A path to understanding accidental coincidence backgrounds in XLZD

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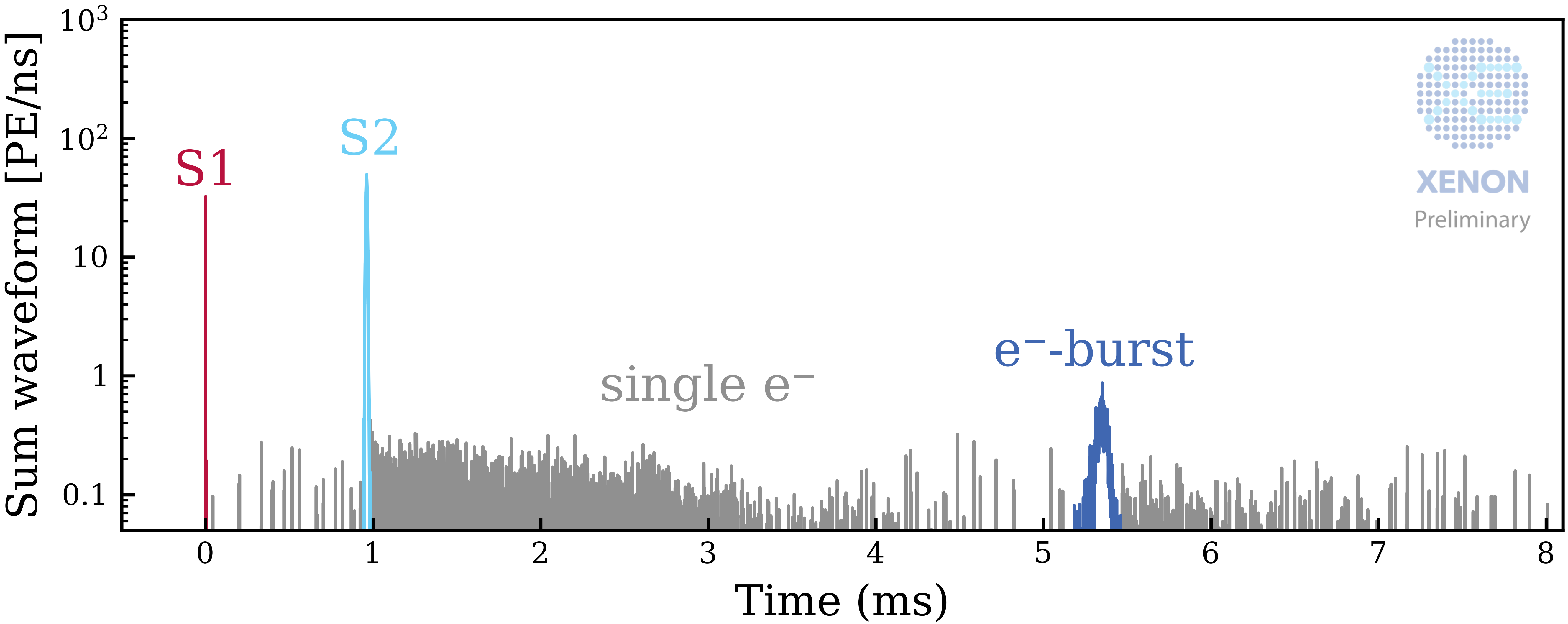
XLZD Collaboration Meeting @ LNGS 2025

In LXe (and LAr) TPCs, many signals besides the standard S1 or S2 are observed.

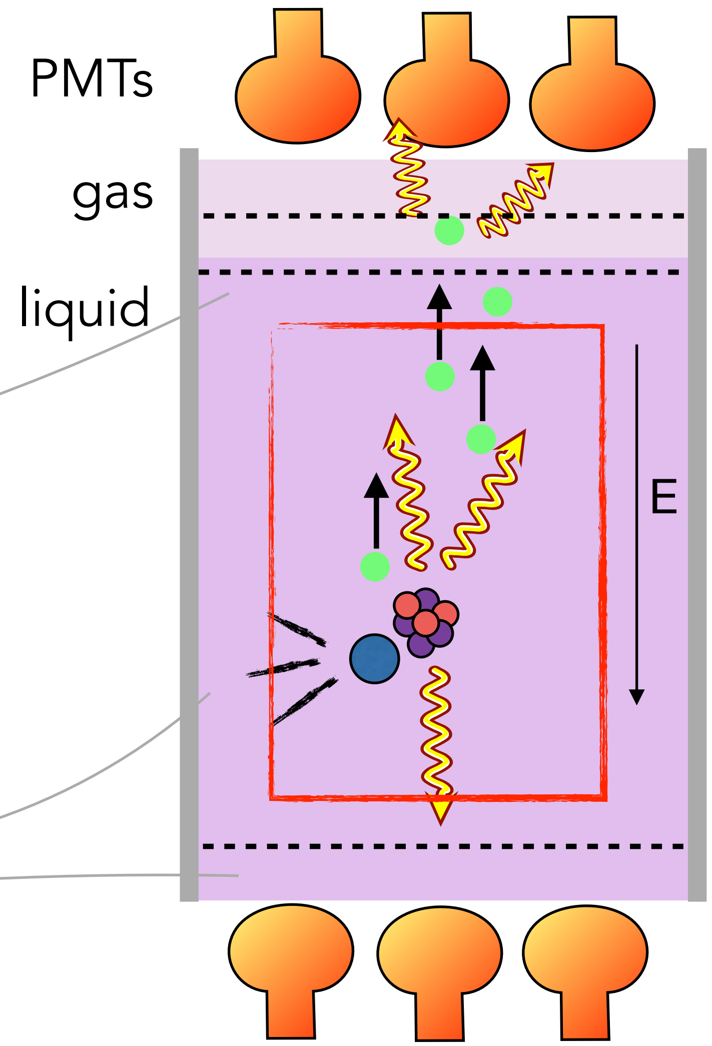


There are many possible sources of lone (a.k.a. isolated) signals

Incomplete events

Lone-S2
- No S1 photon creates a signal in a PMT (low g1, or shadowing from electrodes)
- Event too close to anode or glue ring, S1 swallowed by S2

Lone-S1
- All electrons lost
  - Absorbed on impurities
  - Event in charge-insensitive volume (CIV)
- Light leak from outside TPC



Spurious signals

Lone-S2
- **Grids electrodes**/micro-discharging
- Radioactivity on wires
- (**Fluorescence**-stimulated) release of captured/trapped drift electrons,
- Photoionization
- Delayed extraction at liquid/gas interface
- Scintillation in GXe

Lone-S1
- PMT dark counts and afterpulsing
- Mis-classification of single electrons as S1
- Few-photon events (Cherenkov, **fluorescence**, small energy deposits in Xe)
- Electroluminescence due to misaligned grids

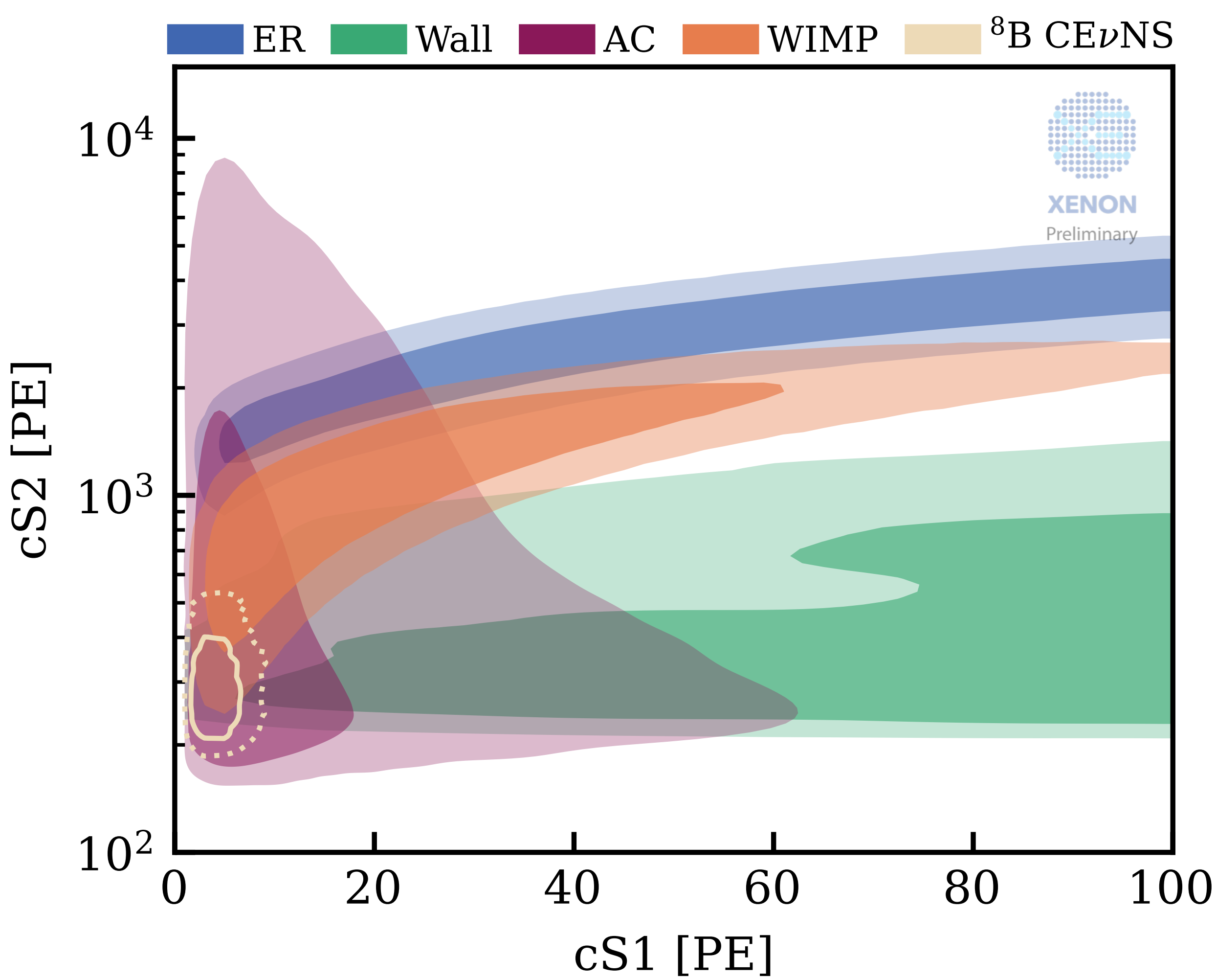
—> A lone-S1 and lone-S2 signal occurring within the maximum drift time create an *AC background event*

