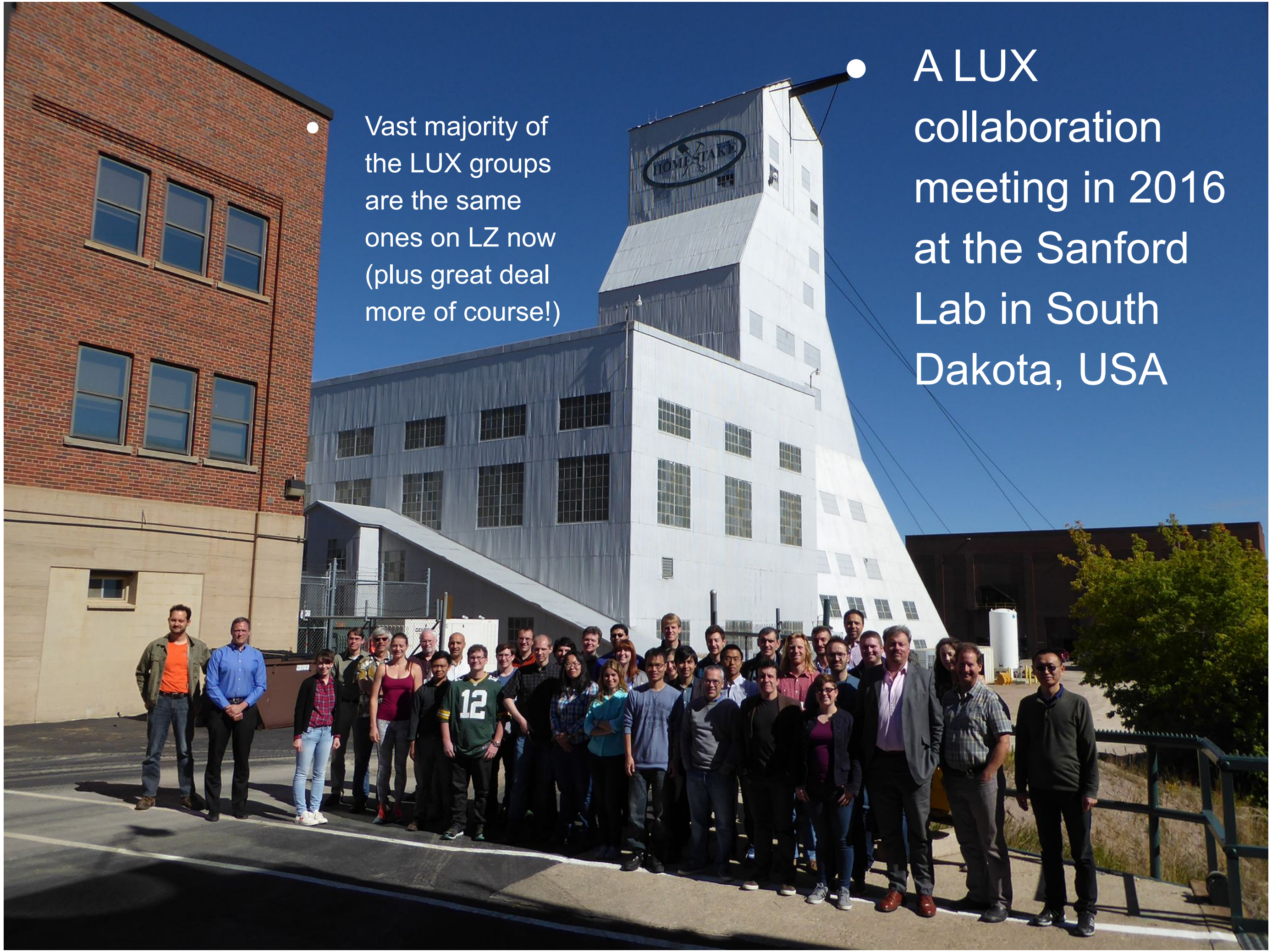
Reduction in Light Collection Efficiency over Time in LUX's Second Science Run

Matthew Szydagis, UAlbany \ LUX LIDINE 2022



- Vast majority of the LUX groups are the same ones on LZ now (plus great deal more of course!)
- A LUX collaboration meeting in 2016 at the Sanford Lab in South Dakota, USA

