Noble liquid detectors near the single-electron limit

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On behalf of the nascent $U_{A'}(1)$ collaboration

LBL, UCSD, Purdue, LLNL, Stonybrook, CERN…

13th Rencontres du Vietnam - Exploring the Dark Universe

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Lawrence Livermore National Laboratory

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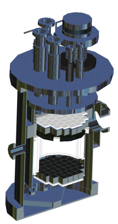
Outline

- Dark matter candidates old and new
- A Standard Model standard candle
- **$U_{A'}(1)$:** A modest (ly sized) proposal
- Turning your back on the greatest invention since sliced bread
- Energy calibration in the few electron regime
- Few-electron noise in noble liquids

Fiducial mass – 5.4 kg



XENON-10: (2007)

Fiducial mass – 145 kg

LUX: (2013)

Fiducial mass – 5600 kg

LZ: (2019 commissioning)

Fiducial mass – 10 kg

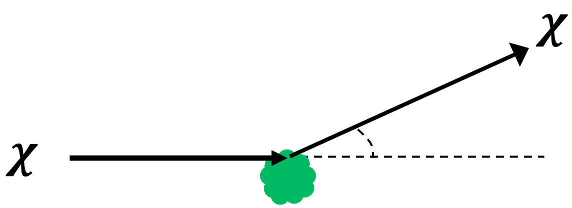
$U_{A'}(1)$ (201?)

The Dark Sector – gravitationally interacting particles with no Standard Model charge, consistent with astrophysical evidence for Dark Matter

Dark Sectors Workshop arxiv:1608.08632

Weakly interacting massive particles

'WIMPs' – ~100 GeV particles with neutrino-level cross sections



Nuclear scatter

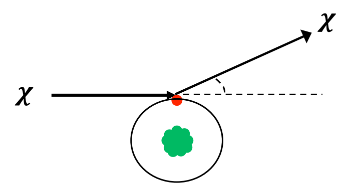
Interacts coherently with nuclei

Phase space thoroughly probed in the 50-500 GeV range by **LUX** and others

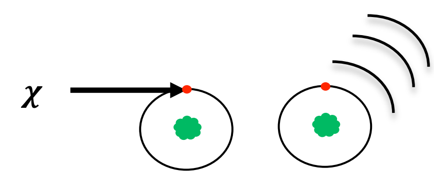
LZ will approach/breach the solar neutrino coherent scatter noise floor

Some other viable Dark Sector interactions

Standard Model Photon → A
<u>Dark photon → A'</u>
the exchange particle for WIMPS or other DM particles ?



shell e^- scatter



e^- absorption

scatters incoherently from or is absorbed by shell electrons

Phase space already probed by **LUX, XENON-10, XENON-100**

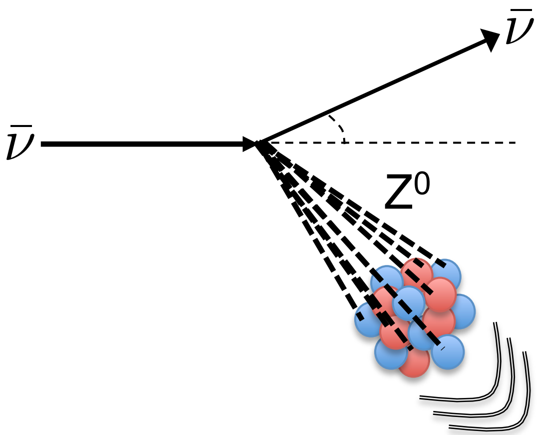
Low cost, fast **$U_{A'}$(1)** experiment may probe more deeply than prior expts.

WIMP interactions look a lot like a Standard Model process that does have a (weak) charge

- Standard Model: (fast, light, Z^0 mediated, blind to charge and flavor, **coherent**)
- WIMP: (slow, heavy, unmediated, blind to charge and flavor, **coherent**)

Coherent Neutrino Nucleus Scattering

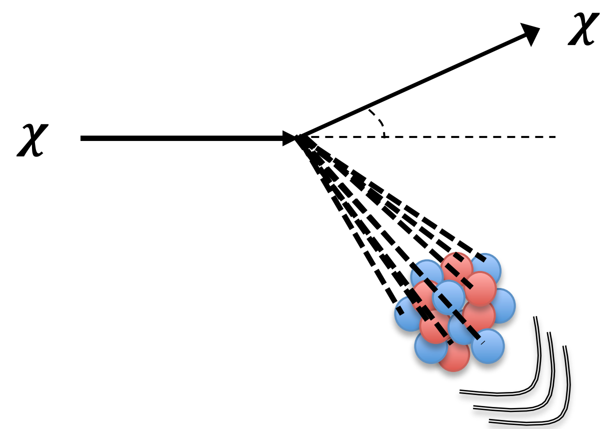
$$\bar{\nu} + Xe \rightarrow \bar{\nu} + Xe$$



$\lambda \sim$ a few fm M = ~ 1 meV

WIMP-Nucleus Scattering

$$\chi + Xe \rightarrow \chi + Xe$$



$\lambda \sim$ a few fm M = ~100 GeV

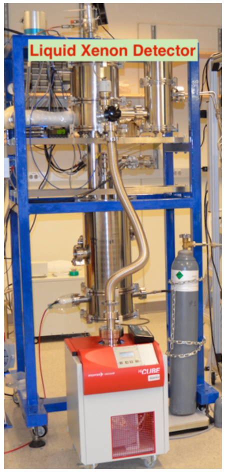
$U_{A'}(1)$– a modestly sized proposal to observe very low energy recoils in xenon

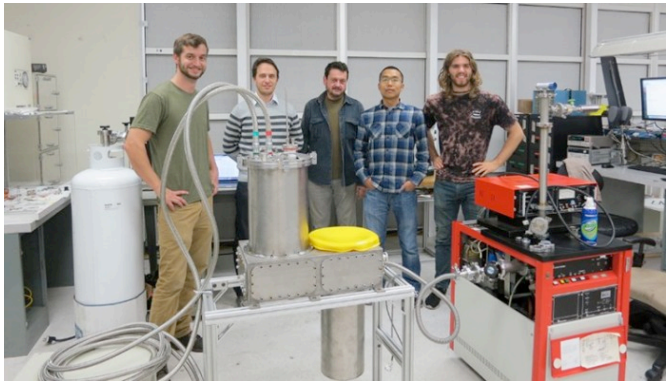
UA1 experiment → $U_{A'}(1)$ experiment

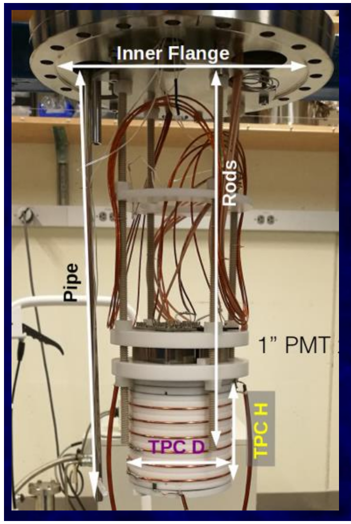
Discovered W and Z bosons, won Nobel prize

Discovery of A', the dark photon ?

