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Electron Emission in Liquid Xenon Detectors

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EXCESS 2022

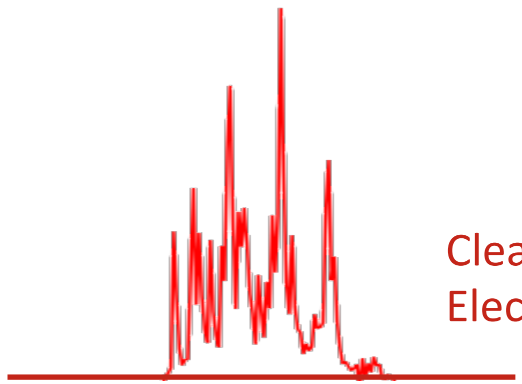
February 15

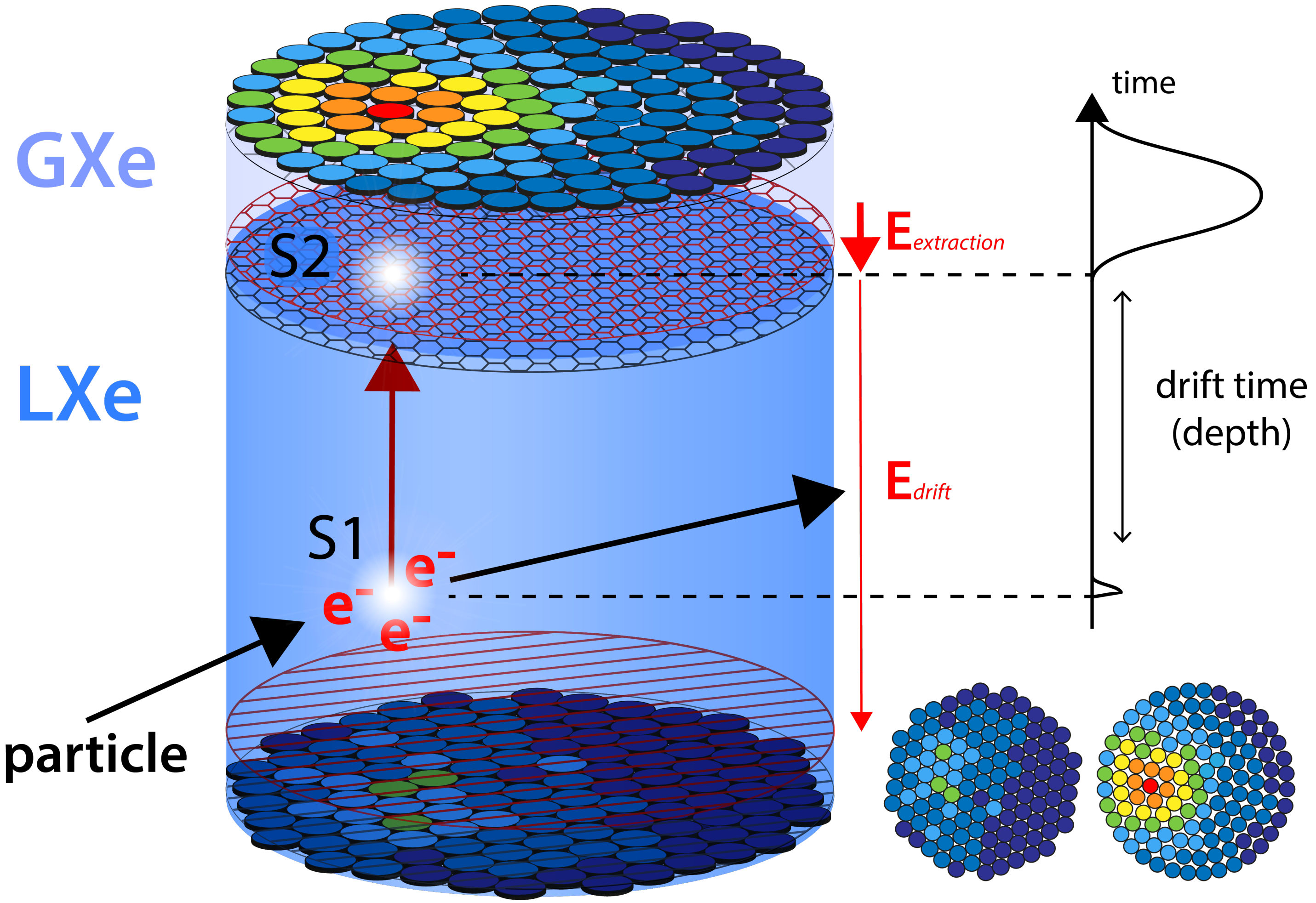
Two-Phase Liquid Xenon Time Projection Chamber

Particle interactions create prompt scintillation light (S1), heat (lost), and electrons that drift to the amplification region (S2).

Gas amplification gives sensitivity to Single Electrons.

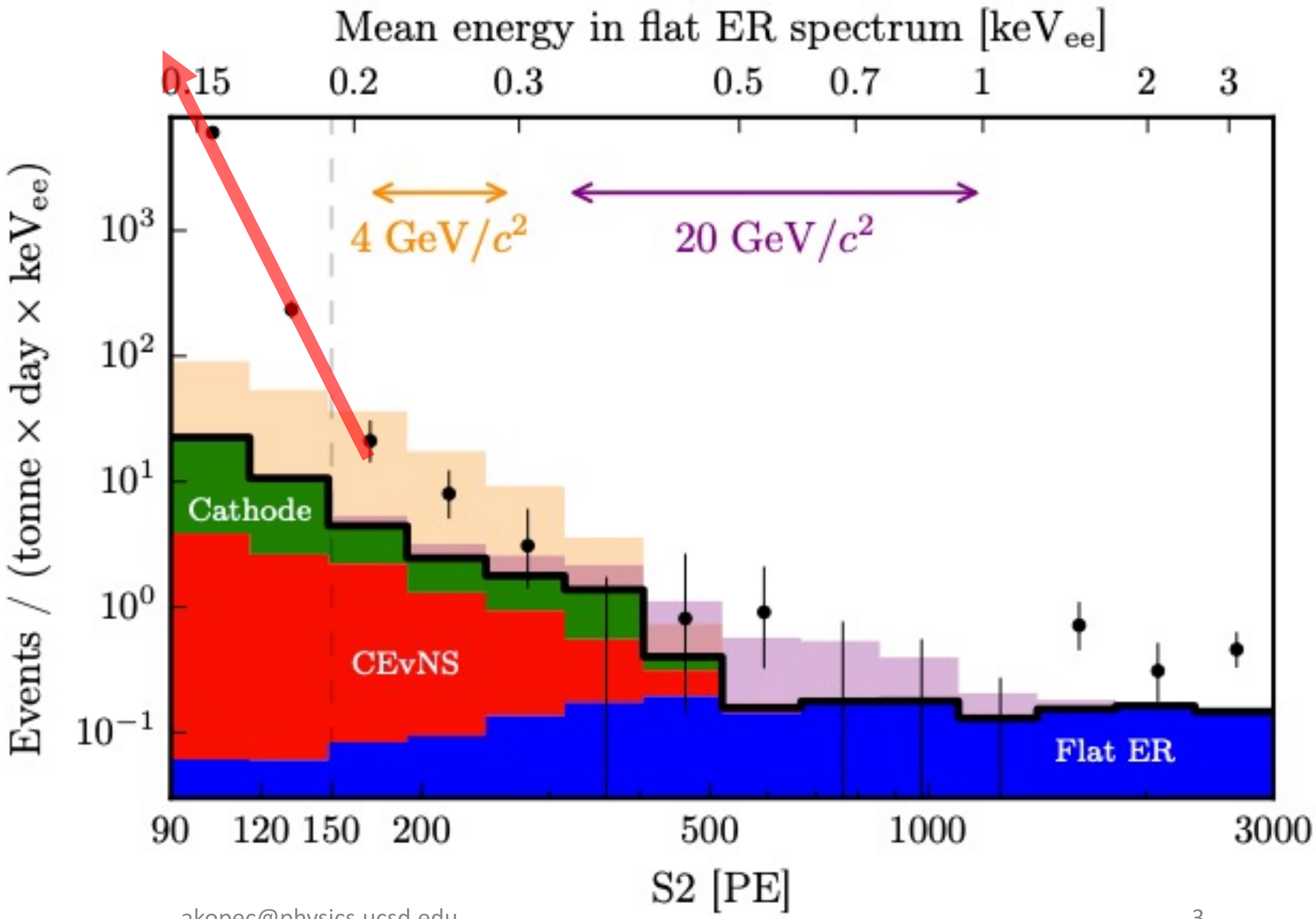
The energy threshold for a Single Electron S2 is ~15 eV for Electronic Recoils and ~250 eV for Nuclear Recoils.





Too Many Electrons

Experiments see an excess of S2 signals smaller than 5 electrons.

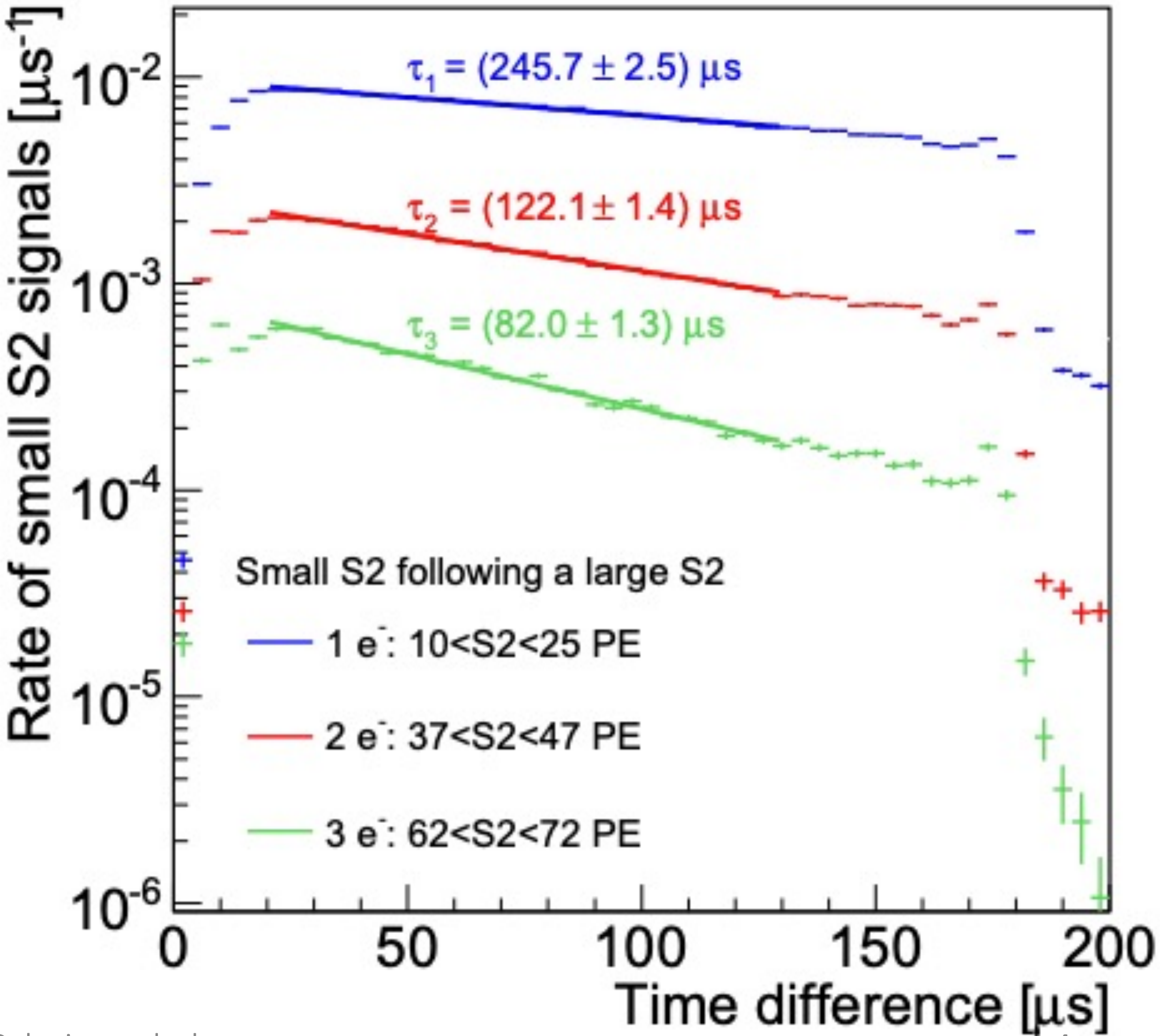


XENON1T: 10.1103/PhysRevLett.123.251801

Correlated Backgrounds: Photoemission

Constrained to one Maximum Drift Time after a bright light event.