- Never thought I'd be giving another LUX talk but here I am
  - Got emotional writing this talk
  - Got launched into Xe on LUX
- Maybe LUX will have some kind of revival? ;-P
  - Like CDF and the W mass (LZ is analogous to ATLAS/CMS)
  - Came out of blue, left field

Large Underground Xenon

- Two-phase Xe detector (TPC) deployed (decommissioned in 2018) underground at Homestake w/ 122 photomultiplier tubes
- Funded primarily by DOE, but also NSF
- Why Xe? Dense, low work function for scintillation and ionization. Few-keV-scale energy thresholds. Exquisitely purifiable.
- Underground to avoid cosmic rays of course
- Properties and stats: fiducial mass varied from 150 to 100 kg, across 95 and 332 live-day runs (Run03 & Run04 were our two science runs)

photos by Jack Genovesi, UAlbany now SDSMT

LUX Publications

- Fast and Flexible Analysis of Direct Dark Matter Search Data with Machine Learning (arXiv:2201.05734)
- **Constraints on Effective Field Theory Couplings Using 311.2 days of LUX Data (arXiv:2102.06998)**
- Improving sensitivity to low-mass dark matter in LUX using a novel electrode background mitigation technique (arXiv:2011.09602)
- Investigation of background electron emission in the LUX detector (arXiv:2004.07791)
- Discrimination of electronic recoils from nuclear recoils in two-phase xenon time projection chambers (arXiv:2004.06304)
- **An Effective Field Theory Analysis of the First LUX Dark Matter Search (arXiv:2003.11141)**
- Search for two neutrino double electron capture of 124Xe and 126Xe in the full exposure of the LUX detector (arXiv:1912.02742)
- Improved Modeling of Beta Electronic Recoils in Liquid Xenon Using LUX Calibration Data (arXiv:1910.04211)
- **First direct detection constraint on mirror dark matter kinetic mixing using LUX 2013 data (arXiv:1908.03479)**
- **Extending light WIMP searches to single scintillation photons in LUX (arXiv:1907.06272)**
- Improved Measurements of the Beta-Decay Response of Liquid Xenon with the LUX Detector (arXiv:1903.12372)
- **Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data (arXiv:1811.11241)**
- **Search for annual and diurnal rate modulations in the LUX experiment (arXiv:1807.07113)**
- LUX Trigger Efficiency (arXiv:1802.07784)
- Liquid xenon scintillation measurements and pulse shape discrimination in the LUX dark matter detector (arXiv:1802.06162)
- Calibration, event reconstruction, data analysis and limits calculation for the LUX dark matter experiment (arXiv:1712.05696)
- Position Reconstruction in LUX (arXiv:1710.02752)
- Ultra-Low Energy Calibration of LUX Detector using 127Xe Electron Capture (arXiv:1709.00800)
- 3D Modeling of Electric Fields in the LUX Detector (arXiv:1709.00095)
- 83mKr calibration of the 2013 LUX dark matter search (arXiv:1708.02566)
- **Limits on spin-dependent WIMP-nucleon cross section obtained from the complete LUX exposure (arXiv:1705.03380)**
- First Searches for Axions and Axion-Like Particles with the LUX Experiment (arXiv:1704.02297)
- Signal yields, energy resolution, and recombination fluctuations in liquid xenon (arXiv:1610.02076)
- **Results from a search for dark matter in the complete LUX exposure (arXiv:1608.07648)**
- Low-energy (0.7-74 keV) nuclear recoil calibration of the LUX dark matter experiment using D-D neutron scattering kinematics (arXiv:1608.05381)
- Chromatographic separation of radioactive noble gases from xenon (arXiv:1605.03844)
- **Results on the Spin-Dependent Scattering of Weakly Interacting Massive Particles on Nucleons from the Run 3 Data of the LUX Experiment (arXiv:1602.03489)**
- **Improved Limits on Scattering of Weakly Interacting Massive Particles from Reanalysis of 2013 LUX data (arXiv:1512.03506)**
- Tritium calibration of the LUX dark matter experiment (arXiv:1512.03133)
- FPGA-based Trigger System for the LUX Dark Matter Experiment (arXiv:1511.03541)
- Radiogenic and Muon-Induced Backgrounds in the LUX Dark Matter Detector (arXiv:1403.1299)
- A Detailed Look at the First Results from the Large Underground Xenon (LUX) Dark Matter Experiment (arXiv:1402.3731)
- **First results from the LUX dark matter experiment at the Sanford Underground Research Facility (arXiv:1310.8214)**
- The Large Underground Xenon (LUX) Experiment (arXiv:1211.3788)
- Technical Results from the Surface Run of the LUX Dark Matter Experiment (arXiv:1210.4569)
- An Ultra-Low Background PMT for Liquid Xenon Detectors (arXiv:1205.2272)
- Radio-assay of Titanium samples for the LUX Experiment (arXiv:1112.1376)
- LUXSim: A Component-Centric Approach to Low-Background Simulations (arXiv:1111.2074)
- Data Acquisition and Readout System for the LUX Dark Matter Experiment (arXiv:1108.1836)
- *The oldest papers are so old that arXiv had 4 post-digits instead of 5 :) Also, these are all papers on which I'm one of the authors*