The $U_{A'}(1)$ experiment consists of a ~10 kg dual-phase xenon detector



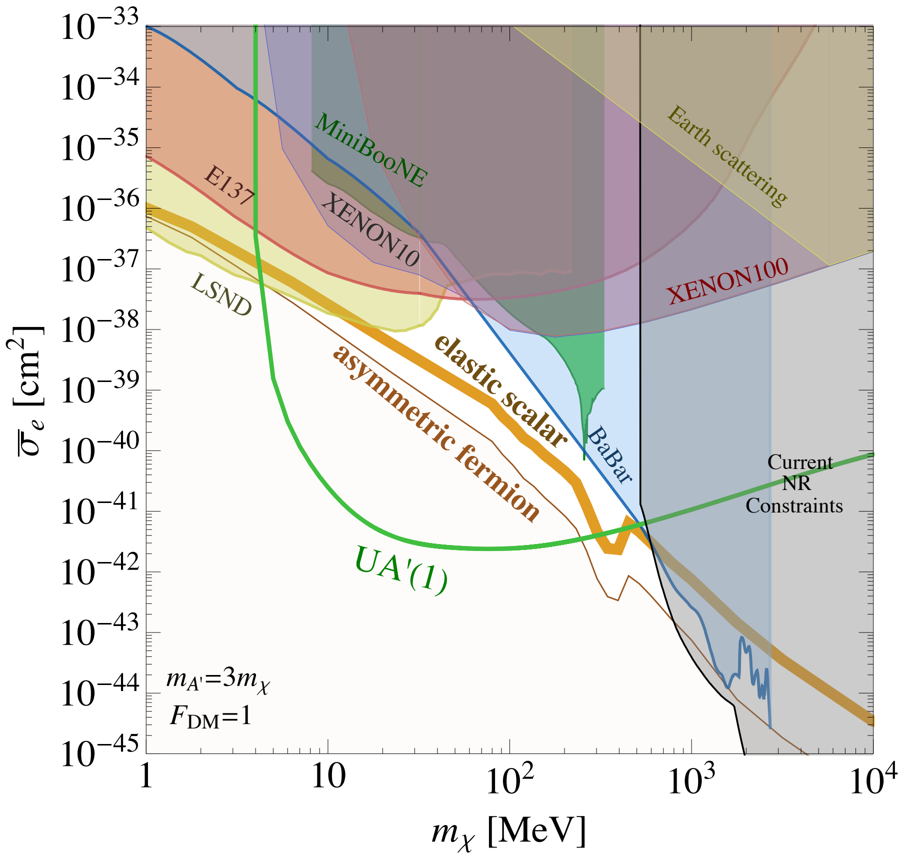




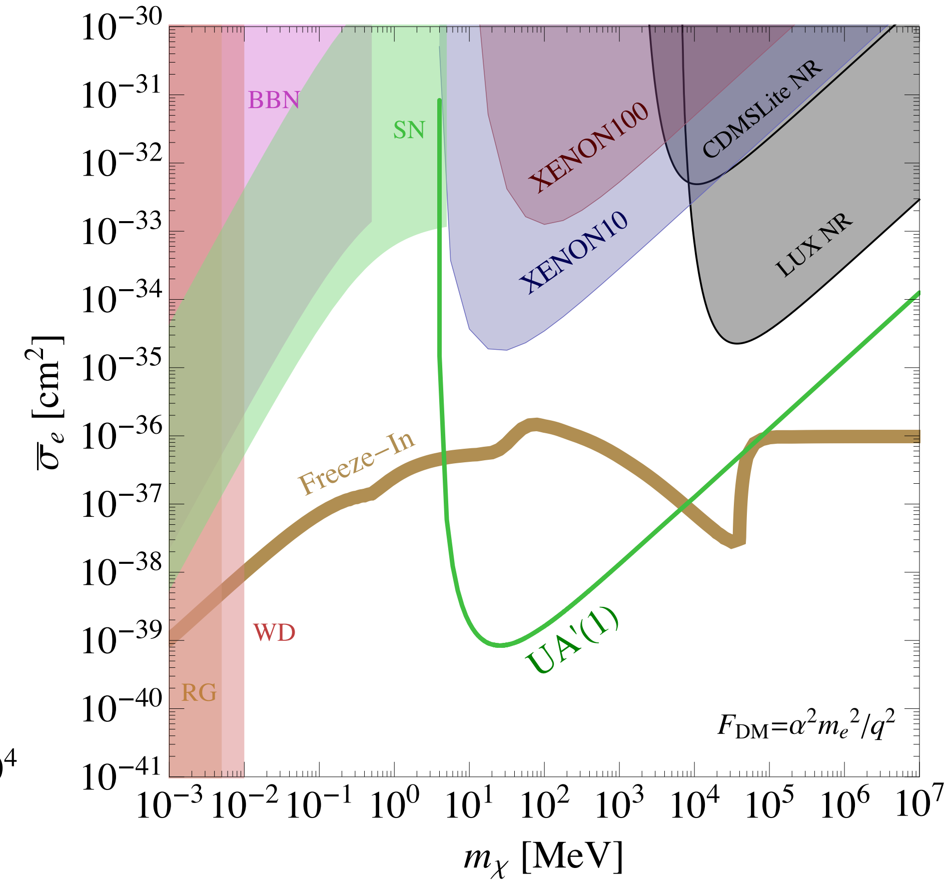
Purdue, UCSD, LBL, LLNL are involved so far.. Others anticipated and welcomed

What kind of dark sector sensitivity might $U_{A'}(1)$ achieve ?