Composed of individual Single Electrons. Higher multiplicities are pile-up.

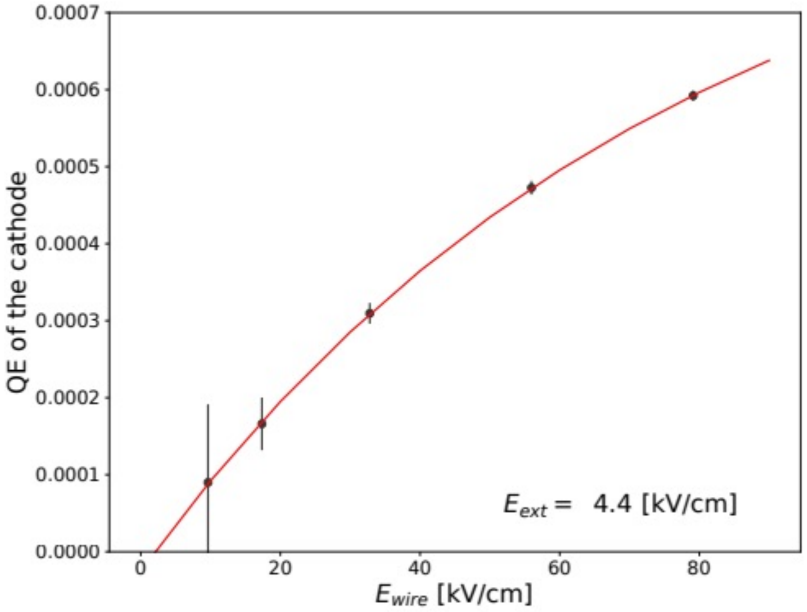


XENON100: 10.1088/0954-3899/41/3/035201

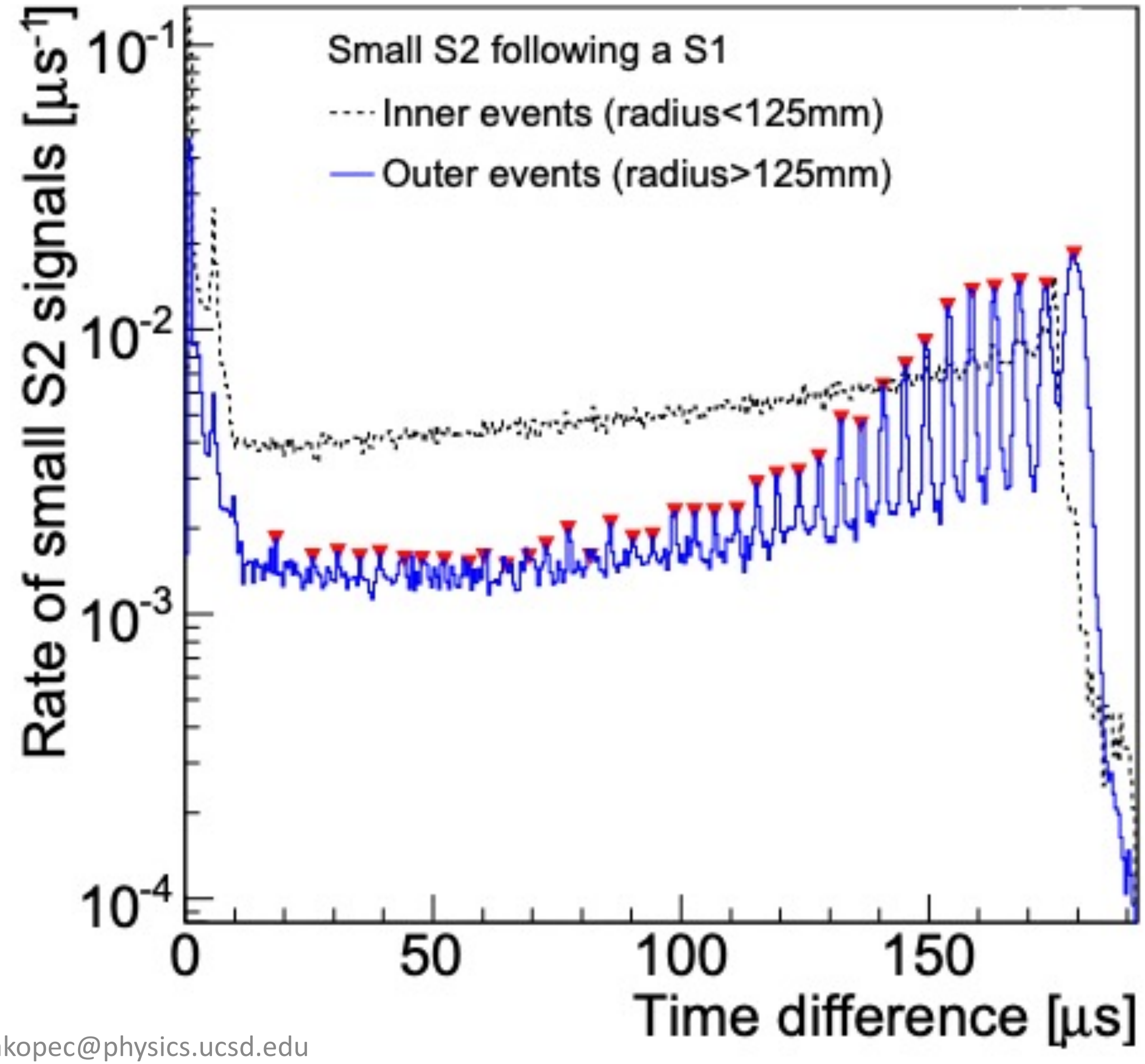
Correlated Backgrounds: Photoemission

Photoelectric Effect

Materials with lower work functions (particularly metals) absorb photons and emit electrons.



PIXeY: 10.1088/1748-0221/16/12/P12015



XENON100: 10.1088/0954-3899/41/3/035201

Correlated Backgrounds: Photoemission

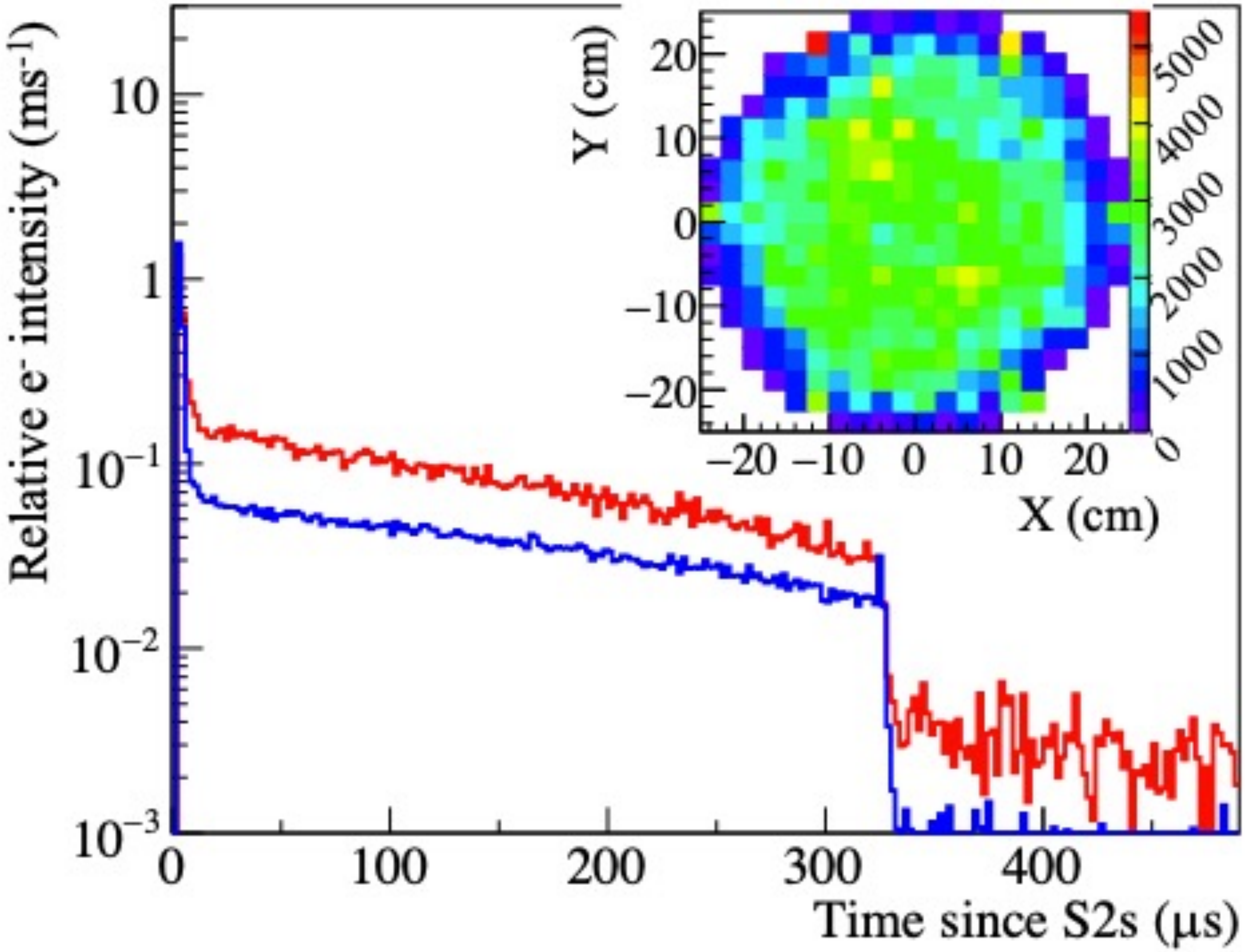
Photoionization

Neutral species lose an electron and become positive ions.