I'm sure I missed one or two in there (e.g., from before I joined) World-leading limits on dark matter for yrs., not just WIMPs

Unrefereed conference proceedings and joint papers with LZ not listed

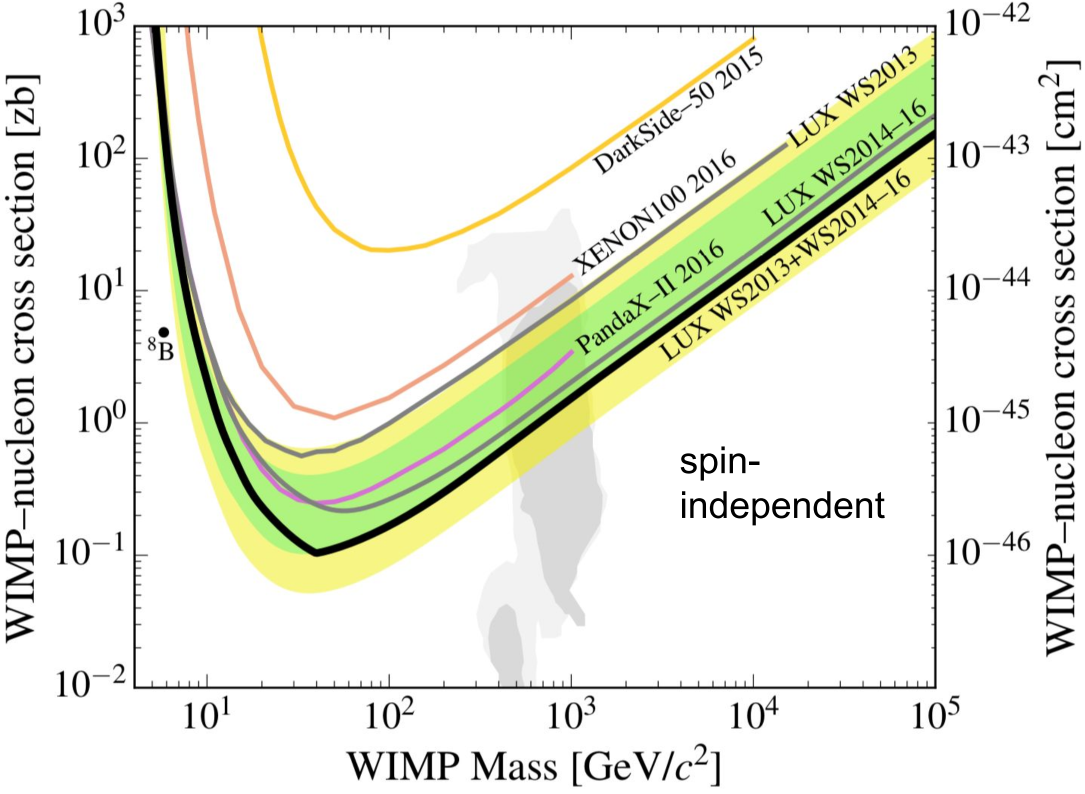
Top one is from this year!