Accidental coincidence backgrounds strongly impact sensitivity to CEvNS and to WIMPs below ~100 GeV

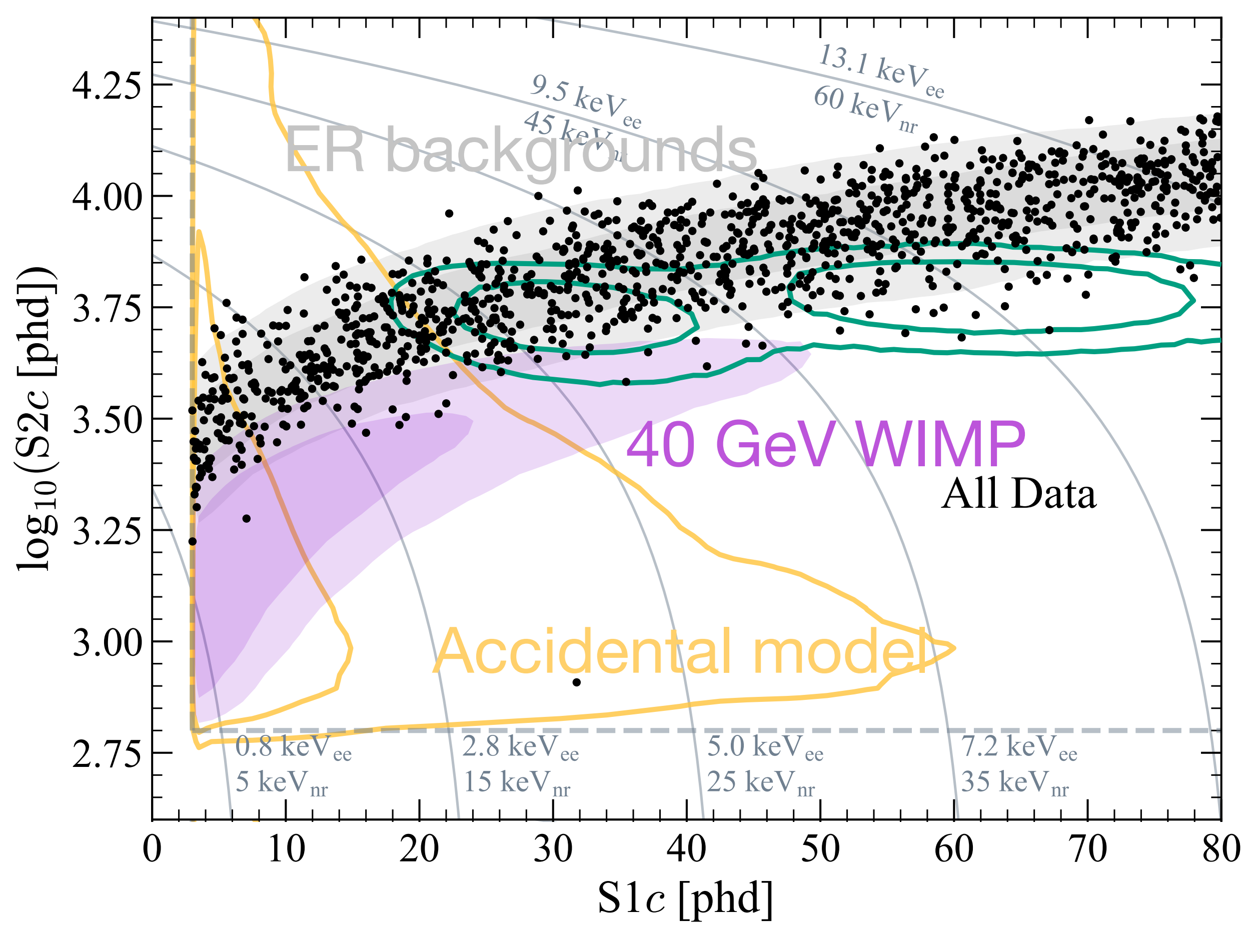
No ER-NR discrimination --> a few counts matter!

None of the XLZD sensitivity predictions include AC templates

Signal and background distributions in XENONnT



Signal and background distributions in LZ



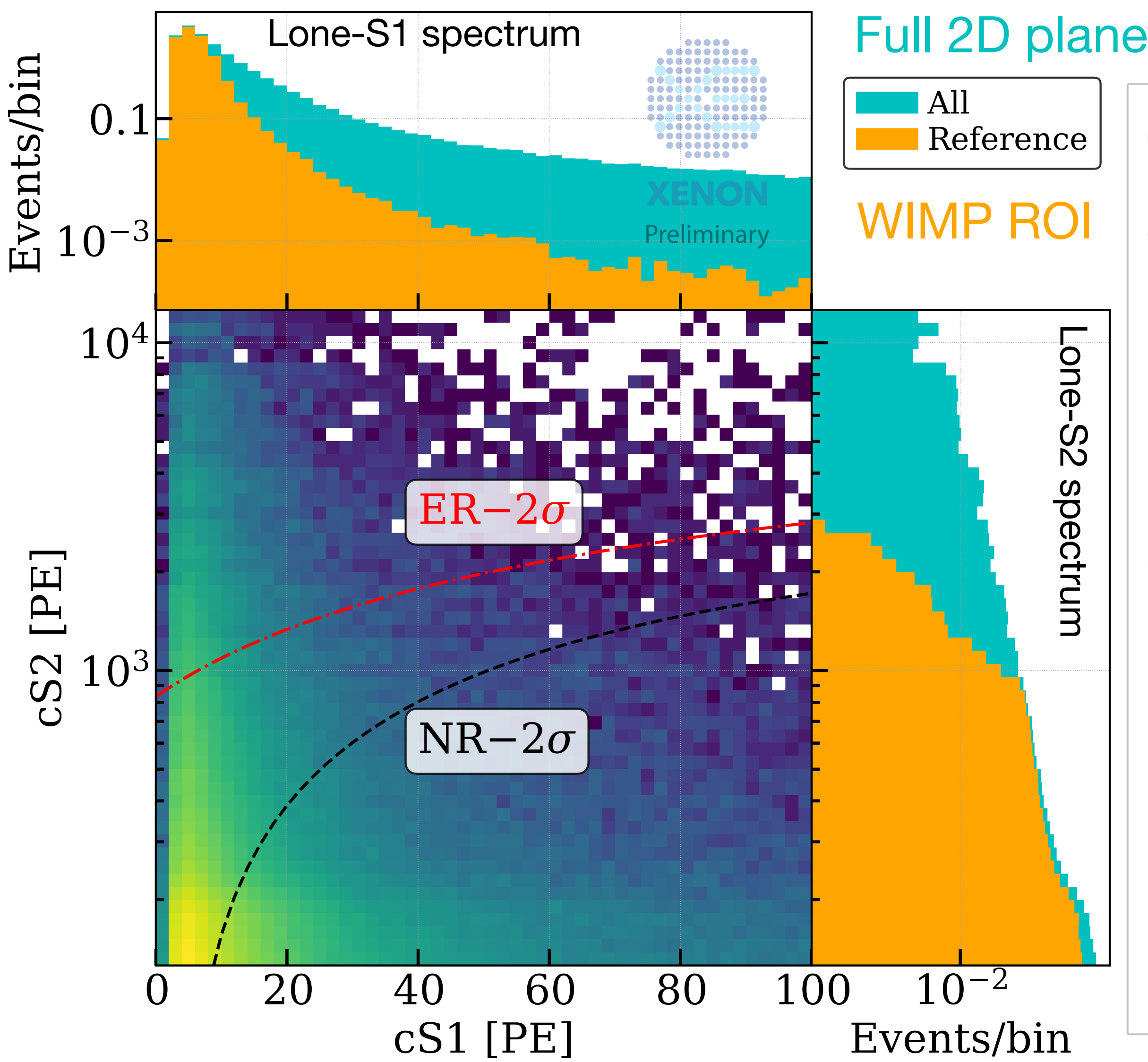
Keeping AC background levels low requires stricter cuts as detectors get bigger.