Heavy Dark Photon model



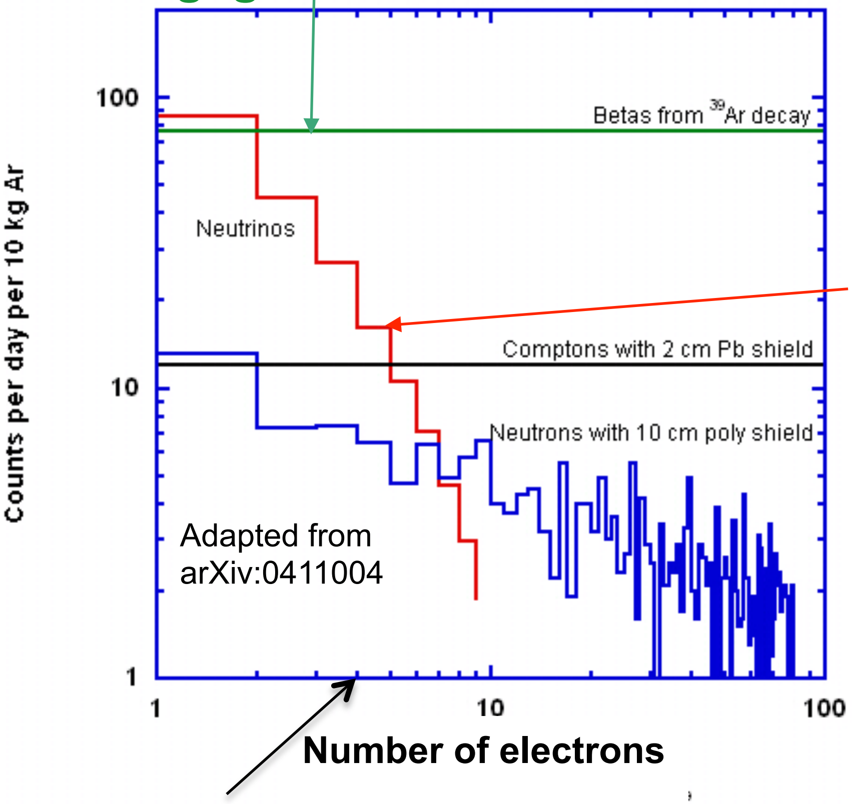
Light Dark Photon model



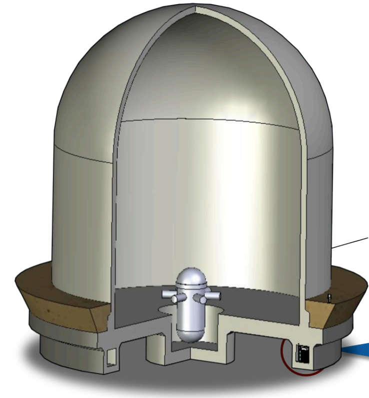
10 kg, 1 year, 1 e^- threshold, 0 background → Optimistic !

10 kg of xenon – or argon - also provides a healthy coherent scatter rate at a typical nuclear reactor

Ar-39 dominates in natural argon
but can be suppressed (Savarese, Fri. 4 pm)
negligible in xenon



4 e$^-$ threshold



~3 GWt reactor
~25 meter standoff
~10 meter depth

Argon (Xenon): ~25 (6) cts/day

But why make a reactor coherent scatter measurement ?

1. First detection ever, an important physics result
2. Close dark matter analog
3. new monitoring tool for nonproliferation an LLNL priority
4. Experimental tour-de-force !

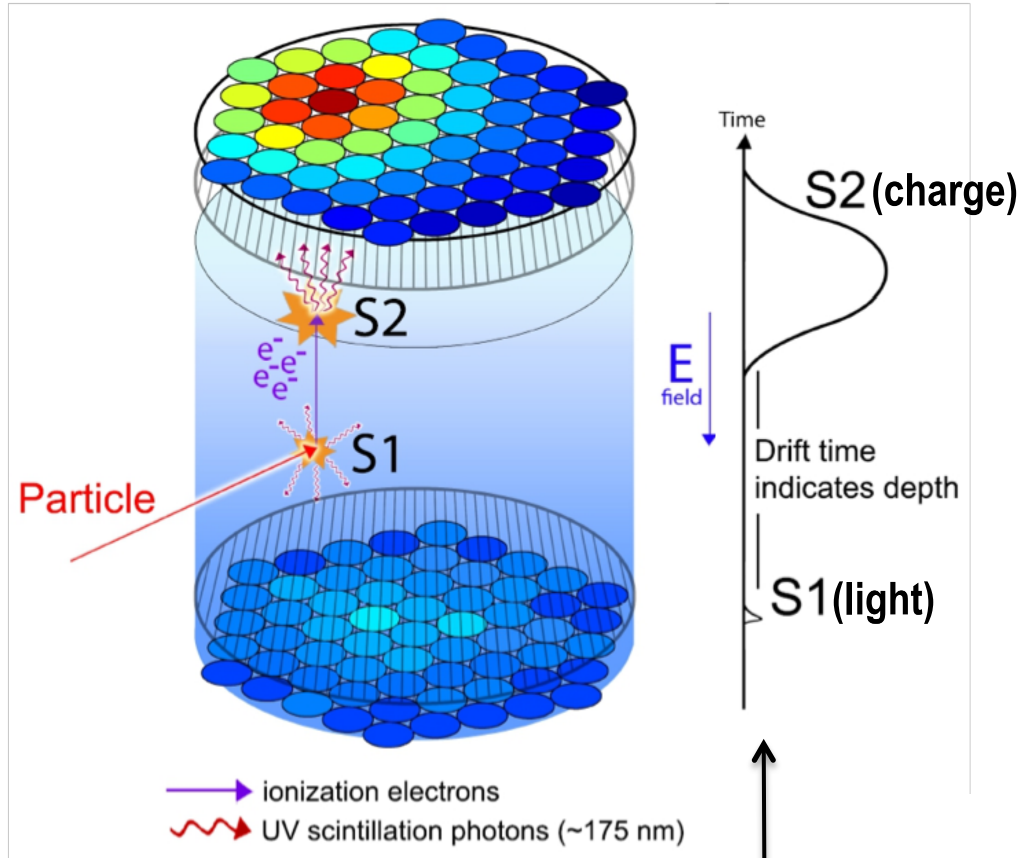
Dual-phase noble liquid Time Projection Chambers

- ~~primary or **S1** scintillation (prompt photons generated in liquid start the TPC clock)~~

  and:

  secondary or **S2** scintillation (delayed electrons, each converted to 10-100 photons in gas blanket)

- Good electron drift properties
- ~~Large self-shielded target mass~~
- ~~**3-D signal localization to ~1 mm**~~
- ~~**Powerful discrimination between nuclear and electromagnetic recoils**~~