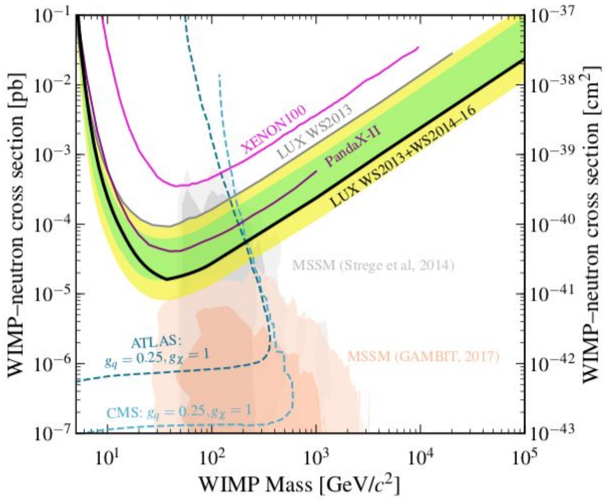
Most in Phys Rev. D or PRL. 39 papers are on this list.

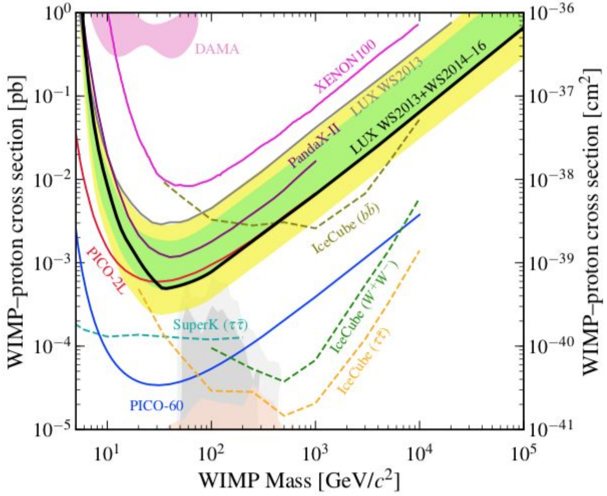
One of the most prolific direct-detection dark matter experiments, ever

In bold are the biggest scientific-impact works but LUX was also a calibration pioneer (tritium, DD, ^{14}C)