Detector	LUX	PandaX-II	XENON1T SR1	PandaX-4t commissioning	XENONnT SR0	LZ SR1
Fiducial volume [t]	0.118	0.329	1.3	3.7	4.2	5.5
S1 n-fold requirement	2	3	3	2	3	3
isolated S1 [Hz]	1	1.5	1	9.5	1.48	2
isolated S2 [Hz]	0.0005	0.012	0.0026	0.0045	0.104	0.02
AC rate w/o cuts based on isolated S's [1/yr] $R_{AC} = R_{isoS1} * R_{isoS2} * T_{drift}$	?	176.0	57.4	1105.5	10678.8	1199.6
		6%	1%	0.3%	0.15%	0.6%
Livetime loss from AC	**0.8%**	**1%-2%**	**4%**	**7.3%**	**~7%**	**25%**
After all cuts in WIMP ROI: #AC/year	0.04	10.04	0.61	3.40	16.52	7.30

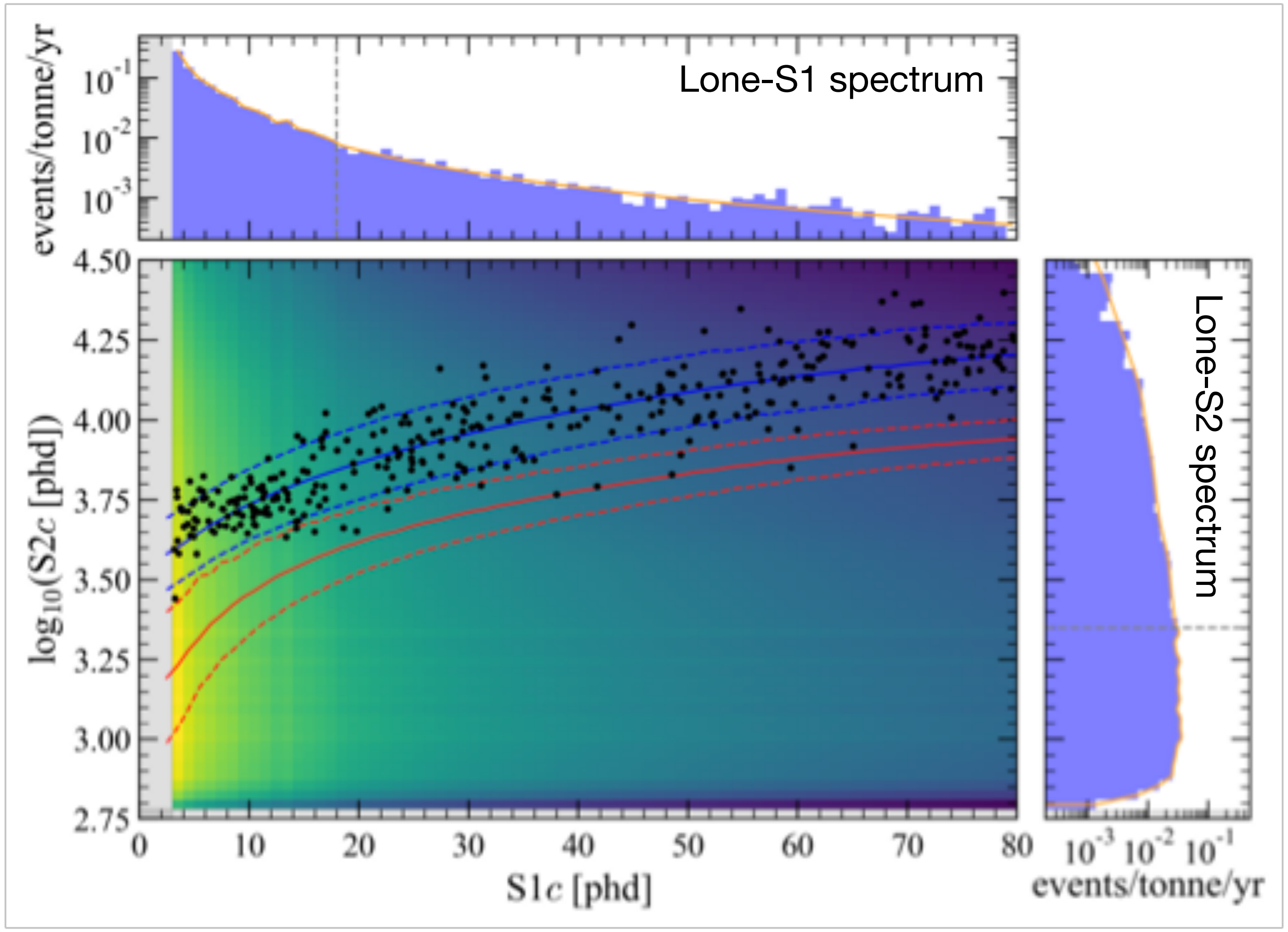
$R_{AC} = R_{isoS1} * R_{isoS2} * T_{drift}$ * (fraction in ROI) * (cut efficiency)

We do not know yet how the different sources contribute to the lone-S1 and lone-S2 spectra. This makes it difficult to create AC background PDFs for XLZD.

XENONnT Accidentals PDF



LZ SR1 Accidentals PDF

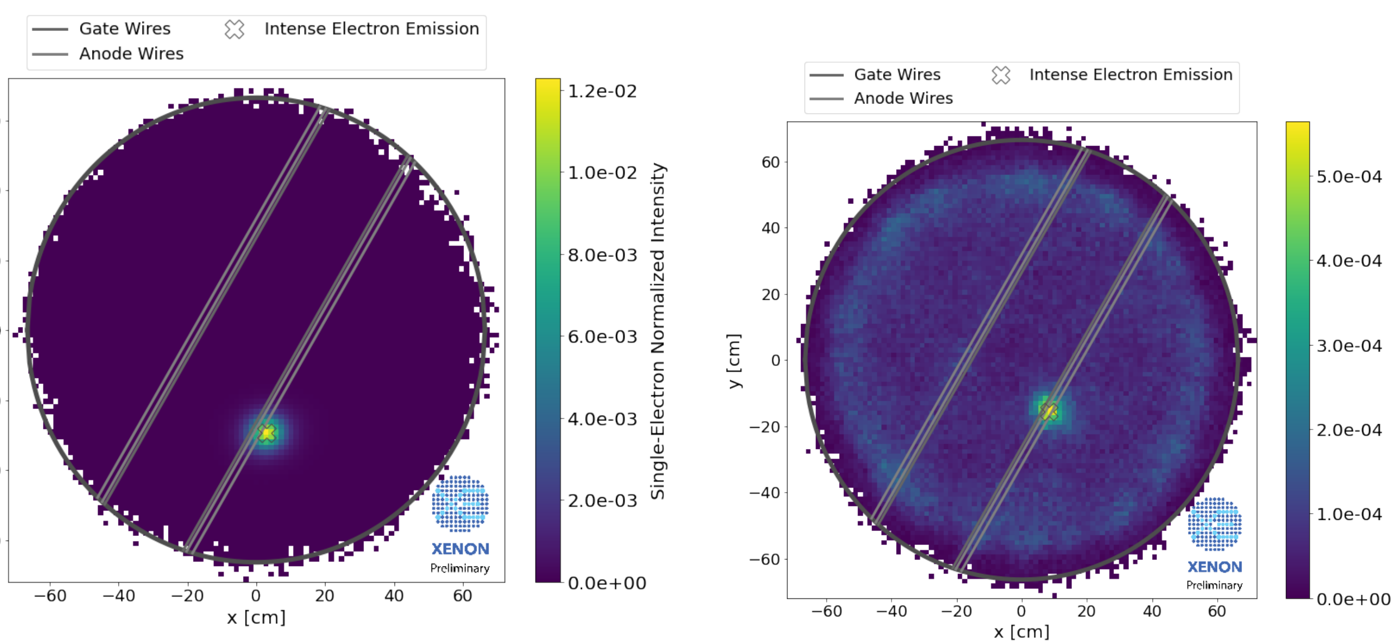


Analysis and R&D so far has raised as many questions as it answered.