Indistinguishable from Photodetachment, except not dependent on purity.

red = lower purity

blue = higher purity

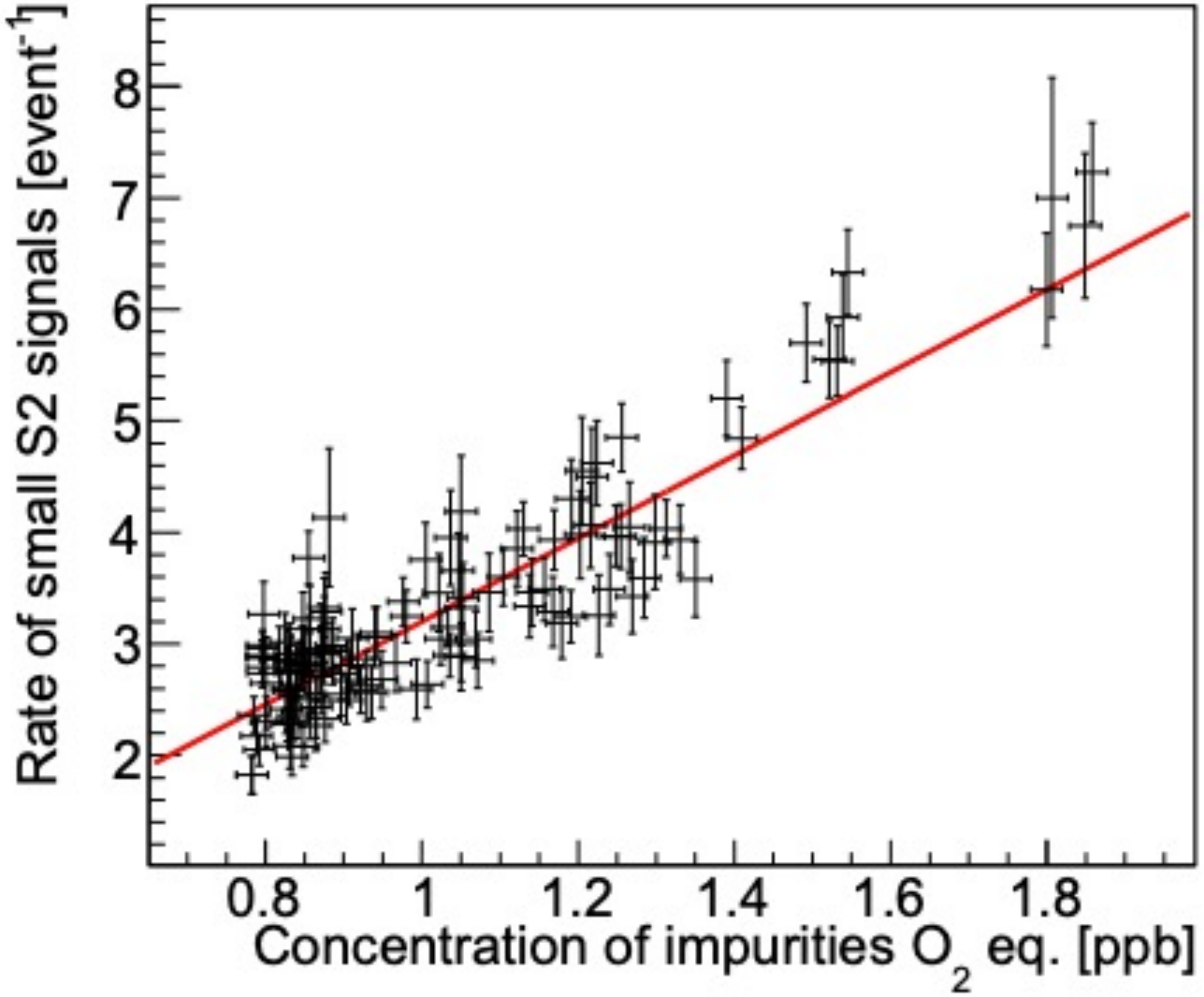


LUX: 10.1103/PhysRevD.102.092004

Correlated Backgrounds: Photoemission

Photodetachment

Photons free captured electrons from electronegative impurities.



XENON100: 10.1088/0954-3899/41/3/035201

Correlated Backgrounds: Photoemission

Mitigation:

- Reduce materials with low work functions: treat (coat, passivate) exposed metal surfaces
- Reduce electronegative impurities and neutral species with low ionization energies.
- Reduce excess light in the detector. Reduce event rates with better shielding and radiopurity. Optimize gas gap and electric fields for best Single Electron resolution but lowest S2 light pollution.

Photoemission – Second Take

Only occurs within a maximum drift time after a bright event, so removed easily from analysis.

With low event rates and small maximum drift times, ignoring this time window does not have a significant effect on exposure.

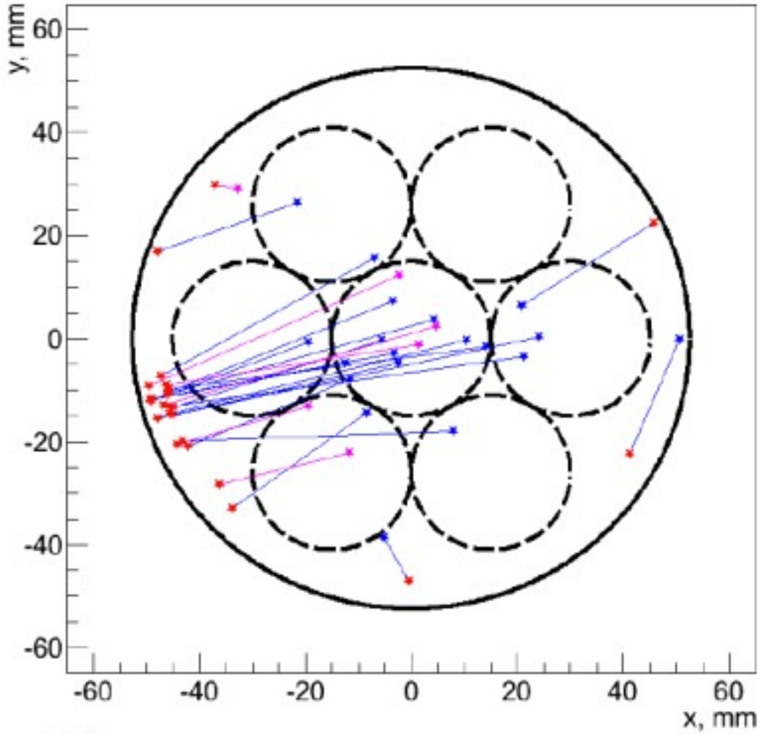
Background problem effectively “solved”

So… after the last photoemission electrons from the cathode are detected, electron backgrounds should be gone, right?

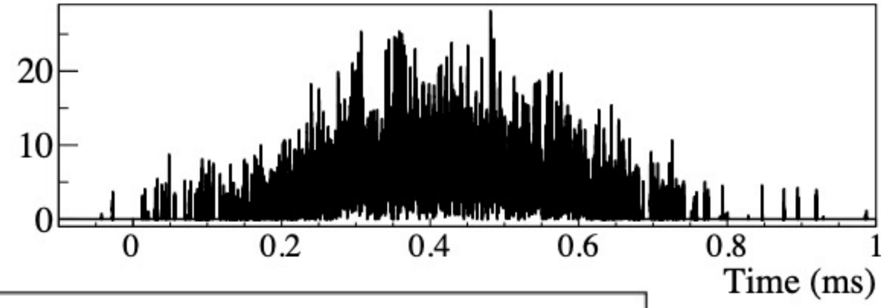
Not exactly.

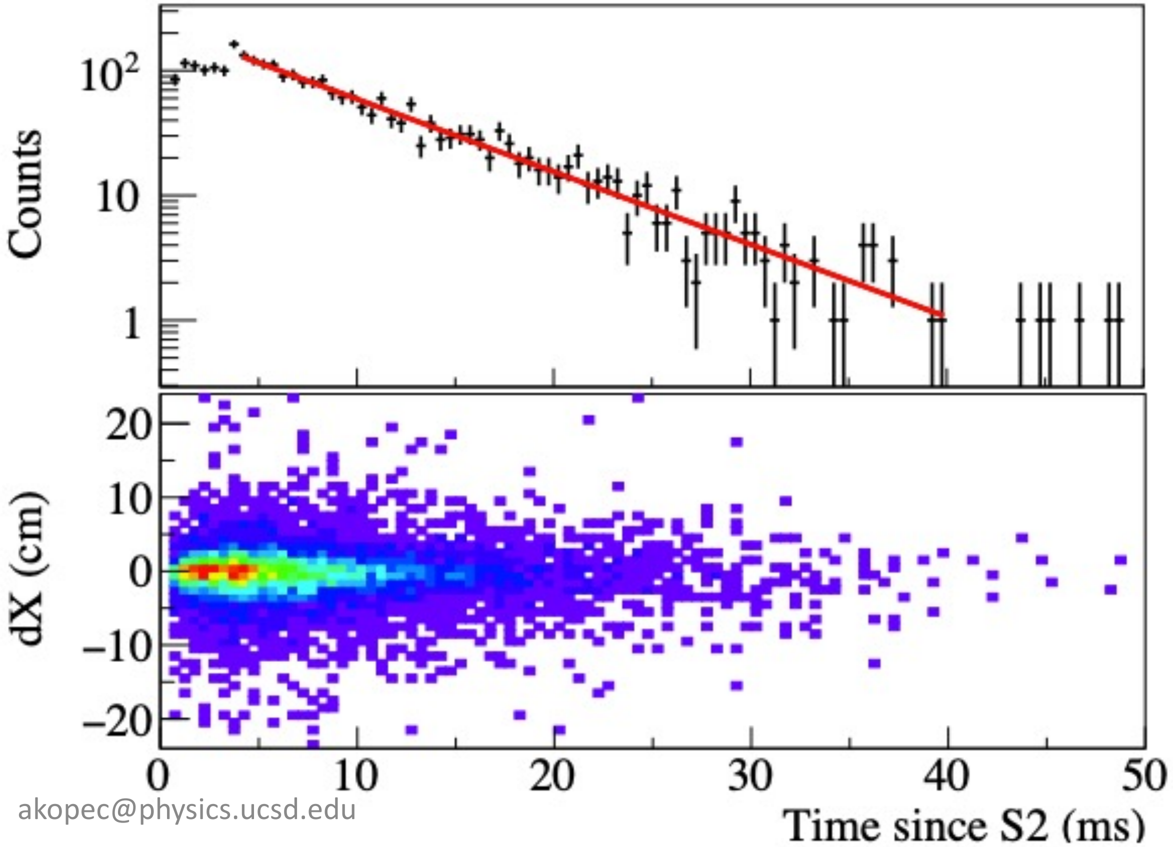
Correlated Backgrounds: S3s/Electron Bursts

With an insufficient extraction field, unextracted electrons build up at the liquid surface and burst through at later times.