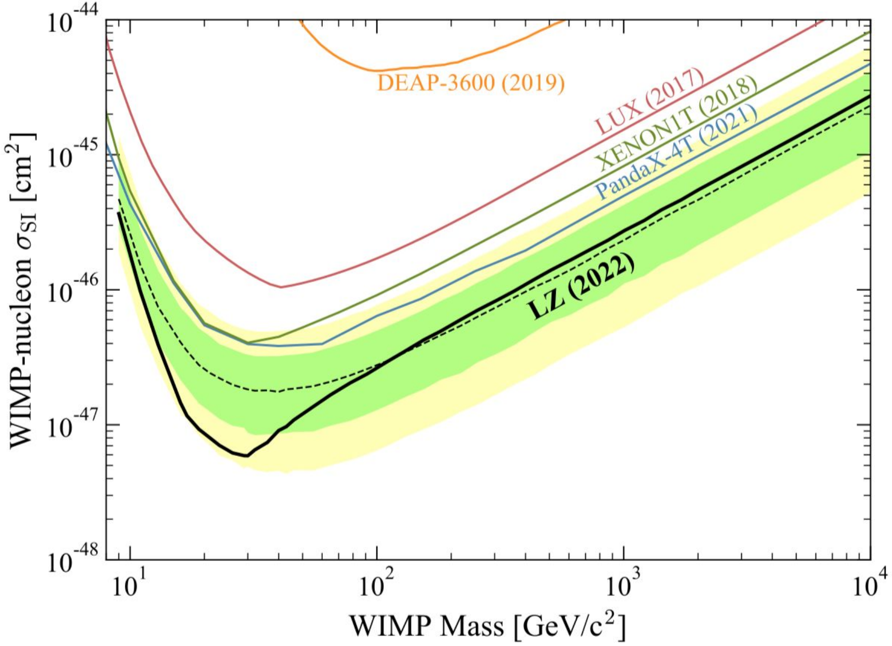
Major Final WIMP DM Results

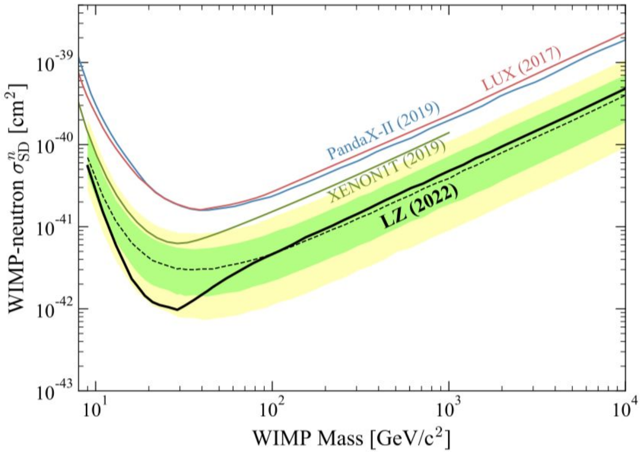


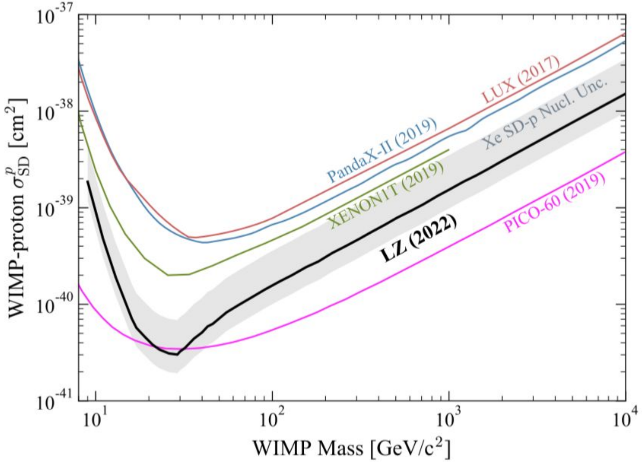




Where is Successor LZ Today? (->2207.03764)







Back to LUX: what am I talking about today?

- Between Run03 and Run04 the central value of g1, the S1 or primary scintillation photon detection efficiency dropped from 0.115 to eventually < 0.1
  - Still great, and double that of multiple detectors that came before LUX. But why the drop?
- Motivation for talk: MicroBooNE might have seen a similar effect? (E-mail chain with Janet Conrad MIT and other LIDINE committee members)
  - Does this bode ill for an experiment like DUNE running many years? (Or LZ for that matter?)
- Apparent step function drop, but there was a multi-month pause between runs (first short, second long) so perhaps it was part of a continuous process?
  - We will look at the time dependence within LUX Run04, which covered >1 yr. of real time
- But first, we revisit the definition of g1 and of its sibling g2, both critical for Xenon-based dual-phase TPCs (one number for each phase)
  - Also, how we measure them, and hypotheses for what could make them time-dependent

What are g1 and g2?

- Reconstructed energy (for electron recoils) is E = (S1c / g1 + S2c / g2) * W
  - S1c and S2c are the primary (liquid) and secondary (gas) scintillation signals, corrected for position, though sometimes the ‘c’ comes in front, or is not stated at all
  - g1 and g2 are called gains not efficiencies. g1 is < 1 but g2 > 1 (1 e- makes many photons)
  - W is the work function, in eV units, averaged over the scintillation and ionization processes
- g2 is a bit complicated
  - Product of many factors!
  - Most simply SE * E_ext
  - SE => single e- pulse area
  - Epsilon or E_ext is ext eff
  - SE is broken down into g1_gas analogous to g1 (term invented on NEST) and photons/e- (Y_e)