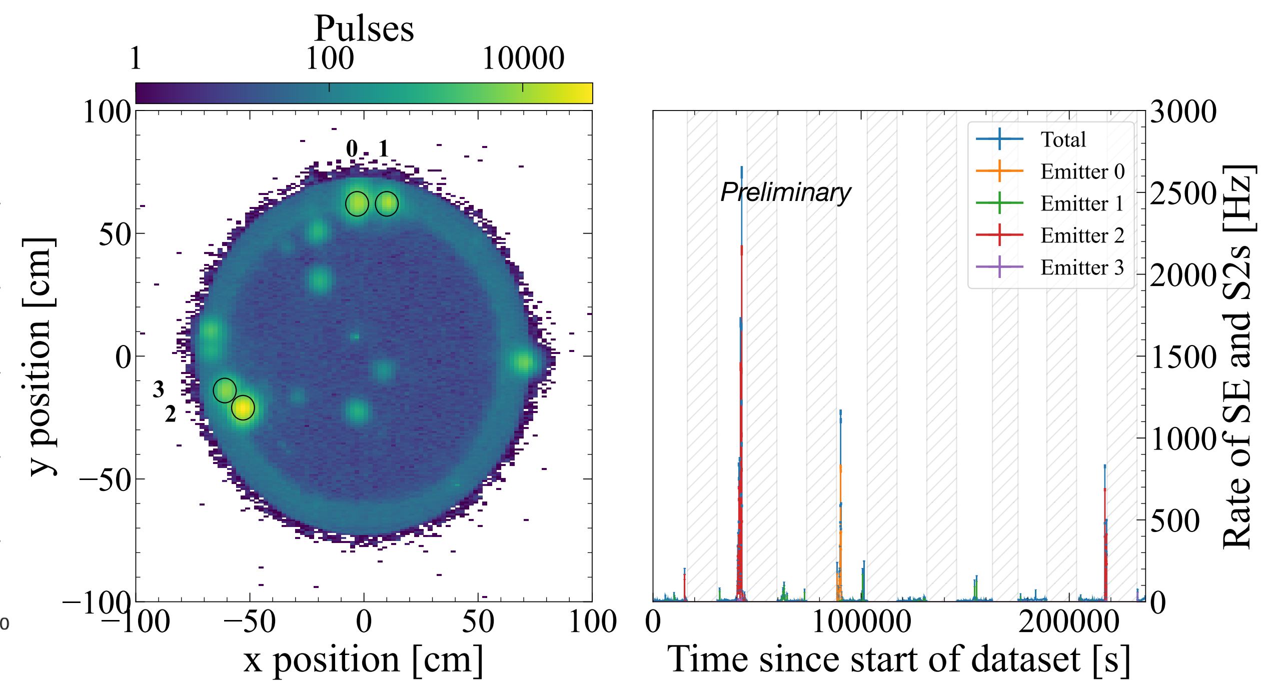
Lone S2s: a few sources have individually been well characterized, e.g. **Hotspots / grid emission:** ongoing analysis from current experiments and test stand R&D to mitigate electron emission, known risk for grid production

Do we understand all the sources of electron bursts?
What, if anything, should we do to prevent this?

Example of XENONnT hotspots



Example of LZ grid hotspots

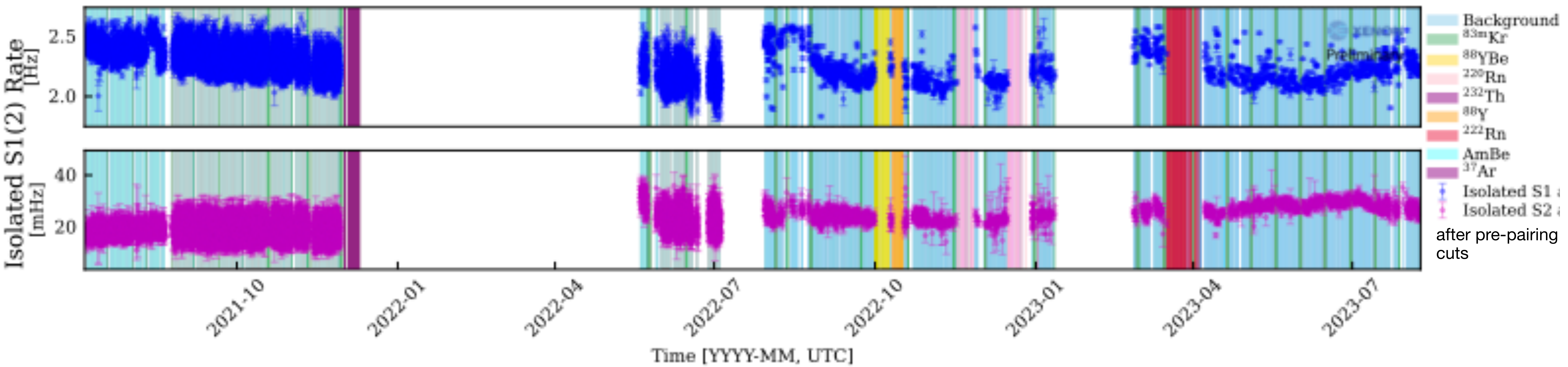


(*) we cannot do justice to the full AC story so far in this short talk, so this just gives a flavour, not a comprehensive overview

Analysis and R&D so far has raised as many questions as it answered.

e.g.: lone S1 and lone S2 rates are not stable in time

lone S1 and S2 rates in XENONnT



What influences them?

What is/are the 'mystery impurity/ies'?

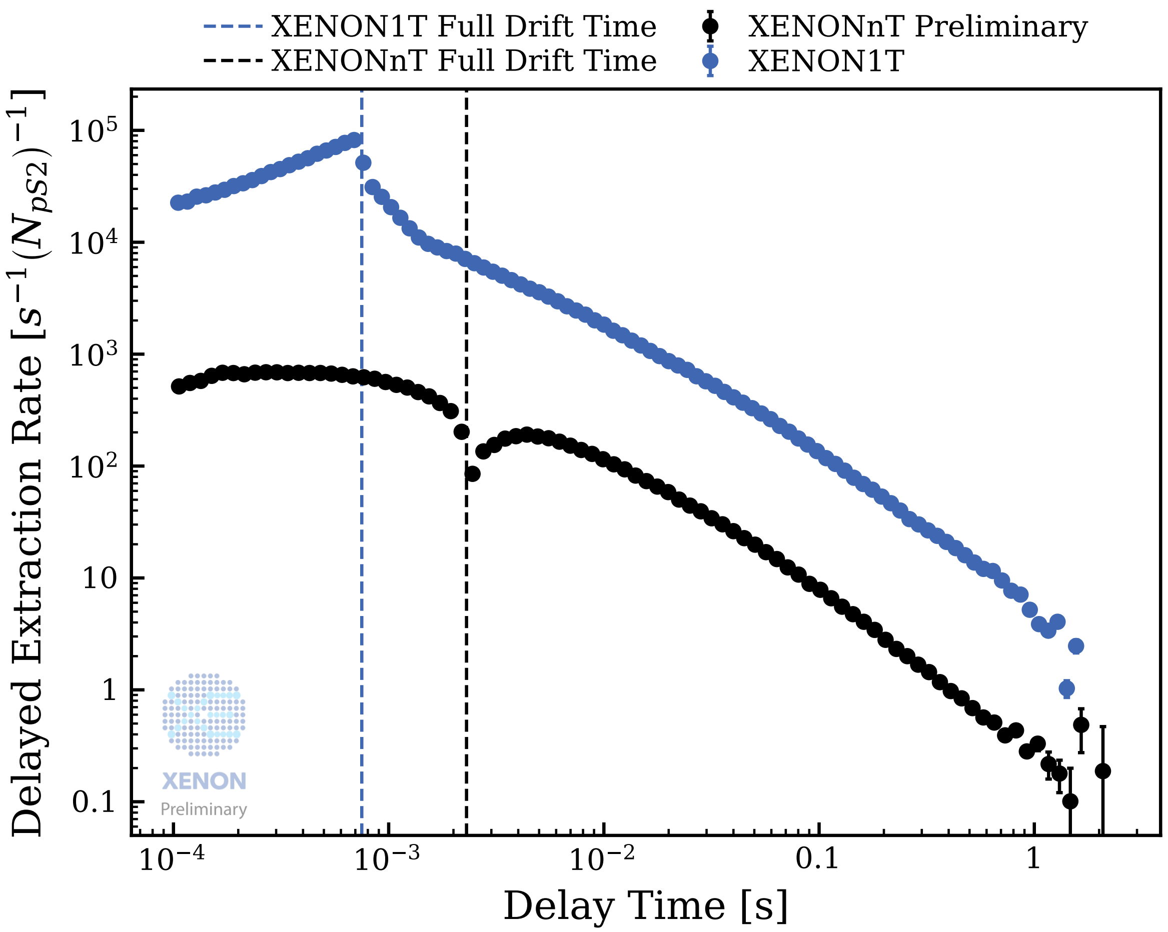
Photoionization (of what?)?