RED-1: 10.1088/1748-0221/11/03/C03007





LUX: 10.1103/PhysRevD.102.092004

Correlated Backgrounds: S3s/Electron Bursts

Mitigation:

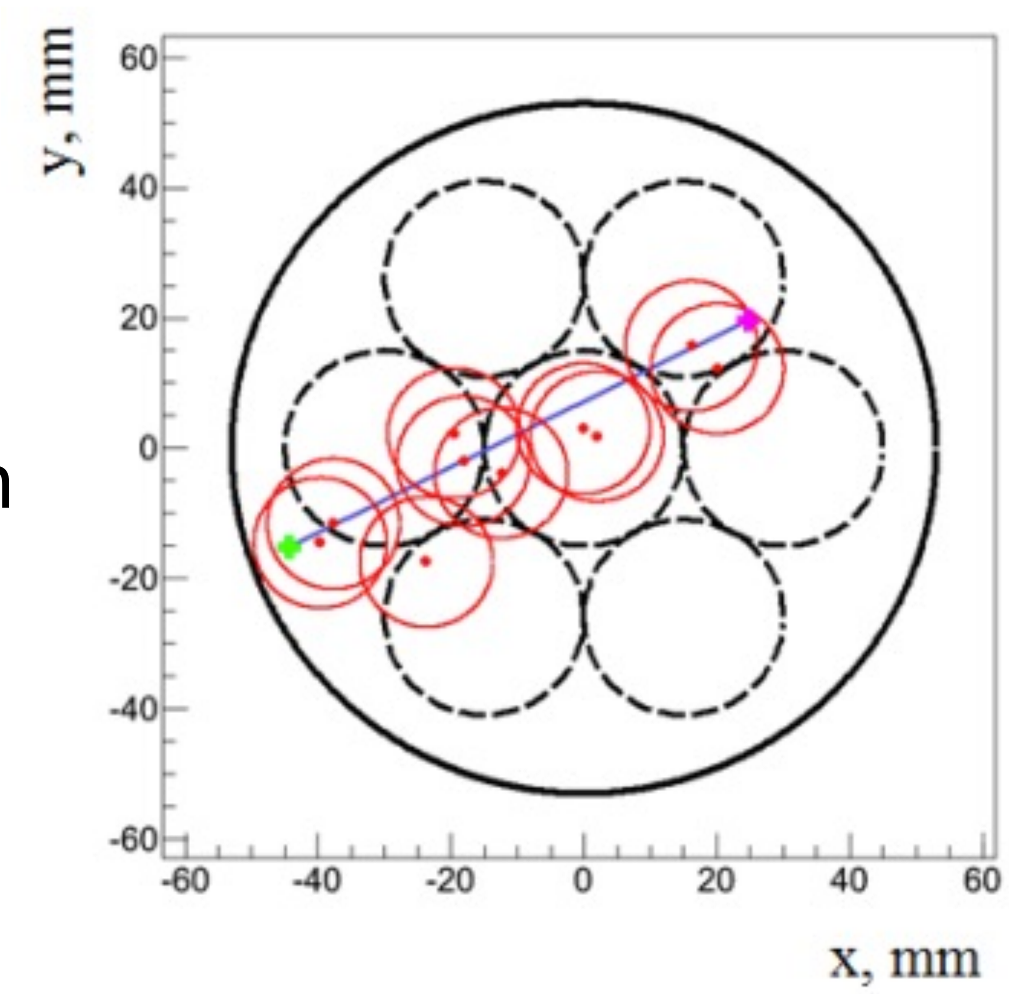
- Improve extraction efficiency*.
- Improve Purity. LUX found that E-bursts happened more promptly with better purity.

(*The threshold field to stop seeing this effect is not clearly defined and may depend on electrode geometry and field variations at the surface.)

S3s/Electron Bursts – Second Take

Uncharacteristically wide S2s are easy to cut from data, and (although not explicitly tested) they should depend on extraction field. They are absent from XENON1T, which had an extraction efficiency >90%.

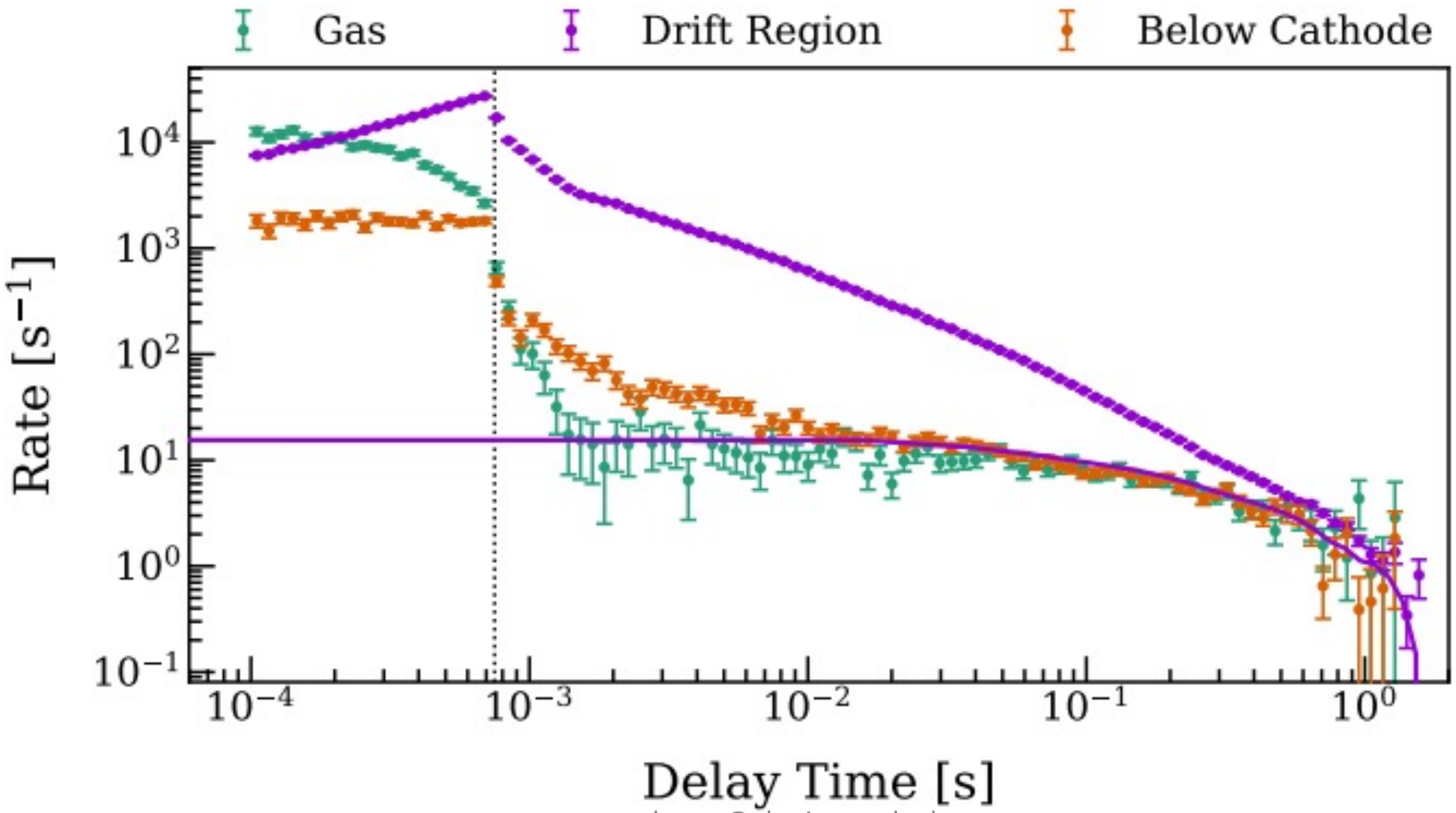
Background problem effectively "solved"… unless the bursts just become much smaller…



RED-1: 10.1088/1748-0221/11/03/C03007

Correlated Backgrounds: Long Times

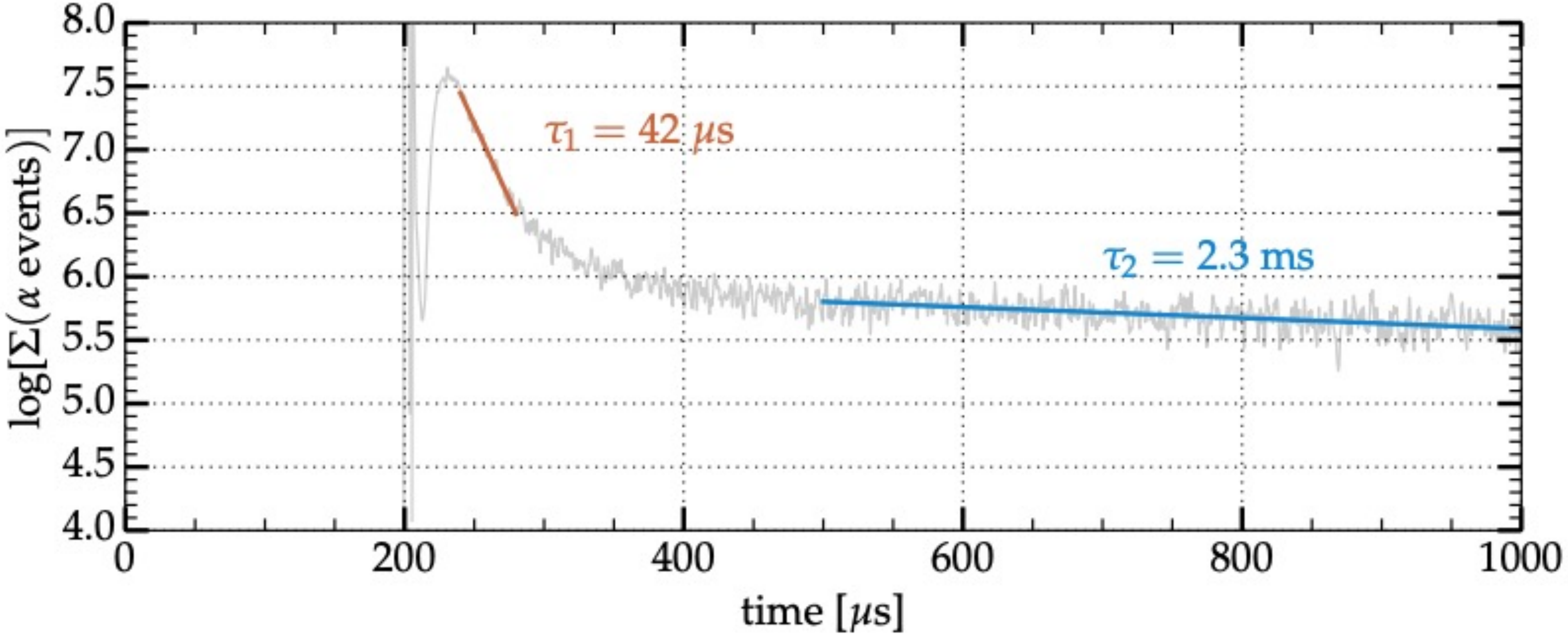
Something happens after events in the xenon bulk for long times.



XENON1T: arXiv:2112.12116

Correlated Backgrounds: Long Times

A sum of exponentials?



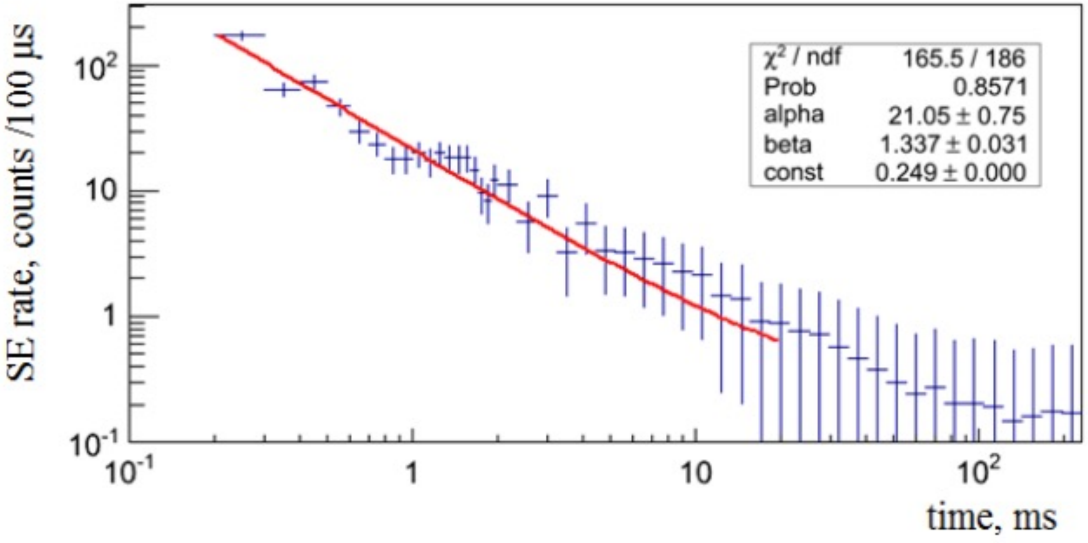
Sorensen & Kamdin: 10.1088/1748-0221/13/02/P02032