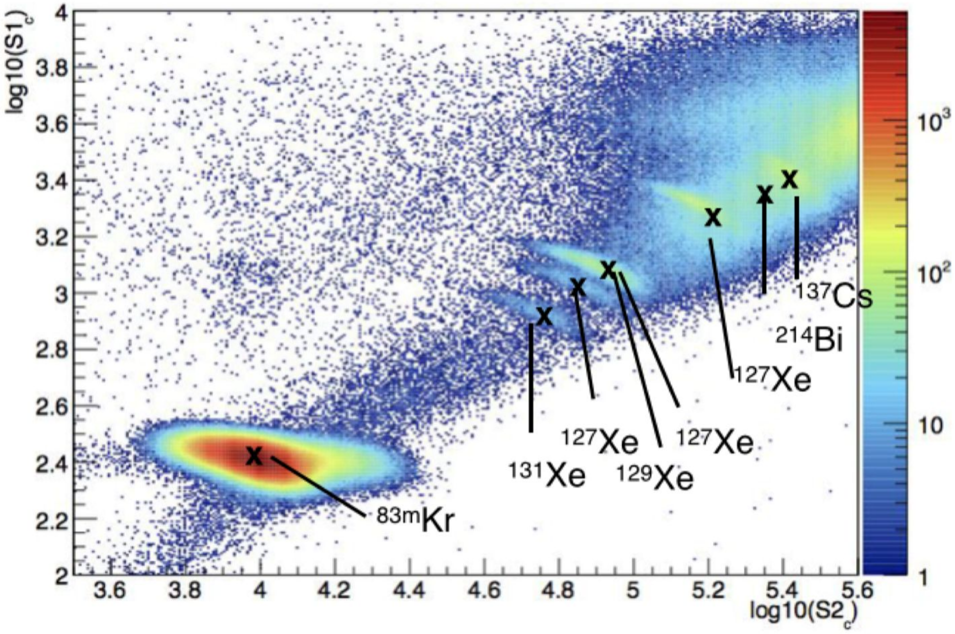
$$g_2 = SE \cdot \epsilon_{ext}(\mathcal{E}_{gas}) = g_1^{gas} \cdot Y_e(\mathcal{E}_{gas}, \Delta z_{gas}) \cdot \epsilon_{ext}(\mathcal{E}_{gas})$$

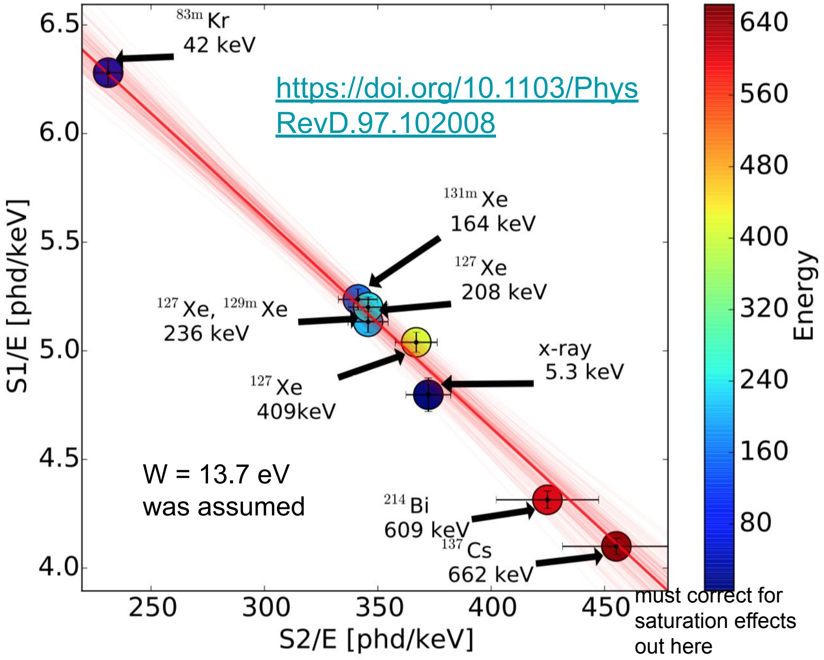
Greg Rischbieter, UAlbany/UMich

- g1 & g2 are determined by a “Doke Plot” named after the late Tadayoshi Doke
  - Alternative methods are: “mini” Doke plot (anti-correlation inside of 1 peak) i.e. EXO style
  - Comparison of S1 and S2 peaks to a (predictive) NEST simulation is another way
  - Optical (ray-tracing) sims (G4, Chroma, Opticks, Garfield for S2) independent predictive means