Fluorescence/photoluminescence (of what?)?

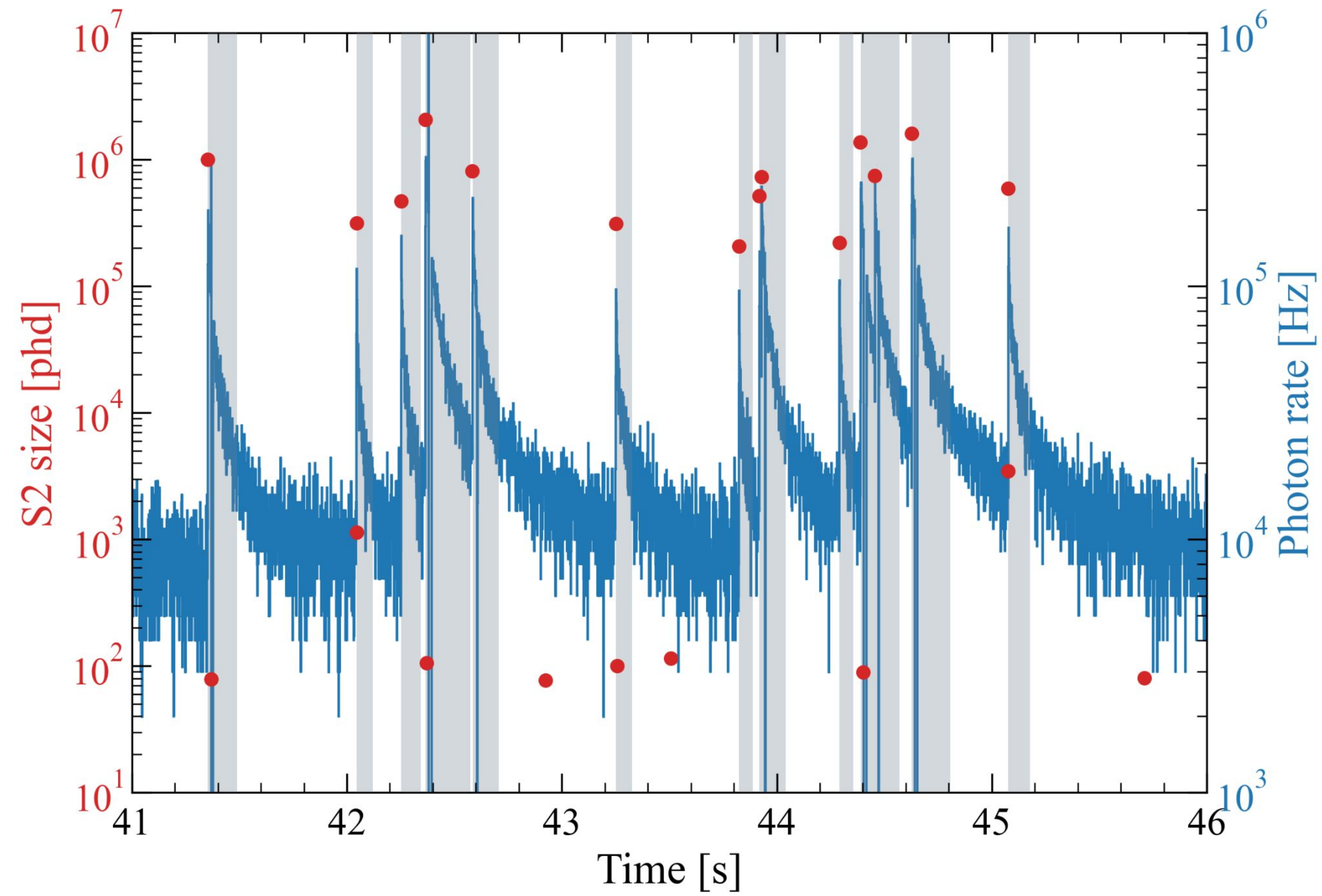
Analysis and R&D so far has raised as many questions as it answered.

e.g. *Phenomenology of* **delayed electrons and photons:** detailed characterization of phenomena done in several experiments

Delayed electron rates in XENONnT



Delayed photon traces in LZ



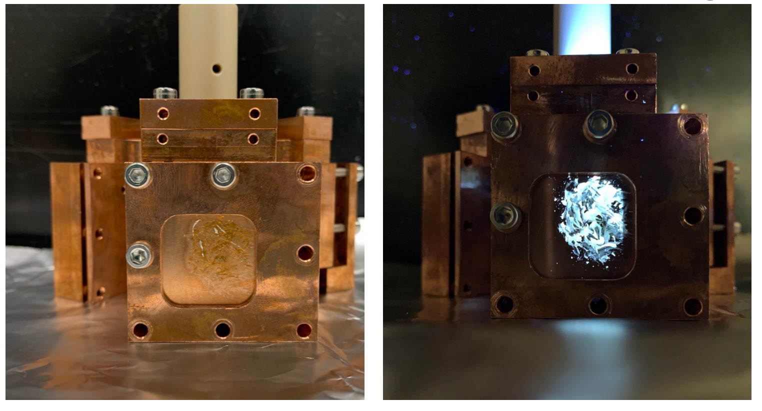
What is the physical reason for this temporal behaviour?

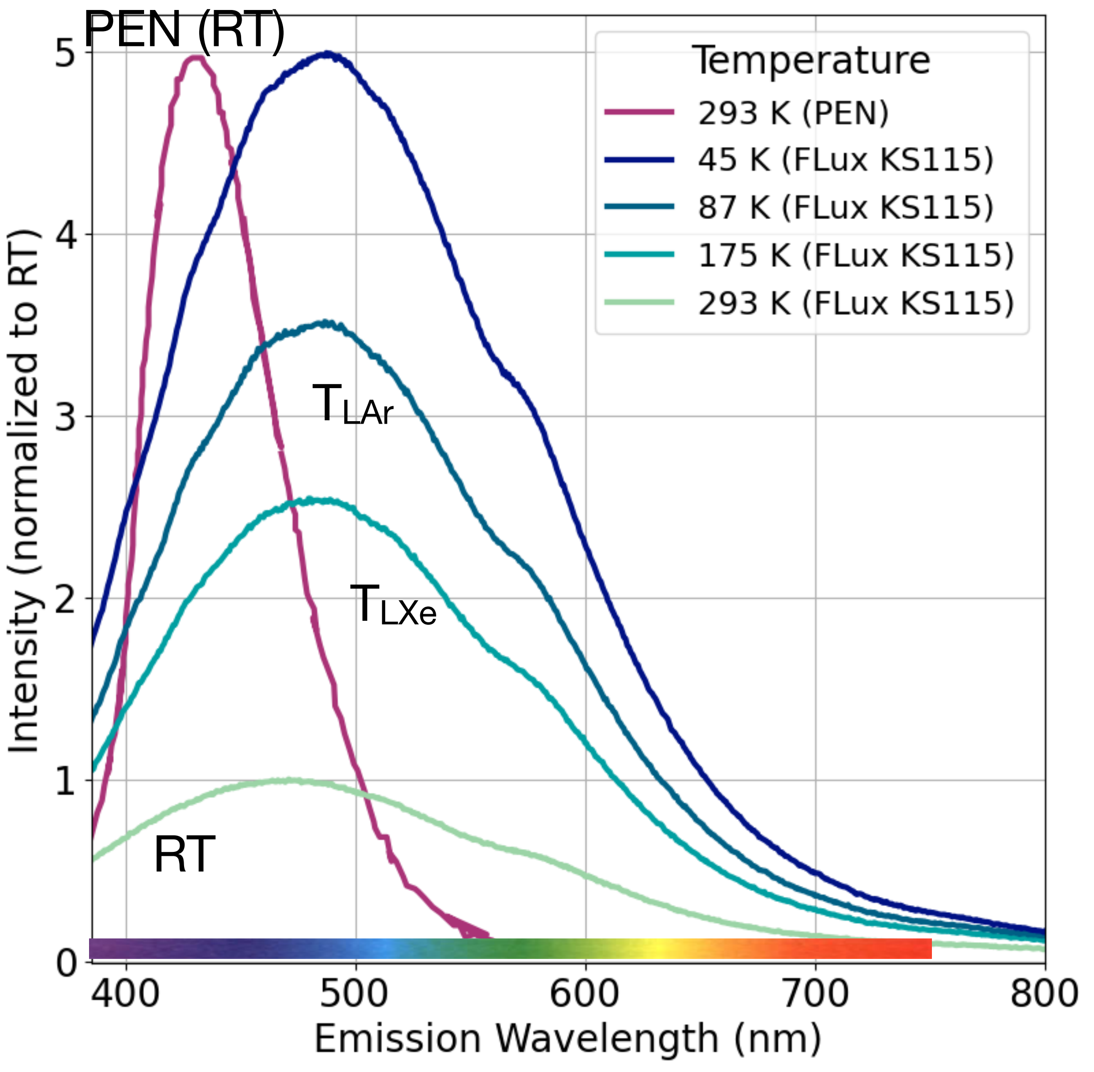
Lone S1s - more recent focus due to high rates in current generation of experiments
-> Two interesting ex-situ results recently reported within XLZD

Solder fluxes used in LZ and XENONnT PL under both UV and VUV excitation - first direct evidence of something in our TPCs photoluminescing

See poster by P. Kharbanda, A. Hurhina

Stannol KS115 flux residue (used in XENONnT) photoluminescing under UV light ..