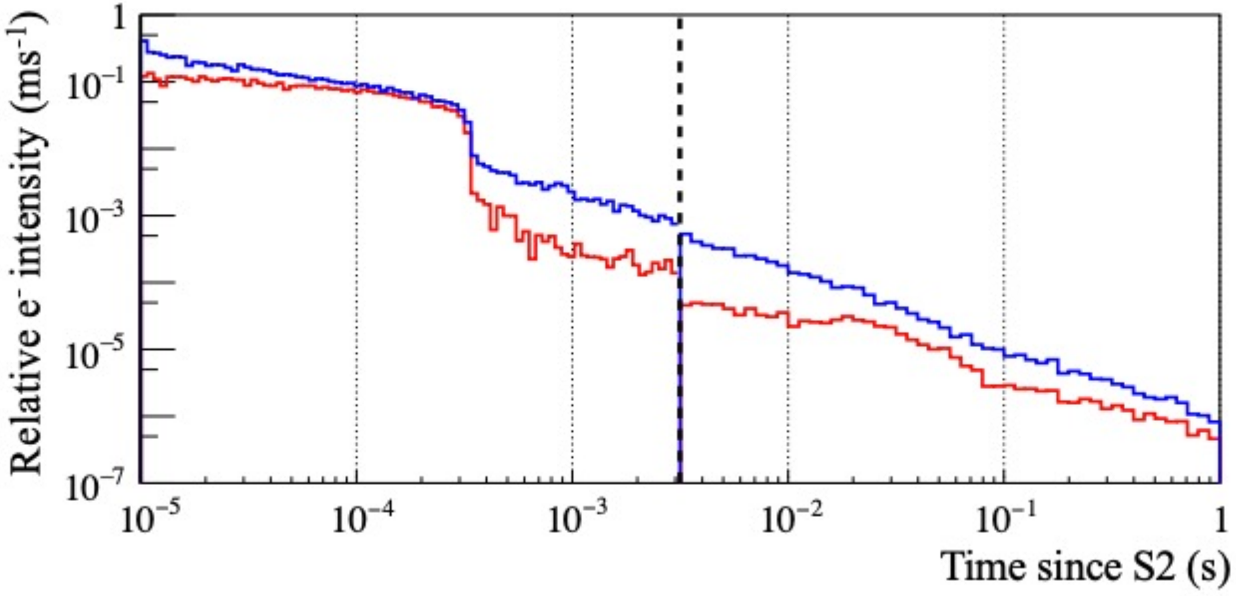
Correlated Backgrounds: Long Times

More like a Power Law

The rates of small S2s after a large S2 decrease according to a power law with time*.

RED-1: 10.1088/1748-0221/11/03/C03007





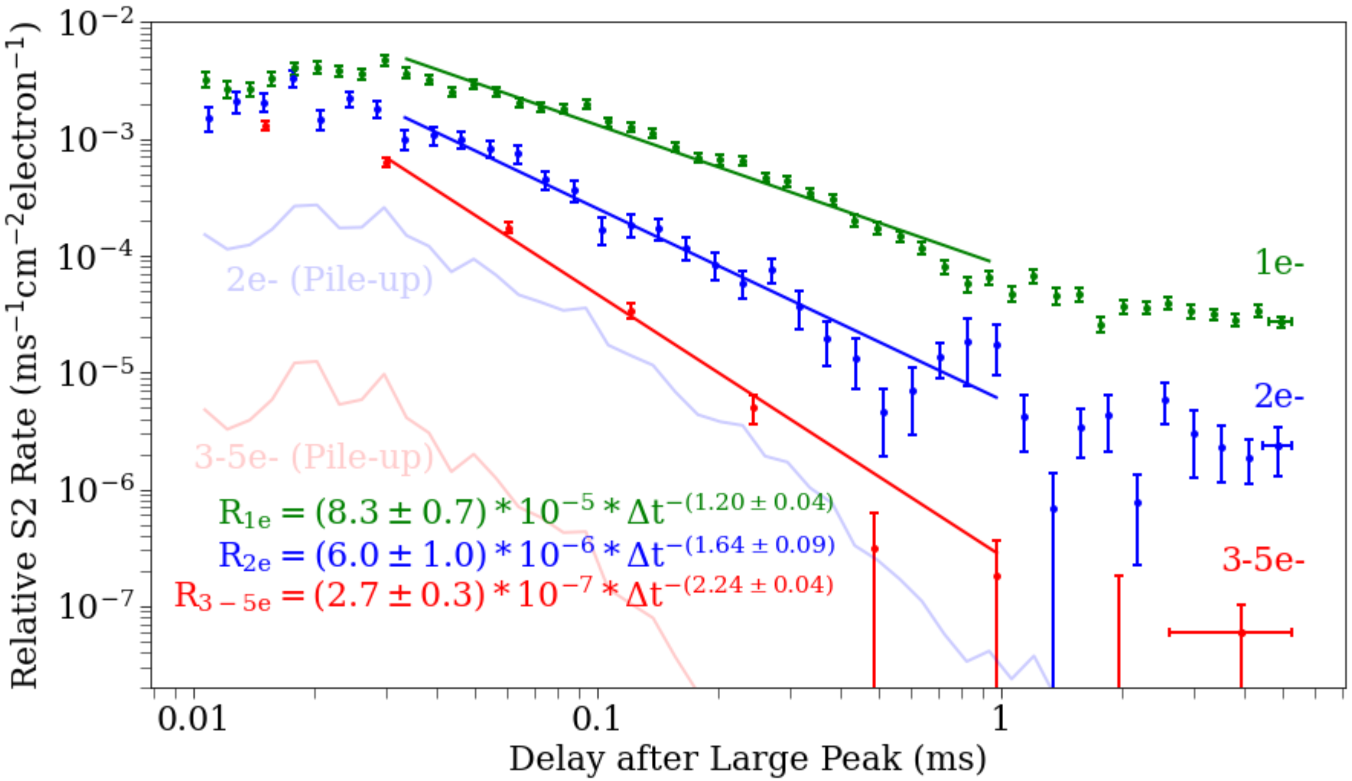
LUX: 10.1103/PhysRevD.102.092004

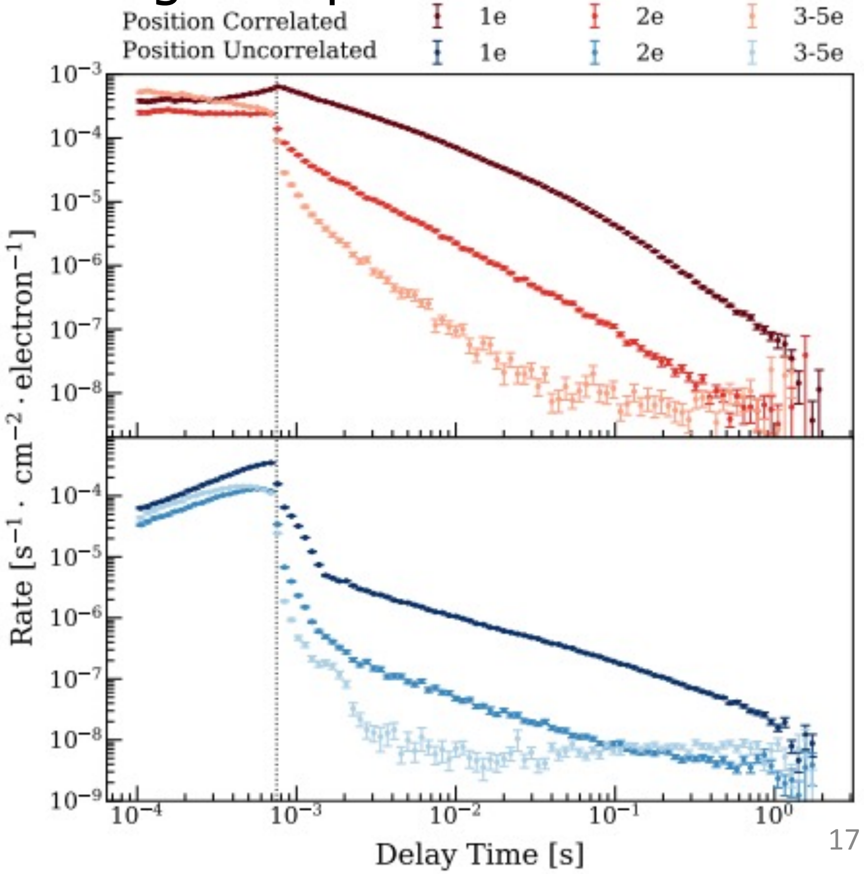
*in most liquid xenon detectors

Correlated Backgrounds: Long Times

A Power Law

The rates of small S2s after a large S2 decrease according to a power law with time*.