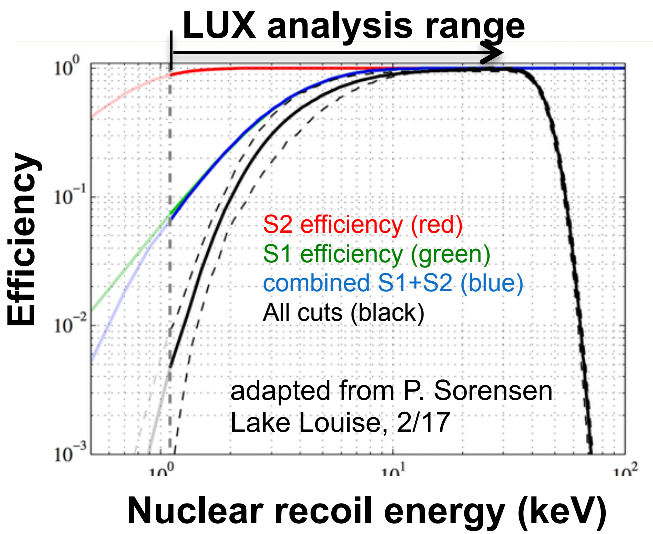


S1/S2 ratio differs for nuclear/E&M recoils

$U_{A'}(1)$ would sacrifice these properties to reduce energy thresholds

Giving up on the best part of xenon TPCs by ignoring primary ‘S1’ scintillation

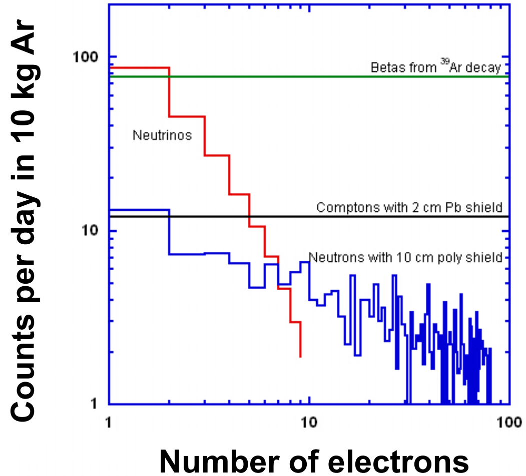
LUX example: Retain efficiency at low threshold using only the charge (S2) signal



First proposed

Hagmann and Bernstein 2004 – arXiv:0411004v1

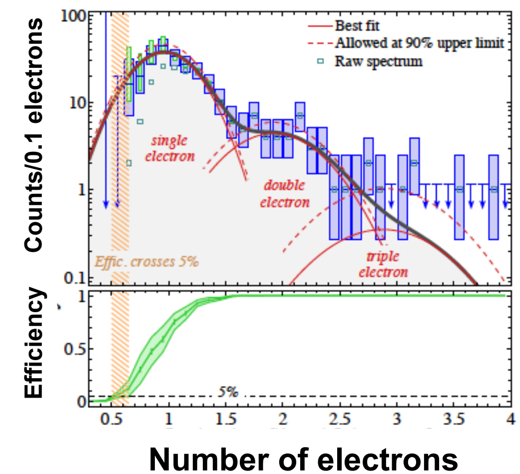
‘Two-Phase Emission Detector for Measuring Coherent Neutrino-Nucleus Scattering’



A recent application

Essig et. al, 2011 – arxiv:1206.2644

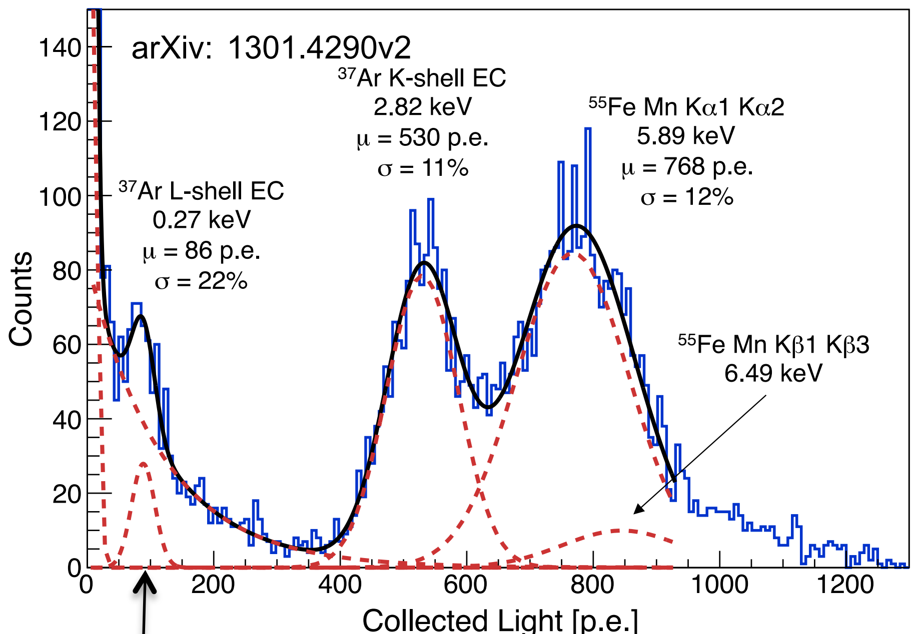
‘First Direct Detection Limits on sub-GeV Dark Matter from XENON10’



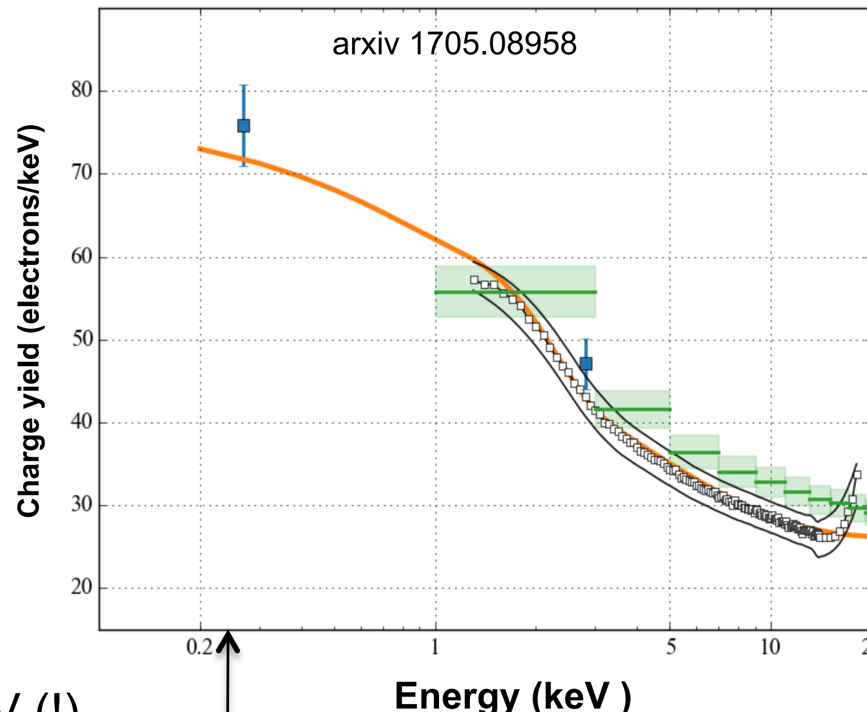
To succeed we must characterize signal strengths, and noise, in the 0 – 1 keV region – about 1-20 liquid electrons

