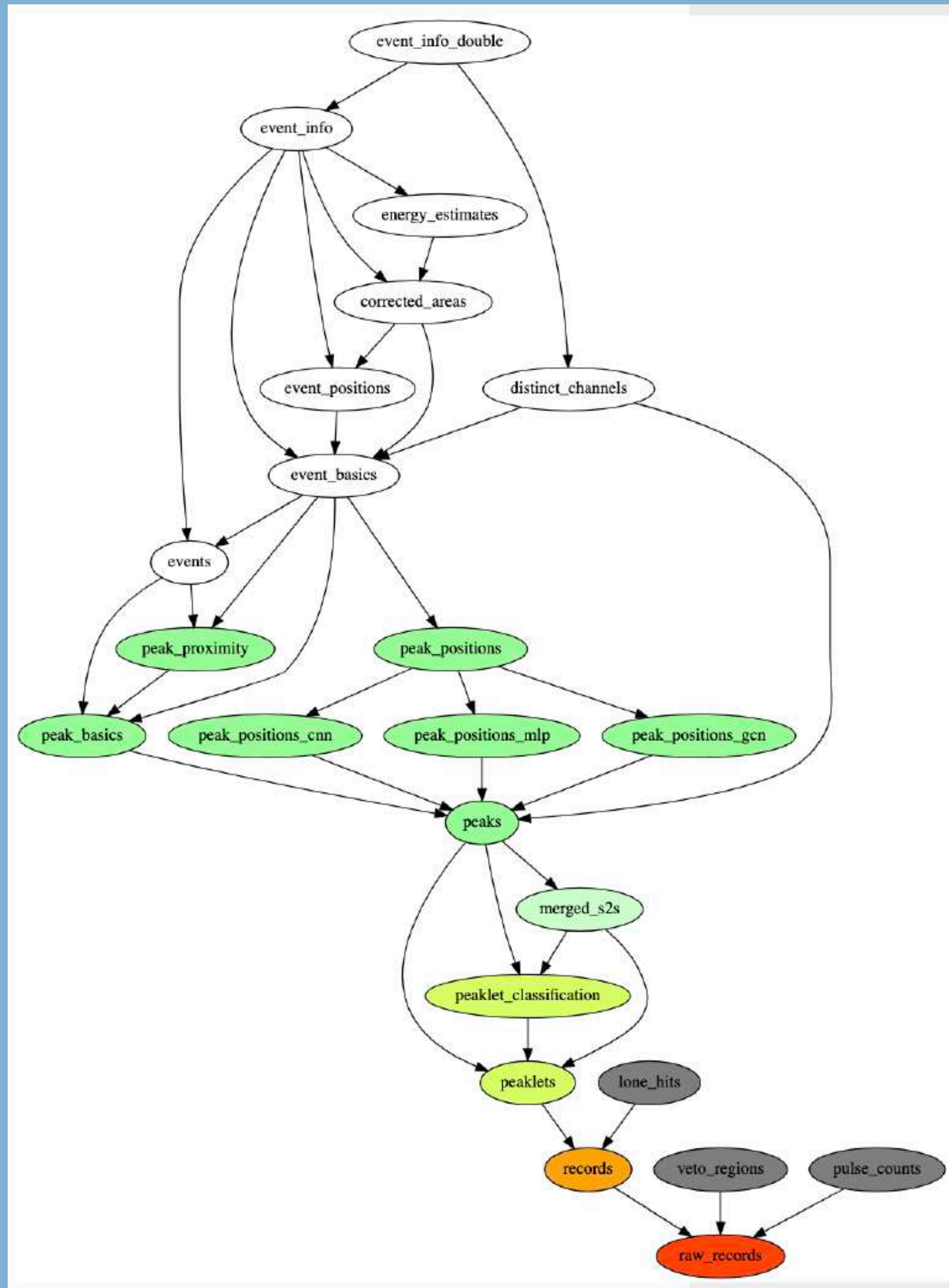




Energy resolution and linearity of XENON1T in the MeV energy range

RECONSTRUCTION SOFTWARE

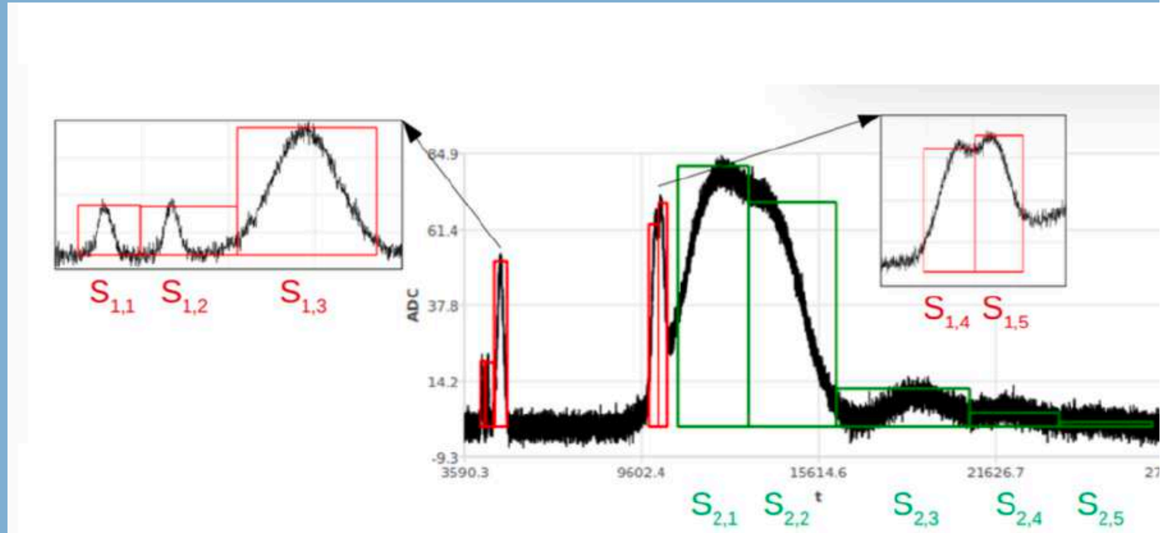
- **Once your detector is running, you need to reconstruct signals from your recorded data**
- **Rare events— you want very high efficiency even for the smallest signals**
- **and as usual you want the reconstruction to be unbiased, quick to run, and able to accomodate updates to calibrations, corrections etc. without too much pain**
  - **This is quite important— this software will often be with you for the livetime of the experiment**

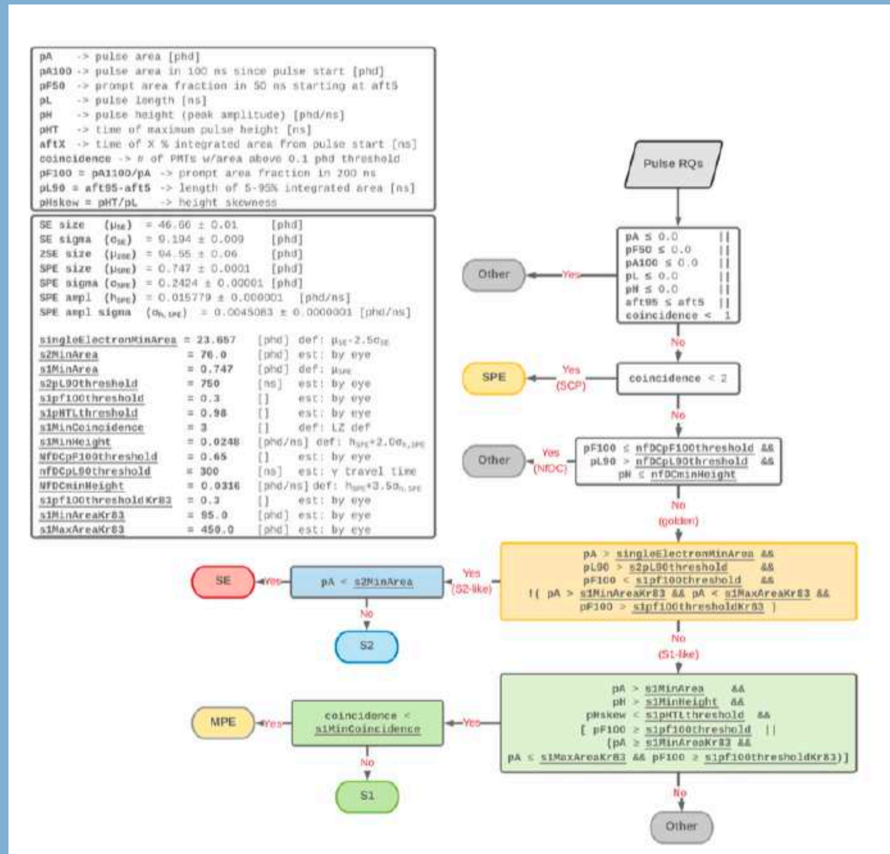


Straxen XENONnT data structure

PULSE FINDING

- As an example, LZ uses a trigger to identify “events” which will be fed to the reconstruction
- Finding the pulses and classifying them as S1 or S2 candidates is typically based on peak width, and with relatively simple algorithm
- Candidates are filtered and further selected based on area, width and shape
- Once complete, an event will have a number of candidate S1 and S2s
    - This is a deliberately loose selection, we do not want to loose an event at this stage

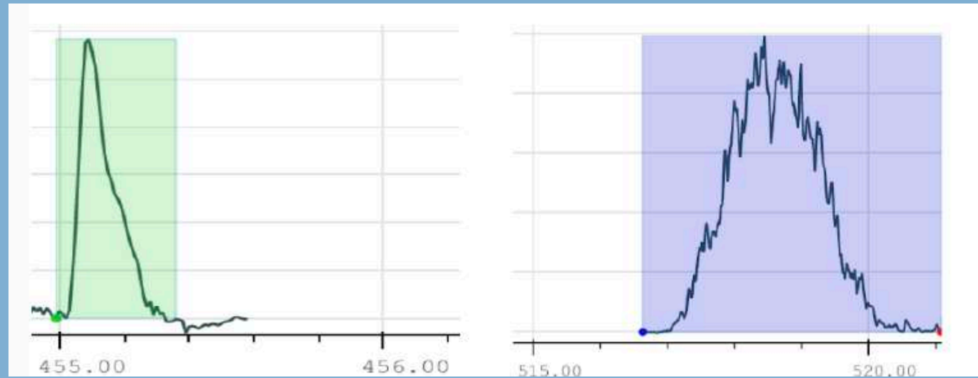


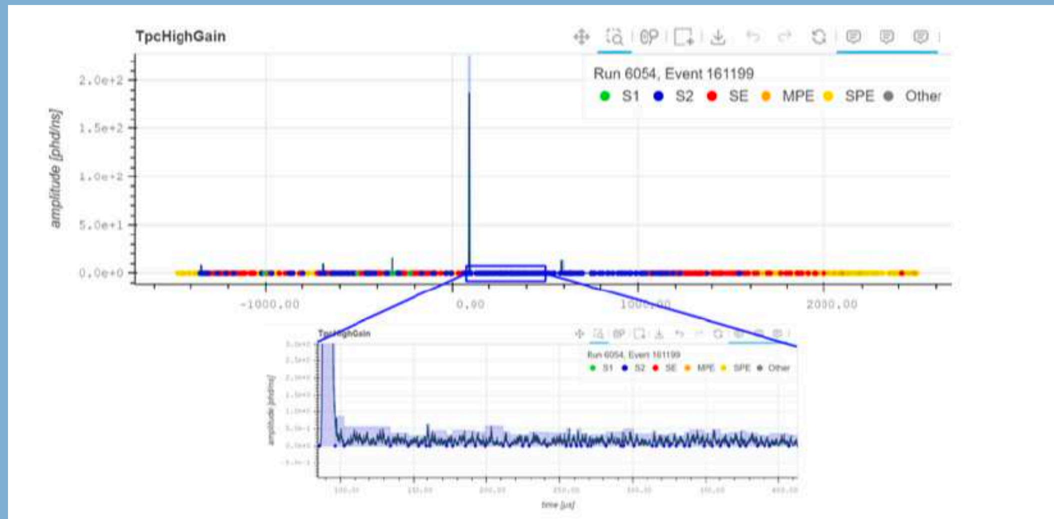


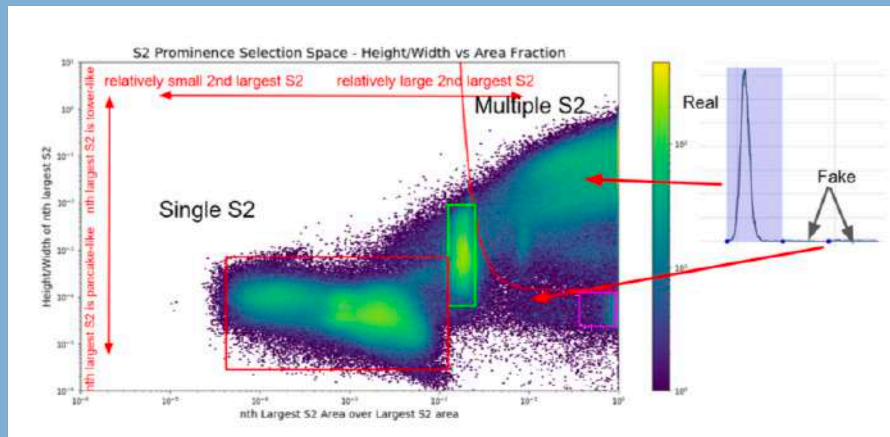
Far and Wide: Searches for Particle Dark Matter with the LZ and TESSERACT Experiments
Michael Williams, PhD thesis

INTERACTION CREATOR

- **Once candidate pulses are identified, the interaction finder will consider whether each pulse looks like a primary S1, or if it is associated with a preceding large pulse, for example,**
- **First guess: grab biggest S1 and S2**
    - **Some oddities can only be identified looking at the data—the green box shows "echo" light**
- **S1 should precede S2 (even if that looses you S1 size!)**
- **Further shape cuts refine and find the reconstructed pairing**





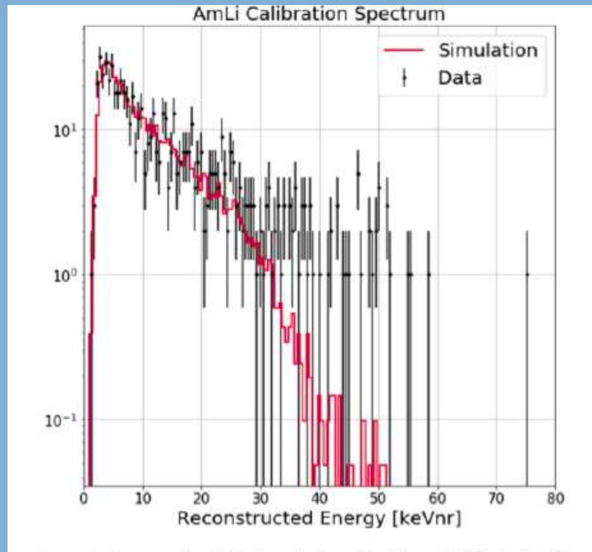


Far and Wide: Searches for Particle Dark Matter with the LZ and TESSERACT Experiments
Michael Williams, PhD thesis

EVENT CLASSIFICATION

- **For dark matter searches, we are looking for events with only one interaction**
- **However, for some cuts and calibrations, it is useful to also consider other event topologies**
- **Finally, for science searches, the efficiency of this process start to finish is required**
- **Calibration-tuned simulations give a good baseline**
- **LZ also considered “handscanning” a method where analyzers inspected calibration events, selected those they considered good and saw how often the classifier found those**