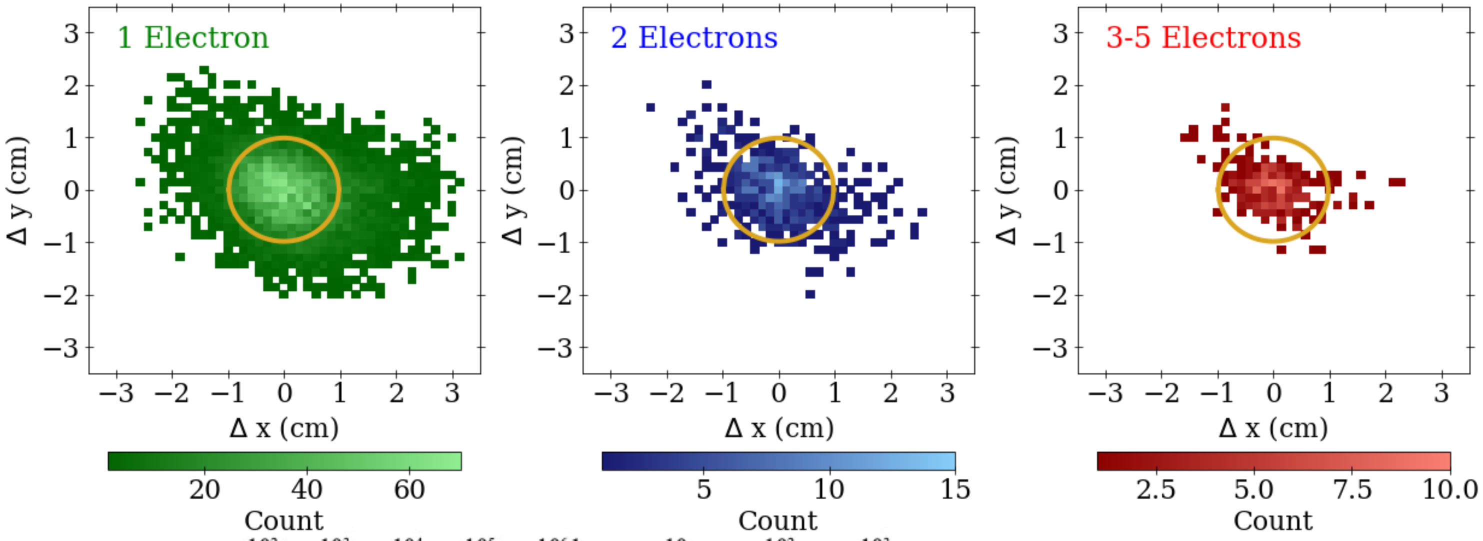
*in most liquid xenon detectors

ASTERiX: 10.1088/1748-0221/16/07/P07014

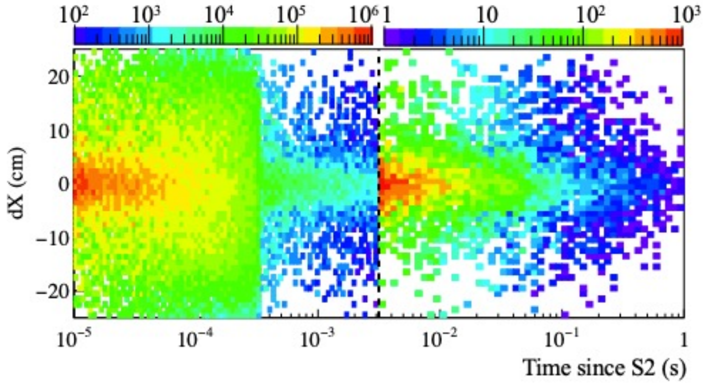
XENON1T: arXiv:2112.12116

Correlated Backgrounds: Long Times

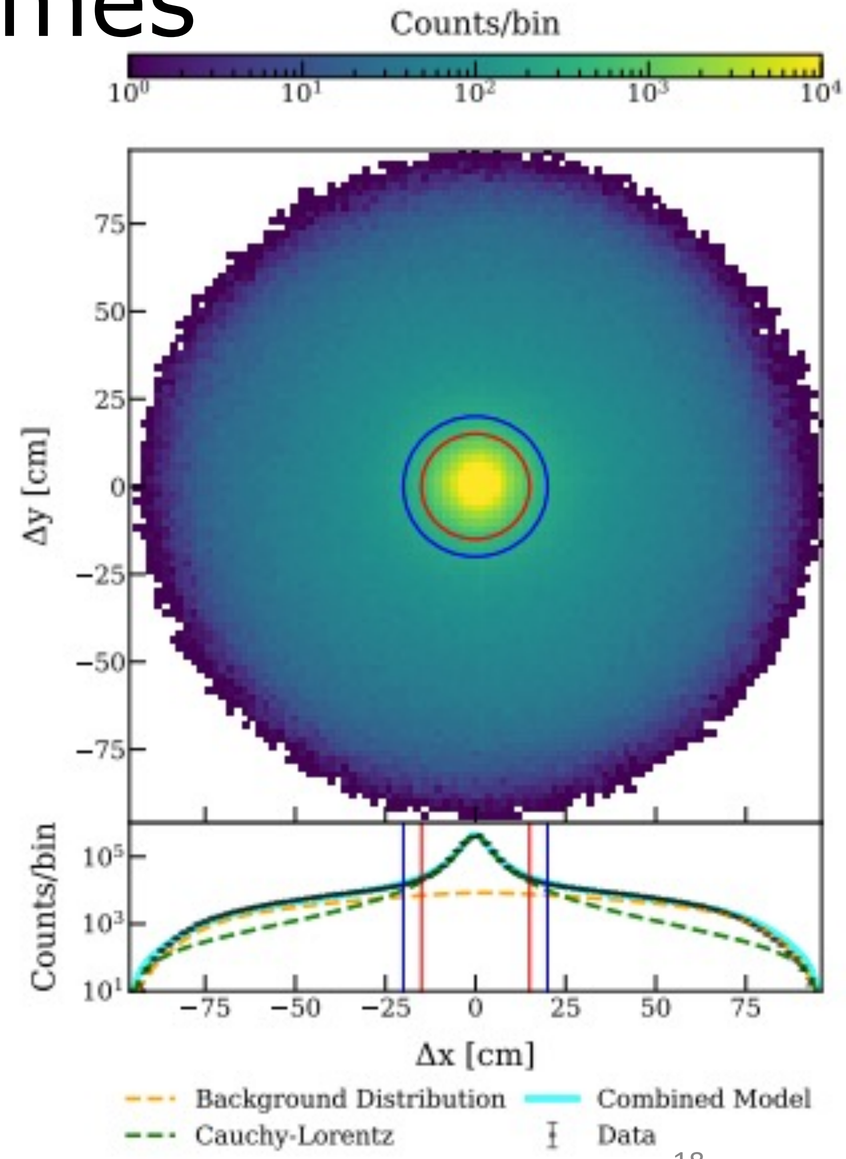
Position Correlated



ASTERiX: 10.1088/1748-0221/16/07/P07014



LUX: 10.1103/PhysRevD.102.092004



XENON1T: arXiv:2112.12116

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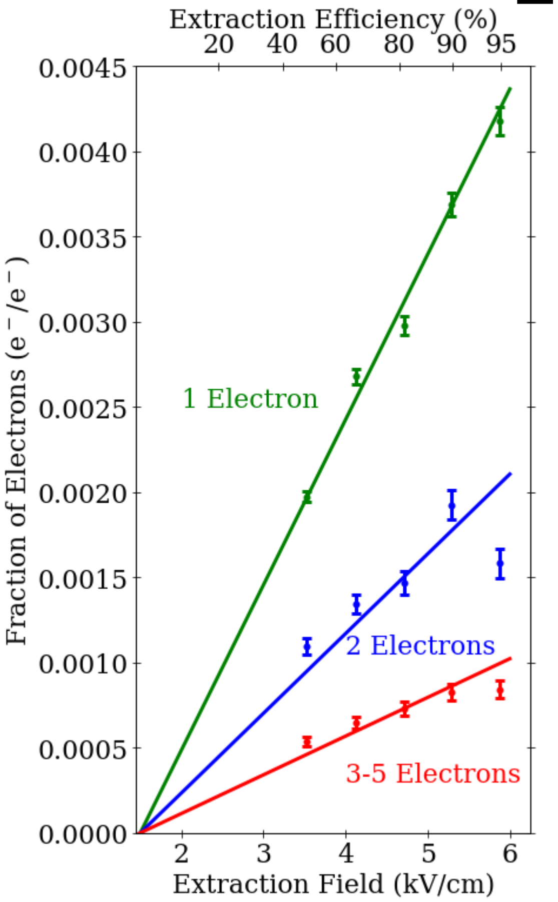
Correlated Backgrounds: Long Times

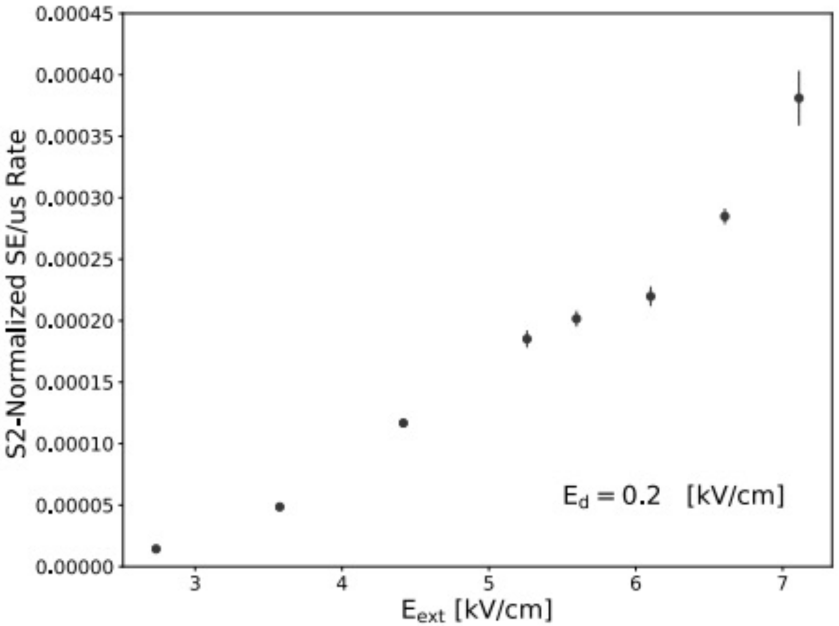
Extraction Field Dependence

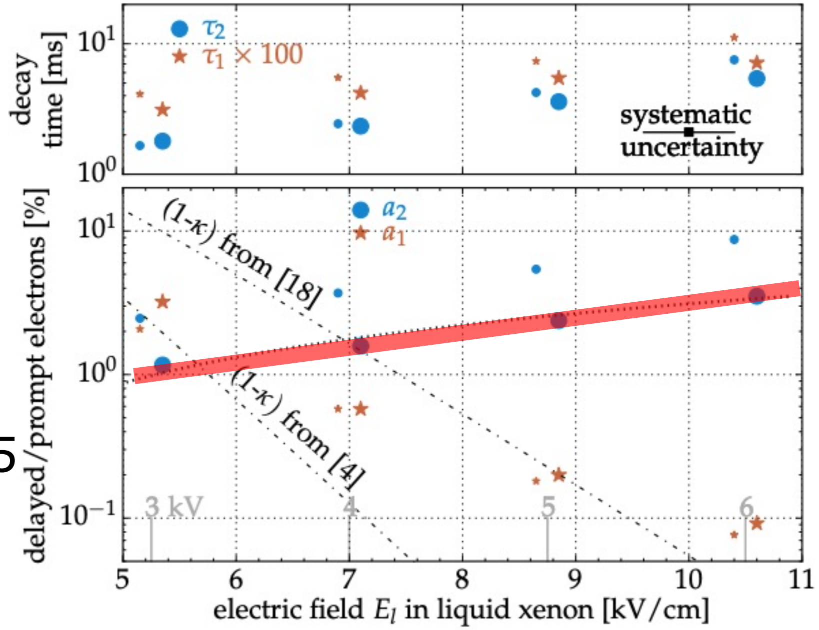
Generally increases with field,
not extraction efficiency.

ASTERiX: 10.1088/1748-0221/16/07/P07014

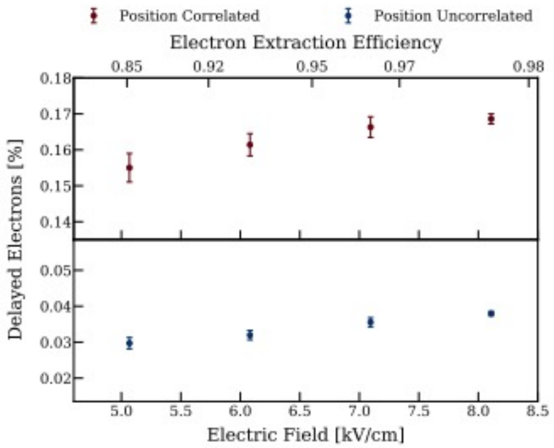


PIXeY: 10.1088/1748-0221/16/12/P12015





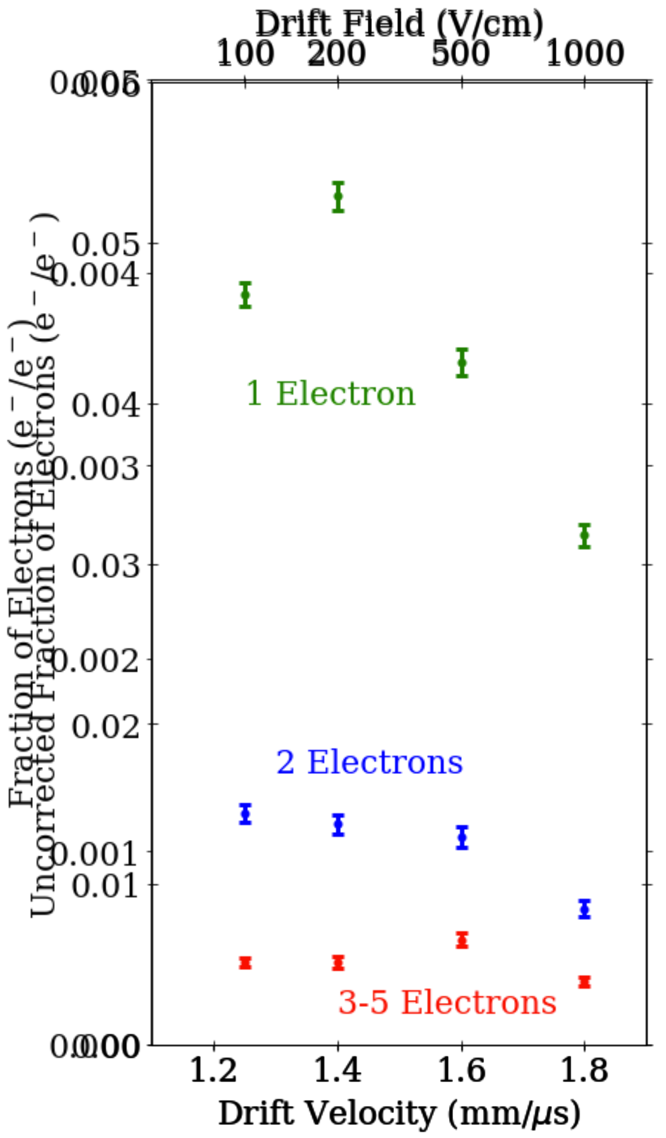
Sorensen & Kamdin: 10.1088/1748-0221/13/02/P02032