Sub-keV measurements of electromagnetic recoils have already been made in argon and xenon

Argon



Xenon

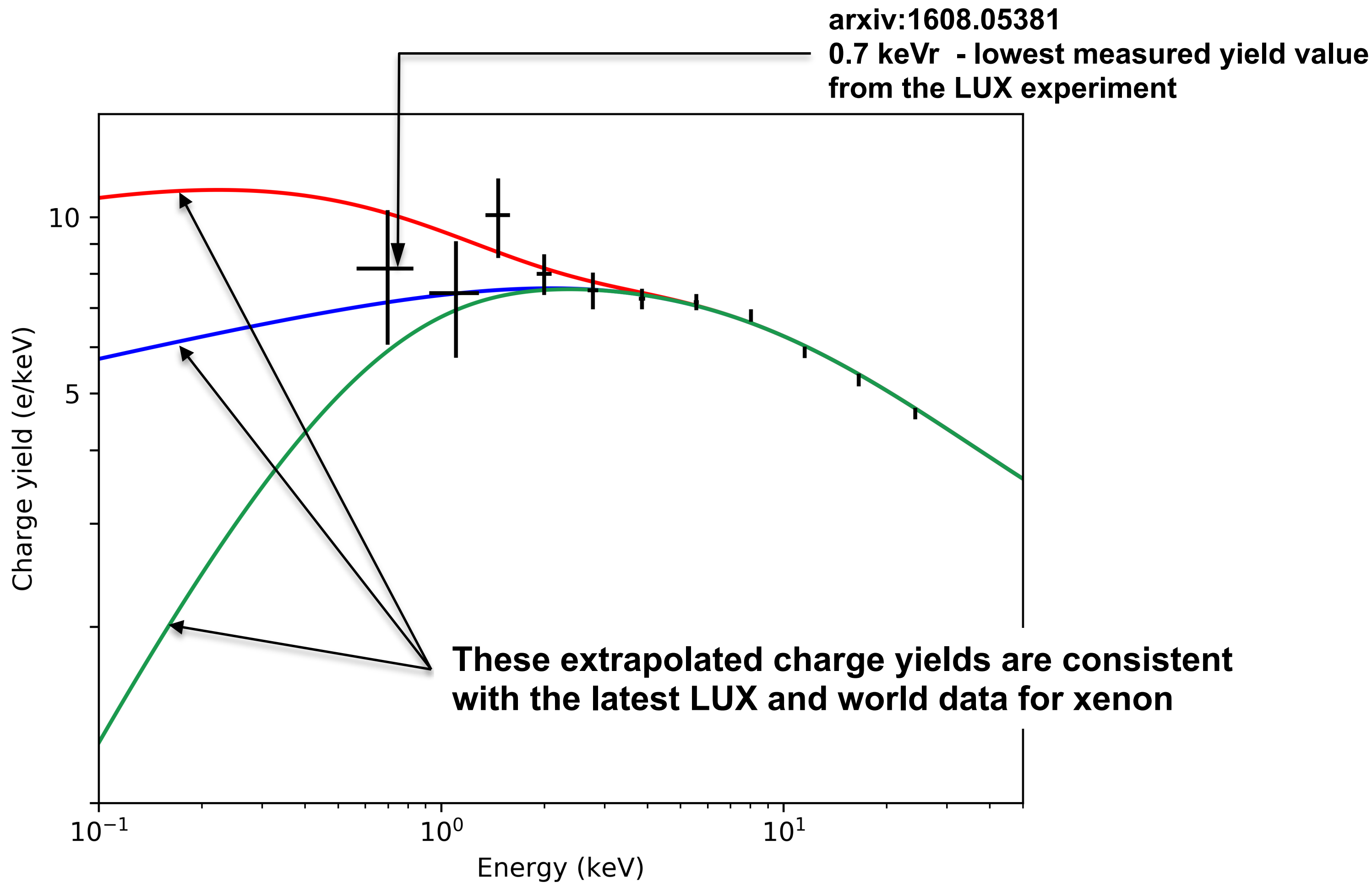


270 eV (!)

LLNL results circa 2013-2014

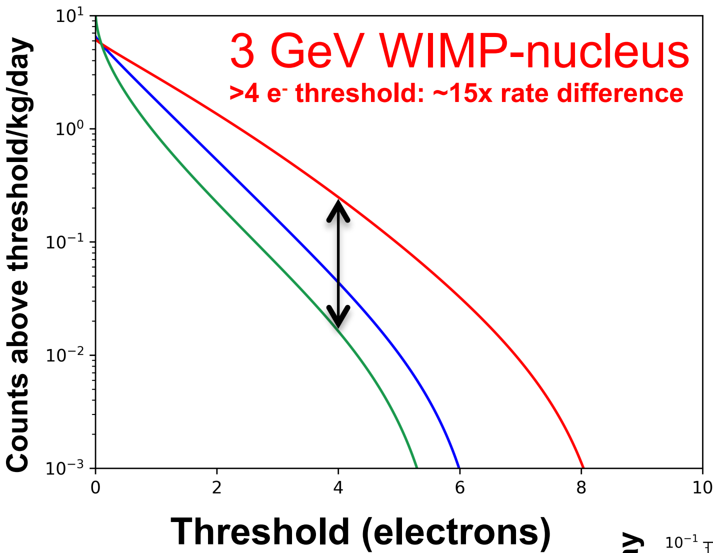
Yale/LBL/UCB results circa 2016-17
E. Boulton et. al arxiv 1705.08958

Even after LUX in-situ nuclear recoil ionization yield measurements, uncertainty remains at the lowest energies