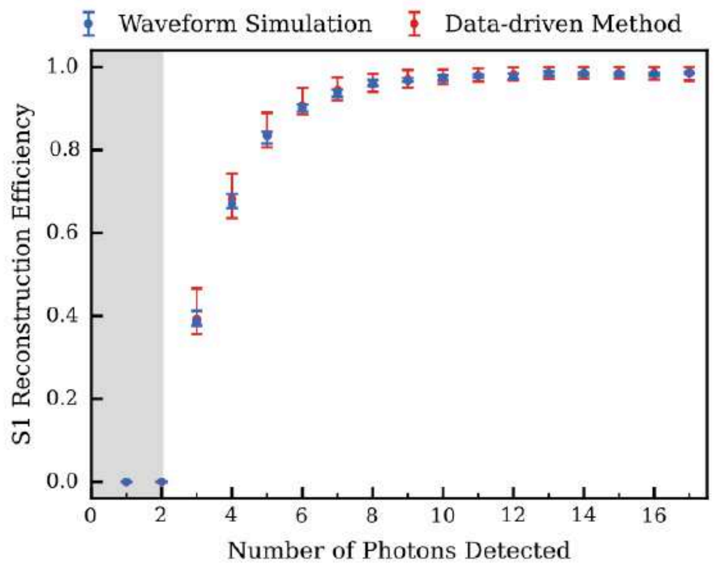
# of S1s \ # of S2s	0	1	2+
0	Other	Other	Other
1	Other	Single scatter	Multiple scatter
2	Other	Single scatter or Other	Pileup
3+	Other	Other	Pileup

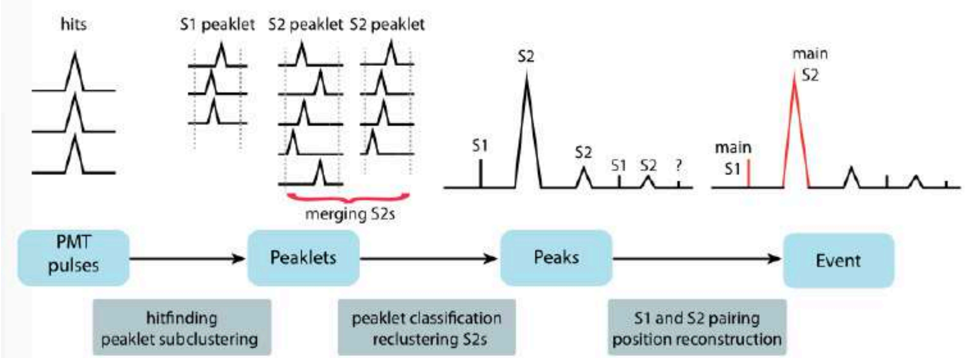


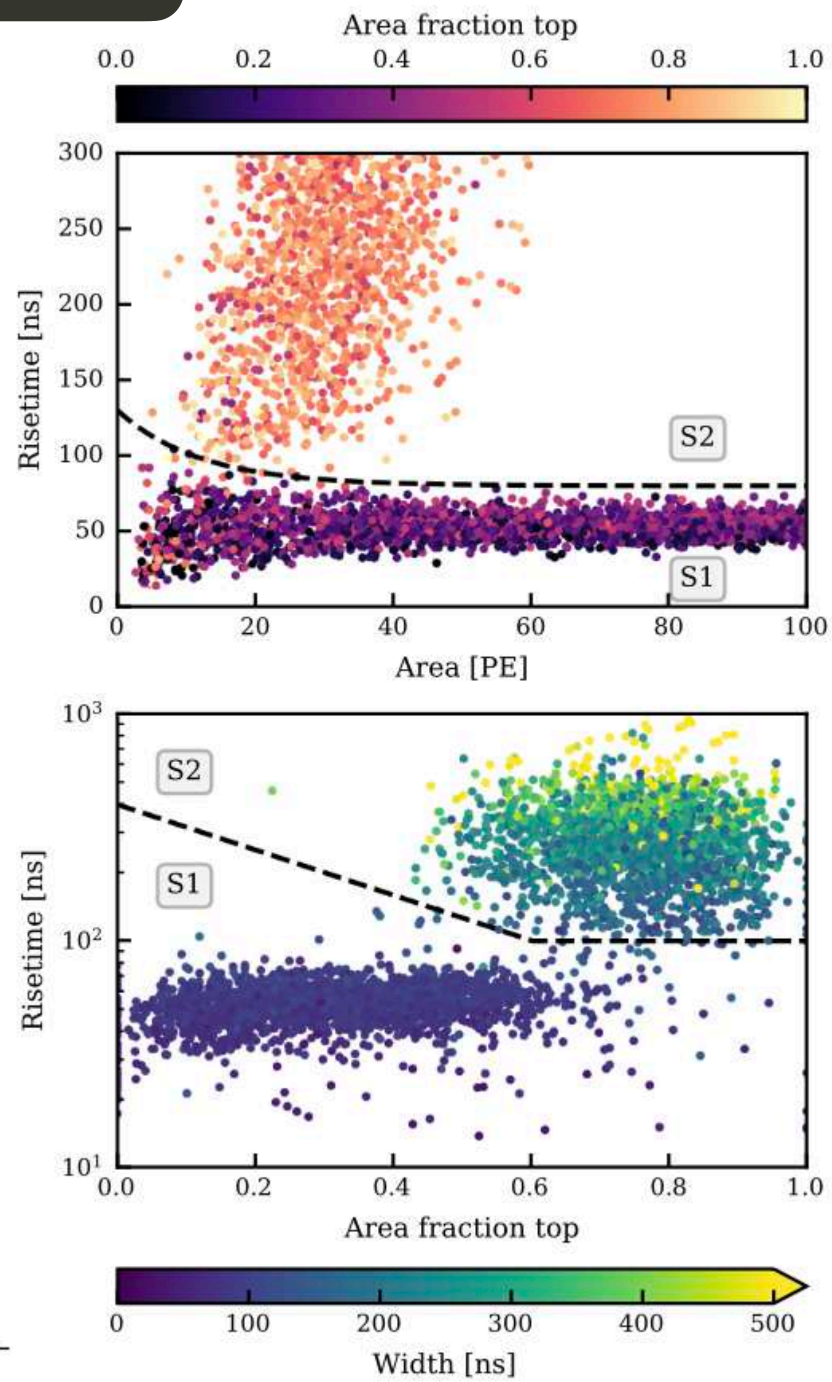
Far and Wide: Searches for Particle Dark Matter with the LZ and TESSERACT Experiments
Michael Williams, PhD thesis

XENON APPROACH

- **XENON performs the reconstruction subtly different— with all PMTs recorded whenever they go above baseline, and peaklets, peaks and finally events built successively from this time-stream of data.**

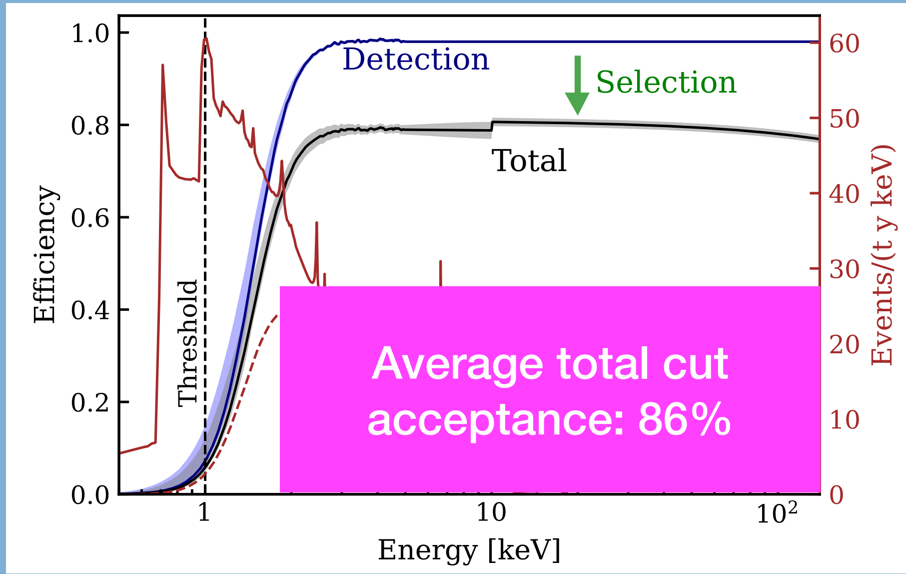


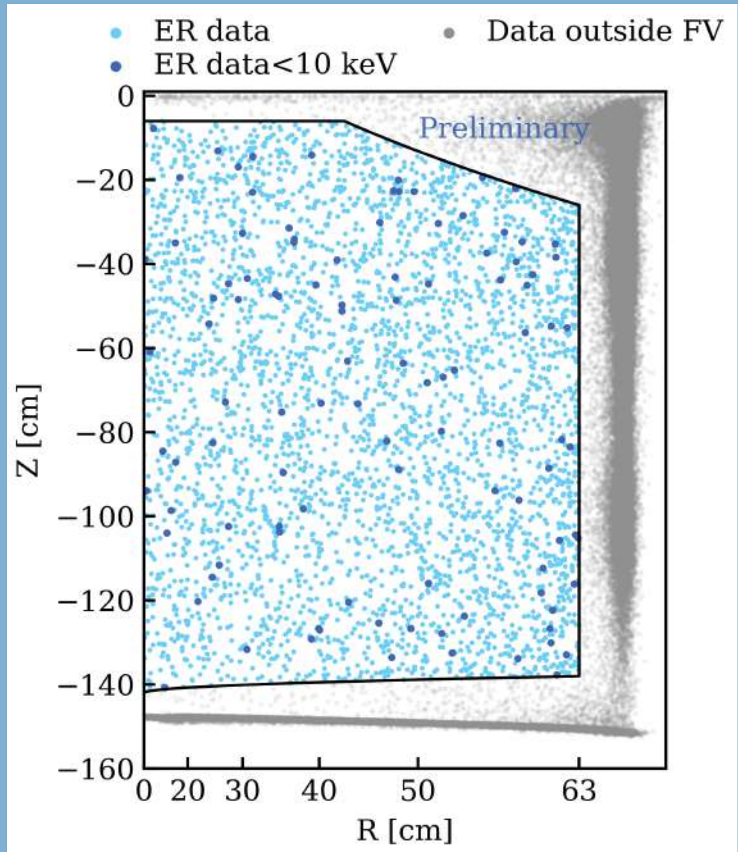




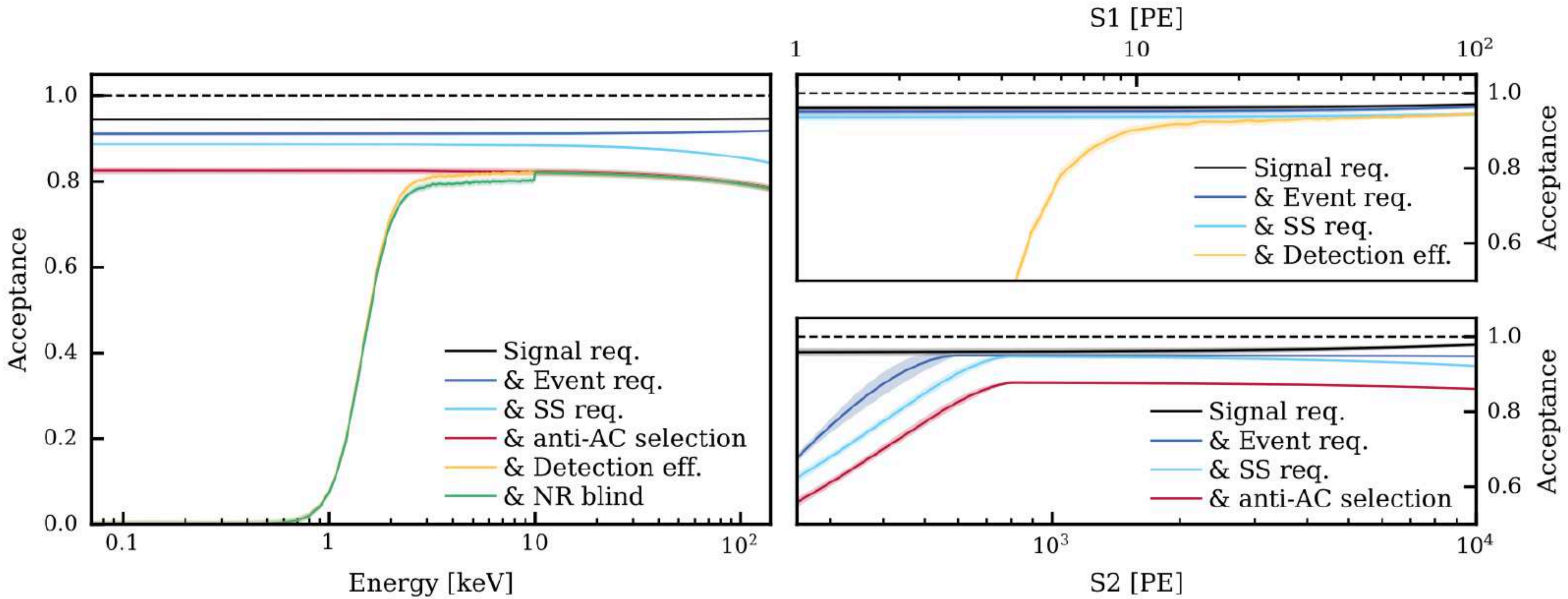
DATA QUALITY CUTS EXAMPLE: XENON

- Events are required to pass a range of quality cuts:
- The S1 and S2 peak should each have patterns, top/bottom ratios etc. consistent with real events
- An S2 width consistent with the expected diffusion
- An S2 over 500 PE
- Not within of a neutron veto event
- Events must be within ER band
- Fiducial volume cut selects a mass of with low backgrounds





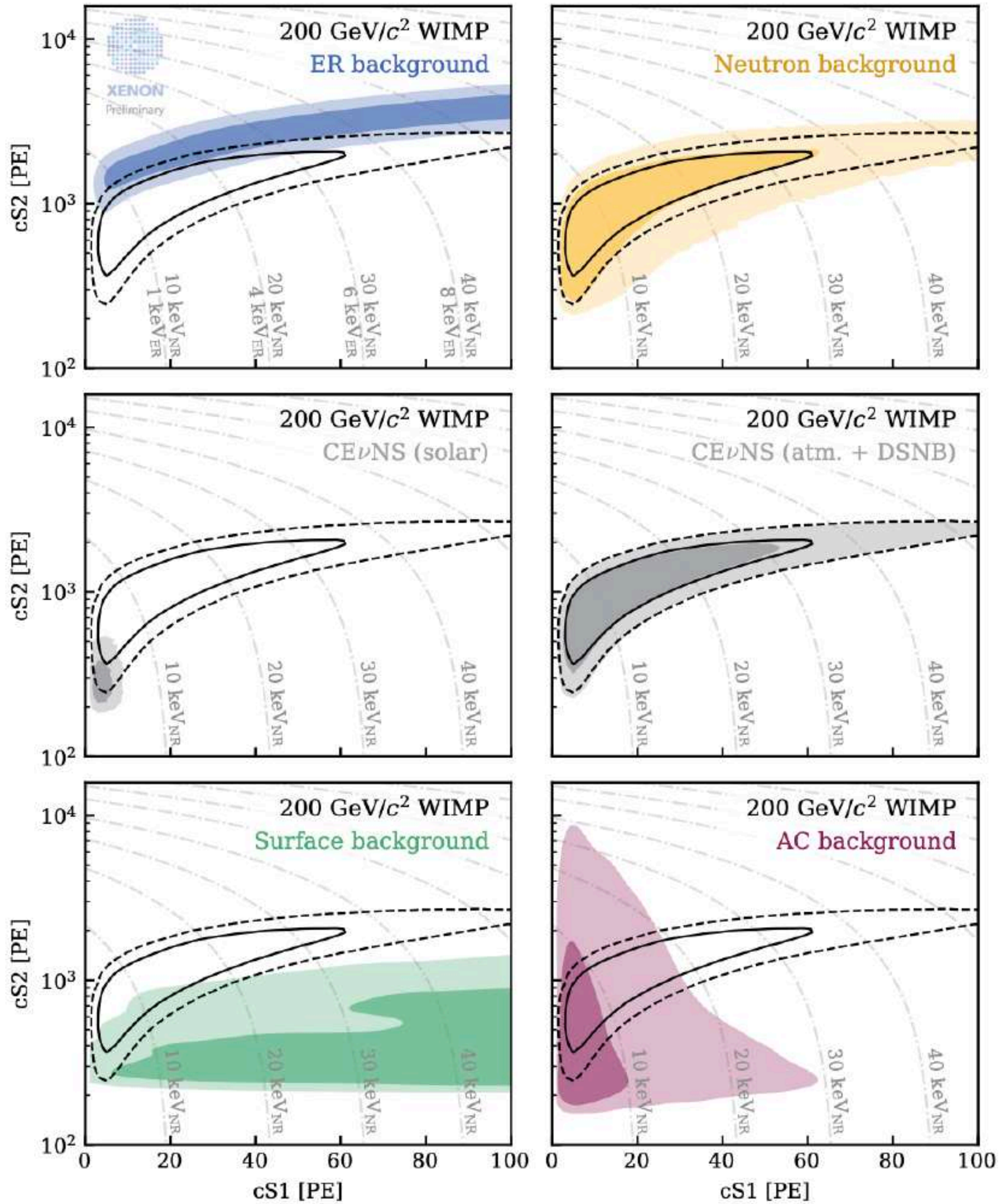
DATA QUALITY CUTS



- Cuts may be considered and applied as function of S1, S2 (note, uncorrected!) or as pairing cuts
- Typically aim for flat acceptance if possible
- By far the most important one for performance is the detection efficiency

BACKGROUND AND SIGNAL MODEL

- The signal and background models rely either on the fit to the xenon recoil
- or on data-driven methods.
- In the end, they will make up the model of our observation, and is how we compare our results to our knowledge.