XENON1T: arXiv:2112.12116

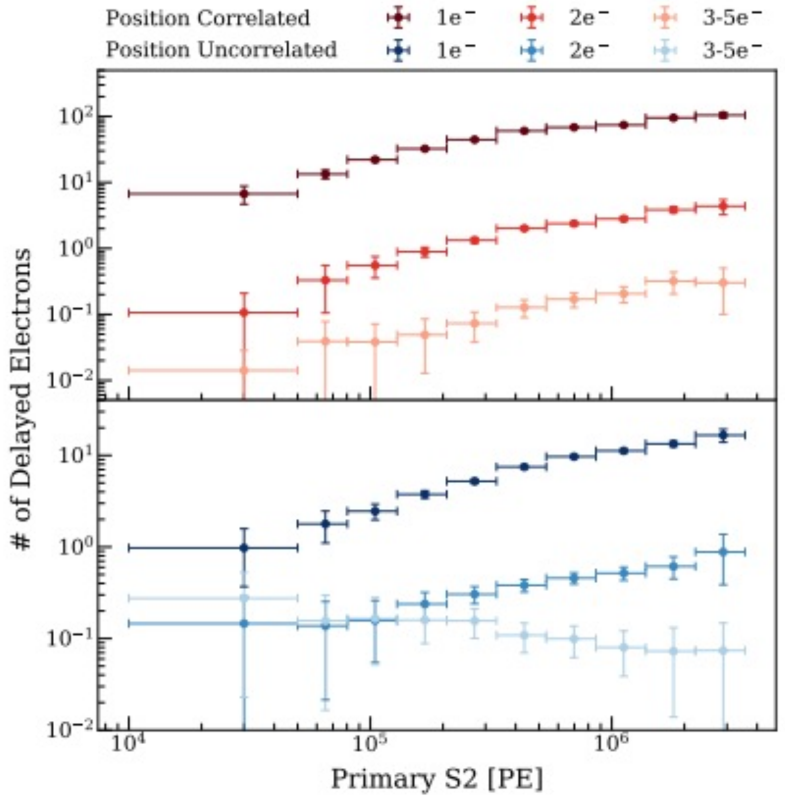
Correlated Backgrounds: Long Times

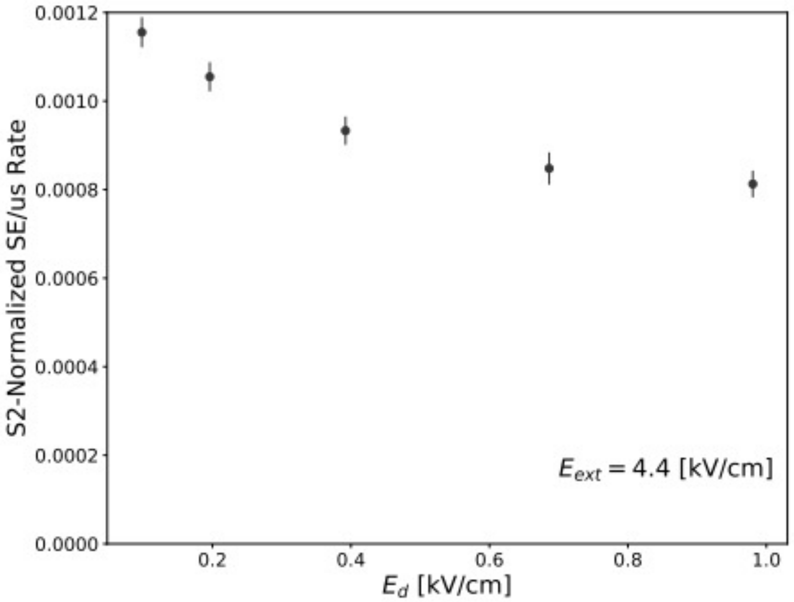
ASTERiX: 10.1088/1748-0221/16/07/P07014



Drift Field Dependence?

Decreases with field if preceding S2 is uncorrected for electron lifetime.
However, increases with increased S2 size.





XENON1T: arXiv:2112.12116

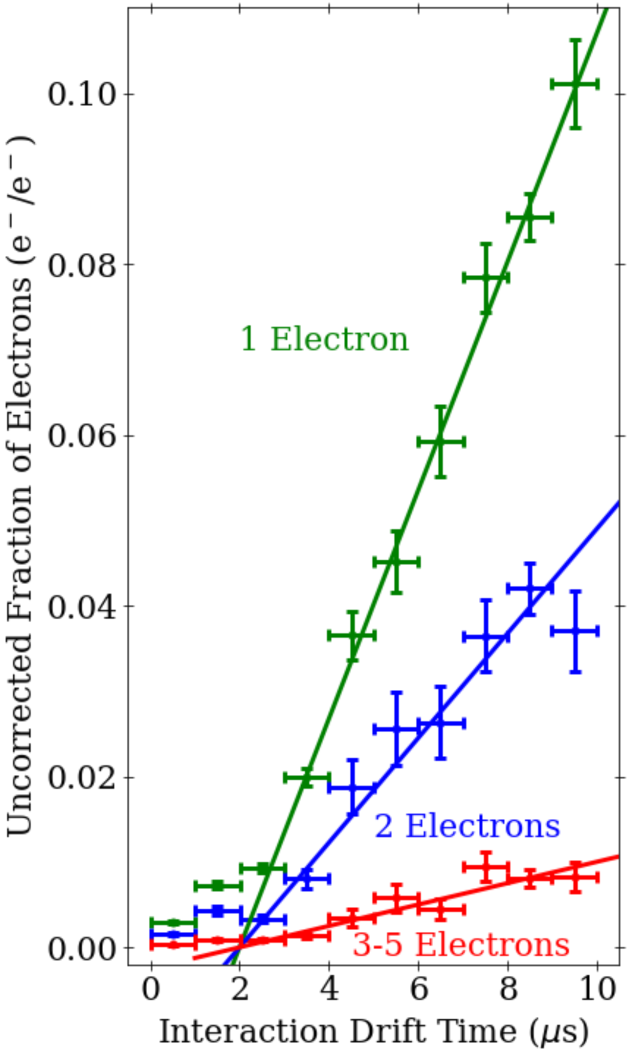
PIXeY: 10.1088/1748-0221/16/12/P12015

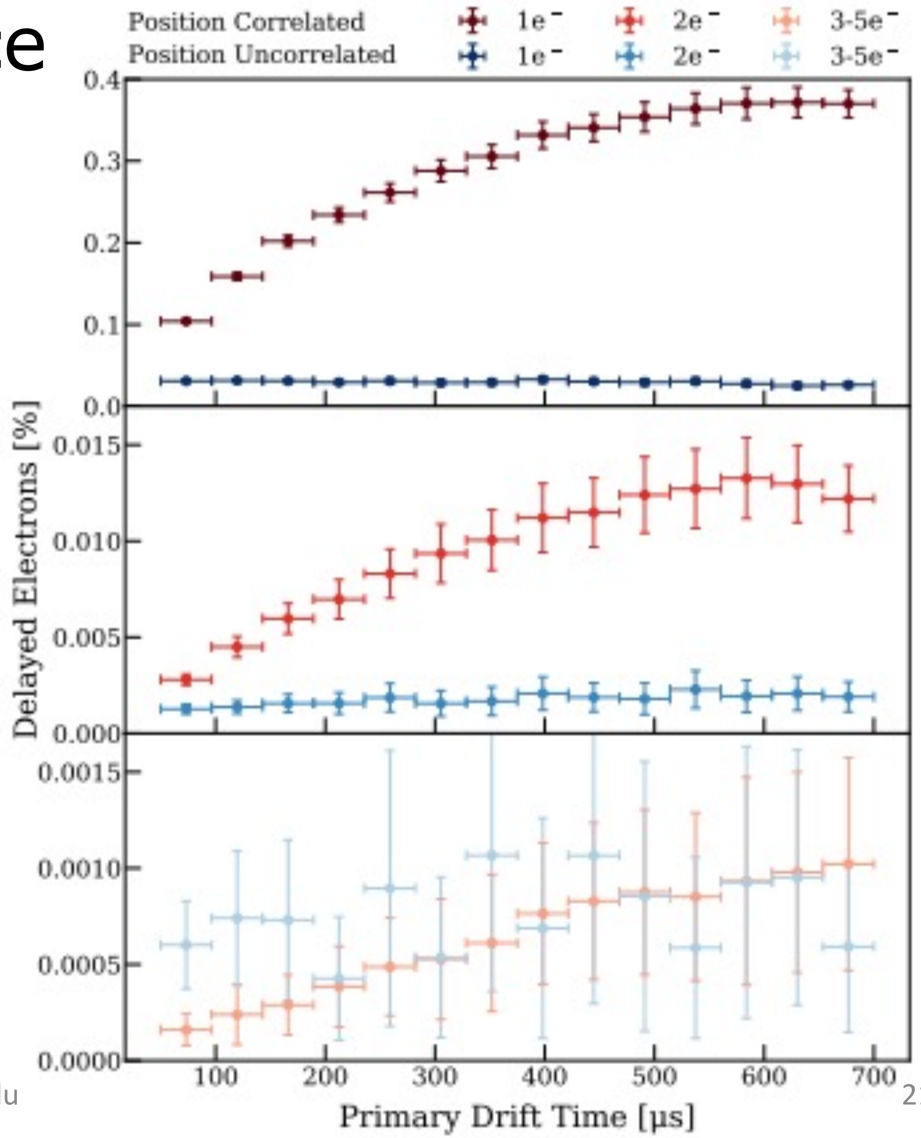
Correlated Backgrounds: Long Times

Drift Time Dependence

Increases with S2 depth, linear with uncorrected S2.