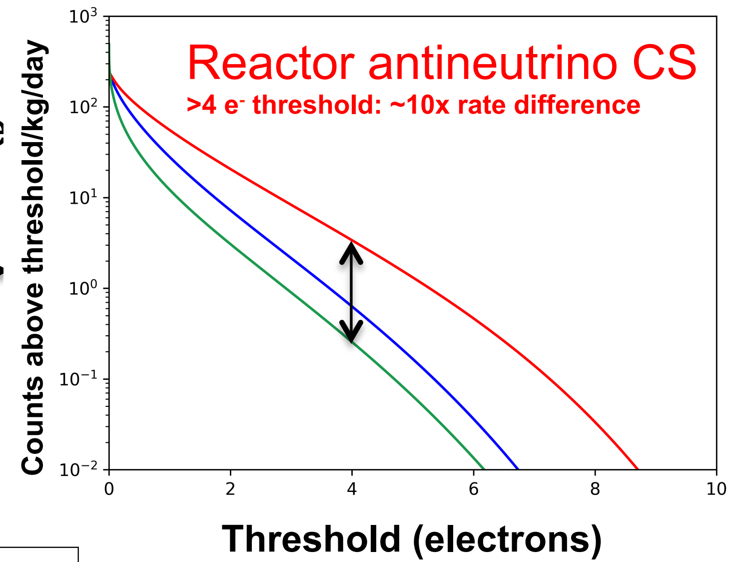


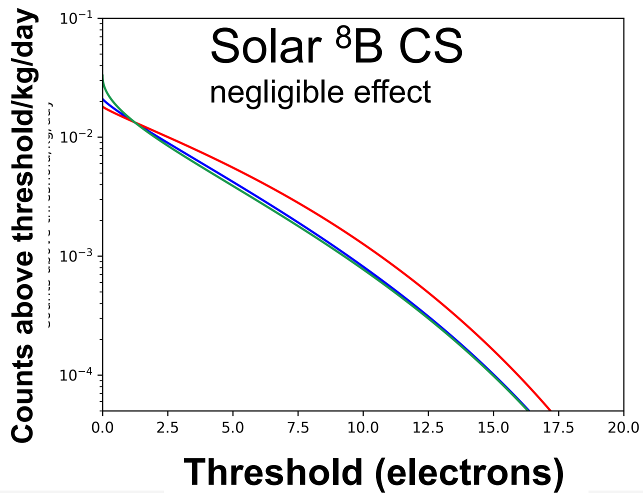
Plot courtesy B. Lenardo
UC Davis and LLNL

Physics reach depends on the ionization yield (e^-/keV) results and achievable threshold