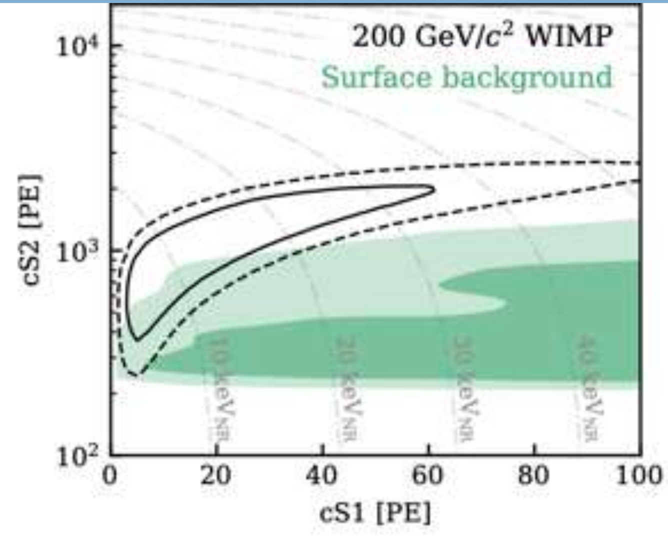
"WALL MODEL"

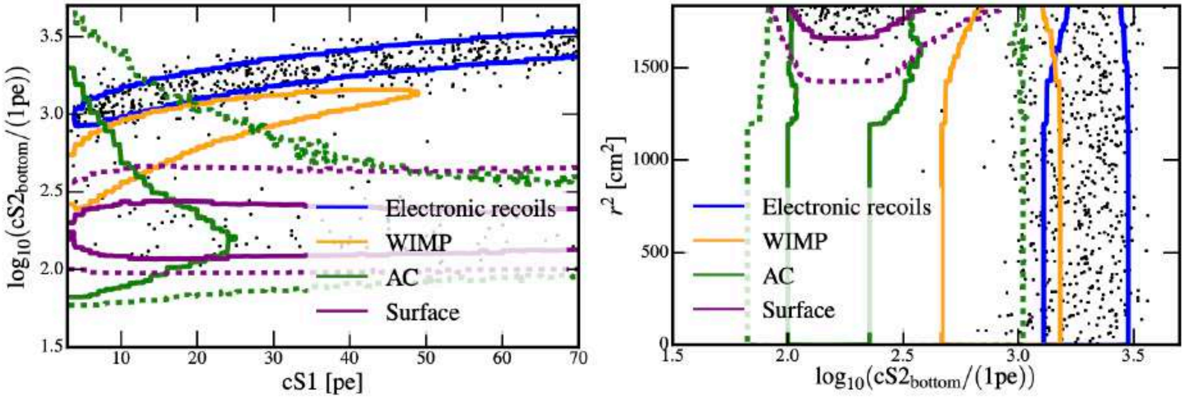
- Radioactive daughters contaminate the surfaces of the TPC, including ^{210}Po and daughters can cause a range of alpha, X-ray, Auger electrons and more.

- However, near or in the surface, energy may be lost, and in particular electrons may not be able to drift exactly along the wall all the way up to the surface

- The result is a "wall background" concentrated at high R and with relatively low S2

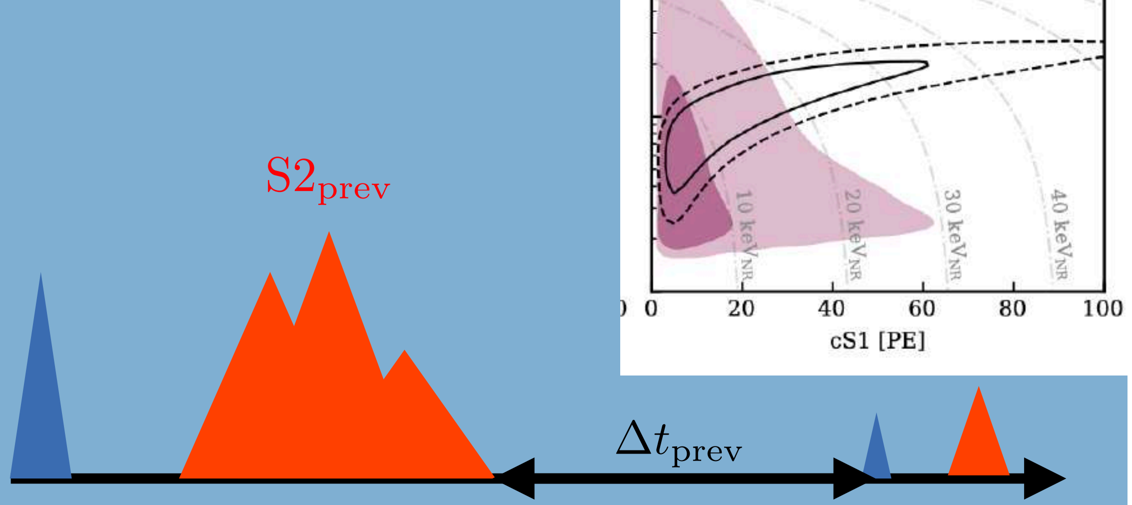
- The model is empirical, with events outside the fiducial volume used to construct a KDE of the distribution

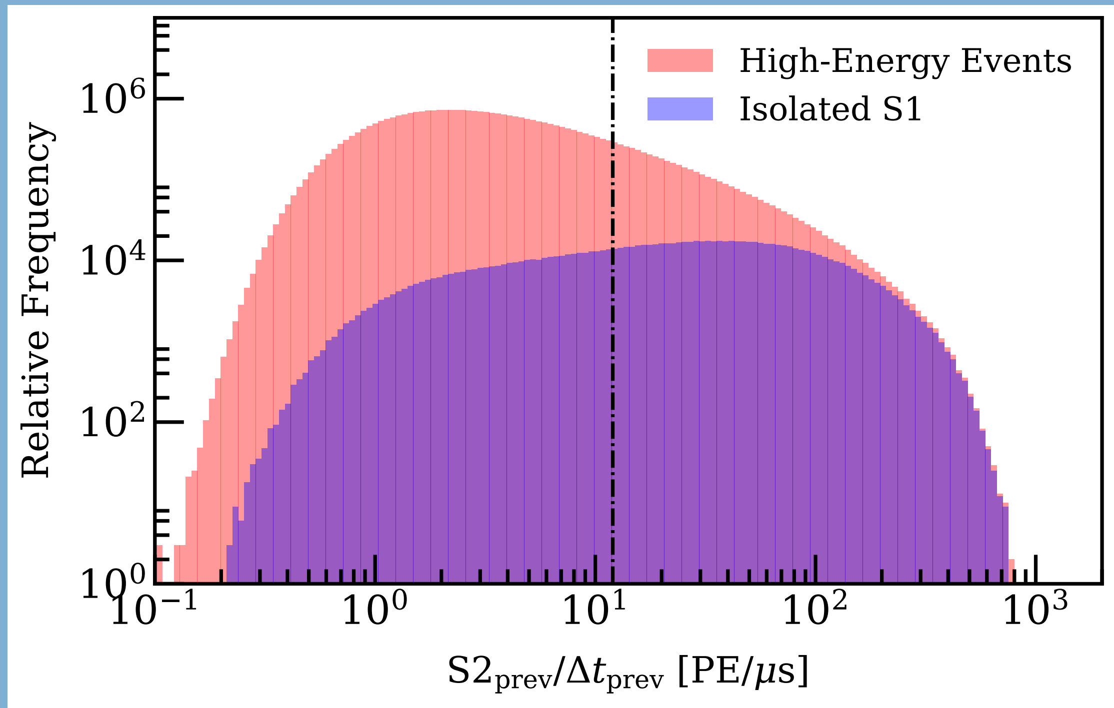




FALSELY PAIRED ("AC") EVENTS

- False events reconstructed from unconnected S1 and S2 signals form the Accidental Coincidence background
- Accepting events with 2-fold S1 coincidence raises the AC background by two orders of magnitude
- Some of the lone S1 and S2s are correlated with preceding high-energy events— the right plot shows that isolated S1s that may be falsely paired is more likely to occur the sooner and larger the previous S2
- A cut is also made on the radial distance between the S2 of events and the preceding high-energy event
- and on the time between the event and other S2s



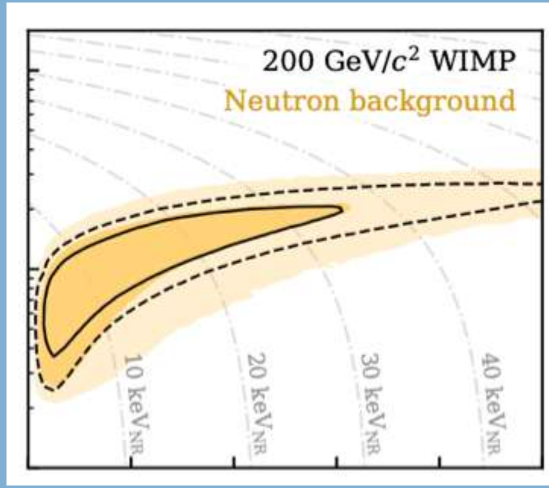


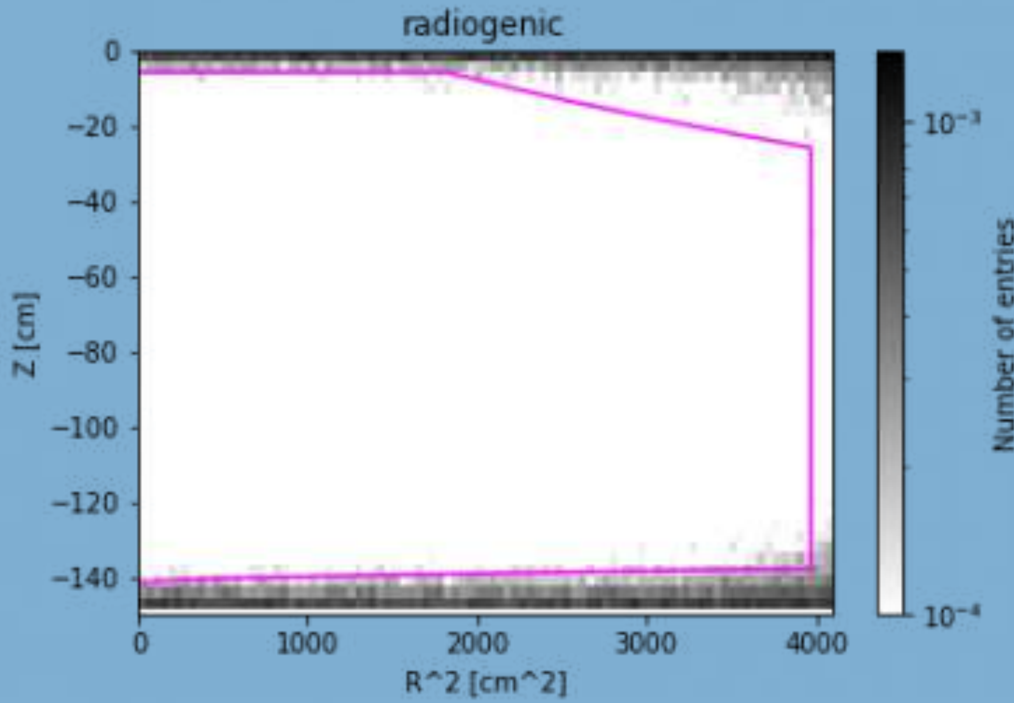
RESULT OF THESE CUTS:

- LONE S1 RATE AND S2 RATES ARE BOTH REDUCED BY 66%
- 18% OF SIGNAL CUT

NEUTRON BACKGROUND

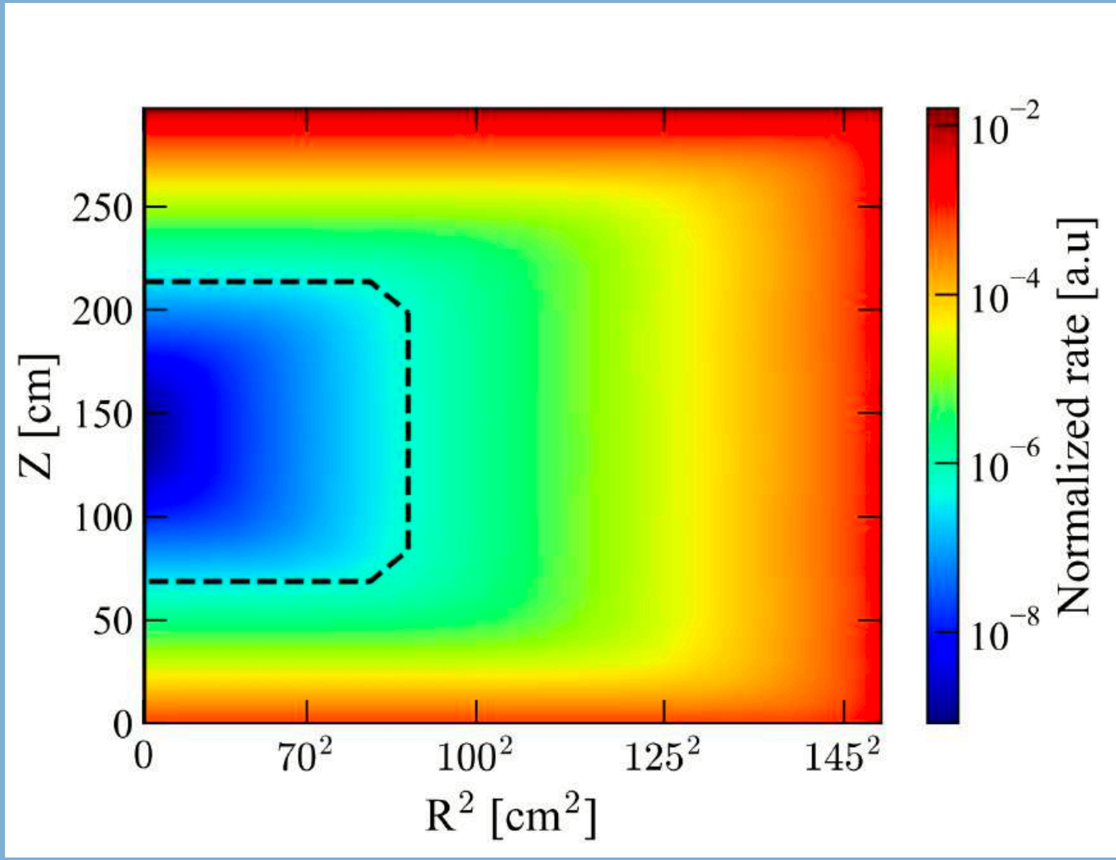
- The neutron background combines the best-fit model of nuclear recoil response with a full-detector modelling of neutron-induced backgrounds
- Microclustering and details of the multiple-scatter resolution matters to get this right
- Simulations have a significant rate uncertainty— in practise the rate is often constrained by data sidebands,
  - multiple-scatter-tagged events
  - or neutron veto tagged events