Solder fluxes used in LZ and XENONnT PL under both UV and VUV excitation - first direct evidence of something in our TPCs photoluminescing

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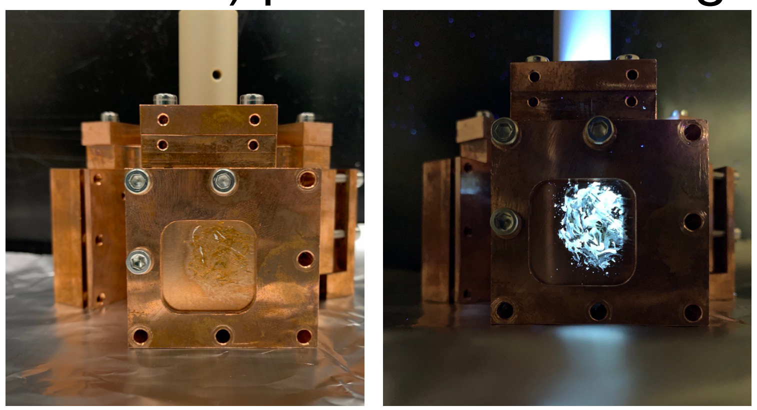
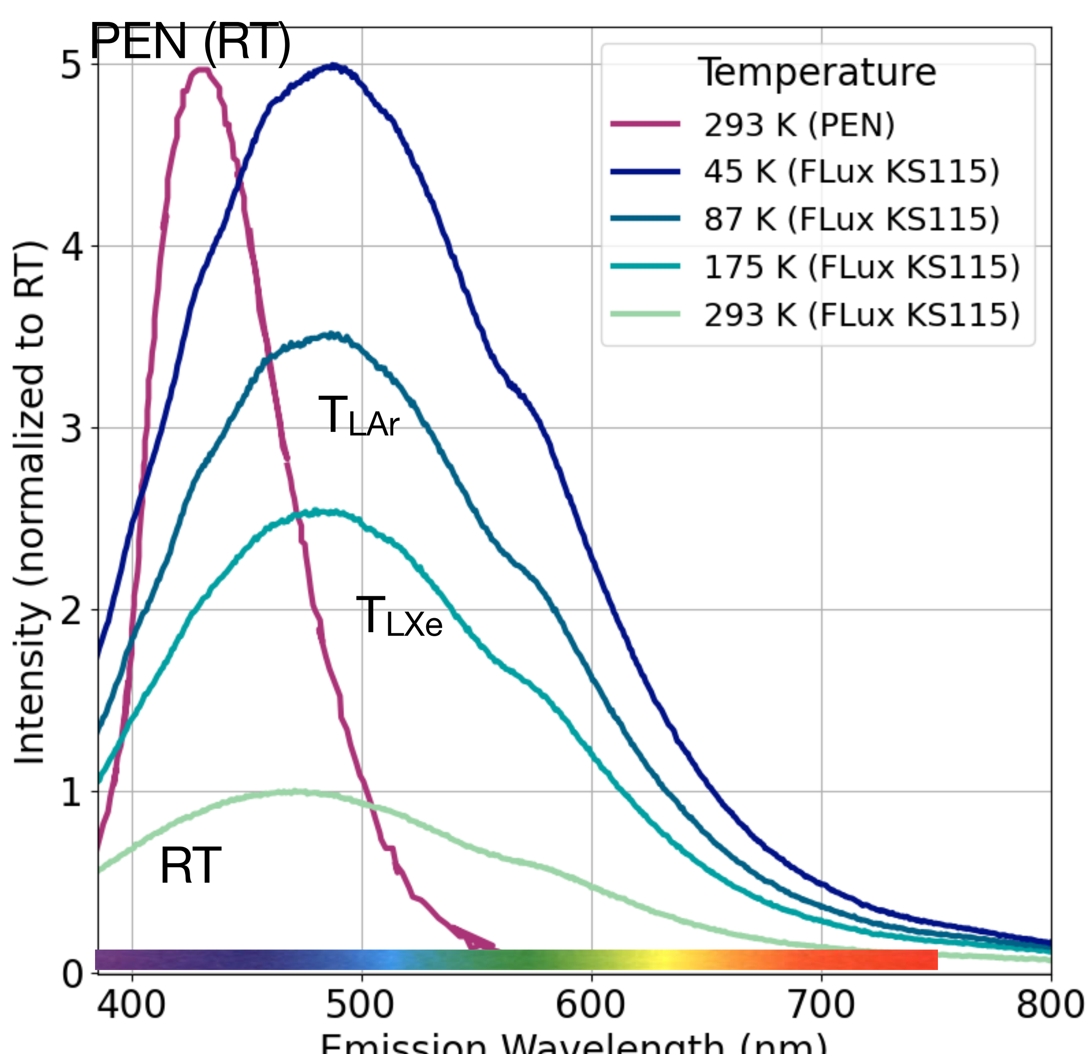
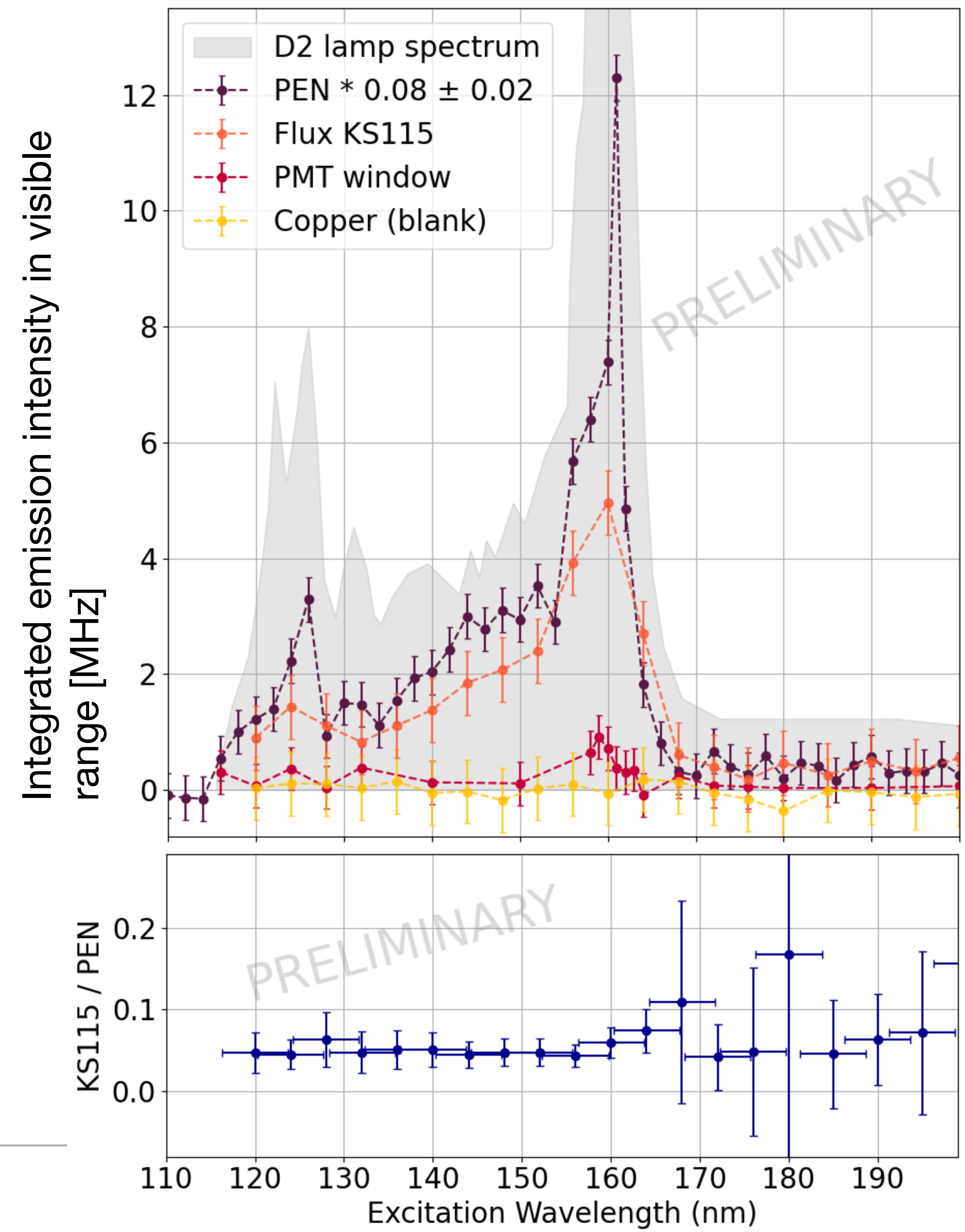
Stannol KS115 flux residue (used in XENONnT) photoluminescing under UV light ..