LUX Run03 Doke Plot

If you assume a W value, you can get g1 and g2 using the slope and intercept of a plot of the S1, S2 central values from a series of peaks

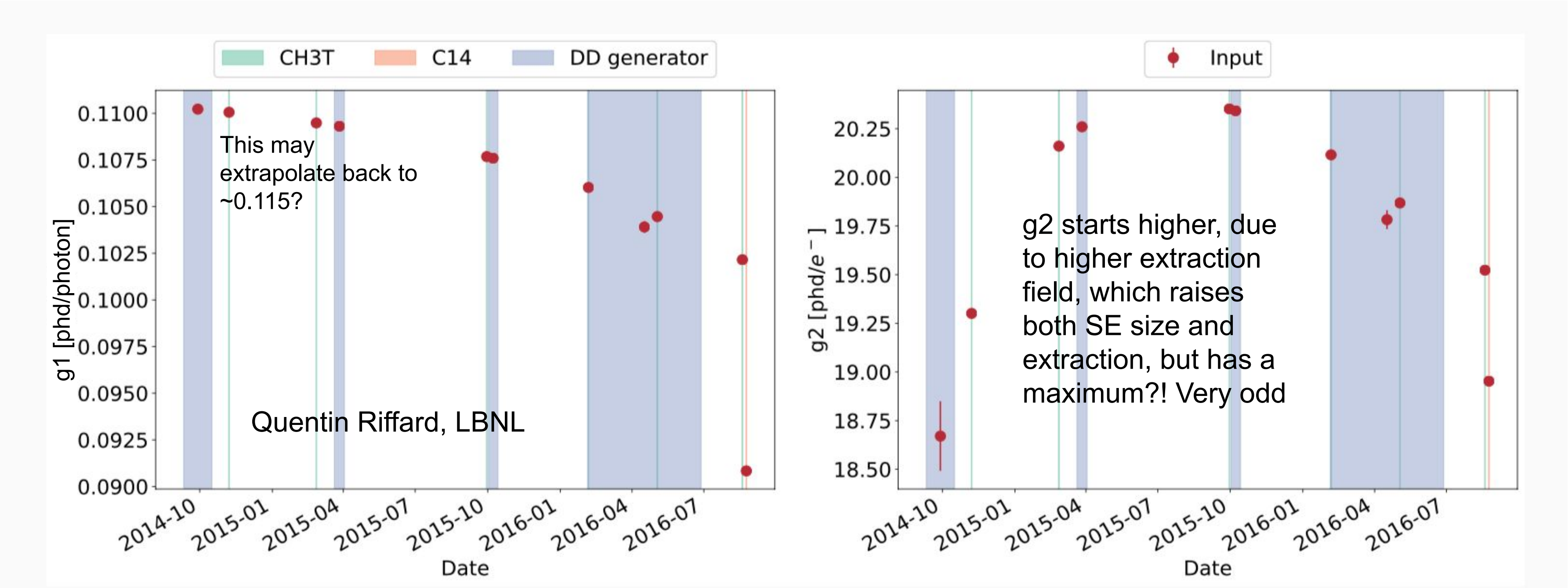




During the WIMP search: g1 = 0.115 +/- 0.005 photons detected (phd) per photon. g2 = 12.1 +/- 0.9 phd/e- (E_ext = 0.509)

LUX Run04

- We start lower in g1, and there's a slow drop that seems to accelerate, with a step function BIG drop at the time of a post-run novel Carbon-14 beta calib (higher Q than tritium)



Some potential explanations for g2 oddness: it depends on a lot of things not just light collection (g1_gas). Field changed for sure but perhaps also the gas density through temperature and pressure, and the liquid level. All of those parameters will change g2. Not simple!