MATERIAL/ GAMMA-RAY BACKGROUND

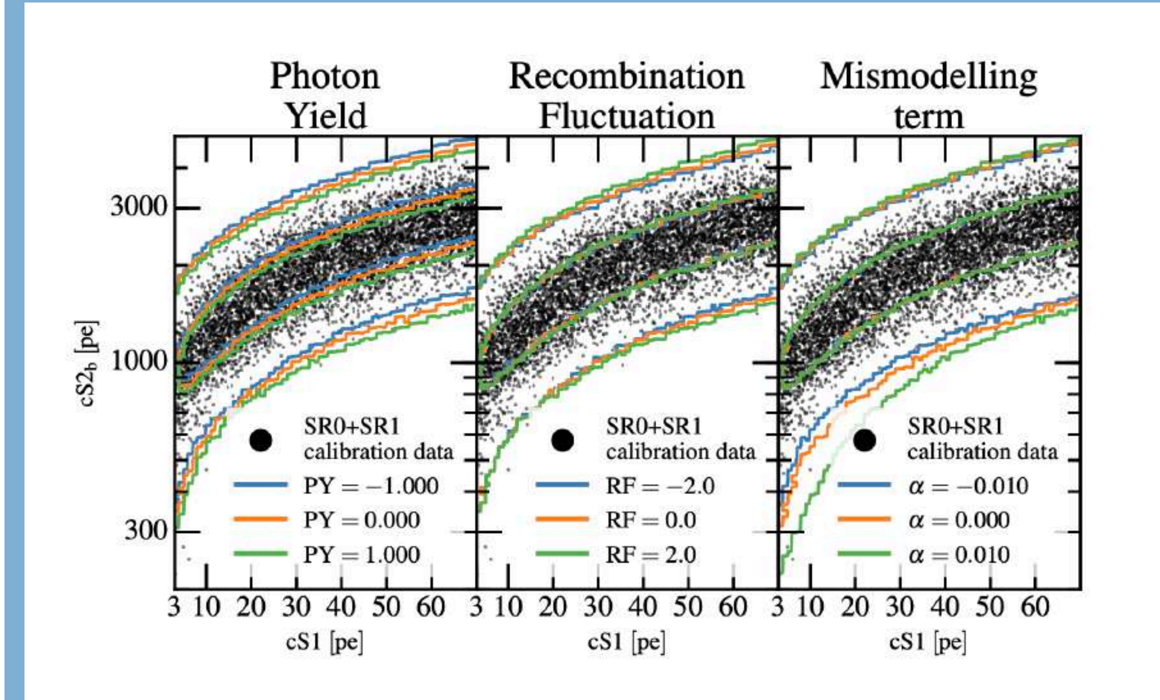
- **The surrounding materials emit some gamma rays that are self-shielded by the fiducial volume**
- **For WIMP searches this self-shielding is typically enough to be able to neglect this component**
  - **Fiducial volume choice partially optimised by demanding homogenous distribution**
- **For higher-energy searches, the gammas punch in farther, and you need to model this for optimum performance**

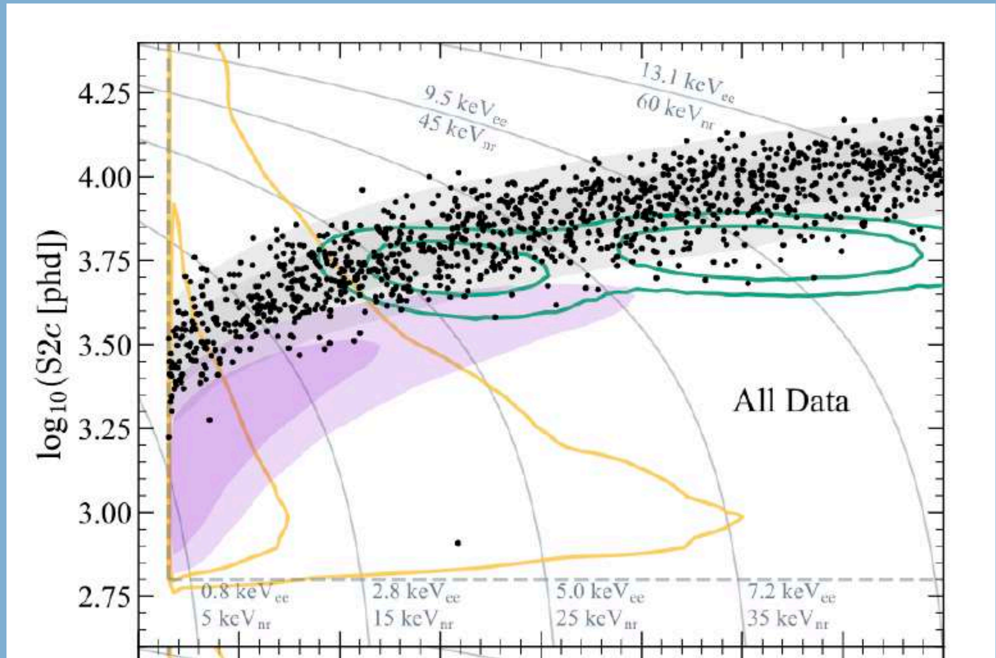


Neutrinoless double beta decay sensitivity of the XLZD rare event observatory, XLZD Collaboration, J.Phys.G 52 (2025) 4, 045102 DOI: 10.1088/1361-6471/adb900

ELECTRONIC RECOILS

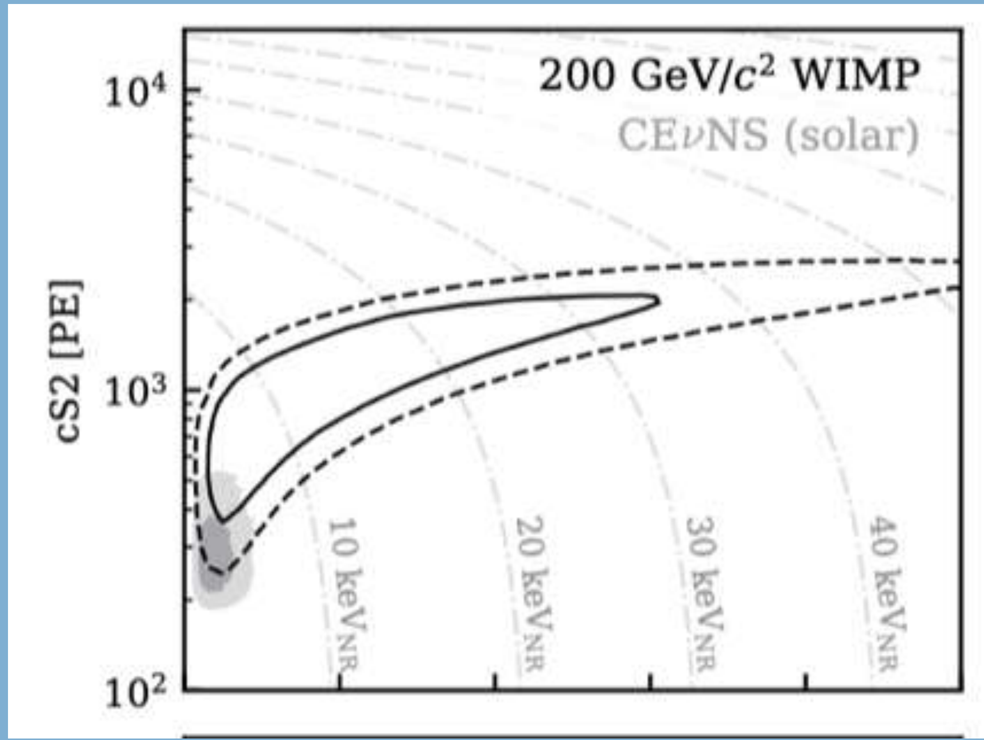
- Well-constrained by calibration datasets (rule of thumb, 10 times your data is great)
- but also most numerous—understanding the ER tail is critical
- The spectrum is typically taken to be flat
- but LZ has shown that there is a population of double electron capture, that is visible when you have a low enough background
  - XENONnT SR0 saw a hint, causing me many ulcers..





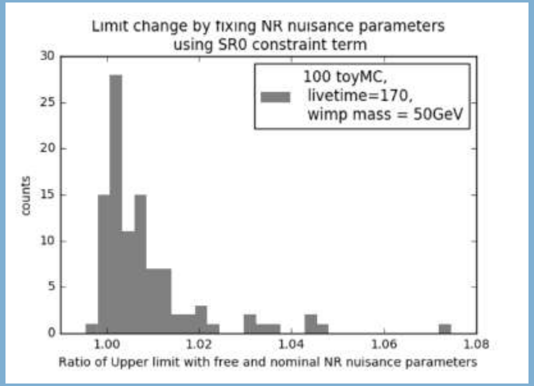
NEUTRINOS

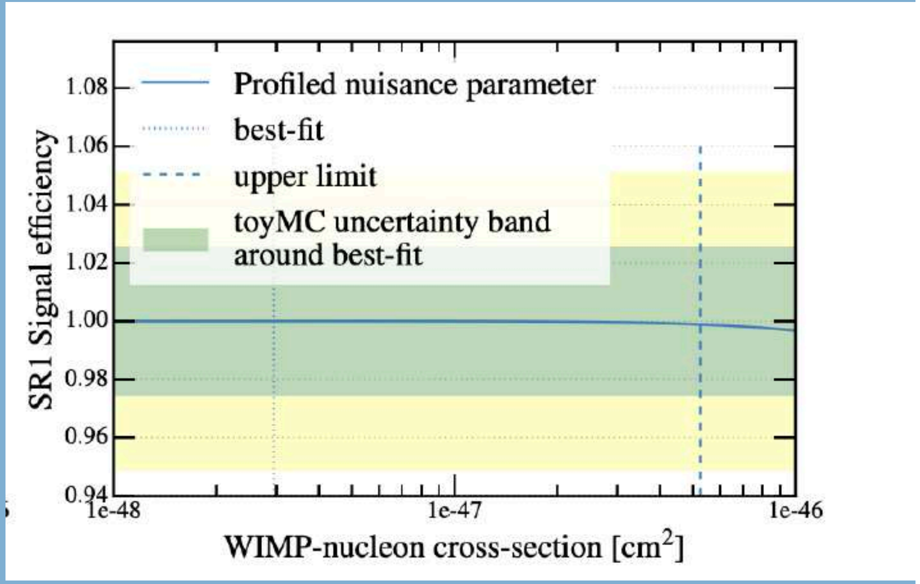
- The perfect signal-like background
- So far, we've only dealt with the low-energy ^8B component from the sun, with a few events expected per tonne-year
- Later today, we'll discuss neutrinos as an interesting science goal on their own
- but as we'll discuss in one of the next lectures, this background will also present the ultimate barrier to continued scaling of lXe TPCs



SIGNAL

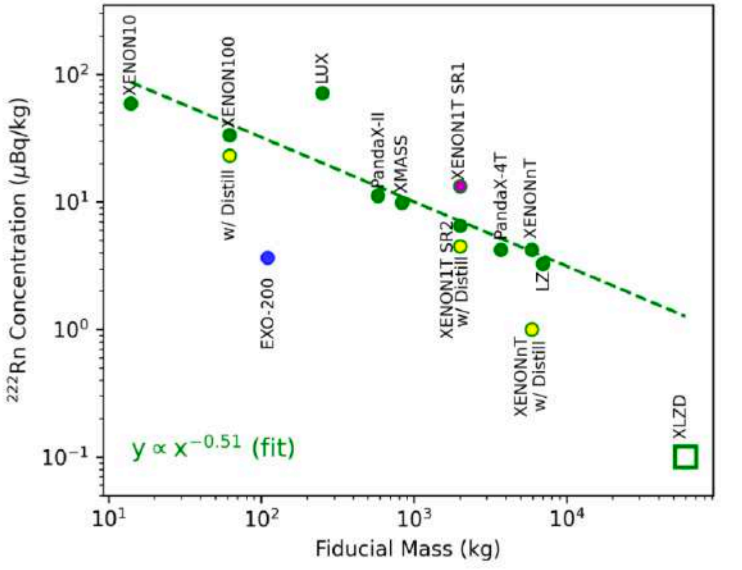
- The signal model uses the standard helm model, standard halo model &c
- Passed into the analysis per-mass, results are also reported per-mass. (between ca. 6 and 1000 GeV)
- In principle the shape is uncertain due to the uncertain NR response, but since we expect only a handful of events, this will have a negligible effect on results
- On the other hand, the uncertainty part that affects the rate matters— this is included as a multiplicative factor that can scale the expectation value up or down.