Note similarities in these cumulative ionization distributions

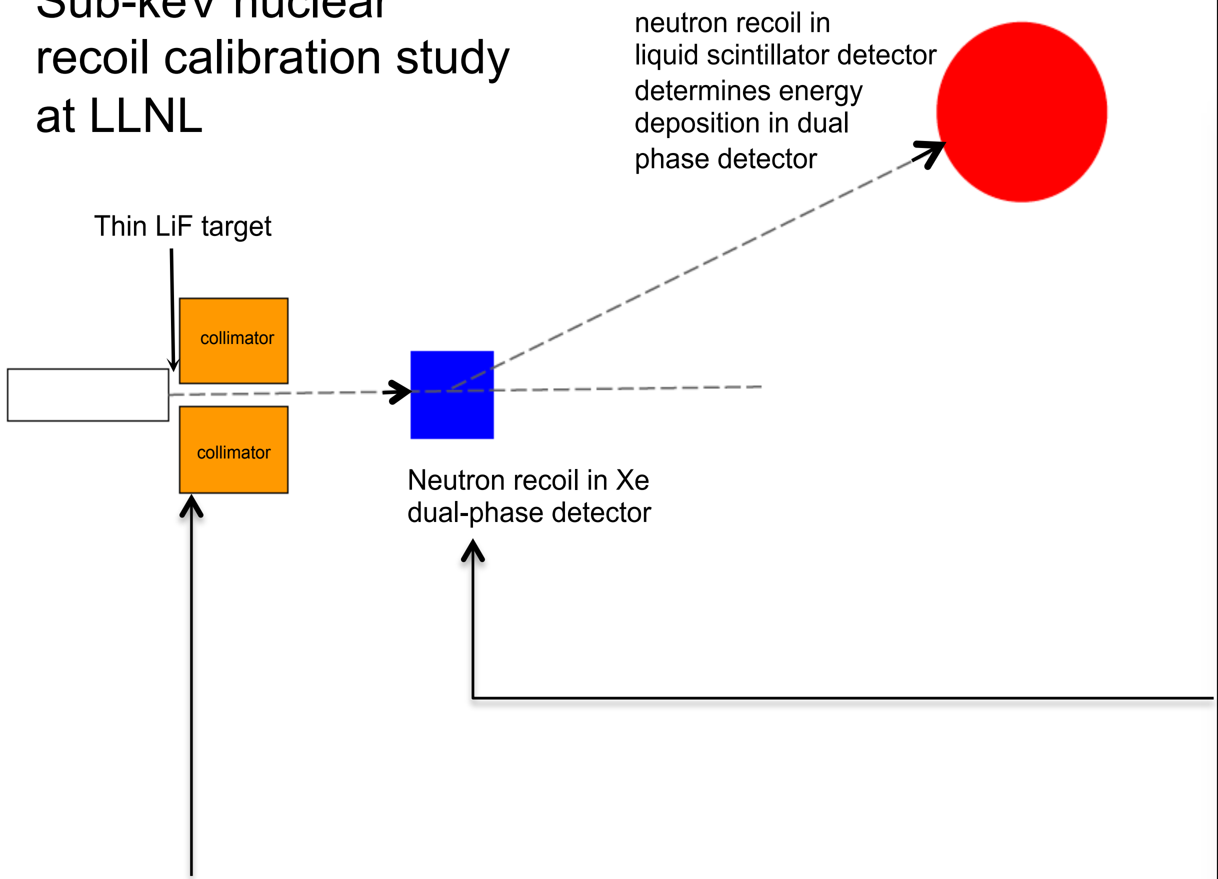




Plot courtesy B. Lenardo
UC Davis and LLNL

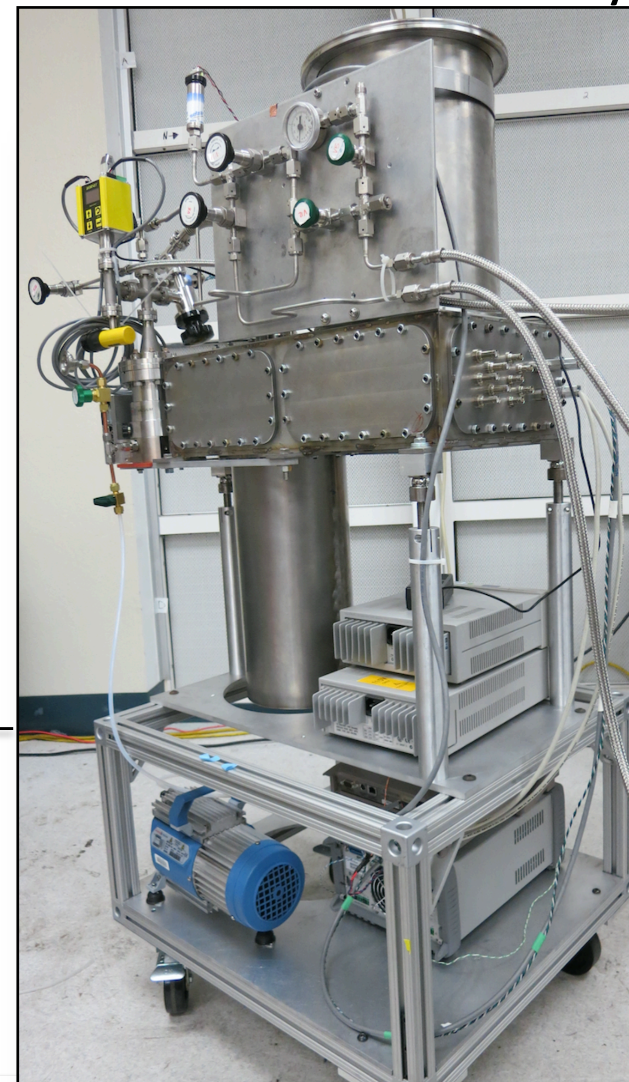
Yield measurements in the few electron regime remain essential

Sub-keV nuclear recoil calibration study at LLNL

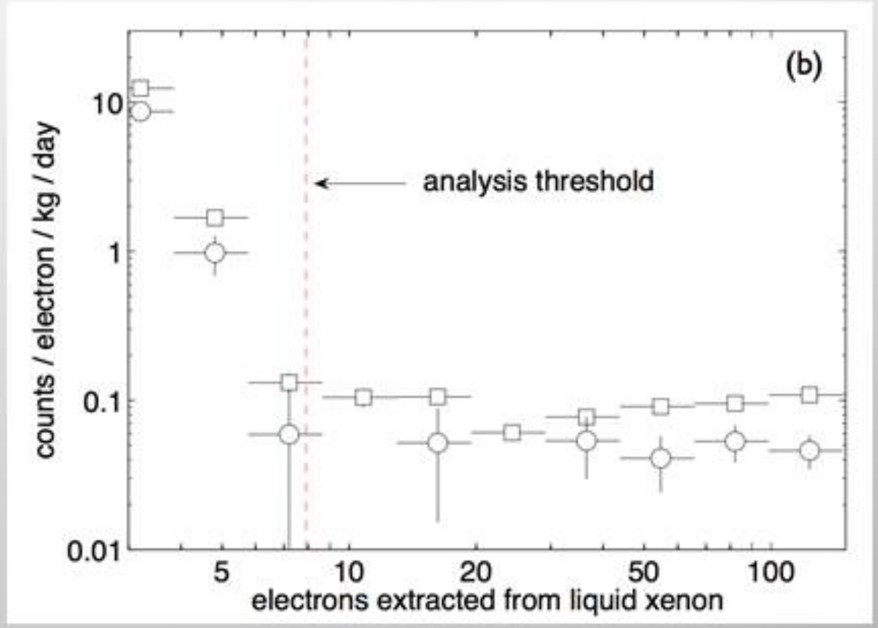


Pulsed low energy neutron beam at Duke Univ. provided by Prof. Phil Barbeau

LLNL Xe Detector Assembly



Assuming we can calibrate signal strengths, we must still confront noise..



Xenon10 S2-only analysis, arXiv:1011.6439

At thresholds ~< 1keV or ~1-10 e^- , we enter **a new domain**:

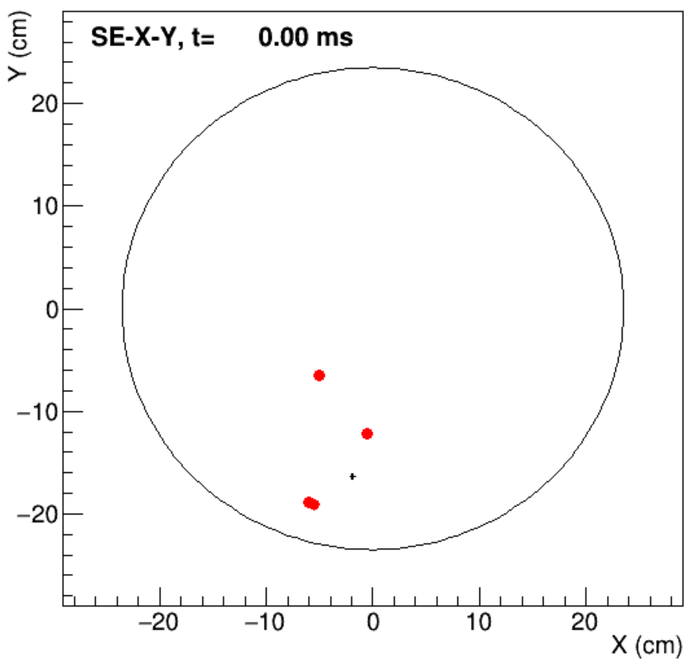
Physics-induced signals are comparable to intrinsic excitations in detector materials – the detector itself is the background, not just external radiation !