(context: Run03 was April-August 2013)

Causes??

credit: Jack Genovesi

- My personal favorite originally was: the grid conditioning campaign between runs
- Attempt to raise the drift field to get better electron recoil background discrimination
  - Turns out LUX was already at good-enough field (180 V/cm), and g1 is more important for leakage, go figure
  - Turned lemon into lemonade: got non-uniform field but higher values, and studied yields and leakage, writing a key paper for future work: 10.1103/PhysRevD.102.112002 (primary writer: Vetri Velan, Berkeley, NEST member)
- Didn't go smoothly. Created sparks, which not only tripped the grids but led to ex post facto evidence: burn marks on the PTFE reflector, at the left are photos from the LUX disassembly
  - Doesn't explain continued drop during run. While the drift field was time dependent due to Teflon charge-up (10.1088/1748-0221/12/11/P11022) we didn't keep sparking

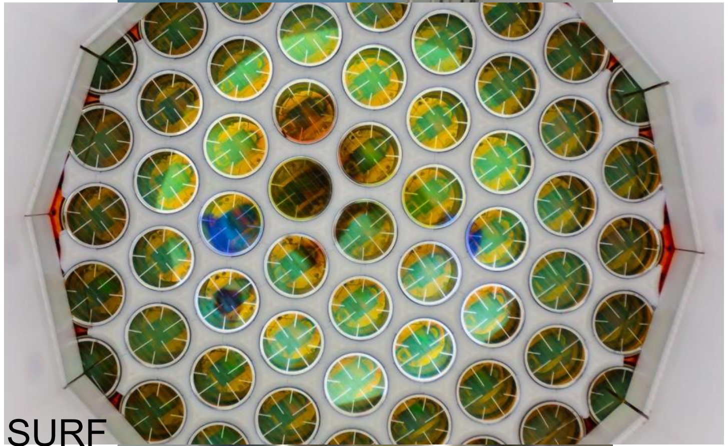
The PMTs, and if so the Gains or Quantum Efficiencies?

- Assuming that visual darkening affects VUV reflectivity not just visible-light reflectivity, the last slide might have explained a step-function drop
  - But not a continuous (and seemingly non-linear) change
- Could this be photo-sensor (the PMT photocathode) degradation with time due to exposure to lots of light?
  - We did not suddenly have a larger background rate in Run04: still same low-BG detector in the same low-BG detector underground
  - Sparking caused light, but again that would have been a step-function drop, not smooth
- This is a known effect, based on *cumulative* exposure of PMTs to photons, and it has been well quantified by Rick Gaitskell and his group at Brown, and LUX didn’t see enough light, fast enough, for this to be a full explanation
- LUX has been unable to place any R8778 PMT in a system after its runs completed in which we could independently check QE
  - With systematic uncertainty small enough to say QE has gone down. Difficult measurement

A New Photo-Absorbing Impurity?

- The g1 versus time in LUX Run04 appeared suggestive of QE falling, due to our careful continuous gain calibrating, monitoring, testing in the DAQ
  - But there could be other causes still
- A new impurity?
  - The RGA did not show anything new, the electron lifetime remained high (nearly 1 ms) throughout Run04, meeting or exceeding Run03, and the circulation system was the same, continuing from Run03
- At the start of Run03 during initial purification when first turning on the TPC, g1 started low and increased, but asymptoted much sooner than e- lifetime
  - Can't find the plot to show you, deep in the bowels of the LUX TWiki from 2013, but I recall this, and collaborators who worked on ZEPLIN recalled the same effect occurring
- This implies photon-absorbing impurities, whatever they are, are different species and come out faster than electron-absorbing impurities
  - Or, same impurities (O_2, N_2?) but very different absorption cross sections (photons vs. e-'s)

Summary



https://doi.org/10.1016/j.nima.2012.11.020

- Unfortunately, we have more questions than answers right now, so summary slide is questions

- Was it the ultraviolet reflector (PTFE i.e. Teflon)?
- Was it the (VUV) photon sensors?
  - If so, gains or QEs, or both?
  - Limited to PMTs only? SiPMs etc. too?
- Intrinsic to the liquid’s purity level?
- On LZ, g1 and g2 go up and down at %-level but no cause for concern
  - Caveat: short run (60 live-days)
  - Counter-argument: LZ PMTs (R11410) extensively tested at Brown, and show very minor (<0.1%) degradation, consistent with single photo-electron gain drop from over-exposure to high incoming photon flux
- Bigger problem for neutrino experiments due to GeV-scale energies and comparable light yield?
  - g1 many orders of magnitude lower, so probably not