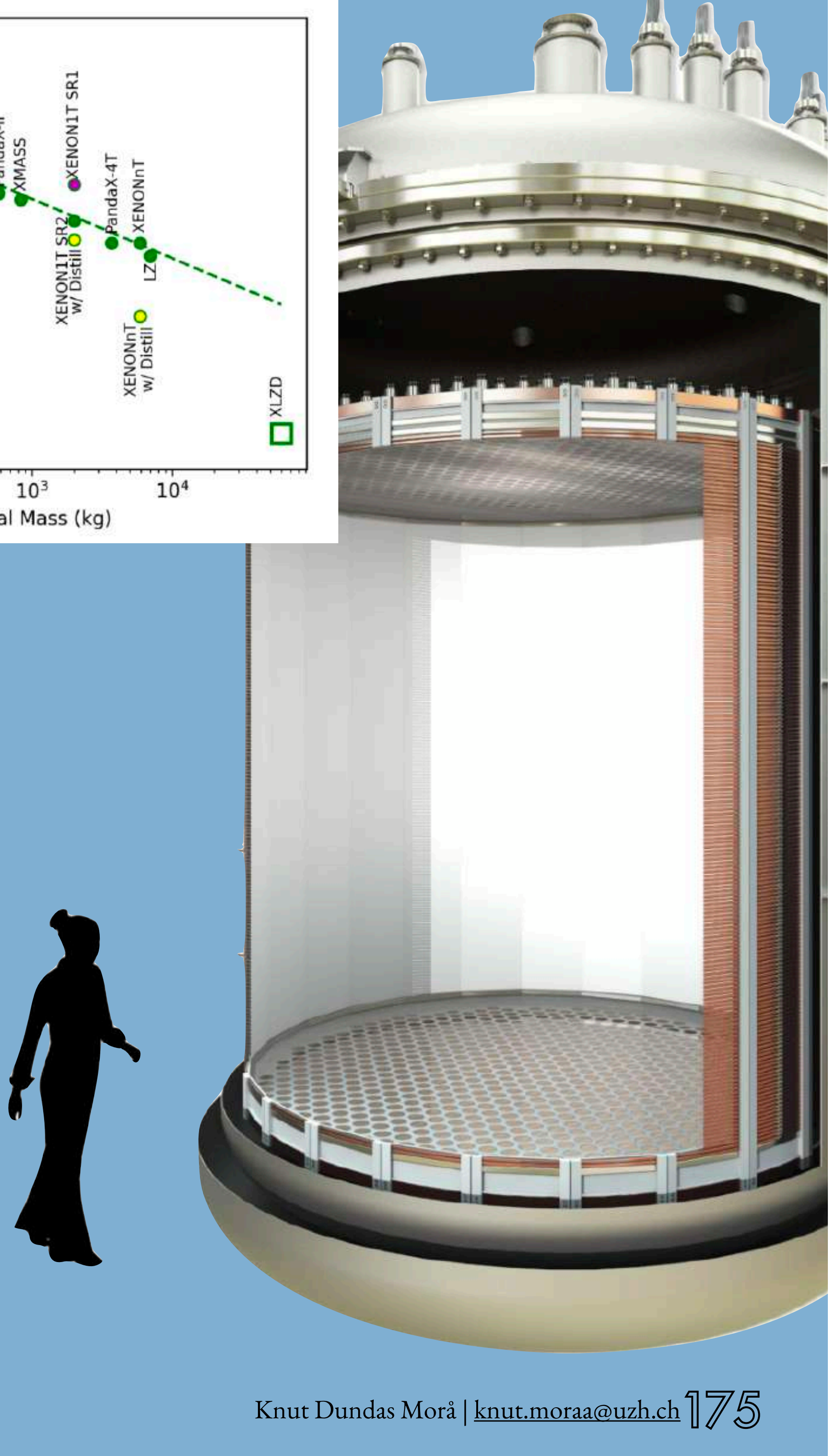




XLZD

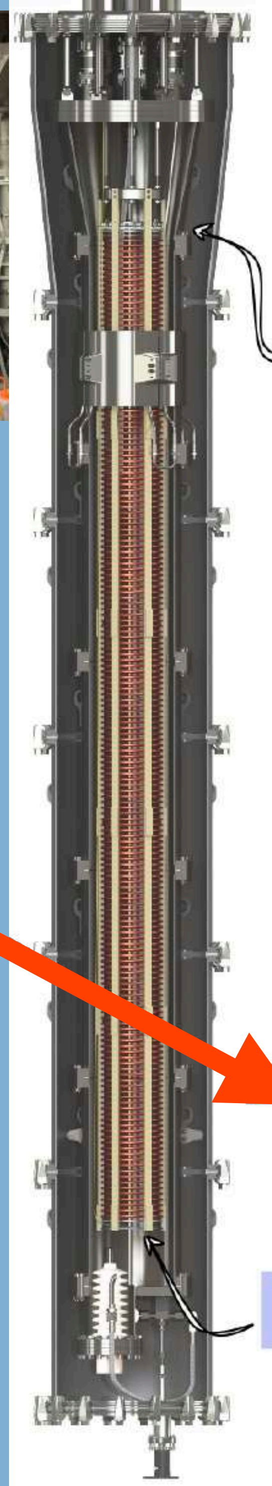
- Combined effort by members of XENON, LZ and the Darwin R&D effort to build a 60-tonne two-phase TPC to reach the ultimate possible sensitivity to dark matter
- Extensive R&D underway
  - to produce stable grids,
  - electron drift and field homogeneity,
  - Photomultipliers
  - Xenon handling
- And background mitigation: aiming for another factor 4-10 lower than current-generation

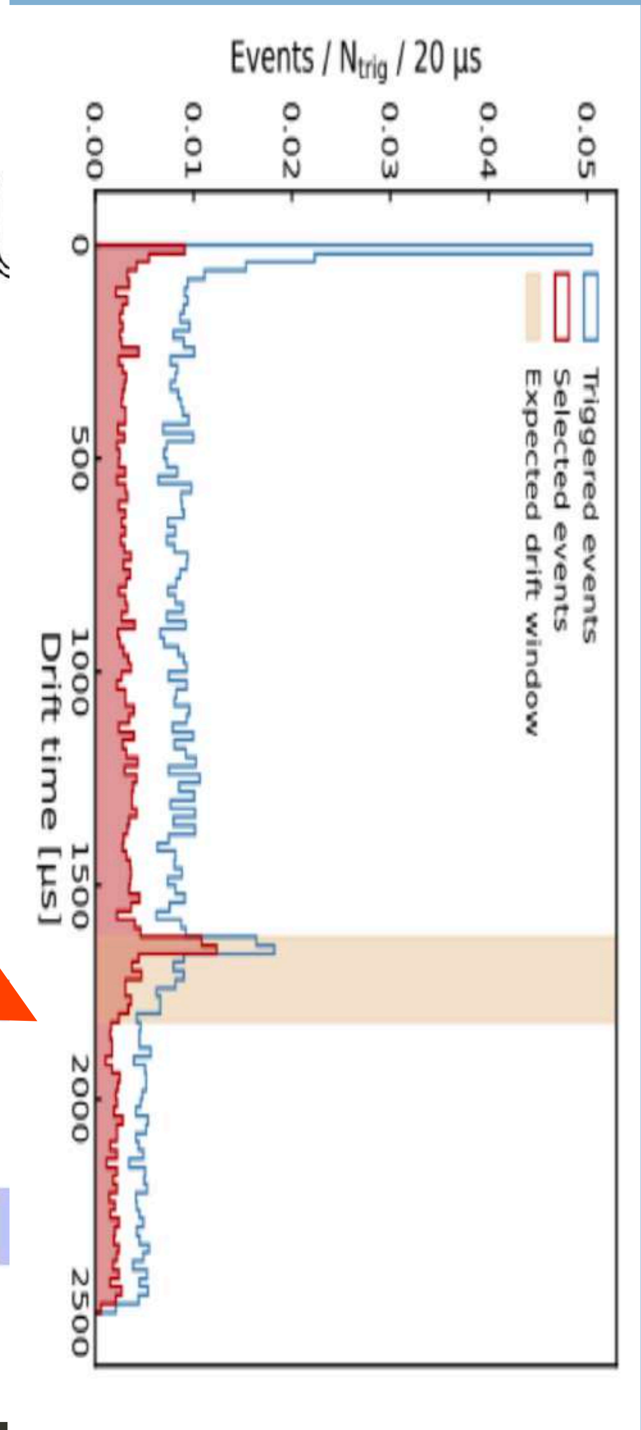




XENOSCOPE

- Demonstrator facility for XLZD/ Darwin at Zürich University
- As large as the previous generation of science lXe experiments— 360 kg Xe
- 2.6 m tall, matching XLZD dimensions
- Designed to study long drift— can we understand the electron cloud diffusion, field stability, and can we reduce backgrounds?
- So far, demonstrated running, S2 from muon interactions, drift speed measurements
- Pending/not successful yet: using a flash lamp to liberate electrons from the bottom cathode for higher precision drift measurements

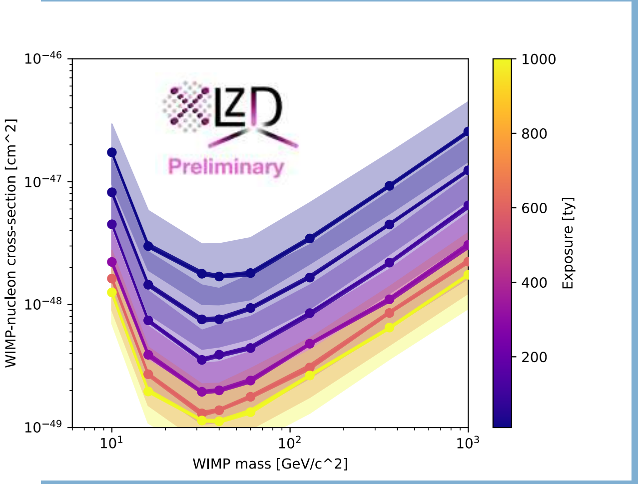




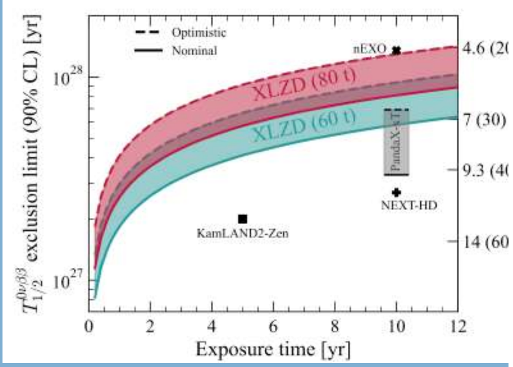
Plot by Rebecca Hampp

REQUIREMENTS

- At its current stage, XLZD is defining high-level performance requirements:
- Exposure (lifetime times fiducial mass)
- analysis threshold
- ER backgrounds
- neutron backgrounds
- More detailed second-level analysis will use these as targets to see if each upstream requirement reaches its targets



WIMP SENSITIVITY



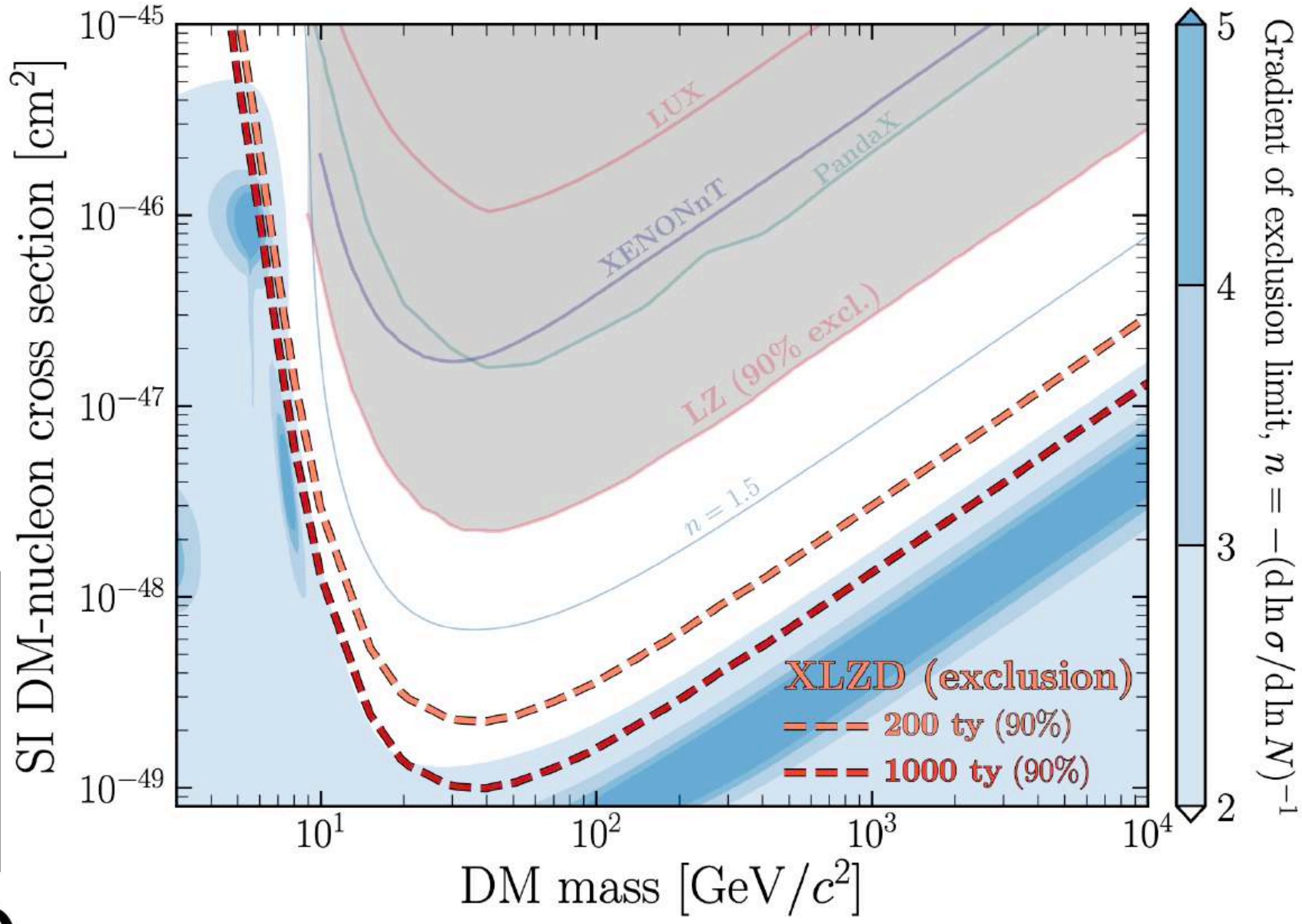
$0\nu\beta\beta$ SENSITIVITY

Energy threshold | Intrinsic Backgrounds | Neutron Rate | Fiducial Volume | Energy Resolution

PMT performance | Detector Size | Veto Performance

Drift Field | Veto Performance | Electron Livetime

XLZD WILL DISCOVER OR CONSTRAIN WIMPS ALL THE WAY TO THE "NEUTRINO FLOOR"



The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics, XLZD Collaboration e-Print: 2410.17137 [hep-ex]

HOW WILL A DISCOVERY LOOK LIKE?

- **A true WIMP signal (marked with a star) first shows up by worse upper limits**
- **As more data is collected, and the significance exceeds , the collaboration would draw two-sided limits and a closed interval**
- **Above , WIMP recoil spectra are almost degenerate, so the mass may not be tightly constrained**

Code to run XLZD requirements projections is available on github!

HOW WILL A DISCOVERY LOOK LIKE?