ASTERiX: 10.1088/1748-0221/16/07/P07014





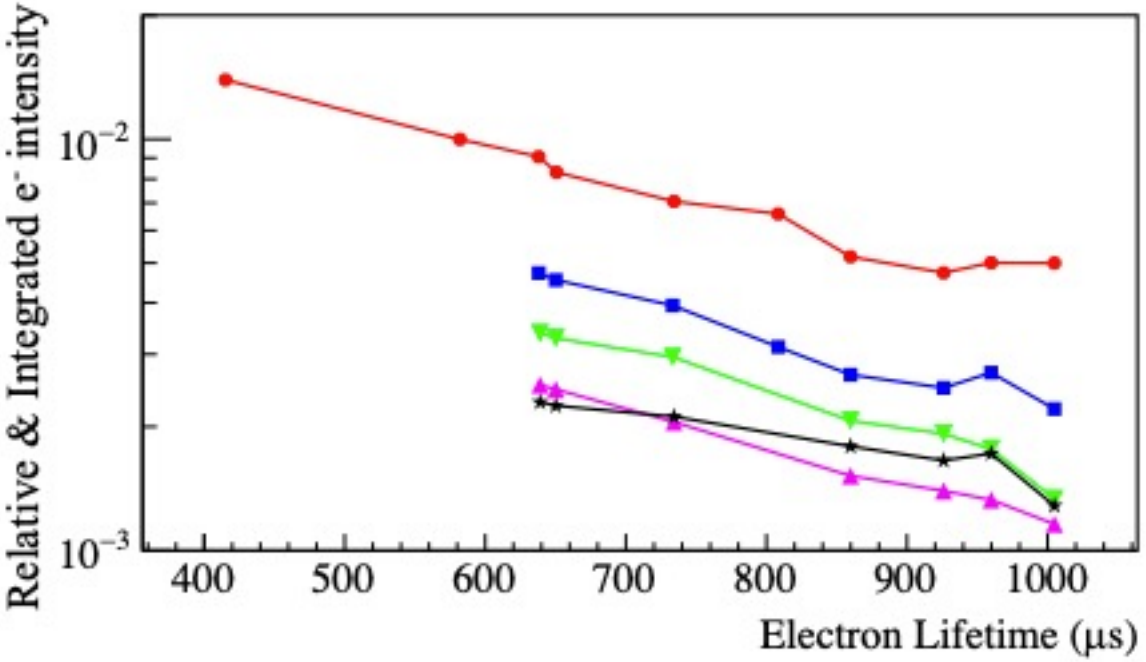
XENON1T: arXiv:2112.12116

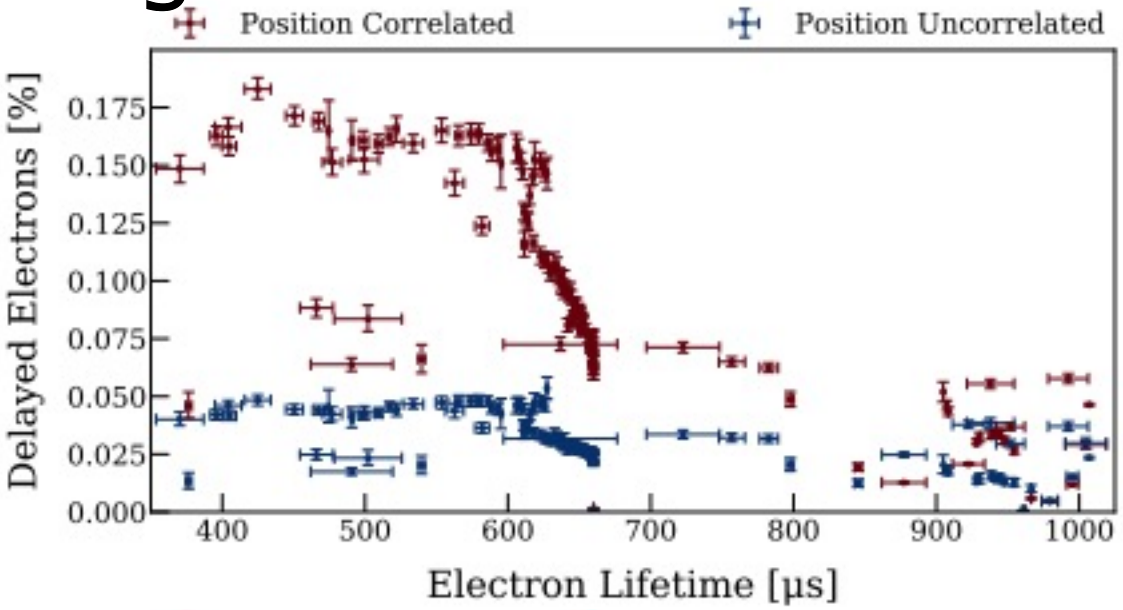
Correlated Backgrounds: Long Times

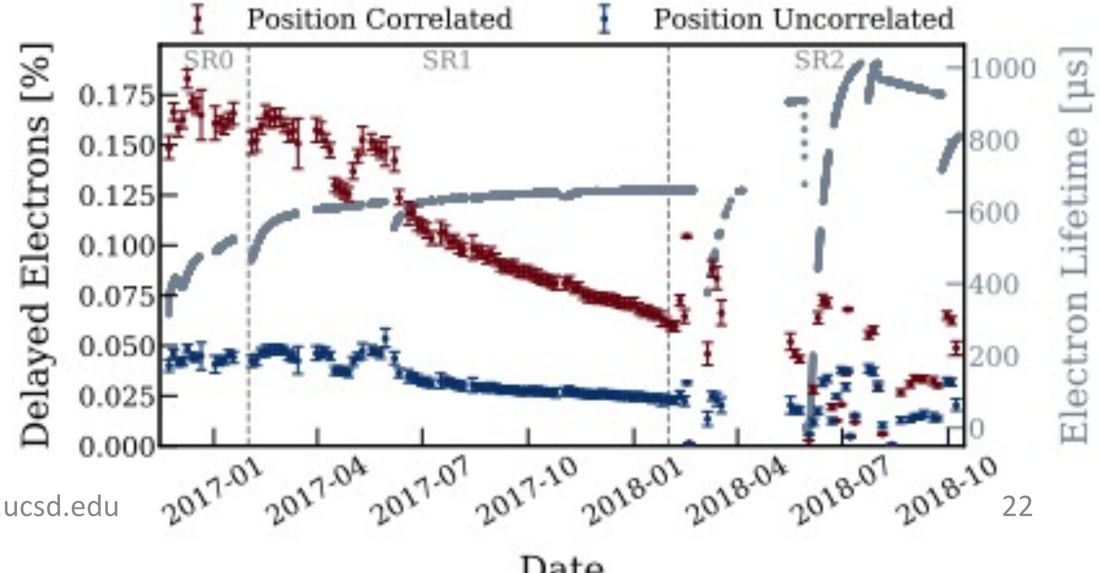
Purity Dependence?

No clear relationship,
But better with better purity.
Maybe Time Dependence?

LUX: 10.1103/PhysRevD.102.092004







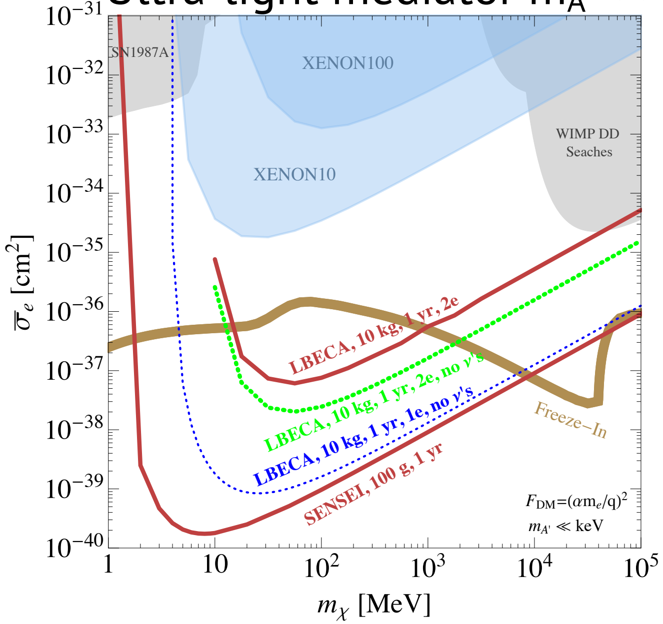
XENON1T: arXiv:2112.12116

Correlated Backgrounds: Long Times

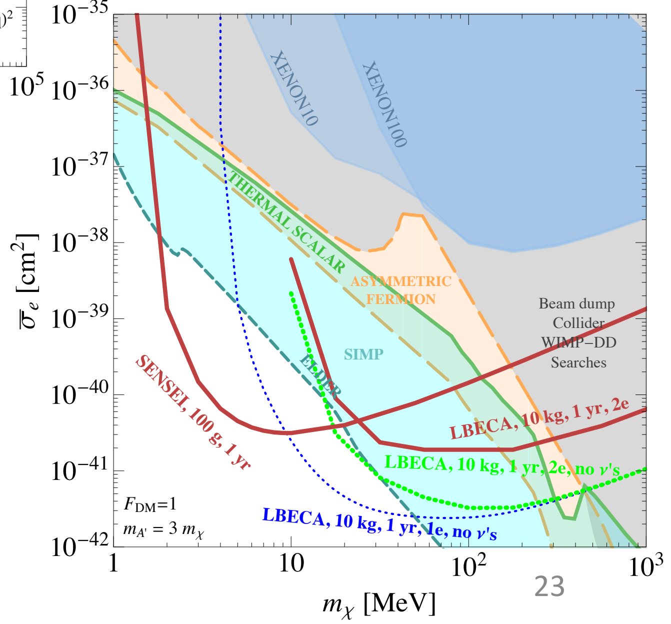
Mitigation:

*Steps are unclear, because the primary mechanism(s) behind this background remain(s) unknown. The background does limit dark matter sensitivity.

Ultra-light mediator $m_{A'} << keV/c^2$



Heavy mediator $m_{A'} = 3m_\chi$



Long Times – Second Take

For analyses using S2s smaller than 5 electrons, cutting the power law at some rate threshold cuts significant exposure.

The position-correlation can be exploited to reduce the amount of exposure cut.

If related to xenon purity, the species emitting electrons does not significantly contribute to electron lifetime, but does decay away or is removed with time.

If more related to electrodynamics at the liquid-gas surface, it could require more careful electrode geometries to control surface charge buildup, distribution and emission. Could use some help from solid-state? Self-organized criticality?

Background problem nowhere near "solved"

Summary

- Photoemission electrons are clearly related to light events in the detector and occur within the maximum drift time.
- S3s/Electron Bursts are from charge accumulating at the liquid-gas surface and disappear at higher extraction fields.
- Single- and few-electron S2s are emitted for long times following drifting primary S2s in the same (x,y) location and the rates seem to depend on extraction field, measured primary S2 size, and depth the primary S2 drifted.
- The mechanism(s) are unclear, but the small S2s' correlation with previous primary S2s is undeniable and not characteristic of dark matter, therefore certainly being a limiting background.

Back-Up Slides

S2s - a poem by Abigail Kopec

A flash of light from xenon struck, an interaction's sign,
heralds electrons drifting up to the liquid-gas line.
While traveling within a cloud, they reach terminal speeds
determined by electric fields, and xenon's properties.

The liquid xenon buffets them, diffusing them around.
They're pursuing the Anode's pull, seeking a place to ground.
But lurking in the xenon are impurities that wish
to catch electrons as they pass, as sharks waiting for fish.
To these electronegative impurities, one should
expect some electrons to lose, but are they gone for good?

The electrons that make it to the surface are not done.
They burst into the xenon gas, but is it every one?
Alas, if the extraction field is just a bit too weak,
Some cannot leave the liquid so they through the gas don't streak.
Trapped at the liquid interface in that layer, one should
expect some electrons to lose, but are they gone for good?

Electrons that have reached the gas cause luminescence bright
And photoionization frees more of them with light.
Measured or trapped, those die away, and none should now be found.
Yet still some electrons appear. Why is there this background?

References

- XENON10 https://arxiv.org/abs/1104.3088
- XENON100 https://arxiv.org/abs/1311.1088
- RED-1 https://iopscience.iop.org/article/10.1088/1748-0221/11/03/C03007/pdf 2016
- RED-100 https://iopscience.iop.org/article/10.1088/1748-0221/15/02/P02020/pdf 2020
- LUX https://arxiv.org/abs/2004.07791
- PIXeY https://arxiv.org/abs/2101.03686
- XENON1T https://arxiv.org/abs/1907.11485 & https://arxiv.org/abs/2112.12116
- ASTERiX https://arxiv.org/abs/2103.05077