LUX shows evidence for **photoionization of bulk impurities, and release of electrons at the gas-liquid boundary**

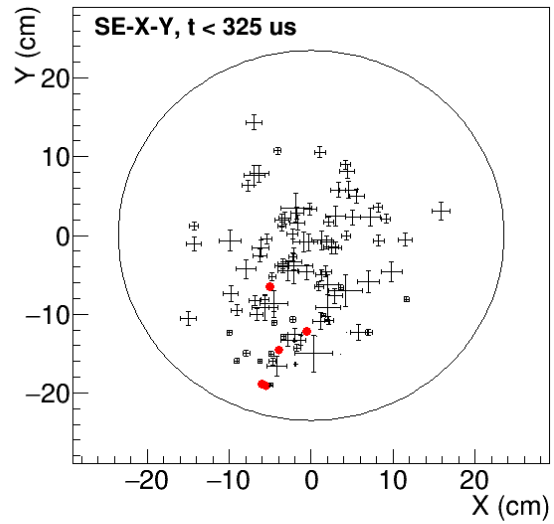
Different X-Y position patterns can be identified for different stages of electron emission:

- Prompt electron emissions from bulk photoionization
- Delayed electrons emissions from liquid surface

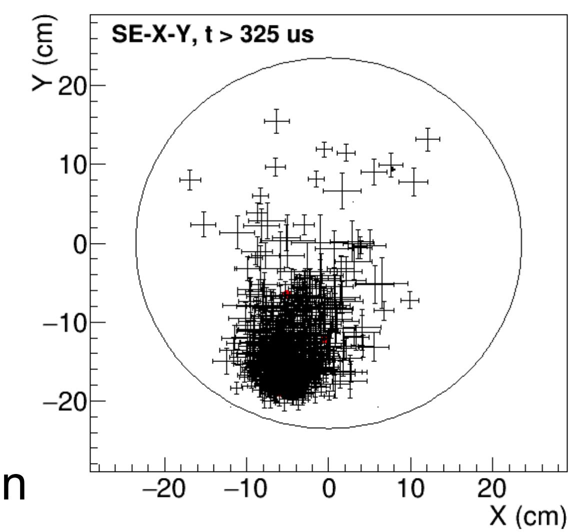
● S2 positions   ┼ single electron positions



Top-down (X-Y) view of single electron distribution



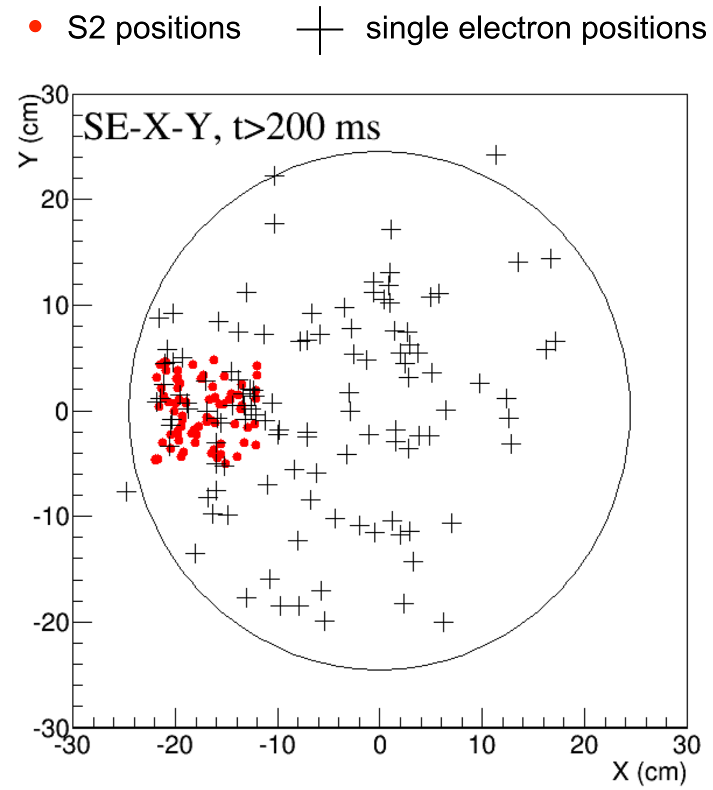
Time correlated prompt events (bulk)



Position correlated delayed events (surface)

Plots courtesy J. Xu
And the LUX collaboration

Some emissions are neither time nor space correlated with prior energy depositions



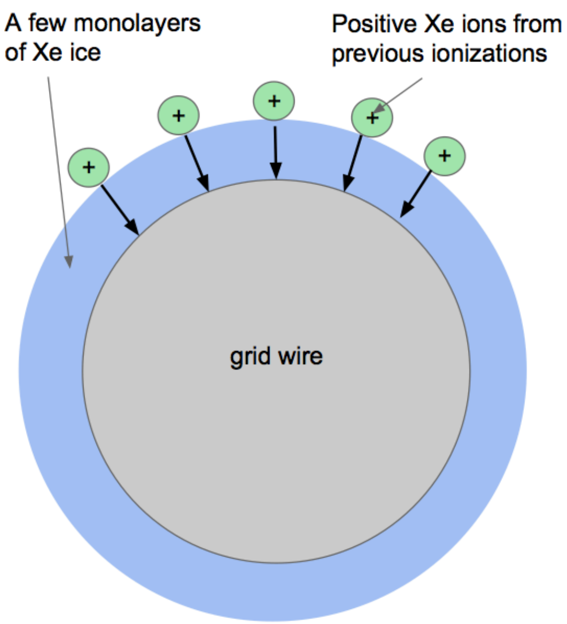
The distribution of few-electron events 200 ms after small, isolated energy depositions is **not** highly space or time correlated with a prior event..

Not seen to come from grid defects or “hot spots”…

Where are these events coming from ?

The Malter effect in noble liquids (?)

- The Malter effect is enhanced e- emission in the presence of dielectric layers on metals, due to accumulation of positive charge on the dielectric surface
- Layers of **solid xenon** are observed to form on metals immersed in liquid xenon (and He, Ne, Ar)
- **Photo-induced electron emission (PIEE)** is observed in rare element solids



Positive ion accumulation at the liquid xenon-metal boundary may result in <u>correlated emissions</u> of a few electrons

Mitigation strategies for few-electron noise can be explored readily in available small detectors

- ? Increase extraction field – may reduce trapped electrons at the liquid gas interface

- ? Apply AC field at the cathode to de-trap positive ions (local, does not disrupt drifting electrons)

- ? Apply an infrared pulse to liberate trapped electrons

We will explore these noise suppression techniques in the coming year as part of the $U_{A'}(1)$ effort

Summary

- **Sub-kev thresholds** permit exploration of new dark sector phase space with relatively small detectors
- **The $U_{A'}(1)$ collaboration** is well positioned to explore this new phase space with a 10 kg xenon detector
- **Low energy calibrations and noise studies** will help us explore the light mass particle regime – and possibly extend the reach of LZ beyond its baseline sensitivity
- **Reactors** provide high statistics sample of (anti)neutrino scatters that closely mimic low-mass WIMPs

In LUX, **photo-ionization in the bulk liquid** can be time-correlated with a prior scintillation or ionization event

- Xe scintillation light can ionize impurities in the bulk liquid
- Produced by both scintillation (S1) and ionization (S2) light
- Time delay up to full drift time in the detector