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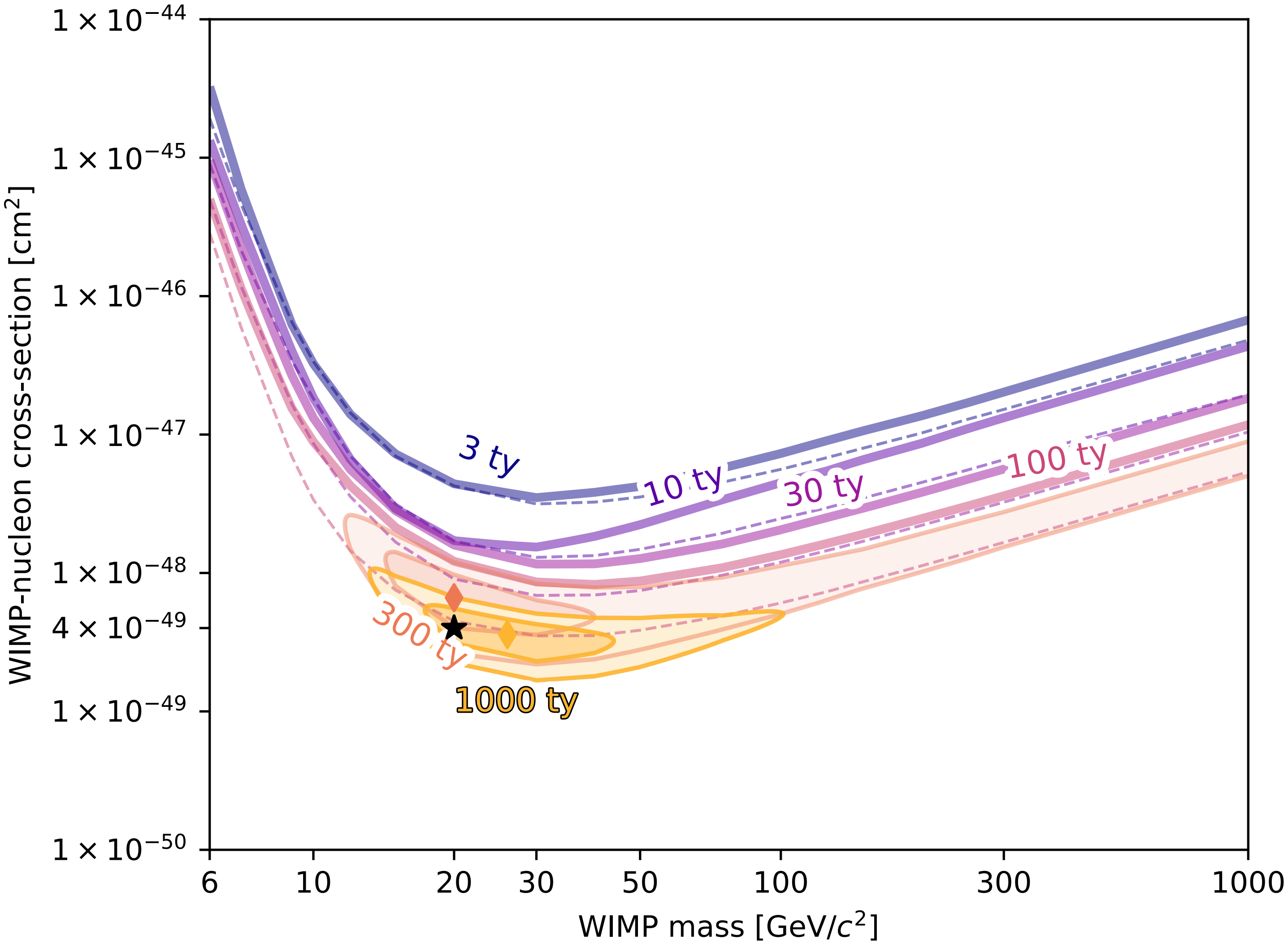
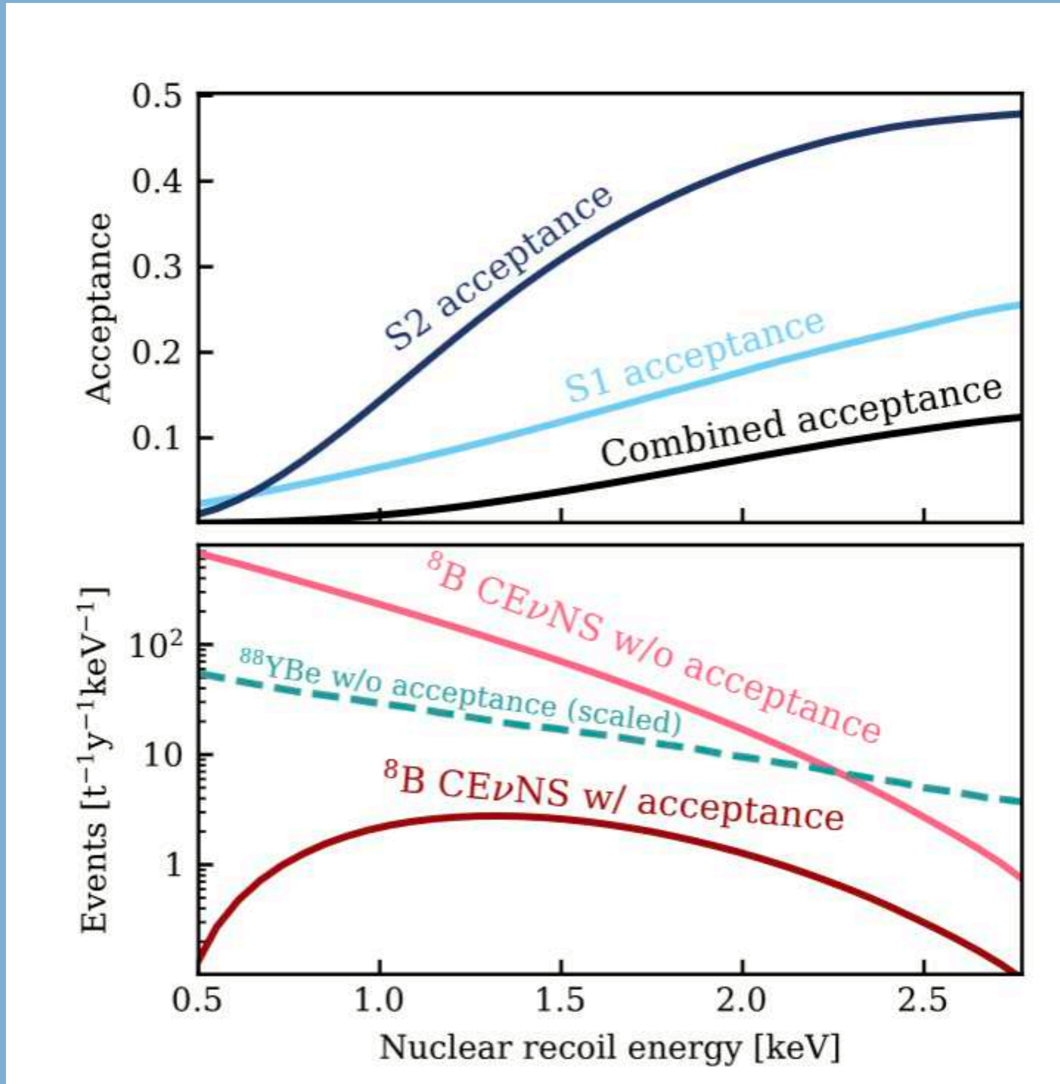


Code to run XLZD requirements projections is available on github!

REACHING LOWER IN THRESHOLD

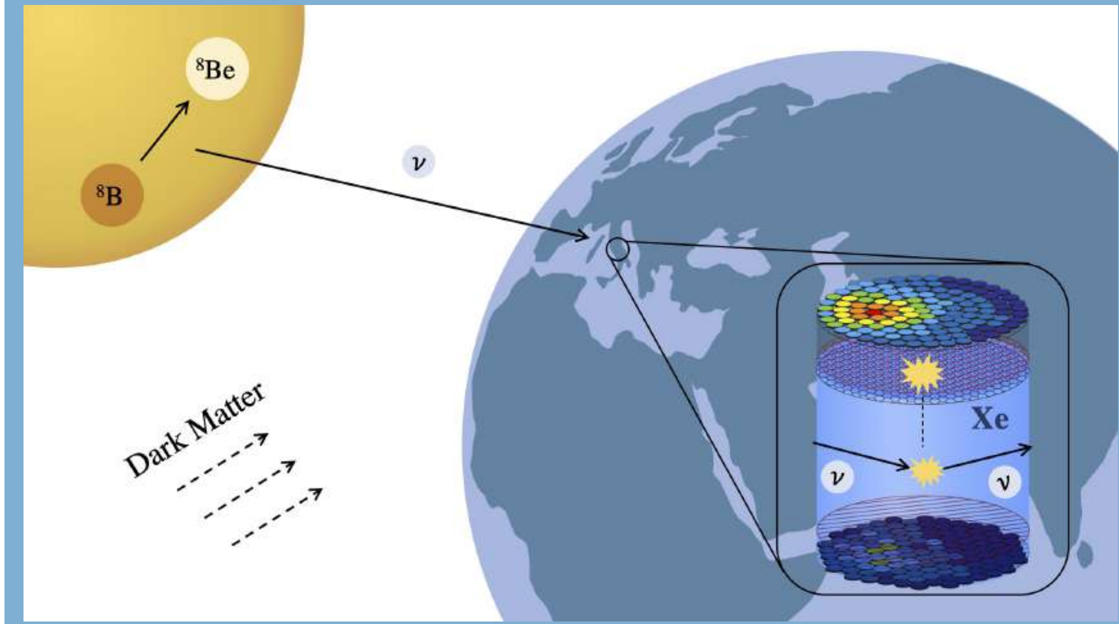
- liquid xenon TPCs are almost perfect— lowest background rate, enormous exposures
- One problem: to make a detectable recoil event you need around 3keV of energy
- The gains from being able to lower the threshold for xenon detectors can be massive, for example by
    - Searching for dark matter-electron scattering
    - Considering the Migdal Effect which predicts a small probability for a more visible event
    - Loosening cuts, even to the point of searching for only S2s

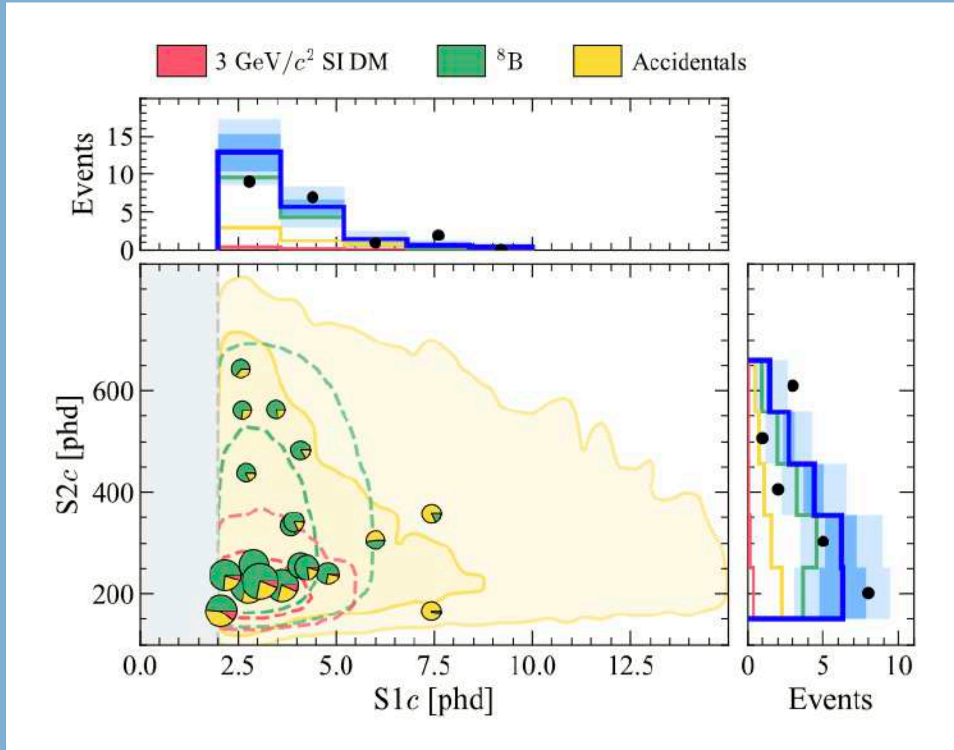


First Indication of Solar 8B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT
https://arxiv.org/pdf/2408.02877

DETECTING ^8B SOLAR NEUTRINOS

- **LZ, PandaX and XENONnT have demonstrated analyses reaching lower in energy by using dedicated analyses**
- **To see the $\sim$ 2keV events, cuts must be relaxed**
  - **XENONnT and PandaX used two-hit requirement for PMTs (PandaX also S2only)**
  - **LZ loosened other cuts**
    - **And had more exposure :)**
- **These results are statistics-dominated, giving little precision**
- **But demonstrate and anchor the lower-energy performance of the detectors**

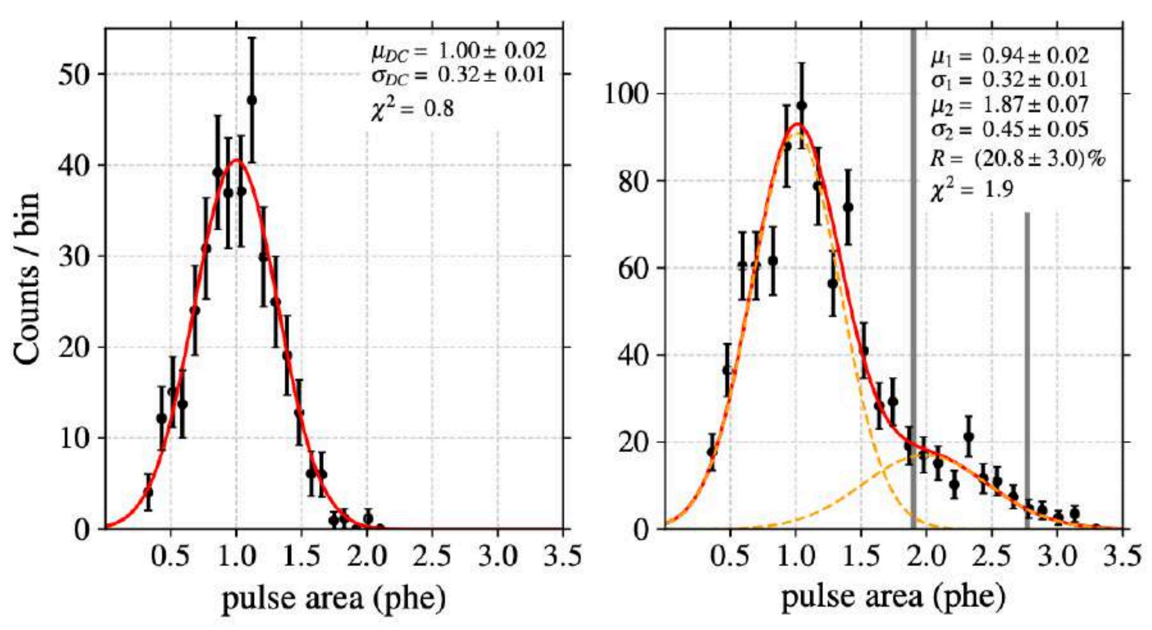


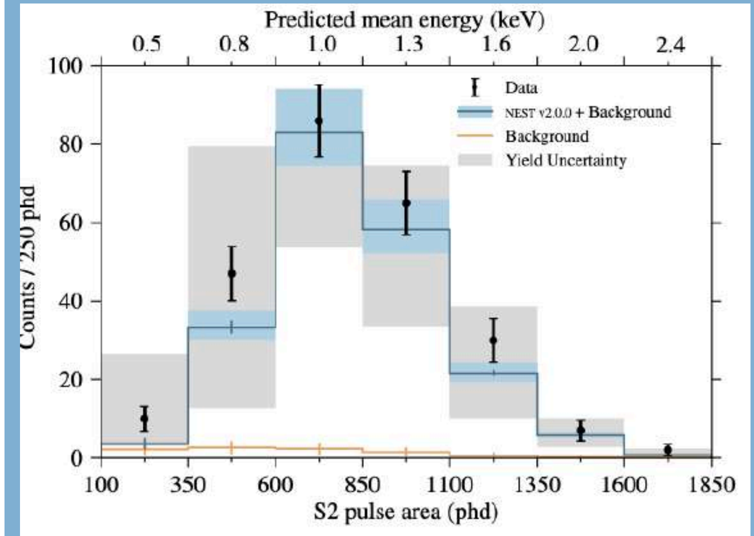


Searches for Light Dark Matter and Evidence of Coherent Elastic Neutrino-Nucleus Scattering of Solar Neutrinos with the LUX-ZEPLIN (LZ) Experimen
https://arxiv.org/pdf/2512.08065v1

DOUBLE PHOTOELECTRON EMISSION

- A trick to preferentially select real S1 signals is that while PMT noise is approximately a Gaussian, a real VUV photon has a chance to emit two photoelectrons, giving a twice as large signal
  - Lux analysis for low-energy events used this double photoelectron emission: a genuine scintillation photon has a probability of $\sim 17\,\%$ to liberate two photoelectrons hitting a PMT