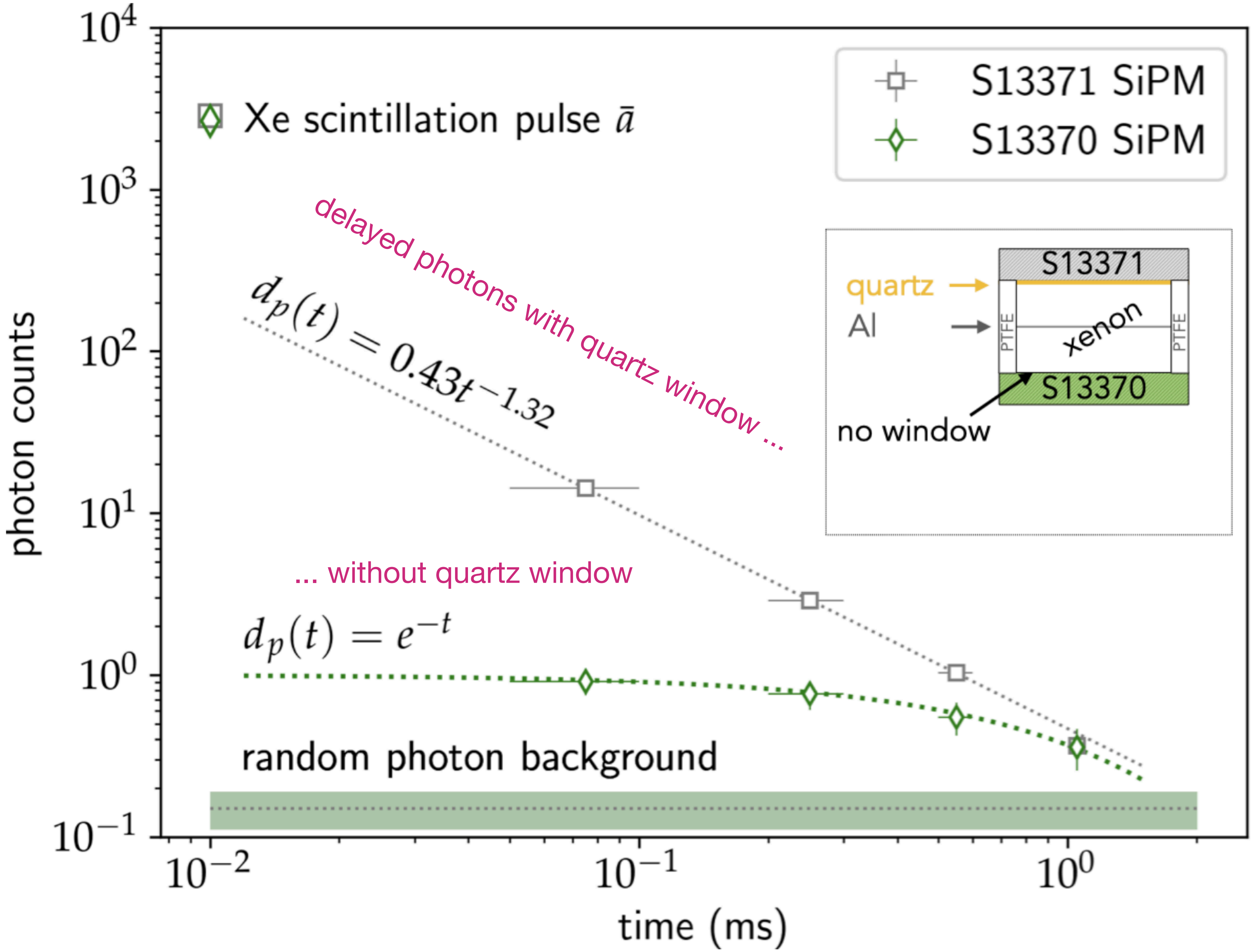
... and under VUV light



Lone S1 rate is enhanced by quartz window in front of photon detector.

P. Sorensen, R. Gibbons, http://arxiv.org/abs/2505.08067

https://wiki.physik.uzh.ch/xlzd/doku.php?id=general:meetings:wg34_20250410



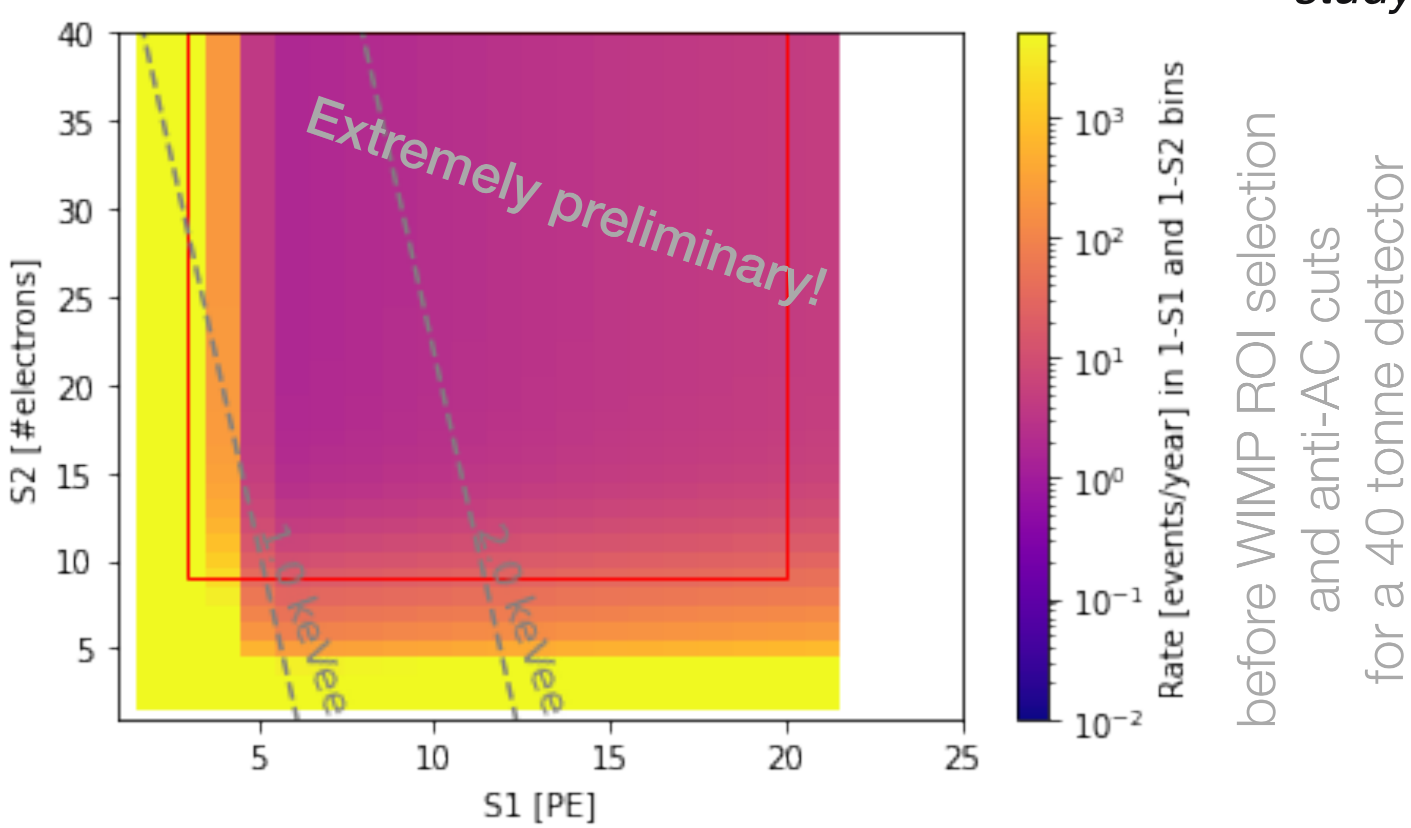
VUV4 SiPMs

What models do we currently have?