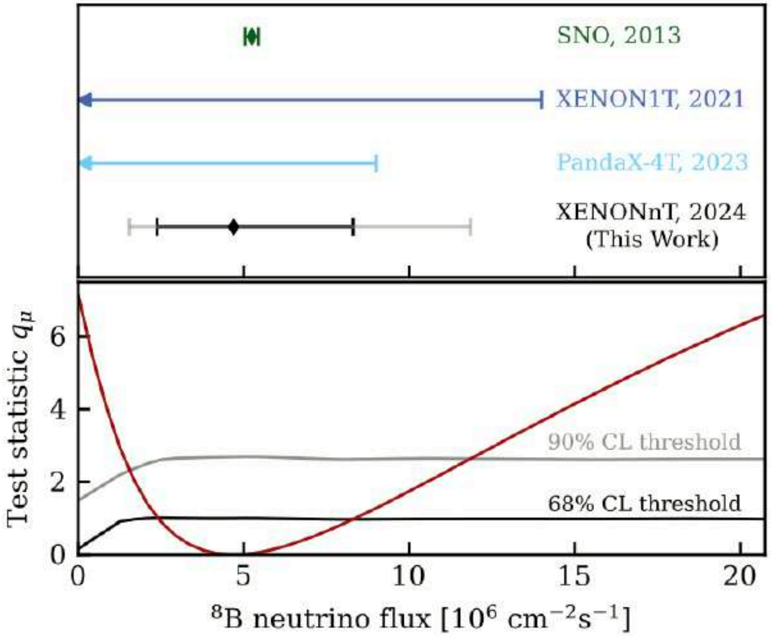


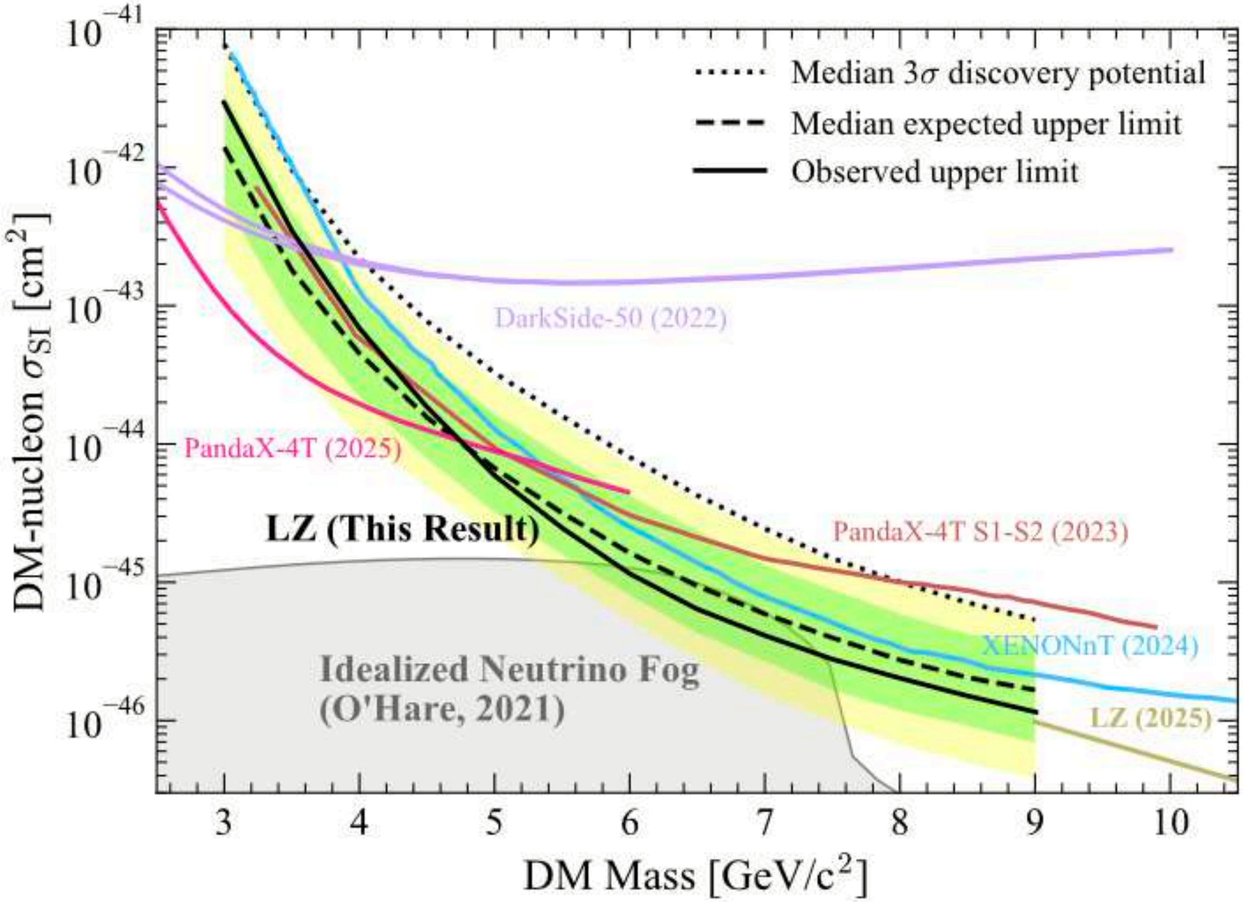


D. S. Akerib et al. (LUX Collaboration). “Extending light WIMP searches to single scintillation photons in LUX”. In: Phys. Rev. D 101.4 (2020), p. 042001. doi: 10.1103/PhysRevD.101.042001.

RESULTS

XENON result— bit less than 3 sigma made some people discuss wording..





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NEW PHYSICS FROM ^{8}B

- The neutrino flux upper limit can be converted into constraints on possible vector neutrino-quark interactions

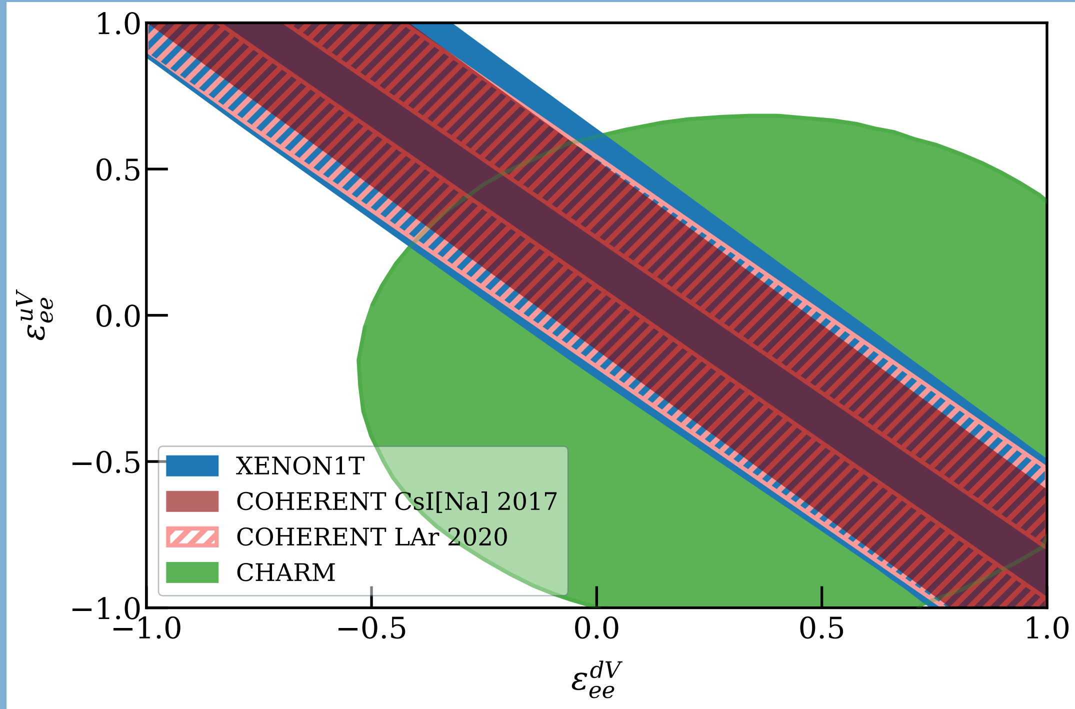
- By including all the external constraints on the signal rate are included; neutrino flux, charge and light yield, we may also constrain a WIMP signal between 6 and 12 GeV/c2

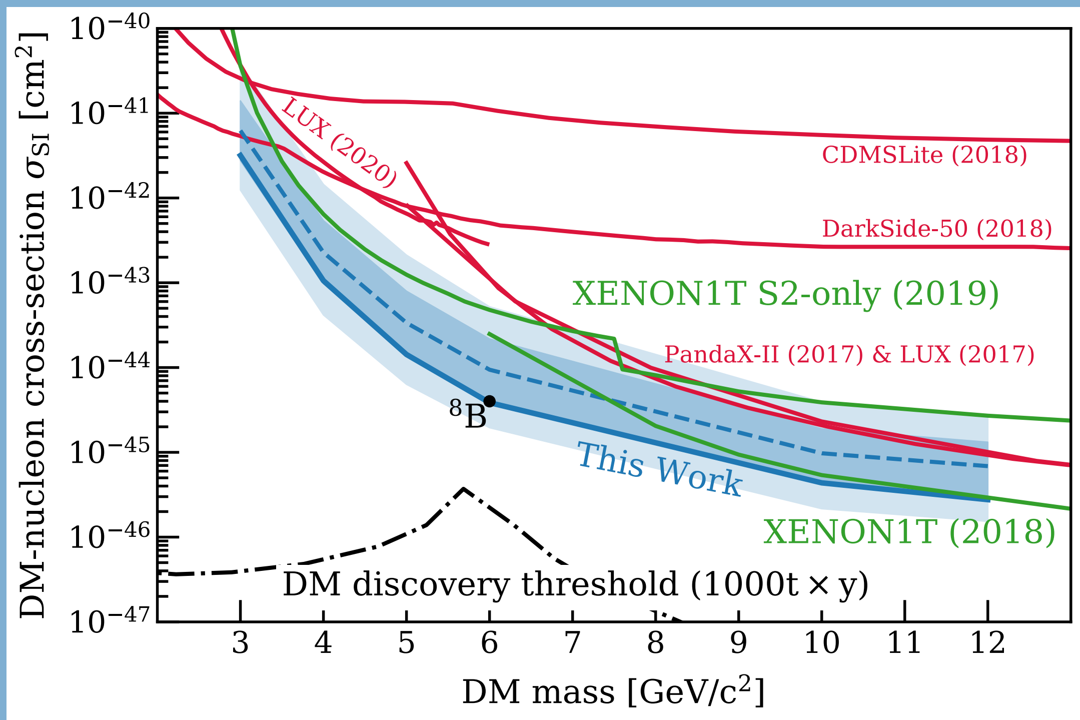
- For the WIMP search, we use the interpolated light yield model rather than the constant, to better represent the best-fit and to accommodate the changing WIMP spectra

- The AC-background-only result, combined with an expectation of observing 2 neutrino events results in the upper limit being a downwards fluctuation with respect to the sensitivity

Search for Coherent Elastic Scattering of Solar ^8B Neutrinos in the XENON1T Dark Matter Experiment

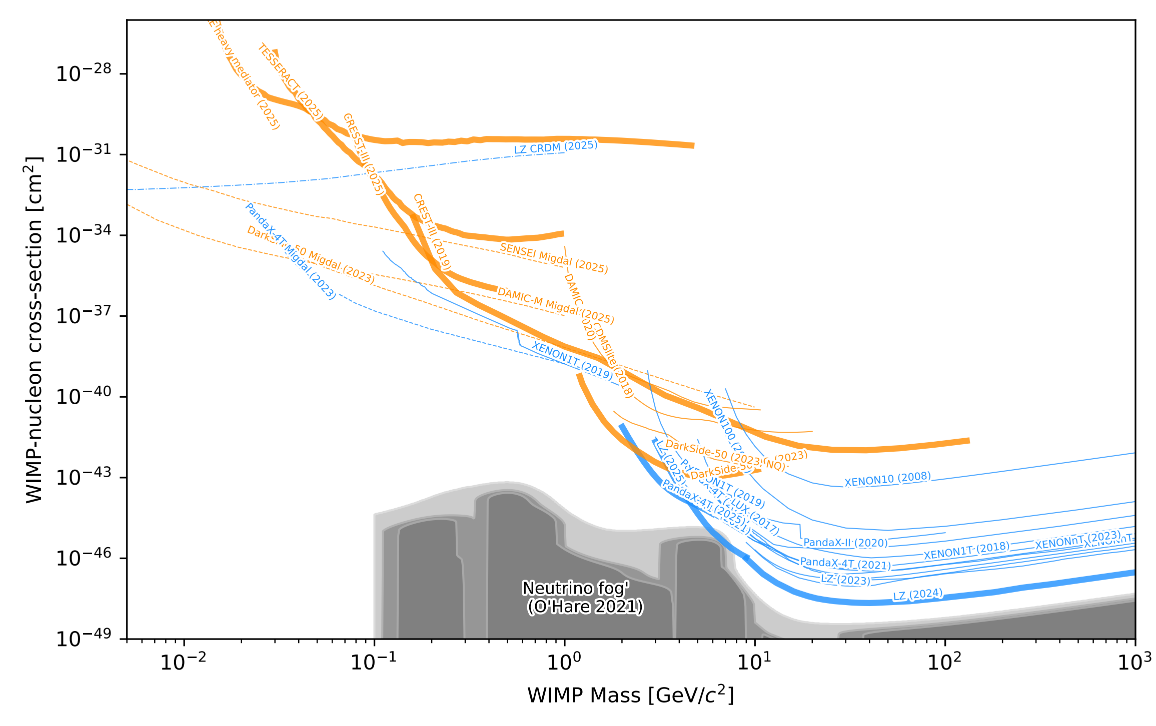
https://arxiv.org/abs/2012.02846

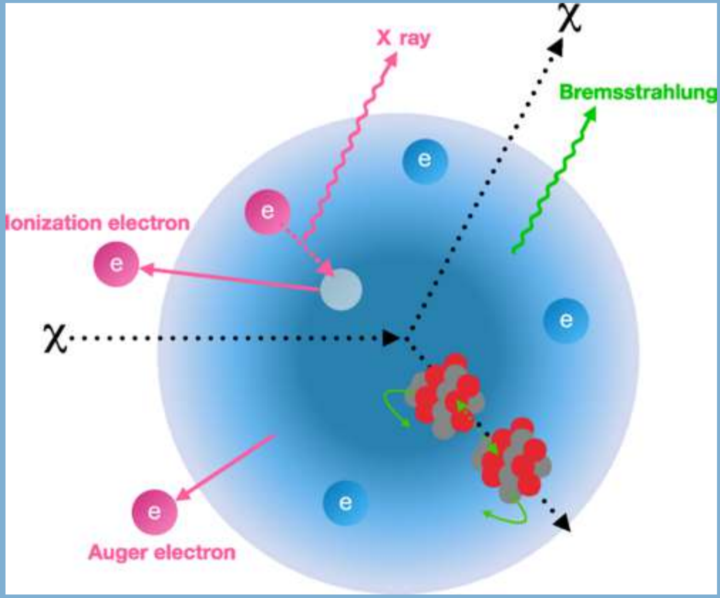




MIGDAL

- The threshold of lXe detectors is determined by the S1 coincidence requirement, but what about all the energy lost to heat?
- If dark matter-matter scattering lost less energy to heat, we could lower the threshold significantly
- The Migdal effect promises such an effect, predicting that in a nuclear recoil, the nucleus recoiling gets a momentum with respect to its electron cloud
- The polarized nucleus-electron cloud system is predicted to lead to bremsstrahlung and ionization — some (mainly outer shell) electrons are simply left behind





Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T
DOI: https://doi.org/10.1103/PhysRevLett.123.241803

MIGDAL SEARCHES

- **Even if the Migdal effect is predicted to be extremely rare— $p = 8 \times 10^{-6}$ for a 1GeV/c^2 WIMP recoil, its effect is drastic for lXe detectors**
- **since it transforms a completely invisible recoil energy into a sometimes-visible one**
  - $\epsilon \times$ **instead of** $0 \times$
- **The Migdal effect primarily yields ionization electrons**
- **A signal with the Migdal effect lies almost in the ER band, and looks like a mixed NR+ER event**

Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T
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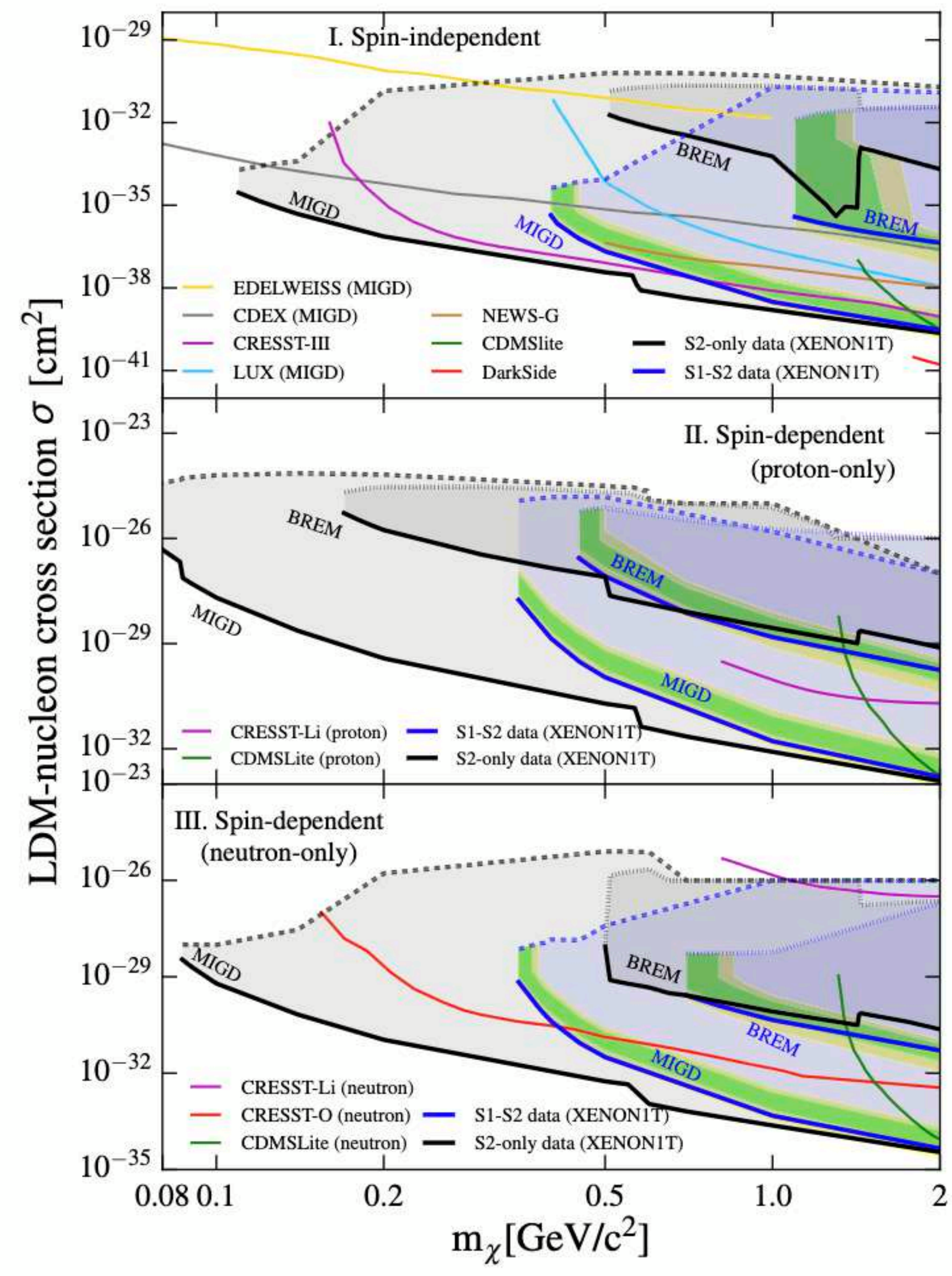
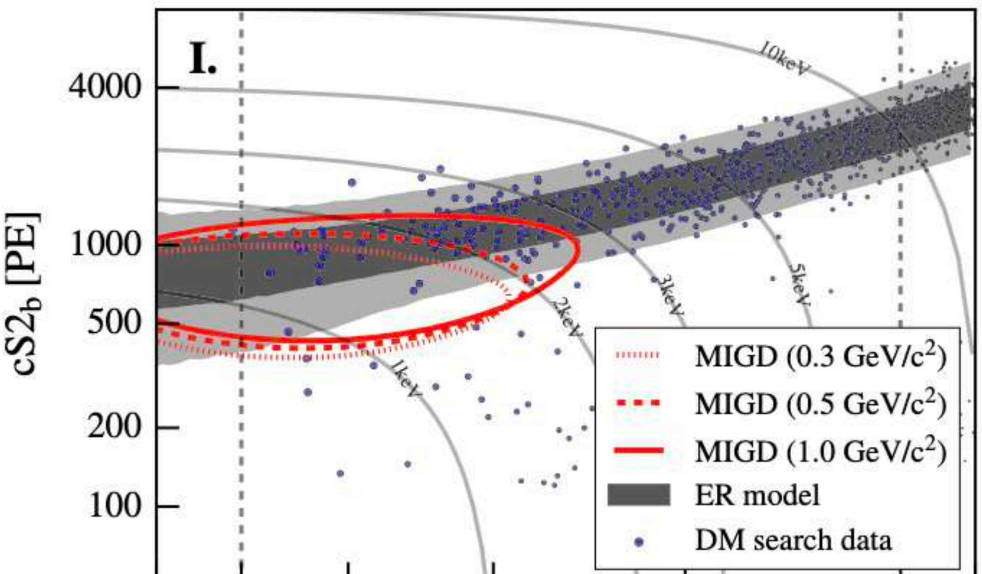
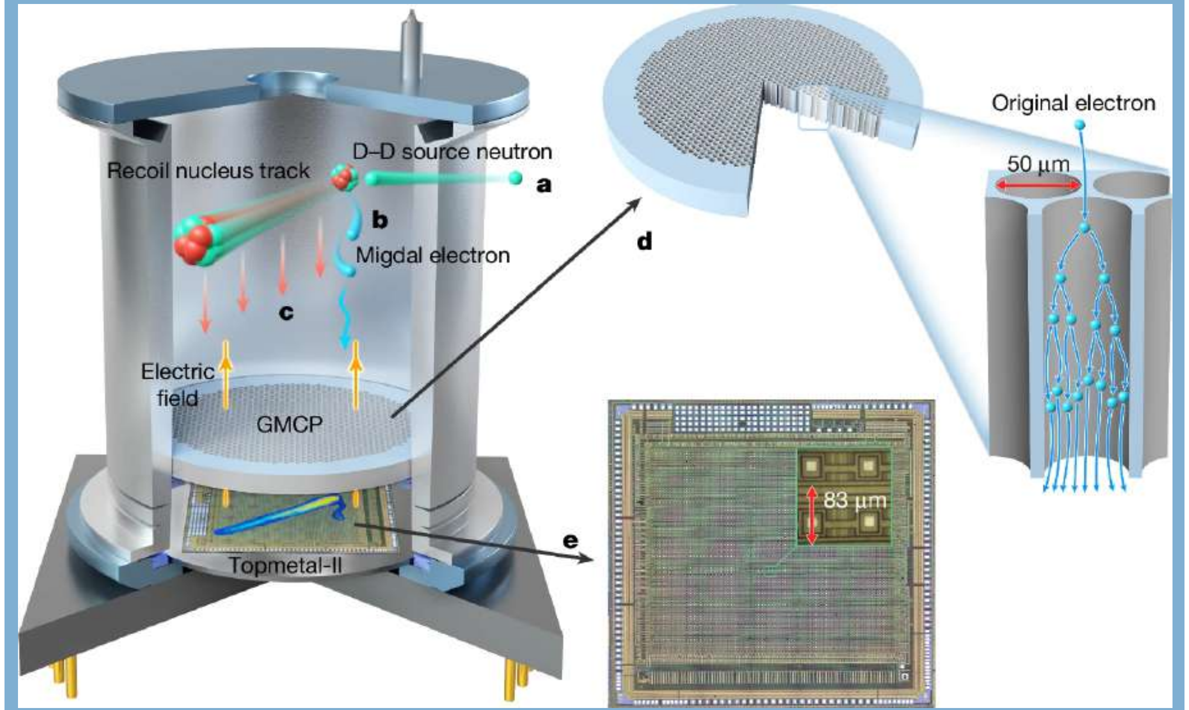




MIGDAL EVIDENCE

- This January, the MARVEL detector published evidence for the Migdal effect
- Using a gaseous time projection chamber, events are spread-out enough that the topology of a separate nuclear recoil and emitted electron can be resolved
  - NRs leave a dense track, while the electron track has a lower density.
  - Image classifier used to select NR- and ER-like tracks based on density and shape



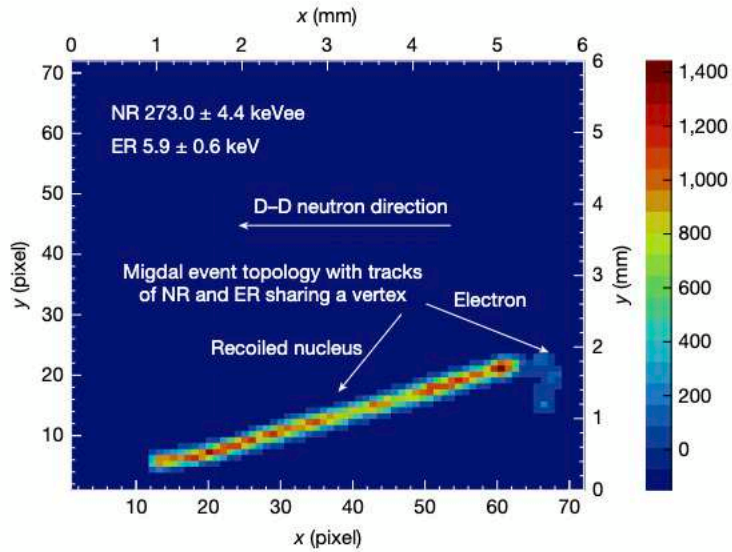
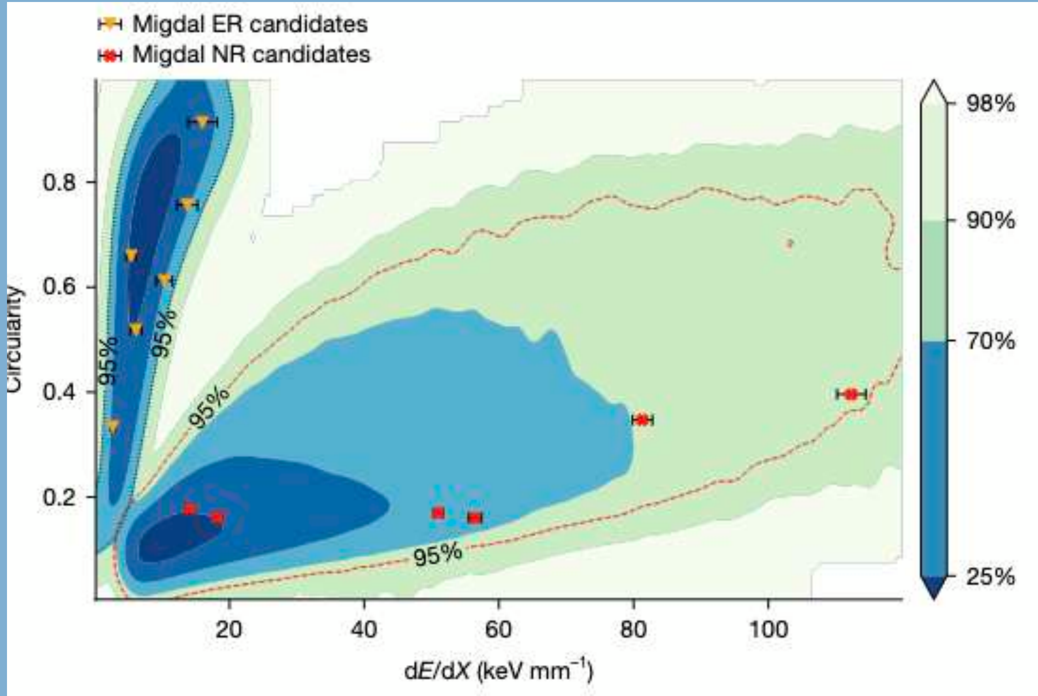


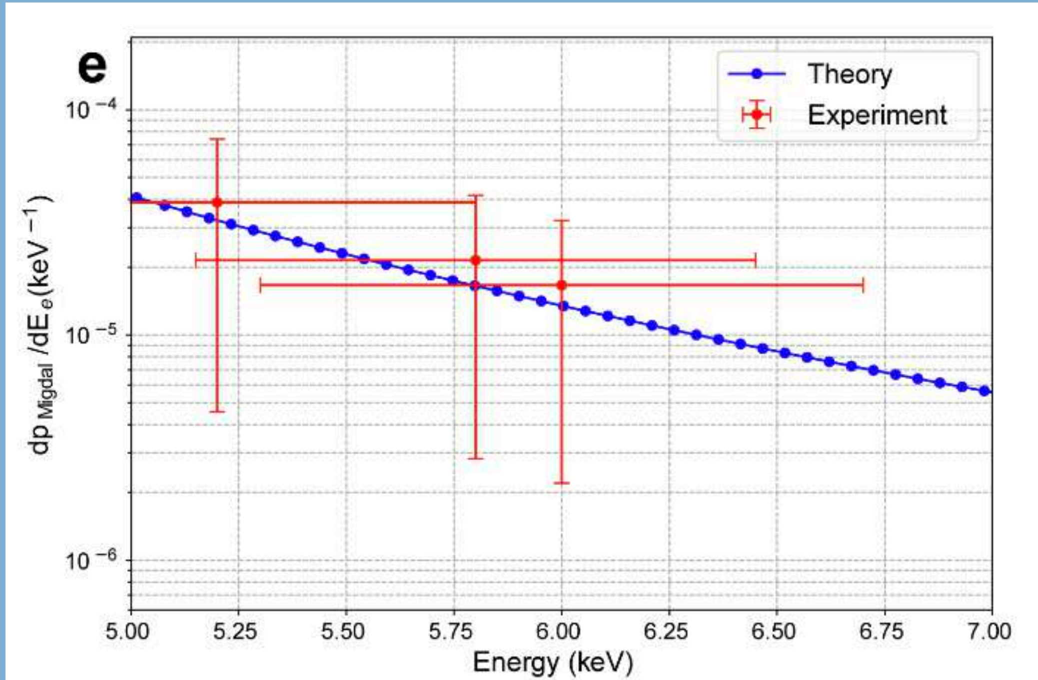
Fig. 2 | A Migdal event recorded in the experiment. The bright, long and straight track in the figure represents the NR track, whereas the faint track circled near the vertex of the recoil nucleus track represents the ER track. The horizontal arrow indicates the direction of the neutron beam.

Direct observation of the Migdal effect induced by neutron bombardment
https://doi.org/10.1038/s41586-025-09918-8

MIGDAL EVIDENCE

- **Calibrating Migdal in situ in lXe detectors would be extremely challenging— rare, and difficult to disentangle from ER backgrounds that are always present.**
- **Within large uncertainties, the MARVEL result agrees with the Migdal prediction**
- **However, this was a Helium + dimethyl ether target— can we extend this to xenon?**
- **Further, liquid recombination physics may be different**
- **So far, Migdal limits are still considered "separate"**





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IF THE MIGDAL EFFECT IS REAL, ALL THE DASHED LINES AT LOW ENERGY WILL OVERTAKE DEDICATED EXPERIMENTS