1. Table listing currently known accidental sources in LZ and how they likely scale *(see backup)*

2. Somewhat naive 'accidentals scaler' code infrastructure that generates or accepts as input lone-S1 and lone-S2 spectra by source, scales them as desired, and generates a backgrounds PDF compatible with our inference tools

See poster by F. Pompa for sensitivity study using AC PDFs from this model



Next steps for understanding the accidental backgrounds picture

Desire an apples-to-apples comparison of accidental sources in current LXe detectors, with the following information:

1. Common criteria for defining isolated S1 and S2 selection
2. Complete table listing known accidental sources and how they scale *(see backup for draft)*
3. Lone S1 and S2 pulse area spectra, broken down into various sources, with and without various cuts
4. Time dependence of lone S1 and S2 sources over the experiment lifetime, and all the detector conditions likely related
5. Comparison of detector conditions associated to the accidental rate spectra, and resulting numbers *(see backup for draft)*

—> We propose creation of a new task force composed of active XENONnT and LZ members working in the respective analyses.

Goal is to generate enough understanding to build an accidentals background model for use in XZLD detector design and sensitivity projections

Timeline/discussion points

Summer 2025	Fall 2025	Winter 2025	Spring 2026	Summer 2026
Form cross-experimental task force				
		First comparison of 'apples-to-apples' plots, Initial integration of new info into existing accidentals modelling tools, start iteration with sensitivity studies		
				Report on our best understanding of lone-S1 and lone-S2 sources, their spectra and their scaling, based on comparison of LZ and XENONnT data

Points for discussion:

- What is the best way to share a sufficient amount of data? Does the taskforce have full access to each experiment's data? Can they freely show each other plots? Do we need a formal request to the leadership of current experiments? Or does each side make plots, get them through the process for approval to show in public before sharing?
- Ex-situ studies and R&D needs.

Backup

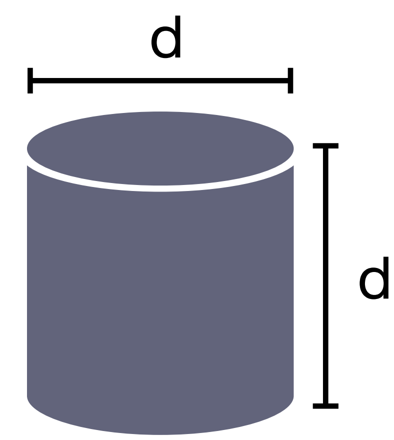
Summary

- Accidental coincidence backgrounds gain in significance as detectors get larger, necessitating more and more analysis effort with significant remaining unmitigated background levels and high loss in lifetime from cuts
- Better understanding is need for to predict how lone signal sources scale up, and what sources need special consideration in XLZD design/construction
- Both analysis and R&D efforts are needed to characterize, understand, and control these backgrounds for XLZD

Detector parameters & accidental coincidence numbers

Detector	PandaX-II	XENON1T SR1	LUX	PandaX-4t commissioning	XENONnT SR0	LZ
reference	10.1103/PhysRevD.93.122009	10.1103/PhysRevLett.121.111302, 10.1103/PhysRevD.99.112009	arXiv:1310.8214	10.1103/PhysRevLett.127.261802	arXiv:2303.14729, xenon wiki	arXiv:2207.03764, XLZD meeting
TPC height [cm]	60	97	48	118	149	150
TPC diameter [cm]	64.6	96	47	118	133	150
Fiducial volume [t]	0.329	1.3	0.118	3.7	4.2	5.5
live days	80	279	85	86	95	60
drift field [V/cm]	400	100	181	110	23	193
max drift time [us]	310	700	324	820	2200	951
ER events in WIMP window	381	627	587	2	134	250
AC events in WIMP window	2.2	0.47	1.1	0.8	4.3	1.2
S1 n-fold requirement	3	3	2	2	3	3
isolated S1 [Hz]	1.5	1	1	9.5	1.48	2
isolated S2 [Hz]	0.012	0.0026	0.0005	0.0045	0.104	0.02
AC rate w/o cuts based on isolated S's [1/yr]	176.0	57.4	5.0	1105.5	10678.8	1199.6
Livetime loss from AC cut	1%-2%	4%	0.8%	7.3%		25%
After all cuts in WIMP ROI: #AC/year	10.04	0.61	0.04	3.40	16.52	7.30
Max drift time correction: #AC/(year ms)	32.38	0.88	0.12	4.14	7.51	7.68
Surface area correction: #AC/(year ms m^2) * 100	17.275	0.201		0.631	0.834	0.724

How does the AC rate scale with detector mass?



In a 1:1 aspect ratio TPC, d=h
Target mass $m \sim V \sim d^3$
$d \sim m^{1/3}$

1: Max drift time: $T_d \sim d \sim m^{1/3}$

2: Lone S2 rate likely dominated by surface area: $r_{lS2} \sim A \sim m^{2/3}$

3: Lone S1 rate dominated by PMT dark noise
$r_{DN} \sim N_{PMT} \sim A \sim d^2 \sim m^{2/3}$
$r_{lS1} = r_{DN}$ * Poisson(2, r_{DN}) (nfold = 3)
$\sim m^2 \exp(-m^{2/3})$

Total AC rate
$r_{AC} \sim T_d * r_{lS1} * r_{lS2}$ * (fraction in ROI) * (cut efficiency)
$= a * m^3 * \exp(-m^{2/3})$

XENON1T:
r_{AC}(1.3 t) = 0.6 1/yr => a = 0.9

XENONnT:
r_{AC}(4.2 t) = 16 1/yr => a = 2.9

LZ:
r_{AC}(5.5 t) = 7.3 1/yr => a = 1.0

Example of table with breakdown of S1 sources - 1

Source	Reason	Contribution region	Associated cuts / exclusions	Easy to remove in analysis?	Scaling	Design impacts
Dark counts	PMT dark counts randomly piling up	Mostly significant for small S1s	>= coincidence requirement	No	N(PMTs)^3 * coincidence window (scales with detector)	PMT choice
Photon trains	Potential fluorescence photons piling up after a large signal, fluorescence source is still unknown	Mostly significant for small S1s	E/ph-train veto	No. Baseline photon rate remains quite high, even after e/ph-train veto	Interaction rate* g2	Surface area/ volume of fluorescing source
High single channel S1s	Likely malfunctioning PMTs of some sort, some fraction due to after pulsing	Significant population across large range of S1 pulse areas	High single channel cut	Somewhat. HSC cut is effective at large pulse areas, less effective at small pulse areas due to statistical fluctuations	N(PMTs), PMT voltage	Front-end electronics with large gain to minimize PMT voltage

Example of table with breakdown of S1 sources - 2

Source	Reason	Contribution region	Associated cuts / exclusions	Easy to remove in analysis?	Scaling	Design impacts
Stinger S1s	Electrons drift up pass the anode and create a flash of light following a SE/S2	Significant population across large range of S1 pulse areas	Remove S1-like pulses ~us after SE/S2	Yes	Single electron rate	Better alignment would reduce this effect. However, very useful tag to remove hotspot events
RFR S1s	Events in the reverse field region or charge of the detector have no associated S2	Mostly significant for large S1s	S1 TBA cut	Yes, generally large S1s and easy to remove in analysis	Volume of RFR region	Reduction of RFR region

Example of table with breakdown of S2 sources - 1

Source	Reason	Contribution size	Associated cuts/ exclusions	Easy to remove in analysis?	Scaling	Design impacts
Electron trains	Electrons captured and released as they drift through the liquid bulk	Mostly < 3 electrons after removing large amounts of livetime	E/ph-train veto	Yes, but results in significant amounts of livetime removed	Overall rate ~ volume of bulk, Length of train ~ drift length	Purity/electron lifetime
Grid emission	Many theories, including high fields associated with defects, oxide layers, etc.	Can have significant impact up to ~5 or so electrons	High electron rate veto, spatial cylinder veto	No. Time-dependent and hard to detect low level emission. Also causes operational problems	Area of grids, grid voltage	Grid design, treatments + testing

Example of table with breakdown of S2 sources - 2

Source	Reason	Contribution size	Associated cuts/ exclusions	Easy to remove in analysis?	Scaling	Design impacts
Radiogenic grid decays	Rn plateout on the grid wires	Significant population across large energy range. Key background for S2-only	Drift time cut, Pulse width cut for S2-only	Easy to remove gate contribution. Cathode can be mitigated but fraction is irreducible due to diffusion.	Area of grids, amount of diffusion ~ drift length	Determine ideal drift voltage
Near liquid surface and gas S2s	S1 and S2s overlap/merge and/ or S1 is missing	Significant population across large energy range	S2 shape cuts	Generally targeted by shape cuts, so easier to remove at large pulse areas, harder at small pulse areas	Volume of gas region	Extraction region design
Glue ring events	Events in the glue ring region are mis-reconstructed inwards and often have a merged S1	Significant population across large energy range	S2 position reconstruction quality cut	Easier to remove at large pulse areas, harder at small pulse areas	Volume of glue ring region	Eliminate or reduce size of glue ring region